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Present status of the USR project

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Abstract The Facility for Low-energy Antiproton and Ion Research (FLAIR) and a large part of the wide physics program decisively rely on new experimental techniques to cool and slow down antiprotons to 20 keV, in particular on the development of an ultra-low energy electrostatic storage ring (USR). The whole research program connected with anti-matter/matter interactions is only feasible if such a machine will be realized. For the USR to fulfil its key role in the FLAIR project, the development of novel and challenging methods and technologies is necessary: the combination of the electrostatic storage mode with a deceleration of the stored ions from 300 keV to 20 keV, electron cooling at all energies in both longitudinal and transverse phase-space, bunching of the stored beam to ultra-short pulses in the nanosecond regime and the development of an in-ring reaction microscope for antiproton-matter

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rearrangement experiments. In this contribution, the present status of the USR project is summarized and the new machine lattice is presented.

Keywords Particle accelerators · Storage rings · Antiprotons · Beam cooling

1 Introduction

Antiprotons stored and cooled at low energies in a storage ring or at rest in traps are highly desirable for the investigation of a large number of basic questions on fundamental interactions, on the static structure of exotic antiprotonic atomic systems or of (radioactive) nuclei as well as on the time-dependent quantum dynamics of correlated systems. Fundamental tests include, e.g. CPT tests by high-resolution spectroscopy of the 1s-2s transition or of the ground-state hyperfine structure of antihydrogen as well as gravity experiments with antimatter. Structure measurements extend from few-particle QED, correlation, and relativistic effects in antiprotonic atoms to the investigation of the low-energy limit, i.e. of non-perturbative QCD and to nuclear skins exploration.

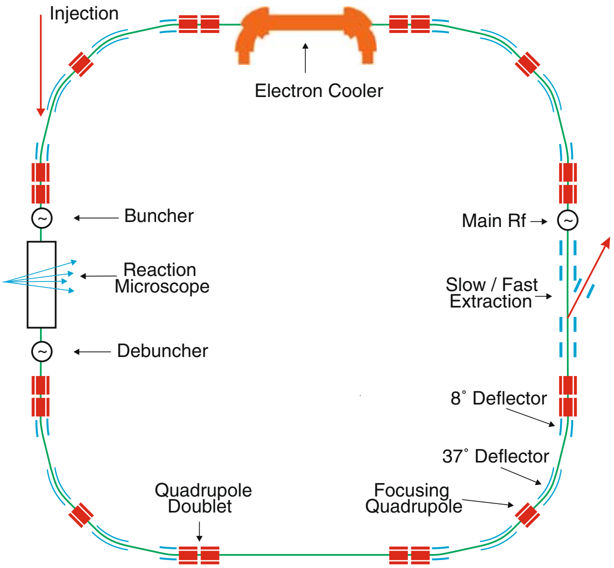
In addition, low-energy antiprotons are the ideal and perhaps the only tool to study in detail correlated quantum dynamics of few-electron systems in the femto and sub-femtosecond time regime [1, 2]. Advanced storage ring and detection technologies in combination will enable, for the first time, access to kinematically complete antiproton-induced rearrangement and fragmentation measurements. These will allow to ultimately benchmark contradicting predictions of existing theories and to explicitly address the few-body Coulomb problem one of the most fundamental, yet unsolved problems in physics.

To enable the efficient investigation of essentially all of these important questions in detail, a novel electrostatic cooler synchrotron and a state-of-the-art in-ring spectrometer are under development in close collaboration between the QUASAR group (http://www.quasar-group.org), the Max-Planck Institute for Nuclear Physics, the GSI Atomic Physics Division, and groups from the University of Heidelberg with the aim of slowing down antiprotons as well as possibly highly charged ions (up to bare uranium) to low energies between 20 and 300 keV/q. This will provide world-wide unique conditions for both in-ring studies with an intensity of up to 10^{12} cooled and stored antiprotons or highly charged ions per second, as well as for experiments requiring extracted slow beams and will therefore push the limits in all fields concerned.

