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Electron cooling experiments in CSR

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The six species heavy ion beam was accumulated with the help of electron cooling in the main ring of Cooler Storage Ring of Heavy Ion Research Facility in Lanzhou (HIRFL-CSR). The ion beam accumulation dependence on the parameters of cooler was investigated experimentally. The 400 MeV/u $^{12}C^{6+}$ and 200 MeV/u $^{129}Xe^{54+}$ were stored and cooled in the experimental ring CSRe, and the cooling force was measured in different conditions.

heavy ion beam, beam accumulation, electron cooling, cooling force

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1 Introduction

Heavy Ion Research Facility of Lanzhou (HIRFL) [1] is an accelerators complex with multi-purposes, whose research field includes radioactive ion beam physics, heavy ion physics, high energy density physics, super-heavy elements synthesis, atomic physics, and cancer therapy. It consists of two cyclotrons, SFC and SSC, and two synchrotrons, CSRm and CSRe. It can provide the ion beam with an energy range from 10 MeV/u to 1 GeV/u. The ion beam delivered from SFC or SSC was injected into CSRm, after accumulation with the help of electron cooling, and acceleration, and then delivered to the cancer therapy terminal and other experimental terminals, or injected into CSRe. In CSRe, the ion beam was cooled by an electron cooling device, and various physics experiments were completed in this ring. The ion beam with higher energy in CSRe was stripped, and higher charge state ion beam will be decelerated to lower energy, in the case of low energy of higher charge state ion beam. Atomic physics experiments will be performed in CSRe.

2 Electron cooling devices

The electron cooling device was equipped in each ring of CSR. The purpose of electron cooling in CSRm is ion beam accumulation. The cooler is adapted as the way to increase the stored particle number in CSRm, and continuous electron cooling is applied to the stored ion beam for compensation of the heating by an internal gas jet target in CSRe. The most important feature is the ability to cool ion beam to highest quality for experiments with stored highly charged ions.

In CSRm, the electron cooling device plays an important role in the heavy ion beam accumulation at the injection energy. The new state-of-the-art electron cooling device was designed and manufactured by 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 electron cooling devices of HIRFL-CSR were

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reported in many conferences [2–7]. The previous results have been given in the COOL05-P02 [8], COOL07-TUM-1I02 [9] and COOL09-FRM1MCIO02 [10].

3 Ion beam accumulation in CSRm

In order to demonstrate the performance of HIRFL accelerators complex, and satisfy the requirements of different physics experiments, ion beams with different energy, different charge state were accumulated with the help of electron cooling in CSRm. During accumulation, two injection modes were applied, and in the case of lighter ion beam, stripping injection was adapted. For heavier ion beam, repeated multi-turn injection was performed. Due to the injection beam intensity, ion beam was delivered by different injectors, SFC or SSC. In the case of fixed energy, if a proper injection interval and partially hollow electron beam are chosen and the direction and position of the electron beam and ion beam match, the maximum accumulation results can be achieved.

Some accumulation results are summarized in Table 1. I_{inj} indicates the beam intensity in the beam line, which was limited by the capability of the injector. ΔT_{inj} is the injection interval that depends on the transverse cooling time, the electron cooling parameters for different ion beams with different energy. I_{single} is the average ion intensity in one standard multi-turn injection, which depends on the ion beam pulse length of injector. $I_{10\,s}$ is the final ion beam intensity accumulated in 10 s, the cycle for ion beam accumulation. A typical DCCT signal of injection results of $^{12}C^{6+}$ is displayed in Figure 1.

3.1 Stripping injection

Firstly, the 7 MeV/u $^{12}C^{4+}$ was injected into CSRm from the small cyclotron SFC through a stripping foil with a thickness of 15 μg/cm^2 placed in the first dipole of the ring. The average pulse intensity was about 8.4 μA in the injection line. In the absence of magnetic field of the electron cooler, the single-turn stripping injection beam was tested in CSRm with a bumping orbit, the stored beam signal was observed from BPM signal, the closed orbit correction was done roughly, and the machine parameter such as work-point was measured and tuned, and acceleration attempted. The average particle number of stored $^{12}C^{6+}$ was about 4.7×10^8 in one standard multi-turn injection. With the help of electron cooling of partially hollow electron beam, 2.5×10^9 particles were accumulated in the ring after 10 times injection in 10 s.

