THE CERN DESIGN STUDY FOR A 300-GeV PROTON SYNCHROTRON

The CERN Study Group for Future High Energy Projects

(Presented by K. JOHNSEN)

1. HISTORY

In the autumn of 1961 the CERN Council officially authorized CERN to prepare a design study for two possible future CERN projects: a set of storage rings for the CERN Proton Synchrotron and a proton synchrotron of 300 GeV, and the Accelerator Research Division was given the task of organizing the Study Group. This Study Group has been composed of both CERN staff and visitors from other laboratories. The names of those who have worked with the Study Group more or less full time over extended periods are: G. Bronca, E. H. S. Burhop, J. Gervaise, K. Johnsen, G. Neyret, J. Parain, B. de Raad, L. Resegotti, W. Schnell, A. Schoch, R.B.R. Shersby Harvie, K. R. Symon, C. J. Zilverschoon. In addition we have had very valuable part-time help from specialists from both inside and outside CERN, and also from outside CERN member states, e. g. from USA und USSR.

In this paper we shall report on that part of the Study Group activity that has been concerned with the big synchrotron. Some of the most important details will be treated in other contributions to the Conference. This report will therefore be mainly a summing up of the conclusions arrived at so far by the Study Group. In an appendix to this paper are listed CERN reports related to the 300-GeV study and from which more details can be found in addition to the details to be found in other contributions to this Conference.

2. BASIC PARAMETERS

The main results of the work can best be interpreted in terms of tentative parameters and by giving the background that has led to the various choices. Only the basic parameters will be given here to show the magnitude of the project and to illustrate the general lines followed by the Study Group. Similar studies have gone on and are going on in other places, in particular in the USA. Therefore cross checking of the results against the results of other studies is fortunately possible and makes one feel on safer ground.

The theory of alternating gradient focusing machines has been well understood for many years. One can now also base the design of future machines on a fairly solid practical experience gained with the CPS and the AGS. New ideas that have come in over the last few years have been more on details than on issues of fundamental character. Altogether it has therefore been possible to start from a rather well founded basis. This, however, does not mean that an order of magnitude extrapolation does not present practical difficulties and difficult choices and decisions.

At the time when the study was started it was decided to concentrate the effort mainly on one energy, but to keep in mind how scaling up or down should be made. 300 GeV was chosen as the energy figure on the basis that this would be somewhere in between a likely energy for a European machine and a likely energy for an intercontinental machine. Since then the European Committee for Future Accelerators, established in January this year, has given a strong recommendation that the energy of the next big accelerator in Europe should be about 300 GeV. The Scientific Policy Committee of CERN has submitted the report of the European Committee to the CERN Council with its endorsement of the conclusions.

The next important figure to consider is the maximum magnetic field on the central orbit. This parameter, however, is not independent of other important parameters, such as profile parameter and aperture, and many different alternatives were worked out in some detail by Resegotti before we could arrive at a conclusion. The variation of radius being counter-balanced by variation in aperture, the economical optimum with respect to this parameter is fairly flat, and a somewhat different choice would perhaps be about equally justifiable. The main considerations in the choice of $B_{0\max}$ are the field at the minimum

