REPORT ON THE CERN 300 GeV STUDY

K. Johnsen
CERN, Geneva (Switzerland)

I. INTRODUCTION

Since the autumn of 1961, when the CERN Council set up, within the Accelerator Research Division, a special Study Group for New Accelerator projects, this group has concentrated its effort on two large projects: a proton synchrotron of several hundred GeV and a set of proton storage rings for the CERN-PS. In this paper we shall report on that part of the Study Group activity that has been concerned with the large synchrotron.

With the great success of the AG principle since its invention 15 years ago, and with no sign of the largest present day machines being near to the limit of the applicability of this principle, it has become natural to base also the design of the next generation of accelerators on the same principle. Several early studies, in particular the one at Brookhaven four years ago (1), found such machines feasible at least up to 1000 GeV. Our study has confirmed this view.

Other accelerator ideas that have emerged during the last ten years have either not been sufficiently promising to compete with the more conventional AG design or have been based on technology that is not sufficiently well advanced to be applied on a very large scale at this time.

Accelerator designers both in Europe and USA have, therefore, concluded that the design of a several hundred GeV accelerator to be constructed within the next decade should be based on conventional steel magnets with alternating gradient focusing. This, however, is far from being only a scaled-up version of present machines. On the contrary, such a machine will contain a series of new ideas and improvements in the various parts by which the performance of the accelerator will be improved and its cost reduced as compared with simple scaling. Some have emerged because of the higher energy and higher intensity compared with existing machines, some are the results of the experience gained in the construction and operation of the CPS and the Brookhaven AGS, and some are the results of the advance in technology over the last ten years.

In carrying out such a study it is necessary to fix from the start certain basic aims that the design has to fulfil, in particular with regard to energy and intensity. The design energy has been taken as the one recommended in the Amaldi Report, i.e. 300 GeV. In recent years intensity has become almost as important in the discussion of experimental possibilities as energy. It has therefore been the aim of the Study Group to make a design that would allow a high proton current, but still without requiring extreme solutions. After some study it was concluded that the design should be made such that all essential components would handle a beam current of about $10^{13}$ protons/sec, which, with the repetition rate arrived at, means about $3 \times 10^{13}$ protons/pulse at full energy. It should be noted that although we think that the design presented in this report will ultimately meet this requirement, it will be a difficult task that may not be achieved during the initial period of operation. The design aim is much nearer to inherent limitations than was the case in past accelerator designs. The 1953 design figure for the intensity at the CPS was a factor 200 lower than the level corresponding to the design figure for the 300 GeV machine. The latter level was reached in the CPS after 4 years of operation.

Although the aim will be to produce $10^{13}$ protons/sec, this would put unreasonable requirements on the design if we permit all particles to interact inside the machine. Since it has been found reasonable to assume a general use of external targets the average particle loss inside the machine will be restricted to $2 \times 10^{11}$ protons/sec, losses on ejection devices etc. included. Consequently, only limited internal target facilities are proposed in the present design.
When it comes to the machine itself, there is a number of design choices to be made that depend strongly on such things as: the state of certain technological advances at the time decisions have to be made; the time one may expect to have at one's disposal for further development before designs are frozen; the experimental physics requirements, which may change with time; and even the choice of the site. Since there will still be some time between now and the placing of orders, many of the choices made should be considered open for future revision. In most cases we have chosen to present the solution that we would adopt if we were to go ahead at once. This means that often the solutions presented are conservative ones. In order to arrive at an optimum overall design some of the individual components, regarded independently, may not appear to be optimum. As an example can be mentioned the booster synchrotron.

With the decision to use ordinary steel magnets the diameter of such a machine scales approximately proportional with energy. We have arrived at a diameter of 2400 m. The transverse dimensions change very little with energy. They should in principle increase a little as the energy goes up. Taking advantage of the experience gained on the CPS and the AGS and the better understanding of orbit behaviour it has been possible to reduce the cross section as compared with existing proton accelerators, and we are basing the design on an aperture requirement of 6 cm × 9.5 cm. About half of this aperture will be occupied by the beam, the remainder being taken by various errors in fields and alignment.

II. SUMMARY DESCRIPTION OF THE MACHINE

There is no time to go into the technical details of our design, but reference can be made to our Design Study Report issued late last year (2). The general magnet lay-out is shown in Fig. 1. The steel core of each of the 864 magnet units will be about 6 m long. 29000 tons of steel sheet and 2100 tons of copper will be required for the main magnet. The stored energy will be 72 MJ and the dissipation will be 26 MW.

