BEAM ALIGNMENT FOR ELECTRON COOLING AT HIMAC

T. Furukawa, Chiba University, Chiba, Japan
K. Noda, S. Shibuya, M. Muramatsu, T. Honma, NIRS, Chiba, Japan
T. Fukushima, H. Izumiya, H. Ogawa, T. Iwashima, AEC, Chiba, Japan
T. Nagafuchi, K. Maeda, Toshiba, Tokyo, Japan

Abstract

An electron cooler was installed at HIMAC-synchrotron in order to provide high-quality and high-intensity beam for medical and other applications. The alignment between electrons and ions is essential to carry out highly efficient electron-cooling. The closed orbit distortion (COD) of the ring was corrected by using a best-corrector method. After COD correction around the ring, additional COD due to toroid and solenoid of the cooler was successfully corrected by a local-bump method. The axis of ion beam was consequently aligned with center of central solenoid within 0.8 mm and 0.6 mrad. The dependence of the cooling time on the alignment between ions and electrons was measured.

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 more than 1000 patients had successfully been completed by August 2001.

High-intensity or high-quality beams have been strongly required for basic and applied research at HIMAC [2]. For this purpose, an electron cooler was designed and constructed, because of its strong phase-space compression. It is essential for efficient cooling to match the electron velocity with the ion one. It is also important to align precisely the ion-beam axis with the electron-beam one. For precise alignment, it is necessary to correct COD around the ring before setting up the electron-cooler.

The electron cooler has toroids and solenoids in order to transport the electron beam without increasing the electron temperature. The vertical component of the magnetic field in the toroids distorts horizontally the ion orbit, and the longitudinal magnetic field of solenoid causes rotational motion of ions. In order to compensate these effects, the kick angle of correctors was calculated by the local-bump method [3]. Consequently, ion beam was well aligned with electron one. In the experiments, fully stripped carbon and argon-ions with the energy of 6.0 MeV/n were used in DC operation of the ring and the all sextupole-magnets were switched off for keeping condition of linearity.

This paper reports the experimental results of the COD correction around the ring and beam alignment for electron cooling. The dependence of the cooling time on the alignment accuracy is also described.

2 COD CORRECTION

In order to correct COD, HIMAC-synchrotron has twelve correctors at same place of position-monitors for horizontal direction and eleven pairs of them for vertical one. The horizontal COD has been successfully corrected by the response-matrix method [4].

The response-matrix method can not correct the vertical COD at HIMAC, however, because the vertical position-monitors and correctors are not symmetrically assigned around the ring; one pair of position-monitor and corrector is lacked at an extraction point. The response-matrix method leads beam loss, because the vertical COD was estimated at 50 mm at the extraction point when COD at other position are completely corrected. The vertical COD was corrected by the best-corrector method [3], therefore, which requires the vertical position-data at the extraction point. In order to estimate the vertical beam-position at the extraction point, the Fourier-expansion method [3] was used as follows.

Using eleven measured COD, the Fourier coefficients can be calculated. The COD at the extraction point is approximately estimated at –12.5 mm by using Fourier coefficient of third and forth order, thus, because of the vertical tune of 3.13. The observed COD and fitted curve are shown in figure 1. As the virtual monitor was additionally taken into account, the vertical monitors are to be symmetrically assigned. In this calculation used by MAD program [5], CODs at each side of the extraction point remain about -3.0 mm after the correction. For the actual correction, as the excitation current of the correctors is required, one should know accurately the each effective-length of the correctors. The each effective-length was measured experimentally as follows. The current of one corrector was set 0.5 A, which is estimated at 0.36 mrad from the results of the magnetic-field measurement. The difference between COD before and after the kick was compared with COD after same kick (0.36 mrad) calculated by MAD. As a result of the comparison, the effective-length was calculated between 50 and 70% compared with those from the field-measurement. This result was strongly related to the place of the each corrector.

Using the best-corrector method and each effective-length, the vertical COD has been successfully corrected. The corrected COD was almost consistent with that calculated by MAD, as shown in figure 2. After the vertical COD correction the beam-intensity was increased by several times compared with that before correction.

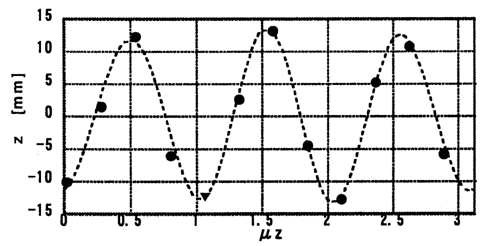

Figure 1: Estimation of vertical COD at lacked position monitor (μz=1.070). Phase advance μz is normalised by 2π. ▼ and ● indicate estimated COD and observed one, respectively.

