Optimization of Compact Electron Cooler for the S-LSR Ring

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Abstract

The electron cooling technique in the S-LSR will be used to cool and store $^{12}C^{6+}$ ions with total energy 2MeV/u produced in a laser induced source. The S-LSR has a total circumference of 22.56m and a straight section length of 1.86m. A compact electron cooler with cooling solenoid length of 0.8m and toroid radius of 0.25m was designed and will be installed in the S-LSR. The electron gun with Perveance of 2.2μP achieves a maximum current of 80mA necessary for efficient carbon beam cooling. The gun geometry is optimized by numerical simulations in order to reduce the transverse electron beam temperature.

1 INTRODUCTION

The S-LSR project initiated by ICR of Kyoto University and NIRS, consists of a $^{12}C^{6+}$ carbon ions injector system utilizing a laser induced ion source, and a compact cooler ring equipped with both an electron cooling and laser cooling devices [1-2]. The cooling of carbon ions in the S-LSR has the peculiarity that the injected beam has a large momentum spread ($\Delta P/P=1\%$). Feasibility studies for effective cooling of carbon ion beam with large momentum spread had been carried out at the TSR with positive results [3-4]. Numerical simulations of cooling times with BETACOOL [5] code for $^{12}C^{6+}$ with energy 2MeV/u, momentum spread of 1% and emittances of 50/10π.mm.mrad, have shown that a cooling time of 200ms in all degrees of freedom is possible with electron current of 50mA, electron beam radius of 2cm and an adiabatic expansion factor of 2 at S-LSR [6]. In this work we present the computer simulations carried out in order to optimize the electron cooler for the specifications of the S-LSR project.

2 SPECIFICATIONS

The compact cooler ring S-LSR has a total circumference of 22.56m and a maximum magnetic rigidity of 1Tm. The ring super-periodicity is 6, which limits the length of the straight section to about 1.86m. The ring will store and cool 7MeV protons from the existing proton linac at ICR and 2MeV/u carbon ions from the laser ion source. The electron cooling device is

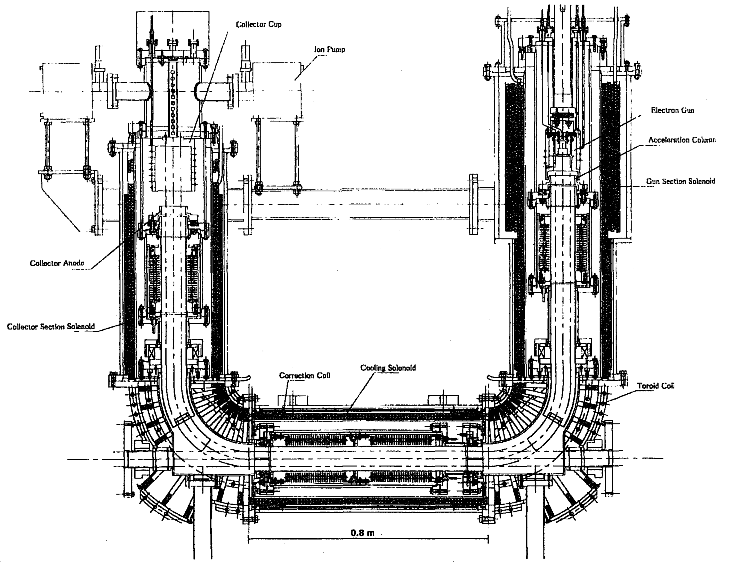

Fig.1 Schematic view of the S-LSR cooler

designed and optimized for operation in two energy modes corresponding to carbon and proton cooling. For 2MeV/u carbon ions, the electron beam energy is 1.1keV, which limits the available beam current. The main parameters of the cooling device are shown in table 1. Numerical simulations of the cooling time [6] showed that the magnetic expansion factor B_{gun} / B_{cool} of 2 or 3 is sufficient to efficiently cool the longitudinally hot carbon ion beam. The magnetic field of 1.5kG in the gun section and of 0.5kG in the cooling section is utilized for the current design.