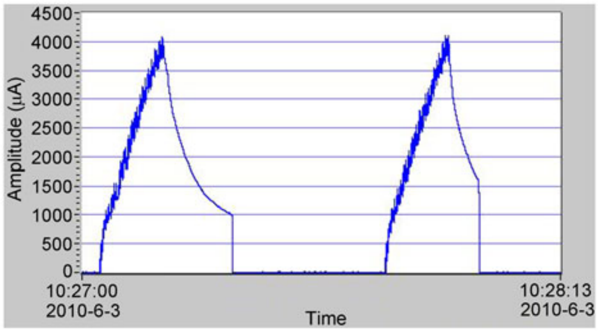

Figure 1 DCCT signal during $^{12}C^{6+}$ accumulation in CSRm.

Due to intensive commissioning of Carbon ion beam in CSRm, some accumulation results were listed in Table 2. The repeated multi-turn injection of $^{12}C^{6+}$ was attempted. $^{12}C^{4+}$ directly extracted from ECS ion source, and stripped into $^{12}C^{6+}$ in the beam line. The accumulation rate was about 3.5. In the later commissioning, the stripping injection was applied. The accumulation rate increased to 5.8 in the second row in Table 2. After the fine tune of the electron cooling parameters, especially the position and angle between the ion and electron beams, and the injection interval shortened, 2100 μA $^{12}C^{6+}$ was obtained in 10 s. According to the gain formula, gain=repetition frequency×lifetime. It is helpful to increase the injection number, and to shorten the injection interval. In the latest commissioning, near 1.8×10^{10} particles were accumulated in 10 s.

The two components accumulation fitting compared with the experimental data was demonstrated in Figure 2. From the results, the average intensity in one standard multi-turn injection was about 350 μA. One part of ion beam decayed with the lifetime of 6 s, the other part of ion beam decayed with 0.35 s. In this condition, the measured work-point was 3.612/2.657, and the improper work-point was the reason for the short lifetime and fast decay of ion beam.

3.2 Repeated multi-turn injection

At the end of the transfer line, a magnetic septum and an electrostatic septum inflector guide the beam parallel to the

Table 1 Accumulation results in CSRm

Ion	E_{inj} (MeV/u)	Injector	M	I_{inj} (μA)	ΔT_{inj} (s)	I_{single} (μA)	$I_{10\,s}$ (μA)
$^{12}C^{6+}$	7.09	SFC	ST	12	1.0	167	700
$^{12}C^{4+}$	7.1	SFC	MI	6	1.0	20	105
$^{36}Ar^{18+}$	21.7	SFC+SSC	MI	4	0.35	6	250
$^{129}Xe^{27+}$	2.9	SFC	MI	3	0.35	6.5	70
$^{12}C^{5+}$	8.26	SFC	MI	3	0.9	11	70
$^{78}Kr^{28+}$	4.04	SFC	MI	2.4	0.2	5	80

Table 2 Accumulation parameters of the ion beam

Ion	E_{inj} (MeV/u)	Injector	M	I_{inj} (μA)	ΔT_{inj} (s)	I_{single} (μA)	$I_{10\,s}$ (μA)
$^{12}C^{6+}$	7.09	SFC	MI	4.3	0.5	12.5	150
$^{12}C^{6+}$	7.09	SFC	ST	12	1.0	104	700
$^{12}C^{6+}$	7.09	SFC	ST	11	0.5	260	2100
$^{12}C^{6+}$	7.04	SFC	ST	8.4	0.25	400	4000

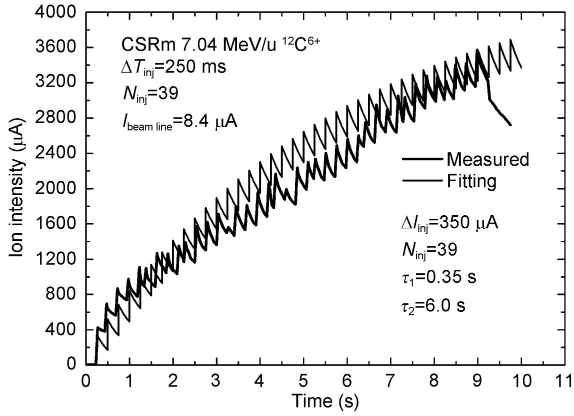

Figure 2 Two components decay fitting compared with experimental data.

ring orbit; four in-dipole coils create a DC bump of 50 mm amplitude at the electrostatic septum. For multi-turn injection four fast bump magnets produce a time dependent bump orbit to fill the horizontal acceptance of the ring.

