ELECTRON COOLING EXPERIMENTS AT HIRFL-CSR

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Abstract

Two new-generation electron coolers have been operated at the main ring (CSRm) and the experimental ring (CSRe) of HIRFL-CSR facility to provide high quality heavy ion beams for the nuclear and atomic physics research. The electron beam with a variable profile helps to get an ion beam with the emittance and intensity that meet the demands of specific physical experiments. The cooler in the CSRm is operated at the injection energy to increase the intensity of highly charged ions. By a combination of multi-turn injection (or strip injection for light ions) and fast electron cooling, the ions can be accumulated up to the intensity limited by space charge limitation. The cooler in the CSRe is mainly used to compensate the intrabeam scattering and other heating effect to provide high quality heavy ion beams. After optimization of the accumulation and cooling process a current increase by more than two orders of magnitude has been achieved. Momentum spread in the 10^{-6} range has been demonstrated in the CSRe for few thousands particles. In this paper, the experiments on the electron cooling effect investigation are reported.

INTRODUCTION

The Heavy Ion Research Facility of Lanzhou & Cooling Storage Ring (HIRFL-CSR) is an accelerator complex aimed to provide all species of ions from proton to uranium at the magnetic rigidity up to 10.4 Tm for the nuclear physics, atomic physics and cancer therapy [1]. It consists of ECR ion sources, two cyclotrons SFC and SSC, two synchrotrons, CSRm and CSRe. The ions delivered from SFC or SSC can be injected into CSRm with multi turn injection and strip injection scheme. After accumulation with the help of powerful DC magnetized electron cooling at the injection energy in CSRm, the intense beams will be accelerated to the required energy and then fast extracted and transferred either to the CSRe or the external experimental terminals. A slow extraction system was also equipped in the CSRm for a wide range of applied research in material science and cancer therapy. The electron energy of the CSRm cooler is 35 keV in order to cover the energy of ions provide by the larger cyclotron SSC. In the CSRe, the electron cooling system is mainly used to compensate the heating effect such as intrabeam scattering and residual gas scattering. The maximum electron energy is 300 keV.

Electron cooling is a well-established method to improve the phase space quality of ion beams in storage rings. The cooling process is based on the energy transfer due to coulomb interaction of the ions in a superimposed cold electron beam with the same average velocity [2]. After sufficient cooling time, the transverse emittance and momentum spread of beams will be reduced.

In the HIAFL-CSR, several detectors are used to measure the electron cooling process and the properties of the cooled ion beams, such as DCCT, Schottky detector, stripper and so on. The measurement results related to the electron cooling are reported in the article.

LONGITUDINAL COOLING FORCE

The electron energy-step method is one of the straightforward techniques for measuring the longitudinal cooling force [3]. After the ion beam was cooled to equilibrium, the electron energy was changed rapidly by changing the cathode potential, creating a well defined velocity difference between ions and electrons. The ions will be accelerated or decelerated toward the new electron velocity. The acceleration is determined via Schottky spectra from the change in revolution frequency per unit time. The longitudinal cooling force at each time can be calculated in accordance with the relation

$$F_{\parallel}(t) = \gamma A \frac{1}{n}\frac{1}{\eta}\frac{C_{ring}^2}{L_{cooler}}\frac{E_0}{c^2}\left.\frac{df}{dt}\right|_{f(t)} \tag{1}$$

where A is the mass number of measured ion, n is harmonic number, η is the off-momentum factor, C_{ring} is the ring circumference and L_{cooler} is the cooling section effective length, E_0 is the atom mass unit equal to 938 MeV, c is the speed of light, $\frac{df}{dt}$ is variation of the n harmonic centre frequency. Correspondingly, the relative velocity between ion and electron is

$$v_{ion-electron}(t) = \frac{\beta c}{\gamma^2}\frac{1}{\eta}\frac{f(t) - f_{final}}{f_{final}} \tag{2}$$

Where β and γ are Lorenz factor, $f(t)$ and f_{final} are the n harmonic centre frequency at t time and final equilibrium, respectively.

The behavior of a cooled 400 MeV/u C^{6+} ion beam after applying a step of 300 eV was illustrated in figure 1. The data was recorded by the Schottky detector at CSRe. The shift of revolution frequency can be calculated by this data. Up to now, the cooling force for the C^{6+} ions at the energy of 7 MeV/u, 200 MeV/u and 400 MeV/u, the Ar^{18+} ions at the energy of 21.6 MeV/u, the Xe^{54+} ions at the energy of 200 MeV/u were measured systemically.

The longitudinal cooling forces were measured with the energy step method for a series of different electron densities. The maximum cooling force as function of the

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electron density is shown in figure 2. The result shows that the force increases with increased density at the electron beam center.

