EXPERIMENTAL BUILDINGS AND BEAM LAYOUT FOR A 300-GeV PROTON SYNCHROTRON

by

B. de Raad, CERN, Geneva

1. Introduction
2. Internal target operation.
3. Characteristics of external targets.
4. Experimental areas for external targets.
5. Beam layout.
7. Conclusions.

* Paper prepared for the August 1963 Accelerator Conference in Dubna.
1. Introduction.

In trying to design the experimental facilities for a 300-GeV proton synchrotron, one is immediately struck by the following two aspects of this problem.

a) The extreme forward collimation of secondaries.

b) The large buildings and enormous quantities of shielding which are required.

Obviously it is not sufficient just to build movable shielding walls and large halls near the accelerator, but their shape and their position and orientation with respect to the machine must be studied with great care, taking into account everything that can be predicted or reasonably expected about the characteristics of particle production and the type of beam transport systems one is likely to use in the energy range under consideration. A straightforward scaling up of experimental facilities and methods of machine utilisation from lower energy machines may lead to large errors, which are very expensive to correct later.

Experience with existing accelerators shows that at the time of their completion the interesting fields of high energy physics and the experimental techniques are entirely different from those prevailing at the time when the accelerator and shielding design were frozen. Therefore the experimental facilities must have a large flexibility so that they can accommodate entirely new experiments, like e.g. the neutrino experiment for the present generation of 25-GeV machines. Great care must be taken in the design of fixed concrete walls or earth banks for shielding purposes and in choosing the position of other buildings whose presence might limit the possibility to extend the experimental halls. On the other hand the desire for flexibility should not lead to a large increase in the cost of the experimental facilities, since they are already a major item in the budget.

In this paper we shall present some preliminary ideas about machine utilisation which were developed in the course of a design study for a 300-GeV proton synchrotron, carried out at CERN. Unless stated otherwise, numerical examples will apply to the CERN design.
2. Internal Target Operation.

The way in which internal targets are used is familiar from existing accelerators and needs no comments. Various improvements over present practice have been invented during the 1961 Brookhaven design study 2) and have also been summarized by Sands 3). Following these ideas we shall first discuss how the beams from an internal target might look and which difficulties are connected with their use.

In the CERN design the matched straight sections, as proposed by Collins 4), have a total length of 54.3 m, the longest free section being 28.7 m. Fig. 1 shows a possible layout of a matched straight section. Magnets F432 and D1 are the strong focusing magnets in between which the regular machine lattice has been interrupted. Q_D and Q_F are the matching quadrupoles. M1 to M4 form a so-called bending magnet triplet. The magnetic field has the same value in all four magnets. They are pulsed approximately in synchronism with the accelerator magnet units and reach a maximum field of 1.6 Wb/m^2. The polarity in M1 + M4 is the opposite from that in M2 + M3. Therefore the primary proton beam is not disturbed, whereas negative secondaries produced in target 1 are deflected away from the machine. The trajectories shown in Fig. 1 have 0° production angle.

When the polarity of M1 to M4 is reversed, positive secondaries below 150 GeV/c are deflected outwards. Positive particles with larger momenta pass through the stray field of M4 and Q_F and are deflected back toward the machine. For positive secondaries with momenta close to that of the primary beam e.g. diffraction scattered protons, one makes the best use of the matched straight section by placing the target in position 2, since their trajectory then undergoes an outward deflection in the defocusing quadrupole Q_D.

This is a good reason to make the upstream matching quadrupole defocusing, since from the machine point of view there is no preference. It can readily be shown, that this choice also leads to the minimum strength of the septum magnets for ejection. The matching quadrupoles could be made with an open median plane, as shown in Fig. 2 in order to present a minimum obstruction to secondary beams. In Fig. 2 it has been assumed that the quadrupole is made of stamped laminations held together by welding heavy steel strips along their outside, but obviously there are several alternative methods of construction.
The minimum angle at which a diffraction scattered proton beam can be set up is about 2.3 mrad. The 25-GeV diffraction scattered proton beam at the CERN-PS has a production angle of about 20 mrad. According to extrapolations made by A.M. Wetherell (private communication) the differential cross-section \( \frac{d\sigma}{d\Omega} \) \(_{\text{lab}}\) would be approximately the same in the two cases. The acceptance of the 300-GeV beam would be an order of magnitude smaller but this is compensated by the larger primary beam current. This means that the intensity of the 300-GeV diffraction scattered proton beam would be roughly the same as at the CERN-PS.

