STUDIES OF COOLING AND DECELERATION AT CRYRING FOR FLAIR

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Abstract

FLAIR will be a facility for low-energy ions and antiprotons at FAIR, the proposed centre for nuclear and hadron physics in Darmstadt, Germany. As a preparation for a possible transfer of CRYRING from the Manne Siegbahn Laboratory to FLAIR, where it would serve to decelerate antiprotons and ions, machine studies have been performed at CRYRING to ensure that that it meets the requirements at FLAIR. In these experiments, the space-charge limit for protons at 300 keV, cooling times for H^- ions and deceleration of protons from 30 MeV to 300 keV have been investigated. It is found that CRYRING as it is configured already today can decelerate more than 3×10^8 protons from 30 MeV to 300 keV.

FLAIR

At FAIR [1], the proposed new centre for nuclear and hadron physics in Darmstadt, Germany, antiprotons will be produced at rates at least as high as at CERN during the time of operation of the proton–antiproton collider, and much higher than today's rates at the antiproton decelerator AD. Also, beams of radioactive ions will be available at intensities far superior to those at RIB facilities like GSI today. While much of the physics at FAIR will use these beams of antiprotons and ions at high energies, FLAIR, the Facility for Low-energy Antiproton and Ion Research [2], will give the possibility to make experiments with antiprotons and ions at very low energy, or even at rest.

Figure 1: Layout of the FLAIR hall.

FLAIR was not part of the original conceptual design report for FAIR that was submitted to the German government in 2003. Since then, however, a thorough review has been made of the experimental programme at FAIR, and the FLAIR proposal has been part of this process. As a result of the very positive review of the physics programme with low-energy antiprotons, and also of the atomic-physics programme within the SPARC [3] collaboration, FLAIR is now part of the proposed core experimental programme at FAIR.

FLAIR will receive beams from a chain of synchrotrons and storage rings at FAIR ending with the NESR ring. These beams can supply FLAIR experiments, including HITRAP, directly, or they can be directed to the first deceleration ring in the FLAIR hall, the LSR (Low Energy Storage ring). Antiprotons will be transferred to LSR at a fixed energy of 30 MeV, and ions will be transported at the same rigidity as 30 MeV antiprotons, independently of their charge-to-mass ratio.

LSR will bring the antiprotons from 30 MeV down to a minimum energy of 300 keV, and ions will be decelerated through the same range of magnetic rigidities. This matches the energy range of CRYRING, which is approximately 200 keV to 96 MeV for (anti-)protons. CRYRING also has the electron cooling required to keep the beam emittance small at deceleration, good vacuum (better than 1×10^{-11} torr N_2-equivalent pressure which is necessary for storing highly charged ions), operational deceleration, easy and frequent shifting between positive and negative particles, etc., and it is therefore proposed that CRYRING will be transferred from the Manne Siegbahn Laboratory to FLAIR for use as the LSR ring.

LSR will provide beams of antiprotons to HITRAP, the electrostatic USR ring or directly to experiments, and the same possibilities will exist for ions. The USR ring will decelerate antiprotons from 300 keV to 20 keV and cool them, and from 20 keV, antiprotons can be brought to rest for capture in traps just by using a small voltage gap. Compared to today's Antiproton Decelerator, AD, at CERN, antiprotons at FLAIR will thus be cooled at much lower energies, providing phase-space densities of very-low-energy antiprotons which are orders of magnitudes higher than at the AD.

Several experiments have been made at CRYRING in order to evaluate its performance relating to deceleration of antiprotons at FLAIR. The throughput of antiprotons will be determined by the maximum number of particles that can be decelerated in each machine cycle and by the length of the cycle. The maximum particle number is set by the space-charge limit, and the length of the machine cycle may be limited by the time required for electron cooling. Both the space-charge limit and cooling times have been investigated, and tests of deceleration of protons from 30 MeV to 300 keV have been performed in order to verify that existing control and diagnostics systems are adequate for the deceleration of such a beam with acceptable particle losses.

SPACE-CHARGE LIMIT

For a storage ring like CRYRING, the maximum beam current is determined by the space charge of the beam which induces an incoherent tune shift ΔQ according to the simple expression

$$\Delta Q = -\frac{N r_0}{4\varepsilon\beta^2\gamma^3},$$

where N is the total number of particles stored in the ring, r_0 is the classical particle radius, ε is the un-normalized beam emittance and β and γ are the usual relativistic factors. We assume a round beam with unit charge and mass, with a Gaussian density profile, and we use the 1σ emittance. Protons or antiprotons at 30 MeV or below have γ close to 1, so plotting N as a function of particle energy, for a fixed ΔQ, gives straight lines as shown in Fig. 2.

