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

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Abstract

A compact electron cooler was designed and constructed at Kyoto university. 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.

DESIGN OF THE ELECTRON COOLER

Electron Cooling[1] 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. The S-LSR[2] is a compact cooler ring of total circumference of 22.56 m and maximum rigidity of 1 $T\ m$. The super-periodicity is 6 and the straight section length is 1.86 m. A single period of the lattice contains one $60°$ dipole magnet of curvature radius $\rho = 1.05\ m$, which also provides horizontal radial focusing, and 2 vertically focusing quadrupoles of pole length of 200 mm. Due to the rather short straight section of the S-LSR (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 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 coil, in addition to a solenoid coil in the gun section utilised 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). The expanded beam has a diameter of $5.2\ cm$. 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

$$\Delta_{tor} = 2\pi \frac{m_e}{v_e} eB \tag{1}$$

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 $\Delta_{tor} = 1.3\ cm$. Since the vertical aperture available is only $\pm 4\ cm$ 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 primary electrons 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 optimised with 3D finite element calculations (TOSCA) and actual measurements of the magnetic field of entire electron cooler in all 3 components were performed. The agreement between the calculation and the measurement was found to be good. The effective cooling length is $0.45\ m$ with a field quality better than 5×10^{-4}. The gun was designed with the EGUN code and the layout is shown in figure 2. 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 minimise the electron beam transverse temperature (figure 2 down). Further details of the design of the electron cooler can be found in [3] and [4].

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

COMMISSIONING OF THE COOLER

The construction of the electron cooler was finished in March 2005, and the first tests were performed before in-

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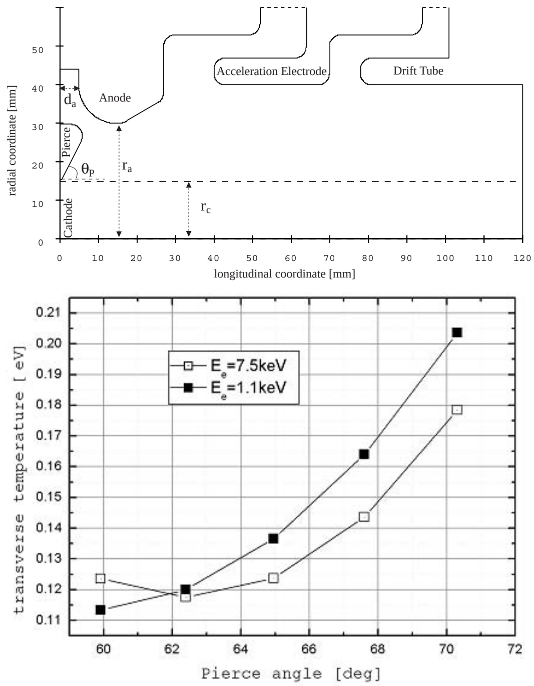

Figure 2: Up; schematic view of the electron gun, the cathode has a diameter of 30 mm and the Pierce electrode has an angle of θ_P. Down; the transverse electron temperature is minimised for $\theta_P = 62.9°$.

stalling 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 3 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 $\pm 1.25\ kV$. 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. Details about the commissioning of the new S-LSR ring can be found here [5]. 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. Further details are given in [6]. Horizontal

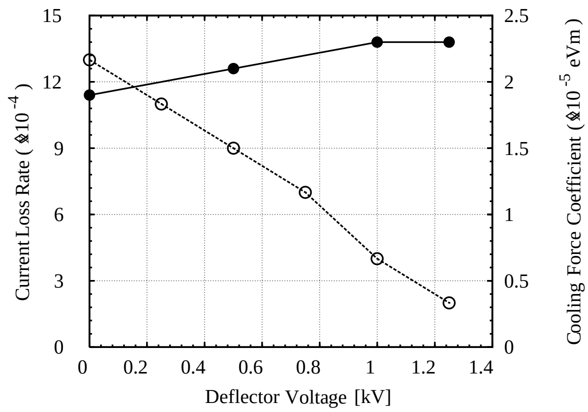

Figure 3: Reduction of the measured cathode loss current with applied electric field on the toroid electrostatic deflectors (white circles), while the longitudinal cooling force is almost unchanged (black circles).

