AWAKE status report

AWAKE Collaboration

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Contents

1 Executive Summary

We have made great progress in installation and commissioning of equipment since the last review of AWAKE by the SPSC in October 2015. The installation of the proton and laser beam lines are complete and the commissioning has been a big success. We have transported the proton beam through the AWAKE beam line including plasma cell and diagnostic stations, and the design parameters on beam size and beam jitter have been met or exceeded. The same is true for the laser beam, and the proton beam and laser beam have been synchronized at the sub-nanosecond level. The fine tuning of the synchronization is underway. The proton beam has been measured using standard beam line instrumentation, and we have also observed the proton beam using optical transition radiation with the streak camera, and determined that we generate a strong enough light signal to observe the proton beam and also anticipate having enough light to see the modulation of the beam. The layout of the electron beam line is frozen and the magnets have been ordered. The manufacturing of vacuum elements has been started and necessary infrastructure elements are under detailed design. The integration planning of the PHIN photoinjector is also largely completed and many elements are under construction. The major part of the design and installation of the RF synchronization system for the proton and laser beams has been completed in 2016 and has been successfully commissioned.

The new design for the plasma cell ends was presented at the October 2015 SPSC meeting. Since then, we have studied prototype elements and have performed extensive simulations that have led to some detailed design changes that guarantee sufficient temperature and vapor density control across the full length of the cells to the aperture. We have also had extensive reviews and discussions at CERN, in particular with the vacuum group and safety groups, that have led to revised specifications on the materials that must be used in the fabrication of the cell ends. The final system has been designed and constructed, and nearly all parts are currently at CERN for both the system that will be installed in the AWAKE tunnel and also the system on the surface that will be used to study temperature control and Rubidium handling. The commissioning of the systems by WDL (Wright Design Limited), the Max Planck Institute for Physics, and CERN is currently ongoing. The modifications in the design have led both to increased cost for the design and construction of the cell ends as well as to some delay in the delivery dates relative to last October. The Max Planck Institute for Physics has acquired additional funding of 0.5 MEUR to offset the increased costs in the plasma cell.

The detailed definition of the AWAKE DAQ and Control systems took place within the last year and a significant effort has been expended to getting these ready. The control system has been exercised in a dry-run in September and most functionalities were successfully tested. Missing functionalities were identified and we are currently implementing these in time for the data taking run later this year.

Discussions concerning the CERN beam schedule have taken place over the year. AWAKE is now in the running plan in December, but there have been further schedule adjustments due to shifting of technical stops for the LHC which have affected our commissioning schedule. The current schedule is very tight with the plasma cell commissioning as the major remaining milestone until we attempt the observation of the self-modulation instability. This is foreseen for the last weeks of operation of the SPS in 2016. It is our firm intent to observe proton beam modulation in a Rubidium plasma in 2016. Summarizing the preparations for data taking – we are on schedule to take data with the proton beam through the plasma cell at the end of the year.

The AWAKE Collaboration has created a status of Associate Membership as a stepping stone to full membership in AWAKE. It is understood that AWAKE Associate members will have a 'fast-track' path to becoming full members upon the definition of a concrete project to be performed within AWAKE and the signing of the MoU Addendum. The institutes given Associate Membership to-date are UNIST (Korea), the Swiss Plasma Center (SPC), and the Wigner Research Center (Hungary).

We have created a new Coordination package on preparations for Run II of AWAKE. Run I comprises the observation of the self-modulation instability as well as the observation of electron acceleration with GV/m scale fields until LS2 of the LHC. Run II would likely include a two cell setup with density step, short bunch electron injection, and measurements of the electron bunch emittance. Erik Adli leads this coordination package. Helicon plasma cell R&D efforts at CERN with the aim to have a 10 m version of the helicon cell for Run II are under discussion. We are performing simulation studies related to the setup for Run II so we can define our setup and start preparations, and we have also started physics studies related to the long term goals of proton-driven PWA. The CERN AWAKE Project Leader Mandate has been extended and includes leading the CERN AWAKE project towards and during Run II and coordinating the general proton driven plasma wakefield acceleration studies at CERN.

Some changes in leadership positions have also occurred: Steffen Doebert is now Deputy to Patric Muggli for the Physics and Experiment Board and Ans Pardons is now Edda Gschwendtner's deputy of the CERN AWAKE project.

2 Primary Beam lines

2.1 Proton Beam line

The installation of the proton beam line was finished in May 2016. Directly afterwards the hardware commissioning of power converters, magnets, beam instrumentation, interlocks and test of the vacuum system started. In a two week commissioning period all circuits were tested, including a heat run of all new magnets that had been installed in the AWAKE beam line. In parallel the power converter RBI.410010 was upgraded to be able to switch the beam between TI8 (beam to LHC) and TT41 (beam to AWAKE). All systems performed well in those tests.

Due to the shortened technical stop of LHC in June 2016 ("TS1" in Fig. 29), it was not possible to perform the heat run of the main dipoles during this hardware commissioning period. With the DSO test (access safety tests) at the end of the hardware commissioning in June, a beam permission was given for a two hour long run with pilot beam (5×10^9 protons/bunch). The first beam with the AWAKE cycle was extracted on 15 June 2016 from the SPS onto the beam dump at the end of TT40. A day later, it was sent into the TT41 beam line. The beam reached the end of the TT41 beam line within the first shot. Screenshots of the first recorded bunches at both places are presented in Fig. 1. This beam time was used mainly for system checks. One of the outcomes was an issue of the BPM readings; the BTVs were checked and performed well.

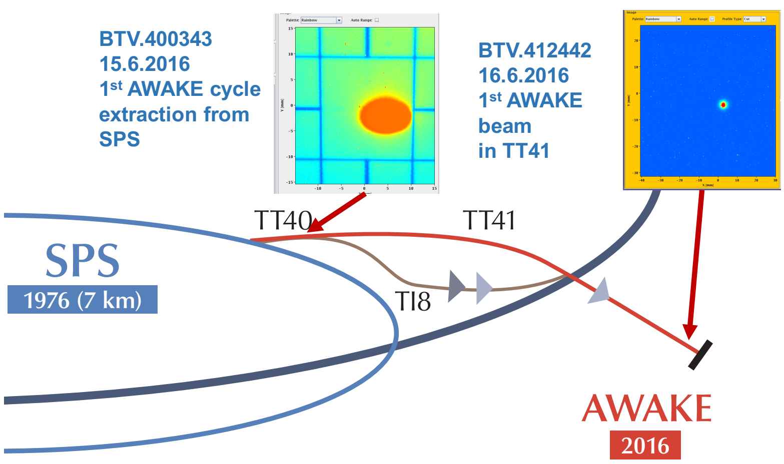


Fig. 1: First extraction of the proton beam with the AWAKE cycle from SPS and the first shot on the last BTV in the AWAKE beam line one day later.

After this first test run, the heat run of the main dipoles was finished during the next technical stop in September 2016 ("TS2" in Fig. 29), just before the 2 weeks beam commissioning period for the AWAKE proton and laser beam. During the first week of this beam time, the BPMs were checked again and compared to the BTV readings. The systems performed very well in general. The proton beam trajectory could be corrected to a maximum offset compared to the nominal trajectory of about 3 mm in the range of the main dipoles and less than 0.5 mm in the range of the laser merging mirror to the end of the beam line. A picture of the reference trajectory, which was set for the alignment with the laser beam is shown in Fig. 2. Based on this reference, optics and stability measurements have been done. The standard deviation of beam position during a 2 hour stability run with nominal AWAKE intensity of 3×10^{11} protons/bunch was measured to be $< 150\,\mu$m at the laser merging mirror and $\sim 60\,\mu$m up and downstream of the plasma cell (see Fig. 3). Measurements of the bunch characteristics at extraction from the SPS showed a bunch length of 1.2 ns and transverse normalized emittance of less then 2.5 mm mrad. The next commissioning step in November 2016 (see Fig. 29) will be the fine alignment with the plasma cell ends.

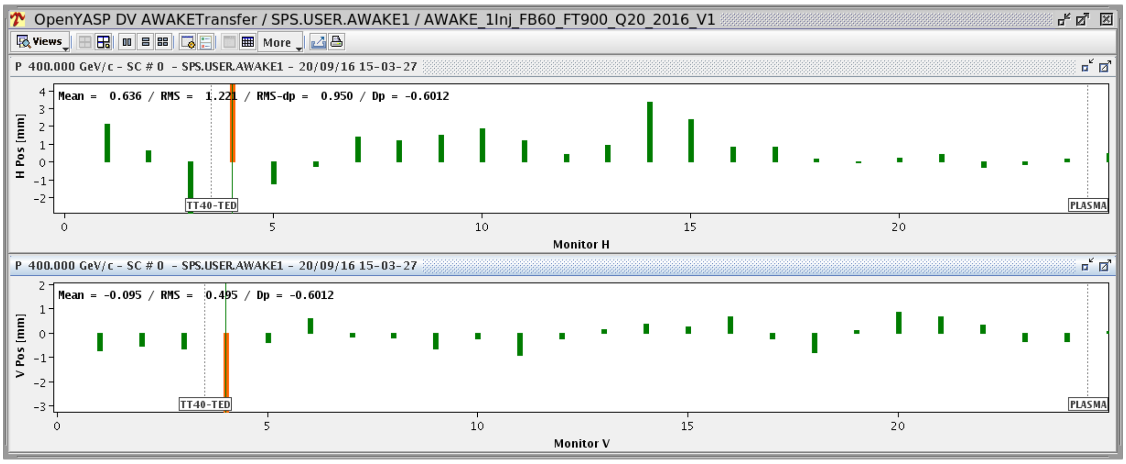
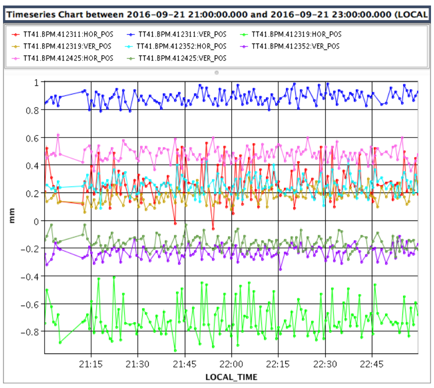


Fig. 2: Horizontal and vertical proton beam reference trajectory for laser alignment. Each point corresponds to a BPM along the beam line.



Variable Name	Count	AVG	StandardDev
upstream laser merging mirror			
TT41.BPM.412311:HOR_POS	138.00	0.27	0.12
TT41.BPM.412311:VER_POS	138.00	0.89	0.045
downstream laser merging mirror			
TT41.BPM.412319:HOR_POS	143.00	-0.71	0.11
TT41.BPM.412319:VER_POS	134.00	0.18	0.051
upstream plasma cell			
TT41.BPM.412352:HOR_POS	142.00	0.26	0.062
TT41.BPM.412352:VER_POS	134.00	-0.23	0.044
downstream plasma cell			
TT41.BPM.412425:HOR_POS	137.00	0.48	0.052
TT41.BPM.412425:VER_POS	138.00	-0.16	0.049

Fig. 3: Two hour stability measurement of the BPMs at the laser merging mirror and the plasma cell.

2.2 Electron Beam line

The layout of the electron beam line has been frozen and the magnets have been ordered. Manufacturing of vacuum elements has been started and the technical drawings of supports are about to be finished. TRIUMF has provided prototypes of the BPMs for the electron beam line (with 40 and 60 mm diameter of the beam pipe). The 40 mm prototype has been tested in CALIFES (see Section 3). A test of the

60 mm prototype in the common beam line with the proton beam is being prepared. The goal of this test is to verify the suppression of the signal from the proton bunches on the electron BPM. It will be installed just upstream of the plasma cell in October 2016.

In June 2016 measurements of the earth magnetic field and stray fields from the proton line magnets have been performed and compared with correction capabilities in the primary electron transfer line. From this tests, no issues are expected from the magnetic field background. The installation of the electron line is planned to start in spring 2017.

2.3 Electron Beam Transport Through the Empty Plasma Cell

Transporting the low-energy primary electron beam through the empty plasma section (or through the neutral Rb vapor) is an interesting option useful for the commissioning of electron beam injection. By observing the electron beam at the downstream BTV screen it is possible to make sure that the steering is correct and the electron beam passes through the beam line aperture. It could also be possible to observe the effect of electron beam attraction by the field of the proton beam if both beams travel at the distance comparable to the proton beam radius along ~ 1 m section of the beam line [1]. This can be a sensitive indication of the temporal and spatial overlap between the beams. However the Earth's magnetic field was measured in the AWAKE facility in summer 2016 and with a typical value of 0.4 G it makes it difficult for the low-energy electrons to pass through the empty plasma section without additional steering. It might be still possible to pass the electron beam through the empty plasma section if initially the electron beam is injected with a small (4 mrad) angle.

3 Electron Source

The design and layout integration of the electron injector in the AWAKE experiment has been largely completed. Figure 4 shows the latest integration version of the electron injector in the AWAKE facility. It was decided to construct a radiation shielding around the electron source defining a separate access zone in the area. This allows local commissioning of the electron accelerator while access to certain areas such as to the klystrons can be maintained. From this decision we expect more operational flexibility and additional protection of the equipment in the area.

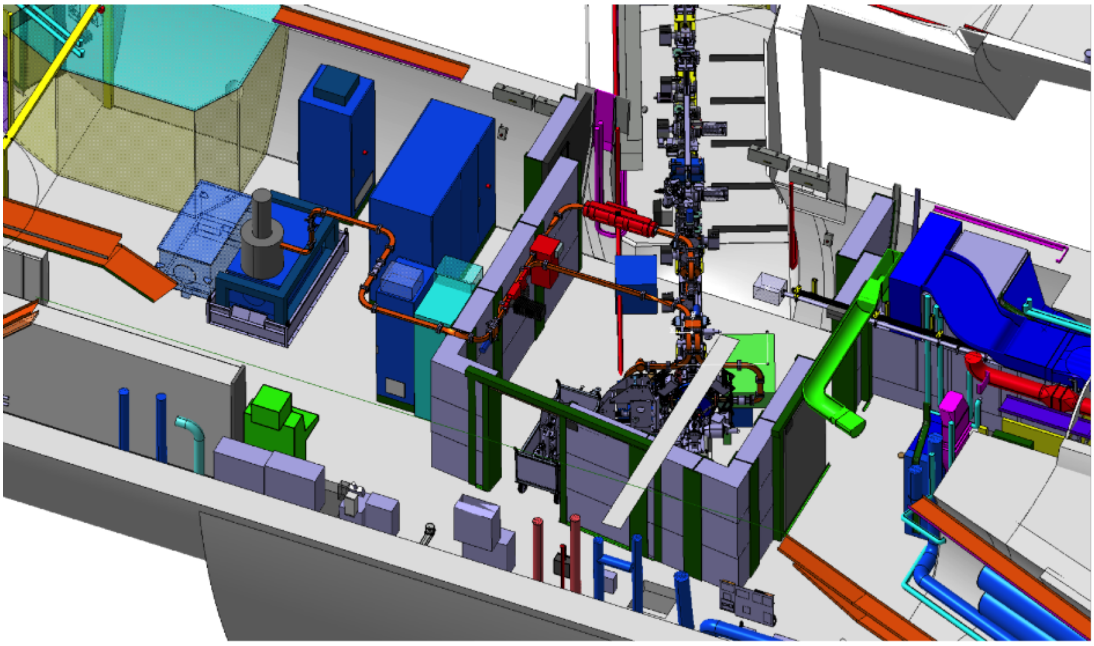


Fig. 4: Latest integration model of the electron injector in AWAKE.

The focus shifted from the design to fabrication of hardware related to the electron source. Numerous elements are in the fabrication stage. All necessary safety documentation and system descriptions have been produced and approved.

The various contributions from within the collaboration to the electron injector progressed well. The RF design of the booster structure from Lancaster University has been transferred to a mechanical design at CERN. The structure is currently under production in the CERN main workshops and is supposed to be completed at the end of the year. The pepper-pot emittance measurement device has been completely designed by Manchester University and ordering of the relevant hardware has started.

Finally a preliminary schedule has been produced to dismantle the existing hardware of the electron source within the CLIC test facility and subsequently install the whole electron injector into the AWAKE area. The dismantling will start in October 2016 and the installation of the electron source will be done during the first six months of 2017. The installation will be followed by hardware and beam commissioning with the aim to be able to send a first beam to the plasma cell at the end of 2017.

Excellent progress has been made within the electron source work package by the entire collaboration indicating that the goal of a first experiment at the end of 2017 seems attainable.

4 Laser and Laser Beam Lines

4.1 Laser Room and Beam Lines

The laser room and the vacuum beam line for delivering the laser beam to the plasma cell have been constructed before the laser delivery to CERN. This was necessary in order to avoid any dirty work in the presence of the laser system. As required for laser installation, the room (TSG40) was equipped with air conditioning systems capable to ensure clean room conditions of class 7 (ISO 16644-1), temperature stability within $\pm 1\ ^{\circ}$C and the relative humidity in the range of $40 - 60\%$.

