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Design of a compact electron cooler for the S-LSR

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Abstract

The Small Laser-equipped Storage Ring (S-LSR) project has been initiated by ICR of Kyoto University and NIRS, with the purpose of demonstrating the feasibility of electron beam cooling of laser produced ions. A compact electron cooling device with a cooling solenoid length of 0.8 m and two 90° angle toroid magnets of radius 0.25 m will be installed in the S-LSR, which is required to reduce the velocity spread of a laser induced carbon ion beam with a mean energy of 2 MeV/u from 1% to 0.1%. The magnetic field of the main solenoid is 500 G, and the maximum expansion factor is 3. The design of this electron cooler is presented.

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Keywords: Electron cooling; Heavy ions; Storage ring; Electron gun

1. Introduction

Electron cooling [1–2] is important for the production of high quality ion beams, which have several applications. The Institute of Chemical Research of Kyoto University and the National Institute of Radiological Sciences have initiated the Small Laser-equipped Storage Ring (S-LSR) project with the aim of demonstrating the feasibility of a compact accelerator system for heavy-ion cancer therapy. The S-LSR will store carbon ions $^{12}C^{6+}$ of mean kinetic energy 2 MeV/u, coming from a laser induced source, and an electron cooling device will be utilized to reduce the phase space volume for further acceleration [3].

2. Cooling times

The peculiarity of the electron cooling scheme at the S-LSR is the large velocity spread of the ion beam ($\Delta P/P = 1\%$). Experimental studies were performed at the TSR [4] to test the feasibility of an efficient cooling scheme for longitudinally hot ion beams. A combination of electron cooling and energy sweeping will be utilized at the S-LSR in

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order to accelerate the damping of the longitudinal degree of freedom [5]. Cooling times for carbon ions were calculated using the BETACOOL code developed at JINR [6]. The simulation results for $^{12}C^{6+}$ with energy of 2 MeV/u, velocity spread of 1% and horizontal and vertical emittances of 50π mm mrad and 10π mm mrad, respectively, show that a cooling time of about 200 ms in all degrees of freedom is possible with electron current of 50 mA and electron beam radius of 2 cm [7].

3. Specifications

The S-LSR is a compact cooler ring of total circumference of 22.56 m and a maximum magnetic rigidity of 1 Tm. The ring super-periodicity is 6, which limits the length of the straight section to 1.86 m. The S-LSR is designed for storing 7 MeV protons from the existing proton linac at ICR and 2 MeV/u carbon ions from the laser induced source. It will be also utilized to store and laser-cool $^{24}Mg^{+}$ ions. The electron cooler device is designed for maximum electron energy of 5 keV. The limited space in the straight section puts stringent restrictions on the length of the cooling section and the radius of the equilibrium electron orbit in the toroidal section. In the current design the length of the cooling solenoid is 0.8 m and the toroidal bending radius is 0.25 m. The main specification parameters are shown in Table 1, and a schematic layout of the cooler is shown in Fig. 1.

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	5×10^{-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

4. Hardware design

4.1. The electron gun and collector

The cooling of $^{12}C^{6+}$ with energy of 2 MeV/u corresponds to electron energy of 1.1 keV. For such low energy, the current is limited by the perveance of the gun. The design of the gun aims at providing a high enough perveance in order to achieve fast cooling of the carbon beam. The gun design was investigated by the EGUN [8] code. The cathode radius is 15 mm and the anode aperture radius is 30 mm. The calculated gun perveance is 2.2 μP. For carbon beam cooling, the maximum current is 80 mA. To cool a 7 MeV proton beam the maximum current is more than 400 mA. The magnetic field in the gun section is provided by two solenoid coils which can achieve a maximum field of 1.5 kG. The maximum field in the cooling section is 500 G. The adiabatic variation of the magnetic field from the gun section to the cooling section corresponds to an adiabatic transverse expansion of the electron beam and results in a reduction of the transverse temperature [9]. The adiabatic expansion process was simulated by tracking the particles with the EGUN code. The transverse temperature $T_\perp$ is defined by

$$k_B T_\perp = \frac{1}{2} m_e \left(\frac{1}{N} \sum (v_t - \bar{v}_t)^2 + \frac{1}{N} \sum (v_r - \bar{v}_r)^2 \right) \tag{1}$$

where k_B is Boltzmann's constant, m_e the electron mass and v_r and v_t are the radial and azimuthal velocities, respectively. Fig. 2 shows the dependence of the transverse temperature on the longitudinal coordinate z for the cases with and without expansion and electron current of 300 mA. The cathode is positioned at $z = 0$. We see that the transverse temperature is reduced by factor 3 from more than 120 meV to about 40 meV due to adiabatic expansion.

