

SIMULATION OF LOW ENERGY ION BEAM COOLING WITH PULSED ELECTRON BEAM ON CSRm

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Abstract

The pulsed electron beam can be applied to high energy beam cooling and the researches of ion-electron interaction in the future. In this paper, we studied the pulsed e-beam cooling effects on coasting and bunched ion beam by simulation code which is based on the theory of electron cooling, IBS and space charge effect etc. In the simulation, a rectangular distribution of electron beam was applied to 7 MeV/u ¹²C⁶⁺ ion beam on CSRm. It is found that the coasting ion beam was bunched by the pulsed e-beam and the rising and falling region of electron beam current play an important role for the bunching effect, and similar phenomenon was found for the bunched ion beam. In addition, the analyses of these phenomena in simulation were discussed.

INTRODUCTION

There are several high energy facilities that need electron cooler to acquire high quality, high intensity or short bunch length ion beam are under discussion or construction [1,2]. Classical DC cooler cannot satisfy these requirements because of the large power and the high voltage. The bunched electron beam from cooler or a Linac should be applied in that case. Before the application of high energy cooling, the investigation on low energy beam cooling with bunched electron beam is studied by simulation. It is observed that the grouping effect was happen for coasting or bunched ion beam and the rising and falling edge of e-beam has a strong effect on cooling rate and beam distribution. The simulation code is based on the theory of electron cooling, IBS and space charge effect. The simulation results and some analysis are given in the paper.

COASTING ION BEAM COOLING

In the simulation, a pulsed electron beam was used to cool the coasting ion beam. The initial beam emittance and momentum spread are 0.3/0.2 pi mm.mrad and 2E-4. The parameters are listed in Table 1. It is observed that the coasting beam is bunched by pulsed electron beam and almost all of the particles are bunched into the region where have electrons as shown in Figure 1.

The revolution period of ion beam is about 4.44 us and the width of pulse electron beam is 2 us with peak current 30 mA. Considering the e-beam current increases linearly to peak with rising and falling time 10 ns, which will generate the electric field due to the space charge effect, and the longitudinal electric field in Laboratory Reference Frame (LRF) is given by

$$E_z(z) = -\frac{g}{4\pi\epsilon_0\beta c\gamma^2} \frac{dI_e(z)}{dz} \quad (1)$$

where g is the geometric factor. It is obviously the electric field only exist in the rising and falling region. The electric field in longitudinal is calculated ($E_z=67.7$ V/m) as shown in Figure 1. When particles passing through cooling section, some of them meet the electric field will be kicked by the electric field and the effective voltage seen by the particle in this region is $V_{kick}=E_zL_{cooler}=230.5$ V. It is found that the kick voltage plays a crucial role in the bunching process that all particles are bunched to the e-beam region, as shown in Figure 2. When using the pulse electron beam without the kick voltage, the bunch effect is so weak that only part of particles will be bunched. It can be explained by the barrier bucket theory that the particles are restricted in the region between the two barriers [3]. Because of cooling effect, all particles even that with large momentum spread will be cooled to that region and can't pass through the barrier during the motion in longitudinal phase space.

Table 1: Initial Parameters Used in Simulation

Name	Initial Value
Ion energy	7.0 MeV/u
Particle number per bunch	1E7
Emittance (RMS)	0.3/.2 pi mm mrad
Momentum spread (RMS)	2E-4
Betatron function @cooler	10/10 m
Cooler length	3.4 m
Transition gamma	5.42
E-beam current	30 mA
E-beam radius	3.0 cm
E-beam Temp.	0.2/1E-4 eV
Magnetic field @cooler	1000 Gs
Pulse width	2 us
Rising/falling time	10 ns

In the cooling section, the electrons at different radius inside the beam have different longitudinal velocities because of the space charge effect. Accordingly, the longitudinal velocity component of an ion at a certain radius should be corrected with respect to that of an electron at the same radius [4]. For coasting beam, most ions will be cooled down to positive momentum respect to the reference particle in the equilibrium status. Considering the electric field of electron beam, the motion of particles in phase space is a circle when it is cooled down to the poten-

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tial well. So the distribution of particles show a non-uniform behaviour that most particles are accumulated in the beam head, as shown in Figure 2.

