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DESIGN OF A COMBINED FAST AND SLOW EXTRACTION FOR THE ULTRA-LOW ENERGY STORAGE RING (USR)*

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Abstract

The Ultra-Low energy Storage Ring (USR) within the future Facility for Low-energy Antiproton and Ion Research (FLAIR) will decelerate antiproton beams from 300 keV to energies of only 20 keV. Cooled beams will then be extracted and provided to external experiments. The large variety of planned experiments requires a highly flexible longitudinal time structure of the extracted bunches, ranging from ultra-short pulses in the nanosecond regime to quasi DC beams. This requires fast as well as slow extraction in order to cover whole range of envisaged beam parameters. A particular challenge was to combine elements for fast and slow extraction in one straight section of this electrostatic ring. In this contribution we present the results of beam dynamic simulations and describe the overall extraction scheme in detail.

INTRODUCTION

The modified layout of the USR [1,2] is based on a split–achromat geometry which gives the necessary flexibility to satisfy a variety of USR operation modes. It is specifically optimized for short bunch operation, a round beam mode, as well as for fast and slow beam extraction. Four 4 m long straight sections are incorporated into the ring to accommodate the so-called *reaction microscope* (RM), different RF systems, the electron cooler, elements for fast and slow extraction, and beam diagnostics installations.

LAYOUT OF A FLEXIBLE EXTRACTION SCHEME FOR THE USR

The design of the USR extraction system has been substantially improved during a recent optimization process. An overview of the modified version of the extraction set up, including a detailed layout of all elements is shown in Fig.1.

To accommodate all components of the slow and fast extraction systems, as well as to simplify the design and the future operation of the synchrotron, most of the elements are located in one of the USR straight sections. This includes parallel plate bump electrodes, adjustable septum electrodes and an electrostatic extraction channel that will be shared by both extraction modes.

The 4-RMS emittance of a 300 keV antiproton beam injected into the USR is expected to be ~5π mm·mrad. After electron cooling, the beam emittance will be reduced to ~1.5π mm·mrad. The maximum value of the betatron function in some of the operation modes can be as large as $\beta_{x,y}$=20 m. This means that the diameter of the antiproton beam can exceed 20 mm, while the increment of the radial amplitude during slow resonant extraction will not exceed 7 mm. Thus a location of the extraction elements very close to the equilibrium orbit is not desirable. To overcome this problem, a local orbit bump was introduced to the machine lattice.

The combined extraction system is located in the free straight section of the USR and consists of the following elements: two parallel plate deflectors with a gap of 60 mm, two large parallel plate deflectors with a 90 mm gap, a 6° extraction septum and a 30° cylinder deflector. The electrostatic septum, located in-between two central bump electrodes, is displaced by 50 mm from the central orbit to provide free space and safety margins for the circulating as well as for the extracted beam, see Fig. 1.

The bump electrode #1 bends the circulating beam by 4.5÷6°. The large bump electrode #2 returns the beam to the initial direction on the displaced orbit. As a result, the beam is again parallel to the equilibrium orbit, but shifted from the ring axis by 30÷40 mm during the passage of the 1240 mm long part of the straight section. A second pair of bump electrodes moves the beam back on the ring axis. Thereby, the beam is locally displaced and gets closer towards the septum, thus reducing the necessary voltages on the extraction elements and granting more space for the circulating beam.

For fast extraction, an additional pulsed kicker voltage of opposite polarity will be applied to the plates of the large bump deflector #2 when the beam moves along the bump. This will switch off the deflector and ensure that the beam can pass directly into the electrostatic septum deflector.

The entrance of the septum deflector is tilted with respect to the ring axis by roughly 6°. The septum inclination is adjustable to accept both, ions with a small angular momentum during slow extraction, as well as tilted trajectories of up to 6° during fast extraction. Particles diverted into the extraction septum will experience an additional deflection of 6° towards the outside of the ring, i.e. in total 12° with respect to the ring axis, followed by a 30° bend in the cylindrical electrostatic deflector. The last element of the extraction system will guide the beam to the external experiments.

