THE H^- CHARGE-EXCHANGE INJECTION SYSTEM IN THE BOOSTER OF THE KEK 12 GeV PROTON SYNCHROTRON

T. Kawakubo, I. Sakai, H. Sasaki and M. Suetake

National Laboratory for High Energy Physics
Oho-machi, Tsukuba-gun, Ibaraki-ken, 305, Japan

Summary

In the KEK 12 GeV proton synchrotron, recently the injection scheme of the booster synchrotron was converted from the proton multiturn injection method into the H^- charge-exchange injection. The injection energy was also up-graded from 20 MeV to 40 MeV. In this paper, the new charge-exchange injection system is described. Moreover, the performances of this system at different injection energies and different thickness of the carbon stripping foils are reported and analyzed. In spite of the lower injection energy compared with those of the other proton synchrotrons applying the charge-exchange injection method, it is shown that this injection scheme is quite effective to increase the beam intensity of the booster synchrotron.

1. Introduction

A multi-turn injection scheme using direct injection of 20 MeV protons was initially designed for the injection of the 500 MeV booster synchrotron. In spite of the great effort to increase the accelerated beam intensity since the commissioning in the fall of 1974, the maximum achieved intensity remained at 6.8×10^{11} ppp, while the final design value was 1.1×10^{12} ppp.

To remove the intensity barrier, a charge-exchange injection scheme using an H^- ion beam was proposed, and the project was started in 1980. In this scheme, negative hydrogen ions from the linac are injected into the synchrotron and stripped to protons by a charge-stripping foil on the injection bump orbit, which is formed for only the injection period. In this scheme, it is possible to make the orbit of the recirculating proton coincide with that of the injected H^- ions at the stripper position. In principle, therefore, by continuous injection of H^- ions, such an injection scheme has no limitation on the accumulation of protons in the same orbit in the synchrotron, except for the limitation from the space-charge effects. In practice, however, the number of accumulated protons is limited by blow-up of the beam emittance and by broadening of the energy spread of the circulating beam at traversing the charge-stripper. The mean scattering angle and energy loss of protons penetrating through a material are approximately proportional to the inverse of the kinetic energy of the incident protons in the energy range of interest. In order to reduce those effects, therefore, it is desirable that the injection should be done with a highest possible injection energy and with a finest possible charge-stripper.

At the initial stage of the commissioning, the injection energy of 20 MeV in the KEK booster was lowest among those at the laboratories where the H^- charge-exchange injection scheme has been applied, e.g., 50 MeV at ANL, 200 MeV at FNAL, 200 MeV at BNL and 70 MeV at RAL. In spite of such circumstances, the maximum accelerated beam intensity of 1.0×10^{12} ppp was achieved with the 20 MeV H^- ion beam.

At the fall of 1985, the injection energy was raised to 40 MeV, and the maximum intensity of the booster synchrotron reached 1.6×10^{12} ppp. This was mainly limited by the RF beam loading, and the captured beam intensity just after injection process was almost twice the beam intensity at the maximum energy.

In this paper, the injection system and parameters of the components are described. The performances of this system at the 20 MeV and 40 MeV injection and with different thickness of the carbon stripping foils are also reported.

2. Injection System and Components

The H^- charge-exchange injection system at 20 MeV was installed in the straight section No.1 of the booster ring as shown in Fig. 1a.[1] In order to remove the septum magnet and simplify the beam handling at 40 MeV, the bump magnet are arranged asymmetrically as shown in Fig. 1b. The dotted line and solid line in these figures indicate the orbit of the H^- ion beam and the circulating proton beam in the injection period, respectively. The equilibrium orbit of the circulating proton beam traverses the stripping foil in the injection period and moves to the central orbit after completion of injection. The displacement of the injection orbit from the central orbit is 55 mm at the stripping foil position.

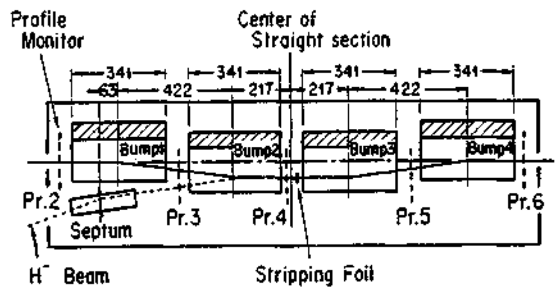

Fig. 1a 20 MeV injection.

