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THE ELECTRON COOLING SYSTEM FOR HIAF PROJECT IN CHINA*

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Abstract

A classical 450 keV magnetized DC electron cooling system is proposed to boost the luminosity of high-density internal targets experiment in the spectrometer ring (SRing) at HIAF. Electron cooling will provide highest phase space density of the stored highly charged heavy ion beams and compensate beam heating during internal target experiments. In addition, it will be used to suppress the beam loss in the deceleration mode. In this paper, the technical design of the electron cooling system is reported. The manufacturing of the key components such as the electron gun and collector is described.

INTRODUCTION

High Intensity heavy-ion Accelerator Facility (HIAF) is a new accelerator complex being constructed at the IMP site in China [1]. SRing is a versatile storage ring employed in nuclear and atomic experiments with stored stable or radioactive ion beams. Especially, the highly-charged stable ions can be used either at the injection energies or at lower energies after deceleration. A powerful electron cooling system is needed for the stable ion beams in the energy range of 800 to 30 MeV/u. It also allows few intermediate energies cooling in the deceleration operation mode, to obtain a high efficiency and low losses during the deceleration of ion beams. The electron beam should be turned off during the ramping of the high voltage deceleration. In addition, the electron cooling involves isotopes beam cooling together with the stochastic cooling system. Figure 1 shows the layout of the HIAF accelerator complex. The electron cooler will be installed in the 16 meter-straight section of SRing. The length of the cooler in ion beam direction is 11.2 m. the height is limited by the tunnel up to 6 m. Therefore, the high voltage tank is equipped on the side of the cooler.

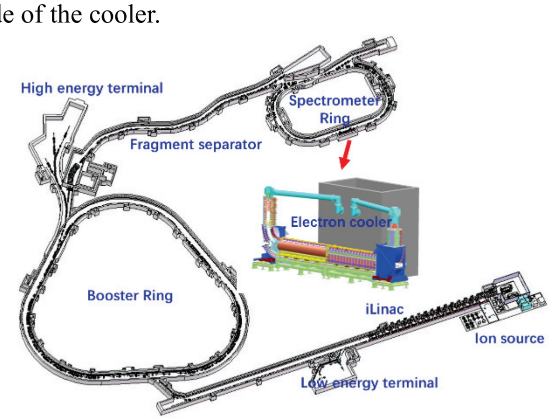

Figure 1: Layout of the HIAF accelerator and its cooler.

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CHOICE OF PARAMETERS

The ion beam $^{238}U^{92+}$ is taken as a reference in the simulation and design work of SRing. The ion energy ranges from 800 MeV/u to 30 MeV/u (deceleration) that corresponds to the electron energy range of 15 keV and 450 keV. The initial beam parameters are defined by the fast extraction system of the booster ring (BRing), as listed in Table 1. The calculations in this paper were performed a multi-particle tracking code, in which the cooling rate was derived from Parkhomchuk cooling force formula:

$$G = \frac{1}{\gamma^2}\frac{4cr_er_in_e\eta_c}{\left(\beta^2\gamma^2\frac{\varepsilon_\perp}{\beta_\perp}+\beta^2\left(\frac{\Delta p}{p}\right)^2+\left(\frac{v_{eff}}{c}\right)^2\right)^{\frac{3}{2}}}\frac{Z^2}{A}\ln\left(1+\frac{\rho_{max}}{\rho_{min}+\rho_l}\right). \tag{1}$$

the definition of the parameters can be found in [2]. All parameters should be written in the laboratory reference system.

Table 1: Initial Beam Parameters of SRing

Parameters	Value
Ion	$^{238}U^{92+}$
Energy	800 MeV/u
Emittance (hort./vert.)	4.0/2.0 π.mm.mrad
Momentum spread	8.0×10^{-4}
Stored particle number	10^9

The circumference of SRing is 277.3 m and the longest straight section is 16.0 m. The cooling rate grows linearly with the cooler length. Thus, a long cooler has a high cooling rate. Especially it is essential at the injection (top energy) stage when the emittance and the momentum spread are large. Based on the CSR cooler design, a U-shape electron cooler was proposed with the bending radius of 1.0 m. Further, a space for the compensation solenoids and correctors was considered at upstream and downstream of the cooler. Finally, an 8 m cooling solenoid was chosen for the SRing cooler. The designed β function at the centre of the cooler is 10.0 m, we estimated the maximum β function is not larger than 13.0 m according to the formula $\beta + s^2/\beta$.