Three optical tables with vibration damping honeycomb internal structure and ferromagnetic high grade steel surface plates were arranged to form an optical surface of 7.2 m long and 1 m wide for laser installation. The laser room was equipped with four racks for laser control and RF timing electronics, electrical, control and Ethernet cables, supplies for compressed air and laser cooling water, an exhaust pipe for pumping system and vacuum line connecting the laser room with the proton beam line [2]. This equipment was installed prior the clean room commissioning and the laser delivery to CERN.

A schematic view of the laser beam lines can be seen in in Fig. 5. The beam line between the laser and plasma comprises five mirrors (MP1 – MP5) on motorized vacuum compatible mirror mounts (New Focus 8823-UHV and 8823-AC-UHV), a precise linear translator holding the laser–proton merging mirror mount MP5, laser safety shutters LSSP1 and LSSP2 and three laser beam dumps LBDP1–LBDP3. Most of these elements have been manufactured, assembled and installed in beginning of 2016. The installation of laser line elements was preceded by vacuum outgassing tests which confirmed the compatibility of the devices with the requirements of the SPS/AWAKE vacuum system.

In addition, a diagnostic laser beam line for measuring the beam properties at the plasma cell position has been built. A low energy (1%) replica of the ionizing laser beam is extracted from the vacuum chamber through the viewport behind the mirror MP4 and passes an optical delay line which is mounted in the TT41 tunnel next to the proton beam line. The diagnostic line includes three CCD cameras with motorized filter exchange devices (wheels and flip mounts) for taking beam images at the laser optical distances corresponding to the entrance, middles and the exit of the plasma cell. Two more cameras serve for monitoring the laser beam position on the merging mirror MP5 and within the optical delay setup.

The FESA control system of motorized and measuring equipment installed in the laser beam lines has been developed by EN-STI group. The equipment and its control have been successfully tested during the laser beam commissioning period in July 2016.

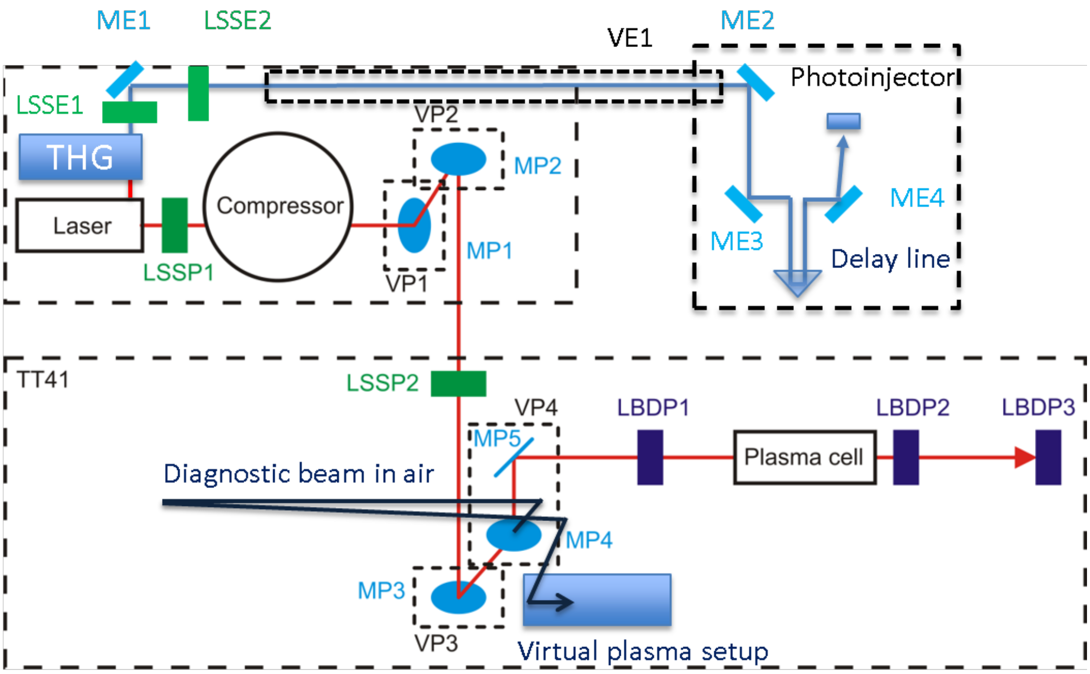


Fig. 5: Functional schematic of the laser beam lines to the plasma cell and photoinjector indicating the mirrors (blue) and their surrounding vacuum tanks, the laser safety shutters (green) and laser beam dumps (violet).

4.2 Laser Commissioning

The laser system, including the vacuum compressor, was provided by MPP, installed and an on-site acceptance test was completed by Amplitude Technologies in April 2016. The laser parameters as measured during on-site acceptance tests are presented in Table 1.

Table 1: AWAKE Laser Parameters

Performance	**Measured Value**
Repetition Rate	10 Hz
Central Wavelength	780–785 nm
Spectral Bandwidth	24 nm
Pulse duration	120 fs
Output Energy (uncompressed)	663 mJ
Output Energy (after compression)	500 mJ
Secondary output (uncompressed)	3 mJ
Energy stability	1.02%
Beam pointing stability	4.2 μrad
Temporal intensity contrast	2×10^{-7}
Polarization (linear)	250:1

Following the installation of the laser system, the work on setting up the optical beam path towards the plasma cell has been performed. The mirrors were pre-aligned using the low power HeNe laser beam injected into the proton beam line using the mirror installed on specially designed LBDP1 holder. The visible HeNe laser beam was sent upstream the main laser beam propagation, facilitating setting up the mirrors MP5–MP2 at the required angles. Then the main laser beam was sent through the beam line and the mirrors have been aligned to deliver it to the plasma cell. The beams have been observed on the BTV screens installed upstream and downstream the plasma cell.

An appropriate focusing of the laser beam is performed by slightly increasing the beam expanding telescope's intra-lens distance from the collimation position. This results in a lens that effectively has a focal length of 50 m.

Profiles of the laser are captured on a diagnostic beam line at the virtual beginning, center, and exit of the vapor source. These profiles can be seen in Fig. 6. With 100 mJ, the laser intensity will be at least a factor of 2 above the ionization threshold of $2\,\mathrm{TW/cm^2}$ at a radius of 1 mm from the center of the proton beam, which is the requirement for the experiment.

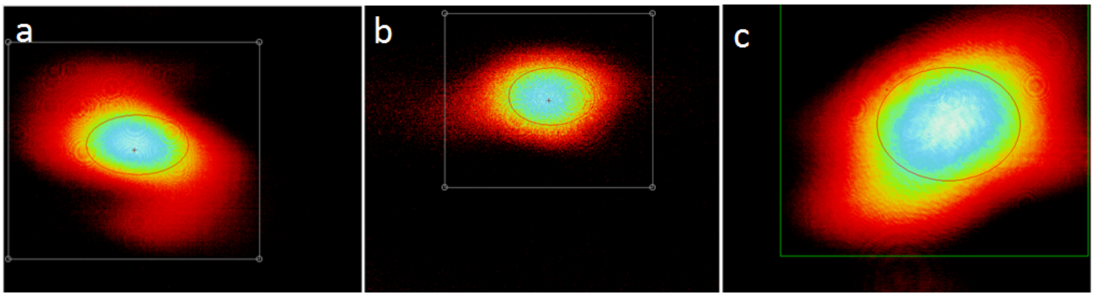


Fig. 6: Laser transverse profiles on the virtual transport line. a) Entrance, b) center and c) exit of the virtual vapor source.

4.3 Laser Alignment

Laser alignment required two steps. The first is the final positioning of the merging laser mirror, MP5, with respect to the proton beam. Once the proton beam's final trajectory was determined in the merging chamber, the mirror was positioned on a translation stage until a signal was measured on the nearest downstream beam loss monitor. The final translation position was set 1 mm away from first signal detection. To verify, the proton beam was run at full intensity of 3×10^{11} protons for two hours with no beam losses detected. The mirror position versus beam loss monitor can be seen in Fig. 7.

The second step is the spatial overlap of the laser with the proton beam by using profiles measured on the BTVs immediately upstream (TT41.BTV412353) and downstream (TT41.BTV412426) of the vapor source. The alignment was performed by an angular steering of MP4 and MP5 to place the laser onto the proton beam (see Fig. 5). These are the two final mirrors in the transport before the vapor source, with MP5 being the merging mirror. Comparison images of proton beam and laser on these BTVs after alignment of the centroids of the profiles to within 300 μm are shown in Fig. 8.

4.4 Laser Dumps

The function of laser beam dumps is to protect equipment from the laser impact. The first dump LBDP1 is needed for performing different tests with the laser beam, using the virtual laser line setup, without sending the beam downstream to the plasma cell and other beam diagnostics and experimental equipment which may not be ready for accepting the laser beam. This dump has in addition two mirrors on the same vertical actuator which enable injection of low power alignment laser beams downstream and upstream of its position. These beams were used for pre-alignment of the beam diagnostics equipment downstream (BTV, OTR and CTR screens) as well as for pre-alignment of the mirrors transporting the main laser beam. The LBDP1 should be in the "OUT" position during the proton beam operation. Therefore, its control is linked to the AWAKE Beam Interlock System (BIS) via the standard CIBU interface.

The second dump LBDP2 is needed to protect the screens installed for SMI diagnostics from the laser impact. To minimize the secondary radiation effects it is made of 200 μm thick aluminium foil

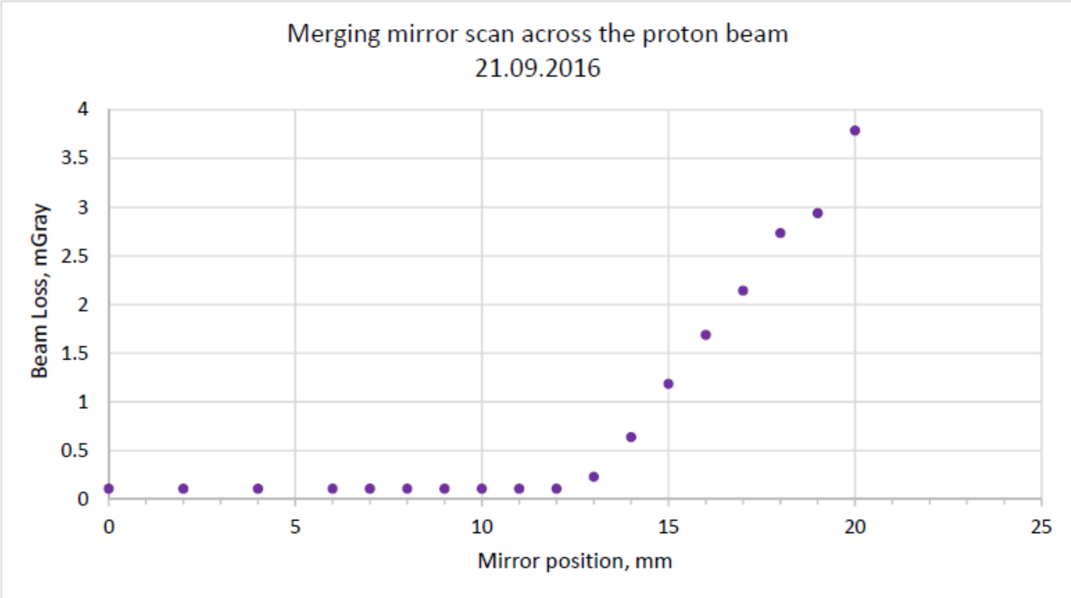


Fig. 7: The radiation signal measured on the beam loss monitor TT41.BLM412315 versus the position of laser mirror MP5. This measurement determined the safe position of the final mirror with respect to the proton beam in the merging chamber.

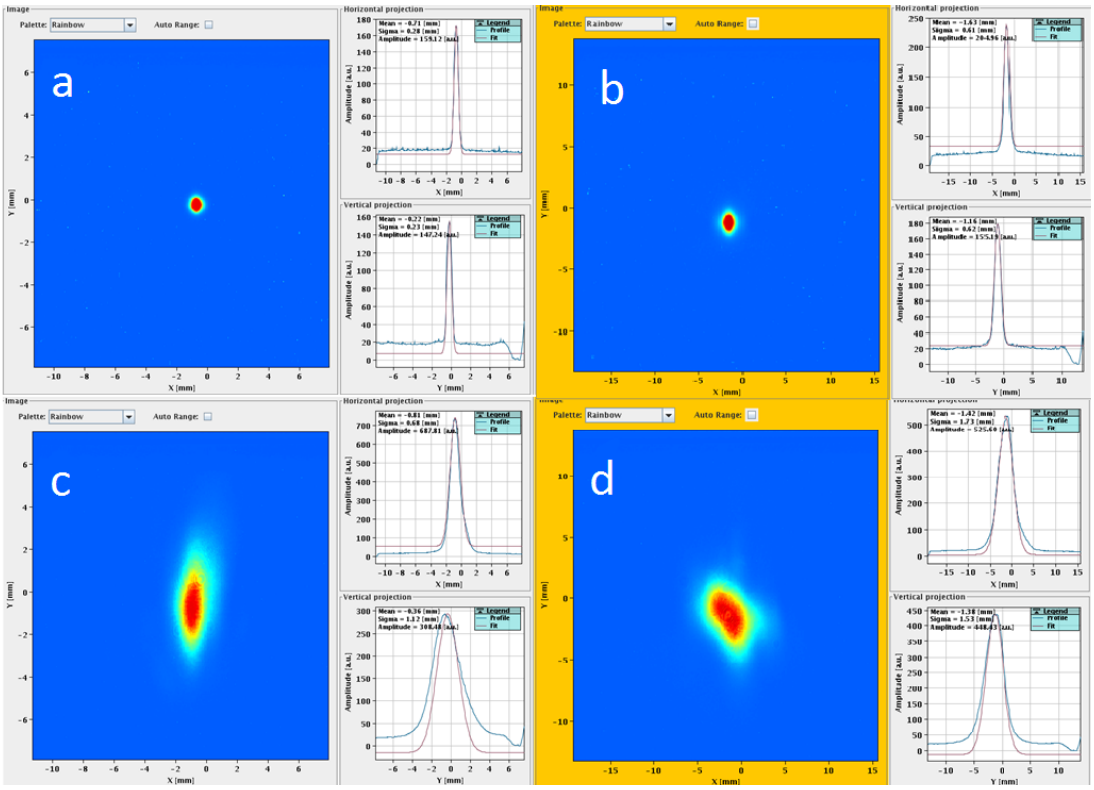


Fig. 8: Positioning of proton (top panel) and laser (bottom panel) beams on BTVs a) and c) upstream and b) and d) downstream the plasma cell. Horizontal and vertical projections of the 2D intensity profiles are shown next to the 2D intensity images. The projected laser profile peaks were placed on the projected proton peaks to within 300 μm.

fixed on the linear actuator. The high power laser pulses may ablate the dump material and eventually produce a hole in the foil. The speed of ablation has been studied at MPP and it was found that at the conditions of AWAKE experiment it can accept 600 high power shots with a 50 % safety margin. Therefore, the function of periodic shifting of the LBDP2 dump has been developed and integrated in its control software. The shot counting will be established before the experiment.

The third dump LBDP3 is installed at the end of the AWAKE proton beam line. Its function is to protect the proton beam window at the end of the AWAKE vacuum beam line. Its design is identical to LBDP2. However, it does not need to be periodically shifted as the laser beam size at that position is to be much larger making the ablation effect negligible.

5 RF Synchronization and Distribution

The low-level RF (LLRF) synchronization and distribution system for AWAKE provides RF signals and beam synchronous pulses in a wide frequency range from 5.995 GHz down to 9.97 Hz [3]. These signals are required to assure a simultaneous arrival of proton, electron and laser beams in AWAKE. Additionally, precision trigger pulses for instruments like the streak cameras are generated. The lowest distributed frequency of 9.97 Hz represents the basic repetition rate of AWAKE and is used directly to continuously trigger the laser. Hence the laser pulses have been chosen as a reference with respect to which the arrival times of the other beams, protons during the first phase and later also electrons, are aligned in time. The delays of synchronous precision triggers can also be adjusted with respect to the laser pulses. All RF signals in AWAKE are derived by integer or fractional division from a master oscillator at 5.995 GHz, which itself is locked to a GPS-based 10 MHz as frequency reference. The major part of the installation of the RF synchronization and distribution (Fig. 9) has been completed in preparation of the first beam commissioning with proton and laser beams in late September 2016. The status of its main components and their commissioning without and with beams is summarized below. The preparation of future improvements for installation in late 2016/early 2017 like, e.g. new precision trigger units and a dedicated fractional divider for the RF signal to the SPS, has been launched.