The lines in Fig. 2 are drawn for a coasting beam and a conservative value of the maximum permissible tune shift equal to –0.02. For a bunched beam, which is relevant for deceleration, the maximum particle number must be multiplied by the bunching factor which has a value around 0.3.

In order to verify that CRYRING can store particles up to this space-charge limit, protons were injected into the

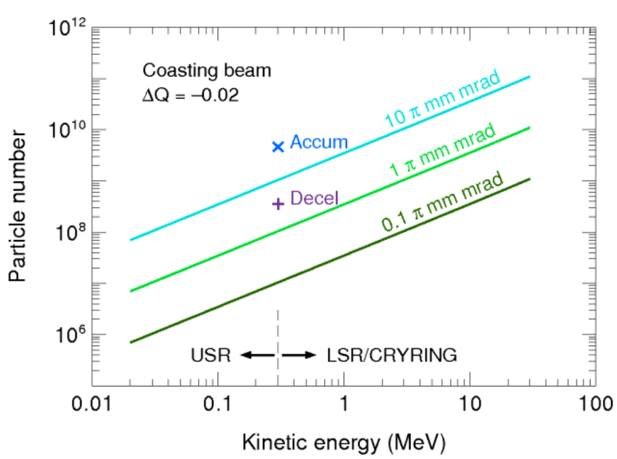

Figure 2: Space charge limit in LSR/CRYRING and USR for a coasting beam with ΔQ = –0.02. The crosses represent the maximum number of protons that could be accumulated in CRYRING and the maximum number that has been decelerated.

ring in batches every 0.5 s at 300 keV while the electron cooling was on, moving the particles away from the injection orbit and continuously increasing the beam current and the phase-space density of the beam. The highest particle number observed, after several minutes of accumulation, was 4.7×10^9 as indicated by a cross in Fig. 2. The emittance could be estimated, using residual-gas beam-profile monitors [4] in both planes, to 15π mm mrad horizontally and 5π mm mrad vertically, indicating a ΔQ of approximately –0.1.

This beam was, however, quite unstable. Taking into account also the bunching factor, one can conclude that an upper intensity limit for decelerated antiprotons in LSR/CRYRING is in the order of 1×10^9 particles at an emittance of 10π mm mrad.

Also indicated in fig. 2 is the maximum number of particles that has actually been decelerated from 30 MeV to 300 keV according to the experiments on deceleration described below. This number is 3.6×10^8, and it should thus be possible to increase it somewhat through better adjustment of magnet ramps and more cooling.

ELECTRON COOLING OF H^- IONS

Electron cooling is in the first approximation based on the Coulomb interaction between the electrons in the cooler and the stored ions, and cooling rates should thus be sensitive only to the ion charge squared. However, the magnetic field in the cooler makes the ion–electron interaction more complicated and can make cooling rates depend on the sign of the ion charge. Such effects were seen in measurements of drag forces on protons and H^- ions in Novosibirsk [5], where a stronger drag force was observed for the negatively charged particles.

The first measurements at CRYRING concerned transverse cooling times for H^- ions at 3 MeV. It is anticipated that cooling at a similar energy is desirable for the deceleration of antiprotons from 30 MeV to 300 keV, and transverse cooling times are expected to dominate over longitudinal ones.

Fig. 3 shows a set of vertical beam profiles, measured with a residual-gas-ionization beam-profile monitor [4]. The initial beam emittance was approx. 5π mm mrad, which is more than expected for antiprotons at 3 MeV if they are injected with an estimated 0.25π mm mrad 1σ emittance at 30 MeV. The beam was cooled using an electron current of only 18 mA, giving an electron density of 3.8×10^{12} m^{-3}.

The resulting cooling time can be compared to previous measurements of transverse cooling times for singly and multiply charged ions in CRYRING [6]. In those measurements, hollow ion beams were produced by misaligning the electron beam with respect to the ion beam, such that all ions performed betatron oscillations with the same amplitude, and cooling rates could thus be determined as a function of betatron amplitude. Such hollow beams were not used in the present studies of H^- ions. Instead markers were put manually in an attempt to get a representative beam width, as indicated in fig. 3.

