AR/Int. SG/63-6

4th February, 1963

EXPERIMENTAL AREAS, SHIELDING AND BEAMS OF A 150 GeV AND 300 GeV PROTON SYNCHROTRON

by

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PS/3652

1. Introduction

This report contains some preliminary ideas for the layout of experimental areas and the amount of hardware involved in the setting up of beams for a PS whose energy exceeds that of the CPS by an order of magnitude. In view of the present discussions about the most desirable energy of such a machine, we shall consider separately two different energies, namely 150 GeV and 300 GeV and also make a cost estimate.

2. Experimental areas and beam layout

a) Number and location of the experimental areas

In a previous report[1)] we have studied the relative advantages and problems connected with internal and external target operation. We concluded that in general the external targets are at least equivalent to internal targets and have the enormous advantage of accessibility from all sides which results in a flexible beam layout. It looks feasible to extract 90 o/o of the circulating beam in a long ($\sim$ 0.5 sec) or short ($\sim$20 μsec) burst and with an emittance not much larger than that of the circulating beam.

We propose therefore to discard internal target operation entirely and to plan two general purpose experimental halls that are completely separated from the PS ring tunnel and use only external targets. While beams and detectors are changed in one hall experiments can be made in the other hall and vice versa, but the setting up of experiments never interferes with the operation of the PS itself. In addition to the experimental halls there should be a special area for neutrino experiments. The latter needs only a small building around the detector since the rest of the experiment is mainly shielding.

A schematic layout of a 150 GeV machine with its experimental areas is shown in Fig. 1. It would have 6 long straight sections where the beam can be ejected. One of these is needed for injection so that in Fig. 1 there remain two free long straight sections that could be used for future extensions. The distribution of the experimental areas around the PS circumference could, of course, be entirely different from that shown in Fig. 1 and will depend on the shape and flatness of the site.

The distance from the point of ejection from the PS to the entrance of the experimental hall should be large enough (say 300 m) to allow sufficient freedom to manipulate the external beam. One could blow up the beam and then focus it down onto a small target or otherwise shape its emittance to suit specific experiments. One might want to apply an R.F. deflection to the external beam in order to decrease the overall length of an R.F. separator[2,9]. It is also desirable that one can deflect the beam sideways onto different targets or upwards in case the PS tunnel would be underground and the experimental hall at ground level.

There may be occasions when experiments are ready to run in two or even all three of the experimental areas listed above. We intend therefore to incorporate into the machine the possibility of sharing the beam between different experimental areas.

A 300 GeV machine would have 12 long straight sections but we would plan the same three experimental areas as described above.

b) Beam layout

As is well known the average transverse momentum of the secondaries is independent of the primary proton energy so that the production angles of the secondaries will be of the order of 1° in the energy range under discussion. Fortunately the external target makes it possible to use 0° production angle and for the optics of the secondary beams this is also the best choice. It looks possible to focus the external beam onto a target with a diameter of about 0.5 mm at 150 GeV or 0.35 mm at 300 GeV and with a length of 10 cm (1 n.m.f.p. of tungsten). For an average transverse momentum of 0.40 GeV/c and a secondary particle energy of 40 GeV one would already catch a large fraction of all the available secondaries if the beam accepts a cone with a half opening angle of 10 mrad (see section 4b). In that case the apparent target broadening is only 0.2 mm if the beam looks "head on" at the target. In fact most beams at the CPS accept appreciably smaller solid angles and this situation is likely to persist at higher energies. It appears therefore that the optics of secondary beams from external targets can be made as good as that from internal targets.

We propose to place the target at the entrance of a sweeping magnet, which might be 6 m long and have a field of 1.6 Wb/m^2. The secondaries of different energies are then fanned out over quite reasonable angles, so that it is possible to set up several simultaneous beams from one target, all of which have effectively 0^o production angle and look "head on" at the target. A 15 GeV/c secondary particle would be deflected over 11^o so that the angular range available to set up beams is about equal to what is used for good intensity beams at the CPS. Since for equal outside dimensions the focal distances of the quadrupoles will be larger than at the CPS it should be possible to set up more simultaneous beams than at the CPS. In this scheme there is a rather close relation between beam direction and momentum, so that each beam covers a momentum band of only about $\pm$ 20 o/o, beyond which its intensity drops rapidly. Of course the central momentum of all beams can be changed simultaneously by the same factor if the field in the sweeping magnet is changed.

A possible beam layout based on this principle is shown in Fig. 2 for a 150 GeV machine. The target is located at the entrance of the experimental hall, rather close to the right hand (looking in the beam direction) side wall, so that one would mainly work with secondaries that are deflected towards the left by the sweeping magnet. The main experimental area would consist of two adjacent halls, one of 40 x 275 m^2 and the other of 20 x 225 m^2.

There is no partition in between the two halls except a row of steel pillars to support the crane rails and roof structure. The pillars should be constructed in such a way, possibly with a hole in the centre at beam level, that they present a minimum obstruction to the beams. At the downstream end of each experimental area we foresee a 15 m wide extension for special long beams. The length of these extensions might be 400 m and 700 m respectively, with a somewhat wider building at the end to house a detector. From Fig. 2 we see that by a suitable choice of bending angles practically the whole area of the halls can be used for experiments and that there are few "dead" corners. We do not suggest, of course, that all these beams should be set up simultaneously.

For reasons discussed in section 2 there is a large quantity of shielding downstream of the target. The first elements of each beam will usually be buried in the shielding. It may appear that it is superfluous to construct a building around a pile of shielding and that therefore the experimental halls could start somewhat further downstream of the target. In this connection one should remember that this shielding must in any case be covered by heavy cranes and that one may quite often work in this region when beams are changed. There is no doubt, however, that a more detailed study will be necessary to determine the optimum shape and location of the experimental buildings to maximize their usefulness for experiments.

In Fig. 2 we assume that negative particles are deflected to the left and we have also drawn a small angle scattered proton beam. The latter needs a very long collimator in the shielding and the scattering angle could therefore be varied most conveniently by keeping the collimator fixed and changing the field in the sweeping magnet. A large deflection is necessary to obtain a momentum resolution which is adequate to study the structure in the energy spectrum of the scattered protons[3)]. To avoid interference with other beams we have chosen a deflection to the right so that this beam leaves the building again. This would not have been necessary, of course, but it suggests that especially along the right hand side wall of the building it would be desirable to foresee a sort of apron where simple beams could be set up in open air. This would also give the possibility to derive parasitic beams from the target that can be used to test apparatus that is located in temporary shacks on this apron.

