COMMISSIONING OF ELECTRON COOLING IN CSRe*

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Abstract

The 400MeV/u $^{12}C^{6+}$ ion beam was successfully cooled by the intensive electron beam near 1 Ampere in CSRe. The momentum cooling time was estimated near 15 seconds. The cooling force was measured in the cases of different electron beam profiles, and the different angles between ion beam and electron beam. The lifetime of ion beam in CSRe was over 80 hours. The dispersion in the cooling section was confirmed as positive close to zero. The beam sizes before cooling and after cooling were measured by the moving screen. The beam diameter after cooling was about 1 millimeter. The bunch length was measured with the help of BPM signals. The diffusion was studied in the absent of electron beam.

INSTRUCTION

HIRFL-CSR[1] is a new ion cooler-storage-ring system in IMP China. It consists of a main ring (CSRm) and an experimental ring (CSRe). The two existing cyclotrons SFC (K=69) and SSC (K=450) of the Heavy Ion Research Facility in Lanzhou (HIRFL) are used as its injector system. The heavy ion beams from HIRFL is injected into CSRm, then accumulated, e-cooled and accelerated, finally extracted to CSRe for internal-target experiments and other physics experiments.

Table 1: Lattice Parameters of CSRe

Lattice Parameter	Value
Transition gamma	$\gamma_{tr} = 2.629$
Betatron Tune	Q_x / Q_y=2.53/2.57
Max. Betatron amplitude	$\beta_x / \beta_y = 17.6/8.2$m(Dipole) $\beta_x / \beta_y = 30.9/22.3$m(Quadruple)
Max. Dispersion	D_x=6.5m(Dipole β_x=13m) D_x=7.8m(Quadruple β_x=16m)
Injection section	β_x=30.4m, D_x=0m(Septum) β_x=30.9m, D_x=0m(Quadruple)
Electron cooling section	$\beta_x / \beta_y = 12.5/16.0$m, D_x=0
Internal target	$\beta_x / \beta_y = 5.4/1.5$m, D_x=0
RF station	$\beta_x / \beta_y = 4.0/8.4$m, D_x=4.5m

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CSRe is a 128.8m circumference cooler storage ring with sixteen 22.5 degree C-type bending dipole magnets. The maximum Betatron functions are 30.9m and 22.3m in horizontal and vertical respectively. The maximum dispersion is 7.8m, and the dispersion at injection point is zero, the Betatron function is 30.4m in the Septum. The Betatron functions at electron cooler are 12.5m and 16m in the two transverse directions respectively, the dispersion is near zero here. The tunes are about 2.53 and 2.57, the transition gamma is 2.629, and the transverse acceptance of CSRe is about 150πmmmrad, and the longitudinal one is $\pm 5\times10^{-3}$.

Accelerated ion beam from the CSRm through the radioactive beam separator line with the length of 100m was injected into the CSRe. Generally the CSRe operated with the DC mode. A gas jet internal target was installed in the opposite side of electron cooler.

Table 2: Parameters of the CSRe Electron Cooler

Maximum electron energy	300 keV
Maximum electron current	3A
Gun perveance	29 μP
Cathode diameter	29mm
Current collection efficiency	≥99.99%
Maximum magnetic field in gun section	0.5T
Maximum magnetic field in cooling section	0.15T
Field parallelism in cooling section	4×10^{-5}
Effective length of cooling section	3.4m
Vacuum pressure	$\leq 3\times10^{-11}$mbar

The electron cooling device plays an important role in HIRFL-CSR experimental ring for the heavy ion beam. Continuous electron cooling is applied to the stored ion beam for the compensation of the heating by various scattering. The most important is the ability to cool ion beams to highest quality for physics experiments with stored highly charged ions. The new state-of-the-art electron cooling device was designed and manufactured in the collaboration between BINP and IMP, it has three distinctive characteristics, namely high magnetic field parallelism in cooling section, variable electron beam profile and electrostatic bending in toroids. The main parameters are listed in table 2. It was reported in many conferences[2],[3],[4],[5],[7]The previous commissioning results have been given in the COOL05-P02[6] and COOL07-TUM1I02[8]

BEAM COOLING EXPERIMENTS

Beam Position Monitor

The basic principle of electron cooling requires the ion beam is parallel with the electron beam. In this case, two sets of capacitive cylinder beam position monitors were installed in the ends of electron cooling section. The electron beam was modulated by an external 3MHz signal. The signals picked up by four probes were magnified by four independent preamplifiers. The NI-5105 (8 channel High-Density Digitizer) was employed as main data acquisition and the data was processed by the special code of LabView.