For the USR installed in FLAIR, new and challenging techniques need to be developed to ensure multi-user operation and pave the way for a true multi-purpose facility:

- Combination of the electrostatic storage mode with beam deceleration from 300 keV/q to 20 keV/q;
- Availability of fast and slow extraction to enable both trap experiments with pulsed beams and nuclear physics type experiments requiring extracted quasi-DC beams;
- Electron cooling at all covered energies for a variety of different ions ranging from antiprotons to bare uranium;

Fig. 1 Schematic layout of the ultra-low energy storage ring. The ring features a four fold symmetry and has a circumference of 42.6 m



- Particle detection techniques and beam diagnostic elements, operating at cryogenic temperatures and designed for lowest beam energies and currents.

The USR will combine these features for the first time and will thus be one of the essential tools for low-energy physics at FLAIR.

2 Storage ring layout

The USR will allow for an efficient deceleration, cooling and storage of antiprotons within FLAIR [3, 4]. In order to be adjustable to the different needs of the experimentalists, the storage ring has to be set to different operation modes. Apart from the basic cooling and deceleration schemes, internal experiments ask for short bunches in the ns-range [5] while external experiments have to be provided with extracted beams of most different pulse duration.

The synchrotron is designed, similar to the initial layout of the USR [6], as a square with four straight sections—each 4 m in length—which are reserved for extraction, electron cooling and the planned experiments, see Fig. 1. The ring itself has a four-fold symmetry and an overall circumference of 42.6 m. The bending sections of the ring are designed in a novel "split-achromat" geometry. The total deflection of the beam by 90° in each of the corner sections is realized by a combination of 8°-37°-37°-8° electrostatic cylinder deflectors. For the transverse modulation of the beam quadrupole doublets placed at the entrance and exit of every experimental straight section are used. An additional focusing quadrupole, placed in between the two 37° deflectors, is included to control the dispersion of the beam. The linear lattice functions for one possible operation mode, providing a round beam suitable for beam cooling and for experiments, are shown in Fig. 2 (left). Due to the special split-achromat lattice, an additional operation mode is possible: In this case, the

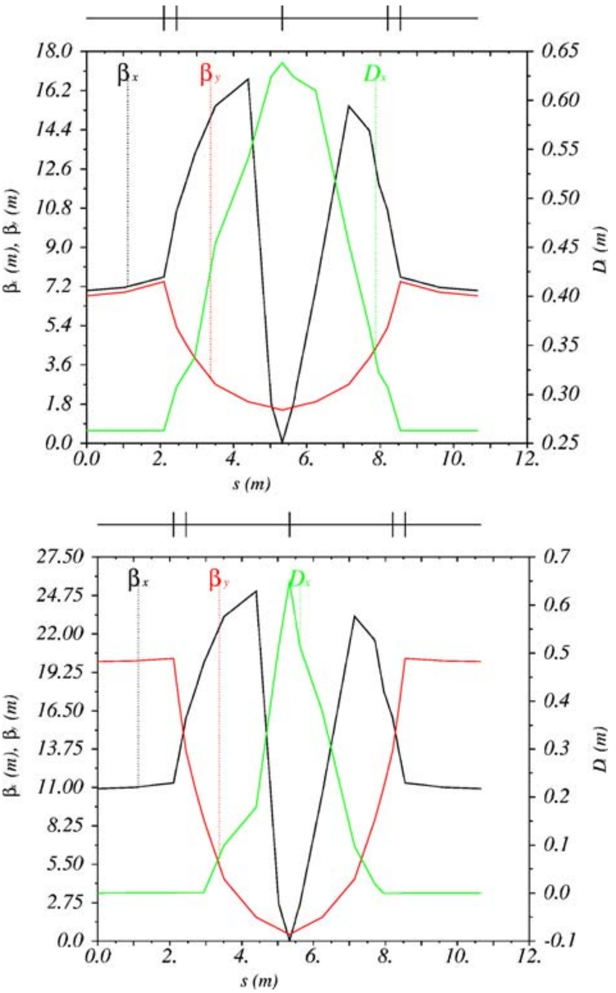


Fig. 2 Overview of the USR lattice in two different modes of operation. *Top*: Lattice functions with round beam in experiment. *Bottom*: Lattice function in "zero dispersion" mode

dispersion is reduced to zero in the center of the straight sections, and reaches its maximum value of only $D_x = 0.7$ m in the central focusing quadrupole, as shown in Fig. 2 (right). The present machine parameters of the USR are summarized in Table 1.

