THE FIRST EXPERIMENT OF H^-CHARGE EXCANGE INJECTION IN THE KEK BOOSTER

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Abstract

The first test experiment of the H^-charge-exchange injection was carried out in the 500 MeV booster of the 12 GeV proton synchrotron at KEK during three weeks beginning in late September 1983. Experimental results showed that, in spite of the injection energy as low as 20 MeV such an injection method is promising for increasing the beam intensity of the booster. And also, some further improvements are proposed.

Introduction

A multi-turn injection scheme using a 20 MeV proton beam was initially designed for injection of the 500 MeV booster synchrotron. Since commissioning of the booster synchrotron in the fall of 1974, a great deal of effort was spent in increasing the beam intensity of the booster. The design intensity, which should be attainable with only minor modifications of the accelerator components, was 6 x 10^{11} protons per pulse. In 1977, a beam intensity of 6 x 10^{11} ppp was attained. However, the maximum intensity achieved hitherto remains at 6.8 x 10^{11} ppp in the booster.

To remove the intensity barrier, a charge-exchange injection scheme using an H^-ion beam1) was proposed.2) The charge-exchange injection project started in 1980. In this injection scheme, negative hydrogen ions from the linac are injected and stripped to protons by a charge-stripper foil, which is located in the injection point of the booster. It is possible, in this scheme, to make the orbit of the returning proton beam 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. In practice, however, the number of accumulated protons is limited by blow-up of the beam emittance and by broadening of the energy spread in the circulating beam through traversing the charge-stripper. The mean scattering angle and energy loss of protons penetrating through a material are approximately proportinal to the inverse of the kinetic energy of the incident protons, in the energy range of interest. The kinetic energy of injected protons in the KEK booster is 20 MeV, which is lower than that available at other facilities where the H^-charge-exchange injection scheme has been tried.3)

Another problem associated with the injection energy is the space-charge limit in the booster synchrotron. From the space-charge limit, which is estimated to be 2.6 x 10^{12} protons, the beam intensity may be increased by a few times the presently achieved value. In order to expect a considerable increase in intensity, however, the energy of the injector linac must be increased.

Figure 1 shows the calculated stacking efficiency ε for an injected beam with a pulse width of N-revolutions. The calculation is carried out for various hitting probabilities η of the circulating 20 MeV proton on a 120 $\mu g/cm^2$ thick carbon stripper. Even in an inefficient case of η = 1.0 and N = 160 revolutions (100 μsec wide injected beam), for example, the number of stacked protons amounts to 3.75 x 10^{12} protons with a 10 mA injected H^-beam, which is enough to exceed the space-charge limit of the booster synchrotron, provided that a 100 % stripping efficiency is assumed.

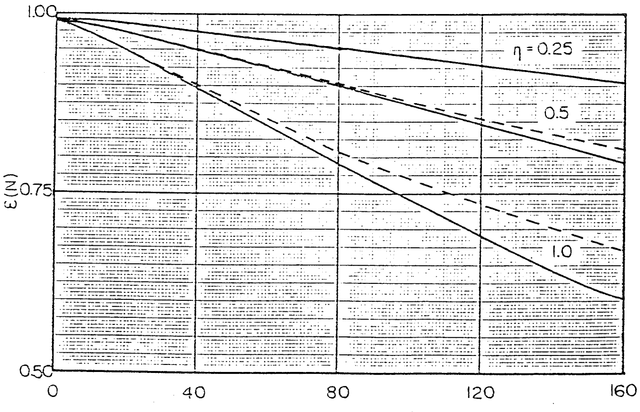

Fig. 1 Calculated stacking efficiency ε of the injected beam vs. the pulse width of N-revolutions. Dotted and solid lines are stacking efficiencies neglecting and taking account of the orbit shift due to the energy loss in traversing the charge stripper, respectively.

Injection system

The H^-charge-exchange injection system is installed in straight section No. 1. Figure 2 illustrates the beam orbit and the arrangement of the magnets. The dotted line and solid line indicate the H^-ion beam and circulating proton beam, respectively. The equilibrium orbit of the circulating proton beam traverses the stripping film 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.

The parameters of the bump magnet are listed in Table 1. The magnet consists of seven ferrite plates sandwitched with fiber-reinforced polymer plates. A 3 mm thick conductor carrying an excitation current of 8 kA is fixed on the polymer plate. The current and field for nominal operation are estimated to be 7.49 kA and 0.235 T, respectively.

