INJECTION AND BEAM TRANSFER SCHEME OF THE JAPANESE PROTON SYNCHROTRON PROJECT

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Abstract

The machine which will be installed at the National Laboratory for High Energy Physics in Japan is an 8-GeV slow-cycling separated-function type proton synchrotron. For financial reason and man power problems, the machine will be operated at about 8-GeV and at a moderate intensity at the first stage. The energy, however, can be raised up to 12-GeV with an additional fund for power stations and the intensity to 10^{13} p/s by successive improvements. The injection scheme for this machine has been examined in various points, and a combination of a 500-MeV fast-cycling booster and a 20-MeV linac was chosen. In this paper, some physical and technical problems concerning such a cascade injection scheme of relatively low energy machines will be discussed. In particular, emittance-acceptance matching between the booster and the main ring and between the linac and the booster should be carefully studied together with the space-charge problems. The beam-transfer system from the booster to the main ring is also an important problem in respect that a very fast timing control is needed for the synchrotrons phase matchings.

1. Introduction

The machine which will be installed at the National Laboratory for High Energy Physics is an 8-GeV slow-cycling separated-function type proton synchrotron. The bending magnet of this synchrotron has a gap of 5.6 cm and a useful width of 12.0 cm. Several injection schemes for this synchrotron have been considered; namely

A) 20-MeV Linac + 500-MeV Booster
B) 50-MeV Linac
C) 2~4-MeV Van de Graaf + 500-MeV Booster
D) 20-MeV Linac

Consideration of space charge effects indicates that the highest energy beam can be attained with Scheme A, although several problems are present in the beam transfer system. Scheme B is conventional and the most reliable method, but the space charge limited intensity is about 1/10 of that of scheme A. The intensity can be raised somewhat to about 2.5 x 10^{12}p/s by increasing the gap of magnets to 8 cm (case B'). Scheme C has the advantage that heavy ions can be accelerated as well as protons, but the intensity is low and the range of RF modulation is wide (about 1:12). In scheme D, the intensity is low and the magnetic field of the main synchrotron must be carefully controlled due to low injection energy although this method is immune from financial difficulties. Intensity vs. cost is shown in Fig. 1 for various schemes mentioned above, where C and C' denote injection with 2-MeV and 4-MeV van de Graaf accelerators, respectively.

Among these injection schemes, scheme A has been chosen primarily because of its high space charge limited intensity though the emittance-acceptance matching from the linac to the booster and from the booster to the main synchrotron sets somewhat lower intensity and some technical difficulties are as yet present.

2. Booster Injector

The 500-MeV booster is an alternating gradient synchrotron capable of ac excitation at 20 Hz with a maximum field of 11.018 kG. The design emphasis is on raising the space-charge limited current in the 8~12-GeV main synchrotron ring, but the booster will also be used for intermediate energy physics experiments as future option. The general layout of the synchrotron is shown in Fig. 2. Consideration of the equipments installed in the booster requires about eight field-free sections of approximately 2m in length. We fixed the number of field-free straight sections as eight and compared the lattices of the type DFDO, FDFO, FDO and DFO, where F(D) denotes a horizontally focusing (defocusing) sector and O denotes a field-free section. In all these lattices, acceptance consideration favors the number of betatron oscillations per revolution ν of ν =1.75 (corresponding to phase advance per period μ of 78.5°) and ν = 2.25 (corresponding to μ = 101.25°). The resonant depolarization of the polarized proton beam occurs at 240-MeV for ν =2.25 while no such effect occurs for ν =1.75. Since the booster synchrotron will be used for low energy physics experiment, the ν-value of 1.75 is chosen. The synchronization process between the beam bunch in the booster and the rf bucket in the main synchrotron requires a large separation between the transition energy and the final energy of the booster. The transition energies T of the booster lattices are listed in Table 1. When the path-length perturbation method is employed for synchronization, for example, the outward displacement of the beam of 15mm is required for T =760-MeV and RF accelerating voltage of 1KV, while the outward displacement of 68 mm is required for T =600-MeV, an unacceptable value. Thus, from the results in Table 1, the FDFO structure must be selected.

