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 multiturn 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 five 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 beam in the presence of electron beam were roughly measured with the help of DCCT signal.

INSTRUCTION

HIRFL-CSR 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: Parameters of the CSRm electron cooler

Maximum electron energy	35 keV
Maximum electron current	3A
Gun perveance	29 μP
Cathode diameter	29mm
Current collection efficiency	≥99.99%
Maximum magnetic field in gun section	0.25T
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

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

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

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 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 1.

In 2005 the main construction of the CSR project was completed, and from then the preliminary commissioning of CSRm was performed, including the first turn commissioning as a beam line, the stripping injection, and the zero-bumping orbit test, fixed-bumping orbit test with four in-dipole coils, bumping orbit test, C-beam accumulation and some investigations of the closed orbit with BPM.

Shortly after last workshop of COOL2005, the cooler started routine operation during CSR commissioning. Up to now five species of ion were cooled and accumulated with the help of electron cooling. In this paper the recent results of commissioning of CSRm and its cooler are presented. The previous results have been given in the APAC2007-THXMA03 [1]

BEAM DIAGNOSTICS

The closed orbit is monitored by 16 shoebox-shaped BPMs, the length of electrodes is 150mm, the cross-section is rectangular, and the width and height are 170mm and 100mm respectively. Two additional cylindrical BPMs were installed at the ends of cooling section to measure the positions of electron beam and ion beam. A Schottky pickup was placed behind the cooler, the length of the plate electrodes is 395mm, and the widths are 160mm in horizontal and 100mm in vertical directions, the gaps between electrodes are 110mm in vertical and 160mm in horizontal. A DCCT developed by company Bergoz is used to monitor the ion beam current in the ring, with precision of about 0.5μA. The direct determination of beam's transverse emittance was presently ruled out due to the magnesium jet monitor was out of order during commission. In order to measure the work-point, the Schottky pickup electrodes were used to

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excite the ion beam, a BPM was used to monitor the Schottky signal, the length of its electrodes is smaller than Schottky pickup electrodes. The lifetime of ion beam was measured by DCCT signal roughly. The work point of ring was monitored during the process of acceleration. Due to lack of the transverse ion beam monitors, the transverse profile of the ion beam was not measured during the commissioning.

CLOSED-ORBIT CORRECTION

The closed-orbit is monitored during acceleration by the BPM system. 16 steering in-dipole coils, 8 pairs of horizontal and vertical bidirectional correction dipoles and 6 additional vertical correction dipoles are used to correct the closed-orbit.

The longitudinal field produced by electron cooler is compensated by two compensation solenoids at the both ends of cooler. The transverse field introduced by the toroids is corrected by four pairs of horizontal and vertical correction dipoles. The displacement and direction of ion beam in the cooling section can be adjusted by these dipoles.

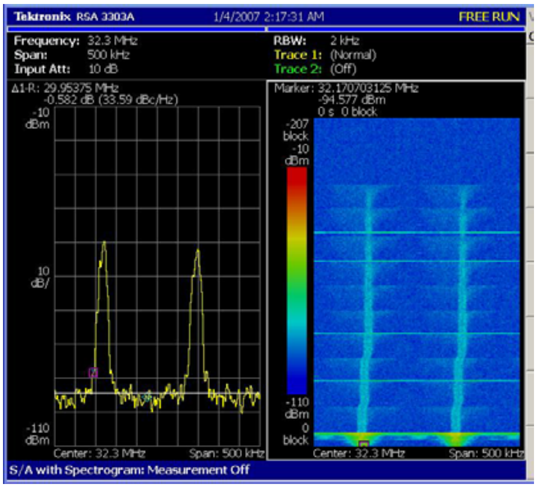
The global closed-orbit correction was performed according to the ion beam decay in the ring after accumulation process. After turning on the magnetic field of electron cooler and related correction coils, the local closed-orbit correction was carried out in the region of electron cooler.