For a 300 GeV machine the transverse dimensions of the experimental halls would be the same but the longitudinal length scale would be multiplied by a factor of about 1.5.

c) Implications of long distances

The long distances make it impossible to follow the CPS practice of having centralised services like generator buildings or counting rooms.

The magnets will be excited with rectifier sets placed adjacent to the beams and the power distributed as a.c. at a conveniently high voltage. Small transformer stations might be placed along the long extensions for R.F. separators. For the cooling one central heat exchanger and cooling tower per experimental area is probably still the most economical solution.

The use of central counting rooms would lead to an enormous investment in fixed cables and for many experiments, particularly those involving spark chambers, the delay in these cables would be far too long. Each beam should therefore have its own signal cables running along the magnets and its counting and control bay should be located at such a position that the overall length of cables and signal delay times are minimized.

The installation of these long beams will involve a large amount of work so that the half life of elaborate beams might become several years. Existing beams will be displaced only when there are very strong reasons to do so. On the other hand most detectors, like counters, spark chambers or even bubble chambers, are quite mobile so that in general one will rather bring the detector to the beam instead of bringing the beam to the detector.

3. Shielding for external targets

a) Shielding against strongly interacting particles

The shielding around the target perpendicular to the beam direction is determined by the thickness required to absorb nuclear particles, mainly neutrons. Lindenbaum[4)] has calculated the transversal shielding for a 1000 GeV accelerator by assuming that the total radiation flux is distributed isotropically in a 2π forward cone and that the fast neutron build up factor is approximately 50.

Rather extensive measurements have been made at various times on top of the shielding bridge in the South Hall of the CPS. Taking a build up factor proportional[5)] to $E_p^{1/2}$ (where E_p = primary proton energy) we have calculated the fast neutron flux on top of the shielding bridge, using Lindenbaums method. The result comes out about 2 to 3 times higher than the measured fast neutron flux. Allowing for uncertainties due to the geometry, target efficiency etc. we conclude therefore that Lindenbaums calculation agrees reasonably well with experiment and is probably slightly on the safe side.

There exists also a measurement[6)] of the background on top of the CPS tunnel with a target operating in straight section 82. These measurements give a background which is more than an order of magnitude lower than would be calculated from the data taken on top of the shielding bridge. It is probable that the target operation has been very inefficient during these measurements and therefore these results should not be used in shielding calculations.

The maximum permissible dose (mpd) is 2.5 mrem/hr. Taking into account the associated background flux of slow neutrons and γ's this corresponds to 7 fast neutrons/cm^{2}sec. The shielding design of the Stanford 2 mile linac[7)] allows 30 o/o of the mpd or 2 neutrons/cm^{2}sec and we shall use the same figure. The beam intensity is taken as 10^{13} protons/sec for the 150 GeV machine and 2×10^{13} protons/sec for the 300 GeV machine. Taking a build up factor 20 at 150 GeV we find for the fast neutron flux at 10 m from the target perpendicular to the beam direction

$$n = \frac{20 \times 10^{13}}{2\pi \times 10^{6}} e^{-x/\lambda_r} = 3.2 \times 10^{7} e^{-x/\lambda_r} \qquad (1)$$

With $\lambda_r = 150$ g/cm^2 we find a thickness of 7.1 m baryte ($\rho = 3.5$). On top of the shielding, where one does not normally work, we could allow a somewhat smaller thickness, say 6.5 m baryte. For the 300 GeV machine we find 7.6 m baryte on the side and 7 m baryte on top of the target.

In the forward direction 15 m baryte gives sufficient shielding against the neutrons, but we shall show below, that the forward shielding is entirely determined by the muons.

b) Shielding against muons

Let us assume that a target with a thickness of 1 n.m.f.p. is placed in the beam. The high energy secondary particle flux then corresponds to 1.8×10^{12} interacting protons/sec at 150 GeV and 3.6×10^{12} interacting protons/sec at 300 GeV. We assume that there is a drift space of 2.5 m in which the π-mesons can decay before they are absorbed in the collimators downstream of the target. It seems difficult to do better in the case that several beams are operated from the same target. The fraction of the primary beam surviving after the target can be dumped in a block of steel. The flight path of the π's produced in this process is so small that they give only a small contribution to the muon flux.

For the π-production spectra we use the formula proposed by Cocconi et al[8]. The validity of this formula at high momenta is open to discussion, but we shall only use it up to secondary momenta below 2/3 of the primary energy, where it checks reasonably well with measurements made at the CPS. By integrating Cocconi's formula over the whole forward cone one finds that the total number of π's of one sign, whose momentum exceeds a value p_π, per interacting proton, is

$$N_\pi = 1.6 \times e^{-0.078\, p_\pi} \quad \text{at } 150 \text{ GeV}$$
$$N_\pi = 1.9 \times e^{-0.048\, p_\pi} \quad \text{at } 300 \text{ GeV} \qquad (2)$$

The average momentum of a decay muon is 0.8 p_π. These data allow us to calculate the number of muons surviving after a given shielding thickness.

For simplicity we shall first consider the case that there is no sweeping magnet and that only baryte is used to stop the muons. The muon beam then spreads out laterally due to the π-production angles and multiple scattering in the baryte[10], the latter effect being dominant at large baryte thickness. Therefore the results worked out below are fairly independent of the exact angular distribution of the π's at production. The muon flux density ($\mu^+ + \mu^-$) in the forward direction at various depths in the baryte is shown in Fig. 3 for the two machine energies.

If we allow 30 o/o of the mpd this corresponds to 8 muons/cm^{2}sec and therefore the shielding thickness required in the forward direction is about 130 m baryte at 150 GeV and 220 m baryte at 300 GeV. To reduce the muon flux to 8 muons/cm^{2}sec everywhere along the side surface of this baryte mass its shape should be roughly cylindrical with a radius of about 5 m at 150 GeV and 5.5 m at 300 GeV.

Taking now into account the effect of the sweeping magnet, we note that it produces a deflection inversely proportional to π-momentum, but since the range in baryte is approximately proportional to muon momentum, all muons have the same lateral displacement at the end of their range of about

3.7 m, the direction of the displacement, of course, depending on the sign of their charge. Since the muons are now spread out over a larger area, we can allow somewhat less shielding on top and we can also make the length of the shielding somewhat shorter. The beam is at 2.5 m above floor level. We therefore end up with a baryte shield of 7 x 18 x 125 = 1.6 x 10^4 m^3 at 150 GeV and 7.5 x 19 x 205 = 2.9 x 10^4 m^3 at 300 GeV.

