EIGHTY YEARS OF CYCLOTRONS

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Abstract

Lawrence's invention of the cyclotron in 1930 not only revolutionized nuclear physics, but proved the starting point for a whole variety of recirculating accelerators, from microtrons to FFAGs to synchrotrons, that have had an enormous impact in almost every branch of science and several areas of medicine and industry. Cyclotrons (i.e. fixed-field accelerators) themselves have proved remarkably adaptable, incorporating a variety of new ideas and technologies over the years: frequency modulation, edge focusing, AG focusing, axial and azimuthal injection, ring geometries, stripping extraction, superconducting magnets and rf... Long may they flourish!

INTRODUCTION

It was 80 years ago this month that Ernest Lawrence [1] first announced successful tests of a "magnetic resonance accelerator" - what was later to become known by its nickname "cyclotron". We can also celebrate the round-number anniversaries of a couple of cyclotron family members (counting from experimental demonstration):

- 60 years of isochronous cyclotrons (1950)
- 10 years of proton FFAGs (2000).

In the space available it's been impossible to do justice to the achievements of the whole 80 years at the same level of detail. Instead, I will concentrate on the earlier, perhaps less familiar, years, and only mention highlights from the later ones. For those seeking more detail, I recommend my sources [2-7] and also [8].

INVENTION

Lawrence had moved from Yale to Berkeley in 1928, hoping to advance from research on the photoelectric effect to nuclear physics – the exciting new field promised by Rutherford's 1919 Manchester discovery that nuclear reactions could be induced by MeV particles – and especially exciting if radioactive sources could be replaced by intense beams accelerated artificially!

In the 1920s dc voltages >200 kV were hard to produce and control. But perhaps energy could be added in a series of low-voltage steps, using pulsed or ac voltages, synchronized to the particle's arrival at the accelerating gaps: "resonance acceleration"?

The first such proposal, by Gustav Ising in Stockholm (1924), was to feed high-voltage pulses by transmission line to a series of drift tubes. But nothing was built, and publication in Swedish had little impact. His work was however noted by a Norwegian grad student in Germany, Rolf Widerøe, who in 1928 built a two-gap linac powered by a 1-MHz 25-kV oscillator, accelerating Na^+ and K^+ ions to ~50 keV [9]

At Berkeley, the 27-year-old Ernest Lawrence came across Widerøe's article in 1929. Interestingly, the paper had also reported an unsuccessful attempt to build a "beam transformer" - i.e. a betatron, where particles circulating in a magnetic field would be accelerated by raising the field – attributing his failure to inadequate "stabilization" – i.e. focusing – by the field. Perhaps this juxtaposition led Lawrence to consider combining the drift tubes with the magnetic field, using the latter to return the particles repeatedly to the same accelerating gaps - but not understanding German, he luckily missed the focusing caveat.

When Lawrence worked out the dynamics, he found an unexpectedly favourable result: for a particle with mass m, charge q, moving with velocity $\mathbf{v}$ normal to uniform magnetic induction $\mathbf{B}$, the Lorentz Force $\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$ produces a circular orbit, and

$$q\,\cancel{r}\omega B = m\,\cancel{r}\omega^2 = m\,\omega.$$

"r cancels r", as Lawrence explained excitedly to each of his students, so that the "cyclotron frequency" is independent of v and the orbits are "isochronous":

$$\omega = \frac{qB}{m}$$

The electrodes can therefore be excited at a fixed rf frequency, the particles will remain in resonance throughout acceleration, and a new bunch can be accelerated on every rf voltage peak, allowing continuous-wave (cw) operation. Also radius is directly proportional to velocity: $r = mv/qB$.

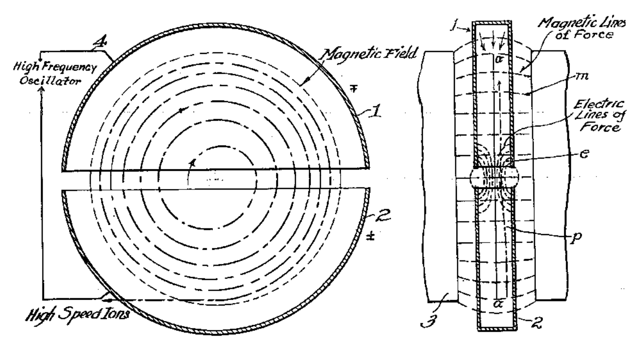

Figure 1: The cyclotron concept, from Lawrence's patent.

Early in 1930 Lawrence persuaded Nels Edlefsen, who had just completed his Ph.D., to join him in experimental work. Two rather crude models were built, one with dees formed by silvering a flattened glass flask, the other with copper "duants". They observed signals on a detector at the outer edge, though no definite resonance, but by September felt able to publish an optimistic report [1].

That month two new students arrived: Dave Sloan, who was set to work on a linac (and by December had achieved 200-keV Hg ions with 11-kV rf, and in 1931 1.26-MeV Hg with 25-kV rf), and Stanley Livingston, on the cyclotron. He also had rapid success, building a new all-brass 4-inch model (Figure 2), finding clear evidence of magnetic resonance in November, and 13-keV protons. By January 1931 Lawrence had obtained a stronger magnet and the energy was raised to 80 keV.

REVIEW OF HIGH-POWER CYCLOTRONS FOR HEAVY-ION BEAMS

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Abstract

Since the development of heavy ion cyclotrons in the 1980s for use in the field of radioactive beam physics considerable effort has been made to upgrade these cyclotrons in terms of beam intensity and beam energy. This paper presents an overview of cyclotrons that provide heavy-ion beams with powers in the range of several hundred W and above. Some technological issues related to high-power heavy-ion beams are also discussed on the basis of the experiences of those cyclotrons.

INTRODUCTION

Several cyclotrons producing a wide range of heavy-ion beams were developed in 1980s to meet the increasing demand for heavy-ion beams [1]. They were designed to accelerate ions typically in the range of Q/A=1/2-1/3 at 50-100 MeV/nucleon and very heavy ions like uranium at 10-15 MeV/nucleon. Two types of cyclotrons were developed for this purpose: superconducting AVF cyclotrons and separated-sector cyclotrons (ring cyclotrons). The advent of ECR ion sources dramatically improved the performance of these cyclotrons [2,3]. These sources replaced the PIG-type ion sources that were originally used for the production of heavy ions. The use of ECR ion sources resulted in beams with higher intensities. Furthermore, the requirements for radioactive ion (RI) beam have promoted us to obtain much higher intensities as well as higher energies.

At present, several facilities worldwide operate cyclotrons with beam powers of approximately equal or greater than 1 kW. This paper describes the general features and status of six facilities that operate such cyclotrons along with some technological issues related to high-power heavy-ion beams.

HIGH POWER CYCLOTRONS NOW OPERATING FOR HEAVY ION BEAMS

In this section, the general feature and status of six facilities worldwide that operate high-power heavy-ion cyclotrons, along with their upgrade history, are described.

Table 1 lists the key parameters of the main cyclotrons at these facilities, and Figure 1 shows the statistics of beam power for the heavy ion beams produced.

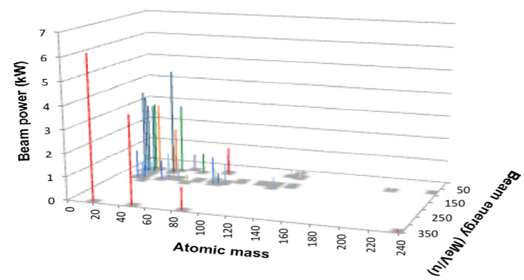

Figure 1: Statistics for the beam power of heavy ion beams obtained from high power cyclotrons so far.

GANIL

The Grand Accelerateur National d'Ion Louds (GANIL) in France is a heavy-ion accelerator facility that accommodates an accelerator complex consisting of three cyclotrons in series: a compact cyclotron (C01 or C02, K=30 MeV) and two separated-sector cyclotrons (CSS1 and CSS2, K=380 MeV) [4-7]. The first beam from the CSS2 was extracted in 1982. The number of sector magnets of the CSS2 is 4, and its maximum sector field, extraction radius and total magnet weight are 1.6 T, 3.0 m and 1,700 t, respectively. The facility delivers a wide spectrum of high intensity ion beams ranging from C to U at energies up to 95 MeV/nucleon.

The GANIL accelerator complex was originally designed taking into consideration the characteristics of PIG ion sources. However, several years later after its commissioning, it was redesigned and modified in order to meet the demands for very heavy ions with higher energies (OAE project) [8]. With these modifications, the output energies of the CSS2 for very heavy ions were increased by a factor of approximately two from 10 MeV/nucelon.

RI beams are obtained using two complementary methods: the projectile fragmentation method and the ISOL method. The RIs produced by the ISOL method are post-accelerated with a K265 compact cyclotron (CIME) at energies from 1.2 MeV/nucleon to 25 MeV/nucleon (SPIRAL1)[9,10]. The first beam from the CIME cyclotron was obtained in 1998. Upgrade in terms of beam intensity for the SPIRAL1 facility was performed [11-13].

Table 1: Key parameters of the six high power cyclotrons for heavy ion beams.

Facility	Main cyclotron	K-value (MeV)	Type	Main coil	No. of sectors	R_{ext} (m)	B_{max} (T)	Magnet weight(t)
RIBF	SRC	2,600	SS	SC	6	5.36	3.8	8,100
NSCL	K1200	1,200	AVF	SC	3	1.01	6.1	260
KVI	AGOR	600	AVF	SC	3	0.89	5.1	390
FLNR	U400M	550	AVF	RT	4	1.6	2.6	2,300
HIRFL	SSC	450	SS	RT	4	3.21	1.6	2,000
GANIL	CSS2	380	SS	RT	4	3.0	1.6	1,700

(SS: separated-sector, SC: superconducting, RT: room-temperature)

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GANIL OPERATION STATUS AND DEVELOPMENTS

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Abstract

The GANIL (Grand Accélérateur National d'Ions Lourds) produces and accelerates stable ions beams since 1982. The first radioactive beam post-accelerated with the CIME cyclotron happened in 2001. In 2013, stable beams with higher intensities and new energy range will be available from the new superconducting linear accelerator SPIRAL2. In 2014, new exotic beams will be accelerated with the existing cyclotron CIME. This paper will show how GANIL facility is preparing the arrival of SPIRAL2 accelerator. To achieve this goal two main objectives have to been set:

- Continuing the delivery of high intensity and exotic beams.
- Pursuing the developments of the machine capabilities in a project structure in order to keep equipments running with a high reliability yield and still responding to physics demands.

The progress in ion source production (both beam intensities and new species) will be presented together with the foreseen GANIL beam delivery capabilities when SPIRAL2 will be in operation.

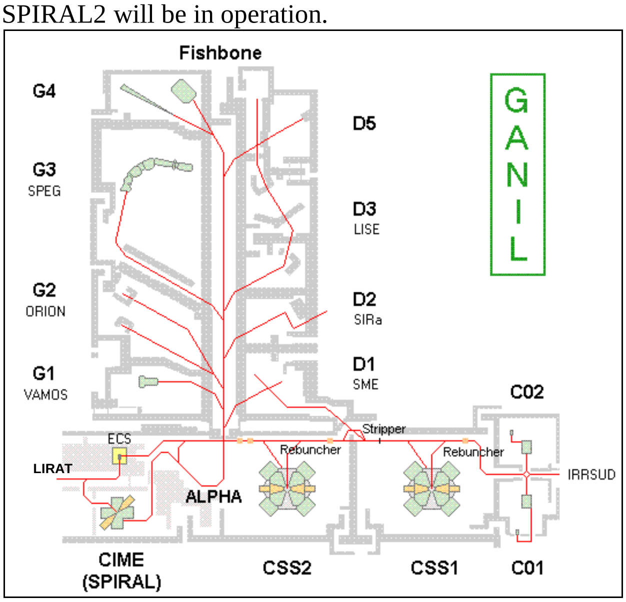

Figure 1: GANIL layout

RUNNING MODES AND BEAM REVIEW

Multi-beam delivery is routinely done at GANIL using its 5 existing cyclotrons. Up to five experiments can be run simultaneously in different rooms with stable beams:

- Beams from C01 or C02 are sent to an irradiation beam line IRRSUD (<1MeV/u).
- A charge state of the ion distribution after the ion stripping downstream CSS1 is sent to atomic physics, biology and solid states physics line D1 (4-13MeV/u).
- A high-energy beam out of CSS2 transported to experimental areas (<95MeV/u).
- An auxiliary experiments shares the previous CSS2 beam (10% of the pilote experiment time)
- Finally, stable beams from SPIRAL1 source can be sent to LIRAT (<34keV/A) or post-accelerated by CIME and given to detector tests for example.

During radioactive beam production with SPIRAL1, the combination are reduced to the four first and with radioactive beam sent to the 2 experimental areas.

Intense Primary Beams

The facility delivers a wide spectrum of high intensity ion beams ranging from ^{12}C to ^{238}U accelerated ranging from 95MeV/u for the lighter ones (12C) to 24MeV/u for Uranium beams. The acceleration scheme lies on the use of three cyclotrons in line. One compact injector cyclotron (C01 or C02, K=30) and two separated sector cyclotrons (CSS1 and CSS2, K=380). Those accelerators and beam lines have been adapted to transport intense ion beams. More than 10 beams are available at a power exceeding 1kW (Table 1) over the 50 stable beams available from the GANIL sources [1]. The beam losses detectors, beam transformers and control system allow the transport of intense stable beams with power exceeding 3kW in routine operation. The main limitations come now from the SPIRAL1 target ability to withstand beam power greater then 3kW and the GANIL safety limitations rules (beam < 2 10^{13}pps or 6kW).

Table 1: The GANIL high intensity beams

Beams	Imax [µAe]	10^{13} [pps]	Emax [MeV/u]	Pmax [W]	Used with Spiral
$^{12}C^{6+}$	19	2	95	3 600	planned
$^{13}C^{6+}$	18	2	75	2 900	X
$^{14}N^{7+}$	15	1.6	95	3 400	planned
$^{16}O^{8+}$	16	1	95	3 000	X
$^{18}O^{8+}$	2.3	0.18	75	400	
$^{20}Ne^{10+}$	15.7	1	95	2 400	X
$^{22}Ne^{10+}$	15	1	80	2 600	planned
$^{24}Mg^{12+}$	20	1	95	3 800	planned
$^{36}S^{16+}$	11	0.43	77.5	1 900	X
$^{36}Ar^{18+}$	24	0.8	95	4 600	planned
$^{48}Ca^{19+}$	4.5	0.15	60	700	X
$^{58}Ni^{26+}$	4	0.1	75	700	
$^{76}Ge^{30+}$	3.5	0.07	61	500	
$^{78}Kr^{34+}$	7	0.13	70	1 200	X
$^{124}Xe^{44+}$	2	0.03	50	300	

PROGRESS TOWARDS HIGH INTENSITY HEAVY ION BEAMS AT THE AGOR-FACILITY*

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Abstract

The AGOR-facility has an on-going upgrade program aiming at intensities beyond 10^{12} pps for heavy ion beams up to Pb. The main elements of the program are: further development of the ECR-source, improvement of the transmission into and through the cyclotron, and protection of equipment against excessive beam loss. Further improvement of the ECR ion source is facilitated by the installation of a second source. Redesign of the Low Energy Beam-line, to compensate for aberrations, is in progress; simulations predict a significant increase in transmission. A new, cooled, electrostatic extractor is being commissioned and the beam loss control system has been completed. The main remaining issue is vacuum degradation induced by beam loss caused by charge exchange on the residual gas. Tracking calculations of the distribution of the beam losses over the vacuum chamber to determine the optimum location of scrapers are underway. A gold coating was recently applied to relevant parts of the vacuum chamber aiming at reduction of beam loss induced desorption.

INTRODUCTION

The AGOR-facility delivers heavy ions beams up to Pb for experiments in the framework of the TRIμP programme on fundamental symmetries.

Experiments on violation of time reversal symmetry in β-decay are performed with beams up to ^{40}Ar at energies between 20 and 30 MeV per nucleon. The objective for the beam intensity during the final production runs of these experiments is around 10^{13} pps, corresponding to a beam power of around 1 kW. Currently the beam intensity for these experiments is limited to 4×10^{12} pps (300 W) by constraints in the experimental setup. During test experiments we have achieved an extracted beam intensity of 1.3×10^{13} pps for a $^{20}Ne^{6+}$ beam at 23.5 MeV per nucleon, corresponding to 1 kW beam power.

For experiments on permanent electric dipole moments and atomic parity violation in Ra-atoms and –ions, beams of various Pb-isotopes with an energy in the range 7 – 10 MeV per nucleon are used. In the on-going development phase of these experiments beams with an intensity up to 3×10^{11} pps (100 W) have been delivered. For the production phase of these experiments we aim at a beam intensity exceeding 10^{12} pps. In this paper we describe the on-going improvements, in several areas that directly or indirectly limit the beam intensity for these beams, which are needed to achieve this goal.

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ION SOURCES AND LEBT

Following the phasing out of the experimental programme with polarized proton en deuteron beams the polarized ion source POLIS was decommissioned. The source and the associated Lamb shift polarimeter have been transferred to PNPI, Gatchina for experiments in low energy nuclear physics. At the location of POLIS we have now installed a 14 GHz Supernanogan ECR source that we have obtained on a long term loan from HZB, Berlin. The source will be used to produce the beams of gaseous compounds, while the 14GHz AECR-source will be dedicated to the production of metal beams.

The performance of the 14 GHz AECR-source has been significantly improved during the last years by a number of modifications that are elaborated in ref. 1. We now routinely produce 50 μA of Pb^{27+} beams and more than 500 μA of $^{16}O^{6+}$ and $^{20}Ne^{6+}$.

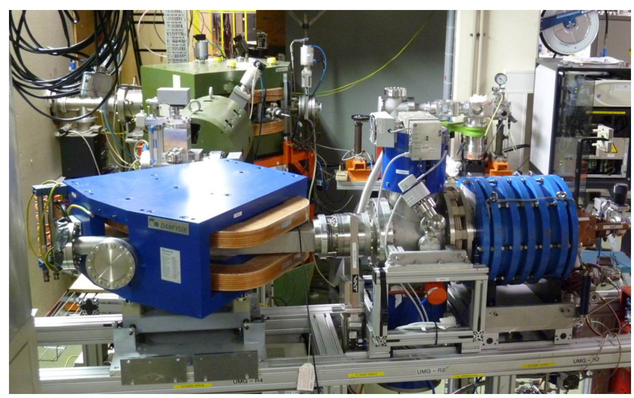

Figure 1: Supernanogan ECR source and beam line.

In the 20 m long beam transport line between the ECR ion sources and the cyclotron up to 50 % of the beam is lost. Detailed simulations and emittance measurements show that these are mainly due to the aberrations in the various magnets, which lead to an increase of the apparent emittance [2]. The beam line is currently being redesigned on the basis of these findings. The redesign of analyzing magnet of the AECR-source, similar to that developed at LBNL [3] has been completed; production of the new magnet poles is about to start.

RECENT PROGRESS ON THE FACILITY UPGRADE FOR ACCELERATED RADIOACTIVE BEAMS AT TEXAS A&M *

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Abstract

The Cyclotron Institute at Texas A&M University is involved in an upgrade, one goal of which is to provide radioactive ion beams accelerated to intermediate energies by the K500 superconducting cyclotron. The old 88” cyclotron, now the K150, has been refurbished to be used as a driver and also to provide higher intensity, low-energy, primary beams for experiments. Two external ion sources, an electron-cyclotron-resonance ion source (ECRIS) and a multi-cusp negative ion source, have been installed on a new axial line to inject beams into a modified K150 central region. Acceleration of negative ions of protons and deuterons with stripping for extraction will be used in order to mitigate activation of the K150. Beams from the K150 will be used to create radioactive species via a light-ion guide and a heavy-ion guide. Singly charged ions from either ion guide will be transported to an ECRIS that is configured to capture these ions and further ionize them. One charge-state from this second ECRIS will be selected for subsequent acceleration by the K500. Progress on the upgrade, including the acceleration and extraction of both negative and positive beams by the K150, is presented.

INTRODUCTION

Since 2005 the Texas A&M Cyclotron Institute has been extensively upgrading its facility (fig. 1). Described previously [1] this upgrade involves the axial injection of beams from both a 14.5 GHz ECRIS and a multi-cusp negative ion source for acceleration by the recommissioned K150 cyclotron. Although K150 beams will not be as energetic as beams from the K500 superconducting cyclotron, the K150 will be capable of providing much more intense beams for experiments and for the creation of radioactive ions that will then be accelerated by the K500 into an energy range unique for such beams. Two immediate goals for the refurbished K150 are 14 μA of 30 MeV protons and 0.9 pμA of 13.7 AMeV ^{40}Ar. Using intense beams from the K150, radioactive ions will be produced by stopping products from beam-target collisions in helium-filled cells in a light-ion guide, utilizing p, d and α beams, and in a heavy-ion guide. Low-charge-state radioactive ions collected from such a cell will be transported to a charge-boosting electron-cyclotron-resonance ion source (CB-ECRIS). Higher charge-state ions from the CB-ECRIS will then be injected into the K500 cyclotron for acceleration. The CB-ECRIS and its analysis line have been installed and are now being tested [2]. The analysis line will become the first leg of the low-energy-beam transport leading to the existing axial line for injection into the K500 cyclotron.

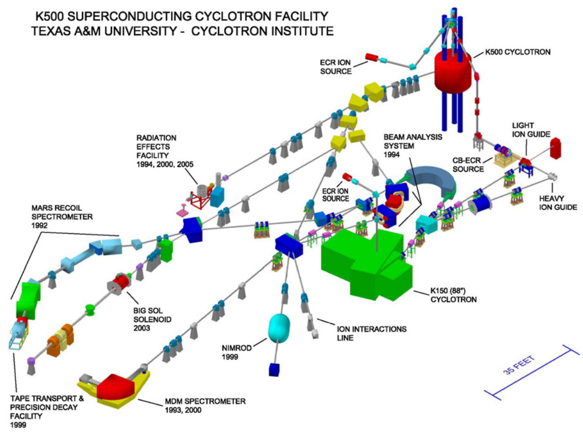

Figure 1: Overview of the Cyclotron Institute Facility.

K150 CYCLOTRON

In late 2007 a beam of protons was axially injected, accelerated to 20 MeV by the K150 and extracted at an intensity of 25 nA with an extraction efficiency of ~10%. This provided a first trial of the extensively refurbished K150, including its new rf system, new magnet power supplies, new vacuum system and new axial injection system as well as its original rf panels and dee, its original mirror inflector and deflector and its original beam probe. A substantial fall-off in intensity from the center to outer radius was observed, presumably due to poor matching in the center region. After some tests the axial injection system, including the upper central steel plug, and the dee were removed so that modifications could be made to improve the transmission. Most recently, a negative-ion, multi-cusp source along with an extraction-by-stripping system were added to the K150.

Axial Injection Line

The injection line (fig. 2) was augmented by the addition of a Glaser lens and steering coils to a new upper steel plug in order to improve beam injection. The upper and lower steel plugs shape the central magnetic field so particular care was taken in alignment with respect to the median plane. Also, extra focusing einzel lenses were added to accommodate the new multi-cusp, negative ion source which was mounted on axis directly above the 90º analysis magnet which bends the beam from the ECRIS onto cyclotron axis.

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INTENSE BEAM OPERATION OF THE NSCL/MSU CYCLOTRONS*

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Abstract

Intense heavy-ion beam acceleration by superconducting compact cyclotrons presents significant challenges since surfaces impacted by lost beam are subject to high thermal loads and consequent damage. High transmission efficiencies allow 0.7 – 1.0 kW beams to be routinely delivered for experiment at the NSCL, with minimal negative impact on reliability. Net beam transmission measured from just before the K500 to extracted beam from the K1200 is often about 30% and usually above 20% depending on the ion used (factoring out the unavoidable loss due to the charge stripping foil in the K1200). Results, techniques and examples are discussed.

INTRODUCTION

The National Superconducting Cyclotron Laboratory (NSCL) consists of two coupled cyclotrons, the K500 and K1200 [1], which accelerate ion beams produced by an ECR-type ion source (ECRIS). For the majority of running time, the machines are used as "drivers", impacting the beam onto a target at the object of the A1900 particle separator to produce fragments which are then purified and sent downstream as a rare ion beam (RIB) suitable for nuclear science experiments with exotic nuclei.

Presently, two ECRIS's are available for axial injection into the K500. Besides providing a measure of redundancy in the event of a failure of one source, being able to alternate between two sources is a significant benefit to operations overall in that the next beam can be prepared while the present experiment is running. This is particularly important when the ions come from a solid rather than gaseous material, which may require venting the source, special hardware, cleaning the plasma chamber, or long periods of conditioning. The older source, called ARTEMIS-A (Advanced Room Temperature Ion Source), is a modified version of the Berkeley AECR-U operating at a frequency of 14.5 GHz. (A duplicate, ARTEMIS-B, located on an independent test stand is used for development purposes.) A new, 3rd generation, ECRIS named SUSI (SUperconducting Source for Ions), presently operates at 14 or 18 GHz [2], [3]. Both sources run with extraction potentials ranging from 18 – 27 kV depending on the K500 injection requirements.

Beams in the range of 8 – 15 MeV/u from the K500 are injected mid-plane into the K1200 through a 200 - 800 μgm/cm^2 stripper foil (usually amorphous carbon) located at a radius of about 32 cm. Transport dynamics require the ratio of beam charge going into the foil to the charge coming out to be between 2.3 and 2.7.

In the evolution of the NSCL to a provider of RIB's almost exclusively, the emphasis has shifted from "maximum energy" to "maximum intensity". Development toward producing higher-power beams continues, but must remain consistent with an active experimental physics program which requires reliability, consistency, and the avoidance of unscheduled downtime that may result from running at high power.

PRESENT LIMITS

A list of most of the NSCL beams, together with their present estimated intensity limits and the reason for those limits, is provided in Tables 1, 2 and 3 below. These intensity restrictions fall into the general categories of power-limited, source-limited, and stripper foil-limited. Several additional NSCL-run beams are not listed because they have not yet been developed to their full potential, due either to being only recently introduced (^{82}Se, for example) or due to limited user demand. About half of the NSCL running time uses five beams (^{48}Ca, ^{40}Ar, ^{78}Kr, ^{76}Ge, and ^{86}Kr) of the 22 ion species available, so consequently, these beams are the most thoroughly developed. The values given in theses tables are generally not the peak recorded intensities, nor are they what is guaranteed to experimenters for planning purposes (those are made available on the NSCL website), but are values considered reasonably achievable and maintainable for some hours. However, days-long RIB production using beam powers greater than that presently run will require additional machine protection features than are presently available in order to limit damage in the event of beam position excursions. It will also require active feedback from non-intercepting probes to precisely monitor and maintain the high extraction efficiency obtained in the initial tune throughout the duration of the high-power run.

Table 1: Beams presently limited by ECRIS output.

Ion	Mev/u	pnA	Watts
58-Ni	160	40	370
64-Ni	140	15	134
76-Zr	120	3	37
112-Sn	120	10	120
118-Sn	120	3	38
124-Sn	120	3	44

Refractory-metal beams are an area of experimental interest, but are difficult to produce in the ion source because of the high temperatures required. Continued

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HIGH INTENSITY CYCLOTRONS FOR SUPER HEAVY ELEMENTS RESEARCH OF FLNR JINR

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Abstract

Main theme of FLNR JINR is super heavy elements research. From 2000 up to 2010 more then 40 isotopes of elements 112, 113, 114, 115, 116, 117, 118 were synthesized in the laboratory. As a target we used 243Am, 242Pu, 248Cm, 249Bk, 249Cf et al. Total flux 48Ca ion beam was on the level $5\cdot10^{20}$ ion. 48Ca matter consumption in ion source averaged 0.4 mg/hour at the beam intensity of 1 pμA .

According plan after U-400 cyclotron modernization (2012) 48Ca beam intensity will be increased up to 3pμA on the target and 48Ca. New cyclotron DC-200 planed to be put in to operation in 2014 will allow to reach 10 pμA of 48 Ca beam intensity.

INTRODUCTION

At present four isochronous cyclotrons: U-400, U-400M, U-200 and IC-100 are under operation at the JINR FLNR. Total operation time is about 71 000 hours per year. In the DRIBs project for production of accelerated exotic nuclides as 6He, 8He etc. the U-400M is used as radioactive beam generator and U-400 is as postaccelerator. Layout of FLNR accelerators complex presented at fig.1 [1].

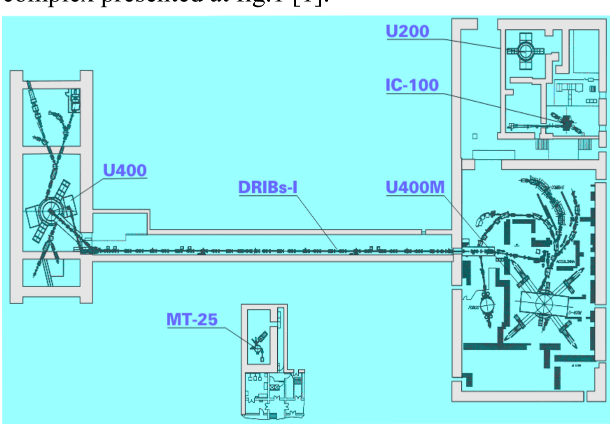

Figure 1: Layout of FLNR JINR accelerator complex

U400→U400R CYCLOTRON MODERNIZATION

The cyclotron U-400 (pole diameter 4 m) has been in operation since 1978 [2], [3]. In 1996, the ECR-4M ion source (GANIL) was installed at the U-400. The axial injection system with two bunchers (sin and linear) and spiral inflector was created to inject ions in cyclotron Fig.2. Since 1997 total operation time of the U400 amounts 71 000 hours. About 66% of the total time was used for acceleration 48Ca5+,6+ ions for synthesis of new super-heavy elements. Within the mentioned period elements with number of 113, 114, 115, 116, 117, 118 were synthesized. Chemical properties of 112 element were studied. The 48Ca beam intensity on the target was 8·1012 pps (1.2 pμA) at 0.4 mg/hour 48Ca substance consumption. Extraction efficiently of 48Ca beam by stripping foil was on the level 40% due to charge spread. The U-400 modernization in to U-400R is planned to start in 2011 and finishing in 2012. The aim of the modernization:

- increasing 48Ca, 50Ti, 54Cr, 58Fe, 64N, beam intensity on the target up to 2.5÷3 pμA;
- providing the smooth ion energy variation by factor 5 by magnetic field variation in the range of (0.8 - 1.8) T instead 1.93÷2.1 T now;
- improvement of the energy spread in the ion beam at the target up to 10^{-3};
- improvement of the ion beam emittance at the target up to 10π mm·mrad.

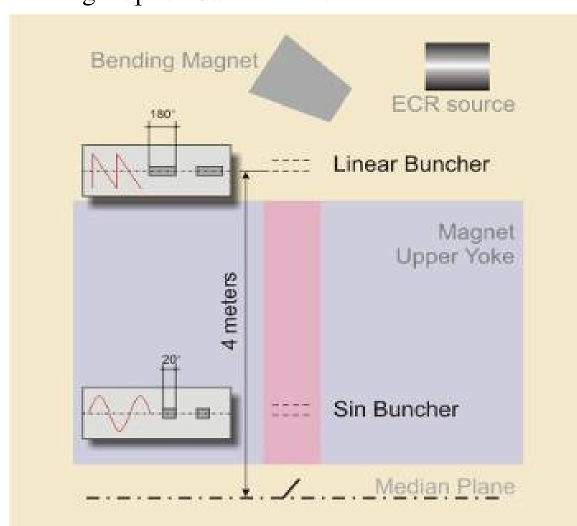

Figure 2: Scheme of the beam bunching system

The project of modernization intends changing axial injection system, magnetic structure, vacuum system, RF system, power supply system, beam diagnostic system and additionally electrostatic deflector instillation. The main comparative parameters of U-400 and U-400R are presented in Table 1.

The working diagram of the U-400R cyclotron with 48Ca beams intensities presented on Fig.3.

Scheme of the ion beam extraction from U-400R by stripping foils in two opposite directions A and B and by deflector in direction A are presented on Fig.4.

HIRFL-CSR FACILITY STATUS AND DEVELOPMENT*

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Abstract

The HIRFL-CSR facility come into operation by the end of 2007. During operation in recent years, CSR supplied beam for experiments at several terminals and inside both CSRm and CSRe rings. The experiments covers high resolution mass measurement, cancer therapy research, neutron wall, atomic physics using electron target and internal gas target, using injection beam mainly from the SFC of cyclotron injector. New methods and further developments are required to improve the performance of CSR system including multi-gradients measurement method for beam spot commissioning and beam transfer, nonlinear effect correction and stabilization of isochronous mode of CSRe. For suppling of heverier ion beam with proper ernergy, the cyclotron complex should be enhanced and new injector is proposed to replace SFC as injector of SSC.

INTRODUCTION

The layout of HIRFL-CSR project including injector system is shown in Figure 1[1,2,3]. The main parameters are listed in Table 1. For injection and acceleration of low energy beam(<10MeV/u) directly from SFC, as the span of RF cavity is insufficient, harmonic capture and acceleration (H=2 or 3) is adopt.

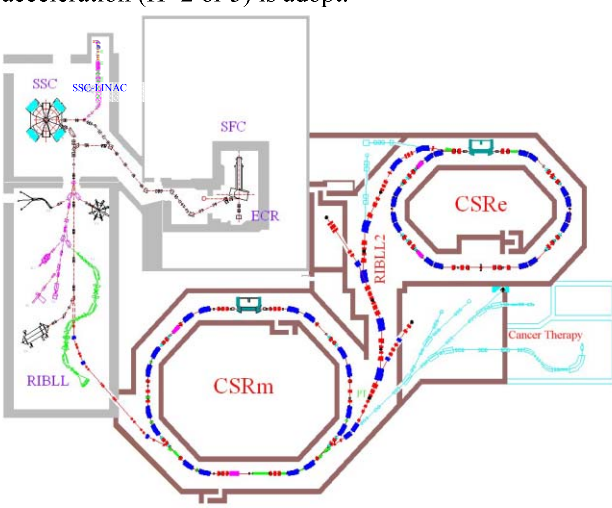

Figure 1: Layout of HIRFL-CSR.

The HIRFL-CSR facility come into operation by the end of 2007. During operation in recent years, CSR supplied beam for experiments at several terminals and inside both CSRm and CSRe rings. The operation parameters of supplied beams are listed in table 2. The operation time with HIRFL-CSR took about half of the total running time of HIRFL.

Table 1: Major Parameters of CSR

	CSRm	**CSRe**
Length	161.0m	128.8m
Ion species	Carbon~Uranium	Carbon~Uranium
Magnet rigidity	0.7~11.5Tm	0.6~9.4Tm
Acceptance		Normal mode
ε_x (π mm-mrad)	200($\Delta P/P = \pm 0.15$ %) 50($\Delta P/P = 1.25$%)	150($\Delta P/P = \pm 0.5$%) 10($\Delta P/P = \pm 1.3$%)
ε_y (π mm-mrad)	30	75
Tunes	3.63/2.62	2.53/2.58
e-Cooler	2-35kV (3-50MeV/u)	50-300kV (70-420MeV/u)
Vacuum Pressure	$<6\times10^{-11}$mbar	$<6\times10^{-11}$mbar
RF cavity	0.24~1.7MHz 7kV	0.5~2MHz 2×10kV
Injection	Multi-turn Charge exchange	Single turn
Extraction	Fast Slow(RF KO)	-

Table 2: Major parameters of CSR operation

Beam	$^{12}C^{6+}$	$^{36}Ar^{18+}$	$^{78}Kr^{28+}$	Xe^{27+}
Injector	SFC	SFC+SSC	SFC	SFC
Accumulation Scheme	Charge exchange	Multi-turn	Multi-turn	Multi-turn
Energy(MeV/u)	150~300/600	368~500	300~500	197~235
Extraction Scheme	Slow/fast extraction	Fast ext.	Fast ext.	Fast ext.
Intensity(ppp)	$2\times10^8/7\times10^9$	4×10^8	2×10^8	1×10^8
Exp. Terminal	Cancer Therapy/ Neutron Wall	CSRm/ CSRe mass spect.	CSRe mass spect.	CSRe internal target

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CURRENT STATUS AND FUTURE PROJECTS OF THE ITHEMBA LABS CYCLOTRON FACILITIES

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Abstract

The cyclotron facilities at iThemba LABS have been utilized for isotope production, nuclear physics research, proton therapy and neutron therapy for nearly 25 years. The upgrading and replacing of redundant systems is essential, in order to keep the interruptions due to equipment failure to a minimum. The computer control system will be replaced by an Experimental Physics and Industrial Control System (EPICS) and the analogue low-level RF control systems will be replaced with digital systems. The Minimafios ECR ion source is being replaced with an ECR source that was used at the former Hahn Meitner Institute. Another source, based on the design of the Grenoble test source, will be commissioned later this year. To increase the production of radioisotopes, the 66 MeV proton beam is split with an electrostatic channel to deliver two beams simultaneously. The first results with the beam splitter will be reported. A phase measuring system for the separated-sector cyclotron, comprising 21 fixed probes, has been installed. The progress of these projects and the status of the facilities will be presented. Plans for new facilities for proton therapy and radioactive beams will also be discussed.

EPICS CONTROL SYSTEM

During the past 2 years iThemba LABS has been developing an EPICS-based control system, which will eventually replace the current control system that was developed during the 1980's. The current system is based on a LAN of PCs with an in-house developed distributed database, in which portions of the database reside on PC nodes close to the equipment. This is very much the philosophy of EPICS with the EPICS process variables (PVs) implemented in Input/Output Controllers (IOCs) constituting a distributed database. Our I/O structure is defined by a series of crates and I/O cards. The various types of cards allow a range of controls, including analogue and digital signals, power supply, stepper motor and actuator control. There are approximately 25000 variables connected in this way. EPICS driver software has been developed to connect to this I/O structure.

So far EPICS has been installed on a rotating wire scanner, the beam splitter devices, slits, pneumatic actuators and vacuum system components and also constitutes 90% of the controls of the tandem Van de Graaff at iThemba LABS Gauteng.

During the transition phase when both the old and the new control systems have to run concurrently, it was necessary to develop bridging programs that allow operator screens to access both systems. So far the IOCs which are running on standard PCs with Ubuntu Linux ver. 10.04 have proved to be very stable.

RF CONTROL SYSTEM

A prototype of a digital low-level RF control system has been successfully developed at iThemba LABS. The system as illustrated in Fig. 1 utilizes a Xilinx Virtex 5 FPGA that is interfaced with high speed 16 bit 500MHz DACs from Analog Devices to synthesize the RF signals. Amplitude and phase information is extracted from the feedback signals using quadrature demodulation. A closed loop controller within the FPGA is utilized to keep the phase and amplitude at an operating point and to reject system disturbances. Amplitude and phase information as well as system parameters can be streamed to a LabVIEW client via Ethernet allowing monitoring and diagnostics of the RF signal to be performed in real time. The system has the capability to generate, under closed loop conditions, an RF signal with an intrinsic amplitude and phase accuracy of 0.006% and 0.005 degrees respectively.

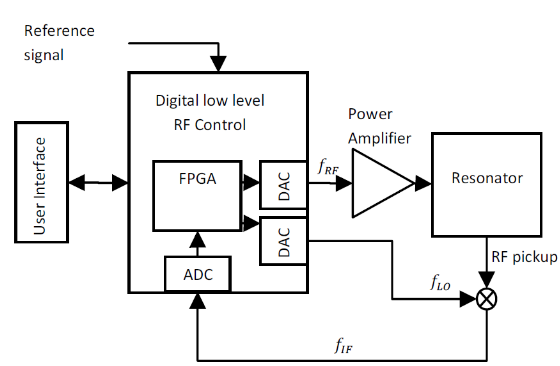

Figure 1: New prototype digital low-level RF control system

*Supported by BMBF and NRF, project-code 39.1.B0A.2.B

STATUS OF THE LBNL 88-INCH CYCLOTRON HIGH-VOLTAGE INJECTION UPGRADE PROJECT

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Abstract

The goal of the project is to design and install a new center region that allows external beam injection at voltages between 20 and 30 kV for high intensity beams. This new center region will make use of a spiral inflector to eliminate the use of a gridded mirror for high intensity beams. At the same time the mechanical design must be flexible enough to allow use of the existing center region for less intense beams. The use of two or more different center regions is necessary to cover the wide range of operation parameter space utilized by the 88-Inch Cyclotron nuclear science and applied research programs. The project also includes HV upgrades to the external injection lines and HV insulation of the AECR and VENUS sources with the goal to provide focusing for beams up to 25 kV or if feasible up to 30 kV. The current spiral inflector design is based on extensive 3D FEM simulations for which results will be presented. In addition results from ongoing efforts to improve on the transport efficiency from the AECR ion source to the current mirror inflector will be discussed.

INTRODUCTION

Beam development experiments at the LBNL 88-Inch Cyclotron using the AECR-U injector source and particularly when using the high intensity beams available from the fully superconducting 28 GHz ECR ion source VENUS have demonstrated that for high intensity beams the space charge effect reduces the injection efficiency into the 88-Inch Cyclotron. At injected currents above 100 eμA the ion beam transmission decreases due to beam losses in the center region of the cyclotron and injection line. While for many experiments conducted at the 88-Inch Cyclotron, ion beam intensity on target is not a limiting factor, luminosity is crucial for the super-heavy element research program. Therefore, this upgrade is mainly focused on increasing the beam intensity of key ion beams in the mid mass range (A=20 to A=136) for the heavy element program at energies around the Coulomb barrier, in particular for ^{48}Ca and ^{50}Ti ion beams.

The goal of the four year upgrade project is to increase the injection energy into the cyclotron to take full advantage of the high intensity beams available from the VENUS ECR ion source. In addition, the project includes an upgrade to the external cyclotron injector beam line. While this upgrade is focused on the BGS ion beam requirements in the mid mass range, a crucial requirement is to preserve the versatility and wide parameter space of beams, intensities and ion beam energies available at the 88-Inch Cyclotron.

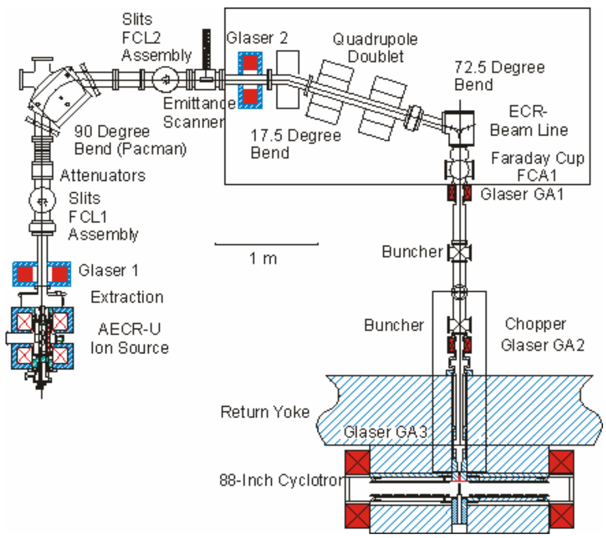

Figure 1. Schematic view of the AECR ion source, the injection beam line and the 88-Inch Cyclotron at LBNL.

DESIGN

Overview

During operation a beam is extracted from either one of the three ion sources and transported through an injection beam line system until it reaches the center region of the cyclotron; see Figure 1 for a schematic view. At the cyclotron mid plane it is necessary to redirect the beam horizontally which presently is done by the use of a mirror inflector. The great advantage of the mirror inflector is its versatility to support all the requested beams of the 88” Cyclotron. As mentioned above the goal of the project is to increase the injection voltage of the beam in order to improve on transmission efficiency at high current operation and reduce the required maintenance time of the inflector. However, due to limitations in vacuum it is not possible to operate the current mirror inflector at higher potentials required for beams injected at higher voltages. The plan is thus to temporary replace the mirror inflector during high intensity operation with a spiral inflector which can be operated at significantly lower voltages. The spiral inflector also does not utilize a grid which in the case of the mirror inflector requires frequent replacement during high current operation. Another equally important advantage of the spiral inflector is that it can be designed to better center the beam which is critical at higher injection energies. It should be emphasized though that the spiral inflector has a limited operating range so the goal is to quickly be able to switch between the two systems by utilizing the existing ion source mechanism which before the early 1990’s was regularly used in a

THE ISOCHRONOUS MAGNETIC FIELD OPTIMIZATION OF HITFIL CYCLOTRON*

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Abstract

A new project named HITFiL（Heavy Ion Therapy Facility in Lanzhou）is being constructed. In this project, a 7Mev C125+ cyclotron is selected as the initial injector providing a 10 uA carbon beam. The isochronous magnetic field optimization of the cyclotron is introduced in this paper. Optimization result shows that the deviations between calculation values and theory are smaller than 5Gs. In the design process, the sofware OPERA has been utilized for the field calculation and optimization.

INTRODUCTION

At present, the activities on the development of isochronous cyclotron for the HITFiL are carried out at IMPCAS (Fig.1). This project include cyclotron, synchrotron and four high energy beam lines, which intended for obtaining the carbon beam to treat tumors. The cyclotron magnet has the pole diameter size of 1.68m and provides the maximum magnetic fields 1.8T between sectors. Its main parameter is shown in table1 [1].

Table1: Main parameters of the cyclotron

Maximum energy, [Mev]	7
Beam species	C_{12}^{5+}
Number of sectors	4
Ion source	outer
Hill angle, [^{o}]	56
Valley angle, [^{o}]	34
Maximum average magnetic field,[T]	1.2
Harmonic number	4
Cyclotron frequency,[MHz]	7.755
Magnet aperture, [mm]	50
Injection radius, [mm]	27
Extraction radius, [mm]	750
Extraction beam current, [uA]	10

The main magnet has a round yoke, four pairs of straight-line sectors. The relation of the distance in the “valley” to the distance in the “hill” is equal d_{valley}/d_{hill} =7.2. In this paper, we introduce the main magnet with particular emphasis on the isochronous mangetic field design. It is the important criterion of the designing of the cyclotron magnetic structure.

*Work supported by HITFiL
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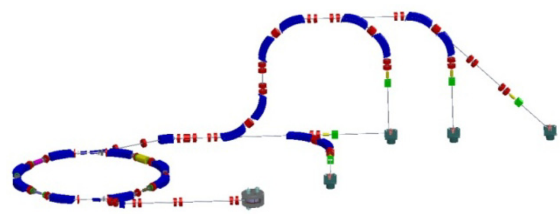

Fig.1 the layout of HITFiL

MAGNETIC FIELD DESIGN

The shape of the magnet yoke is optimized by OPERA-2D and 3D magnetic field calculation [2], Fig.2 shows the 2D cross section along the radial direction of this magnet. As the result of simulation, the straight line sectors with the flat surface are used. The sectors are placed on the magnet pole with the radial displacement with 10mm from the centre of magnet. In addition, for the axial injection of the beam, a cylinder which diameter is 200mm (is used to settle two solenoids) and a cone is designed in the center of magnet. For magnetic field calculation in the valley region, which is obtained with the help of OPERA-2D program [Fig.3]. Total current per each coil is 68734.4 ampere-turens and the current density is about 3.4A/mm2.

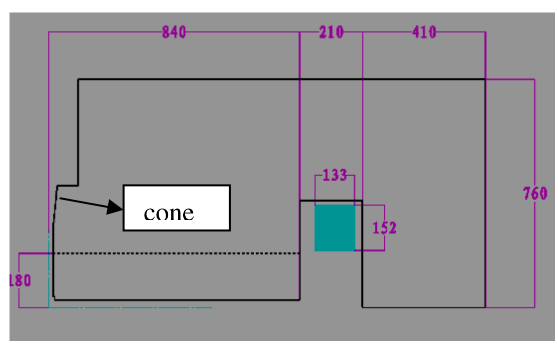

Fig.2：The cross section of cyclotron

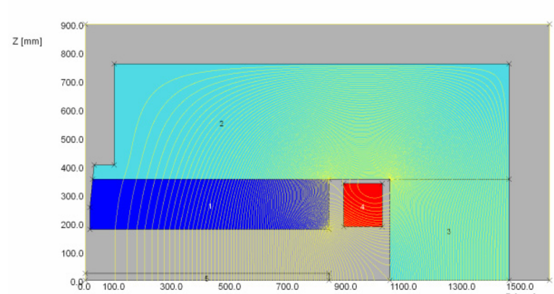

Fig.3 Opera-2D calculation (valley region)

APPLICATION OF CYCLOTRONS IN BRACHYTHERAPY

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Abstract

Cyclotrons are particle accelerator machines which have many applications in industry, technology and medicine. Cyclotrons play an important role in medicine and about 50% of the all particle accelerators running in the world are used in medicine for radiation therapy, medical radioisotopes production, and biomedical research. In this short review the use of cyclotrons for a radiation therapy method, brachytherapy, is discussed.

Brachytherapy is a form of radiotherapy where a radioactive source placed on or in the tissue to be irradiated. For a long period the production of radioactive isotopes for medical applications was essentially done in nuclear reactors but due to some advantages of radioisotopes production with cyclotron over a nuclear reactor, in the last two decades several types of cyclotrons have been developed to meet the specific demands of radionuclide production.

This talk will briefly explain the technical design, beam transfer and beam delivery systems of cyclotron for brachytherapy radioisotope production; and also will shortly describe some detail of 103Pd production in the following: production, targetry, radiochemical separation and seed fabrication.

INTRODUCTION

Brachytherapy is a special form of radiotherapy where a radioactive source is carefully placed on or inside the area to be treated. Brachytherapy sources are usually encapsulated; they can be used within the body cavities close to the tumor, placed in a lumen of organs, implanted in to the tumor or placed over the tissue to be treated. Depending on the dose rate of the sources at the dose specification point, brachytherapy treatment classified in three categories: high dose rate sources (HDR) >12 Gy/h, high energy photon emitters s like ^{137}Cs, 60Co, ^{192}Ir, ^{198}Au are used, medium dose rate (MDR) 2-12 Gy/h, is not common use; and low dose rate sources (LDR), less than 2 Gy/h with low energy photon emitters such as ^{125}I and ^{103}Pd. The use of radioactive sources for treatment of cancerous tumours started shortly after the discovery of radium (^{226}Ra) in 1898 by Madame Curie. Quantities and forms of radioactivity useful for brachytherapy were not available until 1940s, when civilian applications of nuclear reactors were encouraged, and also after for a long period the production of radioactive isotopes for medical applications was mainly based on neutron induced nuclear reactions. This was essentially done in nuclear reactors but their availability is slowly decreasing so that the accelerators based production facilities are growing up. The development of particle accelerators started in the past century and various radio-isotopes which are suitable for medical applications, produced.

In this study the accelerator production method for ^{103}Pd, is investigated. The production of 103Pd is carried out via the ^{103}Rh(p,n)^{103}Pd reaction which is well suited to low-energy cyclotrons. The irradiation of the electroplated Rh target was performed in a cyclotron (Cyclone-30, IBA) at 18 MeV energy [1-2] of proton and a beam current intensity of 200 μA at the Agricultural, Medical and Industrial Research School (AMIRS) [3].

The main problem in the 103Pd radiochemical separation stage is dissolution of target material due to extremely low chemical reactivity of rhodium metal. The other problem is the high quantity of rhodium in solution. Well known palladium extractor is dimethylglyoxime, but to prevent the decrease of extraction yield, the α-furyldioxime is used [5]. Pure obtained 103Pd is then absorbed in to resin; the active resins are encapsulated inside the titanium brachytherapy seed.

MATERIALS AND METHODS

According to Sadeghi et al. [4] manuscript, to prepare copper backing for proton bombardment, $RhCl_3$.3H2O was dissolved in water. sulfamic acid (stress reducing agent) was added to this solution followed by filtration to remove any solid particles. The resultant solution was transferred to the plating vessel, heated up to 40 °C and then a DC current was applied to the electrodes. The plating continued for 24 hours to complete Rh depletion. The copper carriers of electroplated ^{103}Rh targets were dissolved in concentrated nitric acid. A mixture of alcoholic solution which contains dimethylglyoxime (DMG) and chloroform as the organic phases were added to the Rh/^{103}Pd/HCl solution. The mixture was vigorously stirred for 10 minutes. The separated organic phase was washed with HCl. After complete degradation of organic compounds, in order to remove the residue oxidizing agent and form 103Pd chloride, the residue evaporated in hydrochloric acid, this process repeated for two times. The final product was dissolved in hydrochloric acid with desired concentration. ^{103}Pd radioactivity was measured by HPGe detector coupled with a CanberraTM multi-channel analyzer and the extraction process was repeated several times in the same conditions. Produced paladium-103 is then absorbed in (20-50 mesh) IRA-93 resin beads to encapsulate inside the titanium brachytherapy seed. Generally brachytherapy are packed inside a titanium cylinder of 4.8 mm length, 0.7 and 0.8 mm internal and external diameter respectively, in different format like resin beads or loaded on silver or copper rods. Because low energy photon emitting sources, such as ^{103}Pd, are sensitive to specifications and fabricating practices, according to American Association of Physicists

KHARKOV COMPACT CYCLOTRON CV-28: PRESENT AND FUTURE STATUS

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Abstract

Reported are the present and future statuses of the Kharkov Compact Cyclotron CV-28 donated to the National Science Center - Kharkov Institute of Physics & Technology (NSC KIPT) by the Forschungszentrum Juelich (Germany). The cyclotron configuration and special features of new installation at the NSC KIPT are described. Consideration is given to the use of the cyclotron beam as a promising means for investigation and development of materials for fusion reactors and generation-IV nuclear reactors, investigation and production of medical radionuclides, possible applications of a high-energy neutron source based on a deuteron beam and a thick beryllium target.

INTRODUCTION

A compact isochronous cyclotron CV-28, supplied by Cyclotron Corporation (USA) to the Jülich Research Center (Germany) provides the generation of light ion beams (H^+, $^2H^+$, $^3He^{++}$, He^{++}) in the continuous mode of operation with output energies adjustable in a sufficiently wide range [1].

Table 1 gives the performance characteristics of cyclotron CV-28.

Table 1: Cyclotron CV-28 performance characteristics

Particles	Beam energy range	External Current at Minimum Energy	External Current at Maximum Energy	Internal Current
H^+	2-24 MeV	70 μA	70 μA	500 μA
D^+	3-14 MeV	100 μA	100 μA	500 μA
$^3He^{++}$	5-36 MeV	15 μA	70 μA	150 μA
He^{++}	8-28 MeV	10 μA	50 μA	100 μA

It should be noted that the above-mentioned advantages of the cyclotron are supported by the fact that it can be readjusted for ion production with different energies or for acceleration of ions of other species more than once per working shift, i.e., sufficiently promptly.

The cyclotron is really operated as a multi-particle and variable-energy machine, as it is common practice with it to have several different beams a day, mostly on different targets, too. The general view of the compact cyclotron CV-28 is shown in Fig. 1.

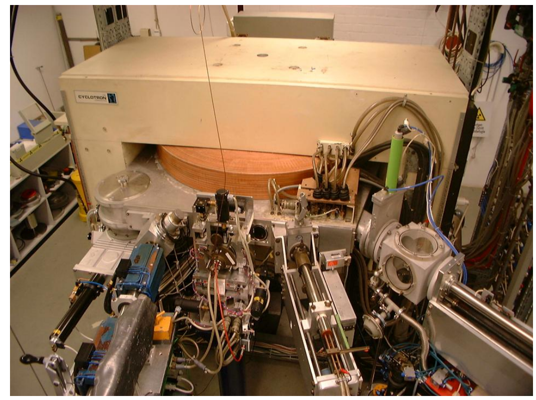

Figure 1: View of cyclotron

An accelerated beam can be guided to the target located inside the acceleration chamber, and can be extracted by means of the deflector and the magnetic channel outside the acceleration chamber.

The ion guide with ion-optical elements arranged on it directs the beam to the switching electromagnet.

PRESENT STATUS OF CV-28

In 2006, the cyclotron complex CV-28 equipment (except ventilation and water-cooling systems) was dismantled, packed and, by the end of 2006, was brought to the NSC KIPT. The layout of the cyclotron complex equipment is shown in Fig. 2

We have designed a new scheme of locating the cyclotron in a specially assigned building at the NSC KIPT. This scheme follows the German version of the equipment arrangement in many ways. The main feature consists in the ejection of the accelerated ion beam to three radiation-isolated target rooms, which accommodate five channels altogether. Two more ion beam channels are located in the cyclotron room.

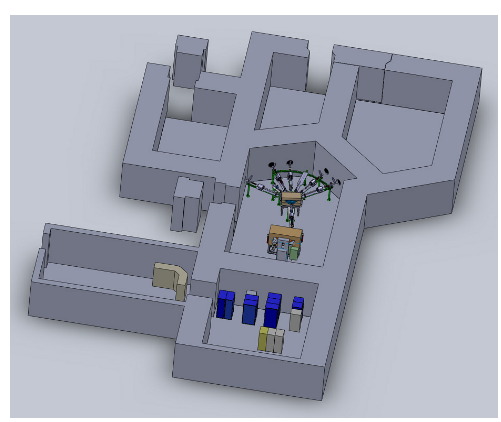

Figure 2: Layout of the cyclotron complex equipment

CONTROL SYSTEM OF CRYOGENIC PLANT FOR SUPERCONDUCTING CYCLOTRON AT VECC

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Abstract

Cryogenic Plant of Variable Energy Cyclotron Centre consists of two Helium refrigerators (250W and 415W @ 4.5K), valve box with sub-cooler and associated sub systems like pure gas storage, helium purifier and impure gas recovery etc. The system also consists of 3.1K liters of liquid Nitrogen (LN_2) storage and delivery system. The plant is designed to cater the cryogenic requirements of the Superconducting Cyclotron. The control system is fully automated and does not require any human intervention once it is started. EPICS (Experimental Physics and Industrial Control System) architecture has been adopted to design the Supervisory control and data acquisition (SCADA) module. The EPICS Input Output Controller (IOC) communicates with four Programmable Logic Controllers (PLCs) over Ethernet based control LAN to control/monitor 618 numbers of field Inputs/ Outputs(I/O). The plant is running very reliably round the clock, however, the historical data trending of important parameters during plant operation has been integrated to the system for plant maintenance and easy diagnosis. The 400 KVA UPS with 10 minutes back up time have been installed to keep the cryogenic system running with one 160KW cycle compressor during utility power interruptions.

PROCESS DESCRIPTION

Superconducting Cyclotron at VECC requires a dedicated Helium Refrigerator for operation of the Superconducting Cyclotron Magnet at a temperature of about 4.2 K. The process diagram is as shown in Figure 1.

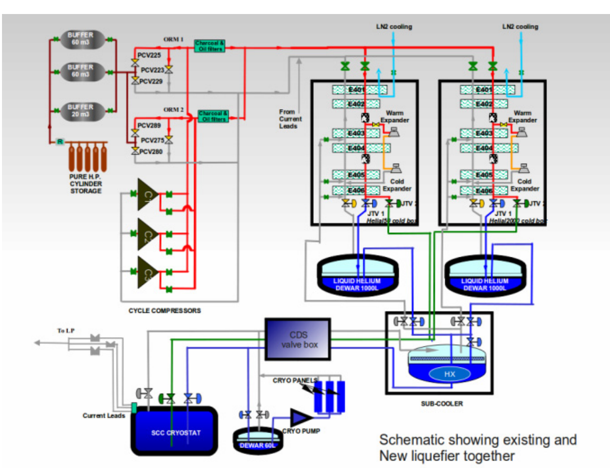

Figure 1: Process Diagram

The heat load of the liquid Helium(He) Cryostat of superconducting cyclotron system is around 160W @ 4.2K. One of the existing two helium liquefiers is connected at a time to the cryostat through a sub-cooler. Each liquefier is having Dewar of 1K litres capacity each. Liquid helium is transferred by keeping a constant pressure of 1.4 bar at Dewar and 1.2 bar at Cryostat. The liquefiers are operating in modified Claude Cycle with two turbo expanders running in series. There are six heat exchangers and two Joule-Thompson expansion valves in the system. The bigger liquefier requires 85 gm/s compressed helium gas at 14 bar pressure and the smaller one requires 50 gm/s. The system is having two Oil Removal Modules (ORM) (100gm/s and 50gm/s capacity) and three numbers of helium screw compressor of 50gm/s capacity each. The high and low pressure lines are common to both the liquefiers and the compressor selection with the ORM has been made flexible so that any compressor can be operated with any liquefier. The higher size liquefier requires two compressors running for its operation cycle. The advantage of such arrangements gives the benefit of compressor isolation for maintenance without stopping the operating liquefier. One 20 m^3 and two 60 m^3 of water capacity helium buffer gas storage tanks at a maximum working pressure of 14 bar are connected to the system.

Four liquid nitrogen storage Dewars of 2x2KL, 1x12.5KL and 1x14.5KL are also operating to receive LN_2 from the supplier tanker and the stored LN_2 is transferred to the Superconducting Cyclotron radiation shield cooling system. LN2 cooled external helium purifier of $20m^3/hr$ @ 140 bar, pneumatic air system for control valve, turbo-expander water cooling system and impure helium gas recovery system are also connected for the proper operation of the plant.

Out of the three, one compressor is powered through 400 KVA UPS. This has been done because in case of normal power failure the liquefier which is connected to the cryostat keeps operating. However, in case the bigger liquefier is in operation, the second compressor is started from the normal power or Diesel Generator (DG) power automatically after 5 minutes. This facility provides the non interruption of the cryogenics operation and also saves the restoration time and pure helium gas loss. Highly skilled manpower need not to be deputed round the clock for restoration job.

CONTROL SYSTEM OVERVIEW

Control architecture of our cryogenic system control is a three layer architecture comprising of device layer, IOC server layer and user Interface layer. The device layer consists of PLCs which controls the automatic process

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DEVELOPMENT OF POWER SUPPLIES FOR 3-Φ, 240 KW RF SYSTEM WITH CROWBAR PROTECTION FOR SUPERCONDUCTING CYCLOTRON AT VECC

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Abstract

RF system of K-500 Super-conducting Cyclotron at VECC is a complex three phase system operating in the frequency range of 9 MHz to 27 MHz with maximum acceleration potential of around 100KV feeding to each of three Dee cavities placed in median plane of cyclotron 120º apart through coupling capacitors. Each phase consists of chain of amplifiers and resonator operating in synchronization and at final stage of each phase, high power water cooled Tetrode Tube (Eimac4CW150,000 E) is used as high power amplifier each capable of delivering 80 KW of RF power. Individual power supplies for biasing Anode, Filament, Grid and Screen for all three high power Tetrode Tubes are designed and developed in house. Anode supply is common to all three tubes, rated at 20KV, 22 Amp, 450 kW along with fast acting crowbar protection using Ignitron. All these power supplies are commissioned and have been in operation for more than one year successfully. This paper describes about the technical aspects of the power supplies for RF Amplifier Tubes and special features of protection systems.

