SIMULATION STUDY OF BEAM COOLING WITH ELECTRON ENERGY MODULATION*

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Abstract

The electron cooling is less efficient for hot ion beam because that the cooling force reduces rapidly at high electron-ion relative velocity. A possibility scheme of electron cooling for ion beam with large velocity spread was studied by simulation method. In this scheme, the average electron beam velocity was modulated through the ion velocity distribution during cooling procedure. Therefore the average friction force at high electron-ion relative velocity range will be increased. The results show that the hot ions can be captured and cooled. A fast beam momentum spread shrinking could be achieved through this electron energy modulation method. The capture rate dependence on the modulation parameters was investigated. The simulation results also show different ion beam longitudinal velocity distribution can be produced via electron energy modulation.

INTRODUCTION

The electron cooling method is an important technique to produce high quality ion beams in storage rings. Based on energy transfer between the ions and a cold external electron beam, the heat is transferred from ions to electrons and the phase space of ions is reduced.

The experiments and theory research work on the electron cooling showed that the “magnetized” electron cooling has an extremely sharp dependence of the drag force on the difference relative velocity of ions and electrons. In the small relative velocities range, the drag force is a linear function of the relative velocity. The ions in this region will be attracted by cold electron beam and cooled down fast. In the relative velocities out of this linear range, the drag force decreases very fast as scale as $F \sim v^{-2}$. Therefore, the electron cooling is less efficient and not well suited for cooling the hot ions.

One of the most important applications of the electron cooling is used to cool the ion beam after injection, in order to increase the number of ions in a storage ring by a combination with multi-injection. Generally, the ion beam after multi-turn injection has large momentum spread and emittance. In order to cool down the ion beam as fast as possible, especially for the hot ions in the tail of phase space, a possibility of efficient electron cooling of ion beams with wide velocity spread has been investigated experimentally [1]. The results show that the reduction of the cooling time could be achieved by the electron energy modulation method. In this paper, the cooling effect with electron energy modulation scheme was studied by simulation method.

PRINCIPLE

The basic parameter describing this energy transfer in electron cooler between ions and electrons is the cooling force. A useful practical formula of the cooling force was written by Parkhomchuk by fitting to the experimental data [2]. The cooling rate for ion originated from this formula can be described as below:

$$\lambda_{cool}(v) = \frac{-4Z^2 n_e m_e c^2 r_e^2 L_c}{m_{ion}} \frac{1}{\eta} \frac{1}{\left(v^2 + v_{eff}^2\right)^{3/2}} \quad (1)$$

Here v is the ion electron relative velocity. v_{eff} is the effective electron velocity. L_c is the coulomb logarithm of the impact parameters. η is the part of cooling section at the ring circumference. r_e is the electron classic radius.

The intra-beam scattering (IBS) is another important effect in the cooling process. The final cooled-down ion beam parameters are mainly determined by the equilibrium between the cooling effect and IBS effect. Usually, the growth rate caused by IBS is much less than the cooling rate of hot ions, therefore it’s not a significant role for our calculation. Here we used a simple gas relax model for IBS diffusion coefficient calculation [3].

$$D_{IBS} = \frac{2}{(\beta\gamma)^3} \frac{1}{\left(\varepsilon_{h,v}\right)^{3/2}} \frac{N_{ion} c}{\sqrt{\beta_{h,v}}} r_{ion}^2 \frac{1}{C_{ring}} Lc \quad (2)$$

According to the Fokker-Planck equation and stochastic dynamics principle [4], the momentum transfer of each particle after once integration step can be described as:

$$\theta_{final} = \theta_{start} \exp\left(\frac{1}{\gamma^2} \lambda_{cooling} t\right) + \sqrt{D_{IBS} t}\,\xi \quad (3)$$

Here ξ is a Gaussian random number. The integration step t is much shorter than the cooling time in the calculation.

Additionally, the beam dynamics in synchrotron was also considered. Since the momentum changing in each integration step was very small, and we assumed the particle position was constant in each integration step. We applied the matrix with a stochastic tune number after once step.

Based on principle above, a compute code was written for simulating the cooling process with electron beam

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energy modulation. The electron energy modulation means that the average velocity of the electron beam is modified in time, In order to make the mean velocity of the electron beam swept through the ion velocity distribution. The friction force will be swept through all ions capturing them to the equilibrium point. The cooling time reduces with this scheme. The modulation principle was shown in Fig. 1.