The electron intensity also determines the cooling rate. Generally, the cooling rate is proportional to the electron beam current. But on the other hand, the effective velocity induced by a space charge electron drift in the longitudinal magnetic field could reduce the cooling rate. Thus, a very high electron current becomes useless. Figure 2 shows the cooling rate versus the electron current at different values of the magnetic field. The other parameters used in the calculation are listed in Table 2. Based on the operation experience of CSRe 300 kV cooler, and in consideration of the power consumption on the high voltage terminal, the maximum electron currents up to 2.0 A was designed for the

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SRing cooler. A thermionic electron gun with an oxide cathode is proposed to use in the cooler. The Ni sponge cathode radius is 15 mm, the emission current density is 0.25 A/cm^2 at the temperature of 700 °C and 0.50 A/cm^2 at the temperature of 750 °C, respectively. A prototype of the cathode was already developed [3].

Table 2: Simulation Parameters of SRing Electron Cooling

Parameters	Value
Electron energy	438.8 keV
Lorentz factor	β=0.842, γ=1.853
Electron beam radius	3.0 cm
Electron beam current	2.0 A
Electron beam density (PRF)	9.3×10^6/cm^3
Longitudinal magnetic field	8.0×10^{-4}
Electron beam temperature (horizontal / longitudinal)	0.5 / 3×10^{-5} eV
Magnetic field homogeneity	1×10^{-4}
Beta-function	9.9 m / 9.7 m
Cooling length/circumference	2.6%

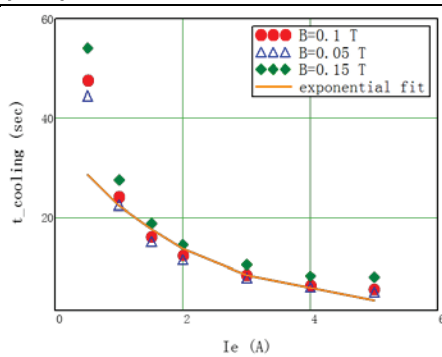

Figure 2: cooling time versus electron current at different values of magnetic field.

It is also observed that the longitudinal magnetic field changes the cooling time. As the magnetized cooling theory, the radius of electron Larmor gyration should be much less than the maximum impact parameter, and more importantly, the electron drift velocity in the space charge fields of the electron beam and the longitudinal magnetic field should be much smaller than the effective velocity induced by the magnetic field homogeneity. Finally, a longitudinal magnetic field up to 1.5 kGs was used for the SRing cooler.

Magnetic field homogeneity in the cooling section is an important parameter in Parkhomchuk formula. It makes a largest contribution to the effective velocity. Figure 3 shows the cooling time versus the field homogeneity. It shows a good magnetic field homogeneity starts at 10^{-4}, further decrease of the homogeneity does not lead to the variation of the cooling time. A pan-cake structure of the cooling section solenoid, which was already used in coolers for CSR successfully [4], obtained a high precise magnetic field with the homogeneity better than 3×10^{-5}. Based on the simulation results and the CSR cooler commissioning experience, a longitudinal magnetic field homogeneity better than 10^{-4} is required at the cooling section solenoid.

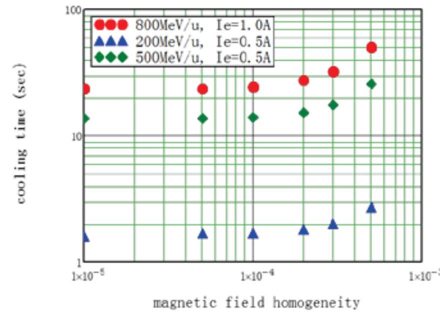

Figure 3: cooling time versus longitudinal magnetic field homogeneity at different energies of cooling.

