Electron Cooling with an Ultracold Electron Beam

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The efficiency of electron cooling can be improved by adiabatically expanding the electron beam in a decreasing magnetic field, thereby lowering the transverse electron temperature. An electron beam expanded by a factor of 10 has been implemented at the CRYRING electron cooler, decreasing the transverse electron temperature from 100 to 10 meV. This has resulted in an increased drag force between ions and electrons and in large reductions of cooling times. Also, the energy resolution in electron-ion recombination experiments at low relative energy has increased by a factor of 10.

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Several small storage rings, where atomic and molecular physics are the principal fields of research, have been taken into operation during the last five years. An important part of the experimental program at these rings is devoted to studies of the interaction between the stored ions and free electrons in an electron cooler [1]. The processes investigated include radiative and dielectronic recombination—spontaneous or laser induced—of atomic ions and dissociative recombination of molecular ions. In these and other storage rings, the electron cooler is, as its name indicates, also used for beam cooling and for other manipulations of the ion beam, such as accumulation of ions [2].

An electron cooler is thus a versatile device whose properties in several respects influence the performance of the machine and the experimental conditions. It basically consists of an intense, cold electron beam that is guided by a longitudinal magnetic field from the gun to the collector (see Fig. 1). During cooling the electrons are given the same velocity as the ions, and in the interaction region where the electron beam is merged with the ion beam, heat is transferred from the hot ions to the electrons. When the cooler acts as an electron target, the electron energy may be shifted in order to obtain a nonvanishing collision energy. When the energy shift ΔE of the electrons is transformed to the center-of-mass system, it becomes reduced by a factor $\Delta E/4E_e$, where E_e is the electron energy in the laboratory system. Collision energies in the meV range are thus easily obtained, although the ion energies are more than ten orders of magnitude higher.

For beam manipulations, the most important property of a cooler is the force that the electron beam exerts on the ions. This drag force can, nonrelativistically, be expressed as

$$\mathbf{F}(\mathbf{v}_i) = -4\pi\left(\frac{Ze^2}{4\pi\epsilon_0}\right)^2 \frac{n_e L_C}{m_e} \int f(\mathbf{v}_e)\, \frac{\mathbf{v}_i - \mathbf{v}_e}{|\mathbf{v}_i - \mathbf{v}_e|^3}\, d^3 v_e\,, \tag{1}$$

where $\mathbf{v}_i$ and $\mathbf{v}_e$ are the ion and electron velocities, Z the charge state of the ion, n_e the electron density, L_C the Coulomb logarithm for the ion-electron collisions, and $f(\mathbf{v}_e)$ the electron-velocity distribution. One usually assumes that the electron velocities have an anisotropic Maxwellian distribution with longitudinal temperature $T_{e\parallel}$ and transverse temperature $T_{e\perp}$,

$$f(\mathbf{v}_e) = \frac{m_e}{2\pi k T_{e\perp}} \left(\frac{m_e}{2\pi k t_{e\parallel}}\right)^{1/2} \times \exp\left(-\frac{m_e v_{e\perp}^2}{2kT_{e\perp}} - \frac{m_e v_{e\parallel}^2}{2kT_{e\parallel}}\right). \tag{2}$$

Because of the acceleration of the ions, the longitudinal temperature becomes much smaller than the transverse one and is in many cases negligible. For a given ion beam, the only parameters one can use to maximize the drag force are thus the electron density, the electron temperature, and the Coulomb logarithm. The electron density is usually optimized from one run to the next, depending on the particular experimental requirements. The Coulomb logarithm can be increased by increasing the magnetic

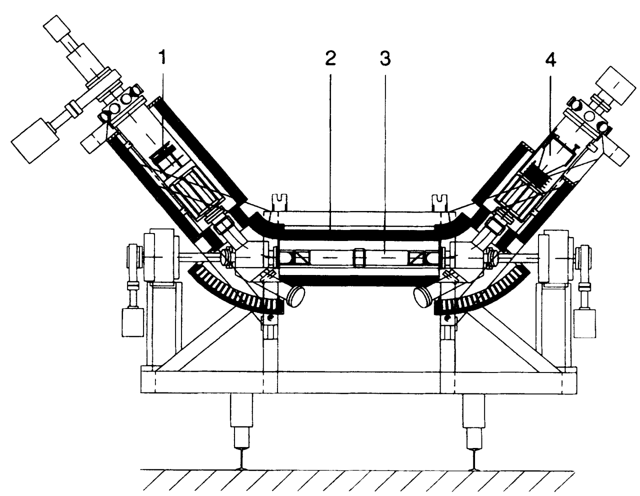

FIG. 1. Schematic of the CRYRING electron cooler with electron gun (1), magnet coils (2), interaction region (3), and collector (4).