2.1 Nanosecond bunches

In order to reach a high resolution in the envisaged experiments with the novel in-ring reaction microscope, presently being developed in the QUASAR group in collaboration with the Ullrich group at MPIK, ultra-short pulses of 20 keV antiprotons with a time structure of only a few nanoseconds have to be provided. It is clearly impossible to create ultra-short bunches of a few ns duration in one step from a coasting beam: With a revolution period of 20 μs the required buncher voltage

Table 1 General parameters of the USR at extraction energy (only antiprotons are considered)

Energy [keV]	20
Circumference [m]	42.984
Rotation period [μs]	21.957
Rotation frequency, F_{rot} [kHz]	45.5436
RF frequency F_{RF} [MHz]	20.0392
RF harmonic number h_{RF}	440
RF bucket width [ns]	49.9
Buncher drift space [cm]	200
Buncher voltage [kV]	0.37
Expected pulse width [ns]	2
Momentum spread (after e^- cooling)	$5 * 10^{-4}$
Achromatic mode dispersion D_{max} / D_{min} [m]	0.7 0
Momentum compaction α	0.207
Frequency slip factor η	-0.8

to provide a 2 ns time focus would exceed 10 kV and thus the induced energy spread by the phase compression would simply destroy the beam circulating in the ring.

An operation with ultra-short pulses for in-ring experiments might be realized by applying the sequence of the following procedures: Once the beam has been slowed down to 20 keV, the coasting beam of antiprotons is cooled down to a momentum spread of 10^{-4} [7]. Then the cooled beam is adiabatically captured into $\tau \approx 50$ ns stationary buckets formed by a 20 MHz cavity operating at a high harmonic mode of the ring revolution frequency ($h_{RF} = 300$–400).

The desired ultra-short pulses of $\tau = 2$ns duration will then be formed in the symmetry point of the straight section where the reaction microscope is located. The focus will be provided by an additional $3\beta\lambda/2$ double drift buncher, placed at the beginning of the straight section. Once the experimental section is crossed, a debuncher will provide phase decompression and limit the growth of the equilibrium momentum spread. Otherwise the increasing energy spread introduced by the phase compressor would cause a beam blow up in the bending sections of the ring. As it was already pointed out, the phase compression will lead to an additional energy spread. This requires that any manipulation of the beam towards short pulses needs to be limited to the straight sections of the ring, where the dispersion function needs to be zero. To allow for this special operation mode, the USR lattice was recently modified substantially [8], as described in the previous section.

3 Beam diagnostics

The boundary conditions of the USR project put very high demands on the machines' instrumentation: If one thinks of not only storing antiprotons, but also highly charged ions, ultimate vacuum pressures have to be realized extending to below 10^{-14} mbar to ensure reasonable beam life times. Hence, an approach considered in the present study is to cryogenically cool the vacuum chambers of the USR to a temperature of only a few Kelvin. Such a cryogenic electrostatic ion storage ring (Cryogenic Storage Ring CSR) is presently pioneered at the Max Planck Institute for Nuclear Physics [9]; another cryogenic electrostatic storage ring is under construction at the University of

Stockholm [10]. The extremely low vacuum pressure of the (cooled) USR together with a beam energy of only 20 keV and low currents of singly charged antiprotons between 1 nA and 1 μA require the development of new diagnostic methods as most of the standard techniques will no longer work. Different techniques are presently under consideration [11, 12], including ultra-low current pickups, schottky pickups, a cryogenic current comparator, and a novel beam profile monitor based on an extended gas jet curtain [13, 14].

4 Conclusion and outlook

The ultra-low energy storage ring marks a significant evolution step forward as compared to existing schemes to decelerate antiprotons and possibly highly charged ions to lowest energies. The storage ring layout was adapted to match the requirements of the different users, as well as of specific machine operation conditions, like short bunch mode operation or electron cooling. The chosen split-achromatic geometry promises utmost flexibility while maintaining the compactness and simplicity of the storage ring. In a next step we will analyse the dynamic aperature of the machine in detail, perform real field simulations, and develop field compensation schemes for both the electron cooler as well as the reaction microscope.

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