COOLING PROCESS SIMULATION

The main task of the SRing electron cooler is to reduce the beam phase volume at the injection energies, and provide continually cooling effect at experimental energies for the internal target operation mode. A typical operation scheme is shown in Fig. 4. At the injection energies, the electron cooling is turned on for a few seconds to reduce the emittance several times. It is not necessary to cool down the ion beam to the equilibrium status. Then the electron beam is turned off for the decreasing of the high voltage. After the deceleration, the electron beam is turned on again, to supress the heating effects and compensate the energy loss of the internal target experiments. Optionally, an intermediate cooling is also available to optimize the beam quality in the deceleration mode.

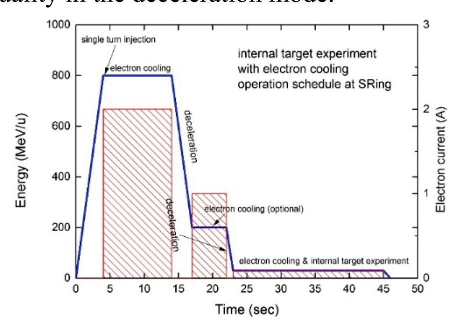

Figure 4: SRing operation scheme with electron cooling.

A cooling process of 800 MeV/u $^{238}U^{92+}$ beam is simulated, as shown in Fig. 5. The input parameters are listed in Tables 1 and 2. It is seen that the emittances and momentum spread are effectively decreased during 10 seconds.

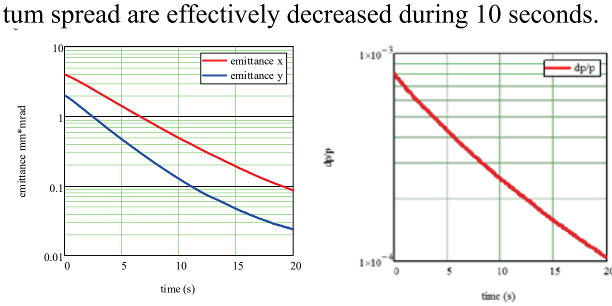

Figure 5: Beam emittances and momentum spread versus time at electron cooling of 800 MeV/u ^{238}U92+ beam.

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SRING ELECTRON COOLER

The general layout of the SRing electron cooler is shown in Fig. 6. Basically, a strong longitudinal magnetic field is used to guide the electron beam and to magnetize the electrons. The electron beam extracted from the gun is accelerated to an energy up to 450 keV and bent into the cooling section. After the interaction, the electron beam is guided to the collector and absorbed in it. The cooler consists mainly of electron gun, collector, acceleration tube, guiding magnets and high voltage tank. The main technical parameters of the SRing electron cooler are listed in Table 3.

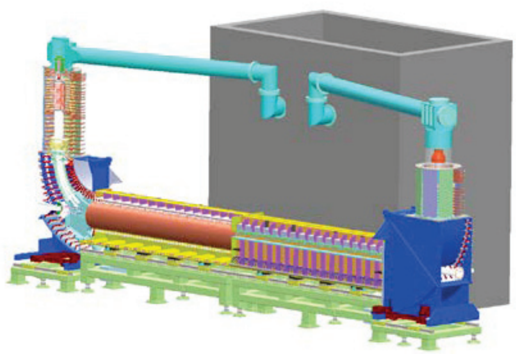

Figure 6: Layout of the SRing electron cooler.