The 5.995 GHz master oscillator of AWAKE has been delivered to CERN in early July and, following improvements by the manufacturer, performs now close to specifications. Further improvements are foreseen in early October, but the present signal quality will already be sufficient for the 2016 run. The main divider module has been developed at CERN. It generates all RF signals and synchronous pulses which can be derived by integer division from 5.995 GHz. The prototype hardware of this dedicated electronics design for AWAKE has been completed and, following minor modifications, successfully put into operation. It delivers 2.999 GHz for the future electron acceleration, the mode-locker frequency, f_{ML}, at 88.2 MHz, as well as double and half that frequency. Furthermore it generates the common frequency, f_{c}, of 8.68 kHz for coarse re-phasing with the SPS and the basic 9.97 Hz repetition rate, f_{rep}, of the laser. A second revision of the main divider board to improve its signal quality, notably of the 3 GHz for the electron beam, is being considered. The light pulse of the optical fibre ring oscillator with a fundamental repetition rate of about 88.2 MHz, the mode-locker frequency, f_{ML}, is firstly synchronized to the 68th sub-harmonic of the 5.995 GHz from the master oscillator to guarantee an unambiguous phase relationship of laser pulse with respect to f_{ML} from the divider chain. Once locked, the synchronization loop will be switched to the 5.995 GHz to minimize the jitter of the laser with respect to the signals from the LLRF. The first stage of the laser synchronization has been successfully commissioned by Menlo Systems in August 2016. The commissioning of the balanced optical microwave phase detector by Menlo Systems has only been scheduled for November. For the synchronization of the SPS to AWAKE a set of three signals ($2f_{\mathrm{RF,SPS}}$, f_{c} and f_{rep} shifted with respect to the AWAKE internal f_{rep}) must be transmitted from the laser room below BA4 to the SPS beam control in BA3, over a distance of more than 3 km. The drift of a standard optical link would be unacceptably large and an active link stabilization to the picosecond level has been developed for AWAKE [4]. It relies on actively compensating the round-trip delay of the optical fibre transmitting 400.8 MHz from AWAKE to the SPS. The prototype modules, in-

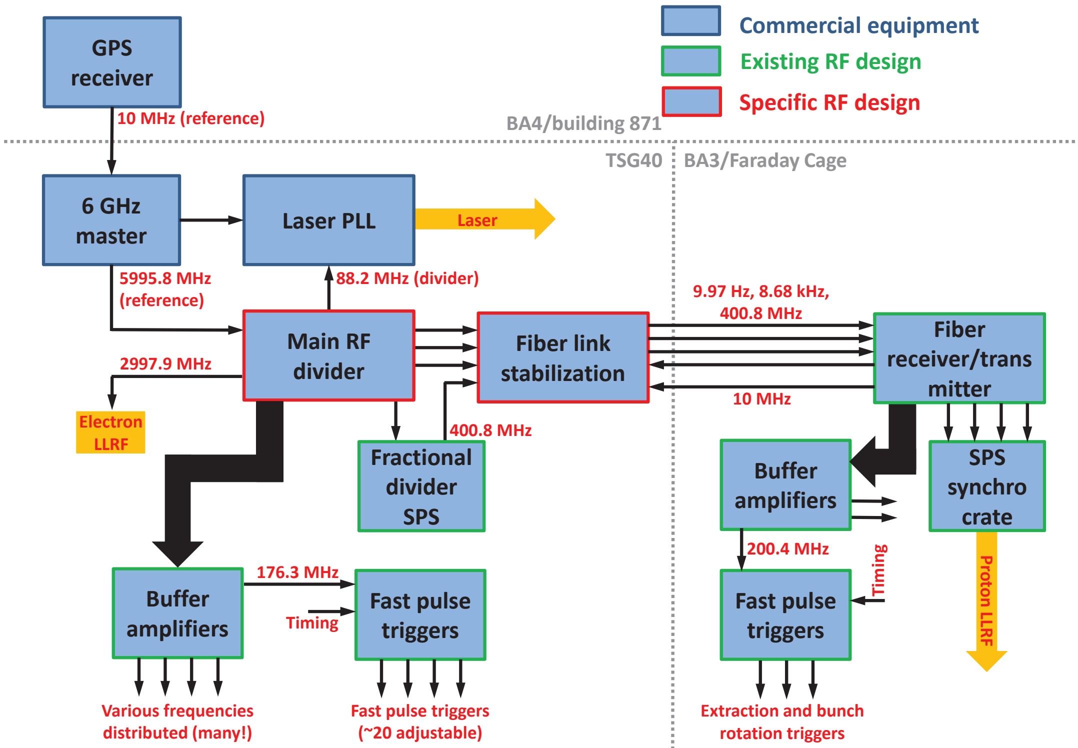


Fig. 9: Overview diagram of the AWAKE RF synchronization and distribution.

stalled in late July, fully meet the requirements and no further version of the hardware should be needed. A fractional divider by $25/11$ translates twice the mode locker frequency into twice the frequency of the main 200 MHz acceleration system in the SPS, needed for re-phasing of the proton bunch to AWAKE. The frequency choices were determined by the existing set-up in the SPS for the transfer towards the LHC. Due to the lack of remote control, surveillance and signal quality issues, the presently installed prototype fractional divider will be however replaced by a dedicated design in 2017. The re-phasing to simulated signals locally generated in BA3 has been set-up in spring while the first synchronized extraction with signals from AWAKE was observed in late September, during the initial commissioning with proton beam. Beam instrumentation, like the streak cameras in AWAKE, must be triggered with a small jitter in the range of few picoseconds. It has been foreseen to install so-called Chopper Trigger Units (CTUs), originally developed at CERN for Linac4, for that purpose. While the series production of these modules is in full swing, they will not become available before November 2016. New firmware must be developed in addition for their application as trigger units in AWAKE. A limited number of spare VME Trigger Units (VTUs) have thus been temporarily installed in AWAKE.

A big milestone has been reached during the beam commissioning period at the end of September, when the SPS proton beam was synchronized below 100 ps accuracy with respect to the laser beam. Figure 10 shows the streak camera measurement in the BTV upstream the plasma cell. This figure shows that the proton bunch and the laser pulse overlap in space and in time, a necessary condition for the seeding of the SMI (See Fig. 19).

6 Rubidium Plasma Source

AWAKE uses a laser-ionized, rubidium (Rb) vapor as plasma. The required vapor density ($1 \times 10^{14} \leq n_{Rb} \leq 10 \times 10^{14}\,\mathrm{cm}^{-3}$) and its uniformity ($\delta n_{Rb}/n_{Rb}$) are achieved by evaporating the Rb in a heat exchanger (see Fig. 11) that imposes a very uniform temperature ($\delta n_{Rb}/n_{Rb} = \delta T/T \leq 0.2\%$) along its 10 m. The Rb density is reached within a 180–230 °C temperature range. The requirement of very

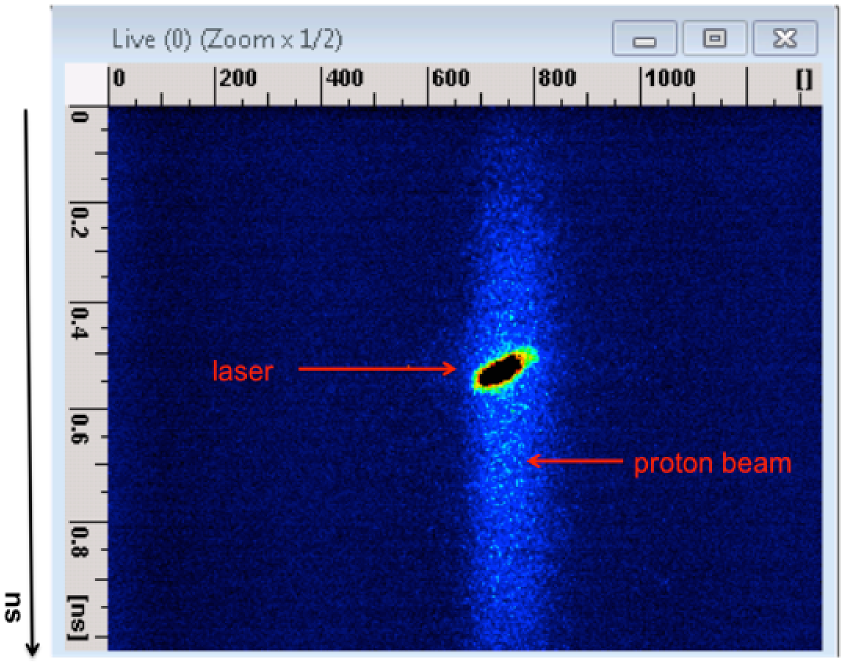


Fig. 10: Synchronization of the AWAKE proton and laser beam. Streak camera measurement with the BTV upstream of the plasma cell.

sharp (a few cm) density ramp at the entrance and exit of the source is achieved by letting the vapor expand through a 10 mm diameter aperture into the vacuum of a large (∼170 l) expansion chamber (see Fig. 12) whose walls are kept below the Rb condensation temperature of 39 °C. The Rb evaporates from two reservoirs located near the end of the source (see Fig. 12). The system consists of 15 independently

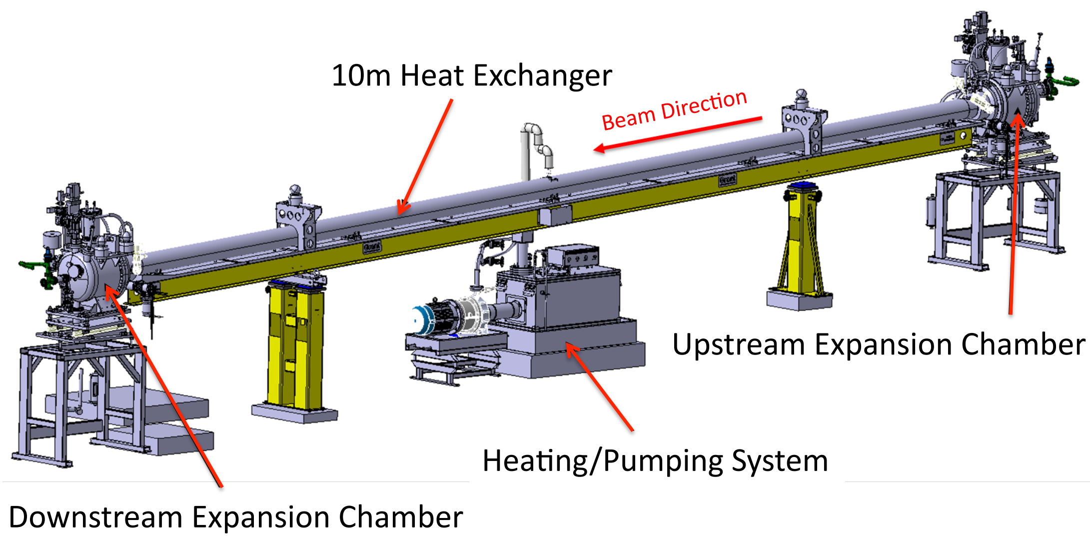


Fig. 11: CAD drawing of the Rb vapor source with its main components labeled.

controlled heating zones and of four cooling zones. Temperatures are monitored by 79 probes (see Fig. 13) and heating is controlled by independent PID loops. The monitoring and control system uses standard CERN Siemens hardware and is by design fully integrated in the control and DAQ system. The expansion volumes are being installed at the time of writing and will be commissioned immediately after (see general schedule). The heat exchanger was installed in the AWAKE facility in February 2016. A large number of cables were pulled for remote control and monitoring of the source since all electronic

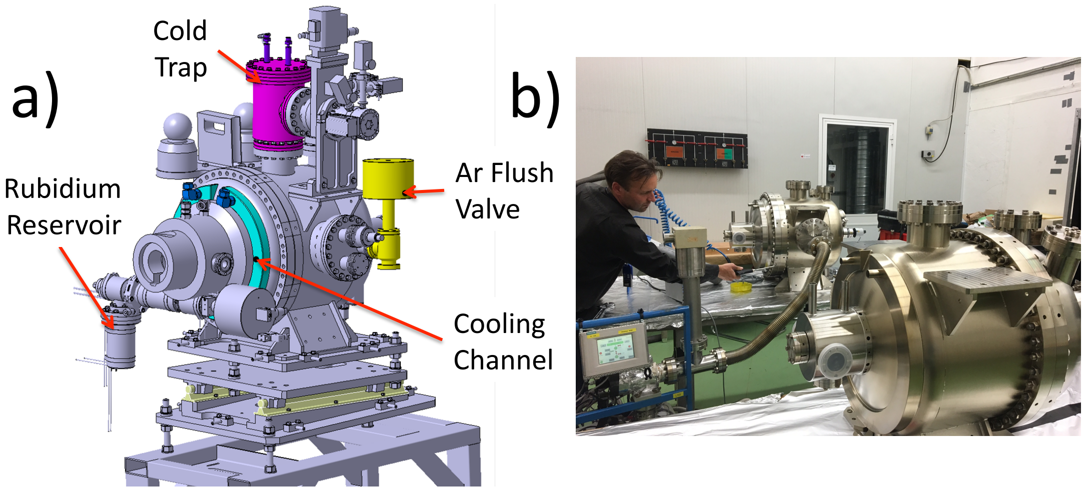


Fig. 12: a) CAD drawing of one source expansion volume. b) Picture of the vacuum vessels undergoing vacuum test in EHN1.

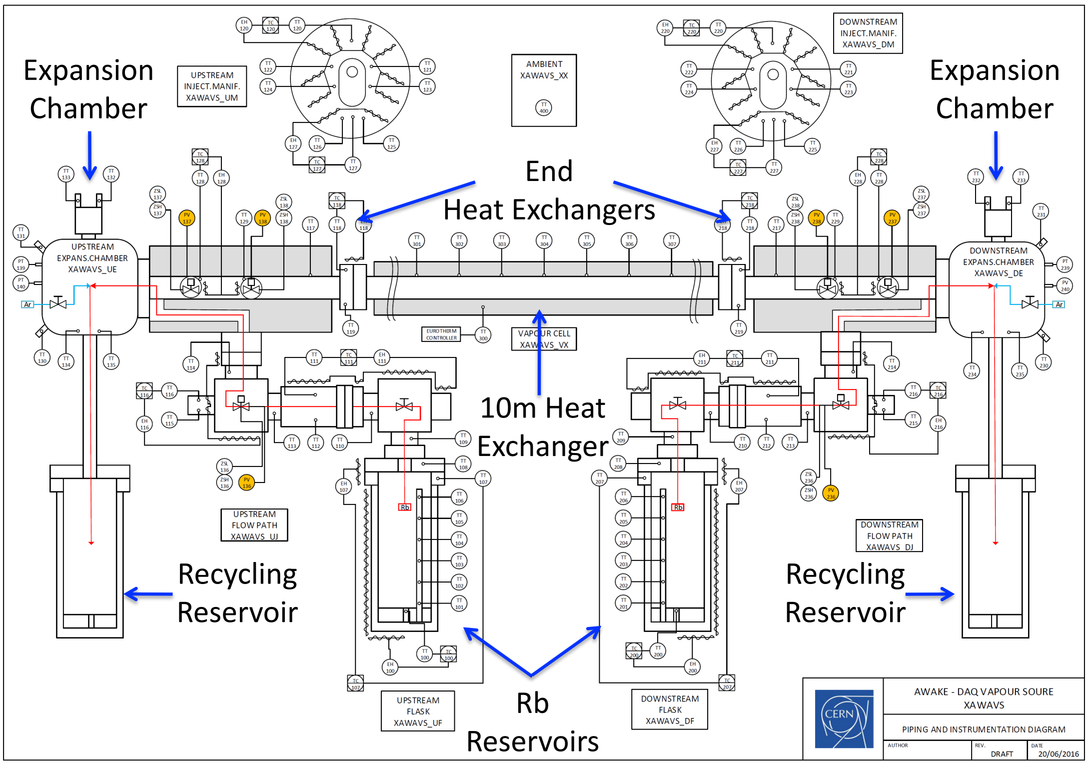


Fig. 13: Schematic of the Rb vapor source control system (not to scale). A detailed caption is not given, but the schematic shows its complexity. The faint red arrows show the Rb vapor path, from the Rb reservoirs to the heat exchanger and into the expansion volume. The faint blue arrows show that the system can be filled with argon to prevent the Rb from reacting with air and moisture in case of emergency event. Rb will be recycled by heating the expansion volumes to 50 °C and collecting the liquid in the reservoirs below the expansion volumes.

equipment must be located in radiation shielded areas (25 or 100 m away). Integration of the source in the tunnel is shown in Fig. 14.