The ion beam becomes bunched one after RF capture, the ion beam position was measured at this moment.

From these results, the angles and displacements between ion and electron beams in horizontal and vertical planes were derived. According to the information, the closed-orbit of ion beam in the ring was corrected, ion beam positions at the ends of cooling section were close to parallel with the electron beam, the electron beam was slightly adjusted with the help of correction coils of cooler in the cooling section, finally the ion beam and electron beam were matched well, the cooling was observed. A small displacement between two beams was not critical due to the bigger size of the electron beam.

Beam Cooling Results

Due to the electron cooler located near the injection point and just before the injection septum kicker. The injection efficiency and the closed-orbit correction should be compromised. In this case, four additional correction coils in the dipoles before and after electron cooler operated as ramping mode. In the injection interval, these coils were ramped to the proper value, and then return to the normal value to keep the correct orbit in the cooling section. During the commission, the electron beam was set as plat profile.

At the beginning, 200MeV/u $^{12}C^{6+}$ was injected into CSRe, the magnetic field of electron cooler was set as quarter of maximum value. In this case, the magnetic field in cooling section is 0.0385T, the electron beam current was set as 300mA. After orbit correction and regulation of electron beam angle, the cooling was observed, but the cooling process is not fast enough. It could be caused by poor quality of the high energy electron beam confined by a weak magnetic field in toroid, additional transverse temperature was introduced. For lack of proper transverse beam profile monitor, the moving screen was employed as scrapper to measure the profile of cooled ion beam. After the screen was moved near the centre of ion beam, the DCCT signal of ion beam became not recognized from the noise, but the Schottky signal was clear to observe the ion beam. The momentum spread in the range of 10^{-6} was observed in the case of low ion intensity.

At given value of the stored particle number, the momentum spread is determined by the equilibrium between the electron cooling and various heating effects, main of which is an intrabeam scattering. At large intensity the momentum spread $\Delta P/P$ is scale with the stored particle number N in accordance with a power law $\Delta P/P \propto N^{\kappa}$, where the power coefficient κ depends on the settings of a storage ring and cooling system[9], the value is determined by the misalignment angle between the ion beam and electron beam during the cooling. The minimum momentum spread at low intensity is determined by the stabilities of the magnetic field of the ring dipole and the electron beam energy, it is also limited by the detection technique.

Schottky signal in the electron cooling process is illustrated in Fig. 1, The momentum spread vary as the time in cooling is shown in Fig. 2, The Schottky signal distribution before and after electron cooling is shown in Fig. 3.

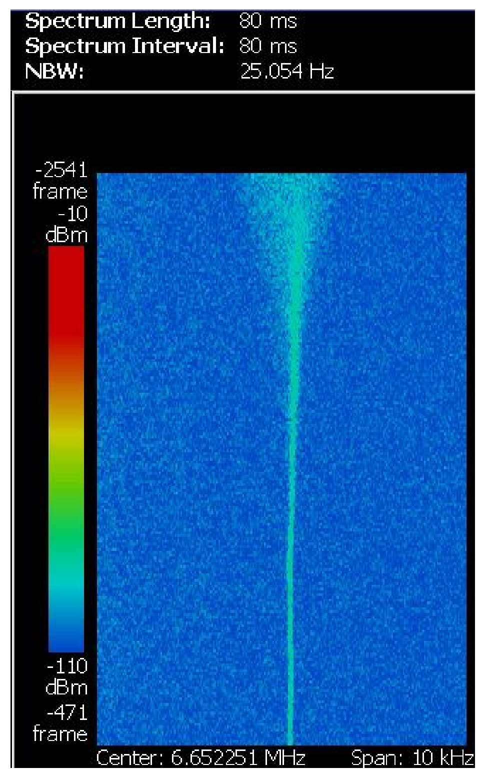

Figure 1: Schottky signal of electron cooling process.

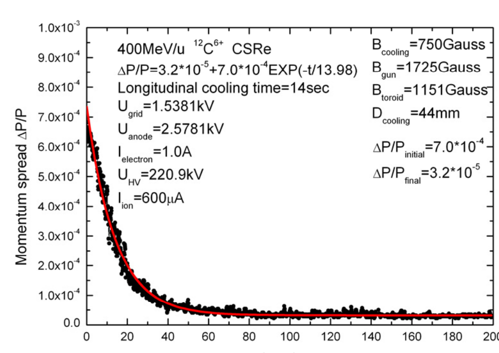

Figure 2: The momentum spread vary as the time in cooling.