The length of baryte can be reduced by placing an iron cone in the path of the highest energy muons. Since 1 m iron has about the same stopping power as 2 m baryte, a 30 m long iron cone would reduce the total shield length to 95 m at 150 GeV, while a 50 m long iron cone at 300 GeV would give a total shield length of 155 m.

The muon problem is not related to the fact that we use an external target, because also with internal targets one will devise schemes, like a bending magnet triplet[1)], to accept particles produced at 0^o in the secondary beams. The better one succeeds in doing so, the more the muon shielding for internal target operation will look like the muon shielding for external targets. In general it will be possible to place collimators that absorb the π's before they can decay, closer to an external target than an internal target, since in the latter case one must leave the full PS vacuum chamber aperture free for the injected beam. One could, of course, consider moving collimators that are brought into position towards the end of the acceleration cycle, after the beam diameter has shrunk sufficiently, but this is not easy either.

c) Some practical aspects of the shielding problem

The layout of the shielding for an external target at 150 GeV is shown schematically in Fig. 4. It consists of 2000 tons of steel and 48000 tons of baryte. For the 300 GeV machine the transversal dimensions would be nearly the same, but the length scale magnified by a factor 1.65. The shielding would contain 3700 tons of steel and 90000 tons of baryte.

The bulk of the shielding should be made of large blocks with a weight of about 40 tons. When new beams are made, parts of the shielding can be demounted successively and new collimators and magnets buried in it. Assume that there would be two cranes of 50 tons each, and that a crane needs 5 minutes to displace a 40 ton block. The whole shielding mass behind and around the external target of the 150 GeV machine can then be demounted in 50 hours and that of the 300 GeV machine in 100 hours. This would, of course, be done only on rare occasions. In particular the baryte below beam level needs seldom be touched. Since all muons go in the forward direction, one can leave passages open in the shielding that are transversal to the beam direction, so that it is possible to have continuous access (after turning off the external beam) to collimators or other elements that may have to be displaced when setting up a beam.

One might think that a large fraction of the muon shielding could be dispensed with by lowering the floor of the experimental hall well below ground level or by erecting an earth dike around it since then the muons are stopped automatically in earth. Firstly this does not solve the problems for background sensitive detectors, like bubble chambers and for the experimenters around it. Experience at the CPS has shown that a bubble chamber placed at the far end of the South Hall, approximately in the forward direction from target, can easily be swamped with muons if no special shielding against this is installed. Secondly the price of shifting earth is not negligible. For a 13000 m^2 hall such as discussed in section 2 the excavation price per metre depth would be about 0.5 MSF in hard soil and 0.2 MSF in soft earth. The cost of excavating to a useful depth, say 8 m, might therefore be quite comparable to the saving in the baryte blocks (for shielding prices see below under d). Finally this arrangement would have the disadvantage that future extension of the experimental area then becomes considerably more expensive on account of the excavation work. We therefore think that it is best if the floor of the experimental hall is approximately at ground level. In this way long beams in the open air can be improvised in the shortest time and at a minimum cost.

The ring tunnel of the PS must be covered with 10 m earth to shield the neutrons and at the outside there must be adequate shielding against muons. Therefore it should be underground with its beam level about 10 m below ground level. The external beam tunnel connecting the PS ring and the experimental hall should then have a slope of about 1 in 25 with suitable vertical deflecting magnets at each end in case the site is horizontal. Also in cases where the site is not horizontal, it looks convenient if the beam level of the PS tunnel and experimental hall are independent so that for both the most economical solution can be chosen.

One could suggest, that more intelligent schemes instead of stopping the muons in steel and baryte should be devised. One possibility might be to let the external beam pass through a deep trench in the experimental halls and to perform the first momentum analysis of the secondary beams in a vertical plane in order to bring them at ground level. Another possibility is to magnetise part of the steel downstream of the target in order to deflect the muons into the ground or into the air, depending on their sign. Such a magnetic field must be horizontal and since there are collimators in the median plane it is difficult to magnetize the iron there. The iron blocks must be reasonably well machined and stacked in order to provide a continuous path for the magnetic flux and to avoid that the steel moves when it is magnetised. Finally there must be a foolproof interlock system so that the external beam cannot be turned on if the steel is not magnetized. Although a further study of these schemes is desirable our present feeling is that they limit the flexibility of the beam layout and will give little (if any) reduction in the total cost of the shielding in a general purpose experimental hall.

On the other hand, for a neutrino experiment the use of earth shielding and magnetised iron to remove the muons from the neutrino beam may be quite an interesting proposition, especially since in this case the required shielding thickness is about twice the value we have worked out above for the external target, since the neutrino shielding must be able to stop muons with momenta practically equal to the primary proton energy[11]. The external beam tunnel would now be horizontal and the pion decay tunnel simply its continuation. Then comes a large amount of magnetised steel deflecting the muons sideways and a drift space in earth where the muons get a sufficient lateral displacement. Finally there is the detector located in a pit.

The assumptions that have been made when designing the muon shielding may look too generous. If one wants to work with secondaries of only one sign, the absorber for the π's of the opposite sign could be placed appreciably closer than the 2.5 m we have assumed. The muons emerging from the top surface of the shielding are directed upwards and therefore relatively harmless. (The upward directed neutrons are scattered back from the air and give rise to a general skyshine background, but this is not the case for muons.) Therefore the height of the muon shielding could be reduced.

On the other hand we have not allowed for any manipulations of the external beam. It might be desirable to refocus the external beam on a second target, from which additional secondary beams are derived. With iron quadrupoles the minimum distance to a second target cannot be made smaller than about 40 m. One should always allow for a few per cent beam loss at any point along the external beam path so that the external beam over its whole length must be shielded on all sides with about 1 m less baryte (the attenuation in 1 m baryte is about a factor 10) than the external target itself. This argument also makes a layout where the external beam would run through the whole experimental hall with targets placed at convenient intervals rather unattractive and suggests that targeting should be concentrated as much as possible at the far upstream end of the experimental hall.

If it is not possible to set up enough beams from a single target the relative immobility of the muon shielding can be partially counteracted by using 2 or 3 target positions, a few metres apart laterally, or maybe only 10 cm above each other. Each of these target locations could have a different collimator arrangement designed for specific beams. In some cases it may even be possible to split the external beam with a septum magnet so that two of these targets could operate simultaneously.

From Fig. 2 we see that the first momentum analysing section of the secondary beams and a reasonable beam path behind it is located inside the muon shield. The latter therefore also plays a very useful role in absorbing the off-momentum particles rejected from the secondary beams.

