INJECTION INTO A 300-GeV PROTON SYNCHROTRON

The CERN Study Group for Future High Energy Projects
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INTRODUCTION

The problem of particle injection into a high energy proton synchrotron presents itself as the search for a compromise between cost of the injector and cost of the main machine, for a required machine peformance. In this respect, the choice of injector type and the choice of injection energy are strictly interconnected, since the characteristics and the limitations of each type of injector may make it most suitable for a given energy range. We shall therefore discuss first the influence of the injection energy on the parameters of our 300-GeV machine design [1] in order to show the arguments that have led our Study Group* to consider more closely the characteristics and the requirements of injection from an alternating gradient proton synchrotron, which will be treated in the second part of the paper.

A. INFLUENCE OF INJECTION ENERGY ON MACHINE DESIGN

1. Injection Energy and Injection Field

The relation between kinetic energy and magnetic field is shown in Fig. 1 for some existing machines and for the 300-GeV PS studied at CERN. Each curve corresponds to a machine, and the crosses show the chosen injection values. It may be noted that the preferred injection field used to be around 300 Gs for weak focusing structures (some lower values seem rather due to limitations in the available injector) and was reduced under 150 Gs in AG machines, in which the magnet is typically less expensive. In our 300-GeV design, a field of 150 Gs corresponds to a kinetic energy of about 3 GeV. From the point of view of field, an injection energy of 1 GeV would correspond to 10 MeV in the CPS.

* The members of the Study Group are listed in ref. [1].

2. Injection Field and Orbit Distortions

The field distribution along the machine circumference at injection results from the addition of the «dynamic field» produced by the excitation current in the magnet and of the remanent fields which exist not only in the magnet gap but also in the straight sections, because of the presence of steel parts in the surrounding structures. The widespread remanent magnetization is quite a conspicuous phenomenon in the CPS tunnel, where stray fields up to a few Gauss can be measured in the straight sections (Fig. 2). It has been found that the magnetization of the tunnel influences also the remanent field distribution inside the gap (of the open blocks, at least), and there are reasons to believe that the channelling of the stray remanent flux modifies the initial permeability in the yokes. The resulting distortion of the closed orbit at injection is a few times larger than at medium fields: a typical value for the radial distortion is 4 cm peak to peak under good conditions.

The focusing properties of the machine are also disturbed by remanent field effects, because the gradient of the remanent field is different from that of the dynamic field. The external fields even introduce vertical gradients which produce serious coupling of the vertical and radial betatron oscillations. The distortions produced by a random distribution of field errors in the units, of given r. m. s. value, increases with the fourth root of the machine radius, if the phase advance and the profile parameter are kept constant [2]. The displacement produced by a localized angular kick increases, under the same hypothesis, as the square root of the radius. The influence of field errors can be somewhat reduced by increasing the profile parameter, as is possible in a machine of smaller aperture, but this is obtained at the cost of a further increase in sensitivity to misalignments and to gradient errors. M. Sands [3] has shown that the