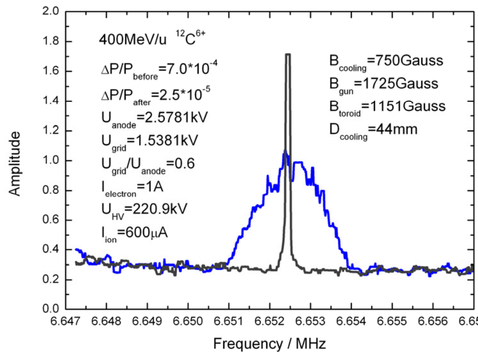

Figure 3: The momentum spread before and after electron cooling.

Longitudinal cooling force measurement

The electron energy-step[10] method is one of the straightforward techniques for measuring the longitudinal cooling force. Ion beam has been cooled firstly, the ion and electron velocities was been matched well. The electron energy was jumped rapidly by changing the cathode potential, a well defined velocity difference between ions and electrons was created. The ions will be accelerated or decelerated toward the new electron velocity. The acceleration is determined via Schottky signal from the change in revolution frequency per unit time.

The Tektronix RSA3303A real-time spectrum analyzer was used in experiments. The 4th harmonic centre frequency shift will be calculated using the spectra files recorded by analyzer. This method was applicable to relative velocities from 10^3 to 10^6 m/sec. The behavior of a cooled $^{12}C^{6+}$ beam after applying a step of 410eV was illustrated in fig 4.

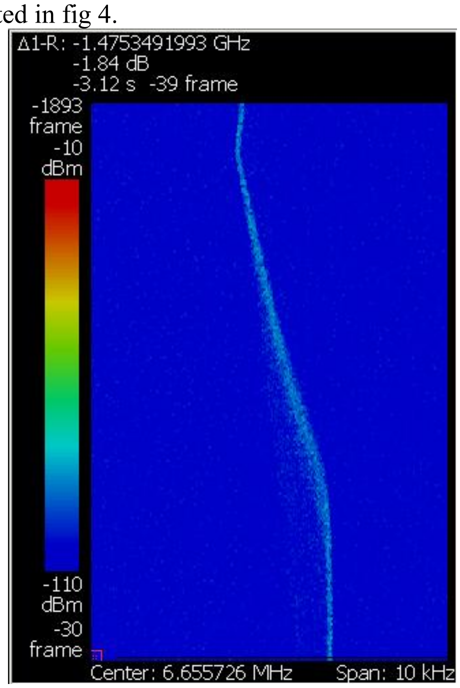

Figure 4: Schottky signal after 410eV electron energy step.

The experiments were performed using the electron energy-step method described above. The experimental conditions were summarized as table 2. These standard operational parameters were determined by HIRFL-CSRe optimization. The profile of electron beam was controlled by the ratio between potential of grid and anode.

Table 2: Parameters of Electron Cooler in Experiments

Items	200.0MeV/u	400MeV/u
B_{gun} [T]	0.1428	0.1725
B_{toroid}[T]	0.073	0.1151
$B_{cooling\ section}$ [T]	0.075	0.075
$I_{electron}$ [A]	0.3~0.5	1.0
Energy step [eV]	200	410

Further experiments studied the influence of the electron beam intensity on the longitudinal cooling force for $^{12}C^{6+}$ beam. Fig 5 shows that the force increases with increased electron beam centre density.

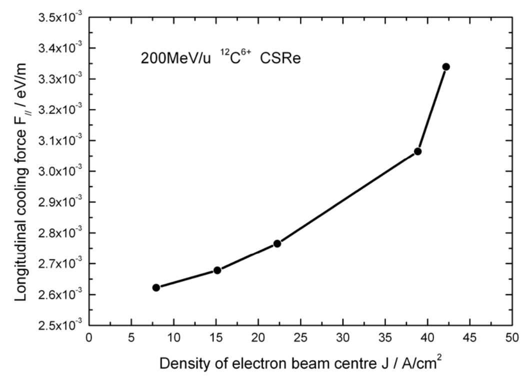

Figure 5: Longitudinal cooling force measured for $^{12}C^{6+}$ ion as a function of different centre density of different electron beam profiles