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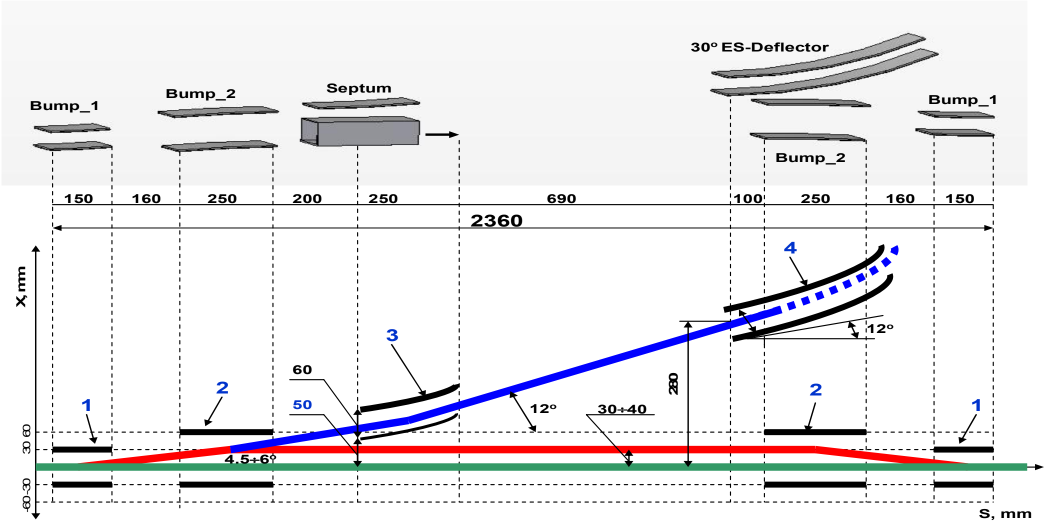

Figure 1: Location of elements in the extraction system: 1- parallel plate bump electrodes #1; 2 – parallel plate bump electrodes #2; 3 –6° Electrostatic septum deflector of cylindrical shape; 4 - 30° electrostatic deflector.

COMPUTER SIMULATION OF FAST EXTRACTION

The beam dynamics during fast extraction in the USR was investigated using the code "Dyn", written in the frame of the "Matlab" software package [3]. In addition, the commercially available computer program "COMSOL Multi-physics" was used to model the 3D electrostatic fields of the USR extraction system elements.

The initial conditions at the entrance of the extraction setup are matched to the parameters of the un-cooled beam circulating in the ring. The ion energy and energy spread are E=20 keV and ΔE=±20 eV, respectively. The beam current density was approximated by a Gaussian distribution in both, x- and y-transverse plane. The beam size is ±10 mm. More than 1,000 particles were randomly populated inside a 5π mm·mrad phase space area and were tracked over the extraction elements in the model.

Initially, the electric field between the parallel plate electrodes was calculated without grounded shields. In order to limit the fringe fields, all plates have been surrounded by grounded shields of pill box shape with holes for the beam.

The maximum value of the electric field strength during the extraction of 20 keV antiprotons is 300 V/cm. This is much less than the sparking limit. Even in the case of beam extraction at 300 keV beam energy, the electric field strength will not exceed 4.5 kV/cm and thus should not affect ring operation.

To limit the fringe fields and guarantee ion motion in the homogenous part of the electric field, the gap between two electrodes is kept as small as possible, but at least twice as large as the expected beam dimensions.

These conditions lead to a distance of 40 mm between the electrodes for a beam of 20 mm diameter. The lower electrode of the large bump deflector #2 was moved 30 mm upwards to be able to reduce the gap between the plates from 120 mm to 90 mm. To provide a homogenous electric field distribution along the beam axis, one should design all electrodes at least twice as long as the gap between the plates. In the USR extraction setup, the bump deflector #1 is 150 mm and deflector #2 is 250 mm long, see Fig.1.

The beam trajectories during extraction are well-defined and 1,000 particles were tracked through all extraction elements without any losses, see Fig.2.

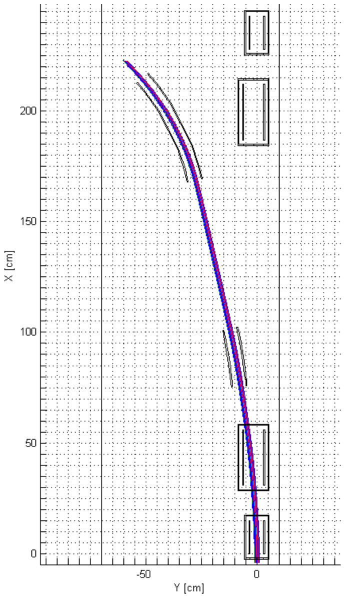

Figure 2: Beam trajectories in the extraction section.

