Experimental studies of stability issues at HIMAC cooler

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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. We have observed a transverse coherent oscillation and the lifetime reduction when the cool stacking increased the intensity and/or density of the circulating ions. Using a cooled beam, further, we observed also the particle trapping when crossing third-order resonance. We report the experimental studies of the stability at the HIMAC cooler.

1. INTRODUCTION

The heavy ion medical accelerator in Chiba [1] (HIMAC) is an accelerator-complex facility dedicated to the heavy-ion cancer therapy, which was constructed in National Institute of Radiological Sciences (NIRS). One of the objectives of HIMAC is to develop new technologies in heavy-ion therapy and related researches. For the purpose, the electron cooling has been applied, because it can provide high-intensity beams and high-quality beams by its strong phase-space compression [2].

Since 2000, thus, the electron-cooling experiments have been carried out at the HIMAC synchrotron. Among of them, especially, the cool-stacking method has been studied in order to increase the ion-beam intensity at the HIMAC [3, 4]. When the ion-beam density was high, the stacked ion beam was rapidly lost by the coherent transverse instability. Further the stacked intensity was saturated by the lifetime reduction with increasing the ion-beam intensity. In order to damp the coherent oscillation, we have applied the RF-heating, cleaning the trapped ions in the cooler and the transverse feedback. Damping the coherent oscillation can increase the stack intensity.

Using a cooled beam and the Oxygen gas-sheet beam profile monitor (SBPM) [5], the behaviour of the ion-beam was investigated when crossing a third-order resonance. In this experiment, a particle trapping was observed.

We describe the cooling experiment at the HIMAC cooler.

2. BEAM LOSS AT COOL STACKING

2.1 Cool-stacking

Cool-stacking has been studied in order to increase the beam intensity at the HIMAC cooler. The experiment was carried out using fully stripped argon-ion with the energy of 6 MeV/n. The experimental condition is summarized at Table 1.

In the cool-stacking method, stacked intensity at K'th injection is given by

$$N_K = N_{inj} \cdot G$$
$$G = \frac{1-\exp(-KT_{inj}/\tau)}{1-\exp(-T_{inj}/\tau)} \qquad (1)$$

where N_{inj} is the intensity of one-batch injection, G the gain, T_{inj} the injection-repetition time, τ the ion lifetime. Figure 1 shows typical intensity evolution during the cool stacking.

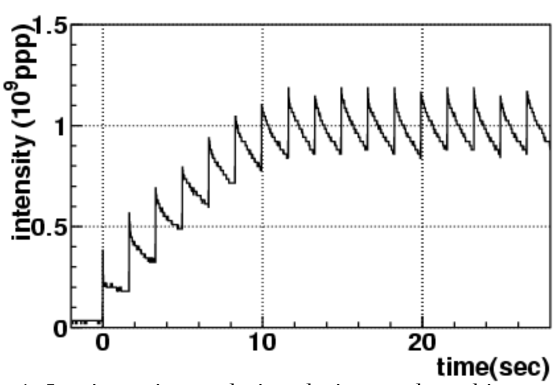

Fig. 1. Ion-intensity evolution during cool stacking under T_{inj} = 1.6 s, I_e = 150 mA, R = 3.3.

The gain (G) of the cool-stacking is determined by the τ and the T_{inj}. In the case of Fig. 1, the maximum stack intensity is around $1.2 \cdot 10^9$ ions, corresponding to the stacking gain of 3-4. In order to increase the stack intensity, both the ion lifetime and the cooling rate should be increased. Further, transverse coherent instability, which is caused in the high intensity, should be suppressed.

Table 1. The experimental condition of the cool-stacking

Electron energy (T_e)	3.4 keV
Electron current (I_e)	25 – 200 mA
Expansion factor	R = 1.7, 2.8, 3.3, 3.8
Cathode Diameter	35 mm
Solenoid at cooling section	0.05 T, 1.2 m
Ring Circumference	129.6 m
Argon-ion energy	6.00 MeV/n
Tune (Qx/Qy)	(3.69/2.89) or (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
Vacuum pressure	~$5 \cdot 10^{-8}$ Pa

2.2 Beam loss and its cure

2.2.1 Injection loss

A part of the ion-beam is lost by the bump-orbit excitation for the injection, which effectively decreases N_{inj}. The number of the ions to be lost is determined obviously by the relation among the cooling rate (λ), the injection repetition time (T_{inj}) and the available space between maximum bump orbit and the septum electrode.

