Operation of the Superconducting Electron Cooler at the Cooler Ring TARN II

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Abstract

A superconducting electron cooler with an expansion factor of 100 first came into operation at the cooler ring TARN II. The initial transverse electron temperature of 100 meV was reduced to the order of 1 meV by changing the electron guiding field from 3.5 T to 35 mT with a superconducting magnet. The dissociative recombination spectra of helium-hydride ions show a clear change in the resolution from the corresponding ones measured earlier in TARN II. The liquid-helium-free superconducting magnet realized a compact design and easy operation.

1 Introduction

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

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

where $T_{\parallel}$ and $T_{\perp}$ are the longitudinal and transverse temperatures, respectively, and the energy widths are given by $\delta E_{\parallel} = (1/2)kT_{\parallel}$ and $\delta E_{\perp} = kT_{\perp}$. $kT_{\parallel}$ is usually much smaller than $kT_{\perp}$, as described later. Thus, $kT_{\parallel}$ limits the energy resolution at high relative energies, whereas $kT_{\perp}$ limits the energy resolution at low relative energies. For electron cooling, a reduction in either temperature leads to an increase of the cooling force. In first-generation coolers, the cooling time and the resolution of experiments at low relative energies had been limited by a transverse electron temperature of about 0.1 eV, which corresponds to a cathode temperature of about 1200 K. In this paper we report on the superconducting electron cooler with an expansion factor of 100 at TARN II, which realized a fast cooling and extremely high-resolution experiments. The improvement of the resolution is demonstrated by the experiments on the low-energy dissociative recombination (DR) of HeH^+ ion ($HeH^+ + e \rightarrow He + H$).

2 Adiabatic Expansion of an Electron Beam

When an electron moves sufficiently slowly along the varying axial field (B), the relation $E_{\perp} / B = const.$ holds, where $E_{\perp}$ is the transverse energy. This 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) along the axial coordinate (z) as follows: $\xi = (\lambda_c / B)|dB/dz|$, where λ_c is the spiral length of the cyclotron motion, given by $\lambda_c = 2\pi\sqrt{2m_e E_{\parallel}} / eB$, and $E_{\parallel}$ is the longitudinal energy. The transition is adiabatic if $\xi << 1$. If the axial field strength is reduced from the initial value (B_0) to a final value (B), the transverse energy 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. This equation also holds for the transverse energy spread of an electron beam, given by $\delta E_{\perp}$. 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 $R = R_0\sqrt{B_0/B}$. The longitudinal energy spread ($\delta E_{\parallel}$) consists of two terms: (1) the term resulting from the transformation of the thermal energy to a frame of reference traveling at the electron velocity, and (2) the term from the Coulomb field of the surrounding electrons and random relaxation motion [1]. At high energies and at the usual electron density, the first term (typically of the order of μeV) is much smaller than the second one (typically ~0.1 meV). The increase in the longitudinal energy spread due to adiabatic expansion is on the same order as the first term and is negligible at high energies [2]. Therefore, for the adiabatic expansion, the longitudinal temperature remains almost unchanged compared with the standard arrangement. The principle of the adiabatic expansion was first implemented at CRYRING [3] in Stockholm in 1993. Since then a lot of electron coolers, including the cooler at TARN II [4], have been converted to such a type. However, so far, the expansion factors were limited to about 10, resulting in a transverse electron temperature on the order of 10 meV. This is mainly because

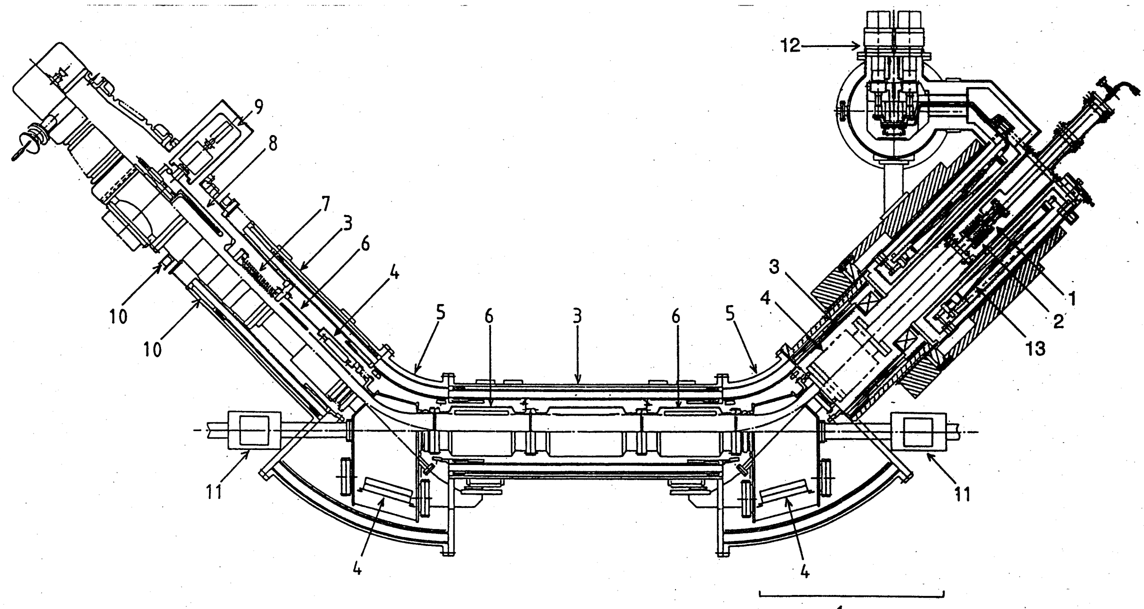

Fig. 1 Layout of the superconducting electron cooler: (1) electron gun, (2) acceleration tube, (3) normal-conducting solenoid, (4) NEG pump, (5) toroid, (6) beam position monitor, (7) deceleration tube, (8) collector, (9) ion pump, (10) correction coil, (11) steering magnet, (12) refrigerator, (13) superconducting solenoid.

it is technically hard to increase the field strength with normal-conducting solenoid coils, despite the requirement for the higher magnetic field in the electron gun region to attain an even higher expansion factor. A superconducting magnet is inevitably needed to further reduce the electron temperature.

