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THE KEK BOOSTER TO MAIN RING BEAM TRANSFER SYSTEM

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Abstract

The construction and operation of the system to transfer the 500 MeV proton beam from the fast cycling booster synchrotron to the main ring are described. The observations of beam properties in the transfer process show that the emittances of the beam extracted from the booster are properly transformed to the acceptances of the main ring. The transfer efficiency is measured to be close to 100 %.

Introduction

The KEK 12 GeV proton accelerator is a cascade type synchrotron, and has a 500 MeV fast cycling synchrotron, booster, between a 20 MeV lianc injector and a 12 GeV main synchrotron. The linac and booster are operated at 20 Hz, while one main ring cycle takes about 2 sec. The main ring has a flat injection field porch lasting about 0.5 sec. and starts the acceleration after accepting nine successive booster pulses. The beam transfer from the booster to the main ring is composed of three processes: (i) the extraction from the booster, (ii) the beam transport between the booster and the main ring, and (iii) the injection into the main ring. To achieve the least possible transfer loss, we adopt a system in which the beam is transferred to the main ring with preserving its longitudinal bunch structure in the booster.[1] Accordingly, the booster extraction and the main ring injection are done by the fast process using fast kicker magnets. In the transport line, the beam shape from the booster is matched to the main ring acceptance in the transverse phase space and the momentum dispersion characteristics.

Booster Extraction

The 500 MeV booster beam is extracted horizontally within one turn by a system consisting of a pair of bump magnets, three units of fast kicker magnets, and two septum magnets. The arrangement of these elements in the booster ring is illustrated in Fig.1. As the booster field reaches the top, the two bump magnets excited with 35 μs wide halfsine pulsed currents produce a half-wavelength orbit bump which has the maximum amplitude at the upstream extraction septum. The septum is positioned out of the horizontal booster aperture required for the multi-turn injection, and beam is brought close to the septum coil at the top of the bump field. The final inflection of about 15 mr to put the whole beam into the septum aperture is given by the fast kickers located upstream of the septum by 3/2 π radians in the betatron oscillation phase.

The harmonic number of the booster is one, and the phase spread of the bunch at the end of the acceleration is about 150° for the acceleration frequency of 6 MHz. Therefore, for the one turn bunch extraction, the kicker field must rise within 90 nsec including travelling time of the pulsed current through the magnet, and keep a constant amplitude for about 80 nsec. The present kicker magnet is a full aperture and transmission line type, which has C shaped ferrite cores and fin plates forming capacitances distributed along the magnet.[2] The specifications for a unit of the kicker are length = 32 cm, number of unit cell = 12, inductance = 3.5 μH/m, capacitance = 2.9 nF/m, characteristic impedance = 25 Ω, pulse rise time = 30 ns, pulse travelling time = 40 ns, and field strength = 450 G/40 mm gap. The driving current pulse of 1.6 kA/40 kV is generated by discharging a coaxial cable charged at 80 kV into a matched resistance through the magnet. Deuterium filled thyratrons (EEV-CX1171) are used as the switches.

Two septum magnets of different septum thickness are used in series to eject the booster beam into the transport line.[3] The specifications for the thick/thin septum magnet are length = 0.8 m/0.5 m, gap height = 25 mm , septum thickness = 10 mm (two turn)/5 mm (one turn), deflection angle = 150 mr/50 mr, and field strength = 6.6 kG/3.6 kG. The currents to drive the magnets are 4 msec wide halfsine pulse of 20 Hz, and the peak values are 6.6 kA/7.3 kA for the thick/thin septum. To make the power supply voltage and current reasonable values, 0.5 ∿ 1 kV and ≤ 1 kA, a step down transformer is inserted between the power supply and septum magnet. Undesirable effects of the pulse transformer due to pulse drooping are eliminated by feeding the pulse current to the septum through high current series diodes and shunting the secondary winding of the transformer with high resistance.

