COMMISSION OF ELECTRON COOLER EC-300 FOR HIRFL-CSR *

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Abstract

HIRFL-CSR, a new ion accelerator complex, is under construction at IMP, Lanzhou, China. It is equipped with two electron cooling devices. This article describes the commissioning of cooler at electron energy 300 keV. The cooler is one of the new coolers with some unique features manufactured in BINP, Russia. It has a new electron gun producing a hollow electron beam, electrostatic bending and a new structure of solenoid coils at the cooling section. The test results of cooler are reported.

INTRODUCTION

HIRFL-CSR is a multi-purpose system that consists of HIRFL (injector), main ring (CSRm) and experimental ring (CSRe) [1]. It is planned, that the heavy ion beams with the energy range of 8-50 MeV/u from the HIRFL is accumulated, cooled and accelerated to 100-450 Mev/u in CSRm. After that the ions is extracted fast to produce RIB or highly charged heavy ions. The secondary ions are stored by the experimental ring for many internal-target experiment or high-precision spectroscopy. Two electron coolers are manufactured for CSR complex. In CSR-m, electron cooler will be used to increase the beam intensity at injection energy. It was commissioned in Lanzhou in Spring, 2003 [2]. In CSRe, electron cooler will be used to compensate the growth of beam emittance induced by internal target processes and to provide high-quality beams for the high-resolution mass spectroscopy experiment. It was commissioned in Lanzhou in Spring, 2004.

The main parameters of the CSRe cooler are shown in Table 1.

Table 1:

Parameters	**CSRe**
Operation Energy: Ion [MeV/u] Electron [keV]	10-450 5-300
Max. electron current [A]	3
E beam radius at cooling section [cm]	2.5
Cathode radius [cm]	1.5
Beta-functions at cooling section [m]	12.5, 16.0
Magnetic field of cooling section [kG]	0.5-1.5
Length of cooling section [m]	4.0
Installation length [m]	7.2
Collector voltage, kV	1-5
Magnetic filed of collector, kG	0.5-2.9
Magnetic filed of gun, kG	0.5-5
Pressure of residual gas, mbar	3×10^{-11}

The general view of the electron cooler devise is shown in Figure 1. The electron beam is generated by the electron gun (16) and passes the following device: accelerated tube (15), toroidal section (11) for convergence of the electron and ion beams, cooling section (8), toroidal section (7) for divergence of the electron and ion beams deceleration section (4). Finally, the electron beam is absorbed by the collector (3). The electron beam is immersed into the magnetic field from the gun to the collector. The collector is under a potential slightly different from the cathode potential.

The high voltage is generated by the special power supply (5 – 300 kV) located in the vessel (9). The high voltage is applied to the central tube of the feeder (1) connecting the collector and gun. The secondary winding of the collector rectifier is located inside the feeder. The collector power supply (2 - 5 kV, 0 - 3 A) generates the potential between the gun and the collector. The vessel (9), feeder (1) and accelerated tube is placed in isolating gas SF_6. The pressure of the gas is about 1.7 standard atmospheres.

The centrifugal force for electron in the bending section is induced by both electrostatic plates and magnetic correction coils.

The leading magnetic field is generated by the set of coils. This set consists of three parts: the gun/collector system (13,5), the toroid system (7) and the main solenoid system (8). All coils are placed in the frame manufactured with soft magnetic iron (10,11,14). This frame is closed the magnetic flux and is magnetic shield. In the place of input and output of the ion beam the dipole correction (20) is placed. These compensate the deflection of the ion beam induced by the vertical component of the magnetic field in the torod section (7).