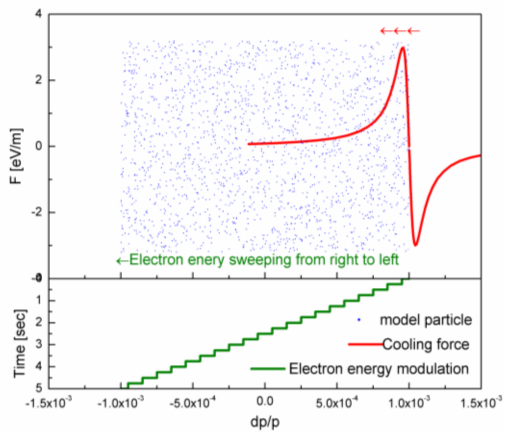

Figure 1: Principle of the electron energy modulation through the ion velocity distribution.

SIMULATION RESULTS

In the simulation program, thousands model particles were generated randomly by the initial ion beam parameters. The momentum kick of each model particle caused by electron cooling and IBS effects, as well as the dynamics in storage ring were calculated for each integration step. And then, the beam emittance, momentum spread and distribution in phase space were calculated statistically. Figure 2 shows a cross-checked calculation which was made by this simulation program and the TRUBS code which developed by Parkhomchuk. The main parameters of simulation were listed in Table 1. The COSY ring transfer matrix was used for dynamic calculation. The results show an acceptable agreement with two simulation tools. The difference of the final cooled ion parameters were mainly caused by the different intrabeam scattering models.

An evolution of the momentum distribution during the cooling process was shown in Fig. 3. It's obviously that the particles in tail (hot ions) were difficult to cool down. It's the main motivation why we studied the cool scheme of the beam with large momentum spread by the electron energy modulation.

Table 1: The Main Parameters of Simulation

Proton beam parameters	
ion kinetic	45 MeV proton beam
Initial emittance (x/y)	10 / 10 π*mm*mrad
Initial momentum spread (dp/p)	$1.0*10^{-3}$
Particle number	$1.0*10^{10}$

Electron cooler parameters	
Electron beam radius	10.0 mm
Magnetic field in cooling section	0.1 T
Cooler length	1.4 m
Electron beam current	0.1 A
Magnetic field misalignment	$1.0*10^{-5}$
Beta function at cooler (hori / vert)	10.0 / 10.0 m

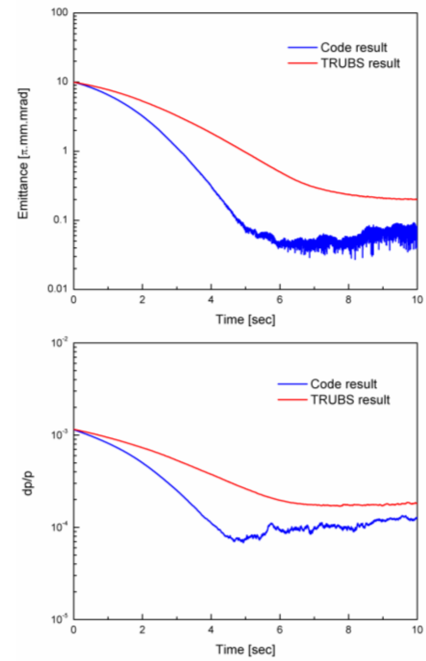

Figure 2: The cooling process calculated with different computer codes.

In order to explain this efficient cooling method of hot ions with electron energy modulation, a simulation was performed using hot ion beam shifted in momentum towards -10^{-3} with respect to the electron momentum. The calculation parameters are the same as in Table 1. Figure 4 shows the time evolution of beam momentum distribution with and without electron energy modulation, respectively. For the cooling without electron energy modulation, the electron average velocity locates at the relative momentum position -10^{-3}. The ions moved from right to left and finally were captured by the electron beam in the left. For the case with electron energy modulation, the electron momentum shifts in linear from right to left. The sweeping time is 5 seconds. The sharp peak on all the distribution corresponds to the position of the electron beam energy, finally locates at the respect position -10^{-3}. From these results, we can see that the ions in the tail can be captured and cooled toward to the final equilibrium momentum easily and efficiently with electron energy modulation method. This behaviour can be explained that the hot ions could be captured in the linear region of drag force during the electron energy sweeping process.

