Письма в ЭЧАЯ. 2011. Т. 8, № 1(164). С. 85–99

МЕТОДИКА ФИЗИЧЕСКОГО ЭКСПЕРИМЕНТА

STUDY OF SLOW AND FAST EXTRACTION FOR THE ULTRALOW ENERGY STORAGE RING (USR)

G. A. Karamysheva [a], *A. I. Papash* [a,b,c], *C. P. Welsch* [d,e]

[a] Joint Institute for Nuclear Research, Dubna

[b] Max-Planck Institute for Nuclear Physics, Heidelberg, Germany

[c] Kiev Institute for Nuclear Research, NAS, Ukraine

[d] University of Liverpool, Liverpool, UK

[e] The Cockcroft Institute for Accelerator Science and Technology, Daresbury, UK

The Facility for Antiproton and Ion Research (FAIR, GSI) will not only provide future users with high fluxes of antiprotons in the high-energy range, but it is also intended to include a dedicated program for low-energy antiproton research in the keV regime, realized with the FLAIR project. The deceleration of antiprotons with an initial energy of 30 MeV down to ultralow energies of 20 keV will be realized in two steps. First, the beam is cooled and slowed down to an energy of 300 keV in a conventional magnetic ring, the Low energy Storage Ring (LSR) before being transferred into the electrostatic Ultralow energy Storage Ring (USR). In this synchrotron the deceleration to a final energy of 20 keV will be realized.

This paper describes the ion-beam optical and mechanical layout of the beam extraction from the USR and summarizes the expected beam qualities of extracted beams.

Ускорительный комплекс FAIR не только обеспечит физиков высокоинтенсивными пучками антипротонов высоких энергий, но и реализует программу исследований на пучках антипротонов с энергией на уровне десятков кэВ в рамках проекта FLAIR. Уменьшение энергии антипротонов от начальной 30 МэВ до ультранизкой 20 кэВ будет осуществляться поэтапно. Сначала пучок охлаждается и замедляется до энергии 300 кэВ в магнитном кольце, так называемом накопителе антипротонов низкой энергии (LSR), далее пучок инжектируется в электростатическое кольцо — накопитель антипротонов ультранизкой энергии (USR). В этом кольце пучок замедляется до минимальной энергии 20 кэВ.

В статье дано описание оптической структуры системы вывода пучка из USR и приведены расчетные параметры выведенного пучка.

PACS: 29.20.db

INTRODUCTION

The next-generation Facility for Antiproton and Ion Research (FAIR) at GSI (Darmstadt, Germany) will include a dedicated complex of accelerators and ion traps for research with low-energy antiprotons and exotic heavy ions in the keV regime or even at rest, named FLAIR [1]. External experiments for precision studies, like, e.g., trap experiments, will form an integral part of FLAIR [3, 4].

A novel Ultralow energy electrostatic Storage Ring (USR) [2–4] to be integrated at FLAIR [5, 6] is being developed to provide electron-cooled beams of antiprotons and probably highly charged ions in the energy range between 300 and 20 keV/A, with possibility to reduce energy of stored beam to ~ 1 keV [7]. The use of electrostatic elements has the significant advantage that, as compared to their magnetic counterparts, high field homogeneity in combination with a fast ramping of the fields over a wide range is possible. In addition, remanence and hysteresis effects do not occur in electrostatic elements [8].

A high luminosity, low emittance and low momentum spread of the beam together with a flexible beam shape are required. Different modes of operation have to be included in the USR: deceleration and e-cooling of antiprotons and high-charge-state heavy ions [9], in-ring experiments with ultrashort bunches [11, 12, 14], optimization of the beam shape, size, and dispersion with respect to the specific experiment. To allow for these specific conditions, the USR lattice was modified substantially [15].

The new USR lattice is flexible and allows for different modes — particular with zero dispersion in straight sections during ultrashort bunches operation, with variable negative and positive dispersion for slow extraction, etc. Different betatron tunes and deep variation of beta functions are foreseen as well [16].

To fulfill its role as a multipurpose experimental facility, the design of the USR has not only to cover in-ring experiments, but also needs to include highly flexible beam extraction. In order to allow for a broad range of beam characteristics of the extracted beams, from short pulses with up to 10^7 cooled antiprotons in some hundreds of nanoseconds to quasi-DC beams for nuclear physics–type experiments, the USR needs to feature both fast and slow resonant beam extraction, for the first time in an electrostatic storage ring [10].

The modified layout of the USR [10, 15, 17] is based on a split-achromat geometry which gives the necessary flexibility to satisfy a variety of USR operation modes and specifically optimized for short bunch operation, round beam mode and fast/slow extraction (Fig. 1).