Although the layout discussed above is certainly usable, it has several limitations and practical difficulties which make it impossible to achieve the most efficient utilisation of the accelerator.

The trajectories of high energy secondaries remain close to the machine over a large distance so that in general it will only be possible to set up one secondary beam above 100 GeV/c. Secondaries below 60 GeV/c leave the magnet M3 by passing the edge AC at a small angle. This leads to aberrations which for typical beams might correspond to an apparent target broadening of the order of 1 to 2 mm. This is already too large for high quality separated beams.

The magnets M2 and M3 as shown in Fig. 1 have a weight of about 350 tons each and together with their power supply and special vacuum chambers represent an expense and engineering effort, which is considerably larger than is needed for a good ejection system.

Since the secondary beams are produced at such small angles, their path in a shielding wall, which is more or less parallel to the machine tends to be very long, say about 100 m. As we shall see in sec. 6, this shielding thickness is required in any case, in order to stop the high energy muons from the decay of \( \pi \)-mesons.

To reduce the muon background, the shielding should be placed as close as possible to the target and have a large density. The first beam transport elements of each beam would then be embedded in the shielding. This makes the setting up of beams a rather laborious procedure, which necessitates long machine shut-downs. Although this can be avoided by the construction of beam sidings \( ^{4} \) these appear to be a rather expensive solution.

The manipulation of large amounts of shielding close to the accelerator is likely to upset its alignment while the structural steel in the shielding (Lindenbaum \( ^{2} \) even proposes the use of steel blocks for muon shielding) will
create magnetic stray fields which lead to orbit distortion at injection.

Due to the expected large intensities and higher energy the induced radioactivity in the target area will be about two orders of magnitude larger than in existing machines. This means that personnel access will have to be restricted and leads to serious difficulties e.g. when it is necessary to carry out modifications to the accelerator vacuum system in order to make new beam exits.

Although with sufficient ingenuity several of the limitations mentioned above can be overcome, there is certainly a strong reason to look for alternative solutions.


The theory of beam extraction from alternating gradient accelerators has been reasonably well developed in recent years and ejection schemes for several accelerators are under construction. The fast ejection scheme, proposed by Kuiper and Plass \(5, 6\) for the CERN-PS has been put into operation in June 1963. Its efficiency is essentially 100 \%/o. The diameter of the focal spot is slightly larger than 1 mm, and agrees with the predictions, based on the characteristics of the circulating beam.

Resonant ejection schemes using linear gradient perturbations have been discussed by various authors \(7, 8\). They have the disadvantage that the rate of spillout is difficult to control. Hereward \(9, 10\) has proposed a resonant slow ejection scheme using a non-linear lens (quadrupole and sextupole). After the R.F. voltage has been switched off the beam debunches automatically. By changing the magnetic guide field the beam is then steered slowly into the unstable region of the non-linear lens. Protons with different betatron amplitudes become unstable at different mean radial positions so that the duration and smoothness of the beam spillout is essentially determined by the accuracy with which the slope and magnet ripple during the flat top can be controlled. The tolerances are tight but it looks possible to meet them if the power supply is designed with this requirement in mind from the start. We believe therefore that a slow ejected beam with a duration of about 0.5 sec can be made.

The required strengths of the special magnets for ejection at 300-GeV are only 2 or 3 times larger than at 25 GeV, since the betatron wavelength is also
longer and the septum magnets can be placed at the upstream end of a long matched straight section. The calculated efficiency of Hereward's proposal is 78 o/o. The author has worked out a slow ejection scheme for a 300-GeV machine, which has a calculated efficiency of 90 o/o. Some proton trajectories through the exit channel are shown in Fig. 3. It has two septum magnets SM1 and SM2 in series with septum thicknesses of 1 mm and 9 mm respectively.

It is often desirable to share the beam between different experimental areas. One possibility is a beam splitter in the ejected beam. This might absorb some 5 to 10 o/o of the protons. In an accelerator with 12 matched straight sections it is always possible, of course, to eject part of the beam at one place during the first half of the flat top and the rest later somewhere else. This procedure has the disadvantage that the maximum counting rate does not decrease when the total number of protons attributed to an experiment is reduced. It looks quite possible, however, by choosing a suitable Q-value and betatron phase shifts in between the experimental areas, to use a single non-linear lens to excite the betatron oscillations but to share the protons simultaneously between two septum magnets at different azimuths and with the appropriate radial positions.

