MODIFICATIONS OF CRYRING FOR TRANSFER TO FAIR

H. Danared, A. Källberg and A. Simonsson, Manne Siegbahn Laboratory, Stockholm, Sweden
D. Reistad, Intégro Utbildnings AB, Sigtuna, Sweden

Abstract

FLAIR will be the next-generation facility for physics with low-energy antiprotons, providing antiprotons at energies from tens of MeV down to rest. Also highly charged ions at very low energies will be available at FLAIR. A key component of the FLAIR facility will be the Low-energy Storage Ring LSR which will decelerate antiprotons from 30 MeV to 300 keV. The LSR will consist of the present CRYRING at the Manne Siegbahn Laboratory, which is being modified mainly with respect to injection and extraction, to allow injection of 30 MeV antiprotons and to provide it with both fast (single-turn) and slow (resonant) extraction at a variable energy. We here describe some aspects of the design of these modifications.

FLAIR AND CRYRING

FLAIR [1,2], the Facility for Low-energy Antiproton and Ion Research at FAIR [3], is expected to become the next-generation facility for physics with low-energy antiprotons, providing the world's highest fluxes of antiprotons at energies from tens of MeV down to rest. It will also offer unique possibilities for physics with highly charged ions at very low energies.

FLAIR will obtain beams of already decelerated antiprotons and ions from the NESR ring. The particles will then be further decelerated in one magnetic deceleration ring, the Low-energy Storage Ring LSR, which will be the modified CRYRING, and in one electrostatic ring, the Ultralow-energy Storage Ring USR, such that antiprotons can be delivered to experiments at a kinetic energy of only 20 keV. Also ions can be decelerated to low energies, limited in many cases by the increasing rate of recombination in collisions with residual-gas atoms as the energy is reduced, and by the consequent rapid reduction of the lifetime of stored beams of highly charged ions at low energies. Furthermore, antiprotons and ions can be decelerated by HITRAP for other experiments at very low energies or sent directly to experiments from the NESR or the LSR.

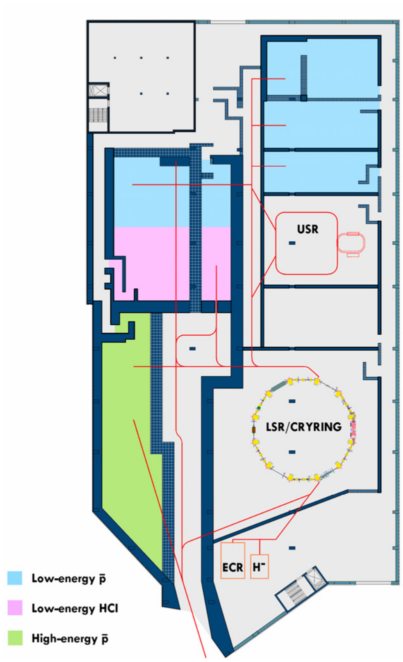

Figure 1: Proposed layout of the FLAIR hall.

The perhaps most important new feature at FLAIR, as compared to the Antiproton Decelerator, AD, at CERN, is that antiprotons will be phase-space cooled at lower energies during the deceleration process. The high production rate of antiprotons at FAIR, similar to that at CERN at the time of proton–antiproton collisions in the SPS but much higher than today's rate at CERN, can thus be combined with beams that have the smallest possible emittance and results in unprecedented beam intensities at low energies. Another difference is that the AD does not have the slow extraction that will be available at FLAIR.

A preliminary layout of the FLAIR hall is seen in fig. 1. Antiprotons will be delivered from NESR to the LSR at a kinetic energy of 30 MeV. In the LSR, the antiprotons can be decelerated down to 300 keV, or possibly somewhat lower if this is desirable. At 300 keV, the antiprotons are extracted to the electrostatic Ultralow-energy Storage Ring, USR, for further deceleration down to, at minimum, 20 keV. At that energy the particles can be trapped electrostatically and brought to rest by lowering the trap potential to zero. The LSR will, however, not be limited to extraction at the lowest energy, but antiprotons can be extracted at any energy between 30 MeV and 300 keV. For example, antiprotons will be delivered to HITRAP at 4.2 MeV.

