A 60 GeV PROTON SYNCHROTRON WITH SEPARATED FUNCTION MAGNETS

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1. Introduction

An alternative to the concept presented in „Vorschlag zum Bau eines 40 GeV Protonénsynchrotrons" (Proposal on the Constuction of a 40 GeV Proton Synchrotron[1]) is discussed in which the wish for an increase both in energy and in intensity will be taken into account. The design energy is 60 GeV, the design intensity 10^{13} p/pulse.

For the proposed accelerator the experimental program at least during an initial operating period, is concentrated on counting experiments; however, this does not exclude the possibilities of future extensions in favor of bubble chamber and neutrino physics.

Counting experiments require a „long" beam pulse of constant intensity. An accelerator is used most efficiently when it provides this long beam pulse as an external beam. Therefore, the project submitted has been determined mainly by the requirements of an effective slow extraction.

The advantages offered by a booster synchrotron for reducing the beam cross-section in the main synchrotron and dividing the functions of RF-acceleration have been retained. Observation and correction of the closed orbit oscillations is needed and envisaged from the outset in order to attain the design intensity.

The machine is optimized for the design energy and intensity. If, for financial reasons, operation at lower energy or intensity is necessary during the initial phase (e. g., 40 GeV or 10^{12} p/pulse), the additional expense required to obtain full energy or intensity will be very low. This applies also to the shutdown period of the machine which is required for the installation of components.

The magnet lattice of the main synchrotron now is a separated function SF- structure: the circulating beam is bent and focussed by separate magnets; the former design provided for a structure with combined functions. To reduce the stored energy, the aperture of the bending magnets is adapted to the variable betafunction.

The conditions of calculation of the apertures of the magnets are identical to those in[2], p. 87 ff., except that the value of 1 so far assumed for the ratio of horizontal and vertical emittances following a 5-fold injection into the booster has been replaced by the value of 2.5 for injection into the main synchrotron.

The cost of the accelerator expressed as a function of rise time of the magnetic field increase strongly for rise times of less than 0.5 sec. This value was defined as the lowest permissible value. Cycle time was extended to 2 sec with the ejection time remaining constant at 0.4 sec.

2. Parameters Relating to Structure and Orbit

a) Separated-Function Structure

The proposal for the construction of a 40 GeV machine provides for the use of conventional gradient magnets in the main synchrotron. The structure selected is a FOFODODO structure. Medium-size free sections (1.22 m) extending between similar magnets will accomodate additional magnets and beam monitoring elements. Eight long free sections of the Collins type have a field-free length of 6.84 m between the adaptation quadrupoles. A favorable selection of structural parameters makes the maximum betafunction comparatively small (19. 2 m). Consequently, the vertical dimensions of the vacuum chambers can remain small also.

Meanwhile, the advantages of a structure using separated functions of the magnets have been stated repeatedly[2-5]. The 200 GeV NAL accelerator is built with the bending magnets and quadrupoles separated[6] . We selected the appropriate parameters for a bending magnet and a quadrupole; the corresponding magnets are under construction. There is a good chance of exceeding the anticipated fields of 1.8 T by a considerable percentage. The advantages offered by pure bending magnets against gradient magnets lie in the higher useful fields, since the symmetrical arrangement makes saturation effects appear later than in the case of gradient magnets. Though, in a way, the latter automatically provide for focusing, a machine equipped with gradient magnets will require a larger radius than a machine with separate bending and focusing fields (e. g., 225 m instead of 180 m for a 60 GeV machine). This increase in radius implies a corresponding additional expenditure for RF-power, vacuum equipment, tunnel houses and for general supply systems. It results in a proportional increase in radius of the booster synchrotron if the ratio of radii is fixed for other reasons (filling time, field-free sections required).

The result of cost studies[9] shows a slight increase in capital costs of the magnet system with increasing equilibrium orbit field, which is set off by a much stronger decrease of the capital costs for RF-system, vacuum system and ring tunnel. Additional savings in our case result from the smaller radius of the booster. In an SF-structure, insertions for accommodation of ejection, injection, and RF-acceleration resonators can be obtained easily by removing bending magnets from normal unit cells at places of the structure which are arranged symmetrical to each other (superstructure). It appears that appropriate selection of the length of a unit cell and proper positioning of the bending magnets help to attain effective ejection. The resulting structure is more compact than it would be if Collins insertions were used[9].

