Simulation of Beam Bunching using Electron Cooling for the Ion Storage Ring of RIKEN RI-Beam Factory Project

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Abstract

Beam bunching using electron cooling is planned to be carried out under the control which keeps the momentum spread constant. The simulation of the bunching for a 150 MeV/u U^{92+}_{238} beam in DSR has been done on which space-charge effects including the transverse dipole effects are taken into account. Results of the simulation show that the dipole effect interferes with the decrease of the transverse emittance due to the cooling and results in helping the decrease of the bunch length.

1 INTRODUCTION

Collision experiments are planned with ion-ion beams and ion-electron ones in Double Storage Rings (DSR) which is currently being designed. The luminosity of the beams can become high when the beams are bunched. Ion beams are bunched by using the electron cooling together with RF application. As the bunching goes, not only the longitudinal space-charge force but also the transverse one, which are dominant over 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, become large. The former is known to disturb shortening the bunch length below the transition energy. The dipole component of the latter is known to make betatron-tune shifts coherently which has possibility to make the beam size of the equilibrium state large. Both the phenomena are not good for getting the high luminosity. The simulation of the bunching has the aim to reveal whether there is any obstacle against getting the high luminosity.

The bunching of ion beams is planned to be carried out under the momentum-spread control. The previous simulation of the bunching, on which the dipole component of the transverse force was not taken into account, showed that non-linearity of the lattice does not make a problem even when the incoherent betatron-tune spread reaches 0.5, the bunching process is stable, and the transverse emittance turns to increase near the equilibrium [1]. The simulation has been improved as follows in order that the behavior of the transverse emittance is understood better;

- refinement of the longitudinal space-charge impedance,
- taking the dipole component of the transverse space-charge force into account.

The simulation results of the behavior are showed here.

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 the Accumulator and Cooler Ring (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 the voltage increases. The smaller the spread is, the lower is the threshold of the beam line density due to the microwave instability [2]. The momentum-spread control is necessary to a high line-density beam. The simulation has been done just for beams in DSR.

3 SIMPLIFICATION

The following simplification has been done on 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 current concerning is just about the beam behavior under space-charge effects, or the effects through the broad-band impedances. Although the simulation is for the case where an ion beam occupies all RF buckets, it does not deal with coupled-bunch phenomena.

iii) 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 at the distance r from 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;

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

$$\left[\frac{Z_{\|}}{n}\right]_{sp} = i \frac{g(r)}{2\beta\gamma^2} Z_0,$$

$$g(r) \approx -\int_{x=\frac{r^2}{2\sigma^2}}^{\infty} \frac{e^{-x}}{x} dx + 2\log\left(\frac{b}{r}\right),$$

$$g(0) \approx 0.577 + 2\log\left(\frac{b}{\sqrt{2}\sigma}\right),$$

where the beam of velocity v has the 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 in evaluating the impedance. The deviation σ has been replaced by the horizontal rms beam size σ_h and the vertical one σ_v;

$$\sigma = \sqrt{\frac{\sigma_h^2 + \sigma_v^2}{2}}.$$

iv) As the transverse electric field due to the space charge, just the monopole component and the dipole one have been taken into account. They have been estimated as if they are in the ultra-relativistic case, and the monopole field has been let be that in free space. The impedance due to the dipole has been estimated as a ring type;

$$Z_\perp = i\frac{Z_0 R}{\beta^2\gamma^2}\left(\frac{1}{9\sigma_h\sigma_v} - \frac{1}{b^2}\right).$$

4 PARAMETERS OF THE RING AND A BEAM

The simulation has been done just for a 150 MeV/u U_{238}^{92+} 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 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. The average current of 3.4 mA is the threshold due to the longitudinal microwave instability in the case where the beam bunches in 6×rms length of 0.4 m, of 6×rms momentum spread of 10^{-3}, and of rms transverse emittance of $10^{-6}\pi$ mrad.

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_h /ν_v)	7.38/5.8
Natural chromaticity (ξ_h)	-35
Twiss parameters at the cooling section	
$\alpha_h^{ec} = \alpha_v^{ec}$	0
$\beta_h^{ec} = \beta_v^{ec}$	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 ($\epsilon_h = \epsilon_v$)	$10^{-6}\pi$ 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

5 RESULTS

Two kinds of simulation results are shown, the one being about the longitudinal space-charge impedances, and the other about the transverse space-charge impedance.

5.1 Longitudinal space-charge impedance

The longitudinal space-charge impedance is dependent on the transverse charge distribution of a beam, or not only on the beam size but also on the position within the beam. As described in Section 3, it has been approximated to be that for the Gaussian distribution. Figure 1 shows the difference between $g(r)$ taking the position dependence into account and non-taking $g(0)$. The results are ones of the simulation on which the transverse space-charge impedance has not been taken into account yet. The equilibrium state seems to be realized after bunching of 60 ms.

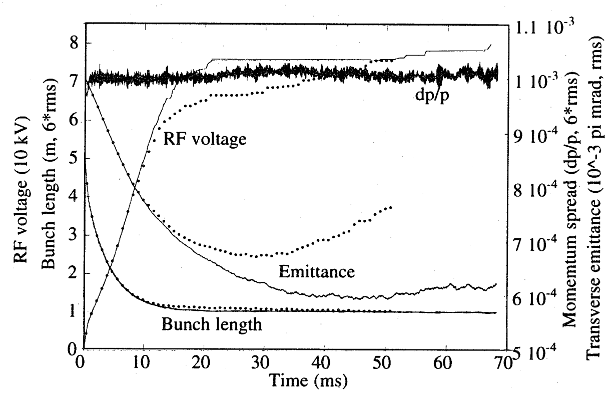

Figure 1: Transition of the bunching. The solid curves are for the position-dependent longitudinal impedance, and the dotted ones for the position-independent one.