After repeated multi-turn injections, the emittance of ion beam will be close to the transverse acceptance of the ring. And the radius of ion beam will be 3.8 cm in the cooling section. The ion beam is completely surrounded by the electron. The accumulation was improved in the case of bigger expansion factor.

3.3 Accumulation optimization experiments

The accumulation rate is subjected to the cooling time and injection repetition rate. It is determined by the electron beam parameters and injected ion beam stability. The optimum time interval between the two adjacent multi-turn injections corresponds to the transverse cooling time of ion. With the observation of the accumulation, the parameters related to accumulation were optimized experimentally. The dependence of accumulated ion intensity in 10 s on the injection interval was shown in Figure 3. From this result, in the case of the injection interval with 0.25 s, the maximal ion intensity was obtained.

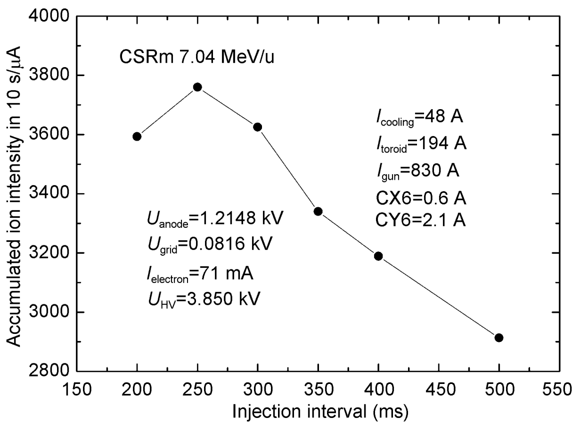

Figure 3 Accumulated ion intensity in 10 s depends on the injection interval.

The position and angle between ion and electron beams in the cooling section determined the cooling force and time. The accumulated ion intensity in 10 s as a function of the current in cooling section corrector CX6 was illustrated in Figure 4. The electron beam angles in horizontal and vertical directions with respect to ion beam were changed by these correctors. It's obvious that perfect alignment is helpful for obtaining maximum ion intensity. Due to the improper orbit of ion beam in the cooling section, the results were not as the usual parabolic curve. The current regulation range of correctors was limited by the aperture of electrostatic bending plates in the toroids of cooler because of the condition of bigger expansion factor. Excessive regulation caused the fast increase of the load current of high voltage system.

The accumulated ion intensity in 10 s was measured as a function of the ratio U_{grid}/U_{anode} of electron gun at different electron currents as presented in Figure 5. It is clear that optimum accumulation happens in the partially hollow electron beam, and the ratio U_{grid}/U_{anode} is close to 0.1. In this

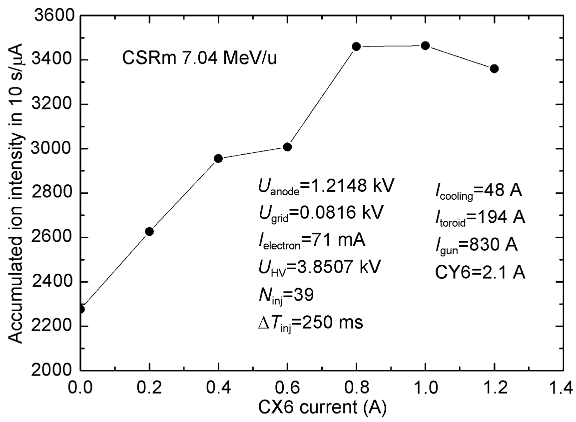

Figure 4 Accumulated ion intensity in 10 s for the different currents of corrector CX6 in the cooling section.