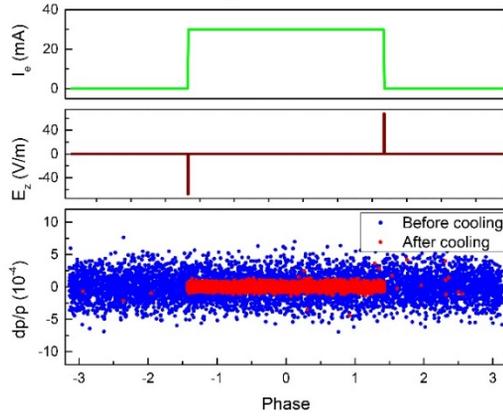


Figure 1: The distribution electron beam current and its electric potential at the edge, and distribution of particles in phase space when pulse e-beam is applied.

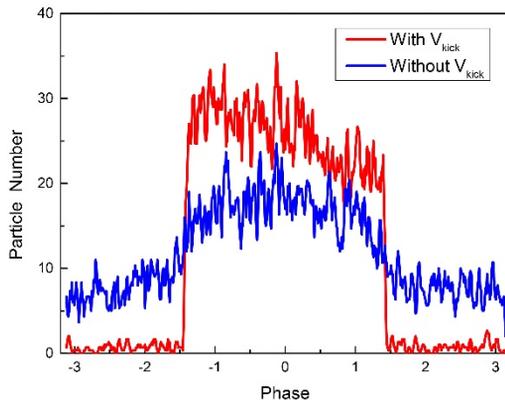


Figure 2: Final beam distribution after cooling with V_{kick} and without V_{kick} .

Similar to synchrotron motion in RF, the oscillation caused by the pulsed e-beam is shown in Figure 3. We can see that the potential field is a heating resource for the beam outside the electron beam. If there is no electron cooling force, only part of particles will be bunched to the region and the other particles that outside the region and that with larger momentum spread than the potential field will finally lost because of other heating resource like IBS and gas-scattering effect. When the cooling effect is applied, all particles will finally be cooled and bunched to the pulse region.

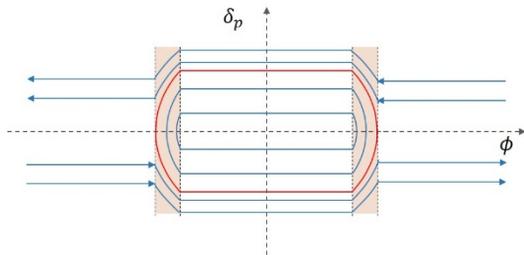


Figure 3: Particle motion in pulsed e-beam.

Since the particle motion in phase space is circle, we would like to study the period time of the bunched beam.

Firstly, the cycle time for a single particle that with momentum spread $\Delta p/p$ include two parts: cooling section and e-beam edge section, and the period t_0 is

$$t_0 = 2(t_{cool} + t_{edge}) \quad (2)$$

where t_{cool} is the period time in the cooling section which is determined by the momentum spread

$$t_{cool} = \frac{pulse_width}{\eta \Delta p/p} \quad (3)$$

η is the phase slippage factor. t_{edge} is the period time in e-beam edge section that can be calculated by

$$t_{edge} = \frac{2 \frac{\Delta p}{p} \beta^2 E}{e V_{kick} Z} \frac{A}{Z} T_0 \quad (4)$$

where the synchrotron mapping equation was used $\delta_{n+1} - \delta_n = \frac{e V_{kick} Z}{\beta^2 E} \frac{Z}{A}$ [5]. Assuming the particles are been bunched in the cooling region and the distribution of momentum spread is Gaussian, the distribution of t_0 can be calculated by [6]

$$g(t) = f[\phi_{cool}^{-1}(t)] |\Psi'_{cool}(t)| + f[\phi_{edge}^{-1}(t)] |\Psi'_{edge}(t)| \quad (5)$$

where $f(\delta_p)$ is the beam momentum spread distribution, and $\delta_p = \Psi(t) = \phi^{-1}(t)$. Finally, we get the distribution of t_0 as shown in Figure 4.

