THE CRYRING SUPERCONDUCTING ELECTRON COOLER

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Abstract

The CRYRING electron cooler is equipped with a superconducting gun solenoid since one year in order to reduce the transverse electron-energy spread to 1 meV. The design of this magnet is described, and some results of measurements of electron temperatures, cooling forces, and ion–electron recombination are presented

1 INTRODUCTION

The electron cooler at CRYRING has been operating with an adiabatically expanded electron beam [1] since 1993. The expansion was achieved using the original cooler magnets plus a shunt with a fixed resistance to reduce the current through all magnets except the gun solenoid. Usually, an expansion factor of 10 (in the cross-sectional area of the beam) has been used. This is typically obtained by having 3 kG in the gun solenoid, equal to its maximum design field, and 300 G in the rest of the cooler. The beam expansion has reduced the transverse electron-energy spread from its initial value of 100 meV, deriving from the cathode temperature of 900°C, to 10 meV, i.e. with a factor equal to the expansion ratio. The effect of this reduction has been observed in numerous measurements of radiative, dielectronic and dissociative recombination and also in measurements of the cooling force, or drag force, that the electrons exert on the ions. Some results of studies of the cooling force and the electron-energy spread are reported in [2].

2 SUPERCONDUCTING SOLENOID

A further increase of the expansion factor and reduction of the transverse energy spread of the electrons requires a higher magnetic field at the electron gun. For this reason, a superconducting gun solenoid, replacing the earlier 3-kG normal-conducting solenoid, was ordered in 1995 from Everson Electric Co. and was delivered at the end of 1996. As seen in Figure 1, the cryostat consists of two parts. The lower part houses the coil and has a rather compact design since it had to fit on the existing support frame, with additional restrictions set by the ring dipole magnets next to the cooler. The bore of the solenoid has an inside diameter of 123 mm and a length of 640 mm. Its

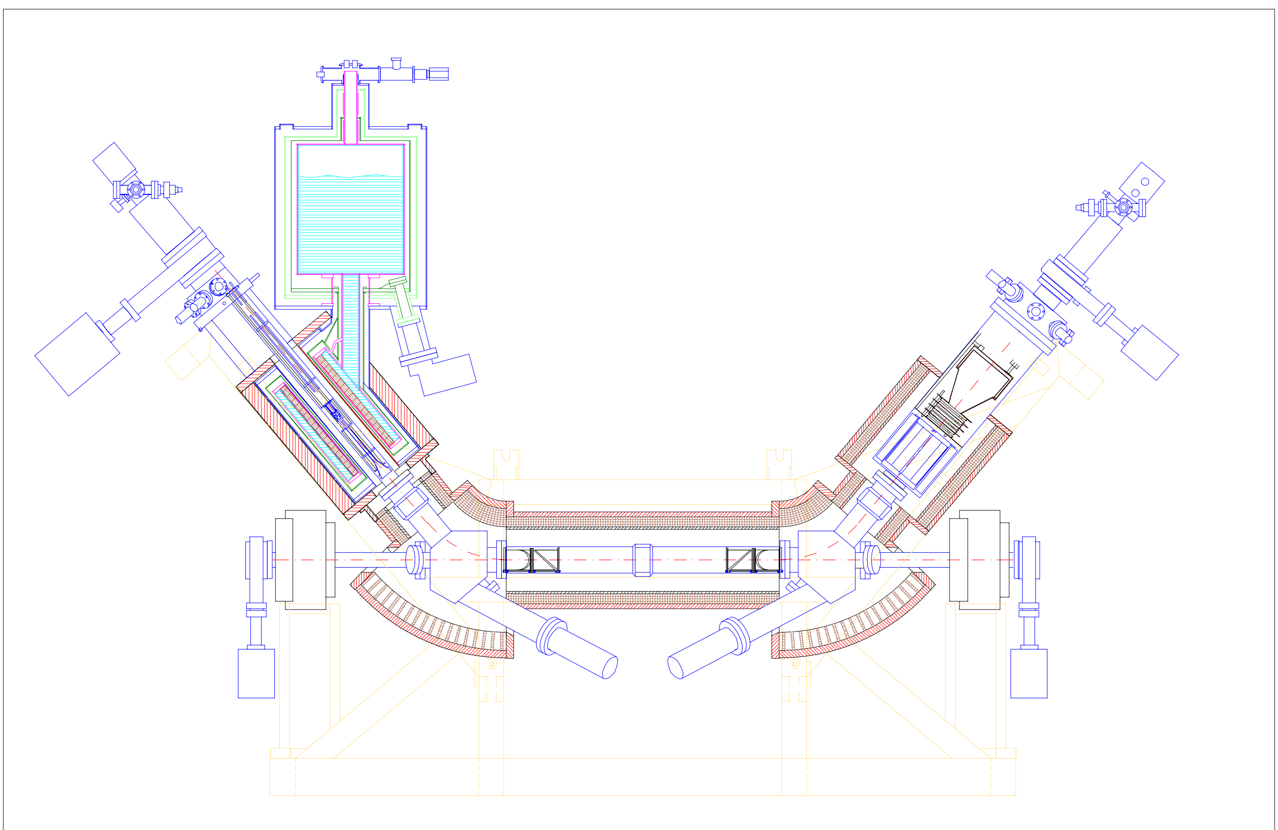

Figure 1. Schematic diagram of the electron cooler. To the left is the superconducting gun solenoid with its helium reservoir on top.

