Helium Beam Acceleration in The KEK Proton Synchrotron with A Newly Developed Injection System for Positive/Negative Ions

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A helium beam has been successfully accelerated in the KEK 12 GeV Proton Synchrotron up to 23 GeV of the limiting energy of the main ring. The first physics experiment with a helium beam was carried out in April, 1994. Although a charge exchange injection of negative hydrogen ions has been used in the booster synchrotron, it cannot be applied to the injection of positive ions, such as helium ions. A newly developed injection system realized alternative use of both negative and positive ion injection schemes.

I. INTRODUCTION

The acceleration of heavy ion beams in the KEK-PS was discussed more than about 10 years ago. Recently, as one possible candidate among the future plans for the KEK PS, the PS-Collider was proposed [1]. This report proposed easier acceleration scheme for heavy ions with a Q/A of 0.5 in the KEK PS than one discussed before. Modifications of the KEK PS aimed at deuteron beam acceleration have been performed. On Jan. 31, in 1992, deuteron beam was successfully accelerated up to the limiting energy of the ring. The first physics experiment using a deuteron beam was carried out in April, 1992.[2]

The charge exchange injection scheme has been used to inject proton and deuteron beams into the booster synchrotron. This scheme, however, cannot be applied to positive ions, such as helium ions. Therefore, a conventional multi-turn injection scheme must take the place of the charge exchange scheme. There is no space for another injection system because of the booster designed well-compact. To replace the injection devices every operation cycle is not practical. To avoid this, a certain technical break-through is indispensable. A new injection system has been developed to realize both negative and positive ion injection. With this system, in April, 1994, a helium beam was successfully accelerated, and a physics experiment has been carried out. Also, a high intensity proton beam has been acclerated by using this system until now.

This new injection system has opened new uses of the KEK PS, i.e. from high intensity proton beam acceleration to high energy heavy ion beam acceleration . The principle of the newly developed positive/negative ion injection system and the first helium acceleration is summarized in this paper.

II. BOOSTER NEW INJECTION SYSTEM

A schematic layout of the new injection system, which is presently being used for proton, deuteron and helium ion acceleration, is shown in Figure 1. The system comprises four bump magnets (the main bump magnets) placed in one of the straight sections of the ring. The main bump magnets have single turn conductor plates, and are arranged asymmetrically so as to enlarge the angle between the injection and central orbits under a limited magnetic field. In Figure 1, the dotted line indicates the beam orbit for charge exchange injection. These bump magnets are used to change the closed orbit so that the beam impinges on a carbon stripping foil. The negative hydrogen ions are fully stripped at the foil, and start to circulate in the ring. In order to prevent an emittance blow-up by multiple scattering at the foil, the bump magnets must be turned off just after the completion of injection.

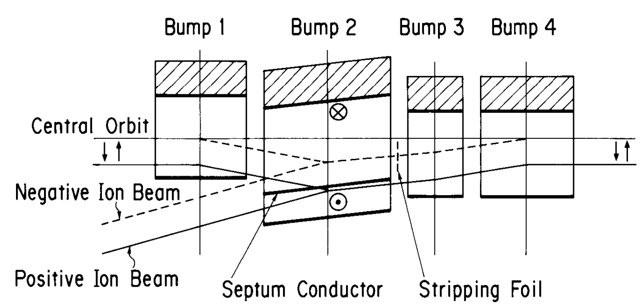

Figure 1. New injection system for the booster

The solid line indicates the positive ion orbit during multi-turn injection, which overlaps the charge exchange injection by Bump 2. This has been newly developed and plays the role of both bump and septum magnets. A cross-sectional view of Bump 2 is shown in Figure 2. This Bump 2 has three single-turn conductor plates in the pole faces. The electric currents flowing through these conductors produce two dipole magnetic fields with opposite signs, which are separated by a middle thin conductor plate (1mm thick), which forms a septum.

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During positive beam injection, the closed orbit must be shifted by 60mm toward the septum magnet in parallel, which is achieved by exciting two additional bump magnets (not shown in Figure 1). 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 the additional bump magnets.