We used a pulse forming network (PFN) and fast thyristor switch to supply a current pulse of 8 kA for the bump magnets. The PFN with a characteristic impedance of 1 Ω provides a square-wave current pulse of 100 μsec. The PFN circuit is turned on by the thyristor switch, which consists of 20 thyristor units

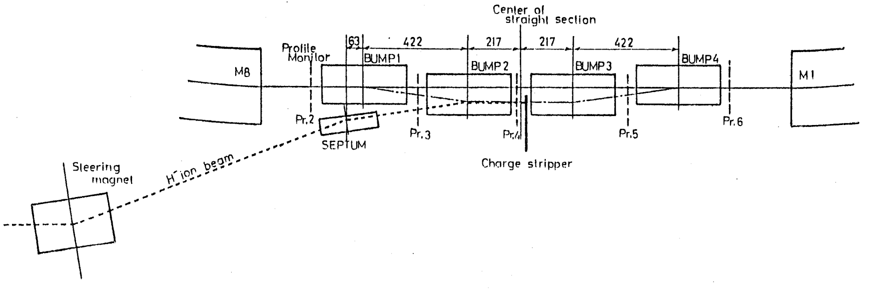

Fig. 2 Layout of the charge-exchange injection system.

in series and forms a coaxial network. A maximum current of 12 kA is fed through 15 parallel coaxial cables, each 50 m in length. To save energy, a return path including a reactor is added to the PFN. The power of the current pulse returns to the PFN with an efficiency of 80 %.

Table 1 Parameters of the bump magnet

half gap	20 mm
gap width	154 mm
length	341 mm
inductance	1.8 μH
ohmic impedance of coil	1.0×10^{-4} Ω

Experimental Results

In the test period, the beam current of H^- ions at the 20 MeV beam line ranged from several hundred μA to several mA and finally reached 8 mA. Measurements were carried out on various items as follows:

1) Emittance of 20 MeV H^- ion beam.

The beam emittance on the 20 MeV beam line was mesured:

ε_x (normalized, 2σ) 1.3 ± 0.5 mm•mrad
ε_y (normalized, 2σ) 1.8 ± 0.3 mm•mrad

2) Beam size of the circulating beam.

The beam size of the circulating beam, just after completion of injection, was measured with a combination of beam scraper and pulsed bump magnets. The half size of the beam at the straight section was:

Horizontal size a 40 mm
Vertical size b

3) Energy loss of the circulating beam.

In normal operation of the booster, the coasting beam disappears from the accelerator ring about 1 msec after injection, due to the change of the guide field. The energy spectrum of the circulating beam was obtained by the following procedure: The circulating proton beam was scanned with a small-size RF bucket by changing the accelerating frequency, and the beam survival at around 1 msec after injection was measured for each RF frequency. Figure 3 shows the shift of the central frequency of the spectrum caused by changing the injection timing of a chopped H^- ion beam to the injection bump field. The frequency shifts are interpreted as those due to energy loss in the process of multi-traverse of the circulating beam through the stripping film. From the data, we obtained the energy loss of the beam per revolution ;

$$dE/dn = 0.727 \text{ keV/revolution}$$

On the other hand, the energy loss of a 20 MeV proton traversing a 120 $\mu g/cm^2$ thick carbon film is estimated to be 2.88 keV, which is four times the observed value. This fact seems to mean that the hitting probability of the circulating beam on the stripper is very low, i.e., only 25 % !

4) Pulse width of the injected beam and stacking efficiency.

The correlation between the pulse width of the injected H^- ion beam and the stacking efficiency was surveyed. Figure 4 shows an example of such a case where data were obtained just after the data-taking of the data shown in Fig. 3. The experimental results yield features quite different from the calculated stacking efficiency shown in Fig. 1. Namely, beam loss during stacking is found even at the starting point of injection. This fact can be explained by introducing an injection error into the calculation. For cases of the hitting probability η = 0.5, 0.25 and 0.125, the stacking efficiency with a best-fit injection error Δ was calculated. The results are shown in Fig. 4. It appears that a large injection error is probable, i.e., 37 mm, independent of the hitting probability η over a wide range. This should be compared with the useful semi-aperture of 40 mm. Furthermore, a low hitting probability of 0.125 to 0.25 seems to explain the experimental data. This is consistent with the experimental results described in the item 3). Such a low hitting probability originates from the large injection error.