The main correcting devices for the magnet will be 72 quadrupoles, 144 sextupoles and 72 octupoles. The octupoles will also have windings to provide for a skew quadrupole field.

The alignment system of the magnets is based on geodetic methods, and largely on precision length measurements by invar wires with minimum use of theodolites to avoid refraction in the air.

We plan on a magnet cycle as follows:

| Injection time | 0.6 s |
| Front porch    | 0.1 s |
| Rise time      | 1.0 s |
| Flat top       | 0.7 s |
| Fall time      | 0.8 s |
| Rest time      | 0.1 s |
| Cycle          | 3.3 s |

This choice is a compromise between the obvious gain in average intensity with increasing repetition rate and the problems that arise in the design of the various machine parts when a short cycling time is specified.

The main power supply, which has to provide a peak power of 180 MW and a magnet dissipation of 26 MW, will consist of two centrally placed motor-alternator sets and 12 rectifier stations at equal intervals round the ring.

The r.f. requirements for a 300 GeV accelerator are very different from those of existing machines. It was natural, therefore, that a number of proposals for novel solutions have come up during the last few years. After having looked at the four possibilities:

- Ferrite tuned systems;
- Mechanically tuned cavities;
- Fixed frequency, phasejump system, and;
- Wide-band untuned systems, we favour at present the last one for the main ring.

A separate paper on this subject has been presented to the Conference (3).

From the experience on all machines built so far it looks as if one can hardly overemphasize the usefulness of much beam observation equipment in an accelerator. We shall install 216 pick-up stations, each containing both radial and vertical electrodes, around the machine, i.e. 8 per betatron wavelength. There is, however, space for doubling this number if the need arises.

There will further be electrodes for observation of the circumferential distribution of the beam. The bulk of the beam observation system will be designed for a minimum threshold intensity of 10^9 particles per pulse. However, individual pick-up stations, especially the ones driving the beam control system, can be equipped in such a way that they remain usable for intensities down to the order of 10^7 particles per pulse.

The vacuum requirements for this machine are not very severe. A pressure of 10^9 torr would be sufficiently low. Nevertheless it has been decided to design the vacuum system for a pressure of 10^-7.
Fig. 1 - Layout of a 30° machine sector.
torr in order to obtain a reasonable lifetime of the titanium sputter ion pumps, which are considered the best for the purpose.

The vacuum system will be designed with metal gaskets to avoid radiation damage. The design of the vacuum chamber will be appreciably influenced by the requirement that all operations on the system must be carried out without exposing the personnel to high doses of radiation.

The injection problems and the choice of a suitable injector warrant careful attention. The CERN Study Group presented a special paper on this subject to the International Accelerator Conference two years ago (4), and the conclusions arrived at then have governed the further study. At present we favour as an injector a fast cycling synchrotron of 8 GeV, fed from a linear accelerator of 200 MeV. The repetition frequency of this booster synchrotron will be 20 Hz and 12 pulses are needed to fill the main ring.

The r.f. system constitutes one of the most difficult problems in the booster design and has received special attention by our Study Group. A mechanically tuned system for the range 100-180 MHz has been tested in the laboratory and has given encouraging results, in particular after the insertion of a special air bearing for the tuning piston. Figure 2 shows a laboratory model of a mechanically tuned cavity.

Although it is believed that such a booster will be a very good injector, we still plan to reconsider certain aspects of this part of the project. The choice of linac energy has largely been governed by the fact that the well-tried Alvarez structure was known to become rather inefficient above about 200 MeV. With the invention of new structures believed to have better performance in the 200-400 MeV range (5), there are good reasons to increase the linac energy somewhat, in order to improve on the space charge limit.

Although an injection time of 0.6 s is not a large fraction of the total cycle it would be an undeniable advantage to reduce it if it could be done without losing other advantages. The possibility of a slow-cycling booster with very large acceptance has been mentioned by several people, and we have started studying this. So far this has given as a by-product a proposal by Hardt for a special circular injector for the CERN-PS (6) whereas a similar possibility for a 300 GeV has so far not been found economical. However, this will be studied further.

I would then like to make some remarks about radiation protection in such a machine. The calculations of the roof shielding of the accelerator are based on the design intensity and on the internationally accepted mpd of 2.5 mrem/hr just outside the shield, but with an overall safety factor of about 10 due to uncertainties.

We have assumed that internal target or ejection magnet would absorb at most 20% of the circulating beam and that at any point in the rest of the ring the beam loss would not exceed 0.6% of the circulating beam.

