DESIGN AND COMMISSIONING OF A COMPACT ELECTRON COOLER FOR THE S-LSR

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Abstract

The commissioning of the compact electron cooler of the S-LSR in Kyoto university was carried out with successful observation of both longitudinal and horizontal cooling of a 7 MeV proton beam. By varying the electric potential on the Pierce electrode in the gun, we have investigated the possibility of generating a hollow shaped electron beam and studied its effect on the electron cooling process. The design of the electron cooler and the results of the first electron cooling experiments will be presented.

1. INTRODUCTION

The Small Laser-equipped Storage Ring (S-LSR) has been constructed by the Institute of Chemical Research of Kyoto University and the National Institute of Radiological Sciences as a part of the Advanced Compact Accelerator Project which aims to demonstrate the feasibility of a compact accelerator system for cancer therapy [1]. The role of the S-LSR is to store and cool ions prior to their injection in a pulsed synchrotron for further acceleration, to a suitable energy for therapy. The S-LSR is a compact cooler ring of total circumference of 22.5 m and maximum rigidity of 1 Tm. The super-periodicity is 6 and the straight section length is 1.86 m. A single period of the lattice contains one dipole magnet of curvature radius ρ=1.05 m, which also provides horizontal radial focusing, and two vertically focusing quadrupoles of pole length 200 m.

2. DESIGN OF THE ELECTRON COOLER

Electron Cooling [2] is a widely used method for increasing the phase space density of a stored ion beam in a storage ring. A new electron cooler was designed and constructed, which will serve as the main cooling scheme of the S-LSR. Due to the rather short straight section of the SLSR (1.86 m) the cooler is rather compact with a cooling solenoid length of 0.8 m and a toroid radius of 0.25 m. The main parameters of this device are summarized in table 1. The layout of the electron cooler is shown in figure 1. The magnetic confinement of the electron beam is provided by three solenoid coils and two toroidal coils, in addition to a solenoid coil in the gun section utilized for the adiabatic expansion. The nominal field for cooling experiments is 0.5 kG in the cooling section and 1.5 kG in the gun section (expansion factor 3). A special feature of this device is the use of electrostatic deflectors in the toroid section in order to compensate for the drift motion of the electrons. With the usual magnetic drift correction, secondary electrons emitted from the collector will suffer a drift displacement on passage through both bending toroids of

$$\Delta_{tor} = 2\pi \frac{m_e}{v_e} eB$$

Table 1: Parameters of the Electron Cooler

Cooling Solenoid Length (m)	0.8
Toroid radius (m)	0.25
Magnetic field (gun/cooling) (kG)	1.5/0.5
Adiabatic expansion factor	3
Field uniformity in cooling solenoid	2×10^{-4}
Electron energy (keV)	1 - 5
Electron beam current (mA)	50 - 300
Expanded electron beam radius (mm)	26

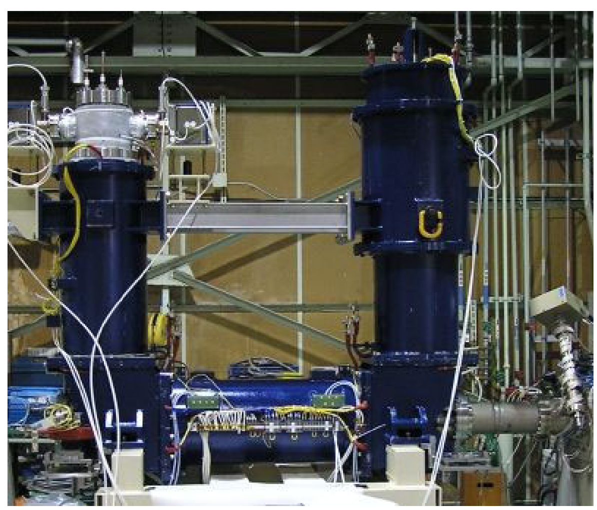

Figure 1: Picture of the constructed compact electron cooler. The cooling solenoid length is 0.8 m the magnetic field 0.5 kG and the maximum expansion factor is 3.

