ELECTRON COOLING EXPERIMENTS AT HIMAC

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Abstract

Electron-cooling experiments have been being carried out at HIMAC in order to provide high-quality and high-intensity beam for medical and other applications. In the transverse cooling-experiments, a cooling time and an equilibrium emittance at horizontal direction were measured and an intrabeam scattering was also observed. Beam intensity was increased by one order through the cool-stacking method. Beam bunch was compressed from around 400 ns to 40 ns by the electron cooling.

1 INTRODUCTION

Clinical trials of heavy ion therapy in the HIMAC (Heavy Ion Medical Accelerator in Chiba) [1] has been successfully progressed since June 1994.

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 radiation-response, and (3) short-bunched beams for time-resolving measurements. As the first step, an electron cooler was designed and constructed [2], and was installed at HIMAC-synchrotron. After the preliminary test [3], the transverse-cooling measurement, the cool stacking and the short-bunched beam production have been carried out. The paper reports the experimental results.

2 ELECTRON COOLER

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. 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%. Figure 1 shows the electron cooler of HIMAC.

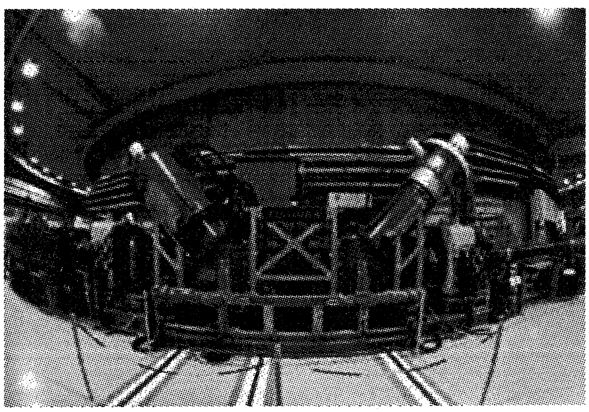

Fig. 1: Fish-eye view of the electron cooler at HIMAC.

3 COOLING EXPERIMENTS

3.1 Experimental conditions

The experimental conditions are summarised at Table 1. In the cooling experiments, fully stripped argon-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 atound 10 π·mm·mrad is kept constant.

After precious COD-correction around the ring, the ion beam was aligned with electron one in a cooling section by the local-bump method [4]. The alignment accuracy was verified by using a pair of position monitors in the central solenoid. A revolution frequency of circulating ions was measured by observing its higher-harmonics component from a Schottky monitor in order to determine electron energy roughly. The electron energy was determined precisely by changing the energy so as to maximise a bunch signal in applying rf-field with an amplitude of ±10V. The bucket height corresponding to the rf-amplitude is almost consistent with a linear regime that is proportional to a gradient of a velocity profile.

Table 1. The conditions of the cooling experiment

Electron energy	3.465 keV
Electron current	200 mA
Expansion factor	3.3
Electron beam diameter	64 mm
Field strength at gun section	0.167 T
Field strength at cooling section	0.05 T
Argon-ion energy	6.00 MeV/n
Initial momentum spread	$1\cdot10^{-3}$ at FWHM
Tune (Qx/Qy)	3.68/2.88
βx/βy 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
Intensity	10^6 - 10^9 ppp

3.2 Transverse cooling

(1) Cooling-time measurement

First, the position and the angle of the electron-beam axis was preciously adjusted to minimise the ion-beam size after cooling for 2 sec by using Helmholtz coil in both the gun solenoid and the central one. Next, the cooling time in the horizontal direction was measured by using a non-destructive profile monitor (MCP monitor) [5]. The horizontal beam-profile just after the multiturn injection and that after the cooling for 3.5 sec are shown in figure 2. The cooling time is estimated at around 0.5 s in relatively small beam-size, as can be seen in figure 3. Considering the spatial resolution of the MCP monitor of 0.5 mm at FWHM and the beta function in the monitor position, further, the equilibrium emittance can be estimated less than 0.1π mm·mrad.

(2) Intrabeam scattering

When the electron beam was switched off after cooling the ion-beam sufficiently, the ion-beam size was growing up due to the intrabeam scattering (IBS), as shown in figure 4. According to the analysis described in the ref. [6], the beam size after switching the electron off is represented as follows; $\sigma(t) = [\gamma\cdot D_0 \cdot t+\sigma_0^{\gamma}]^{1/\gamma}$, σ_0 is an initial beam-size, D_0 is a constant which depends on the ion current. As the result of the fitting, γ is estimated at 6.0±0.7, which is slightly larger than the expected value of 5 from the analytical result.

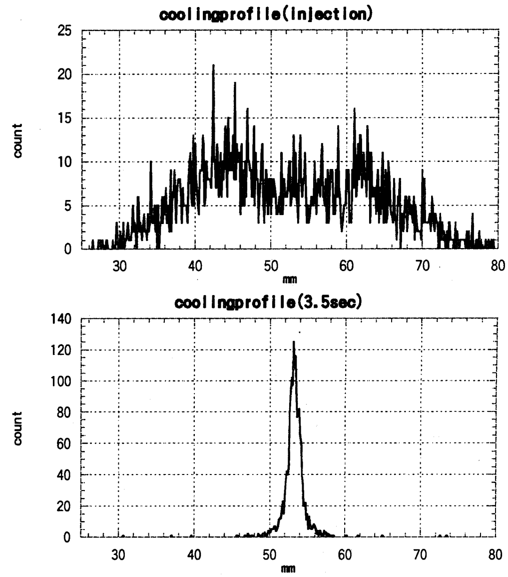

Fig. 2: Upper figure: Horizontal beam-profile with FWHM of around 30 mm just after multiturn injection. Lower: that with FWHM of 4 mm after cooling of 3.5 sec.