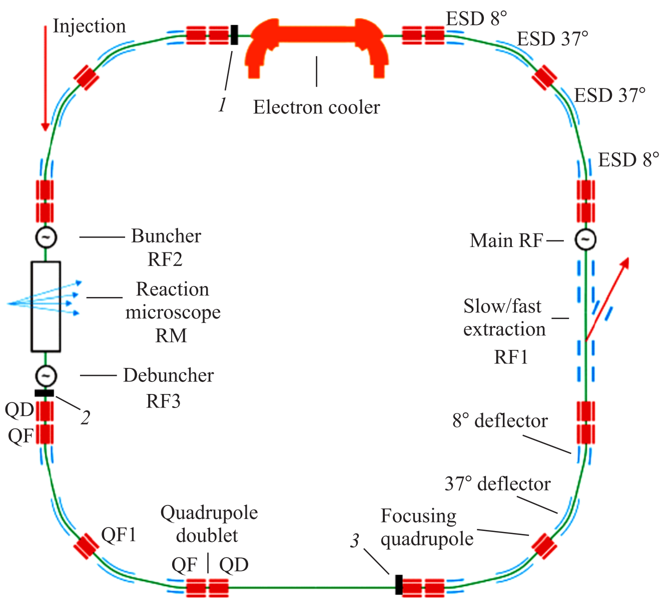

Fig. 1. Modified layout of the USR. Extraction section is outlined. Possible locations of sextupole for slow extraction: *1* — at 12 m; *2* — at 23 m; *3* — at 33 m

Four 4-m-long straight sections are incorporated into the ring to accommodate the «Reaction Microscope» (RM), different RF systems, the electron cooler, the elements for fast/slow extraction [16], diagnostics, vacuum systems and other equipment.

The USR has a periodicity of four, resulting in identical sections for each quarter of the ring. Each cell is formed by two half straight sections with 90° bending section centered in-between. The 90° bending section is composed by electrostatic cylinder deflectors, arranged in an achromat-type lattice as well as by electrostatic quadrupoles. The cylinder deflectors are split further into an 8 and 37° bend. The reason for that is twofold:

• Splitting of the deflectors allows the injection of the beam along one of the 8° elements, thus avoiding the installation of a dedicated injection section.

• Neutral particles emerging form experiments in the RM section will leave the central orbit in the bend, allowing their detection outside of the ring.

Two of the four straight sections are reserved for internal experiments like a reaction microscope and setup for ultrashort bunch operation [14], while in the third section an electron cooler will be placed [9]. Only one straight section is left for installations of elements of both fast and slow extraction.

1. LAYOUT OF A FLEXIBLE EXTRACTION SCHEME FOR THE USR

To provide experiments requiring single short pulses of antiprotons per deceleration cycle (e.g., for filling a trap once per each 5–10 s), fast extraction is used. To deliver beams to nuclear/particle physics type of experiments, a slow-extraction scheme will be available. The USR is the first electrostatic ring that will feature slow extraction. As was mentioned above, both types of extraction should be housed in one 4-m-long straight section of the USR.

Preliminary simulations of the extracted orbits have been performed using the computer codes SIMION [20] as well as OPERA3D [21], and results were reported earlier [10, 16]. The design of the USR extraction system has been substantially improved during the optimization process [18, 19]. An overview of the modified version of the extraction setup and a layout of the elements are shown in Fig. 2.

To accommodate the parts 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; i.e., parallel plate bump electrodes, adjustable septum electrodes and electrostatic extraction channel will be used for both extraction modes.

The 4 RMS emittance of 300-keV antiproton beam being injected into the USR is expected to be $\sim 5\pi$ mm · mrad. After e-cooling the beam emittance should be reduced to $\sim 1.5\pi$ mm · mrad [9]. The maximum value of the betatron function in some modes of the USR operation could be as much as $\beta_{x,y} = 20$ m and the diameter of $\bar{p}$ beam might exceed 20 mm, while the increment of the radial amplitude during resonance slow extraction will not exceed 7 mm. Thus, the location of extraction elements close to the circulating equilibrium orbit is not desirable. To overcome this problem, the local bump of orbit is applied.

The combined extraction system is located in the free USR straight section and consists of the following elements: two parallel plate deflectors with a gap of $d_{\rm gap} = 60$ mm, two large parallel plate deflectors with $d_{\rm gap} = 90$ mm gap, the 6° extraction septum and a 30° cylinder deflector. Parameters of the elements are listed in the table. The electrostatic septum which is located in between two central bump electrodes is displaced at 50 mm from the central orbit