BEAM ACCUMULATION

Stripping Injection of $^{12}C^{6+}$

Firstly, the 7MeV/u $^{12}C^{4+}$ was injected into CSRm from small cyclotron SFC through a stripping foil with thickness of 15μg/cm^2 placed in the first dipole of the ring, the average pulse intensity was about 12μA in the injection line. In the absent of magnetic field of 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, acceleration was attempted.

The average particle number of stored $^{12}C^{6+}$ was about 4.7×10^8 in one standard multiturn 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 final energy of 1GeV/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 final momentum spread increased linearly with the stored particle number. The Schottky noise signal of $^{12}C^{6+}$ during accumulation was presented in Figure 1, and the dependence of momentum spread upon the stored ion number was shown in Figure 2. The momentum cooling time was about 0.3sec. About 1.6×10^{10} particles were stored in the ring after longer time accumulation which is displayed in Figure 3.



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S/A with Spectrogram: Measurement Off

Figure 1: Schottky signal of $^{12}C^{6+}$ during accumulation.

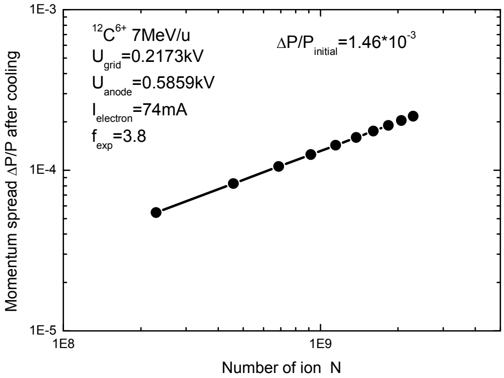

Figure 2: Momentum spread of cooled $^{12}C^{6+}$ as a function of the stored particle number at the injection energy determined by Schottky signal of a coasting beam in Fig.1.

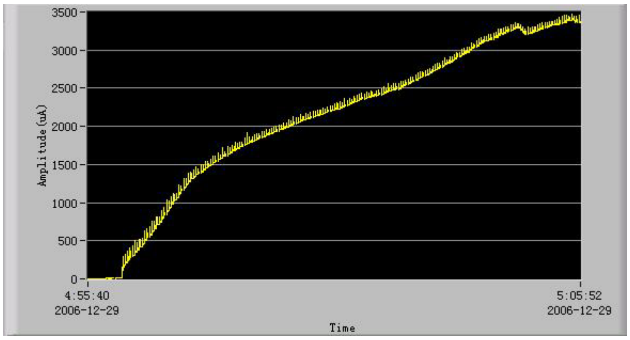

Figure 3: $^{12}C^{6+}$ beam accumulation.

Multiturn Injection of $^{12}C^{4+}$

At the end of the transfer line one magnetic septum and an electrostatic septum inflector guides the beam parallel to the ring orbit; four in-dipole coils create a DC bump of 50mm amplitude at the electrostatic septum. For multiturn 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 multiturn injection, repeated multiturn injection was carried out with 7MeV/u $^{12}C^{4+}$ without stripping. The average pulse intensity was about 6μA in the injection line. Only 47% of beam intensity left after turned on the cooler magnetic field and related correction, it is smaller than the results of SIS. The average particle number of $^{12}C^{4+}$ per pulse is about 1.2×10^8 in one standard multiturn 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 final energy of 300MeV/u. The measured lifetime of $^{12}C^{4+}$ is 28 seconds, which is shorter comparing with 255s of $^{12}C^{6+}$, after longer time accumulation, the particle number was saturated at 7.0×10^8.

