CRYRING MACHINE STUDIES FOR FLAIR

H. Danared, A. Källberg and A. Simonsson
Manne Siegbahn Laboratory
Frescativägen 28, S-104 05 Stockholm, Sweden

Abstract

It has been proposed that CRYRING, a 1.44 Tm synchrotron and storage ring at the Manne Siegbahn Laboratory, be transferred to the future FAIR facility at GSI. There it would be used for deceleration of antiprotons and highly charged ions. We here describe some experiments that have been made recently at CRYRING to investigate its performance for deceleration of these particles. 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 studied.

FLAIR

After the decision by the Swedish Research Council in 2002 to discontinue its support to the Manne Siegbahn Laboratory as a national research facility, followed by an agreement with Stockholm University in 2003 about a three-year decommissioning period, discussions were initiated about transferring CRYRING to the future FAIR facility at GSI, Darmstadt. The reason was a proposal that FAIR would include a Facility for Low-energy Antiproton and Ion Research, FLAIR [1], where physics with low-energy and stopped antiprotons as well as highly charged ions would be performed. Since then, FLAIR has become part of the proposed core experimental programme at FAIR.

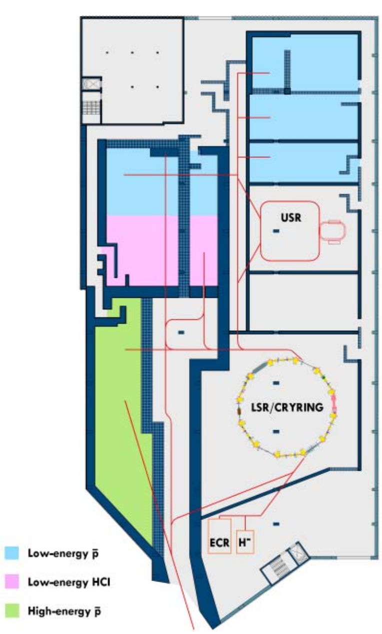

Figure 1: Layout of the FLAIR hall.

At the heart of the FLAIR facility there will be two deceleration rings. The first one, named LSR (Low-energy Storage Ring), will be a conventional synchrotron taking antiprotons from the NESR ring at an energy of 30 MeV and decelerating them to experiments such as HITRAP which will take antiprotons at 4 MeV or down to the minimum energy of 300 keV. At 300 keV the antiprotons will be transported to an electrostatic Ultra-low energy Storage Ring, USR [2], which will decelerate them further to 20 keV. From that energy, the particles can be brought to rest and for instance be captured in traps just by using a small voltage gap. LSR can also take highly charged ions from NESR at the same rigidity as 30 MeV antiprotons and decelerate these to experiments or to the USR.

The parameters of CRYRING are quite similar to what is required from the LSR ring, which makes it attractive to use CRYRING as the LSR. For instance, it has the right energy range (CRYRING can run protons from 96 MeV down to approximately 200 keV), it has a vacuum of better than 1×10^{-11} torr N_2-equivalent pressure which is necessary for storing highly charged ions, it is equipped with electron cooling which is required to keep the beam emittance small at deceleration, it has already been used both for acceleration and deceleration, etc. The most important modification that has to be made to CRYRING is to install a new injection system that can accept antiprotons at 30 MeV instead of 300 keV which is the present injection energy for protons in CRYRING. Also, a beam extraction must be implemented. CRYRING does not have an extracted beam at present, but it was designed with extraction in mind, such that it has, e.g., the space needed in one of the straight sections and sextupole magnets suited for driving a resonant extraction.

MACHINE EXPERIMENTS

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 as 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.

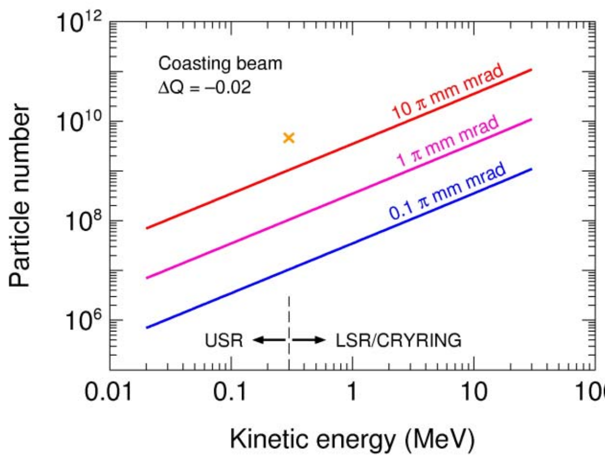

Figure 2: Space charge limit in LSR/CRYRING and USR for a coasting beam with $\Delta Q = -0.02$. The cross represents the maximum number of protons that could be stored in CRYRING.