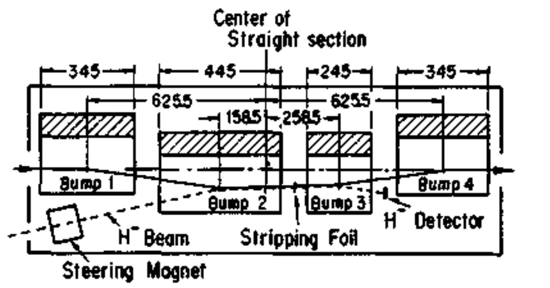

Fig. 1b 40 MeV injection.

Fig. 1 Injection system of the KEK booster synchrotron, where the dotted and solid line indicate the orbits of the H^- ion beam and the circulating proton beam in the injection period

Ferrite was initially used for the material of the bump magnet core of the 20 MeV injection system. However, its maximum induction was not enough for 40 MeV injection. Therefore, the ferrite core was replaced by the core laminated with silicon steel sheets of 0.1 mm in thickness, which has a time response of the order of 10 μsec and the maximum induction of 1 T.

The parameters of the bump magnets are listed in table 1.[2] Figure 2 shows the cross section of the magnet for the 40 MeV injection. A 3 mm thick conductor carrying an excitation current of 10.9 kA is fixed on glass fiber reinforced polymer plates (GFRP). In order to reduce the eddy current heat generated by the fringing field and the iron loss in the core with repetition rate of 20 Hz, slits are introduced into the ends of the magnet core and the surrounding of the core is covered by copper plates cooled by water.

Table 1 Parameters of the bump magnet for 40 MeV H^- ion beam injection.

gap height (mm)	40
gap width (mm)	200
core length (mm)	329,429,229,329
effective length (mm)	376,476,276,376
total inductance (μH)	15
total resistance (mΩ)	29
gap field (kG)	3.4

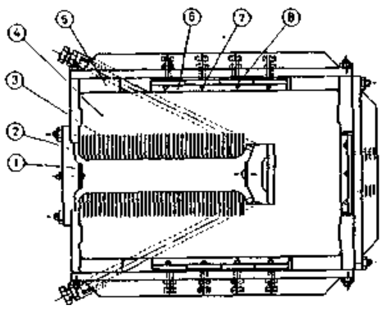

Fig. 2 Cross section of the bump magnet for the 40 MeV injection
1. conductor of copper plate (3 mm in thickness)
2. insulator of GFRP
3. slits at the end of core (0.5 mm in width, 30 mm in depth and at 5 mm space)
4. magnet core of laminated silicon steel of 0.1 mm in thickness
5. frame of stainless steel fixing the core
6. water cooled copper plates, which cool the core
7. water pipe welded to the copper plate
8. stainless steel plate to press the cooling plate to the core

For supplying the square-wave current pulse of 10.9 kA with 80 μsec flat top to the bump magnets, a pulse forming network (PFN) of 0.87 Ω characteristic impedance and fast thyristor switch are used as shown in Fig. 3. The maximum charging voltage of PFN is 12 kV. The thyristor switching system is formed by 32 thyristors in series connection, whose maximum rating of voltage is 1.2 kV. A return path including a reactor is added to the PFN for energy saving. The power of the current pulse returns to the PFN with an efficiency of 80%.

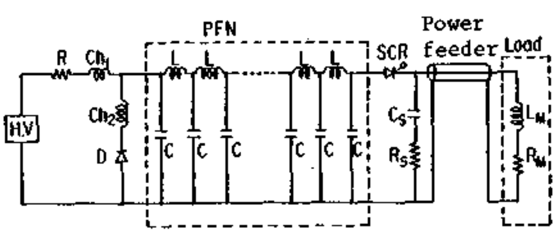

Fig. 3 Circuit of the power supply for the bump magnet, where the maximum charged voltage to PFN is 12 kV, the PFN has the impedance of 0.87 Ω and consists of 18 units of inductances and capacitances, the thyristor switches formed by 32 thyristors in series whose rise time is 1.5 kA/μsec, and the 45 m power feeder consists of 23 coaxial cables of 20 Ω in parallel.
(R = 100 Ω, Ch1 = 0.5 H, Ch2 = 35.2 mH, L = 4 μH, C = 5.3 μF, C_s = 0.58 μF, R_s = 30 Ω, L_M = 15 μH, R = 29 mΩ)