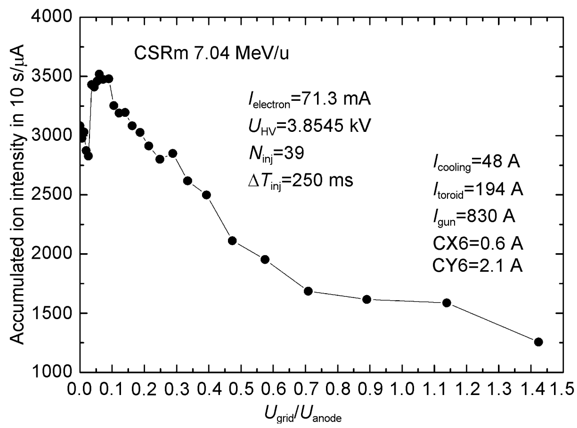

Figure 5 Accumulated ion intensity in 10 s as a function of the ratio U_{grid}/U_{anode} of the electron gun.

case, the central density is less than the edge one in the electron beam. The energy of electron beam was fixed. The potential drop caused by the space charge of electron beam with a different profile was not taken into account in the experiments.

The optimal electron beam energy in the case of different electron beam profiles was shown in Figure 6. The intensity of ion beam was normalized by the maximum value. The electron beam current was kept fixed in the experiments. The effects of space charge for the solid and hollow electron beams are demonstrated.

4 Ion beam cooling in CSRe

The ion beam of $^{12}C^{6+}$ was injected into CSRe from CSRm after acceleration from 7 MeV/u to 200 MeV/u. The magnetic field of electron cooler was set as a quarter of the maximum value. In this case, the magnetic field in the cooling section was 0.0385 T, and the electron beam current was set as 300 mA. After the global and local orbit correction and regulation of the electron beam angle and position in the cooling section, the cooling was observed, but the cooling process was not fast enough. This could be caused by the poor quality of the high energy electron beam confined by a weak magnetic field in toroid, where additional transverse temperature was introduced. With the increase of the magnetic field in toroid and the electron beam current, as well as the improvement of the angle between ion beam and electron beam, about 14 s longitudinal cooling time was obtained. Then the ion beam was accelerated to 400 MeV/u, the corresponding high voltage of electron cooler was 220 kV, and the electron beam current achieved 1 A, and a reasonable momentum spread of 3.2×10^{-5} was measured in the case of 600 μA ion beam in CSRe. Some results have been reported in COOL'09 [10].

In order to explore the minimum momentum spread, the intensity of injecting ion beam was reduced by means of changing the current of last quadrupole in the injection line before CSRm, which resulted in no obvious signal at the DCCT of CSRm. In this case, the particle number was less than 1.5×10^{6} in CSRm, after acceleration, less than 9×10^{4} particles were stored in CSRe. However, a clear signal was observed in the Schottky monitor. The minimum momentum spread was measured as 1.35×10^{-5} demonstrated in Figure 7. Generally, the measured minimum momentum spread was limited by the detection technique, stability of dipole power supply, the stability of high voltage power supply of cooler, and also the particle number stored in the ring.

From the experience of CSRe cooler, the stability of dipole power supply and high voltage power supply of cooler should be improved in the future. The detection technique should be upgraded to measure the momentum spread in the case of low ion intensity, and precision calibration should be done to determine the stored particle number.

In the internal gas target experiments, the 200 MeV/u $^{129}Xe^{27+}$ was stripped into $^{129}Xe^{54+}$ before entry of CSRe, and stored in CSRe. The longitudinal cooling time was measured as a function of magnetic field of toroid. The result was presented in Figure 8. The angle and position of the electron beam change during only regulating the current of toroid was not taken into account. From this result, one can see the dependence of cooling time on the magnetic field of toroid. This is consistent with the results of GSI [11].

The influence of the magnetic field in toroid on the longitudinal cooling force for 200 MeV/u $^{129}Xe^{54+}$ beam was studied experimentally. Longitudinal cooling forces were obtained by means of the electron energy-step method [12]. The cooling force varying with magnetic field in toroid was shown in Figure 9. The different line represents the different electron energy step. In the case of high energy, the influence of magnetic field on the electron transverse energy should be paid sufficient attention. The experimental results were in partially agreement with the experiment results in GSI [11].

