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SIMULATION OF ELECTRON COOLING ON BUNCHED ION BEAM

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Abstract

A combination of electron cooling and RF system is an effective method to compress the beam bunch length in storage rings. A simulation code based on multi-particle tracking was developed to calculate the bunched ion beam cooling process, in which the electron cooling, Intra-Beam Scattering (IBS), ion beam space charge field, transverse and synchrotron motion are considered. In the paper, the cooling process was simulated for C beam in HIRFL-CSRm, and the result was compared with experiments, according to which the dependence of the minimum bunch length on beam and machine parameters was studied in the paper.

INTRODUCTION

Electron cooling is a powerful method for shrinking the size, the divergence and the momentum spread of stored charged-particle beams in storage rings for precision experiments [1]. It also supports beam manipulations involving RF system to provide beams with short bunch length. Short-bunched ion beam has a wide range of application in rare isotope production, high energy density physics experiment, collider and cancer therapy [2]. In order to study the cooling process of bunched ion beam, a simulation code was developed, in which the electron cooling, IBS and space charge effect are considered, and simulation of electron cooling with a sinusoidal wave RF field were carried out in CSRm under various intensities of cooled 6.9 MeV/u C^{6+} ion beams. The simulation results have also compared with the experiment in CSRm. The simulation results show a good agreement with the experiment. Meanwhile, the investigation about the limitation of the bunch length is give in the paper.

SIMULATION CODE

The simulation code is developed based on multi-particle tracking, in which the ion beam is represented by a number of model particles and the beam dynamics is calculated by statistical method. In the code, a certain number of charged particles are generated according to the initial beam emittance, momentum spread and bunch length. Particularly, it assumes that the initial ion beam distribution is Gaussian in transverse and longitudinal. Each particle is presented as a six-coordinate vector: $(x, x', z, z', \varphi, \Delta v)$, where x and z are the horizontal and vertical coordinates, x' and z' are the corresponding angles in horizontal and vertical, φ is the phase angle with respect to the ring, and Δv is the relative velocity of particle in Laboratory Reference Frame (LRF). For each turn, the coordinate of model particle will be tracked and the beam dynamics is based on the synchrotron and transverse motion [3].

The calculation of electron cooling is based upon the energy exchange between ions and electrons, which can be described in terms of a velocity-dependent friction force. In the simulation, the Parkhomchuk force formula was used to calculate the friction force on each particle at Particle Reference Frame (PRF) [4]. Additionally, the longitudinal velocities of electrons at a certain radius due to space charge effect should be corrected by

$$\frac{\Delta V_e}{V_e} = \frac{I_e}{4\pi\varepsilon_0\beta^3\gamma^3 c}\frac{e}{m_e c^2}\frac{r^2}{r_b^2} \tag{1}$$

where ε_0 is the vacuum permittivity, I_e is the electron beam current, β,γ and c are Lorentz factors and r_b the radius of electron beam.

On the other hand, the heating effects which can induce beam blows up should be analysed seriously. However, the IBS effect is the most important effect, which is a multiple Coulomb interaction of the charged particles within the beam. In the code, the Martini IBS model was applied in the calculation, in which the growth rates are calculated from a complicated integration that connected the 6-dimentional phase space density of the beam with the optics of the storage ring [5].

The ion beam density will increase as it was cooling down, during which the space charge effect becomes much stronger to prevent the cooling effect on bunch length and beam profile accordingly. In the code, the space charge effect is considered only in longitudinal and this effect is represented by a potential applying to particles which is similar to the RF voltage, the space charge potential is given by [6].

$$V_{SC} = \frac{gh^2}{2R\varepsilon_0\gamma^2}\frac{d\rho(\phi)}{d\phi} \tag{2}$$

in which ρ is the linear charge density of ion beam, h is the harmonic number, R the radius of the ring. The geometric factor $g=1+2ln(b/a)$ depends on the radio of beam radius a to pipe radius b. The change of particle velocity caused by the space charge potential together with the RF voltage for each turn is applied based on the synchrotron motion.

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SIMULATION ON CSRM

An application on CSRm is dedicated to the bunched beam cooling of the typical ion beam C at the injection energy of 6.9 MeV/u. The main parameters used in the simulation are listed in Table 1. The variations of beam emittance, momentum spread and bunch length with time under the combined actions of the IBS, space charge and electron cooling are shown in Fig. 1. The distribution of momentum spread and bunch length in the cooling process are showed by the contour map in Fig. 1 to reveal the evolution of particle distribution.