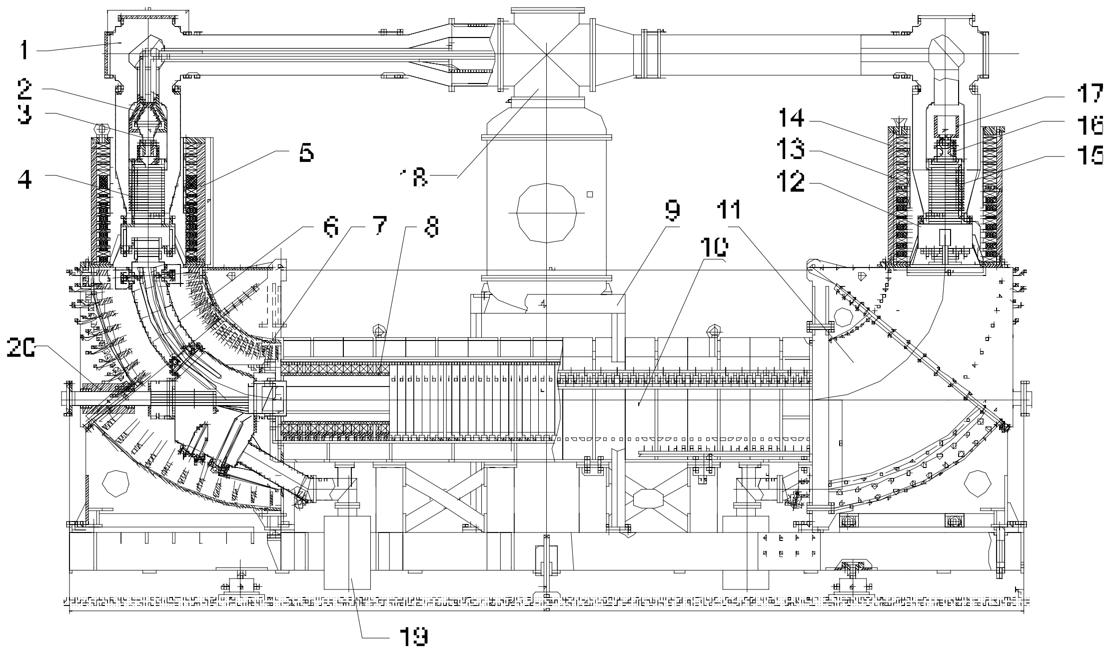

Figure 1: General view of EC-300 cooler device. 1 – high-voltage feeder, 2 – magnetic flux concentrator of collector, 3 – collector, 4 – acceleration (deceleration) tube of collector, 5 – coils of magnetic field of collector, 6 – toroid section with electrostatic bending, 7 – coils of toroidal magnetic field, 8 – coils of cooling section, 9 – vessel of high-voltage power supply, 10 - magnetic circuit of cooling section, 11 – magnetic circuit of toroid, 12 – titanium getter pumps, 13 – coils of electron gun magnetic field, 14 – magnetic circuit of electron gun section, 15 – acceleration tube of electron gun, 16 – electron gun, 17 - magnetic flux concentrator of electron gun, 18 – high-voltage terminal for the electronic equipment, 19 – ion pump, 20 – dipole correction for ion beam.

The vacuum vessel is pumped by the two ion pumps located about toroidal section (19). The additional pumping is done with the titanium pump located about acceleration and deceleration column (12). The residual pressure is 10^{-10} – 10^{-11} torr.

DYNAMIC OF ELECTRON COOLING

The experience of working with electron cooler shows that the cooling of intense ion beam leads to the high losses of the ion beam during the initial stage of cooling. This effect was observed in experiment in CELSIUS [3], IUCF [4], COSY [5]. One reason leads to this effect respected to the formation of the ultra-high dense core of the ion in the beam centre. It leads to the development of some kind instability.

The oscillogram of the pick-up signal at cooling of an ion beam is shown in Figure 2. The instability appears at some threshold value of the ion current.

It is known [6] that the rate of magnetized electrons cooling increases very fast for ion with small amplitude of betatron oscillation:

$$\lambda(a) = \lambda_0 \frac{a_{eff}^3}{\left(a_{eff}^2 + a^2\right)^{3/2}} , \qquad (1)$$

here a is amplitude of betatron oscillation, a_{eff} is parameter characterized the quality of the magnetic field in the cooling section, the drift of electron induced by the space charge ant other effects restricted the cooling rate, is the maximum of the cooling rate. Thus, the ion with small amplitude of the betatron oscillation is cooled very fast, but the ion with large amplitude is cooled very slowly.

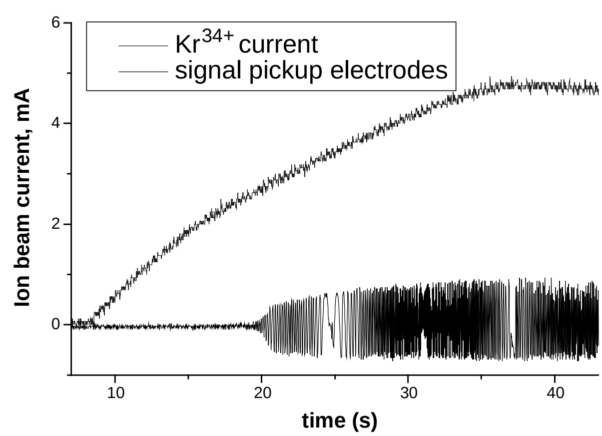

Figure 2: Instability for intensive electron and ion beam

This problem can be overcome by the cooling with help of the electron beam with non-uniform radial density of the current. In this case the balancing cooling is possible without the formation ultra-high dense core.

