COOLING FORCE MEASUREMENTS FOR THE SUPERCONDUCTING ELECTRON COOLER AT THE STORAGE RING TARN II

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Abstract

A superconducting electron cooler [1] at the storage ring TARN II has been operated since November 1996 and high-resolution atomic physics experiments have been performed with the ultracold electron beam from the cooler. In this cooler, an electron beam is expanded by a factor of 100 in a gradually decreasing solenoid field from 3.5 T to 35 mT and an electron temperature on the order of 1 meV was attained for the first time. In order to estimate the cooling force accurately, we newly installed an induction accelerator in the ring. The linear portion of the cooling drag force is determined from the velocity shift of the ion beam under the balance between the drag force of the electron beam and the external force of the induction accelerator. This paper summarizes the results of the cooling force measurements for the superconducting electron cooler.

1 INTRODUCTION

Since the late 1980s, electron-cooling devices have been used in storage rings for cooling stored ion beams, and as a target for atomic-collision experiments. The electron cooler at the TARN II storage ring has been operated since 1989 [2]. In the standard 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. In this type the transverse temperature is much higher than the longitudinal temperature. There is a method used to reduce the transverse temperature with the thermocathode, as usual, 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 [3]. This method allows the transverse temperature to decrease in the cooling region by a factor given by the ratio of the field strengths involved, called the expansion factor. 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. As a next step, we attained even higher expansion ratios of up to 100, which should lead to a transverse temperature on the order of 1 meV. The superconducting electron cooler at the storage ring TARN II with an expansion factor of 100 has been operated since 1996 [4,5].

It is important to estimate the cooling force (or drag force) of this new device. The dependence of the electron cooling force is characterized by two regions of the relative velocity v_r between electron and ion: In the low v_r region ($|v_r| < \Delta_e$, Δ_e is the velocity spread of electrons) the force approximately varies as v_r , while in the high v_r region ($|v_r| > \Delta_e$) it changes as v_r^{-2}. For these two regions, different measuring scheme must be applied. In the high velocity region, the force measurements are made by first cooling stored ions, then jumping the electron energy and observing the time spent for the ion velocity change toward the new electron velocity. On the other hand, the force in the low-velocity region can precisely be measured by the ‘induction accelerator’ method: First the ion beam is cooled and then an external force is added to the beam by an induction accelerator. As a result ion velocity shifts to an equilibrium velocity determined under the balance between the drag force due to the electron and the external force added by the induction accelerator (IA). In order to measure the drag force, an induction accelerator was designed and constructed. The longitudinal drag force was measured by means of above two methods for 40-MeV alpha-particle.

2 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. The electron beam is produced from a flat cathode with a diameter of 5 mm and expanded to a diameter of 50 mm. A feature of the superconducting magnet is that it is liquid-helium free. The refrigerator-cooled NbTi magnet realized easy operation and compactness [1]. 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 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 same spectrum with the colder electron beam expanded by a factor of 100. The obtained spectrum is compared with our previous results in Fig. 1. As can be seen in this figure, the spectrum changed dramatically, which is clear evidence of a temperature decrease. Comparison of the spectrum with atomic physics theory indicates that the transverse temperature decreased to the order of 1 meV.

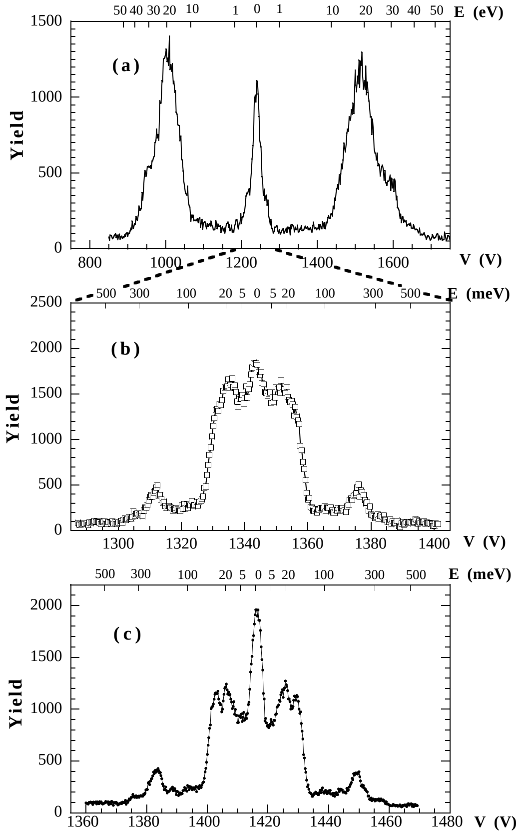

Figure 1: Comparison of the ^{4}HeH$^+$ dissociative recombination rate as a function of the electron acceleration voltage measured at different expansion factors (approximate resolutions) of (a) 1 (0.1 eV), (b) 10 (0.01 eV) and (c) 100 (0.001 eV).

3 INDUCTION ACCELERATOR

The principle of the IA is similar to the betatron accelerator. A toroidal iron core encloses the circulating ion beam. A time-varying current ΔI through the primary windings excites a varying magnetic flux $\Delta\Phi$ inside the core, which in turn induces an electric field E_s to accelerate the ions. A ring-averaged force acting on a stored ion of charge q passing through the hole of the IA is given by,

$$F = \frac{dp_s}{dt} = qeE_s = \frac{qe}{2\pi R}\frac{d\Phi}{dt} \qquad (1)$$

In order to produce a constant induced field in time for certain time intervals, the induced voltage in the secondary windings is fed into a feedback system regulating the current of the primary windings. The IA installed at the TARN II is shown in Fig. 2.