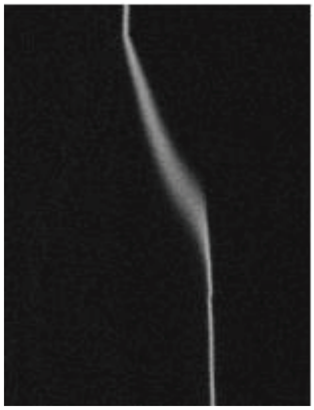

Figure 1: The spectra a cooled 400MeV/u $^{12}C^{6+}$ beam at CSRe shift after increasing electron energy 300eV rapidly

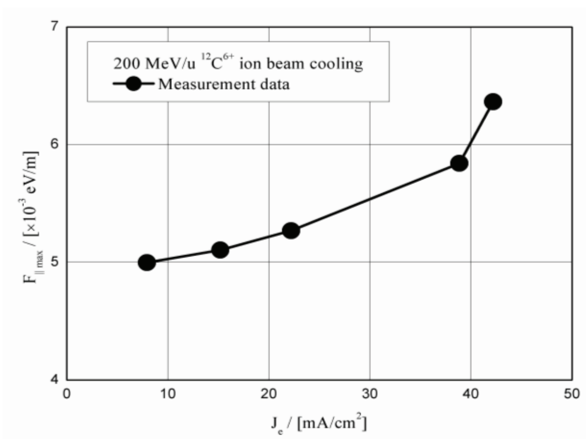

Figure 2: the longitudinal cooling force depends on the density at electron beam centre measured by 200.0 MeV/u $^{12}C^{6+}$.

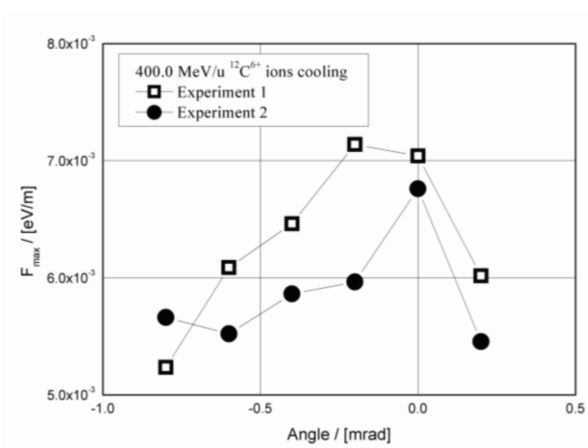

Figure 3: Longitudinal cooling force at different horizontal alignment angles between the ion and electron beams.

The alignment angles between the ion and the electron beam in horizontal direction was measured also. In the electron cooling process, the energy spread of the ion beam is given to electron s having the same speed as the ions and moving parallel to them. If the ion and electron beams are not perfectly aligned, cooling still occurs, but is less efficient. For this reason, we should optimize this angle in operation. The longitudinal cooling force as function of the alignment angle was shown in figure 3. It's obvious that perfectly alignment is good for obtaining maximum longitudinal cooling force; therefore the maximum cooling efficiency would be obtained.

LONGITUDINAL COOLING FORCE

The spectra of measured and fitting data at different intensity of $^{12}C^{6+}$ ion beam at the energy of 7 MeV/u and $^{36}Ar^{18+}$ ion beam at the energy of 21 MeV/u are show in figure 4. The double-peak phenomenon was obvious at intense cooled beam but disappeared while ion current small enough, due to a distortion of the shape caused by collective particle motions can be neglected and the shape can be approximated by a Gaussian with moderate phase space density [4].

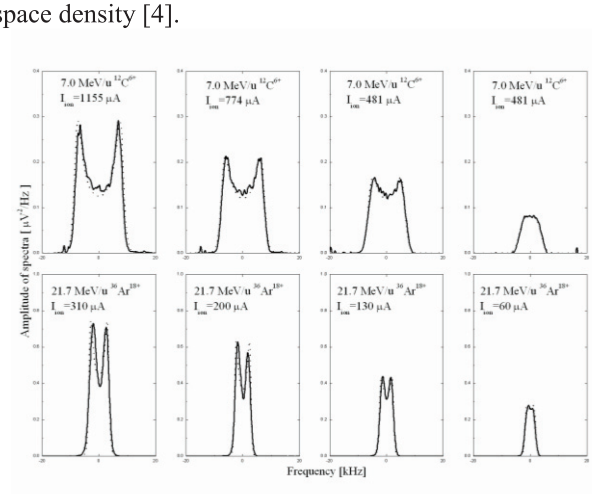

Figure 4: Schottky spectra of measured and calculated for various ion beam currents. Solid line shows the measurement data and dash line is simulation result.

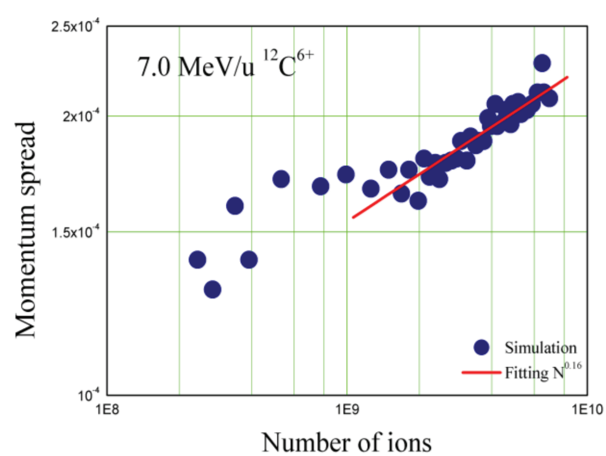

Figure 5: the function of momentum spread depends on the stored C^{6+} ion number at the energy of 7 MeV/u.

