LIQUID-HELIUM FREE SUPERCONDUCTING ELECTRON COOLER AT THE STORAGE RING TARN II

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Abstract

An electron cooler at TARN II has been operated since 1989 at INS. In 1994, it was converted into an adiabatic expansion type with a strong normal conducting solenoid. The device produced an ultracold electron beam on the order of 7 meV after expanding the electron beam by a factor of 14, allowing high-precision experiments on molecular ions to be performed. In order to further reduce the electron temperature, a superconducting electron cooler with an expansion factor of 100 is now under construction. The gun solenoid is a liquid-helium free refrigerator-cooled NbTi superconducting magnet with a 20 cm room-temperature bore, which can produce a high magnetic field of up to 3.5 T. The electron beam is expanded from a diameter of 5 mm to 50 mm in a gradually decreasing solenoid field from 3.5 T to 0.035 T. With this cooler it can be expected to reach an electron temperature on the order of 1 meV, resulting in an extremely fast cooling time and a very cold ion beam.

1 INTRODUCTION

TARN II is a storage ring with a six-fold symmetry and a circumference of 78 m. An electron cooler was installed in one of the straight sections, and has been operated since 1989 [1]. After a fundamental cooling test, the cooler has been mainly used for atomic-physics experiments concerning the dielectronic recombination of atomic ions, the dissociative recombination of molecular ions and the detachment of negative hydrogen ion. In the first-generation cooler, the cooling time and the resolution of experiments were limited by a transverse electron temperature of about 100 meV, corresponding to a cathode temperature of about 1200 K. In order to further reduce the electron temperatue, the cooler was converted in 1994 into a second-generation cooler, an adiabatically expanded electron beam [2] with a strong normal conducting solenoid of up to 5 kG. With this renovation, faster cooling and high resolution experiments have been realized [3]. We are planning to extend this method. In principle, it is possible to further reduce the electron temperature in transverse direction by increasing the expansion factor with a higher field in the electron-gun region. However, a solenoid field higher than 5 kG is almost impossible with a normal conducting coil, and inevitably a superconducting coil is required. We are thus now constructing a superconducting electron cooler with an expansion factor of 100, aiming at a temperature of 1 meV, by modifying the electron-gun region of the existing cooler. A feature of the superconducting solenoid is that it is liquid-helium free [4], resulting in easy operation and compactness.

2 EXPERIMENTS AT AN ADIABATIC EXPANSION-TYPE COOLER WITH A NORMAL-CONDUCTING SOLENOID

Here, we describe the actual performance of the cooler with a normal conducting strong magnet. To attain an expansion factor of about 10, the electron gun and its surrounding coils were altered leaving the rest of the cooler unchanged. The main modification points were: 1) the cathode diameter was reduced from 5 cm to 1.4 cm while keeping a perveance of 1 μ P, and the Pierce electrode surrounding the cathode was changed accordingly; 2) to attain a maximum field of 5 kG, the ampere-turns of the gun-solenoid were increased by a factor of approximately 10 while keeping an inner-bore diameter of 35 cm and by rewinding the coil; and 3) a magnet power supply which can supply the solenoid with a 1 kA DC current was newly prepared. The electron cooler after the modification is shown in Fig. 1.

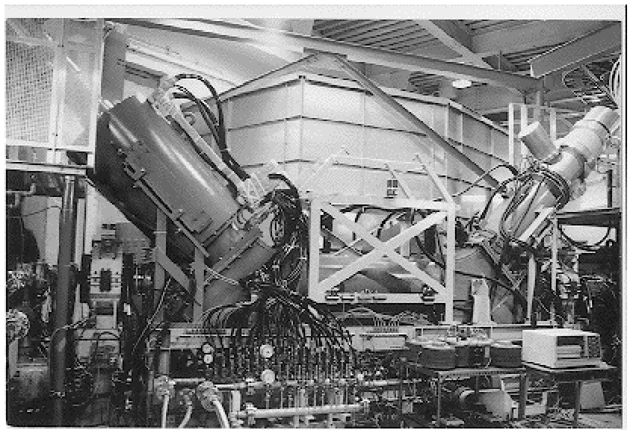

Figure 1: Photograph of the adiabatic expansion-type electron cooler with a normal-conducting magnet. The electron gun is installed in the big solenoid on the left-hand side.The length of the cooling section is 1.5 m.