Ions will be injected into the LSR at the same magnetic rigidity $B\rho$ of 0.80 Tm as 30 MeV antiprotons have, or at an energy of 30 Z^2/A^2 MeV/u, where Z is the charge state of the ion and A is its mass number. The ions can be decelerated and extracted over the same range of rigidities as the antiprotons, although the lowest limit may in practice be determined by the beam lifetime as already mentioned.

LSR will consist of the present CRYRING at the Manne Siegbahn Laboratory. This is a 1.44 Tm synchrotron and storage ring with 52 m circumference. CRYRING's properties closely match those required by the LSR as has been discussed earlier [4], and in that paper it was also shown that CRYRING already as it looks today is able to decelerate protons from 30 MeV to 300 keV with intensities close to the space-charge limit and in excess of the commissioning goal of 1×10^8 particles being decelerated to 300 keV.

The major modifications that have to be made to CRYRING before it can be used as the LSR ring concern injection and extraction.

INJECTION

At present, CRYRING has a 10-turn horizontal electrostatic multiturn injection designed to match the output of the RFQ that serves as a pre-accelerator for the ring. The RFQ delivers particles with charge-to-mass ratios of 0.25 or higher at a fixed velocity corresponding to 300 keV per nucleon. Also particles with lower charge-to-mass ratios can be injected into the ring, but these are only focused by the RFQ, not accelerated.

In order for the ring to accept higher-energy antiprotons and ions from the NESR, a new injection system has to be developed. Antiprotons will be delivered from the NESR at an energy of 30 MeV, which is equal to a magnetic rigidity of $B\rho$ = 0.80 Tm, and highly charged ions will be delivered at the same magnetic rigidity irrespective of their charge or mass.

LSR will, however, retain a low-energy injector similar to the injector for singly charged ions at CRYRING today. This will be used for commissioning of the ring and the beamlines in the FLAIR hall with, e.g., protons or H^- ions, and possibly also for tests of experiments, such that physics can start as soon as possible after antiprotons and/or ions are available from the FAIR accelerator chain. For these low-energy ions, a multiturn injection resembling the present injection at CRYRING is foreseen.

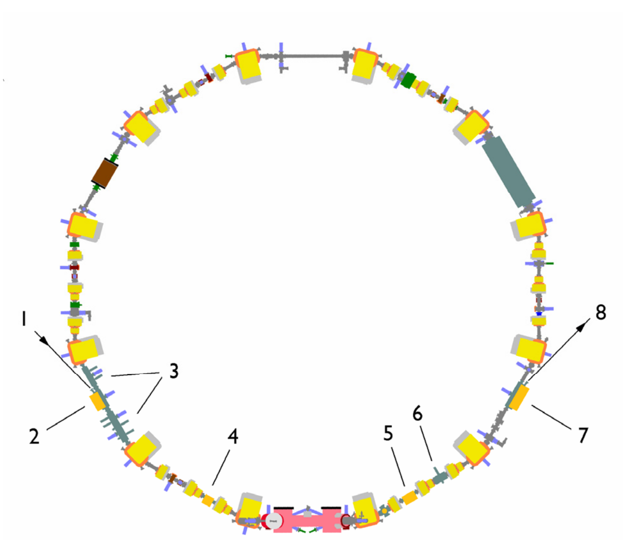

Figure 2: Schematic illustration of new components for injection and extraction. 1) Injected beam from NESR, 2) Injection septum magnet, 3) Electrostatic kickers for multiturn injection, 4) Injection kicker magnet, 5) Extraction kicker magnet, 6) Electrostatic extraction septum, 7) Extraction septum magnet, 8) Extracted beam.

