Performance of CRYRING with improved electron cooling

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Abstract

A report of the performance of the CRYRING is given. The status and important improvements of vacuum, the RF system, diagnostics and, most importantly, the electron cooler is given. The cooler has since the summer of 1993 incorporated a magnetically expanded electron beam, giving a transverse electron temperature of 10 meV. A number of experiments have used the low electron temperature of the upgraded cooler for high-resolution experiments on electron-ion recombination. The low temperature has made possible the accumulation of D^+ ions at the low injection energy of 290 keV/u. New modes of operation are reported, such as the use of the RFQ as a focussing and transport device for slow ions far off the resonance condition, e.g. N^+ at 40 keV that subsequently also were stored and accelerated in the ring.

All the parts of the system that were originally planned in the first phase of CRYRING have been installed and some important technical improvements have been made. The general layout of CRYRING is shown in figure 1 and a technical overview of the project can be found e.g. in [1].

1 INTRODUCTION

The accelerator/storage ring CRYRING is now in regular operation. The most important improvement that has been made is the successful modification of the electron cooler to give an electron beam with a transverse temperature which is a factor of ten lower. This lower temperature has been of great importance for the experiments. The resulting shorter cooling time has also enabled us to increase the maximum current of D^+ in the ring by accumulating the injection pulses through transverse stacking. The maximum current of D^+ after acceleration to 21 MeV/u has been 170 μA. The highest current observed in the ring for any ion species is 200 μA, which was obtained with a beam of $^3He^+$. The cooler modification is described in detail later in this article.

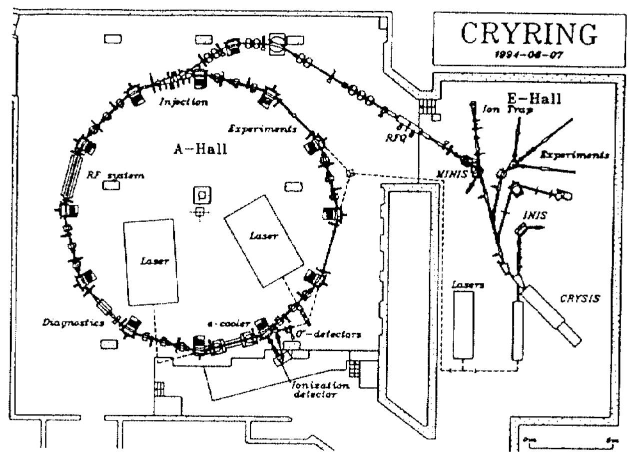

Figure 1: Layout of the CRYRING facility.

2 OPERATING EXPERIENCES

Singly charged atomic and molecular ions from the plasmatron source, MINIS, and highly charged ions from the EBIS source, CRYSIS, have been used for experiments in the ring since August 1992. Beams from CRYSIS have also been used for several experiments without storing the ions in the ring. E.g. beams of Xe with charge states up to 44+ have been delivered to experiments. During tests of the source, 1.5×10^5 ions per pulse of Xe^{52+} have been produced [2].

All the atomic and molecular experiments in the ring have used the electron cooler, both for cooling the ions and as an electron target for recombination studies. Nuclear physics experiments have also been performed with a $^{36}Ar^{10+}$ beam, using fixed targets of nickel and aluminium. The reason for the use of the rather rare (and expensive) isotopes ^{36}Ar and ^{3}He (in the $^3HeH^+$ case) is that the RFQ was designed to accelerate ions with $Q/A\geq0.25$. A ^{3}He beam was also used in some of the experiments to fulfill requirements from the experimentalists for as high energy as possible in order to reduce background from interactions with rest gas molecules. A further reason for the use of ^{3}He, before an upgrading of the differential pumping in the injection line was performed, was to avoid an increase in the partial pressure of ^{4}He in the ring, which could disturb the leak detector. As can be seen in table 1, particles with a wide range of energies have been stored in the ring. The total energy of the particles ranges from 40 keV up to 420 MeV and the energy per nucleon from 2.9 keV to 24 MeV.