Due to the possibility of varying the Q-value, which is independent of the bending fields, a separated function structure is more flexible and easier to adapt to new conditions. Thus, Q-values=(integral—1/4) could prove to be more favorable for a future increase in intensity than the proposed Q-value of 10.25.

Separate excitation of bending and quadrupole magnets allows control of the Q-value during the acceleration cycle. Mereover, stabilization of the quadrupole excitation is possible at less expenditure than in case of common supply; the stability of the focusing fields is important for the quality of slow extraction.

The loss of accessibility to the vacuum chamber does not play any part compared to the advantages offered by an SF-structure because experience has shown that there will be no rupture of the vacuum chamber within the magnet units. A sufficient number of field-free sections are available for beam manipulation and extraction.

The arrangement of magnets finally selected is a result of optimization determined by the requirements of ejection.

Six long straight sections ($N_s=6$) of 2 x 8 m=16 m each will be provided for in the main synchrotron: two for RF-acceleration, one for injection, two for extraction—one of them for another extraction channel to be installed at a later date—and one as a reserve for future extensions serving other purposes. A FODO structure with two bending magnets between the quadrupoles was chosen. The possibility of a FOFODODO structure was rejected.

The selected number of unit cells is N=48, the number of betatron oscillations per revolution is Q=10.25.

If a different operating point, e.g., Q=10.75, were to appear more favorable for a possible increase in intensity through compensation of fields exciting the half-integral resonance[8], this can be achieved by a variation of the quadrupole fields relative to the bending fields. In this case the phase advance/unit cell increases by a factor of 10.75/10.25, while the betafunction and the momentum compaction function will decrease slightly. The maximum gradient of quadrupoles is 25 T/m instead of 24 T/m. All element lengths are unchanged. According to the criteria of selection used in[1] both Q-values are permissible.

b) Mean Radius

Apart from the structural parameters N, Q, N_s mentioned above, the mean radius depends significantly on the length of field-free sections, the maximum bending field, and the maximum gradient of the quadrupoles. In our case, the mean radius is 180 m. The maximum bending field (1.8 T) and the maximum gradient of the quadrupoles (24 T/m for a diameter of 8.5 cm) have been selected so that there is a reserve of about 20% for a possible increase in energy.

c) Maximum Beta Function and Apertures of the Magnets

In the structure selected the maximum beta function is obtained in the F-quadrupoles where it amounts to about 35 m. The horizontal and vertical apertures of the bending magnets are adapted to the shape of the β-function in the unit cell; the bending magnets B_1 adjoining the F-quadrupoles have the larger horizontal apertures, whilst the B_2 adjoining the D-quadrupoles have the larger vertical apertures This considerably reduces the energy stored in the bending magnets as well as the necessary magnet power: the stored energy is reduced from 9.5 MJ to 8.0 MJ and the average loss power from 4.5 MW to 3.9 MW. Moreover, the magnets are adapted to the course of the curved orbits in the radial direction. In this way, there will be no sagitta and, consequently, the horizontal aperture can be reduced by about 1 cm. Despite the separated function structure and the higher energy of particles the total number of magnets is increased only by a negligible amount relative to the number contained in the original proposal (300 instead of 256).

The calculation of apertures of the magnets was based essentially on the same conditions as stated in[1,2]. However, it is assumed now that the asymmetrical filling of the four-dimensional phase-space produced by multiple injection is not completely removed in the booster synchrotron during acceleration. The ratio of vertical to horizontal emittance during injection into the main synchrotron is assumed to be 1:2.5. Full symmetrization can be reached only by strong coupling mechanisms. Coupling can be achieved through positioning errors or space charge effects. There is complete coupling when the space charge density is infinitely high[7]. Experimental results obtained at intensities of 10^{12} particles in the circulating beam justify the assumptions. Experimental verification is necessary to find out whether a much stronger coupling exists for 10^{13} particles in the circulating beam. On the other hand, the correction of focusing fields in the future can be expected to bring about an increase in intensity over the conventional assumptions underlying all projects, this one included; cf[8]. Therefore, the intensity indicated can only be a guideline attainable under the assumptions made herein.

