POSITIVE-ION MULTI-TURN INJECTION WITH BI-WAVEFORM FAST ORBIT-BUMP MAGNETS

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Abstract

An injection system for both negative-ion charge-exchange injection and positive-ion multi-turn injection was developed in order to accelerate heavier positive ions in the KEK proton synchrotron. As for positive-ion multi-turn injection, a further device for effective beam injection was also tried in order to suppress the losses of incoming beams to reduce the residual radioactivity. Using this system, helium ions have been successfully accelerated in the KEK 12-GeV proton synchrotron.

1 INTRODUCTION

A charge-exchange injection scheme has been used to inject proton and deuteron beams into the booster synchrotron. This scheme, however, cannot be applied to heavier positive ions, such as helium ions. Therefore, a conventional multi-turn injection scheme for positive ions must take the place of the charge-exchange scheme. For this project a new injection system for both negative-ion charge-exchange injection and positive-ion multi-turn injection was developed [1].

Positively charged helium ions are injected into the KEK booster synchrotron by means of a septum magnet and two fast orbit-bump magnets system. In this system, positive-ion beams are gradually injected from the center of the horizontal phase space to the outside by shifting the closed orbit, which is controlled by two fast orbit-bump magnets. To fill the ring acceptance with incoming beams effectively, a nonlinear slope of the fast orbit-bump magnetic field is required. An approximated waveform can be realized by a newly developed bi-waveform power supply system.

An outline of effective multi-turn injection using the nonlinear slope of the fast orbit bump magnet and experimental results of positive-beam injection are summarized in this paper.

2 OPTIMUM WAVEFORM OF FAST ORBIT BUMP MAGNETS

2.1 Injection Beam Line

In Figure 1, a schematic layout of the combined injection system which is presently being used for charge-exchange injection and positive-ion multi-turn injection is shown. The solid line indicates the positive-ion multi-turn injection beam orbit, which overlaps the charge-exchange injection (indicated by the dotted line) by a combined bump-septum magnet [2].

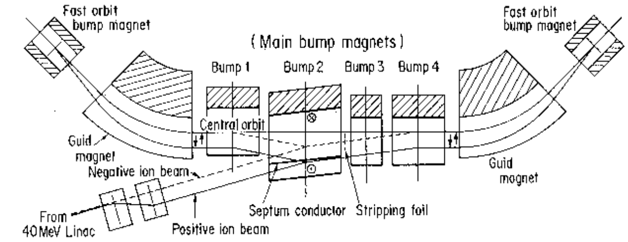

Figure: 1 Injection system for positive-negative ions

The positive-ion beams injected from the linac are bent by the septum magnet so as to enter the joining point parallel to the closed orbit in the ring.

During positive-beam injection, the closed orbit is shifted toward the septum magnet in parallel by exciting two fast orbit-bump magnets. Their positions are one quarter of the betatron wavelength upstream and downstream from the injection point. Beams are gradually injected from the center of the phase space to the outside by changing the field excitation of these two fast orbit-bump magnets.

2.2 Parameters of 40-MeV helium-Beam Injection

The optimum shift of a closed orbit is determined by the distance between the center of the closed orbit and the septum conductor, the size of the injected beams, and the fraction of the betatron oscillation number around the ring. The typical operating parameters of 40-MeV helium beam at the injection to KEK Booster are as follows.

Emittance ε_H / ε_V,	0.94 / 0.75mm.mrad
Beam size, horizontal	9 mm (half)
vertical	9 mm (half)
Aperture of the ring, horizontal	50 mm (half)
vertical	20 mm (half)
Revolution frequency (Injection period),	1.1 MHz
Betatron oscillation Q_H / Q_V,	2.17 / 2.30

2.3 Injection Process in Phase Space

To suppress any residual radioactivity caused by lost particles at the septum, multi-turn injection by non-sliced beams was tried. As shown in Figure 1, the distance between the center of the closed orbit and the septum conductor can be controlled by the excitation level of the four main bump magnets for charge-exchange injection. In Figure 2, the injection process in phase space at the end of the septum conductor is shown.

