CHARACTERISTICS OF ELECTRON-COOLED BUNCHED BEAMS PREDICTED BY A SIMULATION

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Abstract

Characteristics of electron-cooled bunched ion beams have been studied using the particle-tracking simulation in which the space-charge force and the force induced through the transverse broadband impedance are taken into account. The beams become space-charge dominated during the bunching of coasting beams. The simulation results show that beams of beam current of 4 mA are stabilized by a transverse feedback to be bunched by the bunch length of 16 cm for the bunch spacing of 3 m at the third harmonic RF voltage of 290 kV. The characteristics of the bunched beams are predicted by analyzing the simulation results.

1 INTRODUCTION

The Radioisotope Beam Factory (RIBF) [1] will have an electron-RI beam collider (e-RI Collider). We have studied ion-beam bunching at low energies for collision experiments, using a particle-tracking simulation. In the previous papers [2] we have shown that during the electron-cooling bunching the beams meet the transverse dipole-mode instability which can be cured by a transverse feedback and that the seed of the instability originates in the toroid fields of the electron-cooling (EC) section, and have referred to some characteristics of the stabilized beam.

In the particle-tracking simulation, we have taken the same sources of force acting on particles into account as previous, and have used the same beam parameters, too. Using 40,000 macro-particles, we have simulated U^{92+}_{238} ion beams of 4 mA, or 5.4×10^6 ions per bunch at 150 MeV/u. Since our interest is a single bunch phenomenon, we have assumed that every bunch behaves the same along the azimuthal direction. The simulation has showed that the longitudinal and transverse electron-cooling times are 6 ms and 18 ms for a faint-current beam, respectively.

From the next section, using the simulation results we give a more detailed description of characteristics of the stabilized beam than previously.

2 BEAM BUNCHING

We have the RF system which supplies a fundamental RF voltage and a third harmonic RF voltage. The system is located at the azimuth π from the EC section since the momentum spread can be the smallest at the EC section in this location case. The evolution of the beam bunching is shown in Fig. 1. At first the coasting beam is cooled to the sixfold-rms momentum spread 5×10^{-4}. Then, the fundamental RF voltage is increased in such a way that the momentum spread at the EC section is maintained at 5×10^{-4}. When the sixfold-rms bunch length reaches 1 m, the increase stops. When the momentum spread reaches 1.9×10^{-4} or most of the beam stays within the one-third bunch spacing, the third harmonic RF voltage is increased up to 290 kV holding the momentum spread.

The toroid fields at the both ends of the EC section make resonances $\nu_h + \nu_y = i$ (i=integer) with the half resonance width of 0.01 on the $\nu_h + \nu_y$ scale near the operation point. The resonances are seeds of the transverse instability for electron-cooled bunched beams. In order to cure the transverse instability, we have used a following transverse feedback after 30 ms. Picked up at the end of the EC section where the dispersion is zero, the horizontal and vertical beam-position signals along a bunch are fed to the bunch downstream the phase advance $\pi/2$ with feedback gains $0.8/\beta_h$ and $0.8/\beta_v$, respectively, and bandwidth 6 GHz. Around 60 ms 0.5 percent of the beam is lost around the bunch center (z=-10 mm to 10 mm). After 80 ms, there is no beam loss and the instantaneous beam current at the bunch center is 120 mA.

We show the characteristics of the beam at 135 ms in the next section.

3 CHARACTERISTICS OF THE STABILIZED BEAM

Transverse symmetry of the ion distributions shown in Fig. 2 means that the feedback to cure the transverse instability works well. Since the weaker the effective longitudinal space-charge impedance seems to the ions with the larger betatron amplitudes in a space-charge-dominated beam, the weaker the RF-wave-form distortion seems to the ions. Therefore, when the momentum spread of the beam is considerably small compared with the RF separatrix height, the more the ions with the larger amplitudes are centralized on the bunch profile as shown in Fig. 2.

Figure 3 shows the longitudinal phase-space distribution and the projections at the EC section and just after the RF section. Just before and after the RF section the distribution is one with the opposite slop in the phase space. The momentum spread just after the RF section becomes five times larger than at the EC section. The bunch length becomes the longest at the RF section and the shortest at the EC section. The longitudinal space-charge effect makes such a longitudinal quasi-elastic motion of the bunch at the frequency tune 1 instead of a synchrotron oscillation. At the same time, as we have assumed the same dispersion along the ring except for the EC section, the bunch has a horizontal oscillation with the head-tail mode number 1 and the frequency tune 1 due to the momentum deviation. The bunch profile has an excess around the center compared with the parabolic profile [3]. The microwave structure of the phase-space distribution is a reflection of the longitudinal space-charge impedance that smears fluctuations within the impedance bandwidth in bunch profiles. But, the structure seems to have a little lower frequency than the microwave structure of the bunch profile, which is referred to just below.