To save space in the FLAIR building, the beamlines from the NESR and from the low-energy injector should be merged upstream of the LSR, and both kinds of particles should use the same injection channel in the ring. The system will consist of a septum magnet, a fast injection kicker for the NESR antiprotons and ions, as well as electrostatic deflector plates similar to the ones used at present to produce the closed-orbit bump for the multiturn injection. The closed-orbit bump will remain local to the injection-straight section while the kicker magnet will be positioned at the end of the magnet section following the injection, where the horizontal betatron phase advance with respect to the injection point is close to $\pi/2$. The new components for injection and extraction and their approximate position are shown in fig. 2, where also the straight sections have been rearranged compared to the current layout of CRYRING in order to match the geometry of the FLAIR building.

The magnetic septum and the multi-turn injection are being designed at present. The kicker magnet will be similar to the extraction kicker and is discussed further in the following section.

EXTRACTION

CRYRING at present does not have an extracted beam, although extraction was foreseen when the ring was designed. This means that there is a straight section available for an extraction septum magnet, sextupole magnets that can drive a third-integer resonance, etc. The LSR will, in contrast to the Antiproton Decelerator at CERN, implement both slow resonant extraction and fast single-turn extraction. New components for the extraction are the septum magnet, an electrostatic septum for the resonant extraction and a fast kicker for the single-turn extraction, and their positions are indicated in fig. 2.

Ideally, both the kicker and the electrostatic septum should be positioned at a betatron phase advance close to $\pi/2$ before the extraction septum which means in the first half of the magnet straight section before the septum magnet. However, there is not room for both devices at that position, and in addition the limited horizontal aperture through the quadrupole magnets prevents the electrostatic septum from being too far away from the magnetic septum. (The aperture is a more severe restriction for particles deflected by the electrostatic septum than by the kicker magnet since the former already have a horizontal displacement when they are deflected.) For these reasons, the electrostatic septum is positioned after the kicker magnet as seen in fig. 2.

Both the slow and the fast extraction will cover the energy range up to the injection energy both for antiprotons and for ions. Although LSR is a low-energy ring, its rather small circumference makes the rise or fall time of the kicker magnets quite short, and the space available in the ring for these is also quite short. Injection and extraction kickers will be similar although the injection kicker operates only at $B\rho$ = 0.80 Tm while the extraction kicker has to work for all rigidities between $B\rho$

= 0.80 Tm and the 0.079 Tm corresponding to 300 keV antiprotons. The extraction kicker needs to have a longer pulse length for lower energies and slower particles, but then the rise time can also be longer. Preliminary parameters of the kicker magnets which are now being procured are shown in tab. 1.

Table 1: Preliminary Parameters for Injection and Extraction Kicker Magnets

Parameter	Value
Beam rigidity (injection)	0.80 Tm
Beam rigidity (extraction)	0.079 – 0.80 Tm
Nominal deflection angle	17 mrad
Aperture (width × height)	107 mm × 87 mm
Length	457 mm
Fall time (injection)	280 ns
Rise time (extraction)	280 − 4140 ns

The slow extraction takes place near the third-order resonance Q_x = 2 1/3, where sextupole magnets are excited to divide the horizontal phase space into a stable area for particles with small betatron amplitudes and an unstable area for larger betatron amplitudes. Noise is applied to a transverse electrostatic kicker to excite the particles into the unstable part of phase space. Particles on unstable trajectories move further and further out from the equilibrium orbit until they cross a thin electrostatic septum. There they are deflected by an electrostatic field such that they can cross also the magnetic septum and end up in the extraction channel.

At the electrostatic septum, the particles need to be deflected by 11 mrad in order not to hit the magnetic septum, translating into an electrostatic septum voltage of less than 30 kV for 30 MeV antiprotons.

Several conditions have to be fulfilled for the particles to reach the extraction channel with minimum losses apart from the $\pi/2$ betatron phase advance which determines the relative position between electrostatic and magnetic septa: 1) The stable phase-space area inside the separatrix has to have the right size. The betatron amplitude growth from turn to turn increases with smaller stable area, decreasing the probability of particles hitting the septum foil but increasing the size of the extracted beam. 2) The outgoing leg of the separatrix has to have the right orientation so that particles cross the electrostatic septum with an angle x' that leads them into the extraction channel. 3) The Hardt condition should be fulfilled so that particles with different momentum offsets Δp cross the electrostatic septum at the same x', which again minimizes the number of particles hitting the electrostatic septum. 4) The sextupole fields should not be unnecessarily strong to avoid higher-order nonlinearities.