3 THE RF SYSTEM

The RF section is of the non-resonant driven drift-tube type. This design was chosen because of the broad frequency range of such a system and the simplicity of the construction [4]. The unique broad-band properties of this structure enables investigations such as studies of bunching and acceleration with arbitrary, non-sinusoidal waveforms. However, due to these properties noise on the RF signal is more easily transfered to the beam than with the conventional resonant cavities normally used for acceleration. In order to explore the possibilities of the combination of our broad-band system with modern synthesizer techniques, a collaboration with the RF group at COSY, KfA Jülich, has been established. During the initial stage of this collaboration the previously used voltage controlled oscillator has been replaced by a digital Numerically Controlled Oscillator, NCO, which was constructed and built in Jülich [3]. The exceptional spectral purity and stability of the NCO and a general elimination of noise sources in the RF system have resulted in a substantial increase in the beam lifetimes observed when the RF voltage is applied to the drift-tube. The frequency resolution of the NCO is at present 40 Hz and the update rate of the function generator is once every 10 μs. The resulting steps in the frequency ramp during acceleration have not been noted to cause any negative effects during the acceleration and the NCO is now routinely used in the RF system.

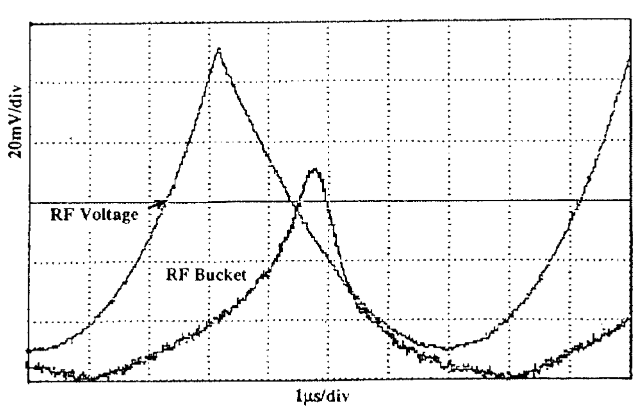

Figure 2: A parabolic RF waveform and the corresponding bunch of the beam measured on a pickup in the ring.

To study the effects of the use of non-sinusoidal waveforms, an arbitrary-waveform generator was used for tests with a sawtooth shaped accelerating voltage. Since the beam is affected by the difference between the voltages in the two gaps of the system, the actual waveform of the RF applied to the drift tube was a squared sawtooth. Figure 2 shows the measured bucket shape together with the parabolic RF waveform. The case with the inverted parabolic waveform which leads to a short RF bucket was also studied. The properties of the RF bucket will be investigated further during the collaboration.

4 DIAGNOSTICS

The beam diagnostical devices in the ring and the associated injection lines have been continuously improved. The closed-orbit measurements are performed using a fast peak detector and ADC-system [5]. By gating the peak detectors with a timing signal from the control system, the closed orbit deviation in all the 22 pickups can be recorded simultaneously during the machine cycle. The minimum time between two closed orbit samples is at present $\approx$2 ms. The lower detection limit for the system is a few μA of beam current.

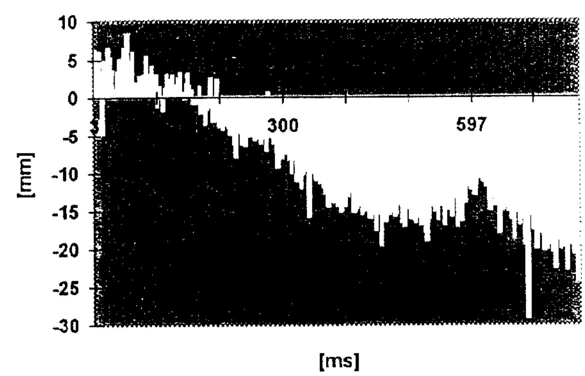

Figure 3: The closed orbit deviation in one pickup during an acceleration cycle with an improperly adjusted frequency ramp.

5 VACUUM

All the vacuum gauges in the ring are showing a pressure of less than 7.5 ptorr, which is the lower limit of the gauges used. Attempts have been made to estimate the pressure by comparing the measured lifetimes of the beams with theoretical calculations. The decrease in revolution frequency of a 42 MeV D^+ beam, which was stored in the ring during 75 hours, measured with the Schottky detector, was also used to estimate the average pressure. The decrease in revolution frequency in this case was 0.015%/h. The results of these measurements indicate that the average pressure is about 60 ptorr. The discrepancy between this value and the one given by vacuum gauges can, at least partly, be explained by the fact that the gauges are situated close to the vacuum pumps in the ring and that they are calibrated for nitrogen, while 90% of the rest gas is hydrogen. Furthermore, the beam-related methods are quite sensitive to the amounts of heavier components of the rest gas. Up till now only half of the ring, including the electron cooler, has been baked to 300° C. The rest of the ring will be baked in August this year.

