Design and Magnetic Field Measurement of the S-LSR Compact Electron Cooler

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Abstract

A compact electron cooler has been designed and constructed for the cooler ring S-LSR. A homogeneous magnetic field in the cooler provides confinement for the electron's transport from the gun through the cooling section to the collector. The field distribution was investigated with 3-dimensional calculations and precise field measurements were performed after construction of the electro-magnets. The length of the good field region of 0.43m is achieved. Adiabatic condition is satisfied for the electron motion along solenoid axis. The magnetic field distribution inside the collector is also investigated and optimized in order to optimize primary and secondary electron capture.

1 INTRODUCTION

The S-LSR [1] electron cooler is shown in figure 1. It consists of an electron gun that generates an electron beam at the thermionic cathode and a transport system consisting of solenoid and toroid guiding fields. The electron gun, of Perveance 2.2μP delivers a maximum current of 80mA at electron energy 1.1keV. After the interaction of the electrons with the ion beam in the cooling section, the electron beam is recaptured at the collector. The detailed design of the electron gun and magnetic guiding system were presented previously [2-3]. The design value of the longitudinal field is 500G and the maximum field in the gun section is 1500G corresponding to a maximum expansion factor of 3.

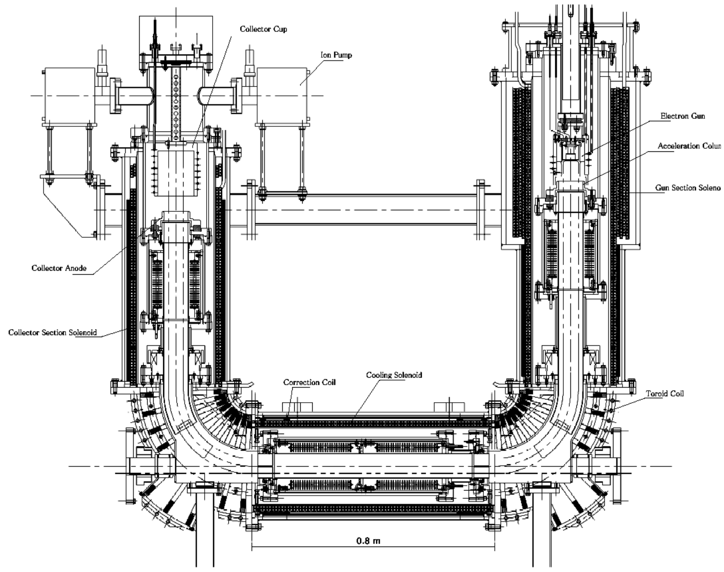

Fig.1 Schematic view of the S-LSR cooler

2 FIELD MEASUREMENTS

After the construction of the electron cooler magnets was completed, measurements of all 3 components of the magnetic field were performed. We have utilized a high resolution Hall probe with precision better than 0.1G or 2.10^{-4} for a main field component of 500. The measurement along the straight section was done with a 3-axis stage controlled by a computer. The measurement of the fields inside the toroid, gun and collector was done with a aluminium rail installed inside the electromagnets prior to assembly. Figure 2 shows the measurement with the stage. The three probes are installed on an aluminium rod which is inserted inside the cooling section via the pening in the toroid. The probes are calibrated against MR data, and also perform automatic temperature alibration.

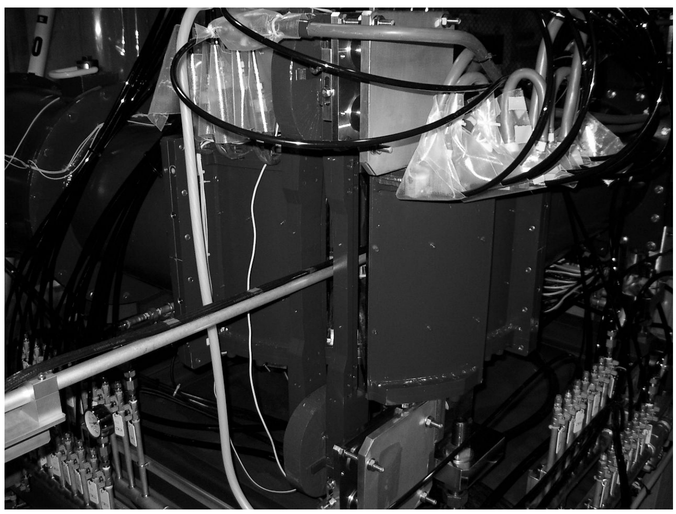

Fig.2 Measurement of the magnetic field with the 3-axis stage. The picture shows the upstream toroid section and the steering magnet.