As a result of all these arguments we feel, that even if one would relax the demands on the muon shielding and although the final beam layout may look quite different from what we have sketched in Fig. 2, the figures quoted above should still give a reasonably close estimate of the amount of shielding placed in the vicinity of an external target.

d) Cost of the shielding

The price of steel blocks is about 800 SF/ton and that of baryte blocks (with angle irons) 150 SF/ton. The shielding for the external target quoted at the beginning of 3 c) then amounts to 1.6 MSF steel + 7.2 MSF baryte = 8.8 MSF at 150 GeV and 3.0 MSF steel + 13.5 MSF baryte = 16.5 MSF at 300 GeV.

The shielding walls along the secondary beams of the CPS have a thickness of about 1 m and this would remain approximately the same at higher energy. A baryte wall of 1 m thickness, 5 m high and 100 m long has a weight of 1400 tons. We estimate per experimental hall 1.5 km baryte wall = 3.2 MSF at 150 GeV and 2 km baryte wall = 4.2 MSF at 300 GeV.

For a neutrino experiment we estimate 7500 ton steel = 6 MSF at 150 GeV and 11000 ton steel = 8.8 MSF at 300 GeV. The total price of the shielding for two experimental areas and a neutrino experiment then becomes 30.0 MSF at 150 GeV and 50.4 MSF at 300 GeV.

4. Scaling of beams to higher energy

a) General

From the beam layout presented in section 2 it appears that the number of beams per experimental area for the machines under consideration would be approximately the same as at the CPS. Rather than to design detailed beams in the 100 GeV range we shall start from the sort of beams that are existing now around the CPS and see how their components might scale up to higher energy beams. The CPS expenses for beam transport are known and we can then try to extrapolate this figure to the energy range in which we are interested.

The problem of optimizing the acceptance of a quadrupole system as a function of different parameters is rather complex and much has been written about it. Therefore we shall not enter into any details. For simplicity we shall first assume that the aperture of the quadrupoles and bending magnets would be the same as at the CPS and that only their length or number might be increased. Afterwards we shall consider the use of smaller apertures than at the CPS.

b) Scaling of quadrupoles

The present secondary beams from the CPS use a rather meagre fraction[12)] of the available particles but this comes mainly from the fact, that the CPS magnet units downstream of the target make it necessary to use large production angles. With the external beam this limitation is not present and it is instructive therefore to see what performance could be obtained with a doublet of 2 m long, 20 cm aperture standard CPS quadrupoles, centered on the forward direction, for a high secondary momentum, say 18 GeV/c.

With a gradient of 10 Wb/m^3 and a distance of 1 m in between the quadrupoles one can e.g. choose a layout where the distance from the target to the first quadrupole is 9 m, and the distance from the second quadrupole to the image 18 m. We limit the maximum excursion from the axis to 8 cm to stay in the good field region. The maximum angles accepted at the target are then $\alpha_h = \pm 4$ mrad and $\alpha_v = \pm 9$ mrad and the corresponding maximum transverse momenta are $p_{th} = 0.07$ GeV/c and $p_{tv} = 0.16$ GeV/c leading to an average transverse momentum of 0.11 GeV/c.

According to Cocconi et al[8)] the transversal momentum distribution of the secondaries is independent of their longitudinal momentum and given by the equation

$$g(p_t)\ dp_t = \frac{p_t}{p_o^2}\ e^{-\frac{p_t}{p_o}}\ dp_t \tag{3}$$

where the average transverse momentum is $2p_o$. As a round figure we take $2p_o = 0.4$ GeV/c. The fraction of the particles with transverse momentum smaller than p_t is found by integrating (3) and is

$$f(p_t) = 1 - \left(1 + \frac{p_t}{p_o}\right) e^{-\frac{p_t}{p_o}} \tag{4}$$

The functions $g(p_t)$ and $f(p_t)$ have been plotted in Fig. 5. The maximum of $g(p_t)$ occurs for $p_t/p_o = 1$. An optimum solid angle for a quadrupole system would therefore be around $p_t/p_o = 1$, where $f(p_t) = 0.26$ since for larger solid angles the cost increases much more rapidly than the gain in particles. For our numerical example $p_t/p_o = 0.55$ and $f = 0.10$ which is reasonably close to the optimum.

The trajectory of a particle that enters a focusing quadrupole with a displacement from the axis x_o and slope x'_o is

$$x = x_o \cos \left[\frac{dB/dx}{B\rho}\right]^{1/2} s + \left[\frac{B\rho}{dB/dx}\right]^{1/2} x'_o \sin \left[\frac{dB/dx}{B\rho}\right]^{1/2} s \qquad (5)$$

where dB/dx = field gradient, $B\rho = p/e$ = magnetic rigidity and s = distance along the quadrupole axis. In a defocusing quadrupole the same expression holds if the goniometric functions are replaced by hyperbolic functions. If we keep the aperture and therefore dB/dx constant, the orbits at a lower momentum p_2 will remain similar to those at a higher momentum p_1 if all distances along the beam, including the quadrupole length, are decreased by a factor $(p_2/p_1)^{1/2}$. However, the maximum transverse momentum then also decreases as $(p_2/p_1)^{1/2}$ so that the fraction of all particles that can be accepted at lower energies becomes smaller in a way that can be seen from Fig. 5. Most beams at the CPS fall considerably short of the ideal cases discussed above, because of the many other constraints, like interference with adjacent beams, availability of magnets etc. that limit the freedom of the beam designer.

If we now scale up from CPS momenta to a higher energy machine we see that one could consider $f = 0.10$ at 18 GeV/c as satisfactory. Considering the quadrupoles in a first approximation as thin lenses, one could design a 180 GeV/c beam with the same performance by simply placing all quadrupoles 10 times further apart. On the other hand a 1.8 GeV/c beam which would be set up at the CPS with, say 0.5 m long quadrupoles, would not be scaled up to 18 GeV/c by only placing the 0.5 m quadrupoles further apart, but one would probably increase their length as well in order to let the beam resemble more the numerical exemple discussed above. On the basis of intensity arguments we would therefore expect a moderate increase in the total quadrupole length required for a higher energy machine.

The drift space between two cavities of an R.F. separator increases as p^2. Using the same quadrupoles, their focal distances increase proportional to p, so that the total number of quadrupoles, required to image the first cavity on the second (via several intermediate images) increases proportional to p. It is unlikely that the ratio between the number of separated and unseparated beams will become smaller at higher energies and therefore this argument indicates a quite significant increase in the number of quadrupoles at higher energies.

c) Scaling of bending magnets

If we place two bending magnets with a length of 2 m and a magnetic field of 1.4 Wb/m^2 behind the 18 GeV quadrupole doublet discussed above, the lateral displacement of the image is about 1 m, so that a 1 cm wide slit gives a momentum resolution of $\pm$ 1 o/o. This example is reasonably typical for CPS beams. If we scale towards higher energy by placing the quadrupoles further apart the lateral displacement of the image and therefore also the momentum resolution for the same slit width remains the same.