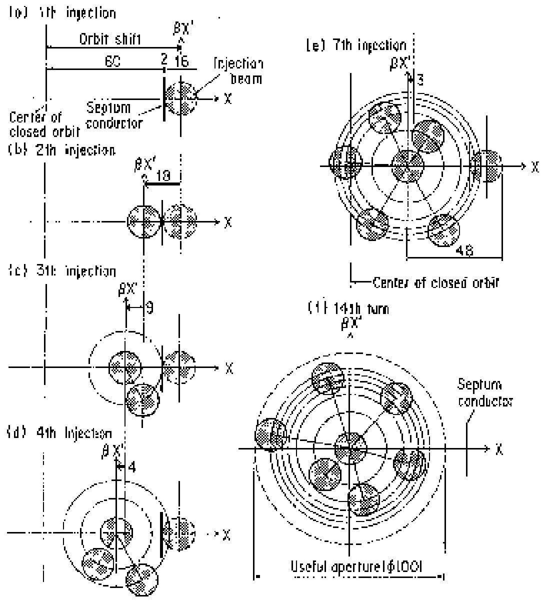

Figure: 2 Injection process in phase space at the septum conductor. (Unit ; mm)

At first, as shown in Figure 2(a), the center of the closed orbit at the injection point should be shifted toward the outside of the septum conductor so as to join the incomming beams, which is located as close as possible to the septum conductor. The positive ions injected at this first stage are placed to the center of the phase space.

Next, as shown in Figure 2(b), the closed orbit is shifted back to the center of the circulating orbit before the first injected ions go around the ring and return to the septum conductor.

In this way, as the closed orbit is shifted back to the center of the ring, beams are gradually injected from the center of the phase space to the outside by changing the field excitation of the additional bump magnets.

The slope of the decreasing field of the fast orbit-bump magnets, which determines the shifted distance per turn, has an important effect on the efficiency of beam injection. From the phase-space motion in the Figure 2, the optimum orbit shift per turn is indicated as in Figure 3.

3 BI-WAVEFORM POWER SUPPLY FOR FAST ORBIT BUMP MAGNET

The dimensions of the fast orbit-bump magnet are as follows.

Gap height	40mm
Effective length	150mm (measured at 0.1T)
Winding turns	4
Inductance	13µH
Material of the core	Ferrite

The calculated excitation current for the optimum helium-beam injection in Figure 2 is indicated in Figure 3.

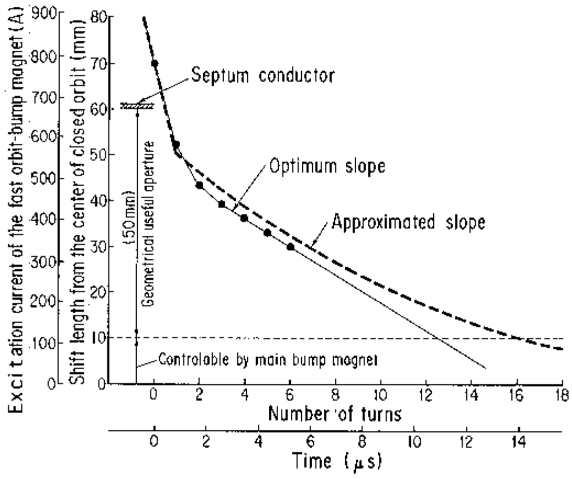

Figure: 3 Optimum slope of the fast orbit-bump magnet and approximated slope of bi-waveform power supply.

The nonlinear slope of the excitation current of the orbit-bump magnets is required. This slope is, however, approximated by the composition of a steep decent and gentle descent. The proposed bi-waveform circuit, which is a kind of crowbar circuit, is shown in Figure 4. The required nonlinear slope is accomplished with the waveform of a LC harmonic circuit and a LR current decay circuit. The operating excitation current for the fast orbit-bump magnet and the voltage of C2 are given in Figure 5.

For $t_0 < t < t_1$, SW1 and SW2 are both opened, and C2 is charged by a DC power supply. At $t = t_1$, SW1 is turned on, and the choke current discharges through Lm; the fast orbit bump magnet. The C2 and Lm form a LC harmonic circuit.

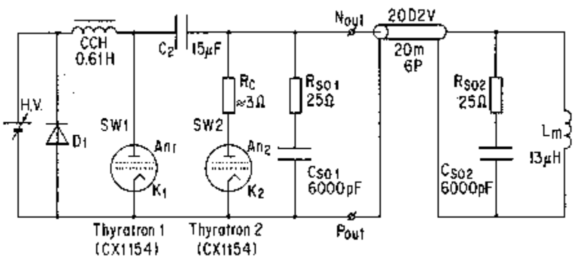

Figure: 4 Bi-waveform circuit to approximate ideal slope of fast orbit-bump magnet.