Basic idea of new cooler is to have high electron current but low density at accumulation zone (centre) [7].

Another merit respected to the control of the radial shape of the current is regulation of the recombination losses.

ELECTRON GUN

The electron gun of EC-300 has the ability to control the beam profile by changing the control electrode potential [8]. The control electrode is located near the cathode edge, so its potential strictly influences the emission from this area. At negative voltage on the control electrode the emission is strongly suppressed on the beam edge of cathode so the pencil beam is formed. At positive voltage the main part of the beam is emitted on the cathode edge so the ring beam is formed.

The profile of the electron beam is measured at special test bench is shown in Figure 3. One can see that the variation of the voltage of control electrode changes the radial profile of the electron beam.

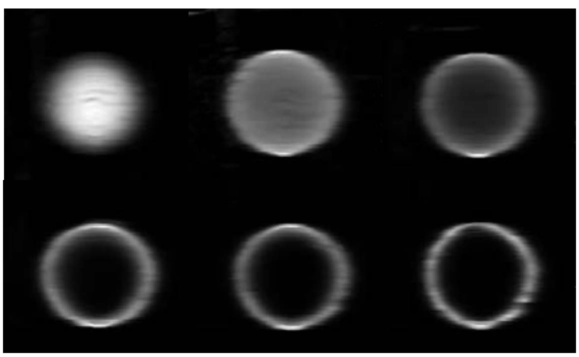

Figure 3: The radial profile of the electron beam at different values of the voltage applied to the control electrode. U_{contr} = 0, 100, 200, 350, 400 and 600 V (from left to right).

ELECTROSTATIC BENDING

An electron has drift under the centrifugal force at bending. It can be compensated by the additional magnetic field with opposite direction

$$B_{corr} = \frac{p_0 c}{eR} \qquad (2)$$

This is the correction of forward electron trace only. The backward electron has double shift in the toroid section. During the time of several oscillations from the gun to the collector and back the electron escapes from the beam and losses.

Another idea is to complete compensation of the centripetal force by the electric field in the bending section. In this case there is no drift of the electron crosswise the driving magnetic field. The value of the electric field is

$$E_{\perp} = \frac{pV}{eR} = \frac{\gamma+1}{\gamma} \cdot \frac{E_e}{eR} \qquad (3)$$

The electrostatic field affects equally on both primary electrons of beam and secondary electron reflected from collector. Thus, the secondary electron from collector has a number of attempts for absorption in collector. The leakage current is very small in this case.

The figure 4 shows the dependence of the leakage current versus voltage of the electrostatic bending plates for different value of the cathode voltage. In this experiment the voltage of the electrostatic plates and the current in the correction coil was chosen in such a way that the electron beam doesn't shift in the collector and cooling section. So, the integral of drift motion of electron in the toroid section was constant. If the voltage of the electron from the collector bending plates corresponds to the energy of the reflected then the leakage current achieves the minimum. The electron not absorbed into the collector has some attempts to be absorbed during a few their oscillation between the collector and cathode.

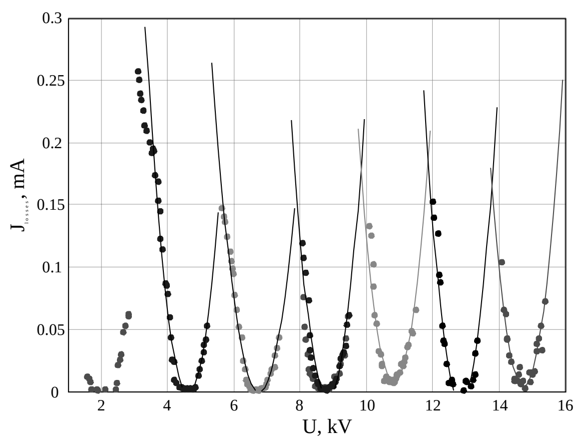

Figure 4: Loss currents for different beam energy 25, 50, 75, 100, 125, 150, 175 keV (from left to right)

The obtainable value of the recuperation efficiency is better than 10^{-6} in optimum. It leads to high vacuum condition of cooler, the pressure of residual gas was better than 10^{-11} at commissioning in BINP. There are no electrons falling on the vacuum chamber and inducing the degassing process. Really, after some training procedure the switching on of electron beam improves the vacuum pressure.