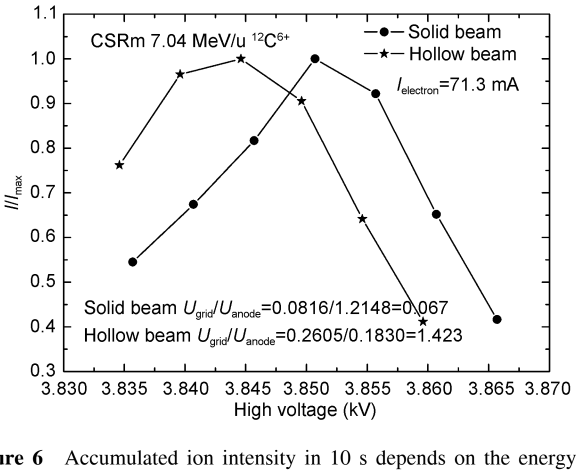

Figure 6 Accumulated ion intensity in 10 s depends on the energy for solid and hollow electron beams.

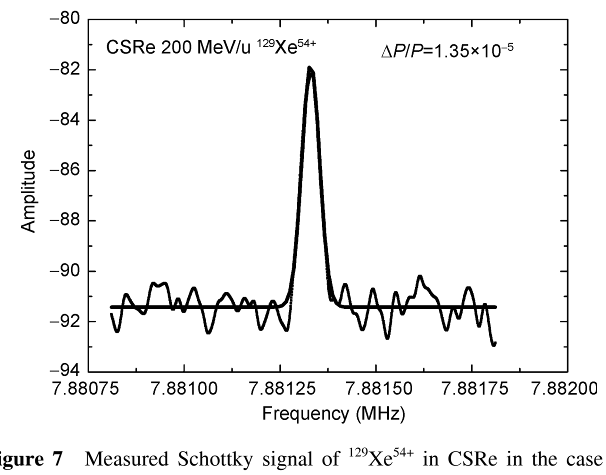

Figure 7 Measured Schottky signal of $^{129}Xe^{54+}$ in CSRe in the case of low ion beam intensity.

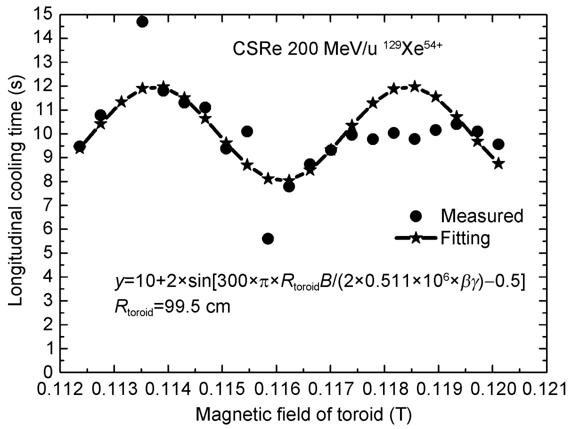

Figure 8 Longitudinal cooling time measured at the different magnetic fields in toroid.

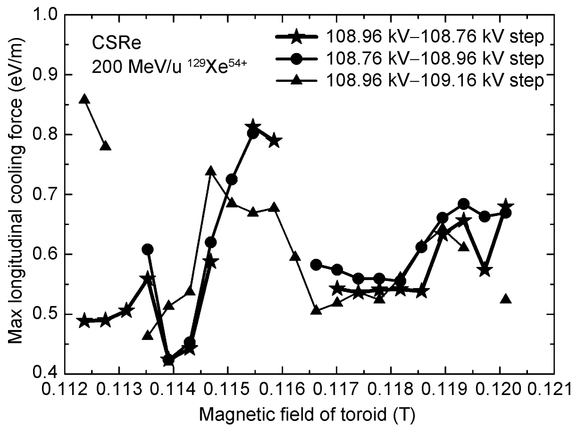

Figure 9 Maximum longitudinal cooling force as a function of the magnetic field in toroid in the case of the different electron beam energy steps.

5 Summary

A few species heavy ion beam with different injection energy was cooled, accumulated and accelerated in CSRm. 400 MeV/u $^{12}C^{6+}$ and 200 MeV/u $^{129}Xe^{54+}$ were cooled with internal target in CSRe. Two cooling devices came into routine operation. Electron beam energy modulation system was installed and tested in CSRm cooler. Coolers were ready for physics experiments.

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