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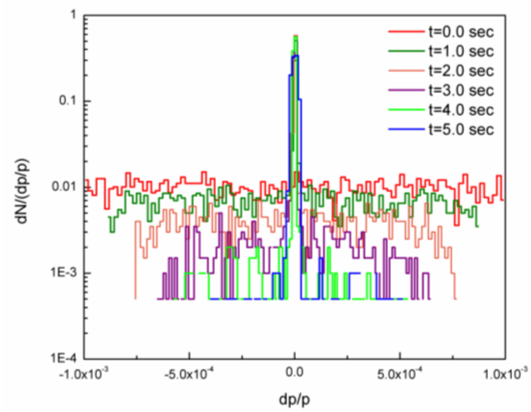

Figure 3: The momentum distribution during cooling process.

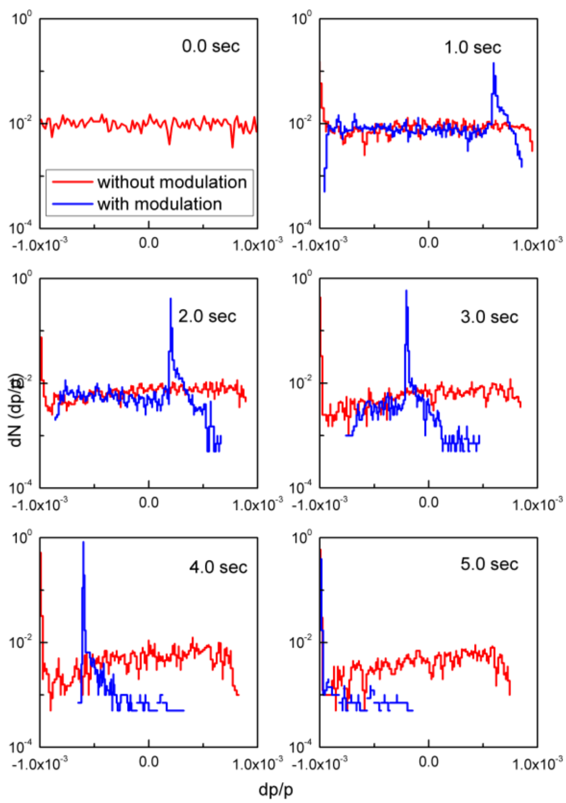

Figure 4: Time evolution of the momentum distribution. The read lines show the evolution without electron energy modulation. The blue lines show the evolution with electron energy sweeping from right to left.

In order to explain the cooling efficient of electron energy modulation scheme, a capture rate was defined as the ratio between the particle number at the momentum distribution around the point $-10^{-3}\pm2*10^{-4}$, and the total particle number [5]. Figure 5 shows the dependence of the capture rate at the end of different sweeping time. The rate without modulation was also calculated respectively.

It's clear that the capture rate increases by the electron energy modulation method. But we can also see the capture rate falls rapidly for sweeping time shorter than 2 seconds. That means the mean electron velocity shift is too fast to capture the ions with large momentum spread. Therefore, in this case the electron energy sweeping time was limited to be about 2 seconds.

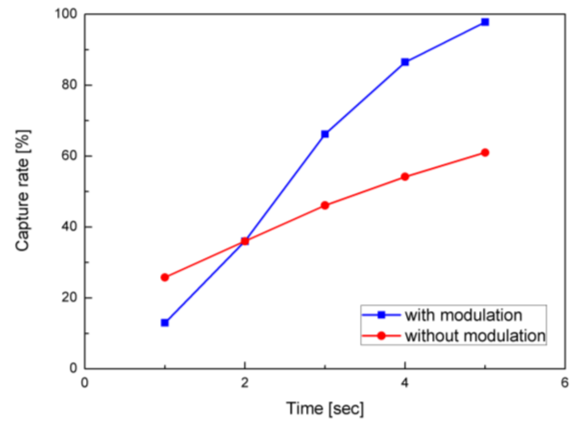

Figure 5: Dependence of capture rate on the electron energy sweeping time.

CONCLUSION

The cooling process with electron energy modulation was investigated by simulation. The possibility for an electron cooling scheme of ions with large momentum spread has been studied. With an electron energy modulation method, the hot ions can be captured efficiently and cooled toward the equilibrium point. A shorter cooling time has achieved compared with conventional electron cooling. The sweeping time is an important parameter in the electron energy modulation scheme. The hot ions were no longer captured with a very short sweeping time.

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