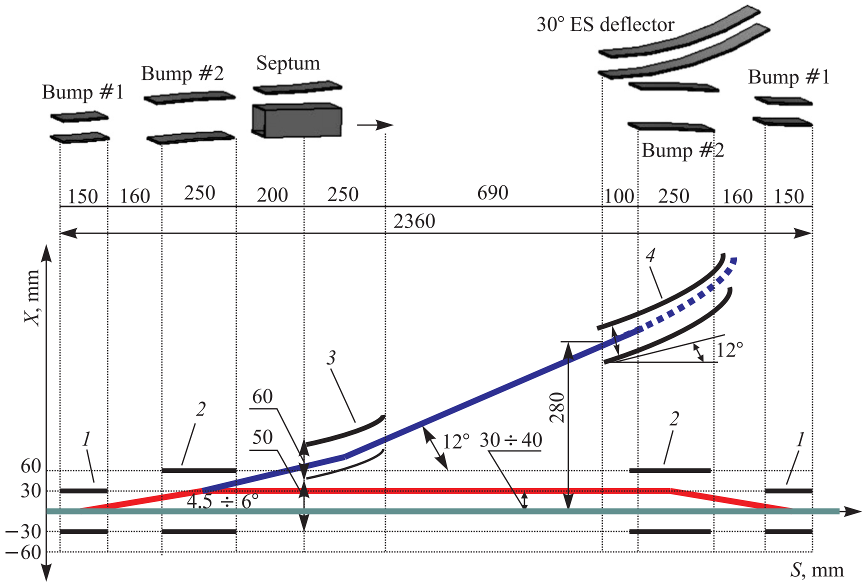

Fig. 2. Location of elements of the combined extraction systems in one of the USR straight sections: *1* — parallel plate bump electrodes #1; *2* — parallel plate bump electrodes #2; *3* — 6° electrostatic septum deflector of cylindrical shape, entrance tilt angle to the axis is variable from 0 to 6°; *4* — 30° electrostatic deflector

in order to provide free space and safety margins for a circulating as well as for an extracted beam (Fig. 2).

To initiate extraction, at first the beam will be moved by a local orbit bump slowly towards the extraction septum. To allow for the most flexibility during this process, a local orbit bump will be created by four dedicated parallel plate electrostatic deflectors. This controls not only the bump displacement but at the same time, in contrast to three bump elements option, a parallel beam in the center between the electrodes is created.

Bump electrode #1 bends the circulating beam through $4.5{-}6°$. The large bump electrode #2 returns initial direction to the displaced orbit. As a result, the beam is 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. The second pair of bump electrodes moves the beam back to the ring axis. Thereby the beam will be locally displaced closer towards the septum, reducing the necessary voltages on the extraction elements and allowing more space for the circulating beam. The tolerance between the bumped beam and the septum electrode depends on beam parameters and might be optimized by variation of the voltage between plates.

For the fast extraction, as soon as the beam moves along the bump, an additional kicking pulse voltage of opposite polarity is applied to the plates of the large bump deflector #2, thus switching it off so that the beam can pass directly into the electrostatic septum deflector.

The entrance of the septum deflector is tilted to the ring axis at $\sim 6°$. Septum inclination is adjustable in order to accept ions with small angular momentum during slow extraction as well as tilted trajectories (up to 6°) during fast extraction. The particles diverted into the

Parameters of the USR extraction elements*

Element	Shape	Curvature, mm	Length, mm	Gap, mm	Bending angle, °	Voltage on plates upper bottom, V	Voltage ramp time, ms	Voltage stability	Pulse width, μs	Pulse front, ns
Bump #1	Parallel plate	Flat	150	60	$+(4{-}6)$	$+560$ -560	$\leqslant 100$	10^{-4}		
Bump #2	Parallel plate	Flat	250	90	$-(4{-}6)$	-520 $+520$	$\leqslant 100$	10^{-4}		
ES kicker (Bump #2)	Parallel plate	Flat	250	90	$+(0{-}2)$	$+690$ -690		10^{-3}	4–20	$\leqslant 200$
Septum deflector**	Cylindr. shape	$+2500$	262	60	$+6$	$+800$ ground	$\leqslant 100$	10^{-4}		
Electrostatic deflector	Cylindr. shape	$+1000$	523	60	$+30$	$+2400$ ground	DC	10^{-4}		

*Nominal deflection voltage is estimated for 20-keV antiprotons.
**Septum thickness is 0.2 mm.

extraction septum will experience an additional deflection by 6° towards the outside of the ring — in total 12° with respect to the ring axis, followed shortly afterwards by a 30° bend in the cylindrical electrostatic deflector. The last element of the extraction system will guide the beam to the external experiments.

2. COMPUTER SIMULATIONS OF FAST EXTRACTION

Beam dynamics during fast extraction in the USR was investigated using a complex of codes «Dyn» written in the framework of the «Matlab» software package [22]. Full differential equations of the particle motion in the electric and magnetic fields are integrated in the program by the Runge–Kutte method of the fourth order. These codes have been used to study the beam motion in the cyclotron CYTRACK (JINR, Dubna) [24], the commercial cyclotron for proton therapy C235 and the superconducting cyclotron C400 for heavy-ion therapy (IBA, Belgium) [25].

