The First Year with Electron Cooling at CRYRING

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Abstract— The experimental program at CRYRING storage ring began shortly after the installation of the electron cooler in May 1992. The performance of the ion sources and the ring is reported. Results of electron cooling are reviewed and a method to improve the efficiency of electron cooling is presented.

I. Introduction

CRYRING is a low-energy synchrotron and storage ring equipped with electron cooling [1]. The ring receives light atomic and molecular ions from a plasmatron ion source (MINIS) or highly charged, heavy ions from an electron-beam ion source (CRYSIS). The ring has been running for experiments using light ions such as D^+, H_3^+, and $^3HeH^+$, but also Ar^{13+} has been accelerated and cooled. The EBIS source is regularly delivering beams for low-energy atomic-physics experiments using gas injection. It has also produced highly charged argon and xenon ions using injection of singly charged ions from an external ion source (INIS). Electron cooling has been applied both to atomic and molecular ions at energies between 290 keV/u (the injection energy in CRYRING) and 10.9 MeV/u [2]. By measuring the longitudinal drag force on the ions, the electron temperature has been determined to 0.1 eV transversally and around 10^{-4} eV or less longitudinally. We expect to reduce the transverse temperature a factor of 10 by using a magnetic field that is 10 times higher in the gun solenoid than in the rest of the electron cooler.

II. Ion sources

CRYSIS [3] has been running mainly with argon and xenon ions using gas injection. Ar has been produced in all charge states and Xe in charge states up to 49+. Atomic-physics experiments have used Xe ions in charge states up 44+. Typical electron currents are between 150 and 300 mA and confinement times reach up to 5 s for the highest charge states. The ion source has also been used with ion injection. Injection of ions from an external ion source has several advantages compared to gas injection. The most important one is that the interior of the EBIS can be kept cleaner since no gas is adsorbed on the cold surfaces of its interior. This makes it easier to switch between different ions, also metallic ions can be used with a suitable ion source. Unlike the gas, the ion current can easily be switched on and off, so that ions can be injected only for a very short time during the beginning of each ionization cycle. This results in a narrower charge-state spectrum. The ion injector is built as an isotope separator, which means that heavy elements, such as xenon, no longer have to be isotopically pure in order to allow separation between the high charge states. One can summarize the experience from using ion injection by saying that the output of CRYSIS is at least as good (concerning intensity and charge states) as with gas injection, while operation is considerably simpler.

The plasmatron ion source, MINIS, has recently been upgraded in order to improve the vacuum in the injection line. It has also been provided with an analyzing magnet.

III. Ring

Since the installation of the electron cooler in May 1992, all major components of the ring are in operation. The layout of the facility is shown in figure 1. The RFQ and the electrostatic injection system were designed for ions with charge-to-mass ratios above 0.25. The range between 0.25 and 0.5 has been covered by ions such as D^+, H_2^+, $^3He^+$, H_3^+, Ar^{13+}, D_2^+, and $^3HeH^+$. All these ions have also been accelerated to full energy, $96(q/A)^2$ MeV/u, and

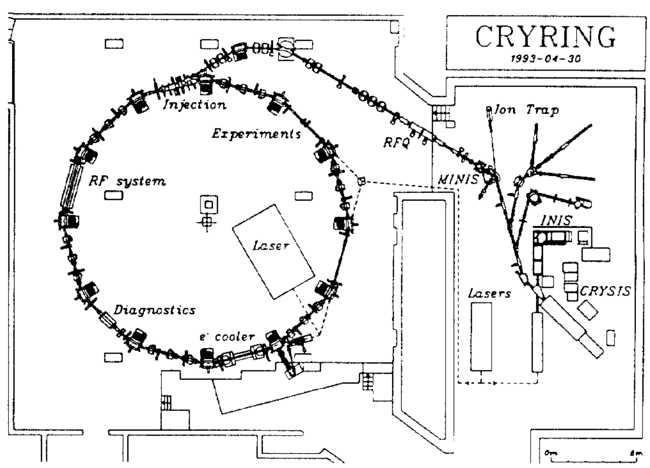

Fig. 1 Layout of CRYRING

cooled. The number of ions stored at full energy is typically between a few times 10^7 and 10^8. For some cases, where the ion-source output is high, up to 2×10^9 ions have been stored. Four of the twelve straight sections in the ring have been baked to 250°C, and there the pressure is below 1×10^{-11} mbar (the lower limit of the vacuum gauges used at present). In the other straight sections the pressure is $1-3 \times 10^{-11}$ mbar. Most of the pumping speed is provided by NEG (Non-Evaporable Getter) pumps, and, to a lesser degree, by ion pumps [4]. Rest-gas analysis shows that the partial pressure of gases heavier than H_2, mainly CH_4 and H_2O, constitutes about 10% of the total pressure.