From the view point of the reduction of the effect of the multiple scattering and the energy loss of the circulating beam at traversing the stripping foil, the thickness of the foil should be as thin as possible. In order to expect the perfect charge stripping from H^- ion to proton, on the other hand, the thickness of the carbon foil should be more than 10 $\mu g/cm^2$ and 30 $\mu g/cm^2$ at 20 MeV and 40 MeV injection, respectively.[3] As the mounting frame of the foil is as large as 40 mm high and 20 mm wide, the special technique was developed to mount a thin carbon foil.[4] By extrapolating the life time of carbon foil for heavy ion charge stripping at low energy,[5,6] the life time of the stripping foil in the KEK 20 MeV booster was estimated to be 1.4 day. Therefore, in order to keep continuous operation for 10 days without exposing the system to the atmosphere, a magazine provided with 40 foils is installed. For the normal operation, the thickness of the carbon stripping foil to charge-exchange the H^- ion beam at 20 MeV and 40 MeV is 20 $\mu g/cm^2$ and 30 $\mu g/cm^2$, respectively. Fortunately, the foil has never been broken by bombarding with a typical 8 mA H^- ion beam of 22 μs with the repetition rate of 20 Hz for 20 and 34 days at the 20 MeV and 40 MeV operation, respectively. Therefore, the total number of H^- ions which has passed through the stripping foil at 40 MeV is estimated to be 6.6×10^{19} ions. The large difference between the estimated value and the observed one may come from a fact that the bombarding energy of 3 MeV by A_r^+ ion, which was used to estimate the life time of carbon foil, is too low to extraporate the proton bombarding energy of 20 MeV.

3. Experimental Procedures and Results

In order to clear the effect of the injection energy, we compare the experimental results at 20 MeV with those at 40 MeV.

1. Emittance of H^- ion beam

By changing the current of a quadrupole magnet in the H^- ion beam transport line and observing the beam size at the downstream of the Q magnet, the beam emittance of the H^- ion beam was measured:
(unit: π mm mrad)

absolute (normalized)
ε_x = 8.2 (1.7) ε = 14 (4)
ε_y = 9.8 (2.0) at 20 MeV, ε_y = 14 (4) at 40 MeV

2. Energy Loss of the Circulating Beam

The energy spectrum of the circulating beam in the booster synchrotron was obtained by the following procedure: When the accelerating RF voltage in the booster is not applied, the beam is completely lost from the accelerator ring about 1 msec after injection due to the change of the guide field. The circulating proton beam was scanned with a small-size RF bucket by changing accelerating frequency as shown in Fig. 4, and beam survival at around 1 m sec after injection was measured for each RF frequency. Thus the energy spectrum of the proton beam in the accelerator is obtained. The frequency shifts of the spectrum are interpreted as those due to the energy loss in the process of multitraverse of the circulating beam through the stripping foil.

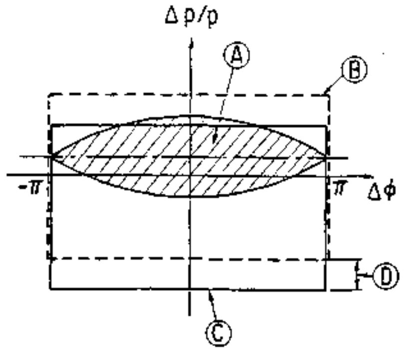

Fig. 4 Captured proton beam just after injection and a small RF bucket in longitudinal phase space
(A): RF bucket much smaller than the normal size
(B): Captured proton beam without momentum loss by a stripping foil
(C): Captured proton beam with momentum loss by a stripping foil
(D): Momentum loss due to the multi-traversing of the proton beam through a stripping foil

From the data, we obtained the averaged energy loss of the beam per revolution (dE/dn|obs.). On the other hand, the energy loss of a proton traversing a carbon foil is calculated by Bethe's equation (dE/dn|cal.).[7] If the circulating beam goes through the stripping foil in every revolution in the ring, both values should be equal to each other. With growing-up of the betatron oscillation amplitude due to the multi-traverse of the beam through the stripping foil, however, there take place the chances of missing to hit the foil with the beam. Therefore, the observed energy loss at every revolution has the following relationship with the calculated one,

$$dE/dn|_{obs.} = \eta \cdot dE/dn|_{cal.},$$

where η is the hitting probability. Figure 5 shows injection timing dependence of the averaged hitting probability with a stripping foil of 240 μg/cm^2 in the 40 MeV injection. The observed data are in good agreement with those calculated by a simple model[8].