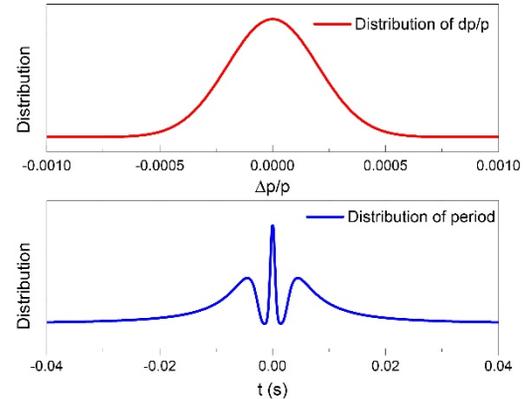


Figure 4: The distribution of momentum spread and period time for ion beam.

It is found that the distribution of period for particles have three peak value. One is the centre part which is correspond to the reference particle and that part is caused by the t_{edge} . The other two peaks beside the centre are caused by t_{cool} . It means there exist sidebands in the frequency domain and according to Eq. (5) the frequency sideband is proportional to $\delta p/pulse_width$. In the simulation, we tracked several hundreds of particles for each turn and base on the particle momentum and Fourier transform, the beam spectrum was obtained as shown in Figure 5, in which the simulation results that with and without cooling are included. It is shows that the RMS momentum spread is decrease from $2E-4$ to $5E-5$ when cooling effect applied and when there is no cooling, it stays at around $2.5E-4$. The oscillation of the result and the little difference of the value at beginning in Figure 5 are caused by the potential at the

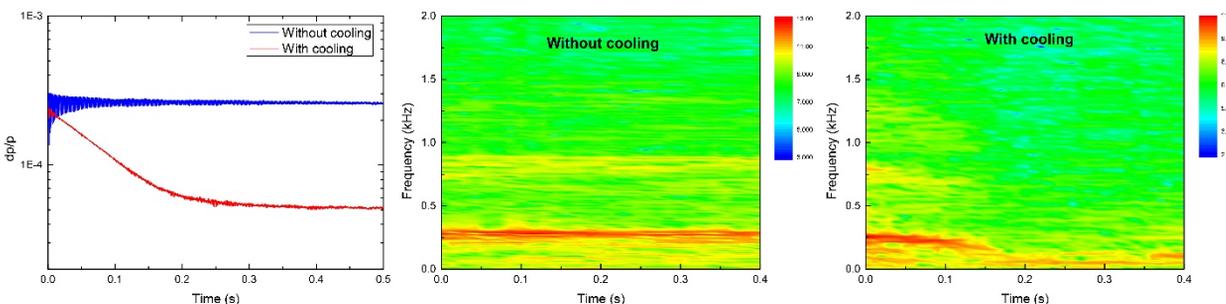


Figure 5: Beam spectrum in frequency domain for pulse e-beam cooling. The initial momentum spread and pulse width are $2E-4$ and 600 ns respectively. The sidebands is caused by the oscillation within pulse electron beam.

edge. According to the calculation in Eq. (5), the sidebands should decrease from 225Hz to 56 Hz and stay at 280 Hz respectively. The spectrum results show a good agreement with the calculation. Because the cooling time is quite small, the resolution of beam spectrum is not very good.

BUNCHED ION BEAM COOLING

The simulation on ion beam cooling by pulsed electron beam combined with RF voltage was carried out. The ion beam is bunched by the RF voltage and the bunch length will decrease as the cooling process going on. There the pulse e-beam cooling can divided into two conditions: long pulse width which is larger than the RMS bunch length of the initial status before cooling and short pulse that close to the final bunch length of cooled beam.

The initial emittance and momentum spread of ion beam are $0.3/0.2$ pi mm.mrad and $5E-4$ with the RF voltage 1.0 kV. The parameters of pulsed electron beam are list in Table 1. Firstly, the initial RMS bunch length of ion beam is 100ns and the pulse e-beam length is larger than that. The simulation results are shown in Figure 6. The cooling process and the particle distribution are given, which shows a little difference for different pulse e-beam. The cooling rate almost same with each other. It is due to the synchrotron motion of particles that each particle will meet the electron beam quickly, and with the cooling process the ion beam will fast cooled down to the pulse e-beam region where the cooling force is same with other conditions.