The acceptance of the main synchrotron left for betatron oscillations, in which the closed orbit distortion of 98% probability, the sagitta and the aperture for momentum spread are subtracted from the aperture, is 6.09 πcm.mrad horizontally and 1.98 cm.mrad vertically, which correspond to normalized acceptances of 7.0 πcm. mrad and 2.30 πcm.mrad, respectively. The normalized emittance of the booster is chosen to be about 5 πcm.mrad horizontally and about 1.2 πcm.mrad vertically, taking into account the emittance blow-up factor of 1.4 in beam transfer system, while the design value of the normalized emittance of the linac is πcm.mrad for 100 mA peak current. The intensity of the main synchrotron set forth by this emittance-acceptance consideration amounts to about 2 x 10^{12} p/s. In order to attain the space-charge limited intensity, various improvements, such as the improvement of the linac emittance, the injection into vertical phase space etc., are required. The correction of the closed orbit distortions further increases the intensity.

The general parameters of the booster synchrotron are summarized in Table 2.

3. Beam Transport System

The schematic layout of the beam transport system is shown in Fig. 3. The beam from the linac is debunched by a debuncher to reduce longitudinal space-charge effects and passes through the phase space matching section and the achromatic system. The achromatic matched beam is injected into the booster by multiturn injection using an inflector and pulse magnets. The fast ejected beam from the booster is injected into the main ring by use of an inflector and a fast kicker magnet. In this beam transport system, matching is taken not only in phase space but also in momentum dispersion. Thus, the first section (from the septum magnet to the bending magnet B_2) makes the beam dispersionless, the second section (between bending magnets B_2 and B_3) makes transverse phase space matching feasible, and the last section (from B_3 to the inflector in the main ring) is used for matching in dispersion.

4. RF acceleration

In order to reduce the momentum and radial spread of the beam in the accelerating process, it is preferable to make the accelerating voltage as low as possible, while higher RF voltages are preferred from the consideration of RF capture efficiency and longitudinal space-charge effects. In the present scheme, the RF programming, in which the beam is accelerated while filling up the stable bucket of phase oscillation with a beam$^{1)}$, is employed. The RF voltage at injection Vinj of 1KV will be used from aperture consideration. To supply a beam whose amplitude of phase oscillation is about ± 90°, the voltage at ejection will be 0.4 kV.

5. Synchronization

The bunched beam from the booster should be injected into the RF bucket of the main synchrotron with 100% efficiency. In this process, not only is the energy of the beam from the booster the same as the injection energy of the main synchrotron, but also the phase of the booster beam bunch must be synchronized with the phase of the RF bucket of the main ring. Since this synchronization process makes use of the synchrotron oscillation of the beam in the RF bucket of the booster, the synchrotron oscillation frequency should be high enough, and thus the transition energy of the booster must be separated from the final energy of the booster as much as possible. Three methods of synchronization have been proposed$^{2)}$, namely,

a) Path-length perturbation method
b) Phase lock method
c) Long range homing method

When the path-length perturbation method is used, the beam must be displaced outward by 15 mm at the start of the synchronizing process in the case where the transition energy is 760-MeV and RF accelerating voltage is 1KV. In the phase lock method, the magnetic field at ejection is made lower than the maximum field and the synchronizing is done while the magnetic field is higher than the field at ejection. The long range homing method is preferable since the phase change of the beam is slow, but the method suffers from technical difficulties.

There is another method utilizing phase slip due to small difference between the two RF frequencies. Let the tolerable momentum error of the beam captured in the main ring be 10^{-3} . Near the maximum energy of the booster, i.e. 500-MeV, the revolution frequency of the beam having 99.9% of the final momentum is fmax-2kHz. This state is reached about 525 μs before the time of maximum field. If the magnetic field is held constant during this period, the phases of the booster beam and the main ring RF system coincide twice in one ms. The coincidence circuit measures the phases and triggers the ejection system when the two phases coincide. Alternatively, the frequency difference can be made by slightly changing the effective radius of the booster.