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where v_e is the electron velocity and B is the magnetic field. For a secondary electron energy of 1 keV and B=0.5 kG we find that Δ_{tor}=1.3 cm. Since the vertical aperture available is only many secondary electrons will be lost after a few oscillations between the collector and the gun, causing a deterioration of the vacuum conditions. With electrostatic correction, both the primaryelectrons moving from the gun to the collector and the secondary electrons having the opposite motion will be corrected similarly. The guiding magnetic field structure was optimized with 3D finite element calculations (TOSCA) and actual measurements of the magnetic field of entire electron cooler in all components were performed. The agreement between the calculation and the measurement was found to be good. The effecting cooling length is with a field quality better than. The gun was designed with the EGUN code. Thermionic electrons are generated in the cathode, and accelerated with the anode-cathode potential difference U_A. The Pierce electrode angle of 62.9 °was found to be optimal to minimize the electron beam transverse temperature. Further details of the design of the electron cooler can be found in [3] and [4].

2. COMMISSIONING OF THE COOLER

The construction of the electron cooler was finished in March 2005, and the first tests were performed before installing the device in the ring. After an initial bake out and pumping the first electron beam was produced. The measured perveance of 2.3 μP agrees with our design value. Also the new electrostatic deflectors in the toroid were tested. Since the compensation of the electron drift can be done in the S-LSR cooler either with conventional dipole magnets or with electrostatic deflectors, we have measured the dependence of the cathode loss current with a gradual shift from magnetic to electrostatic correction in the toroid. A typical result is shown in figure 2 where we observe a reduction of almost an order of magnitude of the loss current when we apply a potential on the electrostatic deflectors of ±1.3 kV. The cooling rate is not affected. The alignment of the elements of the S-LSR was performed in summer 2005, then the ring was baked-out and the commissioning was started by the fall 2005. The 7 MeV proton beam from the existing Linac at ICR Kyoto university was successfully injected and stored in the S-LSR using multi-turn injection scheme. The stored beam current can be as high as 500 μA, but for cooling experiments we have typically used 50 μA. The beam diagnostics were performed mainly with a longitudinal Schottky monitor, and a horizontal residual gas monitor for beam size measurements. Horizontal and vertical beam position pickups were also used to measure the beam position. After the successful storage of the proton beam, measurement of the closed orbit was performed and was found to be below 2.5 mm horizontally and 2.0 mm vertically. Horizontal electron cooling was successfully observed as shown in figure 4. In this case the proton beam was stored then cooled with an electron beam of current of 100 mA, and the measured cooling time is about 8 s. Longitudinal cooling was observed on the Schottky spectra with a typical cooled beam momentum spread of $\Delta P/P=2\times10^{-4}$.

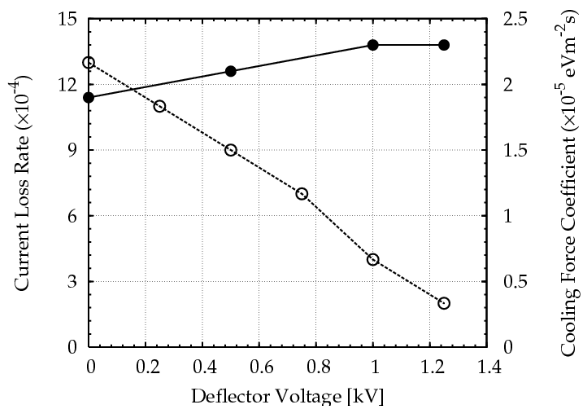

Figure 2: Reduction of the measured cathode loss current with applied electric field on the toroid electrostatic deflectors.

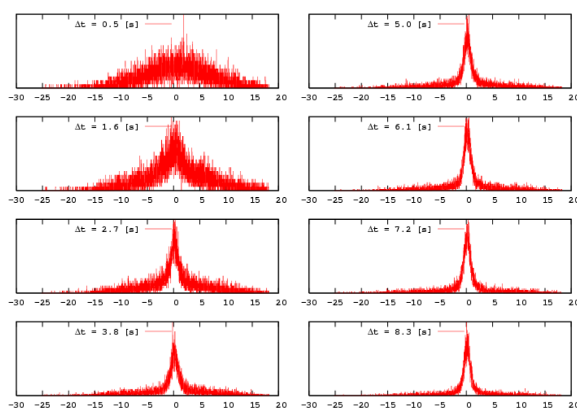

Figure 3: Successful horizontal cooling of the 7 MeV protons with 100 mA electron beam.