A prototype of the source consisting of a replica of the heat exchanger and a simplified version of

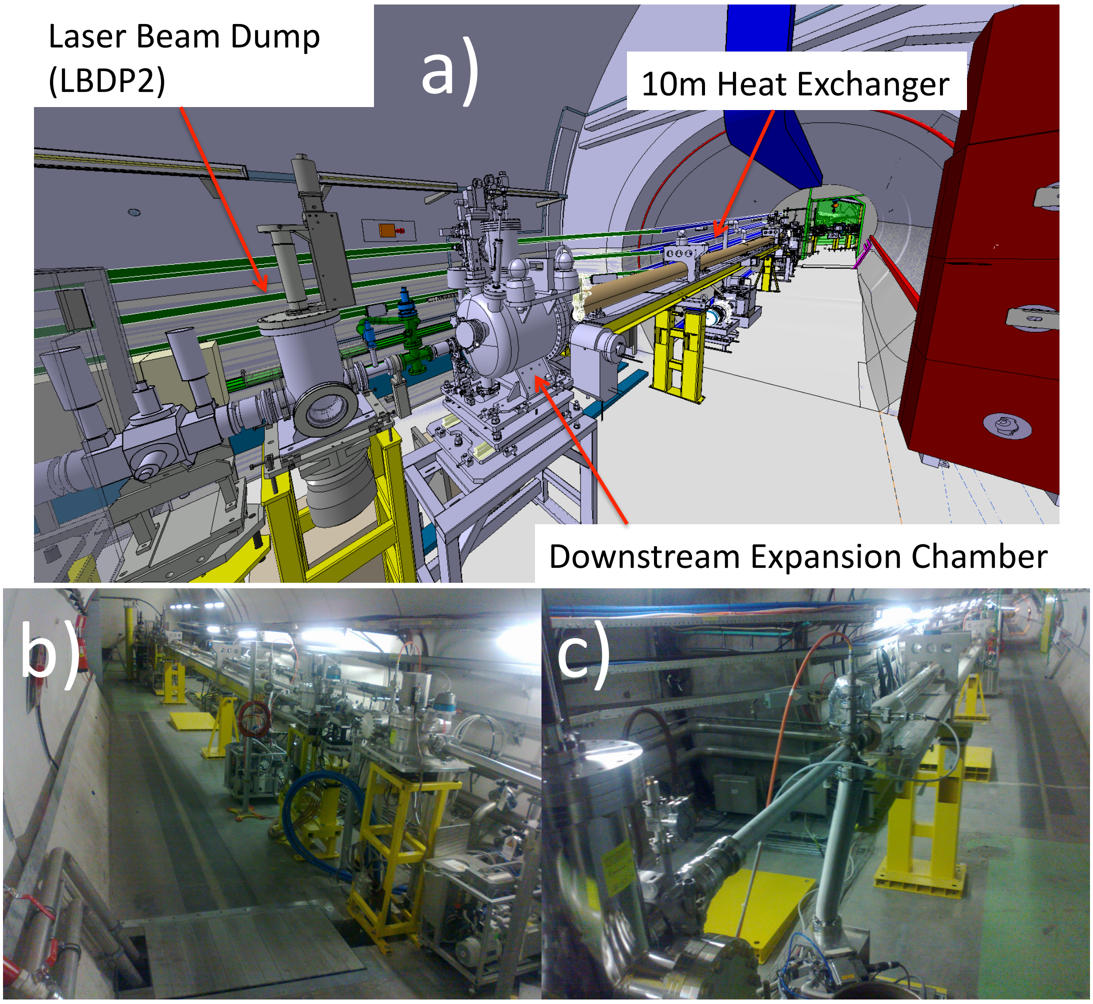


Fig. 14: a) Integration CAD for the complete Rb vapor cell in the AWAKE facility. Pictures of the heat exchanger as installed in AWAKE (no expansion volumes) looking b) downstream and c) upstream.

the expansion volume (including all functions) is installed in EHN1 (see Fig. 15). All control, operation and safety procedures will be developed, tested and approved on this system, first without Rb and then with Rb. After full safety approval, Rb will be inserted into the AWAKE system.

The system is the result of a strong collaboration between MPP, Wright Design Limited, UK, and CERN.

Since the system has two Rb reservoirs and two expansion chambers it offers the possibility of having a (linear) density gradient along the source. It is well known that plasma density gradients may be used in plasma-based accelerators to compensate for dephasing between accelerated particles and the wakefields. In the AWAKE case, simulations show that a gradient on the order of +3% over 10 m may have beneficial effects. The Rb vapor density must thus be measured with sub-% accuracy at both ends of the source. We showed that using white light interferometry and the anomalous dispersion around the D2 line of Rb at $\sim$780 nm, the vapor density can be measured within 0.2%, i.e. with sufficient accuracy (see Fig. 16) [5]. This diagnostic will be implemented at the one end of the prototype in EHN1 as well as at the two ends of the source in AWAKE. The density measurement is also fully integrated in the DAQ, and density and gradient values will be displayed on the experiment fixed display.

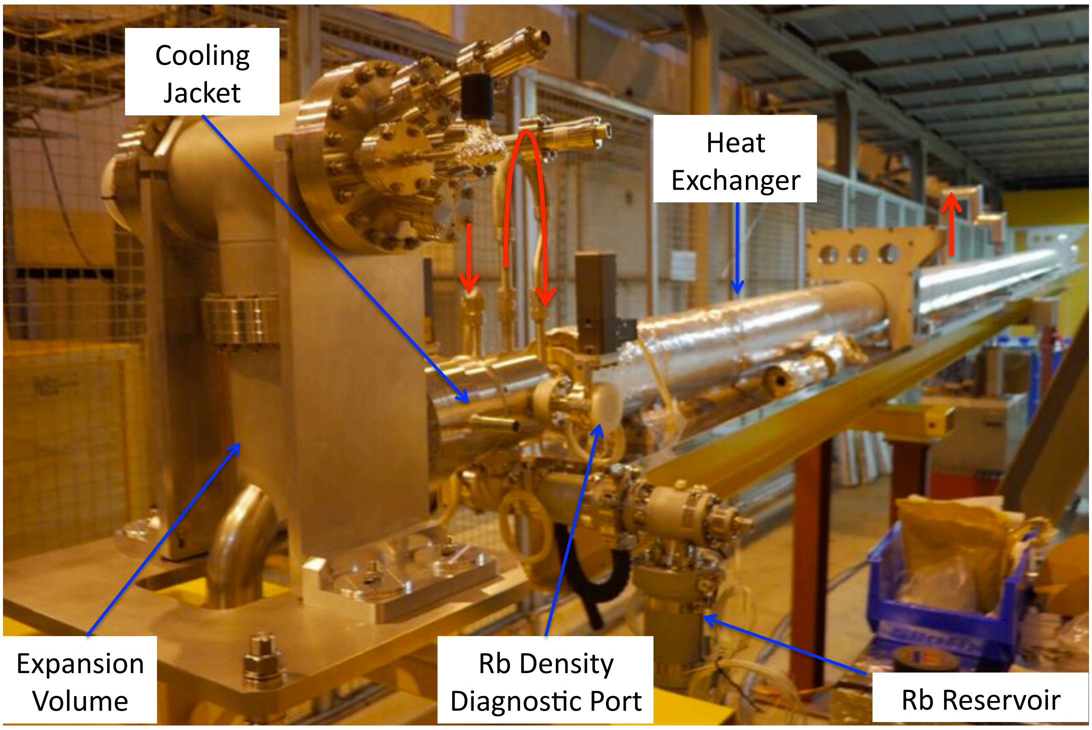


Fig. 15: Picture of the end of the heat exchanger with the simplified expansion volume attached, at the time of installation in EHN1. The red arrows indicate the heating fluid path that circulates first through a short heat exchanger and then through the 10 m heat exchanger and returns to the heating/pumping bath from the middle of the system.

7 Diagnostics

The first phase of the experiment, starting at the end of this year, will focus on SMI studies. We show here that proton bunch diagnostics aimed at detecting the occurrence of and at measuring the characteristics of the SMI are ready.

7.1 Proton Bunch Defocusing Diagnostic

The most evident effect of the SMI on the proton bunch is the defocusing of approximately one quarter of the bunch particles with a typical angle in AWAKE of 1 mrad. This defocusing can be observed on screens recording the (time integrated) transverse image of the bunch downstream from the plasma. The defocused proton form a halo around the bunch core. Numerical simulations indicate that analyzing the size and shape of the profile on two screens yields information on the SMI development and saturation.

Tests were performed with HiRadMat bunches to determine the light yield of various screen materials: chromox, alumina, aluminum, etc. (see Fig. 17). Based on these results various screens were installed in two BTV diagnostic stations located 2 and 10 m from the plasma exit. For example a screen with an aluminum disk in the center where the dense bunch core will produce OTR light with a low photon yield, surrounded by a chromox screen where the more diffuse halo will produce scintillating light with a high yield will allow for simultaneous observation and characterization of the bunch core and halo. Since this diagnostic uses standard CERN equipment it is already installed and commissioned and fully integrated in the CERN control and DAQ system.

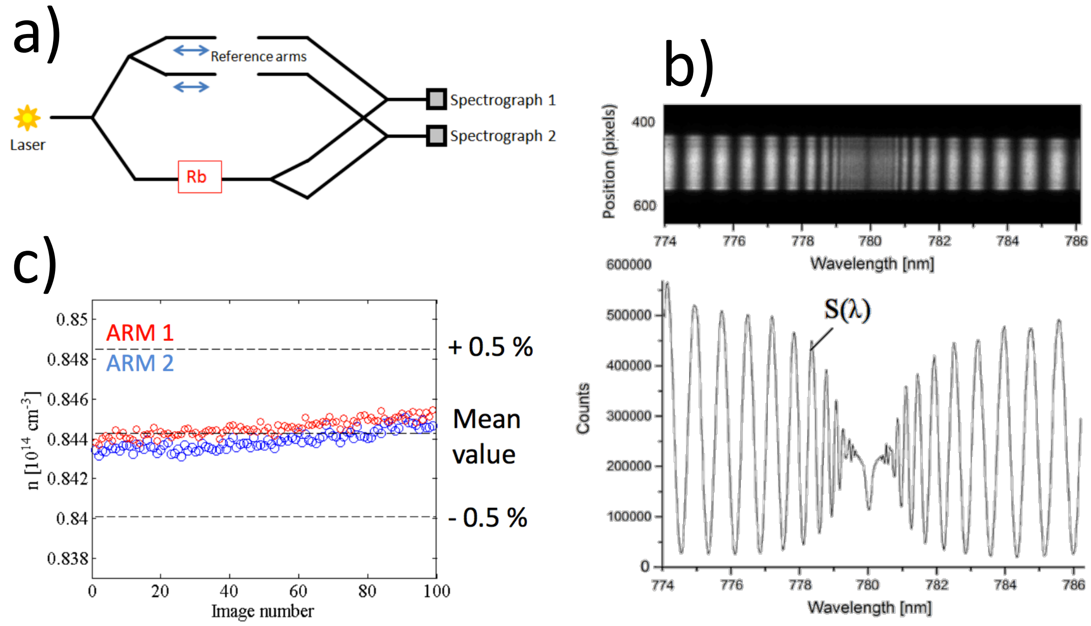


Fig. 16: a) Schematic of the double, white light interferometer system used to determine the accuracy of the Rb density measurement. Here the two interferometers measure the same density-length product. In the experiment the two interferometers share the same reference arm and measure the density at both ends. b) Top: example of a white light spectrum and its line out (S(λ)). Bottom: the vapor density-length product is deduced from the changing period of the interference pattern around 780 nm. c) Result of 100 measurements showing that despite vibrations the signal of the two interferometers and the ensuing analysis yield densities within about 0.1%.

7.2 Time-Resolved Modulation Measurement

An aluminum-coated, 150 μm-thick silicon screen was installed in a diagnostic station $\sim$3 m downstream from the plasma exit and at a 45° angle to the beam axis. The proton bunch will produce incoherent, but prompt optical transition radiation (OTR) when entering the screen. This light will be imaged on a CCD camera to obtain transverse images of the bunch similar to those described above. Figure 18 shows a schematic of the OTR setup on the beam line. The OTR light is also transported $\sim$25 m by a lenses/mirrors line to a streak camera with picosecond time resolution. The time-resolved image of the OTR light will provide information about the seeding of the SMI by the laser ionizing front at the nanosecond scale (see Figs 19 a) and b)) and on the period of the modulation at the fastest picosecond time scale (see Fig. 19 c)). For the AWAKE density range the modulation period is between 11 and 3.5 ps. Test results with gated and modulated laser light mimicking the expected OTR light have shown that modulation frequencies up to 350 GHz (corresponding to a period of less than 3 ps) can be measured from the FFT of the streak images (similar to Fig. 19 c)), i.e. better than needed for the AWAKE 90–285 GHz range expected from the plasma density range [6].

The OTR station on the beam line (Fig. 20 a)), the optical transport line (Fig. 20 b)) and the streak camera (Fig. 20 c)) have been installed and commissioned and the whole diagnostic is operational. The control of the streak camera and of the mirror motors as well as the data acquisition and preliminary analysis are fully implemented into the CERN control and DAQ system and the results sent to the fixed displays. Figure 21 shows one of the first streak camera images of the proton bunch obtained during the commissioning of 1/10/2016, corresponding to Fig. 19 a).

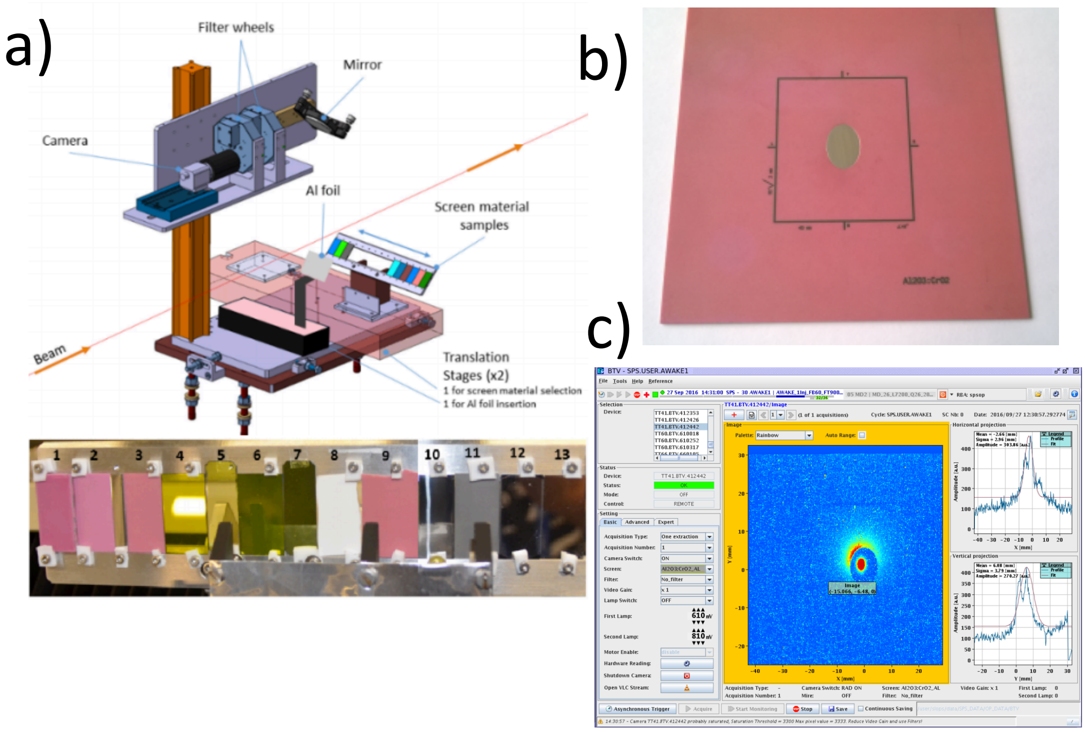


Fig. 17: a) Top: experimental set-up used in HiRadMat to test various screen for beam transverse profile recording. Bottom: holder with the various screens tested. b) A screen consisting of a disk of aluminum around the beam axis and chromox at larger radius. c) Image of the proton bunch on the screen of b) obtained during the beam comissioning (17/9/2016). In this case the screen is not centered on the bunch trajectory, the OTR light shows the strong core of the bunch while the chromox screen shows the fainter wing of the bunch.

7.3 Heterodyne Measurements

A second diagnostic station similar to the OTR has been installed upstream of the OTR diagnostic (see Figure 18). Instead of looking at the time structure of incoherent OTR it will measure the frequency of the coherent transition radiation (CTR) emitted at the bunch modulation frequency. This frequency is also the plasma electron frequency. The CTR is in the microwave range, between 90 and 285 GHz in AWAKE. In this diagnostic, the frequency of the CTR, f_{RF}, will be determined by mixing the signal on a diode with the signal of a local oscillator at a known frequency f_{LO}. The diode will generate an intermediate frequency signal at $f_{IF} = |f_{RF} - f_{LO}| \ll f_{RF}, f_{LO}$. The f_{LO} value will be chosen from the value "guessed" from the plasma electron density $n_e = n_{Rb}$: $f_{RF} \propto n_{Rb}^{1/2}$ to bring the f_{IF} frequency into reach of a $10 - 20$ GHz-bandwidth oscilloscope. Note that because of the absolute value in the f_{IF} expression, two measurements with slightly different values of f_{LO} are necessary to determine f_{IF} unambiguously. The f_{IF} frequency must be kept large enough to be able to record multiple oscillations of the signal within the CTR emission time, i.e. within $\cong \sigma_z/c \cong 400$ ps.

Calculations of the CTR characteristics (emission angle, frequency, power, etc.) with the actual proton bunch distribution obtained from numerical simulations show that the modulation signal with frequency near $\omega_{pe}/2\pi$ has significant power (Watts) and is emitted at an angle that varies with modulation frequency.

Two heterodyne systems will be installed.