A commercially available computer program «COMSOL Multiphysics» has been developed to simulate electric and magnetic field distribution by relaxation method and was used to model 3D electrostatic fields of the USR extraction system elements [23]. Four parallel plate bump electrodes, 6° electrostatic septum deflector of cylindrical shape and 30° cylindrical electrostatic deflector were combined into the AD-REC extraction model (Fig. 3). Geometric dimensions, position as well as distances between elements have been estimated earlier [15, 16] and incorporated into the model for further optimization.

The initial conditions at the entrance of the extraction setup are matched to the parameters of the uncooled beam circulating in the ring. The ion energy and energy spread are $E = 20$ keV and $\Delta E = \pm 20$ eV, correspondingly. The beam current density was approximated by distribution of Gaussian type in both X- and Y-transverse planes. The beam size is ± 10 mm. More than 1000 particles randomly populated inside of 5π mm · mrad phase space area were tracked over the extraction elements in the model.

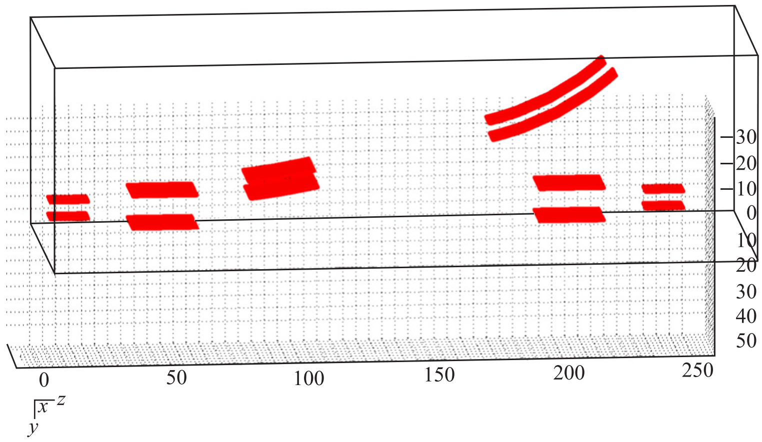

Fig. 3. Model view of the USR extraction system created in «COMSOL Multiphysics» [23]

Originally, the electric field between parallel plate electrodes was calculated without ground shielding. However, it was found that the field is spread out far beyond the geometric boundaries of the extraction elements and the trajectories of the bumped beam are of poor quality (Fig. 4, *a*). In order to localize fringe fields, all plates have been surrounded by grounded shields of pill box shape with holes for the beam (Fig. 5). The distance 20 mm between the housing and the electrodes was estimated as an optimum one to exclude any sparking problems during operation and at the same time to efficiently limit the field boundaries. The diameter of the holes in the shield is equal to the gap between the plates, i.e., 60 mm for parallel plate deflector #1 and 90 mm for deflector #2.

The electric field of shielded bump electrodes is restricted mostly by the geometric boundaries of the grounded housing and the beam practically does not experience the influence of fringe fields (Fig. 4, *b*). The maximum value of the electric field strength during extraction of 20-keV antiprotons is 300 V/cm which is much less than the sparking limit. Even in case of extraction of the 300-keV-energy beam the electric field strength will not exceed 4.5 kV/cm and the ring operation should be stable.

Trajectories of the circulating beam in the bump region of the extraction section are shown in Fig. 6, *a*. To limit the fringe field and guarantee the ion motion in the homogeneous electric fields, the gap between the electrodes should be as small as possible but at least twice as much as the beam dimensions.

The condition of good region field requires a 40-mm distance between electrodes for a beam 20 mm in diameter. Taking into account the necessity to accommodate a slow-extraction setup in the same compartment, the gap between plates could not be less than 60 mm. At least 30-mm bump shift is required to move the beam close to the septum electrode; i.e., 90-mm gap is necessary to accommodate the beam for different operation modes. Thus, we have decided to displace the lower electrode of large bump deflector #2 at 30 mm up and reduce the gap between plates from 120 to 90 mm.

To provide a homogeneous electric field distribution along the beam axis, one should design electrodes at least twice as long as the gap between the plates. In the USR extraction setup, bump deflector #1 is 150 mm long and deflector #2 is 210 mm long (Fig. 2).