The beam measurements in the transport line following the booster extraction channel have proved that the extraction has been performed without giving any observable deteriorations to the beam in its intensity and structures in the transverse and longitudinal phase space.

Transport Line between the Booster and the Main Ring

The transport line which links the booster with the main ring is 50 m long and has two bends of 21°. At the middle of the line, there is a branch to send the booster pulses, which are not used for the main ring injection, to the facilities which utilize high intensity intermediate energy protons. The booster is expected to afford an average proton current of about 1.5 μA to them. As the focusing structure of the booster is quite different from that of the main ring, the transport line must transform the transverse emittances and momentum dispersion characteristics of the extracted beam to those which match to the main ring.

The configuration of the present transport line is illustrated in Fig.2. The line consists of ten quadrupole magnets, two bending magnets, and nine steering magnets. To tune the line, six secondary emission type beam profile monitors and two beam current monitors are installed in the line. The most distinctive of this structure is in concentrating the role of all matching functions on four quadrupole (Q_1 ∿ Q_4) which are inserted between the booster extraction septum and the first bend of the line. The following six quadrupoles (Q_5 ∿ Q_{10}) are so aligned that the main ring focusing structure is extended back to the first quadrupole (Q_5) after the first bend.[4] This matching scheme is very simple and can provide only limited degree of tuning, but the computer calculations prove that the combination of the four quadrupoles has matching solutions for possible variation of the booster beam emittance including the momentum dispersion.

The beam emittances in the transport line have been obtained by the same procedure as used at BNL.[5] Assuming the shape of the emittance to be an ellipse in the phase space, horizontal and vertical half beam width Δx and Δy at a distance ℓ downstream from a quadrupole with focusing strength g (inverse of the focal length) change as $(\Delta x)^2 = a_x g^2 + b_x g + c_x$ and $(\Delta y)^2 = a_y g^2 + b_y g + c_y$, when g is varied. As the measurements are performed in the region of g where the focal length is much longer than the length of the quadrupole magnet, the thin lens approximation is applied to the quadrupole. The coefficients a, b, c are parameters related with the emittances at the quadrupole. For instance, horizontal and vertical emittance size ε_H and ε_V (phase space ellipse area divided by π) are expressed as $\varepsilon_H = (a_x c_x - \frac{b_x^2}{4})/\ell^4$ and $\varepsilon_V^2 = (a_y c_y - \frac{b_y^2}{4})/\ell^4$.

In the present experiment, we used the combination of the profile monitor P_r2 and the quadrupole Q_3, and determined the parameters a, b, c by least square fitting $(\Delta x)^2$, $(\Delta y)^2$ measured as a function of g to the quadratic. The obtained horizontal and vertical emittance size of the 500 MeV extracted booster beam are ε_H = 36 mm·mr and ε_V = 16 mm·mr, which somewhat smaller than the designed value of the main ring acceptance size A_H = 80 mm·mr and A_V = 20 mm·mr. Figure 3 shows an example of the quadratic fit to the measured $(\Delta x)^2$. The phase space ellipse shapes at Q_3 deduced from these parameters were found to agree with those expected from the design calculation. The horizontal and vertical beam half widths at the profile monitors along the transport line are plotted in Fig.4. The solid lines indicate the calculated beam envelopes for ε_H = 36 mm·mr and ε_V = 16 mm·mr which satisfy the matching requirements between the booster and the main ring. It is seen that the matching in the transverse phase space is realized fairly well by the present transport system.