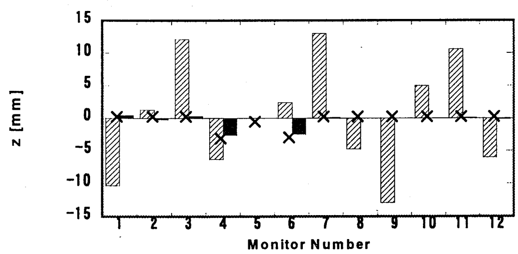

Figure 2: The shaded and black bars represent the vertical COD before and after correction, respectively. X denotes calculation results of corrected COD by MAD. The electron cooler has been located between monitor number 10 and 11.

3 SETTING UP BUMP ORBIT

The vertical component of magnetic field in the toroid kicks ions horizontally. Thus, we should compensate this kick by using correctors and to align ion beam precisely with the center of cooling section. For this purpose, two pairs of horizontal and vertical steering-magnets are prepared at each side of the cooler. The local-bump method has been used to calculate the correction value. Longitudinal solenoidal-field and transverse field in the toroid can be separately considered. Thus, the position of central orbit can be written upstream and downstream the toroid section:

$$\begin{pmatrix} x_{out} \\ x'_{out} \\ z_{out} \\ z'_{out} \end{pmatrix} = M(sol) \begin{pmatrix} x_{in} \\ x'_{in} \\ z_{in} \\ z'_{in} \end{pmatrix} + \begin{pmatrix} \Delta x \\ \Delta x' \\ \Delta z \\ \Delta z' \end{pmatrix}$$

M(sol) represents matrix of solenoid-field from the longitudinal field in the toroid and $\triangle$ indicates the transverse kick and displacement. The transverse kick can be calculated analytically with three assumptions as follows: (1) the magnetic field B is inversely proportional to the radius measured from the center of curvature in the toroid, (2) ion beam is injected to the center of the toroid, (3) B is constant in horizontal plane. Figure 3 shows a definition of coordinate and the sign of upstream toroid.

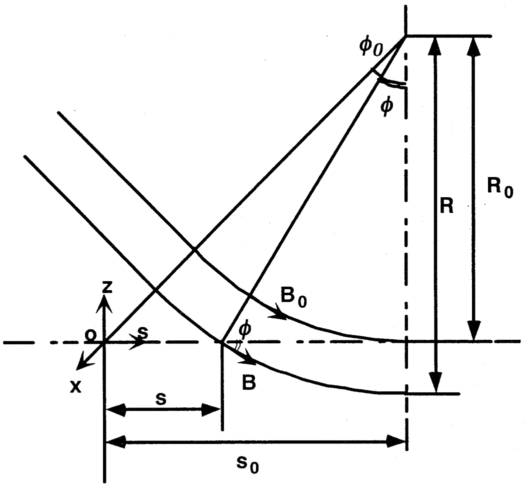

Figure 3: Schematic side view of the upstream toroid.

It should be noted the difference of displacement was given at upstream and downstream toroid. The horizontal displacement and kick at upstream are represented:

$$\Delta x = \frac{B_0 R_0{}^2}{B\rho}\left[\phi_0 - \tan\phi_0\right]$$

$$\Delta x' = \frac{B_0 R_0}{B\rho}\ln\left[\cos\phi_0\right]$$

At downstream:

$$\Delta x = \frac{B_0 R_0{}^2}{B\rho}\left[\phi_0 - \tan\phi_0\left(1 + \ln\left[\cos\phi_0\right]\right)\right]$$

$$\Delta x' = -\frac{B_0 R_0}{B\rho}\ln\left[\cos\phi_0\right]$$

The vertical displacement and kick has no difference at upstream and downstream, as follows:

$$\Delta z = -\frac{B_d}{2B\rho}s_0^2$$

$$\Delta z' = -\frac{B_d}{B\rho}s_0$$

Where B_d is the dipole magnetic-field for bending the electrons to avoid drift motion in the toroid. In actual calculation, the each toroid was divided into 10 sections for more preciseness.

The effective-length of correctors was also measured with the use of method as mentioned above. Moreover, leakage flux from the gun solenoid was measured. Magnetic field of upstream toroid increased up to 4.0 % compared with downstream one. Considering these effects, each kick-angle of correctors was recalculated. Consequently, the local-bump orbit was successfully set up, and no change of COD was observed outside the local-bump orbit. It was confirmed by using two position-monitors in the cooling section that the ion-beam axis was precisely aligned. The displacements at each monitor (Δx , Δz) were (0.8 mm, 0.4 mm) and (0.3 mm, 0.7 mm), respectively.