Figure 2 compares the increase of the stacked intensity at the first, the second and the third injections for different e^--beam currents. The T_{inj} and the bump height were fixed here. The reduction of the N_{inj} at the second injection corresponds to the ion-beam loss due to the bump excitation. Figure 2 shows that the loss became small when the e^--beam current, ie the cooling rate, was high. Maximum stacked intensity was also increased with increasing e^--beam current.

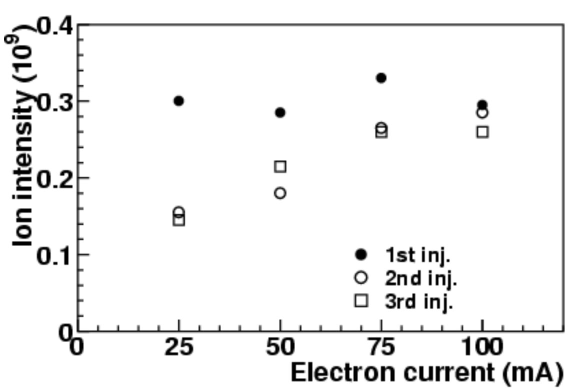

Fig. 2. Increase of the ion intensity as a function of the electron current. Closed circles, open circles and open squares are the first, the second and the third injection, respectively.

2.2.2 Rapid loss

<u>Coherent instability</u>

Coherent instability was observed when the densities of ions and electrons were high, which was correlated with the dipole-mode transverse oscillation of the ion-beam as shown in Fig. 3. The instability restricted the high intensity accumulation. In the observed beam profile as shown in Fig. 4, it is clearly shown that the direction of the oscillations was inclined in the transverse space at the instability. This fact indicates the x-y coupling of the betatron oscillation. One of sources of the x-y coupling is related to the ion-electron coupling instability [6-8]. The electron-beam space charge and the solenoid field produce coupling between the horizontal and vertical oscillations of the circulating ion beam. As a result of the simulation for the coupling instability, it is found that the growth rate becomes maximum at the difference resonance, Q_x - Q_y = 1 and minimum at the operation point (3.725, 3.2).

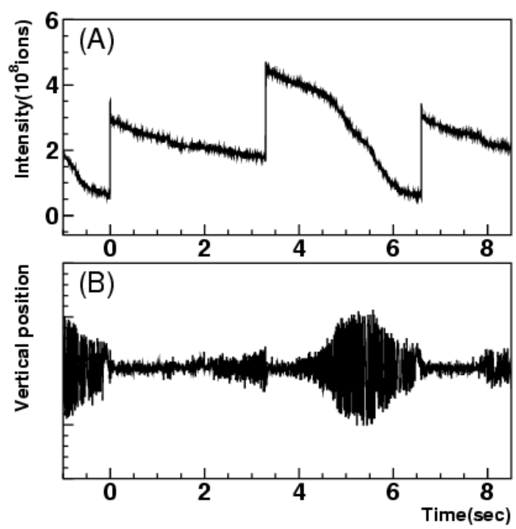

Fig. 3: (A) Time evolution of the ion intensity and (B) the vertical differential pickup signal corresponding to an amplitude of the vertical coherent oscillation. I_e = 130 mA, R =3.3 and the working point was (3.69, 2.89).

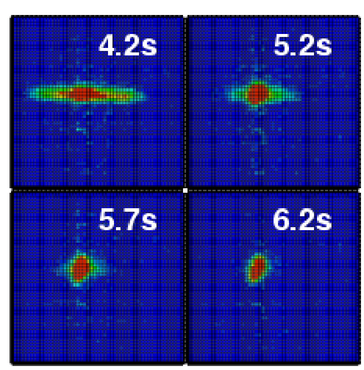

Fig. 4. Two-dimensional beam profile when an instability developed.

Damping of instability by RF-heating

Since the instability was occurred at high ion density, it could be damped by reducing the peak density of the ion-beam by applying transverse RF-heating with a frequency near to the transverse betatron frequency [9]. Figure 5 shows that the coherent instability was damped and the stack intensity was considerably increased.