CRYRING has six focusing and six defocusing sextupoles and thus a more than sufficient number of free parameters to allow all four conditions to be satisfied simultaneously. Details will be presented elsewhere, and in this paper we just show in fig. 3 an example of the output from a particle-tracking code for a set of sextupole values that gives the desired result. Here the chromaticities are first controlled such that the Hardt condition gets satisfied using the focusing and defocusing sextupoles as two families. Superimposed on that, two focusing and two defocusing sextupoles are excited to optimize the other three conditions.

In fig. 3, the gray area in the centre is the area of stable motion for particles with reference momentum. The tracking is made with the assumption that the beam is cooled longitudinally to a relative momentum spread of $\Delta p/p = \pm 5 \times 10^{-4}$, and the blue and red triangles are stable

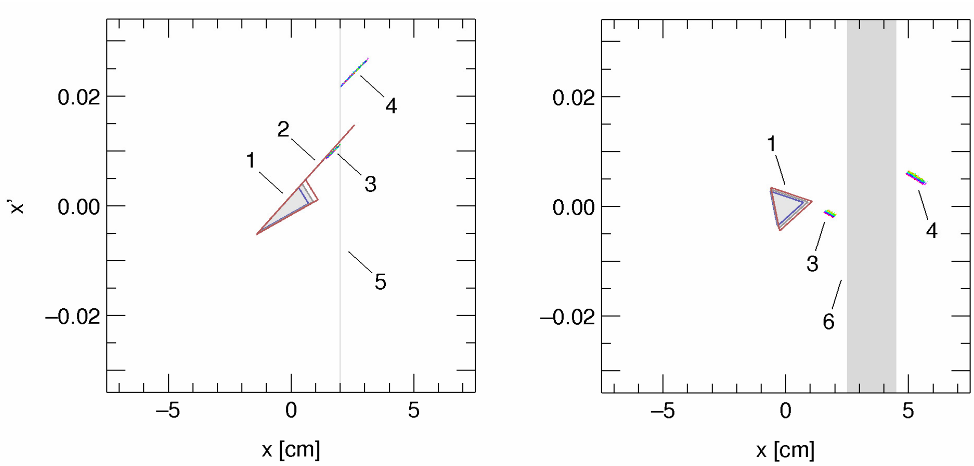

Figure 3: Particle distributions in phase-space at the electrostatic septum (left plot) and magnetic septum (right plot), illustrating resonant extraction. Particles are colour-coded according to momentum. 1) Area of stable motion for different particle momenta (see text), 2) Outgoing part of separatrix, 3) Particles to be extracted three turns before deflection in electrostatic septum, 4) Particles after deflection in electrostatic septum and (to the right) after deflection in magnetic septum, 5) Position of electrostatic septum, 6) Position of magnetic septum.

areas for particles with the lowest and highest momentum offsets respectively. At the location of the electrostatic septum, the dispersion and its derivative are D = 1.8 m and D' = 0.53, and with horizontal tune Q_x = 2.326 and the chromaticity adjusted to Q'_x = −1.6, the Hardt condition is fulfilled. As seen in the left part of the figure, all particles then reach the electrostatic septum at virtually the same x', although not exactly on the calculated line due to higher-order non-linearities. This condition cannot be fulfilled simultaneously at the magnetic septum, resulting in the slightly wider particle distributions in the right plot of fig. 3.

With a septum foil that is 0.1 mm thick, an extraction efficiency of 98.5% is obtained in this example, the remaining 1.5% of the particles hit the septum foil.

The electrostatic septum is now being manufactured and tests to extract the particles in CRYRING into a particle detector sitting at the future position of the magnetic septum will take place during the autumn of 2009.

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