It is to be hoped that these values will be surpassed as a result of appropriate improvements.

The apertures indicated in the list of parameters include the vacuum chamber with a wall thickness of 2 mm in the main synchrotron and of 7 mm in the booster synchrotron. The horizontal aperture selected allows a theoretical efficiency of ejection of 97 % for a conventional thickness of the septum[9].

3. Slow Extraction

The beam is extracted slowly from the synchrotron in the following way: the horizontal Q-value of the machine is brought to the third-integral resonance at $\bar{Q}=10\ 1/3$ and the beam is excited to unstable non-linear betatron oscillations by a perturbing sextupole $\left(1 \text{ m long}, \frac{\partial^2 B}{\partial x^2} \approx 0{,}3 \text{ KG/cm}^2\right)$ ([1], section III, 7).

For the Q shift not the whole system of quadrupoles but only a single additional one is used; it must have a gradient of only 7 T/m for a length of 1 m, which means that it can be controlled more easily than the main quadrupoles. It is envisaged to install a fast control system for the power supply of the perturbing quadrupole to compensate for deviations of the Q-value from the ideal value caused by fluctuations of the current, and to keep the intensity of the extracted beam as constant as possible.

A cascade of septum magnets installed in a long field-free section guides the particles out of the zone of the ring magnets.

The septa are fixed and are not moved during each cycle. In selecting the structure, special attention was paid to allowing the most favorable configuration, with respect to extraction, of quadrupole, and septum. More details can be found in[9] p.25 ff. and[10].

The free section of 1.5 m length was arranged so as to be directly in front of the F-quadrupole; in this way it could accommodate a pre-septum.

4. Injection System

a) Selection of the Injection System

The selection of an injection system is governed by the two aspects of reliability and costs of the entire system; it might well be that the two criteria for selection show opposed tendencies. We re-examined the injection system, in particular weighing a multiring-booster against a fast synchrotron. Moreover, our considerations included the direct injection from the linear accelerator into the main synchrotron. Other schemes of injection were set aside for the same reasons as indicated in[1].

The arrangement employed in existing accelerators is the direct injection through a linear accelerator. As long as no excessive magnet apertures or injection energies are used, the number of particles is limited to comparatively small values as a result of space charge effects. A solution of this type could be considered, therefore, for the first stage of development.

With the given acceptances of the main synchrotron the space charge limit at 30 MeV is 2.5×10^{11} p, at 50 MeV it is 5×10^{11}p, and at 100 MeV it is 10×10^{11}p. To reach these values, the closed orbit oscillations must be reduced from the outset to less than 5 mm by means of beam correction magnets. The injection fields corresponding to the energies indicated are 70.8, 91,3 and 131 G, respectively. These low fields call for compensation of remnent and other perturbing fields during injection.

This has been achieved with the 70 GeV acceleretor in Serpukhov, but it requires additional expenditure in terms of correction magnets. The large variation in frequency (1:4) can be achieved by two separate RF-systems, the additional system of which accelerates the particles up to an energy of 2 GeV. This additional system could be installed in the long free section which is to constitute the reserve. The cycle time is hardly longer than that required with a fast booster synchrotron, since the particles reach the necessary energy of 2 GeV within the filling period (0.5 sec). The maximum savings in costs achieved by such a first stage represent the costs of the booster; additional expenditures are needed for correction of the injection field and another RF-system. The running in period will probably take longer than with a "full" design; the transition to full intensity by adding a booster will require a prolonged interruption of operation. These grave disadvantages are set off by savings of not more than DM 15 million during the first phase of the accelerator which will be overcompensated in the course of the subsequent development program.

Therefore, the use of a booster is planned from the outset. In the first draft a triple booster was proposed with the same cycle frequency as the main synchrotron. Meanwhile, the fast booster synchrotron has been included in the investigations.

The fast booster offers the advantage of a simple structure of the magnet system. The resonance supply of the magnets has been proven with existing electron and proton synchrotrons. Space charge effects are less critical in the case of high multiplicity. Greater expense is needed for RF-and control systems. The necessary filling time presents a clear disadvantage. On the other hand, a multi-ring system requires practically no filling time. Being a slow synchrotron, it is equipped with a simple RF-and magnet supply system.