In one case the local oscillator signal will be generated directly on the diode itself from the rectification of the signal of two laser pulses with beating frequency f_{LO} [7]. In this case, the laser beams

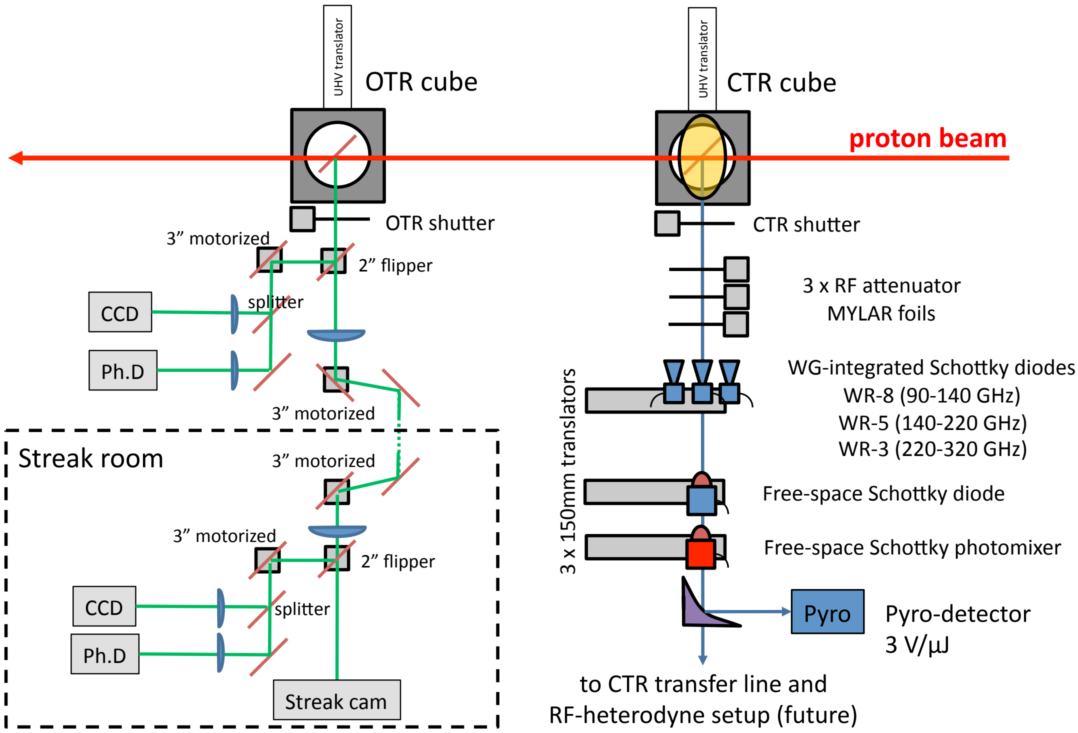


Fig. 18: Schematic of the OTR and CTR setup installed on the proton beam line.

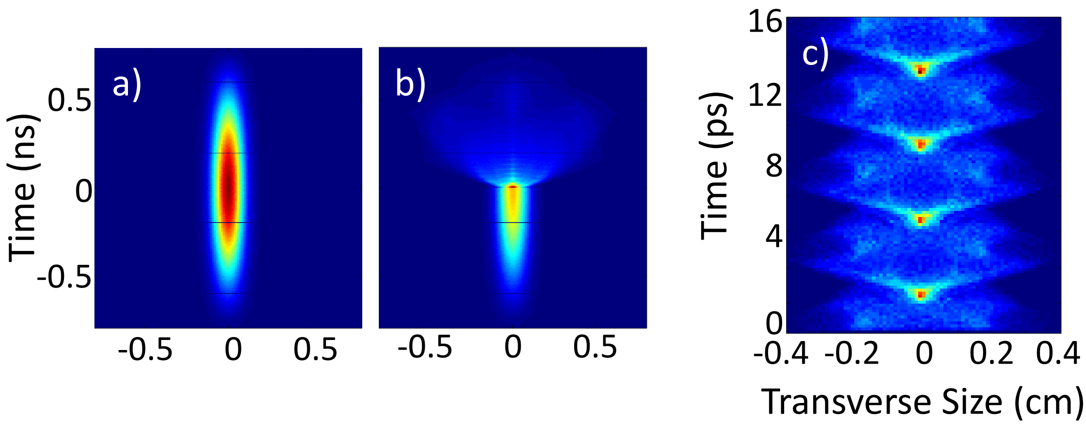


Fig. 19: a) Image of the proton bunch obtained from simulations in the case of no plasma (no SMI), similar to that expected from the streak camera on a $\sim$ ns time scale. b) Image of the bunch when the SMI is seeded by the laser pulse placed in the middle of the bunch showing the first half of the proton bunch propagating in the neutral vapor (no SMI) and the second half defocused by the SMI occurrence. c) Zoomed in image (near 0.4 ps on b)), on a fast time scale (ps-resolution) showing the structure of the proton bunch modulated by the SMI, at the plasma period. Charge density proportional to the color from blue to red. Bunches moving down, simulation results from LCODE.

with wavelength around $1.5\,\mu$m will be brought to the diode by an optical fiber and the $10-20$ GHz f_{IF} signal will be brought to the oscilloscope using a high-frequency coaxial cable and an amplifier.

In the other case the signal at f_{RF} will be transported to the waveguide-based heterodyne mixer using an over-moded X-band rectangular waveguide to reduce transmission losses. Initially a waveguide-based heterodyne system (above 220 GHz) will be borrowed for the Swiss Plasma Center, Lausanne.

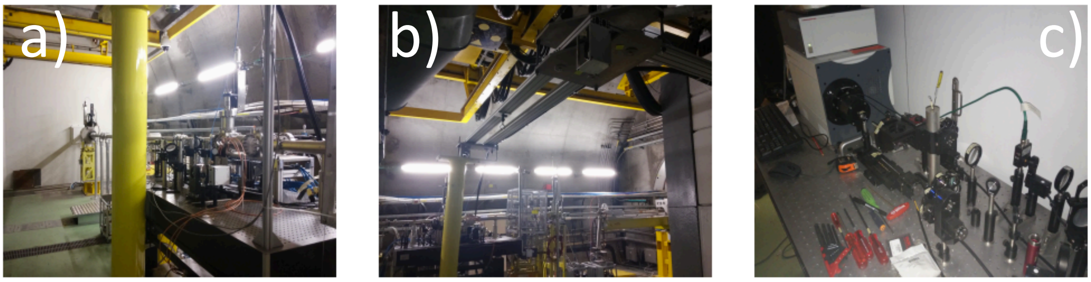


Fig. 20: a) Picture of the OTR diagnostic station installed on the proton beam line. b) Picture of the optical transport line from the beam line to the streak camera. c) Picture of the streak camera on the optical table.

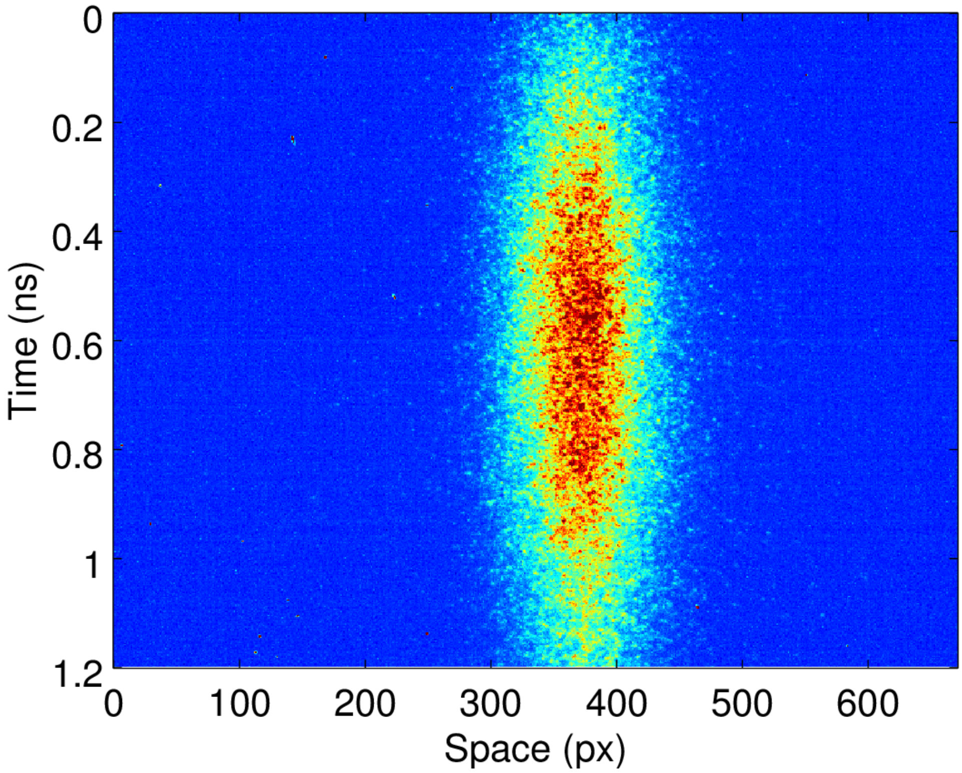


Fig. 21: Streak camera image of the proton bunch obtained on 1/10/2016. This image is similar to that expected in Fig. 19 a). Time is along the vertical axis and the bunch has the expected length.

The first system offers the advantage of the very broad spectrum application, possibly over the entire desired range ($90 - 285$ GHz), at the expense of signal sensitivity. The second system offers high sensitivity at the expense of working only within microwave bands and therefore requiring three heterodyne systems to cover the desired frequency range.

The CTR diagnostics have been installed (see Fig. 22) and hardware commissioned.

7.4 Accelerated Electrons Energy Measurement

The second phase of AWAKE RUN I will focus on the acceleration of externally injected electrons. Numerical simulations indicate that electrons may reach an energy larger than 1 GeV with a finite energy spread of a few percent. Since the length of the injected bunch will be on the order of the wakefields

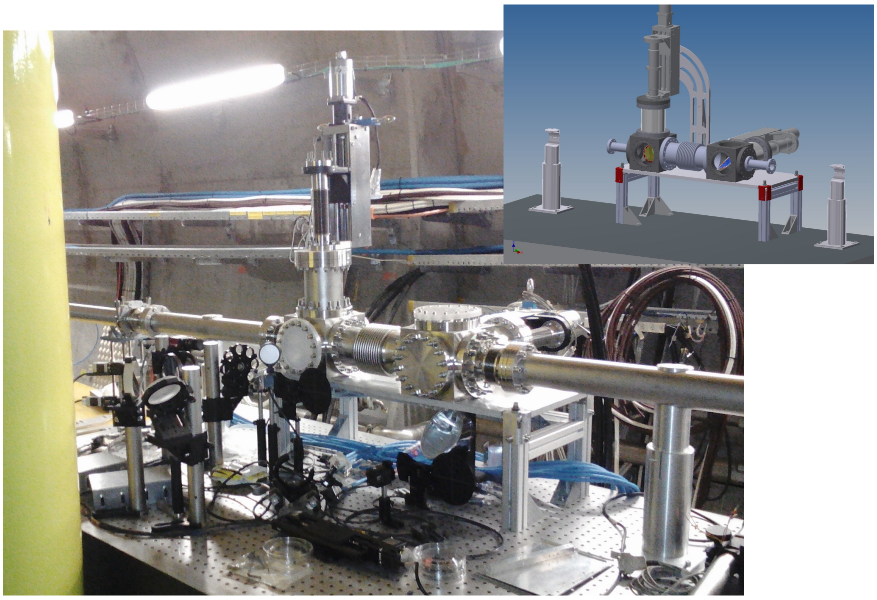


Fig. 22: Picture of the CTR and OTR diagnostic stations installed on the proton beam line. See Fig. 18 for the corresponding schematic.

period, the capture efficiency will be limited to less than 50 %.

The magnetic spectrometer is based on a CERN HB4, C-shaped magnet and two quadrupoles to reduce the beam size at the spectrometer screen and increase its resolution (see Fig. 23). Figure 24 a) shows the focusing effect of the two quadrupole magnets on an electron beam with a divergence of 2 mrad. In this case the bunch radius at the screen is reduced from more than 15 mm to less than 1 mm, even in the out-of focus x-plane. Currently a shunt resistance is used to change the current in the quadrupoles powered in series and to obtain a small focus in both planes. Figure 24 b) shows the relative energy spread $\Delta E/E$ as a function of the magnetic gradient in the two quadrupoles and the electron's energy. The resolution of the energy measurement is greatly improved, to the % level, by using the quadrupoles.

Extensive numerical studies have been performed to determine the light yield caused by charged particles emitted by the protons traversing the various windows and screens placed in the proton bunch path. These studies show that with the quadrupoles energized, a signal to noise ratio exceeding 1:1000 can be reached between the accelerated electrons energy spectrum and the background [9].

Light yield as well as light collection efficiency measurements were performed using the CTF3 electron beam. These measurements show that sufficient light should be collected by the large aperture, long focal length lens and intensified CCD camera, despite their 17 m distance from the spectrometer screen (see Fig. 23).

The vacuum chamber for the spectrometer is relatively narrow vertically and long and wide in the horizontal plane. Mechanical stress calculation results show that a thickness of 2 mm is sufficient to mitigate the risk of buckling of the window when the vacuum chamber is under vacuum. Scattering of the electrons in this relatively thick window does not degrade the spectrometer resolution. The vacuum chamber and window are in the fabrication phase and will be installed in AWAKE at the beginning of

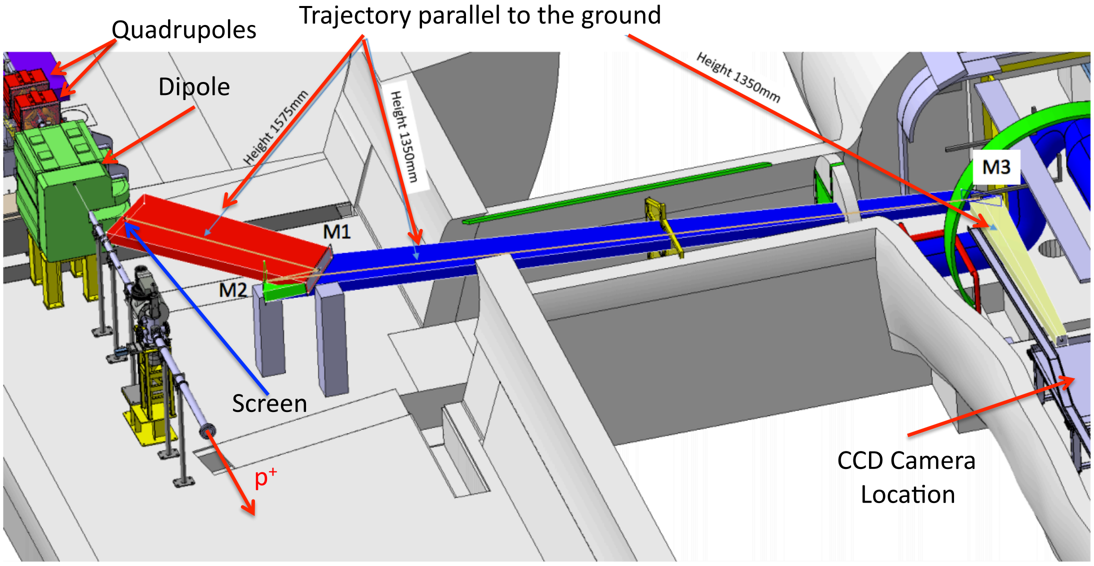


Fig. 23: CAD drawing of the electron magnetic spectrometer integration in AWAKE, including the light transport line from the spectrometer screen to the CCD camera in the shielded area. Optical mirrors for the screen light are labeled M1 to M3. The optical line is enclosed in a light shield.

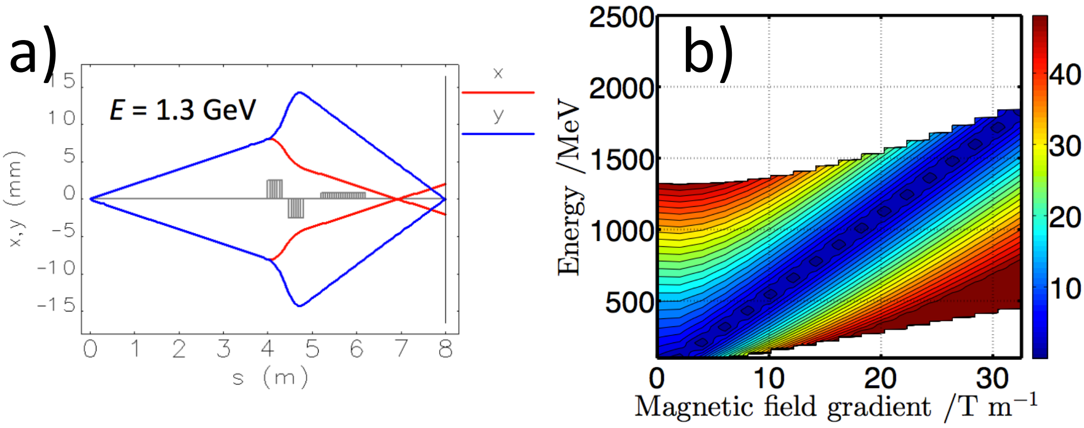


Fig. 24: a) Envelope from ELEGANT simulation results showing the trajectories of electrons with angles at the plasma cell of 2 mrad. The first quadrupole (indicated by the left hand side grey rectangle) has K_1=+4.07 m^{-2} and the second quadrupole (indicated by the second grey rectangle) has K_1= -4.07 m^{-2}. The third grey rectangle represents the spectrometer dipole magnet. b) Energy spread ΔE/E (in percent) as a function of energy and quadrupoles strength with the HB4 dipole current at 40 A [8].