INTRODUCTION

For three RF amplifiers, which uses Tetrode Tube (Eimac 4CW 150,000E), three set of power supplies each for Filament (15.5V, 215A), Grid (-500V, 0.1 A), Screen Grid (1600V, 0.5 A) and a common power supply (20KV, 22 Amp) for Anode are designed and developed in house. Each of the power supplies are equipped with control and monitor systems with Local/Remote control facility, power switchgear with interlocking, protective systems etc as shown in Fig-6. A PLC system is interfaced with individual power supplies by which each power supplies can be controlled as well as interlocking and monitoring of parameters can be done in Remote mode of operation.

FILAMENT POWER SUPPLY

A variac controlled, voltage regulated power supply with a regulation of ± 1%. This consists of a step down 3-ph transformer with full bridge rectifier followed by a filter. A control circuit added with variac auto zero and soft start feature in the power supply adjusts the variac, corresponding to its set value. The input 415V, 50 Hz, 3-ph ac supply ramps up in steps through variac from zero to around 80% voltage corresponding to output 15.5 V dc in approximately 3 minutes. Soft start is an added feature to limit the filament current during cold condition. Heater current is approximately 210 A corresponding to 15.5 V.

GRID POWER SUPPLY

It is a series regulator type power supply that uses IGBT as series element for voltage regulation as shown in Fig-1. A low ripple and highly regulated power supply with adjustable voltage which ranges from -200 V to -500V for setting the Grid biasing of amplifier.

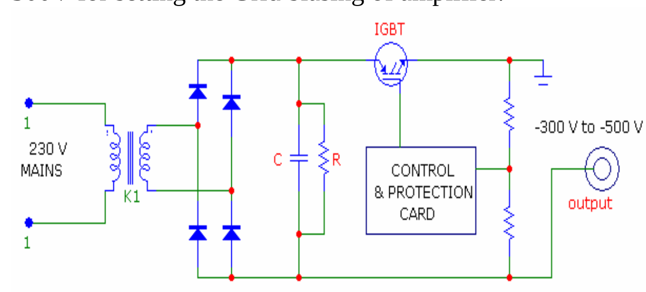

Fig-1: Schematic of Grid Power Supply

SCREEN POWER SUPPLY

Screen Grid power supply (1600V, 0.5 Amp, 60 ppm) is a series regulator type which uses water cooled tetrode tube (Eimac 4CW2000) as regulating element connected in common cathode mode. Three individual regulator tubes with their respective circuitry are used except their common anode voltage which is kept at around 2500Vdc. Part of output voltage is sampled and fed back to an error amplifier which ultimately drives the transistor for adjusting Grid biasing of series regulator tube as shown in Fig-2. A very stable power supply with very low ripple voltage is designed and developed along with fast crowbar protection feature which is initiated by either main anode crowbar as well as screen over current.

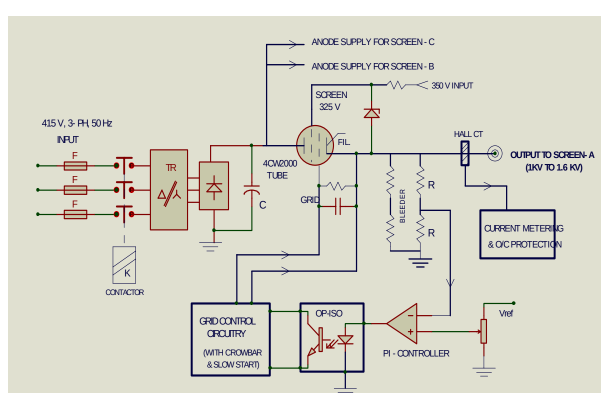

Figure 2: Schematic of Screen power supply.

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ACTIVITIES AT THE COSY/JÜLICH INJECTOR CYCLOTRON JULIC

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Abstract

The operation and development of the accelerator facility COSY is based upon the availability and performance of the isochronous cyclotron JULIC as the pre-accelerator. The cyclotron has been commissioned in 1968 and exceeded 241 000 hours of operation. In parallel to the operation of COSY the cyclotron beam is also used for irradiation and nuclide production. A brief overview of activities, performance, new and improved installations und procedures is presented.

INTRODUCTION

The institute for nuclear physics at the Forschungszentrum Jülich is dedicated to fundamental research in the field of hadron, particle, and nuclear physics. The aim is to study the properties and behaviour of hadrons in an energy range that resides between the nuclear and the high energy regime. Main activities are the development of the high energy synchrotron ring HESR, operation and improvement of the Cooler Synchrotron COSY-Jülich [1], with the injector cyclotron JULIC [2-4], as well as the design, preparation, and operation of experimental facilities at this large scale facility, and theoretical investigations accompanying the scientific research program.

The accelerator HESR, part of the GSI FAIR project [5], synchrotron is dedicated to the field of high energy antiproton physics with high quality beams over the broad momentum range from 1.5 to 15 GeV/c to explore the research areas of hadron structure and quark-gluon dynamics. An important feature of the new facility is the combination of phase space cooled beams with internal targets which opens new capabilities for high precision experiments. The tools to reach the required quality are tested at COSY. The cooler synchrotron COSY offers excellent research opportunities for hadron physics experiments and for essential preparatory studies for the machine development of HESR. A 2 MeV electron cooler is under construction, Detector tests for PANDA and polarization build-up studies for PAX are performed.

EXPERIMENTS AT COSY

The cooler synchrotron and storage ring COSY delivers unpolarized and polarized beams of protons and deuterons with momenta up to 3.7 GeV/c for three internal experiments — ANKE, PAX and WASA — and one experiment — TOF — at an external target position. All four detection systems are operated by large international collaborations [6].

At ANKE, Apparatus for Studies of Nucleon and Kaon Ejectiles, is a large acceptance forward magnetic spectrometer at an internal target station in the COSY ring. First double polarized experiments have been performed with a polarized internal target with a storage cell.

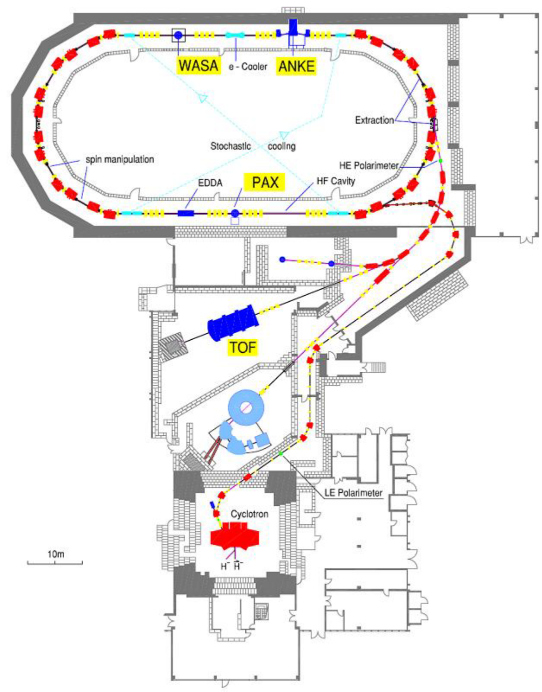

Figure 1: Layout of the COSY facility.

The 4 pi spectrometer for neutral and charged particles, WASA, Wide Angle Shower Apparatus, is operated also with the internal COSY beam. The barrier bucket cavity of COSY was successfully used to optimize the compensation of the main energy loss, which is introduced by the WASA frozen-pellet target.

An advanced grant of the European Research Council has been obtained for the polarization of anti-protons. Additionally installed quadrupoles in the mid of the straight target section provides the needed low beta values for the newly installed former HERMES polarized target as a polarized internal gas target. This is an important step to provide polarized antiprotons for FAIR.

In addition, the unique COSY capabilities are used by the SPIN@COSY-, dEDM- and PAX-collaborations to investigate spin-manipulations, to build a dedicated EDM-storage ring experiment, and to prepare experiments on polarization build-up in storage rings.

NEW METHODS AT COSY

The 2 MeV electron cooler project for COSY is funded and is expected to boost the luminosity in the presence of

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25 YEARS OF CONTINUOUS OPERATION OF THE SEATTLE CLINICAL CYCLOTRON FACILITY

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Abstract

The clinical cyclotron facility at the University of Washington Medical Center has now been in continuous operation for over 25 years. It is highly reliable, and fast neutron therapy remains its primary application, mostly for salivary gland tumors. Neutron therapy accounts for about 85% of the facility use time. In cases where the tumor involves the base of the skull, significant improvements of patient outcome have been achieved by combining the neutron treatment with a Gamma Knife® boost to areas where the neutron dose is limited by adjacent healthy tissue.

Production of 211-At and 117m-Sn with alpha particles at 29.0 and 47.3 MeV and currents between 50 and 70 μA have become routine. These isotopes are used for medical applications presently under development.

The introduction of a new control system using EPICS (Experimental Physics and Industrial Control System) is progressing systematically. All the user interfaces are up and running, and several accelerator subsystems have been migrated to the new controls. No interruption of therapy or isotope production operation is planned for the conversion to the new control system.

INTRODUCTION

The cyclotron facility at the University of Washington Medical Center in Seattle has now been in clinical operation for over 25 years. It is fully integrated in the Radiation Oncology Department, together with four linear accelerators used for standard external beam radiation therapy. Initially it was designed and built to treat tumors with fast neutrons. This remains its primary application. However, the production of certain radioisotopes for medical applications has become an important part of today's operation.

For fast neutron therapy, a 50.5 MeV proton beam is transported from the cyclotron vault into a treatment room with an isocentric gantry with 360 degree rotation capability. Neutrons are produced in a semi-thick beryllium target with copper backing. The neutrons are collimated by a 40-leaf variable collimator to achieve the desired treatment field shape. From the first day of operation in 1984, all the set-up information for patient treatments has been transferred to the neutron therapy system electronically via a network connection from the treatment planning computer, and the set-up has been verified by the control system.

Fast neutron therapy has turned out to be effective for just a few special tumor sites, primarily inoperable salivary gland tumors. Great progress has been achieved in situations where the neutron dose is limited by adjacent structures in the base of skull region by adding a precision photon boost delivered by a Gamma Knife®.

The Scanditronix MC-50 cyclotron is designed for multiple particles and variable energy. Initially, only deuteron operation was envisioned besides the protons, primarily to produce fast neutrons having a different energy spectrum. This was only used rarely. However, as demand for alpha beams emerged, the internal ion source and the central region were optimized to improve the performance for this modality. Isotope production with alpha beams has now become routine.

Over the years many components have been upgraded, in particular power supplies and other electronic parts. A major effort is in progress to replace the original Scanditronix control system based on a PDP11/23 computer and a proprietary I/O system. The new system is based on EPICS and commercially available components. Migration to the new system is being done in stages with both systems controlling part of the facility at this time.

FAST NEUTRON THERAPY

Fast neutron therapy remains a niche therapy, primarily for inoperable salivary gland tumors and sarcomas or after surgical intervention for these tumors, where gross disease is left behind. It remains the treatment of choice for these cases. Apart from the new light ion treatment beams, neutrons are the only high LET (Linear Energy Transfer) radiation available for the clinical treatment of tumors. While the local control rate and survival is excellent for certain patients with good prognostic factors, there are subgroups of patients where success is elusive. In some of these cases the cancer extends to areas where the neutron dose must be kept sub-optimal to protect adjacent anatomical structures. Because of scatter within the patient's tissues, the field edge for neutrons is intrinsically not as sharp as would be desirable. In particular for patients with salivary gland tumors involving the base of the skull, recurrences in this region were frequent. When a Gamma Knife® unit became available to the oncologists, a photon boost was added to the fast neutron treatments to supplement the radiation to the underdosed area. Several years of data are now available. The local/regional control rate for these patients

MAGNETIC FIELD CALCULATION AND MAGNET SHIMMING SIMULATION FOR CYCHU-10 CYCLOTRON

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Abstract

The compact internal ion source cyclotron CYCHU-10 developed in Huazhong University of Science and Technology (HUST) is in magnet machining, and will be assembled soon later. The accuracy of the finite element analysis (FEA) prediction of the magnetic field compared to the measurement is an important guarantee for virtual magnet shimming. In this paper, a further study on magnet field computation using FEA is implemented. Both An 1/8 and a 1/4 models are established to make a comparison. Based on the computation, researches on virtual magnet shimming are also carried out. A new shim tool using an improved matrix method combining the multiple linear regressions is employed to simulate the virtual shimming process. With the aid of 3D finite element code and beam dynamics code, an iterative shimming process has been accomplished successfully. The results verify the feasibility and effectiveness of the shimming method.

INTRODUCTION

Commercial cyclotrons are widely applied in medical field, especially for proton therapy and isotopes production in recent years [1]. A compact H- cyclotron with 10MeV extraction energy CYCHU-10 is being developed in HUST, which is designed for short-life isotopes production in PET system. The essential parameters of the cyclotron are exhibited in Table 1. Some details of the model are optimized by iterative computation, and a good isochronism of the magnetic field is observed.

Table 1: Parameters of the cyclotron

Number of pole	4
Extraction energy	10MeV
Extraction radius	27.2cm
RF frequency	100.12MHz
Dee voltage	35KV
Dee angle	40°
Average flux density	1.64Tesla

When machining of the main magnet is completed, measurement of the magnetic field using mapping system will carried out to confirm if it meets the requirement for particle accelerating [2]. According to experience, the initial machining will not reach the goal of a good isochronism, for there exists about ±0.5% difference by TOSCA software comparing to the real magnetic field, so magnet shim work should be put on the agenda [3][4]. Generally, there are mainly two ways to shim the magnetic field: (1) adjust the trim coils; (2) change the shape of the magnet pole. To CYCHU-10, only primary coil is employed to supply excitation, so method (2) will be adopted [5].

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CALCULATION OF THE MAGNET

The model of the main magnet of CYCHU-10 cyclotron has been constructed by using pre-processor of TOSCA. To reduce the amount of elements, an 1/8 model was formerly adopted, and periodic symmetric boundary condition is applied on the edge of the magnet pole. Nevertheless, the periodic symmetric boundary condition is actually an approximate dispose in this model, since the magnet yoke of the cyclotron is not strictly periodic symmetrical. What we concerned is whether it will bring unpredictable error to the calculated magnetic flux density ***B***. In fact, we could gain a more accurate field result by using a 1/4 model in theory. So a 1/4 magnet model is created for a comparison. Fig. 1 shows the 1/8 and 1/4 models of the CYCHU-10 with scalar plot of magnetic field, which are meshed by 190,000 and 450,000 quadratic hexahedra elements, respectively.

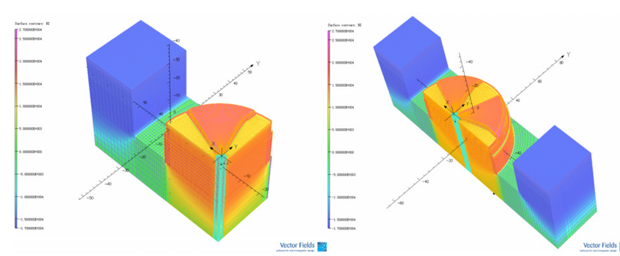

Figure 1: 1/8 and 1/4 models of the main magnet.

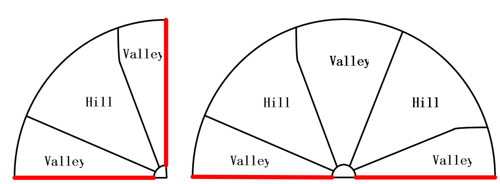

Figure 2: The periodic symmetric edge on two models

The periodic edges on the two models are shown in Fig. 2 decorated with red-thick line. Fig. 3 gives the calculated circular magnetic field difference between 1/8 and 1/4 models at various radiuses. We can obtain that the influence is smaller at the hill of the pole. And the subtraction of the two fields at different radius is about 13 Gauss on average.

Fig. 4 exhibits the isochronous ***B*** in mid plane of the

ACTIVATION OF A 250 MEV SC-CYCLOTRON FOR PROTON THERAPY

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Abstract

Beam losses in dedicated 230-250 MeV cyclotrons for proton therapy cause radioactivity in machine parts. A systematic study has been performed of the activation of PSI's 250 MeV SC-cyclotron for proton therapy. Since the start of the cyclotron operation dose rate measurements have been made as a function of time at several locations in and around the cyclotron. Gamma ray spectra have been measured of selected iron inserts in the pole and of copper disks in the liner of the RF system. The isotopic composition of the activation has been derived and compared with activations calculated with Monte Carlo calculations (MCNPX). The data and beam history of the cyclotron allow predictions of the dose rate during service activities shortly after beam interruption as well as after a specified period of operation.

INTRODUCTION

Dedicated Cyclotrons of 230-250 MeV have been used at proton therapy facilities since ~12 years [1]. Beam losses during the acceleration and extraction cause build up of radioactivity in the cyclotron, having consequences for accessibility, service and decommissioning. At the Center of Proton Therapy at PSI a dedicated 250 MeV SC-cyclotron [2,3] is in operation since 2007. Although the cyclotron is compact, the design has been optimized to achieve an extraction efficiency of 80%, which is achieved routinely at PSI.

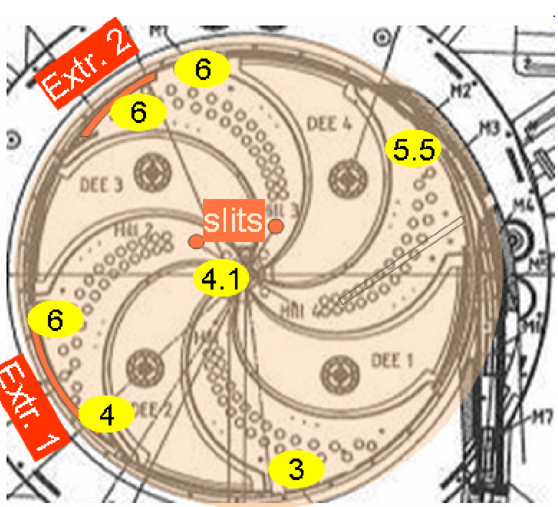

Figure 1: Dose rates (mSv/h) at different locations in the cyclotron, 10 cm from the surfaces, measured in 2010. The two phase slits and the two electrostatic extraction channels are indicated. The beam direction is clock wise.

The 20% beam loss at extraction will result in activation of the cyclotron. The other source of activation is the set of phase slits at 20 cm radius. Depending on the beam emittance from the source, 20-80% of the 11 MeV protons are intercepted by these slits. The here created neutrons and scattered protons thus also cause activation. The (tungsten) slits themselves (~6 mSv/h at 10 cm, 1 h after beam stop) can be retracted into the pole and therefore hardly contribute to the dose to the service staff. In order to estimate the activity and dose rates during future service tasks and at decommissioning of the cyclotron after many years of operation, a systematic study is going on since the first beam has been extracted.

METHODS AND MATERIALS

At every service activity that needs opening of the cyclotron, the dose rate is measured routinely with a standard dosimeter at several locations in the cyclotron, see fig.1. The measurements are performed at 10 cm distance from the surfaces and, as an indication for the dose to service staff, in between the pole caps in their open position.

At three occasions, dose rates at several locations have been measured as a function of time during 48 hours after beam switch off, using Genitron GammaTRACERs. The first time was in 2006 during the commissioning phase of the cyclotron, just after an acceptance test at which a beam with an intensity of 500 nA was extracted during 1 hour. The integral of all extracted beam until the moment of the measurement was only 2 μAh. The other two measurements have been done at service weekends, scheduled since the start of the patient treatment program. In 2010 an isotopic analysis has been made of the activation produced in iron inserts in the pole and in copper disks in the liner covering the pole. Gamma spectra from these samples have been measured in a calibrated HPGe setup at the Radiation Safety and Security Department at PSI. The spectra have been analysed automatically, yielding absolute activities of the gamma-ray emitting isotopes in each sample, at the reference moment in time: 1 hour after switching the beam off. The sample locations have been selected at different proton energies (radii).

A Monte Carlo calculation has been made with MCNPX 2.5.0 [4] to calculate the activity of created isotopes. A very simple model was used: 1 m^3 of iron or copper was hit by 10^6 protons of 50, 100 and 200 MeV or 10^6 neutrons of 6, 10, 50,100 and 200 MeV. The data generated by MCNPX have been processed with CINDER'90 [5,6] to obtain the activation at different moments in time, assuming a certain beam history.

STATUS OF THE HZB# CYCLOTRON: EYE TUMOUR THERAPY IN BERLIN

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Abstract

The mission of the ion beam laboratory (Ionenstrahllabor) ISL was the provision of fast ions for solid state physics, materials analysis and medical applications in basic as well as applied research. Eye tumours are treated since 1998 with 68 MeV protons in collaboration with the University Hospital Benjamin Franklin, now Charité - Campus Benjamin Franklin. In autumn 2004 the board of directors of the HMI decided to close down ISL at the end of 2006. In December 2006, a cooperation contract between the Charité and the HMI was signed to assure the continuity of the eye tumour therapy, at this moment being the only facility in Germany.

We have now experienced the first three years under the new boundary conditions; treating more than 600 patients in that time. The main challenge is to supply protons for the therapy with less man-power but keeping the same high reliability as before. The conversion process is not yet finished. The installation and commissioning of a new, facile injector for protons will be discussed. In addition to the routine treatment, proton therapy of ocular tumours for very young children under general anaesthesia was performed.

ACCELERATOR OPERATION

Since 2007, the cyclotron was operated for the most part for medical purpose. Hence, the scheduled beam time hours decreased tremendously (fig. 1). The new financial boundary conditions lead to a reduction of the man-power for accelerator operation to a third of the original crew. Hence, the accelerator operation was changed from a three-shift to a two-shift mode. Over night the machine idles, monitored by new control programmes.

Nevertheless, operation continued smoothly. The reliability of the machine was kept at a high level: Beam time losses due to break-downs were between 2% and 5%. Due to the small number of scheduled beam time hours, single major breakdowns have huge impacts on the beam statistics. An example is an internal water leak in the RF system of the cyclotron, leading, for the first time since 1998, to an interruption of the therapy week. In 2008, one fifth of the unscheduled down time was caused by failures in the electric power supply of the laboratory. Some of these failures lasted for almost 1 sec. Beam tests were performed for the change from the three-shift to two-shift mode in order to test the monitoring control programs. Further tests were made for the commissioning of the tandetron (see below).

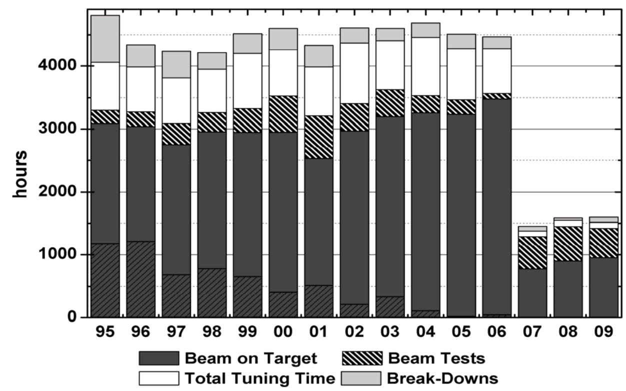

Figure 1: Operation statistics of ISL (1995-2006) and the HZB cyclotron (since 2007)

EXPERIMENTS

The increase of beam time as shown in fig. 1 in the past two years is due to an increasing patient number. In addition, a small number of experiments were carried out. These experiments comprised radiation hardness tests for the Deutsches Zentrum für Luft- und Raumfahrt as well as detector tests and dosimetry.

In addition, a new way to correlate the axis of the proton beam to the x-ray positioning system was developed: The patient positioning is performed with the aid of tantalum tumour position markers observed by two, orthogonal X-ray systems. Usually one X-ray system is mounted in the axial direction, anti parallel to the proton beam, creating an inverse beams eye view. For patient positioning it is important that the axes of the proton beam as well as the axial X-ray system are identical. With a CCD system [1] consisting of a scintillating foil, a mirror, and a CCD camera, the two dimensional dose distributions can be measured and analysed with high precision in a very fast way. The CCD system is mounted on the patient chair thus allowing the checking of position and direction of the proton beam. A 0.2 mm tantalum cross-hair is mounted in front of the CCD camera. By moving the patient chair both cross-hair and CCD camera are moved. The chair is brought into a position where the centre of the mounted cross-hair superimposes the centre of the beam-line’s cross-hair, as observed by the axial X-ray system. Thus the centre of the mounted cross-hair lies on the central axis of the axial X-ray system. In this position the dose distribution is measured by the CCD camera. The tantalum cross-hair in front of the CCD can be seen clearly in the resulting CCD image.

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# The Helmholtz-Zentrum Berlin für Materialien und Energie has been formed by the merger of the Hahn-Meitner-Institut Berlin (HMI) and the Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung

PRESENT STATUS OF THE RCNP CYCLOTRON FACILITY

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Abstract

The Research Center for Nuclear Physics (RCNP) cyclotron cascade system has been operated to provide high quality beams for various experiments in nuclear and fundamental physics and applications. In order to increase the research opportunities, the Azimuthally Varying Field (AVF) cyclotron facility was upgraded recently. A flat-topping system and an 18-GHz superconducting Electron Cyclotron Resonance (ECR) ion source were introduced to improve the beam's quality and intensity. A new beam line was installed to diagnose the characteristics of the beam to be injected into the ring cyclotron and to bypass the ring cyclotron and directly transport low energy beams from the AVF cyclotron to experimental halls. A separator is equipped to provide RI beams produced by fusion reactions at low energy and by projectile fragmentations at high energy. A muon capture beam line (MUSIC) was constructed in this spring Developments have been continued to increase secondary beams as white neutrons, ultra cold neutrons, muons and unstable nucleri.

INTRODUCTION

The Research Center for Nuclear Physics (RCNP) is a national user's facility founded in 1971 and is the major research institute for nuclear physics in Japan. RCNP, as a national laboratory, is open to all users in Japan and from abroad. The cyclotron facility is its major facility and consists of an accelerator cascade and sophisticated experimental apparatuses. Research programs cover both pure science and applications. Demands for industrial applications have been growing more and more.

A schematic layout of the RCNP cyclotron facility is shown in Fig. 1. The accelerator cascade consists of an injector Azimuthally Varying Field (AVF) cyclotron (K=140) and a ring cyclotron (K=400). It provides ultra-high-quality beams and moderately high-intensity beams for a wide range of research in nuclear physics, fundamental physics, applications, and interdisciplinary fields. The maximum energy of protons and heavy ions are 400 and 100 MeV/u, respectively. Sophisticated experimental apparatuses are equiped like a pair spectrometer, a neutron time-of-flight facility with a 100-m-long tunnel, a radioactive nuclei separator, a super-thermal ultra cold neutron (UCN) source, a white neutron source, and a RI production system for nuclear chemistry. A pion capture beam line was installed to provide muons. Such ultra-high-resolution measurements as $\Delta E/E=5x10^{-5}$ are routinely performed with the Grand-Raiden spectrometer by utilizing the dispersion matching technique. The UCN density was observed to be 19 UCN/cc at the experimental port at a beam power of 400 W. The white neutron spectrum was calibrated and the flux was estimated to be 70 % of that obtained at Los Alamos Neutron Science Center (LANSCE) in the USA. Neutrons are used for the radiation effect studies on integrated circuits and so on.

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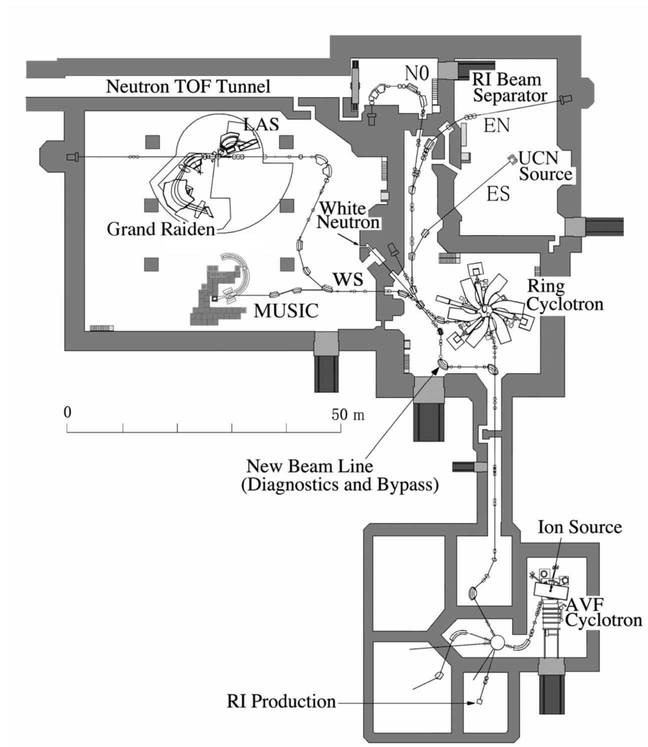

Figure 1: Layout of the RCNP cyclotron facility.

ACCELERATOR DEVEPOLMENTS

User's demands on the beam characteristics are expanding rapidly: ultra-high resolution, high intensity, a variety of heavy ions. Since there are no slits or collimators in the beam lines downstream of the ring cyclotron, the beam quality on targets is determined by the characteristics of the injected beam. The AVF upgrade program for these items is in progress [1-3]: Some of them are presented in these proceedings [4,5].

ECR Ion Source

An 18-GHz superconducting ECR ion source was installed in order to increase beam currents and to extend the variety of ions, especially for highly-charged heavy ions, which can be accelerated by RCNP cyclotrons. The production development of several ions beams and their acceleration by the AVF cyclotron has been performed since 2006.

NEW HIGH INTENSITY COMPACT NEGATIVE HYDROGEN ION CYCLOTRONS

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Abstract

Best Cyclotron Systems Inc (BCSI) has been established in Springfield, Virginia, US, for the design and production of commercial cyclotrons. The company is a subsidiary of Best Medical International renowned in the field of medical instrumentation and radiation therapy. Cyclotrons are manufactured and tested at Best Theratronics, Ottawa. BCSI is initially focusing on three different energy cyclotrons 14, 35 and 70MeV negative hydrogen ion accelerators.

CYCLOTRON CHARACTERISTICS

Various small cyclotrons had successfully been developed with compact structure for isotopes production in 1990s. CIAE has dedicated to the exploration of the cyclotron physics and key technologies with the compact structure remained and the energy range extended to 70~100 MeV since late 1990s. The cyclotrons developed by BEST began with referring to 10 MeV CYCIAE-CRM, as well as the advanced design of CYCIAE-14[1] and CYCIAE-70[2]. As preceded by CIAE, the sophisticated technologies on compact cyclotrons with high intensity and relatively high energy have taken the lead in the developing trends to some extent, as the case of BEST.

All BEST's cyclotrons have room temperature magnets, deep valley design with four radial sectors, two dees in opposite valleys, external ion source and simultaneous beam extraction on opposite lines. The BEST 14 cyclotron is designed for both internal and external ion source configuration. The cyclotrons are illustrated in Figure 1.

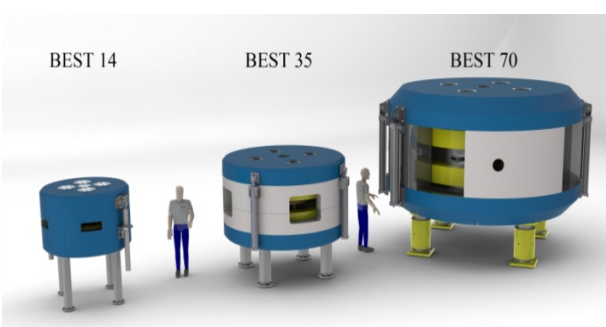

Figure 1: BCSI Cyclotrons

The main characteristics of the cyclotron magnets are shown in Table 1 with power specifications, including four beam lines each for the 35 and 70MeV cyclotrons.

Table 1: Comparative Specifications

Energy	Dimension (dia. x height)	Weight	Electric power
14MeV	1.7 m x 1.0 m	14 t	60KVA
35MeV	2.7 m x 1.5 m	55 t	280KVA
70MeV	4.5 m x 2.2 m	195 t	400KVA

BEST 14 CYCLOTRON

The BEST 14p cyclotron system is designed for negative hydrogen ion (H^-) acceleration and fixed energy 14MeV dual beam extraction using multi-foil extraction carousel. The cyclotron has the unique feature of compatibility between the uses of an internal or external ion source. The design allows for field upgrade from internal to external ion source.

Main Magnet

A strong axial focusing magnet design has been chosen to allow for future beam intensity increase with $\nu_z > 0.5$ and $> \nu_r/2$ as shown in Figure 2.

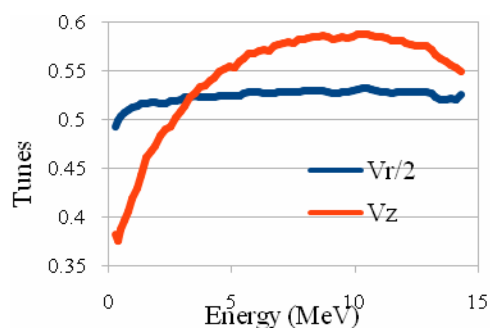

Figure 2: Tune diagram

Table 2: Magnet parameters

Number of sectors	4
Sector angle	52º
Average magnetic field	1.2T
Radius of sector magnet	50.0cm
Hill gap	2.6cm
Magnet coil	100kAT
Coil power	20kW

Ion Source

The internal ion source option is based on a PIG source as shown in Figure 3, designed to provide an extracted beam current in excess of 100µA.

EXPERIENCE OF CYCLOTRON OPERATION WITH BEAM SHARING AT TSL

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Abstract

Following a reorientation in 2005/2006, the focus of activities at TSL was shifted from nuclear physics to proton therapy and radiation testing with protons and neutrons. In order to use the beam as efficient as possible beam sharing is employed. The paper describes the development of a range of control system utilities, for example switching of the beam between users by the principal user instead of being controlled via a cyclotron operator.

INTRODUCTION

The Gustaf Werner cyclotron, completed in the early 1950s as a fixed-energy 185 MeV proton synchrocyclotron was converted during the eighties to a variable-energy multi-purpose sector-focused cyclotron and has been since then in use for a wide range of applications. An interesting feature of the accelerator is that it is operated both as an isochronous cyclotron and as a synchrocyclotron.

The principal users are now the proton therapy facility of the Academic Hospital, Uppsala, as well as accelerated testing of electronics at the neutron and proton irradiation facilities. Other applications are detector development and calibrations, as well as nuclear data measurements. Heavy ion beams are produced mainly for biomedical research [1].

THE GUSTAF WERNER CYCLOTRON

With a k-value of 192, non-relativistic ions can be accelerated up to an energy of 192 x Q^2z/A MeV, whereas the maximum energy for protons is limited to 180 MeV. In the isochronous cyclotron mode proton energies between 25 and 100 MeV can be delivered, whereas the synchrocyclotron mode is employed for proton beams with energies between 100 and 180 MeV. In this mode beam stretching is often used to provide a beam (macroscopic) duty factor of about 15%. This is achieved by reducing the *df/dt* and the accelerating voltage during extraction. More details may be found in [2, 3].

Heavy ion beams are mostly utilized for the biomedical research program where the most frequently used beams are fully stripped ^{12}C and ^{14}N with a highest achievable energy of 40 MeV/nucleon. The ECR ion source is of an older generation and was upgraded in 2002 in collaboration with JYFL [4], which resulted in a significant improvement of the performance of the source.

IRRADIATION *FACILITIES*

Proton Therapy

The average number of radiation fractions given per treatment week for 2009 was 28. This includes mainly treatments of intracranial tumors and cancer of the prostate [5]. Prostate cancer patients are treated with protons in combination with photons. Treatments of eye melanomas have been given but occur less regularly depending on the need. Experience indicates that the technical design of the switching procedure functions well.

Facilities in the Blue Hall

There are three irradiation facilities in the Blue Hall: ANITA, QMN, and the proton facility.

The ANITA facility (Atmospheric-like Neutrons from thIck TArget) provides a neutron beam with atmospheric-like spectrum (”white”, ”spallation”, cosmic-ray induced neutrons), primarily for studies and testing of electronic components and systems for neutron-induced single-event effects (SEE), which cause one of the major reliability concerns in semiconductor electronic components and systems [6], [7]. The proton beam is guided to a tungsten target, which fully stops the incident protons. The resulting neutron beam is formed geometrically by a collimator aperture. A modular design of the aperture allows the user to select the size of the neutron beam spot between 1 and 120 cm. The highest neutron flux is available at the Standard User Position (SUP), located 250 cm downstream of the production target. The energy-integrated neutron flux above 10 MeV amounts to $\approx 10^6$ $cm^{-2} \cdot s^{-1}$ for "the standard ANITA neutron field", defined as the field at the SUP for the standard incident proton beam current of 200 nA on the production target. The user can choose lower flux at any time, down to ≈200 $cm^{-2} \cdot s^{-1}$ at the SUP and further down to ≈5 $cm^{-2} \cdot s^{-1}$ at the downstream end of the beam path. At a given position, the available range of immediate flux variation amounts to a factor of at least 150, which is achieved by altering the repetition frequency of the beam macropulses. All mentioned features are fully compatible with the beam sharing mode. Further details can be found in Ref. [8], [9].

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PRESENT STATUS OF JAEA AVF CYCLOTRON FACILITY

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Abstract

In order to supply ion beam stably we have recently constructed an all-permanent-magnet type ion source. Ion beams such as H, O and Ne were produced stably. A beam attenuation system with metal meshes has been improved. By using new meshes with denser hole arrangement and lengthening the space of meshes, beam intensity can be controlled more precisely with maintaining the beam profile. The power supplies of the magnet coils used in the cyclotron were modified to stabilize the coil current with the stability $\Delta I/I$ of the order of 10^{-6}. In addition, developments of new irradiation techniques such as quick change of microbeam by cocktail beam acceleration technique and large-area uniform beam irradiation using multipole magnets are in progress.

INTRODUCTION

The JAEA AVF cyclotron with a *K* number of 110 MeV accelerates various ions, 5 to 90 MeV protons and 2.5 to 27 MeV/n heavy-ions at TIARA (Takasaki Ion accelerators for Advanced Radiation Applications) facility. TIARA is a very unique accelerator facility established for utilization of ion beams exclusively for the research in the field of biotechnology and materials science; for example, estimation of radiation hardness of space-use devices and plant breeding using ion-induced mutation. We have been developing ion sources, acceleration techniques and beam irradiation techniques for providing useful irradiation fields to researchers.

MACHINE OPERATION

Scheduled irradiation experiments were completely accomplished in fiscal year 2006 and 2008 without any serious troubles. Integration of operation time since the first beam in 1991 reached 60,000 hours on May 2010. Table 1 shows the detail of the cyclotron operation in fiscal year 2009. We usually operate the cyclotron from Monday morning to Friday evening through day and night, and the yearly operation time amounted to 3148.3 hours. The number of switching ion species, energy, or beam course amounts to 547 times, the number of changing acceleration harmonics 56 times. The number of machine troubles including minor breakdowns was 130 times. The severest trouble in 2009 was a breakdown of a high voltage power supply of the RF system. Cancellation of experiments in fiscal 2009 resulted from only this trouble.

Table 1: Statistics for cyclotron operation in fiscal 2009

Beam time	2461.8 h
Machine tuning	620.9 h
Beam development	65.6 h
Total operation time	3148.3 h
Switches of particle and/or energy	238 times
Change of beam course	309 times
Change of harmonic number	56 times
The number of experiments	633
Experiment cancelled due to machine trouble	2(8.5h)

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NEW ION SOURCE

The AVF cyclotron has three external ion sources; Multicusp ion source for H^+ and D^+, OCTPUS (ECR) for gaseous heavy ions, and Hyper nanogan (ECR) for highly- charged heavy ions including metal ions. In addition to them, a new ECR ion source has been developed to provide highly-stabilized beams [1]. Since this source is of all-permanent-magnet type, fluctuation of beam current intensity is less than that of ECR ion sources with room temperature coils, which cause considerable heat transfer to the plasma chamber and the sextupole magnets. The mirror magnetic field distribution of the new ECR ion source is adjustable by radially moving the permanent magnets in order to form the magnetic field suitable for various ion species. Highly stable ion beams such as H, O and Ne can be produced by this ion source. Figure 1 shows the stability of the $^{16}O^{6+}$ beam intensity, which is better than 3.2% for 8 hours.

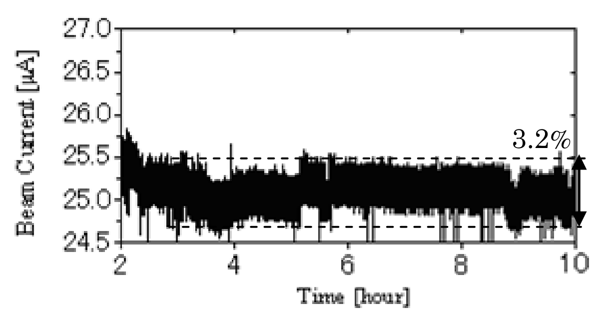

Figure 1: Stability of the $^{16}O^{6+}$ beam intensity produced by the all-permanent-magnet ECR ion source. The long-time stability of the beam is better than 3.2%.

BEAM ATTENUATOR IMPROVEMENT

A beam attenuation system using thin metal meshes, which have many regularly-arrayed holes, is installed in the injection line for quick attenuation of beam intensity with the beam size and the emittance almost maintained. Each metal mesh has the opening ratio of 1/2, 10^{-1}, 10^{-2} or 10^{-3}. However, when single mesh with low opening ratio of 10^{-2} or 10^{-3} or combined meshes were used for high beam attenuation, the beam profile changed or vanished at

BEAM EXTRACTION SYSTEM FROM DC60 CYCLOTRON

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Abstract

The results of numerical simulation of the heavy ions beam extraction system (A/Z=6÷12, W=0.35÷1.77 MeV/amu) from the DC60 cyclotron are presented. The parameters of the extraction system elements (electrostatic deflector and focusing magnetic channel) and diagnostic elements are chosen. The experimental extraction efficiency of $^{14}N^{2+}$ and $^{84}Kr^{12+}$ beams is equal to 60÷65% with intensity 1.5÷2.5 μA.

INTRODUCTION

The DC60 is a sector cyclotron with variation of the magnetic field level at range Bo=1.25÷1.65 T. The energy range of the accelerated and extracted ion beams W is continued with interval 0.35÷1.77 MeV/amu for ratio of the ion mass (A) to ion charge (Z) A/Z=6÷12. The main parameters of DC60 cyclotron are given in Table 1.

Table 1. Main parameters of the DC60 cyclotron

Pole diameter [mm]	1620
Number of the sectors	4
Azimuthal width of sector [deg]	52
Valley gap [mm]	176
Sector gap [mm]	33
Bo [T]	1.25÷1.65
Number of dee	2
Azimuthal width of dee [deg]	35
Udee [kV]	50
Frot [MHz]	1.83÷4.35
q	4 , 6
Frf [MHz]	11.0÷17.4
A/Z	6÷12
W [MeV/amu]	0.35÷1.77

For beams extraction from the cyclotron is used the electrostatic deflector. The extraction system of the DC60 cyclotron consist a next elements:

1. Electrostatic deflector (ESD);
2. Focusing magnetic channel (MC);
3. Elements of diagnostic
   a) Extraction probe;
   b) profilometer.

NUMERICAL SIMULATION OF THE BEAM EXTRACTION

For numerical simulation the 5 test ions in accordance with working diagram are used. The parameters of there ions are given in Table 2.

Table 2. Parameters of the test ions

N	A/Z	W [MeV/amu]	Udef [kV]	Bo [T]
1	6	1.07	30.8	1.25
2	10	0.38	18.6	
3	8	0.79	29.4	1.45
4	6	1.77	51.9	1.65
5	12	0.46	25.6	

The extracted trajectory is shown in Figure 1. The average radius of the maximal accelerated orbit is equal ≈70 cm (Figure 2).

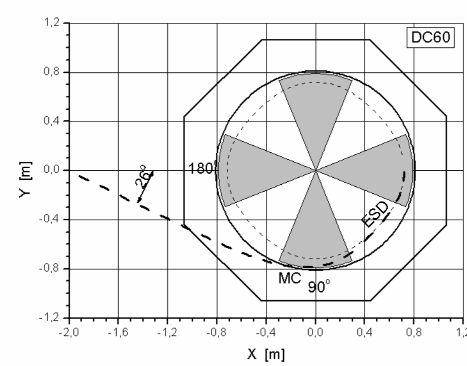

Figure 1. Trajectory of the test ion (A/Z=8, Bo=1.45T) extracted from DC60 cyclotron

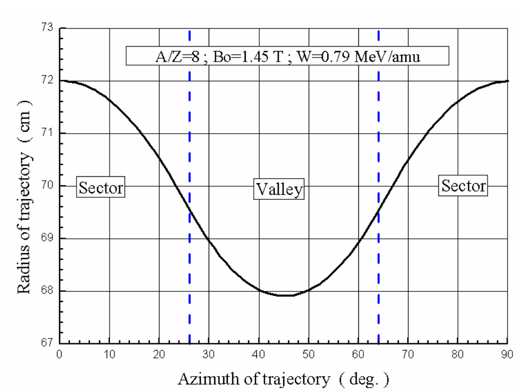

Figure 2. The maximal accelerated orbit for test ion

AUTOMATED OPERATION AND OPTIMIZATION OF THE VARIAN 250 MeV SUPERCONDUCTING COMPACT PROTON CYCLOTRON

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Abstract

The 250 MeV superconducting compact proton cyclotron of Varian Medical Systems Particle Therapy is specially designed for the use within proton therapy systems. During medical operation typically no operator is required. Furthermore, several automated control system procedures guarantee a fast, simple and reliable startup as well as beam optimization after overnight shutdown or regular service actions. We report on the automated startup procedures, automated beam centering and automated optimization of extraction efficiency. Furthermore we present an automated beam current setting as used during medical operation by means of an electrostatic deflector located at the cyclotron center at low beam energies.

INTRODUCTION

The VARIAN medical proton accelerator is a compact four sector AVF isochronous cyclotron incorporating a superconducting main coil. The design of this compact machine, proposed by Henry Blosser and his team [1] and further developed and manufactured by VARIAN, proved to be very successful. The beam energy is 250 MeV, the maximum beam current during medical operation is 800 nA and the typical extraction efficiency is 80%. More detailed technical information and dedicated cyclotron parameters are provided in our last status report [2] which dealt with the commissioning of VARIAN's superconducting 250 MeV proton cyclotrons at PSI, Switzerland and RPTC, Germany.

Both machines are fully operational and are used to provide beam for proton therapy treatment systems with scanning techniques. Since the last report considerable progress has been made in the field of automation procedures for the control system. The announced optimization procedures for beam centering and extraction are operational and have proved reliable. For power saving reasons the standby condition of the RPTC cyclotron has been modified. Furthermore, a fast beam current variation procedure has been implemented and several new automatic characterization procedures are implemented in the cyclotron control system.

AUTOMATED CYCLOTRON STARTUP

Five cyclotron states have been defined and automatic transition routines have been introduced to guarantee reproducible system settings and a fast startup especially following overnight shutdown. Tab. 1 gives an overview on these cyclotron states and a short explanation of the respective cyclotron condition. An operator can easily change between the states by using automated transition procedures.

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Table 1: Cyclotron States

Off	cyclotron vented, magnet off ⇒ cyclotron can be opened
Standby 1	cyclotron closed and evacuated ⇒ long shutdown period
Standby 2	additionally magnet energized, cooling water temperature increased ⇒ access to bunker, overnight shutdown
RF ready	additionally RF operating at reduced power ⇒ short standby period, alternative overnight shutdown
Beam ready	all active cyclotron components operating at predefined set values ⇒ cyclotron ready for beam operation

At RPTC currently "Standby 2" is used as overnight shutdown state. To reduce the power consumption of the system, all active components except the cryo-cooling, the superconducting magnet system, and the vacuum system are switched off. To maintain the thermal stability of the magnet iron the cooling water is set to an increased temperature. This minimizes the transient effects caused by heating from RF losses when coming back to standard beam operation. In addition this state enables access to the bunker to allow service actions if necessary.

Starting from "Standby 2" beam operation is possible within several minutes. With the transition to the state "RF ready" the RF amplifier is switched on and the RF system is set to operation at a reduced power of about 75 kW. A subsequent transition to the state "Beam ready" sets all other active components (ion source, extraction deflectors, …) to their nominal values. The time flow diagram in Fig. 1 illustrates this startup procedure for the important subsystems. The transition algorithm computes and sets the required magnet current as a function of the iron temperature. After setting the voltage of the vertical deflector – an electrostatic component located at the center of the cyclotron – to $U_{VD} = 0$ V (Fig. 1 at 8 min) beam is extracted from the cyclotron. A phase feedback loop ensures the optimal fine setting of the magnet current and also tunes the extraction efficiency and the beam current stability to its optimal values to ensure reliable and stable beam operation. The feedback system utilizes the signal of a non-destructive beam phase detector [4], mounted as the first beam line element. This phase pickup is designed to measure and quantify the effect of beam phase shifts due to magnetic field drifts.

PRESENT OPERATIONAL STATUS OF NIRS CYCLOTRONS (AVF930, HM18)

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Abstract

Since Japanese government launched a new program of the “Molecular Imaging Research Program” in 2005, the NIRS AVF930 cyclotron has been mainly operated to produce radio-isotopes together with a small cyclotron (HM18) for PET imaging. There are also machine operations of the AVF930 for physical experiments and tests of radiation damage on electric devices. To carry out cyclotron operations for these purposes, some improvements have been done in the facility. In this report, we will present recent operational status of the NIRS cyclotron facility (AVF930, HM18), and its improvement points.

INTRODUCTION

In 1974, operation of the NIRS (National Institute of Radiological Sciences) isochronous cyclotron (AVF930) was started, which was for clinical trial of radio-therapy with fast neutron. Besides this main purpose, production of short-lived radio-nuclides and proton radio-therapy were intended to study. In June 1994, because a new facility of heavy ion accelerator complex of the HIMAC (Heavy Ion Medical Accelerator in Chiba) has started its operation for carbon ion radio-therapy, the fast neutron therapy with the AVF930 had been terminated. In conjunction with start of the HIMAC operation, a new small cyclotron (HM-18 by Sumitomo heavy industry) was installed just beside the AVF-930 as shown in Fig. 1. With the HM18, short-lived radio-isotopes of ^{11}C and ^{18}F are produced to get radio-pharmaceuticals for PET diagnosis before and after carbon ion radio-therapy in the HIMAC. Corresponding this change of situation, the utilization of the AVF-930 also has been shifted to general experiments and radio-isotope productions except for above common isotopes such as ^{11}C, ^{13}N, ^{15}O and ^{18}F. The axial injection system has been installed to provide various kinds of heavy-ions for general experiments, where an ECR ion source with permanent magnets has been equipped. With this ECR ion source, we can supply not only proton but also light ions for cyclotron user.

In 2005, MEXT (Ministry of Education, Culture, Sports and Technology) of Japan launched a new program called the “Molecular Imaging Research Program”, and the NIRS was selected as one of centre in Japan. One purpose of this program is the application of imaging technology with PET by use of radio-pharmaceuticals with super-high specific activity. For this purpose, an old RF system of the AVF930 cyclotron has been replaced to a new one for its stable operation[1].

For production of common short-lived radio-isotopes such as ^{11}C, ^{13}N, ^{15}O and ^{18}F, the target stations of C1 and C2 can be used, where the beams are provided from both cyclotrons, but not simultaneously (see Fig. 1). With the AVF930 cyclotron, beam will be transported to target stations of C4 and C9, where radio-nuclides with longer life times will be produced. Physical experiments will be arranged in the target stations of C3, C6, C8, and C10 according its requirements.

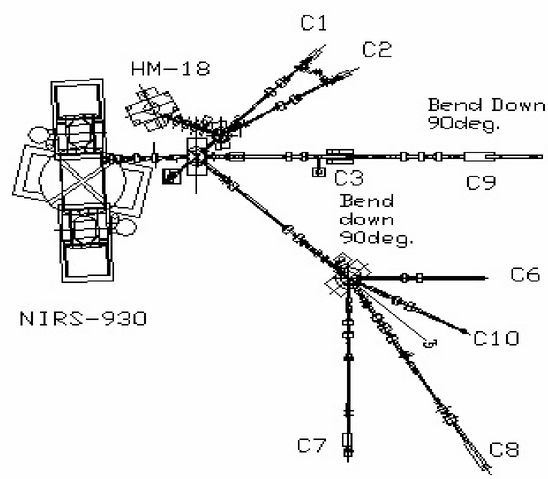

Figure 1: Layout of cyclotrons and beam lines.

OPERATIONS

In annual schedule of the AVF930 and the HM18 cyclotrons operations, there are two maintenance periods, which are planed in March and August with two or three weeks. Weekly maintenance is scheduled in Monday with full and half day every two weeks. Though the main purpose of the AVF930 cyclotron is RI production, there is about one day for general experiments in a week. Daily operations of the AVF930 and the HM18 cyclotrons will start at 9 am until evening. With those operational conditions, annual operation times in recent several years are shown in Fig. 2. Last year, there was no serious break-down in the AVF930 and the HM18, and both cyclotrons could be operated about 1500 hours as scheduled. In 2005 and 2006, operation times were short, which was due to renewal of an acceleration system of the AVF930, where D-electrodes, resonators, RF amplifiers, and control systems have been replaced[1]. With this renewal,

DESIGN OF RF SYSTEM FOR COMPACT AVF CYCLOTRON*

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Abstract

RF system is one of the most important parts for producing good and efficient accelerator system. The ion beam will be derived by a K100 SSC (Separated-Sector-Cyclotron). 8 MeV SF(Sector-focused) Cyclotron which produces 8 MeV proton beam is used as injector of K100 SSC cyclotron. In this paper, we designed RF system including RF cavity. The total specification of system is on the following. The frequency of this RF system is 70 MHz coaxial type cavity. Also we applied 4th harmonic, dee voltage of 50KV. We simulated the RF system using commercially available simulator, CST Microwave studio.

INTRODUCTION

A design research about RF system of 8MeV cyclotron was recently conducted. This cyclotron produce 1 mA proton beams at 8 MeV for K100 SSC. The high-intensity beam will be derived to SSC of above 1 mA. Then this extracted beam of this cyclotron goes to ISOL target

This paper mainly describes a development study of 8 MeV injector Sector-Focused cyclotron RF system. RF system is designed to have a few thousand of Q value with resonance frequency of 74.33MHz which based on the magnet design. Because of the limitation caused by magnet, we satisfied the condition of λ/2 by adjusting stem, liner, gap of Dee and so on. H^- particles having 24KeV for average energy are safely supplied in middle plane of poles through inflector and accelerated from central region by 50KV Dee voltage. Then accelerated particles having same angular frequency by isochronous magnetic field are ejected from final extraction stage with 8MeV energy. 3D modelling process was done by 3D CAD system, CATIA P3 V5 R18 [1] and analyzed by CST-MWS. By repeating this process, we completed the fully satisfied design.

RF SYSTEM DESIGN

The RF system has total 4 vertical stems. [2] Before designing this RF system, magnet design was preceded. Almost parameters of whole size are decided from magnet design. Material of RF Cavity is OFHC copper to get electric conductivity better and not affect magnetic field intensity. OFHC copper (model name : NBM C11000) has good electric conductivity($5.91\times10^{7}\,S/m$) compare with electric conductivity of normal copper ($5.8\times10\ \ S/m$) .

Dee angle is 40° which is located both of valleys. Total length of each dee is about 30cm. Cavity is coaxial type which has λ/2 resonant mode:

$$\lambda = \frac{c}{f} \tag{1}$$

Where c is the light velocity and f is frequency of RF system. Supposed resonance frequency of RF system is 70MHz, the wavelength, λ, is 4.28m. We set the length of whole inner conductor to half-wave length for resonance mode of λ/2. Based on this, the length of the stem which becomes an inner conductor is set to 36.5 cm.

This value, 36.5 cm, is applied for magnet design and the length of inner conductor approaches to 2.14 m, the value of half-wave length through 4 stems.

The radius of outer conductor is 40 cm based on the size of magnet. Liner is designed to have 39 cm height along the valley gap and exactly fit into the valley. Then the outer conductor which has 7.5 cm for radius is constructed by a hole in the valley of magnet. Particles are accelerated in E-field formed by two 5cm length dummy dees attached at both sides of outer conductor.

Table 1: Specification of RF system for 8MeV Cyclotron

Parameters	Values
Resonant Frequency	74.33MHz
Harmonic Number	4^{th}
Dee Voltage	50kV
Resonant mode	λ/2
Material	OFHC Copper
Pole radius	0.40 m
Hill/Valley gap	0.03 / 0.39 m
Dee angle	40°
Number of Sector/Dee	4 / 2

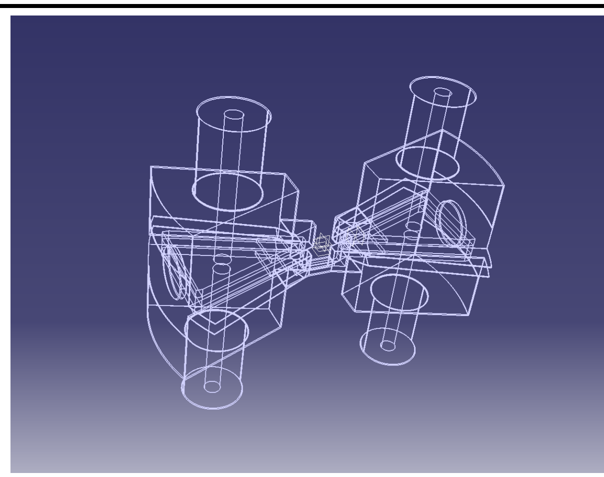

Figure 1: Wireframe of RF cavity basic model

*Work supported by Ministry of Education, Science and Technology, Republic of Korea and Department of Energy Science and School of Information and Communication Engineering of SungKyunKwan University
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CONSTRUCTION OF NEW INJECTOR LINAC AT RIBF

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Abstract

A new injector linac called RILAC2 has been constructed in order to enable the independent operation of the RIBF experiments and super-heavy element synthesis. Construction of the RILAC2 started at the end of FY2008. The RFQ linac and three DTL tanks were installed in the AVF-cyclotron vault and the excitation of rated voltage have succeeded. Two rebunchers are in fabrication and alignments of LEBT and HEBT are performed now. We plan to start the beam commissioning in December 2010.

INTRODUCTION

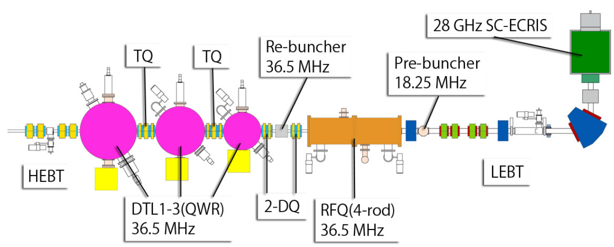

Figure 1: Schematic-layout view of the RILAC2.

A new additional injector linac called RILAC2 has been constructed at the RIKEN Nishina Center for performing independent RIBF [1] experiments and super-heavy-element synthesis [2]. As shown in Fig. 1, RILAC2 consists of a 28-GHz superconducting ECR ion source (SC-ECRIS) [3], a low-energy beam transport (LEBT) [4] with a pre-buncher, a four-rod RFQ linac, three drift-tube linac tanks (DTL1-3), a rebuncher between the RFQ and DTL1, a high-energy beam transport (HEBT) from the DTL3 to the RIKEN Ring Cyclotron (RRC) [5], and strong quadrupole magnets between the acceleration cavities for transverse focusing. Another rebuncher is located at the HEBT to focus the longitudinal phase spread at the injection of RRC by a combination of the rebuncher and an existing rebuncher. Very heavy ions with mass-to-charge ratio (m/q) of 7, such as $^{136}Xe^{20+}$ and $^{238}U^{35+}$, are accelerated up to an energy of 680 keV/u in the cw mode and injected into the RRC without charge stripping. The rf resonators excluding the pre-buncher are operated at a fixed rf frequency of 36.5 MHz, whereas the pre-buncher is operated at 18.25 MHz. The basic design of the RILAC2 was finished in 2006 [6] and the construction has started since the budget was approved at the end of FY2008. We decided to relocate the SC-ECRIS, which was originally fabricated for the existing linac called RILAC and tested in the RILAC, to a new room for the ion source of RILAC2. Other equipments for the RILAC2 are placed in the existing AVF-cyclotron vault. This article mainly presents the details for the construction of linac part.

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CONSTRUCTION OF RF CAVITIES

RFQ Linac

To save construction cost, we decided to recycle a four-rod RFQ linac which was originally developed by Nissin Electric Co., Ltd. in 1993 [7] for ion implantation. In November 2007, the RFQ system was transferred to RIKEN through the courtesy of Kyoto University. The RFQ linac can accelerate heavy ions with an m/q of 16 up to 84 keV/u in the cw mode with an rf frequency of 33.3 MHz. The maximum rf input power was designed to be 50 kW(cw). If the RFQ resonator is so modified to have a resonant frequency of 36.5 MHz, ions with an m/q of 7 can be accelerated to 100 keV/u for RILAC2 without changing the vane electrodes. The intervane voltage required for RILAC2 is 42 kV, which is less than the originally designed value of 55 kV. The basic parameters corresponding to the RFQ linac after the conversion are listed in Table 1; the parameter values were obtained by scaling the original values.

For modification of the resonant frequency, we inserted a block tuner into the gaps between the posts supporting the vane electrodes. The size of the block tuner was optimized by 3D electromagnetic calculations using the computer code Microwave Studio 2009 (MWS) and rf measurements using cold-model test pieces made of aluminum. The rf power required to excite the intervane voltage of 42 kV was evaluated to be 17.5 kW by taking into account 80% derating of the shunt impedance (63 kΩ) determined by the MWS calculation.

The heat load distribution was also evaluated by MWS calculations to decide the cooling conditions. The Maximum current density in the block was 32 A/cm, which was very small. The total heat load estimated for the five blocks was approximately 2.1 kW. The size of the cooling

BEAM EXTRACTION SYSTEM DESIGN FOR CYCIAE-14

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Abstract

A 14MeV medical cyclotron is under design and construction at CIAE (China Institute of Atomic Energy). H^- ion will be accelerated in this cyclotron and proton beam will be extracted by carbon strippers in dual opposite direction. Two stripping points are chosen in each extracting direction to extract proton beams to different targets to extend the use of the machine and the stripping points can be selected only by rotating the stripping foil. Two modes have been considered of the extraction system, one is designed to be installed on the wall of the vacuum chamber, the other is designed to be inserted vertically from the sector poles. Final choice will depend on the agility, the simpleness and the results of the experimentation. The angle between the stripper and the beam orbit is optimized to improve the extracted beam quality. Numerical simulation shows the two stripping points, the beam orbit and the beam characteristic at each extraction direction. The optimized azimuth of the stripper is also presented in this paper to show its influence for the beam quality. Based on the concept design, the mechanical design and the correlative experimentation have been done; the results are shown in the paper.