For ions with large cross sections for electron loss in collisions against restgas molecules, such as the light molecules or He^+, this pressure should give life times of around 30 s at the injection energy. Measured lifetimes are in the order of a few seconds, indicating that the true pressure is higher than the measured one or that the restgas composition is different from what has been measured. The lifetime for Ar^{13+} is even shorter due to the large capture cross section at the injection energy. Such lifetimes makes rapid acceleration necessary, in our case the acceleration to full energy is done in about 1 s. (Although the power supplies allow the ramping to be done in 150 ms, this fast mode has not been used yet.) At full energy the lifetime is 5 – 20 s for these ions. Bare ions have much longer lifetimes: for electron-cooled D^+ ions at 6 MeV/u, where single-scattering is the dominant loss mechanism, 21 h has been measured.

IV. Electron cooler

The electron cooler was assembled outside the ring during April of 1992 and tests with the electron beam were performed for a few weeks. Then the cooler was inserted into the ring, and on the 20 May the electron beam was again turned on, and cooling of deuterons at 5.4 Mev/u was observed. A few weeks later, H_2^+ ions were cooled at the same energy. The momentum-cooling time is around 1 s for these ions and an electron current of 150 mA. The transverse cooling time has not been measured, but should theoretically be about 5 s, roughly the same as the lifetime of the beams. We have generally used electron currents between 100 and 150 mA. Higher currents gives a tune shift at injection energy that is so high that it has to be compensated with the ring quadrupoles. An alternative, which also has been used, is to turn off the electron beam during the injection and beginning of acceleration.

The relative momentum spread of the ion beam after cooling is usually $5-10 \times 10^{-5}$ and occasionally somewhat smaller. With Ar^{13+}, where the cooling is considerably stronger than for the light ions, 1.6×10^{-5} was recorded. The diameter of cooled D^+ beams has been measured with a position-sensitive channelplate detector located at the zero-degree extension after the electron cooler, which detects ions that have been neutralized in the cooler. A beam of 10^7 D^+ ions at 6 MeV/u created an image on the detector that had a width of 0.5 mm and a height of 0.25 mm (FWHM). Considering that the neutralized D beam had a certain divergence, the size of the stored beam should have been still somewhat smaller. The image size was sensitive to changes in the angle between ion and electron beams down to a few tenths of a milliradian.

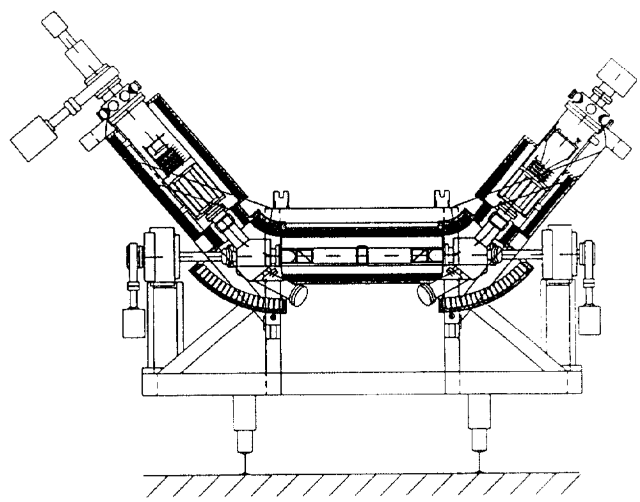

Fig. 2 Layout of the electron cooler

An interesting subject for study at CRYRING is electron cooling at very low ion energies. The reason is both that electron-cooler stacking in CRYRING would have to be performed at 290 keV/u (which thus is the injection energy) and that experiments have been suggested with heavy molecular ions where the maximum energy per nucleon is very low. Using an electron current of only 7 mA the goal to momentum-cool at the injection energy was reached with a beam of 2×10^9 H_2^+ ions. This energy corresponds to an electron energy of 170 eV. The momentum-cooling time was $3-5$ s, which was about twice the lifetime of the ion beam. Schottky spectra of the cooled and uncooled H_2^+ beam at the 20th harmonic are shown in figure 3.