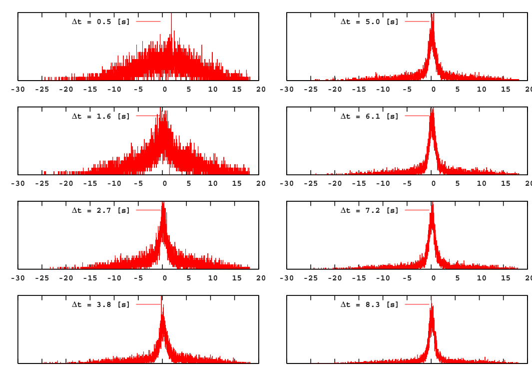

Figure 4: Successful horizontal cooling of the 7 MeV proton beam with 100 mA electron beam.

electron cooling was successfully observed as shown in figure 4. In this case the proton beam was stored then cooled with 100 mA electron beam, 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 $\Delta P/P = 2 \times 10^{-4}$.

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 coherent instabilities of the cooled ion stack. The reduced electron density in the centre of the beam is thought to be favourable 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

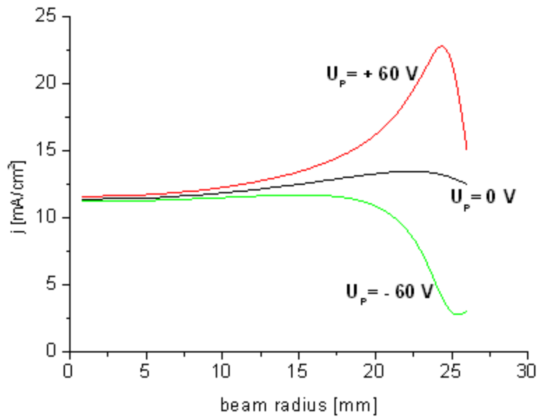

Figure 5: Various electron beam density profiles obtained by varying the Pierce electrode voltage.

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 cathode. The reverse effect of inhibited emission can be obtained with a negative voltage. It should be noted that the 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 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 proved 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 centre of the electron beam. The longitudinal cooling force is then measured using the induction accelerator method[7]. The measured cooling rates for four different cases are shown in figure 7. Run 1 corresponds to $U_P = -60\ V$ and $U_A = 0.6kV$, run 2 to $U_P = 0\ V$ and $U_A = 0.6kV$, run 3 to $U_P = 60\ V$ and $U_A = 0.6kV$ and run 4 to $U_P = 0\ V$ and $U_A = 1.1kV$, where U_A is the anode potential. As can be seen in figure 7, the cooling rate is almost independent on the Pierce voltage U_P although the 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 $U_P = 0$ and increase the anode voltage to get a total current of $100\ mA$ similar to run 3, we

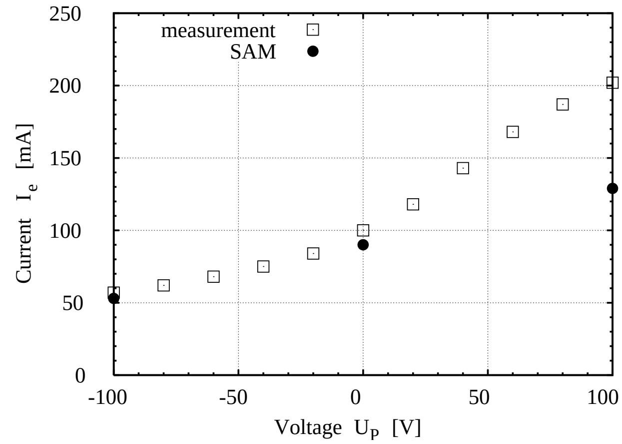

Figure 6: Dependence of the total electron beam current on the Pierce electrode voltage, and comparison with simulation with SAM code.

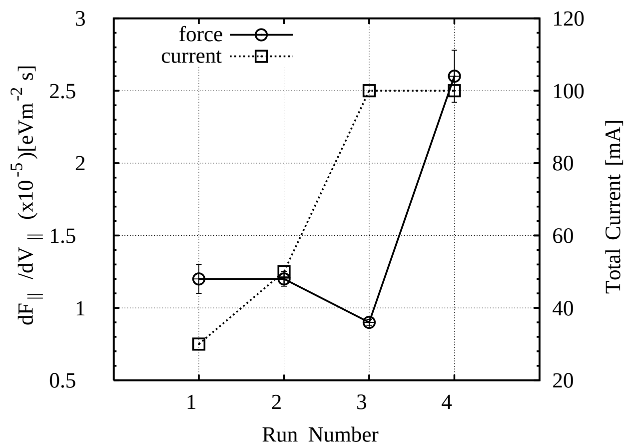

Figure 7: Measured longitudinal cooling rate for the four cases mentioned in the text.

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. This condition might be favourable for efficient electron cooling stacking.

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