SIMULATION OF BEAM BUNCHING WITH ELECTRON COOLING FOR THE ION STORAGE RING OF RIKEN RI-BEAM FACTORY PROJECT

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Abstract

Beam bunching with electron cooling can be carried out under the control which keeps the momentum spread constant. Simulation of the bunching for a 150 MeV/u U^{92+}_{238} beam in DSR has been done in which space charge effects and a transverse nonlinear effect are taken into account. Results of the simulation are presented about the transition of the bunching and the longitudinal and transverse behavior of the beam near the equilibrium.

1 INTRODUCTION

Collision experiments are planned with ion-ion or ion-electron beams in Double Storage Rings (DSR). Coasting ion beams are supplied from the cooler storage ring (ACR) or the booster synchrotron (BSR). The luminosity of the beams can become high by bunching them. The longitudinal space charge force is dominant over the longitudinal forces induced through the coupling impedances between beams and the vacuum chamber in the energy region 100 MeV/u to 1.5 GeV/u of the ring. As the currently-designed ion storage ring runs below the transition energy [1], the space charge force makes the bunch long. Electron cooling force can make the bunch short under an RF-voltage application. The bunching with electron cooling has been carried out at IUCF [2] and GSI [3] focusing on study of the longitudinal behavior of beams at the equilibrium, and on study of the longitudinal and transverse ones at the equilibrium, respectively.

The previous simulation of beam bunching under the momentum-spread control showed effectiveness of the cooling in the bunching, but whether the bunching process is stable or not was left to be answered [4]. The question is answered here. The simulation has been improved not only in taking into account more force elements, but also in the following;

- representation of a bunch of beam line density, which is used for evaluation of the longitudinal space charge force, by Fourier series expansion up to seventieth series,
- evaluation of the space charge forces every one-eightieth revolution.

2 BUNCHING PROCEDURE

A beam is injected to DSR, after it is accumulated as a coasting beam and cooled down to a given momentum spread and to such a transverse emittance in ACR that it does not meet resonances. The beam is cooled again there by electron cooling while RF is applied under the momentum spread control which increases the RF voltage so that the momentum spread stays constant. The beam becomes bunched as RF voltage. The larger the spread is, the higher can be the threshold of the beam line density due to the microwave instability [5]. The momentum-spread control is necessary to a high line-density beam. The bunching makes the space charge effects strong. The betatron tune shift due to the effects is dependent on the transverse amplitude, when the transverse charge distribution is not flat. Resonances make the transverse amplitude of ions large. So, the ions become off resonance. The longitudinal oscillation simultaneously makes crossings of resonances. The ions can have small amplitude due to the electron cooling again. Therefore, the beam can be expected to eventually dodge resonances. It is, however, dependent on the strength of the nonlinearity whether the ions have small amplitude again or not. The simulation has been done just for beams in DSR.

3 FORCE ELEMENTS

In the simulation, the following forces have been taken into account as forces acting on ions:

- the RF force,
- the longitudinal electron cooling force and the transverse one [6],
- the transverse linear force coming from the ring lattice and nonlinear one,
- the longitudinal space charge force and the transverse one.

The other collective forces induced through the vacuum chamber or RF cavities have been neglected because of, except for the resistive-wall force, their smallness by comparison with the space charge forces in the DSR energy region [7] and because the instability up to the fifth synchrotron mode due to the transverse resistive-wall force can be damped even at the chromaticity of -30 near the vertical natural one for the full bunch length of 1 m [8]. The space charge effects due to a colliding electron beam are left to be

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considered. The above electron cooling force does not include the component which induces betatron tune shifts of 0.02 for the flat transverse distribution of the electron beam at the cooling section. The component has been neglected because of the smallness by comparison with the shift due to ion-beam's own space charge.

4 SIMPLIFICATION

The following simplification has been done in the simulation mainly in order that one reduces CPU-time load and keeps statistic accuracy.

i) Except for the Twiss parameters during the cooling section, β function along the ring has been equal to the average one $\overline{\beta} = r/\nu$ where r is the mean radius of the ring and ν the betatron tune. α function has been 0.