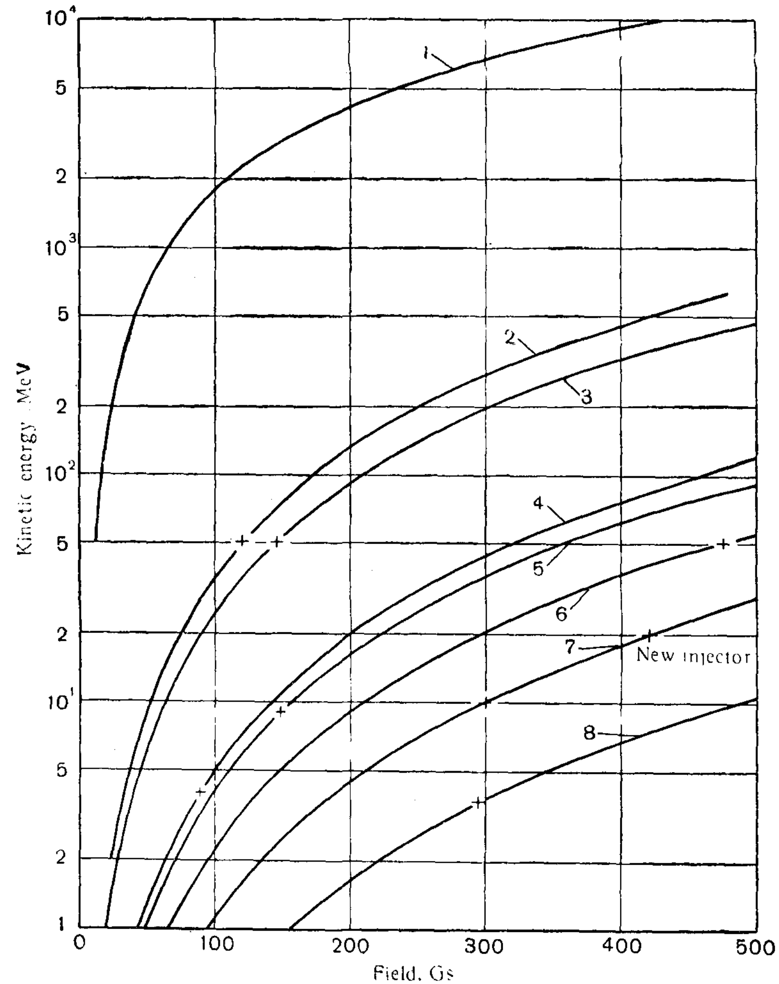

Fig. 1. Field-energy relation in large proton synchrotrons:
1 — 300 GeV PS; *2* — AGS; *3* — CPS; *4* — ITEP 7 GeV; *5* — Synchrophasotron; *6* — ZGS; *7* — Bevatron; *8* — Cosmotron.

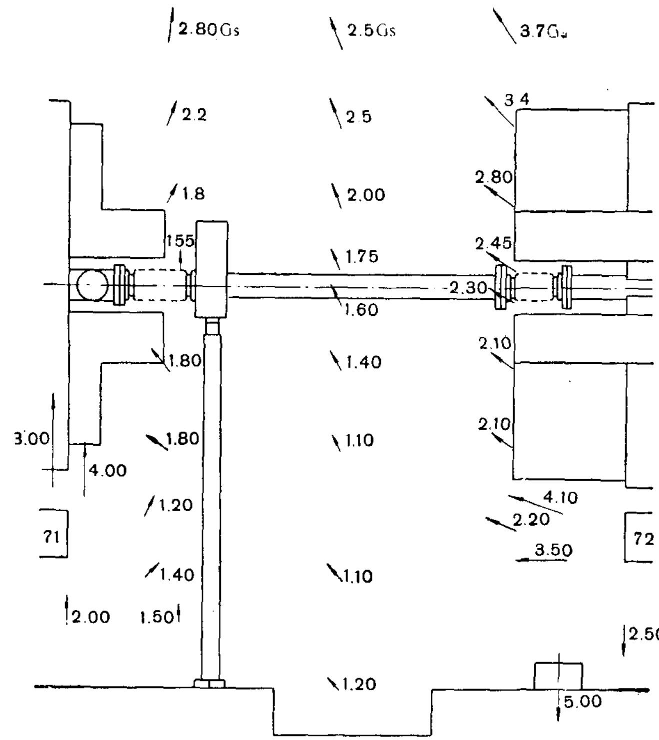

Fig. 2. Stray remanent field pattern in straight section 72 of the CPS (B in gauss).

injection field at which gradient errors produce a given shift of betatron frequency increases with the square roots of the machine energy and of the profile parameter.

In conclusion, in order to achieve at injection the same distortion situation as in the CPS or in the AGS the injection field should be substantially increased with respect to these machines (Fig. 3). With the parameters of our 300-GeV design, and scaling up the closed orbit distortion of the CPS as if it were due to a random distribution of field perturbations (in the units) the vertical and radial peak to peak distortions due to field perturbations would be as follows:

Injection Energy, GeV	Injection Field, Gs	Vertical Distortion, mm	Radial Distortion, mm
1	67	60	120
3	151	27	54
6	273	15	30
10	434	9	18

while the distortions due to misalignments and mechanical tolerances are expected to be, with 98% probability, less than 28 mm and 38 mm respectively. The injection field required to give the same betatron frequency shift due to remanent gradient errors as in the CPS would be 620 Gs.

It is sure that correcting elements (back leg windings, vertical magnets ordinary and skew quadrupoles, vacuum chamber windings) shall be used at injection and it is conceivable that automatic correction systems may be brought into practical operation. However, the effectiveness of these devices will always be limited by the size of the correction required and this limit to injection field may be lowered, but not removed.