Multiturn Injection of $^{36}Ar^{18+}$

For the sake of the performance of accelerator complex of HIRFL, 22MeV/u $^{36}Ar^{8+}$ beam extracted from SSC was stripped into $^{36}Ar^{18+}$ by the foil with thickness of 350μg/cm^2, and then injected to CSRm, the average pulse intensity was about 4μA in the injection line. The average pulse particle number of $^{36}Ar^{18+}$ was about 5.4×10^6 in one standard multiturn 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 final energy of 1GeV/u. 3.8×10^8 particles were stored for long time accumulation. The best results were demonstrated in Figure 4. Comparing with the results in reference[2], 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 6 in the commissioning of CSRm. It seems slightly better than the maximal value 5 in the reference.

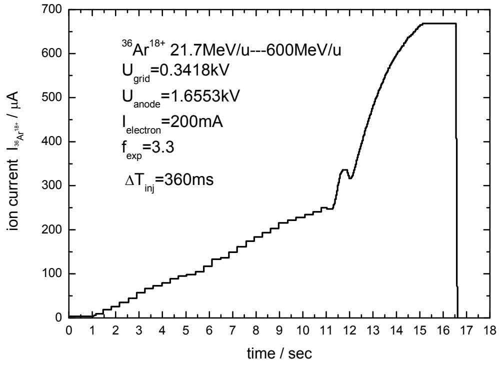

Figure 4: A complete cycle of accumulation and acceleration of $^{36}Ar^{18+}$ with electron beam.

Multiturn 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[3]. $^{129}Xe^{27+}$ delivered by the SECRAL was accelerated by SFC to 2.9MeV/u and then injected into CSRm, the average pulse intensity was about 3.0μA in the injection line. The average pulse particle number of $^{129}Xe^{27+}$ was about 1.0×10^7 in one standard multiturn 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 final energy of 235GeV/u. 1.1×10^8 particles were stored after long time accumulation.

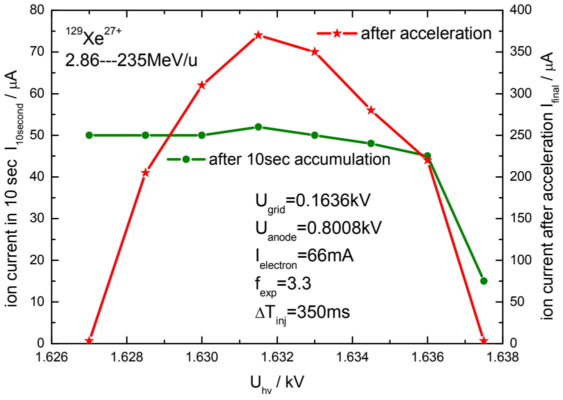

Figure 5: $^{129}Xe^{27+}$ intensity after accumulation and acceleration as a function of electron beam energy.

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

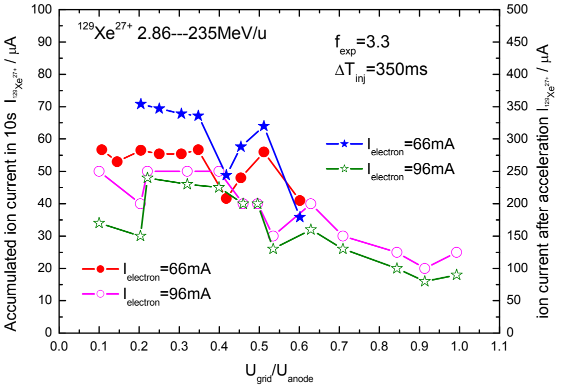

Figure 6: $^{129}Xe^{27+}$ intensity after 10 seconds accumulation and acceleration as a function of the ratio U_{grid}/U_{anode} of electron gun.

In the interest of optimization the electron beam profile for accumulation, the electron beam profile was changed at fixed electron beam current. The results were shown in Figure 6. One can see that at the larger ratio U_{grid}/U_{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 increase. Optimum accumulation happened when the ratio U_{grid}/U_{anode} is near 0.2.

