BEAM DYNAMICS WITH ELECTRON COOLING

T. Uesugi, K. Noda, NIRS, Chiba, 263-8555 Japan
I. Meshkov, E. Syresin, JINR, Dubna, Moscow region, 141980 Russia
S. Shibuya, AEC, Chiba, 263-0043 Japan

Abstract

Electron cooling experiments have been carried out at HIMAC 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 maximum stack intensity was 2 mA, above which a fast ion losses occurred simulatneously with the vertical coherent oscillations. The instability depends on the working point, the stacked ion-density and the electron-beam density. The instability was suppressed by reducing the peak ion-density with RF-knockout heating.

INTRODUCTION

The electron cooling experiments at HIMAC[1] synchrotron have been carried out since 2000 in order to develop new technologies in heavy-ion therapy and related fields. One of the objectives of the HIMAC cooler is to increase the beam intensity of heavier ions such as Fe, for risk estimations under low-dose exposure in space [1]. For the purpose, the cool-stacking method has been studied at the HIMAC synchrotron, because the electron-cooling method can provide high-intensity beams by its strong phase-space compression. The electron cooling experiments were carried out with coasting beams of Ar^{18+} ions at injection energy of 6 MeV/u.

The HIMAC synchrotron adopts the multi-turn beam injection using the horizontal space. The full emittance of a beam after one batch injection is around 260 πmm-mrad in horizontal and 10 πmm-mrad in vertical spaces, respectively. The intensity and momentum spread of a beam are typically $(0.3{\sim}0.7)\times10^9$ particle per pulse (ppp) and ±0.1%, respectively.

The stack intensity of ion beam at K'th injection is given by

$$N_K = N_0\frac{1-\exp(-KT_0/\tau)}{1-\exp(-T_0/\tau)}\,, \qquad (1)$$

where N_0 is the number of ions in one-batch injection, T_0 the injection-repetition period and τ the ion-beam lifetime. Our experimental results showed that the lifetime was decreased at higher ion-beam intensity (N), depending on electron-beam current (I_e) and its magnetic expansion factor (R). The lifetime reduction was small at higher electron beam density, as described in Sec. 2.

The maximum stacked intensity with $N_0 = 0.03\times10^9$ and $T_0 = 3.3$ s was $(0.3 \sim 0.4)\times10^9$ ions [2]. However, the intensity higher than that was restricted by ion-beam instability [3]. The ion-beam instability occurred when the ion- and electron-beam density was high [4]. The instability correlated with the burst of coherent vertical oscillations, as descibed in Sec. 3. Such instability was observed at CELSIUS, Indiana cooler, SIS and COSY [5]. The instability at the HIMAC synchrotron essentially depends on the working point and had a maximum increment at a coupling resonance $Q_x - Q_y = 1$. The instability was related with so called electron heating [6, 7, 8]. The instability could be suppressed by RF-knockout heating, which is also described in Sec. 3.

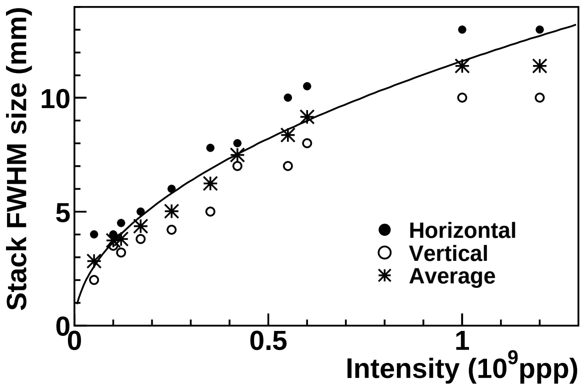

Figure 1: Transverse FWHM beam-sizes during stack-decay. The curve corresponds to Eq. (2).

COOL STACKING

Transverse Beam Density

The profile of a coasting ion-beam was measured during cooling with R=3.3 and I_e=50 mA, which corresponds to electron-current density of 1.55 mA. Ion-beam intensity corresponds to 0.5×10^9 ions and was very slowly decreased with the lifetime of $5 \sim 6$ s. The transverse cooling was saturated at the FWHM sizes of (6 mm,6 mm). The peak ion-density, when Gaussian distribution was assumed, corresponds to

$$\frac{1}{2\pi}\frac{N}{\sigma_x\sigma_y} = 0.16\times10^9\ \mathrm{ions/cm}^2\,, \qquad (2)$$

where $\sigma_{x,y}$ are the horizontal and the vertical rms sizes, respectively. The cooling time corresponds to around 2∼3 s.