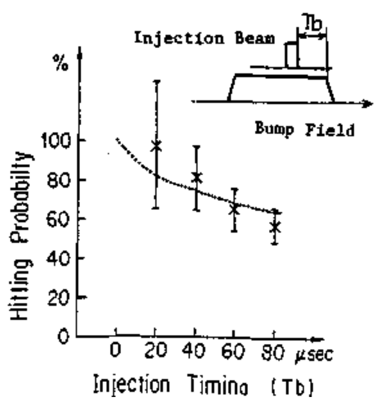

Fig. 5 Injection timing dependence of averaged hitting probability of the chopped beam at 40 MeV on the 240 ug/cm^2 thick foil. Dotted line is the calculated value by the model[8].

3. Injection Efficiency

During the injection, the horizontal and vertical beam size and energy loss of the circulating beam are increased by the multiple scattering at the stripping foil. If the beam size become larger than the aperture of the ring, the circulating beam begins to be lost. When the chopped beam are injected at various injection timing to the turn-off time of the bump field, the dependence of the injection efficiency of the chopped H^- ion beam on the injection timing together with the parameters of the foil thickness are shown in Figs. 6a and b. Here, the "injection efficiency" is the ratio of the number of captured protons in the ring just after turning off the bump field to those of the H^- ions from the injector linac. These figures show under the condition neglecting the space charge effect that decreasing the foil thickness and increasing the injection energy are very effective to increase the injection efficiency.

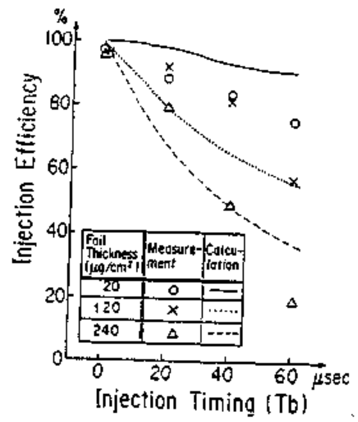

Fig. 6a 20 MeV injection.

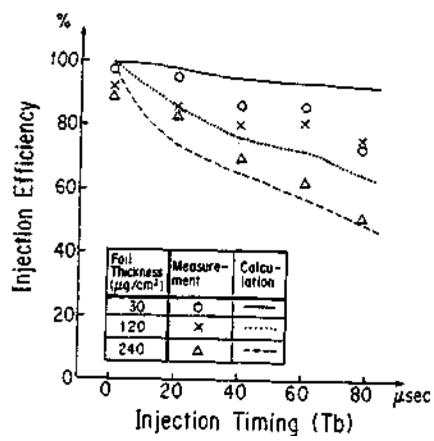

Fig. 6b 40 MeV injection.

Fig. 6 Dependence of the injection efficiency of the chopped beam on the injection timing to the bump field.

4. Numbers of Captured Protons in the Ring

Figures 7a and b show the relationship between the number of protons captured in the ring just after injection period and those of the injected H^- ions from the linac at 20 MeV and 40 MeV, respectively. As the intensity of the H^- ion current from linac is difficult to change, the number of injected H^- ions into the synchrotron is changed only by adjusting the pulse duration of the H^- ion beam. Therefore, the effect of changing the number of ions contains not only the effect of the space charge but also the multiple scattering and the energy loss in the stripping foil. It is clear that the effect at 40 MeV injection is considerably small compared with that at 20 MeV injection.