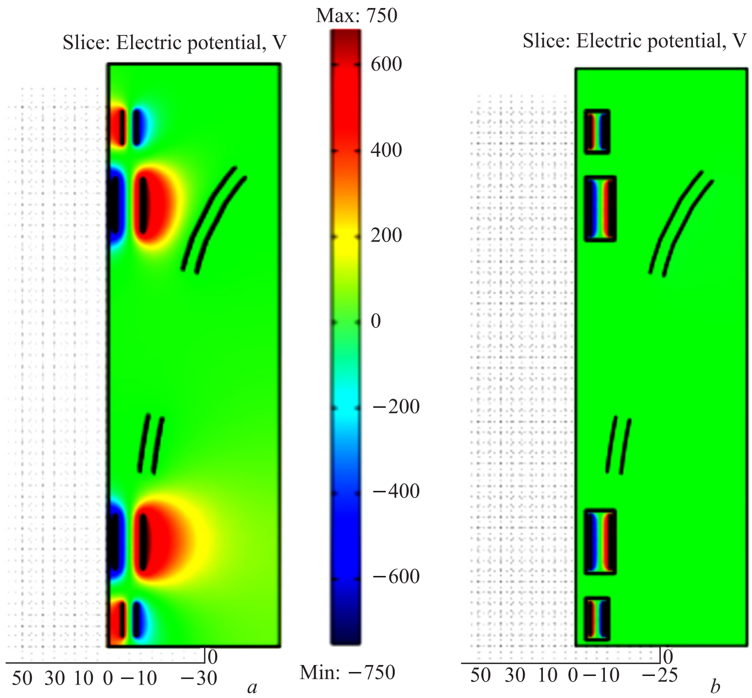

Fig. 4. Electric potential distribution in the model: *a*) original version without shields; *b*) modified model with shielded electrodes

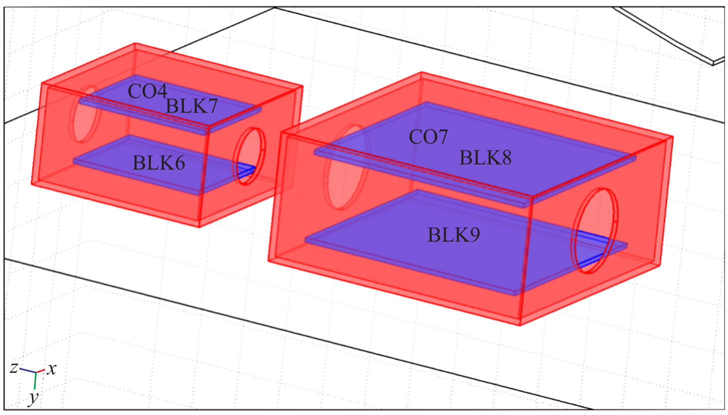

Fig. 5. View of the grounded housings

Local parallel bump will be produced by shifting of 20 keV $\cdot$ pbar at 38 mm out of the ring axis by applying $+(-)560$ V to the upper (lower) electrodes of deflector #1 and $-(+)530$ V to the upper (lower) electrodes of deflector #2 (table). The voltage between plates might be tuned to optimize the bump position.

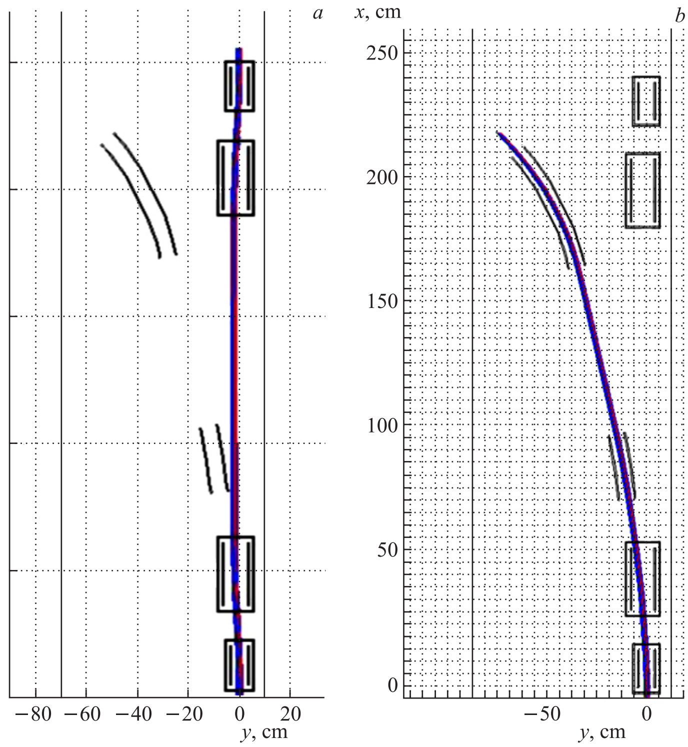

Fig. 6. Ion trajectories in the extraction section: *a*) circulating beam in the bump region; *b*) extracted beam

The circulating bumped beam should be extracted in one rotation period of ions in the ring. In order to transfer the ring operation from the bump mode to the fast-extraction mode, it is necessary to change the polarity of voltage applied to the plates of bump deflector #2. Additional pulsed voltage of opposite polarity is applied to the plates of deflector #2 in order to direct the beam towards the septum and match the beam position and angle at the septum entrance. The pulse width depends on the beam rotation period and is varied from 6 μs for 300-keV beam to 22 μs for 20 keV $\cdot$ pbar.