Table 3: Technical Parameters of SRing Cooler

Parameters	Value
Maximum acceleration voltage	450 kV
Voltage ripple	$<5.0\times10^{-5}$
Cathode radius	1.5 cm
Maximum electron current	2.0 A
Gun solenoid field	4.0 kGs
Cooling solenoid field	1.5 kGs
Collector solenoid field	2.0 kGs
Effective cooling length	7.4 m
Vacuum chamber diameter	200 mm
Vacuum	2.0×10^{-11}
Total power consumption	700 kW

Gun and Acceleration

In order to control the electron beam temperature out of the acceleration, the thermionic electron gun together with the acceleration tube immerse in the same longitudinal magnetic field up to 4.0 kGs, as shown in Fig. 7. We use a similar gun geometry of CSRe cooler for the calculation. A 502 mm tube with 23 electrodes and an electrical gradient of 10 kV/cm was used for the acceleration of the electron beam up to 450 keV. Generally, the transverse electric field at the exit of the acceleration tube significant leads to an increasing of the electron beam temperature due to the $E\times B$ drift velocity. An increasing of the longitudinal magnetic field reduces the electron Larmor radius and the drift velocity, thereby obtaining an adiabatically motion. An additional transverse temperature less than 0.1 eV was obtained while the longitudinal magnetic field was 4.0 kGs.

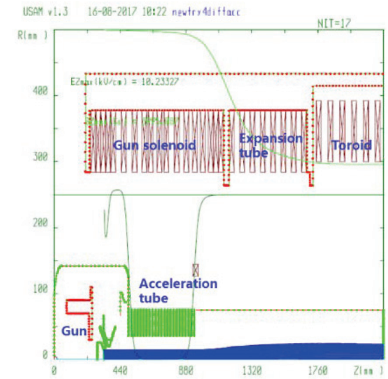

Figure 7: electron trajectory in gun and acceleration tube.

As the same as the CSR coolers' gun, the grid electrode placed between the cathode and the anode is used to produce a variation of the transverse electron beam density distribution [5]. A "hollow" electron beam will be obtained by increasing of the ratio of grid-to-anode voltages V_g/V_a. The calculation by UltraSAM also shows a linear increase of perveance with the increasing of V_g/V_a:

$$P(\mu P) = 15.9\frac{V_g}{V_a} - 1.3. \tag{2}$$

Collector

The SRing cooler collector consists of an oil-cooled oxide-free cupper cup, a suppress electrode and an anode. The magnetic field is optimized in order to minimize secondary electrons emission. The maximum magnetic field in the collector is around 2.0 kGs. The supress electrode is used to form an electrostatic potential barrier to supress electrons escape from the collector. The supress electrode voltage is 400 V. The electrostatic potential and the magnetic field in the collector are shown in Fig. 8. In the ejected electrons trajectory simulation, 200 secondary electrons are generated randomly in the energy range between 0 and 3 keV, the azimuthal angle range between 0 and 2π. The trajectories show that most electrons go back to the collector cup but only few electrons can escape successfully. The simulation results show a collect efficiency better than 10^{-3} is available.

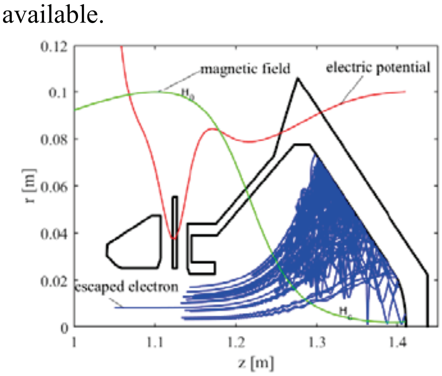

Figure 8: Secondary electrons trajectory in collector.

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Magnetic Field

A high-quality magnetic field is required for the SRing cooler, the allowable magnetic field homogeneity is estimated to be less than 10^{-4} in the cooling section and 10^{-3} in other sections, respectively. A 3-D Opera module was used for the analysis, as shown in Fig. 9. The field calculation was done in ion beam direction, especially the toroid section.

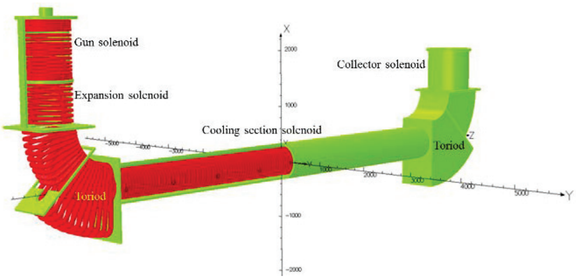

Figure 9: 3-D Opera module of SRing electron cooler.