6 TRANSPORT OF PARTICLES THROUGH THE RFQ

Since there has been a considerable interest in making experiments using ions with Q/A<0.25, heavy, singly charged ions from the MINIS source have been transported through the RFQ without acceleration and then injected into the ring. The ions were given 40 keV total energy

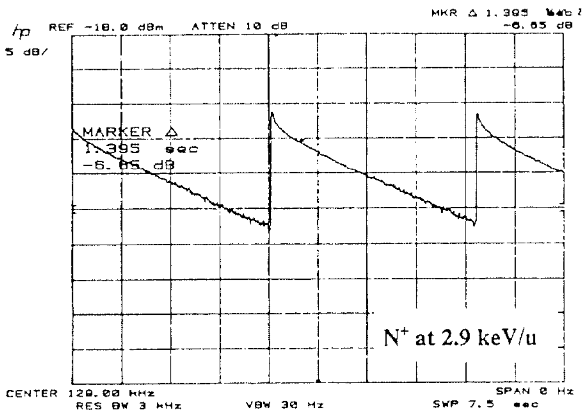

Figure 4: The decay of N^+ ions stored in the ring at 2.9 keV/u

and a reduced voltage was applied to the RFQ to make use of its focusing properties. Transmissions between 50% and 90% were obtained through the RFQ. Successful injection and subsequent acceleration of N^+ ions to close to full energy was achieved. The beam at its very low injection energy of only 2.9 keV/u, was very sensitive to the settings of the elements in the ring, especially the twelve correction dipoles. This fact, together with instability problems that seemed to be due to collection of charges on the isolators that are installed on several places in the beam pipe, made the adjustment of the ring parameters very difficult. For the acceleration a peak-to-peak voltage of only 7 V on the 9th harmonic was used. 40 keV D_3^+ ions have also been stored successfully in the ring. In this case the magnetic field of the dipole magnets is close to the lower limit set by the current supplies. Due to lack of time, no attempts to accelerate D_3^+ were made. Signals from stored N^+ are shown in figure 4.

7 ELECTRON COOLER

The electron cooler [6] was completed in May 1992. During its first year of operation, it was used as an electron target in a number of experiments studying various aspects of ion–electron recombination, including dissociative recombination of molecular ions and radiative and dielectronic recombination of light atomic ions. Beam cooling was used in these experiments and studied for both the light ions and for highly charged argon ions at beam energies between 0.29 and 21.9 MeV/u.

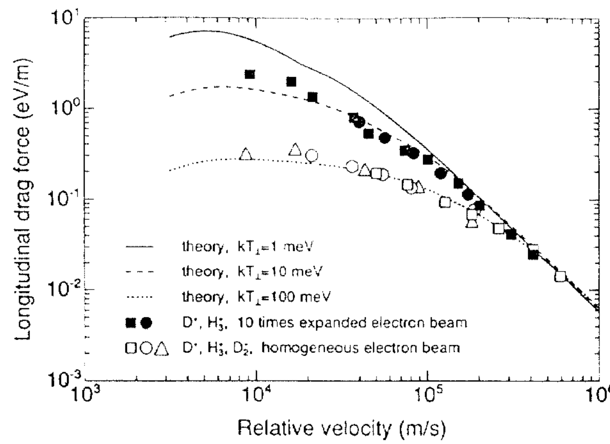

Figure 5: Experimental and theoretical longitudinal drag force as a function of relative velocity between ions and electrons. The theoretical curves are not quite smooth due to the non-analytic expression used for the Coulomb logarithm.

Measurements of the longitudinal cooling force were performed by making a step in the electron energy and observing via the Schottky spectrum how quickly the ions followed. The result is shown in figure 5 as open symbols (squares for D^+, circles for H_3^+, and triangles for D_2^+). Also shown is a theoretical curve (obtained as in [7], but with a slightly different Coulomb logarithm) for a transverse electron temperature $kT_{e\perp}$ of 100 meV and a longitudinal temperature $kT_{e\parallel}$ of 0.05 meV. The good agreement between the experimental points and the theory clearly shows that the transverse temperature is close to 100 meV. It is not possible to deduce a definite value for the longitudinal temperature from the measurements, since, when it is small, the cooling force is sensitive to this temperature only at very small relative velocities between ions and electrons. It could only be concluded that the longitudinal temperature was lower than about 10^{-4} eV. However, through measurements of the energy resolution in dielectronic-recombination experiments, a value of $kT_{e\parallel} = 8 \times 10^{-5}$ eV was obtained [8]. The relative momentum spread $\Delta p/p$ of cooled beams was typically $5 - 10 \times 10^{-5}$ and in some cases, in particular for highly charged ions, a few times smaller. Beam diameters were recorded for D^+ beams, which have long lifetimes and thus can get well cooled and are easy to manipulate. By monitoring neutralised D^+ ions with a position-sensitive channelplate detector immediately after the cooler, beam diameters down to 0.5 mm FWHM (horizontally) and 0.25 mm (vertically) were recorded.