Main Ring Injection

At the end of the transport line, the matched beam is injected horizontally into the main ring by use of the septum magnet system, which are similar in design to those for the booster extraction. The two septum magnets are located in series in the first long straight section of the main ring for injection, and give a deflection of 200 mr to the beam emerging out of the transport line. Though the septum magnets are positioned entirely out of the main ring aperture, the leakage field on the main ring side of the septum must be made as weak as possible. The septum magnets are excited nine times in the injection period of about 0.5 sec, during which the beams transferred successively from the booster keep coasting in the main ring and receive effects of the leakage field. Then, the leakage field of the injection septum is reduced to less than 5 G at the outside surface of the septum plate by shielding the septum surface with a specially shaped 0.35 mm thick iron sheet.[3]

The main ring injection orbit following the septum inflectors has a horizontal position of 50 mm and an angle of -15 mr with respect to the central orbit at the main ring defocusing quadrupole I-1D, and after a unit cell of the main ring lattice it crosses the closed orbit with an angle of -9 mr at 1.5 m downstream of the focusing quadrupole I-2F in the second long straight section for injection as illustrated in Fig.5. At the crossing point four units of the fast full aperture kicker magnet, which is same type as the booster kicker, are installed, and complete the injection process by deflecting the beam on the injection orbit onto the central orbit. As the harmonic number of the main ring is nine and the booster bunch structure is exactly preserved in the main ring during the injection period, the booster bunch phase spread of about 150° at the beam transfer affords time separation of about 90 nsec between the head of the bunch and the tail of the preceding one in the main ring. The rise and fall time of 80 nsec of the present kicker are just enough to satisfy the requirement that the kicks for the injection should not affect the bunches coasting in the main ring.

As even small errors in the injection orbit may cause a loss of the beam injected in the main ring, the injection system should carefully be tuned so that the coherent betatron oscillation amplitudes due to the injection errors do not exceed the aperture allowance of the main ring. The fine tuning of the injection line is performed by using the pairs of vertical and horizontal steering magnet, St6-St7 and St8-St9, in the transport line, and the destructive profile monitors which are installed in the injection orbit and extracted after the tuning. The injection errors are directly measured as deviations of the beam positions at the injection from the closed orbit, while the errors in the phase space matching cause an increase of the beam envelope which can be measured by the profile monitor of the moving thin wire type. The observations have shown that the emittance growth due to these errors are less than 40 % and 10 % in the horizontal and vertical phase space, respectively. Th beam transfer efficiency has been measured by using three identical current monitors installed in the booster, the transport line, and the main ring, and found to be 100 % within about 5 % of the monitor errors. Figure 6 is a typical example of the main ring beam intensity at injection which shows step like increases of the current corresponding to nine successive transfers of the booster pulse.

Acknowledgements

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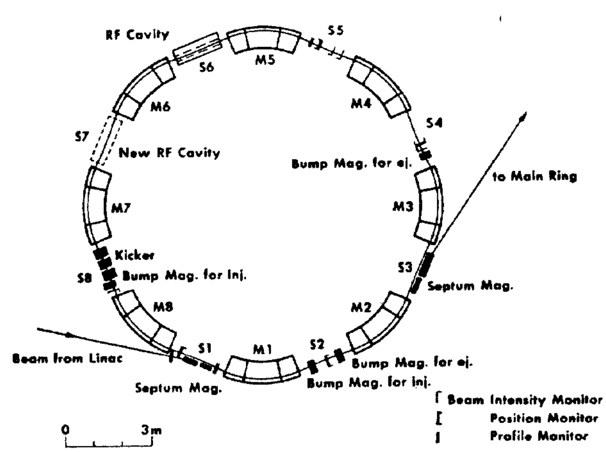

Fig. 1 Arrangement of the beam handling elements in the booster ring.

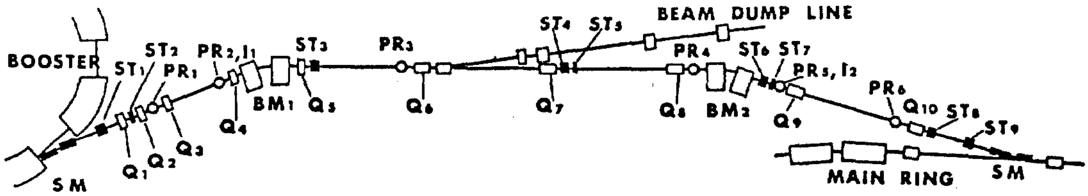

Fig. 2 Beam transport line between the booster and the main ring. The line is 50 m long and the elements indicated are Q=quadrupole magnet, BM=bending magnet, ST=steering magnet, SM=septum magnet, PR=profile monitor, and I=intensity monitor.