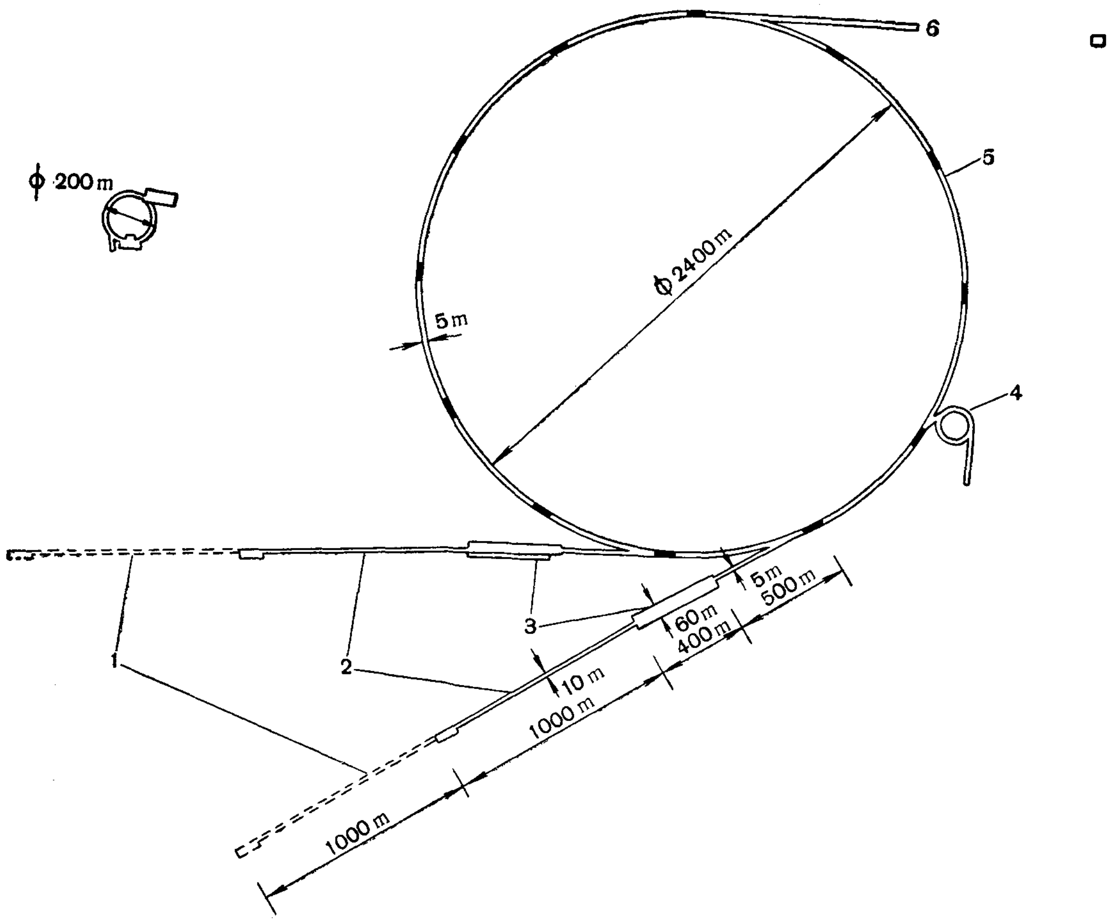

Fig. 1. *Layout of a 300 GeV proton synchrotron. (The figure at left shows CERN 25 GeV proton synchrotron to scale):*

1 — possible extension for separated beams; *2* — long separated beams; *3* — external target hall; *4* — booster injector; *5* — long straight section; *6* — neutrino area.

gap, again determined by the necessary aperture and profile parameter n/ϱ, as well as the philosophy one adopts on the high-field correcting devices one is prepared to put in. After balancing the various factors the following list was arrived at:

$$B_{0\,\max} = 12 \text{ kGs}$$
$$B_{\max} = 18 \text{ kGs}$$
$$n/\varrho = 6 \text{ m}^{-1}$$
$$\varrho = 840 \text{ m}$$
$$R = 1200 \text{ m}$$

The choice of the average radius R is made after an estimate of the space needed for equipment between the magnets both for the machine itself and for its experimental utilisation. The straight sections will not be uniformly distributed but will comprise 12 extra long straight sections each being $L_{\text{l. s. s}} = 52$ m; the matching lenses leaving only $(L_{\text{l s. s.}})_{\text{free}} = 34$ m free from obstructions.

One more basic parameter to be mentioned is the phase shift of betatron oscillations per period. This is known to have a fairly flat optimum near $\pi/4$— $\pi/3$. $\mu \simeq \pi/4$ was chosen. The actual value will be adjusted to fit the superperiodicity requirements in the final design, by slightly altering the n-value. As a consequence of the various choices $Q = 28.75$ was arrived at.

3. APERTURE CONSIDERATIONS

One important fact to be taken into account in extrapolating the design of present day alternating gradient synchrotrons to higher energies is the increase of the relative importance of closed orbit distortions. This is partly due to the fact that less space is needed for betatron and synchrotron oscillations and partly due to the increased betatron wavelength that such scalings give.