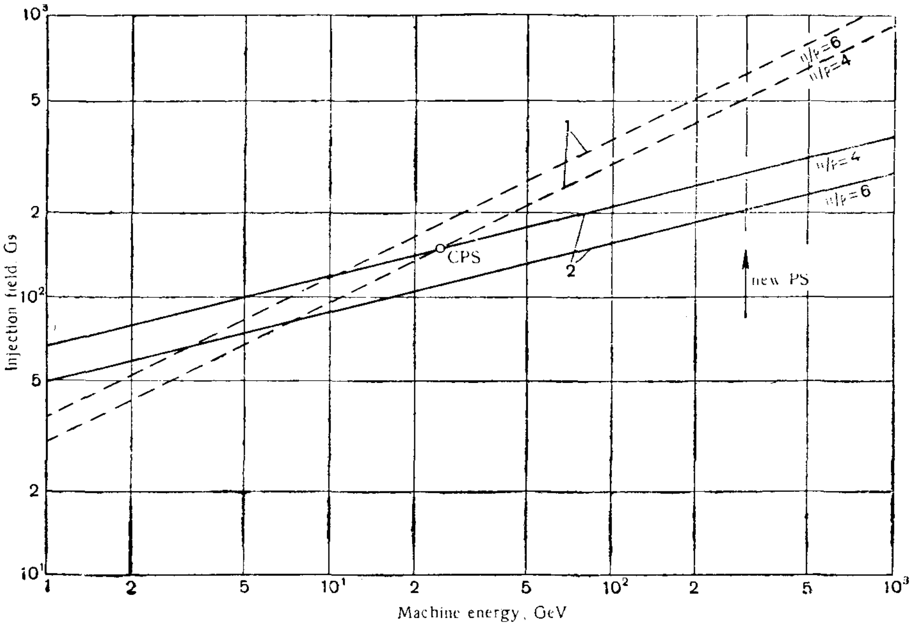

Fig. 3. Relation of injection field to machine energy for equal orbit distortions: *1* — curves for equal ΔQ to CPS; *2* — curves for equal c. o. distortion to CPS.

3. Space Charge Limits

The normal formula for the space charge limit can be written, following K. Johnsen [4]

$$N_{s.c.} = \frac{8\pi m_0 c}{e^2 \sqrt{\mu_0/\varepsilon_0}} \frac{\beta^2\gamma^3}{|b-\nu\gamma^2|} A\Delta Q,$$

where $N_{s.c.}$ is the total number of particles in the beam, b is the bunching factor, ν is the neutralization factor, ΔQ is the permissible change in Q. Image forces from the walls of the vacuum chamber and the magnet poles are neglected here for simplicity, since they would not alter the basic argument.

If we assume that the beam emittance is adjusted in the injector so that it equals the available acceptance A of the machine, the space charge limit for a given machine depends on the injection energy through the term

$(\beta^2\gamma^3)/|b - \nu\gamma^2|$. If the beam is not neutralized ($\nu = 0$), this term increases as $\beta^2\gamma^3$. If partial or total neutralization is present, the influence of γ will depend on the bunching factor at injection. However, as long as $\nu\gamma^2 < 2b$, the situation is better than with no neutralization. In practice, it would be difficult to rely on an effective bunching factor smaller than 20, bearing in mind the higher particle density near the centre of the bunch, so that even with full neutralization the increase in space-charge limit would be fast up to injection energies in the region of 3 to 6 GeV. When the term $\nu\gamma^2$ becomes large with respect to b, the increase becomes simply proportional to γ.

As an example, the limiting intensities of our 300-GeV design, with a design acceptance of $1.8 \times \pi \times 10^{-6}$ *rad·m*, for a *bunching* factor of 20, and the most unfavourable neutralization condition, would be:

Injection energy, GeV	γ	$\beta^2\gamma^3$	Neutralization factor	Particles per pulse
1	2.06	6.73	0	1.2×10^{12}
3	4.20	69.8	0	1.2×10^{13}
6	7.40	395	1	4.0×10^{13}
10	11.65	1570	1	4.8×10^{13}

These values have been calculated by putting $\Delta Q = 0.5$ in the formula, as it seems reasonable, in view of the conclusions of the latest work on space charge by Lloyd Smith [5].

4. Limits to the Accelerating System

The injection energy determines the frequency swing of the RF accelerating system and limits the choice of the harmonic number to meet the requirements of accepted momentum spread and of phase oscillation frequency. W. Schnell's proposal to use mechanically tuned accelerating cavities [6] takes advantage of relatively high injection energy.

As explained in Schnell's paper [7], presented in another session of this conference, a rapid decrease of the operating frequency and a consequent substantial increase in size of the cavities and in power consumption would become necessary at energies lower than 3 GeV: in addition the tuning system would soon become unable to follow the rate of change of frequency at injection, even if the magnetic field had an initial reduced rate of rise. On the other hand, the smaller the tuning range, the higher the safety margin on accelerating voltage and the reliability of operation.