Multiturn Injection of $^{12}C^{5+}$

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

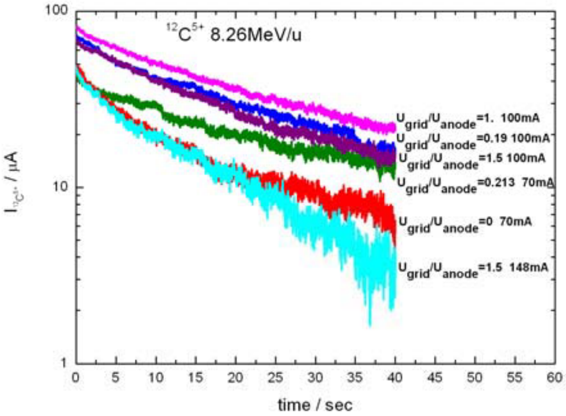

Figure 7: Decrease of the stored $^{12}C^{5+}$ intensity with time for different profile electron beam at different current.

The charge state of ion $^{12}C^{5+}$ is medial, so that 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. Figure 7 reveals the decrease of the stored $^{12}C^{5+}$ ion current during cooling at different electron current and profile. Figure 8 shows the lifetime of the stored $^{12}C^{5+}$ ion with the ratio U_{grid}/U_{anode} in electron gun at different electron current. 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 accumulation becomes higher. Much higher accumulation efficiency for higher ratio U_{grid}/U_{anode} can be explained by improving the vacuum conditions. Vacuum condition along ring depends on the degasification by action of ion beam and it will be improved with time.

The effect of the electron beam expansion factor on the accumulation is shown in Figure 9. After repeated multiturn injection, the emittance of ion beam will be close to the transverse acceptance of the ring. And the radius of ion beam will be 3.8cm 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.

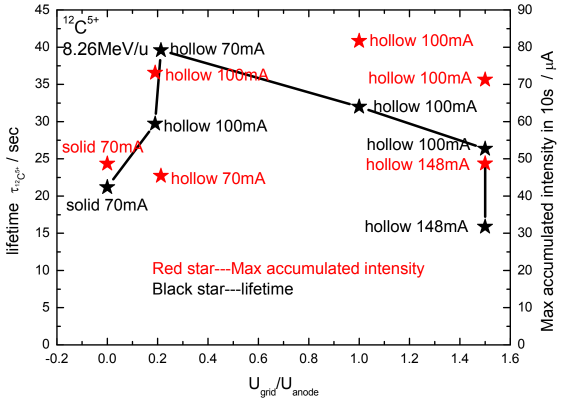

Figure 8: Lifetime of the stored $^{12}C^{5+}$ ion as a function of the ratio U_{grid}/U_{anode} of electron gun at different electron current.

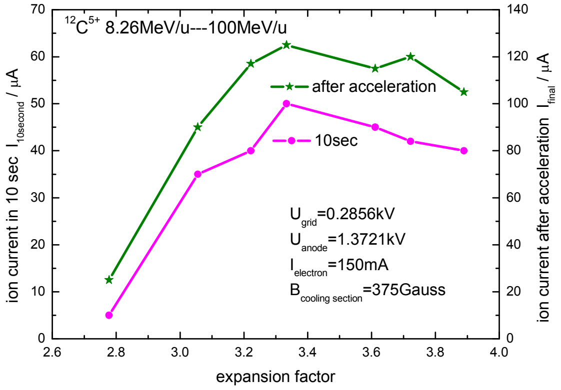

Figure 9: $^{12}C^{5+}$ intensity after 10 seconds accumulation and acceleration as a function of expansion factor.

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. Variation of the time between two successive multiturn injections is illustrated in Figure 10. The optimum time interval between the two adjacent multiturn injections corresponds to the transverse cooling time of ion.

The influence of the electron beam current on the accumulation is illustrated in Figure 11, The accumulated ion intensity in 10s was measured as a function of the electron current for the different electron beam profile. 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.