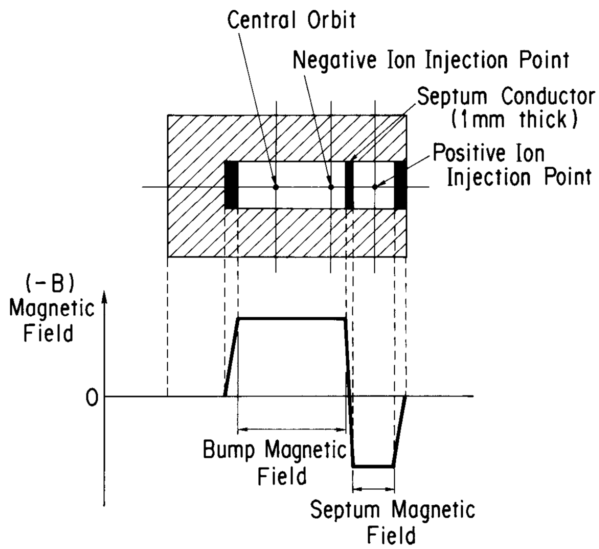

Figure 2. Cross-sectional view of Bump 2 and the excited filed pattern for positive beam injection.

During positive beam injection, both the bump and septum currents flow into the thin septum conductor instantaneously. Bump 2 is operated under a pulsed mode in order to eliminate any cooling problems. Pulsed operation can be realized using a PFN-type pulsed power supply. The PFN is electrically insulated from the ground potential and controlled through an optical fiber[3].

III. ACCELERATION OF HELIUM IONS

Most of the problems in accelerating heavy ions of Q/A = 0.5 at the KEK-PS had been solved at the time when deuteron acceleration succeeded in 1992. However, in the acceleration of helium ions, there remains difficulties with respect to multi-turn injection of the positive ions.

A. ION SOURCE AND INJECTOR

The injector comprises a 750 keV Cockcroft-Walton preinjector and a 40 MeV Alvaretz linac. There are two sets of Cockcroft-Walton preinjectors, the first preinjector is used to accelerate a high intensity beam of H^- and D^- ,whereas the second preinjector is for a polarized beam.

Some modifications of the second preinjector have been made in order to accelerate positive ions. The electric polarity of the Cockcroft-Walton high voltage generator and the power supply for bending magnets of low energy beam transport(LEBT) have been inverted. A multi-cusp ion source is utilized to produce singly charged helium ions. An extraction voltage of 50kV is supplied to the ion source, and a 50 keV-He^+ beam is injected into the 700 kV accelerating column of the preinjector. In order to convert a He^+ beam to a He^{2+} beam, a gas stripper cell has been installed in the LEBT.

The 750kV He^{2+} ion beam is injected into the linac. During linac acceleration, the helium beam is accelerated under the 4π mode operation scheme[3]. Its velocity is half that in the case of proton acceleration. As a result, at the end of the linac it has 3% less momentum than that of proton beam. The beam transport parameters and booster injection parameters must be optimized according to the beam momentum.

B. BOOSTER INJECTION

During multi-turn injection the beam is painted on the horizontal phase space. As shown in Figure 3, trace (c), by changing the decay current of additional bump magnets, the circulating beam orbit during an injection period was moderately shifted for efficiently stacking the linac beam. This is also a new attempt in accelerator technology. Four turns of the linac beam were accumulated with this technique.

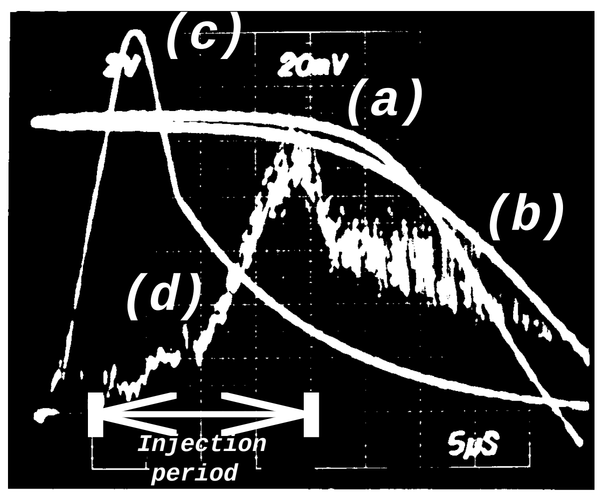

Figure 3. Current waveforms of the injection magnets and beam current monitor at the booster injection: (a) septum, (b) main bump, (c) additional bump with two time-decay constants and (d) beam current.