2017.

8 Data Acquisition and Controls

The AWAKE control system is built on the architecture provided by the CERN Controls group (BE-CO). The challenge was to integrate a set of generic hardware and software services from BE-CO with controls components that are specific to the AWAKE Experiment. The strategy has been to use as much as possible standard BE-CO components in order to optimise development and maintenance resources. For the devices designed or built by AWAKE, a joint effort was made by BE-CO and AWAKE as well as certain CERN equipment groups (e.g. EN-STI (laser), BE-BI (beam instrumentation)) to explore technical solutions for their integration. Figure 25 illustrate the 3-tier standard architecture and an example of integration of devices from AWAKE.

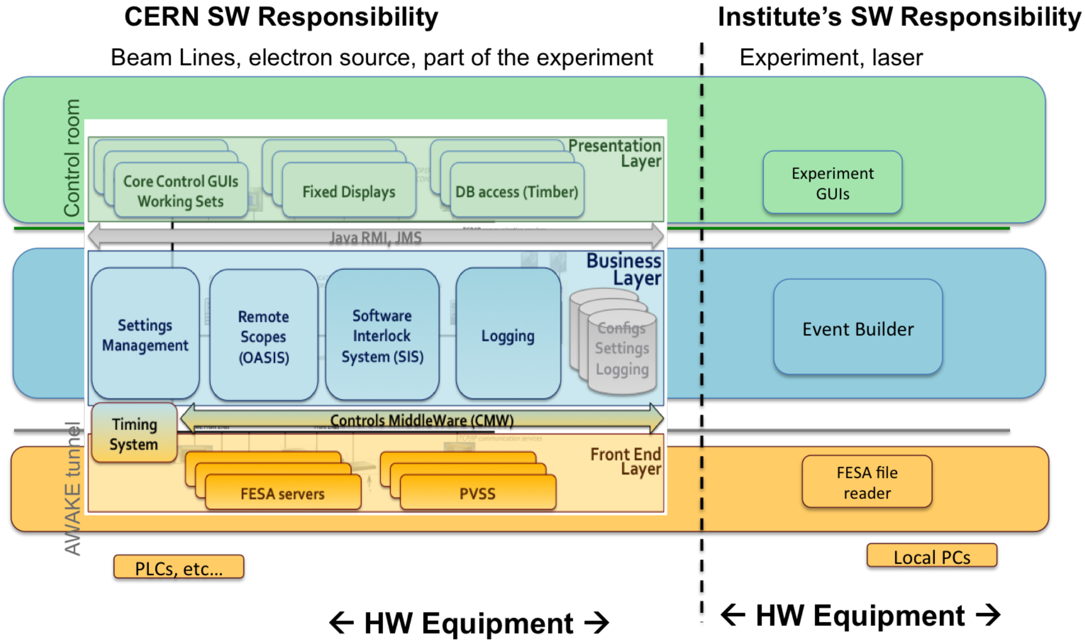


Fig. 25: CERN accelerator control system architecture.

Starting with the hardware (HW) layer, there are 2 types of HW components: those designed at CERN by RF, BI (e.g. RF synchronization equipment, BTVs, etc.) and those designed by AWAKE (e.g. OTR, CTR) and both equipped with CERN standard controls. The second type of HW components are provided by AWAKE and equipped with a custom stand-alone control system. The integration of AWAKE HW components relies on a well-defined software interface (API), which allows handling those as if they were CERN components. Thanks to this interface, AWAKE components mimic the behavior of those from CERN and therefore can be accessed in exactly the same way, i.e. from the upper software layers, up to the graphical user interfaces used by the Operators in the controls room. For certain key equipment parameters (i.e. laser power, plasma density measurements, SMI scopes) those responsible for the given instrument have developed specific FESA classes to read the data from a file written by the stand-alone system and to re-publish this data in a standard format understandable by the upper layers.

The main components of the AWAKE controls systems are the following:

- $\sim$ 10 front end computers (FEC), each driving one piece of equipment, one FEC for the generation and distribution of all timing events to the other FECs, one FEC to connect and transport the analogue signals from several equipments to a generic viewer (OASIS).
- One back end (or Application server) Linux machine for data processing, hosting the event builder and the concentrator processes.
- $\sim$ 30 timing events to trigger control and acquisition commands of each equipment. These have been defined to allow pulsing equipment either during operation (when there is a beam extraction from the SPS to AWAKE) or during dry-runs (when there is no beam extraction).
- Software (SIS) and hardware beam (BIC) interlock systems.
- Logging: all device data are stored for long term in the standard logging data base (DB).
- Interactive GUI to send commands to the equipment : generic applications configured from device data defined in the standard Controls Configuration DB (WorkingSets/Knobs), BTV Application for TV camera controls, beam steering application (YASP).
- Two fixed displays presenting the status of the most important parameters of the machine. These displays are convenient for monitoring, see Fig. 26.

– Eight standard Linux consoles have been installed in the AWAKE control room in BB4, situated in the AWAKE access shaft, $\sim$ 1 km away from the experiment.

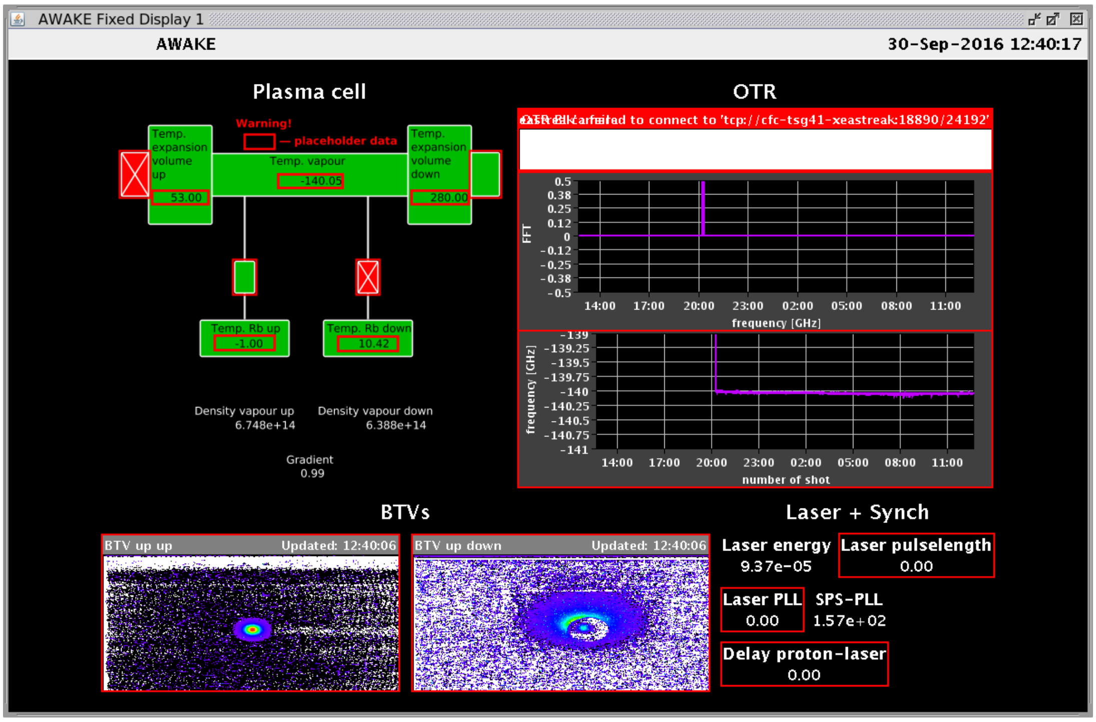


Fig. 26: AWAKE Fixed Display.

The control system has been validated in a dry-run on 6 September 2016, where the last missing SW functionalities were identified, which were eventually commissioned during the 2-week beam commissioning period end September 2016.

9 Infrastructure, Radiation Protection, Fire Safety

The infrastructure for the proton phase of AWAKE is fully installed. This includes electrical infrastructure, ventilation and cooling equipment, GSM and Ethernet cables, safety equipment etc.. The AWAKE control room was equipped with all services needed and made available to the users in June 2016.

Several demands for services in the experimental area were received during the last few months, their design and integration is completed, with installation to be completed before November 2016. For example a dedicated chiller unit for the plasma cell end flanges has been integrated in the experimental facility, including additional piping for chilled water, heating liquids and Argon.

9.1 New Radiation Area Classification of the SPS AWAKE Area

Following dismantling works to remove radioactive CNGS equipment from the AWAKE area as well as cleaning works and installation of a shielding to separate the CNGS target area from the AWAKE experimental area, the AWAKE underground area received the new classification of a supervised radiation area (previously limited stay radiation area) in December 2015. Surveys show the dose rates in the area during access well below 15 μSv/h and contamination below the legal detection limit. A consequence of the new classification is that AWAKE users no longer need to follow an 8-hour classroom radiation safety course, nor do they have to acquire an operational dosimeter. Note that a short on-line course and a personal dosimeter are still necessary for accessing AWAKE.

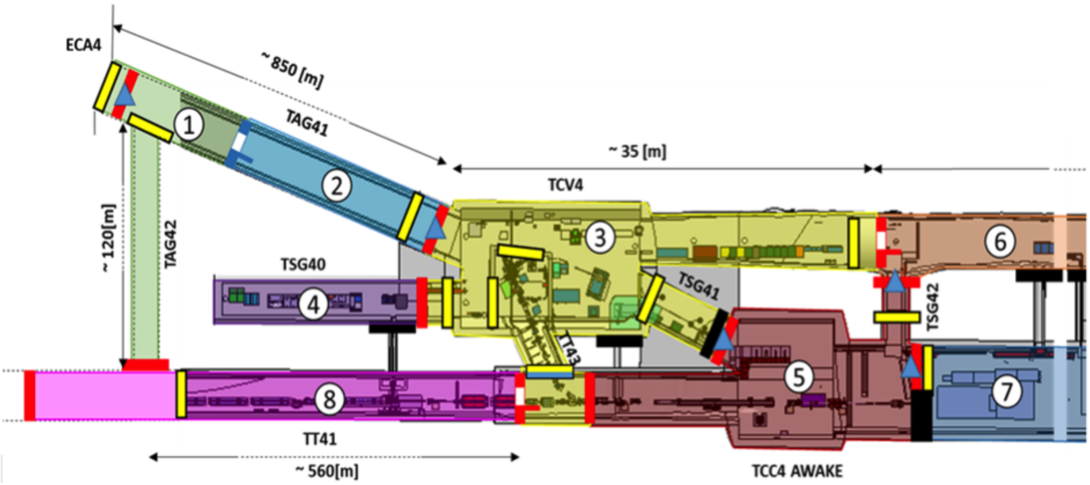


Fig. 27: New fire compartments in the AWAKE underground areas. fire separation walls or doors are shown in red and black, smoke doors in blue and access doors in yellow.

9.2 Fire Safety Improvement of the AWAKE Facility

The CNGS facility had four smoke compartments, justified by the absence of fire load and of personnel (both a consequence of the high radiation) in the area. Since both fire load and personnel presence in the underground area are significantly higher for AWAKE than it was for CNGS, a full fire compartmentalisation is needed to allow a safe offensive approach of the fire brigade and help evacuation of personnel. Fire retardant structures, doors and fire dampers were installed between the eight new compartments (see Fig. 27) between April and September 2016 to ensure containment of smoke and fire. Special effort was needed to integrate fire doors and walls in an existing facility, where many services as well as beam lines must cross from one fire compartment in the next. Figure 28 shows three fire doors and walls installed around the proton beam line, two just upstream of the plasma cell and one at the downstream end of the AWAKE experimental area.

Fig. 28: Fire doors upstream the proton beam line (left and middle) and wall downstream of the plasma cell (right).

The smoke detection system as well as the fire water system have been extended into the full underground AWAKE area (including the experimental area and the rack area). Smoke extraction ducts have been installed to allow cold smoke extraction, after smoke detection, for each of the eight fire compartments independently. The extended fire water system is equipped with connections for the fire brigade's equipment every 70 meters and on both sides of each fire door, allowing the intervening fire fighting team to approach a fire with extinguishing measures from either side. In total, several hundred meters of piping for fire water and smoke detection were installed as well as about 20 additional fire water connections. Ten meters of trenches and cores were made by the civil engineering team in order to ensure smoke extraction from each compartment and route the new fire water pipes. About twenty passages were fitted with a fire-proof or fire-retardant wall and all other openings between compartments were closed with fire retardant material.

9.3 Plasma Cell Test Area above Ground

In order to allow extensive testing of the plasma cell and the plasma cell end flanges before installation in the tunnel, a fenced area in the EHN1 North Area was equipped with the necessary infrastructure to receive, power and test the replica of the plasma cell and all its accessories. The 50 m^2 area is equipped with the necessary electrical infrastructure, exhaust pipes, gas lines, alignment equipment as well as a glove box for Rubidium handling. A clean room for the assembly of vacuum components is available in the same building. The plasma cell test area is a valuable asset to the AWAKE infrastructure, both for the assembly and test of the current 10 m vapor plasma cell, and for the development, assembly and tests of future plasma cells.

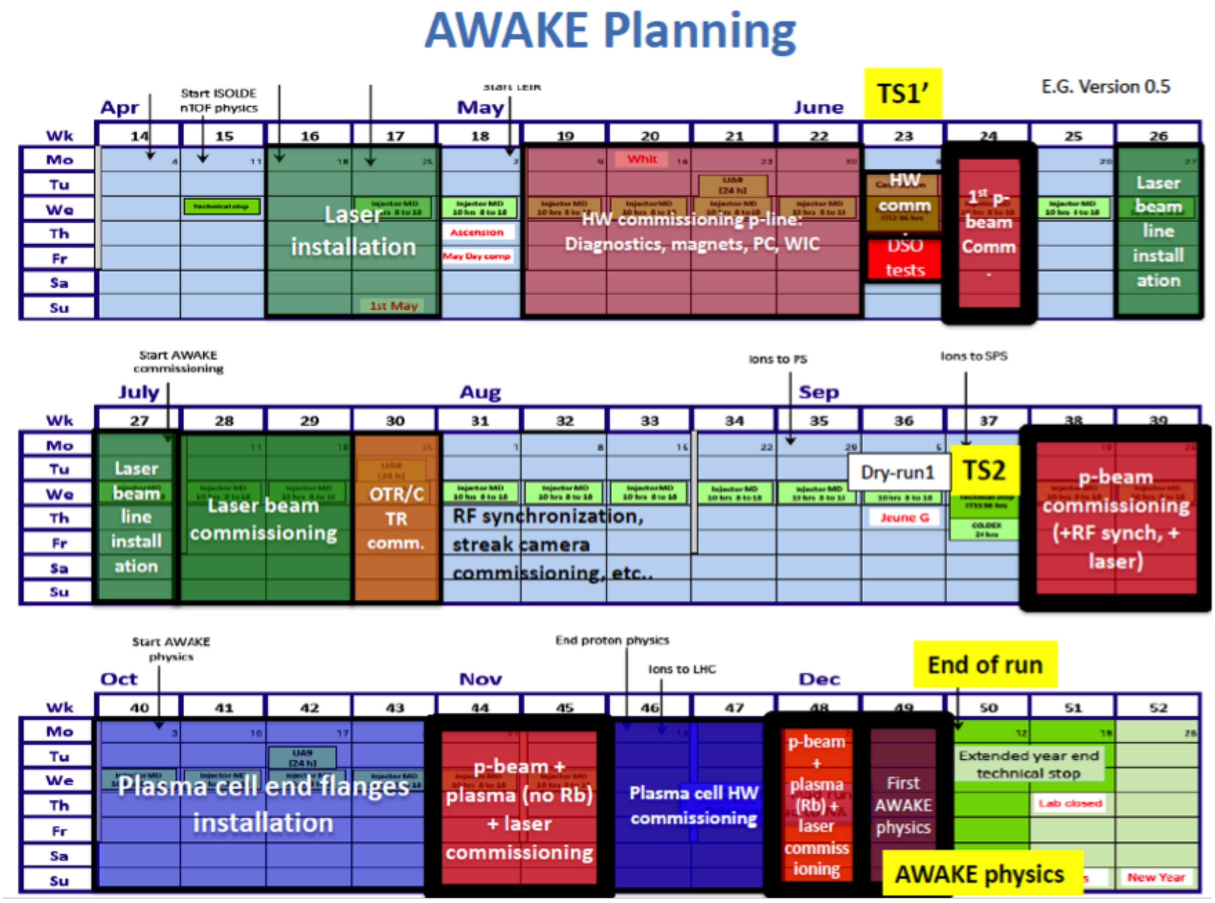


Fig. 29: AWAKE Schedule 2016.