Figure 4 shows the spectrum of the longitudinal monopole moment which has following features:

1. Along $\Omega/\omega_0 = kh$ ($k <\sim 200$, h =RF harmonic

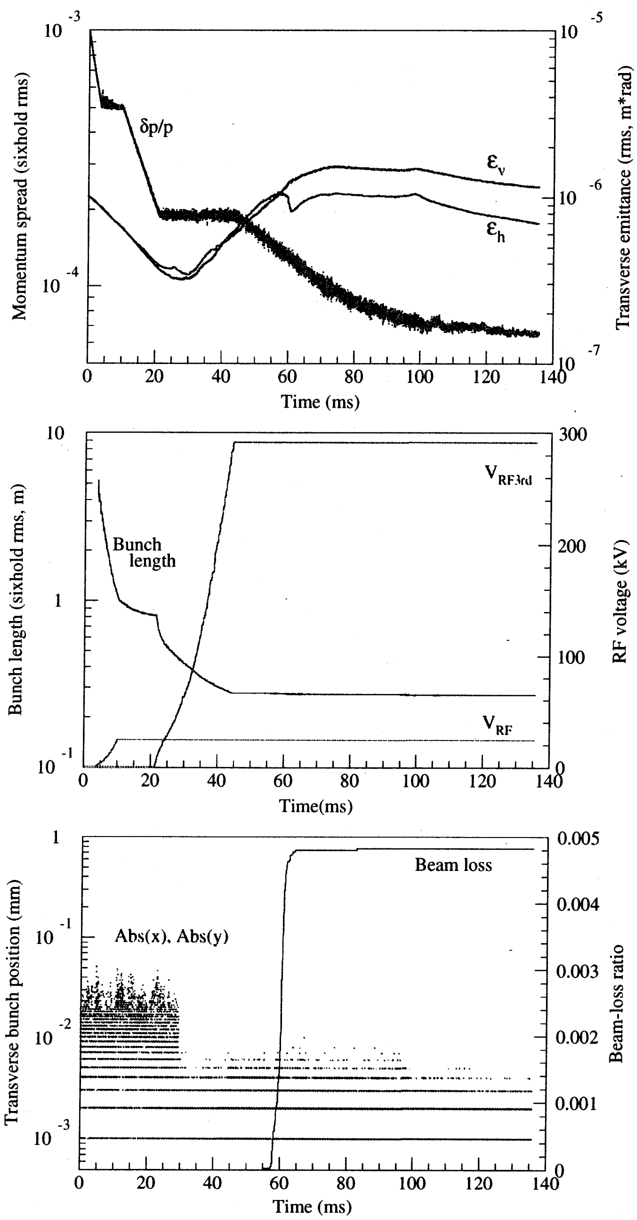

Figure 1: Evolution of the bunching of a U^{92+}_{238} ion beam of 4 mA. The momentum spread is one at the EC section. The transverse feedback works after 30 ms.

number) a series of signals due to the parabolic bunch profile.

2. Along the two-spread-wings frame a series of signals due to the reflection of the longitudinal space-charge impedance. The position of the signals can be described by the following equation which is derived by applying the Vlasov equation to the case of bunched beams with little momentum spread under the dominance of the space-charge impedance;

$$\Omega - n\omega_0 = \pm n\omega_0 \sqrt{\frac{iqe\eta I}{2\pi\beta^2 E}\frac{Z_{\parallel}^{eff}}{n}},$$

where I is the instantaneous beam current averaged over the bunch, and $Z_{\parallel}^{eff}$ the effective longitudinal space-charge impedance. The dynamics of the signal production is equal to that of splitting Schottky spectra of cooled coasting beams. As the longitudinal impedance has been assumed to be cut off over $k = 232$, the difference $|\Omega - n\omega_0|$ decreases over the k.

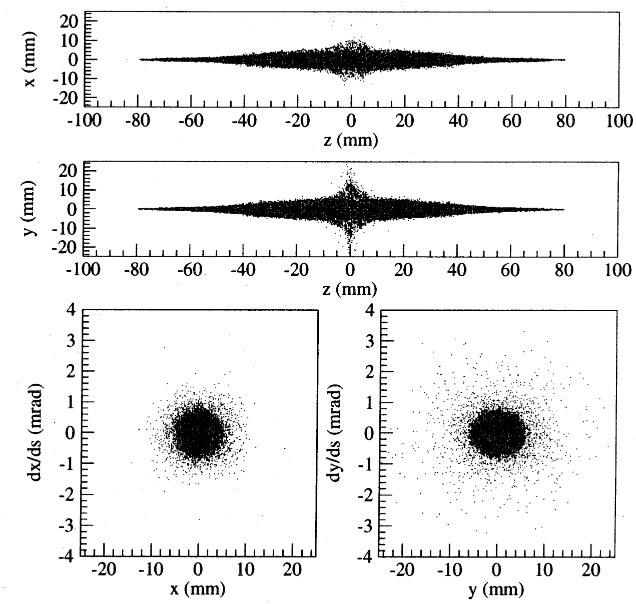

Figure 2: Ion distributions at 135 ms.