The S-LSR collector consists of a water cooled oxide-free cupper cup of radius 60 mm and length of 150 mm. A short solenoid coil creates an image magnetic field which reduces the magnetic field significantly on the bottom of the cup. After making a preliminary design of the collector, efforts are now being made to optimize the

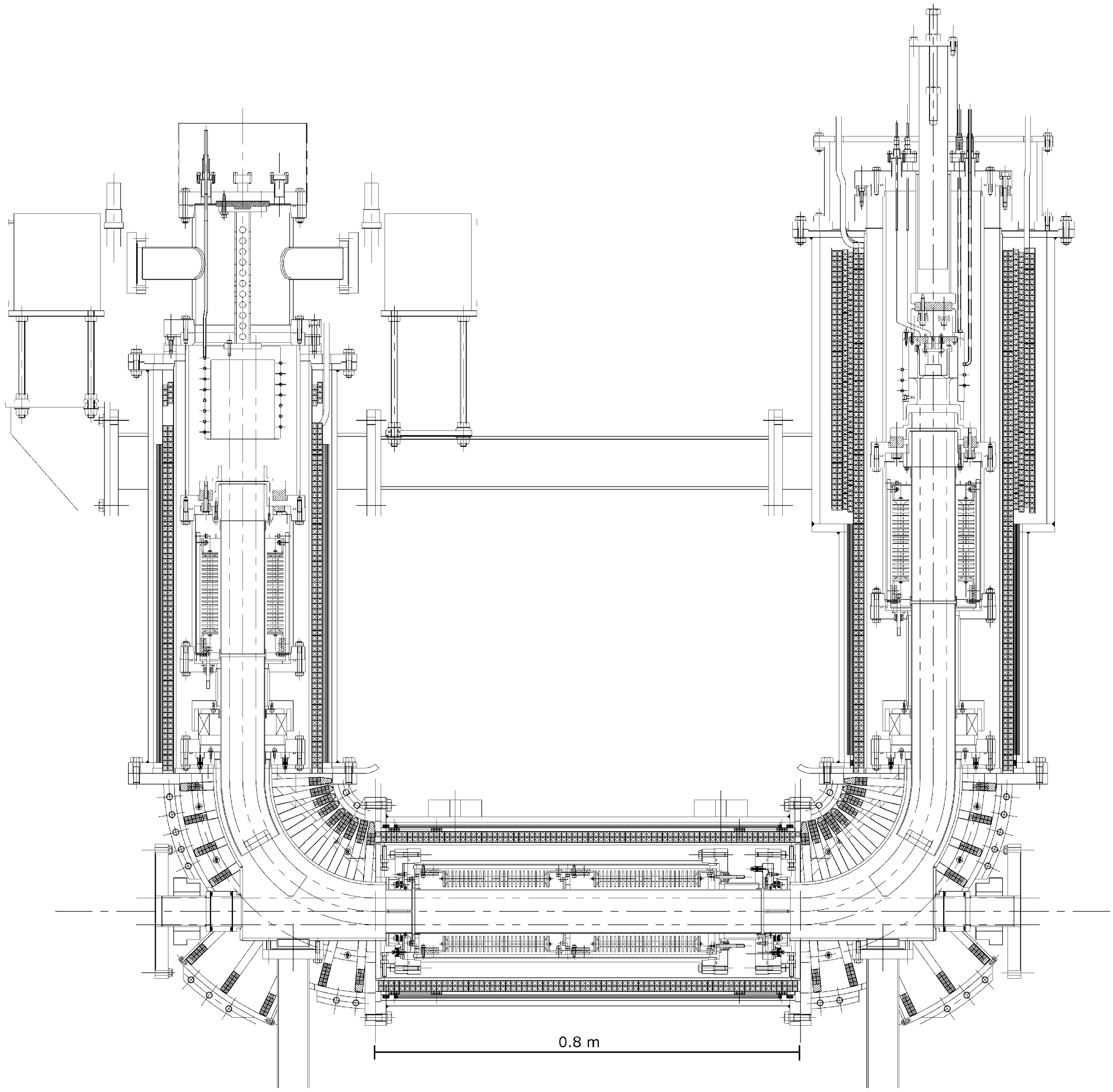

Fig. 1. A cross-sectional view of the S-LSR electron cooler. The toroid of radius 0.25 m has 9 discrete coils. The straight section is 0.8 m in length. The magnetic field in the cooling section is 500 G and the maximum expansion factor is 3

