COOLING FORCE MEASUREMENTS WITH VARIABLE PROFILE ELECTRON BEAM AT HIRFL-CSR *

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Abstract

Two electron coolers have been operated at HIRFL-CSR for fast phase space cooling of heavy ion beams. The variable profile electron beam can be produced by these coolers. This should be one of the solutions for electron heating problems. In order to demonstrate the particularity of variable profile electron beam cooling, the longitudinal cooling force has been measured by electron energy-step method. In this paper, the measurement results were presented. It's clear that the cooling force is function of the electron beam density at ion orbit for variable profile electron beam. Moreover, parameter dependence on the alignment angles between the ion and electron beam was investigated.

INTRODUCTION

HIRFL-CSR is a new heavy ion cooling-storage-ring in IMP [1]. It consists of a main ring (CSRm) and an experimental ring (CSRe). The two existing cyclotrons SFC and SSC are used as injectors. The heavy ions were accumulated in CSRm with the help of electron cooling at injection energy, then, accelerated and extracted to CSRe for nuclear and atomic physical experiments. Two electron coolers were installed at CSRm and CSRe respectively.

Electron cooling is a well-established method to improve the phase space quality of ion beams in storage rings [2]. However, the ultra cooled ion beam leads to the formation of a core with extremely high density and gets lost easy. This sort of phenomena has been found at CELSIUS and COSY called electron heating. Using variable profile electron beam is one of the possible solutions for this problem. The variable profile electron beam is adopted in the electron coolers installed at HIRFL-CSR for first time.

The most important characteristics of the electron cooler are the attainable values of the cooling force as well as the dependencies of the cooling force on electron parameters. The electron coolers at HIRFL-CSR offer the opportunity to study cooling force with variable profile electron beam. The longitudinal cooling force was measured by the electron energy-step method with the aid of Schottky spectra system.

ELECTRON COOLERS AT HIRFL-CSR

The 35keV electron cooler was installed at CSRm for beam accumulation and the 300keV electron cooler was installed at CSRe for improving the luminosity even with strong heating effects of internal targets. The main parameters are listed in table 1.

The electron beam is generated in a gun which is immersed in a longitudinal magnetic field. With the help of a 2kV power supply connected between the cathode and grid electrode one can produce the negative electric field at the cathode edge thereby suppressing the emission of electrons at this place. By varying the potential of gird it is possible to obtain the electron beam with parabolic, flat or hollow profile, which is shown in fig 1.

Table 1: Parameters of the E-cooler at HIRFL-CSR

Parameters	CSRm	CSRe
Maximum electron energy [keV]	35	300
Maximum electron current [A]	3.0	3.0
Cathode diameter [mm]	29.0	25.0
Maximum magnetic field in gun section [T]	0.24	0.5
Maximum magnetic field in cooling section [T]	0.15	0.15
Magnetic expansion factor	1 - 4	1-10
Effective cooling section length [m]	3.4	3.4
Parallelism of cooling solenoid field	10^{-5}	10^{-5}
Maximum potential between the cathode and grid electrode [kV]	2.0	2.0
Maximum potential between the cathode and anode electrode [kV]	5.0	5.0

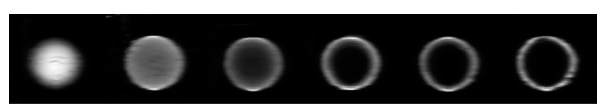

Figure 1: Electron beam profiles at grid potential U_{grid}=0V, 100V, 200V, 350V, 400V and 600V, the anode potential U_{anode}=500V.

LONGITUDINAL COOLING FORCE MEASUREMENT TECHNIQUE

The electron energy-step [3] method is one of the straightforward techniques for measuring the longitudinal cooling force. 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

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

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

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

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 Tektronix RSA3303A real-time spectrum analyzer was used in the measurement. This method was applicable to relative velocities from 10^3 to 10^6 m/sec. The behaviour of a cooled 400MeV/u $^{12}C^{6+}$ beam at CSRe after applying a step of 300eV was illustrated in fig 2.

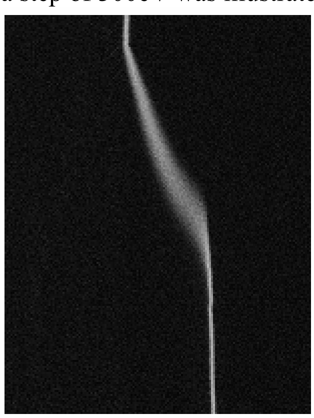

Figure 2: The spectra a cooled 400MeV/u $^{12}C^{6+}$ beam at CSRe shift after increasing electron energy 300eV rapidly.

The central frequency is calculated by formula,

$$f = \frac{\sum_{n=0}^{50}\sum_{is} f_{is} * Amp_{is,n}}{\sum_{n=0}^{50}\sum_{is} Amp_{is,n}} \quad (3)$$

It means the "barycentre" of spectra. Amp is the amplitude of Schottky signal.