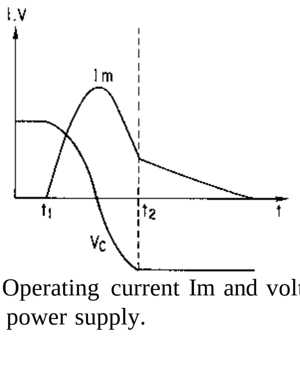

Figure: 5 Operating current Im and voltage of C2 in the bi-wave form power supply.

At $t_1 < t < t_2$, the fall in a sine wave is used to form a steep decent current of the fast orbit-bump magnet at the early injection indicated in Fig. 2b. The inclination is changed by the height of the half sine, which is controlled by the charging level of C2. At $t = t_2$, SW2 is turned on, The Lm and Rc form the current-decay circuit. At $t_2 < t$, the stored current in the Lm exponentially decays through Rc. The current decay forms a gentle descent of the excitation current of the fast orbit-bump magnet. The inclination is controlled by the Rc, which is adjusted for optimum beam injection.

Rs and Cs have a role to eliminate reflection at the transmission line by a sudden change in the excitation current at $t = t_2$. The waveform can be easily modulated by three components charging the voltage of C2, resistance Rc and timing of SW2.

4 EXPERIMENT OF POSITIVE-ION MULTI-TURN INJECTION

As shown in Fig.3, during the injection period, the field slope of the fast orbit-bump magnet for an ideal orbit shift is well approximated by a bi-waveform circuit. A computer simulation of the phase-space painting by the actual slope shows that 7 turns of linac beams can be accepted in the KEK booster.

In a helium-beam acceleration experiment conducted in April, 1994, four turns of the linac beam were accumulated with this system, a very fast beam loss were observed and only half of accumulated beams were extracted from the booster [1]. This beam loss occurred at the time that the main bump magnet field fell sharply to zero. Field measurements of the main bump magnets showed the existence of an error field at this period, which seemed to be caused by an eddy current in the core. As for the septum magnet, the same field error was also observed, and was opposite. These field errors were made to cancelled out each other by adjusting the falling time of both magnets [2].

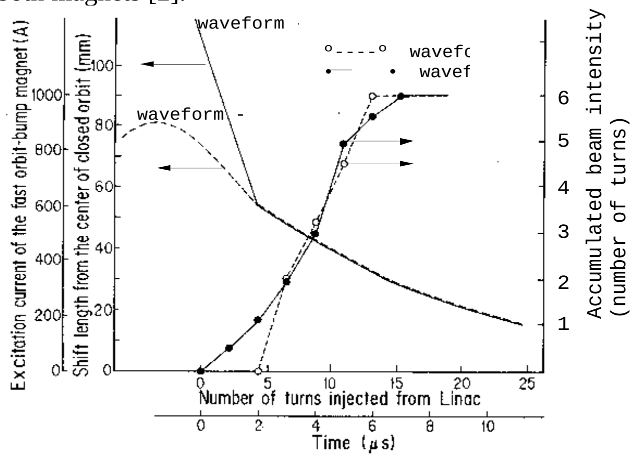

Figure: 6 Difference of accumulation states by the composition of steep and gentle descent slopes and by the gentle descent slope only.

In 1995, positive-ion injection has been studied using 40-Mev H^+ beams to refine the method of positive-ion injection, thus solving the problem of fast beam loss at this period. The beam emmitance of H^+ beams is almost the same as that of helium beams, and the velocity of incoming beams are almost twice as helium beam's velocity. The slope of the fast orbit-bump magnet was modified to the optimum value of 40-MeV H^+ beams.

It was verified that the fast beam loss at the fall down period of the main bump magnet was able to be overcome by adjusting the falling time of the main bump magnet and the septum magnet. The difference of injection state by the composition of a steep and gentle descent slope and by the gentle descent slope only was observed as shown in Figure 6. It indicate that the steep decent slope can inject the beams to the center of phase space. In this situation, the maximum injection efficiency from linac was 68%, and 6 turns accumulation and 5.4 turns extraction have been obtained.

5 SUMMARY

The bi-waveform power supply for fast orbit bump magnets and the main bump magnets enable us to control the orbit shift of the horizontal phase-space painting and the basic position of the closed orbit for effective beam injection.

The combined injection system for positive-negative ions has a performance equal to that of a conventional charge-exchange injection system. The problem of a fast beam loss at the fall-down period of the main bump magnet was also overcome. The positive-ion multi-turn injection method has been refined. Thus at the next chance to accelerate helium beams or other kinds of light ions, more than twice the beam intensity will be accelerated.

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