Design of Beam Bunching System for the Ion Storage Ring of RIKEN RI-Beam Factory Project

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Abstract

In the operation energy of the storage ring, the longitudinal space charge force is dominant over forces induced through the coupling impedances. It lengthens bunches of beams below the transition energy. Ion beams colliding with electron beams are desirable to be bunched as short as the detectable collision section of length 0.4 m. Electron cooling is considered as a tool to help ion beams to bunch under RF-voltage applying. Results of a simulation of the bunching are present. An RF cavity is presented for the bunching.

1 INTRODUCTION

The ion storage ring has been designed as the one of the twin storage ring that is called Double Storage Ring (DSR), of RIKEN RI-Beam Factory Project. Electron beams or ion beams are stored in the other. Colliding experiments are planed with ion beams and electron beams in DSR. Coasting, or nearly coasting ion beams are supplied from a cooler storage ring or a booster synchrotron. The luminosity of the beams can become high by making coasting beams bunch. The longitudinal space charge force is dominant over 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 today-designed ion storage ring runs below the transition energy, the force makes the bunch long. Electron cooling force makes the bunch short under RF-voltage applying. Here, results of a simulation of the bunching show effectiveness of the cooling in the beam bunching. In the low energy region, the coupled-bunch instability can be induced easily through RF cavities. An RF cavity is presented with the function of higher order mode damp.

2 PROCEDURE OF BEAM BUNCHING

The tool of the bunching is RF voltage applying and electron cooling. The former is just for rotating ions on the longitudinal phase space. The latter is for pushing ions towards the synchronous energy level where the velocity of ions is equal to that of the electron beam. As the results, ions gradually get together at the center of the RF separatrix. It would be possible to realize very small bunching factor if there were no force but the RF force and the cooling force. The ring has been designed to run below the transition energy [1]. There, the main longitudinal beam-self-induced force, or the space charge force pushes ions outward from the bunch center. Roughly speaking, the bunch length settles on the equilibrium among the three forces. The bunching is possible without increase of the momentum spread, though bunching just with RF voltage applying always increases the momentum spread.

A bunching procedure is proposed as follows. One tunes the RF voltage and the electron current from the gum as operation parameters. They are controlled so that the momentum spread of the ion beam may be kept around a given spread which is, for example, one just before the bunching, or one required for an experiment for nuclear physics. If the beam is not of equilibrium, or the cooling force is stronger than the space charge force, the momentum spread decreases. Then, the increase of the voltage ideally can keep the spread constant and promotes the centralization of the ions. One can easily get the equilibrium by increasing the voltage, paying attention not to load over-voltage.

3 SIMULATION OF BEAM BUNCHING

The simulation has been carried out using Runge-Kutta method. One has taken following forces acting on ions into account there; 1) the RF force, 2) the longitudinal electron cooling force and the transverse one [2], 3) the transverse linear force coming from the ring lattice, 4) the longitudinal space charge force, and 5) the cooling limit for the momentum spread and the transverse emittances, because of intra-beam scattering and gas scattering. The space charge force is evaluated each turn by fitting two polynomial curves to the central region of the beam line density and the region of both the end sides, respectively, and by using the gradient of the curves. One has assumed the values of the cooling limit. Just after passing the cooling section, if the momentum deviation or the transverse velocity becomes less than two-thirds of the cooling-limit one, it is replaced by one selected randomly from the Gaussian cooling-limit distribution.

In Table 1, are shown parameters of the ring, coasting beams, and the electron cooling, which have been used as input data of the simulation. One has assumed the coasting beam with Gaussian transverse distribution and Gaussian momentum one. The energy of 500 MeV/u is the designed maximum where the cooling will be available. The electron density of 2.5 kA/m^2 is the designed maximum. The longitudinal space charge impedance has been evaluated under the assumption that the transverse profile still be Gaussian during the bunching. The simulation has been carried out on the condition that the momentum spread is kept around 10^{-3} as 6 rms, the value being tolerable to beam users.