B. INJECTION FROM A FAST CYCLING SYNCHROTRON

1. AGS Injectors

The alternating gradient synchrotron is at the moment the accelerator best fitted to the range of energy of special interest for injection into the 300-GeV machine, i. e. above 3 GeV. The CERN Study Group has considered also the possibility of a high energy linac, and in particular R.B.R. Shersby-Harvie and J. Parain, in close contact with the Rutherford Laboratory [17], have devoted their efforts to the design of the most suitable structure and to the *problems of power, phasing and de-bunching.* Linacs as injectors are at present being favoured by various groups in the USA, and in particular at Yale University, at the Lawrence Radiation Laboratory and at the Brookhaven National Laboratory [9]. It seems for us appropriate to expand here specifically on the properties of the synchrotron type of injector.

The possibility of using a smaller AGS as a «booster», for injection into a large accelerator, was one of the leading ideas in Sand's original proposal [8] for a 300-GeV AGS in 1959, that powerfully stimulated the interest in ultra-high-energy machines. In order to fill entirely the circumference of the large machine, Courant, Snyder and Walker [14] suggested that many successive pulses from a fast-cycling synchrotron could be injected into it in suitable azimuthal sequence, while the main guiding field would be held at injection value during the necessary number of injector cycles.

K. Johnsen pointed out that it was possible to design an injector having the same circumference as the main machine, which could be placed in the same tunnel [9]. This injector would have very long straight sections between relatively short magnets: in these regions the vacuum chamber would require good shielding against the strong stray magnetic fields. The costs of the increase of tunnel size, and of the long vacuum system also reduce the advantage of the common location. The intensity in this injector would be severely limited by space charge effects unless a stacking process in longitudinal phase space, as proposed in ref. [4], were adopted. This idea was followed by N. I. Dojnikov, N. A. Monoszon, and I. A. Shukeylo [10] in their tentative parameter list for a 300-GeV machine.

The GERN Study Group has concentrated on a small, fast-cycling booster, because of the practical advantages of a separate construction and also because of the intrinsic interest of this machine.

2. Properties of a Fast Cycling Booster

The number n of booster pulses to fill the circumference of the 300-GeV accelerator is given by the ratio of the average radii of the two machines, R_m and R_b:

$$n = R_m / R_b$$

If f is the cycling frequency of the booster, the filling time τ, which determines the limitation set by this method of injection to the duty cycle of the m 'n machine, is

$$\tau = n/f = \frac{R_m}{f R_b}$$

Due to the sinusoidal variation of the magnetic field produced by the resonant magnet power supply, the energy gain per revolution must vary sinusoidally during acceleration. Its maximum value is:

$$(\Delta E_{\text{rev}})_{\max} = 2\pi^2 R_b f\,(p_m - p_i) = 2\pi^2 \frac{R_m}{\tau}(p_m - p_i)$$

where p_i and p_m are the injection momentum of the booster and its maximum momentum respectively. Thus, the energy gain per revolution is practically proportional to the maximum momentum of the booster, and varies inversely with the filling time of the main machine, but does not depend on the particular values of cycling frequency and of average booster radius by which this filling time is achieved. Of course, the radius should be sufficiently larger than the magnetic radius to leave enough straight section space available for the accelerating structures. It is worth recalling that, contrary to ordinary proton synchrotrons, in a fast cycling machine the cost of the accelerating system is a large fraction of the total cost, and the peak RF power may be several megawatts. General optimization criteria have been presented by H. Bruck at the 1961 Accelerator Conference [11].

In the case of the 300-GeV machine, it is of particular interest to consider a booster having injection energy of the order of 200 MeV, for which the range of frequencies is such that mechanically tuned cavities, as proposed by Schnell can be adopted [7]. The cost of the more powerful linac is compensated by the saving in magnet aperture and in the RF system.

The shunt impedance of the mechanically tuned resonators varies inversely with the cycling frequency, so that for given booster energy and filling time, the RF power is inversely proportional to the booster radius R_b. In this case, the booster energy can be increased with a less than linear increase in cost, by increasing in the same proportion the average radius, the magnetic radius, the stored energy in the magnet and the number of RF cavities, while the total RF power remains constant. A limit to average radius eventually arises from the gap voltage required to capture the protons before acceleration: for 200 MeV injection, difficulties are expected above 10 GeV. On the other hand, for small booster energies, it is not advantageous to reduce the radius below a certain value, because of space requirements and of the difficulty of increasing the cycling rate of the RF tuning.