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 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 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.

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 [3], where a stronger drag force was observed for the negatively charged particles.

The 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}.

It can be estimated from the figure that the cooling time (reduction of the beam radius with a factor e) is 0.8 s in the outer parts of the beam where the cooling is slowest. The beam reached a cold equilibrium state in about 1.5 s. The cooling time agrees quite well with those for singly and multiply charged positive ions that have been measured previously at CRYRING, if the cooling times

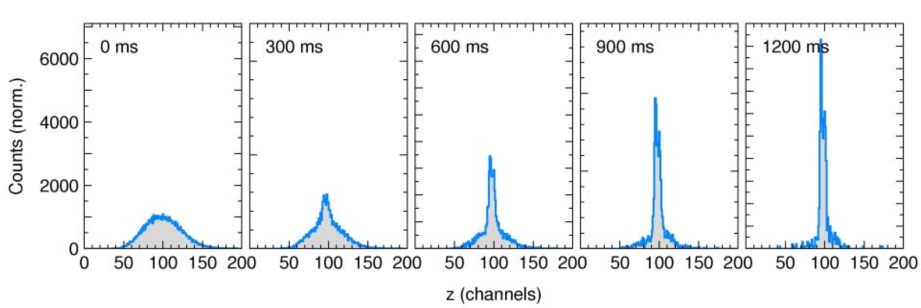

Figure 3: Transverse beam profiles during electron cooling of H^- ions. The full horizontal scale of 200 channels corresponds to 40 mm, and the time interval between the profiles is 300 ms.

are properly scaled with respect to the charge state of the ions [5].

Deceleration of Protons

CRYRING has been used for deceleration in a few cases were users have requested light ions at energies lower than the injection energy of 300 keV per nucleon, as given by the RFQ. Since this injection energy is fixed, tests of deceleration of protons from 30 MeV 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. 4 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.)

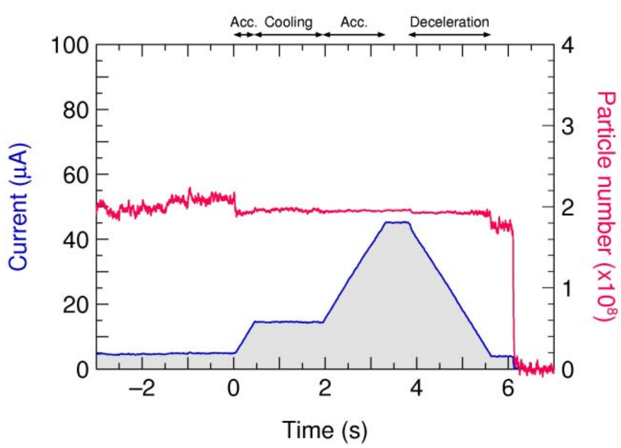

Figure 4: Proton beam current and particle number as functions of time during acceleration and deceleration.

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.

The beam was stored for 0.5 s at 30 MeV, still bunched, and then decelerated back to 300 keV without further cooling in 1.8 s. 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. 5 shows a similar acceleration–deceleration cycle but with an initial beam current almost twice as high.

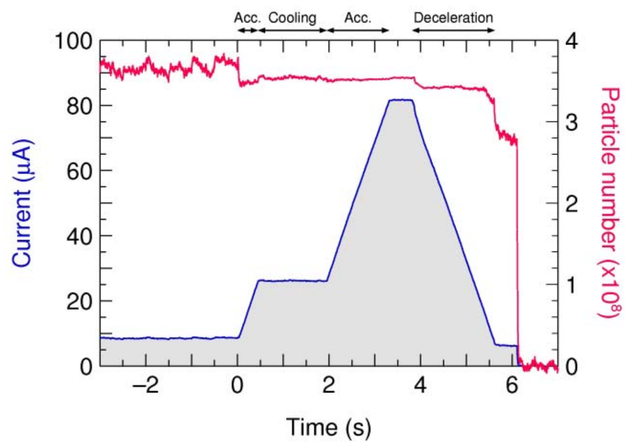

Figure 5: Proton beam current and particle number as in fig. 4 but at higher beam intensity.

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. Although the beam emittance was not measured during these experiments, one can assume that the space-charge limit at 300 keV is being approached, and that the increased losses are due to space-charge effects.

Nevertheless, these deceleration tests prove that CRYRING, as it is set up and operated already today, is able to decelerate protons with high efficiency over the 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 was exceeded by almost a factor three according to fig. 5, showing that CRYRING should be able to perform very well as an antiproton and ion deceleration ring at FLAIR.

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