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2.1 Gun and toroid Section

The electron gun of the S-LSR cooler will be mainly utilized for the regime with expansion factor of 3. This regime corresponds to maximum magnetic field of 1500G at the cathode surface. The measurement was performed for maximum field of 1500G, 1000G, 500G and 350G. The variation of the magnetic field along the beam axis is characterized by the adiabatic parameter χ_{ad} defined as

$$\chi_{ad} = \frac{\lambda_{\|}}{B} \left| \frac{\partial B}{\partial s} \right| \qquad (1)$$

where, $\lambda_{\|}$ is the spiral length of the cyclotron motion

$$\lambda_{\|} = \frac{2\pi v_{\|}}{\omega_c}, \omega_c = \frac{eB}{m_e} \qquad (2)$$

The adiabatic condition is $\chi_{ad} << 1$. Figure 3 shows the measured magnetic field from the gun section to the cooling section. The cathode is positioned at s=-1550mm and the centre of the cooling solenoid corresponds to s=0.

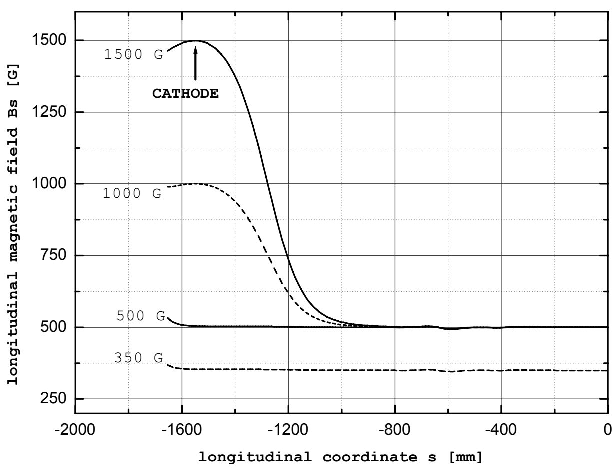

Fig.3 Distribution of the longitudinal magnetic field along the beam axis of the S-LSR electron cooler for various expansions.

Using equations 1 and 2 we calculated the adiabatic parameter along the electron beam axis form the measured distributions. The result for electron energy 1.1keV is plotted in figure 4. We observe that the adiabatic condition is fulfilled for all field magnitudes with a maximum adiabatic parameter bellow 0.04 for 1500G. Also it should be noted that the adiabatic condition is also satisfied inside the toroid section. This shows that an optimized discrete coil topology can achieve good adiabatic conditions for electron motion.

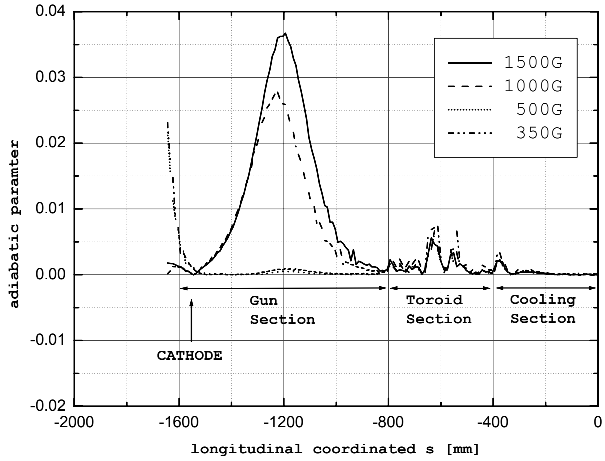

Fig.4 Variation of the adiabatic parameter along the beam axis from the gun section to the centre of the cooling solenoid.

2.2 Cooling section

The length of the cooling section of the S-LSR cooler is 0.8m. The cooling time measured in the laboratory frame depends on the ring averaged cooling force and is proportional to the effective length of the cooling section. The electron beam motion is constrained by the field lines of the guiding magnetic field. The transverse field components in the cooling section cause a transverse relative velocity component between ions and electrons which affects the efficiency of the cooling. Moreover, due to this transverse motion there is a detuning of the longitudinal velocity matching between electrons and ions, which reduces further the cooling force. The effective length of the cooling section is therefore limited by the transverse field of the toroid magnets, which in the case of this device is rather large, about 70G in maximum, due to the small radius of the equilibrium orbit of the toroid (250 mm). Two additional Helmholtz coils of length 100mm, radius 150mm and 8 turns each, are placed at both ends (s=±325 mm) of the cooling section outside the main solenoid in order to compensate the transverse magnetic field. The measured transverse field $B_{\perp}$ is shown in figure 5. When the Helmholtz correction coils are not excited the effective length of the cooling section L_{eff} is 240mm, where the good field region is defined as $| B_{\perp} | \leq 0.25$G or $| B_{\perp} / B_{\|} | \leq 5.10^{-4}$ for $B_{\|}$ = 500G. L_{eff} is increased to 430mm or about 2% the circumference of the ring when the dipole coils are excited with a current of 10A. Therefore we have succeeded to recover more than 50% of the cooling section (800 mm) for effective cooling by this correction scheme. However, in order to improve further the field