PACS: 29.20.HM CYCLOTRON;
Key words: cyclotron, proton beam, extraction system, stripping foil

INTRODUCTION

Since the incidence of cancer and cardiovascular disease is increasing, the domestic demand for PET cyclotrons in China is increasing rapidly. For productions of medical radioactive isotope, a compact cyclotron is under design and construction at CIAE. H^- ion is accelerated up to 14MeV in this machine. Except the radioactive isotopes usually produced by PET cyclotrons such as ^{18}F and ^{201}Tl, this cyclotron is also designed to produce the isotopes that usually produced by reactors such as ^{99}Tc, so the intensity of the extracted proton beam is up to 400 μA. In most PET cyclotrons, stripping method is used [1, 2] for high extraction efficiency. CYCIAE-14 [3] will use carbon foils to extract proton beam in dual opposite direction. In each extraction direction, two beams are extracted to extend the use of the machine, as shown in figuer 1: in primary design, the beam 2 is to hitting the liquid target directly for ^{18}F production, the beam 1 is to be sent to a beam line to hit the solid target to produce medical radioactive isotope such as ^{124}I and ^{201}Tl. Two stripping points in each extracted direction can be selected only by rotating the stripping foil to allot beam to different target or beam line easily.

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For the cyclotrons whose extraction energy can be changed, the combination magnets are necessary in the extraction region. But for most PET cyclotrons with single extraction energy, there is no combination magnet, as shown in figure 1.

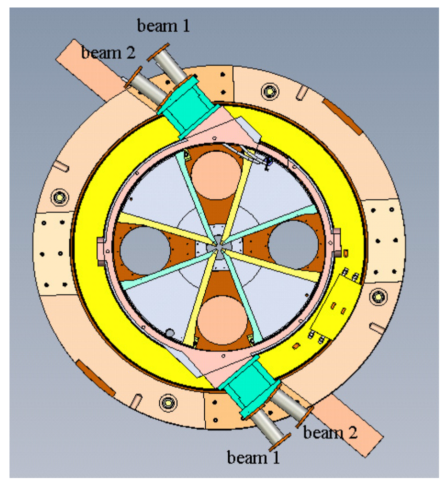

Fig.1 The extracted proton beams of CYCIAE-14

Two types of mechanical design for extraction system have been accomplished, one is designed to be installed transversely on the vacuum chamber and the other one is vertically from the sector poles, the design and the corresponding experimentation are also shown in this paper.

STRIPPING POINT AND THE BEAM DISTRIBUTION

Stripping Points on Each Direction

There are two stripping points in each extraction direction to allot proton beam to different targets, they can be calculated under the affirmatory magnetic field and target. Table 1 shows the radius and angles of two points in one direction, in which the point 1 is the right one shown in figure 1, they are calculated by using the code GOBLIN [4].

Table 1 Stripping points of CYCIAE-14

Points	Radius/ cm	Angle/ deg
1	45.69	57.09
2	45.22	61.38

FACILITY FOR MODIFICATION AND ANALYSIS OF MATERIALS WITH ION BEAMS (FAMA)*

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Abstract

The facility for modification and analysis of materials with ion beams (FAMA) is the low energy part of the TESLA Accelerator Installation, in the Vinča Institute of Nuclear Sciences, Belgrade, Serbia. It presently comprises two machines: a heavy ion source (M1) and a light ion source (M2), and two experimental channels: a channel for analysis of ion beams (C1) and a channel for surface modification of materials (C2).

In April 2009 the Vinča Institute signed a contract with the Joint Institute for Nuclear Research, Dubna, Russia, on the upgrading of FAMA. The contract comprises: (i) the refurbishment of the M1 and M2 machines and the C1 and C2 channels, (ii) the construction of a channel for surface physics (C3) and a channel for deeper modification of materials (C4), (iii) the construction of a small isochronous cyclotron (M3), and (iv) the construction of a channel for analysis of materials in vacuum (C5) and a channel for analysis of materials in air (C6). This presentation is devoted to the upgraded FAMA and its research program.

PRESENT STATUS OF FAMA

The facility for modification and analysis of materials with ion beams (FAMA) is the low energy part of the TESLA Accelerator Installation (TAI), in the Vinča Institute of Nuclear Sciences, Belgrade, Serbia. It has been used by several user groups performing experiments in different basic and applied research projects. FAMA presently comprises two machines and two experimental channels: a heavy ion source (M1), a light ion source (M2), a channel for analysis of ion beams (C1) and a channel for surface modification of materials (C2). Fig. 1 gives a scheme of present FAMA without M2 machine.

The M1 machine is an ECR ion source providing different kinds of multiply charged ions from gaseous and solid substances [1]. It operates at 14.5 GHz, while the maximal extraction voltage is 25 kV. This machine was designed and constructed jointly by the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research (JINR), Dubna, Russia, and the Laboratory of Physics of the Vinča Institute. It is in operation since 1998.

The C1 channel is used for analysis of heavy ion beams produced with the M1 machine. It comprises a beam emittance meter of the pepper-pot type. This channel was put in operation in 2003 [2].

The C2 channel is used for surface modification of materials with heavy ion beams produced with the M1 machine [3]. It includes a beam scanning system, enabling uniform irradiation of the samples inside the interaction chamber. The main components of the vast (1 m^3) interaction chamber are the following: (a) the target holder enabling positioning and rotation of the samples, (b) a low energy (2 keV) argon gun enabling one to employ the technique of ion beam assisted deposition (IBAD), (c) an electron-beam evaporation source for thin film deposition, (d) a sample heater (T_{max} = 800 ºC) and separate cooling unit with liquid nitrogen, (e) a quadrupole mass spectrometer (1-100 amu). The channel was constructed by Danfysik, Jyllinge, Denmark and commissioned in May 1998.

In addition, there is a separate multicusp ion source (M2 machine) that produces positive or negative light ions (H^-, H_2^+, H_3^+, D^-, D_2^+, D_3^+, He^+). The maximal extraction voltage is 30 kV. It was constructed by AEA Technology, Abingdon, UK and commissioned in July 1997. Initially, this machine was planned to be an injector to the main cyclotron of TAI, but after the TESLA Project has been stopped, it has been occasionally used for surface modification of materials with light ion beams.

UPGRADING THE FAMA FACILITY

The experience of the user groups of FAMA has shown that the facility needs several improvements. These improvements should be (i) to integrate the M2 machine in FAMA and provide irradiation of targets with light ion beams in parallel with heavy beams, (ii) to enable irradiation of targets to high fluences (above 10^{17} cm^{-2}) in relatively short period of time, (iii) to enable one to bombard single crystals, (iv) to increase the beam energy, and (v) to introduce some techniques for analyzing the modified targets.

In April 2009 the Vinča Institute signed a three-year contract with the Joint Institute on the upgrading of FAMA. The contract comprises: (i) refurbishment and upgrading of the M1 and M2 machines and C1 and C2 channels, (ii) construction of a channel for surface physics (C3) and a channel for deeper modification of materials with post-accelerated ion beams (C4), (iii) construction of a set-up for analysis of materials comprising a small isochronous cyclotron (M3) providing proton beams for analysis of materials in vacuum (channel C5) and for analysis of materials in air (channel C6), and (iv) purchasing of a scanning probe microscope. These jobs are performed on the basis of the concepts made by the Laboratory of Physics of the Vinča Institute, in accordance with the previously mentioned necessary improvements of FAMA. Figure 2 gives a scheme of the upgraded FAMA without the M3 machine and the C5 and C6 channels.

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THE INJECTION LINE AND CENTRAL REGION DESIGN OF CYCIAE-70*

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Abstract

A 70MeV compact cyclotron is under design at CIAE, which is aimed to provide both proton and deuteron by stripping two electrons from H^- beam and D^- beam respectively. Both of the negative charged beams are produced in a single external multi-cusp ion source, injected axially by a low energy beam injection line and bent onto the median plane through a spiral inflector. In the central region, the electrode structures and the shape of Dee tips are constructed and optimized to achieve matching at the inflector exit and to maximize the acceptance of the central region. The preliminary design results of the injection line, the spiral inflector and the central region are elaborated in the paper.

INTRODUCTION

China Institute of Atomic Energy (CIAE) is carrying out the physics design of a multi-purpose 70MeV compact cyclotron, CYCIAE-70[1], which will be applied in radioactive ion-beam production and nuclear medicine. This machine adopts a compact structure of four straight sectors. It will be capable of accelerating both H^- and D^- beam and extracting proton and deuteron beam in dual opposite directions by charge exchange stripping devices. The energy of the extracted proton beam is in the range 35~70MeV with a beam intensity up to 700μA. The energy of the extracted deuteron is 18~35MeV and the required beam intensity is only 40μA. For both particles, the energy is continuously adjustable.

As is well known, the internal PIG ion source is incapable of providing the high intensity beam of milliampere level, therefore the external ion source, and accordingly, the beam injection line and inflector are essential for this cyclotron. Considering the fact that a single multi-cusp ion source is capable to provide both H^- beam and D^- beam by filling with H_2 gas and D_2 gas respectively, only a single ion source and a single beam injection line are needed. After extracted by the ion source located underneath the cyclotron, the beams are injected into the cyclotron axially by an injection line upwards to the spiral inflector which bends beam by 90° onto the median plane of the central region. The detailed design methods and results of the central region, the spiral inflector and the injection line are reported in the following sections.

CENTRAL REGION DESIGN

The central region is one of the most challengeable sub-systems of a compact isochronous cyclotron. The principle of the design is that the central region is capable of accepting both 40keV H^- beam and 20keV D^- beam without replacing any components.

The approach for central region design is as follows:

(1) Build a 3D finite element model of the cyclotron main magnet and create the isochronous field maps on the median plane for both H^- and D^- particles respectively. The conversion between the two isochronous fields can be achieved by moving 8 additional shimming bars and tuning the ampere-turns of the main coils. Orbit centering in the central region is achieved by tuning the ampere-turns of the centering coil.

(2) Draw a preliminary geometry of the central region in AUTOCAD, which is then imported into RELAX3D[2] with the help of the pre-processing code Pre_Relax3D[3], that can read the geometry information and generate the finite difference grid with the boundary conditions. Then the 3D electric potential map around the median plane can be calculated. The central region structure must be compatible with the main magnet and the electrode of inflector. In order to avoid voltage breakdown, the accelerating gap was chosen not smaller than 6mm.

(3) Search the AEOs of a given energy points W_0 at the high energy region for H^- and D^- beam. Then do the backtracking from the AEOs of high energy towards the central region.

(4) Observe and analyze the backtracking results of H^- and D^- particles and check whether the following conditions are fulfilled: (a) The two orbits cross just before entering the first accelerating gap, the crossing point is the matching point (MP1) with inflector; (b) the energy of H^- and D^- particles at MP1 are approximately equal to 40keV and 20keV respectively; (c) in the central region the distances between the H^- orbit and the posts of two sides are approximately equal.

(5) In case the above conditions in item (4) is not fulfilled, try to do the following changes in sequence: (a) adjust the starting energy W_0; (b) adjust the structure of central region; (c) adjust the magnetic fields by adjusting the magnet structure or tuning the ampere-turns of main coils.

(6) Once the above conditions in item (4) is fulfilled, track the H^- and D^- particles of different phases. Check that whether the phase acceptance of central region is larger than 40º for H^- beam and 20º for D^- beam, and the normalized axial acceptance for both beams are larger than 0.5π mm-mrad. Otherwise optimize the structure of central region.

The iteration of orbit tracking and structure adjusting were performed according to the above approach. Figure 1 shows the final layout of the central region including the electrode structure and accelerating gaps. The

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PHYSICS DESIGN OF CYCIAE-70 EXTRACTION AND BEAMLINE SYSTEM

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Abstract

A driver with beam power of 50KW (70 MeV, 0.75 mA) based on compact H-/D- cyclotron, CYCIAE-70, has been designed at CIAE in Beijing for the RIB production and application in the nuclear medicine recently. CYCIAE-70 is designed to be a dual particle cyclotron and it is able to deliver proton with energy in the range 35~70 MeV and deuteron beam with energy in a range of about 18~33 MeV. About 700μA for H+ and 40μA for D+ will be extracted in dual opposite directions by charge exchange stripping devices and the extraction beam energy is continuously adjustable. The physics design of CYCIAE-70 stripping system has been done and the optics calculation for the extraction proton and deuteron beam has been finished. The dispersion effects for the extracted beam are analyzed and the beam parameters after extraction are calculated. 6 beam transport lines and experiment target stations are designed for different applications. A wobbling magnet is used in one of the beam transport lines, which will rotate the beam to form a beam spot on the target with a size of Φ40mm and uniformity of better than 95%.

INTRODUCTION

In order to afford the applications in the radioactive ion-beam (RIB) production and the filed of nuclear medicine, a multi-functional compact cyclotron CYCIAE-70 [1] is completely designed at China Institute of Atomic Energy under the accumulated experience on the physical research and technology design of the H- high intensity cyclotron [2,3]. The machine adopts a compact structure with four straight sector poles, capable of accelerating two kinds of beams, i.e. H- and D-. The proton beam in the range 35~70 MeV with an intensity up to 700μA, and the deuteron beam with 18~33 MeV and 40μA will be extracted in dual opposite directions by charge exchange stripping devices. For both particles that are extracted, the energy is continuously adjustable.

The cyclotron will be equipped with two combination magnets, placed at 180° one respect to the other. Any proton beam extracted by the stripper in the energy range 35~70MeV, will be transported at a crossover point inside one of the extraction combination magnets. The crossover point is the starting point of the extraction line. One of the two extraction magnets has to be equipped with a beam transport line to transport the full power beam outside the cyclotron and inside the commissioning room. In order to reduce the time of changing foils, the stripping foil changing devices are put in the independent vacuum chamber. Two stripping probes with carbon foil are inserted radially in the opposite direction from the main magnet pole. By comparing the optic calculating results for the extracted beam, the combination magnet is fixed between the adjacent yokes of main magnet in the direction of valley region. To keep all the extracted beams with various energies can be transported through the same crossing point in the combination magnet, the stripping probe can be moved in the radial direction and rotated in the angular direction.

6 beam lines and experiment target stations in the design will meet different users' demands in a variety of application fields. High extraction efficiency and low beam loss are designed for the striping extraction beam lines. Optics matching of the beam lines with the matrix of fringe field and the dispersion effects are taken into account during the extraction. A wobbling magnet is used in one of the beam transport lines, which will rotate the beam to form a beam spot on the target with a size of Φ40mm and uniformity of better than 95%.

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STRIPPING FOIL AND SWITCH MAGNET

The positions of the stripping points and the combination magnet are fixed by calculating the extraction trajectories of extracted proton beams and deuteron beams after stripping foil for different energy with the code CYCTR [4]. In order to reduce the envelope of extracted beam, the combination magnet is fixed at the adjacent yokes of main magnet in the direction of valley region. The main magnetic field used to calculate the extraction trajectories is assumed to have mid-plane symmetry. The extracted proton and deuteron beams energies are chosen by the corresponding static equilibrium orbits.

For 70MeV cyclotron, the radius of magnet pole is 1.4 m and the outer radius of magnetism yoke is 225 cm. The center of combination magnet is located at R＝200 cm and THETA=100o). Table 1 shows the stripping points for the extracted proton beam and deuteron beam for different energies.

Table1: Position of stripping foil at different extraction energies for H- and D-.

H^-			D^-		
Energy (MeV)	R (cm)	Theta (^{o})	Energy (MeV)	R (cm)	Theta (^{o})
70	126.81	58.70	35	132.23	58.39
50	109.18	57.15	25	112.72	56.74
35	92.59	55.97	18	96.07	55.68

DESIGN STUDY OF COMPACT CYCLOTRON FOR INJECTION K=100 SSC*

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Abstract

The Compact cyclotron was designed for injection of K=100 Separated-Sector-Cyclotron (SSC) [1]. It has four magnet sectors with pancake type and maximum magnetic field is 1.92T. The magnet adopting 4 harmonics has three kinds of holes for beam injection, vacuum pumps and RF systems. The pole diameter was chosen about 80 cm with 50kV dee-voltage and 40˚dee-angles. The Injection system of this accelerator consists of a double gap buncher, Solenoid-Qaudrupole-Qaudrupole (SQQ) and a spiral inflector. It will provide a 4~8 MeV, ~1 mA of proton beams and 2~4 MeV, ~0.5mA of deuteron ion beam. In this paper we will describe the conceptual design of this machine including the design of Ion-source, Injection system, Magnet and RF system.

INTRODUCTION

In this research, we designed a cyclotron which can produce beam more than 1mA with relatively small energy, 8MeV. General specifications of this cyclotron are shown at Table 1. The particle of negative hydrogen is accelerated, in the end of the procedure it generates proton beam through a carbon stripper. The H- ion created from ion source runs into the injection system and is accelerated to 8MeV at the middle plane of upper and lower magnet poles. After this acceleration it is ejected to outside by drawn system. For the higher beam current the multicusp ion source of volume type is used and the injection system make DC beam have pulse type to have same phase with RF system. The magnet is designed to produce isochronous magnetic field by shimming and RF system is considered for easily occurring a resonance near 74.3MHz.These process supported by MicroWaveStudio(MWS)[2] andOPERA-3D TOSCA[3].

ION SOURCE

The high intensity and improved TRIUMF type DC Volume-Cusp H^- ion source is used for source of beam. It consists of three major parts: body assembly, lens assembly and vacuum box assembly. Lenses are plasma lens (first electrode) and extraction lens (second electrode) with magnet filter to remove the extracted electron and re-enter beam. Vacuum box is the third electrode and it consists of steering magnet for plasma confinement.

*Work supported by Ministry of Education, Science and Technology,Republic of Korea and Department of Energy Science and School of Information and Communication Engineering of SungKyunKwanUniversity
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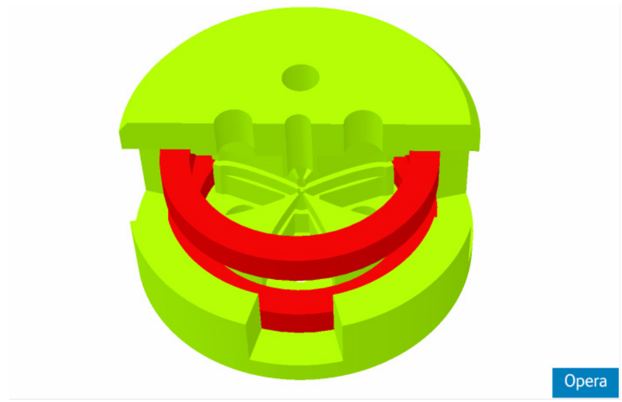

Figure 1:Model of magnet system and main coils.

Table 1: Specifications of 8MeV Cyclotron

Parameters		Values
Ionsource	Multi-cusp DC Type	
	Max. Extracted Beam Current	15mA
	Max. Arc Volt.	150V
	Type of Extracted Ion	H-, D-
Injector System	Buncher Max. E-potential	200 V
	Solenoid-Q doublet OP. power	35kW
	Inflectorelectrode potential	±10 kV
Magnet	Pole/Extraction Radius	0.4m / 0.35m
	Diameter	0.8 m
	Hill Angle	48˚
	Center field	1.15T
	Max./min B field	0.3T / 1.95T
RF System	Frequency/ Harmonics Number	74.3MHz/4th
	Dee Number/Dee angles	2 /40˚
	Dee Voltage/Q-value	50kV/5981

The 15mA H^- beam is extracted with a measured emittance of about 0.860 mm mrad. Beam kinetic energy is about 20 to 30 keV because of bias supply voltage (28 keV).

Filament current is about from 230A to 340A for the ionizing. The ion source is filled with hydrogen gas. When the filament current flows, the thermal electron is extracted from filament. This extracted thermal electron is accelerated to the cusp-body. In this situation thermal electrons are collided with cusp-body's hydrogen and generate H^- ions because of 150V arc voltage. The Ion-source is identical to TRIUMF one. [4]

MAGNET DESIGN OF 70 MEV SEPARATED SECTOR CYCLOTRON (KORIA)*

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Abstract

A K=100 separated sector cyclotron is being designed in SKKU in South Korea, this cyclotron is considered the main drive for ISOL to produce ~ 70MeV proton beam and 35 MeV deuteron beam for production of radioactive material as a basic nuclear research.

In this paper we will describe CST numerical simulation for determining the basic magnet parameters, magnet material, deformation, imperfection fields and preliminary ion beam dynamics study for verifying the focusing properties of the designed magnet.

INTRODUCTION

The purpose of this study is to design a separated sector cyclotron magnet for Korean National project, KORIA, which was started on April 2010 for radioactive ion beam (RIB) production using both ISOL and In Flight Fragmentation. KoRIA will contribute to the various research fields such as nuclear, atomic, material, bio and medical science. Its facilities consist of 3 blocks. Fig 1 is the layout of the KoRIA and the Fig 2 shows separated sector magnet layout.

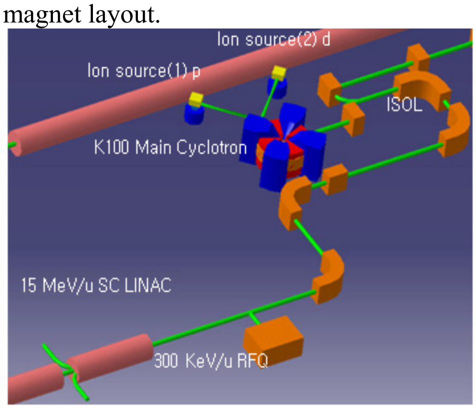

Figure 1: Block 1 layout of the KoRIA project

MAIN PARAMETERS AND DESCRIPTION OF SSC

SSC (Sector Separated Cyclotron) was selected for accelerating high beam current about 1~2 mA. The magnet diameter is 8.8 m, injection radius is 1 m, pole radius is 3.3m and approximately the total weight of iron is ~ 400 tons. For minimizing the energy dissipation at main magnet coil the minimal 3-cm gap between sectors was defined. Cyclotron Parameters cyclotrons are shown in Table 1.

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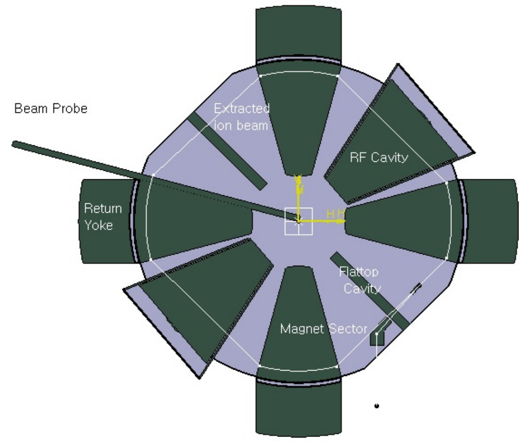

Figure 2: Separated Sector magnet Layout

Table 1: General cyclotron data

Parameters	Values
Energy	70MeV/35MeV
Ion Beam	H^+,D^+
Average field	0.385 T
Relative Field variation	0.38-0.415 T
Sector Gap	0.03m
Number of sectors	4

DESIGN REQUIREMENT FROM BEAM DYNAMICS

Acceleration of intense beams requires a very efficient focusing and extraction process free of beam loss. The main parameters of magnet design should satisfy the following criteria:

Single turn extraction: A large radial gain per turn is requested, i.e. a high energy gain per turn, in order to get an effective turn separation on the extraction radius.

Vertical and radial focusing: the problem of space charge effect is not fully understandable because of the very complicated nonlinearity of it, however many systems that have been designed were very successful for overcoming this problem, a deep valley sector focused cyclotron have been designed to be injector for a separated sector cyclotron.

BEAM OPTICS STUDY OF A FRAGMENT SEPARATOR FOR THE PLANNED RARE ISOTOPE BEAM FACILITY IN KOREA

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Abstract

A heavy-ion accelerator facility based on a linear accelerator is planned in Korea. The facility is designed to provide high-current radioisotope beams, and they will be utilized in the fields of nuclear, material and biomedical sciences. The primary beam energy is in the range of a few hundreds of MeV/u. A major mechanism to produce isotope beams is in-flight fragment separation. The separator system should have high mass resolution and particle identification method to separate and identify rare isotopes of interest, and also large momentum and angular acceptances for maximal utilization of produced isotopes. We are considering improved beam optics design to realize such a system, where second order aberrations are corrected. The study has been performed mainly using COSY Infinity.

INTRODUCTION

A plan to construct a heavy ion accelerator facility has been announced by the Korean government in January 2009. The primary accelerator is a superconducting linac to accelerate U ions to 200 MeV/u at a maximum beam power of 400 kW. It is planned to utilize both ISOL and in-flight fragmentation methods to produce rare isotope beams. In fact, considering the difficulties of using ISOL methods for some refractory elements and short-lived ions, in-flight fragment method is complementary in producing rare isotope beams [1].

The designs of two separators, which are in operation and under design, have been referred: the BigRIPS at RIKEN [2] and the separator design for the FRIB at Michigan State University [3]. BigRIPS is a two-stage fragment separator, which is actively utilized to search for new rare isotopes using heavy-ion beams from the cyclotron complex. We have studied the beam optics of a two-stage separation similar to that of the BigRIPS, also the possibility of symmetric lattice employing larger number of higher order multi-pole components.

The separator design for the FRIB facility, which is aimed to operate with the beam power of 400 kW while the beam power for BigRIPS is 100 kW, adopts a pre-separator to accommodate heavy shielding and remote handling capability. The primary beam not used for reaction is dumped in this area. The design of the FRIB separator includes vertical bending to account for the level difference between the accelerator and the beam lines for experiments. Our separator is designed to be at the same elevation considering technical and maintenance difficulties caused by the vertical bending.

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The use of wedge degrader is essential to separate the isotope with the same q/A ratio by Z-dependent energy loss. The wedge is located in the dispersive focal plane, and then the energy loss makes the beam achromatic at the focal point with appropiate wedge shaping. However, the effect of the wedge is not considered in the present work.

DESIGN OF A FRAGMENT SEPARATOR

The use of 400-kW beam power requires significant enhancement in radiation shielding compared to the usual nuclear science facility handling less than a few tens of kW. A pre-separator is needed to separate the primary beam and most of the unwanted isotope beams so as to dump them into water-cooled shielding structure. The design of pre-separator should consider radiation damage and shielding structures [4].

Configuration of the separator under consideration is given in Fig. 1 together with the beam envelope in the dispersive plane. The entire separator is located at the same level, and the locations of beam dump and shielding walls are schematically indicated. To accommodate the space for the shielding walls, we leave a long drift space of roughly 4 m in the middle of the pre-separator, a 2 m long drift space after the first dipole and a 1 m long drift between the pre- and the main separator.

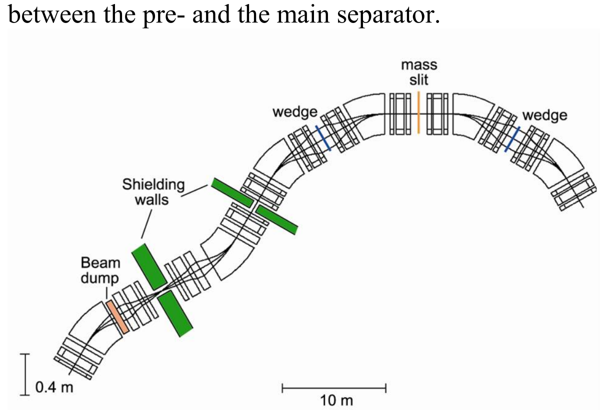

Figure 1: Configuration of a separator under consideration.

The optics of the separator was studied using COSY Infinity [5], including the pre-separator and the following main separator. The use of a matching section in between was considered but eventually dropped due to limited benefit and additional cost it brings.

OPTICS OF THE PRE-SEPARATOR

The pre-separator contains 2 dipoles and 12 quadrupoles, and its maximum magnetic rigidity is 8 Tm.

CENTRAL REGION DESIGN OF A BABY CYCLOTRON

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Abstract

Baby cyclotrons are widely used in short lived β+ radioactive isotope production. A 11 MeV baby cyclotron for PET isotope production was designed and is in construction in CAEP now. Central region design is one of the most important parts of cyclotron design work. In this paper, central region design of the 11 MeV baby cyclotron, including design processes and design results, is reported.

INTRODUCTION

PET (Positron emission tomography) becomes more and more widely used in China. A project was started in the end of 2007 in CAEP, to design and construct a 11 MeV baby proton cyclotron for PET isotope production. Main design parameters of the 11 MeV cyclotron are listed below [1].

Table 1: Main design parameters of the 11 MeV cyclotron in CAEP

Mag-net	Number of sectors	4	Ion source	Type	H-, Internal PIG
	Hill gap /cm	3.8			
	Hill angle /Deg	58			
	Valley gap /cm	140			
	Radius of the pole /cm	45	Central region	Accepted RF Phase /Deg	0-40
	B_{avg} /Tesla	1.18	Extraction	Type	Carbon foil
RF	Number of Dees	2		Number of stations	2
	Dee voltage /kV	42 or 37		Radius /cm	40
	Frequency /MHz	72	Vaccum	Pressure /Pa	1×10^{-3}
	RF power /kW	~10		Pump speed /Ls^{-1}	≥4000

CENTRAL REGION DESIGN

Firstly, the magnetic field map is calculated by Opera3D [2]. The magnetic field map is shown in Fig1. Then, a H- ion with equilibrium momentum starts to decelerate from the extraction radius to central region. Slightly adjusting the dee voltage, we can make that the ion decelerates to rest exactly at the center of the magnet. The position and direction of first several gaps, are recorded as the initial central region electrode position and direction. Then, the CAD model of the central region is constructed, and the electric field map is calculated by MAFIA. The electric field map of median plane is shown in Fig2. Particles are emitted from the slit of ion source, and the Dee serves as the puller. After that, the beam trajectories are calculated by a particle tracking code written in c++. Finally, the first several gaps are adjusted adaptively to improve the accepted RF phase and to improve the centralization.

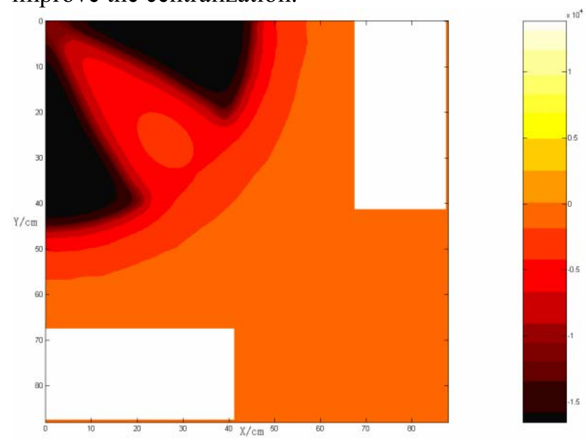

Figure 1: magnetic field map of the median plane

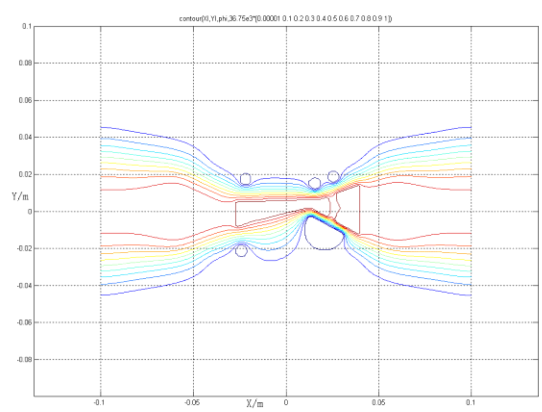

Figure 2: electric field map of the median plane

PARTICLE TRACKING

The beam tracking was done with a code written in c++ by our team. The code synchronizes the magnetic field computed by Opera and electric field computed by MAFIA, and tracks the particles by 4th order Runge-Kutta fixed step method.

H- ions start with zero momentum, from the position of the ion source slit. The width and height of the slit is .4mm and 5mm respectively. After optimization of the first several gaps, all particle emitted from the ion source slit and with initial RF phase of 0-40 degree can be accelerated in central region. The orbit, vertical motion, and energy gain are shown in figure 3-5. The vertical gap of the central region is 12mm, so the maximum expansion factor of the vertical beam size in central region is 2.5. Fig4 shows, the maximum expansion factor is only about 1.7 and all particles emitted with 0-40 degree RF phase will pass through the central region without loss due to vertical motion.

DESIGN OPTIMIZATION OF THE SPIRAL INFLECTOR FOR A HIGH CURRENT COMPACT CYCLOTRON

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Abstract

This paper describes the design of a spiral inflector in an environment where magnetic field is not constant in the region occupied by it and results of studies done on its optical properties in the presence of space charge. We have used the magnetic field data obtained from a 3D code and analytical electric field. We have also checked the orbit centering of the injected beam using a central region code. The effects of linear space charge have been evaluated and optimization of the input beam parameters has been done to minimize the coupling effects.

INTRODUCTION

At the Variable Energy Cyclotron Centre, we are developing a 10MeV, 5mA compact proton cyclotron [1]. A 2.45 GHz microwave ion source presently under testing for beam characterization, will produce ~20mA of proton beam at 80 keV. The extracted beam will be first collimated using slits, bunched using a sinusoidal buncher and will be injected axially in the central region of the cyclotron where a spiral inflector [2] will place the beam on the proper orbit. Two delta type resonators, each having ~ 45 degree angle located in the opposite valleys, will be used for providing acceleration to the beam.

Due to low average magnetic field and large ratio of hill/valley fields (~7), the computed magnetic field in the central region near the axis of the cyclotron is slightly lower than the resonance field (6.89 kG) and it also varies with radius. This makes the design of the spiral inflector more complicated and challenging.

We have developed a code to calculate the central ray in the spiral inflector using the 3D magnetic field data. Results were compared with CASINO [3]. The output of the program was used in code INFLECTOR [4] to find the shape of the electrodes. The electric field in the inflector was calculated using RELAX3D [5]. We have computed the paraxial ion trajectory in the presence of space charge effect and optimized the initial starting conditions of the beam to get minimum coupling effects in two transverse phase planes at the inflector exit.

SPIRAL INFLECTOR

Details of the spiral inflector have been described in classical reference [2] and in many other papers. Here we briefly outline the formulations used to design the spiral inflector. We have used the right handed Cartesian coordinate system x, *y*, *z* whose origin lies on the cyclotron axis. The *z* axis is vertically opposite in the direction of the incoming ion and major component of the magnetic field (B_z) is opposite to the z direction and initial electric field is along the *x* direction. The components of Lorentz force equation in the combined electric and magnet field can be written as:

$$x'' = \frac{q}{mv_0^2}E_x + \frac{q}{mv_0}\left(z'B_y - y'B_z\right) \tag{1a}$$

$$y'' = \frac{q}{mv_0^2}E_y + \frac{q}{mv_0}\left(x'B_z - z'B_x\right) \tag{1b}$$

$$z'' = \frac{q}{mv_0^2}E_z + \frac{q}{mv_0}\left(y'B_x - x'B_y\right) \tag{1c}$$

where v_0 is the velocity, m is mass and q is the charge of the ion. Here the electric and magnetic fields both are the functions of coordinates *x*, *y*, *z* and the prime denotes the differentiation with respect to path length $s = v_0 t$ .The electric fields for tapered electrodes of a spiral inflector can be written as

$$E_x = E_0\left(-\frac{x'z'}{\sqrt{x'^2+y'^2}} - \frac{y'}{\sqrt{x'^2+y'^2}}\tan\theta\right) \tag{2a}$$

$$E_y = E_0\left(-\frac{y'z'}{\sqrt{x'^2+y'^2}} + \frac{x'}{\sqrt{x'^2+y'^2}}\tan\theta\right) \tag{2b}$$

$$E_z = E_0\sqrt{x'^2+y'^2} \tag{2c}$$

Here θ is the local tilt angle and E_0 is the magnitude of the electric field which is always constant and perpendicular to the direction of motion of the ion and decides the height parameter *A* of the spiral inflector;

$$A = 2T/qE_0 \tag{3}$$

T is the kinetic energy of the ion. In fact *A* is the electric radius of the ion in the absence of the magnetic field.

In the case of a tilted inflector a component of the electric field is used to generate a force in the plane of the magnetic force to modify the beam centering. The spacing between electrodes is narrowed gradually to maintain the electric radius constant. The local tilt angle θ is given by

$$\tan\theta = k'\frac{A - z(s)}{A} \tag{4}$$

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BEAM TUNING IN KOLKATA SUPERCONDUCTING CYCLOTRON

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Abstract

The Superconducting cyclotron at VECC, Kolkata, has accelerated ion beams up to extraction radius successfully confirmed by the neutrons produced by the nuclear reactions. The internal beam tuning process started with beam parameters calculated using the measured magnetic field data [1]. Due to some mechanical and electrical problems we were forced to tune the beam with three major trim coils off. Accurate positioning of central region Dee-extensions ensuring the proper acceleration gaps in the first turn was required for successful acceleration of beam through the compact central region clearing the posts in the median plane. Here we present different aspects and results of initial beam tuning.

INTRODUCTION

The superconducting cyclotron at VECC, Kolkata, attained its major milestone in August 2009 when Ne^{+3} beam was accelerated to full extraction radius, after all the major subsystems were tested and operated synchronously. Beam acceleration involves following issues:

- Production of ion beam in the ECR ion source and transport the ion beam through 28 m beam line
- Transmission of beam through vertical beam line (~3 m) and axial cylindrical hole in the magnet yoke (~1.1 m) where high fringing field exists
- deflection of beam in the cyclotron median plane with a spiral inflector and clearing the central region by proper centering of the beam
- Obtaining isochronous magnetic field till extraction radius and accurate knowledge of beam dynamics in the cyclotron, which in turn required a very precise mapping of the guiding magnetic field inside the magnet and calculation of accelerating electric field.

Here we discuss the beam dynamical calculations using measured magnetic field data which helped in obtaining optimum settings for beam acceleration.

BEAM INJECTION

The ECR ion source operates at 14.4 GHz microwave frequency at maximum of 1 kW of power to produce light ion beams such as N, O, Ne, Mg, Al, S etc. and heavier ion beams like Ar, Kr, Xe etc. Till now Argon and Neon ion beams have been successfully injected and accelerated. The heavy ion beams, produced in ECRIS, are charge/mass separated by an analyzing magnet and then guided through horizontal beam line sections and bend downwards (~22 m length in total) to be injected into the cyclotron through its axial hole[2]. The beam injection system consists of solenoid magnets, steering magnets, diagnostics elements, vacuum pumps and the spiral inflector.

Figure 1: The ECR ion source and injection beam line in the high bay (top) and the superconducting cyclotron along with external beam line in cyclotron vault (bottom).

The injection beam line is designed for the maximum beam rigidity of 0.058 T-m, which corresponds to ions with specific charge (η=q/A) equals to 0.12 and energy equals to (20*η) keV/u.

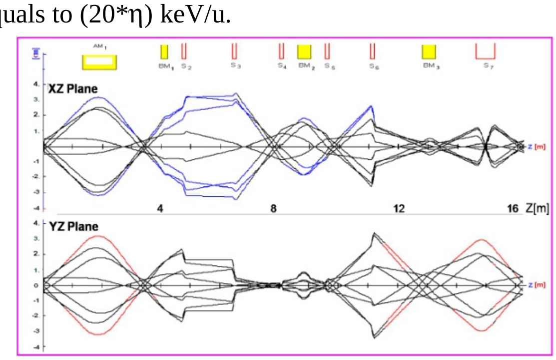

Figure 2: Beam profile along the injection beam line from ECRIS up to the matching point on the vertical beam line.

Along the axial hole large fringing field exists up to several meters from median plane (~10mT at 4m) which couples transverse motions of the charged particles resulting blow up or the beam. A long solenoid

DETERMINATION OF ISOCHRONOUS FIELD USING CALCULATED MAP OF MAGNETIC FIELD IN CYCLOTRON MEDIAN PLANE

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Abstract

In this work a new scheme for calculation of a cyclotron isochronous field using the previously calculated or measured map of the cyclotron magnetic field in its median plane is adduced. The calculating map of the cyclotron magnetic field was set by the matrix having the dimensions 201×181. The flutter part of the magnetic field obtained by subtraction of the zero azimuth harmonic from the magnetic field values was calculated in all net nodes. The magnetic rigidity value in the equation for the particle radius versus the angle was replaced by product of the mean radius and mean along the closed orbit magnetic field. The flutter function was interpolated with the help of the third order Lagrange's polynomials using 16 nodes of the net. At every given radius with the help of the nonlinear simplex method of optimization one can find such value of the isochronous field when the particle path is enclosed with accuracy of 10^{-9}. The results of the fulfilled calculations for the cyclotron DC-110 and their comparison with results of other calculations are given.

INTRODUCTION

A scheme for determination of a cyclotron isochronous field using the previously calculated or measured map of the cyclotron magnetic field in its median plane is adduced. The results of the fulfilled calculations for the cyclotron DC-110 [1] and their comparison with results of other calculations are given.

SCHEME OF CALCULATIONS

The cyclotron DC-110 has 4 "hills" and 4 "valleys". Therefore four full periods of the magnetic field $B(r,\theta)$ are kept within the circuit ($r = const$) when $0 \le \theta \le 2\pi$. The calculated map of the cyclotron magnetic field in its median plane was set by the matrix $Q_{i,j}$ having the dimensions 201 × 181. The values of the flutter part $F(r_i,\theta_j)$ were calculated in the net nodes (r_i,θ_j) by subtraction of the zero azimuth harmonic from the magnetic field values.

The distribution of the flatter versus radius is shown in Fig. 1. The calculated flutter versus the angle θ for r = 80 cm is shown in Fig. 2.

The following differential equation for a reference particle radius r [2] was used in our calculations.

$$\frac{d}{d\theta}\left(\frac{r'}{\sqrt{r^2+(r')^2}}\right)=\frac{r}{\sqrt{r^2+(r')^2}}+\frac{r\left[B(r)+F(r,\theta)\right]}{B\rho} \qquad (1)$$

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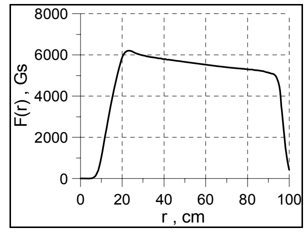

Figure 1: Flutter function $F(r)$ when $\theta = const$

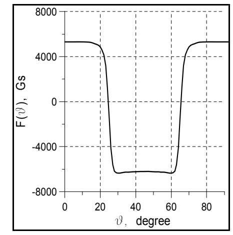

Figure 2: Flutter function $F(\theta)$ when r = 80 cm

The magnetic rigidity $B\rho$ value in (1) was replaced by product of the mean radius $\bar{r}$ and mean along the closed orbit magnetic field $\bar{B}$:

$$B\rho=\bar{r}\bar{B}(\bar{r}) \quad ; \quad \bar{B}(\bar{r})=\frac{B_0}{\sqrt{1-(\bar{r}/r_\infty)^2}}$$
$$B_0=\frac{A}{Z}\cdot\frac{M_p c^2}{e}\cdot\frac{1}{r_\infty} \quad ; \quad r_\infty=\frac{ch}{2\pi f} \qquad (2)$$

Here A is the ion atomic mass, Z is the ion charge, M_p is the atomic unit mass, c is the speed of light, e is the elementary charge, h is the harmonic number and f is the frequency of the cyclotron RF generator.

As a result the isochronous magnetic field was found by solving the following system of equations:

$$\begin{cases} \dfrac{d}{d\theta}\left(\dfrac{r'}{\sqrt{r^2+(r')^2}}\right)=\dfrac{r}{\sqrt{r^2+(r')^2}}+\dfrac{r[B(r)+F(r,\theta)]}{\bar{r}\bar{B}(\bar{r})} \\ \dfrac{d\rho}{d\theta}=\dfrac{r}{2\pi}\cdot\sqrt{1+(\dfrac{r'}{r})^2} \\ 0\le\theta\le 2\pi \end{cases} \qquad (3)$$

Here the function $\rho(\theta)$ defines the mean radius of the closed orbit $\bar{r}=\rho(2\pi)$. During calculation the value $\bar{r}$ was found by iteration with specified accuracy of 10^{-9}.

The function $B(r)$ is the varying magnetic field specified in the points w_i ($i=1,\ldots,N$) along the radius where $N = R_{extr}/\Delta r$ and Δr is the value of chosen radial step. When $r = 0$ then $B(r) = B_0$.

The function $B(r)$ in the range between two points w_i and w_{i+1} was found by means of the linear interpolation:

$$B(r)=B(w_i)\cdot\frac{r-w_{i+1}}{w_i-w_{i+1}}+B(w_{i+1})\cdot\frac{r-w_i}{w_{i+1}-w_i} \qquad (4)$$

MODIFICATION OF THE CENTRAL REGION IN THE RIKEN AVF CYCLOTRON FOR ACCELERATION AT THE H=1 RF HARMONIC

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Abstract

A highly advanced upgrade plan of the RIKEN AVF cyclotron is under way. The study is focused on the formulation of the new acceleration regimes in the AVF cyclotron by detailed orbit simulations. The extension of the acceleration energy region of light ions towards higher energies in the existing RF harmonic equal to 2 and the modification of the central geometry for the RF harmonic equal to 1 to allow an acceleration of protons at several tens of MeV are considered. The substantial redesign of the central electrode structure is needed to accelerate protons with reasonable values of the dee voltage. The new inflector geometry and the optimized central electrode structure have been formulated for the upgrade.

INTRODUCTION

A highly advanced upgrade plan of the RIKEN AVF cyclotron is under way [1]. The computer model of the AVF 3D electromagnetic field was prepared and successfully checked against the measurements [2].

The present study is focused on the formulation of the new acceleration regimes in the AVF cyclotron by detailed orbit simulations. Some experiments already conducted with the beams confirmed the selection of the machine parameters based on the beam dynamics simulations.

The new acceleration regimes include the extension of the acceleration energy region of light ions towards higher energies in the existing RF harmonic equal to 2 (H=2), and the modification of the central geometry for the RF harmonic equal to 1 (H=1) to make it possible an acceleration of protons at several tens of MeV. Clearly, with the realistic dee voltage of about 50 kV many particles would be lost in the channel of the Dee, since the existing structure of the central region (CR) was designed for the 2nd harmonic, not for the 1st one. Thus, the substantial redesign of the central electrode structure is needed to accelerate protons with reasonable values of the dee voltage.

The new inflector geometry and the optimized central electrode structure have been formulated for the upgrade.

PROTONS OF 20 MEV

In the H=2 regime the maximal experimentally available proton energy is 14 MeV for the existing electrode structure. It was found in simulations that under the restricted dee voltage of 50 kV acceleration of protons to the energy 23 MeV is also feasible there. Eventually, the energy of 20 MeV was selected for the detailed study, assuming application of the Flat Top (FT) system to suppress the energy spread in the extracted beam. Parameters of the regime are given in Table 1.

Table 1: Proton H=1 regime parameters. Structure S0 means the existing central geometry and S6 is the newly proposed geometry, which is shown in Fig. 5.

Structure	Final energy MeV	Frf MHz	Winj keV	Uinf, kV	Udee1 kV	Udee2 kV
S0	20	13.60	11.19	3.52	50	50
	23	14.54	11.41	3.71	50	50
S6	30	16.52	16.87	5.26	50	50

The main criteria for selecting the operational parameters of the regime were passing of the reference track as close as possible to the central line of the channel in the 1st Dee and clearance of the central electrodes to ensure maximal transmission of the ion bunch, and good centring of the particle trajectory in the following turns. Also, the RF phase excursion should provide the maximal possible energy gain per turn. For the 84º Dees and H=1 regime the RF phase should be as close as possible to 48ºRF. To ensure the conditions formulated above the Dee voltages and the RF particle phase in initial 4 acceleration gaps were varied.

The estimation of the bunch transmission started from preparing the initial particle distribution in the 6D phase space upstream of the inflector. In Fig. 1 the positions of the bunch at successive turns are given, black points being the lost particle locations. The main channel of the losses is the axial one. At the final radius, just at the entrance of the deflector, the projections of the particle 6D distribution are calculated. Rather large energy spread (~ 0.5 MeV) in the bunch can be explained below with the proposal of how to suppress it substantially.

SHARP TOP SYSTEM

The optimal particle RF phase at the entrance and exit of the Dee is shown schematically in Fig. 2 with the corresponding positions of the bunch (black ellipses) and the Dee voltage performance (red line).

Since the bunch does not sit at the top of the RF wave, the energy gain obtained by particles in the head and tail of the bunch substantially differs at the entrance of the Dee. But at the exit of the Dee the energy spread obtained at the entrance of the Dee gets compensated for to the same reason. The remnant energy spread in the bunch can be explained by the nonlinear dependence of the Dee voltage on time.

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NEW MAGNETIC EINZEL LENS AND ITS BEAM OPTICAL FEATURES

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Abstract

Magnetic cylindrical lens is used mostly in beam lines to focus and transport low energy beam. It is well known that focusing power of a magnetic solenoid lens depends on the ratio of particle momentum and electric charge. A solenoid rotates also an ion beam while focusing it and the phase space areas of the beam in x- and y-plane get entangled and increased. The paper reported here describes an effort to design a new magnetic einzel lens (MEL) using a pair of Glaser solenoid lens (GSL) in anti-solenoid mode for the first time to get zero rotation of the exit beam. Analytical formulae have been generated to deduce the scalar magnetic potential and field along the central axis of the lens. Thereafter, beam optics and particle tracking is done using the combined field of a pair of GSL's constituting the MEL. The required focusing power of the designed lens is achieved for a beam of given rigidity.

INTRODUCTION

We know that an electrostatic einzel lens consists of three co-axial cylinders. The mid-cylinder is kept at some potential which can be varied while the end-cylinders at small gaps are kept at constant zero potential. This creates opposite fields at the two gaps giving accelerating and decelerating force on a charged particle beam passing through the gaps along the central axis. So, the overall energy gained by the beam is zero. The focusing and defocusing effects at the gaps due to the opposite radial components of the electric field give overall focusing to the beam, which depends on the energy of the beam also.

Two iron yoked solenoids create opposing magnetic field along the central axis if they are energized oppositely and equally. They resemble electrostatic einzel lens and so we call them MEL. One solenoid rotates the beam in one direction about the central axis while the other in the opposite direction. So the overall rotation of the beam is negligible and there is almost no coupling of the sub-phase spaces in the horizontal and vertical plane resulting null growth of the phase space area. But the radial component of the magnetic field at the rising and falling regions of the field give overall focusing to the beam, which depends on the momentum of the beam.

Earlier, properties of small such lens were studied for application in electron microscope to produce small rotation-less electron beam spot with little lens aberrations. General theory of MEL was studied by Baba and Kanaya [1]. We will use more simplified model of potential and field. It is easier to construct a solenoid to confirm the axial field distribution. The particles and beam are simulated for transportation to study its beam optical features.

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MAGNETIC POTENTIAL AND FIELD

The sketch of the MEL formed from two GSL; kept attached or at small gap 2G, along the beam line and energized oppositely, is shown in Fig. 1. The hatched area is the iron yoke confirms the bell shaped field for the Glaser solenoid magnet. The diameter D and pole-to-pole distance S are given for the structure of the GSL. These parameters together with the magneto-motive force (NI) set the design of Glaser lens for certain focal lengths individually for a beam of given rigidity. Design and test of Glaser type of solenoid magnet have been presented in InPAC-2009 [2]. If O is the origin, the centre of the two solenoids are at d=(S/2+G) from the origin.

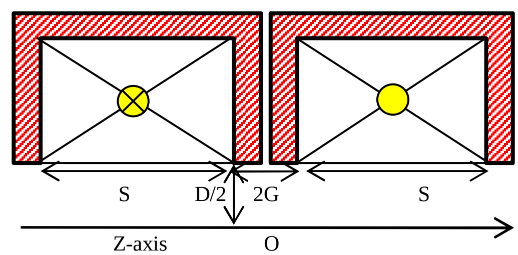

Figure 1: Cylindrically symmetric MEL in which electric current flows into and out of the page in the right and left solenoids respectively.

Magnetic Potential

The magnetic scalar potentials φ_i for a GSL are defined by eqs. (1), (2) and (3) in ref. [2] where subscript i stands for 1, 2 and 3. The forms of scalar potentials along the axis represented by φ_1, φ_2 and φ_3, which depend on the geometry of solenoid that is the pole to pole gap S and diameter D and magneto-motive force (MMF) and were expressed in detail therein.

Magnetic Field

The potential formulae for the magnetic Glaser lens are used to evaluate the field analytically. The net axial field $\varphi_i'(z)$ for a GSL is given in eqs. (1), (2) and (3) below using $\varphi_i'(z) = -\mu_0 d\varphi_i(z)/dz$. Now the magnetic field for a MEL as depicted in Fig. 1 is given by eq. (4) using the three fields from three potentials for i = 1, 2 and 3. The evaluated fields of the MEL for S=10 cm, D=10 cm, G= 0 cm, 5 cm, 10 cm and NI=37000 A-turn are shown in Figs. 2a and 2b. The GSL field is given by eq. (1) in ref. [3].

$$\varphi_1'(z) = \frac{-\mu_0 NI}{\pi S}\int_0^\infty \frac{2\sin(Sx/D)\cdot\cos(2xz/D)}{x\cdot I_0(x)}dx \qquad (1)$$

Where $I_0(x)$ is the modified Bessel function of first kind and order zero. The integration is in radial direction using the dummy variable x. Another field form is given by eq. (2) below.

TOWARDS QUANTITATIVE PREDICTIONS OF HIGH POWER CYCLOTRONS *

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Abstract

The large and complex structure of cyclotrons poses great challenges in the precise simulation of high power beams. However, such simulation capabilities are mandatory in the design and operation of the next generation high power proton drivers. The powerful tool OPAL enables us to do large scale simulations including 3D space charge and particle matter interactions. We describe a large scale simulation effort, which leads to a better quantitative understanding of the existing PSI high power proton cyclotron facility and predicts the beam behaviour of CYCIAE-100 under construction at CIAE.

INTRODUCTION

High intensity problems in cyclotrons draw a lot of attention because of the widely use of high intensity proton beams for palliation neutron sources and accelerator driven transmutation technologies. The 1.3 MW CW proton beam at the Paul Scherrer Institute (PSI) poses great challenges for high intensity beam simulations in cyclotrons [1]. With the fast development of HPC (High Performance Computing), the powerful tool OPAL [2] which includes 3D space charge and particle matter interactions enables us to perform large scale simulations in complex high intensity accelerators.

The Beijing Radioactive Ion-beam Facility (BRIF) is now in the construction phase at the China Institute of Atomic Energy (CIAE). The driving accelerator of this project, CYCIAE-100, a high intensity proton cyclotron, is designed to provide a 75 MeV~100 MeV, 200 μA~500 μA proton beam [3].

In this paper, we report on precise beam dynamic simulations of the PSI Ring Cyclotron. We present a new particle matter interaction model taking into account energy loss, multiple Coulomb scattering and large angle Rutherford scattering together with the 3D space charge. This model is used to obtain the necessary beam loss statistics during the acceleration process in CYCIAE-100 Cyclotron This data is indispensable in the design of an efficient collimation system.

THE 1.3 MW PROTON CYCLOTRON

The high intensity accelerator complex at PSI generates a 1.3 MW proton beam in routine operation. This gives us the unique opportunity to study the beam behavior of high intensity proton beam based on the experience with MW beam powers.

The simulation in this paper starts at the beginning of the 72 MeV transfer line between the Injector 2 and Ring Cyclotron. There are 18 beam profile monitors in both x and y direction. The initial distribution is obtained using Transport [4,5] and fitting the profile monitor data.

For the start of the Ring simulation, the emittance acquired at the end of the transfer line is used. The length of the bunch is measured using the time-structure probes [6]. For a 2 mA beam, the non-normalized radial emittance is $1.5\,\pi\, mm \cdot mrad$, vertical emittance is $0.6\,\pi\, mm \cdot mrad$, and the standard deviation of bunch length is $\sigma = 23\, mm$. A six-dimensional Gaussian distribution is used as the initial distribution of the Ring Cyclotron.

The beam intensity of the Ring Cyclotron is mainly limited by the beam losses at the extraction. To keep the extraction loss lower than 0.02%, the following effects must be considered.

- The turn separation at the position of extraction septum must be as large as possible.
- The radial beam size at the extraction region should be smaller than the turn separation and large amount of halo particles must be avoided.
- Since a long "pencil " beam is used in the Ring Cyclotron, the space charge effect must be effectively compensated to avoid the formation of the S-shape beam which apparently increases the effective radial beam size.

In the original design of the Ring cyclotron, the beam will pass the coupling resonance $\nu_r = 2\nu_z$ four times at 490, 525, 535 and 585 MeV. A large horizontal oscillation is transformed into a large vertical one at the coupling resonances which can lead to beam losses. A trim coil TC15 was designed to avoid the resonance at 525 and 535 MeV. It provides an additional magnet field and field gradient in the radial direction. The effect is shown in Fig. 1. The trim coil provides a maximum magnetic field of 14 Gs. It has a long tail towards the smaller radii in order to make the integrated strength of the trim coil over the radius to zero.

A long beam with bunch length of $\sigma = 23\, mm$ is used in the Ring Cyclotron. To get a beam at the extraction turn with low losses, the flattop phase is adjusted to compensate the distortion caused by space charge forces. For an ideal flattop, the whole beam gains the same energy after one turn. In the case of high beam current, when the space charge force cannot be ignored, the head particle gains additional energy and the tail particle loses energy, so the beam will tend to show an s-shape in an isochronous cyclotron. Through the shift of

ANALYSIS OF BEAM QUALITY OPTIMIZATION OF BUCKET ION SOURCE

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Abstract

The bucket ion source is widely used as the high energy beam source on the high power neutral beam injector system. A hot cathode bucket ion source is studied. The main parameters which influence the performance of bucket ion source are arc voltage, filament voltage, gas inlet rate and extracted voltage. The proton ratio is the dominate parameter for the ion source. In the experiment, the characteristics of ion source are got by regulate the parameter setting. Based on this, the beam proton ratio, are analyzed and optimized. The proton ratio of extracted beam increased from 28 % to 40 %. It is very useful for the experimental operation and study about the bucket ion source.

INTRODUCTION

The high power neutral beam injection (NBI) is wildly used for the realization of controlled thermonuclear fusion sciences. The high current ion source is one of the most important parts on NBI, and it is characterized as high plasma density, large dimensions and high proton ratio. In order to promote the performance of ion source, the researchers did many study and experiments, one of them is the proton ratio.

The proton ratio is define the percentage of the number of atom ions in the over all species ions number. Consider the hydrogen as the experimental gas, it may generate ions of H1+, H2+, H3+, and the proton ratio[1] can be defined as

$$\eta = \frac{I_{H_1^+}}{I_{H_1^+} + I_{H_2^+} + I_{H_3^+}} \approx \frac{n_1}{n_1 + n_2/\sqrt{2} + n_3/\sqrt{3}} \quad (1)$$

Where, n1, n2, n3 is the ion density of H1+, H2+, H3+, respectively.

The ions are used to accelerate from the arc chamber to form the ion beam, but the energy of molecular ions only 1/2 and 1/3 compare with the atom ions, therefore, the number of atom ions in the plasma is expected as high as possible. That is means that, the proton ratio of ion source should be promoted.

The usual used ion source is hot cathode ion source, and also is the wide used, which can be seen in Figure 1. It contains plasma generator and beam extraction system. The plasma generator contains the filaments, and the gas inlet and arc chamber, which surrounded with permanent magnets to form cusp magnetic to confine the plasma.

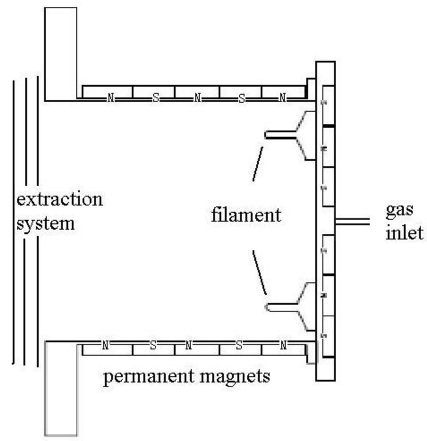

Figure 1: A sketch map of bucket ion source.

THE PHYSICAL MECHANISM OF PLASMA DISCHARGE

The ion source is a complicated device, including the plasma generate part and beam formation part. The particles in the plasma are used to form the ion beam, so, the ion species can decide the proton ration of extracted beam. And the plasma generation is only discussed. The principle of plasma generated in the hot cathode ion source can be described briefly as follows: The filament is supplied by a voltage and is then heated to emit thermo-electrons. When the arc voltage applied on the filament and arc chamber, the thermo-electrons are accelerated by the electric field. When the electrons energy large than the ionization potential of gas, the gas can be ionized and the plasma is generated. In case of hydrogen, it can generate atom ion H+ and molecular ions H2+, H3+. The formation of ions is a complicated thing, it contains many processes, and the collision cross-section of each process can decide the ion species which generated in the plasma. The electrons collide with the gas including one-collision and multi-collision. For the one-collision, mainly produce molecular ion H2+, the atom ion H+ almost produced in the second collision or more[2,3]. The collision processes are listed in Table 1. It can be seen that it including the molecules ionization, molecular ions dissociation, excitation and composition. The table also shows the threshold energy when the process take place, the collision cross-section and the optimize electron energy. Choose the big collision cross-section processes and give

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ION SOURCE RELATED RESEARCH WORK AT JYFL*

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Abstract

In this article the work of the JYFL ion source group will be presented. New bremsstrahlung measurements were carried out in order to compare the results with different electron heating models. Especially attention was paid to study the effect of different heating parameters on the evolution of bremsstrahlung energy. A project to obtain new information about the ion temperatures and their time evolution has been initiated. The study will be performed using spectroscopic techniques measuring the ion temperature from the Doppler broadening of emission lines. The objective is to obtain accurate information about the evolution and the behaviour of highly charged ions in the ECRIS plasma. The work of the JYFL ion source team also includes frequency tuning experiments, beam quality experiments and tests with a so-called collar structure mounted on the plasma electrode. The beneficial effect of collar was first tested and noticed with the ECR ion sources by the KVI ion source group and has been shortly confirmed at JYFL. The JYFL ion source group is also developing a low power electron gun for the needs of spacecraft applications. The results of the development work can possibly be applied also with the ion sources in order to increase the density of cold electrons.

INTRODUCTION

The JYFL ion source group has studied the plasma physics of ECR ion sources. This includes for example the studies of plasma potential and evolution of electron energies via bremsstrahlung diagnostics. The intention is to extend the studies to cover the most of the energy range of the photon emission. In addition to the plasma studies, the ion source group also carries out the active research and development work for developing ion sources and their beams.

EXPERIMENTAL WORK AT JYFL

Electron Heating Limits of JYFL 6.4 GHz ECRIS

The high-energy bremsstrahlung emission generates an extra heat load to the cryostat of superconducting ECR ion sources [1]. An efficient shielding is very difficult to realize because of the limited space inside the ion source. In order to understand the parameters affecting the heating limits the experimental results were compared to the stochastic heating theory presented in ref. [2]. According to the theory the heating limit depends on the gradient of the magnetic field and the amplitude of the electric field E on the electron cyclotron resonance surface. The theory can be expressed as

$$W_s = 0.2\left[m_e L\left(1+\frac{l^2}{L^2}\right)\right]^{1/4} l\omega^{1/2}(eE)^{3/4} \qquad (1)$$

where $\omega = 2\pi f$ (f is the microwave frequency), m_e the mass of the electron, e is the unit charge, L is a parameter, which can be calculated from the axial magnetic field profile ($B = B_{\min}(1+z^2/L^2)$), where the resonances are at $z = \pm l$. Here B_{min} is the minimum magnetic field and z the axial distance from this minimum. Adiabatic heating limit is defined to be $W_a = 5W_s$. The objective of the work was to found out if the end point energy of bremsstrahlung follows the behaviour of adiabatic heating limits.