The septum deflector is tilted $\sim 6^\circ$ with respect to the ring axis to accommodate the incoming beam. The septum electrode is grounded and $+800$ V is applied to the upper electrode in order to bend 20-keV beam at additional 6°. The central particle exits the septum deflector having been bent at 12° with respect to the ring axis. The thickness of the septum electrode should not be more than 0.2 mm and the switching pulse front should be less than 200 ns in order to achieve 95–99% extraction efficiency. The position and voltage of the 30° deflector have been fitted during simulations to accommodate the beam central ray.

Beam trajectories during extraction are well-defined and 1000 particles were tracked through all the extraction elements with no losses (Fig. 6, *b*).

Chronological sequence of orbit bump operation is shown in Fig. 7, *a*. The beam is going to move on the orbit bump at least a few hundreds of turns during fast extraction and up to 10^5 turns in some experiments with long exposition (slow extraction). Thus, the duration of

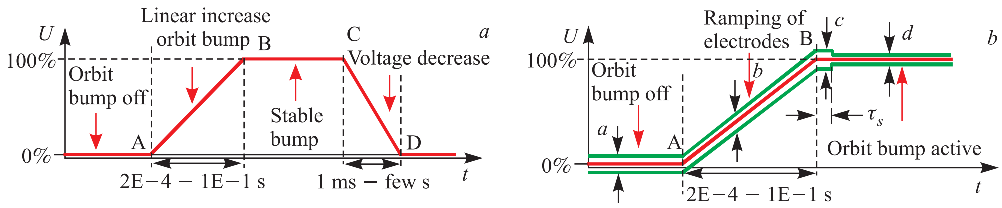

Fig. 7. Chronological sequence of orbit bump operation: *a*) A, B, C, D are the points where voltage starts to rise up or fall down; *b*) voltage offset during ramping, shown are «*a*» and «*d*» voltage stability at plateau $\Delta U/U = \pm 1 \cdot 10^{-4}$, «*b*» and «*c*» voltage stability during transition and stabilizing period $\Delta U/U = \pm 2 \cdot 10^{-4}$, stabilizing time $\tau_s < 100$ μs

stable bump depends on the choice of extraction mechanism and might be varied between ~ 10 ms and up to ~ 2 s. The requests on the needed stability and the range of rise-up and slow-down times of the voltages are quite strict.

The orbit bump, when activated, has to shift the beam from the circulating orbit onto a new orbit which requires an adiabatically slow increasing of the voltage between plates, as not to distort the phase space. In the ramping process the voltage on the bump electrodes is growing from 0 kV up to a maximum of ± 8 kV (300 keV $\cdot$ pbar). A rise-up time might be varied from ~ 200 μs up to ~ 10 ms.

Voltage offset during ramping is shown in Fig. 7, *b*. Absolute value of the voltage on deflector electrodes should be stable better than $\Delta U/U = \pm 1 \cdot 10^{-4}$ while the beam is on the bump plateau. During ramp transition and during stabilizing period, deviations from the reference profile are limited to the $\Delta U/U = \pm 2 \cdot 10^{-4}$. The stabilizing time should be as short as possible and might not exceed $\tau_s < 100$ μs.

3. SLOW EXTRACTION IN THE USR

For the slow extraction of particles from the USR, a well-established «resonant extraction» procedure using a third-integer resonance will be applied [26]. Slow extraction allows one to deliver quasi-continuous beam to the experimental area in demanded times of several seconds in contrast to the fast extraction where a single short pulse is extracted from the synchrotron. Compared to the mechanism using the half-integer resonance, the third-integer resonance allows more controllable spills and could be driven by dedicated sextupoles properly located in the ring.

Similar to the fast extraction, the beam can be moved closer to the extraction septum by the local orbit bump, which 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 should be applied in the USR before starting the beam extraction:

• shift the horizontal betatron tune as close as possible to exact resonance value of $\nu_r = 2.666(6)$ but rather with some small shift, i.e., $\Delta\nu_r = -0.003$;

• activate sextupoles and excite the third-order resonance $\nu_r = 8/3$ by means of formation of the resonance «Separatrix».

The beam extraction might start either by increasing the sextupole strength, 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 ions is increased by applying a high-frequency transverse electric field («exciter») [27]. For the USR we propose to use the «knock-out» extraction technique as it provides:

- a beam extraction without varying the beam optics on the extraction level;
- controllable variation of beam density at the experimental target.

In the «knock-out» extraction mode an RF electric field excites beam oscillations with a frequency that is resonant to a harmonics of the particle betatron frequency. Driven by the transverse electric field, excited particles are moving from the inner area of the resonance «Separatrix» with stable particle trajectories to the edge of the «Separatrix», where they become unstable with exponentially increasing amplitudes.