field that guides the electron beam through the cooler, but this is only a logarithmic effect. The transverse electron temperature, which should be minimized in order to give a high drag force, has, up to now, not been lower than the temperature of the thermionic cathode that the electrons are emitted from, or approximately 1200 K. When the cooler is used as an electron target, the critical parameters are essentially the same as for cooling: The electron density determines the count rate of the experiment, and the electron temperature often limits the energy resolution of the recombination spectra.

The CRYRING [3] at the Manne Siegbahn Laboratory in Stockholm is one of the small storage rings equipped with electron cooling [4], and where much of the experimental activity is in atomic and molecular physics. We have recently modified the magnetic-field configuration of our electron cooler and obtained a transverse electron temperature that is 10 times lower than the cathode temperature, corresponding to a $kT_{e\perp}$ of approximately 10 meV. This has increased the drag force by a large factor and has led to a dramatic improvement of the energy resolution for experiments at low relative electron energies, as shown in an investigation on dissociative recombination of ${}^3\mathrm{HeH}^+$ ions [5].

The beam of an electron cooler is launched into a homogeneous, axial magnetic field, and if the field strength is constant throughout the cooler, the transverse electron temperature in principle remains constant, equal to the cathode temperature. In practice, imperfections in the acceleration optics, in the magnetic field, and space-charge effects may increase $T_{e\perp}$. Such heating is difficult to avoid for coolers operating at high electron energies, but for moderate energies and currents, one can get close to the cathode temperature, i.e., to $kT_{e\perp} = 100$ meV. This is also the value obtained at the CRYRING cooler before it was modified (see open symbols in Fig. 2).

The transverse temperature can be reduced, however, by letting the electron beam pass through a region of decreasing axial magnetic field [6]. When the field changes adiabatically with respect to the cyclotron motion of the electrons, the ratio $W_\perp/B_\parallel$, where $W_\perp$ is the kinetic energy in the transverse motion and $B_\parallel$ is the longitudinal field strength, is an invariant. This can be derived from the adiabatic invariance of the action variable

$$J_\theta = \oint p_\theta \, d\theta \,, \tag{3}$$

where p_θ is the canonical momentum corresponding to the angle θ. The maximum field in the magnets of the CRYRING electron cooler is 0.3 T, and the field gradient was obtained by lowering the field to 0.03 T in all magnets except the solenoid in which the gun is located (see Fig. 1). The transition from the high field in the gun solenoid to the low field in the small solenoid immediately below it has a length which is approximately

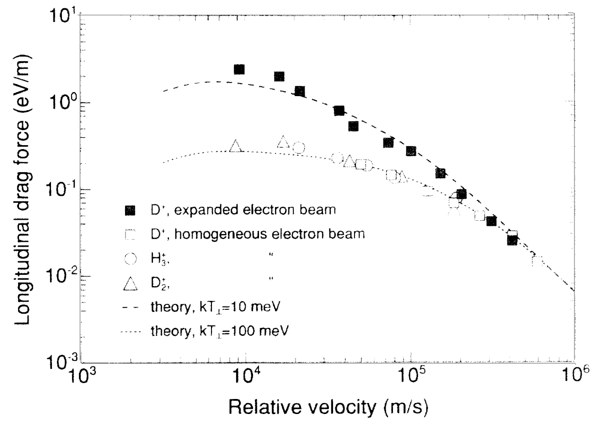

FIG. 2. Drag forces measured with a conventional electron beam at CRYRING before the cooler was modified (open symbols), and with the expanded electron beam (filled symbols). Curves are forces calculated from expression (1) using $kT_{e\parallel} = 0.05$ meV and normalized to an electron density of $10^{14}\ \mathrm{m}^{-3}$.

equal to the solenoid diameter, or about 40 cm. Calculations then show [6] that the transition remains adiabatic up to an electron energy of 40 keV, which is twice the maximum electron energy in the CRYRING cooler.