In conclusion, a fast-cycling proton synchrotron appears specifically suitable for an energy range between 3 and 10 GeV. The parameters of booster injectors of 3, 6 and 10 GeV have been worked out by G. Bronca and W. Schnell for a 300-GeV machine, with radius of 1200 m and a filling time of 0.6 s. The average radii turn out to be 60, 80 and 120 m respectively. The cost of these machines increases less than proportionally with energy, particularly in the step from 3 to 6 GeV. Cost estimates have shown that the saving on the main machine, in going from 3 to 6 GeV injector would be larger than the extra cost of the booster. A further increase of booster energy seems more disputable from the point of view of pure economy, though it may be justified on other grounds, as we shall discuss later.

The relative sizes of the 6-GeV booster and of the 300-GeV machine can be seen from the figure presented by K. Johnsen in his report [1].

3. Requirements of Booster Injection

The injection of protons from a fast cycling booster into the main accelerator presents a certain number of problems, concerning the stabilization of the injection field, the multiple scattering of the injected protons during the waiting time, the synchronization and phasing of the RF systems, the pulsed magnetic system for beam extraction and injection, and the timing of the transfer process. These problems have been previously discussed in a series of CTSL reports by Sands, Walker, Tollestrup and Peterson [3, 12, 14, 15]. They have been reconsidered in our study group for the specific purpose of our 300-GeV project, taking into account new ideas and recent technical developments. We have become confident that they can be solved with a moderate extrapolation of existing techniques, so that booster injection is not basically more difficult than linac injection.

a) **Front porch on the magnetic field cycle.** During the injection of a number of successive pulses from the booster, the magnetic field in the main machine must be kept constant at a rather low value. This can be achieved in a simple way by means of a separate dc power supply, since the power involved is of the order of 20 to 50 kW. A suitable type of circuit has been used at the CPS. The stabilization of such a power supply to within 1 part in 10^4 is quite feasible, so that the equilibrium position of the injected beam could be defined to within a fraction of a millimetre.

b) **Multiple scattering and vacuum requirements.** It has been shown by Peterson [12] that a vacuum of about 10^{-6} mm Hg will be necessary in order to avoid appreciable beam loss through multiple scattering during a 1 s storage at injection energy in the main ring.

With the parameters of our 300-GeV design, the r. m. s. oscillation amplitude due to multiple scattering in air at 10^{-6} mm Hg, after 0.6 s at 6 GeV is 3 mm, and the resulting increase of the original betatron oscillations of 10 mm maximum amplitude is negligible, while at 10^{-5} mm Hg the r. m. s. scattering amplitude would be 10 mm. If a 3-GeV linac were used for injection, a vacuum of 10^{-5} mm Hg would clearly be sufficient. However, with a 1-GeV linac, the situation would be the same as with the 6 GeV booster, because of the important increase in scattering angle with decreasing energy. The experience gathered at CERN on the storage ring model [13] tells us that the required vacuum can be obtained with moderate techniques (metallic joints, but no baking under vacuum).

c) **Synchronization and RF phasing.** A method of synchronizing and phasing the RF systems in the booster and in the main ring, assumed to have the same operating frequency at the time of beam transfer, has been proposed by Tollestrup [14]. The idea of transferring the bunches undisturbed from one machine to the other is especially interesting in order to avoid the loss of a fraction of the beam all around the main machine, during re-bunching. However, the times required for phasing with Tollestrup's method are too long for our planned cycling rate of 25 Hz, in which the field rises by 1% in 1 ms near the top of the cycle.

W. Schnell has suggested that, once the frequency in the booster has reached the value of the main ring frequency, the booster RF system could be locked to the main ring and then the phase shifted by two equal jumps with a time interval of half a period of phase oscillation between them (Fig. 4). In our case this time interval would be about 100 μs. The bunch would be little distorted in this process, because of its small size. The phasing time would then be always the same, and the small radial shift due to field rise could be compensated by having the frequency lock when the beam circulates at a radius smaller than that of the ejection orbit.

When the beam, after synchronization and phasing of the machines, reached the correct radial position because of the increase in field, the correct ejection conditions would be achieved. The further waiting time, to inject at the tail of the stored beam in the main machine, could vary between zero and the time of one revolution, i. e. 25 μs, which involves a very small change in field, near the top of the sinusoid. This method would make it possible to achieve a very good accuracy in position and momentum of the ejected beam without too difficult tolerances on the magnetic field cycle (order of 1‰ in the maximum field).

