

ELECTRON COOLING OF BUNCHED ION BEAM IN STORAGE RING *

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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. Bunched ion beam cooling experiments have been carried out in the main cooling storage ring (CSRm) of the Heavy Ion Research Facility in Lanzhou (HIRFL), to investigate the minimum bunch length obtained by the cooling method, and study the dependence of the minimum bunch length on beam and machine parameters. It is observed that the IBS effect is dominant for low intensity beams, and the space charge effect is much more important for high intensity beams. The experimental results in CSRm shown a good agreement with the analytical model in the IBS dominated regime. Meanwhile, the simulation work offers us comparable results to those from the analytical model both in IBS dominated and space charge dominated regimes.

INTRODUCTION

The HIRFL accelerator complex is a multipurpose research facility for nuclear physics, atomic physics and applied research in medicine, biology and materials science. It consists of two cyclotrons, two storage rings and several experimental terminals[1]. Two electron coolers installed in the storage rings CSRm and CSRe (experimental Cooling Storage Ring) are applied to the stored ion beams for the phase space compression. The electron coolers were designed and manufactured in the cooperation between IMP China and BINP Russian[2]. The layout of HIRFL accelerator complex is shown in Fig. 1.

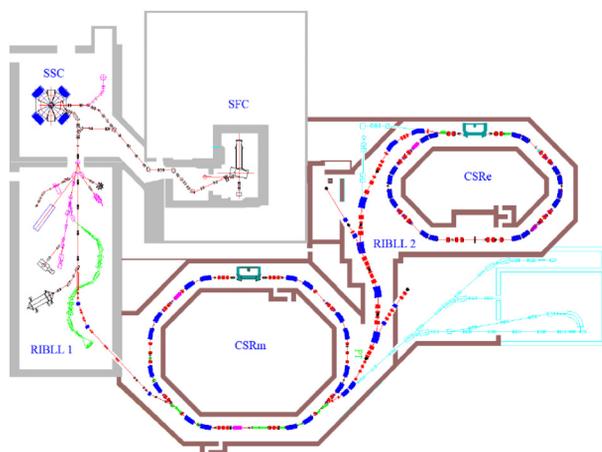


Figure 1: Layout of HIRFL accelerator complex.

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. It also supports beam manipulations involving RF system to provide beam 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. In order to study the cooling process of bunched ion beam, a series of experiments have been done in several cooling storage rings, such as HIMAC, ESR, IUCF and CSRe[3-5]. The results shown that the minimum bunch length of cooled-beam is affected by the equilibrium between electron cooling, IBS effect, ion beam space charge field and RF voltage, but the dependence of the minimum bunch length on the beam parameters has a slight difference in those experiments.

In this paper, we present the recent experimental results which was done at CSRm, and compare with the simulation results based on the multi-particle tracking method. Bothe experimental and simulated results shown a good agreement with the analytical model.

BUNCH LENGTH MEASUREMENT

The experiments were performed with $^{112}\text{Sn}^{36+}$ beam at the energy of 3.7 MeV/u and $^{12}\text{C}^{6+}$ beam at the energy of 6.9 MeV/u, respectively. The range of stored particle number was from 10^6 to 10^9 . A flat distribution electron beam with diameter around 50 mm was used for beam cooling. The electron beam current was set as 135 mA for $^{112}\text{Sn}^{36+}$ beam and 44 mA for $^{12}\text{C}^{6+}$ beam, respectively. A sinusoidal RF voltage from 0.2 to 2.3 kV was applied with the harmonic number of 2.

A typical experimental cycle is as follow: heavy ions are injected, accumulated and cooled with the help of continuous electron beam, and then a sinusoidal RF voltage is switched on with 2nd harmonic number of revolution frequency. The bunch length after 2 seconds of turning on the RF system is measured by a position pick up with the length of 150 mm and the capacitor of 120 pF. The voltage drop at a 50 Ohms resistor between the pick up and ground is amplified by a pre-amplifier with the gain factor of 54 dB. An oscilloscope with bandwidth of 1 GHz is used to read the signal from the pre-amplifier. A RMS bunch length value is evaluated from a Fokker-Plank fitting result of this voltage signal. As an example, a measurement of the voltage signal from pick up for $^{112}\text{Sn}^{36+}$ beam is shown in Fig. 2. In this case, the beam longitudinal linear charge density is obtained by the integration of the pick up voltage signal. The RMS bunch length σ_t is evaluated by the Fokker Plank fitting result of the bunch shape data.