ii) The longitudinal space charge force is induced by beam's space charge through a perfectly conducting vacuum chamber of the inner radius b. The ions of charge qe on the central orbit get the energy ΔE_{sp} from the force during time Δt, when the transverse charge distribution is round and Gaussian with one-dimensional standard deviation σ which is much smaller than the radius b [5];

$$\Delta E_{sp} = iqe \left[\frac{Z_{\parallel}}{n}\right]_{sp} \frac{v}{2\pi} \frac{dI}{ds} \Delta t,$$

$$\left[\frac{Z_{\parallel}}{n}\right]_{sp} = i\frac{g_0}{2\beta\gamma^2} Z_0, \;\; g_0 \approx 0.577 + 2\log\left(\frac{b}{\sqrt{2}\sigma}\right),$$

where the beam of velocity v has current distribution I along the longitudinal direction s, and β and γ are the relativistic constants of v, and Z_0 impedance of free space. Longitudinal variation of the transverse charge distribution has been neglected. The deviation σ has been replaced by the r.m.s. of the transverse charge distribution. All ions at the position s have been made to get the same energy ΔE_{sp}, with the transverse distribution neglected.

iii) To estimate the transverse component of the electric field due to the space charge, the field has been treated the same as the field from a point charge in free space points strictly radially outward in the ultra-relativistic case. The field is not dependent on the structure of the chamber.

iv) The chromaticity has been set zero for both transverse directions. This simplification is just for clearly looking into the betatron tune distribution without noise due to the momentum spread.

5 PARAMETERS OF THE RING AND A BEAM

The simulation has been done just for a 150 MeV/u U^{92+}_{238} beam of current 3.4 mA. In Table 1, are shown parameters of the ring, a coasting beam, and the electron cooling, which have been used as input data of the simulation. The initial distribution of a coasting beam of 10^4 particles for the simulation has been flat along the RF phase axis, and Gaussian along the momentum axis, in the horizontal phase space and in the vertical one, respectively.

Table 1: Parameters of the ring, a coasting beam, and the electron cooling.

Ring	
Circumference	260 m
Momentum compaction factor	0.03772
Betatron tune (ν_x /ν_y)	7.38/5.8
Twiss parameters at the cooling section	
$\alpha^{ec}_x = \alpha^{ec}_y$	0
$\beta^{ec}_x = \beta^{ec}_y$	7 m
RF harmonics	87
Inner radius of the vacuum chamber b	4 cm
Coasting beam	
Momentum spread (6×rms)	10^{-3}
Rms transverse emittance ($\epsilon_x = \epsilon_y$)	$10^{-6}\pi$ mrad
Electron cooling	
Electron current	5 A
Cathode temperature kT_c	0.1 eV
Length of the cooling section	3 m
Electron-beam radius at the section	25 mm
Longitudinal magnetic field at the section	1 kG

6 RESULTS

Here are presented results of two simulated cases, the one being without nonlinear force and the other with it. In the latter case, as a source of nonlinear force a sextupole field has been numerically located at the cooling section with the field strength $B''\ell\beta^{ec}/2B\rho$ of 0.3 m^{-1} , β^{ec} being the beta function at the section. The strength is equal to about one-tenth to one-thirtieth of effective strengths used for beam extractions. The field induces the resonances $3\nu_x = 22$, $-\nu_x + 2\nu_y = 4$, and $\nu_x = 7$ near the working point, whose stop bandwidths are estimated to be about 0.0001, 0.0002, and 0.0004 for the rms emittance of $10^{-6}\pi$ mrad, respectively [9]. Figure 1 shows the transition of the bunching and no remarkable difference between the cases. The fluctuation of the momentum spread stays within ± 2 %, and that of the transverse emittance within ± 1 %. The bunching process is seen to be stable. After 30 ms on, the bunch length decreases slowly still, while the transverse emittance, that is, the mean of the horizontal one and the vertical one turns to increase. The rms transverse emittance is seen not to become so small as $5 \times 10^{-7}\pi$ mrad due to the space charge effects. The bunching factor, or the ratio of the full bunch length to the bunch separation becomes 0.34 at 50 ms, and the maximum peak current becomes 32 mA. It remains to be answered how long it takes to arrive at the equilibrium.

Figure 2 shows the ion distribution in the longitudinal phase space at 50 ms. The ions are classified roughly into two groups. The one locate densely and narrowly in the center, and the other thinly around the one. The distributions projected to each axis can be approximately represented with a broad Gaussian curve and a narrow one. The ion-population ratio of the central narrow group to the whole is estimated to be about 28 %, which includes 10 %

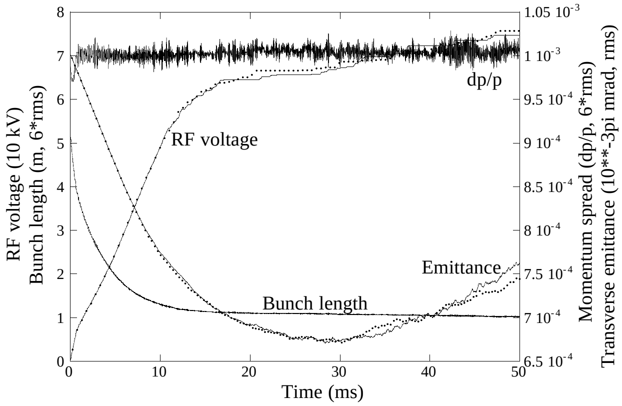

Figure 1: Transition of the bunching. The solid lines are for the case without the nolinearity, and the dotted lines for the case with it.