Already from the very first experiments in CRYRING it was evident that the experimental conditions in many cases are strongly influenced by the electron temperature: A high cooling rate, achieved through a low temperature, is crucial for cooling of short-lived ions. When recombination spectra are recorded as a function of the relative energy between ions and electrons, the energy resolution is often given by the electron temperature. If, on the other hand, the electron energy is kept constant on a sharp resonance in the atomic system, a low electron temperature improves the count rate, for some processes by quite high inverse powers of the temperature.

Since the transverse electron temperature is much higher than the longitudinal one, the biggest gain is in general achieved by lowering the transverse temperature. This can be accomplished by guiding the electron beam through a region of decreasing magnetic field. If the field gradient is small, i.e., the field decreases slowly with respect to the electrons' cyclotron wavelength, then $W_{\perp}/B_{\parallel}$ is an invariant. Here, $W_{\perp}$ is the kinetic energy of the transverse motion, and $B_{\parallel}$ is the longitudinal magnetic field. During the summer of 1993, the CRYRING cooler was rebuilt to accommodate such a decreasing field. We reduced the current through all cooler magnets except the solenoid where the electron gun is located by a factor of 10, using an old spectrometer magnet as a shunt. Exciting the gun solenoid to its maximum design value, 3 kG, the field thus becomes 300 G in the rest of the cooler. This field configuration should reduce the transverse temperature to 10 meV. The longitudinal temperature is not expected to change much, since it is determined by relaxation processes within the electron beam.

As the electron beam passes through the decreasing field, it also expands. The beam area increases by the same factor as the field decreases. For this reason, the electron gun was replaced by one that has a ten times smaller cathode area, resulting in a beam which after the adiabatic expansion has the same area as the old one. The new gun has the same geometry as the old one, except for the scale factor, and thus has the same perveance. Consequently, the current density in the cooling solenoid, where the electrons interact with the ions, is the same as before the cooler was rebuilt.

The longitudinal cooling force was measured with the modified cooler in the same way as described above. The measurements are illustrated with filled symbols in figure 5. The different theoretical curves were calculated using the same method; all parameters are the same, except for the transverse temperature. Again, the close agreement between theory and experiment shows that the transverse temperature was reduced to a value not far from 10 meV [9]. The main uncertainty in the measured values is systematic and is the result of the difficulty to estimate the effective length of the cooler (it is quite possible that the length is 10 – 20% shorter than assumed in the evaluation of the data, which would cause the experimental points in figure 5 to be too low by the same amount). Also the theory has some uncertainty due to a certain arbitrariness in the evaluation of the Coulomb logarithm. For example, no effects of the longitudinal magnetic field were taken into account.

Transverse cooling has been studied using the position-sensitive detector behind the cooler, detecting ions that have been neutralised in the cooler. For example, the transverse cooling time for 6 MeV/u He^{+} ions with 100 mA electrons was found to be around half a second (if the cooling time is defined as the time it takes to reduce the horizontal or vertical emittance by a factor $1/e$). This is close to what one can expect with the electron temperatures mentioned above. Transverse cooling has also been investigated with deuterons at the injection energy, 290 keV/u. The projection of the beam on the detector is shown in figure 6. After approximately 4 s the equilibrium between cooling and intrabeam scattering is reached. In this case, the ion current was in the order of 1 μA and the electron current was 7 mA, which is the highest electron current that can be extracted from the gun at this very low energy and corresponds to a perveance of $3\mu A/V^{3/2}$.

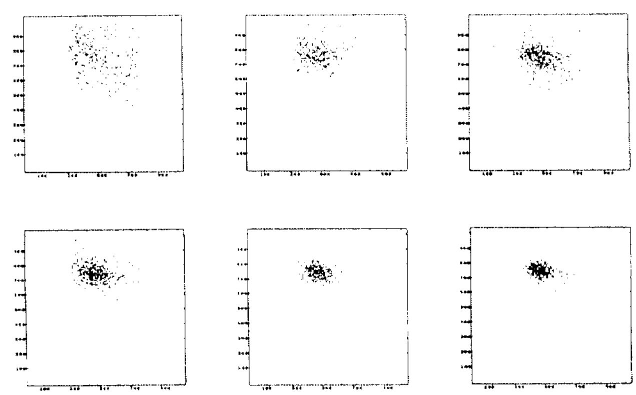

Figure 6: Ion beam cross section during cooling of D^{+} ions at 290 keV/u. The pictures are taken 0, 1, 2, 3, 4, and 10 seconds after the cooling starts. The side of one frame corresponds to about 40 mm, but there is a vertical slit in front of the detector only 20 mm wide.