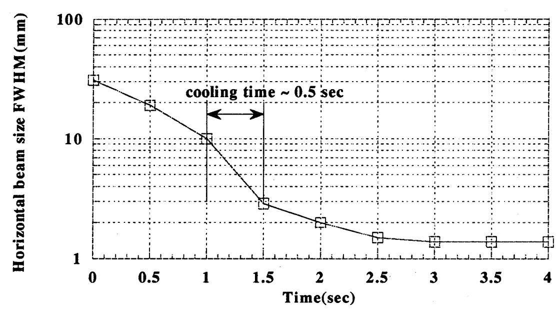

Fig. 3: Compressing horizontal beam-size (FWHM) as a function of time.

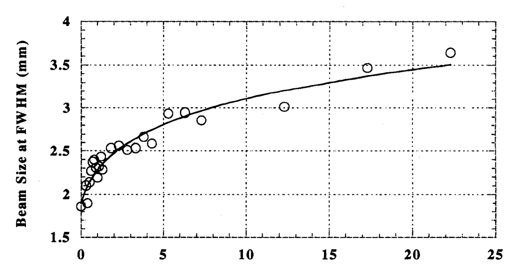

Fig. 4: The beam-size growth due to IBS after switching the electron beam off. Circles are measured ion-beam size. Solid line indicates the fitting result by the analytical formula.

(3) Cool stacking

Beam intensity was increased through cool stacking, as shown in figure 5. The beam was injected to the ring at every 3.3 sec by the multiturn-injection method. The intensity gain by the cool stacking was around 10, which depends on a cooling rate and a beam lifetime.

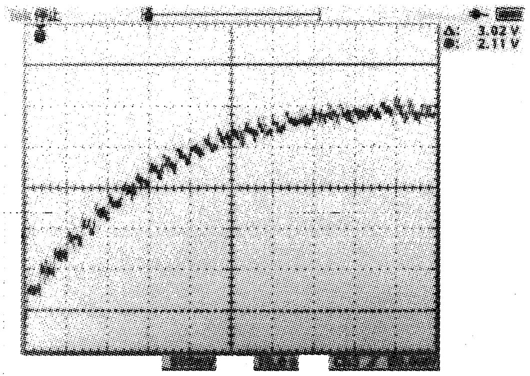

Fig. 5: Intensity increased by cool stacking. Horizontal scale is 10 sec/div. Vertical one around $6 \cdot 10^7$ ppp/div.

3.3 Short-bunched beam

A short-bunched beam can be obtained by the cooling and applying rf-field [7]. A sawtooth-wave rf-field is suitable for production of a short bunched beam compared with a sinusoidal one, because a filamentation is not occurred. As can be seen in figure 6, a short-bunched beam with 40 ns at FWHM was obtained in using the sawtooth-wave rf-field and the cooling, while that with 80 ns in the sinusoidal rf-field. As figure 7 shows the rf-voltage dependency of the bunch width, the bunch width is decreasing as increasing the rf-voltage. In this experiment, the beam was injected and cooled down while the rf-field continuously applied. Further the bunch width was measured by an electrostatic position-monitor and the sawtooth-wave rf-field was applied by a super wide-band cavity [8].

As cooling the ion beam down with the rf-field in the beam-intensity higher than around 10^8 ppp, several peaks were observed in one bunch and the bunch width was considerably widened to around 400 ns at FWHM. At the same time, the beam position was oscillated vertically and the beam loss was begun.

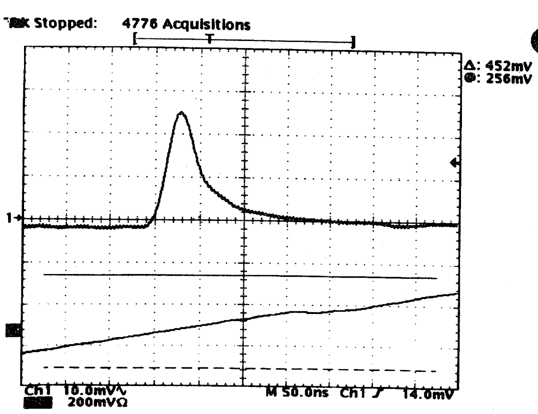

Fig. 6: Bunch shape in cooling and applying sawtooth-wave rf-field. Horizontal scale is 50 ns/div.

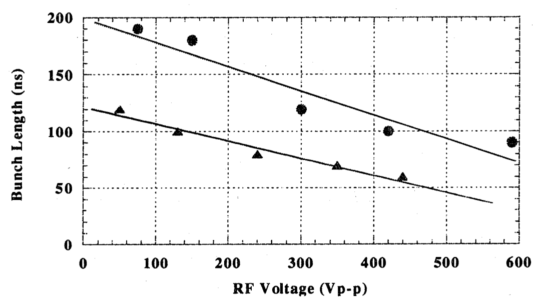

Fig. 7: The rf-voltage dependency of the bunch width. Circles and triangles indicate bunch width in the sinusoidal rf-field and in sawtooth-wave one, respectively.

4 SUMMARY

The cooling experiments have been carried out since the end of March 2000. As the results of the experiments, the horizontal beam-emittance was cooled down less than 0.1π mm·mrad and the cooling time was estimated at 0.5 sec. The cool stacking was also observed with the intensity gain of the one order without adjusting the parameters of the bump-magnets for the multiturn injection. The short bunch with the width of 40 ns was obtained, while the bunch width was widened to 400 ns and instability in the vertical direction was observed in high beam-intensity.

5 ACKNOWLEGMENT

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