It is worth noting that the use of the same frequency in the two machines is made possible by the fact that the mechanically tuned system, which was designed especially for the main ring, is also suitable for the booster, as W. Schnell will show in his separate report. If the machines could not be synchronized, the beam could, of course, be allowed to spread in phase in the booster at the end of the cycle, by switching off the RF voltage. A large fraction of the beam would then be captured in the stationary buckets in the main ring, but

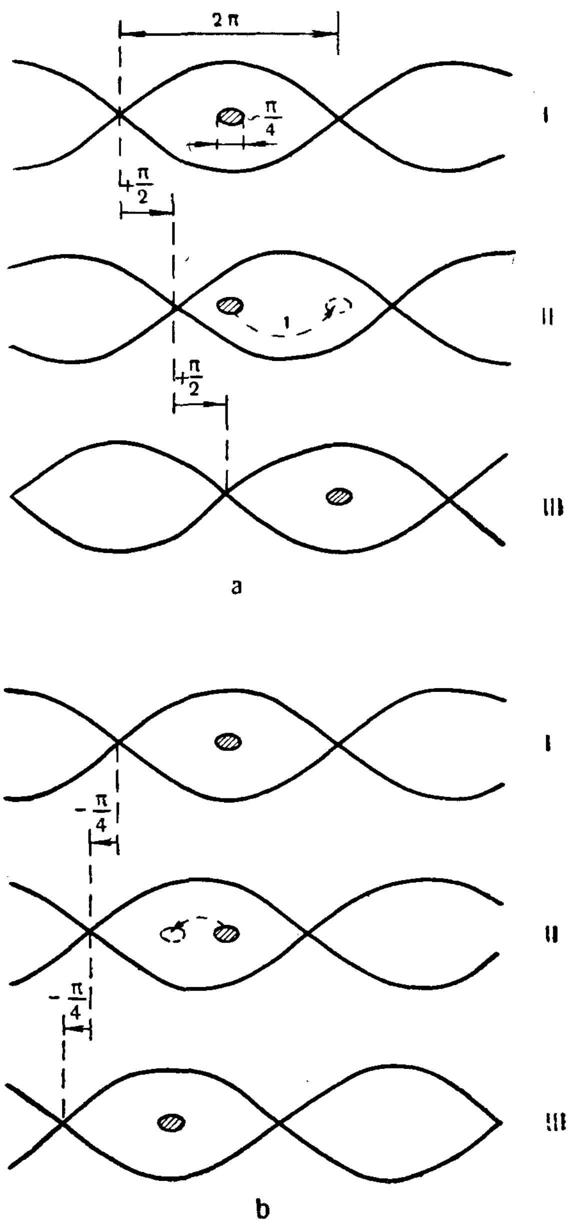

Fig. 4. Booster phasing by phase-jump: *a* — displacement of booster RF phase by $+\pi$; *b* — displacement of booster RF phase by $-\frac{\pi}{2}$; *I* — initial condition; II — first jump $t = t_1$; III — second jump $t = t_1 + \frac{T_s}{2}$; *1* — half a phase oscillation.

a certain loss could never be avoided and phase space would be much diluted.

d) **The pulsed beam transfer system.** The progress of the technique of fast pulsed magnets and the successful experiences in Stanford and at the CPS make it possible to design a pulsed beam transfer system from the booster to the main ring on rather solid ground. Ejection from the booster has been studied by Walker [15]. In our group the whole problem of beam transfer has been considered mainly by de Raad. The ejector consists of one or more fast delay line (kicker) magnets that kick the beam in a single revolution into a septum magnet, which deflects it away from the booster stray field. Owing to the high repetition rate, neither magnet can be moved. The aperture of the kicker magnet must be equal to that of the booster, and the septum magnet must be entirely outside the booster aperture.

Because of the large ratio of average radius to bending radius that can be adopted economically in the booster it is not difficult to find space in the straight sections for relatively long kickers and bending magnets, which make it possible to reduce the required field strength and to ease voltage problems. Moreover, the magnet structure itself can be adjusted to fit ejection requirements and in particular to reduce the aberrations in the ejected beam due to the action of the stray fields. As an example, de Raad has suggested a FODO structure for the 6 GeV, 80 m radius, booster considered at CERN, and has shown that two sets of kickers half a wavelength apart with strengths of about 1 kGs·m would be adequate to deflect the beam into a dc septum magnet, without going through the region close to the minimum gap, where aberrations are strong. With an effective bending length of about 3.8 m, the field in the septum magnet should be less than 3 kGs, and this would make it possible to power it with dc, with increased stability and reliability. The estimated increase in emittance due to the aberration at ejection would be in this case 25% only. An example of booster ejection trajectory is given in Fig. 5.

The matching system of quadrupoles and bending magnets between the booster and the main ring requires careful calculation, construction and alignment but does not present any new problem. For injection into the 300 GeV ring components similar to the ones of the booster ejection system (though with different apertures) could be used.