To estimate the dimensions of the target we shall assume that the beam radius at injection is 20 mm and has been reduced to 3 mm at 300 GeV by adiabatic damping of the betatron oscillations. The maximum angles in the beam are then about 0.07 mrad. The acceptance (maximum angle x maximum displacement) of a target with radius \( r \) and length \( L \) is \( 2r^2/L \). For a high density target, like tungsten, 1 n.m.f.p. might be about 0.1 m. Its acceptance will therefore be equal to the emittance of the ejected beam for \( r = 0.1 \) mm. The maximum angle in the beam is then 2 mrad. Two quadrupoles with a length of about 5 m and aperture 8 cm are required to focus down the beam. The opening angle of secondary beams can be expected to be a few mrad. , so that for beams produced at 0° the apparent target broadening is only a few tenths of mm. It appears therefore that an external target with an effective diameter, as seen by the secondary beam, of about 0.5 mm is feasible. For beams produced at an angle only the apparent horizontal target size increases so that the vertical plane can still be used for precision optics.
Due to self-absorption of secondaries in the target there is an optimum target length which gives a maximum yield. If we neglect tertiaries and assume that an interacting secondary is effectively lost we find that the optimum length is 1 n.m.f.p. and the efficiency \( e^{-1} = 37 \% \). Combined with a 90\% ejection efficiency we find an overall target efficiency of about 33\% which is quite comparable to that of internal targets.

We conclude therefore that from the point of view of the experimentalist external targets have about the same performance as internal targets. In addition they give a much larger flexibility since the target is accessible from all sides, including the 0° direction. This makes it possible to set up beam channels which collect a much larger (say 10\% to 20\%) fraction of the secondaries than with internal targets. It is also possible, to build around the target special focusing devices with large collection efficiencies (possibly superconducting) similar to the magnetic horn 11 designed by van der Meer.

It is obvious, that in particular p-p scattering experiments can be done much better with external targets. The beam size and angular divergence (within the limits of Liouville's theorem) can be adapted to suit the experimental geometry. In large angle scattering experiments it is desirable to detect both the scattered and recoil proton. With internal targets this would require a special small experimental area on the inside of the accelerator ring, but with external targets this presents no problem at all.

4. Experimental Areas for External Targets.

From the discussion in the foregoing sections we conclude that external targets are nearly always preferable to internal targets. The optimum location of the experimental halls and the shielding design are quite different in the two cases and therefore it is difficult and expensive to design experimental areas which are suitable for both types of targeting. We propose therefore to use the 300-GeV machine with external targets only.

There are 12 matched straight sections and in most of these the ring tunnel has a small exit through which an ejected beam can pass. As shown in Fig. 4 we envisage to start operation with two experimental halls and a neutrino area.

While beams and detectors are changed in one hall, experiments can be made in the other hall, but the accelerator itself need never be stopped to change over.
from one experiment to another.

The size of the experimental halls is $60 \times 400 \text{ m}^2$. At the downstream end we have foreseen a 1000 to 2000 m long and 15 m wide extension for an R.F. separated beam. This extension need not necessarily be a building, since it contains only the quadrupoles which keep the beam together in the drift space in between the two separator cavities. In a suitable climate the quadrupoles could be in the open air. Obviously the experimental halls must be placed at such a position, that a minimum amount of earth shifting is required for the long extensions.

a site for

Preliminary investigations have shown that a 300-GeV accelerator which is flat and horizontal within a few metres, is almost impossible to find. One could imagine therefore that at the bottom side of Fig. 4 the ground level is reasonably flat so that the experimental areas would be concentrated there. The other side of the accelerator could pass through a hill in which one could make a tunnel and cave for a neutrino experiment, since this needs a large amount of shielding anyhow. If the ground level is horizontal in only a very limited part of the site, one could eject the proton beam at only one place and divert it into different halls by means of a beam switchyard similar to that of the 2-mile Stanford electron linac.

The distance from the point of ejection to the entrance of the experimental halls should be of the order of 500 m in order to allow a sufficient freedom to manipulate the external beam. As mentioned above, one may want to blow up the beam and then focus it down onto a small target or otherwise shape its emittance to suit specific experiments. It may also be desirable to deflect the beam sideways onto different targets, belonging to different beams or to apply an R.F. deflection to the proton beam which sweeps it across a target in order to decrease the total length of an R.F. separation scheme (private communication B.W. Montague).