Experience with the existing accelerators has confirmed the prediction that the largest distortion would occur at injection, as most non-uniformities have the largest relative values at the lowest field. If one tried to use straightforward scaling criteria assuming unchanged injection fields the closed orbit distortion would go approximately as the power $^1/_4$ of the machine radius. It is felt, however, that scaling the aperture in this way would be unnecessarily conservative.

A few words on the experience with the CERN PS may be appropriate. The closed orbit distortions in the CPS increased considerably during its first two years of operation. This was largely caused by the extra shielding introduced locally in the ring when the work on the new East Experimental Area was started. However, a systematic correction by means of self-powered back-leg windings reduced the residual radial distortion to a somewhat smaller value than the original uncorrected distortion. Consequently, experience has shown that it is possible to correct for most of the distortions, and since the economic consequences of a large aperture are certainly important for very big machines, it was assumed that a big machine will be built with more observation devices and more correcting devices and therefore more possibilities of reducing the closed orbit distortions than on the present CPS. In short, we have assumed that one can do about 50% better than in the CPS.

Betatron and synchrotron oscillations are more straightforward to estimate. Altogether we have concluded that a reasonable choice of inside vacuum chamber dimensions would be 55 × 90 mm.

4. MAGNET AND POWER SUPPLY

The magnet gap at the equilibrium orbit would be 7 cm and the pole width 25 cm. The total stored energy would be 68 MJ. The plate size depends on the material used for the coils: copper would require smaller sections. In this case, the total weight of steelplate before stamping is estimated to be 26,000 t and the copper weight 2500 t, with an rms current density of 200 A/cm^2 and an average dissipation of 20 MW. The characteristics of the standard magnet cycle would be:

cycling period	3.4 s
injection time	0.6 s
rise time	1.1 s
flat top	0.7 s
decay time	0.9 s
rest time	0.1 s

With a 24-turn winding the maximum current required would be 3000 A and a constant voltage of 56 kV would give the required rise time.

The power supply might consist of 2 central motor-alternator-flywheel sets of 220 MVA total peak rating and 12 power converter units distributed at equal distances around the ring, connected in series with the windings and individually earthed to avoid excessive voltages to ground. The magnet design has been considered by Resegotti and the power supply, cooling and ventilation by Grütter and his group. Both Grütter and Resegotti are here and can supply more detailed information during the discussions.

5. RF SYSTEM

There are various possible ways of making the RF system for a big synchrotron. The following three methods have been under consideration during the last few years: a) ferrite tuned systems ($<$ 30MHz), b) mechanically tuned systems (100—300 MHz), c) fixed frequency, phase jump system ($>$ 500 MHz).

A really detailed evaluation of the various systems has not been attempted but the ferrite system should probably be avoided due to its bulkiness and high losses. The mechanically tuned system is attractive because of the high-Q cavities that can be built and the rather convenient frequency range for which it is suitable. This system was first proposed by Schnell, and details will be given in another paper to this Conference. We intend to use this system both for the 300-GeV machine itself and for its synchrotron injector. The fixed frequency method proposed by Robinson requires a rather high frequency, and there is some difficulty in accommodating the injected energy spread. Altogether it seems to have little advantage over the mechanically tuned system, and certain disadvantages.

6. INJECTION

A special paper will be delivered to this Conference on the considerations leading to the choice of injection energy and type of injector. It is, however, probably worthwhile to present a summary of these considerations here.

Two methods of injection are being studied. One is to go directly from a linac into the big synchrotron. This would require a linac in the several GeV range in order to have reasonable injection field in the 300-GeV machine. The other method is to have a booster synchrotron between a fairly low energy linac, say 150—200 MeV, and the big machine. This booster would then have to be a high repetition rate machine. The linac solution is in principle the most straightforward one. However, to build a 3-GeV linac is very much more than an extrapolation of present-day linacs, and it is an expensive device unless an important change in techniques occurs during the next few years. The booster solution applies better established techniques, the main difficulties probably being in the rather strict requirements on the beam transfer from the booster to the synchrotron. It is thought, however, that this can be solved.

