FIRST OPERATION OF THE SUPERCONDUCTING ELECTRON COOLER AT THE STORAGE RING TARN II

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Abstract

A superconducting electron cooler with an adiabatic expansion factor of 100 was designed and constructed at the TARN II ring for high-precision experiments and high-speed cooling. The gun solenoid is a liquid-helium-free superconducting magnet with a 20-cm room-temperature bore, which can produce a high magnetic field of up to 3.5 T. An 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. The cooler first came into operation in November, 1996. The spectrum of the dissociative recombination, ^{3}HeH$^+$+e→^{3}He+H, clearly showed a dramatic decrease in the electron-beam temperature compared with our previous data measured at an expansion factor of 10 with a normal-conducting solenoid.

1 INTRODUCTION

The electron cooler [1] at the TARN II ring has mainly been used for atomic physics experiments since 1989. In the electron cooling device, the electron beam is guided by a uniform magnetic field directed parallel to the beam axis, which is strong enough to counteract the radial space-charge force. The electrons starting at the cathode have thermal energies of ∼ 0.1 eV. The longitudinal temperature ($T_\parallel$) in the beam rest frame, however, is strongly reduced by the acceleration process, while the transverse temperature ($T_\perp$) remains unaffected. In most electron coolers used so far, the typical longitudinal temperature was on the order of ∼ 0.1 meV at electron energies of a few keV, while the transverse temperature was fixed at ∼ 0.1 eV. Thus, the transverse temperature is much higher than the longitudinal temperature.

When the electron beam is used for atomic-collision experiments and for cooling, the longitudinal and transverse temperatures play important roles in somewhat different ways. In electron-ion collision experiments with a resonant relative energy of E_{res} , the energy resolution (δE) is given by

$$\delta E = (1/2)kT_\parallel + kT_\perp \pm \sqrt{2E_{res}kT_\parallel}, \qquad (1)$$

where the energy widths are given by $\delta E_\parallel = (1/2)kT_\parallel$ and $\delta E_\perp = kT_\perp$. Thus, $T_\parallel$ limits the energy resolution at high relative energies, whereas $T_\perp$ limits the energy resolution at low relative energies. For electron cooling, a reduction of either temperature leads to an increase of the cooling force.

There is a method used to reduce the transverse temperature with the thermocathode, in which the electron gun is placed in a magnetic field stronger than the guiding field on the remaining beam path, thus resulting in an adiabatic expansion of the electron beam upon entering the lower field region. This method allows the transverse temperature to decrease in the cooling region by a factor given by the ratio of the field strengths involved [2]. The cooler at TARN II was converted to such a new-generation cooler with a gun solenoid field of 5 kG, aiming at an expansion factor of ~ 10, and came into operation in 1994. With this improvement, the transverse electron temperature was reduced to ~ 10 meV, and, thus, faster cooling and higher resolution experiments have been realized [3]. As a next step, we planned to attain even higher expansion ratios of up to 100, which should lead to a transverse temperature on the order of 1 meV. However, a solenoid field higher than 5 kG is almost impossible when using a normal conducting coil and, inevitably, a superconducting coil is required. We thus, designed a superconducting electron cooler, by modifying the electron-gun region, but keeping the remaining parts of the existing electron cooler unaltered. A feature of the superconducting solenoid is that it is liquid-helium free [4], resulting in easy operation and compactness. The new cooler was first implemented in the fall of 1996.

2 ADIABATIC EXPANSION OF AN ELECTRON BEAM

In a uniform solenoid field, an electron has a helical orbit along a magnetic-field line, and the Lorentz force is directed perpendicular to the guiding line of the orbit along the magnetic field. However, if the magnetic-field lines diverge, the Lorentz force acting on the electron also has a

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component along the guiding line, resulting in acceleration in the longitudinal direction. The increase in the longitudinal energy means a decrease in the transverse energy due to energy conservation.

When an electron moves sufficiently slowly along the varying axial field, the relation

$$\frac{E_\perp}{B} = \text{const.} \tag{2}$$

holds, which is equivalent to the adiabatic invariance of the orbital magnetic moment associated with the electron motion. The condition that the adiabatic invariants are conserved can be more precisely described by introducing an adiabaticity parameter (ξ) as follows:

$$\xi = \frac{\lambda_c}{B}\left|\frac{dB}{dz}\right|, \tag{3}$$

where λ_c is the spiral length of the cyclotron motion, given by $\lambda_c = 2\pi\sqrt{2m_eE_\parallel}/eB$. The transition is adiabatic if $\xi \ll 1$.