SLOW EXTRACTION IN THE USR

For slow extraction of particles from the USR, the well established "resonant extraction" procedure, using a third-integer resonance will be applied [4].

Similar to fast extraction, the beam can be moved closer to the extraction septum by the local orbit bump. This ensures that the septum is the horizontal aperture limitation in the machine during the extraction process and that the minimum necessary sextupole strengths can be used.

The following steps will be applied in the USR before beam extraction starts:

- The horizontal betatron tune is first shifted as close as possible to the exact resonance value of ν_r=2.666(6), with a rather small shift of around $\Delta\nu_r = -0.003$;
- The sextupoles are then activated and are used to excite a third order resonance ν_r=8/3 by means of formation a resonance "separatrix".

Beam extraction can be started either by increasing the sextupole strength, i.e. by gradually shifting the horizontal betatron tune to the exact resonance value, or by using a transverse "knock-out" method, where the radial oscillation amplitude of the ions is increased by applying a high frequency transverse electric field, a so-called "exciter" [5]. For the USR, the "knock-out" extraction technique will be used as it provides beam extraction without varying the beam optics on the extraction level, as well as a controllable variation of the beam density at the experimental target.

The computer code MAD-X was used for slow extraction studies in the USR. In the process of a dynamic change of the ion optics, the electrostatic quads are retuned. As a result, the radial betatron tune is shifted from the ν_r=2.5443 operation point to ν_r=2.6637, which is close to the third-order resonance $3\nu_r$=8.

The stability of the radial motion in the extraction point of the tune diagram, when the sextupoles have been switched off, was checked by tracking many particles over 10,000 turns. It turned out that beam motion is stable even for large amplitudes of radial oscillations, so that ring operation in the vicinity of the third order resonance should not cause problems before the start of the extraction process. As soon as the resonance-driving sextupoles are powered, the stable phase-space ellipse is being shrunk and distorted, creating a separatrix area of triangular shape, where the radial motion is distorted, but still stable. The amplitude of the particles, that exceed the separatrix area, increases exponentially in the horizontal plane until they reach the position of the electrostatic extraction septum.

The effect of different sextupole positions was studied and it was found that a sextupole location at 23 m is optimal. This position is indicate in Fig. 1. A sextupole with a strength of k_{Sx}=5m^{-2} provides the maximum amplitude of radial oscillations. This can be as large as 10 mm. At the same time, it offers a reasonably large entrance angle to the septum deflector of about 4 mrad. Assuming a thickness of the grounded septum electrode of 0.2 mm, the extraction efficiency was estimated to be about 97%. For fast extraction, the exit angle of the ions is about +100 mrad, or 6°, while during slow extraction the septum should be tilted to only +4 mrad, or 0.23°. A variation of the inclination angle of the septum entrance in the range between 0° and +6° will be foreseen in the design of the USR extraction system. An additional 6° deflector could be installed after the septum electrodes to direct the beam into the main 30° cylindrical electrostatic deflector during slow extraction

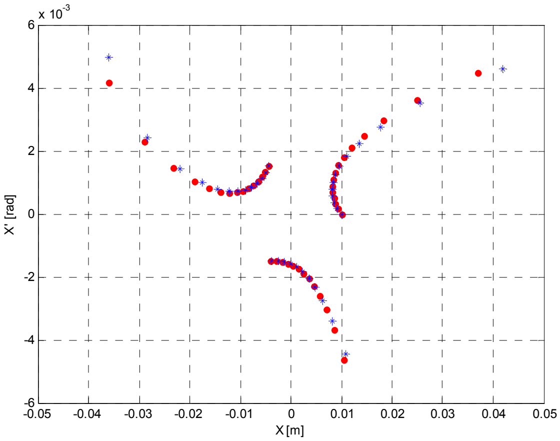

Figure 3: Slow extraction phase space diagram at the position of the electrostatic septum. The sextupole is located at 23 m. Sextupole strengths are $k_{Sx} = -4\text{m}^{-2}$ (red dots) and $k_{Sx} = -5\text{m}^{-2}$ (blue points). "Arms" are directed outwards with positive momentum.

CONCLUSION

A modified layout and results of computer simulations of the USR's slow and fast extraction system was presented in this contribution. The main elements of both extraction systems are combined in one straight section of the ring. The position and dimensions of all extraction elements were checked for consistency and a number of modifications to the extraction scheme were introduced. An optimum position and parameter setting for the sextupole was identified and described.

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