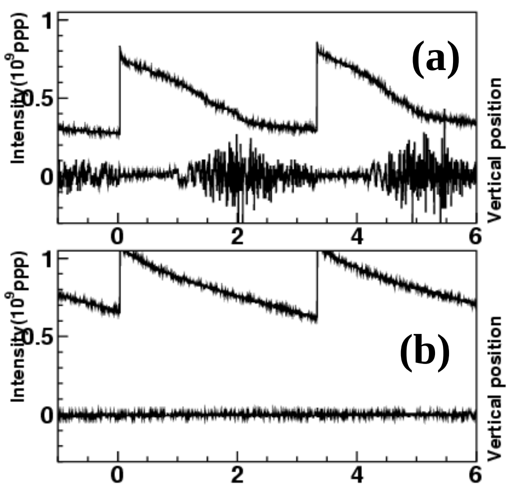

Fig. 5. Damped the instability by RF-heating. (a) without RF-heating and (b) with RF-heating. Upper and lower traces in each figure indicate an ion-intensity and an amplitude of the vertical coherent oscillation, respectively.

Clearing residual-gas ions

It seems that secondary ions trapped in the electron beam cause the electron-beam instability. This "beam-drift instability [10-13] of a partially neutralized electron beam restricts the cooling of the ion stack. The partially neutralized electron beam was itself unstable at a threshold current density. Investigating the relation between the revolution frequency of the circulating ion and the electron energy, the neutralization factor was measured to be around 15%.

For clearing the trapped ions, the shaking technique [10,11] was applied: a transverse sinusoidal electric field was applied on short electrodes in the cooling section. The residual ions with a charge-to-mass ratio of Z/A are shaken out at resonant frequencies of

$$\omega = \sqrt{\omega_{pr}^2(1-\eta) + \omega_{cr}^2/4} \pm \omega_{cr}/2 \qquad (2)$$

where $\omega_{cr} = ZeB_{sol}/Am_p$ and $\omega_{pr} = (2\pi r_p Z n_e/A)^{1/2}$ are the linear cyclotron frequency and plasma frequency of the residual-gas ions, respectively. Shaking out the residual ions changed the potential at the center of the electron beam. Readjusting the acceleration voltage for electron beams so that the revolution frequency of the circulating ion beam remained at a fixed value compensated the potential change. Figure 6 shows the shift of the acceleration voltage as a function of the shaking frequency. Applying a voltage of up to 10 V, clearing the trapped ions at 230 kHz reduced the amplitude of the vertical coherent oscillations quite significantly.

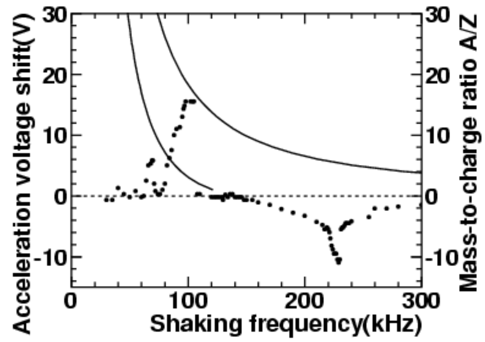

Fig. 6. The acceleration-voltage shift as a function of the shaking frequency when shaking out the trapped ions in the cooler. The solid lines indicate A/Z of the ions resonant at given frequency for the two modes given by Eq. (2).

Transverse feedback

A transverse feedback also was carried out in order to damp the coherent instability. Figure 7 shows the preliminary result of the transverse feedback. Applying the transverse feedback in the vertical direction, the amplitude of vertical coherent oscillation was significantly damped, and the stacked intensity of $2.3 \cdot 10^9$ ions was kept constant for more than 50 s even under T_{inj} = 3.3 s and I_e = 100 mA.

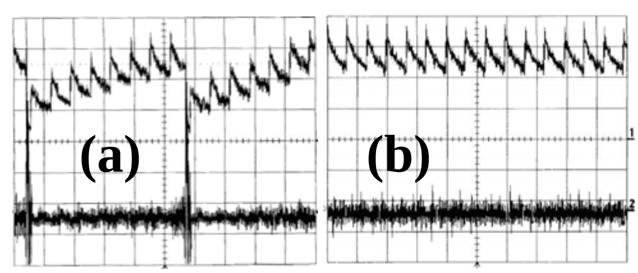

Fig. 7. (a) Without feedback, (b) With feedback. Upper and lower traces in each figure are the intensity and the amplitude of the vertical oscillation, respectively.

2.2.3 Slow loss

The maximum stack intensity is limited by the lifetime, as shown in Eq. (1). It is clearly observed from Fig. 1 that the beam lifetime was decreased with increasing the beam intensity. Degradation of the vacuum pressure is one of the sources of the lifetime reduction at high intensity. The ion lifetime was measured with different I_e and R by analyzing the slow beam-loss waveform after stopping the injection. Figure 8 shows that the lifetime was increased with decreasing R from 3.8 to 2.8 [14]. On the other hand, the dependency of the lifetime on I_e was negligible in the wide range of 50~175 mA. Therefore the dependence of the lifetime on R is not explained by the cooling rate (λ), because, assuming that $\lambda \propto I_e/R$, the change of λ by R was around 30 %, while it was more than 70 % by I_e. The experimental results suggest that the existence of the electron beam outside of the ion beam contributes to the slow-beam loss.