3. HOLLOW BEAM GENERATION

The generation of a hollow electron density distribution has been a subject of recent interest in the electron cooling community, with the main advantage of the hollow beam shape being the avoidance of instabilities of the cooled ion stack. The reduced electron density in the center of the beam is thought to be favorable to reduce the coherent instability effects on the stack, while the higher outer density will cool faster the injected high emittance ion beam, therefore increasing the cooled stacking rate. It has been shown that the electron beam shape can be changed by applying a voltage difference between the cathode and the Pierce electrode (see figure 2). A typical result obtained with the SAM code is shown in figure 5. If the Pierce electrode potential is zero (relative to the cathode) a uniform beam density is obtained, whereas a "hollow" beam with increased density at the edges can be produced if we apply a positive potential. This is due to the enhanced emission from the outer regions of the

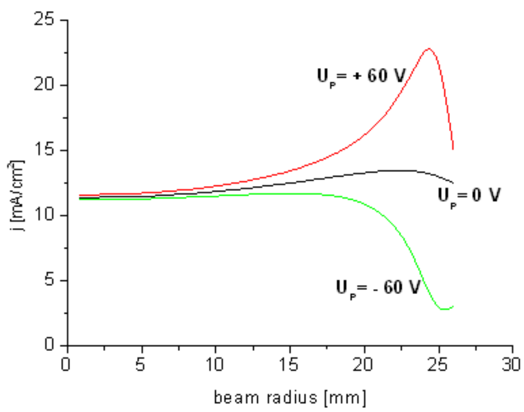

Figure 5: Various electron beam densities obtained by varying the Pierce voltage.

cathode. The inverse effect of inhibited emission can be obtained with a negative voltage. It should be noted that density in the 3 cases is about the same at small radial positions. The dependence of the total electron current on the Pierce voltage U_P was measured and is shown in figure 6. The nominal current for this case at U_P=0 is 100 mA. When we applied a voltage U_P=100 V, the electron current was increased by about factor 2. The agreement between the measurement and SAM code simulations is very good for negative voltage region, while there is a larger disagreement for positive voltages. This is believed

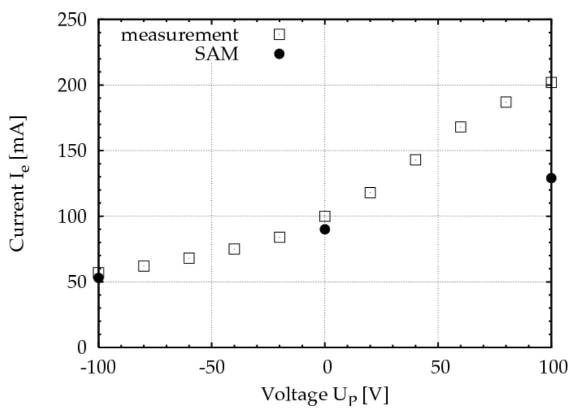

Figure 6: Dependence of the total electron beam current on

to be due to the fact that electron emission happens also on the outer circumference of the cathode and not only on its surface when a positive U_P voltage is applied. The fact that the inner density of the electron beam is independent of U_P can be proven by measuring the longitudinal cooling rates dependence on the Pierce voltage. The proton beam is injected and cooled, after which it is located near the center of the electron beam. The longitudinal cooling force is then measured using the induction accelerator method [6]. The measured cooling rates for four different cases are shown in figure 7. Run 1 corresponds to U_P=-60 V and U_A=0.6 kV, run 2 to U_P=0 V and U_A=0.6 kV, run 3 to U_P=60 V and U_A=0.6 kV, and run 4 to U_P=0 V and U_A=1.1 kV, where U_A is the anode potential. As can be seen in figure 7, the cooling rate is almost independent on the Pierce voltage, although the

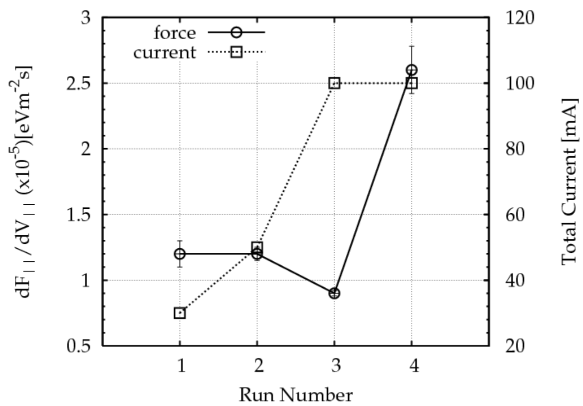

Figure 7: Measured longitudinal cooling rate for the four cases mentioned in the text.

total electron current is increased. This shows that the electron density in the inner part acting on the ion beam is almost constant and that the increased current must come from increased outer region density. In run 4 where we set and increase the anode voltage to get a total current of similar to run 3, we observe that the cooling rate is increased by about factor 2 which is consistent with a uniform increase in the density by the same factor. These results show that by varying the Pierce voltage we can increase the total current of the electron beam while keeping the inner density constant.

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