ELECTRON COOLING EXPERIMENTS AT HIMAC SYNCHROTRON

K. Noda[#], S. Shibuya, T. Uesugi, T. Honma, T. Furukawa, D. Tan, NIRS, Chiba, Japan
E. Syresin, I Meshkov, JINR, Dubna, Moscow region, Russia
S. Ninomiya, RCNP, Osaka, Japan
T. Iwashima, AEC, Chiba, Japan

Abstract

Electron-cooling experiments have been carried out at the HIMAC synchrotron in order to develop new technologies in heavy-ion therapy and related researches. The cool-stacking method, in particular, has been studied to increase the intensity of heavy-ions. The simulation was carried out to optimise the cool-stacking under various injection periods. Further, the beam heating by RF-KO was applied to suppress the transverse instability occurred when the ion density was increased.

1. INTRODUCTION

The HIMAC (Heavy Ion Medical Accelerator in Chiba) accelerator complex has delivered ^{12}C-ions for the cancer therapy and other heavy-ions for basic and applied research [1]. One of the objectives of HIMAC is to develop new technologies in heavy-ion therapy and related researches. For the purpose, the electron-cooling method has been applied, because it can provide high-intensity beams and high-quality beams by its strong phase-space compression [2]. These techniques will lead to the following:

(1) An increase in the intensities of heavier ions, such as Fe and Ni, for estimation of radiation risk in space.
(2) Micro-beam probe for the cellular radiation-response.
(3) Short bunched beam for time-resolving measurements.

Since 2000, thus, the electron-cooling experiments have been carried out at the HIMAC synchrotron. The cool-stacking method, in particular, has been investigated under various conditions. With increasing the intensity through the cool-stacking, the vertical coherent oscillation was developed, which limited the stacking intensity. It is found that the beam heating by the RF-KO can suppress the vertical coherent oscillation. The paper reports the experiment and simulation results.

2. COOL-STACKING EXPERIMENT

2.1 Experimental condition

Fully stripped argon-ions with the energy of 6.0 MeV/n have been used in the cool-stacking experiments. For efficient cool-stacking, the horizontal emittance was decreased to around 65 from 264 π·mm·mrad by decreasing the time-width of the injection beam, while the vertical one is kept around 10 π·mm·mrad. A vacuum pressure is around $5\cdot10^{-8}$ Pa. For measuring non-destructively the beam profile in both horizontal and vertical planes, we have used a gas sheet beam profile monitor (SBPM) for wide intensity range from 10^6 to more than 10^9 ppp [3]. The experimental conditions are summarised at Table 1.

Table 1. The conditions of the cooling experiment

Electron energy (T_e)	3.4 keV
Electron current (I_e)	0.05 – 0.175A
Expansion factor (R_{EXP})	1.7 - 3.8
Electron-beam diameter	64 mm
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) (3.69/3.13)
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

2.2 Transverse cooling

Just after a multiturn-injection batch, the horizontal and vertical beam-sizes at FWHM were measured at 30 mm and 12 mm, respectively, under the typical ion-intensity of $5\cdot10^8$ ions. As shown in Fig. 1, the equilibrium beam size through the cooling was also measured as a function of the ion-intensity. The simulation result by BETACOOL [4] is in good agreement with the experimental one. It is noted, further, that the cooling time was estimated to be around 1.2 s under the electron current (I_e) of 50 mA, the expansion factor (R_{EXP}) of 3.3. Both the experiment and the simulation suggest that the ion density is kept constant, independently of the ion intensity.

#noda_k@nirs.go.jp

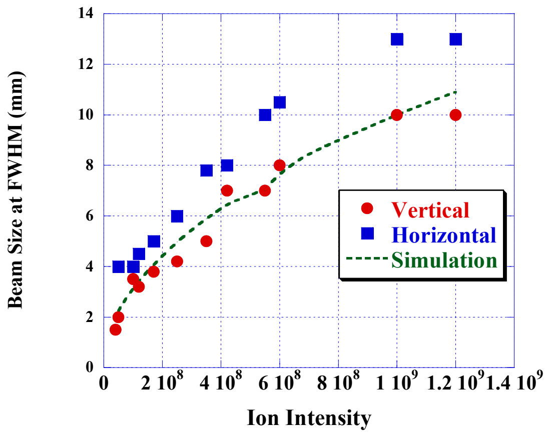

Fig. 1: The equilibrium beam size as a function of the ion-intensity. The closed circles and squares indicate the vertical and horizontal beam size, respectively. The broken line is a simulation result.