5.2 Transverse space-charge impedance

The transverse space-charge impedance has been taken into account just in the horizontal direction on the simulation of which results are shown in Figure 2. The dipole effect through the impedance is seen to interfere with the decrease of the horizontal emittance due to the cooling. As the results, it helps the decrease of the bunch length due to the cooling. The bunch length near the equilibrium becomes 0.5 m, or half that in the previous case. The RF voltage of 300 kV is required for the short bunch.

Figure 3 shows the bunch shape, which is approximately represented by using a Gaussian curve and a parabolic one, after the bunching of 30 ms. The parabolic curve represents the distribution of the group of cooled ions which do hardly synchrotron movement around the center of the bunch. Figure 4 shows the dipole moment, that is, the collective displacement times the instantaneous beam current. The amplitude of the collective horizontal displacement is seen to be 0.1 mm around the bunch center and larger at both the sides. The horizontal emittance along the bunch is shown in Figure 5.

The effect of the dipole may have been overestimated, because on the simulation the beta function along the ring has been let to be constant except for the cooling section and just a ring type of the dipole component has been taken into account as the dipole component of the transverse field.

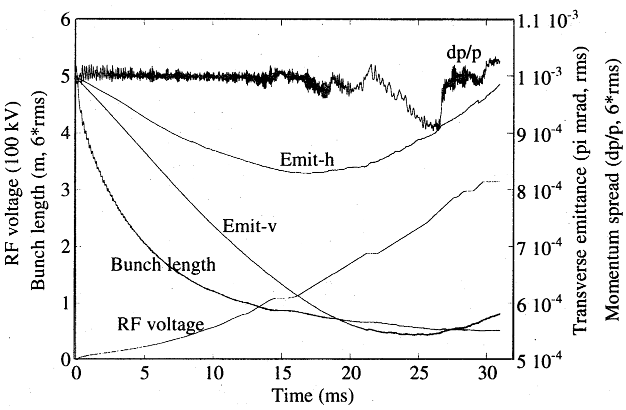

Figure 2: Transition of the bunching. The transverse space-charge impedance has been taken into account just in the horizontal direction.

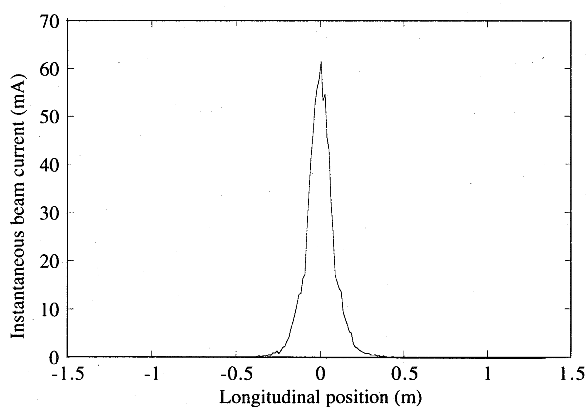

Figure 3: Bunch shape after bunching of 30 ms.

6 CONCLUSION

The simulation of the bunching of a 150 MeV/u U_{238}^{92+} 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.

- The process of the bunching is stable, just when the longitudinal space-charge effect and the transverse monopole one are taken into account on the simulation.
- The transverse dipole space-charge effect interferes with the decrease of the transverse emittance due to the cooling, which helps the decrease of the bunch length.
- The beam near the equilibrium is bunched in $6\times$ rms length of 0.5 m, and with the transverse rms emittance of $10^{-6}\pi$ mrad under RF voltage of 0.3 MV.

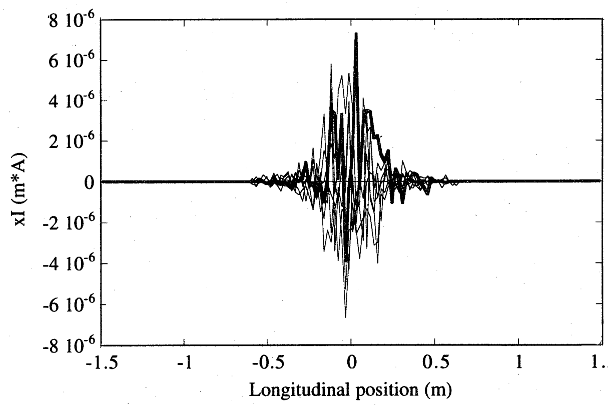

Figure 4: Dipole moment after bunching of 30 ms.

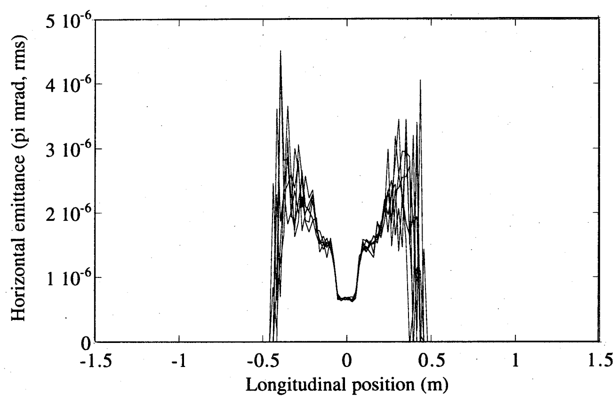

Figure 5: Horizonatal emittance along the bunch after bunching of 30 ms.

7 REFERENCES

[1] M.Takanaka, T.Katayama, Proc. of PAC 97 (1997).

[2] A.Hofmann, CERN 77-13, 139 (1977).