axis is inclined 50 degrees from the horizontal. On top of it there is a liquid-helium reservoir giving a total cryostat volume of approximately 70 litres. The solenoid is surrounded by an iron yoke in order to minimize the stray fields that would otherwise influence other ring magnets nearby and the ion-beam trajectory. The superconducting magnet sits on a 75-mm long extension of the iron yoke of the small solenoid below it. This allows for an adiabatic field decrease without the need of any additional coils to shape the transition between the high and the low fields.

The magnet is cooled with liquid helium and a two-stage Cryodyne cryocooler from CTI-Cryogenics. The first stage of the cryocooler operates at about 68 K under steady-state conditions and is connected to a heat shield surrounding the upper part of the cryostat. The second stage, operating at about 32 K, is connected to shields around the entire liquid-helium-containing volume. The average boil-off of liquid helium is approximately 0.18 litre per hour with current leads retracted. The cryostat volume of 70 litres thus leads to a hold time of a little more than two weeks.

The magnet has a nominal maximum field of 5 T at a current of 85 A. At the acceptance test at MSL it quenched at 4.7 T, approximately the same field that was reached at the factory. The reason was probably the big forces that the slightly asymmetrical iron yoke exerts on the coil together with an inadequate suspension and a small radial misalignment of the coil. Although the alignment was improved after the quench at MSL, and we believe that the magnet works up to 5 T, we have not yet tested it to the full field. The field can be ramped up and down with 1 T/min.

3 ELECTRON GUN

The electron gun now has a cathode with 4 mm diameter, compared to 40 mm originally and 12 mm when 10 times expansion was used. The new version of the cooler is thus designed for an expansion factor of 100. Since the magnetic fields in the gun solenoid and the other cooler magnets now are independent, however, also smaller expansion factors can be used. The shape of the magnetic field in the transition between the gun solenoid and the small solenoid below it is compatible with operation even without expansion. Of course, the electron-beam diameter in the cooling solenoid will then be just 4 mm.

The gun has a conventional Pierce geometry with only two anodes. This is a simplification of the gun geometries used in the previous versions of the cooler, motivated by the fact that the strong magnetic field of the superconducting magnet makes transverse electric fields in the gun relatively less important. The second anode is 300 mm long in order to allow a complete 'longitudinal-longitudinal' relaxation of the electron plasma before the electrons are accelerated to full energy. This is an easily implemented but useful approximation to the adiabatic (with respect to plasma oscillations) acceleration that would minimize the longitudinal electron temperature [3].

The cathode is a conventional dispenser cathode (oxide-impregnated tungsten). It is capable of delivering several amperes per cm^2, which is sufficient for our purposes. Some data for the present version of the electron cooler are listed in table 1.

Table 1. Some design parameters for the superconducting cooler. Values used for cooling or recombination are given within parentheses if they are not the same as the design values.

Magnetic field, gun solenoid	0-5 (0.3-4) T
Magnetic field, cooling sol.	0-0.3 (0.03-0.1) T
Gun diameter	4 mm
Electron energy	0-20 (0.05-4.5) keV
Electron current	0-500 (1-100) mA
Perveance	0-5 (0.1-4.8) $\mu A/V^{3/2}$

4 RESULTS

The cooler has been running with the superconducting gun solenoid since the summer of 1997. It has been working as expected, with the exception that the electron energy has been limited to, first, 1.8 keV; then, after some insulators in the gun were replaced, to about 4.5 keV. We hope that we will be able to make some further modifications during the Christmas break 1998/99 so that we can approach the design voltage of 20 kV. From these problems, however, one can conclude that the small dimensions of the gun together with the strong magnetic field have made the high-voltage insulation considerably more difficult than it was with the previous versions of the cooler.

For most experiments, the cooler has been run with 100 times beam expansion, using 3–4 T in the superconducting solenoid and 300–400 G in the other magnets. We have not run with much more than 100 mA electron current due to the high-voltage problems. Although this has hampered some experiments, it has not been an issue for investigations of dissociative recombination of heavy molecules, where energies and currents are very low. For example, recombination of O_2^+ was studied with a 50 eV electron beam, and although the electron current was only 1.0 mA, a small effect of beam cooling could be observed on a spectrum analyzer.

