COMMISSIONING OF ELECTRON COOLER FOR MEDICAL AND OTHER APPLICATION AT HIMAC

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Abstract

An electron cooler had been designed and constructed in order to provide high-quality and high-intensity beam for medical and other application, and was installed at HIMAC-synchrotron. In the initial experiment of the electron cooler, a momentum spread is reduced from 10^{-3} to $5 \cdot 10^{-5}$ at FWHM by the longitudinal bunched beam cooling. The vertical beam-size at FWHM is reduced to one-third, and the cool stacking is successfully observed owing to the transverse cooling. The paper reports the results of the initial experiment of the electron cooling at HIMAC.

1 INTRODUCTION

Clinical trials of heavy ion therapy in the HIMAC (Heavy Ion Medical Accelerator in Chiba) [1] started on June 1994, and treatments of 776 patients had successfully been completed by February 2000.

One of the objectives of HIMAC is to develop new technologies in heavy-ion therapy and related basic and applied research. For the purpose, it is very important to improve beam property and enhance capability of handling it. The electron-cooling method can provide high-intensity or high-quality beams by cool stacking and by its strong phase-space compression. The aim of our study is to apply those techniques of accelerator physics to medical and other fields. These techniques will lead to the following: (1) an increase in the intensities of positron-emitter beams for the ion range measurements and of heavier ions, such as Fe and Ni, (2) microbeam probe for the cellular response radiation response, and (3) short-pulsed beams for time-resolving measurements. As the first step, an electron cooler had been designed and constructed [2]. The electron cooler was installed at HIMAC synchrotron in this March. In the commissioning of the electron cooler, the longitudinal and transverse cooling are successfully observed although the cooling parameters have not been optimised thoroughly.

The paper reports the results of the off-line electron-beam test and the initial cooling experiment.

2 ELECTRON COOLING SYSTEM

The main design parameters of the electron cooler are summarised in Table 1. In the electron cooler, an adiabatic expansion factor is designed from 1 to 10 for faster transverse cooling. The electron energies range from 3 to 30 keV, which correspond to ion energies from 6 to 55 MeV/n. The electron-beam size at the cooling section is designed to be 100 mm in diameter so as to cover the ion beam with horizontal emittance of 264π mm·mrad [3]. The effective length of the cooling section is limited to 1.0 m, because the available length of the straight section is only 4.0 m. Thus the fraction of the cooling length relative to the ring circumference of 129.6 m is 0.8%.

Table 1. Main parameters of the electron cooler

Electron energy	3-30 keV
Max. Electron current	1.2 A
Gun perveance	1 μP
Cathode diameter	35 mm
Expansion factor	1-10
Electron beam diameter	35-100 mm
Effective cooling length	1 m
Max. Field strength at gun section	0.5 T
Max. Field strength at cooling section	0.06 T

3 ELECTRON-BEAM TEST

The off-line test was performed without baking out the vacuum duct. The intensity of the electron beam was limited to only 0.4 A at 5 kV, thus, because the vacuum pressure was deteriorated to over 10^{-8} from $2 \cdot 10^{-9}$ Torr.

After the off-line test, the electron cooler was installed at HIMAC lower-synchrotron as shown in fig. 1. The vacuum ducts of the ring and of the cooler were baked out at 200°C. The vacuum pressure was measured and reads $7 \cdot 10^{-11}$ Torr without the electron-beam operation by the vacuum gauge located about 2m downstream at the cooler. The vacuum pressure was $1.2 \cdot 10^{-10}$ Torr during the operation with 3 kV and 120 mA. The measured gun-perveance of 1.1 $\mu A/V^{2/3}$ agreed well with the design value. Relative electron-current loss rate is measured as $1 \cdot 10^{-4}$ in the collector voltage of 2 kV, the collector-anode voltage of 1 kV and 400 mA of electron beam with 35 mmϕ. The stability of the power supply for acceleration of electrons was investigated, further, because the stability is essential to obtain an electron beam with low longitudinal temperature. A voltage stability of ± $2 \cdot 10^{-5}$ has been achieved even at 3 kV.