As expected, a vertical field component with a maximum value of about 700 Gs on the collector-side toroid is shown in Fig. 10. The field direction is upwards since the guiding magnetic field is from the gun to the collector. It causes a severe horizontal ion beam deflection which has to be corrected by a set of steerers around the cooler. A weaker but not negligible orbit distortion in the vertical plane is caused by the horizontal field component.

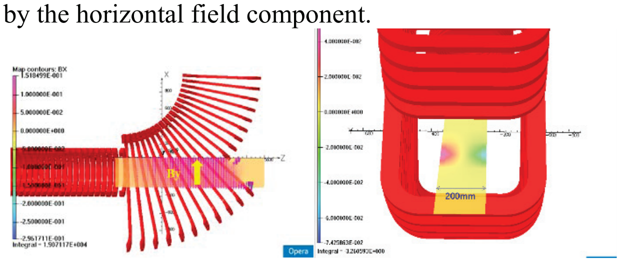

Figure 10: Vertical and horizontal field components on the collector-side toroid.

The magnetic field along the electron beam trajectory was also calculated from the gun side to the collector side. The magnetic field is decreased gradually from 4.0 kGs at the gun section to 1.5 kGs at the cooling section. The transverse electron temperature is expected to be decrease by adiabatic expansion:

$$\zeta = \frac{\lambda}{B_s}\frac{dB}{ds}. \tag{3}$$

where $\lambda = \frac{2\pi\gamma m_e \beta c}{eB_s}$. The total magnetic field and calculated adiabaticity at different electron energies are shown in Fig. 11. It is seen that the adiabaticity parameter is less than 0.15 at the top electron energy of 450 keV, and the parameter decreases with decreasing of the electron energy. The adiabaticity parameter stays always well below 1.0. A good adiabatic condition for electron motion can be achieved.

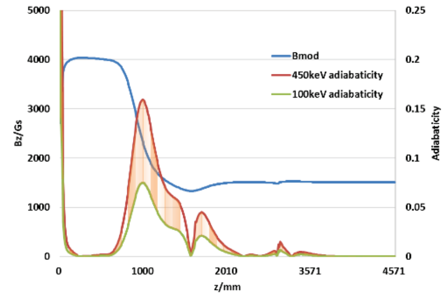

Figure 11: Magnetic field along the electron trajectory and adiabaticity parameters at different energies.

CONCLUSION

The SRing electron cooler has been designed. The effective cooling length is 7.4 m or 2.6% of the ring circumference. The adiabatic parameter along the electron beam trajectory is kept bellow 0.15. This magnetized electron cooler can provide a powerful cooling effects on the highly-charged stable ions or long-lived radioactive isotopes. The main components such as the electron gun, the collector, the magnetic field system have been designed. The technical design of the high voltage system is still under investigation.

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REFERENCES

[1] J.C.Yang *et al.*, *Nucl. Instr. and Meth. B* vol. 317, pp. 263-265, 2013.

[2] V.V.Parkhomchuk, *Nucl. Instr. and Meth. A* vol. 441, pp. 9-7, 2000.

[3] X. H. Liao, Y. Li, M. F. Meng, X. X. Wang, and Q. L. Zhao, “Study on the Oxide Cathode for HIRFL-CSR Electron Cooler”, in *Proc. 7th Workshop on Beam Cooling and Related Topics (COOL'09)*, Lanzhou, China, Aug.-Sep. 2009, paper THPMCP012, pp. 160-163.

[4] L.J.Mao *et al.*, *High Power Laser and Particle Beams*, Vol.17, No.7 pp. 1106-1110, 2005.

[5] A. V. Ivanov *et al.*, “The Electron Gun with Variable Beam Profile for Optimization of Electron Cooling”, in *Proc. 8th European Particle Accelerator Conf. (EPAC'02)*, Paris, France, Jun. 2002, paper WEPRI049, p. 1356.