FEASIBILITY OF SEPARATION OF AN ION SPECIES OF BEAM FROM A SECONDARY BEAM IN A STORAGE RING

M. Takanaka, RIKEN, Wako-shi, Japan

Abstract

A secondary beam of nuclear projectile fragments is injected in a storage ring. The feasibility of separation of an ion species of beam from the secondary beam in the ring is described. The idea of separation is as follows. After stochastic cooling is applied to the secondary beam as a pre-cooling, electron cooling is applied in order to separate ion species of beams in the longitudinal phase space. A given ion species of beam is RF-captured and accelerated for the sake of the horizontal separation. The longitudinal space-charge effects on the separation have been studied in performing particle-tracking simulations.

INTRODUCTION

An ion species of beam is separated from a secondary beam of nuclear projectile fragments usually using a projectile fragment separator in a transport line. It is planned at Radioisotope Beam Factory (RIBF) that the separated beam is injected and cooled in a storage ring before it is used for colliding experiments [1]. The fragment separator has the side effect of enhancing the transverse emittance [2]. A new separation proposed here does not have the side effect.

The space-charge effects on the separation have been studied by using the simulation code which was developed to study bunch shortening of an electron-cooled ion beam [3]. The longitudinal field is calculated approximately as

$$\frac{i}{2\pi}\sum_{k=0}^{2}\left[\frac{Z_{II}^{k}}{n}\right]_{sp}\frac{dI^{k}}{ds}, \tag{1}$$

where s is the longitudinal coordinate, $\left[Z_{II}^{k}/n\right]_{sp}$ the longitudinal space-charge impedance when the transverse charge distribution is assumed to be Gaussian, I^{k} the beam current, and k the moment mode of the charge distribution (monopole, dipole, and quadrupole).

COOLING

The revolution time τ of a particle with the mass deviation Δm and the momentum deviation Δp per charge has the following deviation $\Delta\tau$:

$$\frac{\Delta\tau}{\eta\tau}=\frac{\Delta p}{p}+\frac{\Delta m}{\eta\gamma^{2}m}=\frac{\gamma^{2}\Delta v}{v}+\frac{\Delta m}{\eta\gamma_{t}^{2}m}, \tag{2}$$

where v is the velocity, $\gamma=1/\sqrt{1-v^{2}/c^{2}}$, γ_{t} the transition gamma, and η the slippage factor. If ion species of beams were extremely stochastic-cooled, all the beams with different Δm could be overlapped in the $\Delta t/\eta\tau$ space. When the beams are extremely electron-cooled or the velocity spread $\delta v/v=0$, they are separated by $\Delta m/\eta\gamma_{t}^{2}m$ from the beam with $\Delta m=0$ in the $\Delta\tau/\eta\tau$ space, or they circulate at their own revolution frequencies in the ring. Therefore, a given ion species of beam is RF-captured after the electron cooling.

Using 40,000 macroparticles the particle-tracking simulation has been done in order to realise the separation process after stochastic cooling (a series of electron cooling, RF capture, and acceleration). As a secondary beam, a 220 MeV/u beam of $^{55}\mathrm{Ni}^{28+}$, $^{53}\mathrm{Co}^{27+}$, and $^{51}\mathrm{Fe}^{26+}$ fragments with the sixfold-rms momentum spread of 10^{-3} and the rms transverse emittances of 10^{-6} m rad starts to be electron cooled in the simulation. In order to make the statistic error low the cooled coasting beam has been assumed to have a 0.75 m-periodic charge distribution along itself. For the secondary-beam current of 1 mA the number of ions per 0.75 m is 10^{6} which is 25 times larger that that of the macroparticles.

The simulation results of the electron cooling in Fig. 1 show that after the electron cooling for 80 ms the separation to the three ion species of beams in the $\Delta t/\eta\tau$ space is dependent on the secondary-beam current. The higher the beam current, the larger is the friction among ion species of beams which comes from the longitudinal charge-density fluctuation. Parts of an ion species of beam circulate together with other ion species of beams at their own revolution frequencies in the ring.

RF CAPTURE

After the cooling the separation between two neighbouring beams is 0.5×10^{-4} in the $\Delta\tau/\eta\tau$ space. It takes 7 ms to RF-capture the $^{53}\mathrm{Co}^{27+}$ beam, the RF voltage linearly increasing from 0 V with time to produce the RF-bucket area of $4\pi\delta p/p=1.2\pi\times10^{-4}$