For the 150 MeV/u U^{92+}_{238} beam with the 6 rms momentum spread 10^{-3} and the full bunch length 0.4 m, the threshold number of ions per bunch for the longitudinal microwave instability is 4.5 10^{+6} [3]. Following the above described procedure, the simulation has been done to know how shortly the beam of 4.5 10^{+6} ions per bunch or of the full-bunched beam current 3.3 mA bunches. The results are shown in Fig. 1. When the RF voltage reached 50 kV, the beam got near the equilibrium. The bunch length and the momentum spread are seen to be unstable even under the fixed RF voltage. The unstable dynamics that the simulation shows is as follows. The dense bunch along the synchronous energy level is torn off not by an ion but by a lump of ions when the space charge force in the bunch is superior, which is seen in the phase space plot in the figure.

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

Ring	
Circumference	258.73 m
Momentum compaction factor	0.03772
Betatron tune(ν_x /ν_y)	7.42/5.81
Twiss parameters at the cooling section	
$\alpha_x^{ec} = \alpha_y^{ec}$	0
$\beta_x^{ec} = \beta_y^{ec}$	7 m
RF harmonics	86
Average inner radius of the chamber	4 cm
Coasting beams	
Half momentum spread (3 rms)	0.5 10^{-3}
Rms transverse emittance ($\epsilon_x \approx \epsilon_y$)	10^{-6} πmrad
Electron cooling	
Applicable max. beam energy	500 MeV/u
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
Cooling limit	
for the rms momentum spread	0.5 10^{-5}
for the rms transverse emittance	10^{-8} πmrad

Then, the bunch gets stable, and the lump is diluted during rotation. Ions near the dense bunch are sucked into the bunch. In the meantime the space charge force becomes superior again, and the same phenomenon is repeated. The simulation has be done with 1.6 10^4 particles. The fitting of the line density has been not sufficiently good. One is not able to say whether such tearing off is real, or comes from statistic errors or the fitting. If it is due to the latter, the beam can be considered less unstable. The 6 rms beam bunch length is about 1.4 m, and is not as short as the microwave instability occurs. The bunch structure, or the line density is shown in the figure, where the normalized line density is one of which the integration over the beam bunch is unit, and the density of the coasting beam is 1/3 because the wavelength of the RF is 3 m for the beam. The normalized density averaged over the bunch center region of length 0.4 m is seen to be about 1.7, which means that the percentage of ions staying within the 0.4 m is about 65 % of 4.5^{+6} ions.

The bunch length dependent on the beam intensity and on the energy is shown in Table 2, as well as that of He_4^{2+} beam. Note that the beam with the 6-rms bunch length larger than about 3 m is not bunched. The current of U_{238}^{92+} beam of 4.5 10^{+6} ions is equal to that of He_4^{2+} beam of 2.1 10^{+8} ions in an energy per nucleon. The difference of the length between the two beams comes from the strength of the cooling force per nucleon which is proportional to q^2/A, q being the charge-state number of the ions, and A the mass number. The table shows that the longer the bunch length is, the larger the number of ions within the 0.4 m is after the bunching, and that the RF voltage over 100 kV is not necessary from the viewpoint of increase of ions' number within the 0.4 m. The relation between the bunch length

Table 2: Bunch length (6 rms) dependent on the ions' number per bunch and on the energy. Two numbers in the parentheses tell the percentage of ions staying within the bunch center 40 cm and the final RF voltage in the bunching, respectively.