The differentiation of frequency is calculated using Taylor expansion,

$$\left.\frac{df}{dt}\right|_{t0} = \frac{\sum_{k=-n}^{n} f(t_0 + k\cdot\Delta T)\cdot k}{\Delta T \sum_{k=-n}^{n} k^2} \quad (4)$$

EXPERIMENTAL CONDITIONS

The experimental conditions were summarized as table 2. These parameters were determined by HIRFL-CSR optimization. The longitudinal cooling force has been measured for $^{12}C^{6+}$ and $^{36}Ar^{18+}$ ions at various energies from 7.0 to 400.0MeV/u. At CSRm, the longitudinal magnetic field in cooling section is 0.039T, which is a quarter of design value, because of the coupling effect and compensation. The energy step is determined by the momentum acceptance of storage ring.

Two capacitive pickups are used as Schottky noise probes at CSRm and CSRe respectively. The electrodes have a length of 150mm in beam direction and distances of 170mm and 100mm in horizontal and vertical direction.

Table 2: Experimental Conditions

Ions	$^{12}C^{6+}$			$^{36}Ar^{18+}$
Storage ring	CSRm	CSRe	CSRe	CSRm
Circumference [m]	161.0	128.8	128.8	161.0
Cooler effective length [m]	3.4	3.4	3.4	3.4
Ion energy [MeV/u]	7.0	200.0	400.0	21.7
Electron energy [keV]	3.84	109.71	219.43	11.90
γ_t	5.168	2.629	2.629	5.168
B_cooling section [T]	0.039	0.078	0.078	0.039
B_gun [T]	0.12	0.14	0.21	0.12
Electron beam radius [mm]	25.4	16.8	20.5	25.4
Energy step [eV]	30	100	300	50

RESULTS

Figure 3 shows the longitudinal cooling force measured for $^{12}C^{6+}$ and $^{36}Ar^{18+}$ ions at standard operational parameters in table 2. The solid lines in the figure were calculated using the Parkhomchuk's semi-empirical formula [4]

$$\vec{F}(\vec{v}) = \frac{4\pi Z^2 n_e r_e^2 m_e c^2 (\vec{v} - \vec{v}_e)}{\left(|\vec{v} - \vec{v}_e|^2 + v_{eff}^2\right)^{\frac{3}{2}}} L_c \quad (5)$$

where Z is ion charge state, $\vec{v}$ and $\vec{v}_e$ are ion and electron velocity respectively, n_e is electron beam density, r_e is classical electron radius, L_c is Coulomb logarithm. Fitting the cooling force by Eq (5) can estimate the effective electron beam temperature. Best agreement with the experimental results corresponds to the effective electron beam temperature 0.003eV, the transverse electron beam temperature 0.05eV and the longitudinal one 10-5eV. According to the definition of effective velocity,

$$V_{eff} = \sqrt{<(c\beta\gamma\Delta\theta_B)^2>} \quad (5)$$

where $\Delta\theta_B$ is the magnetic field homogeneity in the cooling section. Due to Eq (6) we estimated the homogeneity is about 8.0×10^{-5} , which was good agreement with measurement data [5].

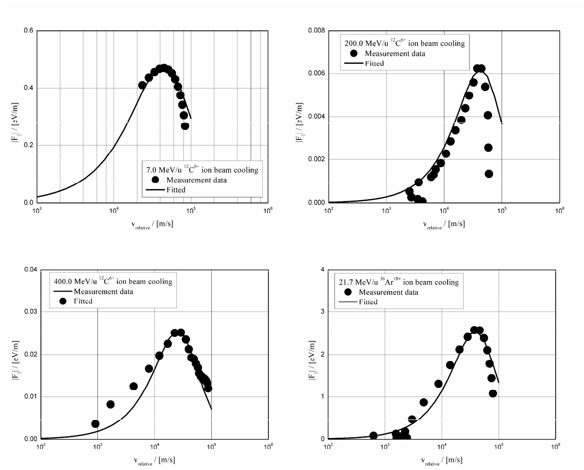

Figure 3: The longitudinal cooling force measured at CSR.

The electron beam profile is determined by the ratio between grid and anode potential. Further experiments studied the influence of the electron beam intensity and profile on the longitudinal cooling force. Table 3 and 4 show the electron beam conditions in experiments. Figure 4 and 5 show the results respectively. These show the force increases with increased density at electron beam centre.