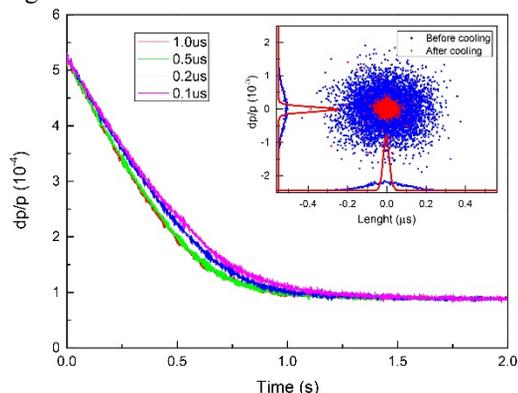


Figure 6: Cooling process with long pulse width of e-beam and the particle distribution before and after cooling.

For the short pulse beam cooling, a multi pulse e-beam with length 20ns , interval 10ns and rising/falling time 10ns is applied. The simulation results are shown in Figure 7.

Because the RF voltage is so small in that small phase region that the distribution of ion beam will restricted by the potential voltage caused by pulse e-beam. So, the ion beam is cooled to two bunches, which are locate in two pulses potential well. In simulation, a single particle motion in phase space was tracked as shown in Figure 7. It is observed that the separatrix orbit of synchrotron is disturbed by the V_{kick} . As ion beam is cooling down, the particle will finally fall into one pulse region. However, some particles will be kicked out by the V_{kick} , so the electron beam peak current should carefully define in simulation.

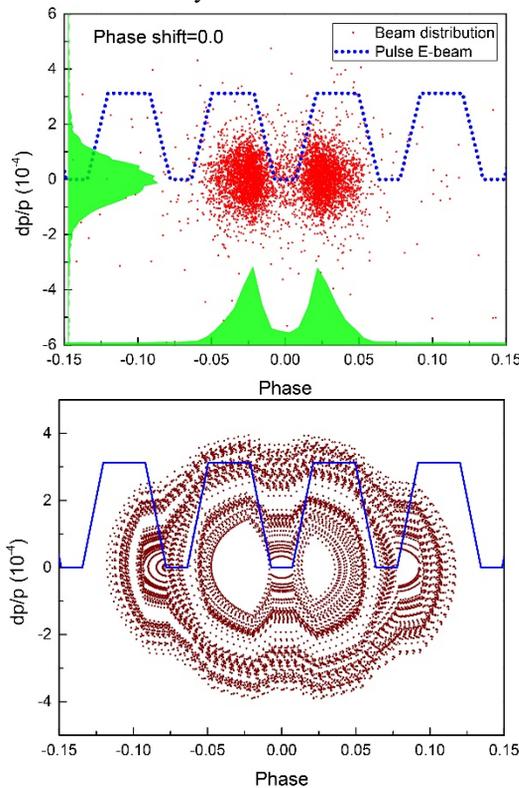


Figure 7: Beam distribution after cooled by short pulse e-beam with pulse width 20 ns and single particle tracking in phase space.

We also tried to introduce a phase shift to the pulse electron beam which is not symmetrical in longitudinal. The result is shown in Figure 8. The bunched ion beam was cooled down to two bunches, but most particles was bunched to one side which is close to the synchronous

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phase ($\Phi_s=0$). It indicates that the potential voltage V_{kick} is important for the status of ion beam. The finally distribution of ions can be modulated by the pulsed electron beam.

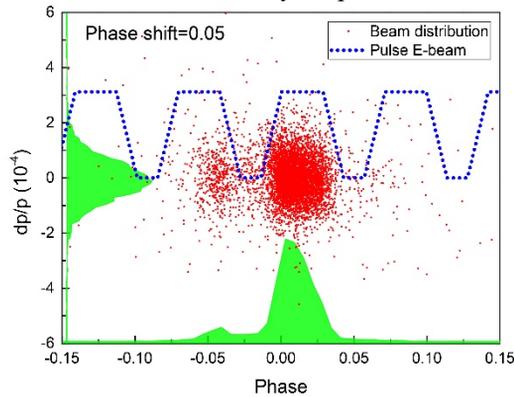


Figure 8: Beam distribution after cooling with the pulsed e-beam which have a phase shift (0.05) in longitudinal.

CONCLUSION

In this paper, we simulated the low energy pulsed electron beam cooling on coasting and bunched ion beam. The grouping effect and some other phenomenon were found. These results are meaningful for the high energy electron cooling in the future.

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