Commissioning of electron cooling in CSRm*

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Abstract A new generation electron cooler has started operation in the heavy ion synchrotron CSRm which is used to increase the intensity of heavy ions. Transverse cooling of the ion beam after horizontal multi-turn injection allows beam accumulation at the injection energy. After optimization of the accumulation process an intensity increase in a synchrotron pulse by more than one order of magnitude has been achieved. In given accumulation time interval of 10 seconds, 10^8 particles have been accumulated and accelerated to the final energy. The momentum spread after accumulation and acceleration in the 10^{-4} range has been demonstrated in six species of ion beams. Primary measurements of accumulation process varying with electron energy, electron beam current, electron beam profile, expansion factor and injection interval have been performed. The lifetimes of ion beams in the presence of electron beams were roughly measured with the help of DCCT signal.

Key words electron cooling, hollow electron beam, accumulation

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1 Introduction

HIRFL-CSR is a new ion cooler-storage-ring system at 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 are injected into CSRm, then accumulated, e-cooled and accelerated, finally extracted to CSRe for internal-target experiments and other physics experiments.

CSRm is a 161 m circumference cooler storage ring with sixteen 22.5 degree H-type bending dipole magnets. The maximum Betatron functions are 15.3 m and 30.5 m in horizontal and vertical directions respectively. The maximum dispersion is 5.4 m, and the dispersion at injection point is 4 m. The Betatron functions at electron cooler are 10 m and 17 m in the two transverse directions respectively, the dispersion is zero here. The emittances of ion beams from SFC and SSC are about 20 πmmmrad and 10 πmmmrad, and the acceptance of CSRm is about 150 πmmmrad.

Two modes of injection are used in CSRm, stripping for lighter ions and repeated multi-turn for heavier ones. The accumulation duration of CSRm is about 10 s, and the acceleration time of CSRm is nearly 3s, and the one whole cycle period is about 17 s.

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

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tured with 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 1. The previous results have been given in the COOL07-TUM1I02[1] and APAC2007-THXMA03[2].

Table 1. Parameters of the CSRm electron cooler.

maximum electron energy	35 keV
maximum electron current	3 A
gun PERVeance	29 μP
cathode diameter	29 mm
current collection efficiency	⩾99.99%
maximum magnetic field in gun section	0.25 T
maximum magnetic field in cooling section	0.15 T
field parallelism in cooling section	4×10^{-5}
effective length of cooling section	3.4 m
vacuum pressure	⩽ 3×10^{-11} mbar

2 Beam accumulation

2.1 Stripping injection of $^{12}C^{6+}$

Firstly, the 7 MeV/u $^{12}C^{4+}$ was injected into CSRm from the small cyclotron SFC through a stripping foil with thickness of 15 μg/cm^2 placed in the first dipole of the ring, the average pulse intensity was about 12 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 bumping orbit, the stored beam signal was observed from BPM signal, the closed orbit correction was done roughly, the machine parameter such as working point was measured and tuned, and acceleration attempted.

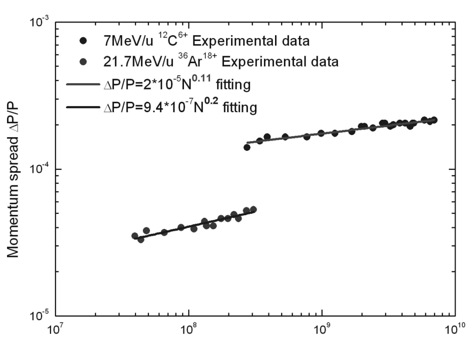

Fig. 1. Momentum spread of cooled $^{12}C^{6+}$ and $^{36}Ar^{18+}$ as a function of the stored particle number at the injection energy.

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 seconds, and 2.2×10^9 particles were accelerated to the final energy of 1 GeV/u. The momentum spread of injected beam was about 1.5×10^{-3}, after electron cooling the momentum spread rapidly reduced to 5.5×10^{-5} in a second at first shot, and then the final momentum spread increased exponentially with the stored particle number as shown in Fig. 1. The momentum cooling time was about 0.3 sec. About 1.6×10^{10} particles were stored in the ring after longer time accumulation. The later best results were demonstrated in Fig. 2.

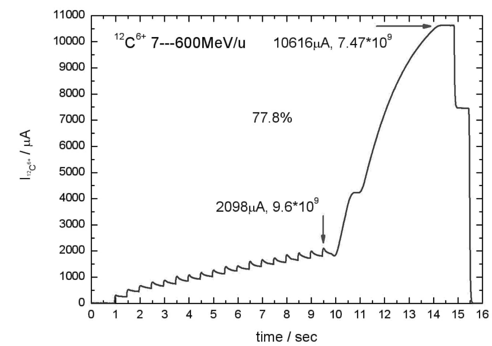

Fig. 2. A complete cycle of accumulation and acceleration of $^{12}C^{6+}$ with electron beam.