2.3 Cool-stacking gain

The cool-stacking gain (G) is given by

$$G = \frac{1-\exp(-KT_{inj}/\tau)}{1-\exp(-T_{inj}/\tau)} \quad (1),$$

where K is number of multiturn-injection batch, T_{inj} the injection period and τ the ion-lifetime. It is noted that the T_{inj} corresponds to the cooling duration. It is obviously shown from Eq. (1) that the G depends strongly on the beam lifetime and the cooling time. As the result of the typical cool-stacking is shown in Fig. 2, the G is estimated to be around 3.

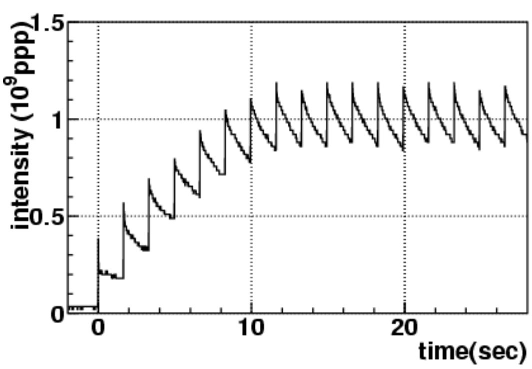

Fig. 2: The intensity growth through the cool-stacking under I_e= 156 mA, T_{inj} = 1.6 s and the working point (Qx/Qy) = (3.73/3.13).

2.4 Lifetime

Since the lifetime is an important parameter for the cool-stacking, the lifetime was measured as a function of the intensity. The measurement result is shown in Fig. 2. The lifetime was around 4 s under the intensity of more than 10^9 ions, while it was increased to be around 20 s under that of around 10^8 ions. It is noted that the I_e is 100 mA in this measurement. The sources of the lifetime reduction with increasing the intensity are considered as follows: (A) the beam-size growth with increasing the intensity, as shown in Fig 1 and (B) the vacuum-pressure increase with increasing the beam loss [5].

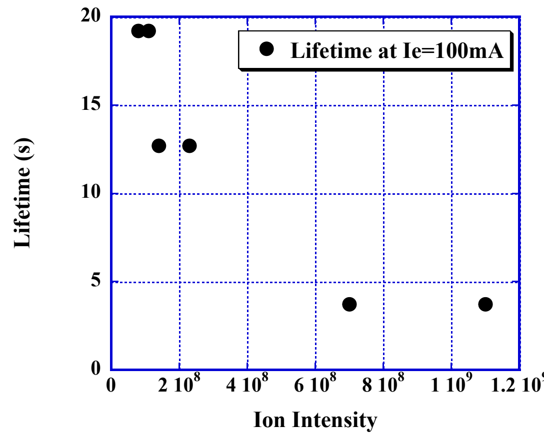

Fig. 3: Ion-lifetime as a function of intensity under the electron current of 100 mA.

2.5 Injection period

In order to increase the cool-stacking intensity, the T_{inj} should be optimized by considering the lifetime and the cooling time. Considering the cooling, IBS and the lifetime, the maximum stacking intensity as a function of the T_{inj} was estimated by using BETACOOL. The broken line with squares in Fig. 4 shows the simulation result. In this simulation, the I_e and the intensity of one multiturn batch were assumed to be 175 mA and $3{\cdot}10^8$ ions, respectively. Further, the lifetime is (A) τ = 7 s, (B) τ = 7 s and (C) τ = 9 s. The closed circles in Fig 4 indicate the experimental results, which are consistent with the simulation result.

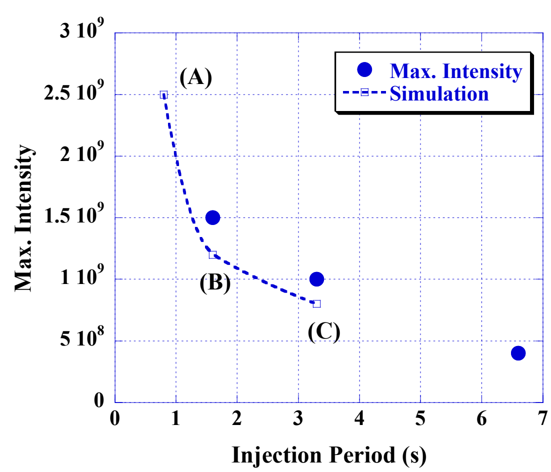

Fig. 4: Maximum stacking intensity as a function of the injection period. Closed circles are the experimental results and the squares the simulation ones.

2.7 Suppressing transverse instability

The vertical coherent oscillation (the transverse instability) was observed with increasing the ion density, which mainly gives the limit of the stacking intensity. The electron heating is one of sources for the transverse instability [6]. In order to suppress the transverse instability, the followings were carried out [7]: (1) changing the working point to avoid the coupling resonance, (2) applying the RF-KO to reduce the beam density, and (3) clearing the secondary ion trapped in the cooler to suppress the electron heating.