As discussed above, a 1.8 GeV/c beam would be scaled up by making the quadrupoles longer and increasing the distances along the beam less than proportional to p. To keep the lateral displacement of the image and therefore the momentum resolution the same, more bending magnets are needed. In other words, the stronger the quadrupoles, the stronger the bending magnets must be.

We now wish to present some arguments to show that at higher energies a better momentum resolution might often be desirable. A general argument might be that the momentum uncertainty should never exceed about one pion mass (140 MeV) in order that a complete analysis of a reaction is possible. A more specific example is given by elastic and nearly elastic p-p scattering experiments[3]. The momentum spectrum of the scattered protons has two peaks at 0.7 GeV/c and 1.0 GeV/c (independent of primary momentum) below the elastic scattered peak. The p-p scattering experiments at the CPS required two 2 m bending magnets, but Wetherell[13] estimates that about 25 Wb/m would be required to repeat the same experiment at 100 GeV. In these cases we see that Δp rather than $\Delta p/p$ is constant.

In an R.F. separated beam the momentum band is limited by the necessity to make an image of the first cavity on the second.[9] The drift space goes as p^2, the angles in the beam as $1/p$ (using always the same quadrupoles) so that the image broadening for a given relative momentum bite is proportional to p. In other words, $\Delta p/p$ must be reduced as $1/p$. One might argue, that it is possible to correct the chromatic aberration with sextupoles but it is difficult to do that both in the vertical and horizontal plane. Up to now the attempts to improve the CPS separated beams with sextupole correction have had little success. One reason for this may have been that the momentum dispersion was not large enough compared to the imaged size. This argument also suggests the use of more bending magnets.

d) Possibility of using smaller apertures

It is sometimes loosely stated, that when the length of a quadrupole is kept constant, but its aperture is decreased, its gradient can be increased and therefore it becomes stronger, so that it can be placed closer to the target. Consequently the same solid angle can be accepted with a smaller and cheaper quadrupole. This argument only works, when there is a reasonable distance in between the two quadrupoles of a doublet. If this is not the case, the proper scaling law can be derived from eq. 5. When the aperture decreases a factor $1/a$, the gradient increases a factor a similar orbits occur when all distances are reduced a factor $\frac{1}{\sqrt{a}}$, but then the maximum angles in the beam are also reduced a factor $\frac{1}{\sqrt{a}}$.

The choice of an optimum aperture for the beam transport system is very complicated and does not only depend on physics considerations but also on economical factors like the cost of power supplies and the length of the buildings. The best way out is to have quadrupoles and bending magnets with two standard apertures, say a factor 2 different. We limit ourselves here to some arguments which indicate that a reduction in aperture will probably have little influence on the overall cost of the beam transport.

Let us first assume that the beam must be transported over a fixed distance like e.g. the drift space between two R.F. separator cavities. We keep the length of the quadrupoles constant and decrease the aperture and therefore the object and image distances by a factor $1/a$. In that case we have a times more intermediate images and need a times more quadrupoles. For the CPS standard quadrupoles the cost of the power supplies is comparable to that of the quadrupoles themselves (see section 5) and this must therefore also be taken into account when scaling to other apertures. If we scale all transverse dimensions of the quadrupole, including its coil, as $1/a$, the power per quadrupole remains the same and the total power increases proportional to a . The saving on the quadrupoles is then more than counteracted by the increase power supply cost. If we scale the transverse dimensions of the quadrupole (except its aperture, which was scaled as $1/a$) as $1/\sqrt{a}$, both its weight and power scale as $1/a$, so that the total quadrupole weight and power remain constant and there is no saving in total cost.

To obtain a momentum resolution $\Delta p/p$ with a given slit or image width h , the image must be displaced laterally over a distance $hp/\Delta p$. When decreasing the focal distances by a factor a , we need a times longer bending magnetswith an $1/a$ times smaller aperture to obtain the same momentum resolution. As in the case of the quadrupoles this gives little change in the total cost.

e) Cost variation

The above discussion shows that some beam transport elements are rather independent of nomentum, while the cost of others is nearly proportional to the primary momentum E. As a scaling law we shall assume that the total cost is proportional to $E^{1/2}$. From 25 GeV to 150 GeV the variation could be somewhat faster, and from 150 GeV to 300 GeV somewhat slower than proportional to $E^{1/2}$.

5. Cost and manpower for the beams

The expenses on secondary beams for the CPS including the first installation of the East Experimental Area is as follows:

Bending magnets	3.9 MSF
Quadrupoles	3.3 "
Power supplies, switch gear	5.6 "
D.C. distribution	2.8 "
Generator buildings	2.0 "
Cooling plant	2.0 "
Electrostatic separators	3.8 "
R.F. separators	2.5 "
	25.9 MSF

We scale this cost as discussed in section 4e and add 9 MSF at 150 GeV and 14 MSF at 300 GeV for deflection and focusing of three external beams. The total cost estimate is then 75 MSF for a 150 GeV machine and 100 MSF for a 300 GeV machine.

The number of people at the CPS required to shift and align detectors, magnets and shielding, and to operate the generators are as follows

	scientific	technical
Apparatus layout section of the CPS machine group	8	22
Operation and maintenance of generators	2	18
Crane drivers, transport (from SB)		20
	10	60
Estimated at 150 GeV	20	150
Estimated at 300 GeV	25	210

Finally we shall estimate the number of physicists in an experimental team that are required to calculate a beam, to prepare special equipment, like collimators or a vacuum system and to tune it up with counters, hodoscopes etc. Experience at the CPS shows that about 10 physicists are required to operate a separated beam. This includes 3 shift operation. The complexity of the beams will somewhat increase at higher energies, but one cannot have too many people turning knobs at the same time. On the other hand more specialists will be required for complicated components like R.F. separators. Therefore a beam operating team might consist of about 15 physicists.

Acknowledgement

I am grateful for discussions with many people, in particular Drs. E.H.S. Burhop, K. Johnsen, E. Keil, B. W. Montague, L. Resegotti and C.J. Zilverschoon.

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Distribution: (open).