10 Schedule AWAKE Run I

Thanks to the huge efforts from all the CERN groups and collaborating institutes involved today (October 2016) the infrastructures are completed, the laser and proton beam line (including beam instrumentation, vacuum systems and diagnostics) have been installed, aligned, tested and commissioned. Figure 29 shows the AWAKE schedule for 2016: one week of wakefield physics is expected in December 2016 before the Extended Year End Technical Stop (EYETS) of 2016–17. To achieve this important milestone the main efforts concentrate on the plasma cell: the prototype end flange will be tested, operated and safety procedures will be developed in the surface area in EHN1 during September and October 2016, while the two plasma cell end flanges will be installed in October 2016 in the AWAKE facility. Beam commissioning with the plasma cell end flanges (no Rb) will be performed beginning of November 2016 followed by a hardware commissioning period of the plasma cell with Rb inserted (after full safety approval). Before the one week of wakefield physics in December 2016, there will be one week of beam commissioning with the Rb filled plasma cell. The wakefield physics will be interrupted at the beginning of the EYETS and resumed in May 2017; during 2017, periods of physics will be alternated with periods of installation for the electron phase (see Fig. 30). The project will profit of the time available in 2016, to anticipate as much as possible the installation of utilities and infrastructures necessary for the electron phase: a first cabling campaign for the electron phase is scheduled in October 2016. The installation activities for the electron phase will start after the first wakefield physics, in December 2016. According to the present estimations, the installation of the equipment and infrastructures for the electron phase will be completed by mid-2017, and will be followed by a period of electron hardware and global commissioning. The Experimental Areas will be ready for running with electrons and protons by Q4/2017.

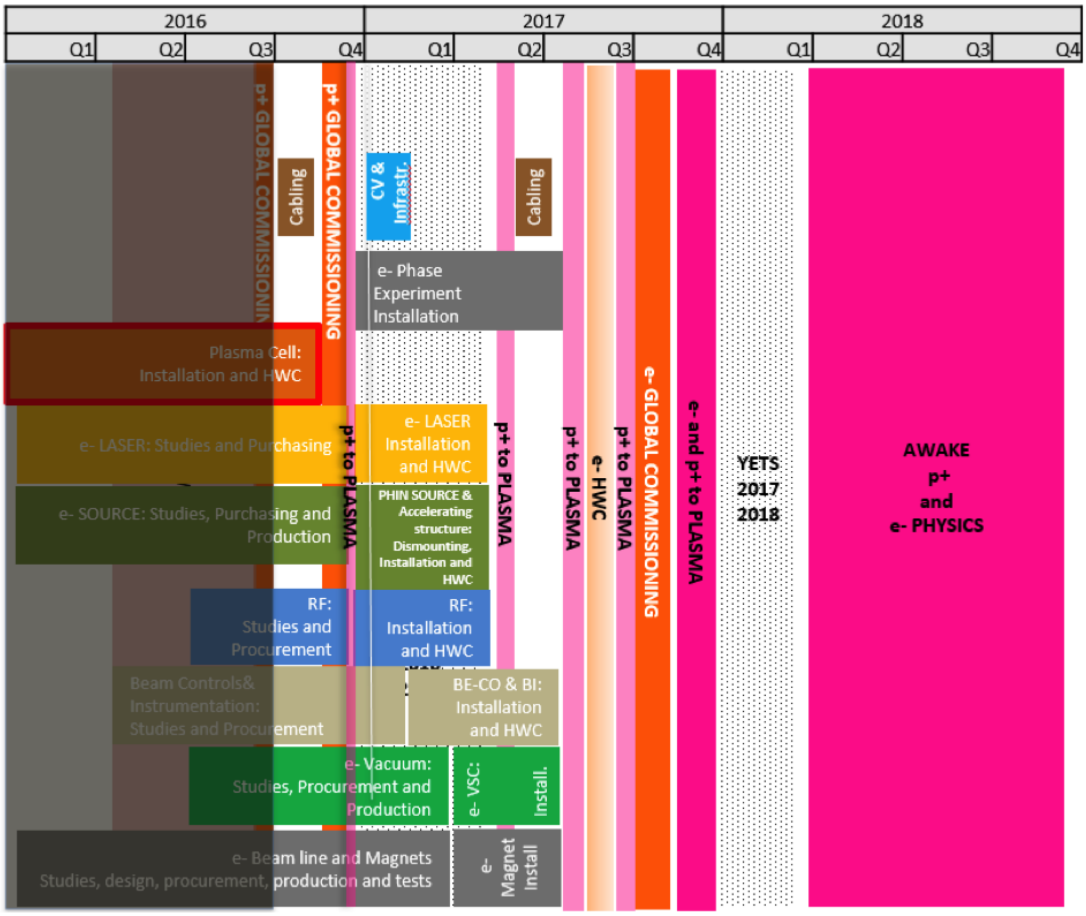


Fig. 30: AWAKE master schedule for the proton and electron phase until LS2.

11 Preparations for Run II

During Run I of the AWAKE experiment, ending with the start of the LHC LS2, the objectives are to demonstrate the proton beam self-modulation instability (AWAKE Phase 1) and to sample the strong wakefield with test electrons (AWAKE Phase 2). Run II of AWAKE is proposed to start right after the

LHC LS2 with the following main objectives: to demonstrate high-gradient acceleration of bunches of electrons to many GeV preserving reasonable beam quality, and to demonstrate scalable plasma source technology. Successful demonstration of these two objectives will open up the path towards high energy physics applications for proton driven plasma wakefield acceleration, as discussed later in the report. By the end of 2017 our goal is to have ready a design study for Run II. We here report on ideas and some preliminary studies for Run II.

Depending on the results of Run I, it may be desired to start Run II with complementary studies with the aim of further understanding the self-modulation instability, for example the effects of density steps and gradients. An option for Run II electron injection is on-axis injection between two plasma stages, as show in Fig. 31. In order to prepare Run II, a significant research effort is therefore required for a number of topics: scalable plasma sources, compact high peak current electron injectors, plasma staging, proton beam optimization and instrumentation development. Most research topics require numerical simulation studies. We now go through these topics in more detail, highlighting the key challenges to be addressed in the preparation for Run II.

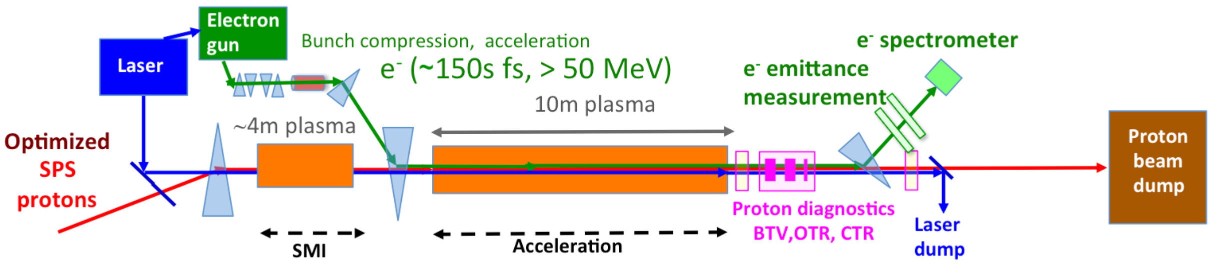


Fig. 31: A possible layout for AWAKE Run II. A first plasma cell is used to self-modulate the proton beam. An electron beam is injected after the first cell and is accelerated by the modulated proton beam in a second plasma cell.

11.1 Scalable Plasma Sources

The high energy proton beams available at CERN contain enough energy to accelerate an electron or positron beam up to TeV energies [10]. With an accelerating gradient of order GeV per meter, hundreds of meters of plasma are required to reach 1 TeV. Most plasma sources for PWFA experiments, including the source for AWAKE Run I [11], have been based on laser-ionization of a vapor. An ionization laser has limited energy and the length of this type of plasma source is likely limited to a few 10s of meters. Many plasma sources would therefore need to be staged together which would be relatively expensive and would require the challenges of interstage beam propagation to be properly addressed [12]. As an alternative the AWAKE project is developing plasmas sources which do not depend on laser ionization and could therefore be better suited for very long plasmas.

11.1.1 Helicon Plasma Source Initiative

The helicon plasma source technology is a promising candidate for a scalable plasma cell: the plasma is generated by a helicon RF wave, driven by external antennas. Adding RF antennas longitudinally can extend the length without creating gaps in the plasma. A 1 m long helicon plasma source prototype was developed within the AWAKE Collaboration at IPP Greifswald, demonstrating that the nominal AWAKE plasma density could be achieved in helicon discharges. The Swiss Plasma Center Lausanne has developed specialized antennas and transportable diagnostics for density and instability measurements.

Further developments are required to meet the spatial and temporal density performance requirements for AWAKE as well as a scalable ($\sim$ 10 m) prototype. It is proposed to address the open tasks at the already existing helicon cell prototype, jointly between IPP Greifswald, SPC Lausanne and CERN. For this purpose and also for the following developments towards an AWAKE helicon cell, discussions have started in order to relocate the IPP prototype cell to CERN and operate the device in test campaigns.

11.1.2 Discharge Source Development

Direct current discharge plasma sources are being developed by Imperial College (London) and IST (Lisbon), AWAKE collaborations members. A 3 m long prototype, capable of reaching the plasma densities required by AWAKE, has been demonstrated in the laboratory [13]. Future work include the development needed for 10 m and longer prototypes. The construction of a prototype deployable to AWAKE is pending funding. Plans for further development and testing with electron beams have been put forward [14]. As for the helicon source, further R&D is required in order to meet spatial and temporal plasma density requirements.

11.2 Electron Injectors

The S-band photo-injector for AWAKE Run I produces an electron beam of several ps duration [15]. The electrons will therefore sample all the wakefield phases. In order to cleanly accelerate an injected beam the beam duration must be a small fraction of the wakefield period, preferably less than a few 100 fs. Even shorter bunch lengths may be necessary in order to achieve a small beam energy spread by beam loading [16] or by sampling a small enough phase range. Furthermore, to minimize phase slip the electron injection energy must be several 10s of MeV, as opposed to the 16 MeV available in Run I. With the limited space available in the AWAKE experimental area, using S-band technology it does not seem possible to generate an electron beam with the required parameters. Several alternative technologies are being considered.

In principle an X-band injector, as recently demonstrated at SLAC [17], could provide the required bunch length and energy in the available space. However, this technology is not yet fully mature and significant resources would be needed to build a reliable X-band injector. This option for injector would mainly be interesting to pursue if other partners would be interested in simultaneously developing the X-band gun further.

Laser wakefield accelerators (LWFA) naturally produce very short, high peak current bunches and could also be considered as electron sources [18]. Beam energies of 50–100 MeV are produced by relatively standard laser systems (a few 10 TW peak power). Several institutes, including MPP and MPQ Munich, UNIST Korea and Cockcroft Institute, are interested in investigating further whether LWFA can be used as a Run II injectors.

11.3 Plasma Staging

As the proton beam self-modulation instability develops, the phase of the wakefield changes rapidly [19]. In order to accelerate an electron beam at a well-defined phase, the electron beam must be injected after the instability has saturated, estimated to happen after a few meters. Such injection would either require to have two separate plasma cells, with the electron beam injected in between the cells, or to develop a method to inject the electron bunch from the side directly into the plasma stage. The latter option, side-injection, was investigated for Run I but at that time discarded due to the technical complexities [19]. Staging of plasma cells cells also has a number of challenges with needs to be investigated. Numerical studies reporting on the effect of a vacuum gap on the proton beam propagation are discussed in Section 12.

11.4 Other Studies

A number of other topics needs to be investigated in order to prepare Run II. Improvement of the SPS proton beam parameters (shorter bunch length, lower transverse emittance, higher intensity) may lead to higher wakefield amplitudes and looser tolerances for plasma density uniformity. Preliminary studies show that the SPS bunch length a factor two shorter than today (about 6 cm rms) could be available for Run II for a bunch intensity of 3×10^{11} [20], while more SPS machine studies are needed to achieve a reduced transverse emittance with respect to Run I parameters. For Run II the AWAKE instrumentation must be upgraded to be compatible with higher electron energy, and emittance measurements must be developed in order to successfully demonstrate the acceleration of an electron beam.

12 Simulations for AWAKE Run II

In order to accelerate significant electron charge (large enough to load the wakefield) with a small energy spread, the electron beam should be injected into the stable wakefield after the saturation of the SMI. Stabilization of the self-modulating beam occurs after the saturation of SMI approximately 8 m from the plasma entrance at the baseline plasma density of $7 \cdot 10^{14}\ \mathrm{cm}^{-3}$. The density step technique [21–24] can be used to increase the number of proton micro-bunches driving the wakefield.

Figure 32 shows the LCODE [25, 26] simulation of the maximum electric field excited in plasma with and without the 1 m long gap needed to inject the electron beam. The small density step in the first plasma section allows one to increase the stable accelerating field in the second section by a factor of $3 - 5$ depending on the width of the gap. The higher electric field is excited by the larger number of micro-bunches driving the wakefield resonantly as shown in Fig. 33. The larger the number of micro-bunches used, the tighter the tolerances on the precision of the required density profile. In the case of the highest achievable accelerating electric field the number of proton beam micro-bunches is around 60. This requires precision of the control over the plasma density profile (from shot to shot) at the level of 0.2% [28].

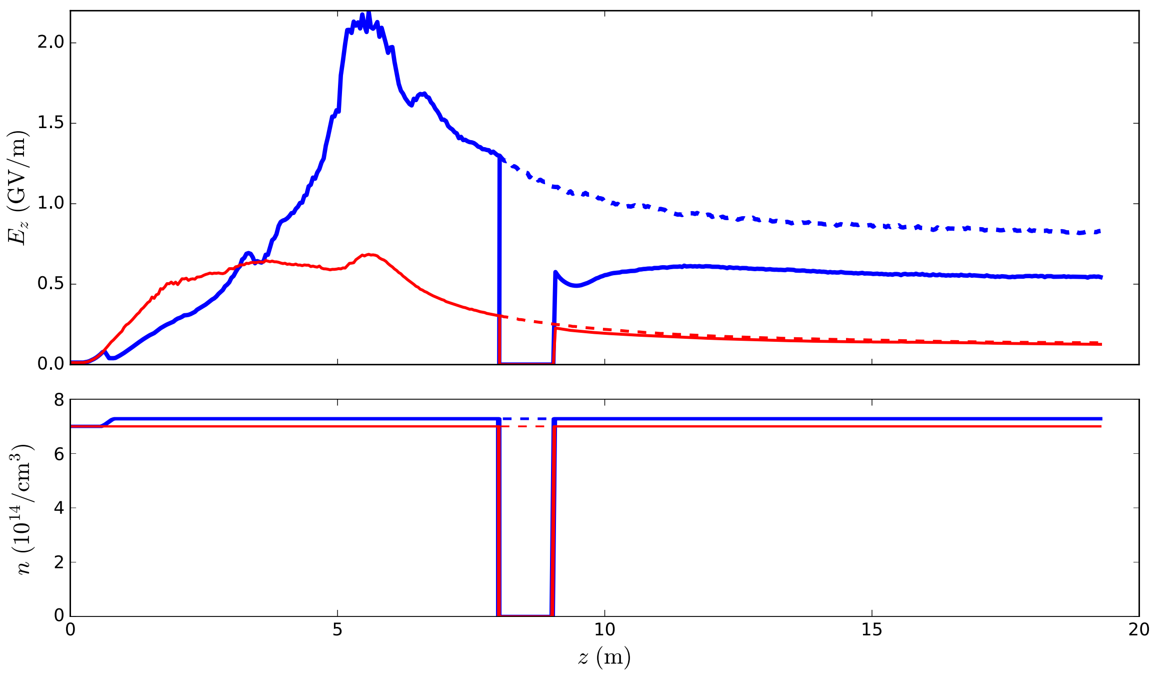


Fig. 32: Amplitude of longitudinal electric field excited by the self-modulated proton beam in plasma with different density profiles (red, constant density and blue with a density step) using LCODE. Initial proton bunch parameters used in this simulation: number of protons $N_p = 3 \cdot 10^{11}$, longitudinal size $\sigma_z = 6\,\mathrm{cm}$ ($I_{\mathrm{peak}} \approx 100\,\mathrm{A}$), transverse size $\sigma_{x,y} = 0.16\,\mathrm{mm}$, normalized transverse emittance $\epsilon_n = 2.2\,\mathrm{mm} \cdot \mathrm{mrad}$ [27]. The ionizing laser pulse is shifted by 5 cm from the center towards the head of the bunch to maximize the useful proton beam charge. Dashed line shows electric field in plasma without the gap. The value of the density step is 4% at $z = 70\,\mathrm{cm}$

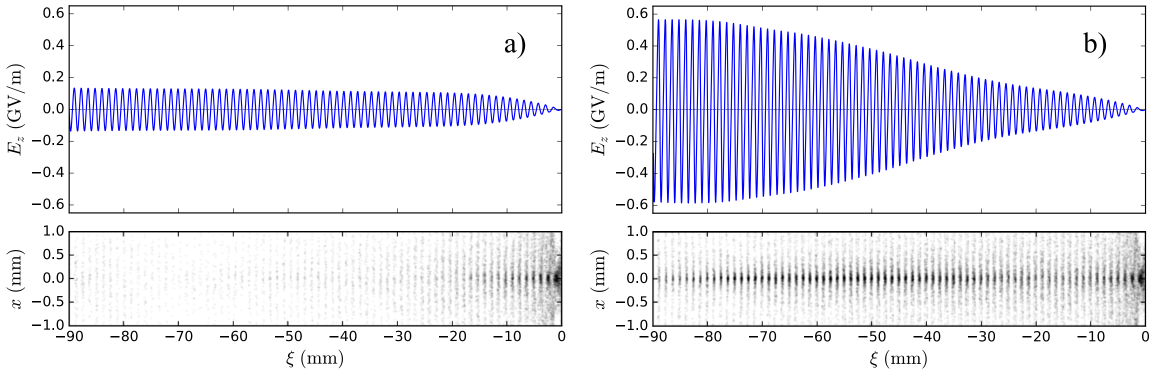


Fig. 33: Longitudinal electric field along the self-modulated proton beam inside the second plasma section. a) The plasma density is uniform in both sections (red line in Fig. 32); b) the density step was used in the first section to stabilize the sequence of micro-bunches (blue line in Fig. 32). The top plots show the electric field. The bottom plots show the transverse positions of protons along the bunch.