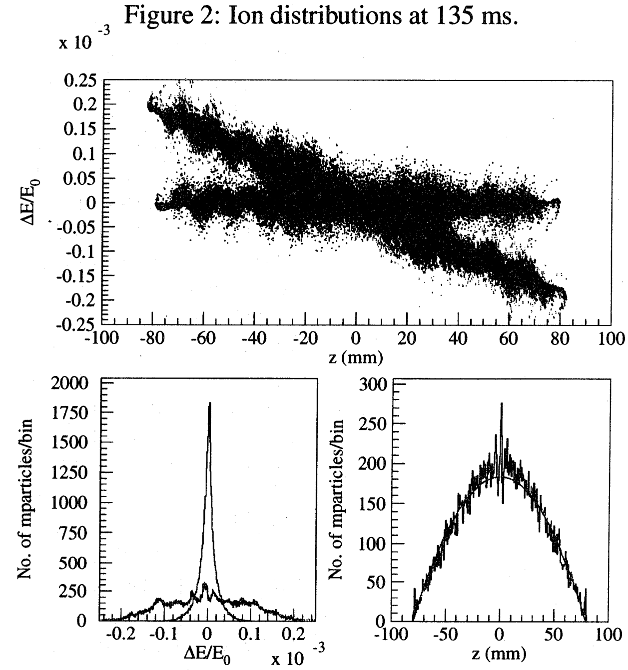

Figure 3: Longitudinal phase-space distribution at 135 ms. In the upper, the slanted distribution is one just after the RF system, and the non-slanted distribution is one at the end of the EC section. In the lower right, the projection with a fitted parabolic curve is one at the end of the EC section.

3. Along $\Omega/\omega_0 = kh$ (k >~200) a series of signals which have the largest peak around $k = 450$. We guess that the signals come from an internal oscillation induced by the longitudinal quasi-elastic motion of the bunch.

4. Along $\Omega/\omega_0 = kh \pm i$ (i=integer not being 0) a series of signals due to the quasi-elastic motion.

Figure 5 shows the spectrum of the horizontal dipole moment which has following features:

1. Around $|\ \Omega/\omega_0 - kh\ | = 4.4$ a series of signals due to the rigid-bunch mode of coherent betatron oscillation which the feedback can not completely damp.

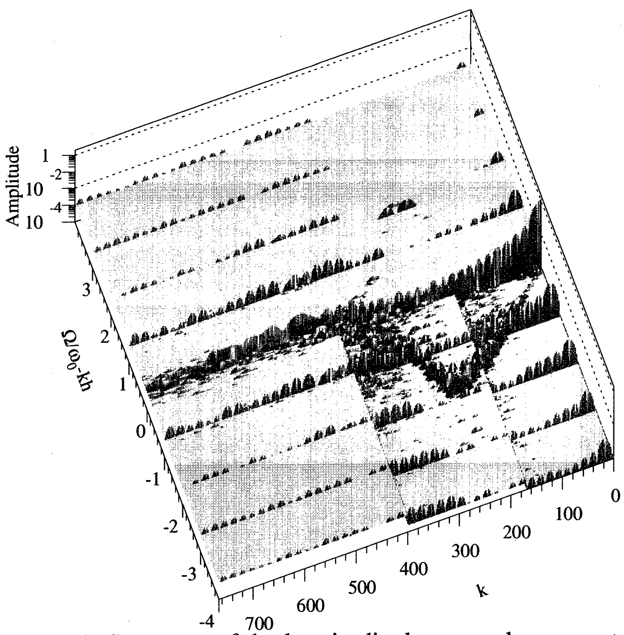

Figure 4: Spectrum of the longitudinal monopole moment at 135 ms. For the sake of clear sight of main signals, the spectrum normalized by the DC component is cut away below the three levels 10^{-3}, 2.5×10^{-4}, and 10^{-4}.

2. At $|\ \Omega/\omega_0 - kh\ | = i$ (i=positive integer) a series of signals due to the head-tail mode 1 of coherent betatron oscillation with a tune of 1 which was referred to above.

The spectrum of the vertical dipole moment does not have the second feature because of no vertical dispersion.