References

1. B. de Raad, Matched straight sections, secondary beams and ejection in a 300 GeV proton synchrotron, AR/Int. SG/63-3.

2. B. W. Montague, private communication.

3. G. Cocconi et al., Phys. Rev. Letters 7 (1961) 450.

4. Design Study for a 300-1000 GeV Accelerator. Brookhaven National Lab. August 1961.

5. S. J. Lindenbaum, Annual Review of Nuclear Science 11 (1961) 213.

6. J. Baarli, Radiation dosimetry and personal radiation exposure at CERN. DI/HP/8, November 1962.

7. W. K. H. Panofsky, Proposed radiation policies for project M. Stanford report M234, December 1960.

8. G. Cocconi, L. J. Koester and D. H. Perkins, Calculation of particle fluxes from proton synchrotrons of energy 10-1000 GeV. Lawrence Radiation Laboratory UCID-1444 (or UCRL-SS-28-2).

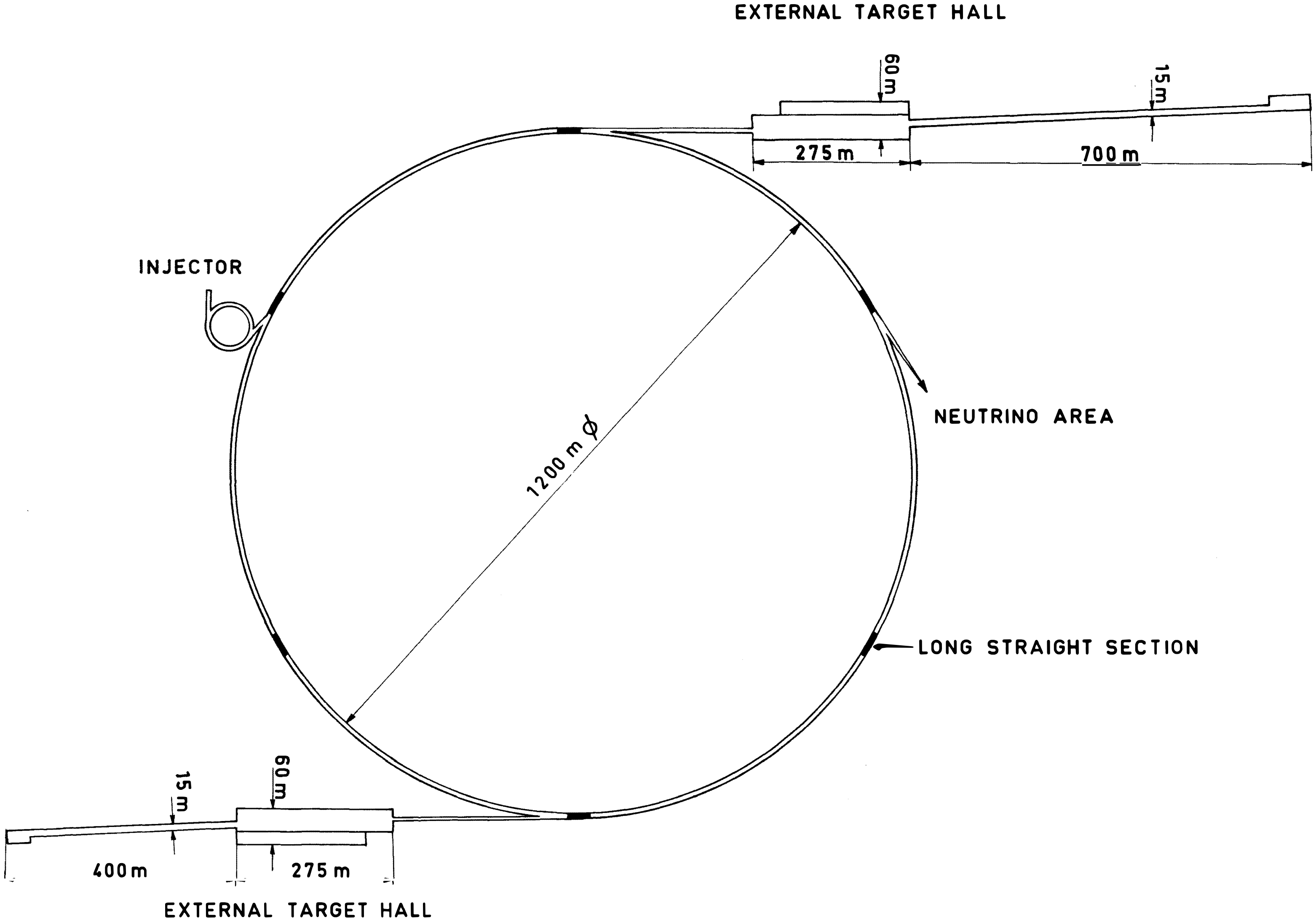
9. E. Keil, Parameters for R.F. separation of π and K at 100 GeV/c design momentum, AR/Int. PSep/62-3.

10. L. Eyges, Phys. Rev. 74 (1948) 1534.

11. G. von Dardel, Empirical formula for the pion production at 20 to 30 GeV bombarding energy. NP/Int. 62-17.

12. B. Hyams, Future program for the CERN PS and the Brookhaven AGS, p. 17
Minutes of a meeting held September 10-14, 1962 at BNL.

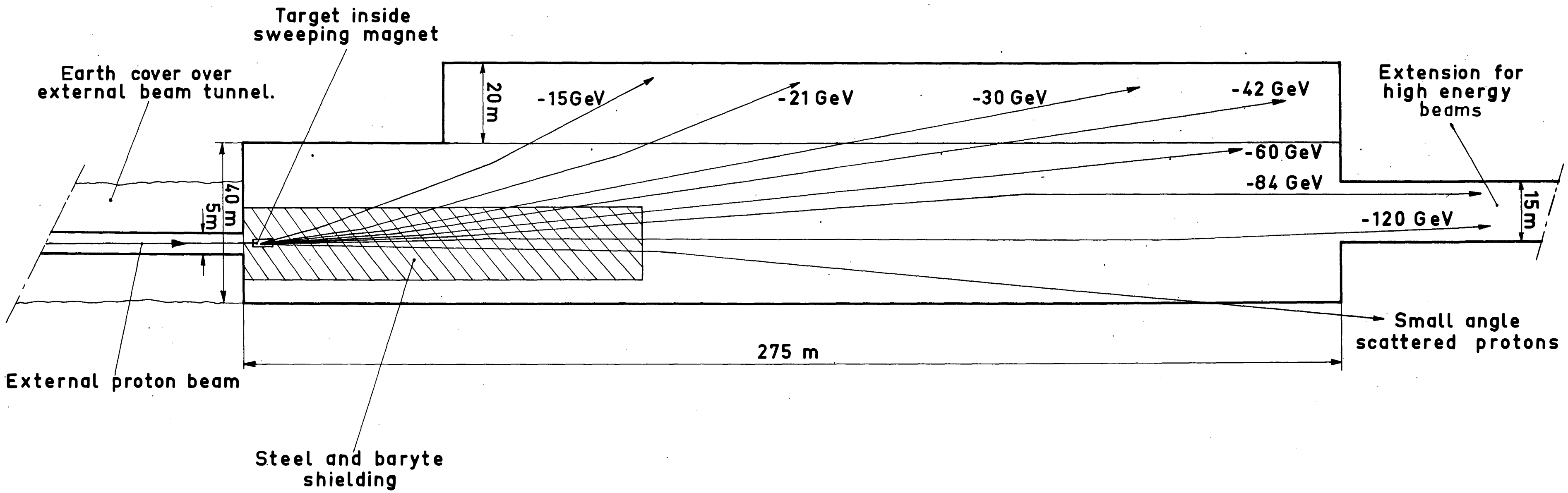
13. A. M. Wetherell, Notes on the measurement of total cross sections
and elastic scattering at energies in the hundred GeV range.
NP Internal report, January 1963.