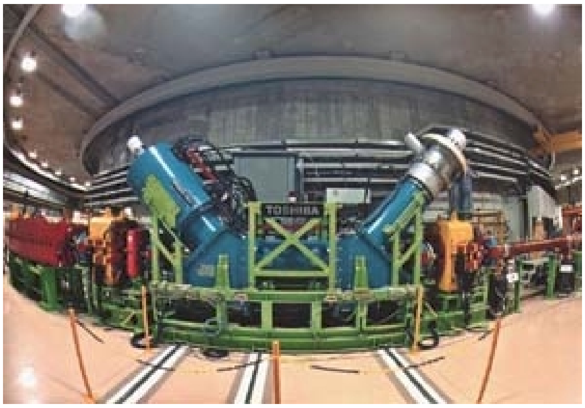
Figure 1: Fish-eye view of the electron cooler at HIMAC

4 ELECTRON COOLING EXPERIMENT

4.1 Experimental Conditions

In the cooling experiments, fully stripped carbon-ions with the energy of 6.0 MeV/n has been used in DC operation of the ring. In order to observe cooling phenomena easily, the horizontal emittance is adjusted to about 60 from 264 π·mm·mrad by decreasing the time-width of the injection beam to half compared with the normal operation, while the vertical one of about 10 π·mm·mrad is kept constant. The ion-beam intensity is typically around $2 \cdot 10^{8}$ ppp.

The stability of the main magnetic fields in the ring was examined, because the fluctuation of the field heats the ion beam. The stability has been achieved at around $\pm 1 \cdot 10^{-5}$ even in the field level corresponding to an injection energy (6 MeV/n). With operation of both rings, however, the overall stability becomes worse to $\pm 1 \cdot 10^{-4}$ due to the fluctuation of excitation current caused by a pattern operation of the other ring. Thus an operation of the upper ring is stopped in the cooling experiments.

It is essential for efficient cooling to align precisely the ion-beam axis and the electron-beam one as well as to match the electron velocity with the ion one. Thus steering magnets in the ring correct CODs in the horizontal and vertical direction firstly. Two pairs of horizontal and vertical steering-magnets are prepared at each side of the cooler, then, in order to compensate both for the horizontal and vertical deflections caused mainly by toroidal field. Both the axis of the ion-beam and that of the electron-beam are measured with a pair of electrostatic position-pickups inside the central solenoid. Finally, the electron-beam is merged with the ion-beam by using Helmholtz coil in the gun solenoid and that in the central one.

The lifetime is about 30 sec in the intensity of around 10^{8} ppp without the electron beam and the solenoid field. The solenoid field of 0.03 T and a space charge effect of the electron beam with 120 mA do not affect considerably on the lifetime. Thus the tune-shift due to the solenoid field and the electron beam is not compensated at present.

A momentum spread of the ion beam is measured by the electrostatic position-pickup as a Schottky monitor. Since a self-bunching phenomenon is observed even when the tuned rf-cavity was turned off, the ferrite-bias current is changed from a tuned value of 10A to 100A. Then, instead of the tuned rf-cavity, a tuning-free rf-cavity [4] has been used for bunching beam, because the Q-factor is around 1, which is much smaller than that of 8 in the tuned rf-cavity. Initial momentum-spread and the revolution frequency in a coasting beam is measured at about $1 \cdot 10^{-3}$ at FWHM and 0.2614 MHz, respectively, by observing a Schottky spectrum at the 57th harmonics of the revolution frequency.

The experimental condition is summarised at Table 2.

Table 2. The conditions of the cooling experiment

Electron energy	3.372 keV
Electron current	120 mA
Expansion factor	3.3
Electron beam diameter	64 mm
Field strength at gun section	0.1 T
Field strength at cooling section	0.03 T
Carbon-ion energy	6.00 MeV/n
Initial momentum spread	$1 \cdot 10^{-3}$ at FWHM
Tune (Qx/Qy)	3.68/3.14
Ion-beam size (x/y)	52/22mm
$\beta x/\beta y$ in cooling section	9.9m/10.7m
Dispersion in cooling section Dx	2.2 m
Transition energy, γ_t	3.7
Phase slip factor, η	0.93
Revolution frequency, f_0	0.2614 MHz

4.2 Cooling Experiment

(1) Longitudinal Cooling

The rf-voltage of ± 10V is applied to the ion beam during the cooling experiments, where the rf frequency is determined by the measured revolution frequency and the harmonic number of 4. The rf-voltage corresponds to the rf bucket-height of $\pm 2.7 \cdot 10^{-4}$ and to Δv of $\pm 9 \cdot 10^{3}$ m/s, which almost consistent with a region of a linear slope of a friction force [5]. After searching the electron velocity to match with the ion-beam one, the longitudinal cooling process is observed. Figure 2 shows a frequency spectrum of a bunched beam after the cooling of 6 sec, when the momentum spread is reduced to $5 \cdot 10^{-5}$ at FWHM. Figure 3 shows the momentum spread and the signal-power as a function of the cooling time. The power corresponds to the intensity of cooled beam. The observed signal-power suggests that almost all ion-beam is trapped at the effective cooling-region after 4 sec. The momentum cooling-time is estimated at about 9 sec in the momentum-spread less than 10^{-4}.