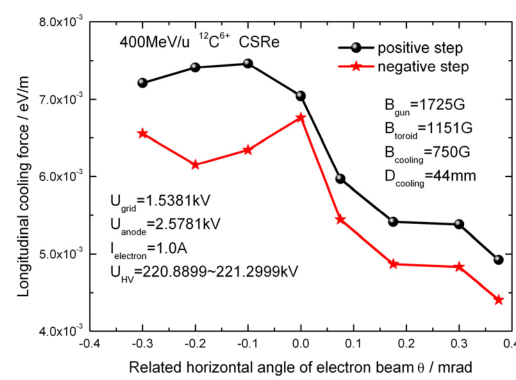

Figure 6: Longitudinal cooling force for different relative horizontal angle of electron beam

The dependence of the longitudinal cooling force on the alignment angles between the ion and the electron beam in horizontal direction was measured for $^{12}C^{6+}$ ions. The longitudinal cooling force as function of the alignment angle was shown in Fig. 6 and Fig 7. It's obvious that perfect alignment is helpful for obtaining maximum longitudinal cooling force.

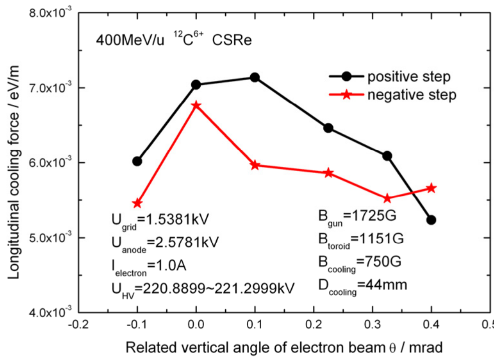

Figure 7: Longitudinal cooling force for different relative vertical angle of electron beam.

Longitudinal cooling forces were obtained for 200 MeV/u $^{12}C^{6+}$ and 400 MeV/u $^{12}C^{6+}$ 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 momentum cooling time of 15sec for 400MeV/u $^{12}C^{6+}$ was obtained in HIRFL-CSRe.

Beam Lifetime

After one injection to CSRe, the injection was stopped and CSRe operated in the mode of DC. The lifetime was measured with the help of DCCT signal. At the beginning, due to the influence of the kicker and other ramping elements, ion beam decayed fastly in the range of , after the field of the kicker and other element disappeared completely, the ion beam decay very slow. The lifetime of 400MeV/u $^{12}C^{6+}$ in CSRe was shown in Fig. 8. From the fitting results, the lifetime was over 80 hours.

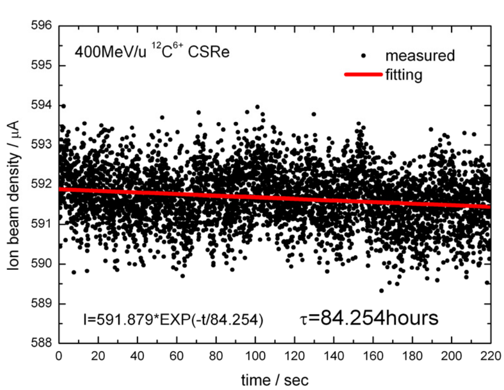

Figure 8: The ion beam lifetime after electron cooling.

Intrabeam Scattering

The electron beam was turn off after the ion beam was cooled to the equilibrium. The Intrabeam Scattering and the diffusion of residual gas were investigated. All particle suffer from the action of vacuum, this caused the energy loss, and the momentum shift. But IBS happened in certain condition, it caused the momentum spread became bigger(longitudinal blow-up). If the electron beam was switched off after cooling, these two processes happened synchronously, after some time the IBS disappear, and only vacuum action still exist. The momentum spread vary with the time was shown in Fig. 9. At the beginning, the momentum spread increase very fast, it is caused by the IBS, after this the scattering of residual gas was dominated, the slide of change became smaller than beginning. The centre frequency shift was shown in Fig. 10. Compared with the simulation results, two results were good agreement each other.

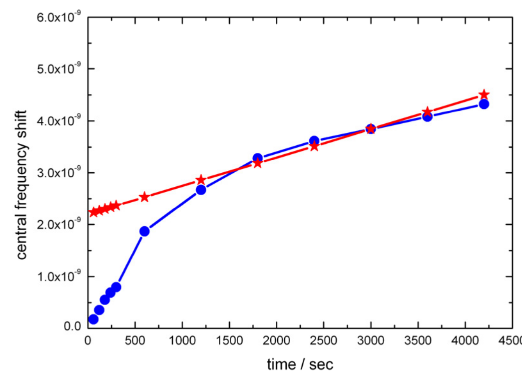

Figure 9: The central frequency shift due to IBS and vacuum.