LAYOUT OF EXPERIMENTAL AREAS FOR A 150 GeV PROTON SYNCHROTRON.

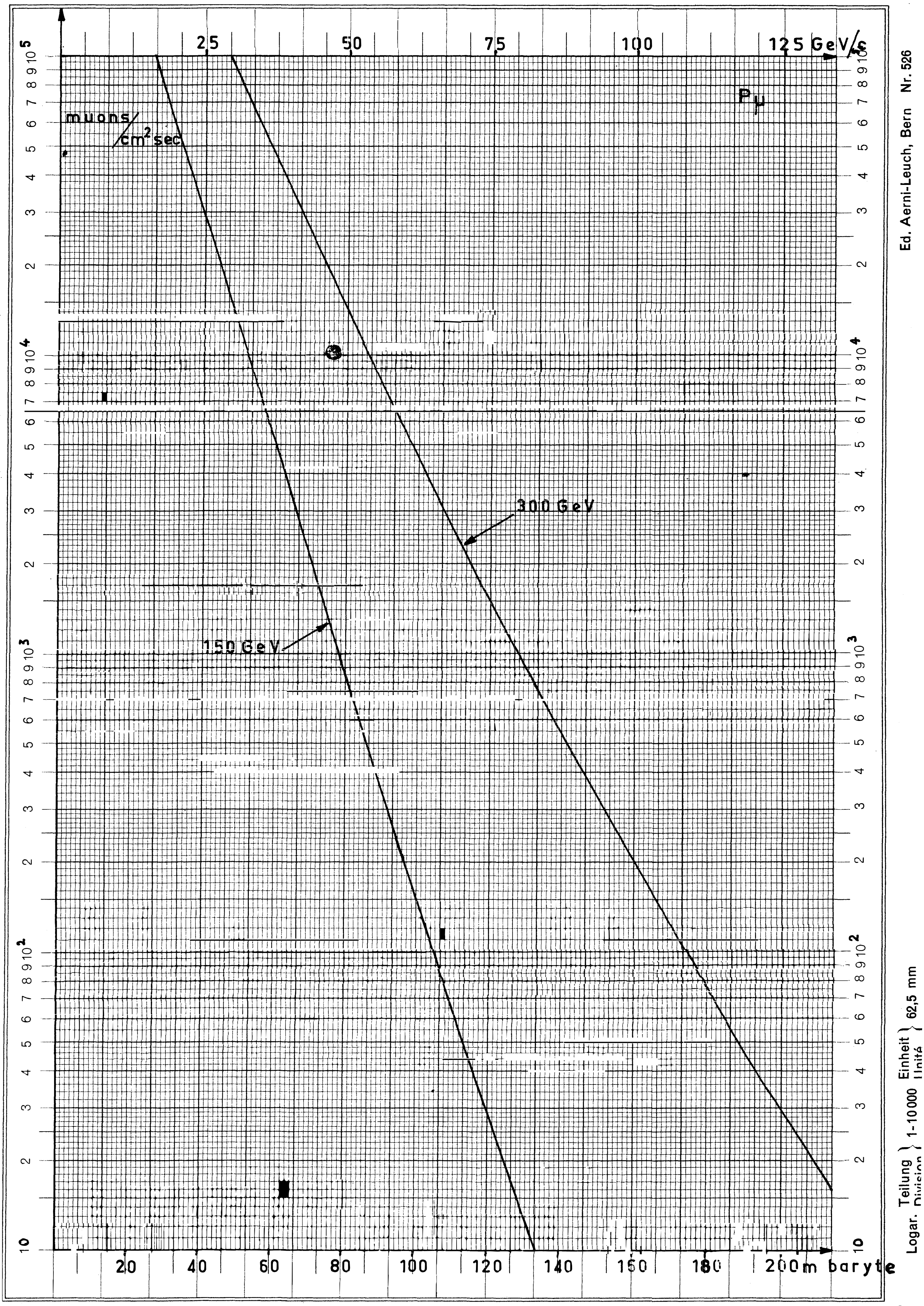
Fig. 1.

SIS/R/5750



LAYOUT OF BEAMS IN THE EXPERIMENTAL HALL OF A 150 GeV PROTON SYNCHROTRON.

Fig. 2.



SIS/R/5751

Fig. 3. MUON FLUX AT VARIOUS DEPTHS IN THE SHIELDING.