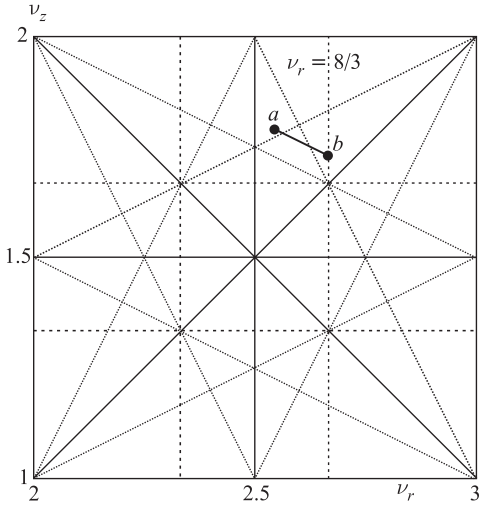

Fig. 8. The USR betatron tune diagram. Shown are: a — operation point of circulating beam $\nu_r = 2.5443$ and $\nu_z = 1.7905$; b — excited resonance $\nu_r = 2.6637$ and $\nu_z = 1.7315$ in the process of slow extraction. Also shown are I, II, III, IV operation points of original USR design [2]

In order to meet the specific requests for slow beam extraction, especially for the slope of dispersion function, a dynamic change of the ion optics settings between the circulating mode and the start of the extraction mode is required. Dispersion-free straight sections are foreseen in the USR ring for the circulating beam in the «ultra-short» bunch operation mode.During the «round beam» operation, the dispersion is slightly deviates from zero to positive as well as negative values because this mode requires tuning of beta functions to achieve specific beam parameters, etc.

For slow extraction the dispersion function is optimized to attain momentum-independent extraction — so-called «Hardt condition» for negative chromaticity. Quads settings during extraction also determine the requested aperture of electrodes, as for the suggested mechanism of slow extraction the amplitude of particle oscillations in the ring over the last three turns, before the extraction takes place, is growing above 20–30 mm and has to be taken into consideration.

The computer code MAD-X was used for slow-extraction studies in the USR [13]. 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 $\nu_r = 2.5443$ operation point to the value $\nu_r = 2.6637$ which is close to the third-order resonance $3\nu_r = 8$ (Fig. 8).

The shift between the actual betatron tune and the exact resonance value $\Delta\nu_r = -0.003$ is required to avoid beam losses before the start of the extraction itself. The value of betatron tune shift $\Delta\nu_r$ has been derived from the sum of a tune spread of $\delta\nu_r = \pm 0.0012$ due to a chromaticity of $\xi_x = -2.3$, maximum momentum spread $\Delta p/p = \pm 0.5\%$ and the calculated stop-band of the third-order resonance $3\nu_r = 8$.

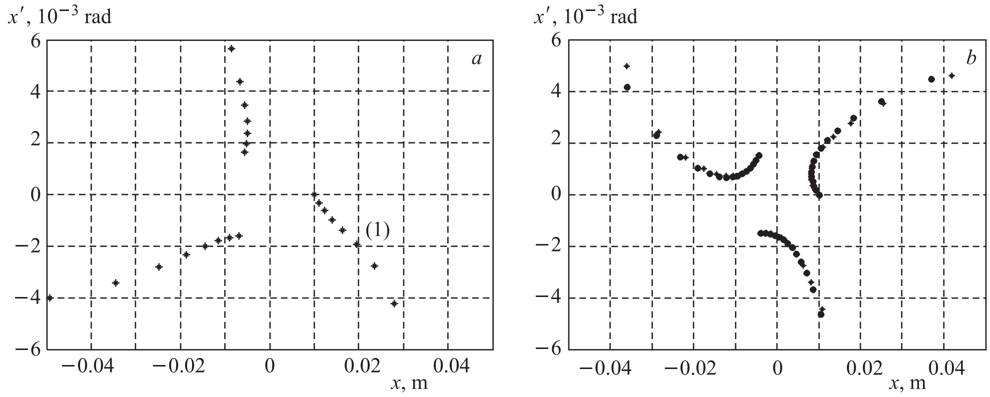

Fig. 9. Slow extraction phase space diagrams at the position of the electrostatic septum. The sextupole is located at 23 m: *a*) sextupole strength is $k_{\mathrm{Sx}} = +5$ m^{-2} and outbound arm #1 has negative momentum, i.e., directed inward; *b*) sextupole strengths are $k_{\mathrm{Sx}} = -4$ m^{-2} (circles) and $k_{\mathrm{Sx}} = -5$ m^{-2} (stars). Outbound arms are directed outwards with positive momentum

The stability of radial motion in the extraction point of the tune diagram while the sextupoles were switched off was checked by the tracking of many particles during 10000 turns. The radial displacement and momentum off-set from the equilibrium orbit have been varied in the range of $X_i = \pm 20$ mm and $P_{X_i} = \pm 4$ mrad. The beam motion is stable even for a large amplitude of radial oscillations. The conclusion was made that the ring operation in the vicinity of the third-order resonance should not cause the 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 the separatrix area of triangle shape where the radial motion is distorted but still stable. For larger amplitudes of radial oscillations, particles leave the stable area and follow separatrix arms on which the particles will eventually move towards the vacuum chamber.