As can be seen in the photograph, the gun solenoid (left) is much bigger than the collector solenoid (right). A typical operating condition is given as follows: An electron beam was produced from a heated cathode with a diameter of 1.4 cm in a soenoid field of 4.8 kG, and then adiabatically expanded to a diameter of 5.2 cm while gradually reducing the field to 0.35 kG. In this way, the electron beam enters into the cooling solenoid after being enlarged by a factor of 14 in cross-sectional area. Since the transverse electron temperature is proportinal to the solenoid field, we can simply expect a temperature on the order of 7 meV, assuming an initial temperature of about 100 meV, corresponding to a cathode temperature of 1200 K. An actual resolution test of the electron beam was performed by an atomic physics process of a dissociative recombination (DR) of a 12-MeV HD^+ ion, $HD^+ + e \rightarrow H + D$. A fine structure of the DR spectrum near to the cooling energy was observed for the first time [3]. From this experiment we can realize that a temperature of less than 10 meV has really been accomplished resulting in a fast cooling time of less than 1 s for the HD^+ ion.

3 DESIGN OF THE LIQUID-HELIUM FREE SUPERCONDUCTING ELECTRON COOLER

3.1 General

To obtain a much lower electron temperature, the solenoid coil in the electron-gun region is converted to a superconducting type, leaving the rest of the cooler unaltered. For the superconducting solenoid, we adopted a refrigerator-cooled magnet, because it is compact and liquid-helium free. The maximum voltage of the initial cooler was designed to be 110 kV. However, for the new design, we reduced the maximum voltage to 20 kV, which is high enough to meet the current experimental demands. The electron beam is produced by a cathode with a diameter of 5 mm in a solenoid field of 3.5 T, and accelerated to 20 keV (maximum value). After acceleration the electron beam is expanded to 50 mm in a gradually decreasing field to 0.035 T. Thus, the electron beam is expanded by a factor of 100 in cross-sectional area.

3.2 Electron gun

The electron-gun optics consists of a flat cathode, a Pierce electrode, an anode and an acceleration column. The design of the electron gun system was studied by a computer simulation with the help of the SLAC program [5]. Electrons are first extracted by an anode voltage, and then further accelerated by an acceleration column of up to 20 kV. The perveance of the electron gun is 1 μ P, and the maximum current is 1 A at a gun-anode voltage of 10 kV. Fig. 2 shows the calculated 20 keV-1 A electron trajectories in the gun region at a magnetic field of 3.5 T. The actual design of the gun region is shown in Fig. 3.

3.3 Superconducting and normal-conducting magnet

The difficulties regarding the superconducting magnet concern the use of liquid helium and a large cryostat size. The system would become much more compact if liquid helium is not neccesary. The refrigerator-cooled NbTi magnet in the present design realizes easy operation and compactness. The superconducting magnet shown in Fig. 3 has a 20 cm

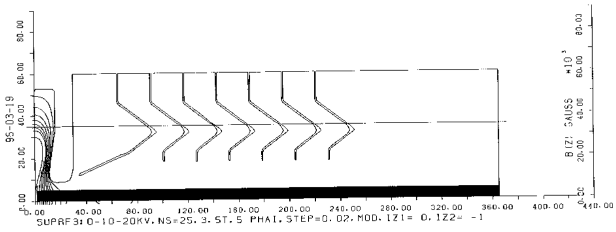

Figure 2: Calculated electron trajectories in the gun region.

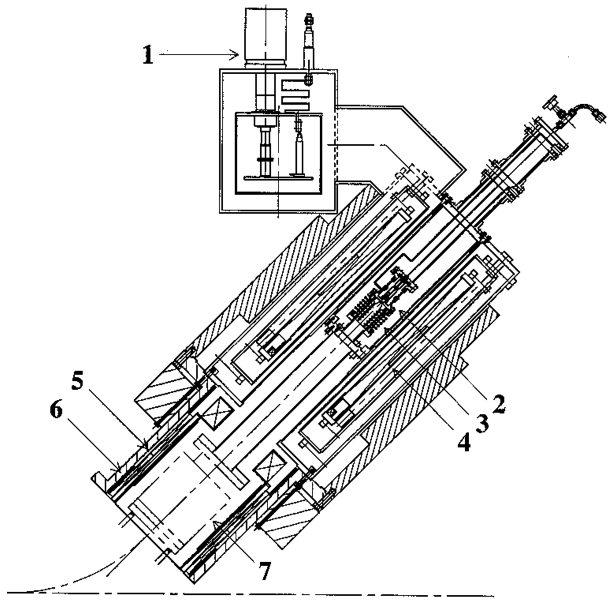

Figure 3: Layout of the electron gun region: (1) refrigerator, (2) electron gun, (3) acceleration tube, (4) superconducting solenoids, (5) normal-conducting solenoids, (6) steering coils, (7) NEG pump.