The main question is whether one solution would have important advantages over the other one when it comes to the performance of the big machine as a physics tool. The interesting point of using the injector as a separate physics tool during the 80% of its time that is not spent on injecting into the big machine has recently been actively put forward as a reason for choosing a high injection energy, say 8—10 GeV, which is an argument in favour of a synchrotron as injector. At present both solutions are being considered. For practical reasons more data have been obtained so far on the booster solution than on the linac.

a) **Booster**. The following are some representative parameters mainly worked out by Bronca end Neyret for a booster, illustrating what is involved.

$$E_{\mathrm{max}} = 8\ \mathrm{GeV}$$
$$E_{\mathrm{inj}} = 200\ \mathrm{MeV}$$
$$R = 100\ \mathrm{m}$$
$$\varrho = 45\ \mathrm{m}$$
$$N_{\mathrm{pulses}} = 12$$
$$\mathrm{Rep.}\ rate = 20\ \mathrm{s}^{-1}$$
$$T = 0.6\ \mathrm{s}$$
$$E_{\mathrm{max}} = 1090\ \mathrm{keV/turn}$$
$$f = 100 \longrightarrow 180\ \mathrm{MHz}$$

b) **Linac.** One will in any case need a linear accelerator of about 200 MeV. This will very likely be an Alvarez type of linac and is not expected to constitute severe difficulties. If one wants to avoid the booster synchrotron, a linear accelerator in the GeV region will be needed. 3 GeV would give 150 Gs injection field in the big machine. The Alvarez structure starts becoming rather inefficient at about $\beta = 0.5$, and a different structure is required for higher velocities. A promising structure for the velocity range of half that of light up to the neighbourhood of that of light is the cross-bar structure developed by the Rutherford Laboratory. It would have a shunt impedance $> 20\ \mathrm{M\Omega/m}$ at 400 MHz and $\beta = 0.5$.

Representative parameters for such a linac from 200 MeV to 3 GeV would be:

Accelerating length . .	1500 m
Total length	1750 m
No. of tanks	250
No. of foc. quadrupoles	250
Frequency	400 MHz
Structure diameter . . .	0.3 m
RF pulse length	80 μs
Rep. rate	3 s^{-1}
Peak power for structure	350 MW
Peak power for beam . .	300 MW ($I_{\mathrm{beam}} = 100$ mA)
Total peak power	650 MW

The linac work is done in our group by Shersby Harvie and Parain in close collaboration with the Rutherford Laboratory.

7. CONTROLS

In an accelerator a large number of control signals have to be transmitted from one place to another. The bulk of these signals are very simple on-off signals, and it has so far been common in accelerator design to use conventional direct cabling for the transmission of such signals. However, on the biggest existing accelerators this starts becoming expensive and also technically inconvenient. Since the amount of cabling scales approximately with the square of the energy we have concluded that ordinary cabling for transmission of control signals should be excluded and Brianti and his group have started a detailed study of alternative methods.

One would have thought that suitable industrially developed multiplex systems would be available. This, however, turns out not to be the case. Most multiplex systems have concentrated transmitting and receiving regions with large distances in between, and some have distributed transmission but concentrated receiving. We have not found systems with distributed receiving and transmission and the flexibility required for a big accelerator in the choice of receiving and transmitting points. One must quickly be able to transmit from almost any point to any other point.

We have studied both time division multiplexing and frequency multiplexing. For the time being we favour the latter and are going to install a pilot system for connecting the East Experimental Area of the CERN PS to the control room. A laboratory model has already been operating. The idea is to use 200—300 kHz as the carrier frequency because simple cables can be used for this frequency and it gives adequate capacity. More details will be given in a talk by Brianti.

8. VACUUM

If a synchrotron is used for injection the whole injection process will take about 0.6 s. This means that a somewhat better vacuum is required than with ordinary injection. The vacuum requirement is nevertheless not difficult to meet as even 10^{-6} Torr gives an insignificant beam blow-up.