Ion-intensity was increased by cool-stacking injection. Ion-intensity of up to $\sim1.5\times10^9$ ppp was stacked with T_0=1.65 s. The beam profiles were measured during the stack-decay after stopping ion-beam injection. The FWHM beam size was proportional to the square root of beam intensity throughout the stack-decay, and was in good agree-

---

[1] Heavy Ion Medical Accelerator in Chiba

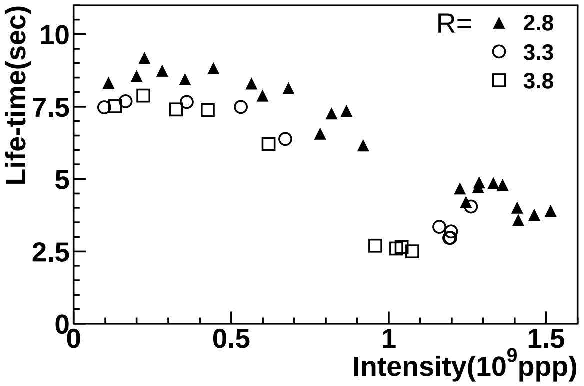

Figure 2: Lifetime vs ion intensity for various expansion factors (R). Electron current (I_e) is 100 mA.

ment with Eq.(2) as shown in Fig. 1. The density limit was constant at $2.8 < R < 3.3$ within the mesurement accuracy.

Lifetime Reduction

The intensity-dependent lifetime of ion-beam was measured by analyzing the beam-intensity waveform during stack-decay. Figure 2 shows the ion-beam lifetime at I_e=100 mA and T_0=3.3 s, as a function of ion-intensity . The lifetime was 8 s at a low-intensity of $\sim 5\times10^7$ ppp, and was decreased to $3 \sim 5$ s at a high intensity of $\sim 10^9$ ppp.

Fig. 2 shows that the lifetime became higher when R is low. The lifetime was also measured with different I_e, as shown in Fig. 3. Here, the COD was fairly corrected and the injection repetition (T_0) was reduced from 3.3 s to 1.65 s, so that the ion-intensity became higher comparing with Fig. 2. Both of Figs. 2 and 3 shows that the ion-beam lifetime was high when electron dencity ($\propto I_e/R$) was high.

Maximum Stacked Intensity

The stacked ion-beam intensity was increased by optimizing I_e, R, T_0 [9], N_0, and the bump-orbit matching. As a result, the maximum stacked intensity of 2.1×10^9 ppp was obtained with T_0=1.0 s, I_e=130 mA, R=1.7, as Fig. 4. Here, a transverse RF of 8 V was applied at 225 kHz in order to suppress ion-beam instability, which is described in the next section.

INSTABILITY

Transverse Instability

Ion instability occurred when the densities of ions and electrons were high [3]. Figure 5 shows the typical waveform of ion intensity and vertical coherent oscillation, when the instability occurred. Here, I_e=150 mA, R=3.3, and working point was (3.69,2.89). The ion beam was suddenly lost during instability at around 5.5 s, which was correlated with the bursts of vertical coherent oscillations.

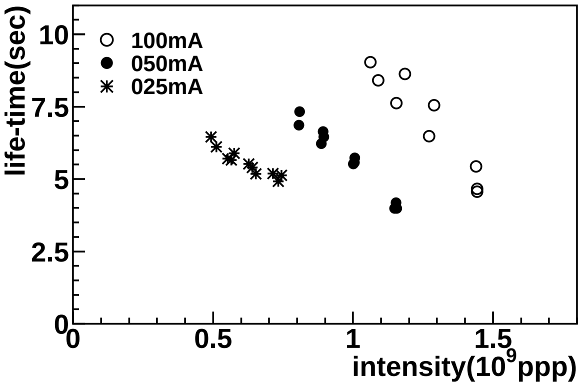

Figure 3: Lifetime vs ion intensity for various electron currents (I_e). Magnetic expansion factor (R) is 3.3.

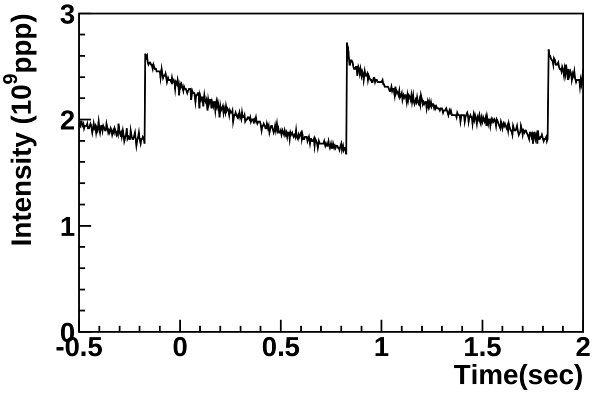

Figure 4: Stack intensity of 2.5×10^9 ppp was obtained.

The frequency of the oscillations agrees with the vertical betatron-sideband frequency.

The instability essentially depends on working point. The working points were surveyed along a line between (3.69,2.89) and (3.72,3.13). It was found that the beam was unstable near to the coupling resonances, $Q_x+Q_y = 7$ and $Q_x-Q_y = 1$. Further, beam-profile measurements showed that the direction of the amplitude growth caused by the instability was slightly inclined in the transverse plane [4]. The bandwidth of the instability was wider at the difference resonance than the sum resonance. These results are consistent with the simulation including the coherent interaction between electron- and ion-beam via space-charge fields [4].