By injecting the electron beam closer to the ionizing laser pulse it is possible to relax the tight plasma density tolerances at the expense of the accelerating electric field. Initially experiments can be started with only several proton micro-bunches driving the wakefield at $50 - 100$ MV/m. Then the precision of the experiment can be increased gradually towards the maximum of around 60 proton micro-bunches driving a 600 MV/m wakefield.

13 Long-Term Perspectives for Proton-Driven Plasma Wakefield Acceleration

Plasma wakefield acceleration is a promising scheme to realise shorter or higher energy accelerators in particle physics. With the aim of demonstrating $\mathcal{O}$(GV/m) accelerating gradients in a plasma, scalable over long distances, by the end of AWAKE Run II, experiments utilising such beams could become reality from about 2025 onwards. Some ideas for future experiments are here presented based on the AWAKE scheme and making strong use of the current CERN infrastructure and facilities. This was also presented [29] at the recent Physics Beyond Colliders Kick-off Workshop held in CERN in September.

Consideration is first given to the use of electron bunches produced in the AWAKE scheme with 10^9 electrons/bunch of energy $\mathcal{O}$(50 GeV). These would be achieved using the SPS protons as the drive beam in $50 - 100$ m of plasma with a repetition frequency of about 5 s. Such a beam could be used for detector test beams or as an accelerator test facility as there is a limited number world-wide. A high-energy electron beam could also be used for fixed-target deep inelastic experiments; many have been done in the past and thorough survey of whether new areas or physics can be probed, such as the proton spin, is first needed. These possibilities are left for further investigation.

The most promising application so far considered is to use this high-energy electron beam for a fixed-target or beam-dump experiment to search for dark photons in a similar manner to that being done by the NA64 Collaboration [30,31]. Currently the NA64 experiment will receive about 10^6 electrons/spill or 2×10^5 electrons/s from the SPS secondary beam which for a 3-month programme would provide $N_e \sim 10^{12}$ electrons on target. Using an AWAKE-like beam with bunches of 10^9 electrons every 5 s, would give 2×10^8 electrons/s which for a 3-month programme would provide $N_e \sim 10^{15}$ electrons on target. Therefore, using the AWAKE scheme could provide an effective upgrade to the NA64 experiment, increasing the intensity by a factor of 1000 and a corresponding extension in sensitivity to the search for dark photons. A higher bunch charge or higher SPS repetition frequency may also be possible and warrants further investigation.

In order to give an idea of the effect of the increased number of electrons on target, the sensitivity is considered as a function of the mixing strength, ϵ, of the dark sector with the Standard Model and the mass of the dark photon, $m_{A'}$. Two decays channels have been considered, $A' \to e^+e^-$ and $A' \to \chi\bar{\chi}$, where the χ are other dark sector particles and are "invisible" in a detector. A very preliminary idea of the sensitivity is shown in Fig. 34 for both channels. They demonstrate the potential of an AWAKE-like beam extending significantly into regions currently unexplored in both channels. However, the results should be considered indicative and more detailed calculations and analysis is needed, in particular the optimal beam energy, evaluation of the backgrounds (currently assumed to be negligible), a careful design of the detector setup and understanding how to count the events when running in fixed-target mode all require further study.

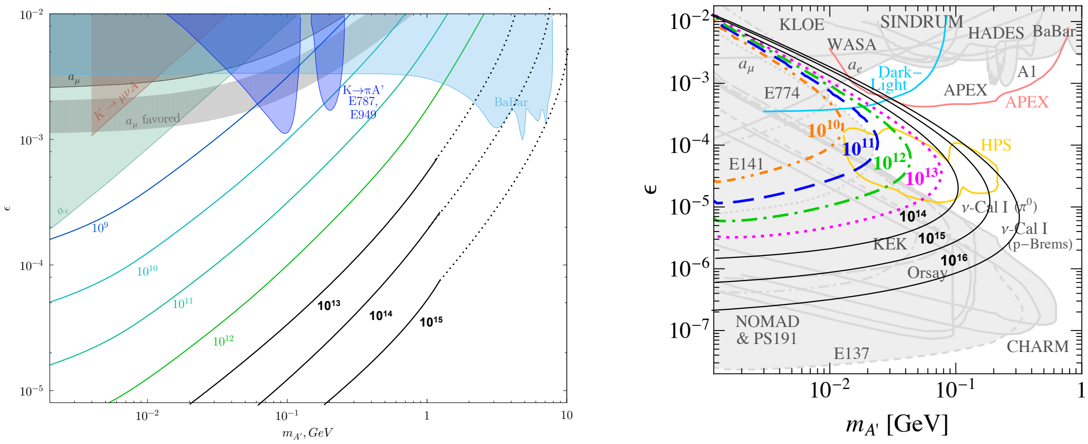


Fig. 34: Sensitivity to dark photons for different number of electrons on target. Left: $A' \to \chi\bar{\chi}$ channel for NA64 experiment ($10^9 - 10^{12}$ electrons on target) and AWAKE-like beam ($10^{13} - 10^{15}$ electrons on target). Right: $A' \to e^+e^-$ channel for NA64 experiment ($10^{10} - 10^{13}$ electrons on target) and AWAKE-like beam ($10^{14} - 10^{16}$ electrons on target).

Another possibility using an electron beam of energy $\mathcal{O}(50\,\text{GeV})$ is an LHeC-like electron–proton collider. With such an AWAKE-like beam, the necessary energy would be reached and a much smaller accelerator complex required. However, the luminosity for a collider based on the AWAKE scheme is estimated [32] to be about $10^{30}\,\text{cm}^{-2}\text{s}^{-1}$, several orders of magnitude lower then for the current LHeC design [33]. This would necessarily lead to a different particle physics focus with intense investigation of the strong force and QCD, but little sensitivity to Higgs physics. The design of this collider based on plasma wakefield acceleration would have many compelling challenges, including methods to increase the luminosity, and could yet lead to a compact high-energy electron–proton collider.

A very high energy electron–proton collider (VHEeP) with a centre-of-mass energy of 9 TeV has recently been proposed [34]. This would use proton bunches from the LHC to drive a wakefield and accelerate bunches of electrons to 3 TeV which would then collide with the proton bunches rotating the other way. Although luminosities are again assumed to be modest, the large increase in energy opens up the opportunity to look for new physics at a centre-of-mass energy 30 times higher than at HERA and an extension in the kinematic range of a factor of 1000. This would allow QCD and the strong force to be probed in a region where they are poorly understood, where models differ vastly in their predictions and a change in the structure of matter is expected. As well as QCD, searches for e.g. leptoquarks will also be greatly enhanced with this increase in energy. These first physics ideas will be further developed as well as the design of a detector and the accelerator.

14 Collaboration Matters

The AWAKE Collaboration is strong and a number of new students and postdoctoral researchers have joined since the last SPSC review. All Run I tasks are covered and discussions with new groups expressing interest in joining are referred to Run II.

14.1 Run II Organization

Our efforts towards Phase I,II (Run I) are progressing well. As discussed above, we have started studying future R&D with AWAKE, and have created a new coordination package for Run II preparations. Erik Adli (Oslo University) leads this coordination package. His (and the team's) task is to get a more structured approach to preparations for Run II:

- Defining the goals;
- Defining technology steps needed;
- Forming work packages to meet the goals (plasma cells, simulations, electron injection, electron diagnostics, etc.).

The Run II coordinator works closely with the Management Team and some of the existing task groups. New task groups will likely need to be defined, and this will give an opportunity to have tasks for new institutes interested in joining AWAKE. As a part of the Run II preparations, a Helicon plasma cell R&D effort at CERN with the aim to have a 10 m version for Run II is under discussion. We aim to have a design study for Run II documented by the end of 2017.

The CERN AWAKE Project Leader Mandate has been extended due to the upcoming Run II activities. The new mandate now includes:

- Leading the CERN AWAKE project towards and during Run II;
- Coordinating and organizing the general proton driven plasma wakefield acceleration studies at CERN;
- Coordinating all resources associated with the AWAKE project and with the proton driven plasma wakefield studies, tests and realization;
- Coordinating and organizing the studies and possible realization for first applications of proton driven plasma wakefield acceleration technology.

14.2 AWAKE Leadership

Some other changes in leadership positions have also occurred: Steffen Doebert (CERN) is now Deputy to Patric Muggli (MPP) for the Physics and Experiment Board and Ans Pardons (CERN) is now Edda Gschwendtner's (CERN) deputy of the CERN AWAKE project.

14.3 Associate Membership

The AWAKE Collaboration has created a status of Associate Membership as a stepping stone to full membership in AWAKE. Associate members:

- Are automatically invited to AWAKE Collaboration meetings and can give presentation in these meetings;
- Can be invited to Technical Board and Physics and Experiment Board and other special meetings and give presentations;
- Can work together with an AWAKE institute on specific projects related to AWAKE and share needed AWAKE information for these tasks;
- Can be given access to (specified) AWAKE data upon consent of the Collaboration Board;
- Can solicit a letter to confirm membership of AWAKE.

It is understood that AWAKE Associate members will have a 'fast-track' path to becoming full members upon the definition of a concrete project to be performed within AWAKE and the signing of the MoU Addendum. The institutes given Associate Membership to-date are UNIST (Korea), the Swiss Plasma Center (SPC), and the Wigner Research Center (Hungary).

14.4 Funding

The redesign of the plasma cell ends led to substantial cost increases. The Max Planck Institute for Physics applied for and received a budget supplement of 0.5 MEUR to cover these extra costs. The UK groups were given a positive review concerning their 3.5-year funding application to STFC, but have to-date been granted only the first 18 months (Apr/2016 – Sep/2017) of funding. This will be sufficient to cover the costs associated with delivering their Phase II responsibilities, but in order to exploit the data, run and maintain the instruments and publish high-quality papers, the additional two years will be needed. This is dependent on a review exercise currently underway within STFC.

15 AWAKE Publications, Presentations and Public Relations

Publications by AWAKE Collaboration Members on Topics Related to AWAKE

- A. Caldwell et al., AWAKE Coll., "Path to AWAKE: Evolution of the concept", Nucl. Instrum. Meth. **A 829** (2016) 3.
- A. Caldwell and M. Wing, "VHEeP: A very high energy electron–proton collider", Eur. Phys. J. **C 76** (2016) 463.
- E. Gschwendtner et al., AWAKE Coll., "AWAKE, the advanced proton driven plasma wakefiled experiment at CERN", Nucl. Instrum. Meth. **A 829** (2016) 76.
- A. Joulaei et al., "Laser pulse propagation in a meter scale rubidium vapor/plasma cell in the AWAKE experiment", Nucl. Instrum. Meth. **A 829** (2016) 339.
- K.V. Lotov, "Physics of beam self-modulation in plasma wakefield accelerators", Phys. Plasmas **22** (2015) 103110.
- K.V. Lotov, "Effect of beam emittance on self-modulation of long beams in plasma wakefield accelerators", Phys. Plasmas **22** (2015) 123107.
- E. Öz, F. Batsch and P. Muggli, "An accurate Rb density measurement method fo a plasma wakefield accelerator experiment using a novel Rb reservoir", Nucl. Instrum. Meth. **A 829** (2016) 321.
- K. Pepitone et al., "The electron accelerator for the AWAKE experiment at CERN", Nucl. Instrum. Meth. **A 829** (2016) 73.
- A. Petrenko, K. Lotov and A. Sosedkin, "Numerical studies of electron acceleration behind self-modulating proton beam in plasma with a density gradient", Nucl. Instrum. Meth. **A 829** (2016) 63.
- J.S. Schmidt, et al., "Status of the proton and electron transfer lines for the AWAKE Experiment at CERN", Nucl. Instrum. Meth. **A 829** (2016) 58.
- A.P. Sosedkin and K.V. Lotov, "LCODE: A parallel quasistatic code for computationally heavy problems of plasma wakefield acceleration", Nucl. Instrum. Meth **A 829** (2016) 350.
- M. Turner et al. "Indirect self-modulation instability measurement concept for the AWAKE proton beam", Nucl. Instrum. Meth. **A 829** (2016) 314.

Conference Presentations and Proceedings on AWAKE

- C. Bracco (speaker) et al., "CERN AWAKE Facility Readiness for First Beam", Contributed talk at IPAC2016, Busan, Korea, May 2016.
- C. Bracco et al., AWAKE Coll., "AWAKE: A proton-driven plasma wakefield experiment at CERN", Talk presented at ICHEP 2015, Nucl. Part. Phys. Proc. **273–275** (2016) 175.
- S. Burger et al., "Scintillation and OTR Screen Characterization with a 440 GeV/c Proton Beam in Air at the CERN HiRadMatFacility", To appear in proceedings of International Beam Instrumentation Conference, Barceleona, Spain, September 2016.

– H. Damerau et al., "RF Synchronization and Distribution for AWAKE at CERN", Proceedings of IPAC2016, Busan, Korea, May 2016, p.3743–3746.
– L. Deacon et al., "A Spectrometer for Proton Driven Plasma Accelerated Electrons at AWAKE – Recent Developments", Proceedings of IPAC2016, Busan, Korea, May 2016, p.2605–2608.
– S. Doebert and K. Pepitone, "Ultra-Short Bunch Electron Injector for AWAKE", To appear in proceedings of 28th Linear Accelerator Conference, LINAC2016, East Lansing, MI, USA, September 2016.
– V. Fedosseev et al., "Integration of a Terawatt Laser at the CERN SPS Beam for the AWAKE Experiment on Proton-Driven Plasma Wake Acceleration", Proceedings of IPAC2016, Busan, Korea, May 2016, p.2592–2595.
– A. Lasheen et al., "Single Bunch Longitudinal Instability in the CERN SPS" Proceedings of IPAC2016, Busan, Korea, May 2016, p.1670–1673.
– A. Petrenko et al., "Beam–Plasma Interaction Simulations for the AWAKE Experiment at CERN", Proceedings of IPAC2016, Busan, Korea, May 2016, p.2596–2598.
– J.S. Schmidt et al., "Commissioning Preparation of the AWAKE Proton Beam Line", Proceedings of IPAC2016, Busan, Korea, May 2016, p.1374–1377.
– M. Turner et al., "Proton Beam Defocusing as a Result of Self-Modulation in Plasma", to be Published in the Proceedings of NAPAC 2016.
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– M. Wing, "An electron beam for physics experiments based on the AWAKE scheme", Talk presented at Physics Beyond Colliders Kick-off Workshop, CERN, September 2016.

Popular Communications

– CERN Bulletin: AWAKE's plasma cell arrives at its destination, CERN Bulletin 07/2016 08 2016, BUL-NA-2016-27.
– CERN EP Newsletter: AWAKE starts installation, November 2015
https://ep-news.web.cern.ch/content/awake-starts-installation
– EP Newsletter: AWAKE, an accelerator R&D experiment, April 2016
https://ep-news.web.cern.ch/content/awake-accelerator-rd-experiment
– Le Temps Newspaper Article on AWAKE, March 2016
http://www.letemps.ch/sciences/2016/03/08/revolutionner-physique-faisant-surfer-particules
– Popular Science: First test for machine that could change the future of particle physics, June 2016
http://www.popsci.com/cern-scientists-test-machine-that-could-change-future-particle-physics
– CERN Courier: AWAKE sees first beam, July 2016
http://cerncourier.com/cws/article/cern/65491
– CERN Movie: Awakening acceleration: AWAKE's plasma cell arrive
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