U_{238}^{92+}

Ions/bunch	150 MeV/u	500 MeV/u
0.9 10^{+6}	0.8 m (75 %, 120 kV)	0.9 m(85 %, 160 kV)
4.5 10^{+6}	1.4 m (65 %, 50 kV)	2.4 m (55 %, 30 kV)
23 10^{+6}	2.4 m (45 %, 27 kV)	2.8 m (50 %, 28 kV)

He_4^{2+}

Ions/bunch	150 MeV/u	500 MeV/u
0.8 10^{+7}	2.4 m (45 %, 14 kV)	3.4 m (30 %, 13kV)
4.2 10^{+7}	2.8 m (40 %, 11 kV)	4.2 m (25 %, 6 kV)
21 10^{+7}	3.9 m(25 %, 7.5 kV)	4.5 m (20 %, 5.5 kV)

and the RF voltage under a given momentum spread is seen to nearly be described by an RF contour whose full height and full width are the same as the spread and the length, respectively, under the RF voltage.

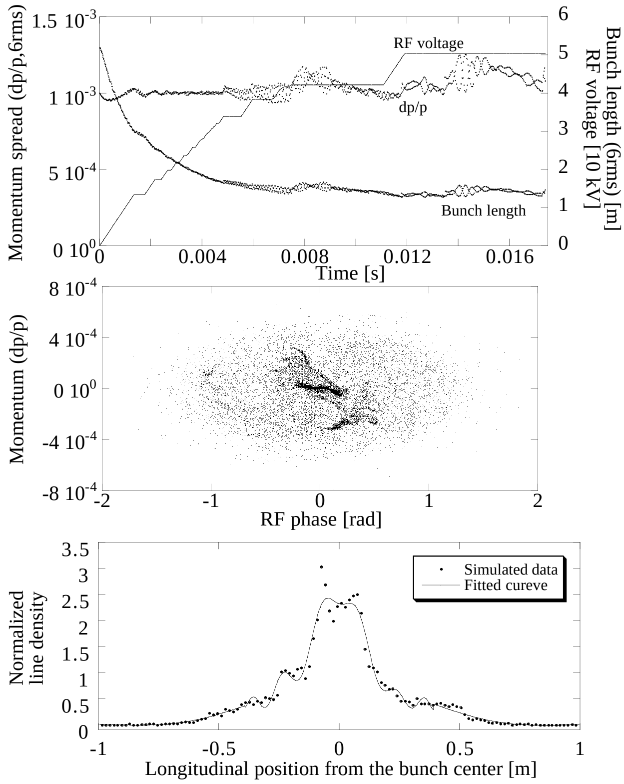

Figure 1: Beam bunching of a150 MeV/u U_{238}^{92+} beam of 4.5 10^{+6} ions per bunch. The longitudinal phase space plot and the line density are at the end of the simulation.

4 RF CAVITY FOR THE BUNCHING

The RF frequency of the cavity with harmonics 86 is 50 MHz to 76 MHz for the beam energy 150 MeV/u to 500 MeV/u. A $\lambda/4$ coaxial cavity without ferrite has been chosen as a cavity which can load RF voltage of 100 kV per cell. The RF potential well is distorted by the space charge effects during the bunching. The distortion makes the synchrotron frequency small, or make the longitudinal stability of beams weak. Higher order modes (HOM) of the RF field can induce coupled-bunch instability. The main cavity is accompanied with another small coaxial cavity as a HOM damper [4] as shown in Fig. 2. Two of more RF power resisters are connected across the entrance of the damper, and become 50 Ω as a whole. The resonant frequency is dependent on the main-cavity length which is tuned by shifting the movable short. The attenuation of HOM is dependent on the damper length which is tuned by shifting the movable short in the damper. The size of the cavity is shown in Table 3. The capacitance of the gap is set about 22 pF so that the length of the main cavity may be at longest 1 m and the gap be 43 mm.

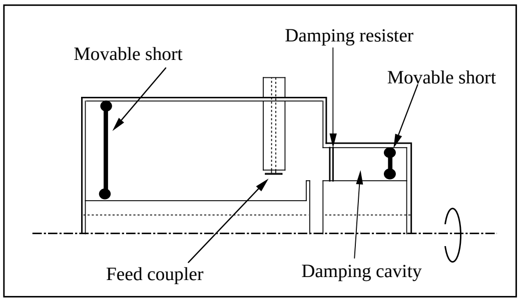

Figure 2: Functional structure of the coaxial cavity.