Though the instability occurred at high ion-density, it is possible to to suppress the instability by decreasing the peak ion-density. The RF-knockout(RF-KO) was applied near the frequency corresponding to the vertical betatron-sideband frequency in order to decrease the peak density of the ion-beam. With the RF-KO, the coherent oscillation was suppressed and the stacked ion-intensity was improved as shown in Fig. 6

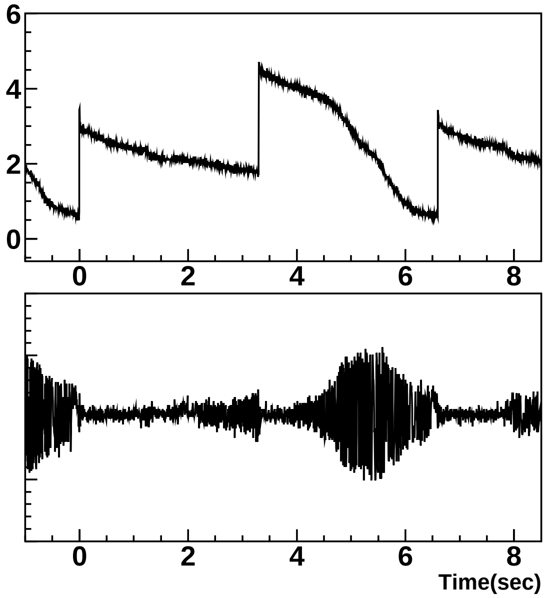

Figure 5: Waveform of ion intensity and vertical differen- pickup signal when instability was developed.

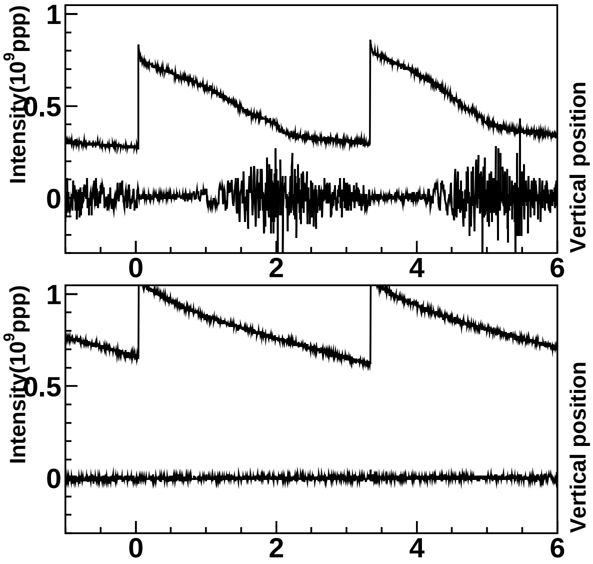

Figure 6: Transverse instability (upper) was suppressed by RF-KO heating (lower).

Electron Beam Instability

Secondary ions trapped in the electron beam may cause electron beam instability. The partially neutralized electron beam is itself unstable at a threshold current den- of [10, 11]

$$j_{\rm th} = \frac{k'\pi\epsilon_0}{2}\frac{\beta^2 c^2 B_{sol}}{L_e} \tag{3}$$

without any ion stack interaction, where B_{sol} is the strength the solenoid for electron focusing, L_e the length of the partially neutralized electron beam, and k' is the numeri- coefficient depending on the structure of ion trap. The threshold current density of HIMAC cooler was estimated to be 9 mA/cm^2.

The maximal electron current, which was available for electron cooling at the HIMAC cooler, was measured a stack intensity of 2.5×10^9 ppp. The stacked ion beam was stable at I_e less than 130 mA at the electron beam diameter of 4.6 cm, which corresponds to the elec- density of 8 mA/cm^2.

SUMMARY

Electron-cool stacking experiments have been done at HIMAC synchrotron. There was a limit of transverse cool- at ion peak-density of 0.16$\times 10^9$ ions/cm^2. By analyz- the stack-decay, it was found that the ion-beam lifetime reduced at ion intensity higher than $\sim$0.5$\times 10^9$ ppp. lifetime reduction became smaller when the density of electron beam was higher. There was a certain thresh- of ion-density, above which a coherent instability occurred. The instability was suppressed by reducing the

REFERENCES

[1] K. Noda et al., NIM **A441**(2000)159.

[2] K. Noda et al., Proc. of the workshop on Ion Beam Cooling Toward the Crystalline Beam, Kyoto, Japan(2001),pp.129.

[3] K. Noda et al., EPAC'02, Paris, June 2002, pp.1380.

[4] T. Uesugi et al., EPAC'04, Lucerne, Jul 2004.

[5] See references listed in Ref. [4]

[6] V. V. Parkhomchuk and V. B. Reva, Journal of Experimental and Theoretical Physics, v.91, N5 (2000), 975.

[7] P. R. Zenevich and A. E. Bolshakov, NIM **A441** (2000), 36.

[8] A. Burov, NIM **A441** (2000), 23.

[9] K. Noda et al., EPAC'04, Lucerne, Jul 2004.

[10] J. Bosser et al., NIM **A391** (1997), 110.

[11] A. V. Burov et al., Preprint BINP 89-116, CERN PS 93-09, 1993.