Applying the transverse RF-field with the frequency corresponding to the tune, the equilibrium ion density can be reduced by widening the beam size. This can lead to suppress the transverse instability. A typical result is shown in Fig. 5. In this case, the RF-KO was applied in the vertical direction under the T_{inj} of 1.0 s, the R_{EXP} of 1.7 and the I_e of 130 mA. It is clearly observed that applying RF-KO can suppress the vertical coherent oscillation. It was verified also that the RF-KO applied in the horizontal direction suppressed the vertical coherent oscillation. It is noted that the RF-KO electrode is located at the different position of the electron cooler. Further, the position monitor with four electrodes in the cooler was used as “Shaker” [8] to remove the secondary ions trapped by the electron-beam potential. When the frequency applied to the electrodes was consistent with the lower-sideband frequency corresponding to the vertical tune, the instability was suppressed, and the stacking intensity was increased. However, the potential was inversely shift compared with clearing the secondary ions. It suggests that the shaker works as the RF-KO or removes the secondary electron with the energy of around 20 eV.

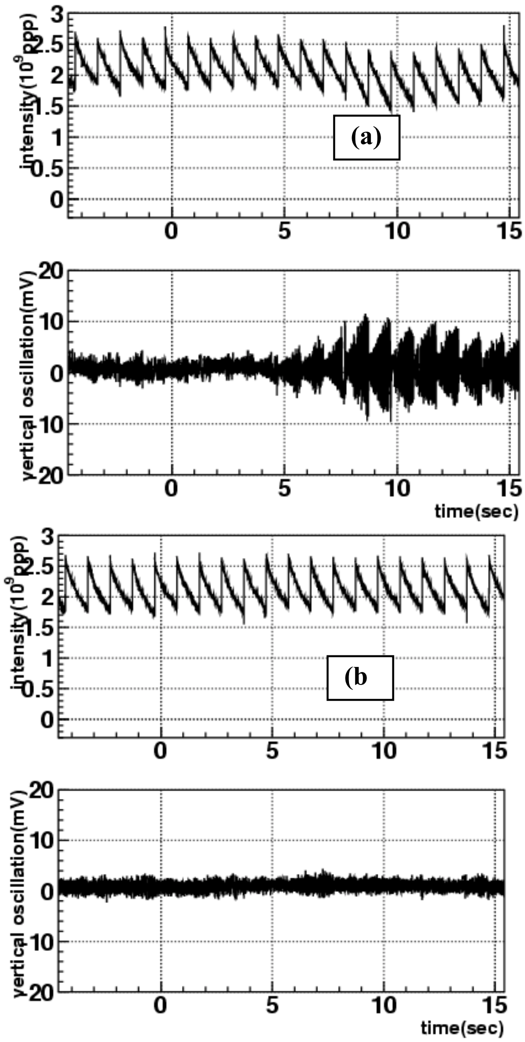

Fig. 5: Suppressed the instability by the RF-KO.
(a) Detuned RF-KO; the frequency corresponds to 3.090,
(b) Tuned RF-KO; the frequency corresponds to 3.150.
Upper and lower figure in each case indicate the stacking intensity and the amplitude of the vertical coherent oscillation.

3. SUMMARY

The electron-cooling at the HIMAC synchrotron has been focused on the cool-stacking experiment. The stacking intensity was limited by the vertical coherent oscillation. Owing to improvements mentioned above, at present, the maximum stacking intensity can be increased to $2.7 \cdot 10^9$ Ar-ions corresponding to around 2 mA.

ACKNOWLEGEMENT

The authors would like to express their thanks to the colleague of Accelerator Physics and Engineering Department of NIRS for continuous encouragement, and the crew of AEC for skilful operation of HIMAC. This work has been carried out as a part of Research Project with Heavy-Ion at NIRS-HIMAC.

REFERENCES

[1] K. Noda *et al.*, Proc. APAC04, Gyeongju , Korea, 2004, to be published.
[2] K. Noda, *et al.*, Nucl. Instr. Meth. **A441** (2000) 159.
[3] Y. Hashimoto *et al.*, Nucl. Istrr. Meth **A527** (2004) 289.
[4] I. Meshkov *et al.*, Proc. ECOOL 2001, Bad Honnef, Germany, 2001.
[5] J. Bosser, *et al.*, Proc. EPAC98, pp.253-255.
[6] V. V. Parhomchuk, Proc. APAC’98, Tsukuba, 1998, pp.462-464.
[7] T. Uesugi *et al.*, TUPLT073 in this conference.
[8] J. Bosser *et al.*, Nucl. Instr. Meth. **A391** (1997) 103.