We observed a very fast beam loss; only half of the accumulated beam was extracted from the booster. This beam loss was caused at the time that the main bump magnet field fell sharply to zero. Field measurements of the main bump magnets showed that the eddy currents induced in the magnets caused a total error field, so as to cause closed orbit distortions, the maximum value of which was about 4 mm. The total error field due to the septum magnet eddy current, as well as the main bump magnet, was also measured. However, both of the error fields induced by eddy currents are of opposite sign and can cancel each other by adjusting falling time of both magnets.

C. ACCELERATION IN THE BOOSTER AND MAIN RING SYNCHROTRONS

For heavy ion accelerations in both the booster and main ring synchrotrons, the radio-frequencies of the accelerating systems are lower during injection, and sweep more widely than in proton acceleration. The tuning systems in both synchrotrons have been modified. The injection frequencies can be changed by attaching additional capacitors in both systems. Especially, in the main ring synchrotron, the bias current power supplies for the ferrite loaded tuning cavities were upgraded.

The intensity of a helium beam was expected to be at most on the order of 10^{10} particles per bunch. To stably accelerate such a low intensity beam the pre-amplifiers of both the position and beam phase monitors for the rf feedback systems have been improved.

Table 1.
Typical Operating Parameters during Helium Acceleration

Ion source	
Type of ion source:	multi-cusp ion source with 19 multi-anode hole
Beam width:	20 μsec
Beam repetition rate:	20 Hz
Extraction gap / voltage:	14 mm / 50 kV
After pre-acceleration	
He^+ beam current:	7.6 mA(750 keV)
After gas stripper	
He^{2+} beam current:	6.6 mA
Linac beam	
Beam current:	1.5 mA(20 MeV) 0.8 mA(40 MeV)
Emittance*: ε_V / ε_H	0.94 / 0.75 πmm.mrad
Booster	
Rf frequency range:	1.1 ~ 3.9 MHz
Beam intensity:	$7\text{x}10^9$ particles per bunch
Extraction energy:	588 MeV
Main ring	
Rf frequency range:	4.0 ~ 7.9MHz
Beam intensity:	$4.7\text{x}10^{10}$ particles per pulse
Top energy:	23 GeV

(* normalized rms emittance)

The typical operating parameters and achieved helium beam intensity are summarized in Table 1. During a commissioning run lasting one month, the helium beam was very stable, it was also extracted at various energies of 8 GeV (2 GeV/u) to 20 GeV (5 GeV/u), based on the requirements of the physics experiments.

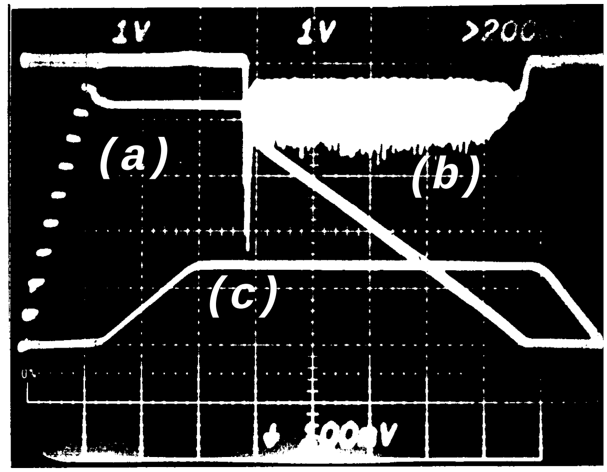

Figure 4. Helium acceleration in the main ring: (a) a helium beam intensity during a cycle, (b) a slowly extracted intensity and (c) a main magnet field pattern.

IV. SUMMARY

During the 1990's, we started to modify the KEK Proton Synchrotron in order to accelerate and extract various beams at different energies. This was closely related to the physics programs using such primary beams. The first step was deuteron acceleration in 1992, helium acceleration was the second step. The new injection system for the booster involves a very sophisticated technique in which both negative and positive beams can be injected into a synchrotron ring pulse by pulse. As primary beam experiments, heavier ion beams in the GeV energy region are desired. However, without upgrading the pre-injector it is difficult to inject fully stripped Q/A = 0.5 ions into the booster.

At present, a heavy ion beam acceleration program has been scheduled for one month every April. Polarized deuteron acceleration is also planned.

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V. REFERENCES

[1] PS-Collider design group, KEK Report 90-13, 1990.
[2] Y. Mori, et. al., Acceleration of Deuteron Beam in the KEK Proton Synchrotron, IEEE Particle Accelerator Conference, 1993, p.3754.
[3] I.Sakai, et. al., A New System to Trigger Fast Rise Thyristers, IEEE Particle Accelerator Conference, 1989, p.2005.