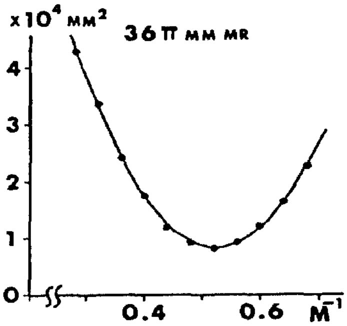

Fig. 3 Squares of horizontal half beam width at PR2 are plotted as a function of Q3 strength. Solid line is a least square fit to the data for emittance of 36π mm·mr.

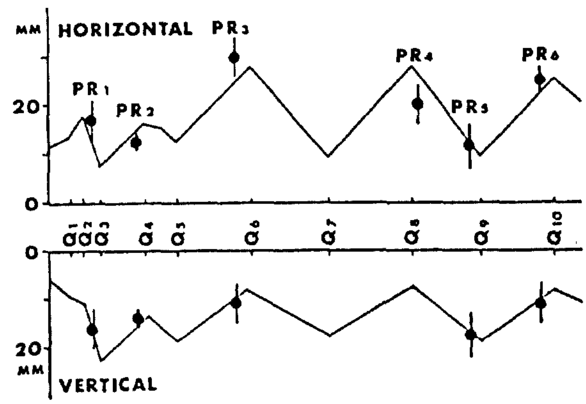

Fig. 4 Horizontal and vertical half beam widths at the profile monitors in the transport line. Solid lines indicate the beam envelopes designed for emittances E_H= 36π mm·mr and E_V= 16π mm·mr.

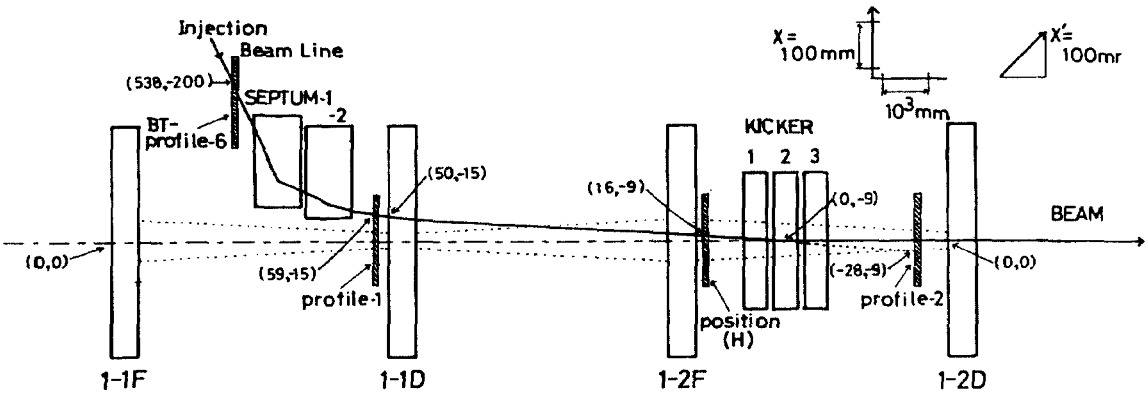

Fig. 5 Main ring beam injection system. Numbers given as (x, x') indicate horizontal position (mm) and angle (mr) of the injection line. 1-1F, 1-2F and 1-1D, 1-2D are focusing and defocusing quadrupoles of the main ring, respectively. Dotted lines are beam envelopes in the main ring at injection.

Fig. 6 A typical example of the main ring beam intensity at injection which shows step like increases of the current corresponding to nine successive transfers of the booster pulse every 50 msec. About 50 % of the beams transferred from the booster are lost in the main ring during the injection period of 0.5 sec.