However, beam guiding and beam matching are more complex. The problems of matching grow with the number of rings. As regards technical details, there is no clear advantage in favor of either of the two versions. Therefore, cost investigations were used to support decision making. The overall costs of the facility were used as criteria for selection. They were normalized to constant useful beam duration and constant cycle time, i. e., constant mean beam intensity. The slow and the fast versions differ, e. g. by the different rise times of the magnetic field in the main synchrotron and the different transfer energies. Within the limits of error of such estimates the two versions corresponding to minimum costs (fast booster synchrotron: $E_{LZ}=30$ MeV, $E_{ZH}=2$ GeV, and slow multi-ring booster synchrotron $E_{LZ}=40$ MeV, $E_{ZH}=3$ GeV), are identical (cf. [9], pp. 40). A fast booster was eventually chosen. An important argument was the possibility of increasing the average intensity at a later date by reducing the filling time.

b) Transfer Energies

The proposed accelerator consists of a cascade of four accelerators: ion source and electrostatic pre-accelerator, linear accelerator, booster synchrotron, main synchrotron. The efficiency and economy of the facility are determined to a large extent by the energies of transfer from one stage to the next. At injection into the linear accelerator, the energy of protons ranges from 0.5 to 1 MeV. Among other factors, it influences the quality of the beam but does not play any part in further considerations. Therefore, an optimization relates exclusively to the energies of transfer from the linear accelerator to the booster synchrotron, T_{LZ}, and from the booster to the main synchrotron, T_{ZH}. T_{LZ} has an upper limit, because the energy produced in the linear accelerator is more expensive than booster energy, and a lower limit, since the required frequency variation and aperture grow disproportionately in the booster. In a similar way, the upper limit of T_{ZH} is provided by the booster costs rising more steeply and the lower limit by the large frequency variation and aperture required in the main synchrotron.

The beam emittance furnished by the linear accelerator and the space charge limits in the circular accelerators exert considerable influence of the level of transfer energy.

It is assumed that for the currents in question (maximum about 70 mA) the beam emittance (ε) of a linear accelerator is proportional to the current supplied. In the course of acceleration, the normalized emittance ($E=\beta\gamma\varepsilon$) rises by multi-turn injection, transfer, and space charge. This is taken into account by the appropriate factors V_i:m-fold injection accompanied by loss (50%) (cf. [9], p. 72) $V_m=0.6m$; transfer linear accelerator-booster $V_{LZ}=1.3$; transfer booster-main synchrotron $V_{ZH}=1.5$, space charge $V_{RL}=1.2$; hence, the normalized emittance exceeds the normalized linac emittance by a total factor of $V=(0.6 \cdot 5 \cdot 1.3 \cdot 1.2 \cdot 1.5= =7.0$ at the end of acceleration and on the condition of a 5-fold injection. Under the assumptions made above the emittance of the beam orbiting the synchrotron is proportional $E\beta_{i,\ zs}$, where E is the normalized linac emittance at a current of 100 mA, and $\beta_{i,\ zs}$ is the particle velocity expressed in units of the velocity of light upon injection into the booster synchrotron. The lower limit of the permissible beam emittance in the synchrotron is given by space charge forces. For calculation the conventional Laslett's formula with an allowed shift of the Q-value of 1/4 is used. It is assumed that an emittance ratio of horizontal to vertical beam emittance obtained by multiturn injection will be not smaller than 2.5 even at the end of acceleration. The set of parameters finally chosen, $n=6$, $T_{LZ}=30$ MeV, and $T_{ZH}=2$ GeV, with a fast booster approaches minimum overall costs. It calls for a normalized beam emittance referred to 100 mA of the linear accelerator of $18.9\pi \cdot 10^{-6}$ m · rad. The vertical aperture of the magnets in the main synchrotron must be at least 43 mm at the point of the maximum vertical beta function.

c) Linear Accelerator

No specific investigations were conducted on the selection of appropriate parameters for the linear accelerator. This paper will summarize only the principal requirements. The current circulating in the booster at injection amounts to 120 mA with an efficiency of transfer of 90% and 10^{13} particles orbiting in the main synchrotron. The injection into the booster extends over five turns with a capture efficiency of 50%; therefore, the required current of the linear accelerator is 48 mA. The useful beam period is 13 μsec, the repetition frequency 10 c/s.