It seems that the slow-beam loss is related to the diffusion process of the ion-beam inside the electron beam [15]. The ions with large betatron amplitude is affected the diffusion to be lost. This process strongly depends on the diameter of the electron beam. It should be noted, however, that the diameter of the electron beam, at the expansion factor of 2.8 ~ 3.8, corresponds to the ion-beam emittance of larger than the vertical acceptance. Thus, the mechanism of the slow beam loss is not clearly understood, and further investigation is required.

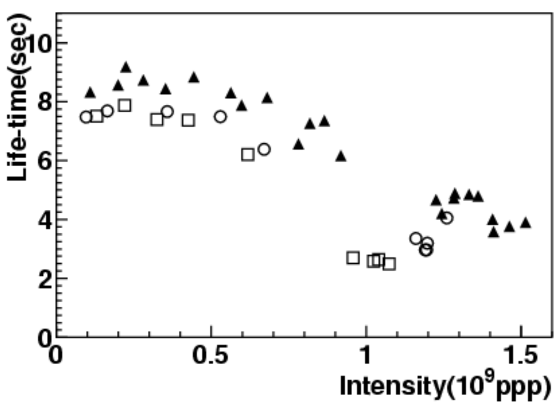

Fig. 8. Ion-lifetime as a function of intensity under the electron current of 100 mA. The expansion factor (R) is 2.8 (triangles), 3.3 (circles) and 3.8 (squires), respectively.

2.2.4 Improvement of stack intensity

Based on the experimental results mentioned above, the parameters for the cool stacking were optimized. Owing to reduction of the peak intensity of the ion beam through the RF-heating, the vertical coherent oscillation was stabilized, which brought the high stack intensity without sudden beam loss at a small T_{inj}. Under T_{inj} = 1 s and I_e = 130 mA and R =1.7, the stack intensity reached at $2.5{\cdot}10^9$ ions. The frequency of the RF-heating was 825 kHz, where the vertical coherent oscillation was suppressed most effectively. This frequency was slightly shifted from the nearest vertical sideband (814 kHz). The applied voltage was around ±1 V corresponding to the kick angle of 0.1 μrad. It is found, further, that the transverse feedback is a strong tool to increase the stack intensity.

2.3 Ion-density at cool equilibrium

The transverse beam-profiles were measured during the electron cooling. The beam-sizes were decreased by the electron cooling, and saturated after cooling of 3 s. In order to investigate the equilibrium beam-size depending on the intensity, the slow loss of a stacked ion-beam were sequentially measured after switching off the injection. In this measurement, the ion-beam is considered as the equilibrium after the cooling time constant of 3 s.

Figure 9 shows that the cross-section of the ion-beam was proportional to the intensity, so that the transverse density was kept constant at $0.9{\cdot}10^7$ ions/mm^2. The density corresponds to the maximum betatron tune-shift of 0.03 [2] on the assumption of Gaussian distributions.

The behaviour of XY $\propto$ N can be related to some betatron resonances, and is also consistent with the Parkhomchuk's simulation result, taking into account the diffusion losses caused by the electron beam [15].

At the low intensity of less than ~10^8 ions/ring, the ion-beam cross-section was restricted by the intra-beam scattering (IBS) and depended on the 2/5'th power of the intensity.

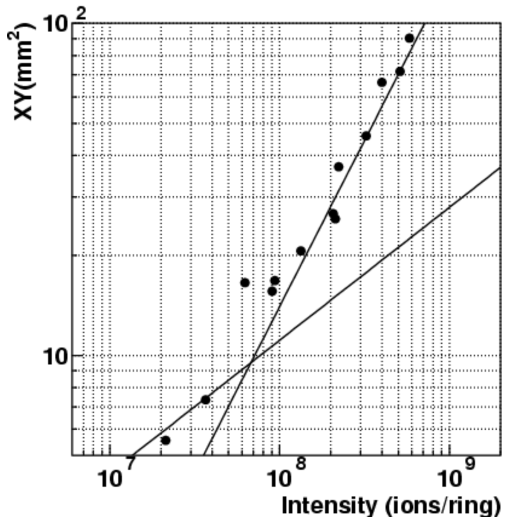

Fig. 9. Products of the transverse FWHM beam sizes of cool equilibrium (XY) at different intensity. Solid lines correspond to XY = $1.1{\cdot}10^{-7}{\cdot}$N mm^2 and XY = $0.017{\cdot}/\mathrm{N}^{2/5}$ mm^2, respectively.