If the axial field strength is reduced from the initial value (B_0) to a final value (B), the transverse energy ($E_\perp$) is reduced according to $E_\perp = (B/B_0)E_{\perp 0}$, where $E_{\perp 0}$ and $E_\perp$ are the initial and final transverse energies, respectively. Here, we call B_0/B the expansion factor. The electron-beam radius (R) increases from the initial value (R_0) according to the relation $R = R_0\sqrt{B_0/B}$. Assuming an expansion factor of 100, $\delta E_\perp$ is reduced to $\sim$ 1 meV as $\delta E_{\perp 0} \sim$ 0.1 eV.

The increase in the longitudinal energy spread due to adiabatic expansion is negligible at high energies. Therefore, for the adiabatic expansion, changes in the longitudinal temperature compared with the standard arrangement are not expected.

3 DESIGN AND CONSTRUCTION OF THE SUPERCONDUCTING ELECTRON COOLER

In the new cooler, the electron beam is expanded by a factor of 100 in cross-sectional area in a gradually decreasing field from 3.5 T to 35 mT.

3.1 Electron Gun

The electron-gun optics consists of a flat cathode with a diameter of 5 mm, a Pierce electrode, an anode and an acceleration column. Electrons are extracted by the anode voltage, and then further accelerated by an acceleration column of up to 20 kV in a uniform solenoid field. The perveance of the electron gun is 1 μ P and the maximum current is expected to be 1 A at a gun-anode voltage of 10 kV. The actual design of the gun region is shown in Fig.1.

3.2 Superconducting magnet

The refrigerator-cooled NbTi magnet[4] realizes easy operation and compactness in the present design. The superconducting magnet shown in Fig. 1 has a 20 cm room-temperature bore, and is approximately 1 m in axial length. The magnet can produce a 3.5 T central field at a coil temperature of about 5 K. There is also a small superconducting coil which produces a reverse field, which 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 $\pm 10^{-3}$ was realized by the superconducting coil system. There are also normal conducting coils, which are used smoothly to join the superconducting field to the subsequent toroidal field, while keeping ξ as small as possible. Helmholz coils can steer the electron beam in both the horizontal and vertical directions. All of the coils are covered by thick mild-steel return yokes. The main purpose of the return yoke is to prevent any leakage field to the outer region of the superconducting coil. The maximum leakage field from the superconducting coil is about 20 G on the beam line. The ramping rate of the magnet is 3.5 T/30 min. The coil temperature became stabilized at 4.8 K for 3.5 T, although it increased up to 5.4 K during ramping.

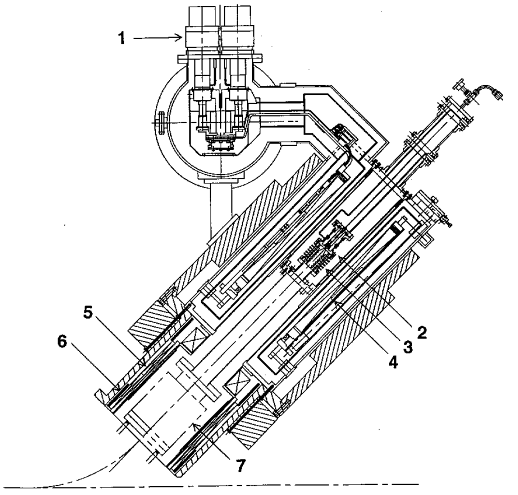

Figure 1: Layout of the electron gun region: (1) refrigerator, (2) electron gun, (3) acceleration tube, (4) superconducting solenoid, (5) normal-conducting solenoid, (6) steering coil, (7) NEG pump.