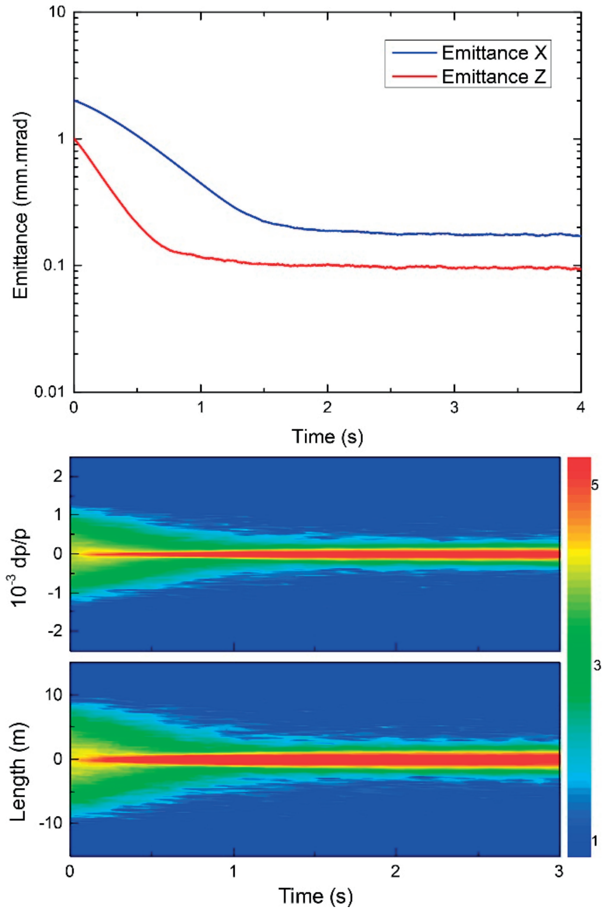

Figure 1: Evolution of beam emittance (RMS), distribution of momentum spread and bunch length in the procedure of cooling combined with RF field (V_{RF}=1.0 kV for 6.9 MeV/u C beam.

The particle distribution in longitudinal phase space and the corresponding separatrix orbits, and beam space charge potential during cooling process are given in Fig. 2. The space charge potential shows the behaviour increasing with the decrease of bunch length as it was cooling down, during which the beam bunch length is prevented from being cooled to much shorter together with the IBS effect. However, the space charge potential at 1 second is larger than that at equilibrium state and there are many particles cooled to the centre as shown in Fig. 2. It is mainly because of that the cooling force in longitudinal is larger than in transverse. Many particles will be quickly cooled to the centre in longitudinal at the beginning of cooling and then diffuse slowly due to Intra-Beam Scattering effect and space charge effect until the equilibrium state achieved. For a cooled ion beam with stationary distribution, the particle charge density in longitudinal can be described by the Fokker-Plank equation [7], which is used to fit the beam distribution during cooling and the fitting results have a good agreement with the simulation results before and after cooling as shown in Fig. 2.

Table 1: Initial Parameters used in Simulation

Name	Initial Value
Ion energy	6.9 MeV/u
Particle number per bunch	1E8
Emittance (RMS)	2.0/1.0 pi mm mrad
Momentum spread (RMS)	5E-4
Betatron function @cooler	10/10 m
RF voltage	1.0 kV (h=2)
Transition gamma	5.42
Electron beam density	3.8E6 cm^{-3}
E-beam Temp.	0.5/1E-5 eV
Magnetic field @cooler	365 Gs

BENCHMARK FOR SIMULATION CODE

The experiments were performed with C beam at the energy of 6.9 MeV/u at CSRm, in which the beam shape is measured by a position pick-up. The beam parameters are close to the value in Table 1. Because the cooling time is too small to measure the cooling process and there is no facility to measure the beam emittance, we only studied the final bunch length at the equilibrium status and it dependence on particle number. The experimental and simulation results are shown in Fig. 3.

In order to investigate the limitation of bunch length for high intensity ion beam, more calculations on 6.9 MeV/u C beam with RF voltage 1.0 kV were done. The particle number is from 1E7 to 1E10 per bunch. However, the IBS and space charge effect are considered independently in the calculation, and the results comparing with the measurement are shown in Fig. 3. According to the results considered the IBS effect only, the experiments of C in CSRm are clearly belong to the IBS dominant regime. The bunch length is proportional to $N^{1/4}$. The space charge dominated beam will attained when the particle number per bunch exceeds 6E8. When only space charge effect is considered, it is observed that the dependency of the particle number is divided into two regions which is mainly due to the amplitude of oscillation in RF bucket.

According to the simulation and experiments, we can know the simulation results is rather well and can give an estimation on the limitation of cooled ion beam bunch length. The limitation result calculated by simulation code can almost apply to any kind of heavy ion beams with different energies and the IBS dominated beam or Space-Charge dominated beam can be distinguished.