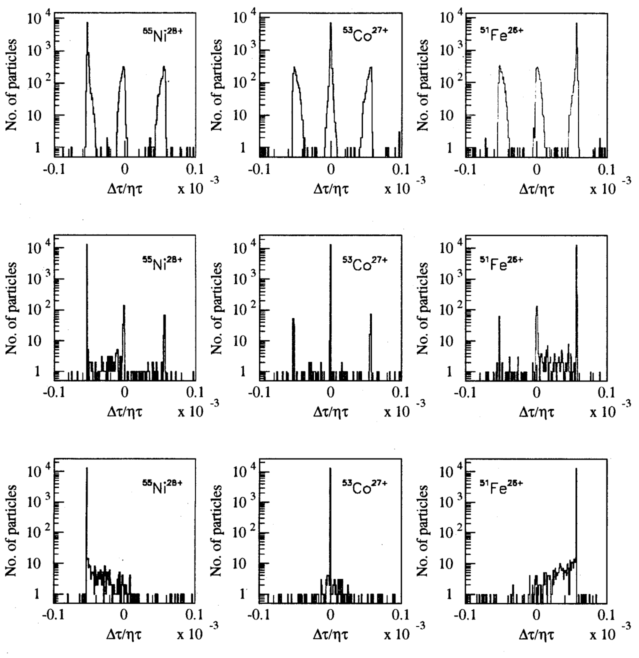

Figure 1: Separation into ion species of beams in the $\Delta\tau/\eta\tau$ space after the electron cooling. The upper, the middle, and the lower figures are for the secondary-beam currents of 1 mA, 0.1 mA, and 0.01 mA, respectively.

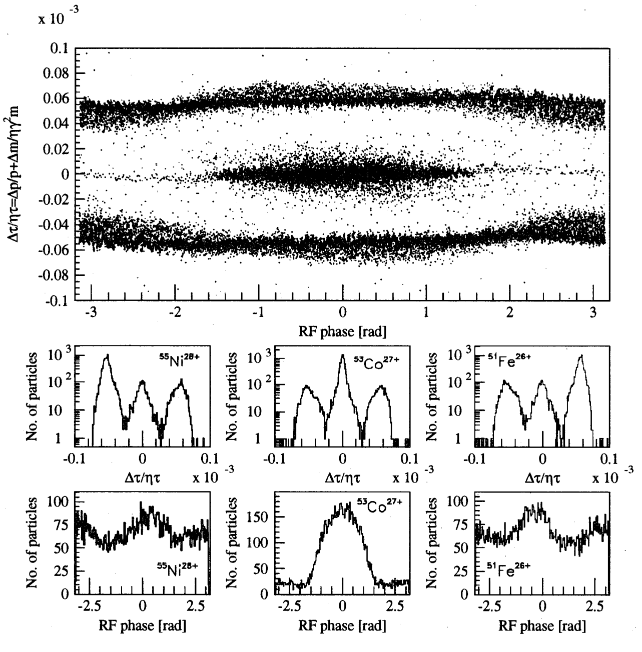

Figure 2: Longitudinal phase-space distribution at the end of the RF capture for the secondary-beam current of 1 mA.

(half spread $\delta p/p = 0.3\times 10^{-4}$) in the simulation. During the capture the electron cooling is repeatedly switched off 0.1 ms and on 0.2 ms in order to suppress a whirling vortex of the bunched beam in the RF bucket in the longitudinal phase space. Then, since the charge line density has few local peaks except a main peak, the longitudinal space-charge effects can be lightened.

After the capture an acceleration is carried out, the RF-bucket area being fixed. As the RF voltage is proportional to the RF harmonics h for the fixed area, the larger h is better from the viewpoint of making the acceleration time shorter. However, as the longitudinal space-charge force is proportional to the charge-line-density gradient or roughly h, the smaller h is better from the viewpoint of lightening the space-charge effects. h is optimised to be 40 for the circumference of the ring 180 m. The RF voltage at the end of the capture is 66 V.

The simulation results of the RF capture in Fig. 2 show that the $^{55}\mathrm{Ni}^{28+}$ and the $^{51}\mathrm{Fe}^{26+}$ beam at the $^{53}\mathrm{Co}^{27+}$ own revolution frequency are captured as well as the $^{53}\mathrm{Co}^{27+}$ beam.

ACCELERATION

After the cooling is switched off, an acceleration to make a momentum gain $\Delta p/p = 1.4\times 10^{-3}$ takes 17 ms with the RF-bucket area fixed. The RF shift Δf_{rf} is carried out as follows:

$$\begin{aligned} \Delta f_{rf} &= at^2 && \text{for } 0 \le t \le t_1 = 5 \text{ ms}, \\ \Delta f_{rf} &= at_1^2 + b(t - t_1) && \text{for } t_1 < t \le t_2 = 12 \text{ ms}, \quad (3) \\ \Delta f_{rf} &= at_1^2 + b(t_2 - t_1) - a(t - t_2)(t - t_2 - 2t_1) && \\ & && \text{for } t_2 < t \le t_2 + t_1, \end{aligned}$$

where a and b are constants determined from two constraints (the continuity of Δf_{rf} at t_1 and $\Delta p/p$). The maximum RF voltage and synchronous phase are 273 V and 20°, respectively.