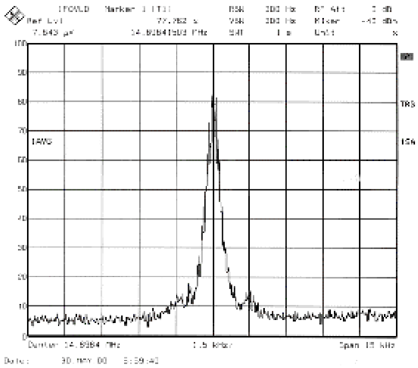

Figure 2: Schottky spectrum of bunched ion-beam after cooling of 6 sec. The frequency spread is 0.7 kHz at FWHM. The central frequency is 14.8984 MHz, the full frequency span 15 kHz, RBW 300 Hz, VBW 300Hz, and the sweep time 1 sec.

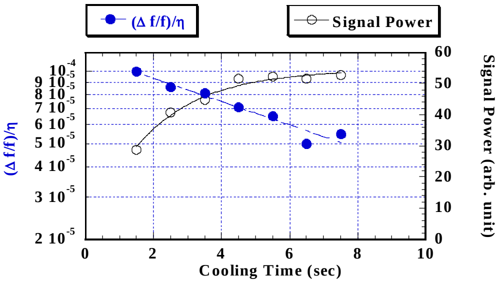

Figure 3: Momentum spread and signal-power as a function of cooling time. Closed and open circles indicate momentum spread at FWHM (left; log scale) and signal-power (right; linear scale), respectively.

(2) Transverse cooling
Adjusting the electron beam to merge more precisely with the ion-beam, transverse cooling is observed by non-destructive vertical profile-monitor, as shown in fig. 4. The vertical beam-size of 14.4 mm at FWHM is cooled down to 5.4 mm at FWHM after the cooling of around 3sec. The emittance of the cooled ion-beam is estimated at 0.7π·mm·mrad. Intensity is also increased through cool stacking for 15 multiturn batches, as shown in fig.5, even with the excitation of the fast bump magnets unchanged from the normal multiturn-injection. It seems that the gain of the cool stacking is not still saturated.

5 SUMMARY

The cooling experiment was started since the end of March 2000. As the preliminary results of the cooling experiments, the momentum spread is shrunk from 10^{-3} to $5 \cdot 10^{-5}$ at FWHM and the vertical beam-size at FWHM is reduced to around one-third. The cool stacking is also observed with the intensity gain of the factor 2 without adjusting the parameters of the fast bump-magnets for the multiturn injection.

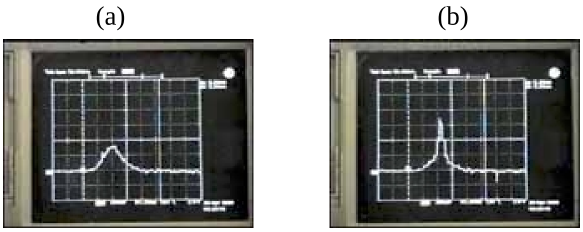

Figure 4: Vertical beam-profile at (a) before cooling and (b) after cooling of 3 sec. Scan full-scale corresponds to 93 mm.

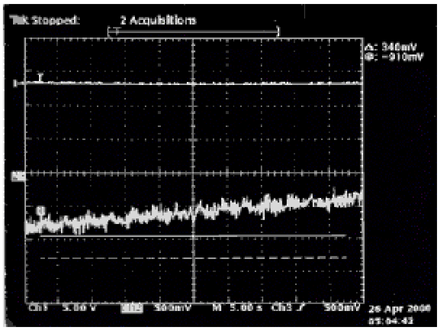

Figure 5: Intensity increases through cool stacking. Time scale is 5 sec/div.

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