4 ALIGNMENT OF ELECTRON BEAM

For more efficient cooling, the position and angle of electron-beam were precisely adjusted by using two Helmholtz coils, respectively. One of them is prepared in the gun solenoid for adjustment of the position, while another one is in the central solenoid for adjustment of the angle. These adjustments were carried out by measurement of beam-size cooled for 2 sec by using non-destructive profile monitor [6]. The experimental condition is summarized in Table 1. First, angle of electrons was adjusted so as to minimize the beam-size. Next, position of electrons was adjusted as the same way. Figure 4 shows these results. Since the change of electron angle is to increase ion-temperature seen from electrons, the data were fitted by using the cooling time been in proportion to 3/2th power of temperature. The cooling time calculated in this fitting was 0.81 times shorter than the estimated value using analytical solution of non-magnetized cooing [7]. This difference may come from magnetized cooling. Figure 4-(b) shows the change of cooling time due to electron position. The measurement data are fitted by using parabolic function, because it seems that the change of cooling time is related to the velocity distribution of electrons due to own space charge.

Table 1. The conditions of the cooling experiment

Electron energy	3.443 keV
Electron current	200 mA
Field strength at gun section	0.167 T
Field strength at cooling section	0.05 T
Argon-ion energy	6.00 MeV/n
Tune (Qx/Qy)	3.68/3.13 or 2.88

5 SUMMARY

The beam alignment plays one of the most important roles on efficient beam cooling. For this purpose, COD of the ring and that due to electron cooler have been successfully corrected. The ions were aligned within 0.8 mm and 0.6 mrad in the cooling section. The dependence of the beam size after cooling for 2 sec on the alignment between ions and electrons was measured. As the result, the cooling time estimated by fitting the cooled beam-size was slightly short compared with that by the analytical formula in non-magnetized cooling; the ratio was around 80 %.

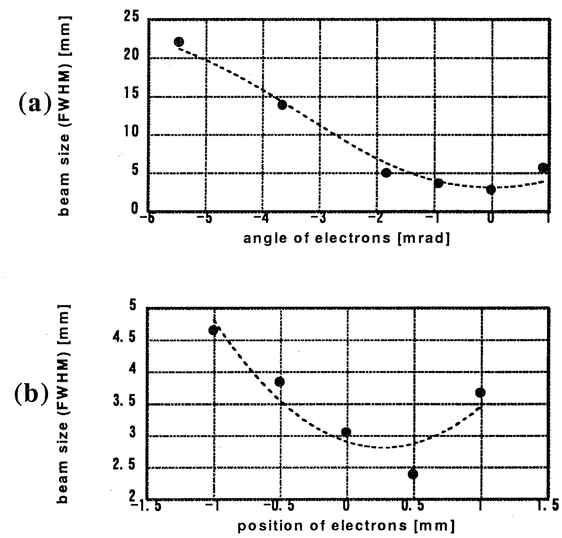

Figure 4: The experimental results of the dependence of the horizontal beam size after cooling for 2 sec on alignment between ions and electrons. (a):the angle dependence of cooled beam-size,(b):the position dependence of cooled beam-size.

6 ACKNOWLEGMENT

The authors would like to express their thanks to Dr. Soga and members of the Department of Accelerator Physics and Engineering at NIRS for continuous encouragement. This work has been performed as a part of Research Project with Heavy-Ion at NIRS-HIMAC.

REFERENCES

[1] Y. Hirao *et al.*, "Heavy Ion Medical Accelerator in Chiba", HIMAC-report-001, 1992.
[2] K. Noda, *et al.*, "Electron cooler for medical and other application at HIMAC", NIM A441 (2000) 159-166.
[3] B. Autin, "Lattice Perturbations", CERN/PS 84-22(AA), 1984.
[4] M. Kanazawa *et al.*, "COD MEASUREMENT AND CORRECTION SYSTEM IN HIMAC SYNCHROTRON", Proc. 5th EPAC, 1996, p.1710-1712.
[5] F. Christoph Iselin, "The MAD Program", CERN/LEP-TH/88-38, 1988
[6] T. Honma *et al.*, "A Non-destructive Beam Profile Monitor Utilizing Charge-division Method at HIMAC", in these proceedings.
[7] P.Lefevre, D.Mohl, "A LOW ENERGY ACCUMULATION RING OF IONS FOR LHC", CERN/PS 93-62(DI) LHC Note 259, 1993.