Cooling at the injection energy makes it possible to use the cooler for accumulation of ions in those cases where the beam lifetime is long compared to the cooling time. At present, this condition is fulfilled for the lightest fully stripped ions. The accumulation is performed through transverse stacking. The cooler voltage is set so that the average momentum of the ions is kept constant, and as the beam shrinks transversally, new injection pulses can be put next to stack in the horizontal phase space. The lifetime for deuterons at 290 keV/u is 300 s, so if one can inject a new pulse every 3 s without loosing anything of the stack, it is possible to improve the stored intensity 100 times through the accumulation. Since the stack occupies a substantial fraction of the phase space where the injection pulse normally goes, the injection efficiency becomes reduced during the accumulation, and the factor 100 is not reached in practise. Nevertheless, 50 – 60 μA has been stored at the injection energy, corresponding to

2.5×10^9 particles. The limit is often set by instabilities that appear rather than by the efficiency of the accumulation itself. The observed limit is some 10 times higher than suggested by conventional stability criteria.

7.1 *Further improvements of the electron cooling*

Clearly, further improvements of the cooling rate, experimental resolution, etc., could be achieved if the electron beam is expanded by a factor larger than 10. With a superconducting gun solenoid, it should be relatively straightforward to reach an expansion factor of 100. If the transition between the high and the low field has the same length as in the present cooler (about 40 cm), and the field changes from 30 kG to 0.3 kG, the adiabaticity condition is fulfilled for electron energies below 40 keV. This is well above the maximum electron energy in the CRYRING cooler, which is 20 keV.

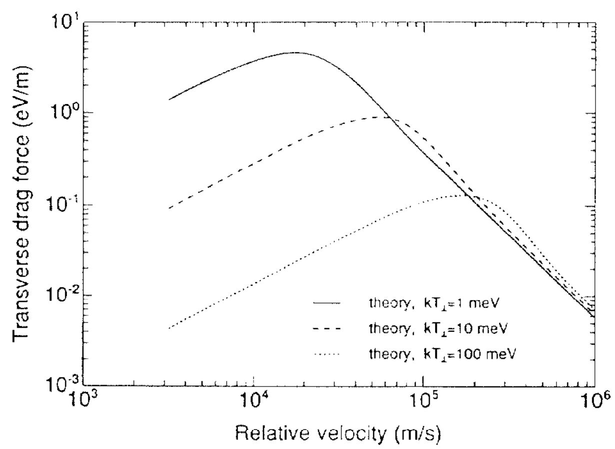

Figure 7: Theoretical transverse cooling force as a function of the relative velocity between ions and electrons.

When the magnetic field in the gun solenoid is increased 100 times, the linear dimensions of the gun are reduced only by a factor of 10, and the electric fields thus become 10 times stronger. This makes it easier to design a gun for the high magnetic field from the optics point of view. The emission per unit area from the cathode, on the other hand, has to be 100 times higher. Scaling down the area of the original cathode (which had a diameter of 40 mm) 100 times, the current density at 500 mA beam current becomes 4 A/cm^2. This is still within the limits for dispenser cathodes, but is approaching maximal current densities.

The solid curve in figure 5 shows the theoretical longitudinal cooling force with an electron beam of $kT_{e\perp} =$ 1 meV. Below 10^4 m/s relative velocity, it is 4–5 times higher than at 10 meV and 30 times higher than at 100 meV. A relative velocity of 10^4 m/s corresponds to a relative momentum spread of 2×10^{-4} at 10 MeV/u, typical values in CRYRING, but also at higher energies or momentum spreads there is a significant gain in using an expanded electron beam, even 100 times expanded. The transverse cooling force is shown in figure 7, calculated in the same way as the longitudinal one. Here, the effect of a reduced transverse electron temperature is, as expected, larger. According to the simplest theory, the longitudinal force is proportional to $T_{e\perp}^{-1}$, while the transverse force is proportional to $T_{e\perp}^{-3/2}$. The Coulomb logarithm, which becomes smaller at low electron temperatures, makes the dependence on $T_{e\perp}$ a little weaker, but still a very significant improvement of the cooling force is obtained by going down to $kT_{e\perp} = 1$ meV. Furthermore, the properties of the cooler when used as an electron target are much improved. The energy resolution in recombination experiments at low relative energy becomes higher, the recombination rate for spontaneous and laser-induced radiative recombination increases, the rate of three-body recombination increases drastically, etc.

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