Table 3: Electron Beam Parameters for 21.7 MeV/u $^{36}Ar^{18+}$ Cooling at CSRm

U_{grid} [kV]	0.2124	0.2490	0.2808	0.1909	0.0317
U_{anode} [kV]	1.4258	1.6690	1.8896	1.1426	1.1426
U_{grid}/U_{anode}	0.1489	0.1492	0.1486	0.167	0.0277
I_e [mA]	136	172	204	82	55
J_e at centre [mA/cm^2]	26.6	33.7	40.6	18.3	17.2

Table 4: Electron Beam Parameters for 200.0 MeV/u $^{12}C^{6+}$ Cooling at CSRe

U_{grid} [kV]	0.4834	0.5127	0.7227	0.8008	1.1157
U_{anode} [kV]	4.7998	5.1123	2.4023	1.6016	1.1133
U_{grid}/U_{anode}	0.1	0.1	0.3	0.5	1.0
I_e [mA]	382	416	422	431	427
J_e at centre [mA/cm^2]	38.8	42.2	22.2	15.2	7.9

Because the electron beam profile is variable, both the electron beam current and profile should be considered during optimization. After consider the ion-electron capture and space charge effect, the ratio between the grid and anode potential is set 0.2 to 0.5 and the current is 100 to 300mA usually at CSRm.

The cooling force is normalized by the factor $\beta^4\gamma^5$ shown in figure 6. Because of the low energy of argon ions, the cooling force decreased when the density is higher.

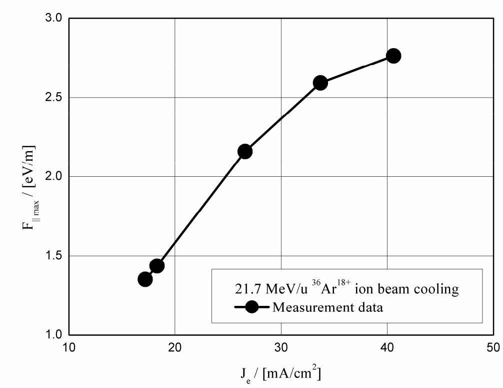

Figure 4: The longitudinal cooling force depends on the density at electron beam centre measured by 21.7 MeV/u $^{36}Ar^{18+}$.

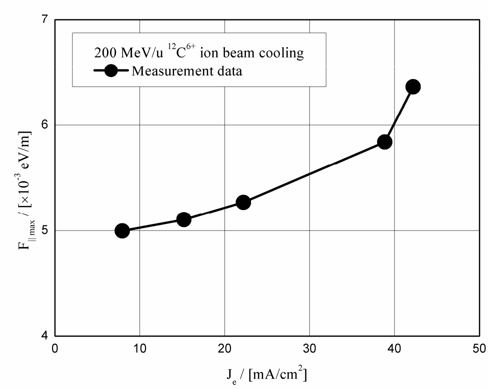

Figure 5: The longitudinal cooling force depends on the density at electron beam centre measured by 200.0 MeV/u $^{12}C^{6+}$.

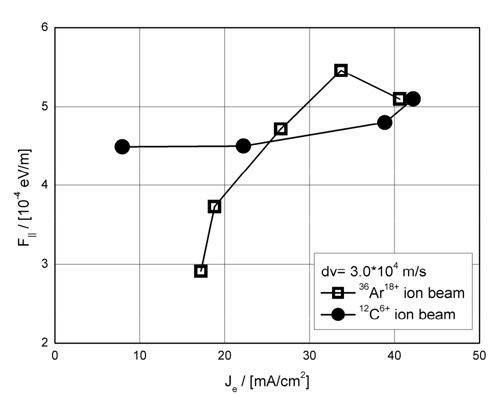

Figure 6: The longitudinal cooling force normalized by $\beta^4\gamma^5$.

The dependence of the longitudinal cooling force on the alignment angles between the ion and the electron beam in horizontal direction was measured also. In electron cooling, the energy spread of the ion beam is given to electron s having the same speed as the ions and moving parallel to them [6]. 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 7. It's obvious that perfectly alignment is good for obtaining maximum longitudinal cooling force; therefore the maximum cooling efficiency would be obtained.

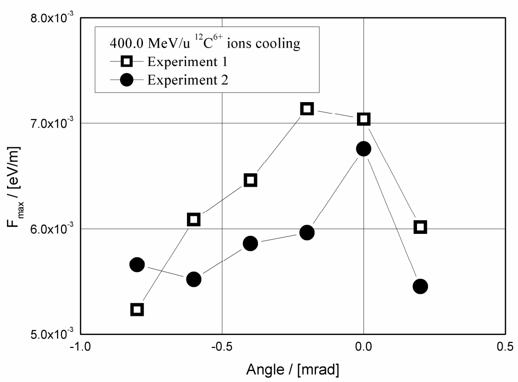

Figure 7: Longitudinal cooling force at different horizontal alignment angles between the ion and electron beams

CONCLUSION

Longitudinal cooling forces were obtained for $^{12}C^{6+}$ and $^{36}Ar^{18+}$ by electron energy-step method. The experimental results were best agreement with semi-empirical formula. The longitudinal cooling force increases with increasing electron beam current or decreasing the alignment angle between ion and electron beams. According the experiment results, the best cooling and accumulation efficiency were obtained in HIRFL-CSRm. For $^{12}C^{6+}$ beam, the stored beam current reached 3.5mA and for $^{36}Ar^{18+}$ beam reached 0.75mA.

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