The equilibrium momentum spread values as function of stored ion number were obtained and plotted in figure 5 and 6. For carbon beam, the momentum spread is

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proportional and reaches 2.09×10^{-4} for particle number 7×10^{9}. For argon beam, the momentum spread is proportional and reaches 5.35×10^{-5} for particle number 3×10^{8}.

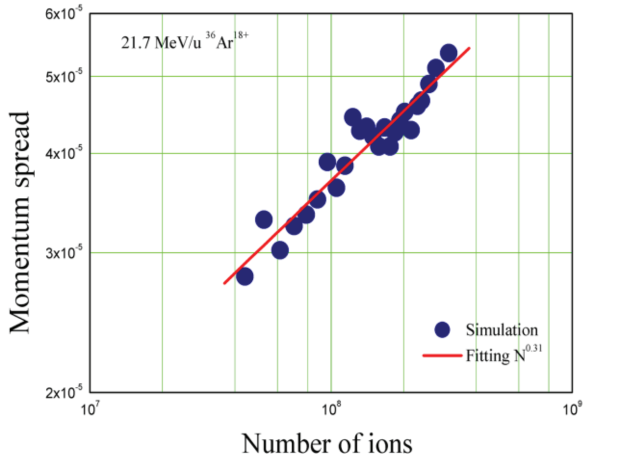

Figure 6: the function of momentum spread depends on the stored Ar^{18+} ion number at the energy of 21.7 MeV/u.

In electron cooling, the momentum spread of cold ion beam is determined by equilibrium between electron cooling process and energy flux caused by intrabeam scattering. The reduction of the phase space volume by electron cooling is inevitably linked to a growth of the heating rate by intrabeam scattering which grows inversely proportionally to the phase space volume of the ion beam. In general case, the cooling rate depends on phase space volume weakly. Due to this reason, the equilibrium momentum spread increases with stored ion number increased. The blue dashed lines in fig 3 show the simulation result correspondingly.

DIFFUSION RATE

In cooling storage rings, the ion beam can be cooled down to the equilibrium state between the cooling effect and other heating effects. Initially an ion beam with very small emittance and momentum spread was created by cooling the beam down to an equilibrium state. And then the electron beam was switched off. The momentum spread blow up because of the heating effect [5]. After few seconds later, the electron beam was turned on again. Figure 7 presents the measured evolution of the momentum spread during such process.

In equilibrium, the distribution function is Gaussian in momentum with an rms spread being expressed as:

$$\sigma_0 = \sqrt{\frac{D}{2\lambda}} \tag{3}$$

Here D is the diffusion rate and λ is the small-deviation cooling rate. Generally the diffusion rate is caused by small angle intrabeam scattering. The total diffusion rate including other unknown heating effects can be measured by turning the electron beam off and letting the beam heat up. Assuming that the diffusion rate D is constant, one can describe the rms momentum spread evolution with no cooling effect as:

$$\sigma(t) = \sqrt{\sigma_0^2 + Dt} \tag{4}$$

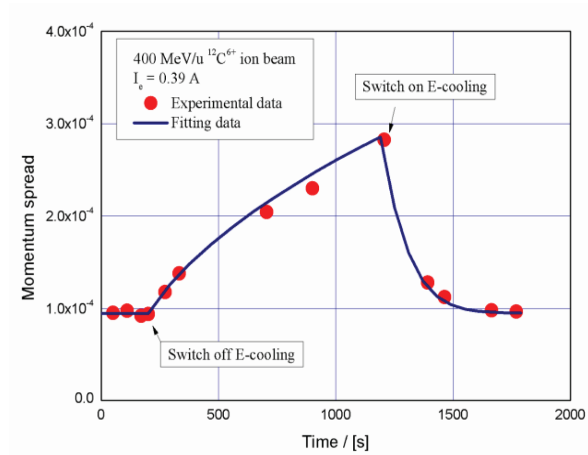

Figure 7: the measurement (points) and the fitted (line) momentum spread as a function of time.

From the measurement and fitted data in figure 7, the best fit corresponds to the diffusion rate is 82 s^{-1}.

CONCLUSION

Two electron cooler have being operated in the HIAFL-CSR facility successfully since 2006. The cooling effect measurements have been done with different species of ions. The parameters of cooler can be optimized by the results of longitudinal cooling force measurement. The equilibrium between the cooling effect and heating effect was measured with different stored particle number. The diffusion rate was also investigated by the evolution of the momentum spread while turn on and off the electron beam.

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