For shielding purposes the accelerator must be covered with about 10 m of earth and in order to stop the energetic muons (see sec. 6) which are produced tangentially to the accelerator ring, the beam level should also be about 10 m underground. In fact, on a rocky site the most economical method of construction may well be to blast an underground tunnel in the rock. On the other hand, the experimental areas should preferably be at the surface in order to avoid large
excavations and to facilitate future extensions. This can easily be achieved by deflecting the ejected beam upwards after it has left the accelerator tunnel.

5. Beam Layout.

An external target gives accessibility from all sides, but the forward collimation of secondaries remains. As is well known, their average transverse momentum is about 0.4 GeV/c, independent of their longitudinal momentum and independent of the primary proton energy. At 40 GeV/c about half the particles are found within a cone with a half opening angle of 10 mrad.

We propose therefore, to place the target at the entrance of a sweeping magnet, which might be 10 m long, with a magnetic field of 1.6 Wb/m². Secondaries of different momenta 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 look "head on" at the target which then has a diameter of about 0.5 mm. A 25-GeV/c particle is deflected over 11° so that the angular range available to set up beams is about equal to what is used for good intensity beams at the CERN-PS. For equal outside dimensions and gradients (limited by steel saturation) the focal distances of the quadrupoles are larger than at the CERN-PS due to the higher particle momenta. Therefore the first quadrupole of a beam is necessarily placed at a larger distance from the target which makes it possible to set up more simultaneous beams, with particles of both polarities, than at the CERN-PS.

In this scheme there is a rather close relation between direction and momentum of the secondary beam and each beam channel covers a momentum band of only about ± 10 c/o. Of course the central momentum of all beams can be changed simultaneously by the same factor by varying the field of the sweeping magnet.

A possible beam layout, based on this principle is shown in Fig. 5. The target is located at the entrance of the experimental hall, rather close to the right hand side wall (looking in the beam direction) so that one would work mainly with secondaries that are deflected to the left by the sweeping magnet. From Fig. 5 we see that by a convenient choice of bending angles beams can be directed into nearly all parts of the experimental hall but, of course, not all these beams will exist simultaneously. The choice of the best location and
direction of the R.F. separator extension requires a more detailed study. In Fig. 5 we have assumed, that negative secondaries 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 can therefore be varied most conveniently by changing the field of the sweeping magnet. A large deflection is necessary in order to obtain a momentum resolution which is adequate to study structure in the momentum spectrum of the scattered protons \(^{14}\).

To avoid interference with other beams we have chosen a deflection to the right which causes the beam to leave the building. This would not be necessary but it suggests that it is desirable to foresee the possibility of constructing along the right hand side wall of the building a sort of apron where simple beams could be set up in the open air. This would also make it possible to derive from the target parasitic beams for the testing of apparatus located in temporary shacks on the apron.


The magnitude of the shielding problem is illustrated best by noting that with an average intensity of $10^{13}$ protons/sec the beam power is 0.5 MW. This is about the same as for the 2-mile Stanford electron linac but in our case the situation is much worse, since the range of the muons in the shielding is an order of magnitude larger. Therefore the design of shielding and collimators will be an important part of each experiment and much more work on shielding is indicated. In this paper we shall restrict ourselves to an approximate estimate of the quantities of shielding that are required.

Following the procedure used by Lindenbaum \(^2\) we find, that the shielding walls on the side and the roof above the target should have a thickness of about 7.5 m and 7 m of baryte ($\rho = 3.5$ g/cm\(^3\)) respectively in order to reduce the background in the experimental hall to about $\frac{1}{3}$ of tolerance. In the forward direction a thickness of about 15 m baryte would be sufficient.

To estimate the muon flux we assume that a target of 1 n.n.m.f.p. is placed in the beam, so that the high energy muon flux corresponds to $3.5 \times 10^{12}$ interacting protons. We assume that there is a drift space of 2.5 m in which the $\pi$-mesons can decay before they are absorbed in collimators. This appears to be an absolute minimum if several beams are operated at the same time from one target.
The fraction e^{-1} of the primary beam surviving after the target can be dumped in a block of heavy material with negligible extra muon production.

The sweeping magnet deflects the π-mesons over an angle which is proportional to their momentum. The average muon momentum is 0.8 times the π-meson momentum and their range in the shielding is approximately proportional to momentum. Therefore all muons at the end of their range have a transversal displacement, due to the sweeping magnet, of about 6 m, which is independent of their momentum. The maximum lateral spread of the muons, due to the π-meson production angles and multiple scattering is about 5 m, again rather independent of their momentum. Therefore the shielding block in front of the target must have a width of about 22 m.