The difficulties of booster ejection would therefore be concentrated mainly in the fast kickers, which should be made to have a relatively large aperture and a short risetime in order to reduce the loss of protons. With our

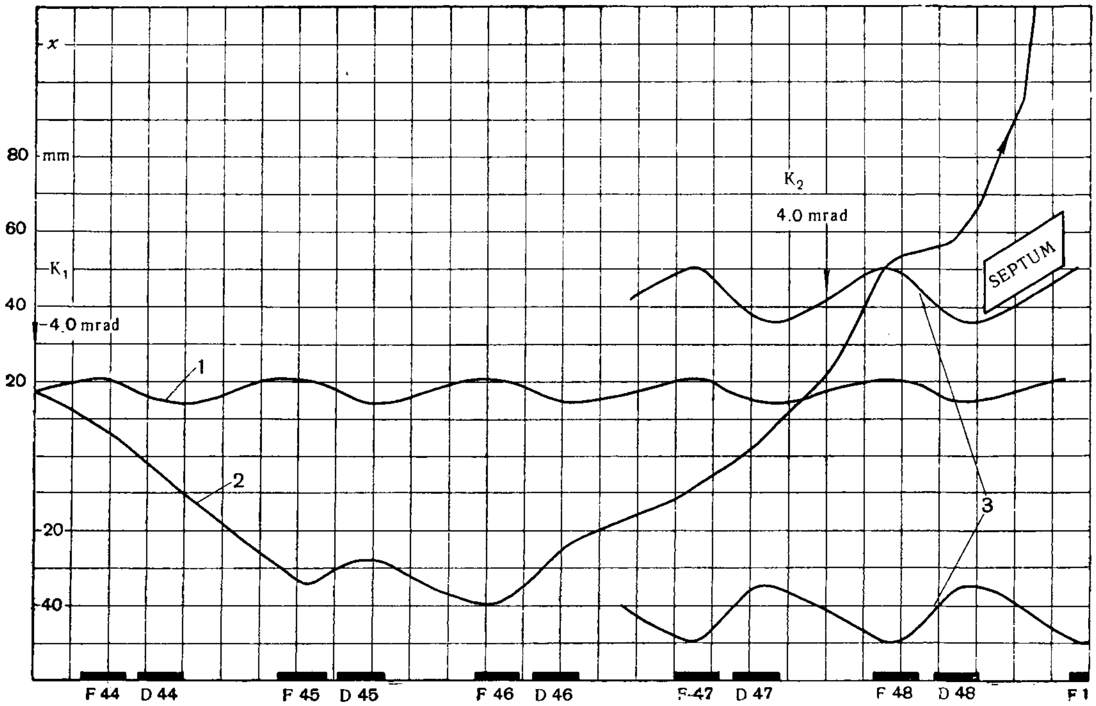

Fig. 5. Ejection from a closed orbit at $x = +16$ mm in the booster: *1* — displaced closed orbit; *2* — ejected beam trajectory; *3* — horizontal aperture.

parameters, a risetime of 80 ns would correspond to a loss of about 5%. This relatively small percentage loss is another advantage of the large average radius. The ejection kicker of the booster and the injection kicker of the main ring must be accurately timed, so that the risetime of the second occurs at the passage of the gap created in the beam by the first. A timing accuracy of 10 ns seems possible.

If a high energy linac were used as an injector, no ejection facility would be required, but fast pulsed electromagnets should still be studied for injection into the main machine, since with electrostatic inflectors, as used in the PS and in the AGS, the required field strength would be uncomfortably high, or the electrodes uncomfortably long.

4. Intensity Considerations

The problem of the beam intensity achievable in the main ring with different injectors has many aspects, because the maximum intensity for a given machine is influenced by the duration of the injection period, by the characteristics of the injected beam (beam emittance, bunching factor, energy spread and energy jitter), by the injection errors and by the intensity limitations in the injector itself.

G. Bronca and W. Schnell have shown that in the case of booster injection into a 300-GeV machine, an injection time of the order of 0.6 s is technically possible and economically reasonable, while it would be difficult to reduce it by a factor of 2. This time is of the same order as the flat top duration, which would be desirable for most of the experiments with a high intensity machine. It represents about 20 % of the total machine cycle, if a rise time of 1 s to maximum field is assumed. These values give the order of magnitude of the decrease of the duty cycle with respect to the case of linac injection when operating at full energy.

If the machine is operated at lower energies than maximum, the cycling frequency can be increased, by keeping constant the rates of rise and decay of the magnetic field. The flat top, however, should remain approximately the same, so that the booster injection time could hardly double the total cycling time as compared with the case of instantaneous injection.