Figure 1 shows the effect of magnetic field gradient on the bremsstrahlung spectrum extracted from the JYFL 6.4 GHz ECRIS. Both the end point energy and the yield of the emission increase. Using the values shown in Figure 1 and Table 1 it can be seen that Eq. (1) fails in predicting the behaviour of high-energy photon emission (compare $W_{end\text{-}point}$ and W_a in Table 1). A possible explanation is that the theory does not take into account the relativistic effect, which tends to move the resonance point towards higher magnetic field values. This is illustrated in Figure 2, which shows that the length l is longer for the relativistic electrons. The maximum length l for the relativistic electrons equals the distance between the B_{min} and extraction aperture and is independent on the magnetic field gradient. Table 1 shows the energy of electron when the resonance takes place at the extraction aperture of the ion source. According to the experiment it is possible that the energy of the electron is limited by the magnetic field configuration (for details see ref. [3]).

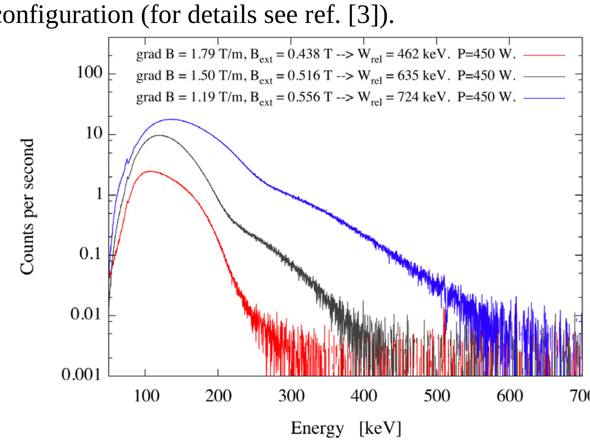

Figure 1: Effect of magnetic field settings on the bremsstrahlung energy and count rate.

* This work has been supported by the Academy of Finland and Magnus Ehrnrooth and Nyyssönen foundations
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STUDIES OF ECRIS ION BEAM FORMATION AND QUALITY AT THE DEPARTMENT OF PHYSICS, UNIVERSITY OF JYVÄSKYLÄ*

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Abstract

During the last couple of years a lot of effort has been put into studies concerning the ion beam formation and beam quality of electron cyclotron resonance ion sources (ECRISs) at the Department of Physics, University of Jyväskylä (JYFL). The effects of microwave frequency fine tuning on the performance of JYFL 14 GHz ECRIS have been studied with multiple experiments in collaboration with INFN-LNS (Instituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud). Also, a number of measurements have been carried out to study the effects of space charge compensation of ion beams on the beam quality. In order to proceed further with these studies, a modified version of the beam potential measurement device developed at LBNL (Lawrence Berkeley National Laboratory) is under development. Simulations are used to study the possibility to improve the beam quality by biasing the beginning of the beam line upstream from m/q separation. With high voltage biasing the beam energy could be increased temporarily over the limit of the injection system of the accelerator. Latest results and current status of these projects will be presented and discussed.

INTRODUCTION

Improving the performance of ion sources is crucial for the future of accelerator facilities. However, increasing the amount of produced ion beam is not enough, as the beam quality determines what fraction of the beam can be utilized by the experiments. In addition, with high beam currents many of the beam quality problems, such as space charge effects, are more pronounced.

At JYFL a significant amount of effort has been put into understanding better the underlying problems of the beam quality, both at the ion source and during the beam transport. The effects of microwave frequency on the phenomena inside the ion source plasma chamber and on the formation of the ion beam and its consequent characteristics have been studied in collaboration with INFN-LNS. The space charge effects play an important role in the high beam current section between the ion source and the analyzing magnet. Possibilities to mitigate these effects have been studied from multiple points of view. One is enhancing the degree of the space charge compensation by decreasing the charge density during the transport by introducing electrons, the other is by altering the beam starting conditions, like energy.

FREQUENCY TUNING

By feeding microwaves into the plasma chamber of an ECR ion source it is possible to excite electromagnetic field structures, or modes, inside the chamber. If the microwave frequency is around 14 GHz, like with JYFL 14 GHz ECRIS, and the chamber has typical ECRIS plasma chamber dimensions, these modes only have separation in the order of some MHz [1]. Thus only a slight change in the feeding frequency can significantly alter the electric field structure inside the plasma chamber. It is not clear how the situation changes when the chamber is filled with plasma. However, if the clear mode structure remains, it should have an influence on the characteristics of the produced ion beam [2].

The measurements were conducted by setting a constant microwave power output and varying the frequency between 14.050 and 14.135 GHz, the normal operation frequency being 14.085 GHz. At the same time, the ion source

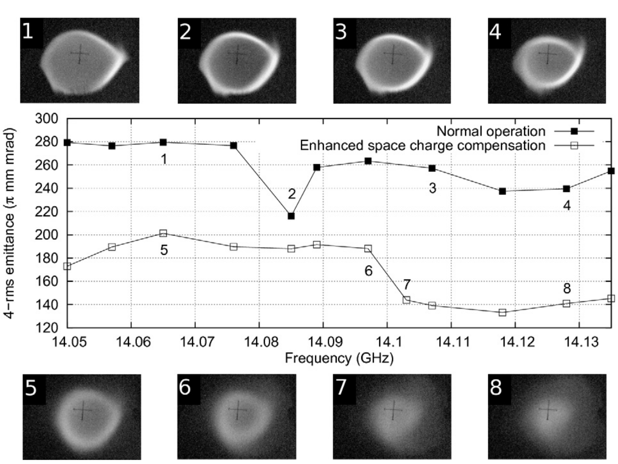

Figure 1: 4-rms emittance of Ar^{9+} with and without enhanced space charge compensation and beam viewer images at selected frequencies.

* Work supported by the Academy of Finland and Nyyssönen foundation. LNS team acknowledges the support of the INFN Strategic Project NTA-HELIOS.
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ECRIS DEVELOPMENT AT KVI*

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Abstract

This paper reports on work performed during the last two years to improve the performance of the KVI-AECR ion source, which is used as an injector for the AGOR cyclotron. We have installed stainless-steel screens at the injection and extraction sides and an additional collar around the extraction aperture resulting in better plasma stability and an increase of extracted ion currents. Source tuning is aided by continuously observing the visible light output of the plasma through the extraction aperture with a CCD camera. We now routinely extract 700 μA of O^{6+} ions and 50 μA of Pb^{27+} ions.

Source optimization is supported by extensive computational modelling of the ion transport in the low-energy beam line and measuring the transverse emittance of the extracted ion beam with a pepperpot emittance meter. These efforts have shown that second-order aberrations in the analyzing magnet lead to a significant increase of the effective beam emittance. Work is underway to compensate these aberrations.

INTRODUCTION

The Advanced Electron-Cyclotron-Resonance Ion Source at KVI (KVI-AECRIS) has been used as an injector of multiply-charged ions into the superconducting AGOR cyclotron for several years already. The main demands on the source are defined by the needs of the TRIμP program on fundamental symmetries (Ne^{6+} and Pb^{27+} beams), as well as by radiobiological studies (C^{6+} ions). The intensities of the neon and carbon beams are exceeding the user's requirements and the main concerns are beam stability and reproducibility. The lead intensity is significantly less than requested for the final production stage of the experiment (by a factor of two to three) and efforts are underway to improve both the source performance and the beam transmission through the low-energy beam transport line. The paper is organized as follows: first the KVI-AECRIS is briefly described together with the recent modifications to improve its performance. Then we discuss the visual diagnostics used to observe plasma light emission through the plasma electrode aperture and finally we report on our efforts to improve beam transport through and imaging properties of the analyzing magnet.

SOURCE DESIGN AND MODIFICATIONS

The KVI-AECRIS design is the same as AECRIS-U of LBNL and the 14 GHz source of Jyväskylä. The source is equipped with soft-iron plugs at the injection and extraction sides (B_{inj}=2.1 T, B_{extr}=1.1 T, B_{min}=0.36 T), has radial slits between the hexapole bars for better pumping, and an aluminium plasma chamber with a length of 300 mm and inner diameter of 76 mm. The radial magnetic field in this geometry is lower than for other 14 GHz sources and reaches 0.86 T at the plasma chamber wall.

In addition to the main 14.1 GHz RF heating system, the source is also equipped with a 11-12.5 GHz, 400 W Travelling Wave Tube Amplifier (TWTA), enabling two-frequency plasma heating. In normal operational conditions, however, no benefits of dual frequency heating have been observed.

In the original design the injection plug was shielded from the plasma by an aluminium screen. Also the plasma electrode was made of aluminium and had a cone-like shape. In these conditions the source output was unstable, with frequent changes in the operational modes and moderate extracted currents. We replaced both the injection screen and the plasma electrode with stainless steel ones and changed the shape of the plasma electrode to a flat one. This resulted in large improvements in source performance, with much better stability and reproducibility. We still see jumps in source output, but they are now more controllable. In addition, the extracted currents increased with e.g. typical outputs of Ne^{6+}, O^{6+} and Ar^{8+} ion currents of around 300 μA.

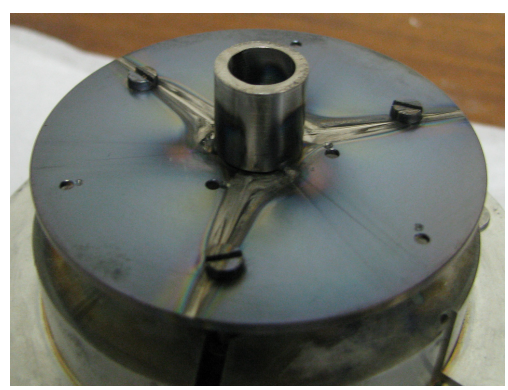

Figure 1: The plasma electrode with its collar.

An additional boost in performance was achieved by installing a collar around the extraction aperture. A picture of the collar is shown in Figure 1. The collar is a stainless steel cylinder with a length of 15 mm, inner diameter of 10 mm and outer diameter of 13 mm. In first instance installation resulted in a significant decrease of the output of the lower-charged ions (O^{4+} and lower). Output of the higher charge states on the contrary increased by a about 20 % The decrease in extracted low charged ions

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A COMPACT SOLUTION FOR DDS-GENERATOR, TURN-ON AND PROTECTIONS IN RADIO FREQUENCY ACCELERATOR SYSTEMS

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Abstract

One single compact rack includes: Direct Digital Synthesizer (RF-generator), turn-on and protection devices. The system synthesizes a highly stable RF signal up to 120 MHz, turns the power on in the RF cavities through a step-ramp modulator, and protects the RF system against mismatching, sparks and multipactoring. A first prototype has been designed, assembled and tested on the RF system of the k-800 superconducting cyclotron at Infn-Lns. The hardware, the software, and the preliminary test results, are shown in this paper. This solution is part of the new computer-based RF control system.

CONCEPTUAL DESIGN

One of the most important aims in an RF control system is to supply the power to the cavities. Terms like conditioning and multipactoring are common in all the RF systems [1]. The conditioning, especially of a new cavity, can be really problematic. The stabilization of the right high voltage on the RF electrodes is often a difficult procedure [2]. Proper modulation of the RF signal in the initial conditioning phase is essential to reduce the risk of sparks, high reflected waves and multipactoring phenomena. In the general frame of the k-800 superconducting cyclotron [3] RF control system upgrade, a prototype single board has been developed. It is able to synthesize and modulate the output RF signal and to protect the system. The specific design can reduce the conditioning time remarkably. Moreover, a programmable modulation to bypass multipactoring has been introduced. Figure 1 shows the conceptual block diagram.

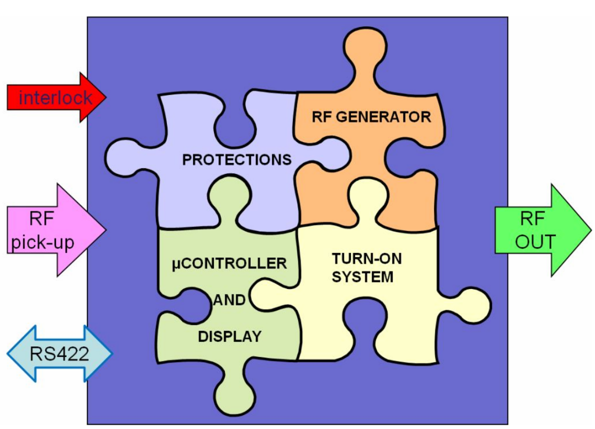

Figure 1: The block diagram of the system.

The puzzle components inside the box summarize the compact concept of the system. The main components inside the box are: the RF generator, turn-on system, protections, microcontroller and display unit. The RF output, the RF pick-up, the RS422 bus and the interlock line are the external connections of the box. The system is a sort of smart RF synthesizer including important and essential components of a radio frequency low level control system. For this reason we have called it the 'Low Level RF Box' (LLRF-Box). On its own it represents half of a typical RF control system. The addition of the stabilization loops (amplitude, phase and tuning) and the control interlock complete the low level RF system. The LLRF-Box can be compatible with most of the cyclotrons and accelerator RF control systems.

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LOW LEVEL RF BOX APPLICATION

In general it is common practice that the RF generator, the turn-on system and the protections are placed in separate and independent racks. We came up with the idea of inserting all the components of Figure 1 in a single board during the upgrade of the low level RF system [4].

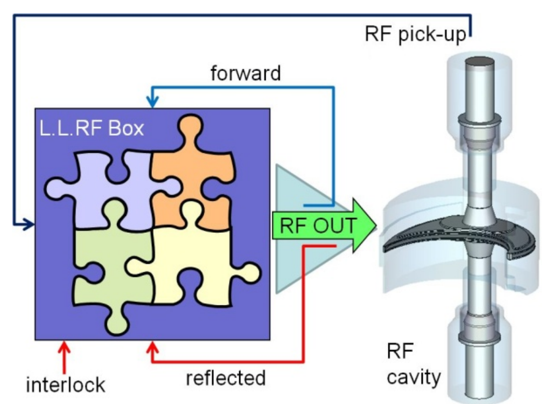

Figure 2: The LLRF-Box connected to the cavity.

The LLRF-Box can be used as a single apparatus for the conditioning of a RF cavity up to 120 MHz. This matches perfectly our RF devices frequency bandwidth at Infn-Lns. The prototype test has been performed on one cavity of the k-800 cyclotron. Figure 2 shows a simple layout where the LLRF-Box is connected to the RF cavity through the amplification section only. The RF box has three RF inputs: forward and reflected wave from the directional coupler and an RF pick-up from the cavity.

THE LOW LEVEL RF BOX

The Low Level RF-Box functions of protections, turn-on and RF-generator are based mainly on the following electronic components: the dsPIC30F4013 by Microchip and the AD9854 by Analog Devices [5,6]. The dsPIC is a

COMMISSIONING EXPERIENCE OF THE RF SYSTEM OF K500 SUPERCONDUCTING CYCLOTRON AT VECC

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Abstract

Radio frequency system of Superconducting cyclotron at VECC, Kolkata, has been developed to achieve accelerating voltage of 100 kV max. With frequency, amplitude and phase stability of 0.1 ppm, 100 ppm and ±0.5o respectively in the frequency range of 9 – 27 MHz. Each of the three half-wave coaxial cavity is fed with rf power (80kW max.) from each of the three high power final rf amplifiers based on Eimac 4CW150,000E tetrodes. Initially, the whole three-phase RF system has been tuned for operation with RF power to the cavities at 19.1994 MHz and thereafter commissioned the cyclotron with neon 3+ beam at external radius at 14.0 MHz. In this paper, we present brief description of the rf system and behaviour observed during initial conditioning of the cavities with rf power and the way to get out of multipacting zone together with discussion on our operational experience. We have so far achieved dee voltage up to 57 kV at 14 MHz with 20 kW of RF power fed at each of the three dees and achieved vacuum level of 4.5 x 10-7 mbar inside the beam chamber. We also present discussion on the problems and failures of some RF components during commissioning stage and rectifications done to solve the same.

INTRODUCTION

The Radiofrequency system of k500 Superconducting Cyclotron including the development of high power rf amplifiers, design aspects of rf cavities and their coarse frequency tuning mechanism, low-level electronic controls like three-phase signal generation, phase detection, amplitude regulation, phase regulation etc. of the complete rf system and Programmable logic controller based interlocks for the safety of the rf system and personnel, have been thoroughly described in various status and review papers presented in a number of conferences [1-8]. In the following sections, we will discuss the commissioning experience of the rf system gained so far, some major problems we faced and finally the solutions or rectification we decided to incorporate in the system for better reliability.

RF AMPLIFIERS

Three high power rf amplifiers (each having 80kW output at 50 Ohm) for feeding power to the three main rf cavities have been installed at the vault of Superconducting cyclotron building (as shown in Fig.1) and are driven by solid-state wideband amplifiers in the specified frequency range.

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Fig.1. High power rf amplifiers installed at SCC Vault

Each of the high power rf amplifiers consists of Eimac 4CW 150,000E water-cooled tetrode as active device and with individual cavity tuneable by moving the sliding short, similar to that used for the main dee resonator cavity. The four identical Bridge-T network in the grid of the final amplifier are driven with equal power levels of up to 300 watts. PLC-based interlock system for all parameters like all water interlocks for main cavities, amplifier cavities and tetrodes, interlocks for DC power supplies related to RF amplifiers, airflow interlocks for dee-stem alumina window cooling, coupler alumina cooling and amplifier internal cooling etc. was in operation before putting on the rf system. DC power supplies for the tetrode – 3 nos. of Filament P/S (15.5V/215A), 3 nos. of Control Grid P/S (–400V to –200V), one no. of Anode P/S (20kV/22.5A) with fast crowbar protection for 3 amplifiers and 3 nos. of Screen Grid P/S (1.5kV/0.5A) were tested and installed. Amplifier cavity was tuned (with VNA connected at Anode pick-up port) by moving the position of its sliding short with the help of a PC-based stepper motor controlled drive system with positional accuracy better than 20µm.

PROBLEMS IN AMPLIFIERS

We encountered a problem in high power RF Amplifier-B after few months of operation with RF. Under DC condition with 2.5A anode current, suddenly we observed RF power appeared in the power meter. It seems the amplifier is oscillating and observed the oscillation at 1.083GHz on a 6 GHz Spectrum Analyzer. As this kind of high frequency oscillation can appear only from the tetrode itself, we replaced that particular tetrode with a new one and the problem got solved.

In one occasion, we found in one amplifier that as soon as screen grid power supply is put on, it trips. On close observation it was found that control-grid current is much higher than the usual operating value (bleeder current).

THEORETICAL ANALYSIS AND FABRICATION OF COUPLING CAPACITOR FOR K500 SUPERCONDUCTING CYCLOTRON AT KOLKATA

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Abstract

K500 SC cyclotron has already been constructed and commissioned after spiralling Ne^{3+} internal beam with 70 nA up to extraction radius (670mm) at variable Energy Cyclotron Centre at Kolkata, India. Several problems have been experienced related to the coupling capacitor of the radio frequency system including its sever burning during commissioning of the cyclotron. Making of the dissimilar joints between alumina ceramic and copper of the coupling capacitor demands the usage of vacuum furnace to avoid the cracking of the ceramic. Therefore exhaustive analysis has been carried out to facilitate the in-house fabrication of the coupling capacitor without using the vacuum furnace in case of emergency. The maximum allowable rate of temperature rise of the ceramic and the optimum thickness ratio of the copper to ceramic have been estimated. Finally, fabrication of the coupling capacitor has been carried out in-house without employing vacuum furnace. At present the coupling capacitor is performing well as maximum 57 KV DEE voltage were been achieved till date. This paper presents the details of the analysis and experiences gained during the fabrication of the coupling capacitor.

INTRODUCTION

K500 Superconducting Cyclotron was installed at VECC last year. After commissioning of all the individual sub-system and having spiralling internal beam up to extraction radius, beam extraction process is going on.

While commissioning of the cavity-C of the Radio Frequency (RF) system was going on, suddenly coupling capacitor of the same cavity was burnt with immediate effect of vacuum degradation to 10^{-1} mbar from $8x10^{-7}$ mbar. Whereas other two cavities were energized satisfactorily up to 15 kW RF power which is equivalent to 40 kV DEE voltage. Several arching marks at some places of the inner conductor of the coupling capacitor were observed. Copper made argon tube was charred and melted copper drop deposition on the ceramic insulator was noticed. The ceramic insulator acts both as electrical insulator between inner to outer conductor of the coupling capacitor and interface between beam space vacuum (around $8x10^{-7}$ mbar) to atmospheres. Subsequent helium leak testing of the burnt coupling capacitor revealed that ceramic to metal joint was leaking. Therefore in-house fabrication of the coupling capacitor was taken up on top priority basis to short cut the delay in commissioning of the K500 Superconducting Cyclotron.

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DESCRIPTION

Coupling capacitor of K500 Superconducting Cyclotron couples the RF power that is to be fed to the DEE of resonating cavity from amplifier. It is connected to the RF amplifier by coaxial transmission line. Inner conductor of the coupling capacitor is insulated by ceramic insulator made of alumina (99.99 % purity) from its outer conductor. It also acts as interface between beam space vacuum and atmosphere. Therefore the ceramic to metal joint of the insulator should have helium leak tightness of the order of 10^{-9} mbar.lit/s.

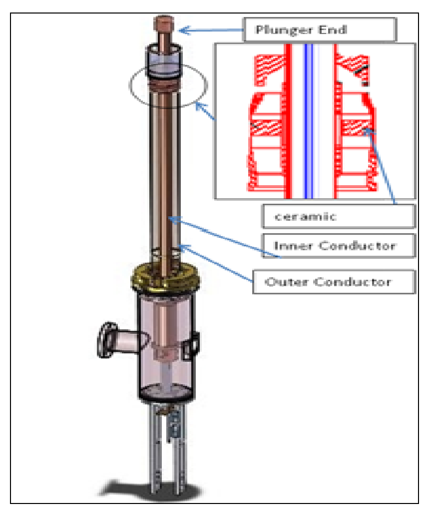

Figure 1: 3D view of the coupling capacitor.

Some part of it is located in the beam chamber vacuum and rest in air. Plunger end of it is positioned within the coupler cup of the DEE after penetrating beam space vacuum from atmosphere. Gap between the plunger and DEE coupler cup is adjusted by moving the inner conductor up and down by hydraulic drive system for the smooth transmission of power. Sliding electrical contact was fabricated by soldering be-cu made contact figure on

DESIGN, CONSTRUCTION AND COMMISSIONING OF THE 100KW RF AMPLIFIER FOR CYCIAE-100

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Abstract

As a major part of the BRIF project, CYCIAE-100, the 100MeV high intensity cyclotron being constructed at CIAE, will provide 200μA-500μA proton beam ranging from 75MeV to 100MeV for RIB production. Two identical 100kW RF amplifiers will be used to drive two cavities independently to accelerate H- beam up to 100 MeV. The detail technical specification has been investigated, fixed, and initial design has been finished by CIAE. Then, the construction design and manufacture is done by China Academy of Aero and Space. The on site test is successful by mutual efforts. The final commissioning is under way with a full scale prototype cavity at CIAE. A general description of the CYCIAE-100 RF system design will be given, as well as the review of 100kW amplifier design. In the commissioning of the amplifier with dummy load, different high order resonances are found when operated at different frequencies between 42MHz to 46MHz. An equivalent circuit model is carried out to hunt down the problems. The model and related analysis will be reported together with the process and results of high power test with the cavity load through about 35-meter 6-1/8” rigid coaxial line.

INTRODUCTION

For the RF system of CYCIAE-100, two 100kW amplifiers will be connected though about 35 meters 6 inch transmission line to power the two cavities individually. A set of digital low level controls will be used to ensure the amplitude of the each cavity, tuning of each cavity and regulation of the phase difference between the two cavities [1][2].

As planned years ago, a full scale OFHC test cavity was fabricated in year 2009, polished and assembled in early 2010. In the mean time, the two amplifiers were designed in year 2008, approved by CIAE, and manufactured by the 23th research institute of CASIC (Changfeng Broadcasting Co. Ltd.). In early 2010, the two amplifiers finished various kinds of factory tests, and one of them is shipped to CIAE cyclotron laboratory. With the full scale cavity and the amplifier on site, the cyclotron laboratory prepared the vacuum system, the water cooling system and the 150kW mains system for the amplifier test with the real cavity load. The amplifier design will be reviewed in Section 2, while the factory test and the on site test with cavity load will be reported in Section 3 and Section 4 respectively. To dump the transmission line high order mode at a frequency of 311.5MHz, a harmonic absorber will be promoted in Section 5 as next step.

AMPLIFIER DESIGN REVIEW

The amplifier chain consists of a 6kW solid driving stage, a 100kW final stage and necessary low level protection circuits.

The driving stage utilizes BLF287 MOSFET as core amplification unit. There are in total 32 these units in the driving stage. The combination of RF power is divided into three stages. Firstly, four 200W units was combined together making an amplification unit capable of delivering 800W power, taking 4U space in a 19 inch cabinet; Secondly, four 800W units combine their power together to get ~3kW RF power; eventually, the two 3kW units were combined together as the driving stage solid amplifier with a capability of delivering more than 6kW power.

The final stage uses a EMAIC 4CW150,000 power tube, a ground grid configuration is selected. To be more specific, both the grid and the screen are RF grounded to the tank wall. Though in ground grid configuration, certain amount of driven power will be directed to output, which in turn means more driven power. Yet, from stability point of view, still it is a good choice for high power amplifiers, especially in the case to power a high Q load, e.g. the cyclotron cavity.

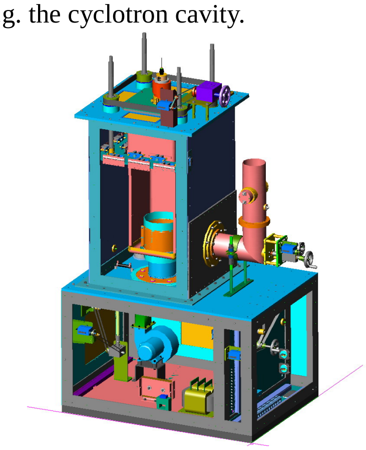

Figure 1: The final stage amplifier

As shown in Fig. 1, the anode tank uses a quarter-wave cavity with a movable short driven by four synchronized worm wheels. The inner conductor is made of copper while the outer is of copper clad aluminium. The output power of the amplifier is channelled out though a

RF CAVITY SIMULATIONS FOR SUPERCONDUCTING C400 CYCLOTRON

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Abstract

The compact superconducting isochronous cyclotron C400 [1] has been designed by IBA (Belgium) in collaboration with the JINR (Dubna). It will be the first cyclotron in the world capable of delivering protons, carbon and helium ions for therapeutic use. $^{12}C^{6+}$ and $^{4}He^{2+}$ ions will be accelerated to the energy of 400 MeV/u energy and extracted by electrostatic deflector, H_2^+ ions will be accelerated to the energy of 265 MeV/u and extracted by stripping. It is planned to use two normal conducting RF cavities for ion beam acceleration in cyclotron C400. Computer model of the double gap delta RF cavity with 4 stems was developed in is a general-purpose simulation software CST STUDIO SUITE. Necessary resonant frequency and increase of the voltage along the gaps were achieved. Optimization of the RF cavity parameters leads us to the cavity with quality factor about 14000, RF power dissipation is equal to about 50 kW per cavity.

RF CAVITY GEOMETRY

Magnetic field modeling and beam dynamics have determined orbital frequency of the ions equal to 18.75 MHz. As RF cavities will be operated in the 4th harmonic mode resonance frequency must be 75 MHz. It is planed to use two normal conducting RF cavities [1] for ion beam acceleration in the C400 cyclotron.

The geometric model of the double gap delta cavity housed inside the valley of the magnetic system of the C400 cyclotron was developed in the CST STUDIO SUITE. We studied a number of models that differ in the width of the accelerating gap, the height of the dee; the final variant of the model is presented in Figure 1. The depth of the valley permits using the cavity with the total height 116 cm. The vertical dee aperture was 2 cm. The accelerating gap width was 6mm at the center increasing to 8 cm at R = 75 cm, and remaining constant to extraction region as shown in Fig. 3.

Distance between dee and back side of the cavity was equal to 50 mm. Cavities have a spiral shape similar to the shape of the sectors. The sector geometry permits azimuth extension of the cavity (between the middles of the accelerating gaps) equal to 45 deg up to the radius of 150 cm, (see Fig. 2). We inserted four stems with different transversal dimensions in the model. We studied different positions of the stems to insure increasing voltage along the radius of the accelerating gap, which should range from 80 kV in the central area up to 160 kV in the extraction region. It is important to have a high value of voltage beginning approximately at R = 150 cm before crossing the 3Qr = 4 resonance.

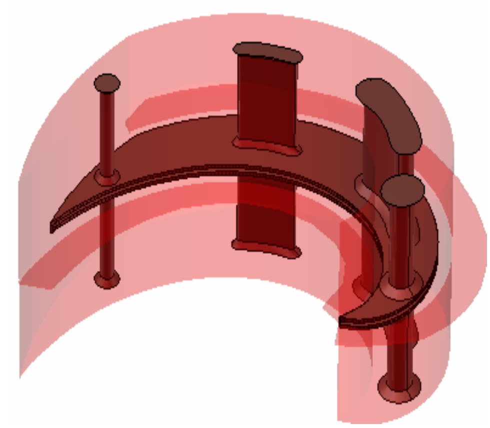

Figure 1. View of the cavity model.

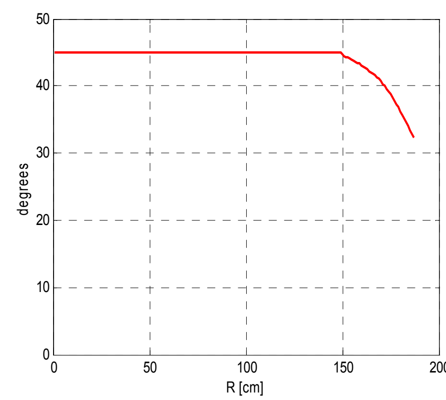

Figure 2. Azimuth extension of the cavities (between middles of the accelerating gaps).

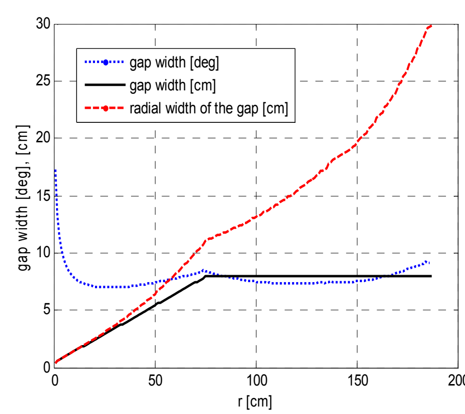

Figure 3. Gap width against radius. Dashed line- radial width in cm, dotted line-azimuth extension in deg, solid line-perpendicular in cm.

TRIUMF CYCLOTRON BOOSTER FREQUENCY TUNING SYSTEM

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Abstract

For the auto frequency tuning of TRIUMF cyclotron booster, a new control module based on the VXI Bus has been designed, tested, and put into commission. This new auto tuning control module, which replaced the old analogue control box, has more features, including the implementation of PIC16C71 microprocessor to generate Pulse Width Modulation (PWM) pulse, the utilization of digital RF phase detector, and the most important aspect of computer control capability. Thus, the resonant frequency of the cyclotron booster RF cavity is tuned automatically by this control module, and the reflected RF power is kept at the minimum level in the operation.

INTRODUCTION

For an accelerator RF cavity, the auto frequency tuning system keeps the cavity at resonant frequency to achieve the desired RF voltage with minimum RF power input. If the RF cavity is out of tune, RF power is partially or totally reflected and the reverse power may damage the RF power amplifier or the transmission line, especially in cases of high power operation.

Thus, the auto frequency tuning system is essential for the RF resonant structure. The TRIUMF RF Booster operates at 92MHz with a nominal voltage of 150kV[1]. In order to realize the auto frequency tuning, two capacitor tuners called Master Tuner and Slave Tuner, are implemented in the TRIUMF cyclotron booster cavity to cover the resonant frequency excursion.

This design uses the microprocessor PIC16C71 to generate a PWM waveform to drive the DC motor of the cyclotron booster tuner. Such a design has good flexibility to adjust the PWM pulse width by using programming software. Furthermore, a digital type of RF phase detector is implemented in the new tuner control module and covers a wider phase error range. These new features make this control module more flexible and reliable.

PRINCIPAL CIRCUITS AND FUNCTIONS

Figure 1 shows the block diagram of the new booster tuner control module. It mainly consists of two logarithmic amplifiers, a RF phase detector, a PIC16C71 microprocessor, a RF amplitude detector, and a driver amplifier.

PIC16C71 Microprocessor

The PIC16C71 is a low-cost high-performance 8-bit micro-controller. It has 36 bytes of RAM and 13 I/O pins. Also, a 4-channel high-speed 8-bit A/D converter is provided within the chip. The 8-bit resolution is ideally suited for applications requiring low-cost analogue interface (e.g. tuner control, thermostat control, etc).

In the booster tuner control PCB, two PIC16C71 microprocessors are used to control the master tuner and the slave tuner separately. For the master tuner PIC16C71 controller, RB0 and RB1 of port B are set up as the PWM pulse output channels. Port A 4-channel A/D converter is set up like the following: RA0 is the RF phase input; RA1 is the RF amplitude input; RA2 is the master tuner position input; and RA3 is the standard ADC reference voltage input. As to the slave tuner PIC16C71 controller, Port B RB0 and RB1 are similarly set up as PWM pulse output channels. Port A RA0 is the master tuner position ADC and RA1 is the slave tuner position ADC.

For timing insensitive applications such as the RF cavity frequency tuning controller, the "RC" oscillator for the microprocessor is good enough to let the controller running. The RC oscillator frequency is mainly a function of the supply voltage, the external resistor (Rext), the external capacitor (Cext) values, and the operating temperature. For Rext values below 2.2kΩ, the oscillator operation may become unstable, or stop completely. For very high Rext values (e.g.1MΩ), the oscillator becomes sensitive to noise, humidity, and leakage. Thus, Rext values should be chosen between 3.3kΩ and 100kΩ. As to Cext, the oscillation frequency can vary dramatically due to residual capacitance with no or small external capacitance. Therefore, it is recommended to choose Cext values above 20pF for noise and stability reasons.

In this design, 3.3kΩ is selected as Rext value and 22pF is selected for Cext. The oscillation frequency is about 6MHz, including residual capacitance on the PCB board.

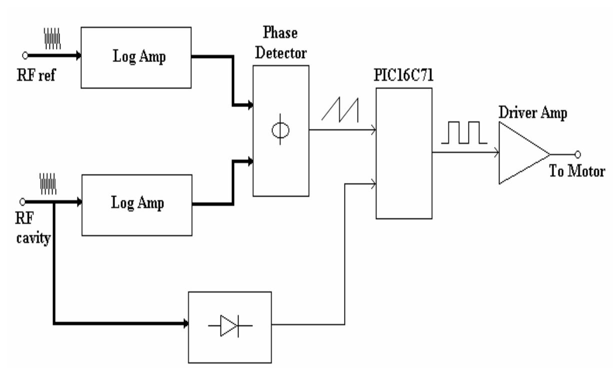

Figure 1: Block diagram of booster tuner control module.

RF Phase Detector

In the old booster tuner control unit, a SRA-1 mixer was used to detect the RF phase error. For the new tuner control module, a different type of phase detector is utilized. This phase detector uses two F100304 chips, which is a low power quintuplet AND/NAND gate chip.

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AMPLIFIER TEST STAND FOR THE CRM CYCLOTRON

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Abstract

The final stage amplifier stability has proved to be an important issue in the commissioning of CRM cyclotron at CIAE. An air cooled 4CX15,000 tube final amplifier was designed to evaluate the anode circuit and neutralization, both of which are weak points of the CRM cyclotron amplifier. Instead of strip line, the new designed anode structure adopts coaxial form, resulting less chance of parasitic resonance in the circuits. A tuneable neutralization circuits was also included in the design, giving an opportunity to fine tune in high power operations. First, the instability in CRM RF system will be analyzed in this paper, followed with the new amplifier designs including the tube operating line calculations, input/output circuits designs and finite integral simulations. The mechanical design for tube socket and anode tank were successfully carried out using the data provided in this paper. The final stage amplifier was then manufactured, assembled and commissioned. In the power test with dummy load, more than 9.2kW RF fundamental power was provided at the frequency of 44.5MHz.

Key Words: RF Amplifier; neutralization; coaxial resonator

INTRODUCTION

In the commissioning of CRM cyclotron at CIAE[1], a parasitic resonance mode was found having significant influence to the RF system stability[2], showing an unreasonable screen current incensement of 200% once the amplifier output exceeds 6kW when driving cavity load. The reason of this parasitic mode concerns the interaction of the transmission line and cavity and will be analyzed in the following section. To solve the instability, the transmission line length was adjusted to multiple of half wave length, and the neutralization of the amplifier was tuned accordingly to have more stable gain margin considering the final stage taking ground cathode configuration[2]. As the plan of upgrading beam current to 1mA put forward, the amplifier anode transformer was changed to a bigger one giving more anode potential, from 7.5kV to 9.2kV, yielding extra 4.5kW output power. In such a case, the stability of the final stage once again is challenged. It was then decided to make an amplifier test stand to evaluate feasibility of high power tuneable neutralization circuits. In the same time, the test stand can be used to test new tubes before it is mounted on the CRM RF amplifier. The frequency of the test stand was decided as 44.5 MHz, in case the 1:1 scale cooper cavity return earlier, it can be used in the cavity power test for 100MeV cyclotron.

The original amplifier of CRM cyclotron was designed and manufactured by a local Chinese company, having 3 parallel strip lines in anode circuits. To have a different choice and expecting less parasitic in anode circuits, the coaxial structure was selected in the amplifier test stand design. Also, the design of the test stand amplifier takes advantage of modern 3D finite integral simulations. While calculation for the active components (e.g. the final stage tube) follows the traditional analytical way, as will be reported in Section 3 of this paper.

INSATBILITY IN THE RF SYSTEM OF CRM CYCLOTRON

The differences between amplifiers used in broadcasting and cyclotron is that for the latter, the amplifier was operated with a narrow band high Q load through a certain length of transmission line[3,4].

The instability showing up in CRM cyclotron RF system is that when the amplifier operated with a dummy load, there was no evidence of instability even at full power level, which is around 10kW[5]. Once connected through about 6 meters rigid 3-inch line to the cavity, it can be stable in low power level. However, if we try to increase power e.g. to 6kW, the screen current will increase rapidly. When continuing to increase the power, the tuning loop in LLRF control starts to tune the cavity in a wrong direction, which will eventually kill the resonance of the cavity.

To evaluate the situation, a set of differential equation model is developed. Specially, in electrical designs, the equation model is often represented as SPICE models.

SPICE Model of CRM RF System

Though modern 3D finite computation tools has offered an integral environment to interactive with electrical design tools, for simplicity, a cavity model was put forward using parameters identified in real operations. In general, the fundamental resonance of a cyclotron cavity can be represented as parallel RLC circuits. Another approach is to split the cavity into two parts: the Dee plate and the coaxial part.

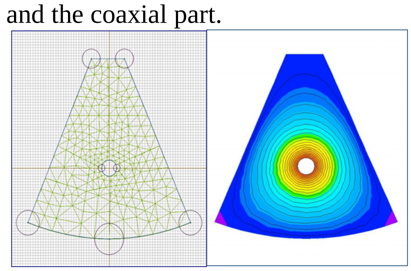

Figure 1: stem impedance calculation

According to the geometry of the cavity[6], in the cavity model, the impedance of two coaxial parts is calculated using analytical equations and 2D Laplace's solver respectively. Then the equivalent components for

CLOSED LOOP RF TUNING FOR SUPERCONDUCITNG CYCLOTRON AT VECC

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Abstract

The RF system of Superconducting cyclotron has been operational within 9 - 27 MHz frequency. It has three tunable half-wave coaxial cavities as main resonators and three tunable RF amplifier cavities. A PC-based system takes care of stepper motor driven coarse tuning of cavities with positional accuracy ~20µm and hydraulically driven three couplers and three trimmers. The couplers, in open loop, match the cavity impedance to 50 Ohm in order to feed power from RF amplifier. Trimmers operate in closed loop for fine tuning the cavity, if detuned thermally at high RF power. The control logic has been simulated and finally implemented with Programmable Logic Controller (PLC). Precision control of trimmer (~20µm) is essential to achieve the accelerating (Dee) voltage stability better than 100 ppm. and also minimizing the RF power to maintain it. Phase difference between Dee-in and Dee-pick-off signals and the reflected power signals (from cavity) together act in closed loop for fine tuning of the cavity. The closed loop PID control determines the final positioning of the trimmer in each power level and achieved the required voltage stability.

INTRODUCTION

The RF cavities are consisting of three numbers of half-wave (λ/2) coaxial sections. Three numbers of RF power amplifiers (each 80 kW) are designed to drive power in each of these RF cavities [4]. These RF amplifiers are narrow band and have to be tuned for the user-required frequency. Output section of each RF amplifier has stepper-motor controlled tuneable sliding short plunger movement system. Similar sliding short movement systems are also developed for the tuning of main resonant RF cavities. There are three numbers of amplifier-cavity and six numbers of main resonator cavities, i.e., nine sliding-short movement system has been developed.

RF TUNING

Because of high-Q (quality factor), both RF amplifier-cavities and main resonator cavities are narrow band structure [2]. From cavity simulation results [1] it is found that in case of main resonator cavities, frequency shift produced at the highest frequency (27 MHz) is around 22 kHz/mm and at the lowest frequency (9 MHz) is around 0.4 kHz/mm. Fine frequency tuning requirement for RF amplifier-cavities is less than that of Main resonator cavities as the former has much less loaded Quality factor (Q). The RF power is capacitively coupled to the dee (accelerating electrode) of the main resonant cavity through Coupler (Coupling capacitor). The coupler is used to match the high shunt impedance of the main resonant cavity to the 50 Ohm output impedance of final RF power amplifier [2]. There is a vacuum variable capacitor formed between a insert and DEE (in each main cavity) called “trimmer capacitor”. Trimmer capacitor operates in closed loop for the adjustment of a small variation in tuned frequency due to thermal effect and beam loading of the cavity. Coupler can travel 100 mm. maximum and trimmer has a maximum of 20 mm. span of travel [5]. The Coupling capacitor and trimmer capacitor movement is based on hydraulic drive system. This system is responsible for the overall tuning of the system in closed loop [3]. Critical coupling between RF amplifier and RF cavity is achieved by analysing impedance matching and minimising VSWR. It also ensures minimal reflection at coupler port.

When RF power is fed to the cavity, it gets detuned because of thermal instability arising due to RF heating. The effect of the cavity tuning error results in decrease in dee voltages and change in phase. The precise movement of trimmer is necessary to compensate the change in volume of the cavity due to thermal expansion. The accurate position and stability depend on the lowest piston speed determined by minimum flow rate. The typical hydraulic valve has dead band and hysteresis error. The dead zone inevitably brings about steady-state position error, so the dead band is set according to position accuracy. The error due to this ultimately affects the stability of Dee voltage substantially. In addition to this variation in dynamic impedance of the RF cavity, increase the VSWR as well as reflected power which is harmful to the RF amplifier. The problem is further complicated as variation in vacuum level occurs due to variation of rf power inside the cavity.

PID CONTROL OF HYDRAULICALLY DIRVEN COUPLERS AND TRIMMERS

This system consists of a proportional-derivative-integral (PID) controller, hydraulic proportional control valve, position sensor and hydraulic drive system. A PID based feedback loop control system is implemented for the positioning of trimmer and coupler. The block

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DESIGN AND PRIMARY TEST OF FULL SCALE CAVITY OF CYCIAE-100

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Abstract

The engineering of the RF cavity for cyclotron concerns several aspects, including the vacuum, cooling, mechanical support etc. Sometimes it is even more complex than RF design itself. Given the space limit in a compact cyclotron, to have a voltage distribution of 60kV in central orbit and 120kV for outer orbit, a double stem double gap lambda by 2 cavity has been designed for CYCIAE-100[1]. The RF resonance of the cavity is simulated [1] by finite integral codes, while the thermal analysis and mechanical tolerance is studied using other approaches[2-3]. The mechanical design and fabrications is then carried out under these directions, resulting in a full scale testing cavity. The simulations and mechanical design will be reported in this paper, followed with low level measurement results of quality factor, shunt impedance curve along accelerating gap etc. After surface polishing, the measurement yields an unloaded Q value of 9300, which matches well with the simulation with a neglectable difference of several hundreds. The high power test of the cavity and will be presented in a separate paper of this conference.

INTRODUCTION

A 100 MeV H^- compact cyclotron, CYCIAE-100, is under construction at China Institute of Atomic Energy (CIAE). It will provide a 75 MeV~100 MeV, 200μA~500μA proton beam [1-2]. In the compact cyclotron, the two cavities are designed to be placed in the two opposite valleys. The operating frequency is in the range of 43MHz ~45MHz, which will be fixed after the magnet field mapping. The unloaded quality factor Q_0 should be not less than 8000. The Dee voltage distribution along radius of the accelerating gap is designed to be 60kV at the central region and 120 kV at the extraction region.[1]

The resonance of the cavity is simulated and the mechanical design has been done accordingly. A 1:1 scale cavity is fabricated using oxygen-free copper, with cooling pipes on the outer surface of the liner, cooling water grooves in the Dee plates and stems as well. The resonant frequency, matching, shunt impedance, etc. are measured and compared with the design value. The difference between them is small and acceptable.

DESIGN OF THE RF CAVITY

The structure of the RF cavity in CYCIAE-100 is complex and a large number of parameters of the structure need to be adjusted. The resonant frequency and the electromagnetic field have been taken into account in design of the cavity; the distribution of cavity power loss should not be ignored at the same time. The RF resonance of the cavity is simulated by finite integral codes.

The preliminary consideration is to adopt the two stems structure to control the voltage distribution well and adjust the frequency by changing the position and diameter of the stems[1]. The structure of cavity is shown in Figure 1[4]

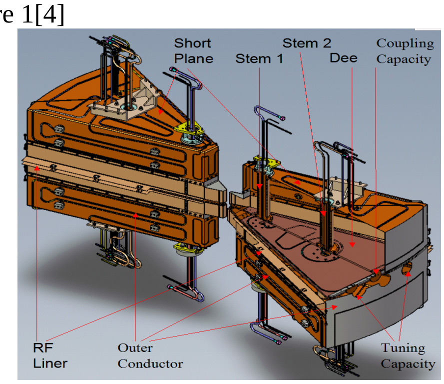

Figure 1: The structure of two stem cavity.

After optimization, the frequency of the cavity simulated to be 44.32MHz, the unloaded Q value is about 10100, Dee-voltage distribution from the center to the extraction area is 60kV to 120kV. The results of the simulation meet the design requirements. The results of the surface current are given by the simulation as well. The power loss distribution of the RF cavity is obvious. The arrangement of the cooling pipes is based on the power loss distribution and the surface current. The E field in the centre plane and the Dee voltage distribution vs. radius are shown in Figure 2.[5] The surface current of the outer conductor and Dee plate are shown in Figure 3.

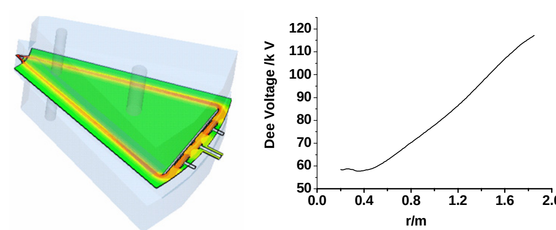

Figure 2: E-Field and the Dee voltage distribution

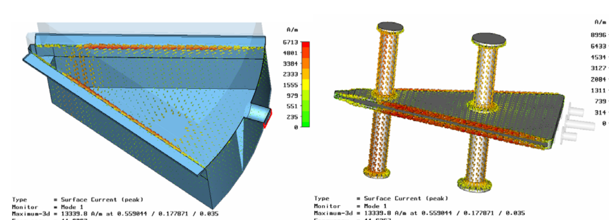

Figure 3: The surface current

STABLE OPERATION OF RF SYSTEMS FOR RIBF

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Abstract

At RIKEN RI-Beam Factory (RIBF), very heavy ion beams like uranium are accelerated up to 345 MeV/u by the RIKEN heavy ion linac (RILAC) and four ring cyclotrons, the RIKEN Ring Cyclotron (RRC), the fixed-frequency ring cyclotron (fRC), the intermediate-stage ring cyclotron (IRC), and the superconducting ring cyclotron (SRC) [1]. In order to provide high intensity beams up to 1 pμA, all the RF systems must be stable enough for a long term (a few weeks) within $\pm$ 0.1% in voltages and $\pm$0.1 degrees in phases. For a stable operation of RIBF, we have started to investigate a degree of stability of the RF systems using a newly developed monitoring system [2]. The efforts to improve the stability will be described.

INTRODUCTION

Since the first beam extraction from SRC in December 2006 [3], intense efforts has been made to increase intensities of several heavy ion beams (^{238}U and ^{20}Ca) with an energy of 345 MeV/u. The goal of beam intensity is 1 puA, whereas maximum beam intensity so far achieved is 0.8 pμA for ^{238}U. In order to achieve this goal, the loss of beams during the acceleration must be minimized. One of the most important factor which makes beams unstable is a fluctuation of accelerating RF. All the RF systems must be stable enough for a few weeks (during a period of operations) within $\pm$ 0.1% in voltages and $\pm$0.1 degrees in phases.

RF CONTROL SYSTEM

Injector Linac RILAC

RILAC consists of 6 tanks [4], and used as an injector for the accelerator complex of RIBF. A block diagram of the RF control system is shown in Fig. 1, which is similar as that for SRC [5]. The reference signal from a master oscillator is divided by a power divider, and is delivered to each tank of RILAC. The RF phase and voltage are stabilized by Auto Phase Control (APC) and Auto Gain Control (AGC), respectively. The grid and plate pickup signals are used to tune a resonant frequency of the tanks through Auto Tune Control (ATC). The main parts of the feedback control circuits (AGCs for tank #5 and #6, and all the APCs) are temperature regulated so that the circuits operates stably. These low level circuits for RILAC were designed to have a stability of $\pm$ 0.1% in voltages and $\pm$0.1 degrees in phases, which is the same specification as that for SRC. Four old type AGSs, which were without temperature control, were upgraded to the new type (the same as that used for #5 and #6) by September 2009.

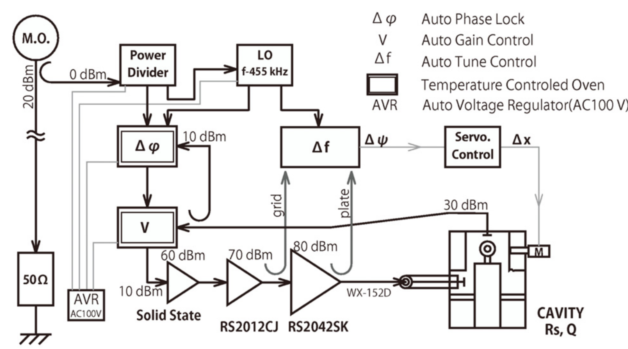

Figure 1: Block diagram of the RF system for RILAC.

Four Cyclotrons, RRC, fRC, IRC, and SRC

In the case of RRC, the low level circuits designed when RRC was constructed (in 1986) had been used until 2008. In order to maintain a relative RF phase between two cavities (#1 and #2), the phase of #1 is locked to the pickup phase of #2. This method was not applied for the other cyclotrons (each cavity is self-locked). It was found that this phase lock system for RRC fails to maintain relative phase in the uranium acceleration (see Fig. 5), which is partly due to a low dee voltage ($\sim$ 70 kV/gap) and low pickup signal. Therefore, all the low level circuits were upgraded to fulfill the stability requirement in September 2008.

The RF control systems for SRC, IRC, and fRC are essentially the same. For details of SRC, refer to Ref. [6].

MONITORING SYSTEM OF RF VOLTAGES AND PHASES

Since several accelerators are used in cascade at RIBF, it is important to maintain the accelerating RF and the matching of beam phases between accelerators. For a stable operation of accelerators in RIBF, a monitoring system using Lock-In-Amplifiers (LIA) SR844 [7] was developed to monitor continuously all the RF voltages and phases as well as the beam intensities and phases [2]. SR844 has a bandwidth of 25 kHz to 200 MHz, which is suitable for the operational RF frequency from 18 to 165 MHz at RIBF. The resolution of LIA was evaluated to be $\pm$ 0.1% in voltage and $\pm$0.03 degrees in phase.

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DESIGN OF IBA CYCLONE® 30XP CYCLOTRON MAGNET

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Abstract

IBA is currently developing an evolution of its famous Cyclone® 30 cyclotron. The Cyclone® 30XP cyclotron will be a multi-particle, multiport cyclotron capable of accelerating alpha particles up to 30 MeV (electrostatic extraction), deuteron (D^-) beams between 7.5 and 15 MeV and proton (H^-) beams between 15 and 30 MeV (stripping extraction). The magnet system has been updated with improved versions of IBA Cyclone 18/9 and Cyclone 70 features.

At first, coil dimensions have been updated in order to raise the free space in the median plane to allow mounting a retractable electrostatic deflector system for the extraction of the alpha particle beam. Gradient corrector pole extensions, have been added to ease the alpha beam extraction. Finally, compensation for relativistic effects between H^- (q/m=1/1) and D^-/alpha (q/m=1/2) beams is made by the use of movable iron inserts located in two valleys, as is done in IBA Cyclone® 18/9 cyclotrons.

These modifications could have an adverse effect on the flutter. In addition, the second harmonic induced by the movable iron inserts drives the machine in the $2.\nu_r=2$ resonance close to the extraction. As a consequence, modifications on the pole sectors and chamfers have been made in order to improve the flutter and eliminate harmful resonance up to extracted energies.

After the presentation of the magnet features, some results on beam extraction are also discussed.

INTRODUCTION

IBA, with more than 20 years of experience in building commercial cyclotrons is developing a new version of its first accelerator: the Cyclone® 30XP.

The Cyclone® 30XP will be able to accelerate beams of H^- ions up to 30 MeV, D^- up to 15 MeV and $^4He^{++}$ (α) to 30 MeV. At first glance, it is an extension of the Cyclone® 30 with Cyclone® 18/9 and Cyclone® 70 magnet features [1,2], but a closer look shows it is a bit more complex.

MAGNET FEATURES

As the α-beam will be extracted by means of an electrostatic deflector, the first modification with respect to classical Cyclone 30 was to reduce the height of the coils in order to allow for deflector and deflector movement mechanisms installation.

Then, movable iron inserts have been installed in two valleys out of four to compensate the differential relativistic mass increase between H^- and D^-/α.

Finally, gradient correcting pole-extension have been added in order to ease the extraction of α beam. Such pole extensions are installed on the IBA Cyclone® 70.

Figure 1 shows a schematic of the preliminary design with the added features.

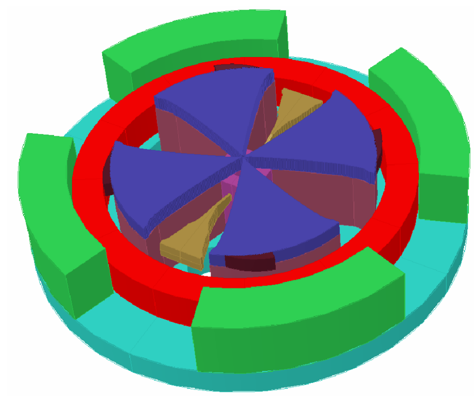

Figure 1: Early structure of the Cyclone® 30XP magnet. One can see the coils (red), poles (in purple), sectors (underneath the poles), movable iron inserts (light brown) and pole extensions (dark purple).

POTENTIALLY HARMFUL RESONANCES

Both the movable iron inserts and the pole extensions have a negative impact on the cyclotron beam optics.

Indeed, the magnetic field change obtained by the movable inserts is as high as 200 Gauss (Figure 2). This implies that the second harmonic of the field changes by the same amount. In addition, the flutter is also reduced when the magnet is in H^- configuration.

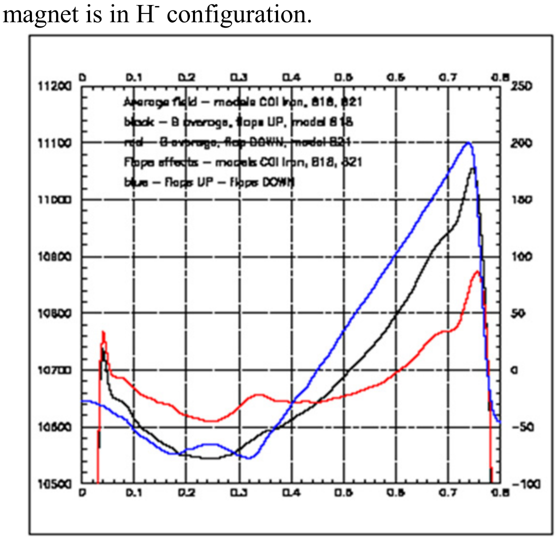

Figure 2: Average field with flaps up (black), down (red) and net effect of the flaps (blue, right scale).

The pole extensions further reduce the flutter by diverting part of the pole's magnetic flux. One can choose to have one, two or four pole extensions, trying to find a compromise between minimal field reduction or minimal impact on first and second harmonics.

DESIGN OF IBA CYCLONE®11 CYCLOTRON MAGNET

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Abstract

The development of a new Cyclone®11 11MeV H^- cyclotron is in progress at IBA. Such machine is designed for the production of radionuclides for nuclear medicine. This cyclotron is based on the existing Cyclone®10 that has been boosted to more than 11 MeV with as minor as possible change to the Cyclone®10 geometry. At first, the magnetic field has been raised by a small reduction of the valley depth. Additionally, the main coil current has been increased. Pole edge milling has been used to obtain the isochronous magnetic field shape. Beam optics in the magnet is excellent. Extraction is ensured by means of stripper foils mounted on carousels located at different azimuths allowing installation up to eight targets and dual beam extraction.

INTRODUCTION

To extend customer choice in the low energy range, IBA is developing the Cyclone®11. It is a fixed energy 11 MeV H^- cyclotron for the production of PET isotopes. The cyclotron magnet is based on the well known Cyclone®10/5 [1,2] with the same yoke dimensions, which is compatible with the IBA self-shielding design [3]. The higher proton energy compared to the 10 MeV machine is beneficial for higher PET isotope production yield.

CYCLOTRON MODEL

The 3D model of the Cyclone®11 cyclotron is based on the Cyclone®10/5 geometry and is shown in figure 1. The movable inserts have been removed and the isochronous magnetic field is obtained by milling one pole edge on each pole. The 90° symmetry has been used for the magnetic field study and 180° symmetry for the extraction study.

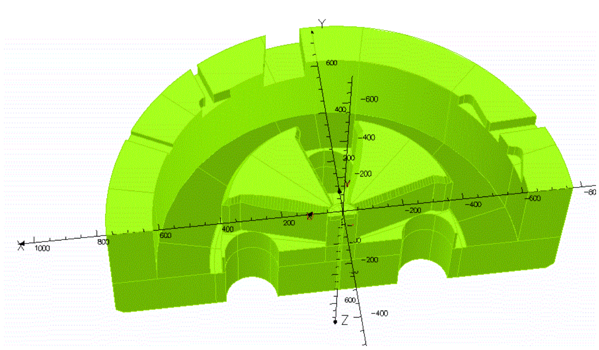

Figure 1: Opera-3D 180° symmetry model of the Cyclone®11 cyclotron.

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MAGNETIC FIELD REQUIREMENTS

The magnetic rigidity is proportional to the particle momentum. Therefore, the energy that can be extracted at a given radius in a cyclotron is proportional to the square of the magnetic field. Hence, the relative increase of energy ΔE/E is

$$\Delta E/E = 2\Delta p/p = 2\Delta B/B \qquad (1)$$

According to the Cyclone®10/5 mapping results, the magnetic field should be increased by at least 520 Gauss to be able to extract H^- at 11.0 MeV instead of 10.2 MeV. The magnetic field increase can be provided by a higher main coil current and/or a reduced valley depth. The magnetic field study has been performed using the TOSCA magnetostatic solver of Opera-3D.

Effect of the Main Coil Current

To increase the average magnetic field, the current in the main coil can be increased. The 90° symmetry model without addition of iron in valleys has been simulated for different main coil currents (176 A, 186 A, 196 A). The resulting increase in the magnetic field is shown in figure 2. The average magnetic field gain at the level of the poles is about 160 Gauss per 10 A. The study has also shown that the quality of the iron has very little effect on the field gain.

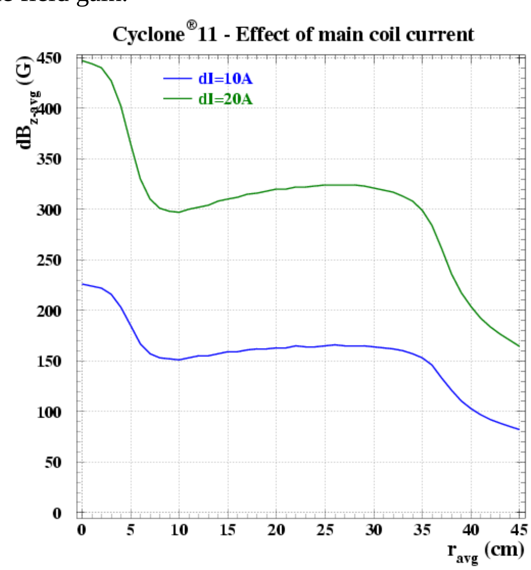

Figure 2: Magnetic field increase as a function of radius for different main coil current increase. The reference map (dI=0 is at IMC=176 A).

VACUUM SYSTEM OF HIRFL'S CYCLOTRONS

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Abstract

HIRFL has 2 cyclotrons: a sector focus cyclotron (SFC) and a separate sector cyclotron (SSC). SFC was built in 1957. In the past 50 years, the vacuum system of SFC has been upgraded for three times. The vacuum chamber was redesigned to double-deck at the third upgrade. The working pressure in beam chamber was improved from 10^{-6}mbar to 10^{-8}mbar. SFC has delivered Pb, Bi and U beams in the past few years since the last upgrading of its vacuum chamber. SSC began to operate in 1987. The vacuum chamber of SSC has a volume of 100m^3. 8 cryopumps keep the pressure from 5×10^{-7}mbar to 8×10^{-8}mbar depending on the used pump numbers (2~8). In the past 20 years, because of the contamination of oil vapour and leaks occurred in some components inside the SSC vacuum chamber, the vacuum condition has worsened than the beginning. It is a big problem to accelerate the heavier ions. The upgrade for the SSC vacuum system will be an urgent task for us. The rough pumping systems of both SFC and SSC have been rebuilt recently. As a result, the oil vapour in two cyclotrons will be eliminated and the vacuum condition of them will be improved.