Table 1 Parameters of the S-LSR electron cooler

Cooler solenoid length, m	0.8
Bending toroid radius, m	0.25
Magnetic field (gun/cooling), kG	1.5/0.5
Maximum adiabatic expansion factor	3
Field uniformity in cooling solenoid	$5x10^{-4}$
Electron energy, keV	1 - 5
Cathode radius, mm	15
Electron beam current, A	0.05 - 0.4
Gun Perveance, μP	2.2
β-function at cooling section, m	1.7/2.4

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3 HARDWARE DESIGN

The schematic layout of the S-LSR electron cooler is shown in figure 1. The limited space in the straight section of the ring puts stringent restrictions on the length of the cooling section and the radius of the equilibrium electron orbit inside the toroidal section. In the current design the length of the cooling solenoid is 0.8m and the toroidal bending radius is 0.25m.

3.1 Electron Gun

An electron gun is proposed for the S-LSR with three electrodes: a flat cathode of diameter 30mm, a Pierce electrode and an anode, which achieves a high enough Perveance of 2.2μP. For carbon beam cooling the maximum current is 80mA and for proton beam cooling the current is more than 400mA. The diameter of anode aperture is 60mm and the distance between the cathode surface and the anode is 5mm. Figure 2 shows the simulated electron trajectories during the adiabatic expansion of factor 3. The adiabatic expansion of the electron beam due to the variation of the axial magnetic field reduces the transverse temparature. This effect was simulated by tracking the electron beam using the EGUN[7] code, and calculating the transverse temperature $T_\perp$ using the equation

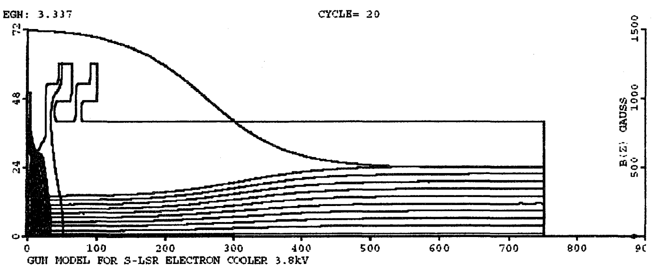

Fig.2 Simulation of electron beam trajectories during adiabatic expansion for B_{gun}=1.5kG, B_{cool}=0.5kG and E_e=3.8keV (plot scales are not equal).

$$k_bT_\perp = \tfrac{1}{2}m_e(\frac{1}{N}\sum(v_t-\bar{v}_t)^2+\frac{1}{N}\sum(v_r-\bar{v}_r)^2) \quad (1)$$

where k_b is Boltzmann's constant, m_e is the electron mass and v_r and v_t are the radial and azimuthal electron velocities respectively. Figure 3 shows the simulation results for cases with expansion factors 1 and 3, electron energy of 3.8keV and electron current of 300mA. The cathode is positioned at the longitudinal coordinate Z=0mm and the cathode temperature is 1400K. For the case without expansion, the calculated electron beam temperature is about 120meVwhich is equal to the cathode temperature. However, with the adiabatically expanded electron beam we reach a transverse temperature of 40meV, which is consistent with the expansion factor of 3.

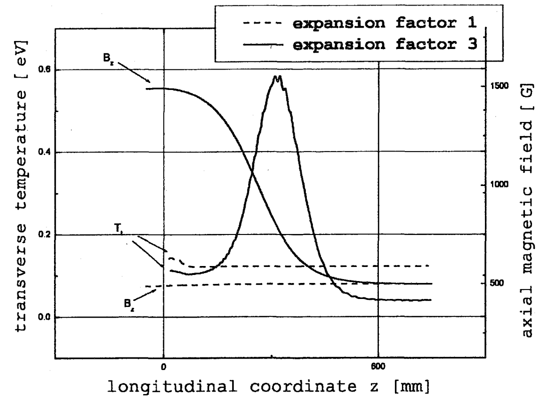

Fig.3 Effect of the adiabatic expansion on the transverse temperature of the electron beam.

3.1 Optimum angle of the Pierce electrode

The Pierce electrode is an important part of the electron gun. For a space-charge dominated electron gun, the shaped electrodes serve to establish correct potential variation along the beam boundary. The analytic derivation of Pierce [8] gives θ_P=67.5° for the angle of the electrode. This result holds when the following condition is satisfied

$$2r_a \ll d \quad (2)$$

where, r_a is the radius of the anode aperture and d is cathode-anode gap. For the current design of the S-LSR cooler gun we have r_a=30mm and d=5mm in order to achieve high enough Perveance. This design does not satisfy equation 2, therefore we have performed numerical simulations in order to optimise the angle of the Pierce electrode. The EGUN simulation was performed with electron energy Ee=3.8keV, electron current Ie=300mA and magnetic field in gun section of 500G. The electron beam radius is 15mm. The results in figure 4 show the dependence of the radial electron velocity at the exit of the gun section (Z=750mm) for different radial positions inside the beam, on the angle of the Pierce electrode. We see that the optimum angle which minimizes the radial velocity for all electrons of different radial positions is located around 62°. The standard angle of 67.5° is clearly not the optimum for this specific design of the S-LSR gun. Similar result was obtained for the azimuthal velocities. It should be noted that this optimum angle depends on the shape of the anode as well as on the gap between the cathode edge and the Pierce electrode. Similar