magnetic field and cup geometry in order to minimize secondary electrons emission. On passage through both bending toroidal magnets the secondary electrons suffer a drift displacement of

$$\Delta_{tor} = 2\pi\, m_e v_e / eB \tag{2}$$

where v_e is the electron velocity and B is the magnetic field. For secondary electron energy of 1.1 keV and a longitudinal field of 500 G, we get a displacement of $\Delta_{tor} = 1.3$ cm. The secondary electrons will be lost on the gun anode or on the walls of the vacuum chamber, causing a deterioration of the vacuum condition. The possibility of an electrostatic deflector in the toroid section instead of the standard dipole correction coil is being investigated in

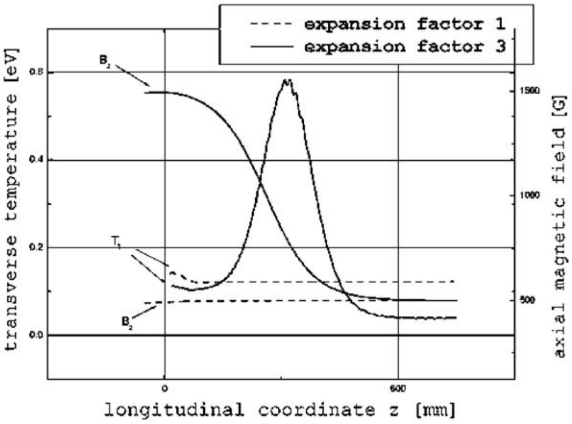

Fig. 2. Reduction of the transverse electron beam temperature by adiabatic expansion ($I_e = 300\,\text{mA}$).

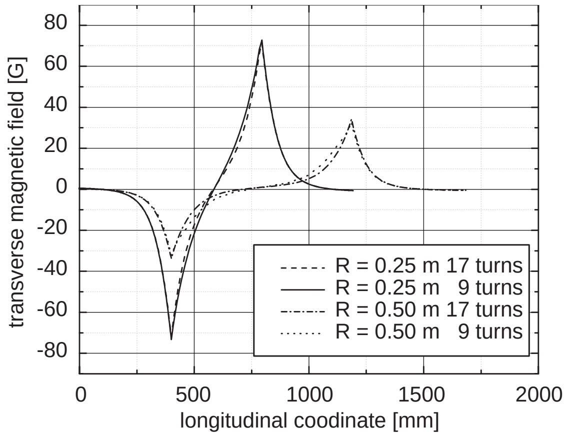

Fig. 3. Dependence of the transverse field on the bending radius of the toroidal section.

order to reduce this displacement of the secondary electrons.

4.2. Magnetic field

The electron beam in the S-LSR cooler is guided by three solenoid coil fields and two toroidal coil fields, in addition to a solenoid coil in the gun section used for the adiabatic expansion. The design of the coils was carried out using 3-dimensional calculation of the magnetic field with the TOSCA code. An important peculiarity of the S-LSR cooler is the rather small bending radius of the toroidal coil of 0.25 m. Also due to the limited space inside the toroidal section a discrete arrangement of the coils was chosen with a total of 9 distinct coils. The dependence of the field distribution on the toroid radius as well as on the number of discrete coils was investigated by numerical calculations of the magnetic field. Result for four configurations with different toroidal bending radius R and number of discrete coils is shown in Fig. 3. We see that the maximum transverse field at the entrance of the cooling section ($z = 400\,\text{mm}$) depends only on the radius of the toroid. For the S-LSR cooler with $R = 0.25\,\text{m}$ the maximum transverse field is about 70 G. This field is corrected with a pair of Helmholtz coils at each end of the cooling solenoid which achieve a good field region of about 0.5 m or 2.2% of the circumference of the ring, with a field quality better than 5×10^{-4}. For the case $R = 0.5\,\text{m}$ the calculated transverse field is 34 G which is about factor two less than the S-LSR case. This indicates that the transverse field due to the toroid has an inverse dependence on the bending radius.