A new small cyclotron will be built in HIRFL as an injector of the Heavy Ion Therapy Facility in Lanzhou (HITFiL). The brief introduction of the vacuum system design is given in the paper.

VACUUM SYSTEM OF SFC

SFC with the energy constant of 69 is the injector of SSC and HIRFL-CSR [1]. It was built in 1957. In the past 50 years, the vacuum system of SFC has been upgraded for three times. The working pressure was improved from 10^{-6}mbar to 10^{-8}mbar. At the third time, the vacuum chamber was redesigned to double-deck [2] (Fig.1). All components with large gas load such as magnet cores, coils and hundreds of electric wires were put into the insulation chamber where the pressure is 10^{-1}mbar pumped by a mechanical pump. Consequently, a pressure of 10^{-8}mbar can be obtained in the beam chamber by 2 cryopumps with a total pumping speed of 40000 l/s. Because the beam chamber was made of thin copper with a thickness of 4mm, the safety valves both in mechanical mode and electrical mode were installed between the two chambers, which are interlocked with the pressure sensors to protect the copper chamber from the damage.

After this upgrade of the vacuum system, 1.1 MeV/u $^{208}Pb^{27+}$ beam was accelerated to confirm the vacuum effect, which turned out that the upgrade of the SFC vacuum chamber was successful. SFC has delivered $^{208}Pb^{27+}$, $^{209}Bi^{31+}$, $^{238}U^{26+}$ beams in the past few years since the last upgrade of the SFC vacuum chamber. So, the heavy ions from C to U can be accelerated in SFC.

Figure 1: SFC double-deck vacuum chamber

VACUUM SYSTEM OF SSC

SSC with the energy constant of 450 began to operate in 1987. It provides beams to about 10 experimental terminals and is also the injector of the cooling storage ring (HIRFL-CSR). The vacuum chamber of SSC (Fig.2), which was made of 316L stainless steel with a permeability of 1.01, has a volume of 100m^3. The magnet cores, RF cavities, injection and extraction components were inside the vacuum chamber with a large gas load. 8 cryopumps with a pumping speed of 20000 l/s for each were installed in the chamber. Depending on the accelerated heavy ion species, 2~8 pumps were used to keep the pressure from 5×10^{-7}mbar to 8×10^{-8}mbar.

SSC has operated for more than 20 years. Because of the contamination of oil vapour and leaks occurred in some components inside the SSC vacuum chamber, which were very difficult to eliminate, at present the pressures in four vacuum gauges which were installed in different positions were $2\sim4\times10^{-7}$mbar with 6 cryopumps operating. It was a big problem to accelerate the heavier ions although the $^{209}Bi^{31+}$ beam was delivered recently. The upgrade for the SSC vacuum system will be an urgent task for us. In order to improve the vacuum condition, one measure is to change the old pumps which have exceeded the time limit by new ones; second measure is to try to reduce the system leaks and the third one is to eliminate the oil vapour contamination.

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UPGRADE OF IBA CYCLONE® 3 CYCLOTRON

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Abstract

Some specific applications of $^{15}O_2$ need a stand alone production machine to avoid disrupting the hospital main PET cyclotron. Due to recent renewal in interest, IBA has decided to improve the design of its Cyclone® 3 which accelerates D^+ ions to energy of more than 3 MeV and which was originally developed for this purpose.

The main improvement relates to the magnetic structure. In the existing design the vertical focusing is obtained by four straight pole-sectors that are mounted on the circular base of the pole. In the new design these are replaced by three spiralled pole sectors. This modification changes the rotational symmetry from four to three and improves the vertical focusing properties of the machine. Also the main coil and the return yoke were slightly modified. This allowed increasing the extraction energy by about 10 % from 3.3 MeV to 3.6 MeV.

This new design will improve the transmission in the cyclotron and will result in an extraction efficiency of more than 80% using an electrostatic deflector. For the prototype the goal is to obtain an extracted current of 50 µA. This value should rise to 70 µA for subsequent machines, representing a doubling of the existing performance.

In the paper, results of magnetic field optimization and extraction calculations are presented.

INTRODUCTION

The Cyclone® 3 has been developed in the early nineties [1-6] as a very compact cyclotron for stand alone production of Oxygen-15 in open flow. Even if still in use, only few machines have been sold. Recently, new markets have shown more interest in the Cyclone® 3 concept. An example is the promotion of new emergency-room evaluation of brain stroke and ischemic attack in remote centres.

As a consequence, IBA decided to review its Cyclone® 3 design and improve it. This paper describes the modifications made on the magnetic circuit of the cyclotron to improve its expected performances.

MAGNET FEATURES

In its first version, the Cyclone® 3 had 4 magnetic poles (fig. 1). That choice was rather natural to avoid impedance imbalance between the two RF cavities. The Cyclone® 3 is equipped with two 90 degrees dees. However, such design had two major drawbacks:

1. Due to the hill-valley small gap difference, the flutter was relatively low and vertical (axial) betatron frequency was about 0.15. This ensures the minimal axial focusing but is far from the axial focusing provided by IBA patented deep valley design.
2. Due to the size of the machine and available space between poles there was very limited place for the electrostatic deflector.

IBA took some distance with its habit to have four-fold rotational symmetry cyclotrons and proposed a new design with only 3 poles that are spiralled to increase the axial betatron oscillation frequency. This new design has the additional advantage to leave more room for the extraction system. The schematic view of the new magnet is shown on figure 2.

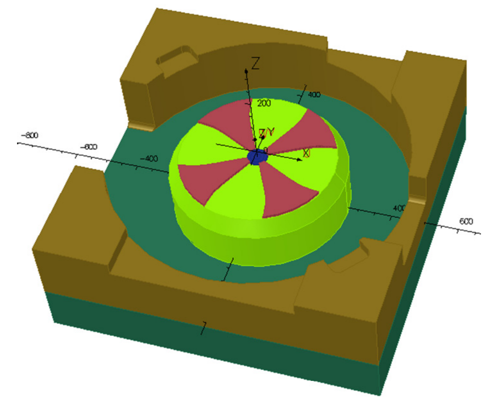

Figure 1: Previous design of the Cyclone® 3 (coils not shown).

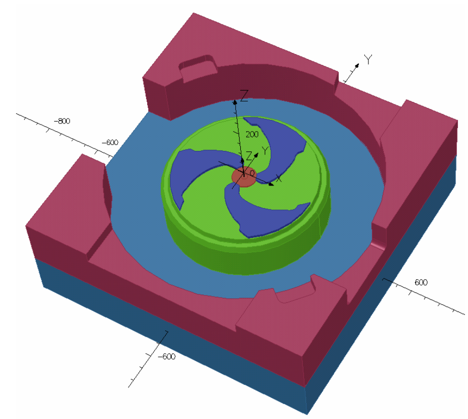

Figure 2: New design of the Cyclone® 3 (coils not shown).

It is also worth to mention that the outer contour of the cyclotron yoke has been modified to limit iron saturation effects.

CLOSED ORBIT ANALYSIS

The OPERA models have first been used to obtain a nominal configuration that is isochronous and shows reasonable frequencies of betatron oscillations.

After a classical correction of the field in the hard-edge approximation, the model proved to be isochronous with the (second harmonic mode) RF

CYCLOTRON VACUUM MODEL AND H- GAS STRIPPING LOSSES

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Abstract

A model to compute the vacuum in the different parts of IBA H- cyclotrons has been developed. The pressure results are then used to compute the beam transmission through the cyclotron by integration of the residual gas stripping cross-section along the ion orbits. The model has been applied to the ARRONAX Cyclone®70 with the initial vacuum design and the results are compared to the experimental data. The pressure and the transmission are in good agreement with experimental data.

INTRODUCTION

Many proton cyclotrons use the advantage of stripping extraction, by accelerating H- ions. However, before extraction, the negative ion beam can suffer losses from stripping by the residual gas. The higher is the pressure, the higher are the losses. Moreover, the stripped beam will be stopped on the inner wall of the cyclotron, inducing an additional degassing that increases the pressure and hence losses in the cyclotron. For high beam currents, degassing can be too large compared to the pumping capacity and the beam transmission can drop down to zero. The pressure inside the cyclotron has therefore a large impact on the current that can be extracted from the cyclotron. A simple model has been set up at IBA to determine the vacuum pressure in the hills and in the valleys of the Cyclone®70 and then deduce the beam transmission.

MODELS

A first model to compute the beam transmission through the cyclotron has been set up. The succession of hills and valleys leads to pressure inhomogeneities in the machine. Therefore, we have set up a model to compute the vacuum in the pole gaps and in the valleys.

Beam Transmission

The number *dN* of H- ions that can be stripped by the residual gas is obtained from:

$$dN = -\sigma n N v dt \qquad (1)$$

where N is the number of incident ions; dt is the time spent by the ions in the residual gas of atomic density n; v is the ion velocity; and σ is the total stripping cross section. We use the analytical fit proposed by the Nakai et al to compute the stripping cross section [1]. The beam transmission in an isobar region for particles with a transit time t is:

$$T = 1 - \frac{\Delta N}{N} = \exp(-vtn\sigma) \qquad (2)$$

The residual gas analysis (RGA) performed on ARRONAX Cyclone®70 have shown that the residual gas was composed mainly by 70% of H_2O, 30% of air and 0.15% of rare gas. However, the parameters of the Nakai et al fit are not reliable for water in the Cyclone®70 energy range. Therefore, we consider the worst case scenario (i.e. largest stripping cross section) of 100% O_2. The cyclotron has been subdivided into three isobar regions: the poles at pressure p_1, the pumping valleys at pressure p_2 and the RF valleys at pressure p_3. The ion orbit is supposed straight segments in valleys and circular arcs in hills (figure 1). The particle track length in the hills and in the valleys is obtained from:

$$r_{magn} = (B\rho)/B_z \qquad (3)$$

$$l_{hill} = \frac{\pi}{2} r_{magn} \qquad (4)$$

$$l_{valley} = \frac{r_{magn}\tan(v)}{1-\tan(v)} \qquad (5)$$

The injection energy is 40keV. Acceleration is supposed to occur once a turn with an energy equal to the energy gain per turn defined by:

$$\mathrm{d}E = q \cdot V_{RF} \cdot 2 \cdot n_{dee} \cdot \sin\left(\frac{\delta}{2} \cdot h\right) \qquad (6)$$

where q=1 is the particle charge, V_{RF}=65kV is the RF voltage, n_{dee}=2 is the number of dees (two gaps per dee); δ=36° is the dee angle; and h=2 is the harmonic mode.
The total transmission is the product of the transmission in the eight regions (4 poles and 4 valleys) for each ion energy.

Vacuum

As the ion travels along its trajectory, it sees a series of vacuum chambers of infinite conductance (valleys) and conducts of finite conductance (hills). However, in the RF valley, the dees limit the conductance and have to be taken into account. The two-fold rotational symmetry allows us to consider only a half-cyclotron as shown on figure 1. Without the beam, the main contribution of

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OPERATIONAL EXPERIENCE OF SUPERCONDUCTING CYCLOTRON MAGNET AT VECC, KOLKATA

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Abstract

The Kolkata Superconducting cyclotron magnet has been operational in the Centre since last few years and enabled us to extensively map magnetic fields over a year covering the operating range of the machine and successful commissioning of internal beam. The magnet cryostat coupled with the liquid helium refrigerator performs satisfactorily with moderate currents (<550A) in both the coils. The superconducting coil did not undergo any training and over the years has not suffered from any quench. Author would share the experience and difficulties of enhanced overall heat load to the liquid helium refrigerator at higher excitations of coils. This creates instability in the operation of liquid helium refrigerator and finally leads to slow dump. Rigorous study has been carried out in this regard to understand the problems and operational logic of liquid helium refrigerator has been modified accordingly to alleviate from. Some other measures have also been taken from cryostat and cryogenic distribution point of view in order to reduce the heat load at higher excitations, optimize the current lead flow, etc.

INTRODUCTION

Variable energy cyclotron centre, Kolkata is successfully operating its superconducting cyclotron main magnet since 2006 that enables us to successfully map magnetic fields over a year covering the operating range of machine and successful commissioning of internal beam. The K-500 Superconducting Cyclotron (SCC) main magnet consists of two superconducting coils (alpha coil and beta coil), which has been energized to different current levels for extensive magnetic field measurement. An annular vacuum chamber, made of magnetic steel, referred as cryostat OVC, surrounds the stainless steel cryostat bobbin. In the following sections, several operational problems of cyclotron magnet encountered over the past few years have been explained.

EXPERIMENTAL OBSERVATIONS

OVC Vacuum during Liquid Helium Filling up

Moisture level in the cryostat was brought down to 20ppm before starting up of cool down process. During the process of cool-down tension in radial support link increases gradually. The positional adjustment is necessary, if the force approaches a maximum allowable level by tightening/loosening the support bolts attached with each link.

It was found that helium leakage would change as the cryostat was filled with liquid helium. Correlating the helium leakage rate with the liquid helium height of cryostat has allowed vertical location of leakage to be found as shown in figure 1.

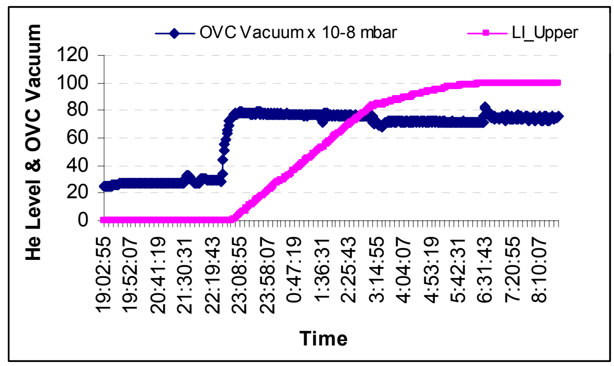

Figure 1: OVC vacuum during liquid helium filling up

Due to inaccessibility of the location of leak (~ low 10^{-4} mbar-lt/s) inside the cryostat, it was not feasible to repair it. However, there are several very small leaks found in the outer median plane region of cryostat and repaired those successfully.

OVC Vacuum during Energization

It is observed that the OVC vacuum deteriorates with current as shown in figure 2. It is interesting to note that the degradation of OVC vacuum is dependent mainly on the current in alpha coil, which is nearer to the median plane. In this regard, detail study has been carried out [1]. Being nearer to median plane, alpha coil has more contribution of magnetic field than beta coil, in the median plane region of OVC. For alpha current of 600 A and beta current of 400 A, OVC vacuum degrades to 3.0E-4 mbar.

Additional pumping module of pumping speed for He ~300 lt/s has been installed with the OVC annular space to improve the vacuum to low 10^{-5} mbar. In addition, observations are kept on cryogenic transfer line if any frostings occur over it and annular space is evacuated to a vacuum level better than 1E-6 mbar.

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MEDIAN PLANE EFFECTS AND MEASUREMENT METHOD FOR RADIAL COMPONENT OF MAGNETIC FIELD IN AVF CYCLOTRONS

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Abstract

The median plane of the magnetic field in AVF cyclotrons rather often does not coincide with the mid-plane of their magnetic system. The idea of an effective median plane formulated by J.I.M.Botman and H.L.Hagedorn [1] for the central region of the cyclotron is extended to the entire working region and tolerances for the horizontal components of the magnetic field are estimated. Equipment based on the search coils is proposed and used for measurement of the radial component of the magnetic field and for correction of the magnetic field median plane.

INTRODUCTION

The vertical deviation of the beam center from the median plane of the vacuum chamber was observed and corrected at some cyclotrons (AVF Cyclotron, Einhoven, Netherlands [1], AGOR, Groningen, the Netherlands [2], U-120M, Rzez, Chech Republic [3], AIC-144, Krakow, Poland [4], JINR Phasotron, Dubna, Russia [5]). Thus it is very important for the cyclotron design to be clear in knowing the tolerances for horizontal components of the magnetic field, their relation to the manufacturing tolerances for magnetic and current elements and the method of magnetic field measurement and correction.

EFFECTIVE MEDIAN PLANE AND TOLERANCES FOR HORIZONTAL COMPONENTS OF THE MAGNETIC FIELD

When the median plane of the magnetic field is symmetric, the equation of free vertical oscillations of the particle near the median plane of the vacuum chamber is:

$$z'' + \nu_z^2 z = 0 \qquad (1),$$

where ν_z^2 is the total vertical focussing force of the magnetic and electric field. When the symmetry of the magnetic system is lost, the horizontal components (B_r and B_φ) of the magnetic field appear in the vacuum chamber median plane. In this case the magnetic field median plane is not physically the plane where B_r and B_φ are equal to zero at the same time. Stable vertical oscillations exist now near the effective medial plane (EMP) (Z_{eff}):

$$z'' + \nu_z^2 (z - Z_{eff}) = 0 \qquad (2).$$

Physically the EMP is the plane in which the sum of all vertical forces acting on the particles is zero. If in the cyclotron there are some vertical forces with factor ν_{zi}^2 and zero point Z_i, the position of EMP can be evaluated as:

$$Z_{eff} = \Sigma_i (\nu_{zi}^2 \cdot Z_i) / \Sigma_i \nu_{zi}^2 \qquad (3)$$

or

$$Z_{eff} = \Sigma_i (\nu_{zi}^2 \cdot Z_i) / \nu_z^2 \qquad (4).$$

The main physical conclusion from (4) is that the influence of each vertical force in the AVF cyclotron on the vertical position of the EMP depends on the relative contribution of this force to the total vertical force ν_z^2.

In a classical cyclotron there is only one vertical force generated by the average radial component of the magnetic field, and the vertical beam position follows the position of the plane with $B_{r\,aver} = 0$. In the AVF cyclotron there are basically two vertical forces, the defocussing force generated by the average radial component of the magnetic field and the focussing force generated by the horizontal components of the magnetic field azimuth variation. When the plane with $B_{r\,aver}=0$ shifts, the vertical beam position follows the plane with the overall vertical force equal to 0 (Fig. 1).

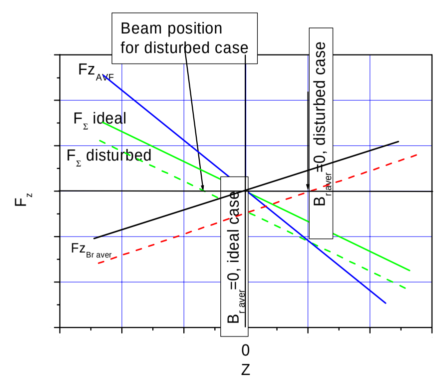

Figure 1: AVF cyclotron: vertical beam position follows the plane with zero overall vertical force

If the vertical component of the cyclotron magnetic field is written in the form

$$B_z = B_{zav} + \Sigma_i B_{zi} \cdot Cos[i(\varphi - \varphi_{zi})] \qquad (5),$$

the vertical beam center position, which arises due to the average radial field component (B_{rav}), and the main (N) harmonic of the radial and azimuth component (B_{rN}, $B_{\varphi N}$), may be found as:

$$Z_{eff} = R / (B_{zav} \cdot \nu_z^2)[B_{rav} + 0.5(B_{zN} / B_{zav}) B_{\varphi N} / N \cdot Sin\{N(\varphi_{\varphi N} - \varphi_{zN})\} - (B_{zN} / B_{zav}) \cdot B_{rN} \varphi'_{zN} R / N \cdot Sin\{N(\varphi_{rN} - \varphi_{zN})\}] \qquad (6).$$

If we take into account only the part of B_{rN} and $B_{\varphi N}$ in the form of their projections on the vector shifted by $\pi/2/N$ from the vector with the phase of the main vertical harmonic designated as B_{rNs}, $B_{\varphi Ns}$ (only these horizontal components of the magnetic field give the vertical force

STUDY OF MAGNETIC FIELD IMPERFECTIONS OF KOLKATA SUPERCONDUCTING CYCLOTRON

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Abstract

Analysis of the magnetic data obtained during the magnetic field mapping of Kolkata superconducting cyclotron showed imperfections in the main magnetic field. Since the main magnet of the superconducting cyclotron is three fold rotationally symmetric, any deviation from this symmetry creates imperfections in the magnetic field. Generally, 1st and 2nd harmonic components are inherently present in the field due to assembling errors in iron/coil. A major portion of these imperfections is attributed to the misplacement/tilting of the iron pole tip with respect to coil. The error in positioning of main superconducting coil with respect to surrounding iron produces another imperfection. Pole tip deformation due to rise of temperature produces field imperfection. This paper reports the various possible sources of imperfection in general and their estimation. The calculation was compared with measured data to find out the actual cause of imperfections and necessary corrections have been carried out.

INTRODUCTION

The Kolkata superconducting cyclotron magnet was commissioned and detail magnetic field mapping and corrections was carried out [1]. Measured data is analysed for field imperfection studies. It is found that the imperfections exist and it is required to identify the actual cause of imperfection in order to carry out the necessary corrections. Magnetic field has three fold rotational symmetry with respect to its axis and mirror symmetry with respect to the median plane. Any deviation from these symmetries creates imperfections in the magnetic field and can be express in terms of different harmonics. A first harmonic of 2 or 3 gauss is sufficient to disturb the beam as it passes through a νr= 1 resonance. This paper discusses the different sources of imperfections in general and it's analysis, which was carried out to estimate such errors. The calculation was compared with measured data to find out the actual cause of imperfections and necessary corrections have been carried out.

MODEL & ANALYSIS

Three-fold symmetry dominated magnetic field distribution is a characteristic feature of the three-sector geometry of this cyclotron. Deviation from the three-fold symmetry arises out of manufacturing tolerances and assembling errors, which create, unwanted harmonics (especially 1st and 2nd harmonics). The contribution of field imperfection comes from the positional errors of superconducting coil and sectored iron pole tips. A major portion of these imperfections is attributed to the misplacement/tilting of the iron pole tip, which produces the main azimuthal variation in the field. It is important to determine the positioning errors of the pole pieces by calculating field imperfections produced from combinations of simple displacement of pole pieces and comparing it with the measured data. The presence of very large magnetic field (~5T), in the superconducting cyclotron creates saturation of iron pole tips near the median plane. So, in the model used to calculate magnetic field produced by asymmetric pole tips, it is assumed that the iron is uniformly magnetised in the vertical direction. And the field can be represented in terms of surface current distribution flowing in the direction perpendicular to magnetization direction in a closed loop. The magnetization current density is given by $\vec{J} = \vec{\nabla} \times \vec{M}$, where $\vec{M}$ is magnetization vector of iron [2]. The accuracy of the calculated field is reasonably satisfactory and calculation of this type has long been used [3]. The uniform M calculations are faster and in view of the reasonable accuracy, we have adopted this method to compute the field of 3-dimensional pole tips.

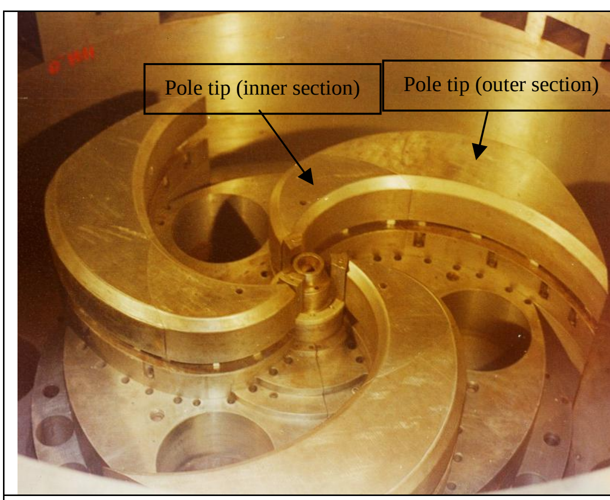

Figure 1. Pole tips view from the top

We have taken saturation magnetization M=21.4 kG. For a given geometry of the iron piece, the code generates the magnetic field using Biot Savart's law and carries out Fourier analysis to calculate field imperfections in terms of different harmonics.

The error in positioning of main superconducting coil with respect to the iron pole pieces produce 1st harmonic which is dominating at higher radius. Tilting of coils and

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OPTIMIZATION OF SECTOR GEOMETRY OF A COMPACT CYCLOTRON BY RANDOM SEARCH METHOD

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Abstract

This paper describes the procedure of optimizing the sector geometry of the magnet to obtain the desired isochronous field. The hill shape of the magnet is described in terms of a small number of parameters which are iteratively determined by random search technique geared to minimize the frequency error. 3D magnetic field data and results of equilibrium orbit code are used as input for the iterative optimization process.

INTRODUCTION

A 10 MeV, 5 mA four sector compact cyclotron for proton is under development at VECC Kolkata. Proton beam at 80 keV from 2.45 GHz microwave ion source (under testing) will be first collimated and bunched [1]. It will be injected axially in the central region where a spiral inflector will place the beam on the proper orbit. Two delta type resonators located in the opposite valleys will accelerate the beam and an electrostatic deflector will be used for the extraction. In general the magnet pole shimming is an iterative process [2,3]. Analytical formulas [4,5,6] are available for calculating the average magnetic field and betatron frequencies for a given configuration of the magnet geometry. But these formulas are not valid for high flutter field and particularly at the lower radii in the case of a compact cyclotron. Hence an equilibrium orbit code becomes necessary to obtain the frequency error. An acceptable phase shift of the particles with respect to rf determines the tolerance of the magnetic field isochronism. In this paper we present a shimming method, which gives smooth sector geometry of the hill. We have approximated the shape of the sector by a polynomial function of the radius, and minimized the frequency error by optimizing the coefficients of the polynomial by using random search technique.

METHOD OF OPTIMIZATION

We have used a 3D magnetic field code MagNet [7] to calculate the field in the median plane and obtained the frequency errors as a function of energy using equilibrium orbit code GENSPEO [8]. These frequency errors are then minimized by modifying the sector geometry.

For an N sector cyclotron, using hard edge approximation, we can write the following relations:

$$\theta_h(r)+\theta_v(r)=\frac{2\pi}{N} \tag{1}$$

$$\bar{B}(r)=\frac{\theta_h(r)\cdot B_h+\theta_v(r)\cdot B_v}{\theta_h(r)+\theta_v(r)} \tag{2}$$

$$\bar{B}(r)=\frac{B_0}{\sqrt{1-ar^2}} \tag{3}$$

where B_h and B_v are the hill and valley field respectively. B_0 is the isochronous field at the center of the cyclotron and $a=\left(\frac{qB_0}{m\cdot c}\right)^2$. Using equations (1-3) we can write

$$\theta_h(r)=\frac{2\pi}{N\cdot[B_h-B_v]}\left[\frac{B_0}{\sqrt{1-ar^2}}-B_v\right] \tag{4}$$

Expanding the above equation we get

$$\theta_h(r)=a_0+a_1r^2+a_2r^4+a_3r^6+...+a_mr^{2m} \tag{5}$$

The polynomial coefficients a_0, a_1 etc. depend on B_h, B_v and average central field B_0. For the optimisation one has to start with an initial set of a_n values, and iteratively correct these to obtain the final optimized hill angle. At first the *z*-component of the magnetic field at the median plane is calculated for the initial sector geometry and frequency errors are obtained at n different discrete energies. The frequency error is defined as

$$\Omega(k)=\frac{\omega_0}{\omega(E_k)}-1 \tag{6}$$

where, ω_0 is the constant rotation frequency of the particle and $\omega(E_k)$ is the rotation frequency for the calculated magnetic field at energy E_k.

The second step involves the calculation of the elements of the $n\times(m+1)$ correlation matrix. For this it is required to calculate the magnetic field by slightly changing the coefficients say $a_i=a_i+\Delta a_i$ of the polynomial one at a time keeping all other coefficients and geometry constant. The same procedure is repeated for all other coefficients one by one. For the small change in polynomial coefficients Δa_i, the deviation in frequency errors $\Delta\Omega(1)$, $\Delta\Omega(2)$,… $\Delta\Omega(n)$ can be related linearly as

$$\Delta\Omega(k)=\frac{\partial\Omega(k)}{\partial a_0}\Delta a_0+\frac{\partial\Omega(k)}{\partial a_1}\Delta a_1+\cdots\frac{\partial\Omega(k)}{\partial a_m}\Delta a_m \tag{7}$$

and
$$\frac{\partial\Omega(k)}{\partial a_i}=\frac{\Omega(k)\big|_{a_i+\Delta a_i}-\Omega(k)\big|_{a_i}}{\Delta a_i}\,. \tag{8}$$

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DESIGN STUDY OF MAGNETIC CHANNEL AT NIRS-AVF930

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Abstract

In the NIRS-AVF930 cyclotron, a current magnetic channel has been used for ten years, and the flow of cooling water gradually decreases. Therefore, the high energy operation such as 70 MeV proton became recently difficult. As the design specification of this magnetic channel is very severe, the flow velocity of cooling water is very fast as 5.4 m/sec. The condition of the current magnetic channel and the design consideration of a new one will be presented.

INTRODUCTION

The NIRS (National Institute of Radiological Sciences) -AVF930 cyclotron is used mainly for RI production [1]. The other utilizations are the studies on radiation dosimeters and radiation damage tests, where height energy proton beam such as 70 MeV was frequently used. The proton energy of 70 MeV is almost maximum in NIRS-AVF930 operation. However, that high energy operation became difficult recently, and the source of this problem is decreases in cooling water of the magnetic channel. The magnetic channel is composed of eight coil units made with hollow conductor, and two coil units among them are cooled with a chiller system in the high energy operation. Those two coils are longest coil in the magnetic channel. Therefore, low power consumption and low temperature at the outlet of cooling water is needed for of high energy operation in the new design magnetic channel.

PRESENT STATE CONDITION OF THE MAGNETIC CHANNEL

In the current magnetic channel, the maximum design current is 1300 A, and the current density is 56.5 A/cm^2. This magnetic channel is composed of a hollow conductor type that size is 6×6 mm^2 and diameter of cooling water hole is 4 mmϕ. The A2 coil(see Figure 1) is the longest coil in a magnetic channel, and has the problem that is rises of the temperature at the outlet cooling water. In Figure 2, measured temperatures of the cooling water at outlet of the A2 coil were plotted against the current of the magnetic channel. The water temperature at the outlet was increased up to 70 degrees at 1000 A, where interlock of water temperature will work.

There are two causes of the temperature rise in the present magnetic channel. One of the causes is decreases in flow of cooling water. At the beginning, flow of cooling water in A2 coil was 3.0 L/min with pressure drop of 1.2 MPa, but that is 2.14 L/min at present with same pressure drop. Another cause is increase in resistance of magnetic channel. At beginning, resistance of magnetic channel was 48.9 mΩ, but now that value is 54.2 mΩ. Therefore, power consumption increased with this higher resistance.

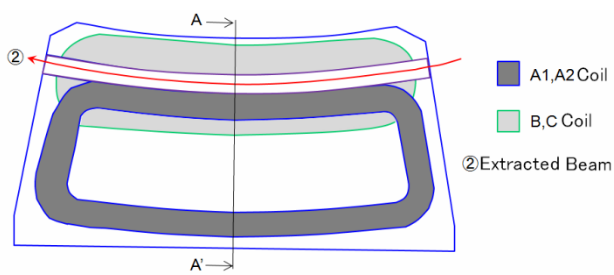

Figure 1a: The horizontal sectional view at median plane.

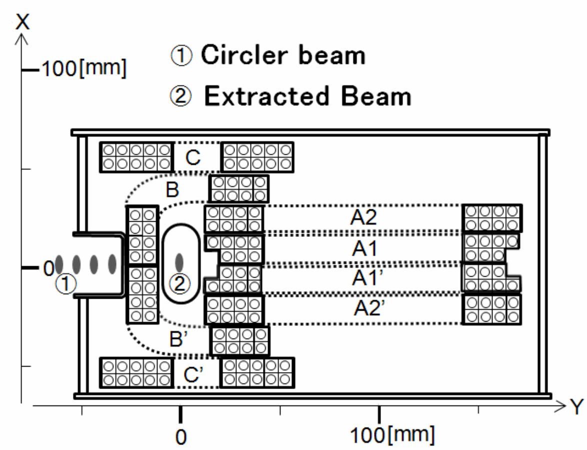

Figure 1b: The vertical sectionals view at a plane A-A'.

STRUCTURE OF THE MAGNETIC CHANNEL AND NEW DESIGN

Figure 1b shows the cross section of the current magnetic channel, which is composed from the eight coils with four types. Those eight coils are made of the hollow conductor that has cross section of 6×6 mm^2 with hole of 4 mmϕ in diameter.

DESIGN STUDY OF AVF MAGNET FOR COMPACT CYCLOTRON*

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Abstract

K=100 separated sector cyclotron and its injector cyclotron design is started on April, 2010 at Sungkyunkwan University. The main purpose of the K=100 separated sector cyclotron is producing proton and deuteron beam for ISOL which generate rare isotopes to accelerate RI beam for basic science research. In K=100 separated sector cyclotron facilities, two 8MeV sector focused cyclotrons will be used as an injector cyclotron for the main cyclotron.

In this paper, an Azimuthally Varying Field (AVF) magnet for the 8MeV injector cyclotron is designed to produce 8MeV proton beam and 4MeV deuteron beam. All field simulations have been performed by OPERA-3D TOSCA for 3D magnetic field simulation. The assignments of these injector cyclotrons are generating 8MeV, 1mA proton beam and 4MeV deuteron beam that inject to the main cyclotron.

INTRODUCTION

An 8 MeV H- injector cyclotron for K=100 separated sector cyclotron is being designed at Accelerator and Medical Engineering Laboratory (AMEL), SungKyun-Kwan University. It will provide an 8 MeV, 1 mA proton and 4 MeV deuteron beams for K=100 separated sector cyclotron and it is the main cyclotron which is located before ISOL for generating RI beam.

A design study of 8 MeV H- injector cyclotron magnets is described in this paper. This injector cyclotron has normal conducting magnet with 4 sectors so that is AVF and fixed RF frequency machine. The diameter of magnet is 1.4 m, pole is 0.4 m and height is 0.76 m. The top and bottom yoke of magnet has one hole at each valley (4 holes total) and those holes will be used for other subsystem devices - vacuum pumps and RF system [1]. The maximum field on the mid-plane is 1.95 T. Other magnet parameters are shown in Table 1 and the 1/8 model of designed magnet is shown in Figure 1.

3D modelling process was done by 3D CAD system, CATIA P3 V5 R18 [2] and whole field calculations were processed under computer simulation. Precise 3D field calculations had been performed by OPERA-3D TOSCA [3]. To reduce the field calculation time, batch files were developed which can generate model, mesh and field map automatically in TOSCA modeller and post processor. The beam dynamics program OPTICY [4] is used for calculation of the tunes.

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MAGNET DESIGN

Three steps were done to design isochronous cyclotron magnet. Some basic calculations were done first to determine parameters of magnet. Harmonic number and RF frequency was set before the calculation of gamma value, magnet rigidity at maximum beam energy and extraction radius. After the consideration of parameters 3D CAD drawing with CATIA P3 V5 R18 [2] is followed. 3D field simulation using OPERA-3D TOSCA [3] is done with those 3D drawings.

Table 1: Parameters of magnet

Parameters	Values
Maximum energy	8 MeV / 4 MeV
Beam species	H-, D-
Central field	1.15 T
Pole radius	0.40 m
Extraction radius	0.35 m
Number of sectors	4
Hill / Valley gap	0.03 / 0.39 m
Hill angle	48°
B-field (min.,max)	0.30, 1.95 T

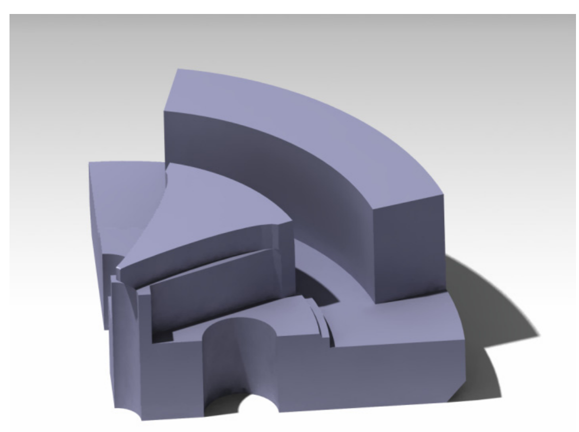

Figure 1: 1/8 model of designed magnet.

0.41 T-m magnet rigidity is needed at the extraction radius and the proton beam energy is 8 MeV at there. The RF frequency is set to 70 MHz, so central field of the magnet is 1.15 T.

3D CAD drawing can be converted to 2D drawings with CATIA P3 V5 R18 [2], and Figure 2 shows that

VACUUM SIMULATIONS FOR HEAVY ION BEAMS IN THE AGOR CYCLOTRON*

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Abstract

The TRIμP program at the KVI requires the development of high intensity heavy ion beams in particular $^{206}Pb^{27+}$ at 8.5 MeV/amu and $^{20}Ne^{6+}$ at 23.3 MeV/amu. For the Pb beam, losses in the cyclotron are one of the factors limiting the intensity that can be achieved. Charge changing collisions between the heavy ion beam and the residual gas cause subsequent desorption off the walls of the cyclotron which in turn leads to vacuum degradation. This causes a positive feedback loop leading to a reduced transmission with increasing beam intensity. We have developed a model to track the trajectory of the particles after a charge changing collision and 3D vacuum simulations to predict pressure profiles from desorption values. We have built and tested an experimental setup to measure beam induced desorption for relevant materials. Preliminary results are described.

INTRODUCTION

The TRIμP program at the KVI requires high intensity Pb beams for which transmission is to be maximized because of the limited intensity from the ion source. Primary beam loss in the cyclotron occurs when collisions of beam particles with the residual gas, mostly H_2O and N_2, lead to a change in the charge state of the ion. The cross-sections for the charge changing collisions depend on ion species and energy (Fig 1).

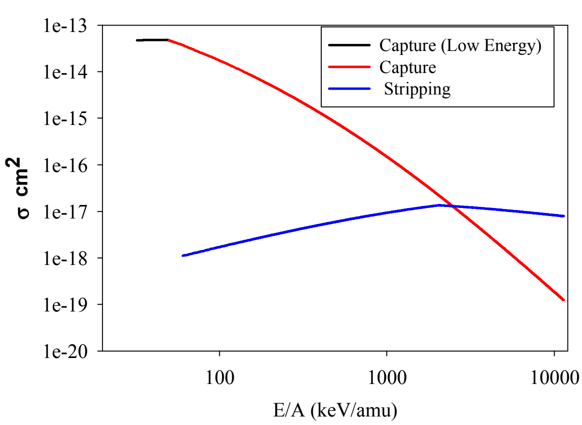

Figure1: Dependence of cross-section of capture and stripping processes on energy [1] [2] [3]

*This work is part of the research programme of the 'Stichting voor Fundamenteel Onderzoek der Materie (FOM)', which is financially supported by the 'Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)' It was supported by the European Commission within the Sixth Framework Programme through I3-EURONS (contract no. RII3-CT-2004-506065).

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Using these cross-sections we predicted the transmission for a beam inside the AGOR cyclotron and the injection line for uniform pressure [4]. To study the effect of particles lost through charge exchange on the pressure, we simulated particle tracks after a charge changing collision. From there we calculated the angle of incidence of these particles when they hit the walls of the cyclotron causing desorption. The desorption is dependent on the energy of the particles, their angle of incidence on the wall, as well as the wall material. Desorption leads to a pressure increase and a different pressure distribution. This leads to increased beam loss creating a positive feedback loop.

We are developing a geometrical model to predict the pressure distribution for an arbitrary fixed value of desorption and outgassing. This will be used for further beam transmission calculations.

PARTICLE TRACK SIMULATION

The magnetic field used in the particle track simulation has a sinusoidal flutter term in addition to average magnetic field. This is a simplification of the actual field for a heavy ion in the AGOR cyclotron and has been used as a test case.

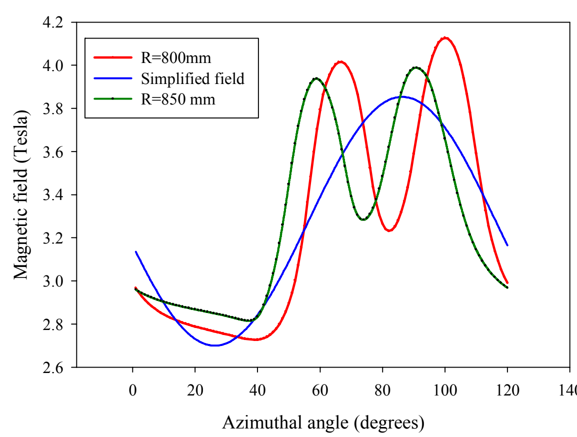

Figure 2: Dependence of the Magnetic field with azimuthal angle, showing actual field at a radius and simplified field as used in simulation.

The equations of motion [5] were solved using the RK4 method of integration for a fixed energy. From a calculated closed orbit, a charge change was simulated and subsequently the particles were tracked.

For a $^{206}Pb^{27+}$ ion, a charge changing collision gives a 4% change in the radius of curvature. Calculations show that the particle then moves in an off-centre orbit

APPLICATION OF HTS WIRE TO MAGNETS *

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Abstract

We have been developing mgnets utilizing high-temperature superconducting (HTS) wire. A scanning magnet was designed, fabricated, and tested for its suitability as beam scanner. After successful cooling tests, the magnet performance was studied using DC and AC currents. In AC mode, the magnet was operated at frequencies of 30-59Hz and a temperature of 77K as well as 10-20Hz and 20K. The power loss dissipated in the coils was measured and compared with the model calculations. The observed loss per cycle was independent of the frequency and the scaling law of the excitation current was consistent with theoretical predictions for hysteretic losses in HTS wires. As the next step, a 3T dipole magnet is under construction now.

INTRODUCTION

More than two decades have passed since the discovery of high-temperature superconductor (HTS) materials in 1986 [1]. Significant effort went into the development of new and improved conductor materials [2] and it became possible to manufacture relatively long HTS wires of the first generation [3]. Although many prototype devices using HTS wires have been developed, these applications are presently rather limited in accelerator and beam line facilities [4].

Our previous study demonstrated a possibility to excite HTS magnets with alternating currents (AC) [5]. Since HTS systems have higher operating temperatures than low-temperature superconductor (LTS) systems, the cryogenic components for cooling are simpler and the cooling power of refrigerators is much larger than at 4K. Because the temperature range for superconductivity is wider than for LTS systems, a larger range pf operating temperatures is available. A high-frequency AC mode operation should be possible in spite of heating loads due to AC losses in the coils.

A two-dimensional scanning magnet was designed and built to model a compact system for such applications as ion implantation or particle cancer treatment. Two sets of single-stage GM (Gifford-McMahon) refrigerators were used to cool the coils and the thermal shields. After performance tests of the design parameters with direct currents (DC), the magnet was operated with AC current to investigate the dissipated losses in the coils. Observed AC losses are compared with theoretical predictions and model calculations.

A 3T dipole magnet is under construction to continue developments. It is a super-ferric magnet and the coil has a negative curvature..

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SCANNING MAGNET

Design and Fabrication

A two-dimensional scanning magnet was designed to model a compact beam scanning system. The size of the irradiation field is 200mm by 200mm for 230MeV protons at the distance of 1.25m from the magnet center. The schematic layout of the coils is shown in Fig. 1. Both the B_x and B_y coils are centered at the same position along the beam axis. The required magnetic field length is 0.185 Tm. We selected the high temperature superconductor Bi-2223 [6] that is commercially available in lengths longer than 1000m. The HTS wire consists of a flexible composite of Bi-2223 filaments in a silver alloy matrix with a thin stainless steel lamination that provides mechanical stability and transient thermal conductivity. The wire, High Strength Wire, was supplied by American Superconductor Corporation [7] and is in thin tape-form approximately 4.2mm wide and 0.26mm thick.

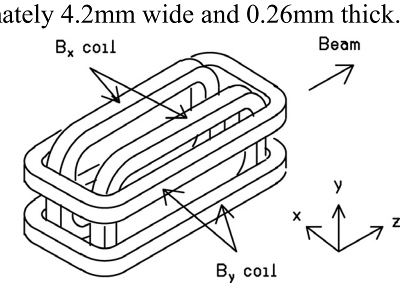

Figure 1: A schematic layout of the scanning magnet coils is shown. They generate the horizontal (Bx) and vertical (By) magnetic fields.

Table 1: Design parameters of the HTS scanning magnet.

Coils	Iner size	B_x: 150mm x 300mm.
		B_y: 150mm x 380mm
	Separation	70mm
	Maximum Field	0.6T
	# of tturns	420 x 2 for B_x and B_y
	Winding	3 Double pancakes/coil
	Inductance/coil	B_x: 75mH, B_y: 92mH
	Temperature	20K
	Rated current	200A
Cryostat	Cooling power	45W at 20K, 53W at 80K

BEAM LOSS MONITORING AND CONTROL FOR HIGH INTENSITY BEAMS AT THE AGOR-FACILITY*

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Abstract

The experiments at the AGOR facility require intense heavy ion beams. Typical examples are 10^{13} pps of $^{20}Ne^{6+}$ at 23.3 MeV/A and $\geq 10^{12}$ pps $^{206}Pb^{27+}$ at 8.5 MeV/A. To prevent damage to components by the beam (power density up to 1 kW/mm^3 in unfavourable cases) a modular beam loss monitoring and control system has been developed for the cyclotron and high energy beam lines. The architecture of the system is described and the considerations for the major design choices discussed. The system uses the CAN-bus for communication and verification of system integrity. The injected beam is chopped at 1 kHz with a variable duty factor between 5 and 90 %. The beam intensity at injection and a number of locations in the high energy beam line is measured by inductive pick-ups. Furthermore, localized beam losses on slits and diaphragms are directly measured. When beam loss in any section exceeds the predefined maximum value, the duty factor of the beam is automatically reduced.

INTRODUCTION

The AGOR-facility delivers heavy ions beams up to Pb for experiments in the framework of the TRIμP programme on fundamental symmetries. Experiments on violation of time reversal symmetry in β-decay are performed with beams up to ^{40}Ar at energies between 20 and 30 MeV. The beam intensity in these experiments is currently limited by constraints in the experimental setup to 4×10^{12} pps (300 W). The cyclotron has demonstrated its ability to deliver the 1 kW beam aimed at by the experiment. For experiments on permanent electric dipole moments and atomic parity violation in Ra-atoms and ions beams of various Pb-isotopes with an energy in the range 7 – 10 MeV per nucleon and an intensity up to 3×10^{11} pps (100 W) are used. A further intensity increase by at least a factor 3 is requested, requiring improvement of both the experimental setup and the cyclotron output

The power density in materials hit by in particular the Pb-beams is up to 1 kW/mm^3, leading to damage at the ms time scale. Therefore a monitoring and control system for the beam losses, both in the cyclotron and in the high energy beam lines, is essential for safe operation of the AGOR-facility for this type of experiments.

*This work is part of the research programme of the 'Stichting voor Fundamenteel Onderzoek der Materie (FOM)', which is financially supported by the 'Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)' It was supported by the European Commission within the Sixth Framework Programme through I3-EURONS (contract no. RII3-CT-2004-506065).
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SYSTEM SPECIFICATIONS

The beam loss monitoring and control system (BLMCS) has to ensure that the unavoidable beam losses in the cyclotron and high energy beam lines remain within preset limits by controlling the beam intensity injected into the accelerator. The system operates in a uni-directional way: deterioration of the transmission leads to automatic reduction of the beam intensity, but intensity increase made possible by improved transmission requires operator intervention. In case of more or less complete loss of the beam, as occurs due to equipment failure, the system suppresses the beam at injection within 10 ms.

The semi-interceptive beam profile monitors in the cyclotron and high energy beam lines can not withstand the full beam intensity. Therefore the system also supervises the status of all beam diagnostics equipment in the cyclotron and high energy beam lines. Under normal operating conditions insertion of a beam diagnostics device leads to immediate interruption of the beam by the BLMCS. After reducing the primary beam intensity to a safe level by inserting a pepperpot in the injection line and switching the BLMCS to tuning mode, beam can be injected into the cyclotron again. Removing the pepperpot while in tuning mode results in suppression of the beam in the injection line.

Lay-out

The path of the beam from the injection beam line below the cyclotron up to the experimental setup at the end of the high energy beam transport system has been divided in seven sections for which the transmission is measured individually. The experiments with high intensity beams are performed at one of the four experimental setups only, so there was no need to implement beam line selector logic. For each section of the high energy beam line and the cyclotron a Beam Loss Control Module (BLCM) has been installed that assesses the beam losses, verifies the status of the beam diagnostic devices and triggers actions if necessary. This modular structure is easily adapted to the operational experience.

The BLCM has six analog inputs for current measurements. Two of these are used for non-destructive pick-ups measuring the beam current at the entrance and exit of the section, the others are used to measure the current on diaphragms and/or slit jaws in the section that intercept part of the beam. The non-destructive pick-ups are shared between sections: the BLCM of section N receives its entrance current signal from the BLCM of section N-1 and sends its exit current signal to the BLCM of section N+1, where it serves as the entrance current

THE SIMULATION ON BEAM INTERACTION WITH BACKGROUND PARTICLES*

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Abstract

A particle simulation with Monte Carlo was developed to study beam interaction with background particles in neutral beam injector (NBI). The collision processes associated with charge state change and reaction cross-section were analyzed for neutralization and re-ionization. Take the neutralization processes as a reference, for positive arc discharge ion source, there are three different original ion species in the energetic ion beam. In evolution, a fast particle will suffer kinds of collisions decided by the collision cross-section or no impact within the target gas. Classify those collisions and their cross-sections according the change of charge state and momentum. The neutralizer is divided into many extremely short segments averagely. So the gas density quantity at middle point can be regarded as that of each segment. According to the collision cross-section, select a random number to determine the evolution of particle states in each segment. With that particle simulation, the neutralization efficiency is estimated.

INTRODUCTION

A NBI system can produce an energetic neutral beam which is used to heat the plasma in the magnetic confinement fusion device [1]. A sketch of the NBI system is shown in Figure 1 [2]. A high energy ion beam from the ion source will undergo neutralization processes in a gas cell named neutralizer, in which part of the energetic ions turn into energetic neutral particles. And then, the mixed particles beam is separated into ions and neutral particles by the bending magnet. Finally, the energetic neutral particles pass through the drift tube and inject into the fusion device, while the residual ions are dumped into a target (i.e., residual ion dump). However, the produced neutral beam will suffer a re-ionization process, due to the limit of vacuum in the drift tube.

Take neutralization processes for example. In the neutralizer, atomic processes involving charge transfer and dissociation will change particles' charge state and momentum. Thus, these processes will determine the species evolution along the neutralizer downstream and the neutralization efficiency. Numerical calculations of this problem have been reported in [3]. Moreover, the functional forms of variation for all species are discussed later, which offer more detailed information of the species evolution [4]. However, both of the researches base on sets of the differential equations (DE) for each species. Although the same problem is considered here, we adopt Monte Carlo (MC) simulation to research instead.

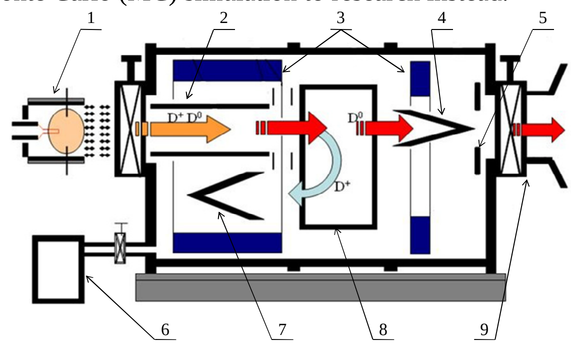

Figure 1: Sketch of NBI beamline: 1. Ion source; 2. Neutralizer; 3. Cryopumps; 4. Calorimeter; 5. Collimator; 6. Pump set; 7. Residual ion dump; 8. Bending magnet; 9. drift tube.

MODEL DESCRIPTION

Collision Processes

For a positive ion source, if the operating gas is deuterium, there are three different original ion species in the energetic ion beam, D^+, D_2^+ and D_3^+ [4]. In evolution these species are independent of each other, so we can analyze the particle species evolution respectively. Enough sample calculations and experiments have been carried out, however, to indicate that D_2 is representative of the better gas neutralizer for D species ion beam [3]. Based on the elementary MC principle, we select the relatively important collision processes between these fast species and slow molecule D and neglect the minute ones, which depend on the values of their corresponding cross sections.

Table 1 lists the various types of collision processes we take into account. From table 1 we can see clearly the close connection of these particles in their various collision processes. Except for the process of secondary D_2^+ production, most of the collisions will change the fast particles' charge state or momentum, which is more concerned for particle species evolution. Particularly, the tiny productions of D^- are considered here to show the rounded system of charge state. Thus, with the number of collisions increasing, the particles species evolution is dominated by inter-conversion between D^+ and D^0 in the neutralizer. Note that, some collision equations are generalized by several collision processes, such as production of fast D from fast D_2, which should be distinguished to avoid repeated calculation. These dates of the cross sections are all taken from [5].

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PROGRESS IN FORMATION OF SINGLE-PULSE BEAMS BY A CHOPPING SYSTEM AT THE JAEA/TIARA FACILITY

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Abstract

The intervals of beam pulses from a cyclotron are generally tens of ns and they are too short for pulse radiolysis experiments which require beam pulses at intervals over 1 μs (single-pulse beam). A chopping system, consisting of two types of high voltage kickers, is used at the JAEA AVF cyclotron to form single-pulse beam. However, we could not provide single-pulse beam stably over 30 min since the magnetic field of the cyclotron gradually decreased and the number of multi-turn extraction increased. The magnetic field is stabilized at present by keeping temperature of the cyclotron magnet constant. In addition, a new technique to measure and control an acceleration beam phase has enabled us to reduce the number of multi-turn extraction easier than before. The single-pulse beam of a 320 MeV $^{12}C^{6+}$ is successfully provided without retuning of the cyclotron over 4 h, as a result.

INTRODUCTION

A *K*110 AVF cyclotron at the JAEA/TIARA facility accelerates various kinds of heavy-ions up to 560 MeV mainly for research in biotechnology and materials science. The cyclotron has two RF resonators with a dee electrode whose span angle is 86°, and the acceleration harmonics h of 1, 2 and 3 are available. More than half of the heavy-ion beams are accelerated at h = 2. Beam pulses are extracted at intervals of 45.5 to 90.9 ns depending on an acceleration frequency ranging from 11 to 22 MHz. The ordinary intervals of beam pulses are too short for a pulse radiolysis experiment in radiation chemistry and for a time-of-flight measurement of secondary particles from a target. For example in a pulse radiolysis experiment [1], one cannot observe decay of a radical in a solution correctly since the following beam pulse hits the target before the radical, produced by the last beam pulse, goes out. We provide beam pulses spaced at intervals over 1 μs (single-pulse beam) using a chopping system as shown in Fig. 1 for the experiments [2].

The ion beam is extracted by multi-turn extraction for all acceleration harmonics in the original design of the cyclotron. In order to form single pulse beam, the number of multi-turn extraction is less than 5 to 9 by the chopping system design. It is very effective to narrow a beam phase width using a phase slit for limitation of the number of multi-turn extraction. However, the beam phase width could not be practically less than 40° in the cyclotron using two pairs of original phase slits in the case of h = 2.

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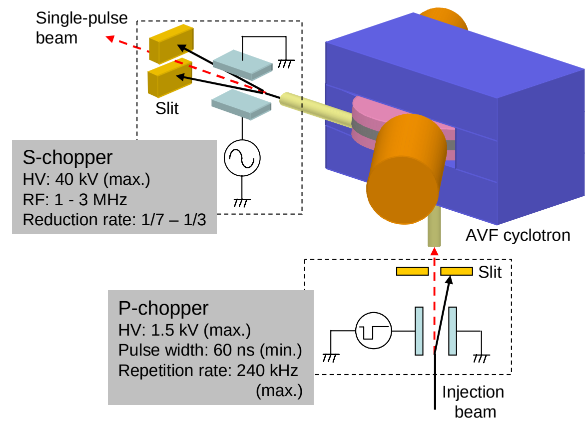

Figure 1: Layout of a chopping system consisting of two types of high voltage kickers: P-chopper and S-chopper.

The number of multi-turn extraction amounted over 30 when good isochronism was formed and the beam current was maximized at the exit of the cyclotron. The most effective way to reduce the number of multi-turn extraction was detuning the magnetic field from isochronism by changing coil current of the outermost trim coil. As a natural result, the beam current considerably decreased. We had formed single-pulse beam using the chopping system in this way. But the beam could not be provided for users stably over 30 min since the magnetic field gradually decreased by the order of 10^{-4} due to temperature rise of the cyclotron magnet, which led growth of the number of multi-turn extraction beyond the limitation.

The central region equipment was improved to precisely define the beam phase width [3], and the magnetic field was stabilized within $\Delta B/B = 1 \times 10^{-5}$ by keeping temperature of the magnet constant [4] mainly for reducing an energy spread of the ion beam using flat-top acceleration technique [5]. In addition, we have developed a new technique to measure and control an acceleration beam phase [6]. These improvements and technique greatly help us to form and provide single-pulse beam stably. In this paper, we describe the chopping system, control of the acceleration beam phase, and result of experiments for single-pulse beam formation of carbon ion.

CHOPPING SYSTEM

Figure 1 shows a layout of equipments of the chopping system consisting of two types of high voltage kickers. The first kicker (P-chopper) installed in the injection line generates beam pulses with repetition period of over 1 μs.

BEAM DIAGNOSTIC COMPONENTS FOR SUPERCONDUCTING CYCLOTRON AT KOLKATA

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Abstract

VEC Centre Kolkata has constructed a K500 superconducting cyclotron (SCC). Several beam diagnostic components have been designed, fabricated and installed in SCC. In the low energy beam line, uncooled slits, faraday cup, beam viewers, and collimators are used. The inflector is also operated in a faraday cup mode to measure the beam inside SCC. The radial probe and viewer probe are respectively used to measure beam current and to observe the beam size and shape inside SCC. The magnetic channels, electro-static deflectors and M9 slit are also used to measure beam current at the extraction radius. Water cooled faraday cup and beam viewers are used in the external beam line. The radius of curvature of the radial probe track was reduced to align the internal and external track during its assembly. It was observed that the probe did not functioning properly during beam trials. Different modifications were incorporated. But, problem with the probe persisted. The paper describes the beam diagnostic components used in the cyclotron, discusses the problems faced in operating the radial probe, modifications tried and outlines the future steps planned to operate the beam diagnostic components.

INTRODUCTION

Beam diagnostic components are used to detect various parameters of the beam of charged particle as it is transported from the ion source to the superconducting cyclotron, accelerated within it and finally extracted from the cyclotron.

BEAM CHAMBER DIAGNOSTICS

The charged particles are axially injected at the centre of the cyclotron and an electrostatic filed is applied across the electrodes of a spiral inflector to inflect the particles at the horizontal median plane of the cyclotron. The inflector can also be used in diagnostic mode to detect the beam injected at the cyclotron centre by measuring the beam current on the electrodes.

Main Probe

The main probe is the most sophisticated diagnostic instrument used for tuning the internal beam from central region up to extraction radius. It consists of a vertical array of three electrically isolated probe segments which measures the distribution of charged particles across the median plane and a differential wire which provides information on the centering of beam. The probe is inserted within the beam chamber along a curved path through the 27 mm aperture between liners along the center of the hill. The probe is a 1100 mm long assembly of several carts and links connected end to end using hinged joints and flexible enough to follow the slotted track. Two guide wheels are mounted at the bottom of each cart which are inserted into the 3.2 mm deep slot of the track so that the probe can follow the track contour as its rear end is pushed to and fro with a linear drive system [1]. The track consists of a curved and straight segment connected together with a transition track. Curved track is brazed on the liner and straight portion of track is laid through the radial penetration of the beam chamber. Probe carts are provided with a spring loaded top wheel which is kept in contact with the upper liner. The downward force due to compression of the spring prevents any upward movement of the probe from the track.

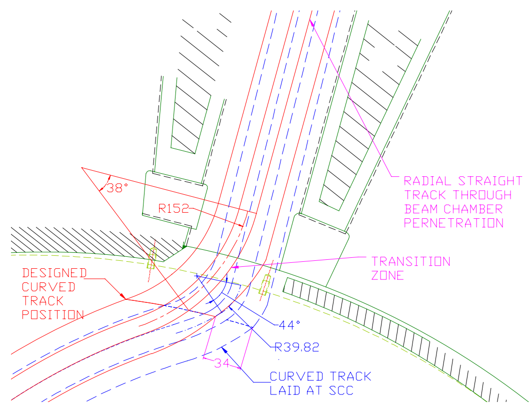

Figure 1: Change in main probe track

It was observed during assembly of magnet with cryostat that the curved track was shifted by 34 mm from the straight track (Fig.1). In order to accommodate this error, the radius of curvature of the transition track was reduced to 38 mm instead of its designed value 152 mm. It was found during initial operations of the probe that the guide wheels were severely worn and finally dislodged on track causing malfunction of probe. Design modifications e.g., change of material of the guide wheel shaft from phosphor bronze to stainless steel and use of larger circlip (6 mm) to clamp the guide wheel shaft with the probe carts were implemented to resolve the problem of disintegration of probe components. The modified probe used to go out of track (see Fig. 2) near the small curvature zone as it is pushed from the rear end and ultimately get trapped between the liners. The problem of derailed movement persists even after the probe was reconstructed with smaller link length so that it can negotiate smaller bend radius. The solid height of the probe was increased such that the space available in

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STUDY ON PXI AND PAC-BASED HIL SIMULATION CONTROL SYSTEM OF CYCHU-10 CYCLOTRON

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Abstract

Using the technology of hardware in loop (HIL), control system simulation model of the CYCHU-10 cyclotron is developed with real-time, simulation and statechart module under the LabVIEW environment. A prototyping design method based on NI PXI operation condition virtual platform and PAC controller is presented. The result indicates that the platform is feasible and effective in completing control system test under hardware virtual environment and shortening development time.

INTRODUCTION

The core problem of cyclotron control system design is how to ensure the high availability (HA) of the control system which involves the reliable operation study, failure mode and detection algorithm analysis, and avoidance of conflict strategy research. Hardware-in-the-loop (HIL) simulation is becoming a significant tool in prototyping complex, highly available system, especially when a portion of the given system is a simulation algorithm and a portion of the same system is a hardware implement. HIL technology is introduced into CYCHU-10 control system design, prototyping and testing because of the complex internal algorithms, possible catastrophe if failed in the testing, and difficulty in building a laboratory test environment with fully real system [1].

In order to improve efficiency and reduce risk, our team has accomplished the whole machine running simulation by use of virtual prototyping (VP) technology relied on the existing control design tool, experimental data and operating experience. But from off-line simulation to prototype test, it is impractical to proceed under fully real facility environment in consideration of safety, feasibility and cost. This paper describes a HIL simulation platform based on NI PXI, PAC and LabVIEW, which accelerating the controller validation test under hardware virtual environment, and shortening the design cycle.

THE HIL SIMULATION SYSTEM

The purpose of the HIL simulator is to achieve an interaction between a real implement of a closed-loop control system and a simulated plant. There are many commercial off-the-shelf (COTS) tools for HIL, such as dSPACE, xPC target, RT-lab [2], etc, which are widely used in the fields of auto industry, aerospace and weapon manufacturing. But dSPACE development tools are expensive while the data acquisition board of xPC Target may bring some inconvenience to user. With the evaluation of performance, learning time, acquisition cost and required coding, we choose NI LabVIEW to simulate a plant model with real-time hardware and add real-world I/O to the model created in Simulink software environment.