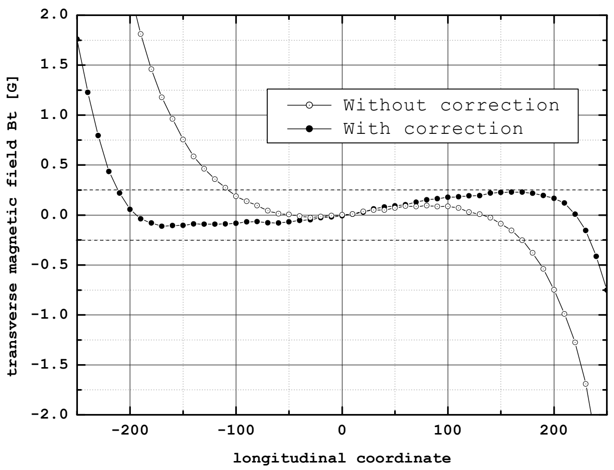

Fig.5 Transverse magnetic field distribution in the cooling section (-250≤ s ≤250) for cases with and without dipole correction; L_{eff} increased from 240mm to 430mm, or 2% the total circumference

In the cooler design, there are excess Ampere-turns at the transitions between the solenoids and the toroids, due to the discrete coil topology in the toroids. The longitudinal field shows a bump at these transitions as can be seen in figure 6. Additional longitudinal field correction coils were placed at the transition locations in order to reduce the field bumps are shown in figure 6 (case with correction).

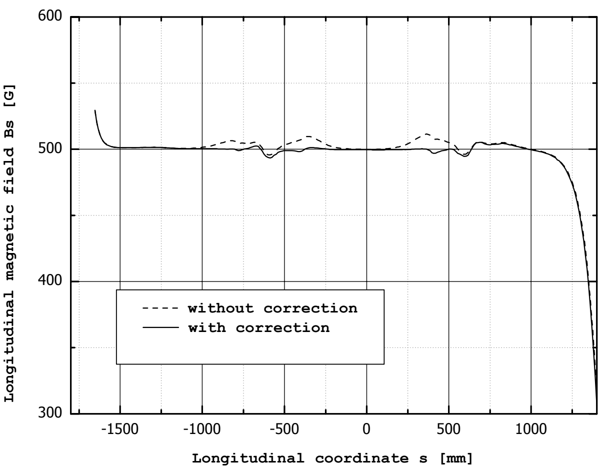

Fig.6 Reduction of longitudinal field bumps with correction coils.

2.3 Collector section

After leaving the cooling section the electrons reach the collector, which should collect the electrons with high efficiency. One relevant factor which influences the design of the collector is the distribution of the magnetic field. We have found that a slightly negative longitudinal field of -1.5G (produced by mirror field coil in the collector) on the bottom of the collector cup is effective in trapping secondary electrons leaving the surface. However as can be seen in figure 7, a too strong negative field of -45G will cause the primary electron being reflected before reaching the cup surface. Therefore configuration (b) with a reverse field of -1.5G is utilized in the S-LSR cooler which is effective in trapping both primary and secondary electrons.

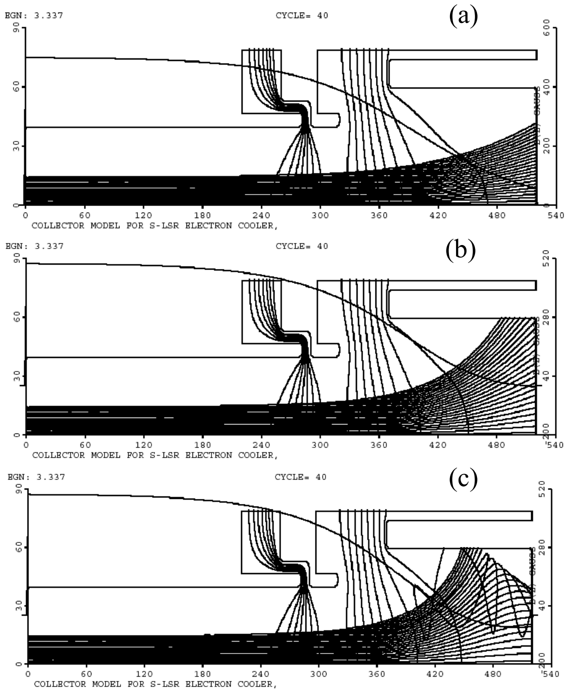

Fig.7 Trajectories of the primary electron beam for different field magnitudes; (a) 57G, (b) -1.5G, (c) -45G

3 CONCLUSION

The S-LSR compact electron cooling device has been constructed. The measurement of all 3 components of the magnetic field has been performed and the device parameters optimized in order to achieve high field quality (adiabatic condition). The effective length of the cooling section is 430mm or 2% of the ring circumference and the adiabatic parameter along the beam axis is kept bellow 0.04. An image field coil is used in the collector in order to create a slightly negative field which is optimized for both primary and secondary electron capture.

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