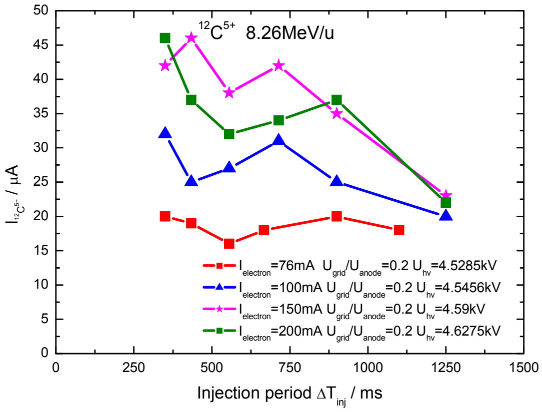

Figure 10: $^{12}C^{5+}$ intensity after 10 seconds accumulation as a function of the time interval between subsequent multiturn injections at different electron current in case of the same electron beam profile.

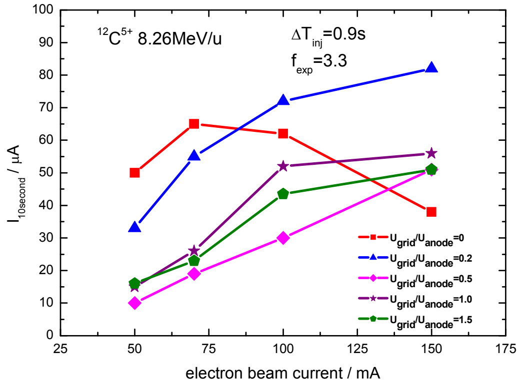

Figure 11: $^{12}C^{5+}$ intensity after 10 seconds accumulation as a function of the electron current at different ratio between U_{grid} and U_{anode} of electron gun.

The impact of the electron beam profile on the accumulation is shown in Figure 12. The accumulated ion intensity in 10s was measured as a function of the ratio U_{grid} /U_{anode} of electron gun at different electron current. It is clear that optimum accumulation happened in the partially hollow electron beam, the ratio U_{grid} /U_{anode} is close to 0.2. In this case, the central density is 2 times less than the edge one in the electron beam.

Table 2: Accumulation parameters of ion beam

Ion	E_{inj}	M	I_{inj} μA	Foil μg/cm^2	ΔT_{inj} ms	Lifetime sec	I_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

The injection parameters of ion are enumerated in table 2, I_{inj} is the intensity of single multiturn shot, ΔT_{inj} is the injection period, and the lifetime of the ion beams with the electron beam is listed in the penultimate column.

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

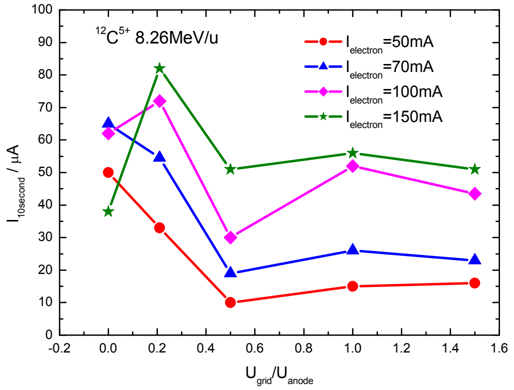

Figure 12: $^{12}C^{5+}$ intensity after 10 seconds accumulation as a function of the ratio U_{grid} /U_{anode} of electron gun at different electron current.

Table 3: Momentum spread of ion beam

Ion	E_{ion}	Mode	$\Delta P/P_{inj}$	$\Delta P/P_{10sec}$	$\Delta P/P_{final}$
$^{12}C^{6+}$	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}

SUMMARY AND OUTLOOK

Experimental results indicate that the partially hollow electron beam has an advantage in beam accumulation. The optimal ratio U_{grid}/U_{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 unanimous contrasted with the SIS cooler. The optimal electron currents are well agreed with 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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