2. RESONANCE CROSSING

The beam behaviour in resonance crossing was investigated. It seemed that the experimental result suggested particle trapping when crossing non-liner resonance [16]. In order to observe the particle trapping clearly, thus, the experiment employed the cooled beam with the emittance of 4.1 π·mm·mrad and the SBPM. In the experiment, a non-structural third-order resonance of $3Q_x$ =11 was chosen, because the routine operation point at the HIMAC synchrotron is near to this resonance line. The experiment was carried out at a flat-base operation. The excitation current of the QF was linearly changed so as to cross the resonance, while other magnetic fields were kept constant. The horizontal tune was changed by $3.5{\cdot}10^{-6}$ (1/turn). As shown in Fig. 10, the particle trapping was clearly observed by using the SBPM when the chromaticity-correction sextupole field was excited so as to change the chromaticity from –6.1 to +1.4. The centre of the profiles is the beam core and both the left and right profiles are trapped ions. The ratio of the trapped ions to the circulating ions was 24%.

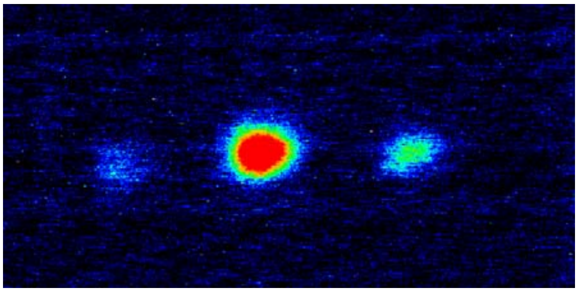

Fig. 10. Particle trapping observed by SBPM.

The simulation was carried out in order to analyse the experimental result. As shown in Fig. 11, the simulation result is consistent with the measured one only when one of the separatrix exciters (SXFr) for a slow extraction is excited to be $B''L/B\rho = 0.092\ m^{-2}$. This means that the HIMAC synchrotron has asymmetric sextupole field. Further, the simulation result can explain the reason why the right profile shown in Fig. 10 is much bright compared with the left one.

(a)

(b)

(c)

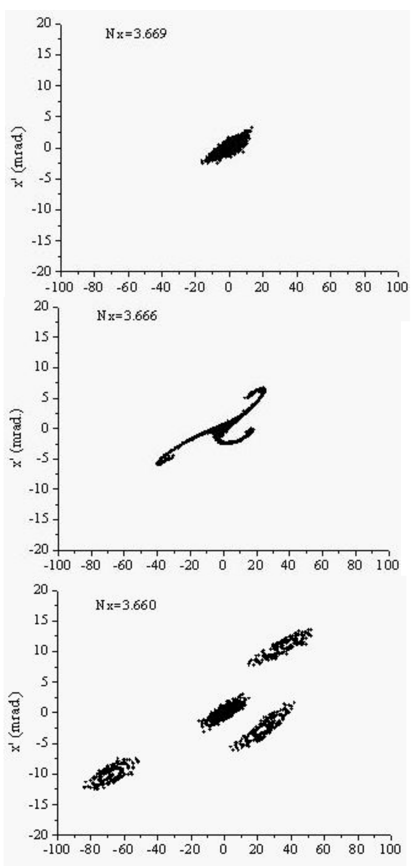

Fig. 11. The simulation result of the particle trapping.
(a) $Q_x = 3.669$, (b) on resonance and (c) $Q_x = 3.660$.

SUMMARY

The electron-cooling at the HIMAC synchrotron has been focused on the cool-stacking experiment in order to accumulate high-intensity ion-beam. The stacked intensity was increased with increasing the cooling rate through increasing the electron current and degreasing the diameter of the electron beam. Coherent transverse instability was observed and caused the rapid beam loss when ion and electron-beam density was high. The instability could be damped by applying RF-heating and the transverse feedback. In addition, it is essential also to choose the betatron tune far from the differential coupling resonance. The slow beam loss was suppressed by reducing the electron-beam diameter. The limitation on the cooling corresponded to the ion-beam density of ~ $0.9{\cdot}10^7$ ions/mm^2.

Using the cooled beam, the particle trapping was observed when crossing the third-order resonance.

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