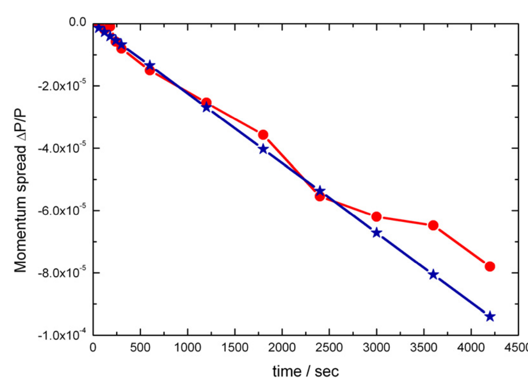

Figure 10: The momentum spread vary as time after switch off electron beam.

Stability of High Voltage

From those results after the electron beam was switched off, the stability of high voltage system of CSRe cooler was derived. The data of HV was recorded as one file, the high voltage value was derived from the ion beam revolution frequencies, Fig. 11 shows the results of stability of HV of CSRe cooler, one can find that due to the electron beam energy slightly decreased, the ion beam was moved from the initial point to the another point with the change of electron energy. From this point of view, the stability of HV system of CSRe cooler should be improved.

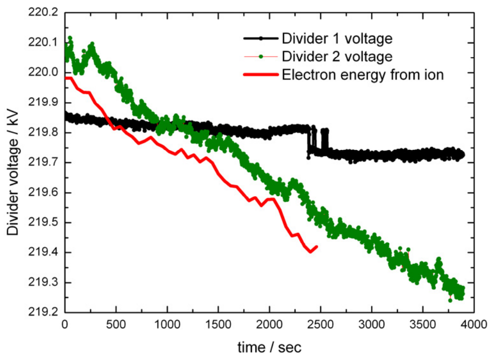

Figure 11: The stability of HV system of CSRe electron cooler.

Beam Transverse Dimension Measurement

Due to the transverse profile monitors were not available in CSRe, a screen drove by step motor was used to measure the transverse dimension of ion beam. The average moving speed is about 1mm/sec, during the screen moving, the ion density signal was recorded by the DCCT in CSRe Fig. 12, the loss rate of ion information was gotten by this way, and the transverse dimension of ion beam was derived from this signal. The transverse dimension was about 24mm before cooling, it reduce to 1mm after cooling. The measurement results were shown in the Fig. 13.

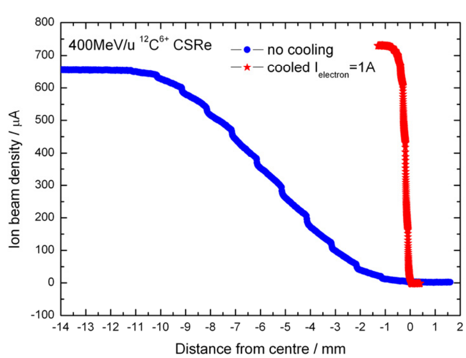

Figure 12: The DCCT signal during the moving the screen.

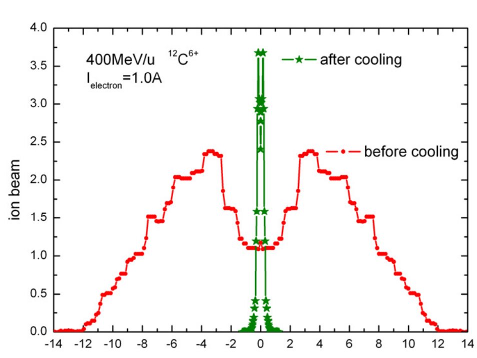

Figure 13: The transverse ion beam size.

SUMMARY AND OUTLOOK

The CSRe electron cooler has come to the routine operation for experiments with stored heavy ion beams in HIRFL-CSR. The cooling process of 400MeV/u $^{12}C^{6+}$ ion beam was studied in CSRe, the main parameters such as momentum spread, transverse ion beam size, and lifetime of stored ion beam was measured. The longitudinal cooling force was measured in the cases of different electron beam profiles, and the different angles between ion beam and electron beam. Some initial results of IBS and residual gas scattering were investigated base on the experimental results.

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