3 Superconducting Electron Cooler

The cooler at TARN II [5] was converted from the normal-conducting type into the superconducting type [6] by changing the electron gun region, but keeping the remaining part of the cooler unchanged. 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. The layout is shown in Fig. 1.

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 up to 20 kV in a uniform solenoid field. The perveance of the electron gun is 1 μP and the maximum current is expected to be 1 A at a gun-anode voltage of 10 kV.

3.2 Superconducting magnet

The refrigerator-cooled NbTi magnet 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 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.

3.3 Electron Trajectories

The electron trajectories were studied using the SLAC program [7]. 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. Figure 2 shows a longitudinal magnetic field on the axis and typical electron trajectories in the gun region. In this case the maximum value of ξ is about 0.05 which is small enough to guarantee the adiabaticity condition.

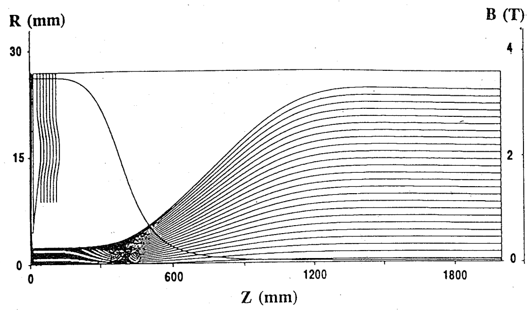

Fig. 2 Axial magnetic field and typical electron trajectories in the electron gun region at an energy of 2.5 keV and a current of 0.1 A.

4 Operation of the Superconducting Electron Cooler

4.1 Off-line Electron Beam Test

A negative accelerating high voltage of 20 kV was readily applied to the gun. On the other hand, the voltage between the gun and the anode was increased up to 6 kV only after a long conditioning time, probably due to the E×B drift motion of electrons under the solenoid field in the space between concentric anode and Pierce electrode. The measured gun perveance of 1.1 μP agrees with the calculations. The tested maximum electron current is 500 mA, which was limited by the currently applicable gun-anode voltage.

4.2 Experimental Results

Figure 3 shows a comparison of the ^{4}HeH$^+$ DR spectra measured at different expansion factors resulting in different energy resolutions. Figure 3(a) is the rate as a function of the electron acceleration voltage over a wide energy range, which was measured earlier at TARN II using the cooler with an expansion factor of 1 [8]. The c.m. energy is also given on the upper horizontal axis. The spectrum is almost symmetric with respect to the central peak for electron velocities both slower and faster than the ion-beam velocity. In this spectrum, the central peak appears to be a single peak with weak shoulders. On the other hand, Fig. 3(b) is a close-up view of the corresponding peak, which was also measured at TARN II using the cooler with an expansion factor of 14 [9]. It was proven that the spectrum consists of several peaks. Figure 3(c) gives the present results measured at an expansion factor of 100. As can be seen in this figure, the resolution was much improved and the splitting of the side peaks was newly observed.

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.

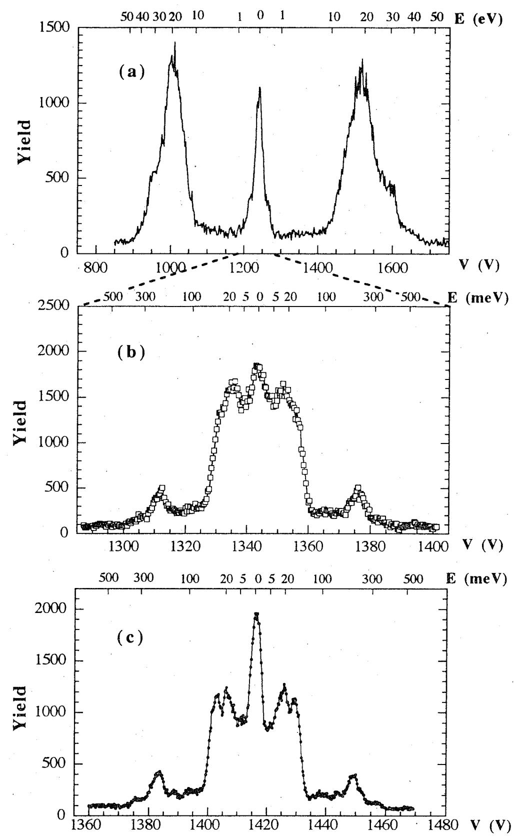

Fig. 3 Comparison of the ^{4}HeH$^+$ DR spectra measured at different expansion factors (approximate resolutions) of (a) 1 (~0.1 eV) [2], (b) 14 (~0.01 eV) [10] and (c) 100 (~0.001 eV).

Acknowledgments

The authors thank the cyclotron staff for their helpful cooperation. They are also grateful to Drs. M.Hoshino, T.Yosiyuki and I.Watanabe of Toshiba Corporation for their efforts in the construction of the superconducting coil and numerical calculations of electron trajectories. This work was performed under Grant-in-Aid for Scientific Research (A) of the Ministry of Education, Science, Sports and Culture.

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