2.2 Multi-turn injection of $^{12}C^{4+}$

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

In order to test the performance of the elements for multi-turn injection, repeated multi-turn injection was carried out with 7 MeV/u $^{12}C^{4+}$ without stripping. The average pulse intensity was about 6 μA in the injection line. Only 47% of the beam intensity was left after turning on the cooler magnetic field and related correction, it is smaller than the results of SIS[3]. The average particle number of $^{12}C^{4+}$ per pulse is about 1.2×10^8 in one standard multi-turn injection, with the help of electron cooling of partially hollow electron beam, 5.8×10^8 particles were accumulated in the ring after 10 times injection in 10 seconds, and 4.6×10^8 particles were accelerated to the final energy of 300 MeV/u. The measured lifetime of $^{12}C^{4+}$ is 28 seconds, which is shorter compared with 255 s of $^{12}C^{6+}$, after longer time accumulation, the particle number is saturated at 7.0×10^8.

2.3 Multi-turn injection of $^{36}Ar^{18+}$

For the sake of achieving the performance of accelerator complex of HIRFL, 22 MeV/u $^{36}Ar^{8+}$ beam extracted from SSC was stripped into $^{36}Ar^{18+}$ by the foil with the thickness of 350 μg/cm^2, and then injected to CSRm, the average pulse intensity was about 4 μA in the injection line. The average pulse particle number of $^{36}Ar^{18+}$ was about 5.4×10^6 in one standard multi-turn injection. With the help of electron cooling of partially hollow electron beam, 1.2×10^8 particles were accumulated in the ring after 29 times injection in 10 seconds, and 1.1×10^8 particles were accelerated to the final energy of 1 GeV/u. 3.8×10^8 particles were stored for long time accumulation. Compared with the results in Ref. [3], the accumulation rate which is defined as the increase of circulating current per unit of time divided by the current in the injection line to the synchrotron, was achieved in the commissioning of CSRm. It is seems which slightly better than the maximal value 5 in the reference.

2.4 Multi-turn injection of $^{129}Xe^{27+}$

It should be mentioned that a new superconducting ECR ion source SECRAL developed by IMP has started operation to provide high intensity heavier ion beam[4]. $^{129}Xe^{27+}$ delivered by the SECRAL was accelerated by SFC to 2.9 MeV/u and then injected into CSRm, the average pulse intensity was about 3.0 μA in the injection line. The average pulse particle number of $^{129}Xe^{27+}$ was about 1.0×10^7 in one standard multi-turn injection. With the help of electron cooling of partially hollow electron beam, 1.2×10^8 particles were accumulated in the ring after 29 times injection in 10 seconds, and 1.0×10^8 particles were accelerated to the final energy of 235 GeV/u. 1.1×10^8 particles were stored after long time accumulation.

The ion intensity after 10 s accumulation and acceleration depending on the electron beam energy was investigated in the case of fixed electron beam current and profile. The accumulated intensity in 10 s does not critically rely on the electron energy compared with the intensity after acceleration. The reason was that the RF capture frequency band is more narrow than the velocity deviation of electrons. The same phenomena were observed in the commissioning of $^{12}C^{5+}$. The potential drop caused by the space charge of electron with a different profile was taken into account at the time of finely tuning the velocity of the electron beam.

In the interest of optimizing the electron beam profile for accumulation, the electron beam profile was changed at fixed electron beam current. One can see that at the larger ratio $U_{\rm grid}/U_{\rm anode}$, the electron density in the centre of electron beam becomes smaller than that at the edge. The ion beam was weakly cooled in this case, and the accumulated ion becomes smaller. When the electron beam current increases, the electron density in the centre slightly increases, and the accumulated ion beam also increases. Optimum accumulation happens when the ratio $U_{\rm grid}/U_{\rm anode}$ is near 0.2.

2.5 Multi-turn injection $^{12}C^{5+}$

In order to examine the performance of the elements for fast extraction, repeated multi-turn injection was done with 8.26 MeV/u $^{12}C^{5+}$ without stripping. The average pulse intensity was about 3 μA in the injection line. The average pulse particle number of $^{12}C^{5+}$ was about 4.0×10^7 in one standard multi-turn injection, with the help of electron cooling of partially hollow electron beam, 3.5×10^8 particles were accumulated in the ring after 10 times injection in 10 seconds, and 4.6×10^8 particles were accelerated to the final energy 100 MeV/u. The lifetime of 16 seconds of $^{12}C^{5+}$ is short compared with 255 s of $^{12}C^{6+}$, after longer time accumulation only 4.6×10^8 particles were accumulated and saturation was reached.