Some cooling-force measurements were performed with the 100 times expanded electron beam. Figure 2 shows data for deuterons taken with an electron beam of 20 mA at 1.7 keV (blue points). Earlier data taken with 10 times expansion (green) and no expansion (red) are also shown in the figure. The difference between 10 and 100 times expansion is not so dramatic, but most probably bigger than the measurement errors. However, the new data were taken at a lower electron energy and a somewhat lower longitudinal electron temperature. It is worth noting that all three measurements agree very well at high relative velocities, indicating that the normalization of the data is correct, at least relative to each other. The curves in the figure show theoretical

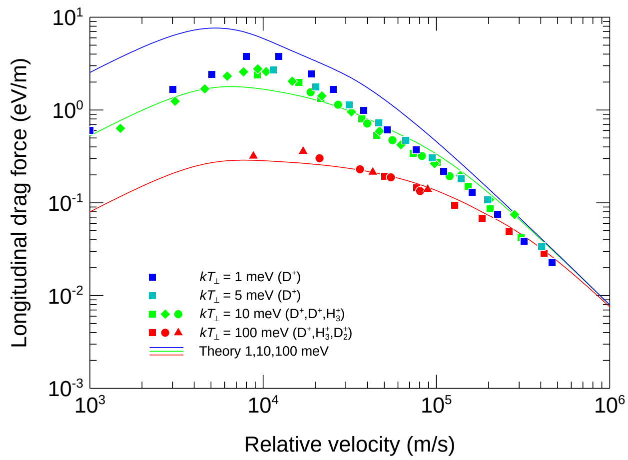

Figure 2. Cooling forces measured at CRYRING with three different beam expansions together with theoretical curves. All data are normalized to an electron density of 1×10^{14} m^{-3}.

cooling forces according to the binary-collision model as described in [2].

An accurate measurement of the temperature of the expanded electron beam can only be made by looking at the peak shape of sharp recombination resonances. The asymmetric peak shape at low relative energies (i.e., energies in the order of the transverse electron-energy spread or lower) makes it possible to determine the transverse and longitudinal temperature simultaneously.

With the ten times expanded electron beam, S. Mannervik et al. studied dielectronic recombination of C^{3+} ions [4], which have narrow recombination resonances around 0.2 eV. An analysis of their data yielded a transverse electron energy spread kT_{perp} = 9.4 meV and a longitudinal energy spread kT_{par} = 0.08 meV. A similar study with the 100 times expanded beam was made by R. Schuch et al. [5]. Here, the experimental background was quite high due to the energy limitation mentioned above. The relative energy of 0.2 eV is also a little too high for measurement of transverse energy spreads below

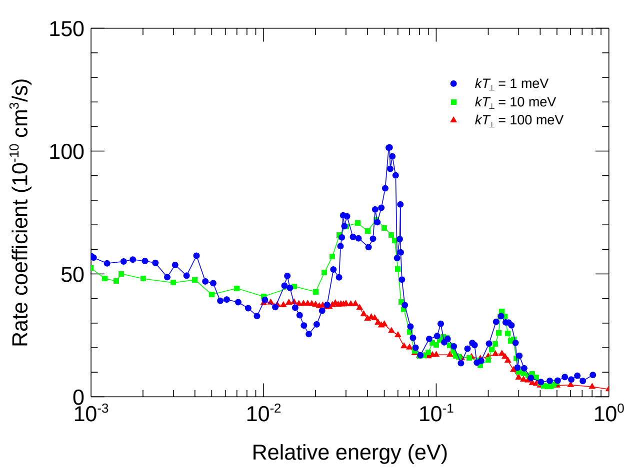

Figure 3. Rates for dissociative recombination of $^3HeH^+$ ions obtained at CRYRING [6–8] with 100 times beam expansion (blue), 10 times (green) and no expansion (red).

10 meV. Nevertheless, it was possible to conclude that the electron energy spread was below 4 meV transversally and approx. 0.05 meV longitudinally. The two measurements used the same electron density, so one can assume that the reduction in longitudinal energy spread from 0.08 to 0.05 meV was due to the change in gun design that was made possible with the stronger magnetic field.

Concerning the transverse energy spread, it can be noted that the measurements of the magnetic field in the cooling solenoid that were performed before the cooler was assembled the first time showed that it deviated by less than ±0.1 mrad from a straight line after all corrections were applied. Even if this would not quite hold today after the installation of the superconducting magnet, the contribution of such field imperfections to the effective electron energy spread should be much smaller than 1 meV at the low electron energies we have been using for recombination experiments and cooling-force measurements. The same holds for the effects of the electron-beam space charge.

The rate for dissociative recombination of $^3HeH^+$ ions has been measured both without beam expansion, with 10 and with 100 times expansion [6–8]. Figure 3 shows the low-energy part of the results of these measurements and clearly illustrates the improvement in energy resolution that has been obtained (similar data were obtained at the TARN-II storage ring, where a superconducting gun solenoid has been in operation since early 1997 [9]). The figure also demonstrates how the total count rate, i.e. the area under the peaks, increases with lower electron temperature, as expected.

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