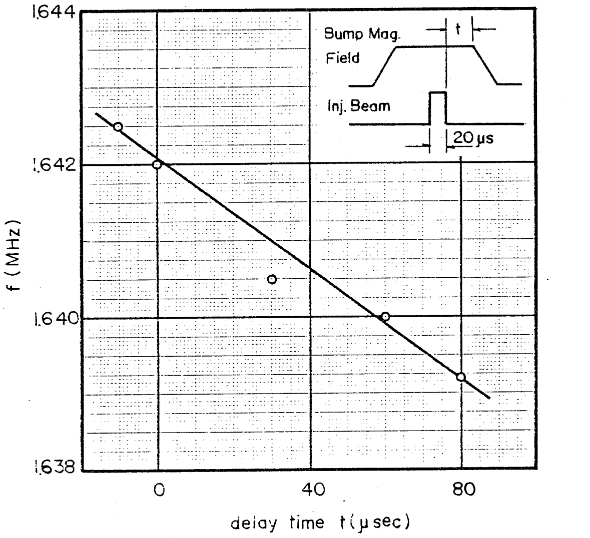

Fig. 3 Frequency shift of the energy spectrum of the circulating beam due to delay of the turn-off time of the bump field relative to beam injection.

Another possibility to explain the stacking inefficiency at the starting point of injection is beam loss on the injection beam line. The intensity of the injected beam is monitored by a Faraday cup, which is located downstream of a bending magnet on the line. If any beam loss takes place on the line from the monitor to the charge stripper position, the apparent stacking efficiency will be reduced.

In any case, in order to explain the experimental data, we should introduce a betatron oscillation amplitude of 10 mm to 37 mm induced by injection error.

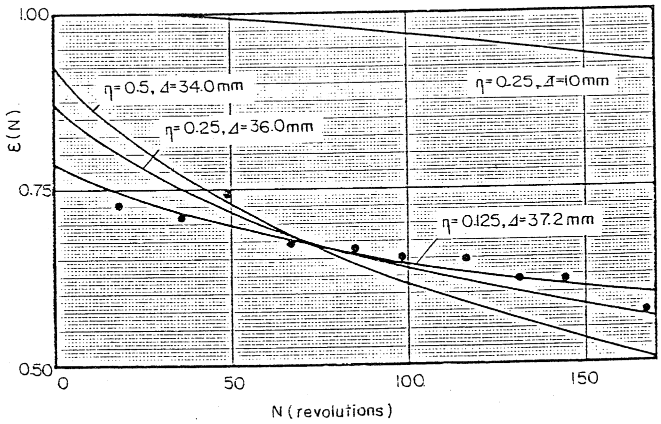

Fig. 4 Observed stacking efficiencies vs. pulse width of the injected H^- ion beam and parameter-fitting with the hitting probability η and the betatron oscillation amplitude Δ induced by injection error.

5) Space-charge effect.

It is very interesting to see how space charge affects the accumulation of protons in the booster. The dependence of the stacking efficiency ε(t) on the time from the beginning of injection was measured. The injected H^- ion beam was 110 μsec wide. The experimental results showed that the stacking efficiency started to decrease at a critical time t_{max} which depends on the injected H^- ion beam intensity. If we take such decrease of the efficiency as a measure of the onset of the space-charge effect, relevant numbers of injected and accumulated particles are estimated as listed in Table 2. Another sign of the space-charge effect is found in Fig. 5, which is a plot of the stacking efficiencies vs. the number of injected H^- ions in each run through the three-week test period. In this figure, the solid curve is an equi-intensity line of stacked protons. As a whole, the stacking efficiency decreases with the number of injected H^- ions.