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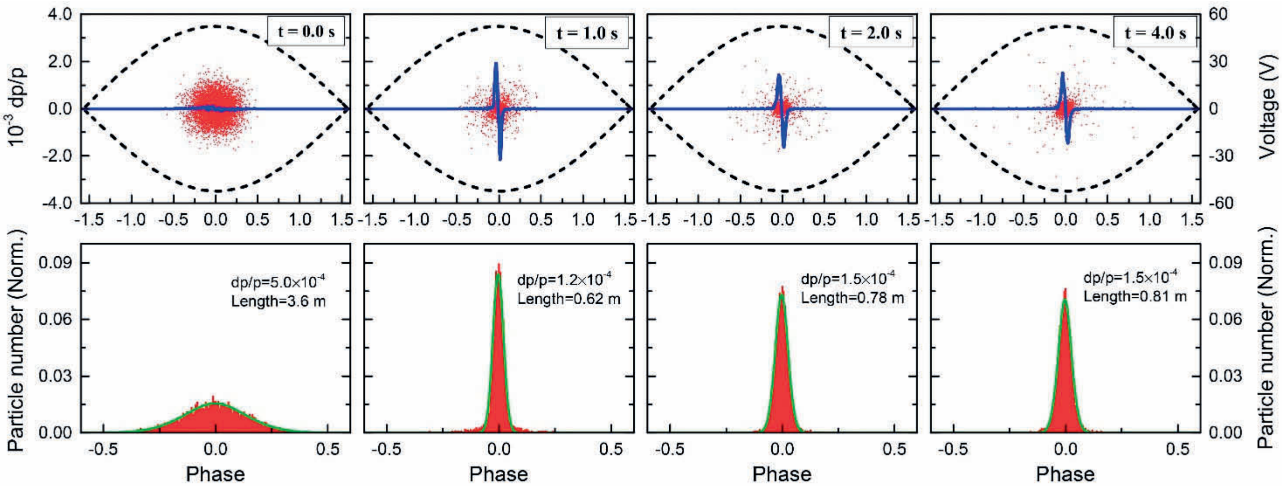

Figure 2: Evolution of model particles distribution in longitudinal phase space (red dot) and space charge potential (blue line) and the particles distribution in longitudinal for one bunch of C beam in CSRm. The black dash line is the RF bucket with V_{RF}=1.0 kV, the green line is the fitted line by Fokker-Plank equation.

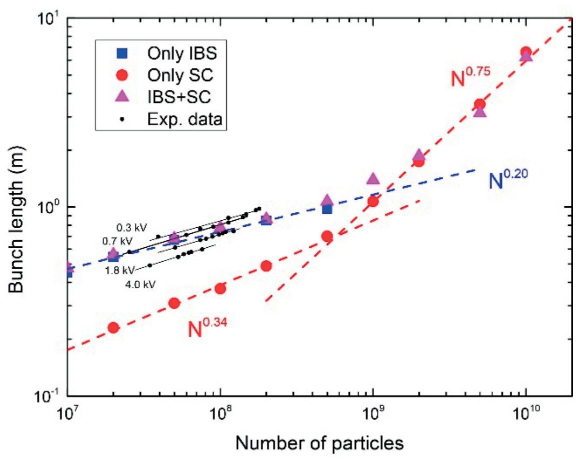

Figure 3: The bunch length versus particle number in the simulation (colored) and experiment (black) for 6.9 MeV/u C ion beam. In the simulation, the IBS and space charge effect are considered independently. The dash lines are fitted to the simulation results.

CONCLUSION

In this paper, we reported bunch beam cooling simulation code and its application in CSRm. According to the benchmark with experimental results, the experimental results in CSRm shown a good agreement with the simulation results in the IBS dominated regime. We also studied the dependence of bunch length on particle number and finally give the estimation of the limitation of bunch length for that condition.

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REFERENCES

[1] H. Poth, “Electron cooling: theory, experiment, application”, *Phys. Rep*., vol. 196, Nos. 3 & 4, p. 135, 1990.

[2] K. Noda *et al.,* “Electron cooling of bunched ion beam at NIRS-HIMAC”, *Nucl. Instrum. Methods Pys. Res.Sect. A*, vol. 532, p. 129, 2004.

[3] S.Y. Lee, “Accelerator Physics”, USA: World Scientific, 2006, p. 255.

[4] V.V. Parkhomchuk, “New insights in the theory of electron cooling”, *Nucl. Instrum. Methods Pys. Res, Sect. A*, vol. 441, p. 9, 2000.

[5] M. Martini, CERN, Geneva, Switzerland, Rep. CERN-PS/84-9 (AA), 1984.

[6] C.R. Prior and E.Fellow, TRACK1D Guide for Users.

[7] S. Nagaitsev *et al*., “The investigation of space charge dominated cooled bunched beams in a synchrotron”, in *Proc. Workshop on Beam Cooling and Related Topics*, Montreux, Swichzerland, 1993, Vol. 94(3), pp. 405.