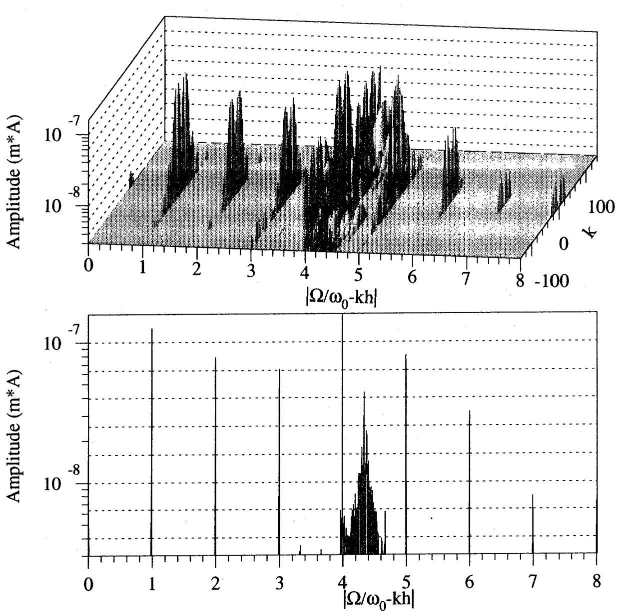

Figure 5: Spectrum of the horizontal dipole moment at 135 ms. The spectrum is cut away below 3×10^{-9}.

Figure 6 shows incoherent tune distributions. While betatron-tune shifts are little for ions at the bunch center, large tune shifts occur for ions on the head and tail sides. But, the large shifts for the horizontal direction are disturbed by the head-tail mode 1 of coherent betatron oscillation. Although the bare incoherent synchrotron tune is 0.09 for the third harmonic RF voltage 290 kV, most of incoherent tunes are nearly 0 except for those for some of ions around the bunch center. This means that the beam synchrotron oscillates hardly because of the RF-wave-form distortion, too.

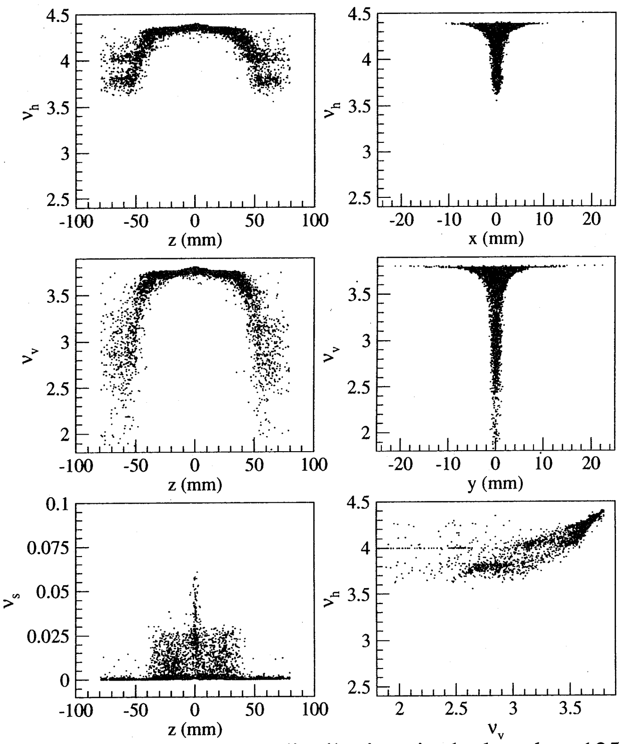

Figure 6: Incoherent tune distributions in the bunch at 135 ms.

4 CONCLUSIONS

We have carried out particle-tracking simulations to study characteristics of electron-cooled bunched ion beams and have reached following conclusions.

Although the incoherent betatron-tune shifts become over 1 during the electron-cooling bunching, the beam of 4 mA can be stabilized by a transverse feedback to be bunched by the bunching factor of 19, by the bunch length of 16 cm, or at the peak current of 120 mA under the third harmonic RF voltage of 290 kV. As the phenomena due to the RF-wave-form distortion,

1. Incoherent synchrotron tune is suppressed to nearly 0 from the bare tune of 0.09.

2. The bunch motion is a quasi-elastic one with the tune of 1 instead of synchrotron oscillation in the longitudinal direction, which is automatically accompanied with a head-tail mode 1 of horizontal dipole oscillation because of the horizontal non-zero dispersion.

3. The beam size can be extremely large at the bunch center. The main bunch profile consists of a parabolic shape and some excess around the bunch center.

There is a microwave structure on the bunch profile beyond the bandwidth of the longitudinal phase-space impedance.

5 REFERENCES

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