As the electron beam passes through the negative field gradient, it also expands. The area of the beam cross section is inversely proportional to the magnetic-field strength, so that in our case, the area increases by a factor of 10. Since the available aperture is limited to the 40 mm diameter that the electron beam had in the original design, a new electron gun was installed, which has a 10 times smaller cathode area. The geometry of the gun is the same as that of the original one, except that the linear dimensions are scaled down by a factor $10^{1/2}$. It is important to note that this new gun has the same perveance as the old one. The current density in the cooling region is thus the same as in the old design when the same voltages are used.

The electron-beam temperatures were estimated, before and after the electron-beam expansion was introduced, using several methods: through measurements of the longitudinal drag force and of rates of transverse cooling, and also from the energy resolution in spectra of dielectronic and dissociative recombination processes.

The drag-force measurements were made by first cooling stored ions, then changing the electron energy and observing, via the Schottky frequency, how quickly the ion velocity changed toward the new electron velocity. This method is quite accurate as long as the step in cooler voltage is sufficiently rapid and accurate, and the velocity change of the ions slow enough to be measurable by a spectrum analyzer. At investigations of the drag force with the expanded electron beam (filled symbols in Fig. 2), we were able to use this technique for relative velocities down to approximately 10 000 m/s. The measurements presented here were made on a deuteron beam of 12 MeV, giving an electron energy of 3.2 keV. The electron current was 50 mA. For the lowest relative velocity, the time between the voltage jump and the triggering of the spectrum analyzer was only a few times larger than the rise time of the voltage supply and the time it takes the spectrum analyzer to make a measurement, giving an error estimate for the drag force at 10 000 m/s of ±30%. For the other points the error is considerably smaller. The exact size of the voltage jump is critical for the low-velocity points, but it is easily checked through a determination of the Schottky frequency when the ion beam has shifted into equilibrium with the new electron energy. Also note that a long rise time of the voltage supply will underestimate the maximum drag force.

The theoretical curves of Fig. 2 were calculated by integrating expression (1), using Maxwell distributions with $kT_{e\perp} = 100$ and 10 meV, respectively. For the longitudinal temperature, $kT_{e\parallel} = 0.05$ meV was used. The longitudinal temperature is in general dominated by relaxation processes within the electron beam. The transfer of energy from the transverse to the longitudinal motion is suppressed, at least to some extent, by the magnetic field. The main contribution instead derives from the transfer of the potential energy between the electrons of the accelerated beam into kinetic energy. These two processes should give a $kT_{e\parallel}$ of approximately 0.05 meV. This is also close to the value obtained experimentally from measurements of the width of dielectronic-recombination peaks [7]. When evaluating the Coulomb logarithm of expression (1), the influence of the longitudinal magnetic field on the ion-electron collisions was not taken into account. This field should in principle increase the drag force since it lowers the effective transverse temperature of the electrons. It is seen in Fig. 2 that the agreement between the curves and the experimental points is quite good. This indicates that the transverse electron temperature indeed was reduced by a factor of 10 to 10 meV through the expansion of the electron beam, and that no significant effects of the longitudinal magnetic field on the cooling is seen.

One could possibly argue that what we see is a beam with a temperature much higher than 10 meV but with a strong contribution of magnetized cooling. In order to resolve this ambiguity, some other way to determine the electron temperature must be used, such as the measurements of the energy resolution in recombination spectra. In one such study [5], the cross section for dissociative recombination of $^3HeH^+$ ions was recorded as a function of the relative energy between ions and electrons. Although this type of recombination does not give rise to line spectra, it was clear that the energy resolution was in the vicinity of 10 meV. Also dielectronic recombination of $^4He^+$ has been investigated with the expanded electron beam. These studies were made at higher relative energies, however, where the sensitivity to $T_{e\perp}$ is smaller, and it could only be concluded that $kT_{e\perp}$ was substantially lower than 100 meV. On the other hand, the longitudinal temperature could be evaluated, and it was found to be 0.06 meV.