The simulation results of the acceleration in Fig. 3 reveal that during the acceleration the beams are partially spilt out of the RF bucket in the case of the secondary-beam current of 1 mA, but are not in the case of 0.1 mA. Only the $^{55}\mathrm{Ni}^{28+}$ and the $^{51}\mathrm{Fe}^{26+}$beam that circulated at the $^{53}\mathrm{Co}^{27+}$ own revolution frequency at the end of the electron cooling are seen to contaminate the separated $^{53}\mathrm{Co}^{27+}$ beam. The contamination rate is 2% for the secondary-beam current of 0.1 mA. The contamination is avoided when the secondary-beam current is less than about 0.01 mA, which is seen from Fig. 1.

The acceleration separates the $^{53}\mathrm{Co}^{27+}$ beam from the remained beams by $\Delta p/p = 10^{-3}$ in the $\Delta\tau/\eta\tau$ space, but does not in the horizontal space because the transverse emittance is not so small ($\varepsilon_{rms} = 0.4\times 10^{-6}$

m rad for the secondary-beam current of 1 mA). Another acceleration has to be applied to the separated beam with a larger RF bucket area corresponding to $\delta p/p = 10^{-3}$ in order to make the separation larger and faster. The RF voltage is larger than in the case of the previous acceleration by three orders. There is an option that the lower h is used for rebunching because the RF voltage is large enough to shorten the acceleration time.

When the accelerations are applied under the fixed bending field, other ion species of beams can be separated from the remained beam in turn by repeating the separation process.

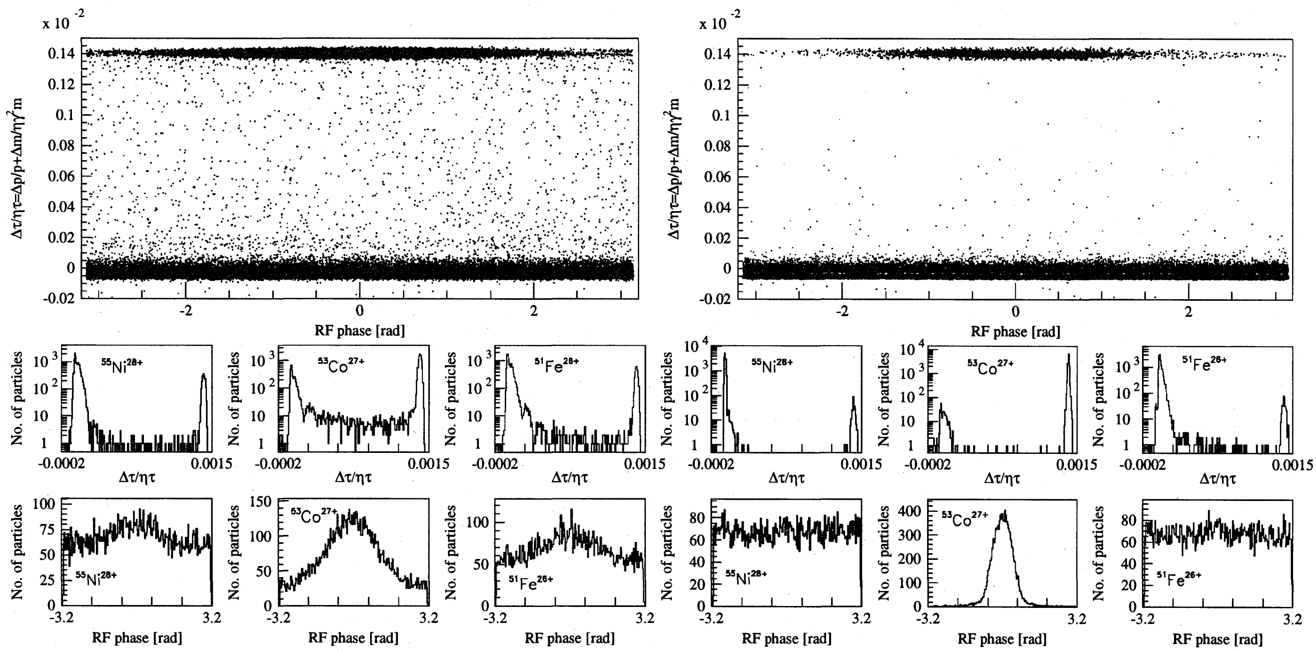

Figure 3: Longitudinal phase-space distribution after the pre-acceleration. The left and the right figures are for the secondary-beam currents of 1 mA and 0.1 mA, respectively.

CONCLUSIONS

Feasibility of separation of an ion species of beam from a secondary beam of nuclear projectile fragments in a storage ring has been studied in performing particle-tracking simulations.

After electron cooling each ion species of beam circulates at its own revolution frequency where the ion velocities equal that of the electron beam. It is a longitudinal space-charge effect on a multi-component beam with little velocity spread that parts of other ion species of beams circulate at the revolution frequency over a threshold of the secondary-beam current. A given ion species of beam separated by applying RF capture and acceleration is contaminated by the parts.

REFERENCES

[1] T. Katayama *et al.*, Nucl. Phy. A626 (1997), 545.
[2] C.C. Yun, RIKEN-AF-AC-30 (2001).
[3] M. Takanaka, to be published in Phys. Rev. ST. Accelerators and Beams.