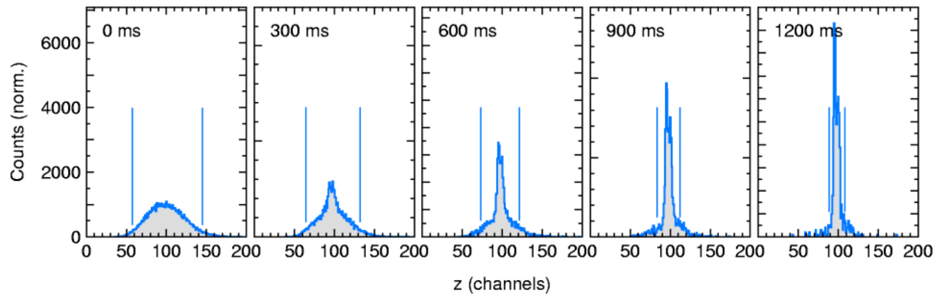

Figure 3: Transverse beam profiles during electron cooling of H^- ions. The full horizontal scale of 200 channels corresponds to 40 mm, and the time interval between the profiles is 300 ms.

The resulting comparison between H^- ions and positive ions is shown in fig. 4. Although there is a small uncertainty due to the difference in the definition of the beam width, no significant difference in cooling times between negative and positive ions is seen. The beam reached a cold equilibrium state in about 1.5 s, which is sufficiently short so that electron cooling in the LSR will not be a limiting factor for the throughput of antiprotons. Note that the cooling time plotted in fig. 4 is shorter than 1.5 s since it is normalized to a higher electron density.

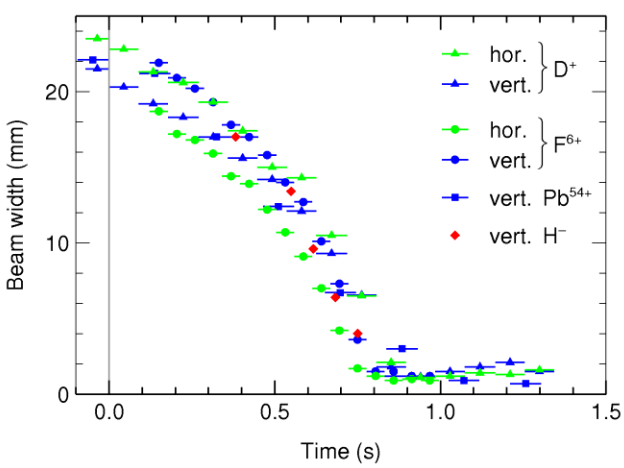

Figure 4: Transverse cooling times of positive ions with different charge states [5] and of H^- ions. The new H^- data are normalized to the same electron density of 1.7×10^{13} cm^{-3} as used for the positive ions, and these were in addition scaled with $q^{1.7}/A$. The new H^- data points were also shifted horizontally so that the beam reaches a cold equilibrium at approximately 0.7 s, as was the case for the positive ions.

DECELERATION OF PROTONS

CRYRING has been used for deceleration in a few cases where users have requested light ions at energies lower than the injection energy of 300 keV per nucleon, as given by the RFQ. For the present investigation of CRYRING properties relevant to FLAIR, however, deceleration throughout the entire range planned for the LSR ring at FLAIR, from 30 MeV to 300 keV, should be performed. Since the injection energy for protons at CRYRING is fixed at 300 keV, these tests must be made by first accelerating the particles from 300 keV to 30 MeV. This does not imply, however, that deceleration can be performed just by reversing the magnet and rf ramps used for acceleration. Remanence and hysteresis effects in the magnets make the deceleration process independent of the acceleration.

Fig. 5 shows an example of beam current and corresponding particle number during an acceleration–deceleration cycle. The beam current was measured using a DC current transformer, and to get a sufficiently good reading of the current, many injection pulses were accumulated at 300 keV, as in the study of the space-charge limit. The resulting stepwise increase of the particle number can be hinted in the figure. Acceleration starts at time zero when the current has reached 4.9 μA, corresponding to 2.1×10^8 stored particles. (The curves are averages from many machine cycles.)

The beam was accelerated first from 300 keV to 3 MeV, and at that energy it was cooled again during 1.5 s while staying bunched before it was accelerated up to 30 MeV. The intermediate cooling was necessary in order to minimize the losses during the deceleration. During acceleration, the current increases with the beam velocity, whereas the particle number should stay constant if there are no losses. It is seen from the figure that there was a small loss of particles at the start of the acceleration, but that the rest of the acceleration and the cooling were made without losses.