Through measurements of the longitudinal drag force that the electrons exert on the ions, the temperature of the electron beam could be obtained. The drag force was measured by cooling the ion beam, then shifting the electron energy by a small amount, and observing, using a spectrum analyzer, how fast the ion velocity changes toward the new electron velocity. Such measurements were made at three different charge-to-mass ratios using D^+, H_3^+, and D_2^+. Since the longitudinal drag force depends both on the transverse and the longitudinal electron temperatures, both these could be estimated. The measured values followed the theoretical curve for a transverse temperature of 0.10 eV, corresponding to the cathode temperature of 900°C, and for a longitudinal temperature of the order 10^{-4} eV or less. Measurements could not be made at relative velocities low enough to resolve longitudinal temperatures lower than 10^{-4} eV. This longitudinal temperature is also consistent with measurements of the rate for radiative recombination of deuterons and electrons. This rate was measured at very low relative energies by sweeping the electron energy around the cooling energy according to a sawtooth function and was seen to increase even at energies below 10^{-4} eV.

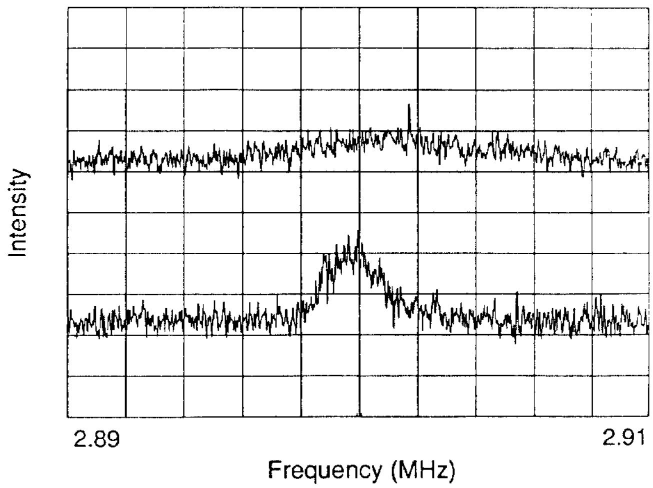

Fig. 3 Schottky spectra of cooled and uncooled H_2^+ at 290 keV/u

Stronger cooling forces, both longitudinally and transversally, would be obtained with a colder electron beam. A method for producing an electron beam that has a transverse temperature which is lower than the cathode temperature is to guide the electron beam through a negative magnetic-field gradient [5]. Since the ratio between transverse energy and longitudinal magnetic field for a charged particle is an adiabatic invariant under changes of the magnetic field strength, a smoothly decreasing field reduces the transverse temperature in proportion to the field decrease. If, as an example, the field in the gun solenoid is ten times stronger than in the rest of the cooler, the transverse electron temperature will decrease from 0.1 eV to 0.01 eV. The transverse energy spread will be transferred to the longitudinal motion. This will not be noticeable, however, after transformation to the moving system of reference—the longitudinal electron temperature will in general still be dominated by the longitudinal relaxation of the electron beam (transfer of potential energy due to the electron–electron interaction to kinetic energy).

The requirement that the electron motion is adiabatic with respect to the decrease of the field strength puts a limit to the electron energy for a given field gradient. In the case of the CRYRING cooler, a gradient can be obtained by having a strong field in the gun solenoid and a weaker field in the rest of the cooler. Calculations show that the transition region between the gun solenoid and the small solenoid below it allows a maximum electron energy of 30 keV when the field is 0.3 T in the gun solenoid and 0.03 T otherwise. Even at 60 keV there is a significant reduction in transverse electron energy.

The field gradient will increase the beam cross section with a factor equal to the ratio of field strengths. A new electron gun with a ten times smaller area is therefore under manufacturing for tests of this technique at the CRYRING cooler. It will be a scaled-down version of the present gun. It will thus have the same perveance as the present one and will give the same electron density in the cooling solenoid.

V. References

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