Hardware Structure

The HIL simulation platform consists of host station, PAC controller, PXI simulator, and external actual auxiliary system (see Fig. 1).

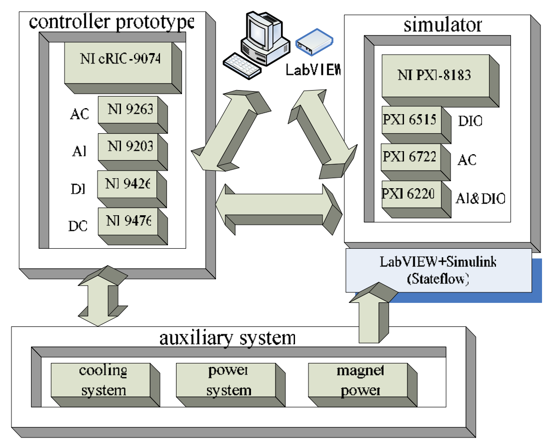

Figure 1: Hardware structure of HIL platform.

- The host station is an industrial PC with a Windows operation system, which serves as the user interface (see Fig. 2) adopting network sharing variable technique and allows user to edit and modify models with any popular model builder software such as LabVIEW. In addition, it also used in fault inserting, parameter configuring, and data recording.

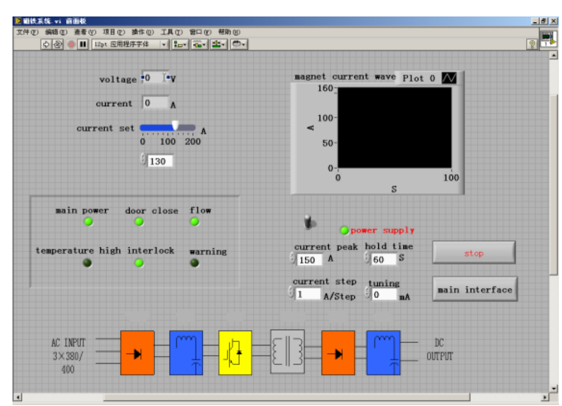

Figure 2: GUI of magnet power supply.

- NI compact RIO platform (Programmable Automation Controller) is used as rapid controller prototype running feedback control algorithm. NI 9203 module (AI board) reads not only the pressure,

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BEAM EXTRACTION SYSTEM AND EXTERNAL BEAM LINE OF KOLKATA SUPERCONDUCTING CYCLOTRON

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Abstract

All the major components of the extraction system of the Kolkata superconducting cyclotron are installed and functional. It includes the Electrostatic deflectors, magnetic channels, M9 slit etc. Internal beam acceleration has already been done successfully and now we are on the verge of extracting and transporting the beam to the cave.

The external beam transport system has been designed comprising of quadrupole magnets, steering magnets, switching magnets, beam diagnostics etc.

One of the four beam lines has been installed, which extends 20 meters up to the experimental cave-1. Control and monitoring system for all these components have been developed and tested. All the beam dynamical and technical aspects of the beam extraction and beam transportation have been discussed.

INTRODUCTION

The extraction system of the Kolkata Superconducting Cyclotron consists of two electrostatic deflectors (the first one is 55o long and the second one is 43o long positioned in the successive hills of the magnet), eight passive magnetic channels, one active magnetic channel and two compensating bars. The active magnetic channel (M9) is located in the yoke hole of the main magnet. Except the active magnetic channel all the other elements are radially moveable as the beam dynamics demands that the extraction components must be moveable to suit extraction conditions of different beams and as the beam traverses almost 330o before being extracted out of the cyclotron. The computer controlled drive system can move the elements precisely.

The extracted beam from the super conducting cyclotron will be transported through four beam lines (channels) to the experimental area. Channel#1 will be at 0 degree. The external beam line layout is shown in figure 6. The beam optics calculation of channel#1 has been carried out. The cyclotron will be operating between 3 Tesla to 5 Tesla average magnetic field. The phase space characteristics of the extracted beam will have wide variations owing to passive magnetic channels being used in the extraction system. So different momentum particle will have different beam characteristics and these wide variations have been considered for beam optics calculation. The optics calculation has been done by Graphic version of Transport code [1].

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Extraction Elements

The extraction system layout is shown in figure 1. All the different parameter of the extraction elements that affects the beam behaviour is listed in Table 1. For the deflectors, the septum to electrode gap is set to 6 mm and the maximum voltage is set at 100 kV. To compensate the field perturbation effects of the magnetic channels on the inner orbits, two compensating bars (C_1 and C_2) are used, C_1 compensates the effect of M_1 while C_2 compensates the overall effect of the remaining magnetic channels.

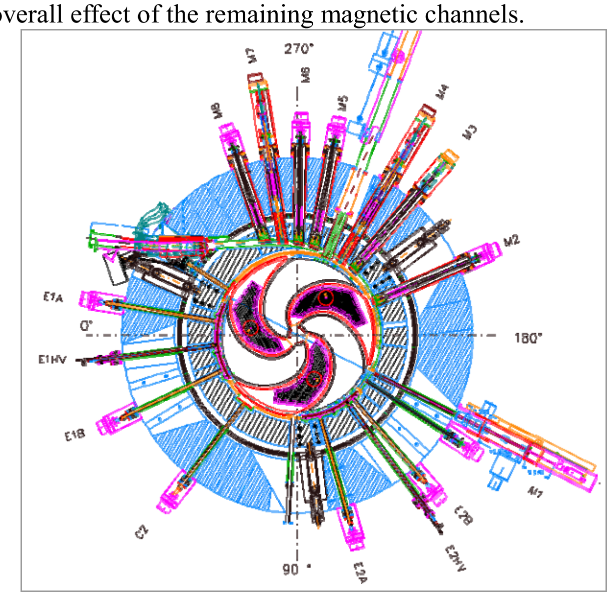

Figure1 Extraction system layout

Table 1: Extraction Element's parameters

	θ_I	θ_F	*R (min)*	*R (max)*	*Rbar (min)*	dR	B	dB/dx
			mm	mm	mm	mm	(kG)	(kG/cm)
E1 A	-23		672.4	678.5	-	6.1		
E1 B	32		678.2	686.4	-	8.2		
E2 A	94		682.2	690.8	-	8.6		
E2 B	137		698	707	-	9.0		
M1	140	153			*702.0*	13.8	1.14	3.46
M2	200	206			*711.0*	17.5	1.14	3.46
M3	226	232			*731.8*	64.0	1.05	5.24
M4	236	242			*730.3*	83.0	1.05	5.24
M5	256	262			*758.8*	18.0	1.05	5.24
M6	266	272			*776.4*	18.0	1.05	5.24
M7	276	282			*800.7*	86.0	1.14	3.46
M8	286	292			*836.4*	17.0	0.97	4.57
C1	320	334			705.5	2.5		
C2	46	58			735.3	6.4		

θ_I , θ_F : Initial and final azimuth of the element listed, Rbar gives the magnetic channel position with respect to cyclotron centre.

CONSISTENCY IN MEASUREMENT OF BEAM PHASE AND INTENSITY USING LOCK-IN AMPLIFIER AND OSCILLOSCOPE SYSTEMS

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Abstract

The phase probes (PPs) are installed in all cyclotrons and beam transport lines of RIBF, and the beam-bunch signals that are detected nondestructively by these PPs are used for tuning of isochronism of cyclotrons and for monitoring the beam phase and beam intensity. We mainly use a newly developed system that incorporates a lock-in amplifier (LIA) for those tuning and monitoring; however, a conventional measurement method using an oscilloscope (OSC) system is also used. In this study, we investigated the consistency in the measurements carried out using LIA and OSC systems by FFT analyzing the observed data. Additionally, we investigated the measurement accuracy of LIA and OSC.

INTRODUCTION

The RIKEN RI beam factory (RIBF) consists of four ring cyclotrons (RRC, fRC, IRC, and SRC) and two injectors (RILAC and AVF) which are all connected in cascade. RILAC, AVF, and RRC began operation in the 1980s, and fRC, IRC, and SRC were installed in 2006. Phase probes (PPs) are installed in all cyclotrons and beam transport lines of RIBF, and the beam-bunch signals that are detected nondestructively by these PPs are used for tuning of isochronism of cyclotrons and for monitoring the beam phase and beam intensity (Fig. 1). We mainly use a newly developed system that incorporates a lock-in amplifier (LIA; SR844, SRS) for those tuning and monitoring;[1] however, in AVF and RRC, a conventional measurement method using an oscilloscope system (OSC; DSO6052A, Agilent) is used. In this study, we investigated the consistency in the measurements carried out using LIA and OSC systems.

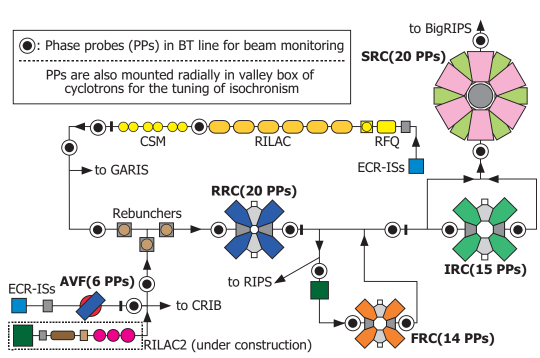

Figure 1: Schematic layout of RIBF.

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MEASUREMENT AND ANALYSIS

The block diagram of the measurement system is shown in Fig. 2. The beam-bunch signals from PPs are divided by a power divider and transported to the LIA and OSC and measured by them simultaneously. LIA use a technique known as phase-sensitive detection and outputs the beam phase and the beam intensity at a specific reference frequency. In order to investigate the consistency with OSC system, the phases and intensities for 1^{st} to 10^{th} frequency components (1f–10f) is calculated by performing FFT-analysis on the data from OSC.[2] These analysis were processed automatically by the LabVIEW program.

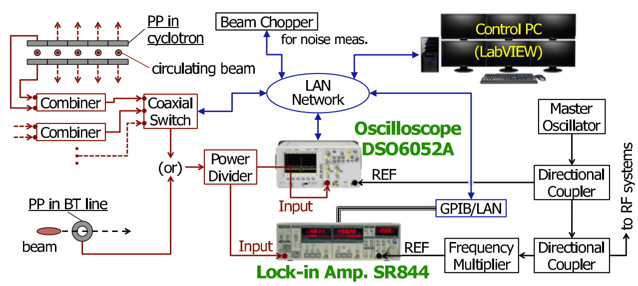

Figure 2: Block diagram of measurement system.

CONSISTENCY RESULTS

Consistency in ischronism of SRC

The comparison of the ischronism of SRC ($^{14}N^{7+}$ beam, Energy: 250 MeV/u, Frequency: 27.4 MHz) that was evaluated on the basis of the results of three measurement methods is shown in Fig. 3. This figure shows the relative beam phase observed by 20 PPs, which are radially mounted in the orbital region of SRC. Here, "LIA-3f"is the beam phase measured using LIA with the third harmonic of acceleration RF as its reference signal, "FFT-3f"is the third frequency component (3f) of FFT-analyzed phase of the beam-bunch signal measured using OSC, and "Zero cross"is the zero-cross points of the beam-bunch shape observed using OSC (conventional method).[2] We measured the 3f component of the beam-bunch signal because it had relatively good S/N ratio. It was observed that the phase differences between the three measurement methods are less than 0.2 ns (approximately 2° at fundamental acceleration RF).

Figure 4 shows the FFT-analyzed phase up to the 10f

EXPERIMENT AND ANALYSIS: PARTIAL LOSS OF INSULATION VACUUM IN K-500 SUPERCONDUCTING CYCLOTRON CRYOSTAT

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Abstract

At higher currents in superconducting coil of the K500 superconducting cyclotron, it was found that the insulation vacuum surrounding the LHe vessel deteriorate with increasing current in the coil and finally leading to slow dump of the coil. This is a limitation for further increasing current value in the magnet coil. On the other hand, once the current value was returned to zero, vacuum reading reaches to its initial value. Experiment and analysis have been done to quantify the contribution of molecular gas conduction (FMGC) on heat load because of this partial loss of insulation vacuum. Experiment was also performed to find out how much betterment in terms of heat load is possible by incorporating an additional vacuum pump.

The cryostat safety analysis because of the loss of insulation vacuum has become very important at this new scenario. An analysis has been done to know what could be the maximum pressure rise with time in case of loss of vacuum. This data has been used to know what should be the relieving mass flow rate to avoid any pressure burst accident. Finally this data has been compared with the existing relief valve. It is found that the existing safety system can take care of total loss of insulation vacuum scenario.

INTRODUCTION

The K500 superconducting cyclotron [Figure 1] at the Variable Energy Cyclotron Centre has got its internal beam circulating up to the extraction radius of the cyclotron. The cyclotron has an 80 Ton superconducting magnet operating at about 5 T magnetic fields. The NbTi superconducting coil carries about 800 A maximum current to produce the desired magnetic field. The superconducting coils are placed in a liquid helium chamber surrounded by a vacuum insulating chamber called outer vacuum chamber (OVC).

At higher currents (>600 A) in the coils, the outer vacuum chamber (OVC) insulation vacuum reading shows deterioration, which finally leads to slow dump of the coil. The deterioration of OVC vacuum with the current in the coil is plotted in Figure 2. It is seen that at about 600 A, the slope of the pressure rise is too high to increase any amount of current. This in result increases heat load to the liquid helium chamber, thus depleting the liquid level in it and slow dump triggers as the liquid level goes below the coil top surface. This has given a tight limitation for further increasing current value in the coil. It was therefore required to determine that how much is the increase in heat load because of this phenomenon and to find out what capacity of additional vacuum pumping could make the situation better.

Figure 1: The K500 superconducting cyclotron

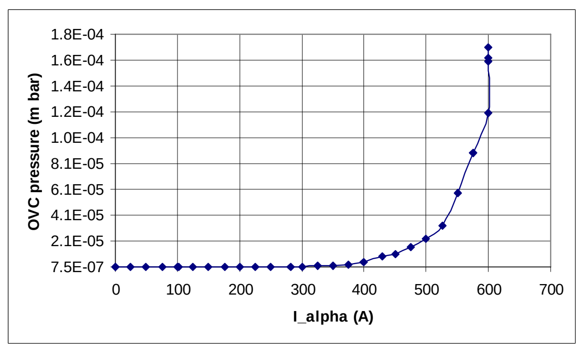

Figure 2: Vacuum reading during increase in coil current

EXPERIMENTS AND THEORETICAL EVALUATION

An experiment was done to find out the dynamic heat load which is coming only with energization of superconducting magnet. Another experiment was done to degrade the vacuum to one order by a control leak without the magnetic field on and heat load was measured. In the first experiment, heat load due to magnet energisation is found to be 100W. In the second experiment, heat load because of worsened insulation vacuum is 90 W. As is seen, the contribution of heat load as a result of degradation of vacuum is almost equal to the contribution of heat load due to magnet energisation. It can therefore be concluded that the reason for limit in the magnet coil energisation is coming from the degradation of vacuum only and an introduction of additional pumping port to improve the vacuum by nearly one order

INFLUENCE OF RF MAGNETIC FIELD ON ION DYNAMICS IN IBA C400 CYCLOTRON

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Abstract

Magnetic components of RF field in C400 [1] cyclotron, being under development by IBA, makes noticeable influence on ion dynamics.

In particular, increase in the dee voltage [2] along radius leads to essential phase compression of a bunch. At the same time RF magnetic field changes a central ion phase by only 2ºRF.

Calculations have also shown that RF magnetic field makes visible but pretty small influence on the radial motion, while an impact of the RF magnetic field on the axial motion has not been detected.

The results are compared for the two RF magnetic field maps: (i) calculated numerically by Microwave Studio and, (ii) calculated analytically from RF electric field map by means of Maxwell' equations.

RF FIELDS COMPUTED BY MICROWAVE STUDIO

RF electric and magnetic field maps that were used in the computations corresponded to the last geometry of the dees in assumption that a dee voltage in the center is of about 80 kV. Three dimensional views of the components E_φ, E_r and B_z are shown in Fig. 1-4.

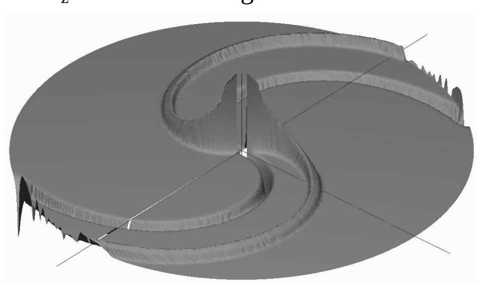

Figure 1: 3D view of E_φ component

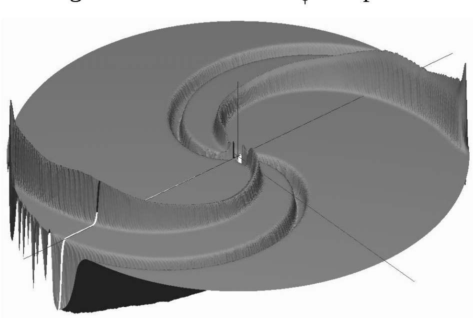

Figure 2: 3D view of E_r component.

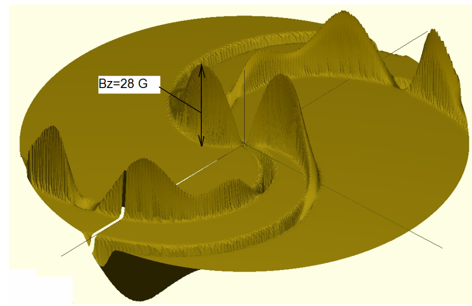

Figure 3: 3D view of the B_z(RF). Maximal positive value of B_z(RF)=28 G at radius 30 cm.

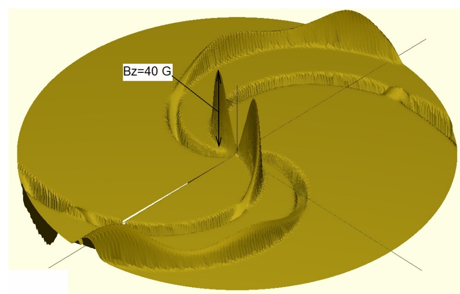

Figure 4: 3D view of the Bz(RF) through a half-period of the high-frequency oscillations in comparison with Figure 3. Maximal value of Bz(RF)=40 G at radius 22 cm.

Distribution of the maximal values of B_z(RF) along radius for two gaps of the dee is shown in Figure 5.

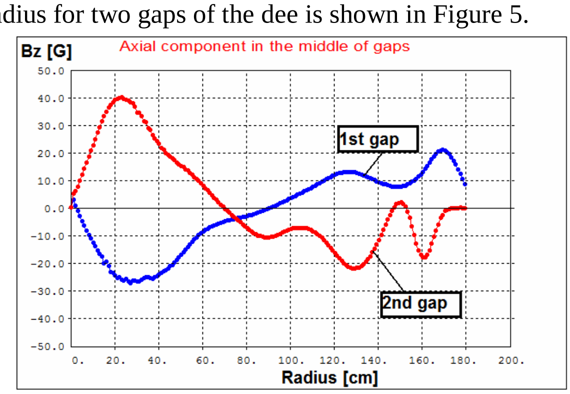

Figure 5: Maximal values of component B_z(RF) in the middle of gaps versus radius

In the case when obtaining of B_z(RF) is provided by Microwave Studio the three RF magnetic field components during acceleration are calculated by the following formulas of first approximation with respect to (z/r):

$$B_r(t) = z \frac{dB_z}{dr} \sin \psi \tag{1}$$

AXIAL INJECTION BEAM LINE OF A COMPACT CYCLOTRON*

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Abstract

Axial injection beam line of the compact cyclotron is presented. It is intended for transportation of the C5+ ion beam obtained in the permanent magnet ion source. The beam line is only 3.486 m from the ion source to the entrance of spiral inflector, it consists of two glasser lens, one double 90-degree bend magnet, one quadrupole and two solenoid lens. The sinusoidal buncher, Faraday cap and chopper are used respectively for increasing seizing efficiency, beam diagnostics and choice of beam utilizing time. The bend magnet and a slit collimator are used for choice of C^{5+} ion beam.

INTRODUCTION

A new compact cyclotron is designed at the Institute of Modern Physics, it is intended for acceleration of C^{5+} ions and energy 7 MeV/u at the extraction radius. The cyclotron will be used as the injector of a compact synchrotron. The overall equipment will be built for the medical application. The main parameters of the cyclotron are contained in Table 1.

Table 1 The cyclotron main parameters

Extraction radius /m	0.75
Magnetic field /T	1.168
Number of sectors	4
RF frequency /MHz	31.02
Harmonic number	4
Extraction energy /MeV/u	7.0
Z/A	0.4167(C^{5+})
RF voltage /kV	70
Number of Dees	2
Ion extraction method	Electrostatic deflector and bend

Axial injection beam line of the cyclotron is designed for transportation of the C^{5+} ion beam obtained in the permanent magnet ion source. A big vacuum box is installed in the vertical part of the beam line. A sinusoidal buncher, a Faraday cap, a slit collimator and a chopper are located in the big vacuum box. The sinusoidal bunchers are used for increasing of the injection efficiency from about 11% to 47%, it is about 1.3 m from the median plane of the cyclotron. The Faraday cap is used for the beam diagnostics and monitoring. The chopper is used for choice of the beam utilizing time, its running period is decided by the synchrotron.

*Supported by National Sciences Foundation of China (Code: 10905078)

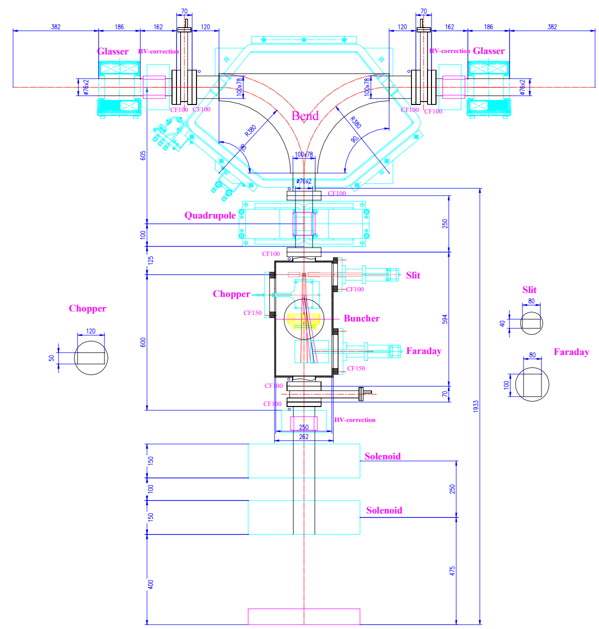

Fig.1 Beam line layout

BEAM LINE DESIGN

The C^{5+} ion beams are obtained in the permanent magnet ion source. The some parameters of beam are contained in the Table 2.

Table 2 Beam parameters

Beam intensity /eμA	200
Emittance /πmm*mrad	150
Energy /keV	100

The beam line is situated above the cyclotron magnet. It consists of the permanent magnet ion source, the double 90-degree analyzing bending magnet (DM90) and two focusing glasser lens that will be placed at the horizontal part of the beam line. A quadrupole and a buncher will be placed at the vertical part of the beam line, two focusing solenoids will be installed above the plug. The spiral inflector will transfer ion beams to the median plane of the cyclotron.

EXTRACTION SYSTEM OF A COMPACT CYCLOTRON

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Abstract

Based on the beam orbit and dynamics simulations, the extraction system of a compact cyclotron is determined, and the beam parameters of the extracted beam are calculated.

INTRODUCTION

HITFiL(Heavy Ion Therapy Facility in Lanzhou) is composed of a compact synchro- tron ,several ion beam lines ， three therapy chamber and a cyclotron injector, Fig.1. is a sketch drawing of the HITFiL. The injector of the synchrotron is a compact cyclotron ,it is now under designing at institute of modern physics Chinese academy of science, it is intended to provide carbon ion with charge number 5,the beam intensity will be more than 10 eμA,and the extraction energy is 7Mev/A.The present paper gives the designing of the extraction system of the compact cyclotron and the beam parameters of the extracted beam.

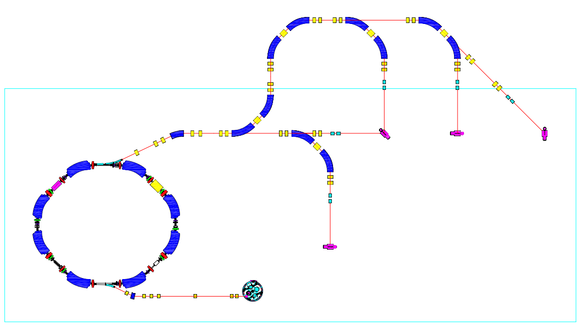

Figure 1: Layout of HITFiL

DESIGNING OF THE EXTRACTION SYSTEM

The designing of extraction system is based on the orbit calculations, the magnetic field used in beam orbit calculation was obtained by a 3D infinite element code, the electric fields used in orbit calculations is an analytical field，Fig.2. is the layout of the reference particle track and extraction elements. The whole extraction system composed of an electric deflector and a bending magnet. The electric field in the gap is 80.0kV/cm,for that its high voltage electrode will be 80kV, A bump filed be used to enhance the turn distance between extraction orbit and accelerator orbit, it is also helpful for deduce the burden of the deflector.

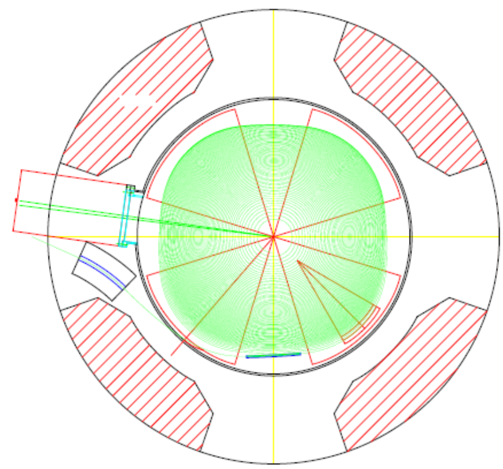

Figure 2: Overview of the cyclotron

Based on the reference particle orbit, extraction elements and it's physical parameter be determined. To obtain higher extraction efficiency and higher beam quality, multi- particle simulation was done, such calculations show that the position of the extraction elements which get from single particle calculations should be optimized.

BEAM PARAMETERS OF THE EXTRACTED BEAM

Extracted beam parameters are obtained based on multi-particle calculation, the initial conditions for such calculations is coming from the injection and center region calculations, The matching point is at the exit of the bending magnet, at this point the beam parameters are as following table, Fig.3. to Fig..5 are the 6 dimensions emittance of the beam, Fig.6.is the dispersion D and D' of the extraction beam.

TRANSMISSION EFFICIENCY STUDY OF SSC

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Abstract

Transmission efficiency of HIRFL-SSC had been studied, found the main reasons of the lower transmission efficiency, and some advices were put forward to improve the transmission efficiency.

INTRODUCTION

HIRFL-SSC is a separated sector cyclotron at IMP(Fig.1.), it was constructed in the 1980's, the first beam extracted from SSC is 50Mev/A $^{12}C^{6+}$ in 1988, from then on SSC has been providing ion beams for 21 years, but the transmission efficiency of SSC is very lower, accelerator physicists at IMP begun to study this problems since1992, then there are four main opinions about which. The first is that the RF voltage of SSC is not reach the designing value. The second is the over trim of magnet. The third is that the designing of injection system had some problem. The forth is that the beam matching between SSC and it's injector cyclotron SFC is bad. The present paper studied those opinions by beam simulations and experiments on SSC.

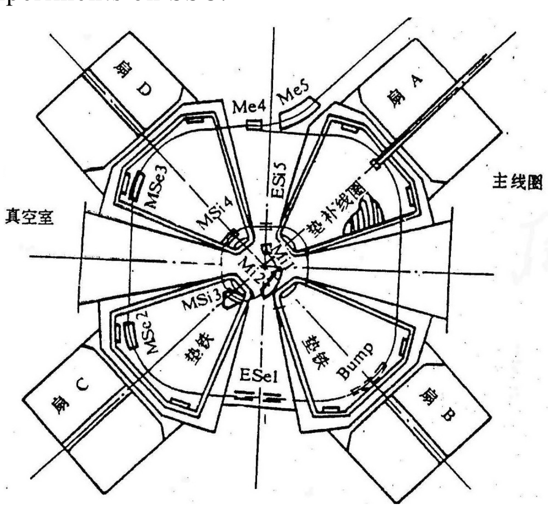

Figure 1: Layout of SSC

LOWER RF VOLTAGE OF SSC

The designing value of SSC RF voltage is 230 kV, as to now, the highest value which the SSC RF system can reach is 180. Some researchers' studies show that for high energy light heavy ions if the RF voltage below 230kV, some particle will hit on the Msi4 or Esi5 for the first accelerate turn, So they point out this is the main reason of lower transmission efficiency of SSC. The authors of the present paper did the same simulations as those researchers did, and got the same results. In our simulations, if the RF voltage is 230 kV the distance between injection beam and first accelerate beam is about 10 mm, and the beam envelope is 8 mm, so there is no beam lose in first accelerate turn, but when the RF voltage bellows 230 kV, there will have beam lost. The above situation is true just for high energy light heavy ions, for other particle beams there is no beam lose even the RF voltage lower than 180 kV. Even for high energy light heavy ions we can increase the distance between injection beam and first accelerate beam to 10 mm by change the location of Msi4 and Esi5. Experiments on SSC verified such moving have the expected effect. So lower RF voltage is not the main reason of lower transmission efficiency.

OVER TRIMMING OF SSC MAGNET

To eliminate the effects of injection elements Mi2 on the main magnet field, some iron was attached on the edge of the magnet sector B and C near Mi2(Fig.1).But the magnet field measurement showed that the iron had a little more than it was needed, such is so called over-trimming. Some researchers thought it is a main reason of the lower

RESEARCH ON ACCEPTANCE OF SSC

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Abstract

The injection, acceleration and extraction of SSC (Separate Sector Cyclotron） is analyzed and simulated to get the transverse and longitudinal acceptance, using two typical ions $^{238}U^{36+}$ and $^{70}Zn^{10+}$ with energy 9.7MeV/u and 5.62MeV/u respectively. In order to study the actual acceptance of SSC, the isochronous magnetic field model in coincidence with the real one is established by Kr-Kb and Lagrange methods based on the actual measurement. The transverse and longitudinal acceptance is calculated under the above isochronous magnetic field model. From the simulation results, one of the major reason of low efficiency and acceptance of SSC is the defaults in the design of MSI3. The simulation results show that the actual efficiency and acceptance of SSC can be improved by redesign the curvature of MSI3 or shim in MSI3 to change the distribution of inner magnetic field.

INTRODUCTION

SSC is the main accelerator of HIRFL (Heavy Ion Research Facility in Lanzhou). Presently higher beam intensity and quality are required to perform higher level experiments. In the view of existing conditions, the accelerator system needs to be upgraded to satisfy physical requirements, where the key issue is the SSC of HIRFL. The low beam transmission efficiency of SSC and the existing beam intensity of SSC's injector - Sector Focused Cyclotron (SFC)[1,2] limited the beam intensity of SSC. As a result from the above reasons, Institute of Modern Physics, CAS planned to build a new linear injector (SSC-LINAC) to get higher intensity beam for heavier elements.

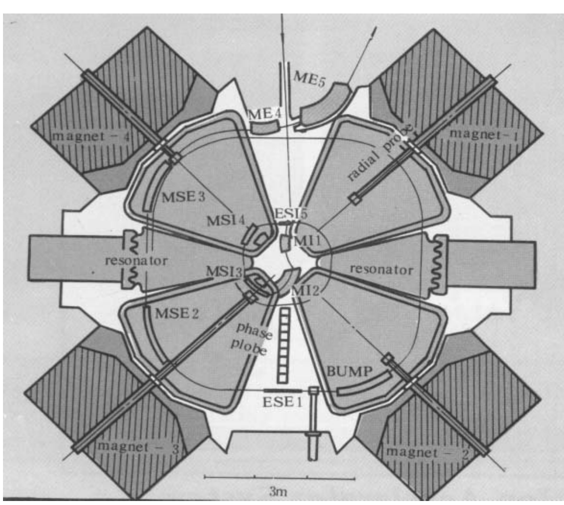

Figure 1: The overall layout of SSC.

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In this paper, the transverse and longitudinal acceptance is calculated under the theoretical isochronous magnetic field model and the real one. It will provide important parameters for SSC-LINAC. In addition, the simulation results will help in machine commissioning and the upgrade of HIRFL by discussing the acceptance of SSC. Fig.1 gives the overall layout of SSC. It shows four sector magnets and the injection and extraction system of SSC, and two RF cavities.

SIMULATION RESULTS UNDER THE THEORETICAL ISOCHRONOUS MAGNETIC FIELD MODEL

The theoretical isochronous magnetic field distribution [3-5] is the hyperbola secant function. In present paper, the acceptance of SSC (the point of the injection orbit, which is 4.08m far from the centre of SSC) is calculated by tracking particles. Fig.2 and Fig.3 show the results of ions $^{238}U^{36+}$ with energy 9.7MeV/u, and $^{70}Zn^{10+}$ with energy 5.62MeV/u respectively. In Fig.2, (a), (b), (c) are radial acceptance of 13.03 π·mm·mrad, axial acceptance of 107.27 π·mm·mrad and longitudinal acceptance respectively. The energy spread is ±0.7% and the phase is from -6 to 6°.In Fig.3, (a), (b), (c) are radial acceptance of 16.43 π·mm·mrad, axial acceptance of 208.34 π·mm·mrad and longitudinal acceptance respectively. The energy spread is ±0.6% and the phase is from -10 to 10°.

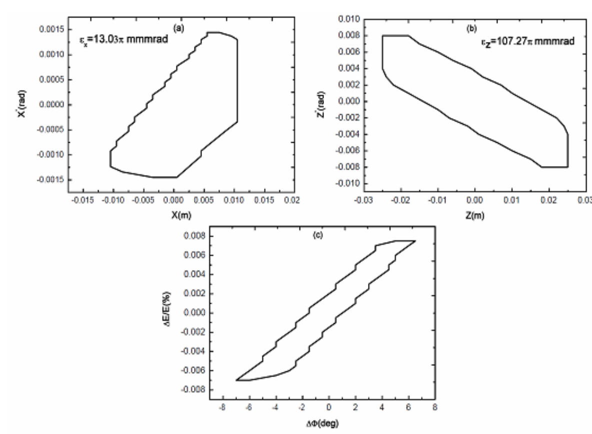

Figure 2: The results of ion $^{238}U^{36+}$ with energy 9.7MeV/u, acceptance of SSC in theoretical magnetic field (a) radial acceptance (b) axial acceptance (c) longitudinal acceptance.

BEAM-PHASE MEASUREMENT SYSTEM FOR HIRFL

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Abstract

The beam phase measurement system in HIRFL is introduced. The system had been improved using RF-signal mixing and filtering techniques and noise cancellation method. Therefore, the influence of strongly RF disturbing was eliminated and the signal to noise rate was increased, and a stable and sensitive phase measurement system was developed. The phase history of the ion beam was detected by using 15 sets of capacitive pick-up probes installed in the SSC cyclotron. The beam phase information was necessary for tuning purposes to obtain an optimized isochronous magnetic field, where the beam intensity was increased and the beam quality was optimized. The measurement results before and after optimized isochronous magnetic field for $^{40}Ar^{15+}$ ion and $^{12}C^{6+}$ ion in SSC were given. The phase measurement system was reliable by optimizing isochronous magnetic field test, and the precision reached $\pm 0.5^{\circ}$, the sensitivity of beam signal measurement was about 10nA as well.

INTRODUCTION

The heavy ion research facility in Lanzhou (HIRFL) is composed of a sector focusing cyclotron (SFC K=69), and a separated sector cyclotron (SSC K=450), which is also the injector of the cooling storage ring (CSR). As to the isochronous cyclotron SFC and SSC, it is very important in optimization of isochronous magnetic field to get the best beam quality and efficiency of beam extraction. The information of isochronous of magnetic field could be provided by the beam-phase measurement system in beam tuning. Plate capacitive phase probe was designed and installed on SFC and SSC respectively. The signal mixing filter technology was applied and the beam signal detected by the phase probes was measured using HP8508A vector voltmeter. The frequency range of the beam phase measurement could be covered by the cyclotron frequency 6.5-14.5MHz in HIRFL, and the measurement sensitivity was about 5uV. That is when beam intensity was 10nA, the signal could be identified, and the system measurement accuracy was 0.5°.

DESCRIPTION OF BEAM-PHASE MEASUREMENT SYSTEM

The beam-phase measurement system in HIRFL mainly includes phase probe for the beam signal detection, the phase measurement signal processing system, as well as computer acquirement system.

Phase Probe

Based on many international researches of accelerator labs, plate capacitive phase probe is the best choice for isochronous cyclotron. The probes are located along the centre of one hill sector on the isochronous trim coil place of the magnet with the same distance along the radius direction. The electrode is made of non-oxygen copper plate and the voltage of induction signal is proportional to the charge of the beam pulse. Two layers of shielding outside of the electrode have been designed to protect the electrode from being attacked by beam and reduce the interference of RF-frequency. To avoid any signal reflection, the probes have an impedance of 50 ohms, the beam signal detected on the probe feed through by double shielding coaxial connector SWH.1S ensure the requirement of vacuum. The 6 sets of phase probes have been installed on the centre of SFC with the size of electrode 50mm × 100mm and the distance of 35mm between upper and lower and the 15 sets of phase probes have been installed on the centre of SSC with the size of electrode 100mm × 100mm and the distance of 40mm between upper and lower. The state of isochronous of magnetic field in cyclotron could be reflected by the results of beam phase measurement fully.

Phase Measurement Signal Process

The detection signal on the phase probe is transformed to voltage by the phase measurement processing system which is related to beam phase. The beam pulse signal with the cyclotron frequency ω_d is shown:

$$u(t) = \frac{1}{2}\sum_{n=0}^{\infty} A_n \cos(n\omega_d t + \varphi_n)$$

While A_n and φ_n are the magnitude and phase of harmonics n respectively. Capacitive phase probes installed on the centre of cyclotron not only detect the beam signal, but also the interference of RF-frequency. Generally the signal to noise rate of the beam to RF-frequency interference increases with the adding of the harmonics, however, the intensity of beam signal decreases with the reducing of harmonics. Therefore, considering the two factors of beam intensity and signal-noise ratio, the second harmonic component is selected as the measurement signal of the beam phase:

$$u_2(t) = A_2 \cos(2\omega_d t + \varphi_2)$$

The structure of beam-phase measurement system in HIRFL is shown in Figure 1.

A DESIGN OF SWITCH MAGNET POWER SUPPLY

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Abstract

The paper introduces a design of power supply for switch magnet in HIRFL. The main circuit topology used Buck chopper regulator, full-bridge inverter output and power units in parallel in the power supply is introduced. The operation principle and control strategy is analyzed in this article. The power supply can be operated in DC and pulse mode, has the very good output current long-term stability, high reliability and dynamic response characteristics. Finally, some experimental data and waveforms of the power supply are shown to demonstrate the performance of the design.

SUMMARY

With construction of CSR and acceleration of proton at HIRFL, the existing beam handling system can not meet the requirements of nuclear physics experiments for more and more beam time. In order to match a new beam distribution system based on time is being constructed in HIRFL, a new switching magnet power supply is designed. Whether there is beam in CSR or not, the new beam distribution system can use the beams from SFC and SSC at the same time to do physics experiments at experimental terminals.

POWER SUPPLY PARAMETERS

- ✓ Maximum Output current: ±1050A
- ✓ Operation mode: DC/Pulse
- ✓ Maximum rise speed: (0-±1050A) /0.15s
- ✓ Maximum fall speed: 0.15s (±1050A-0)/0.15s
- ✓ Output current flat top time: 0.5s to DC
- ✓ Current stability: $<2\times10^{-4}$/8hour (±400-±1050A)
- ✓ Current ripple: $< 2\times10^{-4}$ (±400A-±1050A under 1kHz)
- ✓ Current repeat error: $<2\times10^{-4}$ (±400-±1050A)
- ✓ Current error: 0.1A
- ✓ Load parameters: Resistance: 28.2mohm, Inductance:18.7mH

The waveform of simulation work in pulse mode is shown below, the first picture shows the current waveform, and the next picture shows the voltage waveform.

MAIN CIRCUIT STRUCTURE

Main circuit structure is shown in Figure 2. The bus voltage is 200V after the diode rectifier and the bus voltage is 50V after the buck chopper. In process of rise and fall of the current, the buck chopper does not work and the bus bar voltage holds 200V so as to ensure the current change rate sufficient. When it works in a stable state, the bus bar voltage controlled by the buck chopper maintains at 50V to ensure that the duty cycle is reasonable.

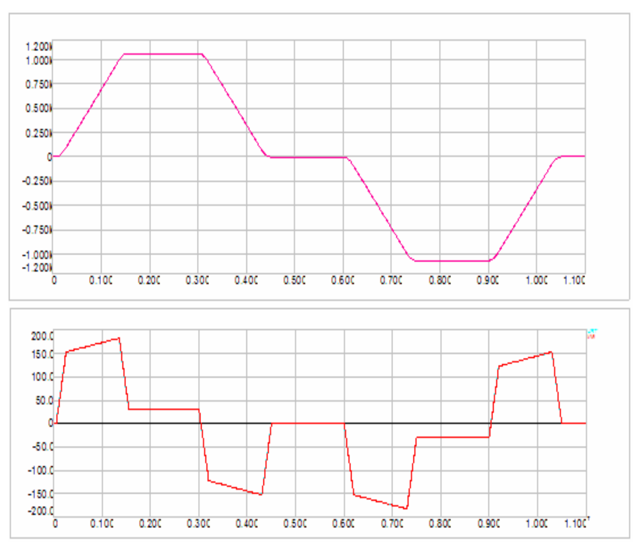

Figure 1.Waveform of power supply in pulse mode

In the power cabinet it has an input rectifier transformer and two power units, and in the control cabinet it has the control circuit for the power supply, the input and output power distribution and output filter circuit. The power supply is operated by PLC control, and displayed by a

DESIGN OF HIGH ENERGY HADRON FFAGS FOR ADSR AND OTHER APPLICATIONS

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Abstract

Design study of high energy proton FFAG accelerator has been carried out at Kyoto University Research Reactor (KURRI) for the next generation ADSR experiment where the proton beam energy covers up to 700MeV. The scaling type of FFAG with spiral sectors was employed. Details of the design issue concerning about the operational working points, lattice parameters and 3D magnet modeling / optimization are described. Also, some possibilities to apply this design to carbon therapy accelerators are presented.

INTRODUCTION

In KURRI, the first Accelerator driven sub-critical reactor (ADSR) experiment has started from March 2009, using a FFAG proton accelerator complex as a spallation neutron driver. At current phase, the output of the main ring in FFAG complex is 100MeV / 0.1nA [1]. Since the output power of the sub-critical reactor is proportional to the intensity of the neutron source, which related to the beam energy and intensity from the accelerator driver, some upgrade plans for the existing FFAG complex have been proposed and carried out [2]. One is to increase the beam intensity by replacing the current injector (Ion-beta + Booster) with a 11MeV H^- Linac injector [3]. The other way is to enhance the extraction beam energy to about 700MeV by adding a new ring. Since the number of neutrons during the nuclear spallation process has a strong dependency on the beam energy of the primary proton, the neutron multiplication rate can be increased by a factor of 30 when the proton beam energy is increased from 150MeV to 700MeV [2].

BASIC PARAMETERS FOR THE 700MEV FFAG RING

The present FFAG complex for ADSR experiment consists of one spiral injector (Ion-beta) with the extraction energy 1.5MeV, one 8-cell radial type booster and one 12-cell radial type main ring to accelerate beam energy covering 1.5MeV∼11MeV and 11MeV∼100MeV. The maximum energy of the main ring can be increased to 150MeV by changing the output energy of the injector.

The 700MeV upgrade ring will adopt the scaling type of FFAG with spiral sectors. For high energy scaling FFAG accelerators, the spiral sector is not so commonly used compared with the DFD triplets, due to the difficulty of controlling vertical tune shift. However, with the aid of 3D magnet modeling and optimization, it is possible to control the tune shift and maintain zero chromaticity. Meanwhile the compactness of the spiral sector makes it attractive.

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For a given momentum ratio p_{ext}/p_{inj}, the radius excursion ΔR is related to the injection radius R_0 and field index k by the scaling law $B = B_0 \cdot (R/R_0)^k$, as Eq. 1. In case of the 700MeV ring, $p_{ext}/p_{inj} = 2.44$, when taking $R_0 = 6.9m$, ΔR is in range of 0.8m∼0.5m when changing k from 7.0 to 12.0.

$$\Delta R = ((P_{ext}/P_{inj})^{\frac{1}{1+k}} - 1) \cdot R_0 \qquad (1)$$

The stable region for (k, ζ) parameter set is searched with first order matrix method, at different cell number $N = 8 \sim 16$. The main design constraints are the following: (1) Field index should be larger than 6.0, to keep a compact magnet dimension; (2) Spiral angle should be smaller than 60 degrees, for considerations on rf cavity installation etc. (3) The working point should be far away from low order normal structural resonances.

For the case of cell number $N = 14$ with the packing factor 0.4 , the working point $(\nu_x = 0.22, \nu_z = 0.14)$ is selected around parameters $(k = 7.0, \zeta = 58°)$ (see Fig. 1). The main parameters are listed in Table 1.

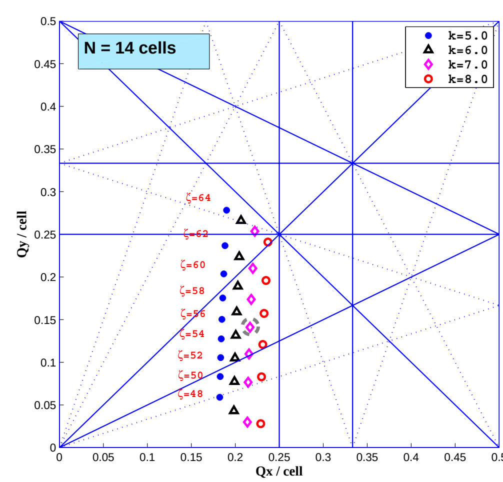

Figure 1: Working point search for $N = 14$. k is the field index, ζ is the spiral angle

The lattice was validated using Zgoubi code with FFAG-SPI procedure [4]. This procedure uses the soft enge model

THE DESIGN OF TRANSVERSE EMITTANCE MEASUREMENT AT HIRFL-CSR

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Abstract

HIRFL-CSR is a multi-purpose heavy ion storage ring in Lanzhou. In order to measure the transverse emittance of the injected beam on the transfer channel to the HIRFL-CSR, two kinds of emittance measurement devices which included pepper- pot and slit-grid were proposed. The pepper-pot is unique in providing an instantaneous measurement of the two-dimensional emittance of a beam. The data acquired by this method is only an image. The slit-grid is a one dimensional emittance measurement device. During the measurement, the slit, driven by the stepper motor is moved stepwise across the beam, and then the signal induced on the grid will be stored in the computer for further analysis. Because slit-grid is one dimensional device, two sets of this device are needed for transverse measurement. In this paper, we introduce the design, parameters, data acquisition and analysis of these two methods. Especially the software integration is given in this paper. Main interest is directed on the software development for emittance front-end control and data analysis such as evaluation algorithms.

INTRODUCTION

HIRFL-CSR (Heavy Ion Research Facility in Lanzhou-Cooling Storage Ring) is a multi-purpose heavy ion storage ring that consists of a main ring (CSRm), an experimental ring (CSRe) and a radioactive beam line (RIBLL2) to connect the two rings [1]. As part of the development program and to provide necessary information for HIRFL-CSR beam dynamic simulation and experiments, high quality emittance measurement are required. So in order to measure the transverse emittance of the injected beam on the transfer channel to the HIRFL-CSR, two kinds of emittance measurement devices which included pepper- pot and slit-grid were proposed. The chamber will be installed in the injection line of HIRFL-CSR which is shown as figure 1. The pepper-pot and two sets of grid-slit devices can be seen in figure 2. Two systems have already been installed in the chamber. There are also some other equipments for measurement such as CCD camera and mirror which are used for alignment in pepper-pot systems. In slit-grid system, I/U converter and DAQ card acquire beam current data for analysis.

*Work supported by HIRFL-CSR project
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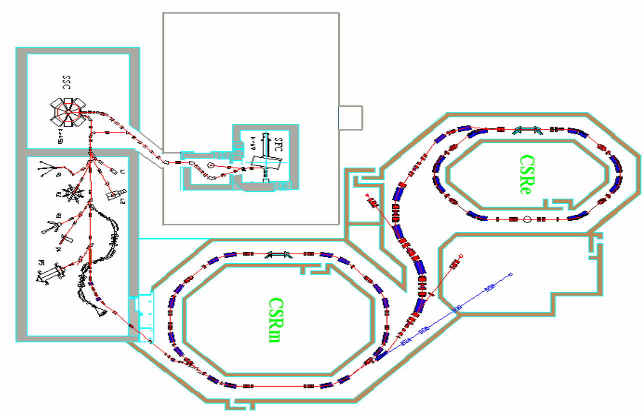

Figure 1: The layout of HIRFL-CSR

Figure 2: The chamber

SLIT-GRID SYSTEM

The slit-grid is a very popular method used for protons/heavy ions emittance measurement. The classical scheme is shown schematically in figure 3[2]. Two sets of slit-grid system with the same parameters are designed for measuring the horizontal and vertical emittance respectively. A narrow slit, driven by the stepper motor, is moved stepwise across the beam. In our slit-grid system, the width of the slit is 0.5mm. The distance between slit and grid is 300mm. There are 49 wires of which the width is 0.2mm and the spacing is 1mm in one dimension. The gird device can be seen in figure 4. During the measurement, we need two coordinates to locate the beamlets: one for the slits(x), the other for the grid(X) [3]. The wire currents are converted into reasonable voltages U using I/U converter. DAQ card is used to acquire data.

TOWARDS THE 2 MW CYCLOTRON AND LATEST DEVELOPMENTS AT PSI

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Abstract

PSI operates a cyclotron based high intensity proton accelerator routinely at an average beam power of 1.3MW. With this power the facility is at the worldwide forefront of high intensity proton accelerators. An upgrade program is under way to ensure high operational reliability and push the intensity to even higher levels. The beam current is practically limited by losses at extraction and the resulting activation of accelerator components. Further intensity upgrades are only possible if the relative losses can be lowered in proportion, thus keeping absolute losses at a constant level. The basic upgrade path involves the reduction of space charge induced extraction losses by implementing improved RF systems and resonators in both cyclotrons. The paper describes the ongoing upgrade program, achievements that were realized since the last cyclotron conference and several operational experiences and difficulties that were observed during routine operation.

INTRODUCTION TO THE PSI FACILITY

The PSI high intensity proton accelerator generates a high power proton beam with 590 MeV kinetic energy. At full energy the relative beam losses have to be kept within the lower 10-4 range to avoid excessive activation of accelerator components in the extraction region. The PSI accelerator consists of a Cockcroft-Walton pre-accelerator and a chain of two isochronous cyclotrons, the Injector II and the Ring cyclotron. The beam is produced in continuous wave (CW) mode at a frequency of 50.6 MHz. The whole facility including the experimental areas fits in a rectangle of 120 m × 220 m. The proton beam is used to produce pions and muons by interaction with two graphite targets that are realized as rotating wheels [1]. The targets have thicknesses of 5 mm and 40 mm. Pions decay into muons that are transported in large aperture transfer lines to the experiments. Muon beam intensities up to 5·108 s-1 are achieved [2]. After collimation behind the meson production targets the remaining proton beam with roughly 1MW is then used to produce neutrons in a spallation target. The actual target consists of a matrix of lead filled Zircaloy tubes. The neutrons are moderated in volumes filled with heavy water (D2O) surrounding the target, and then transported to the 13 instruments installed in the Swiss Spallation Neutron Source (SINQ) facility. In 2010 a pulsed source for ultracold neutrons (UCN) will be brought into operation as well. The research themes at PSI cover a broad range of applications involving neutron scattering, muon spin spectroscopy and few particle physics experiments. Fig. 1 shows an overview.

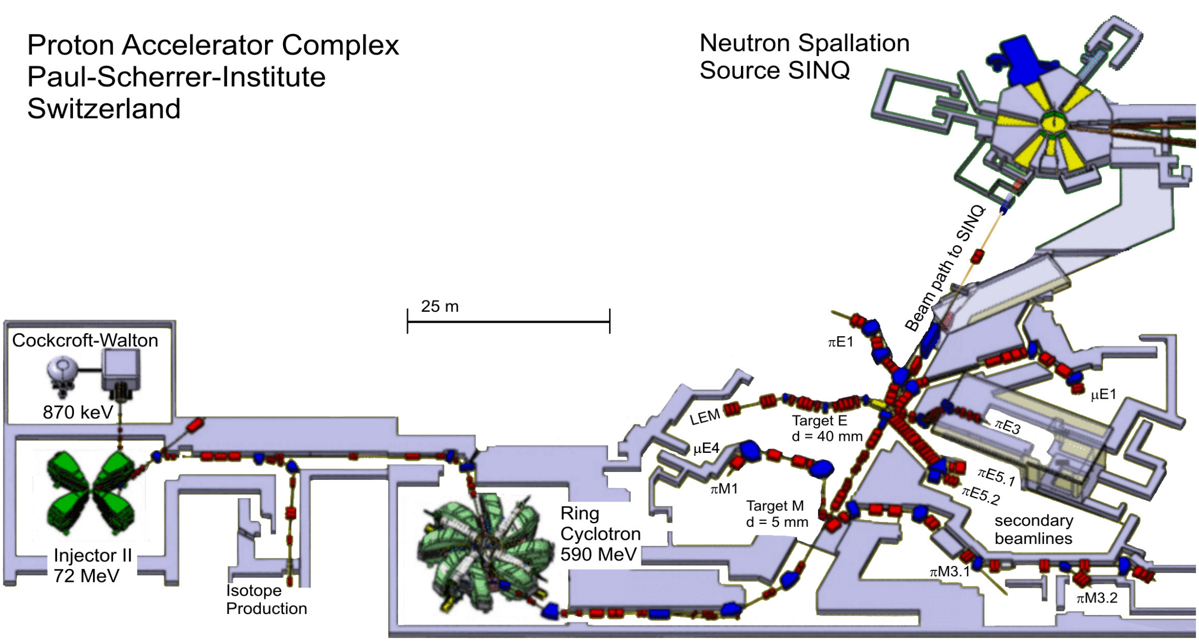

Figure 1: Overview of the PSI accelerator complex.

RELIABLE PRODUCTION OF MULTIPLE HIGH INTENSITY BEAMS WITH THE 500 MEV TRIUMF CYCLOTRON*

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Abstract

In 2001, after 25 years of smooth cyclotron operation with up to 200 μA H^- acceleration, developments towards higher intensities became compelling because of the ISAC expansion. Recently the goal of reliable total proton production current up to 300 μA, within a nominal ~90% duty cycle, was routinely achieved. Beam availability was 90-94% over the last five years. Development highlights are discussed in the paper.

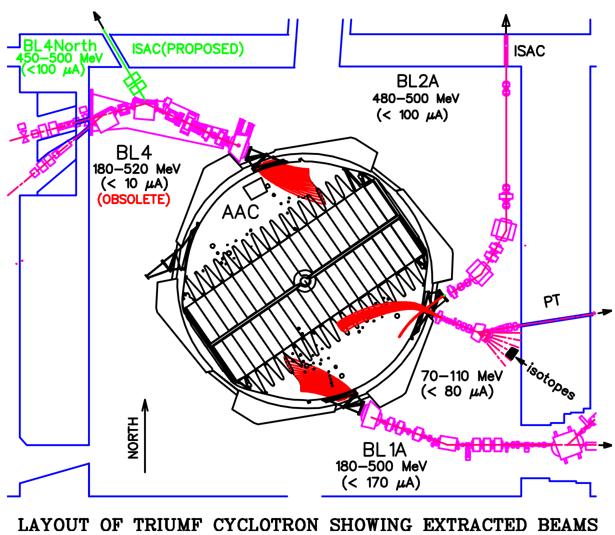

Figure 1: Layout of the cyclotron.

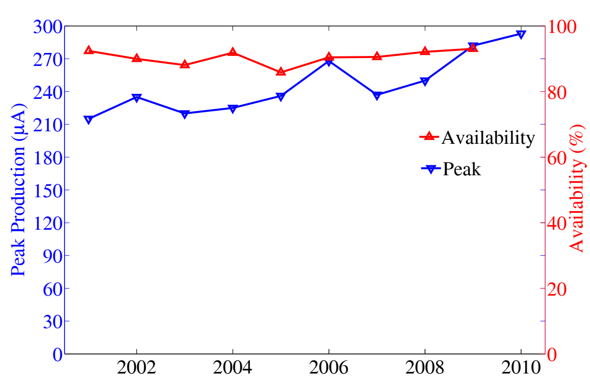

Figure 2: Peak current production and % beam availability for the last 10 years.

*TRIUMF receives funding via a contribution agreement through the National Research Council of Canada.

INTRODUCTION

The TRIUMF cyclotron delivered increasingly intense proton beams during the past 35 years. First beam was extracted at the end of 1974. At the beginning of 1978 the installation of adequate shielding allowed up to 100 μA extraction down the meson production beamline (BL1A) (see Fig. 1). Early production and milestones were summarized at EPAC88, and a one week beam delivery test at $\sim$ 200 μA was also reported [1]. Routine beam production followed during several years up to this current level. In 1995 ISAC was approved and a second high intensity beamline (BL2A) was designed & constructed to transport a 475 to 500 MeV beam to the radioactive isotope source. In order to maintain previous production levels unaltered, it was decided to increase gradually the total cyclotron extracted current from $\sim$ 200 μA to $\sim$ 300 μA, towards a goal of 100 μA for the ISAC primary beam. Higher beam stability and reliability would also be required for this beam [2]. In 2009 a 3 hour test at 290 μA total extracted current was successfully performed. A total peak current of $\sim$ 420 μA at 25% duty cycle was also reproduced. It confirmed previous predictions of a total extracted current in excess of 400 μA [1]. It should be emphasized that reliable extraction of simultaneous multiple high intensity beams hinges on the highest efficiency, reliability and stability of cyclotrons subsystems. Recent improvements to some of these systems will be described below. Peak total extracted intensities and yearly availabilities achieved during 2000-2010 are shown in Fig. 2.

ION SOURCE

Over the years TRIUMF designed H^- ion sources for different types of cyclotrons. High current cusp sources capable of delivering up to 20 mA of H^- beam within a normalized 4RMS emittance of 0.6 πmm-mrad have been first developed for commercial isotope production machines [3]. For the 500 MeV cyclotron, where the acceptance is much smaller, the cusp source is optimized for 700 μA within a normalized 4RMS emittance of 0.1 πmm-mrad. The 12 kV ion source extraction gap is followed by a pair of magnetic steering elements, an einzel lens and iron structures to shield the beam from the $\sim$ 5 gauss main cyclotron stray field. At 1.2 m from the source, a 1 m long acceleration column takes the 300 keV beam to a 34 m long electrostatic injection line. Beam emittance figures from an 'Allison' emittance scanner located at the frontend of the line are shown in Fig. 3 for a 600 μA beam.

THE VARIAN 250 MeV SUPERCONDUCTING COMPACT PROTON CYCLOTRON: MEDICAL OPERATION OF THE 2nd MACHINE, PRODUCTION AND COMMISSIONING STATUS OF MACHINES No. 3 TO 7

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Abstract

Varian Medical Systems Particle Therapy has successfully commissioned its 2nd superconducting compact proton cyclotron for use in proton therapy in 2008. The 250 MeV machine serves as proton source for treatments at the first clinical proton therapy center in Germany which opened in early 2009. Furthermore, Varian is currently commissioning and factory testing its 3rd machine.

We report on the operation and performance of the 2nd machine as well as on the successful cool-down, quench testing, and magnetic shimming of the 3rd machine.

In addition we present RF commissioning plans using a newly developed solid state amplifier, and plans for the upcoming factory beam commissioning in the new Varian cyclotron scanning nozzle test cell, scheduled for October 2010. Finally we provide a brief status and outlook on machines no. 4 to 7.

INTRODUCTION

VARIAN's superconducting compact cyclotron for use in proton therapy is an azimuthally varying field isochronous machine which delivers a 250 MeV cw beam of up to 800 nA. The use of superconduction technology with its closed cycle, zero boil-off liquid helium cryosystem allows a high induction that completely saturates the iron yoke of the compact machine. This results in a reproducible and stable magnetic field which is essential for a reliable beam operation during medical use. The initial design proposal [1] was worked out in detail by ACCEL Instruments GmbH. Some key features of this machine type are listed in Tab. 1; more details are given in our previous status report [2].

In 2007, Varian Medical Systems, Inc. bought ACCEL which had built at that time - amongst diverse advanced technology equipment for research and commercial users - two cyclotrons for use in proton therapy. In early 2009, the respective VARIAN business was re-structured and the particle therapy part is now pursued by the newly formed Varian Medical Systems Particle Therapy GmbH (VMS-PT).

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Table 1: Technical specifications of the VMS-PT cyclotron (engineering goals)

Beam	
Energy	250 MeV
Extracted current	800 nA (more on short term)
Emittance (hor./vert.)	< 3 / 5 π mm mrad (2σ)
Momentum spread	±0.04%
Number of turns	650
Extraction efficiency	~80%
Dynamic range for intensity modulation	1:800
Fast intensity modulation	via electrostatic deflector, >10% in 100 µs
Iron Yoke	
Outer diameter	3.1 m (3.2 m for the first two machines)
Height	1.6 m
Weight	<90 t
4 Sectors AVF SC Magnet	
Stored energy	2.5 MJ
Induction at center	2.4 T
Induction at coil	<4 T
Operating current	160 A
Rated power of cryocoolers	40 kW
RF System	
Frequency	72.8 MHz (2nd harmonic)
Voltage @ center / @ extraction radius	80 kV / 130 kV
RF power	≤115 kW

CYCLOTRONS IN OPERATION

Currently there are two VMS-PT cyclotrons in operation. The first one is located at Paul Scherrer Institute (PSI) in Switzerland as part of the PROSCAN project [3], which is treating patients since the beginning of 2007. The second one passed its commissioning phase in 2008 at the Rinecker Proton Therapy Center (RPTC) in Germany, the first and to date only European proton radiation center that provides since early 2009 a complete hospital setting for the treatment of cancer [4]. Besides the cyclotron this facility is equipped with VARIAN's proton therapy technology, like a degrader for energy adjustment, an energy selection system for the energy

STATUS OF RIBF ACCELERATORS AT RIKEN

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T. Kageyama, M. Kase, M. Kidera, M. Komiyama, H. Kuboki, K. Kumagai, T. Maie,
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Abstract

Recent achievements and upgrade programs in the near future at RIKEN Radioactive Isotope Beam Factory (RIBF) are presented. The beam intensity and available ion species are increasing at RIBF, owing to the continuous efforts that have been made since the first beam in 2006. So far, we accelerated deuteron, helium, nitrogen, oxygen, aluminum, calcium, krypton, and uranium beams with the superconducting ring cyclotron, SRC. The extracted beam intensities reached 1,000 pnA for the helium and oxygen beams. From the operational point of view, however, the intensity of the uranium beam should be much increased. We are, therefore, constructing a new injector linac for the RIBF, consisting of a superconducting ECR ion source, RFQ, and DTL, which will be commissioned in this fiscal year. By using this injector, we also aim at independent operation of the RIBF and GARIS facility for super-heavy element synthesis.