9. EXPECTED PERFORMANCE

The intensity of a 300-GeV machine will be limited either by the number of particles one is able to inject into the machine or by the space charge limit somewhere either in the injecting synchrotron or in the 300-GeV synchrotron itself. No linear accelerator exists at present with a sufficiently high intensity to bring one near the space charge limit of a machine with parameters as presented in this paper.

It is probably conservative to assume that the 200-MeV linac to inject into the booster synchrotron will be able to deliver 100 mA pulses. If this assumption is made, the booster synchrotron will deliver about 2.5×10^{12} protons/pulse and the 300-GeV synchrotron will deliver about 3×10^{13} protons/pulse, or about 10^{13} protons/s. The space charge limit, based on the ordinary simple minded theory, would be at least a factor 3 higher, and there is therefore scope for improvement of the linear accelerator. One should probably aim for say 200 mA pulses from the linac, but not at this stage rely upon this being possible.

10. EXPERIMENTAL LAY-OUT AND UTILISATION

In general it can be said that the higher the energy the more all primary and secondary beams are pointed forward. This has led to the conclusion that transverse dimensions of beam handling equipment and detectors should not in general increase compared with 25-GeV equipment, perhaps the contrary. Longitudinal dimensions, however, scale differently if present-day techniques are going to be used. All beam transport equipment seems to become very long. An RF separator of 100 GeV/c can be taken as an example, where probably nearly 2 km of length would be required. Tentatively it can be concluded that one has to think of experimental areas whose lengths range from about a machine radius to a machine diameter, which is approximately as on the CPS and the AGS in terms of machine dimensions. With such lengths one feels that one should not consider wide experimental halls along the total length to accommodate many different beams, but rather a relatively small hall around the long straight sections, and narrow experimental tunnels extending from these experimental halls.

There has been some discussion on special arrangements being built into the machine to make it as useful as possible for experimentation. Such things as long straight sections, beam sidings and triplet bending magnets can be mentioned. We are planning to have 12 long straight sections although only two will have experimental areas at the beginning. We have, however, not incorporated such things as beam sidings and triplet bending magnets. This is because we believe that most experimentation will be done with fast of slowly ejected external beams, which apart from giving easy access to zero-angle secondaries, also has the great advantage of reducing the contamination difficulties. A separate paper with more details on experimental lay-outs will be given by de Raad. Fig. 1 indicates how we now envisage the lay-out of this machine with two experimental areas.

11. SITE PROBLEMS

The precise lay-out to be adopted will depend very much on the topography of the site that will finally be chosen. It is very desirable that the site is flat and horizontal, but it is not easy to satisfy, at the same time this condition and other important conditions such as stability of the ground, requirements with regard to electrical power and cooling water, adequate transport facilities and attractive living conditions for the staff. The final choice must mean a compromise. Gervaise has started stability measurements on a few types of ground such as limestone, sandstone, molasse and chalk. These measurements are done with invar wires for horizontal directions and with a precision of 0.1 mm over 100—300 m. Level measurements are done by telescope with a precision of 0.2—0.3 mm over the same distance. For gravel, sand and granite we rely on the information from measurements done elsewhere. We have also in an informal way started gathering other relevant information from various parts of Europe, but this must be of a very preliminary nature till we come nearer to a possible authorization of a project.

12. MANPOWER, TIME SCHEDULE, COST

There seems to be no technical reason why one should not build a machine of 300 GeV or more. It is therefore considerations of such things as manpower, time schedule and cost balanced against the scientific justification that will in the end determine the choice of energy, or more generally the choice of size of the project. Our study is still in process and the figures are still likely to change. The data in this chapter are therefore given with reservations.

We have estimated that the 300-GeV synchrotron as presented in this paper would cost about 1000 MSF to build. This would include the accelerator proper with its buildings and two experimental areas with movable shielding included. A sum has to be added, however, for preparing the whole laboratory for the future experimentation with the machine. This sum should include such things as data handling equipment, beam transport equipment, development and construction of some detection equipment and the services to go with this activity. The sum needed for this is uncertain, but our estimate has shown that if the laboratory spent about 500 MSF on such things during the latter part of the construction period, it would be well equipped for doing physics by the time the machine is put into operation. Thus the conclusion is that the total expenditure up to the end of the construction period will be about 1500 MSF. *In* Fig. 2 is shown how this expenditure is expected to vary over the construction period. The shaded area is expenditure on the machine proper with its buildings and the white area gives the expenditure on the other activities mentioned above.