Table 2 Critical beam intensity in space-charge effect

I_{H^-} (mA)	t_{max} (μsec)	NH^- ($\times 10^{12}$ particles)	N_p ($\times 10^{12}$ protons)
8.1	46	2.33	1.28
6.9	55	2.37	1.35
4.5	> 100	> 2.81	> 1.46

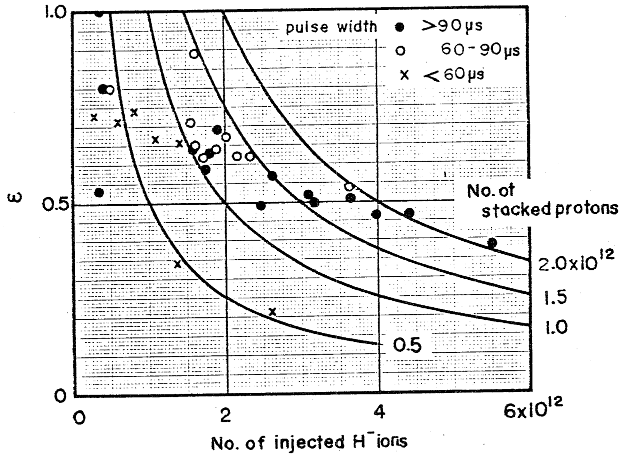

Fig. 5 Plot of the stacking efficiency vs. the number of injected H^- ions in various injection conditions through the test period.

At the end of the test period, a maximum beam intensity of 7.1 x 10^{11} protons per pulse was recorded, which is a new record in the beam intensity from the booster synchrotron. Figure 6 shows the number of accelerated protons in the booster at that time. The beam loss several msec after injection is due to the equipment trouble in the RF accelerating voltage, which unfortunately could not be removed during the test period. We might expect a beam intensity of 9 x 10^{11} protons per pulse at the maximum energy if this RF problem were absent.

Discusstion and Conclusions

The stacking efficiencies for the charge-exchange injection in each run through the test period were almost all distributed in a range between 0.5 to 0.8, as seen from Fig. 5. Problems in the stacking efficiency seem to result from large injection errors. In fact, we found no improvement in the stacking efficiency in spite of using a thinner carbon charge-stripper of 30 and 50 μg/cm^2, which is backed with an organic film of 15 μg/cm^2. In the KEK 12 GeV proton synchrotron, an up-grade of the present 20 MeV linac to 40 MeV is under investigation$^{4)}$. In order to make such an up-grade of the injector effective, in addition to other improvements in the present charge-exchange injection system, the injection error should be minimized. We are proposing that, for injection at 40 MeV, an injection bump magnet system based on silicon steel magnet cores be used in place of the present ferrite-based injection bump magnet system. By moving the charge-stripper from the middle of the bump magnet system to an asymmetric position along the orbit, it is possible to replace the injection septum magnet with a steering magnet, which makes it possible to correct the injection angle without introducing any appreciable radial displacement of the injected beam at the stripper position. Operation with 40 MeV H^- ion beams is within the capabilities of the present pulsed power supply, if the bump magnets are rebuilt with silicon steel core. At the final stage of the test period, the current of the H^- ions delivered from the 20 MeV linac reached 8 mA. The quality of the beam was quite good, i.e, the normalized emittance of the H^- ion beam was less than 2 mm•mrad, which should be compared with that for the ordinary proton beam of 10 mm•mrad$^{5)}$. If we can expect an increase in the H^- ion beam current at the expense of emittance, it may be more favourable for the charge-exchange injection to increase the H^- ion beam current by such a means.

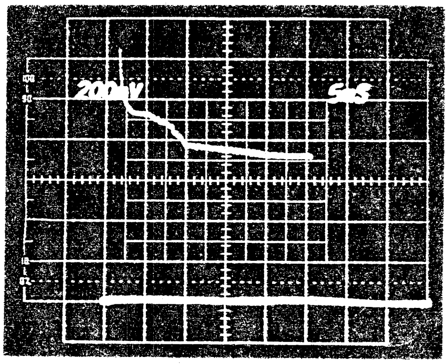

Fig. 6 Accelerated proton beam at the achievement of the intensity record in the booster. Horizontal scale : 5 msec / div., vertical scale : 2 x 10^{11} protons / div.

Charge-exchange injection has never before been tried with an H^- ion beam energy as low as 20 MeV. The test experiment has proved that this injection method is quite promising for increasing the beam intensity of the 500 MeV booster synchrotron at KEK, in spite of its low injection energy. It is not difficult to expect that a factor of two improvement in intensity might be achieved at the booster by improvements such as mentioned above and with a 10 mA, 100 μsec wide H^- ion beam.

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