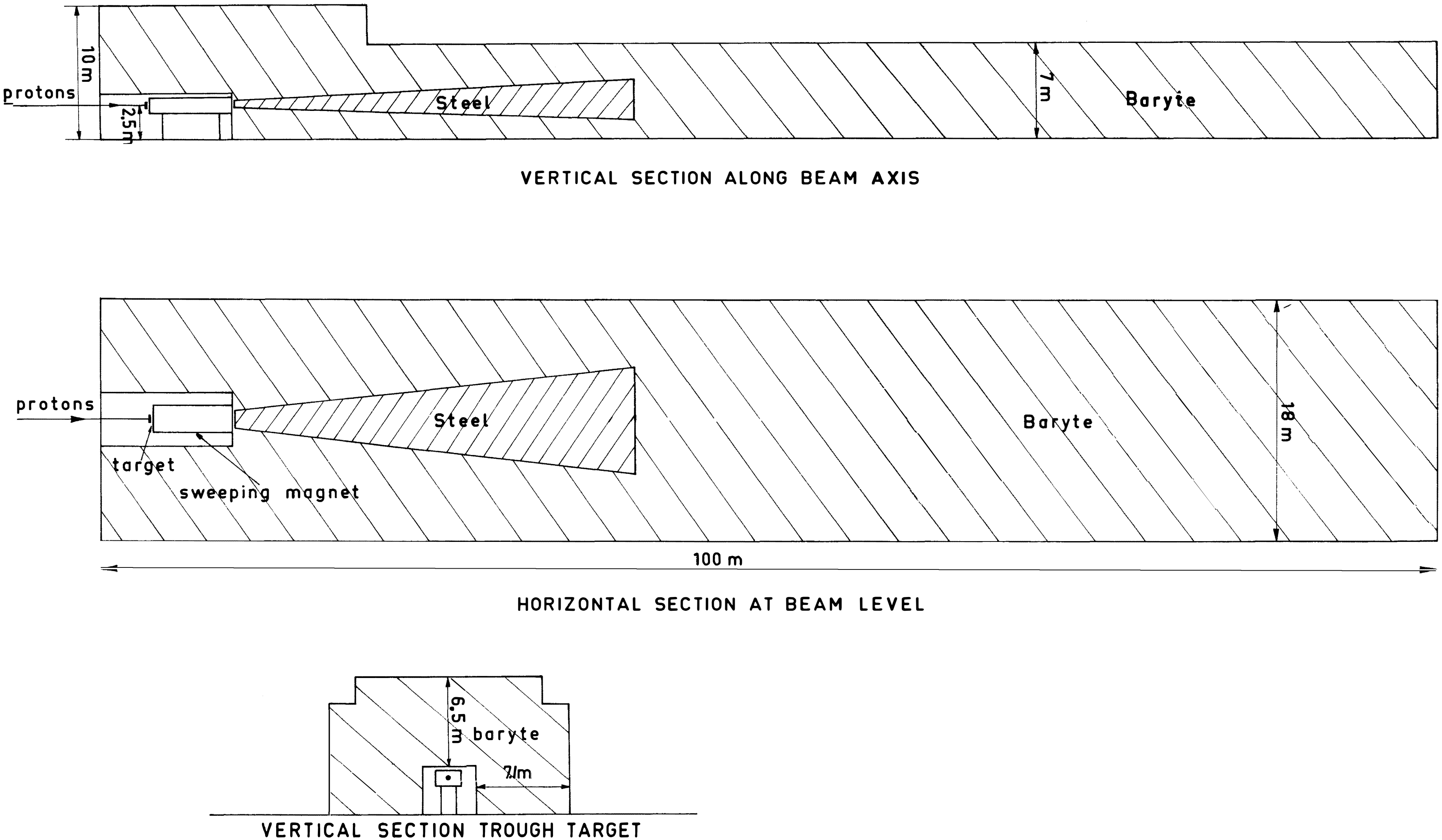


Fig. 4. SHIELDING FOR EXTERNAL TARGET OF A 150 GeV PS.

A.9.

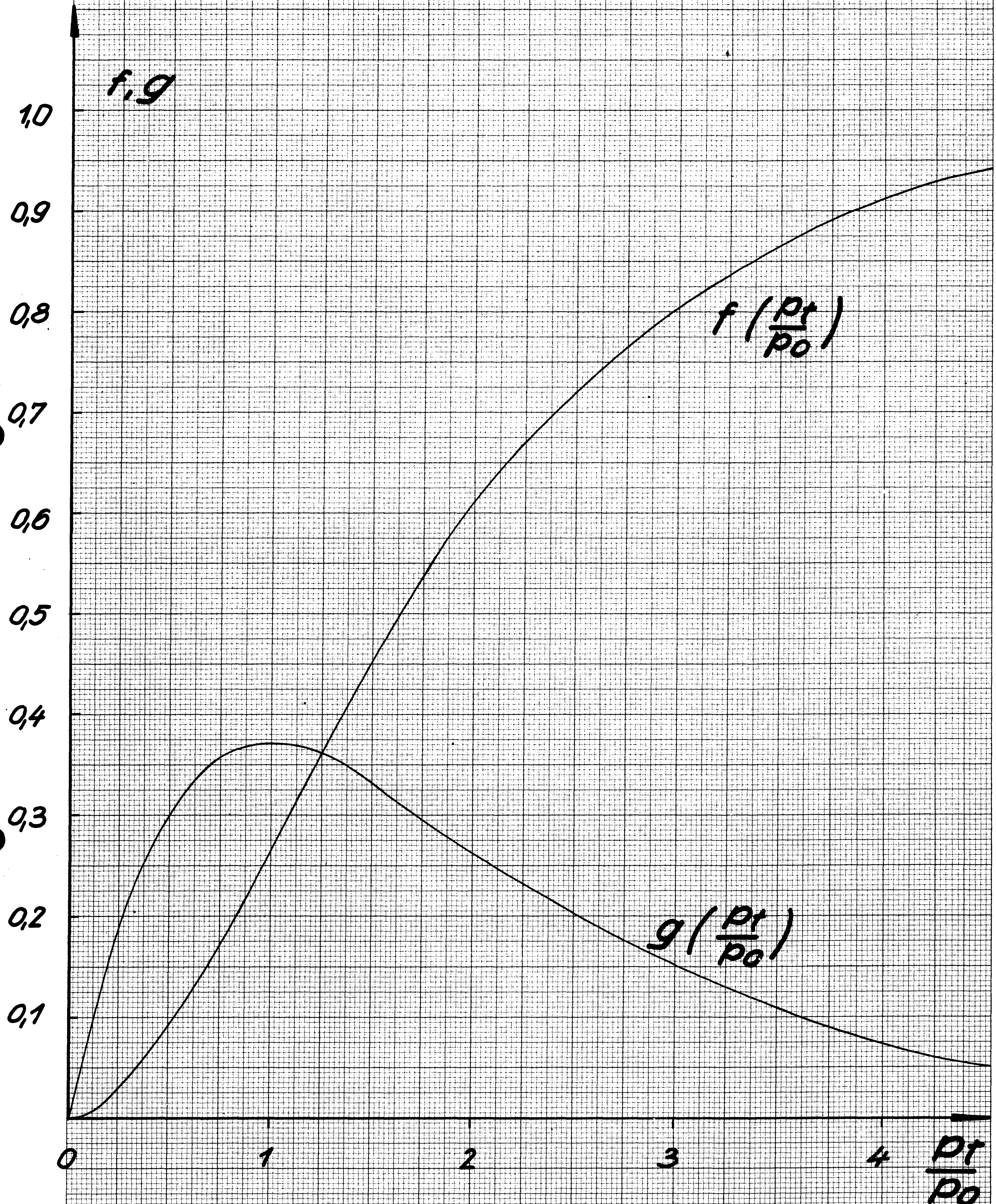


Fig. 5 Dependence of particle flux on the transverse momentum.