INTRODUCTION

The Radioactive Isotope Beam Factory (RIBF)[1] at RIKEN has been constructed to produce the most intense RI beams over the whole range of atomic masses. The powerful RI beams will give us a means to access the unexplored region on the nuclear chart, far from the stability line. The scientific goals of the RIBF include establishment of a new comprehensive way to describe atomic nuclei and improvements of our understanding on the synthesis of the heavy elements in the universe. We are also promoting applications of the RI beams into various research fields such as nuclear chemistry and biological science.

The accelerator chain of the RIBF is schematically shown in Fig. 1. It consists of two injectors (heavy-ion linac: RILAC[2] and AVF cyclotron[3]), and four booster cyclotrons (RRC[4], fRC[5], IRC[6] and SRC[7]). There are three accelerating modes in the RIBF. The first one uses the RILAC, RRC, IRC and SRC for the acceleration of medium-mass ions such as calcium and krypton. The beam energy from the SRC can be changed in a wide range below 400 MeV/u by varying the rf frequency. The second one is the fixed-energy mode, which uses the fRC between the RRC and IRC. The beam energy from the SRC is fixed at 345 MeV/u, due to the fixed frequency operation of the fRC. This mode is used for the acceleration of very heavy ions such as uranium and xenon. The third mode uses the AVF cyclotron as the injector, and two boosters, the RRC and SRC. This mode is exclusively used for light ions such as deuteron and nitrogen. We can change the beam energy from the SRC below 440 MeV/u, by varying the rf frequency.

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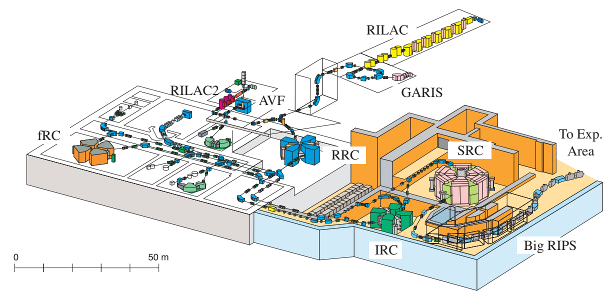

Figure 1: Birds-eye view of accelerator chain of RIBF at RIKEN. Two injectors, RILAC and AVF(K70MeV), are followed by the four booster cyclotrons: RRC (RIKEN Ring Cyclotron, K540 MeV), fRC (fixed-frequency Ring Cyclotron), IRC (Intermediate-stage Ring Cyclotron), and SRC (Superconducting Ring Cyclotron). The new injector (RILAC2), which will be commissioned in FY2010, is also indicated. The specifications of the three new cyclotrons are summarized in Table 1.

The commissioning of the three new cyclotrons, whose specifications are listed in Table 1, started in 2006, and the first beam from the SRC was extracted on December 28[8]. In 2007, two new isotopes, ^{125}Pd and ^{125}Pd, were produced in the BigRIPS spectrometer[9] using the energetic uranium beam from the SRC[10].

ACCELERATOR IMPROVEMENTS

In 2007, however, the transmission efficiency of the uranium beam was as low as 2 % excluding the charge stripping efficiency, which provided low beam intensity of 0.05 pnA at maximum from the SRC. Moreover, the stability of the beam was not good. A lot of obstacles prevented us from getting higher transmission efficiency and stability, and we improved the accelerator system in the last three

FIRST BEAM ACCELERATION IN KOLKATA SUPERCONDUCTING CYCLOTRON AND ITS PRESENT STATUS

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Abstract

Major subsystems of the superconducting cyclotron at VECC, Kolkata were integrated by May 2009. After achieving the required vacuum and Dee voltage a series of internal beam trials were started. The beam was accelerated to full extraction radius on August 25th and beam confirmed by neutron measurements.

The trials were not without difficulty and several problems did crop up during the initial phase. With minor modifications vacuum of the order of 10^{-7} mbar was obtained. Major problems encountered were related to obtaining sufficient Dee voltages primarily due to ceramic insulator cracking at moderate power levels leading to vacuum breakdown. Earlier the 14 GHz ECR ion source was connected with 23 metre injection line without much difficulty.

An analogue beam was also accelerated before taking a shutdown for installation of extraction system and major augmentation of cryogenic plant. Presently extraction of the beam is being tried. It is planned to transport the beam to already installed first experimental station.

INTRODUCTION

The superconducting cyclotron magnet was functional and the magnetic field mapping and corrections were implemented by mid 2006. These developments were reported in the last cyclotron conference. Later the coil was warmed up to assemble other systems of the machine, like RF resonators, cryo-panels, 14 GHz ECR Ion source, 23 metre injection line, extraction system and augmenting main vacuum system. A significant part of the effort related to develop supervisory control and monitoring system for each subsystem incorporating present day tools.

Obtaining vacuum ~10^{-6} mbar in the beam chamber pumped by turbopumps without magnetic field and RF could be obtained relatively easily. Subsequently with magnet energised few leaks were detected and rectified. After having obtained ~10^{-6} RF conditioning was started. Several major problems cropped up in terms of 'viton o-ring' degradation and ceramic cracking at very moderate RF power levels (15 kW). Considerable time was invested in understanding the problem (being detailed later). The problem was circumvented but only partially. However a dee voltage of 45 kV was available and it was decided to try the first internal beam.

FIRST INTERNAL BEAM

It was very tempting to try the first beam as a test beam after 45 kV Dee voltage at 14 MHz was obtained and the phase was stable to provide reasonable condition for acceleration.

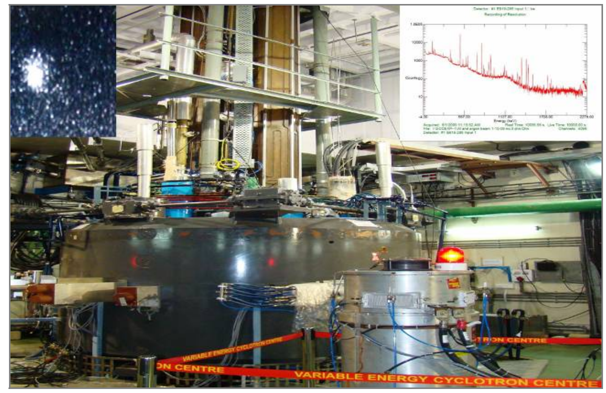

Figure 1: Superconducting cyclotron with first beam spot on left hand corner and gamma spectroscopy of the irradiated target in the right top corner

Initial plan after attempts for higher energy were shelved till suitable Dee voltages are available. And it was decided to accelerate Ne3+ in second harmonic mode at 30 kG at 14 MHz. The 14 GHz ECR Ion source was already relocated from k130 cyclotron to the superconducting cyclotron. All the diagnostics were already made functional after initial problems of measuring low currents in RF environment. In mid-august the above configuration was started as a beam test run. To our surprise it didn't take much time to obtain accelerating beam and the parameters were quite close to the calculated values. The beam was accelerated to full extraction radius on 25th August 2009. To confirm the beam an internal beam experiment with aluminium block attached to main probe was performed and all conclusive signature of beam was obtained.

Initial Observations

It was very satisfying to see that the parameters for magnetic field actually obtained during the test beam run were close to the calculated values. The dee voltages were estimated from pickup probes as the cadmium telluride based detectors are still being implemented to get fairly accurate values.

ECR Ion Source and Injection System

14.4 GHz Electron Cyclotron Resonance Ion Source was relocated from room temperature cyclotron and integrated to the superconducting cyclotron by a 28 metre injection system and a spiral inflector. The injection beam line is designed for the maximum beam rigidity of 0.058 T-m, which corresponds to ions with specific charge (η=q/A) equals to 0.12 and energy equals to (20*η) keV/nucleon, 20 kV being the maximum extraction voltage of ECRIS.

COMMISSIONING OF THE JYFL MCC30/15 CYCLOTRON

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Abstract

The new MCC30/15 cyclotron from NIIEFA, St. Petersburg, Russia, arrived at Jyväskylä on 10th of August, 2009, as a partial compensation of the Former Soviet Union debt to Finland. The cyclotron required an extension for the old experimental hall. The building of the extension started in late August, 2008, and it was scheduled to be ready by Midsummer, 2009. Both the cyclotron and the building projects took a little more time than planned. However, the delay of both projects was less than two months, and so the building was ready to host the cyclotron by the beginning of August, 2009.

The installation of the cyclotron was done by the manufacturer's (NIIEFA) specialists. Before the end of November 2009 the maximum extracted proton intensity (in pulses) was 200 μA, twice the guaranteed value, and 62 μA for deuterons, which is also more than guaranteed (50 μA). The final acceptance protocol was signed on 30th of April, 2010.

BACKGROUND

The operation of the K130 cyclotron has been very extensive. The total cyclotron operating time since 1996 has been over 6000 hours/year, the maximum being about 7500 h/year. So, there has not been much time for machine development, and also the time for maintenance has been limited. About one third of the beam time has been protons and deuterons. Thus it was a natural choice to investigate the possibility of acquiring a separate cyclotron for protons and deuterons in addition to the K130 cyclotron. The plan became a reality when a 30 MeV H^- cyclotron was approved on the list of equipment as partial compensation of the former USSR debt to Finland. An Inter-governmental Agreement between Finland and Russia was signed in 2006 to settle the old debt partially by goods and services. The Contract of the 30 MeV H^- cyclotron, MCC30/15, was approved in June 2007. The cyclotron was be built by NIIEFA, D.V. Efremov-Institute, St. Petersburg, Russia.

THE MCC30/15 CYCLOTRON PROJECT

The first negotiations on the new cyclotron started in 2004. It was already then obvious that the cyclotron should be in the debt conversion program between Finland and Russia. Finally the order could be placed in June, 2007. According to the contract the delivery time was two years from the order plus additional time of six months for installation of equipment and training the local users. There were small delays both in the cyclotron and the building projects However, the building was ready for the cyclotron to be installed in the end of July, 2009. The arrival of the cyclotron was re-scheduled to the beginning of August, 2009.

Everything else but the cyclotron magnet arrived on Friday, 7th of August, on three trucks, two days delayed due to customs problems in St. Petersburg. The Russian team together with the local people unloaded the trucks into the new experimental hall, and everything was prepared for Monday, 10th of August, to get the magnet in the cyclotron bunker. The last two trucks carrying the cyclotron magnet finally arrived at 9.20 pm and the unloading started immediately. Everything took place on the roof of the parking hall, which was supported by hundreds of steel pillars to take the heavy weight. Due to local weight limitations the lifting had to be done with extreme care. The first half of the cyclotron, weighing 24 tons, was put into its final position exactly at midnight (see Fig. 1). The second half was on its place one hour later.

Figure 1: The first half of the MCC30/15 cyclotron is being lifted into the cyclotron cave.

The Russian (NIIEFA) team started the installation of the accelerator immediately after it had arrived. Everything went smoothly and the first beam tests could be carried out in November 2009, and before the end of the month the maximum extracted proton intensity (in pulses) was 200 μA, twice the guaranteed value, and 62 μA for deuterons, which is also more than guaranteed (50 μA).

The final acceptance tests were done in April, 2010. They included maximum intensity test for maximum and minimum energies for both protons and deuterons, as well as stability tests and dual beam tests. All results reached or exceeded the guaranteed values. The maximum proton current at both 30 MeV and 15 MeV was 200 μA. The maximum deuteron current at 15 MeV was 62 μA.

A MULTI MEGAWATT CYCLOTRON COMPLEX TO SEARCH FOR CP VIOLATION IN THE NEUTRINO SECTOR

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Abstract

A Multi Megawatt Cyclotron complex able to accelerate H_2^+ to 800 MeV/amu is under study. It consists of an injector cyclotron able to accelerate the injected beam up to 50 MeV/n and of a booster ring made of 8 magnetic sectors and 8 RF cavities. The magnetic field and the forces on the superconducting coils are evaluated using the 3-D code OPERA. The injection and extraction trajectories are evaluated using the well tested codes developed by the MSU group in the '80s. The advantages to accelerate H_2^+ are described and preliminary evaluations on the feasibility and expected problems to build the injector cyclotron and the ring booster are here presented.

INTRODUCTION

Recently members of the neutrino community proposed a new experiment called DAEδALUS (Decay At rest Experiment for δ_{cp} At Laboratory for Underground Science) a new approach to search for CP violation in the neutrino sector [1,2]. They proposed to utilize high power proton accelerators able to supply a proton beam with about 800 MeV, 1.5 MW average power and a duty cycle of 20% (100 msec beam on, 400 msec beam off). DAEδALUS needs three sources of neutrino; the nearest one located at 1.5 km from the underground detector must have a minimum power of 1 MW. The second source should stay at a distance of about 8 km from the detector and should supply an average beam power of 2 MW or more. The last neutrino source, 20 km far from the detector, has to be fed with a proton beam of average power higher than 5 MW. The neutrino fluxes produced by the three sources are measured by the 300 KTons Cerenkov detector filled with water doped with Gd.

The three sources have their beam time synchronised, so the detector will receive the 100 msec beam bunch from each source in sequence, while for a 100 msec all the three sources will be kept off, to allow the measure of the background.

This configuration allows to measure, how many oscillations $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ occur for each source.

Although the required average power for the first 2 sites is 1-2 MW, the 20% duty cycle has the consequence that the peak power is 5-10 MW and a peak current of about 9.5 mA is necessary. At the same time the lower beam power mitigates the problems related to thermal dissipation and activation.

At a current higher than 1 mA the space charge effects become more and more relevant both for the injection process and for the extraction process. Solutions that mitigate the spaced charge effects are advantageous, see next section.

Accelerator complexes consisting of two or three cyclotrons, one or more injector cyclotrons and a main ring cyclotron booster, have already been proposed as drivers for energy amplifier or waste transmutation plants [3,4,5]. The main constraints for these accelerator complexes are: current higher than 10 mA and energy as high as 1 GeV, minimum beam losses, high reliability and high conversion efficiency from electrical to beam power.

We believe that up to now accelerator driven systems (ADS) based on well known conventional cyclotrons accelerators are the most reliable and economical solution for a plant which requires a peak beam power of 1-5 MW[4,5]. To deliver higher peak power, i.e. 10 or more MW, the key points for the ring cyclotrons are the space charge effects, the extraction devices and the power to be dissipated in each cavity. To overcome these problems a classical solution is to increase the radius of the cyclotron and the number of cavities. But this means to increase significantly the plant cost.

An alternative solution based on the acceleration of H_2^+ molecule has been proposed [6,7]. In this case the extraction of the H_2^+ beam is accomplished by a stripper which produces two free protons breaking the molecule. Due to the different magnetic rigidity as compared to the H_2^+, the protons escape quite easily from the magnetic field of the cyclotron. Extraction by stripping does not require well separated turns at the extraction radius and allows using lower energy gain per turn during the acceleration process and/or lower radius for the magnetic sectors, with a significant reduction of thermal power losses for the RF cavities and construction cost. The extraction by stripper allows to extract beams with large energy spread (0.5÷1%) so the energy spread produced by space charge effect on the longitudinal size of the beam is not crucial in this kind of accelerator, and flattopping cavities are unnecessary.

We believe that the acceleration of H_2^+ beam, despite it needs to handle beam with magnetic rigidity two times larger, offers a remarkable advantage in terms of reliability, easier operations and lower cost.

In the past, a layout for an accelerator complex able to supply a proton beam with energy of 1 GeV and a beam power up to 10 MW was presented by some of the authors [6], in the perspective to drive a sub critical reactor. This previous proposal is now updated to fit the requirement of the MIT scientists. Moreover the number of accelerators required by the experiments, at least 4-5, forces us to minimize the accelerator cost.

The solution, here presented, consists in a two cascade cyclotrons complex. The injector cyclotron, a four sector

DESIGN STUDY OF K100 SEPARATED SECTOR CYCLOTRON FOR ISOL*

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Abstract

Starting from April 2010, KoRIA was launched in Republic of Korea; the main objects of this project are fundamental and applied researches, e.g. production of radioisotope beam for the basic science research, nuclear structure, material and life sciences and medical isotope production. A K=100 separated sector cyclotron will be used as a driving accelerator for ISOL, and it will provide 70-100 MeV, ~1 mA of proton beam and 35-50 MeV, ~1mA of deuteron ion beam, the SSC cyclotron will be injected by 8 MeV proton beam from 2 sector focused cyclotrons. In this paper we will describe briefly about the conceptual design of the cyclotron including the design of injector cyclotron, separated sector cyclotron.

INTRODUCTION

The purpose of this study is to design a separated sector cyclotron as ISOL driver for Korean National project, KoRIA (Korea Rare Isotope production Accelerator), which was started on April 2010 for radioactive ion beam production using both ISOL and in flight fragmentation. KoRIA will contribute to the fundamental research for basic science. Fig. 1 shows the layout of the KoRIA. [1]

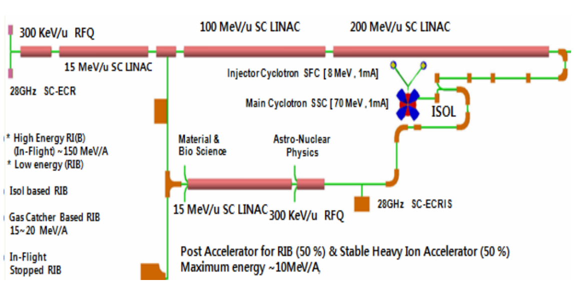

Figure 1: Layout of the KoRIA project

KoRIA facility is composed of cyclotron and superconducting linear accelerator (SC Linac). Stable and unstable ion will be accelerated with SC linac. Unstable ions, radioactive beams are produced with ISOL target bombarded by proton beams with 2 cyclotrons. Main cyclotron, separated sector cyclotron (SSC) has K100 magnet and extraction energy is 70 MeV. SSC is injected by 2 injector cyclotrons. Injection energy is 8 MeV with protons. Radioactive ion beams produced with ISOL are accelerated to 15 MeV/u post linear accelerator which is SC Linac. Accelerated radioactive beams are injected to 200MeV/u main SC Linac for getting the exotic beams.[2] For getting over 1 mA proton beams, we designed separated sector magnet cyclotron even though cost of SSC is higher than sector focus cyclotron. Beam power of protons on the ISOL target is 70kW.

Table 1: Characteristics of Cyclotrons

	SFCyclotron	SSCyclotron
Energy	8MeV	70MeV
Accelerated particles	H^- D^-	Proton Deuteron
Average field	1.155T	0.385T
Pole/extraction radius	0.4/0.35m	3.3/3.0m
Hill angle	48°	30°
Resonant frequency / Harmonics number	74.3 MHz /4th	74.3 MHz/4th
Dee Number	2	2
Dee voltage	50 kV	150kV

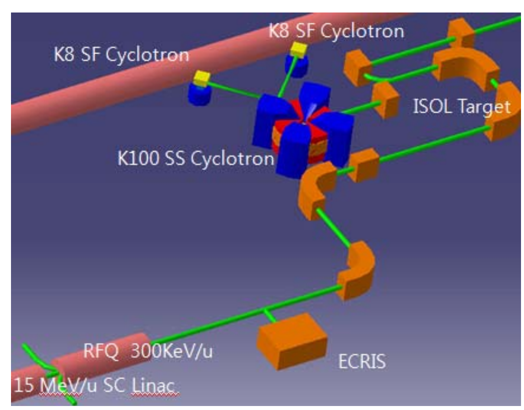

Figure 2: Layout of the cyclotron and ISOL

INJECTOR CYCLOTRON

The compact sector focus cyclotron was designed for injection of K=100 SSC. It has four magnet sectors, and maximum magnetic field is 1.92T. The magnet adopting 4th harmonics has three kinds of holes for beam injection, vacuum pumps and RF systems. Diameter of the pole was chosen to be 80cm with 50kV dee voltage and 40° dee angles. The injection system of this accelerator consists of double gap buncher, Solenoid-Quadrupole-Quadrupole (SQQ) and a spiral inflector. It will provide 8 MeV, 1mA of proton beams[3].

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PROGRESS ON CONSTRUCTION OF CYCIAE-100

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Abstract

Beijing Radioactive Ion-beam Facility (BRIF) is being built at China Institute of Atomic Energy (CIAE). As a driving accelerator for ion beam production, CYCIAE-100 will provide proton beam of 75MeV～100MeV with an intensity of 200μA～500μA. At present, the design for each system has been accomplished and an overall progress has been made for the CYCIAE-100 project. The manufacture of the main magnet has entered into the final assembly stage. Two main magnet coils have been completed, two 100kW RF amplifiers are tested with full output power, the main vacuum chamber and main magnet lift system will be completed soon. The construction designs and suppliers surveys for other systems are finished and ready for purchase. Some key design and technology experiments are in process and significant results have been achieved in verifications. The “Central Region Model Test Stand for High Intensity Cyclotron Development” (CYCIAE-CRM) has successfully passed the formal certification held by the competent authorities. A full scale experimental RF cavity has been fabricated, on which the frequency and Q value measured coincide well with the numerically calculation. The verification test of vacuum cryo-panel structure has provided valuable information to cryo-panel structure design. The key technical problems related to CYCIAE-100 project are being solved along with the progress.

INTRODUCTION

The Beijing Radioactive Ion-beam Facility (BRIF) project being built at China Institute of Atomic Energy (CIAE) is planned for productions of intense proton and Radioactive Ion Beam (RIB) used in fundamental, applied researches and medical isotope production. In this project, a 100MeV H- cyclotron is selected as the driving accelerator to operate together with an existing HI-13 Tandem.

As a key component of BRIF project, CYCIAE-100 will provide a 75MeV - 100MeV, 200μA - 500μA proton beam. Its functions are mainly for a RIB facility, physics experiments, applied science and isotope production research. Its preliminary designs and related earlier stage work were presented at ICCAs in Tokyo of 2004 and in Italy of 2007 respectively.

The preliminary designs for all sub-systems of CYCIAE-100 were accomplished in 2006，followed by the detailed design and construction between 2007 and 2009. An overall progress has been made in design and manufacture and important results have been achieved for CRM and high power experimental RF cavity in 2009 [1]. Figure 1 shows the sketch map of CYCIAE-100.

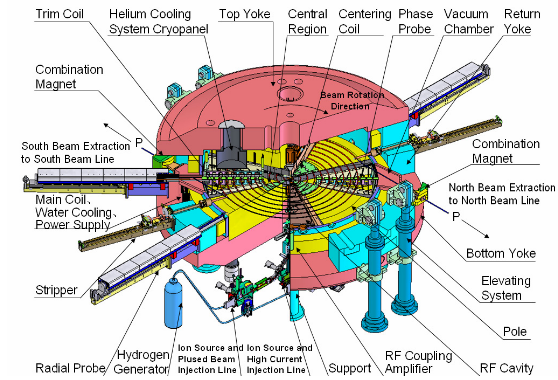

Fig. 1 Sketch map of the major parts of CYCIAE-100.

THE PROGRESS OF MAIN SYSTEMS

A lot of challenges were accepted during the period of fabrications and constructions. A significant progress has been achieved up to now. Some important results will be introduced briefly below. The latest progress of CYCIAE-100 made in recent years will be presented, among which are the final engineering design features, key component fabrication progress, construction status and their pretest specifications.

Main Magnet system

Design Optimization

Due to its large size (6.2m in diameter) and heavy weight (120 ton for one piece), the structure optimization of the main magnet is necessary before stepping into engineering process. While keeping the structure as far as convenient for fabrication, many factors, e.g. the weight, magnetic field force, vacuum force, should be considered together to evaluate its deformations at operating condition after commissioning. As a consequence, some major revisions have been made:

The top/bottom yokes adopts an uneven-height structure instead so that the magnet deformation along radius induced by the atmospheric pressure after pumping can be reduced by 41.26% compared to that of an even-height structure in previous design.

The asymmetric shimming bars are designed in a way that the limited space is best used at the outer radium (R>1200mm) between the shimming bar and the RF cavity. This design eliminates the influence from the coupling resonance on the working path at high energy end in the tune diagram. This kind of asymmetric shimming bar design is a standby solution in case the BH curve of steel is not as good as the designed specification.

Two sets of special measuring tools for main magnet are designed. One is used to measure the angle of the sector, and the other is used to measure the varying gap surface of the sector. Besides, a set of installation tool is specially designed for the shimming bar installation.

INDUCTION SECTOR CYCLOTRON FOR CLUSTER IONS*

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Abstract

A novel scheme of a sector cyclotron to accelerate extremely heavy cluster ions, called "Induction Sector Cyclotron (ISC)", is described [1]. Its key feature is repeated induction acceleration of a barrier trapped ion bunch. The induction cell (transformer) is energized by the corresponding switching power supply, which is controlled by gate signals manipulated from the circulating beam signal of an ion bunch. The acceleration synchronizing with the revolution of any ion beam is always assured. A cluster ion beam such as C-60 [2] can be accelerated from an extremely low velocity to a nearly light velocity. Its fundamental concept including required key devices is described.

CONCEPT OF THE ISC

Definition

It is noted that a terminology "*sector cyclotron*" is used in the following broad sense:

- Sector magnets are employed as guiding magnets.
- A circulating orbit is varied in the radial direction in the fixed guiding fields, associated with acceleration.
- Revolution frequency of circulating ions changes in an acceleration cycle.
- Transverse focussing is resulted from edge focusing effects and field gradient in the sector magnet themselves.

In addition, the ISC is not operated in a CW mode but in a pulse mode due to an essential nature in its acceleration, as described later.

Historical Background

Historically the induction acceleration in a circular ring was invented in Europe and demonstrated in a complete manner as a betatron by Kerst. Topological modification of the betatron acceleration device was achieved. One of them was realized in a linear betatron accelerator (linear induction accelerator) and has been extensively developed [3]. Meanwhile, the concept of induction acceleration in a FFAG ring was proposed and actually demonstrated as an acceleration tool at the initial acceleration stage in the MURA 50 MeV electron FFAG [4]. This acceleration method was nothing but the original betatron acceleration, because the magnetic material cores used for the induction acceleration were excited at the acceleration cycle, yielding a small continuous induced voltage of few tens of volts. That was necessarily always less than 1 Hz; the induction device was ramped just one time during its acceleration cycle.

The induction synchrotron (IS) proposed in 2000 [5] was fully demonstrated using the KEK 12 GeV PS in 2006 [6]. Protons in the IS were accelerated and captured with pulse voltages generated by transformers known as "induction acceleration cells (IC)". The ICs were energized through the corresponding switching power supply (SPS), in which solid-state power devices such as a MOSFET are employed as switching elements and their tuning on/off state is operated through gate signals digitally manipulated from the circulating signal of an ion beam. The ICs were set and reset within a single revolution of the proton bunch in the 12 GeV PS. The ICs were operated at 1 MHz. This feature can be distinguished from any induction acceleration demonstrated in circular rings. Consequently, the acceleration synchronized with the revolution of the ion beam is always guaranteed, regardless of the type of ions and their possible charge state. In this scheme, any ions directly injected from an ion source embedded in a high voltage terminal can be accelerated from an extremely low speed almost to the speed of light. As a matter of fact, the construction of the first AIA through renovation of the existing KEK 500 MeV proton synchrotron is almost complete [7].

A similar induction acceleration of barrier trapped ions can be utilized in cyclotrons operated in a pulse mode. This idea has been proposed in the last year [1]. A sector cyclotron to accelerate cluster ions especially seems to be attractive among them, because there have been no actual methods to accelerate them to high energy in a circular accelerator so far.

Schematic View of the ISC

Figure 1 shows the principle of the ISC, where the varying cyclotron orbit is located in the inner aperture of the induction cell through the entire acceleration period. The induction cell and bunch monitor with a wide aperture are required. This feature is different from that of the induction synchrotron. An ion bunch is captured by the so-called barrier voltages, which are also generated by the other induction cell (see Fig. 2).

INDUCTION ACCELERATION OF A BARRIER TRAPPED ION BUNCH

Induction Acceleration

The concept underlying operation of an ISC is fairly simple. Conventional D-electrodes with a limited frequency bandwidth are replaced by two types of ICs, one of which is used only for acceleration (Cells A and B

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DESIGN AND CONSTRUCTION PROGRESS OF A 7MEV/U CYCLOTRON

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Abstract

The 7MeV/u cyclotron accelerates carbon ions with mass number 12, 5+ charges, the extraction energy of carbon ions is 7MeV/u, and the beam current density is designed to be 10eμA. It designed as injector for the HITFiL(Heavy Ions Therapy Facility in LanZhou) synchrotron, which accelerates carbon ions to the energy 300MeV/u for tumors treatment. Computer modeling results on the axial injection, magnetic, accelerating and extraction systems of the cyclotron are given. Design of the main systems of the cyclotron and the results of beam dynamic simulations are introduced [1], [2], [3], [4]. The construction progress including the ECR ion source, the axial injection beam line, the magnet, the RF system, the vacuum system etc. will be described respectively

INTRODUCTION

The 7MeV/u cyclotron is designed as a commercial cyclotron which is operated in a hospital where the operators of the cyclotron may not be the expert in cyclotron field. At the phase of designing the cyclotron, we aimed to design a compact cyclotron to reduce the cost and a simply operational cyclotron that can be well done by staff in hospital. For these purposes, we designed the extraction average radius to be 0.75 m, the maximum magnetic induction density was about 1.9 Tesla that can be safely achieved with the pure iron material. The magnet of the cyclotron is 4 fold in azimuzal direction with 4 straight edge sectors, the sector's angle is 56 degree. The diameter of the magnet is 2.8 m and the height of the magnet is 1.6 m. We optimized the magnet pole to form the isochronous magnetic field with no trim coils to be used. In two valleys of the magnet, tow 30 degree rf Dees are located. There were eight holes in the magnet four valleys to install vaccum pumps and rf stems. The ion source was designed as a permanent magnetism ECR ion source to remove injection and extraction coils for the ECR ion source. For the axial injection line and extraction system of the cyclotron, we used as less as possible components to simplify the design and construction.

The phase of constructing the cyclotron started in December 2009. The permanent magnetism ECR ion source, the axial injection line, the rf amplifiers and rf cavity are fabricated in plants now. The schedule of the magnetic field measurement is in July 2011, the assembly of the cyclotron is in October 2011, the commissioning of the cyclotron is in December 2011.

DESIGN RESULTS

General Description

As a injector of the HITFiL synchrotron, the 7 MeV/u cyclotron was required to extract $C^{5+}{}_{12}$ beam, while the beam energy was 7 MeV/u, the energy spread was less than 1%, the beam emmitance is about 20 π mm.mrad, the beam current intensity was greater than 10 eμA. The cyclotron was designed as a compact cyclotron with fixed magnetic field and rf frequency, its magnet was 4 fold symmetry with 4 straight edge sectors. The beam produced by permanent magnetism ECR ion source was injected axially into the central region, then accelerated to 7 MeV/u energy by tow 30° Dees located in the tow opposite magnet valleys, finally extracted through a electrostatic deflector(E1) and a magnetic deflector channel(M2).

ECR Ion Source

The permanent magnetism ECR ion source was designed to produce $C^{5+}{}_{12}$ beam solely, the beam current was designed to be 200 eμA with 120 π mm.mrad emmitance, the extraction voltage of the ion source was 22.3kV. The configuration of the ion source is illustrated in Fig. 1.

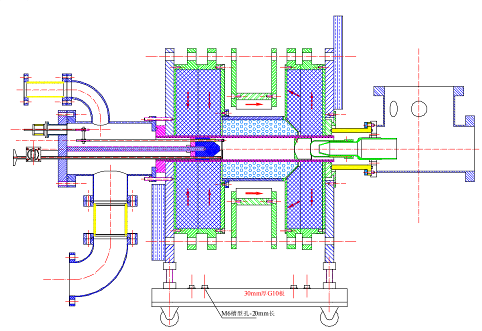

Figure 1: The configuration of the ion source

Magnet

The conceptual design of the 7 MeV/u cyclotron magnet has been performed using OPERA-3D softwar. The B-H magnetization curve of the sectors was measured on the samples, then used in the calculations. The specification of the magnet is given as following. To form the isochronous magnetic field, we cut iron on each sector's surface near the cyclotron median plane, then put a 5 mm thick cover on the sector's surface, changed the quantity of cut iron and the edge shape of cover. The 1/16 model of the magnet is shown in Fig.2. The calculated magnetic field was analysed, the difference of

28GHZ SC-ECRIS AT RIBF

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Abstract

The next generation heavy ion accelerator facility at RIKEN, requires an intense beam of high charged heavy ions. To meet the requirements, we constructed and tested the RIKEN new SC-ECRIS. After producing the first beam in the spring of 2009, we tried to optimize the ion source condition for maximizing the beam intensity with 18GHz microwave. We observed that the gentler field gradient and lager ECR zone size give higher beam intensity. Based on these studies, we produced 500μA of Ar^{11+} and 350μA of Ar^{12+} at the RF power of 1.8kW. We also produced highly charged U ion beam with sputtering method for RIBF. In this article, we describe the structure of the ion source, test experiment and future plan.

INTRODUCTION

Since middle of the 1990s, RIKEN has undertaken construction of new accelerator facility so-called Radio Isotope Beam Factory (RIBF) [1] and successfully produced 345MeV/u U beam (~0.4pnA on target) in 2008[2]. Using it, more than 40 new isotopes were produced with the in-flight fission reactions for only 4 days experiment.[3] It is clear that the intense U beam is strong tool to produce new isotopes in the region of medium mass nuclei and to study the mechanisms of the r-process in nuclear synthesis. For these reasons, the intense U beam is strongly demanded. To meet the requirement, we started to construct the new superconducting ECR ion source (SC-ECRIS) which has an optimum magnetic field strength for the operational microwave frequency of 28 GHz. In the end of 2008, we obtained the 102% of the designed value for the magnetic field strength. In the spring of 2009, SC-ECRIS produced first beam with 18GHz microwaves.[4] Since we obtained first beam, we made various test experiments to increase the beam intensity of highly charged heavy ions with 18 GHz microwave. During the test experiments, we tried to produce U ion beam with sputtering method and produced 0.75~2pμA for highly charged U ions (27~35+) at the RF power of ~1.2kW. In the summer of 2010, the ion source was moved from high voltage terminal to the new ion source room. From this winter, it will be used as an external ion source as a new injector system of RIBF to produce intense U and Xe ion beam[5].

DESIGN OF SC-ECRIS

Detailed structure of the ion source was described in ref. [4]. In this section, we briefly mention the structure and excitation test of the SC-coils

Sc-coils

The schematic drawing and photograph of the Sc-coils are shown in Figs.1 and 2. Inside radii of the hexapole and solenoid coils are 102 mm and 170 mm, respectively. Four coils (SL2 ~SL5) can be used for creating a flat magnetic field region between the mirrors. The hexapole magnetic field in the central region is increased by using iron poles, which is same structure as the VENUS.[6] A NbTi-copper conductor is used for coils and these are bath-cooled in liquid helium. The magnetic stored energy is 830 kJ at the design current. 3D calculations of the deformation of the coil assembly were performed with ANSYS [7]. The hexapole coils were dry-wound to work for turn transitions and was vacuum impregnated with epoxy. On the other hand, the solenoid coils were wet-wound with warm epoxy and cured. The ends of the hexapole coils were fixed with a stainless steel ring to support the large radial magnetic force acting on the current return sections. The six solenoids were assembled with stainless steel spacers and tightened with sixty-four long aluminium-alloy bolts that support a repulsive force of approximately 800 kN at the maximum.

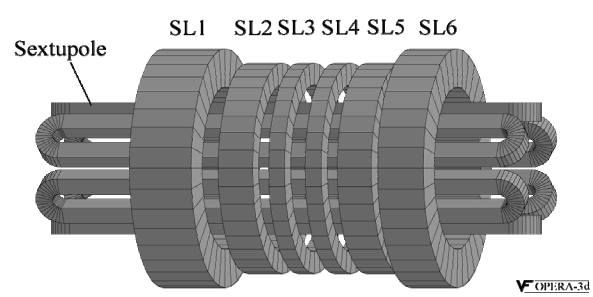

Fig.1 Schematic drawing of the Sc-coils

Using this coil configuration, we can create various shape of mirror magnetic field with six solenoid coils. This magnetic system allows us to produce both of “conventional B_{min}” and “flat B_{min}“[8] configurations. Figure 3 shows the typical axial and radial magnetic field distributions. The maximum axial magnetic fields are 3.8 T at the RF injection side (B_{inj}) and 2.2 T at the beam extraction side (B_{ext}). The maximum hexapole magnetic

NEW TOOLS FOR THE IMPROVEMENT OF BEAM BRIGHTNESS IN ECR ION SOURCES *

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Abstract

According to the model that has driven the development of ECRIS in the last years, a large variation of the pumping microwave frequency (order of GHz) along with the proportional increase of the magnetic field boosts the extracted current for each charge state because of a larger plasma density. Recent experiments have demonstrated that even slight frequency's changes (of the order of MHz) considerably influence the output current, and what's more important, even the extracted beam properties (beam shape, brightness and emittance) are affected. A number of tests have been carried out in the last few years and they will be reviewed along with the results of numerical simulations which are able to explain the observed phenomena. The frequency has been systematically changed and the beam output has been recorded either in terms of charge state distributions and beam emittance. The detected bremsstrahlung X-rays are additionally analysed: they give insights about the electron energy distribution function (EEDF). An overview about the possible future improvements of ECR ion source will be given.

INTRODUCTION

Forthcoming projects aiming to radioactive beams production will be very demanding by the point of view of primary beam intensities and charge states. In this context the ion sources, being the first ring of the accelerator chain, will play roles of growing importance. ECRIS (electron cyclotron resonance ion sources) are largely used on these purpose, because of their ability to produce, in CW and pulsed operations, intense currents of multicharged ions.

However the improvement of ECRIS performances, based on the increase of either microwave frequency (it enhances the plasma density, then the output current) and mirror ratio of the magnetic trap (it confines ions for longer times in order to obtain higher charge states), is now close to saturation, limited by the reliability of the magnets and by the costs.

Concerning the generators, the limitations come not by technology but by the basic principles of plasma heating in multi-mirror devices. Experiments carried out on last generation sources, in fact, have revealed that at frequencies of the order of 28 GHz (with power levels of few kW) suprathermal electrons, with energies of the order of 1-2 MeV, are largely produced. According to theoretical and empirical estimations [1, 2], their number grows with the pumping frequency, and at 28 GHz it is already close to the limits which ensure the safety of the magnetic system. These particles in fact produce large amounts of hard X-rays, which are then partially absorbed inside the cryostat surrounding the superconducting magnets, leading to the boil-off of the liquid helium. Deterioration of the high voltage insulators was also observed. Suprathermal electrons are also useless because their ionization rate vanishes at so high energies. Their nature is still not explained by the current theories describing the ECR heating mechanism, which do not predict electron energies larger than 200-300 keV. Anyway, considering experimental data shown in [3], their production mechanism appears to be strongly related to the magnetic gradient at the ECR, and more generally to the mirror trap profile (taking into account also the distance of the resonance from the minimum field position).

ALTERNATIVE PLASMA HEATING SCHEMES

The necessity to overcome models based on semi-empirical approaches was enunciated already in the last decade of XX century by Richard Geller in order to make advances in terms of extracted currents and production of highly charged ions. For this reason several alternative heating schemes were proposed, by different teams spread over the world. The first one appeared in 1994 and it was named Two Frequency Heating (TFH): it consists in the use of two waves at different frequency instead of one [4], both carrying a total amount of power that is approximately the same of a single wave. It has been observed that the charge state distribution (CSD) peak shifts to higher charge states, and a current increase of a factor 2–4 can be obtained for the highest charge states.

Other variants on plasma ignition schemes were brought at ORNL, using a broadband generator or a flat-B field configuration [5] (i.e. shaping the magnetic field with a quasi-constant profile at the ECR position), but they did not provide remarkable benefits. In some cases they even worsen the performances, producing huge amount of hot electrons.

In the years 2001 – 2004 some controversial results were obtained at INFN-LNS of Catania [6], where the plasma was alternatively heated by TWT or Klystrons: using the first generator the current of each charge state increased considerably, and/or operations at much lower power levels than klystrons were possible, obtaining the

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HIGH POWER RF SYSTEMS AND RESONATORS FOR SECTOR CYCLOTRONS

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Abstract

The Proscan cyclotron is routinely operated for medical cancer treatment and the Injector II and Ring-Cyclotron are routinely used for acceleration of a high intensity proton beam. In the framework of the high intensity upgrade, it is planned to replace two existing 150MHz resonators of the Injector II cyclotron by two new 50MHz resonators. The first prototype resonator has been manufactured by SDMS and first vacuum and RF-measurements have been carried out. Tuners, coupler and pickups have been mounted and high power RF tests are in progress on a teststand. A new building for the RF-installation has been constructed and is ready to house the power amplifiers.

INTRODUCTION

The PSI high intensity accelerator facility routinely accelerates a proton beam of about 2.2mA up to an energy of 590MeV. About 30% of protons are absorbed in the Targets M and E for meson production and 70% of the protons are used in the spallation neutron source (SINQ). This accelerator complex consists of two isochronous, fixed frequency separate sector cyclotrons. The Injector II cyclotron accelerates the proton beam up to an energy of 72MeV which is then transferred to the 590MeV Ring Cyclotron. In 2009, the overall availability of the facility reached about 90% with 8% of outages longer than 5 minutes attributed to the RF systems.

In 2004, a dedicated compact superconducting cyclotron was purchased from ACCEL Instruments GmBH. It routinely accelerates a proton beam up to 250MeV for medical cancer treatment by spot-scanning technique or for treatment of eye-melanoma.

OPERATION OF RF-SYSTEMS

Proscan

The RF-systems of the 250MeV cyclotron (COMET) for cancer treatment has been running without any major problems since 2004. Some minor problems have had to be fixed, such as a broken voltage regulation of the amplifiers. Several RF-contacts were damaged, probably because the field distribution of the dees was not sufficiently well balanced. The RF-window was covered with a metallic layer twice and had to be cleaned.

A newly developed "puller-tip" is now exchangeable and uses tungsten instead of copper to reduce the wear from sputtering.

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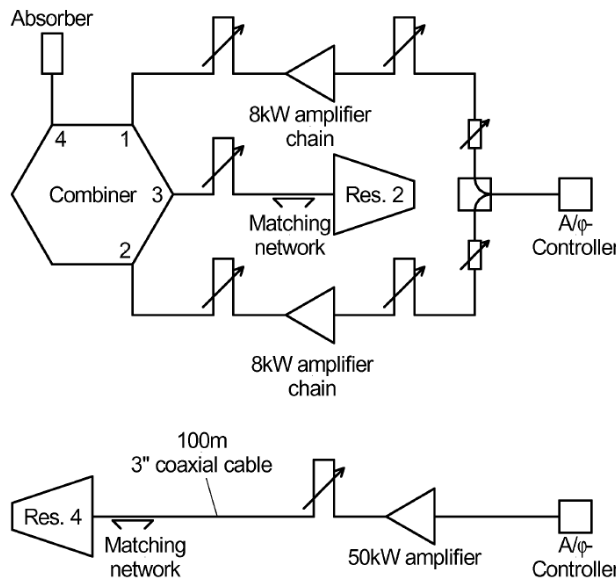

Figure 1: Power distribution in Injector II. The combiner is a 180°-Hybrid ("Rat-Race").

Injector II

The RF system of the 72 MeV Injector [1] consists currently of two double gap-acceleration resonators (50 MHz) and two smaller 150 MHz resonators, which were originally designed as flat-topping resonators. Since the proton bunches are only about 5° long, flat-topping is not efficient and the 150 MHz resonators are therefore operated in acceleration mode.

Fig. 1 shows the present power distribution in Injector II for the Resonators 2 and 4 [2]. Two 150MHz amplifiers are combined to get double power on Resonator 2. A separate power amplifier, located in a different building, is used to feed Resonator 4. This new setup was commissioned in 2003 as a temporary solution, but fortunately has been running since then without major problems. However, tuning and maintenance of the old Resonator 4 amplifier is difficult. A 3dB attenuator was inserted between driver and final amplifier in order to decouple them better and to change the operating point of the driver-amplifier.

Stability problems occurred sometimes when Resonator 4 was switched on after an interrupt. The inner surface of Resonator 4 was then coated with Aquadag [3] to prevent multipactoring by reducing the secondary electron emission coefficient of the surfaces.

OPERATING EXPERIMENCE WITH THE RF SYSTEM FOR THE SUPERCONDUCTING RING CYCLOTRON OF RIKEN RIBF

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Abstract

At RIKEN RIB-factory (RIBF) an accelerator complex as an energy booster which consists of superconducting ring cyclotron (SRC), intermediate-stage ring cyclotron (IRC) and fixed-frequency ring cyclotron (FRC) provides very heavy ion beams like uranium with an energy of 345 MeV/u [1]. In December 2006, the SRC has become operational and it was succeeded to extract the first beam from SRC[2]. Since then, we have experienced various problems with the rf system for SRC and improvements have been made to achieve designed performance solving the problems one by one. This paper will discuss on our efforts to understand the source of troubles and improvements and modifications of the rf system.

RF SYSTEM FOR THE SRC

Superconducting Ring Cyclotron

The K2600 superconducting ring cyclotron (SRC) is the first superconducting separate-sector-cyclotron in the world [3]. The SRC consists of six superconducting sector magnets, four accelerating cavities and one flattop cavity (Fig.1). The rf system is frequency tunable from 18 MHz to 42 MHz so that the beam energy is variable to suite the optimum condition of secondary beam production. Up to now, a number of subjects of nuclear physics experiments utilizing beams of ^{48}Ca, ^{238}U with an energy of 345 MeV/u have been performed with high priorities. The rf frequency of 36.5 MHz for these beam has been mostly used. Designed value of the acceleration voltage is 2 MV/turn.

It was turned out that due to a strong stray field of the K2600 superconducting magnet the rf cavities suffered from very heavy multipactor. In the early stage it took long time, more than a few hours, to recover the rf voltage after breakdown.

This is one of the major problems which reduces the availability of the SRC.

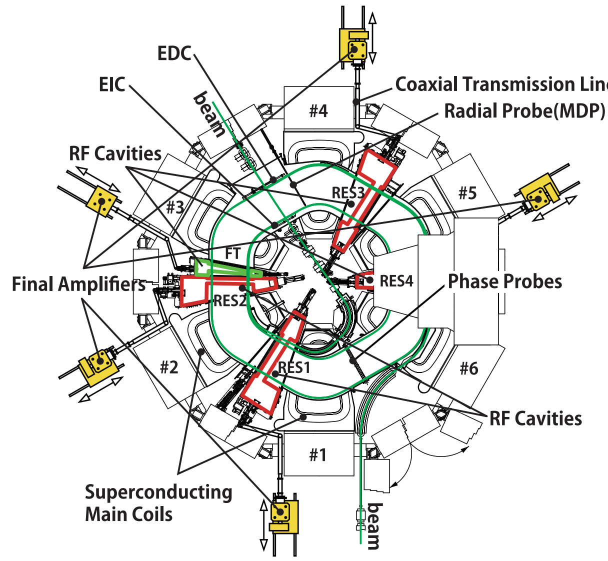

Figure 1: Schematic of the SRC.

Table 1: Present performance of the rf system.

	Acceleration	Flattop
Frequency [MHz]	36.5	109.5
Number of cavities	4	1
Rs [MΩ]	1.5	1.65
Unloaded Q	30000	29000
Voltage [kV/cavity]	550	-240
$P_{w.l.}$ [kW/cavity]	100	18
Vacuum [Pa]	3×10^{-6}	1×10^{-5}
Voltage Stability	±0.03%	±0.03%
Phase Stability	±0.03°	±0.09°
Availability*	92%	99%

* Here availability is defined as all of the cavities are excited.

Cavities

Design, construction, and commissioning of the rf cavities have been reported at Cyclotrons'98, -'01, and -'07 [4, 5, 6]. A present performance of the rf system is summarized in Table1.

The four acceleration cavities have an acceleration voltage of 2.2 MV/turn in total and the third harmonic cavity has a voltage of -0.24 MV with deceleration phase. The voltage of acceleration cavities were initially restricted to 450 kV, since a trouble with contact fingers which were inserted to the gap of cavity wall and the rotating capacitive tuner occurred. The gap was larger than the designed value, then lack of touching pressure made contact resistance large so that the finger got damaged. Modification of the shape of the contact finger was made to reduce the contact resistance.

Since cooling of RF shield adopted to the window of the cryogenic pump was not enough, temperature rise of cryogenic panel occurred and the vacuum pressure was abnormally raised with the cavity voltage higher than 500 kV. To solve this problem installation of water cooling channel

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DISTURBANCE EFFECTS CAUSED BY RF POWER LEAKING OUT FROM CAVITIES IN THE PSI RINGCYCLOTRON

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Abstract

While commissioning the PSI high intensity proton beam facility after the shutdown 2010, direct and indirect phenomena of interaction occurred between the RF power leaking out from the cavities and the electrostatic septa at the injection and extraction region in the Ringcyclotron. As an indirect influence RF fields outside the cavities generate plasma clouds in the peripheral area of magnet poles. Accelerated plasma ions sputtered metallic atoms from the vacuum chamber wall, which then covered the insulator surface with an electrically conductive layer. The septum therefore had to be replaced. Directly, RF power dissipated from the 150 MHz flattop cavity was redirected by a beam stopper in such a way, that a linear correlation between the RF pick up signal monitored at the extraction septum (EEC) and the leakage current across the septum insulator could be observed. As an instant mending action the beam stopper, which is not permanently used, has been removed. The long term attempt to minimize these disturbing effects will be an asymmetrical setting of the hydraulic cavity tuning system and an effective RF grounding of build in components.

INTRODUCTION

In the Ringcyclotron of PSI's high intensity proton facility, the amplitudes in the RF cavities have been raised from 760 MV in 1998 to 860 MV nowadays. In lockstep with this RF upgrade the electrostatic elements had to be modified to meet the new requirements.

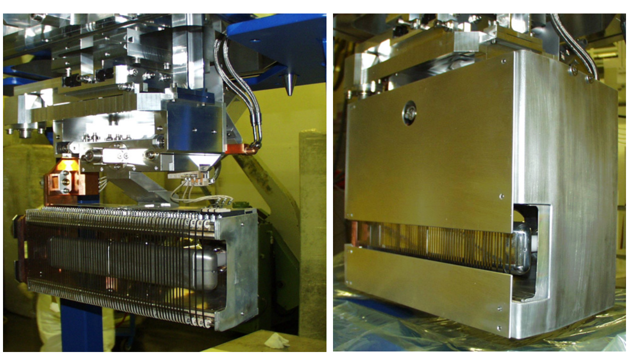

Figure 1: Electrostatic injection channel of the PSI Ring-cyclotron without shielding (left) and shielded (right).

That bundle of measures succeeded to maintain their reliable operation. As an example, the RF shielding of the electrostatic inflection channel, added in 2006, is shown in Figure 1. Despite these efforts, the septa belong to the most critical parts of the cyclotron. In particular their behaviour during the first few weeks after the annual shutdown is a cause for concern. Several times, shortly after the start up of the facility, one or even both of these elements were seriously damaged and had to be replaced.

INVESTIGATIONS IN 2010

In 2010 once more, shortly after the facility commissioning the electrostatic extraction septum EEC lost its electric field strength. The examination of the dismounted EEC septum has exhibited traces of damaging effects. The outer face of a shielding plate at the beam exit side showed a staining on its surface and one of the insulators was contaminated with a strip of conductive material.

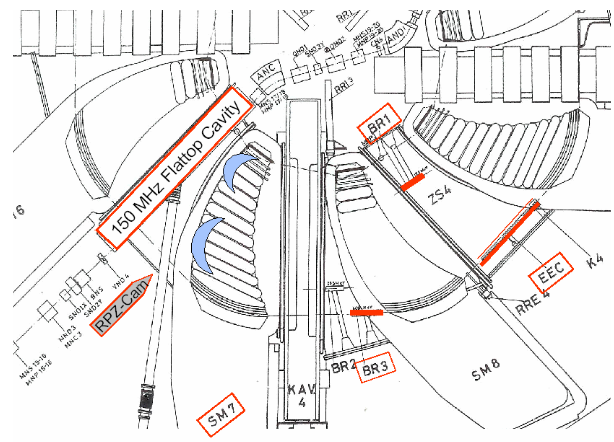

Figure 2: Layout of the PSI Ringcyclotron. The blue coloured patches represent the plasma clouds monitored by the CCD camera in the RF on, beam off state.

After the replacement, various efforts were tackled to get more insight into the damaging incidents that had happened. The scheme in Figure 2 shows coloured in red the cyclotron components involved in them. The experiments uncovered peculiar observations inside the vacuum chamber of the Ringcyclotron.

Interaction of RF with BR1, BR3 and EEC

The two beam stoppers BR1 and BR3 are used for commissioning and tuning purposes. In the beam production state of the machine they are moved out and parked off the beam path. Since years it was a well known fact, that whenever BR1 was set in beam stopping position, BR3 measured a virtual proton beam current of up to 50 µA. The current readout evidently was unreal, since no protons could transit the active stopper BR1. It instead was depending on the voltage level of the flattop cavity. While until the end of last year this fake current signal vanished when BR1 was parked, after this year's

BEAM DIAGNOSTICS FOR CYCLOTRONS

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Abstract

An overview of beam diagnostic systems for cyclotron operation and development is presented. The focus is on devices installed within the cyclotron with its special "environmental" conditions and limitations. Emphasis is placed on the requirements of high current beams, as produced by the PSI Injector 2 and Ring cyclotrons [1].

INTRODUCTION

The first operating cyclotron already used a Faraday cup to detect the accelerated beam current (Fig. 1). Since then, both cyclotrons and beam diagnostic systems have undergone several development cycles, leading to the variety of cyclotrons in operation today at a number of scientific, industrial and medical facilities [2, 3].

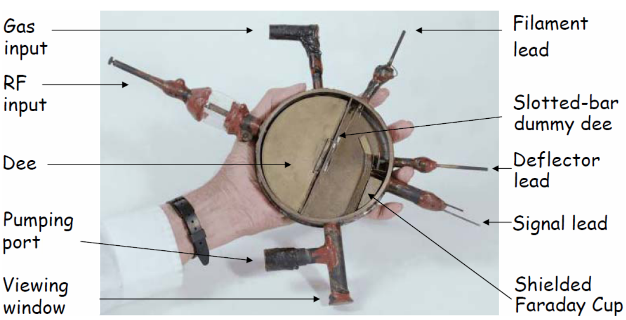

Figure 1: Lawrence & Livingston 4-inch cyclotron which delivered 80 keV protons in 1931 (picture from [4]).

Most of the beam diagnostic techniques in use today at cyclotrons were already present in the 1970s. These are reviewed in [5] and [6-9] and are further described in the proceedings of this conference series (since 1959). In addition, a wealth of detailed information on beam diagnostic techniques is available from the Proceedings of the Beam Instrumentation Workshops (BIW, since 1989) and the Beam Diagnostics and Instrumentation for Particle Accelerators Conferences (DIPAC, since 1993) and other accelerator conferences. Overviews are given in, e.g. [10-14].

Machine design and operation has profited over the years from a number of theoretical and experimental advances. These include improvements in the fields of beam dynamics and magnetic field mapping, and in the stability and reliability of machine components. The experience gained has also played a part. At the same time, requirements to beam quality and availability have also steadily increased. Beam diagnostic systems are thus called on to deliver the missing ε of information during commissioning, beam development, setup and tuning, and searches for anomalies. They are similarly required for beam stabilization and machine protection during standard operation and for the avoidance of excessive activation.

Due to the large variation in cyclotron concepts, uses and parameters, beam diagnostic systems have to adapt to many different environments. Beam current, energy and particle species and their variability, external or internal ion source, sector-focusing or not, separate sectors or compact, normal- or superconducting coils, separated or non-separated turns at extraction as well as standalone or coupled machines, unique or series cyclotron models and the different demands to the availability of the facility - all place their constraints on the requirements.

The boundary conditions within the cyclotron are especially stringent. Already the simultaneous presence of many turns, which eventually overlap, or exhibit beam halo or provide a high power beam, is in itself a complication to the 1-orbit case. The limited space, the strong magnetic field and the presence of large RF fields, beam losses and subsequent radiation, activation and perturbing particles in the direct vicinity of sensor elements, presents a formidable challenge. They hinder or make impossible the use of certain diagnostic techniques and detectors, demanding additional effort. Examples which illustrate this point are shown in Figs. 2, 3.

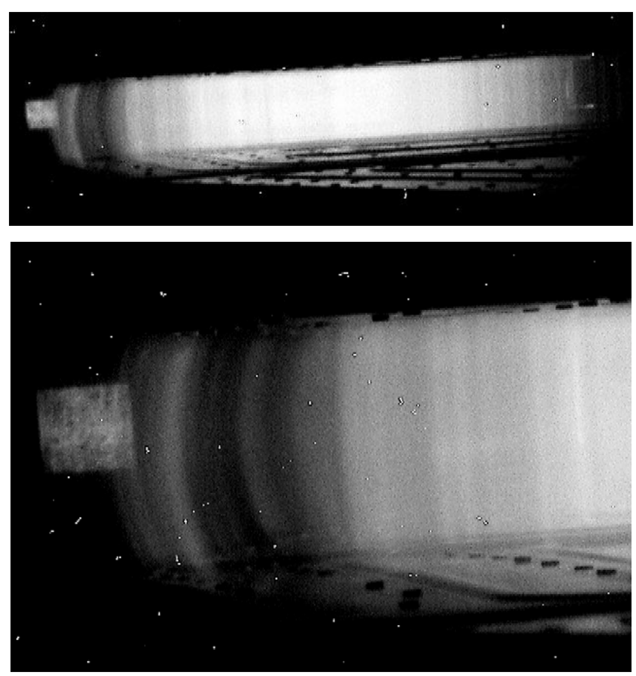

Figure 2: Radial view into the PSI Ring Cyclotron with RF and sector magnets switched on but without beam. A thin plasma is sustained at lower machine radii in the gap of the sector magnet by the RF leaking out from the nearby cavities [15]. One can imagine that the plasma (with associated currents well above the beam current) effects probe measurements.

BEAM DIAGNOSTICS FOR RIBF IN RIKEN

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Abstract

The Radioisotope Beam Factory (RIBF) at RIEKN started its operation in the end of 2006 with the aim of conducting systematic studies on the physics of radioactive isotopes. The simultaneous use of five accelerators in series necessitates precise measurement of beam properties such as beam intensities, beam energies, and bunch lengths. Hence, a beam diagnostic system plays an important role in the efficient and stable operation of RIBF. In this paper, we provide a brief summary of the conventional beam monitors used during the daily operations of RIBF. In addition, new non-destructive monitors that have been developed bearing in mind forthcoming intensity upgrades are described.

RI BEAM FACTORY

The RIBF project [1] aims to produce the world's most intense radioactive isotope beams using a four- or five-step accelerator complex. Our mission is to explore vast unknown fields of physics involving short-lived nuclei including r-process nuclei, which are required to gain an understanding of the process of nucleosynthesis in the universe. The two major acceleration schemes used in the RIBF project are illustrated in Fig. 1. The first scheme involves a variable-energy mode in which we use the RIKEN heavy-ion linear accelerator (RILAC) [2], RIKEN ring cyclotron (RRC) [3], intermediate-stage ring cyclotron (IRC) [4] and the world's first superconducting ring cyclotron (SRC) [5] in series. These accelerators are all of the variable frequency type and their beam energies can be changed. The variable-energy mode is used for ions lighter than those of krypton, and its maximum energy is 400 MeV/nucleon for ^{48}Ca and 345 MeV/nucleon for ^{86}Kr. However, an additional cyclotron, i.e. a fixed-frequency ring cyclotron (fRC) [6] should be used to accelerate ions heavier than those of xenon up to 345 MeV/nucleon, as shown in Fig. 1 (b).

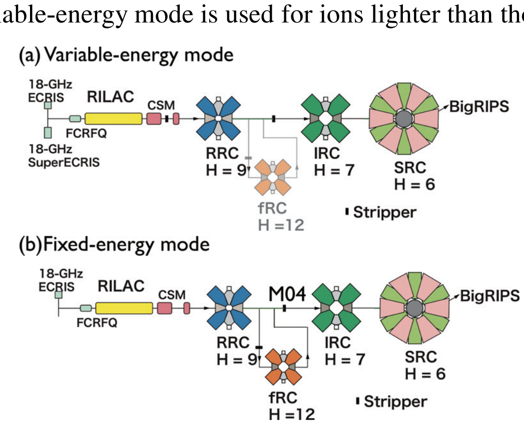

Figure 1: Acceleration schemes used in RIBF.

The beam intensities already achieved is 1 pμA, 0.23 pμA, and 1 pnA for 345-MeV/nucleon ^{18}O, 345-MeV/nucleon ^{48}Ca, and 345-MeV/nucleon ^{238}U, respectively. The total transmission efficiency of the three cyclotrons used in the variable-energy mode is nearly 85%. In contrast, the overall transmission efficiency of the four cyclotrons used in the fixed-energy mode is 40%.

CONVENTIONAL MONITORS

The beam intensities and transmission efficiency mentioned above are achieved by the use of the following conventional monitors (some of which are destructive).

Monitors Used in Beam Transport Lines

Monitors installed in beam transport lines and used in the fixed energy mode are summarized in Table 1. A Faraday cup is used to measure the beam intensity. Its design has been improved during the last three years to reduce uncertainties in the measurements. We originally adopted a compact design with a 1-kV ring suppressor and a relatively shallow cup structure. The original design allowed us to use only a single port of a beam chamber installed in beam lines. However, we found that this design overestimated beam intensities by a factor of 2 or 3 for uranium ions with energies more than 10 MeV/nucleon. The modified design employs a longer cup structure and a 72-mm suppression electrode, using which a uniform distribution of a suppression electric field can be achieved. The modified design still overestimates the beam intensity by a factor of 1.1 or 1.2, but the present overestimation is within acceptable limits for daily operations. The calibration of the beam intensity was carried out using a 40-cm long Faraday.

Table 1: Number of monitors used in beam transport lines. Abbreviations FC, PF, and PS represent a Faraday cup, beam profile monitor, and plastic scintillator, respectively.