During the same $^4He^+$ run, the transverse cooling of the ion beam was studied by monitoring neutralized helium ions hitting a position-sensitive channelplate detector situated immediately behind the cooler. It was found that the 24 MeV beam was essentially cooled after 1 s using an electron current of 100 mA; see the left column of Fig. 3. This result was quite well reproduced by a numerical simulation of the cooling process through particle tracking, using drag forces calculated in the same way as the curves of Fig. 2 (although three dimensionally, since all force components are needed). In the right column of Fig. 3 is shown the simulated cross section of the neutralized beam, as it would look at the position of the channelplate detector. The good agreement indicates that also the three-dimensional friction force between ions and electrons is well described by an electron beam of $kT_{e\perp} = 10$ meV and $kT_{e\parallel} = 0.05$ meV.

The fact that an adiabatically varying magnetic field modifies the transverse temperature in an electron cooler was shown already at the Fermilab cooler [8], which had a converging electron beam, and in Novosibirsk [9], where an expanded beam was used for temperature measurements. An expanded electron beam has also been suggested as a tool for collision physics [10]. Nevertheless, it seems that the impact that this technique can

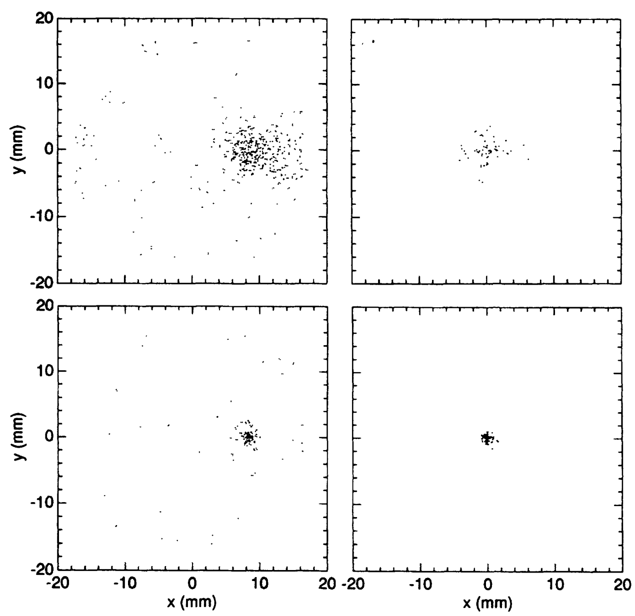

FIG. 3. The left column shows the beam cross section as seen by detecting neutralized 24 MeV $^4He^+$ ions on a position-sensitive channelplate detector behind the cooler; the upper picture is taken immediately after the acceleration and the lower one after 1 s of cooling (the beam spot is just to the right of the center, the rest is background counts). The right column shows the result of a numerical simulation of the cooling process using the same beam parameters.

have on experiments in atomic and molecular physics at storage rings has not been generally recognized, nor has its potential concerning the reduction of cooling times at low or moderate ion energies. We have shown, however, that without introducing any negative side effects on the cooling process, a large reduction of the transverse electron temperature can be achieved. This has created possibilities for a new generation of high-resolution experiments studying electron-ion recombination at low relative energy. Furthermore, we expect that still much lower temperatures can be reached with a larger expansion than the factor of 10 used at present—with a superconducting gun solenoid it should be possible to reach another factor of 10 and electron temperatures of 1 meV.

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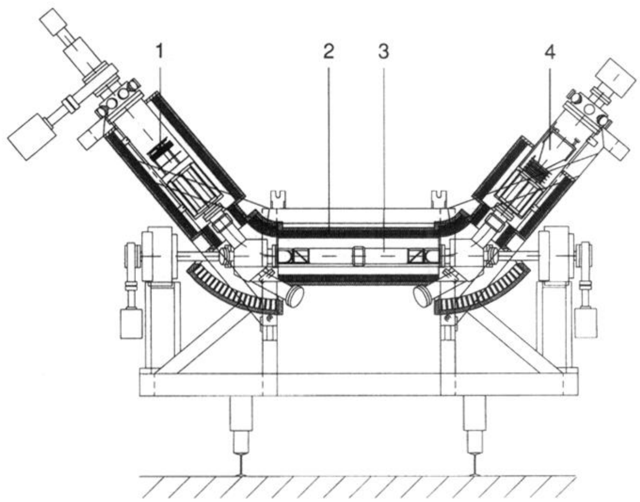

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