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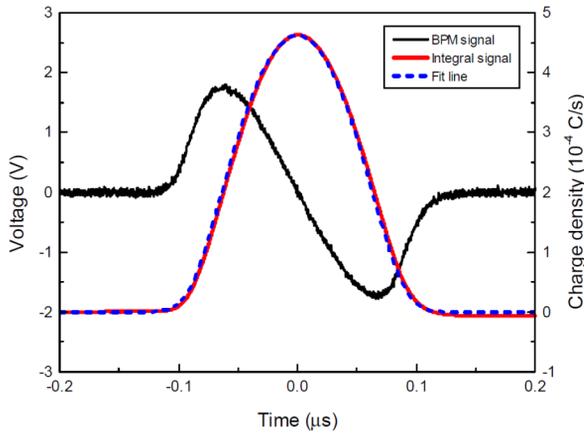


Figure 2: Voltage signal of bunched beam acquired from BPM and the linear charge density calculated by BPM signal with its Fokker Plank fitting result.

The stored beam current was measured by the DC current Transformer (DCCT) in CSRm the particle number per bunch is calculated by Eq. (1):

$$N = \frac{I}{eZh f} \quad (1)$$

Where I is the beam current measured by DCCT, Z is the charge state of particle, h is the harmonic number and f is the revolution frequency.

EXPERIMENTAL RESULTS

The experimental results of $^{112}\text{Sn}^{36+}$ and $^{12}\text{C}^{6+}$ beam are shown in Fig. 3, in which the dependency of the minimum bunch length n particle number at different RF voltage is presented. It is observed that the bunch length increases proportionally to N^k , and the range of k is from 0.22 to 0.28 for such low ion intensities and energies. For space charge dominated beam, k is close to $1/3$ which have been measured and analysed in references. According to these results, the beam charge density in longitudinal is determined by the geometrical factor g and σ , where the value of g influences the width of the central part and σ defines the tails. In our case, we think the bunched beam after cooling belongs to IBS domain and the beam bunch length is mainly determined by IBS effect, even the central part of the beam is strongly affected by space charge effect. As the results shown in reference, the evolution of RMS momentum spread show a different rule with the total beam current and the peak current respectively.

In the experiments, the stored particle number per bunch is from 10^6 to 10^8 . Accordingly, the IBS effect is the main heating source to affect the bunch length for such low ion intensity and low energy, in which the space charge effect only exit at the central part of beam that with quite small momentum spread. Therefore, the distribution of bunched beam is mainly determined by the particles outside the center that with large momentum spread relatively. The space charge potential can be ignored for the particle outside the centre, and the synchrotron motion of these particles can be described by small amplitude oscillation in RF bucket:

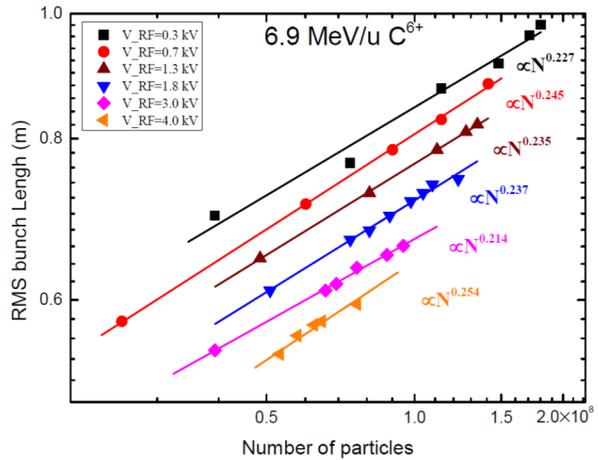
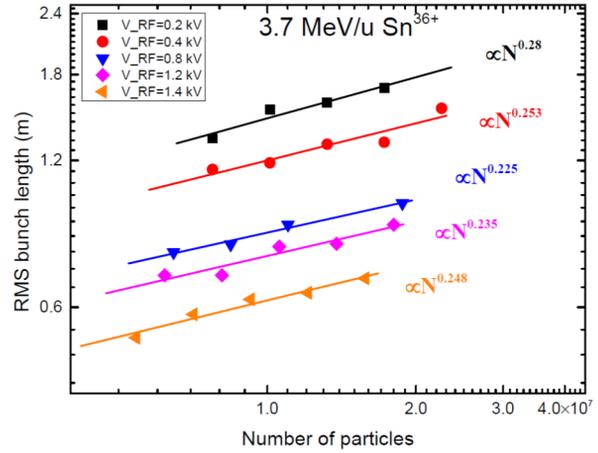


Figure 3: Dependency of the RMS bunch length on the stored particle number for different RF voltages for $^{112}\text{Sn}^{36+}$ and $^{12}\text{C}^{6+}$ ion beams, respectively. The solid lines are fitted to the experimental data.