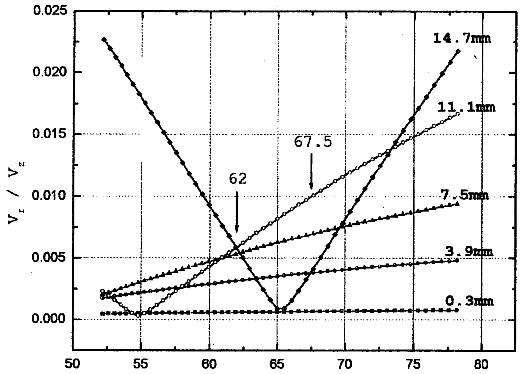

Fig. 4 Dependence of the radial electron velocity on the angle of the Pierce electrode (E_e=3.8keV, B_{gun}=500G, I_e=300A)

calculations for electron energies of 1.1keV and 7.5keV gave similar results with an optimum angle around 62°. The dependence of the transverse temperature defined by equation 1 on the Pierce electrode angle was also

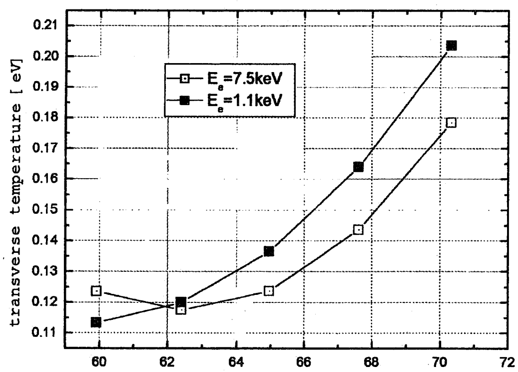

Fig. 5. Dependence of the transverse temperature on the angle of the Pierce electrode.

calculated at the exit of the gun section for electron energies of 1.1keV and 7.5keV. The result is shown in figure 5. We see that the transverse temperature is minimized when the angle of the Pierce electrode is about 62°. The minimum temperature of 120meV is consistent with the cathode temperature of 1400K.

3.2 Electron collector

The electrons exiting the cooling section, are guided by a second toroid coil towards the collector section. The S-LSR electron collector is a water-cooled oxide-free copper cup of diameter 120mm and length of 150mm. The main solenoid in the collector section creates a magnetic field of 500G equal to the filed in the cooling section. A short solenoid at the end of the collector section creates a reverse image field which bends the magnetic field lines inside the cup as seen in figure 5. This achieves a good distribution of the electrons hitting the walls of the cup. The cup geometry and the reverse

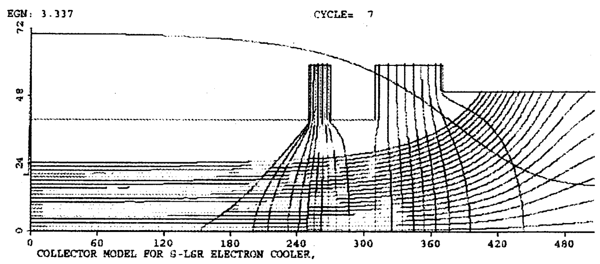

Fig. 6 Electron beam trajectories inside the collector.

image coil will be further optimized for secondary electron emission [8] in order to minimize the loss current and improve the vacuum conditions.

4 CONCLUSION

A compact electron cooling device has been designed for the S-LSR project which will cool 2MeV/u carbon ions and 7MeV protons. Numerical simulations have been carried out in order to optimise the design for these two cooling modes. The Perveance of the gun is 2.2μP and the optimum angle of the Pierce electrode is 62°. The expansion scheme with expansion factor of 3 achieves a transverse temperature of 40meV. The electron collector has been designed with an image field coil which achieved good distribution of the electron beam on the inside walls of the cup. The collector will be optimised in order to reduce the number of reflected electrons.

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