of the part under the narrow structure, by using the representation. The central group rotate at the synchrotron tune near zero in the longitudinal phase space because of the distortion of RF wave form due to the space charge effects, and the other near the tune corresponding to no distortion, as shown in Fig. 3. The transverse profile at 50 ms is seen to be more centralized than a Gaussian distribution, as shown in Fig. 4. The incoherent betatron tune shift due to the space charge effects reaches -0.5, as shown in Fig. 3, which means that the beam can meet major resonances. The effect of the resonaces at least due to the above sextupole has been already described to be negligibly small.

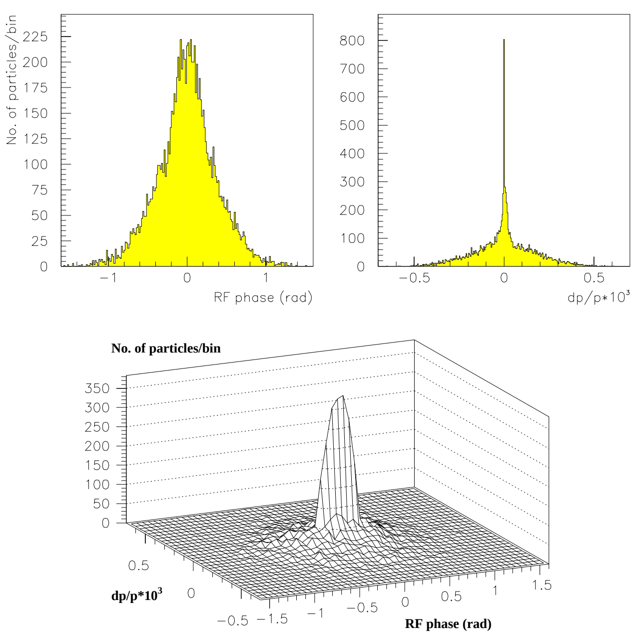

Figure 2: Longitudinal phase space distribution after 50 ms bunching.

7 CONCLUSION

The simulation of the bunching of a 150 MeV/u U^{92+}_{238} beam of 3.4 mA under the momentum-spread control at the electron density of 2.5 kA/m^2 at the cooling section has shown the following characteristic of the bunching.

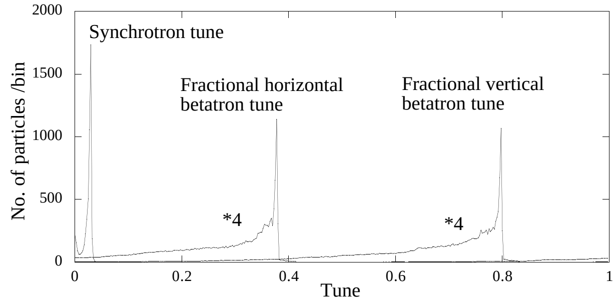

Figure 3: Tune distribution for 5000 particles after 50 ms bunching. The distributions of betatron tune are magnified vertically four times.

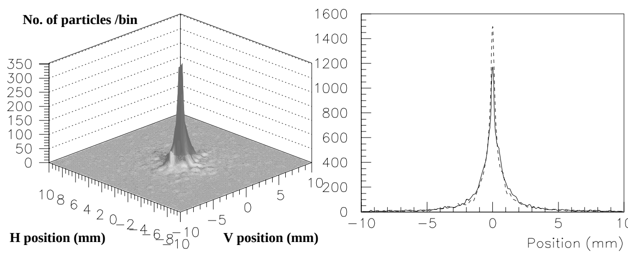

Figure 4: Transverse profile at the cooling section after 50 ms bunching. The solid line shows the vertical profile, and the broken line the horizontal one.

- The process of the bunching is stable.
- The full bunch length becomes1.03 m after 50 ms bunching. The bunching factor is 0.34.
- The rms transverse emittance can not become so small as $5\times10^{-7}\pi$ mrad due to the space charge effects even without the effect of the intrabeam scattering.
- The sextupole field of the strength of 0.3 m^{-1} induces negligibly small effects of resonance, although the incoherent betatron tune spread due to the space charge effects reaches 0.5.

8 REFERENCES

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