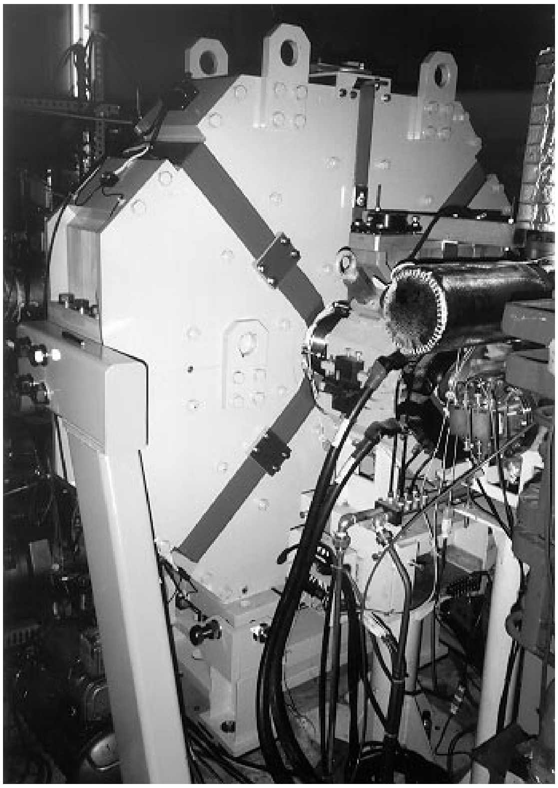

Figure 2: Induction accelerator installed at the storage ring TARN II.

The magnet consists of the toroidal core laminated from 0.5-mm thick iron sheets to prevent the eddy current loss. In order to facilitate carrying and installing work, the core is divided into two halves. The inner diameter of the core is 30 cm which is determined by the dimension of the beam pipe. The core length along the beam line is 30 cm and the width is 60 cm, which means that the cross sectional area is 1800 cm^2. The total weight of the core is about 6 tons. In order to avoid induced currents through the core, the beam pipe has a ceramic ring in the middle of the core. The coil system consists of three kinds of coils: a 20-turn primary coil, a two-turn secondary coil and a two-turn detection coil. As a primary current source we use a bipolar operational power amplifier with a maximum output current of 75 A and an output voltage of 67 V. In order to induce a constant voltage (consequently constant force) despite the hysterisis of the core, a feedback was built to control the current of the power supply. The feedback compares the voltage induced in the secondary winding with a reference voltage and controls the primary current so as to make the difference between these voltages to zero.

4 COOLING FORCE MEASUREMENTS

In the high velocity region, the longitudinal frictional force can be measured by means of the following procedure: The acceleration voltage of the electron beam is suddenly stepped up (down) by a certain amount. Consequently ions are accelerated (decelerated) and their revolution frequencies increased (decreased). The frictional force is determined by measuring the time dependence of the revolution frequencies (Schottky signal) of the cooled beam with the spectrum analyzer which is triggered at the same time as the voltage is stepped up (down). We call this ‘voltage jump’ method. This method is convenient since no additional tool is needed. However, it is hard to measure the linear part of the force where the relative energies are quite small, because the measuring time is extremely short. The force in this region can precisely be measured by the ‘induction accelerator’ method: First the ion beam is cooled and then an external force is added to the beam by an induction accelerator. As a result ion velocity shifts to an equilibrium velocity determined under the balance between the drag force due to the electron and the external force added by the induction accelerator. The longitudinal drag force was measured by means of above two methods for 40-MeV alpha-particle. The solenoid field at the cooling section were fixed to 35 mT with the expansion factor of 100. The intensities of electron and ion beams are 70 mA and about 20 μA, respectively. Results are shown in Fig. 3. The force was normalized at an electron density of 10^8 /cc and multiplied by a factor of L/l where L and l represent the circumference of the ring and the length of the electron cooling section, respectively. Two years ago, we also measured the drag force for the same particle and energy, but for an expansion factor of 10, although they were taken only with the ‘voltage jump’ method. The maximum drag forces for these data looks almost the same despite different expansion factors. The cooling force depends on various parameters. The maximum values of the normalized drag force decrease with the increase of electron density. The force is also sensitive to the alignment accuracy between electron and ion beams. The exact alignment, however, is rather hard as long as we don’t use more sensitive technique like atomic collision spectra. The dipersion function at the cooling section is as large as 4 m at TARN II and the radial position of the ion beam is sensitive to the momentum shift. This makes the experimental condition much more complicated.

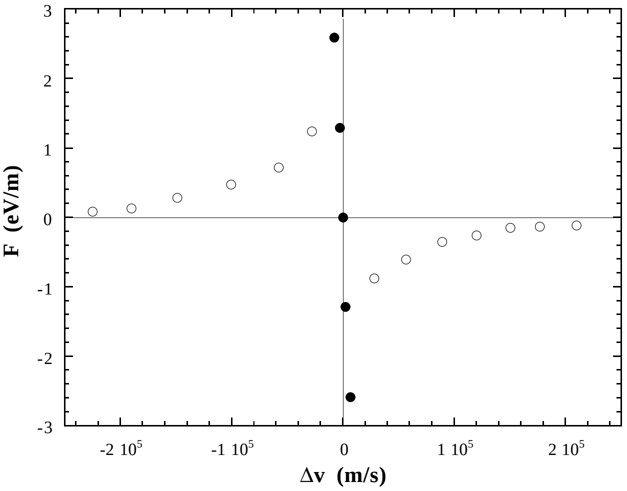

Figure 3: Longitudinal cooling force for 40-MeV alpha-particle. Open and filled dots represent the data measured with the ‘voltage jump’ and ‘induction accelerator’ methods, respectively.

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6 REFERENCES

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