Beam line	FC	PF	PS	Length (m)
RRC - fRC	9	12	3	81
fRC - IRC	10	25	4	119
IRC - SRC	6	13	3	64

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POST-ACCELERATION OF HIGH INTENSITY RIB THROUGH THE CIME CYCLOTRON IN THE FRAME OF THE SPIRAL2 PROJECT AT GANIL

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Abstract

The cyclotron CIME is presently used at GANIL for the acceleration of SPIRAL1 radioactive beams. One of the goals of the SPIRAL2 project is to produce, post-accelerate and use in the existing experimental areas much higher intensity secondary beams induced by uranium fission like neutron-rich krypton, xenon, tin isotopes, and many others. Intensity may reach 10^{10} pps. Specific developments are needed for secondary beam diagnostics. Improvement of mass separation is also necessary, and the Vertical Mass Separator (VMS) is specially developed for this purpose.

However, the main concern is related to the high radioactivity linked to RIB high intensity. Safety and radioprotection issues will require modifications of the installation with special care for the maintenance of the cyclotron. The experience of the SPIRAL1 beams, in terms of beam losses and equipment contamination, is especially useful to define the necessary modifications.

INTRODUCTION

The SPIRAL1 facility is now operated since 9 years, so post-acceleration of radioactive beams at GANIL is now routine operation. The SPIRAL2 new facility will extend the possibilities offered to heavier radioactive beams, with much higher intensities, intense beams of neutron-rich exotic nuclei (10^6–10^{10}pps), in the mass range from A=60 to A=140 0. Extracted exotic beam will either be used in a new low energy experimental area called DESIR, or accelerated by means of the existing SPIRAL1 cyclotron (CIME). Post-accelerated beams will then be driven to existing experimental areas (figure 1).

The intense primary stable beams (deuterons, protons, light and heavy ions) will also be used at various energies for neutron-based research, nuclear physics and multi-disciplinary research, in new experimental areas called NFS and S3 0.

In what follows, we give a brief description of the main parts of the new facility, and the status of its construction. Then, in the existing facility, we develop the necessary developments concerning secondary beam diagnostics, and improvement of the mass separation.

Safety and radioprotection aspects are studied in details. Indeed, expected intensities are up to three orders of magnitude higher than with SPIRAL1, while radiological effects may be much more drastic. The experience on SPIRAL1 beams, in terms of beam losses and contamination, is studied in detail in order to decline the necessary modifications.

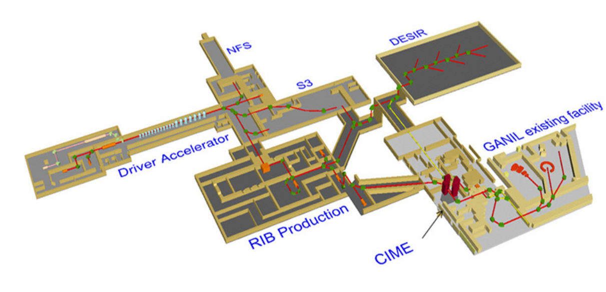

Figure 1: Layout of the SPIRAL2 project, with experimental areas and connexion to existing GANIL

SPIRAL2 DRIVER ACCELERATOR, EXPERIMENTAL AREAS AND PRODUCTION BUILDING

Beams to be Accelerated

Accelerated beams will include protons, deuterons, ions with *A/q*<3, and optionally ions with *A/q*<6. As indicated in table 1, a maximum beam power of 200kW is required for deuterons in CW mode.

Table 1: Beam Specifications

beam	P+	D+	ions	ions
Q/A	1	1/2	1/3	1/6
Max. I (mA)	5	5	1	1
Min. output W (MeV/A)	2	2	2	2
Max output W (MeV/A)	33	20	14.5	8
Max. beam power(KW)	165	200	44	48

Injector-1

The Injector-1, dedicated to protons, deuterons and ions of *q/A*=1/3, is mainly composed of two ECR ion sources with their associated LEBT lines, a warm RFQ and the MEBT line connected to the LINAC.

The 2.45GHz ECR source for deuterons is under test in the CEA/IRFU laboratory at Saclay, with promising results in terms of stability and reliability.

The *q/A*=1/3 heavy ion ECR source and its analysis beam line are installed at the LPSC laboratory (Grenoble). First beam tests give the expected results in terms of transmission, beam tuning and emittance 0.

Developed by CEA/IRFU team, the RFQ0 is a 4-vane, 88MHz 5-meter copper cavity ensuring bunching of the continuous beam, and acceleration up to 0.75Mev/u.

The first 1-meter RFQ segment is just constructed, and under mechanical and RF tests.

The MEBT line achieves the matching at entrance of the LINAC. It allows also connection of the future Injector-2, dedicated to *q/A*=1/6 heavy ions, and a very

ACCELERATION ABOVE THE COULOMB BARRIER – COMPLETION OF THE ISAC-II PROJECT AT TRIUMF*

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Abstract

The ISAC-II project at TRIUMF was proposed to boost the final energy of the radioactive ion beams of the TRIUMF ISAC facility above the Coulomb barrier. The nominal goal of 6.5MeV/u for ions with A/q=6 was recently achieved. The ISAC-II project consists of 40MV of installed heavy ion superconducting linac to broaden the energy reach and a charge state booster to broaden the mass reach. The project and commissioning is described.

INTRODUCTION

TRIUMF has operated a 500MeV H^- cyclotron since 1974. The TRIUMF facility (Fig. 1) was expanded in 1995 with the addition of a radioactive beam facility, ISAC. The radioactive species at ISAC [1] are produced by a 500MeV proton beam of up to 100μA bombarding a thick target. After production the species are ionized, mass separated and sent to either a low energy area or pass through a string of linear accelerators to feed experiments at higher energies. First beams from ISAC were available in 1998 while first accelerated beams were delivered in 2001. The initial accelerator consisted of a 4.5MV RF quadrupole and an 8.1MV Drift Tube Linac delivering beams with A/q≤30 to medium energy users at energies from 0.15-1.5MeV/u chiefly for experiments in nuclear astrophysics.

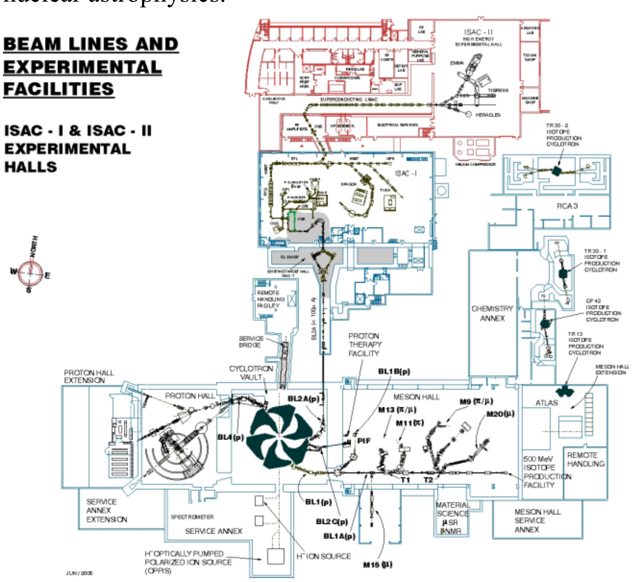

Fig. 1: The TRIUMF facility showing the 500MeV cyclotron and the ISAC-I and ISAC-II facilities.

The TRIUMF ISAC-II superconducting linac, proposed in 1999 [2], was designed to raise the radioactive ion beams above the Coulomb barrier to support nuclear physics at TRIUMF. The goal was to achieve E ≥ 6.5MeV/u for ions with mass to charge ratio of A/q ≤ 6. The first stage of this project, Phase I, commissioned in 2006, involved the addition of 20MV of superconducting linac. Phase II of the project consisting of an additional 20MV of superconducting linac has recently been installed and commissioned. In parallel an ECR ion source was installed to act as a charge state booster to raise the A/q ratio of low energy high mass beams to be compatible with acceleration through the ISAC accelerators. This paper will concentrate on the progress towards higher energies at ISAC and in particular on the recent Phase II upgrade.

LINEAR ACCELERATORS - GENERAL

Since this is a cyclotron conference a talk on a linear accelerator installation may seem somewhat out of place. TRIUMF is at its roots a cyclotron lab with a pedigree not only based on the main 500MeV cyclotron but also on the design, commissioning and operation of the commercial cyclotrons TR30 and TR13. As cyclotron builders we also have to be cognizant of other particle accelerators and their capabilities. These other machines can be used in combinations with cyclotrons either for injection or post-acceleration. The strong advantage of a cyclotron is the improved efficiency of rf utilization in cw application with the same rf system used on multiple turns. This does require a precise magnet to maintain isochronism so that the beam remains in phase with the accelerating field. Injection and extraction are complicated and beam emittance can be broadened due to the dependence of energy and radial position and particularly in cases where a variety of ions require acceleration. Cyclotron builders have imaginative ways of reducing the impact of these complications. Linear accelerators hold some advantage in certain applications. In general injection and extraction from linear accelerators is relatively straightforward and transmission high due to simplified acceleration. In particular RF quadrupoles with their strong transverse focussing and high acceptance have been used successfully in injection beamlines to take the place of large and complicated high voltage platforms that were historically used to reach the required injection energy. Drift tube linac tanks can be made with relatively few gaps (at the expense of rf efficiency) to allow some phase slip of the accelerating beam yielding straightforward ways of achieving variable energy acceleration. Superconducting hadron linacs can achieve, for very short versatile structures, significantly improved rf efficiency (~100 times) over cw room temperature linacs due to the very low resistive losses. It is relatively straightforward to accelerate beams with a normalized transverse emittance

*TRIUMF receives funding via a contribution agreement through the National Research Council of Canada

PROGRESS TOWARDS NEW RIB AND HIGHER INTENSITIES AT TRIUMF*

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Abstract

Over the past five years TRIUMF has operated routinely the ISAC facility at proton beam intensity up to 100 µA. A major departure from other ISOL facilities, ISAC utilizes a modular assembly for the target station. This is mainly to provide enough radiation shielding for operation at high proton beam intensity. So far ISAC was licensed to operate target materials with Z < 82. Two actinide target (UO2) tests have been performed during the past two years to assess the ISAC systems (vacuum, nuclear ventilation, personnel safety) for actinide operation. The uranium oxide target is limited to 2 µA only because of the material low operating temperature. We are now developing a uranium carbide target using similar techniques as for our other carbide targets (SiC, TiC, ZrC) operating up to 75 µA. These developments are essential for the ARIEL (Advanced Rare IsotopE Laboratory) project for which TRIUMF just received funding. This funding includes the construction of a 500 kW, 50 MeV electron superconducting LINAC and a new target hall building capable of housing two new target stations. One of these target stations is rated at 100 kW beam power from both, electrons and protons. The proton beam line utilizes a modified extraction port on the H-520 MeV cyclotron. The other target station will be solely dedicated to the 500 kW electron beam for photo fission.

INTRODUCTION

The TRIUMF-ISAC facility was designed for rare isotope beam production using the protons from the TRIUMF H- cyclotron as the driver beam. Short-lived radioisotopes are produced in a thick target from various nuclear reactions mechanisms. The reaction products are stopped in the bulk of the target material. We operate those targets at very high temperature to enhance the diffusion of the products inside the target matrix to the surface of the grain and then the effusion process to bring the isotopes of interest to the ion source where they are ionized and extracted to form an ion beam.

In this paper we will present the resent progress in target fabrication that can withstand high power for the production of intense RI beam. Finally, we will present the AdvancE Rare Isotope Laboratory that just received funding for installation of a new superconducting electron LINAC and the building housing the tunnel, target stations and remote handling equipment.

ISOL METHOD

Beams of rare isotopes are a challenge to produce. Especially the short-lived ones, they do not exist on earth. They have to be produced artificially in the laboratory. The isotopic separation on-line or ISOL method can be described as a process where the isotope of interest is fabricated artificially by bombarding a target material nucleus with fast projectiles. In a thick target the reaction products are stopped in the bulk of the material. The target container is attached directly or indirectly to an ion source, allowing the reaction products to be quickly ionized and turned into an ion beam that can be mass analyzed and be delivered to experiments. The requirements for producing high intensity RIB are:

- A high energy driver, such as the TRIUMF H^- 500 MeV cyclotron,
- A target material inserted into a refractory oven connected to an ion source,
- An ion source at high voltage to produce an ion beam,
- A high-resolution mass separator.

To solve the problem of producing intense rare isotope beams we need to find the best target material that favors the production of the desired RIB. One more thing to consider is contamination of the ion beam by isobars; isotopes having the same mass number, A, but different atomic number, Z.

Another consideration must be the power deposited inside the target material. If the deposited power density is too high, the temperature of the target material will increase above safe operation level and then the target material will begin to evaporate. This can have disastrous effect on the ion source efficiency, especially for plasma ion sources.

To avoid excessive power deposition by the incoming beam we do not stop the primary beam in the target. This is accomplished by choosing the target length such that the energy degradation of the proton beam is only 200 to 300 MeV. A dedicated water-cooled beam dump is located just behind the target to capture the entire proton beam emerging from the target.

There are three main nuclear reactions accessible to produce rare isotope beams at our energy range. They are:

- Spallation, a breakup or fragmentation of the target material nuclei, in which the product distribution peaks a few mass units lighter than the target nucleus. Because neutron emission is energetically easier than proton emission, (due to the Coulomb barrier that the proton experiences) the production of neutron deficient nuclei is favored. A good example is the high production of Rb isotopes from Nb or Zr target.
- Fragmentation, it is the counterpart of the spallation reaction, where the product is one of the light fragments. The fragmentation method is advantageous when producing light, neutron rich products from heavier target nuclei with high

STRIPPER FOIL DEVELOPMENTS AT NSCL/MSU*

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Abstract

The Coupled Cyclotrons Facility (CCF) at NSCL/MSU includes an injector cyclotron (K500) and a booster cyclotron (K1200). The beam from the K500 is injected radially into the K1200 and stripped at approximately one third of the radius at energies of approximately 10 MeV/u. Stripping is done with a carbon foil. The lifetime of the foil is very short when stripping heavy ions and does not agree with the estimates from formulas that work quite well for light ions. We will present in this paper the studies performed to understand the limitations and improve the lifetime of the foils. A foil test chamber with an electron gun has been built as part of the R&D for the US DOE Facility for Rare Isotope Beams (FRIB) project. It has been used to study different ways of supporting the carbon foils and effects of high temperature operation. Different foil materials (diamond-like carbon, graphene, etc) have been tested in the cyclotron.

INTRODUCTION

The stripper foils are mounted on a C frame with one side open, toward the large radius, where the beam will pass by in the next turn, see Figure 1.

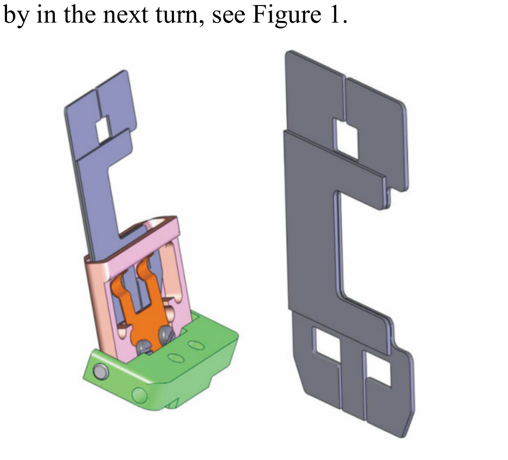

Figure 1 Stripper foil mounting frame (right) and frame holder that attaches to chain.

The lifetime of the foils for light ions is in good agreement with the estimates from Baron's formula [1]. When accelerating heavy ions (xenon and higher) the lifetime of the foils is much shorter than predicted. The foil performance decays so fast that when running high intensity uranium the extracted current has a fast decline in just fifteen minutes, making it impractical to use in regular operation.

The stripper is located inside one of the dees in the K1200 cyclotron, Figure 2. This aggressive environment (in vacuum, in a 5 T magnetic field and inside the high voltage accelerating structure) makes it difficult to install any diagnostics to observe the stripper foil.

Figure 2 K1200 cyclotron. The upper half of the dee has been removed, as well as the RF shield that covers the stripper mechanism. The platter with the chain that drags the stripper foil holders has also been removed. The water cylinders used to drive the platter and locate the platter in the correct position are shown.

To study the thermal and mechanical stresses on the stripper foils under consideration for FRIB we have built a stripper foil test chamber with an electron gun mounted on the side. This chamber allows us to have a detailed look at the foils while irradiating them with the electron beam, overcoming some of the limitations we have to observe the foils inside the cyclotron.

WHY DO FOILS FAIL?

The main reasons for foil failure are thermal and mechanical stresses and radiation damage. In the case of light ions we observe that foils usually develop a tear or the area where the beam hits the foil seems to be sputtered away.

The wrinkling of the foils is a general observation for all ions. In the case of light ions we notice that in many cases the foils detach from the supporting frames. They are mounted with aquadag or similar media. To correct this failure we are testing foil holders with pockets, see Figure 1, where the foils are inserted but not held fixed to the edges.

The failure mode for intense heavy ions (Pb, U) is different. The foil becomes thinner and thinner, moving away from the equilibrium thickness, shifting the charge state distribution toward lower charge states.

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FFAG DEVELOPMENTS IN JAPAN

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Abstract

Fixed field alternating gradient (FFAG) accelerator has been developed in many places for various applications in Japan. This paper presents the recent activities in the development of FFAG accelerators of Japan.

INTRODUCTION

Fixed field alternating gradient (FFAG) accelerator has various advantages. One is the strong focusing in 3D space where the AG-focusing is in the transverse direction and phase focusing in longitudinal direction with rf acceleration. This is just like synchrotron which brings large acceptance is 3D space. Various rf gymnastics such as bunching, stacking, coalescing,etc. become also possible. Static magnetic field gives the fast acceleration and also large repetition rate, which are useful for accelerating the short-lived particles such as muon, and also making an intense averaged beam current.

The first idea of FFAG was brought by Okawa [1], Kerst and Symon [2], and Kolomensky [3], independently, in early 1950s. In MURA project of 1960s, a couple of electron models were developed, however, the proton FFAG was not realized before the POP proton FFAG came out at KEK in 2000 [4]. Since then, development of FFAGs has been implemented in many places and several FFAGs were constructed.

Concerning the beam optics of the FFAG accelerators, there are two types:one is zero chromatic optics and the other non-zero chromatic optics. The ring with zero chromatic optics is called scaling FFAG and the other non-scaling FFAG. The scaling FFAG where the betatron tunes are always constant during acceleration, is free from the problems crossing betatron resonances. Eventually, it could have a fairly large momentum acceptance of more than +-100. On the other hand,the non-scaling FFAG where all optical elements are essentially linear changes the betatron tunes during beam acceleration, Thus, fast resonance-crossing, that is, fast acceleration is essential in the non-scaling FFAG. The orbit excursion of non-scaling FFAG is rather small compared with that of scaling FFAG, therefore, small aperture magnets become available.

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BEAM OPTICS AND DYNAMICS OF SCALING FFAG

The betatron oscillation motions in cylindrical coordinates are expressed with the following equations in horizontal and vertical directions, respectively.

$$\frac{d^2X}{d\theta^2} + \frac{r^2}{\rho^2}(1 - K\rho^2)X = 0. \quad (1)$$

$$\frac{d^2Z}{d\theta^2} + \frac{r^2}{\rho^2}(K\rho^2)Z = 0. \quad (2)$$

Here, K is defined as a form with magnetic field gradient. Keeping the betatron tunes in transverse plane constant for different beam momentum, which means zero-chromaticity, the orbit similarity and constant geometrical field index must be satisfied. These conditions required for satisfying the zero-chromaticity lead the magnetic field configuration as shown in this formula.

$$B(r, \theta) = B_0(\frac{r}{r_0})^k f(\theta - \zeta ln\frac{r}{r_0}) \quad (3)$$

Leading from this magnetic field configuration in the cylindrical or circular orbit, there two types of beam optics allow to realize a zero-chromatic scaling FFAG:one is called the radial sector lattice and the other the spiral sector lattice. In the radial sector lattice, the AG focusing takes FODO with a negative bend gradient magnet. On the other hand, in the spiral sector lattice, the alternating focusing and defocusing can be realized with the edge effect.

So far the scaling FFAG lattice assumes a azimuthal symmetry, therefore, there are some disadvantages. It has relatively a large dispersion and the large orbit excursion which require a large horizontal aperture for the magnet and also for the rf cavity. Another disadvantage is that the length of the magnet-free straight section is rather small and the spaces for the injection/extraction devices and also for the rf cavity is sometimes not sufficient. Having the long straight lines keeping a scaling condition to satisfy the zero-chromaticity, reducing the dispersion and making a good match with circular scaling FFAG lattice, these difficulties can be overcome. What is a configuration of the magnetic field for scaling FFAG straight line? Obviously, it should not be presented in Eq. (3).

$$\frac{d^2X}{ds^2} + \frac{1}{\rho^2}(1 - K\rho^2)X = 0. \quad (4)$$

FIRST COMMISSIONING RESULTS FROM THE NON-SCALING FFAG ACCELERATOR, EMMA

Susan L Smith#, Daresbury Laboratory, Warrington, UK on behalf of the EMMA team

Abstract

The first results from commissioning EMMA - the Electron Model of Many Applications- are summarised in this paper. EMMA is a 10 to 20 MeV electron ring designed to test our understanding of beam dynamics in a relativistic linear non-scaling fixed field alternating gradient accelerator (FFAG). EMMA will be the world's first non-scaling FFAG and the paper will outline the characteristics of the beam injected in to the accelerator as well as summarising the results of the 4 sector 'gantry-type' commissioning which took place at Daresbury Laboratory. The paper will report on recent progress made with the full EMMA ring commissioning, giving details of tune and orbit measurements as well as their correction to the desired lattice series.

INTRODUCTION

EMMA is an accelerator currently being commissioned at Daresbury Laboratory, UK, to demonstrate the world's first operation of a new concept in accelerators called a non-scaling FFAG, (ns-FFAG) [1,2]. First conceived to provide very rapid acceleration for high energy muons, and now adopted in the baseline design of an international neutrino factory design [3], ns-FFAGs are perceived to have a wide range of potential applications ranging from cheap, simple and compact proton/carbon cancer therapy machines e.g. the PAMELA project [4], to highly reliable powerful proton accelerators producing neutrons to drive sub-critical nuclear reactors [5].

THE EMMA EXPERIMENT

EMMA's purpose is to study beam dynamics in linear ns-FFAGs. By using a high-frequency RF system, the machine will focus on dynamics that can be studied in an FFAG that accelerates rapidly. Two particular areas are of interest: the (rapid) crossing of resonances (though "resonance" might not be the best term [6]), and "serpentine" acceleration, a mode of acceleration particular to nearly isochronous linear non-scaling FFAGs [7].

The EMMA ring accelerates electrons from 10 to 20 MeV in kinetic energy. The beam is provided by ALICE (née ERLP) [8,9]. It uses the small ALICE beam to scan a significantly larger phase space (3 mm normalized transverse emittance). We can extract the beam at any point in the acceleration cycle to examine its properties in a diagnostics line.

The main ring lattice was designed to support these goals. It consists of 42 identical quadrupole doublets, where the quadrupole positions (individually) and gradients (for each family) can be varied. This permits independent control of the dipole and quadrupole gradient for each magnet type, which permits us to tune the lattice to a desired configuration, and to modify the tunes and time of flight of the lattice to study the dependence of the machines behaviour on lattice parameters [10]. Making the cells identical eliminates systematic resonances other than those associated with a single cell, preventing undesired orbit distortion and emittance growth [3].

Both the injection and extraction systems [1] consist of a septum and two kickers in successive cells. This configuration permits us to inject and extract a beam at any energy within the energy range of the machine and at any transverse amplitude of interest [11]. We can use this to measure the (fixed energy) tunes and time of flight (ToF) as a function of energy, which is essential for determining the properties of our lattice. We can also inject and extract the beam at any point in an acceleration cycle.

The ring contains 19, 1.3 GHz RF cavities which can create up to 2.3 MV of acceleration per turn [9]. The cavity frequency can be varied over a range of at least 5.6 MHz. The ability to control the RF voltage and frequency allows us to explore the parameters of the serpentine acceleration mode [4].

ENGINEERING & CONSTRUCTION

The construction methodology has been to assemble accelerator components into subsystems offline to enable integration and system testing of modules prior to installation, allowing early detection of problems and minimising assembly work within the working accelerator area. The extremely compact nature of the EMMA lattice has been very challenging for the engineering design and construction, particularly for the injection and extraction fast pulsed magnets. After a poor response from suppliers the design and construction was carried out in-house.

Seven support girders with six lattice cells each are employed to ensure the stable support of the accelerator components in an integrated way, as shown in Figure 1.

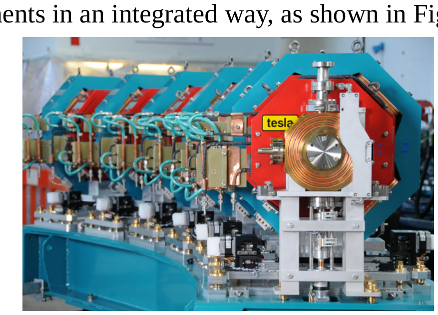

Figure 1: An EMMA girder assembly, 1/7th of the ring

The requirement to deliver close to identical magnetic

INNOVATIONS IN FIXED-FIELD ACCELERATORS: DESIGN AND SIMULATION*

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Abstract

The drive for higher beam power, high duty cycle, and reliable beams at reasonable cost has focused world attention on fixed-field accelerators, notably a broad class of accelerators termed Fixed-field Alternating Gradient accelerators, or FFAGs, (with cyclotrons considered a specific expression or sub-class of FFAGs). Recently, the concept of isochronous orbits has been explored and developed for the most general type of FFAG (termed non-scaling) using powerful new methodologies in fixed-field accelerator design. One application is high-intensity, in particular high-energy (GeV), proton drivers which encounter duty cycle and space-charge limits in the synchrotron and machine size concerns in the weaker-focusing cyclotrons. With isochronous orbits, FFAGs are capable of the high duty cycle, or CW operation, associated with cyclotrons. Further, their strong focusing enables smaller losses, and potential energy variability that are more typical of the synchrotron. With the cyclotron as the current industrial and medical standard, a competing CW FFAG, could potentially have broad impact on research, industrial, and medical accelerators and associated facilities. This paper reports on new advances in FFAG accelerator technology, design, and simulation, and also presents advanced tools developed for all fixed-field accelerators unique to the code COSY INFINITY[1].

INTRODUCTION

The drive for higher beam power, high duty cycle, and reliable beams at reasonable cost has focused world attention on fixed field accelerators, notably a broad class of accelerators termed Fixed-field Alternating Gradient (FFAGs). Cyclotrons can be considered a specific expression or sub-class of FFAGs which employ a predominately constant rather than gradient magnetic field. Recently, the concept of isochronous orbits has been explored and developed for the most general type of FFAG (termed non-scaling) using powerful new methodologies in fixed-field accelerator design. The property of isochronous orbits enables the simplicity of fixed RF and by inference, CW operation. By tailoring a nonlinear radial field profile, the FFAG can remain isochronous, well into the relativistic regime. One application is high-intensity, and, in particular, high-energy (GeV) proton drivers which encounter duty cycle and space-charge limits in the synchrotron and machine size concerns in the weaker-focusing cyclotrons. With isochronous orbits, the machine proposed here has the high average current advantage and duty cycle of the cyclotron in combination with the strong focusing, smaller losses, and potential energy variability that are more typical of the synchrotron. Further, compact high-performance devices like FFAG-type accelerators and cyclotrons often are operated in a regime where space charge effects become significant. The strong focussing attribute, particularly in the vertical of the FFAG, implies some degree of mitigation of space-charge effects and possible stable acceleration of higher currents.

With the cyclotron as the current industrial and medical standard, a competing CW FFAG, could potentially have broad impact on facilities using medical accelerators, proton drivers for neutron production, accelerator-driven nuclear reactors, waste transmutation, and the production of radiopharmaceuticals and open up a range of as-yet unexplored industrial applications. This paper reports on new advances in FFAG accelerator technology, design, and simulation, and also presents advanced tools developed for all fixed-field accelerators unique to the high-order code COSY INFINITY[1].

BACKGROUND

The FFAG concept in acceleration was invented in the 1950s independently in Japan[2], Russia[3] and the U.S[4] (T. Ohkawa[3] in Japan, H.S. Snyder[5] at Brookhaven, and A.A. Kolomenskij[3] in the Soviet Union). The field is weak at the inner radius and strong at the outer radius, thus accommodating all orbits from injection to final energy. Focusing is provided by an alternating body gradient (which alternately focuses in each transverse plane) or through body gradient focusing in one plane (nominally horizontal) and strong gradient-dependent edge focusing in the other (vertical) plane. An extensive discussion of the various FFAG configurations, including derivations of the formulas relating the various accelerator and orbit parameters can be found in the references[6]. The configuration initially proposed was called a radial sector FFAG accelerator. A spiral sector configuration was also invented consisting of magnets twisted in a spiral such that as the radius increases, and the beam crosses the magnet edges, it experiences alternating gradients. With no reverse-bending magnets, the orbit circumference of the spiral-sector scaling FFAG is about twice that for a circular orbit in a uniform field. These machines are the so-called scaling FFAGs (either spiral or radial-sector FFAGs) and are characterized by geometrically similar orbits of increasing radius. Direct application of high-order magnetic fields and edge focusing maintains a constant tune and optical functions during the acceleration cycle and avoids low-order resonances. The

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CYCLOTRON AND FFAG STUDIES USING CYCLOTRON CODES

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Abstract

This paper describes the use of cyclotron codes to study the beam dynamics of both high-energy isochronous cyclotrons using AG focusing and non-scaling (NS) FFAGs. The equilibrium orbit code CYCLOPS determines orbits, tunes and period at fixed energies, while the general orbit code GOBLIN tracks a representative bunch of particles through the acceleration process. The results for radial-sector cyclotrons show that the use of negative valley fields allows axial focusing to be maintained, and hence intense cw beams to be accelerated, to energies >5 GeV. The results for FFAGs confirm those obtained with lumped-element codes, and suggest that cyclotron codes will prove to be important tools for evaluating the measured fields of FFAG magnets.

INTRODUCTION

FFAGs are members of the fixed-magnetic-field or cyclotron family [1] and may be thought of simply as ring synchrocyclotrons with sectored magnets providing AG focusing. Nevertheless, cyclotrons and FFAGs have been developed by two different communities, which have sometimes taken different approaches in their work. The studies described here bridge this gap to some extent by applying orbit codes developed for isochronous cyclotrons to FFAGs, and some FFAG ideas to cyclotrons.

In recent years FFAG designs have generally been developed using synchrotron lattice codes – or adaptations of them – perhaps because their designers have mostly come from a synchrotron background. But synchrotron codes are poorly adapted for use in accelerators with fixed magnetic fields, where the central orbit is a spiral rather than a closed ring, and the magnetic field must be characterized over a wide radial range. Special arrangements must therefore be made to deal with momentum-dependent effects accurately.

Here, we report studies made with the cyclotron orbit code CYCLOPS [2], which tracks particles through magnetic fields specified on a polar grid and determines the equilibrium orbits (E.O.) at each energy and their optical properties. This has the advantages of:

- being designed for multi-sector machines with wide aperture magnets;
- allowing simultaneous computation of orbit properties at all energies;
- having the capability of tracking through measured magnetic fields.

In our initial studies [3, 4] we found good agreement with the orbit parameters determined by J.S. Berg [5] for his F0D0-2 10-20 GeV muon FFAG, and by Johnstone and Koscielniak [6] for their "tune-stabilized" FFAG for cancer therapy with 18-400 MeV/u carbon ions. (Both are of "linear non-scaling" or "LNS" design, where the magnets have constant field gradients.) But in the latter case, non-radial hard magnet edges proved tricky to model with a polar grid, even with a very fine mesh, leading to noisy results. To eliminate the noise, we smoothed the field's hard edges by introducing a sinusoidal field variation – an approximate but effective procedure. A variation extending over 4 grid spacings proved sufficient.

We report studies of three very different FFAG lattices and some cyclotrons. In one case CYCLOPS's sister code GOBLIN [7] has also been used to study accelerated orbits.

ISOCHRONOUS MUON FFAG

Rees [8] has proposed an isochronous radial-sector FFAG design (IFFAG) for accelerating muons from 8 to 20 GeV. This employs a novel five-magnet "pumplet" 0doFoDoFod0 lattice cell (from the Welsh word pump, pronounced pimp, for five), where the d magnets (and Fs at low energy) are reverse bending, and the d, F and D magnets each have special field profiles *B(r)*. With long drift spaces between the d magnets, and 123 cells, the circumference is 1255 m.

Méot *et* al. [9] have used the ray-tracing code ZGOUBI (originally developed for the study and tuning of mass spectrometers and beam lines.) to follow muons through a simulated field grid and confirm the orbit properties Rees predicts: good isochronism, and tunes that rise gently with energy, though ν_z exhibits some deviations (Figure 1). To achieve isochronism and vertical focusing at such high energies is not possible in regular FFAGs or isochronous cyclotrons with only two magnets per cell. By using more magnets, Rees gains additional free parameters.

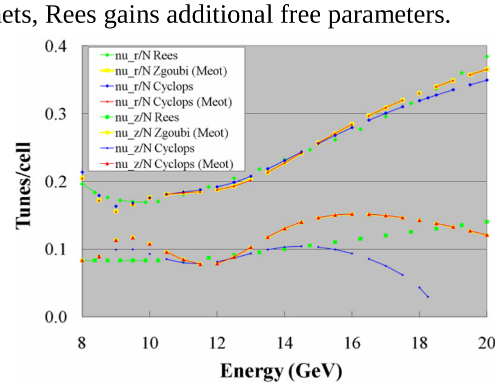

Figure 1: Betatron tunes in the isochronous IFFAG, as computed by Rees, Méot and CYCLOPS.

With CYCLOPS, sinusoidal edges were again needed to suppress noise. The tunes initially obtained [4] agreed

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REVIEW ON CYCLOTRONS FOR CANCER THERAPY

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Abstract

The science and technology of proton and carbon therapy was initially developed in national and university laboratories. The first hospital based proton therapy facility was built at Loma Linda University with the help from Fermilab. After this initial phase, and starting with the tender for the proton therapy system at MGH, many proton and carbon beam facilities have been ordered from industry and built. Industrially made proton and carbon therapy facilities represent today the vast majority of the installed base.

INTRODUCTION: THE HISTORY OF PROTON THERAPY SYSTEMS

Robert Wilson was the first to point out the possibilities offered by the Bragg peak in the field of the radiotherapy of cancer in a paper published in 1946 (1).

A few years later, tests were conducted at Lawrence Berkeley Laboratory to verify Bob Wilson's predictions, and in 1954 protons started to be used on patients in Berkeley.

Similarly, proton treatments were started in Uppsala in Sweden in 1957.

Harvard cyclotron Laboratory (HCL) had a 160 MeV synchrocyclotron. In 1961, Dr. Ray Kjellberg started to use the proton beams at HCL to do radio-surgery of brain malformations. Then, in 1972, Dr. Herman Suit, from Massachusetts General Hospital (MGH), helped by Michael Goitein, started to apply the proton beams of HCL to do fractionated radiotherapy of cancer. A lot of what is today considered as standard proton therapy technology was developed between 1970 and 1990 by Herman Suit, Michael Goitein, and a team of talented physicists at HCL: Andy Koehler, Bernie Gottschalk, and later Miles Wagner, Skip Rosenthal and Ken Gall.

But as successful as HCL was in proton therapy, it quickly became clear that a proton therapy facility located directly within the hospital campus was a much better option. In 1983, the institutions doing or planning to do proton therapy got together to form an informal group named the Proton Therapy Cooperative Group or PTCoG.

One of the first tasks of the PTCoG was to reach a consensus on a set of desirable specifications for an in hospital proton therapy facility. These specifications are still today the bible of those who plan to design a proton therapy system.

Unexpectedly, the first group which succeeded to raise the funds needed to build the first hospital based PT facility was not MGH or Berkeley, but the team led by Dr. James (Jim) Slater at Loma Linda University Medical Center (LLUMC) in California. Jim Slater was a friend of Herman Suit, and they had worked together as interns at MDACC. LLUMC requested the help of the Fermi National Laboratory to design and build the required proton accelerator. The accelerator was designed and built by a group of experienced accelerator physicists from Fermilab and, not surprisingly, the accelerator technology selected by this group was a small, compact synchrotron. The gantry design and construction was subcontracted to SAIC. A private company initially named today Optivus, was established in Loma Linda, CA by Jim Slater to maintain and develop the system at LLUMC. The company is led by Jon Slater, the son of James Slater. Optivus is trying to sell a PT system that essentially is based on the design of the LLUMC system. Although Optivus is probably the oldest company in the PT field, it is the only one that has not designed nor built a PT system. Some members of the company, however, were associated with the development and testing of the LLUMC PT system, first at Fermilab and then at the Loma Linda site.

In the mid-1970s at the Catholic University of Louvain (UCL) in Louvain-la-Neuve, Belgium, Professor Andre Wambersie and Yves Jongen developed a close collaboration to build a fast neutron therapy facility, which was used to treat a large number of patients. In 1986, Jongen left UCL to start the Belgium-based company Ion Beam Applications s.a. (IBA). Wambersie met Jongen in 1989 and suggested that IBA start the design of a cyclotron-based proton therapy facility. The following year, IBA presented the initial design of its PT system based on an isochronous cyclotron and compact, scanning-only, gantries at the Particle Therapy Co-Operative Group (PTCOG) XII meeting in Loma Linda.

In 1991, IBA and Sumitomo Heavy Industries (SHI) in Japan signed a 10-year collaboration agreement to jointly develop a PT system based on the IBA concept. Though this collaboration ended in 2001, it explains why the PT systems developed by IBA and SHI share many common features.

The first official tender to acquire a commercially built PT facility was launched by the Massachusetts General Hospital (MGH) in 1992. Several companies responded, but the competition finally narrowed to three groups: Maxwell-Brobeck, in association with Varian, offered a synchrotron-based system; Siemens offered two versions: one based on a synchrotron and another based on a superconducting isochronous cyclotron (the isochronous cyclotron was designed by Pierre Mandrillon from CERN and CAL, Nice); and IBA, in association with General Atomics, offered a system based on a resistive isochronous cyclotron. The tender process took a long time, but finally the contract was awarded to the IBA-GA team in April 1994.

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IBA-JINR 400 MEV/U SUPERCONDUCTING CYCLOTRON FOR HADRON THERAPY

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Abstract

The compact superconducting isochronous cyclotron C400 [[1, 2, 3, 4] has been designed by the IBA-JINR collaboration. It will be the first cyclotron in the world capable of delivering protons, carbon and α ions for cancer treatment. The cyclotron construction will start probably this year within the framework of the ARCHADE project [5] (Caen, France). $^{12}C^{6+}$ and $^{4}He^{2+}$ ions will be accelerated to 400 MeV/u and extracted by the electrostatic deflector. H_2^+ ions will be accelerated to the energy of 265MeV/u and extracted by stripping. The magnet yoke has a diameter of 6.6 m; the total weight of the magnet is about 700 t. The designed magnetic fields are 4.5 T and 2.45 T respectively in the hills and in the valleys. Superconducting coils will be enclosed in a cryostat. All other parts and subsystems of the cyclotron will be warm. Three external ion sources will be mounted on the switching magnet on the axial injection line located below the cyclotron.

The main parameters of the cyclotron, its design, the current status of the development work on the cyclotron systems are presented.

INTRODUCTION

Today, cancer is the second highest cause of death in industrial countries. Its treatment still presents a real challenge. Protons and light ions allow depositing the radiation dose more precisely in a cancer tumor, reducing greatly the amount of dose received by healthy tissue surrounding the tumor as compared with electrons. But in addition to the ballistic accuracy of protons, light ion beams, like carbon beams, have an extra advantage in radiation therapy: they have a different biological interaction with cells and are very effective even against some type of cancerous cells which resist usual radiations. That is why in the last years an increasing interest in the particle therapy based on $^{12}C^{6+}$ ions has been seen.

IBA, the world's industrial leader in equipment of the proton therapy centers, and the team of accelerator physicists from JINR have developed a superconducting C400 cyclotron based on the design of the current proton therapy C235 cyclotron.

BASIC CONCEPT OF CYCLOTRON

Most of the operating parameters of the C400 cyclotron are fixed: fixed final kinetic energy, fixed magnetic field and fixed RF system frequency (small main magnetic field and RF frequency changes are necessary to switch between different accelerated ions). The cyclotron is relatively small and cost effective.

The most important parameters of the 400MeV/u superconducting cyclotron are listed in Table 1. The view of the cyclotron is presented in Fig.1.

Table 1: Main parameters of the C400 cyclotron

General properties	
accelerated particles	H_2^+, $^4He^{2+}(\alpha)$, $(^6Li^{3+})$, $(^{10}B^{5+})$, $^{12}C^{6+}$
injection energy	25 keV/Z
final energy of ions, protons	400 MeV/u 265 MeV/u
extraction efficiency	~70 % (by deflector)
number of turns	~2000
Magnetic system	
total weight	700 t
outer diameter	6.6 m
height	3.4 m
pole radius	1.87 m
valley depth	0.6 m
bending limit	K = 1600
hill field	4.5 T
valley field	2.45 T
RF system	
number of cavities	2
operating frequency	75 MHz, 4th harmonic
radial dimension	1.87 m
vertical dimension	1.16 m
dee voltage: center extraction	 80 kV 160 kV

Three external ion sources are mounted on the switching magnet on the axial injection line located below the cyclotron. $^{12}C^{6+}$ ions are produced by a high-performance ECR at current 3 μA, α particles and H_2^+ ions are also produced by a simpler ECR source. All species have a charge to mass *q/m* ratio of 1/2 and all ions

FAST SCANNING TECHNIQUES FOR CANCER THERAPY WITH HADRONS – A DOMAIN OF CYCLOTRONS

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Abstract

In protontherapy fast 3D pencil beam scanning is regarded as the most optimal dose delivery method. The requirements to apply this treatment technique and to obtain the maximum possible benefit have a big impact on the accelerator concept. Routinely a very stable, reproducible and adjustable beam intensity is needed, which can be set at a few percent accuracy within a millisecond. Quick changes of maximum intensity from the cyclotron are also needed when changing treatment room. Rescanning the tumour volume at high speed to prevent motion artefacts, needs beam energy variations within 50-80 ms.

It will be shown that a cyclotron offers the most advantageous possibilities to achieve this ambitious performance.

INTRODUCTION

The high spatial accuracy potentially obtainable by hadron therapy has increased the interest for radiation therapy with protons and carbon-ions considerably during the last years. Although in several groups developments are taking place on new accelerator concepts, to date all existing hadron therapy facilities that are in operation or in construction, use a (synchro) cyclotron (protons only) or a synchrotron (protons only or any particle between protons and carbon ions). Protons are accelerated to 230-250 MeV and carbon ions to 400-450 MeV/nucl. Both types of machines have proven to work accurately and safely in a programme of daily patient treatments and show excellent reliability figures.

With regards to beam delivery techniques, most treatments performed today are using passive beam spreading techniques to spread the dose over the tumour volume. However, there is an increasing interest in the possibilities of pencil beam scanning, a technique which is currently in clinical use at PSI Switzerland, HIT and RPTC in Germany and in Houston and Boston, USA. This technique, developed at PSI and GSI [1,2], has shown more possibilities to reduce the dose in healthy tissue than the passive techniques could offer.

The recent developments in accelerator concepts are mainly focussed on scale reduction, with an affordable single room treatment facility as final goal. However, the consequences for the quality of the dose delivery have not been elaborated in all cases. Furthermore, several important specifications of the accelerator and beam delivery system depend on the chosen beam delivery technique.

In this review the relation between accelerator specifications and the quality and type of the dose delivery method will be discussed, followed by a detailed description of the implications for the design and the experience with the cyclotron and beam lines at PSI, where the a fast 3D pencil beam scanning system is being developed for proton therapy.

DOSE DELIVERY TECHNIQUES

Dose Spreading in Depth

The energy of the particle determines its penetration depth in the patient. One should distinguish two purposes of beam energy change: a modulation of the energy to spread the dose in depth over the thickness of the tumour or just to set the maximum penetration depth. Modulation must be done at a much faster time scale and requires much more different energies than a setting of the maximum range in a field. The energy is set at the correct value either when extracted from the accelerator, or in an adjustable degrader in the beam line, or in the nozzle, just before the patient.

In case of a synchrotron the maximum energy needed in a certain treatment is set by the accelerator and can be selected at each spill. In case of a cyclotron, a degrader is used in the beam line, typically just outside the cyclotron. At both accelerator types all magnets in the beam transport system must be set according to the (degraded) energy of the beam. The energy modulation is typically performed just in front of the patient, in the nozzle of the beam transport system. A wheel with an azimuthally varying thickness that rotates in the beam, plates that can be inserted or retracted or plates with a variation in thickness ("ridge filters") are used to give the desired energy spread. A novel approach has been developed at PSI, where the degrader and the following beam transport system have been optimized for speed, to allow fast energy modulation by the degrader at the exit of the cyclotron [3, 4].

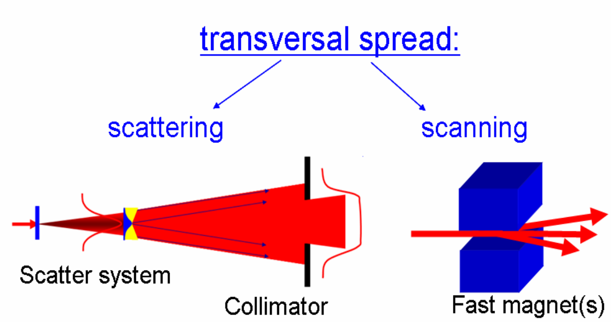

Figure 1: Passive scattering and pencil beam scanning: the tow methods to spread the beam in the transverse plane.

ADVOCACY FOR A DEDICATED 70 MEV PROTON THERAPY FACILITY

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Abstract

Since 1998 we treated more then 1500 patients with eye tumours at the HZB cyclotron with a 68 MeV proton beam.

The 5 years follow up shows a tumour control rate of more then 96%. The combination of a CT/MRT based planning and excellent physical beam conditions like 2 nA in the scattered proton beam, a 0.94 mm distal dose falloff and a dose penumbra of 2.1 mm offers the opportunity to keep side effects on a lowest level.

However all new medical proton facilities are equipped with accelerators delivering beams of 230 MeV and more. While this is needed for deep seated tumours, a lot of physical and medical compromises have to be accepted for the treatment of shallow seated tumours like eye melanomas.

Hence, we suggest a 70 MeV proton therapy facility. It should be equipped with a horizontal beam line and can have optionally a vertical line for more complicated cases under anaesthetics or for biological experiments. By the use of PBO-Lab and MCNPX beam line concepts and a radio-protecting architecture are designed.

MOTIVATION

Experiences from Berlin

Treatment of ocular melanomas at our cyclotron started in 1998. Since then, more than 1500 patients have been treated. In the past years, the number of patients per year increased to more than 200 [1]. The therapy planning and treatment system includes, among others:

- CT and/or MRI-based modelling and planning with the tool OCTOPUS [2,3] (see fig. 1)
- digital image guided patient positioning using TREAT [4]
- use of retractors to avoid irradiation of the eye lids

By far the most of the indications were uveal melanomas, followed by iris melanomas. The subgroup of large uveal melanomas increased. In order to prevent toxic reactions due to the inactivated tumour mass, the irradiation is followed by surgical removal of the tumour (endoresection or transscleral resection) [5]. Peculiar cases were the treatments of small children under anaesthesia, as they were not able to cooperate in the positioning process: Two children (5 and 7 months old) with retinonablastomas and a 5 year old child with an osteoma were treated.

The protons are accelerated by a 5 MV van-de-Graaff generator in combination with a k132 isochronous cyclotron giving a quasi DC, 68 ± 0.3 MeV proton beam. Regarding the depth dose profile, a distal falloff 90 - 10% of 0.94 mm is achieved. A simple single scattering technique provides a beam diameter of 40 mm with a penumbra of 80 - 20% of 2.1 mm.

All required therapeutic beam intensities can be delivered from the cyclotron with a dose rate of at least 15 Gy/min.

Side effects could be minimized due to the properties of our proton beam. The sharp distal dose falloff is often crucial for preventing high dose irradiation of sensitive structures essential for sight (optic nerve, papilla, macula). Furthermore, the sharp lateral penumbra and sharp distal falloff enabled us to spare the bones of the children's skull completely in a frontal irradiation approach.

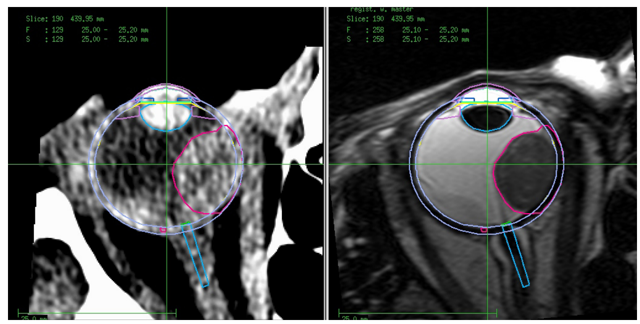

Figure 1a: CT (left) and MRI (right) slice of a right eye with delineated eye ball and lens (blue), papilla (green) on top of optic nerve (cyan), macula (magenta), and tumour (red). These slices are used for treatment planning.

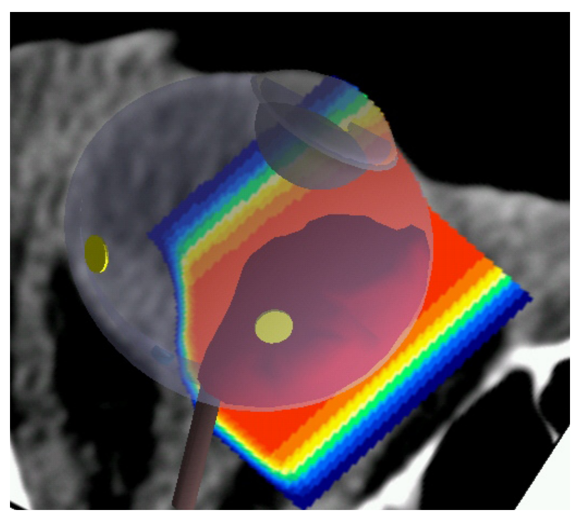

Figure 1b: Dose distribution calculated with OCTOPUS.

New Facilities

So far, 60000 patients have been treated with protons, among them more than 17000 with ocular tumours. Since 1990, an increase of medical proton facilities replacing therapy units at research facilities is observed world-wide. End of July 2010, the particle therapy co-operative group

REVIEW OF CYCLOTRONS USED IN THE PRODUCTION OF RADIO-ISOTOPES FOR BIOMEDICAL APPLICATIONS

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Abstract

Cyclotrons are the primary tool for producing the shorter-lived proton-rich radio-isotopes currently used in the biosciences. Although the primary use of the cyclotron produced short-lived radio-isotopes is in PET/CT and SPECT diagnostic medical procedures, cyclotrons are also producing longer-lived isotopes for therapeutic procedures. Commercial suppliers are responding by providing a range of cyclotrons in the energy range of 3 to 70 MeV. The cyclotrons generally have multiple beams servicing multiple targets. This paper provides a comparison of some of the capabilities of the various current cyclotrons. The use of nuclear medicine and the number of cyclotrons providing the needed isotopes is increasing. In the future it is expected that there will be a new generation of small 'table top' cyclotrons providing patient doses on demand.

INTRODUCTION

Cyclotrons have become the tool of choice for producing the short-lived. proton-rich radio-isotopes used in biomedical applications [1]. Industry has responded with a variety of cyclotrons to address the particular needs of different users groups. Most of these machines have been installed in hospitals, institutes for academic research, and commercial facilities specializing in producing and selling of radio-isotopes. Cyclotrons for biomedical radionuclide production are generally compact, accelerate light ions (proton, deuteron or helium) and are primarily used to produce short-lived, proton-rich radio-nuclides. The main use of these unstable isotopes is for diagnostics and therapy in biomedicine. Other fields using radio nuclides as tracers include agriculture (bio-kinetics in plants and soil), biology (bio-chemical and toxicological studies), ecology (pollution, environmental impact, and ecology studies), Geology (migration of elements in soils and waters) and pharmacology (metabolic studies). The use and need of radio-active isotopes for biomedical applications continues to increase worldwide. However, the list of radio nuclides and the applications have not changed significantly over the past 20 years [2].

Five years after demonstrating the first cyclotron in 1931 [3], G. Lawrence was producing phosphous-32 with by an accelerator and for injection into a patient with chronic leukaemia. Other isotopes generated by his cyclotron also had important applications in medicine. However, his vision to develop a radiopharmaceutical industry at the Radiation Laboratory to help sustain accelerator physics in the late 1930s was an idea ahead of its time. In 1941 the first cyclotron dedicated to the production of radioisotopes was installed at Washington University, St Louis and was used to produce isotopes of phosphorus, iron, arsenic and sulphur. In the mid 1950s a group at Hammersmith Hospital in London put into operation a cyclotron wholly dedicated to radionuclide production. Scanditronix was founded in 1961 as a private company to commercialize cyclotrons for use in the medical field.

Radioactive isotopes have both diagnostic and therapeutic applications in Nuclear Medicine. PET (positron emission tomography), PET/CT and SPECT (single photon emission computed tomography) are the main diagnostic procedures in nuclear medicine. Radioactive isotopes for biomedical applications are produced in reactors and with accelerators. Of particular importance for PET are the short-lived positron emitters, 11C, 13N, 15O and 18F. Carbon, nitrogen and oxygen represent basic constituents of organic matter and this characteristic permits the labelling of a great variety of radio-pharmaceuticals. SPECT uses medium-lived radio-nuclides that are single photon emitters. This is a technique in which a gamma camera rotates around the patient taking 'pictures' which a computer uses to form a cross-sectional tomographic image. Therapeutic applications prefer to use radio-nuclides that have a high linear-energy transfer associated with their decay products and that can be chemically attached to a biologically active molecule which preferentially attaches to a tumour site. Table 1 contains a list of the main radioisotopes produced by cyclotrons along with some of the reactions that are used to produce the radio-isotopes. The production yields come from a variety of sources but primarily from a review article by Ruth et al, vary considerably depending on target design and the chemical form of the radioisotope molecule that is being used for measured the yields and in some cases from calculations [4].

The principle advantage of accelerator produced radio-isotopes is the high specific activity (SA) that can be obtained via the nuclear reactions that produce an isotope that is chemically different from the target element. Another significant advantage is the smaller amount of radioactive waste generated in particle reactions compared to reactor produced radioactive isotopes. (SA is a measure of the number of radioactive decays from an isotope of interest per unit weight of an irradiated sample). Most of the reactions used are of the form (p,n), (p,2n), (p,), (p,xn) and to a lesser extent reactions involving D, 3He and 4He as the projectile. Measured cross sections for many of these reactions along with references for the measurements can be found in an IAEA report titled "Cyclotron produced radio-nuclides: Physical Characteristics and production methods" [5]. For proton/deuteron acceleration the negative ion is preferred in order to reduce activation around the cyclotron whereas for helium acceleration, the positive ions must be accelerated.

In 2005, an IAEA report estimated that, worldwide, there were about 350 cyclotrons that were primarily used

MEDICAL CYCLOTRON AND DEVELOPMENT IN CHINA

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Abstract

The first medical cyclotron CYCIAE-30 in China has been designed and constructed by China Institute of Atomic Energy (CIAE), and its construction was finished in 1995. Since then, medical cyclotron got developed in China, several cyclotrons had been constructed, and some medical experiments and practice had been done with those cyclotrons. Now medical cyclotron develops even quickly in China, several medical cyclotrons are under design and construction. Meantime, a compact cyclotron virtual prototyping was developed to help the cyclotron design and reduce cyclotron R & D cost.

INTRODUCTION

Cyclotron, especially medical cyclotron had a slow development in China in the past few decades, up to now ,there are just a few cyclotrons in China which had be designed and constructed by Chinese accelerator groups themselves, the main medical cyclotrons or cyclotrons on which medical research or practice be done are the CYCIAE-30 and the HIFRL, CYCIAE-30 is a high intensity medical cyclotron which affiliate to China Institute of Atomic Energy (CIAE), The HIFRL is the two-cyclotron complex at Institute of Modern Physics, Chinese Academy of Science (IMP). Recent years medical cyclotron has a quick development, a 10MeV high intensity cyclotron synthesis experimental platform be constructed in CIAE in 2009, several medical cyclotrons are been under designing or construction. Also the technology of cyclotron had gotten development in China especially the Virtual Prototyping was adopted and developed at Huazhong University of Science and technology [1].

MEDICAL CYCLOTRONS AT CHINA INSTITUTE OF ATOMIC ENERGY

There are two cyclotrons at CIAE, one is the CYCIAE-30 (fig.1) which was designed and constructed by Chinese and has been operated since 1995, and it is the first high intensity medical cyclotrons used for accelerated mass production of isotope. Fig 2 shows the total yearly beam times at the first several years.

The other one is a compact cyclotron [2] (fig.3), it is the main part of a high intensity cyclotron experimental platform (CYCIAE-CRM), and it is also the first compact cyclotron which China has Independent Intellectual Property Rights. The main beam parameters of the machine are show in table 1:

Figure 1: CYCIAE-30

Table 1: main parameters of CYCIAE-CRM

Parameters	Value
Accelerated particle	H^-
Extraction energy	10Mev
Internal beam intensity	430μA
Accelerate efficiency	94.5%
Extraction efficiency	99.87%

The success of this machine is a significant affair, it can be used for the developing of PET-cyclotrons which be used for diagnose of cancer and other diseases, this region in China was monopolized by foreign companies in the past.

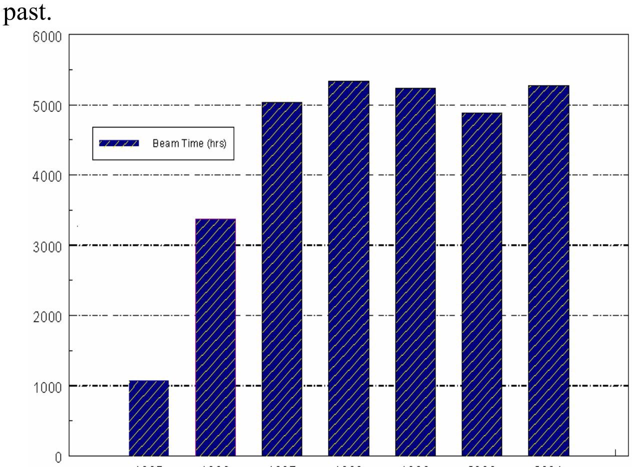

Figure 2: beam time of CYCIAE-30

BNCT SYSTEM USING 30 MEV H- CYCLOTRON

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Abstract

Kyoto University and Sumitomo Heavy Industries, Ltd. (SHI) have developed an accelerator-based neutron source for Boron Neutron Capture Therapy (BNCT) at the Kyoto University Research Reactor Institute (KURRI). In order to obtain 10^9 n/cm^2/sec epithermal neutrons for cancer treatment, a newly designed 30 MeV H- AVF cyclotron named HM-30 was constructed and is being operated. With newly developed spiral inflector, the beam current in the central region can exceed 2 mA. The cyclotron is operated stably at 1 mA. Extracted proton beam is expanded by two scanner magnets in order to moderate heat concentration on the beryllium target, which is directly cooled by water to endure 30 kW heat load. Fast neutrons are emitted from the target, and moderated to epithermal region by a moderator which consists of lead, iron, polyethylene, etc. Thermal neutron flux in a water phantom is measured by gold wire, which is consistent with the calculation using MCNPX. Preclinical studies are being carried out with 10B-p-Borono- phenylalanine (BPA).

INTRODUCTION

In BNCT [1], ^{10}B is selectively taken into the malignant tissues by suitable boron delivery agent such as BPA and sodium borocaptate (BSH). Exposure of thermal neutron flux generates energetic alpha particles and ^{7}Li nuclei, which kill the malignant tissues at the cellular level.

For clinical research of BNCT, thermal neutrons have been provided mainly by nuclear reactors [2,3]. Since it is inappropriate to install nuclear reactors in hospitals, many kinds of accelerator based neutron sources have been considered [4,5,6].

One approach is combination of a high current (~100 mA) low energy (~2.5 MeV) proton accelerator and a lithium target [4]. With this combination, fast neutron yield in the target is 1×10^{14} n/sec, for irradiating 2×10^9 n/cm^2/sec thermal neutrons in tumor.

A serious problem of this approach is that the heat load in the lithium target (~250 kW) is too high. Using a lower beam current (~2.8 MeV, ~20mA) has been proposed [5,6]. This approach sacrifices the neutron yield, nevertheless the heat load is still around 60 kW, and it is too high for the lithium target.

Another approach is to use a middle energy (10~50 MeV) high current (1~3 mA) proton cyclotron and a beryllium target. With a 30 MeV proton cyclotron, 1.9×10^{14} n/sec fast neutrons can be obtained at 1 mA, but the heat load is only 30 kW.

KURRI and SHI started developing the accelerator based neutron source for BNCT in 2007. In order to get high flux neutrons, we selected a combination of the 30 MeV proton beam and the beryllium target. A new AVF cyclotron named HM-30 was designed to generate 30 MeV proton beam with the maximum current of 2 mA.

At the same time, an irradiation system was also designed. Since the thermal neutron does not reach the inner part of a human body, the application of epithermal neutron (0.5 eV ~ 40 keV, in our definition) is more preferable. An epithermal neutron irradiation system optimized for the 30 MeV proton beam was designed with MCNPX [7].

The BNCT system was installed at KURRI in the southern part of Osaka prefecture in 2008. The facility layout is shown in Fig. 1. It is composed of a HM-30 cyclotron, a beam transport system, an irradiation and treatment system with auxiliary systems.

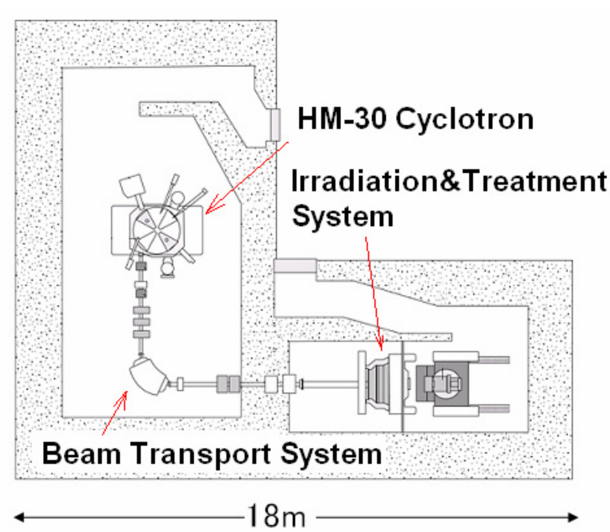

Figure 1: Layout of the cyclotron BNCT system at KURRI.

HM-30 CYCLOTRON

The HM-30 cyclotron, shown in Fig. 2, accelerates H$^-$ to 30 MeV. The proton beam is extracted by a carbon foil stripper. Main specifications are listed in Table 1.

Injection

A volume cusp type H$^-$ ion source (30 keV, 15 mA DC) is used, since it provides high beam current. The normalized effective emittance is around 1 π mm-mrad. The low energy beam transport line consists of two solenoid coils and one buncher. The full beam size at the entrance of the inflector is 6 mm by simulation.