References

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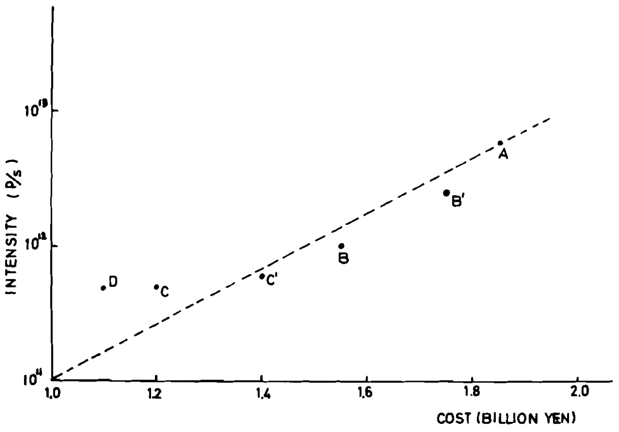

FIG.1 INTENSITY vs.COST

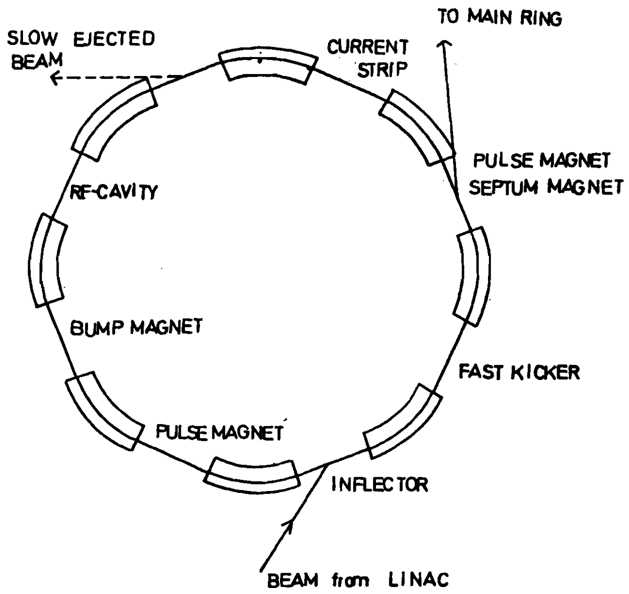

FIG.2 BOOSTER PLAN VIEW

Table 1

Transition Energy of the Booster (MeV)

ν	FDFO	DFO (FDO)	DFDO
1.25	270	205	160
1.75	760	630	490
2.25	1280	980	760

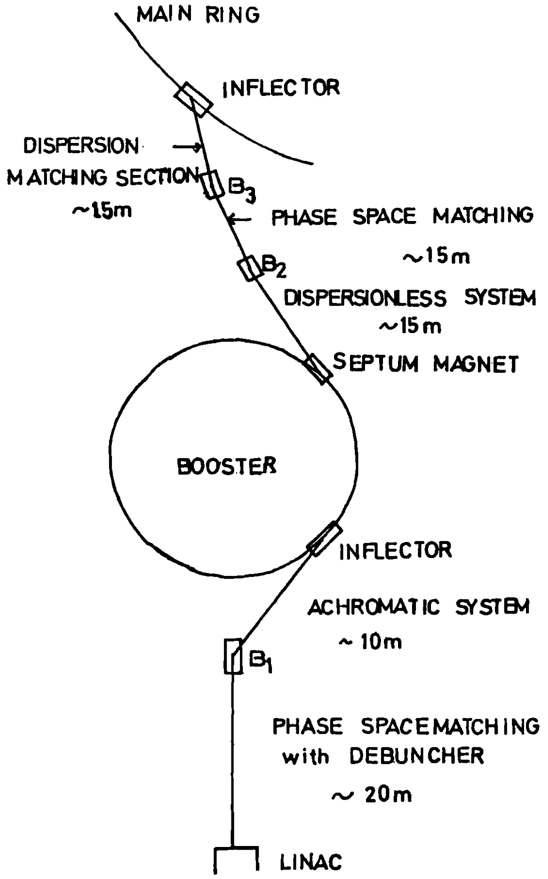

FIG.3 SCHEMATIC VIEW OF BEAM TRANSPORT SYSTEM

Table 2

Booster Parameters

Max. Kinetic Energy	500-MeV
Repetition Rate	20 Hz
Max. Magnetic Field	11.018 kG
Average Radius	6.000m
Radius of Curvature	3.300m
Number of Betatron Oscillation per Revolution	1.75
Number of Cells	8
Structure of Cell	FDFO
Gap of Magnet	72 mm
Useful Half Aperture horizontal	70 mm
vertical	28 mm
Injection Kinetic Energy	20-MeV
Magnetic Field at Injection	1.967 kG
Injection Angle from Linac	22.5°
Energy spread of the Injected beam	±1.0%
Revolution Frequency	1.617-6.031 MHz
Harmonic number of RF	1