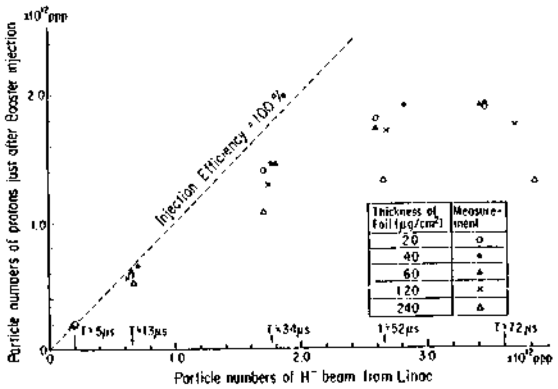

Fig. 7a 20 MeV injection.

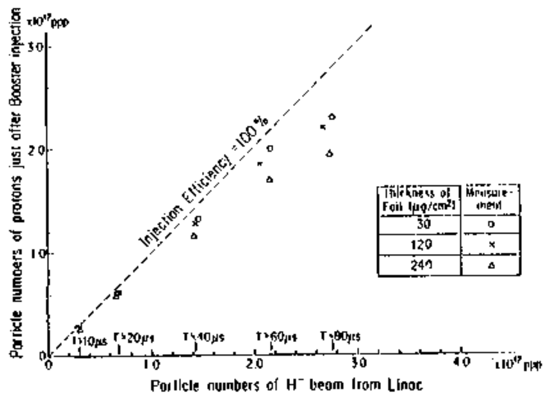

Fig. 7b 40 MeV injection.

Fig. 7 Relationship between the particle number of protons captured in the ring just after injection period and those of the H^- ions from linac, where τ means the duration of the H^- ion beam.

5. Conclusion

In spite of the lowest injection energy of 20 MeV at KEK among those at the laboratories where the H^- charge-exchange injection method has been applied, this method increased the accelerated beam intensity in the KEK booster synchrotron by 85% of the maximum intensity obtained by the multi-turn injection method of the direct proton beam. By up-grading the injection energy from 20 MeV to 40 MeV, the accelerated beam intensity has been increased by 60% of one at 20 MeV injection.

The measurement of the captured protons in the ring with the stripping carbon foils of various thickness at 20 MeV and 40 MeV shows very clearly the advantages of reducing the thickness of the stripping foil and increasing the injection energy. When the intensity of the circulating protons is more than several times of 10^{11} ppp, the captured beam in the ring will gradually be lost till 1 msec. As the bunched beam observed by a fast intensity monitor oscillates with the dipole mode, it seems that the accelerating RF cavity is heavily loaded by the circulating bunched beam. If the RF system will improved for the beam loading, the accelerated beam intensity at 40 MeV will close around the space charge limit of 2.4×10^{12} ppp. While up-grading the injection energy has big advantages in the view point of increasing beam intensity, it results in the enlargement of the emittance of the extracted beam, because adiabatic dumping factor is reduced with increasing the injection energy. In order to increase the intensity of the main ring, therefore, it is important to increase the H^- ion current from linac without emittance growth.

The energy loss of protons at traversing the stripping foil was obtained by measuring the beam survival with small RF bucket. Those measured energy losses are well explained by introducing "hitting probability" of the beam on the stripping foil. The calculation by this model is also in good agreement with the measurement of the injection efficiency.

The success in sticking a very thin carbon foil such as 20 $\mu g/cm^2$ on the frame of 40 mm in gap height was very useful for performing various measurements and getting the beam of good quality in the accelerator ring. Though the injection energy is low, the carbon stripping foil has never been destroyed by the beam bombardment. In the normal operation of 40 MeV injection and 20 Hz repetition rate with the number of H^- ions of 1.1×10^{12} ppp, the life time of the carbon foil with 30 $\mu g/cm^2$ thickness is more than 34 days, which means that the foil can withstand for the bombardment of H^- ions more than 6.6×10^{19} particles.

The maximum induction of ferrite of 0.3 T is not enough to generate a magnetic field in the bump magnet for the 40 MeV injection. Therefore, the silicon steel of 0.1 mm in thickness is used for the material of the bump magnet, whose field has the flat top of 0.34 T and rise time of 20 μsec. To reduce the eddy current heat by the fringing field, some devices were needed. The nominal current of 10.9 kA is transfered to the bump magnet via PFN of 0.87 Ω characteristic impedance. In this circuit, the 80% returning efficiency of energy was achieved.

6. Acknowledgement

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