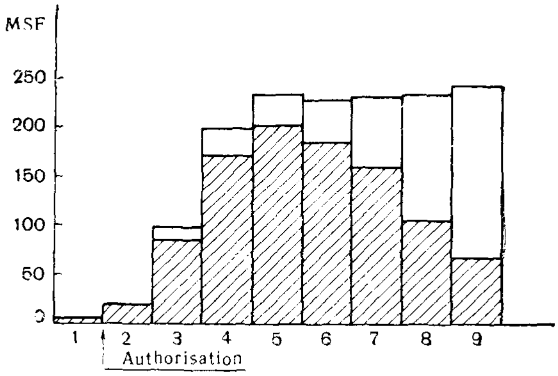

Fig. 2. Estimated yearly budgets during construction of a 300 GeV synchrotron. Expenses for services, supporting activities and nuclear physics are non-shaded.

As seen from the figure, the construction time is estimated at 8 years after authorisation and one year of detailed planning and design before this date. The total staff requirement is indicated in Fig. 3. About one fifth will be scientific staff. In addition to these staff figures considerable short term installation labour will be needed.

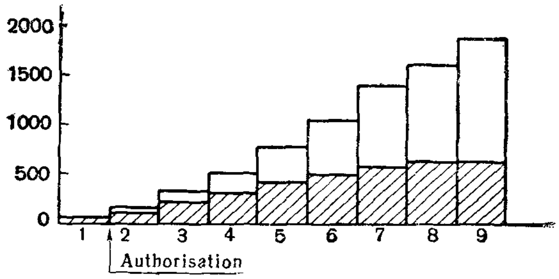

Fig. 3. Staff estimates for a 300 GeV synchrotron. Shaded means staff needed on the PS project proper. Staff for services, supporting activities and nuclear physics is non-shaded.

13. CONCLUSIONS

The design study has not come to an end yet and things may change before it is finished. There are, of course, also many aspects of the work that have not been incorporated in this short account. We hope that the proposal of the 300-GeV synchrotron together with the 25-GeV intersecting storage rings will come up for serious consideration at the political level rather soon. The first preliminary discussion on the proposals took place in the CERN Council in June this year. We hope that authorization will be given some time in 1965, but this depends entirely upon what reception the plans will get in the various CERN member states. In the meantime we expect to get support on a year-to-year basis to continue and in fact increase the effort put into the planning, especially to go into more details by making models and prototypes of various important components.

APPENDIX

The following is a list of CERN Reports related to the 300 GeV Study and from which more details can be found in addition to the details to be found in other contributions to this conference.

Asner A. On Transient and Stationary Harmonics in the Magnetic Field of Rectifier Supplying PS-Magnets. Eng./Int. EE/62-19.

Bayard O., Reitz H. Study on the Electricity Distribution System for a 300-GeV Proton Synchrotron. AR/Int. SG/63-25.

Bronca G. Le Synchrotron Injecteur de la Machine 300 GeV. AR/Int. SG/63-7.

Burhop E. H. S. The Desirable Energy of a Future Accelerator Considerations of the Physics Programme and its Realisation. AR/Int. SG/63-10.

Grütter F. Preliminary Specifications and Inquiry about the Magnet Power Supply for a 300-GeV Proton Synchrotron. Eng./Int. DL/62-7.

Grütter F. The Magnet Power Supply for a 300-GeV Proton Synchrotron. AR/Int. SG/63-26.

Hugi E. Preliminary Study of Air Conditioning Requirements for Large Accelerators. AR/Int. SG/63-15.

Johnsen K. Some Intensity Considerations for High Energy Machines. AR/Int. SR/61-25.

Johnsen K. Comparison of Various Accelerators in the Range 120 – 300 GeV. AR/Int. SG/63-9.