room-temperature bore, and is about 1 m in axial length. The magnet can produce a 3.5 T central field at about a 4 K coil-winding temperature. There is also a small superconducting coil which produces a reverse field, and helps the main field to decrease slightly more steeply. In order to make the field in the gun region more uniform, the outer winding of the main coil has a notch. Thus, a field uniformity of $\pm 2 \times 10^{-4}$ was realized by the superconducting-coil system. Downstream of the superconducting solenoids there are also normal conducting coils, which are used to smoothly join the the superconducting field to a subsequent toroidal field, while keeping the adiabaticity parameter, $\chi = (dB/dz)(\lambda/B)$, as small as possible. Here, λ is the gyro-wavelength of an electron. There are also Helmholtz coils which can steer the electron beam in both the horizontal and vertical directions. All of the coils are covered by mild-steel return yokes. The main purpose of the return yoke is to prevent the leakage field to the outer region of the superconducting coil. The magnetic fields formed both with the superconducting and normal-conducting coils are shown in Fig. 4. The maximum value of χ is about 0.15 for 20-keV electrons. The maximum leakage field from the superconducting coil is about 20 G on the beam line, which can be shielded by thin steel and μ metal layers.

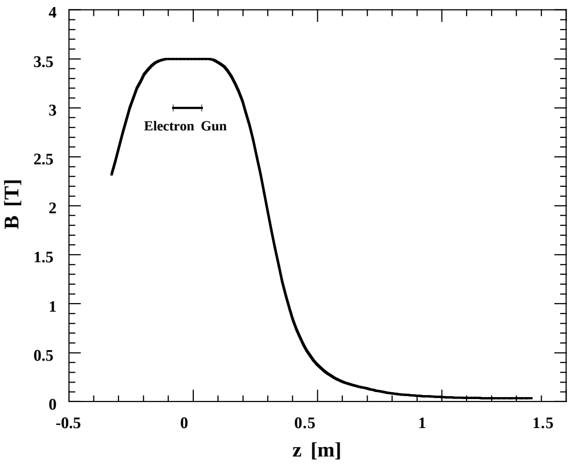

Figure 4: Calculated magnetic field produced by a superconducting solenoid followed by normal conducting solenoids.

The main NbTi coil dimensions are 300 mm in inner diameter, 395 mm in outer diameter and 650 mm in axial length. The coil winding is an epoxy-impregnated structure. The coil conductor has a diameter of 0.889 mm, a filament diameter of 14 μ m and a twist pitch of 10 mm. The current density in the NbTi filament is 537 A/mm^2 . Hysteresis loss limits the magnet ramp rate to 3.5 T/h. The NbTi coil is cooled by metal conduction. The cooled metal wall is attached to the inner part of the winding. The coils are supported by GFRP (Glass Fiber Reinforced Plastic) rods. Oxide Bi(2223) superconducting current leads are used for reducing the heat leakage into the 4K stage. The NbTi coil is cooled to liquid-helium temperature by a GM (Gifford-McMahon) refrigerator which has two stages. The 1st stage provides 0.4 W cooling capacity at 4 K for the coil and Er_3Ni is used as the regenerator material, because its specific heat is as large as 0.1 J/(cm^{3}K) at 4 K. On the other hand, the 2nd stage provides 20 W at 40 K for the radiation shield and has lead regenerator material. The thermal leakage from a 40 K shield into the 4 K level, through a mechanical support (100 mW), thermal radiation (60 mW), oxide current leads (70 mW) and conductor ac loss (50 mW) is conducted to the 4 K refrigerator lead. On the other hand, the thermal heat leakage from 300 K into 40 K amounts to a sum of 12.4 W, which passes through the mechanical support (2.5 W), thermal radiation shields (4.9 W) and current leads (5 W). Liquid nitrogen is used for the initial cooling of the coil from room temperature to near 77 K. The GM refrigerator works to cool the coil and shield to the final equilibrium temperature within 3 days, including the initial cooling. The refrigerator is operated continuously, except for a one-week break dedicated to maintenance every year. A pair of diodes are connected in parallel with the coil, and are used to protect the oxide lead and NbTi coil, even in the case of burnig out of the oxide lead.

3.4 Expected performance and schedule

In principle, the transverse electron temperature is determined by the expansion factor. If the transverse temperature decreases to 1 meV, we can also expect much faster cooling, because the transverse and longitudinal drag forces are proportional to $T_\perp^{-3/2}$ and $T_\perp^{-1}$ under a typical operating condition, respectively, where $T_\perp$ is the transverse electron temperature. However, there are some heating mechanisms, such as a nonuniformity of the magnetic field, a transverse electric field component in gun region, and an instability of the electric and magnetic fields. The realization of the final goal depends on the seriousness of these heating effects. The planned cooling device will be completed this autumn.

4 ACKNOWLEDGEMENT

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