The small leakage current decreases the problem with the radiation condition. At electrostatic bending the radiation level was less than noise level. But the presence of the magnetic force lead to the leakage current and generation of X-rays. The energy 300 keV is enough for producing radiation level 25 mRem/sec per 1 mA losses current at not shielded place of cooler device.

PAN-CAKE STRUCTURE OF THE COOLING SOLENOID

The maximum cooling rate is obtained at the high quality of magnetic field in the cooling section (an angular deviation of the force line of magnetic field in the cooling section should not exceed few units of$\cdot 10^{-5}$ rad). In the cooler manufactured for IMP the transverse components of the magnetic field is eliminated by the adjustment of each coils. The alignment of coil is obtained by the tuning each coil with respect to all three spatial coordinates. Components of such a system for adjusting coils are shown in Figure 5.

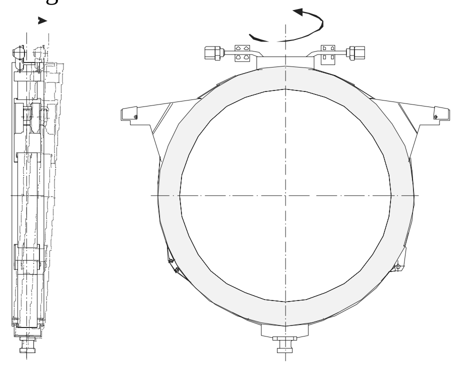

Figure 5: System for adjusting coils.

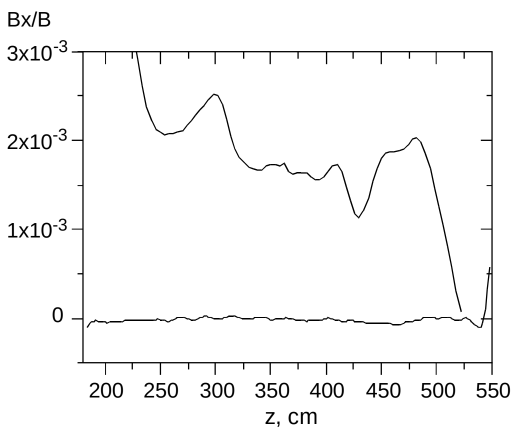

Figure 6: The transverse magnetic field before and after tuning procedure.

The amplitudes of transverse components of the magnetic field on the solenoid axis are measured with a special sensor [9]. The sensor consists of cylindrical ferromagnetic element and mirror which plane is perpendicular to the field direction. This unit is hanged on special wire that allows the ferromagnetic element (rod) to move to any direction near solenoid axis being lined up with the field. The sensor is mounted at the cart that can be moved along the solenoid axis. A mirror is fixed to the rod. In the solenoid magnetic field, the rod is oriented along the field force line and the mirror is perpendicular to the force line. All parts of the probe except for the rod are made with a light (to reduce the friction force in suspension) ferromagnetic materials and the probe is balanced carefully. The main factor limiting its real sensitivity to the variation of the magnetic field is friction in the components of the mirror suspension.

In the process of measurements, the probe placed on the trolley is moved along the solenoid axis (with stops for readings) along the special guide. The displacement angle of the mirror (together with the rod) at each point with respect to the initial position is measured with using optical methods. The basis of the optical part of the measuring device is a ~1 mm thick weakly-divergent laser beam incident onto the mirror and directed (after its reflection,) to the rectangular or round matrix made of four semiconductor photodiodes having respective form of squares 2x2 or sections with small separating gaps (in order to avoid the overlapping of the reflected beam by the radiation source it is removed aside by a semitransparent mirror).

At distances of 10 m between the mirror and detectors the displacement angle of 10^{-4} corresponds to the transverse displacement of a beam by 2 mm. With the mirror slope, the motion of the reflected light spot occurred (with the size less than the matrix diameter) leads to changes in signals from detectors. These changes are used with the feedback system for the current control in special compensating coils located around the mirror. The currents produce weak magnetic fields returning the mirror (and the spot) into the initial position. The value of the angle and the direction of the mirror displacement, i.e. the force line can be determined by the final values of currents in coils. It is essential that in this scheme, which is conceptually simple and cheap, there are no mechanical units, which are potential sources of various errors. Fig.6 show transverse angle magnet line before tuning procedure 3×10^{-3} and after tuning 2×10^{-5}.