Using the formula for π-meson production proposed by Cocconi et al. 15) we then find that a total baryte thickness of 180 m, corresponding to a muon cut-off momentum of 126 GeV/c is required, to reduce the muon flux to the tolerance level of 20 muons/cm^2/sec. The length of baryte can be reduced by placing an iron cone in the path of the most energetic muons. Since 1 m of iron has the same stopping power as 2 m baryte, a 45-m long iron cone would reduce the total shield length to 135 m. This is the shielding layout shown in Fig. 6. It contains 4000 tons of steel and 90,000 tons of baryte.

When confronted with the need for such large quantities of shielding, one starts to look around for other methods to get rid of the muons. The most obvious approach is to make a horizontal magnetic field which deflects the muons down into the earth or up into the air, depending on the sign of their charge. From a preliminary investigation of this idea we feel that it may be interesting for specific experiments but is not suitable for a general purpose beam layout. Moreover it is not easy to make such a system absolutely fail-safe. The use of earth banks for shielding purposes is unacceptable, since it takes away all flexibility in the beam layout. On the one hand the shielding design outlined above can certainly be improved, but on the other hand we have not allowed for any extra manipulation of the external beam, like the use of different targets, located side by side or the refocusing of the external beam on a second target. We believe therefore that the amounts of shielding quoted above are of the correct magnitude.

The first quadrupoles and momentum analyzing magnets of most beams will be
embedded in the target shielding. This has the advantage that the off-momentum particles rejected from the beams are also absorbed in this shielding. It also means that excellent handling facilities for the shielding are required in order to change beams in a reasonable time. For the purpose of illustration we shall assume that there are two cranes of 50 tons each and that most of the shielding is made of 40-ton blocks. If a crane needs 5 minutes to displace a 40-ton block, the complete pile of shielding can be demounted in 100 hours.

In Fig. 5 we have assumed that the target shielding is located completely inside the experimental hall but since one is not likely to place detectors very close to the target and since a pile of shielding can very well stand in the open air, it may be more profitable to place the experimental hall a reasonable distance (say 100 m) downstream of the target. More detailed study is required to settle this question.

After this discussion it may be easier to appreciate the difficulty of designing a suitable target area and movable shielding walls for internal targets, since the muon shielding problem is essentially the same for internal targets. The radioactivity induced in the shielding around the target will be very large, but we feel that external targets leave a large degree of freedom to devise special remote handling techniques. With an extraction efficiency of 90%, the induced radioactivity in the accelerator itself has been reduced by an order of magnitude. The septum magnets of the slow ejection system will become very radioactive and special provision must be made to exchange them rapidly in the event of breakdown.

7. Conclusion.

We have shown that external targets provide the beam quality and flexibility which is necessary for efficient exploitation of a 300-GeV proton synchrotron. By placing the target in front of a sweeping magnet the secondary beams are fanned out laterally over an angle of about 10° so that at least as many beams can be derived from the same target as in present 25-GeV machines. The forward shielding required to stop the muons has a thickness of about 150 m.

Acknowledgement.

I wish to thank Drs. K. Johnsen, W.C. Middelkoop, L. Resegotti, A. Schoch and C.J. Zilverschoon for stimulating discussions.
References.

1. K. Johnsen et al., The CERN design study for a 300-GeV proton synchrotron. Paper prepared for this Conference.


6. B. Kuiper et al.: Experience with the fast ejection system of the CERN-PS. Paper prepared for this Conference.


9. H.C. Horwitz: The possibility of resonant extraction from the CFS. CERN/AR/Int. SG/63-5.

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


15. G. Cocconi, L.J. Koester and D.H. Perkins: Calculation of particle fluxes from proton synchrotrons of energy 10 - 1000 GeV.

Fig. 2. ONE QUADRANT OF A MATCHING QUADRUPOLE WITH OPEN MEDIAN PLANE.
Fig. 3. ENVELOPE OF SLOW EJECTED BEAM (AB) AND TRAJECTORY C JUST GRAZING THE SEPTUM.
FIG. 4. LAYOUT OF A 300 GeV PROTON - SYNCHROTRON

CERN 25 GeV PROTON SYNCHROTRON
(TO SCALE)

NEUTRINO AREA
LONG STRAIGHT SECTION
BOOSTER INJECTOR
EXTERNAL TARGET HALL
LONG SEPARATED BEAMS
POSSIBLE EXTENSION FOR SEPARATED BEAMS

Φ 200m
Fig. 5. LAYOUT OF BEAMS IN THE EXPERIMENTAL HALL OF A 300 GeV PROTON SYNCHROTRON.