The charge state of ion $^{12}C^{5+}$ is medial, so the possibilities of ion loss due to various mechanisms exist in the ring. In the absence of electron beam, the ionization and electron capture process due to residual gas determines the lifetime of ion beam in the ring. In the presence of electron beam, the electron capture process will dominate. It is clear that the lifetime is longer in the case of partially hollow electron beam. The accumulation efficiency demonstrated is higher for hollow electron beam in 10 seconds. In the case of bigger current of hollow electron beam, the lifetime becomes shorter, but the accumulation becomes higher. Much higher accumulation efficiency for higher ratio $U_{\rm grid}/U_{\rm anode}$ can be explained by improving the vacuum conditions. Vacuum condition along the ring depends on the degasification by action of ion beam and it will be improved with time.

After repeated multi-turn injection, 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 is improved in the case of bigger expansion factor. The experimental results don't change smoothly and regularly because of the fluctuation of injected ion beam.

The accumulation rate subjects 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.

The accumulated ion intensity in 10 s was measured as a function of the electron current for different electron beam profiles. For the hollow electron beam, because the electron density in the centre decreases, higher electron current is needed for the same cooling. The effects of higher electron beam current on the work-point should be taken into account.

The accumulated ion intensity in 10 s was measured as a function of the ratio $U_{\rm grid}/U_{\rm anode}$ of electron gun at different electron current. It is clear that optimum accumulation happens in the partially hollow electron beam, the ratio $U_{\rm grid}/U_{\rm anode}$ is close to 0.2. In this case, the central density is 2 times less than the edge one in the electron beam.

The injection parameters of ion are enumerated in Table 2, $I_{\rm inj}$ is the intensity of single multi-turn shot, $\Delta T_{\rm inj}$ is the injection period, and the lifetime of the ion beams with the electron beam is listed in the penultimate column.

2.6 Multi-turn injection of $^{78}Kr^{28+}$

In order to do physics experiment in CSRe, $^{78}Kr^{19+}$delivered by the SECRAL was accelerated by SFC to 4.04 MeV/u, after stripped to $^{78}Kr^{28+}$ by the foil with the thickness of 30 μg/cm^2 placed in the beam line before CSRm, The average pulse intensity was about 2.4 μA in the injection line. The average pulse particle number of $^{78}Kr^{28+}$ was about 6.45×10^6 in one standard multi-turn injection, with the help of electron cooling of partially hollow electron beam, 1.03×10^8 particles were accumulated in the ring after 44 times injection in 10 seconds, and 6.4×10^7 particles were accelerated to the final energy 205 MeV/u. After longer time accumulation only 9.03×10^7 particles were accumulated and saturation was reached due to shorter lifetime in the CSRm.

The momentum spread of the ion beams are summarized in Table 3, after accumulation and acceleration it is in the range of 10^{-4}.

Table 2. Accumulation parameters of ion beam.

ion	$E_{\rm inj}$	M/(MeV/u)	$I_{\rm inj}$/μA	foil/(μg/cm^2)	$\Delta T_{\rm inj}$/ms	lifetime/sec	$I_{\rm e}$/mA
$^{12}C^{6+}$	7.09	ST	12	15	1000	255	70
$^{12}C^{4+}$	7.1	MI	6		1000	27.7	124
$^{36}Ar^{18+}$	21.7	MI	4	350	350	554.7	97
$^{129}Xe^{27+}$	2.9	MI	3		350	12	70
$^{12}C^{5+}$	8.26	MI	3		900	16	151
$^{78}Kr^{28+}$	4.04	MI	2.4	30	200	4.5	172

Table 3. Momentum spread of ion beam.

ion	$E_{\rm ion}$/(MeV/u)	mode	$\Delta P/P_{\rm inj}$	$\Delta P/P_{\rm 10sec}$	$\Delta P/P_{\rm final}$
$^{12}C^{6+}$	7.09—1000	ST	1.46×10^{-3}	3.9×10^{-3}	3.6×10^{-4}
$^{36}Ar^{18+}$	21.7—1000	MI	6.98×10^{-4}	3.2×10^{-4}	2.5×10^{-4}
$^{129}Xe^{27+}$	2.9—235	MI		2.4×10^{-4}	1.8×10^{-4}
$^{12}C^{5+}$	8.26—100	MI		2.3×10^{-4}	1.3×10^{-4}
$^{78}Kr^{28+}$	4.04—205	MI		3.5×10^{-4}	1.4×10^{-4}

3 Summary and outlook

The experimental results indicate that the partially hollow electron beam has an advantage in beam accumulation. The optimal ratio $U_{\rm grid}/U_{\rm anode}$ is near 0.2. In this case, the centre density is 2 times less than the edge density in the electron beam. The equilibrium momentum spread increases with the number of accumulated ions; the result is contrasted with the SIS cooler. The optimal electron currents are well agreed with the simulated one with the help of Vasily's electron cooling simulation code. Systematic investigation of cooling with hollow electron beam will be performed in the future.

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