HIGH VOLTAGE POWER SUPPLY

The The possibility of the obtaining high voltage of the cathode respects with the quality of the insulator gas SF_6. The drying of the gas enables to receive the highest potential of the cathode (see Figure 7). At absence of this procedure the corona happens at 240 kV and the leakage current increases slowly to 1.5 mA. After corona occurrence at 240 kV the corona evolves at smallest voltage yet (up to for 150 kV) and the special training procedure needs for eliminating this process.

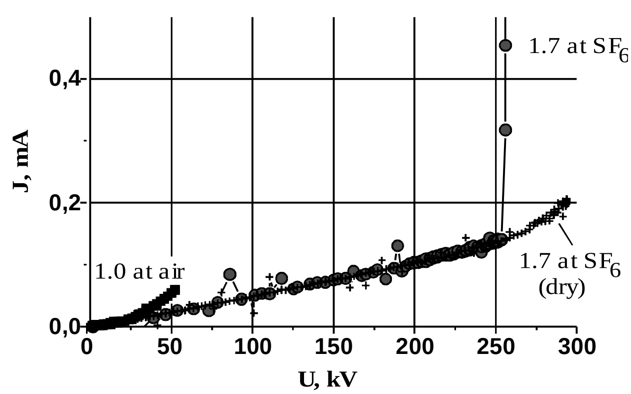

Figure 7: Maximum voltage of the cathode at the different insulator condition.

VACUUM CONDITION

The vacuum equipment of the electron cooler device should guarantee the pressure of the residual gas at level 10^{-11} torr. The vacuum system of CSR cooler consists of 4 vacuum vessels with titanium getter pumps with working surface 0.2 m^2 and pumping speed about 4000 l per sec and 2 ion pump with pumping speed about 500 l per sec. Two getter pumps is located in immediate vicinity to the electron gun and collector. The ion pumps is used for the pumping at the low vacuum.

Before the cathode activation and cooler starting for operation with the electron beam the vacuum chamber was baked at temperature 250 C during 50 hours. The maximum value of the baking temperature was chosen according to the experience of the baking on the test bench. This value of temperature is enough for the good degassing of the vacuum surface but the risk of the damage of the vacuum elements in the place of the metal-ceramic joint and bonding joint is small enough. Right away after baking the desorption coefficient of the collector was 10^{-3}. In a week of the operation the desorption coefficient decreases to $5{\cdot}10^{-3}$. The figure 8 shows the pressure of the residual gas during working with electron beam. One can see that the vacuum is $6{\cdot}10^{-11}$ torr in the device though cathode was heated and the desorption of the gas was induced by the electrons falling on the vacuum surface. The restoring time of the vacuum condition to the initial value was about 2-3 hours.

The isolated peaks on the pressure curve are respected to the evaporation of the dust. The probable cause is that the smallest pieces of the metal is heated and evaporated under the influence of the electron beam. The increasing of the voltage of cathode (high-voltage terminal) is not produced the similar effect. Thus, this phenomenon cannot be explained by the micro-discharges in the accelerator column or another pure high-voltage reasons. Knowing the disturbance of the vacuum pressure and the total volume of the vacuum chamber it is possible to estimate the diameter of the dust particle as 5-10 mkm. The aluminium dust particle with size 10 mkm is heated to the melting temperature during 10 msec under the electron current with energy 200 keV and current 1A.

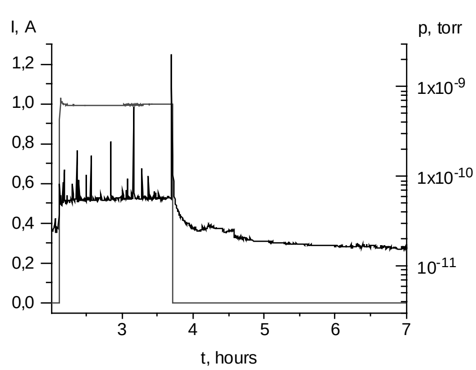

Figure 8: Vacuum pressure in the cooler device versus time.

The electron beam attracts the positive charged dust with the self negative space charge.

COMMISSIONING EC-300 AT IMP

The HIRFL-CSRe cooler EX-300 was commissioned at IMP (Lanzhou) in March-May 2004.

Main parameters achieved are following:

- Vacuum 3×10^{-11}mbar,
- High voltage 250 kV,
- Electron beam current 2.0A,
- Collector efficiency >99.99%,
- Angle of magnetic field line in cooling section: $\approx 2\times10^{-5}$.

Now the cooler is under permanent testing. Long-term stability of all main parameters is studied.

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