It is difficult to make accurate shielding calculations by starting from first principles like angular distributions of secondaries etc. We think that it is preferable to base oneself on measurements of the radiation level on top of an existing accelerator, like the CPS and then to assume a build-up factor proportional to energy. This should give results which are slightly on the safe side. Using data from a shielding experiment on top of the CPS tunnel (7), and extrapolating with a removal mean free path $\lambda = 130$ g/cm$^2$, we find a thickness of 1650 g/cm$^2$ above the major part of the tunnel and 1940 g/cm$^2$ above internal targets and other hot spots.

Muon shielding presents a special problem, since the high current of the accelerator leads to a

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Fig. 2 - Model of a mechanically tuned cavity for the booster synchrotron.
copious production of muons, which can only be suppressed by shields whose thickness exceeds the range of the muons. If the beam of the accelerator is 10 m or more underground, the dose rate at the ground surface due to muons from the accelerator is below tolerance. In the experimental areas the shielding thickness must be sufficient to stop all muons with momenta below about 120 GeV/c in order to reduce the dose rate at the shield surface below tolerance. In order to achieve this aim with the minimum volume of shielding a detailed study of muon orbits downstream of targets, including the effects of secondary beam magnets, will be an integral part of each experimental layout.

The induced radioactivity levels in quiet sections of the CPS, a few hours after shutdown, are about 0.5 mrem/hr behind the yokes and 5 mrem/hr just in front of the coils. Downstream of internal targets these figures are between one and two orders magnitude larger. If internal targeting is limited to 20% of the beam, the activity levels in the 300 GeV machine should be about 10 times larger than in comparable locations at the CPS. To facilitate machine maintenance one should therefore make a large effort, by measuring beam loss with detectors all around the ring and straightening out closed orbit bumps, to limit the random beam loss and to concentrate all induced activity at a few hot spots, like targets and scrapers, which will have to be serviced with manipulators anyhow. One can also ask if the induced activity could be reduced by an appropriate choice of construction materials. Since little can be done about the constituents of the magnet, we have studied possible improvements due to changes in the concrete composition (8). Measurements showed, that in places which are shielded from the vacuum chamber and magnet poles, e.g. behind the yoke of a magnet unit, about 2/3 of the dose rate during the first two days after CPS shutdown comes from the tunnel wall. The dominant components in the radiation from the concrete is due to Na\textsuperscript{23}. This was found by measuring \( \gamma \)-spectra and decay curves of concrete samples from the tunnel wall. By irradiating samples of concrete and concrete constituents without and with thermal neutron shields of cadmium and a boron containing mineral (colemanite) it was found that in the CPS concrete, which contains 0.79% elemental Na by weight, about 2/3 of the Na\textsuperscript{23} activity produced by thermal neutron capture in Na\textsuperscript{23}, while the remaining 1/3 is produced by fast particle reactions in Si, Al, Ca and Mg (in order of decreasing importance). We also irradiated, at various places along the tunnel wall, samples of CPS concrete and concrete from the Brookhaven AGS. The latter contains only 0.06% elemental Na by weight. The average Na\textsuperscript{23} activity of the CPS concrete was only 2.7 times larger than that of the AGS concrete. Therefore boron loading of the concrete to absorb the thermal neutrons will reduce the dose rate in the first two days after shutdown by only a factor 2 and if one can find a concrete with a Na content which is less-than half that of the CPS concrete, boron loading would hardly have any effect at all.

III. EXPECTED PERFORMANCE

At this stage it is worth while to sum up the performance estimates and the inherent limitations. It is estimated that the transverse space charge effect at the injection into the booster is at present the limiting factor giving 2.7 \( \times \) \( 10^9 \) p/pulse in the booster or 10\( ^9 \) p/s out of the main ring at top energy. However, already to obtain this means that certain difficulties must be overcome, in particular the one of artificially increasing the bunching factor to about 1/4.

As mentioned, increased linac energy would improve on this space charge limit. The transverse space charge limit at 8 GeV in the main ring is estimated to be nearly a factor two above the figure quoted above.

Dissipate transverse instabilities may show up, but it is believed that they can be damped by a Q-spread introduced by the excitation of the octupoles and also by a feed-back. Such feedback has been used successfully on the Cosmotron (9) and with rather less clear results on the CPS. Both the octupole method and the feedback method are in use on the Princeton-Stanford storage rings (10).

Longitudinal space charge effects are also expected to cause some difficulties at transition in both rings, and such gymnastics and filamentation may be necessary at some convenient time before transition, to reduce the longitudinal phase-space density.