$$\frac{\delta}{\theta} = \left(\frac{ehV_{RF}|\cos\phi_s|}{2\pi\beta^2 E|\eta|} \right)^{1/2} = \frac{Q_{s0}}{|\eta|} \quad (2)$$

where δ and θ are the maximum amplitudes of the phase space ellipse, E is the total energy of ions, η is the slip factor and Q_{s0} is the synchrotron tune. It is clear that the bunch length for small amplitude oscillation increases linearly with the momentum spread for a certain RF amplitude. In the cooling process, the evolution of momentum spread satisfies the differential equation:

$$\frac{1}{\delta_p} \frac{d\delta_p}{dt} = \frac{1}{\tau_{cooling}} + \lambda_{heating} \quad (3)$$

here the $\tau_{cooling}$ is the cooling time and $\lambda_{heating}$ is the heating rate. For low ion intensities and energies, the heating rate is determined by the IBS heating rate, and when the equilibrium is achieved, we can get:

$$\frac{1}{\tau_{cooling}} = \lambda_{IBS} \quad (4)$$

According to the electron cooling theory, the cooling force value on particle with small momentum deviations Δp is a linear function $F=k\Delta p$, where k is the slop of the longitudinal cooling force which is a constant for a certain electron beam setting. Therefore, the cooling time for the cold beam at equilibrium status with small momentum spread δ_p is:

$$\frac{1}{\tau_{cooling}} = \frac{F}{p_0} = k\delta_p \quad (5)$$

The gas relaxation model can be used for the calculation of IBS heating rate, the longitudinal heating rate for bunched beam is given by:

$$\lambda_{IBS} = \frac{1}{2\delta_p^2} \frac{d\delta_p^2}{dt} = \frac{r_i^2 c N_i \Lambda}{16\beta^2 \gamma^3 \varepsilon_{\perp}^{3/2} (\beta_{\perp}^{3/2}) \sqrt{\pi/2} \sigma_b \delta_p^2} \quad (6)$$

Where Λ is the coulomb logarithm, ε_{\perp} is the transverse emittance, β_{\perp} is the beta function, N_i is the particle number per bunch corresponds to 92% of ion beam in longitudinal direction. In the equilibrium state, we get

$$k\delta_p = \frac{r_i^2 c N_i \Lambda}{16\beta^2 \gamma^3 \varepsilon_{\perp}^{3/2} (\beta_{\perp}^{3/2}) \sqrt{\pi/2} \sigma_b \delta_p^2} \quad (7)$$

According to the Eqs. (2-7), the minimum bunch length after cooling is increase proportionally to:

$$\sigma_b \propto N^{1/4} \quad (8)$$

which has a good agreement with the experiment results shown in Fig. 3.

SIMULATION

A simulation code based on multi particle tracking method was developed, in which the ion beam is represented by a number of model particles and the beam dynamics is calculated by statistical method. The cooling, IBS, space charge field and synchrotron motion are considered in simulation.

In order to investigate the limitation of bunch length under different beam intensities, a calculation of $^{12}\text{C}^{6+}$ beam with RF voltage 1.0 kV were done, the other parameters are the same as experiments. Figure 4 shows a comparison of the simulation results to the experimental results. According to the results considered the IBS effect only, the experimental results 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 6×10^8 . When only space charge effect is considered, it is observed that the dependency of the particle number is divided into two regions. The expected dependence of the bunch length shown in Figure 4 is close to $N^{1/3}$ for the particle number less than 10^9 . Such

results can be explained rather well by the equilibrium between the space charge effect and RF voltage. Beyond this particle number, an additional increase of the bunch length occurs, proportional to $N^{3/4}$, it is also observed that the particles almost out the RF bucket for much high beam density.

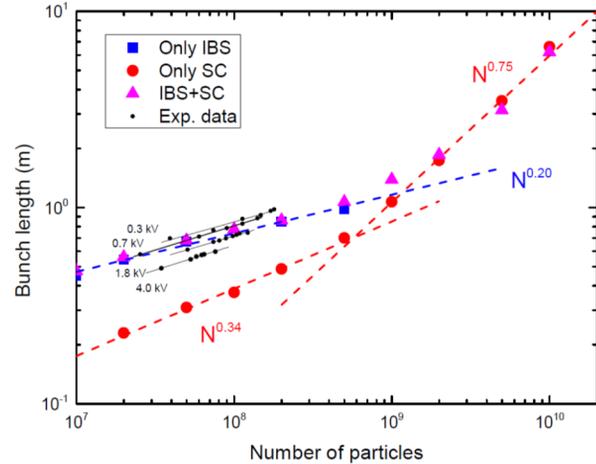


Figure 4: The bunch length versus particle number in simulation and experiment. The dash lines are fitted to the simulation results.

CONCLUSION

In this paper, we reported the experimental and simulated results of the minimum ion beam bunch length obtained by a combination of electron cooling and RF system. It is obvious that such combination is an effective method for beam bunch compression. Both results show that the minimum bunch length increase proportionally to the particle number in bunches with N^q . The dependence can be divided into two conditions. For small particle number, the IBS effect is dominant and the exponent is 1/4. For higher intensity the ion beam space charge effect is dominant and the exponent is 1/3. Additionally, when more particles applied, some blow up effect will happen and the beam almost cannot be bunched in the RF bucket. The experimental results in CSRm shown a good agreement with the simulation results in the IBS dominated regime.

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