Keil E. Parameters for RF Separation of π and K at 100 GeV/c Design Momentum. AR/Int. PSep/62-3.

Keil E. and Montague B. W. Preliminary Cost and Performance Estimates for RF Particle Separation up to 250 GeV/c. AR/Int. PSep/63-2.

Kowarski L. Data Handling and Related Activities around the New Accelerator. AR/Int. SG/63-16.

Parain J. Dégroupage des Particules dans un Accélérateur Linéaire à Protons, en utilisant l'Oscillation de Phase. AR/Int. SG/62-9.

Parain J. Focalisation Radiale dans un Accélérateur Linéaire à Protons entre 20° MeV et 3 GeV. AR/Int. SG/63-12.

Parain J. Erreurs de Phase dans des Accélérateur Linéaires à Protons de 1 GeV et de 3 GeV. AR/Int. SG/63-18.

de Raad B. Matched Straight Sections, Secondary Beams and Ejection in a 300-GeV Proton Synchrotron. AR/Int. SG/63-3.

de Raad B. Experimental Areas, Shielding and Beams of a 150-GeV and 300-GeV Proton Synchrotron. AR/Int. SG/63-6.

de Raad B. Some Beam Transfer Problems in a 300-GeV Proton Synchrotron. AR/Int. SG/63-14.

Resegotti L. Considerations about the Choice of Basic Parameters for a 300-GeV AGS. AR/Int. SG/62-8.

Resegotti L. Tentative Parameters for a 300-GeV AGS. AR/Int. SG/62-13 Rev.

Resegotti L., Grütter F., Noble J. Optimum Current Density in the Magnet Conductors of a 300-GeV Proton Synchrotron. AR/Int. SG/63-17.

Schnell W. On the High Power Radio Frequency System of a Booster Injector for a 300-GeV Proton Synchrotron. AR/Int. SG/63-2.

Zilverschoon C. J. Draft Cost Estimate for a 300-GeV Proton Synchrotron. AR/Int. SG/63-4.

Zilverschoon C. J. Preliminary Considerations on a Site for a 300-GeV Proton Synchrotron. AR/Int. SG/62-1/Rev.

DISCUSSION

A. A. Kolomenskiĭ

Dr. Johnsen mentioned orbit distortion in the CERN 25 GeV synchrotron in his paper. This distortion turned out to be many times greater than initially predicted by theory and, evidently, led to the taking of serious measures for decreasing the disturbances. It is clear what importance the unexpected or not quite understood effects have which were experimentally obtained for designing of super-high-energy accelerators.

I would like to ask Dr. Johnsen: were other effects of the same kind met with during the use of the synchrotron, such as, in the process of synchrotron acceleration, for injection, etc. and how were they eliminated in the design of the 300 GeV accelerator? Is it possible, Dr. Johnsen, to speak about the effect of orbit distortion and about the fact of how representative it is in somewhat more detail?

K. Johnsen

The CERN-PS had over a period larger closed orbit distortions at injection than we expected. Similar things did not happen for instance on the RF, which performed perhaps better than expected after proper phase lock control was put into operation. However, when at the beginning programmed RF was used, the behaviour of the system was somewhat poorer than hoped for. The bad behaviour of the low-field closed orbit gave the necessary encouragement to the successful development of correcting devices, such as back-leg windings.

V. V. Vladimirskiĭ

The aperture chosen in your project is comparatively large. Do you not consider it possible to reduce the aper-

ture by means of increasing the injection energy and improving tolerances?

K. Johnsen

We admit that we do not aim at the smallest possible aperture. There is a strong demand for high intensity, and there should be a slightly too large safety factor in the aperture calculations. This is expected to be very useful in future development of intensity. Still we are not undue conservative in the aperture choice, as we have assumed that we can do twice as well on this new machine than on the GERN-PS.

Yu. F. Orlov

What is the limitation on intensity before it leads to radiation danger?

K. Johnsen

We do not know enough about contamination problems yet, but experience with existing machines indicated that the problem can be handled by fairly conventional methods (without undue remote control, etc.) up to 10^{13} protons/s.