Further, the problem of creating and injecting the linac current required to reach 10\( ^9 \) p/s should not be underestimated. About 100 mA is required from the linac to reach this intensity by single turn injection into the booster. With the progress of multturn injection into the AGS this should certainly also be considered as an alternative.

Although the estimates indicate that 3 \( \times \) \( 10^9 \) p/p is feasible, this is in the intensity range where detailed knowledge and understanding of the phenomena are lacking and few experimental facts are available; which means that no guarantee can be given that this design aim will be reached.
IV. GENERAL LAYOUT, EXPERIMENTAL AREAS

An example of a machine layout is shown in Fig. 3. The layout of the machine will depend on the topography of the site. Since a site has not yet been chosen, we have made the layout study for a hypothetical site satisfying the specifications laid down for the present search for a site in Europe. Although the real site, and therefore also the layout, can be quite different from this hypothetical one, it is believed that the study of this example has resulted in a realistic feeling for the problems and the magnitude of the civil engineering work involved.

Most of the sites considered are on good rock. In the example it is assumed that the characteristics of the site and the quality of the rock make tunnelling for the whole machine the most economical solution.

The tunnel cross section is approximately 5 m × 5 m and set deep enough that the thickest roof shielding required (11.4 m of earth equivalent) exists even at the lowest points. Twelve main access points are foreseen for heavy equipment and further 24 secondary access point for personnel, light equipment and cables. Equipment buildings on the surface are attached to each access point. A similar tunnel is foreseen for the booster. The main control centre is placed in the neighbourhood of the linac and the booster which brings it near the centre of gravity for the controls.

We have assumed that three experimental areas will be in use during the first few years of operation. Area A is foreseen as the major ejected beam area. Both experimental considerations and the requirement of keeping induced radioactivity problems to a minimum have convinced us that most of the experimentation will be done with ejected proton beams. We therefore consider area A as the major experimental area for the project. Its experimental halls have a floor area of 30,000 m². This, however, is not determined by experimental considerations only but by the floor space needed for constructing, assembling and testing the components of the accelerator. The hall is supposed to be on the surface, fed
through an upward sloping tunnel and an open apron.

Area B is planned initially to be for a limited use of internal targets. For reasons of economy and in view of the secondary importance attached to internal target operation it is made of an open-air apron (with portable sheds if the climate requires it) and a 7.5 m wide beam tunnel providing space for up to three simultaneous secondary beams. It is foreseen that this area will be developed later into an external beam area.

Area C is foreseen for specialised experimentation requiring heavy shielding against machine and cosmic background (e.g. neutrino experiments). The hall at the end of the 600 m long tunnel is also assumed to be underground and to be 100 m long, 30 m wide and 20 m high.

The general layout as presented in Fig. 3 shows further buildings for a total staff of about 3000. The possibility of expanding the buildings has been included.

V. SITE STUDIES

Altogether 9 of the CERN member states have put forward site proposals, and these sites are at present being investigated and data are being collected for a later comparative evaluation. The CERN Council has not yet established a procedure for the selection process. The technical evaluations should play the most important role in this selection.

VI. TIME SCHELUDE AND COST

The construction period for the project is estimated to be 9 years and the total cost to be 1600 MSF. Of this the machine proper will require a little more than 1000 MSF. The construction staff will at maximum be 700, but the total staff of the laboratory will have grown to about 2500 at the end of the construction period.

At present little is known about when this project will be authorised, but various aspects of it are being discussed at every meeting of the CERN Council and it is hoped that this will clear the ground for an early decision.

Acknowledgement

The plans for the 300 GeV proton synchrotron are a result of a joint effort of the CERN Study Group on New Accelerator Project. This group has had valuable assistance from other people from CERN as well as from other laboratories.

REFERENCES

(3) W. Schnell: Paper presented to this conference, see Session I.
(5) A. Carne, G. Dôme and W. Jüngst: Paper presented to this conference, see Session XI.
(6) W. Hardt: Paper presented to this conference, see Session IV.

DISCUSSION

KOLOMENSKY: Are there any plans about special (instantaneous) automatic corrections and lock-on of the beam orbits and betatron oscillations in your synchrotron?

JOHNSEN: We plan to incorporate much beam observation equipment in the machine in order to be able to determine directly from beam behaviour any disorder of the machine. However, we do not plan to rely upon automatic corrections, but we intend to try to operate our magnetic correcting devices in automatic way at a later stage.

KOMAR: What is percent of the cost of the construction there is a cost of the separate parts of the installation?

JOHNSEN: Staff expenses about 15%; Civil engineering about 30%; Accelerator components about 35%; Personal of laboratory about 30%.