Table 3: Size of the cavity.

	Main cavity	damper
r_{out}	40 cm	26 cm
r_{in}	10 cm	20 cm
cavity length ℓ for 50 MHz	100 cm	10 cm
cavity length ℓ for 50 MHz	40 cm	3.4 cm

The longitudinal impedance of the cavity is approximated by the equivalent circuit as shown in Fig. 3. Impedance of each cavity is described with that of a coaxial transmission line with an open end and a short end;

$$Z \approx \frac{\imath}{2\pi} Z_0 \ln(\frac{r_{out}}{r_{in}}) \tan(\frac{2\pi\ell}{\lambda})$$

where Z_0 is free space impedance, r_{out} the inner radius of outer wall of the cavity, r_{in} the outer radius of the inner wall, ℓ the cavity length, λ the wavelength. The impedance behavior is shown for the resonant frequency 50 MHz and 90 MHz in Fig. 4. The dissipation power is 13 kW and 16 kW at the frequencies, respectively, when the RF voltage is 100 kV.

5 CONCLUSION

An ion beam colliding with an electron beam is desirable to be bunched in order to increase the luminosity. The simulation of the beam bunching with electron cooling and RF

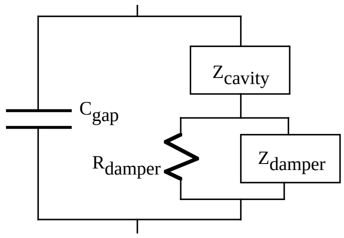

Figure 3: Approximate longitudinal equivalent circuit of the cavity.

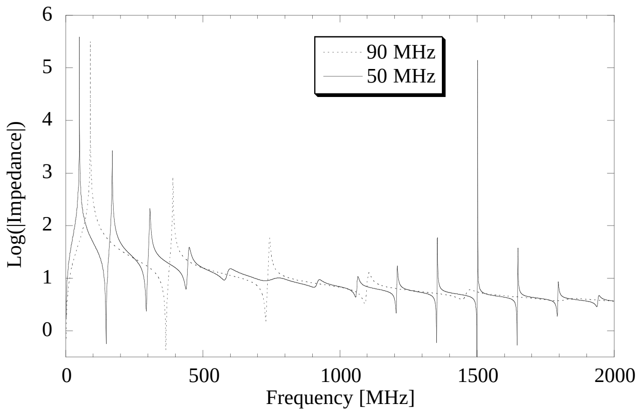

Figure 4: Longitudinal impedance[Ω] of the cavity which is tuned at 50 MHz or 90 MHz.

voltage applying shows that the bunching is possible without increase of the momentum spread, and is efficient for the heavier-ion beam and for the lower-energy beam in the energy 150 MeV/u through 500 MeV/u. Under the electron beam density 2.5 kA/m^2 at the cooling section of the length 3m in the storage ring, the bunching is expectable in the beam current until a few mA for 150 MeV/u U beam, until 1 mA for 500 MeV/u U beam, but not for the He beam in such high current, when the full momentum spread is kept about 10^{-3} and the RF wavelength is 3m for the beam. The RF voltage over 100 kV is not necessary from the viewpoint of increase of the number of ions staying within the bunch center 0.4 m, or increase of the luminosity.

As an RF cavity for the bunching, a $\lambda/4$ coaxial cavity has been designed to be accompanied with another small coaxial cavity as a HOM damper. It loads 100 kV in the frequency 50 MHz through 90 MHz. The approximate estimation says that the impedance of the second higher order mode, which is very serious to the coupled-bunch instability, is attenuated with the damper by about 20 dB.

6 REFERENCES

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