The resulting emittance required (at 50 mA and 30 MeV) is $37\pi \cdot 10^{-6}$ m · rad. The maximum momentum spread after debunching should not exceed ±1%. Compared with other existing and planned proton linear acelerators these are no extreme requirements; so the linac can be built with the conventional technology.

d) Booster

The main data relating to the booster synchrotron are summarized in a list of parameters (Section 5). Some important parameters, such as the multiplicity $n=6$ and the initial and final energies of 30 MeV and 2 GeV, respectively, were defined by cost investigations for the whole system (cf. Section 4.b). Preference was given to an even value of n, because it does not exclude the option for a future twofold injection. This allows to reduce the filling time, which increases the average intensity of the whole facility. This is based on the conditions of managing an effective twofold extraction and control of the space charge instabilities in the booster since twice the number of particles per pulse would have to be accelerated.

The repetition rate together with multiplicity determines the filling period. With the normalization of intensity indicated above minimum costs are around 10 c/s. Conseouently, the filling period is 0.5 sec for a cycle time of 2 sec.

The structure of the booster is a FOFODODO structure with gradient magnets. Gradient magnets represent the more economical solution in all cases where the radius is not determined by the maximum attainable field (cf. [9]. p.152 ff.). In the case of booster synchrotron the radius is fixed by the multiplicity chosen.

The length of the free section required for ejection is 2.5 m. A free section of 1 m minimum length is needed for accommodation of the correction and monitoring elements. The fraction of the circumference occupied by the RF-cavities is about 10% for acceleration from 20 MeV to 2 GeV with a repetition frequency of 10 c/s. Consequently, about 10 RF-resonators of 2 m length each have to be accommodated. Aside from a superstructure with Collins insertions, which is neither necessary nor advantageous as compared with a simple structure, the free sections between the F-magnets can be used for beam monitoring and correction, the longer free sections between the D-magnets for ejection, injection and RF-acceleration.

Minimum costs of a fast booster are achieved for maximum fields between 0.5 and 1 T. The Q-value of the machine should be over 4.5 so that the transition energy is not reached in operation up to 2 GeV. For a phase advance per unit cell of not much more than $\frac{\pi}{2}$, $N > 18$. With the free sections envisaged and the fixed radius as well as the upper limit of 1 T for the maximum field: $N < 30$. For $Q=4.75$ and $N=20$ the operating point is removed from resonances of a low order and favorable for an increase in intensity. The structure selected is characterized by a minimum amount of stored energy, since structures with higher N result in higher maximum fields. The savings in terms of aperture caused by a slightly smaller beta function cannot outweigh this disadvantage with respect to the stored energy.

5. List of Parameters

Scheme: Linear accelerator Alvarez type (30 MeV)
Booster (2GeV)
Fast cycling (10 c/s), gradient magnets
Main synchrotron (60 GeV)
Bending magnets, quadrupoles in FODO arrangement

Characteristics:

Maximum kinetic energy	60 GeV
Number of particles circulating	10^{13} p/pulse
Cycling time for maximum flat top	2 sec
Magnet cycle: filling time	0.5 sec
rise time	0.6 sec
flat top (max.)	0.4 sec
decrease time	0.5 sec

Mean radius of the orbit	180 m
Number of superperiods	6

Main synchrotron:

Injection energy	2 GeV
Transition energy	9.38 GeV
Magnetic bending radius	113 m
Number of unit cells with bending magnets	48
Structure of unit cells with bending magnets	$FO_sB_1O_sB_2O_m$ $B_2O_sB_1O_m$
Number of unit cells without bending magnets	6
Structure of unit cells without bending magnets	FO_1FO_1
Number of betatron oscillations/revolution	10.25
Phase advance per unit cell	68.2°
Maximum beta function	34.9 m
Maximum momentum compaction function	4.7 m
Maximum bending field	1.8 T
Injection field	0.082 T
Maximum gradient of quadrupoles	24 T/m
Apertures of the magnets: quadrupoles	8.5 cm dia.
bending magnet B_1	$8.5 \cdot 4.8$ cm^2
bending magnet B_2	$6.5 \cdot 3.6$ cm^2
Number of bending magnets	192
Length of bending magnets	3.69 m
Number of quadrupoles	108
Length of quadrupoles	0.94 m
Length of short free sections O_s	0.3 m
Length of medium-size free sections O_m	1.5 m
Length of long free sections O_1	9.5 m
Maximum excitation of bending magnets B_1	$7.6 \cdot 10^4$ Awdg.
Maximum excitation of bending magnets B_2	$5.7 \cdot 10^4$ Awdg.
Maximum excitation of quadrupoles	$7.6 \cdot 10^4$ Awdg.
Stored energy	9.3 MJ
Average power loss	5.8 MW
Peak power	36 MW
Maximum current density in bending magnets	400 A/cm^2
Maximum current density in quadrupoles	1.000 A/cm^2
Revolution frequency at injection	0.25 Mc/s
Revolution frequency at final energy	0.27 Mc/s
Number of harmonics	120
Frequency of acceleration voltage	30.2—31.9 Mc/s
Frequency deviation f_e/f_i	1.06
Bandwidth ratio	0.055

Circumferential voltage	840 kV
Average gain in energy/revolution	365 keV
Stable phase	30^0
RF-power	347 kW
Beam power	154 kW

Booster synchrotron:

Type: Fast booster with combined function magnets	
Maximum kinetic energy	2 GeV
Injection energy	30 MeV
Transition energy	4.0 GeV
Numper of particles circulating	2.10^{12} p/pulse
Repetition frequency	10. c/s
Number of cycles of main synchrotron	6
Mean radius of the orbit	30 m
Magnetic bending radius	16.3 m
Number of unit cells	20
Structure of unit cell	$FO_mFO_sDO_lDO_s$
Number of betatron oscillations/revolution	4.75
Phase advance per unit cell	85.5^0
Maximum beta function, horizontal	13.5 m
Maximum beta function, vertical	10.8 m
Maximum momentum compaction function	2.0 m
Maximum bending field at equilibrium orbit	0.58 T
Injection field	0.05 T
Profile parameter n/ρ	$3.71\ m^{-1}$
Field index n	60.2
Number of gradient magnets	80
Length of F-magnets	1.25 m
Length of D-magnets	1.31 m
Length of short free sections O_s	0.30 m
Length of medium-size free sections O_m	1.22 m
Length of long free sections O_l	2.50 m
Useful magnet aperture (including vacuum chamber)	$16.6 \cdot 9.2\ \text{cm}^2$
Stored energy	0.45 MJ
Average power loss	0.72 MW
Time constant L/R	0.98 sec
Maximum current density	$400\ \text{A/cm}^2$
Revolution frequency at injection	0.39 Mc/s
Revolution frequency at ejection	1.51 Mc/s
Number ot harmonics	20
Frequency of acceleration voltage	7.8—30.2 Mc/s
Frequency deviation f_e/f_i	3.84

Bandwidth ratio	1.17
RF-power	164 kW
Beam power	11.8 kW
Maximum circumferential voltage	90 kV

Linear accelerator:

Maximum kinetic energy	30 MeV
Maximum current	48 mA
Emittance	$37\pi \cdot 10^{-6}$ m · rad

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ДИСКУССИЯ

Billinge: Is it not true that 10^{13} protons per pulse at 60 GeV can be achieved with simply a 200 MeV Linac and Main Ring? This would be cheaper and less complicated.

Heinz: Less complicated is right, but cost optimization studies included in[9] show that the booster version is the more economic choice. The main savings are due to the smaller vertical aperture of the magnets in the main ring. A 200 MeV linac is estimated to cost 50 Mill. Deutsche Mark, that is about 60% of the total machine cost including a 30 MeV linac and a 2 GeV fast cycling booster.

Плотников: Каково отношение аксептанса бустера и эмиттанса пучка инжектора?

Heinz: The emittance of the linac is $37\pi\,10^{-6}$ mrad, the acceptance of the booster $148\pi\,10^{-6}$ mrad yielding a ratio of 1:4.