On the other hand, the presence of the intermediate stage of acceleration makes it possible to increase the number of injected particles for a given current in the pre-injector, because the booster ring is filled at a smaller β and has therefore a longer filling time. With injection at 200 MeV into the booster, the number of injected particles could be almost double that with a high energy linac injector of the same initial current. This comparison does not take into account more elaborate injection methods like multiturn injection or stacking in longitudinal phase space, that would be possible with a linac, as pointed out by Johnsen [4]. The following table shows as an example the maximum intensities achievable in the 300-GeV machine studied at CERN with a 10 mA current in the pre-injector linac, for different top energies and different injectors, assuming no transfer losses.

beam emittance may of course compensate for the larger injection errors.

The space-charge limit at injection in the main machine depends inversely on the bunching factor of the injected beam, at least as long as the beam is not neutralized. The beam is expected to be more tightly bunched in phase in a high energy linac than in the booster. As an example, the bunch width in our 6-GeV booster design, coming from a full bucket at 200 MeV, would be about 50°, while in a 3-GeV linac it might be as low as 2° (Parain).

The possible methods of debunching in the linac, by means of acceleration at the unstable point (L. Teng [16]) or by a separate debuncher using magnetic prisms have been studied by J. Parain. The former is limited by non-linearities and can have a substantial effect only

Intensities achievable in a 300-GeV machine with different injectors

Main machine radius: 1200 m.
Injection time from the booster: 0.6 s.
Pre-injector: 200 MeV, 100 mA linac.

	With 3-GeV linac		With 6-GeV booster	
	Cycling period, sec	Average intensity, protons pes second	Cycling period, sec	Average intensity, protons per second
Operation at 300 GeV	2.8	5.7×10^{12}	3.4	8×10^{12}
Operation at 30 GeV with flat top	1.0	1.6×10^{13}	1.6	1.7×10^{13}
Operation at 30 GeV without flat top	0.4	4.0×10^{13}	1.0	2.8×10^{13}

From the point of view of intensity limitations due to the machine aperture, injection errors and emittance blow-up are somewhat worse in the case of booster injection, because of the additional processes of injection into the booster and ejection from it. We have seen, however, that careful design of the ejection path may reduce emittance blow-up to 25% and the field in the dc septum magnets can be very precisely stabilized. For our 300 GeV study, we have estimated that the use of the booster would give an additional emittance blow-up by a factor 1.4 and that the coherent radial excursion of the beam due to injection errors would have maximum amplitude of 7 mm with linac injection and 12 mm with booster injection. If the energy of the booster is larger by a sufficient amount than that of the linac, the larger adiabatic damping of the

at the cost of an increase in length of the linac; the latter would involve an expensive set of magnets. Both might be made partly ineffective by the large jitter in phase and energy in the linac, due to phasing errors. Parain has calculated that probably in a 3-GeV linac the bunching factor could not be reduced below 18.

The booster aperture must be such that the intensity in the main machine is not limited by space charge phenomena at injection into the booster. For example, a booster beam of 2×10^{12} protons per pulse is required to give 3×10^{13} protons per pulse in a machine with 15 times larger radius. This is another reason that makes desirable the relatively high booster injection energy, already required to reduce the RF frequency swing.

The results of the studies by K. Batchelor, A. Carne and J. M. Dickson at the Rutherford

Laboratory [17] show that an energy of 200 MeV could still be reached in a reasonably economical way by a structure of resonant cavities and drift tubes, similar to the present injectors of the CPS and of the AGS, possibly with a modified arrangement of drift tube supports. Other structures with high shunt impedances are also being studied and appear very promising. When it is considered that in the CPS, with a 50-MeV injector, 8×10^{11} protons have already been accelerated, it is clear that 200 MeV represent a comfortably high injection energy into the booster, also from the point of view of space charge phenomena.

5. The High Intensity «Parasitic» Beam

The injection time is only a small fraction of the cycle of the main machine. If the booster were run continuously, which would be an advantage for stability, its beam would be available must of the time for nuclear physics experiments, at the cost of a suitable beam transfer system. The duty cycle of this extracted beam would be unfavourable for many experimental techniques, but it might be improved by the addition of a simple storage ring, which might make it possible to obtain even a continuous spill-out. With a linac current of 100 mA, the average intensity of this «parasitic» beam from the 6-GeV injector discussed in our 300 GeV study might reach 4×10^{13} protons per second. The possibility of this use may be a capital argument in favour of a booster injector. Some increase of the booster energy, for example up to 8 or 10 GeV, may in fact be justified by its usefulness as an intermediate research tool.

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