3.3 Electron Trajectories

The electron trajectories were studied using the SLAC program [5]. The results of field measurements include errors; this unsteady field results in a significant increase in the transverse electron temperature when tracing the electron trajectories in the variable-field region. By correcting to a smooth change of the magnetic field, the correct temperatures were obtained. Fig. 2 shows a longitudinal magnetic field on the axis and typical electron trajectories in the gun region. Fig.3 repesents the radial velocity for one electron trajectories starting from 0.35 mm off axis. During a decrease in the magnetic field, the radial velocity first increase and then decreases. After adiabatic passage, a reduction in the velocity oscillation amplitude by a factor of 10 can be observed in Fig. 3.

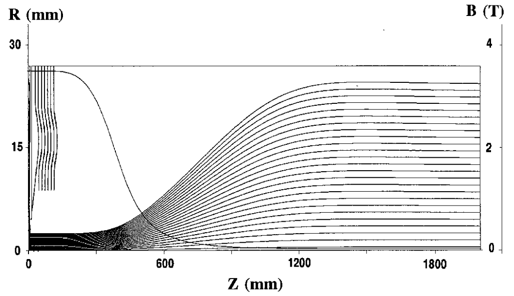

Figure 2: Longitudinal magnetic field on the axis and typical electron trajectories in the gun region at an energy of 2.5 keV and a current of 0.1 A.

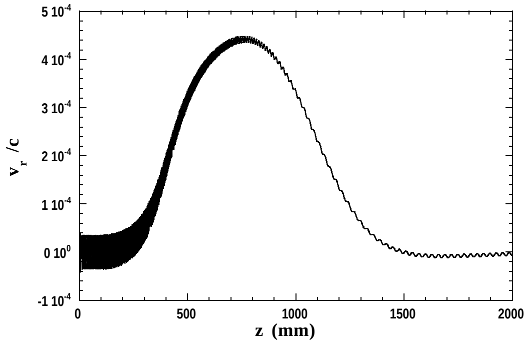

Figure 3: Radial velocity for an electron ray starting from a radius of 0.35 mm at the cathode. The maximum adiabaticity parameter is about 0.05.

4 OPERATION OF THE SUPERCONDUCTING ELECTRON COOLER

The evidence concerning improvements of the electron-beam temperature can be obtained by observing the change in the spectra of the electron-capture process. The fine structure for the dissociative recombination of ^{3}HeH$^+$ was found with a low-temperature electron beam adiabatically expanded by a factor of about 10. Atomic physics theory, however, predicts that the spectrum should have more structure along with a decrease in the electron temperature. We measured the dissociative recombination spectrum for 15-MeV ^{3}HeH$^+$ with the colder electron beam expanded by a factor of 100. The obtained spectrum is compared with our previous results in Fig. 4. As can be seen in this figure, the spectrum changed dramatically, which is clear evidence of a temperature decrease. We further measured the dissociative recombination spectrum of HD$^+$. Comparison of the spectrum with atomic physics theory indicates that the transverse temperature decreased to the order of 1 meV.

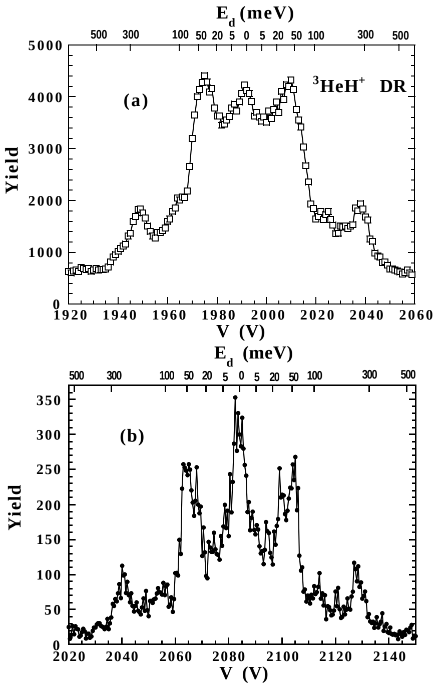

Figure 4: Comparison of the dissociative recombination spectra of ^{3}HeH$^+$ measured at expansion factors of (a) 10 and (b) 100.

5 SUMMARY

The superconducting electron cooler with an expansion factor of 100 came into operation for the first time. An extreme decrease of electron temperatures, probably down to the order of 1 meV, was observed. The liquid-helium-free superconducting magnet realized a compact design and easy operation.

6 ACKNOWLEDGEMENTS

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