4.3. Solenoid coil errors

The quality of the solenoid magnetic field is limited by the errors introduced in the coils during the manufacturing process. Such errors can severely magnify the deviations in the homogeneity of the magnetic field and should be corrected. However, before such errors can be corrected they have to be estimated, usually by actually measuring the field after manufacturing. For the S-LSR, the effect of coil errors was estimated using 3-dimensional field calculations with the TOSCA code. The cooling solenoid is modeled by 79 discrete circular coils, centered on the beam axis, each of length 9 mm and spaced by 1 mm. We have assumed a maximum error $\Delta_M = 0.5\,\text{mm}$ in the transverse and longitudinal coordinates. The longitudinal position of the center of each coils is shifted by random amount Δ_R such that $\Delta_S \leqslant |\Delta_R| \leqslant \Delta_M$, while we have varied the systematic error Δ_S. In the transverse coordinates, each coil is rotated horizontally and vertically by an angle $\alpha_t = \Delta_R / R_c$, where $R_c = 131\,\text{mm}$ is the radius of the solenoid coil. The results are shown in Fig. 4. We observe that the errors of the horizontal

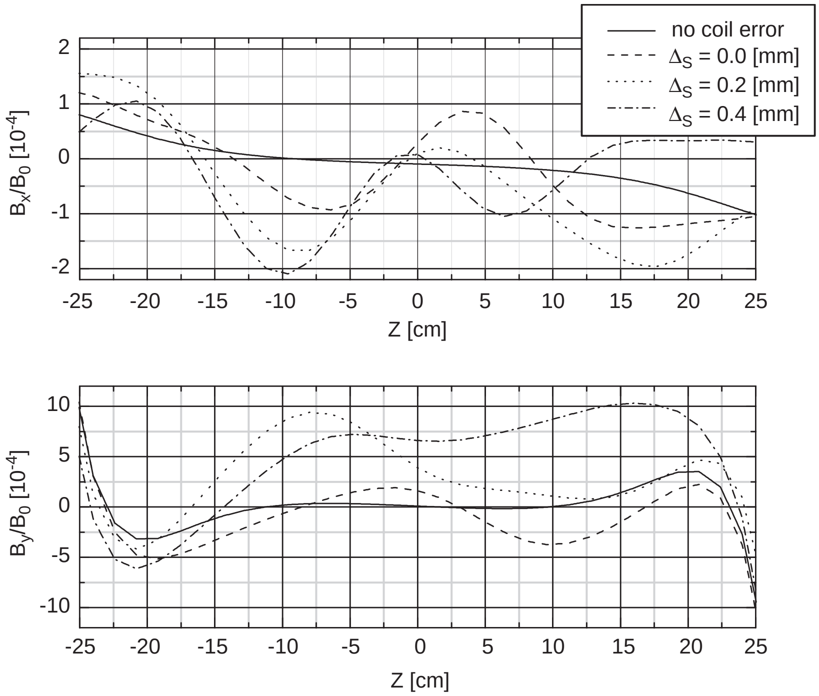

Fig. 4. Dependence of transverse field distributions on the systematic coil errors ($B_0 = 500\,G$).

(B_x) and vertical (B_y) fields increase with the increase of the systematic error. For $\Delta_S = 0.4$ mm we see that the vertical field deviations become as large as 10^{-3}. A correction scheme of the these errors using short flexible Helmholtz coils placed directly on the vacuum chamber is currently being investigated.

5. Conclusion

The basic design of the S-LSR cooler has been completed. Simulation studies have showed that despite the compact size of this device the cooling section length can be extended to 2.2% of the circumference of the ring using an adequate correction scheme. The gun perveance is 2.2 μP and the adiabatic expansion scheme reduces the transverse temperature to 40 meV. The effect of coil errors, have been estimated and a correction scheme utilizing flexible circuit-board type coils is being investigated. The collector is also being optimized to minimize the secondary electron emission.

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References

[1] G.I. Budker, Proceedings of the International Symposium on Electron and Positron Storage Rings, Saclay, 1966, p. II-1-1.
[2] H. Poth, Phys. Rep. 196 (1990) 135.
[3] A. Noda, et al., EPAC 2002, Paris, 2002, p. 224.
[4] E. Jaeschke, et al., EPAC88, Vol. 1, Rome, p. 365.
[5] H. Fadil, et al., Nucl. Instr. and Meth. A 517 (2004) 1.
[6] I. Meshkov, et al., Dubna preprint JINR E9-96-347, 1996.
[7] E. Syresin, et al., HIMAC internal report, NIRS(2002).
[8] B. Herrmansfeld, SLAC 226, NC. 28.
[9] S. Pastuszka, et al., Nucl. Instr. and Meth. A 369 (1996) 11.