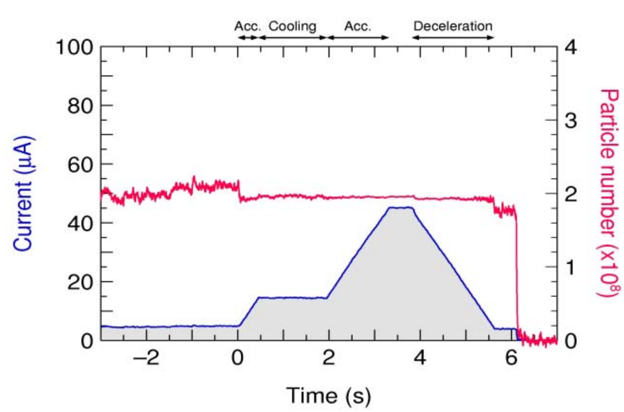

Figure 5: Proton beam current and particle number as functions of time during acceleration and deceleration.

The beam was stored for 0.5 s at 30 MeV, still bunched, and then decelerated back to 300 keV in 1.8 s without further cooling. At 6.1 s, the beam was dumped, and a new cycle started. A very small loss occurred at the start of the deceleration, and somewhat more particles were lost when the deceleration ramp met the flat bottom level. The result was that 1.8×10^8 protons remained when the beam was back at 300 keV. For FLAIR it is the efficiency in deceleration from 30 MeV to 300 keV that is important, and it is thus shown that this deceleration can be made with at least 90% efficiency given the beam properties at 30 MeV of this experiment.

Fig. 6 shows a similar acceleration–deceleration cycle but with an initial beam current almost twice as high. Here the losses were somewhat larger, in particular when the deceleration ramp meets the flat bottom. Still, 2.8×10^8 particles were brought back to 300 keV. With still somewhat higher losses, up to 3.6×10^8 protons have been decelerated down to 300 keV as mentioned above and indicated in fig. 1.

In order to understand why it seems necessary to cool at 3 MeV, the bunch length at 30 MeV has been studied as a function of the amount of cooling at 3 MeV at the same time as deceleration losses were measured. Without cooling at 3 MeV, the space-charge forces were seen to be strong enough for particles to completely fill the rf bucket at 30 MeV even though the beam was cooled at the injection energy. At 3 MeV, the cooling is stronger than at 300 keV since a higher electron current can be used, resulting in bunches that are considerably shorter also at 30 MeV. The result was that a clear correlation between bunch length and deceleration losses was found. At the same time, moderate transverse displacements of the ion beam before deceleration did not cause any losses.

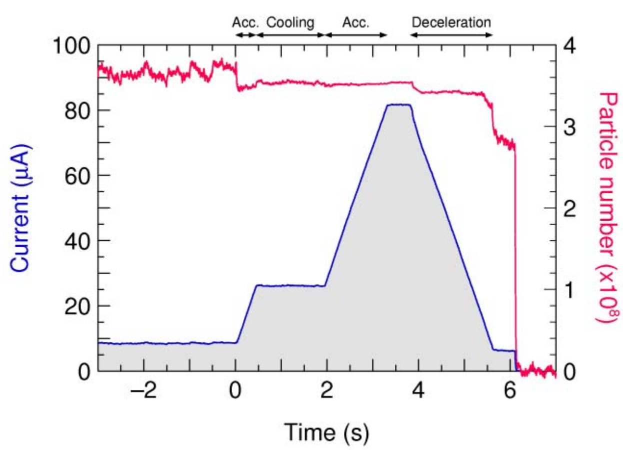

Figure 6: Proton beam current and particle number as in fig. 5 but at higher beam intensity.

It should be added that cooling at 30 MeV was not attempted. The CRYRING cooler in its present configuration uses a 100 times beam expansion and has a quite small electron gun with only 4 mm cathode diameter. This small gun has not been tested to voltages higher than about 10 kV, while electron cooling at 30 MeV would require 16 kV cathode voltage.

CONCLUSION

The deceleration tests presented here prove that CRYRING, as it is set up and operated already today, is able to decelerate protons with high efficiency over the entire energy range required at FLAIR. According to the present planning for FAIR, the end of the commissioning period and the start of operations at FLAIR is defined to occur when 1×10^8 antiprotons have been decelerated to 300 keV. This limit has exceeded by more than a factor three, showing that CRYRING should be able to perform very well as an antiproton and ion deceleration ring at FLAIR.

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