The extraction tracking procedure was started in the middle point of the USR straight section. As the beam will still be moving inside the stable resonance separatrix, the transversal RF noise should be applied to move particles outside of the stable separatrix area. It was assumed that particles are initially displaced from the ring axis by 10 to 20 mm. The excited particles reach the border of the separatrix and are extracted along the outgoing separatrix branch (Fig. 9). This eventually allows the particles to jump over the septum wall into the extraction channel.

As for the RF-knock-out extraction, the strength of the sextupole and quadrupoles is fixed and the shape and orientation of the separatrix arms are kept constant over the extraction period. Therefore, the beam position in the synchrotron extraction channel and the angle of the particles at the electrostatic septum with respect to the reference orbit can be kept constant during slow extraction.

The polarity of the sextupole should be chosen in a correct way. In case of the USR slow extraction, the positive-polarity voltage applied to the sextupole will drive outbound particles with the negative momentum, i.e., directed inwards like arm #1 shown in Fig. 9, *a*, while the

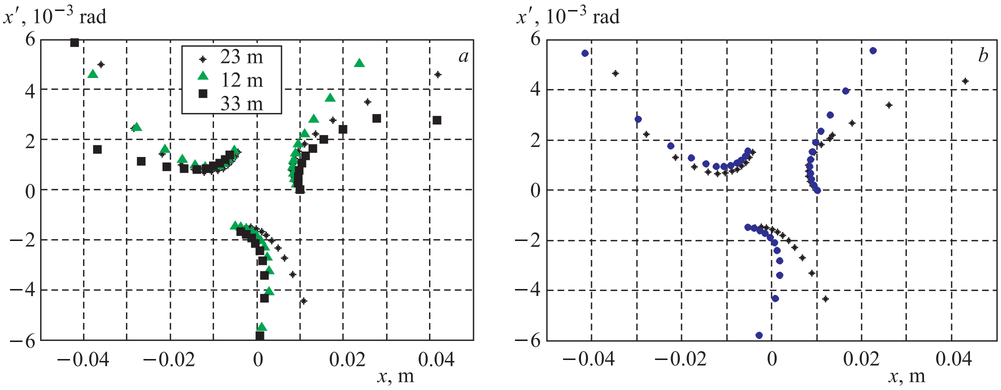

Fig. 10. Resonance extraction separatrices at the position of the electrostatic septum: *a*) different sextupole location at 12 m (triangles), at 23 m (stars) and at 33 m (squares); *b*) adjusting of separatrix arm orientation by simultaneous powering of two sextupoles $k_{\rm Sx} = -6$ m^{-2} at 12 m and $k_{\rm Sx} = +1$ m^{-2} at 23 m (stars) as well as $k_{\rm Sx} = +1$ m^{-2} at 12 m and $k_{\rm Sx} = -6$ m^{-2} at 23 m (circles)

septum deflector is directed outwards. To change the orientation of the phase pattern, we switched the polarity of the sextupole to negative voltage and the particles should enter the septum deflector with a small positive angle of approximately $+4$ mrad (Fig. 9, *b*).

The amplitudes of the particles, that exceed the separatrix area, increase exponentially in the horizontal plane until they reach the position of the electrostatic extraction septum. The ground electrode of the electrostatic septum is tilted according to the separatrix angle at this position at an angle of about $+4$ mrad with respect to the bumped beam orbit. Increasing of the sextupole strength from 4 to 5 m^{-2} will lead to the growth of radial oscillations amplitude over the precession cycle (three turns in the ring) from 5 to 7 mm. The sextupole with a strength of $k_{\rm Sx} = 5$ m^{-2} provides optimum extraction conditions. The spiral step at the position of the electrostatic septum, which means the increase of the particle amplitudes over the last three turns, is about 7–8 mm. For a thickness of the septum ground electrode of 0.2 mm, the extraction efficiency should be about 97%. In our study the distance between the circulating bumped beam and the extraction septum was fixed to 20 mm. Nevertheless, the optimum septum position depends on the beam emittance and might be varied in a wide range from 10 to 40 mm in order to optimize the sextupole strength and the extraction efficiency.

We studied the effect of different sextupole positions and found that three locations at 12, 23 and 33 m are suitable for the USR extraction setup (Fig. 10). The location of the sextupole in other places of the ring would not produce the required resonance excitation. The sextupole at 12 m produces the highest angular deviation of the extracted orbit which might benefit the extraction efficiency, but the step between particles in the last precession cycle is less than 5 mm and the losses during the extraction should be significantly higher than in the case of the sextupole location at 23 or 33 m. We have chosen the sextupole location at 23 m as it provides the maximum amplitude of radial oscillations (up to 10 mm) and a reasonably large entrance angle to the septum deflector (~ 4 mrad).

It is possible to precisely adjust the angle of the separatrix arm while keeping the same precession pattern. During slow extraction, the beam might enter the septum at various angles

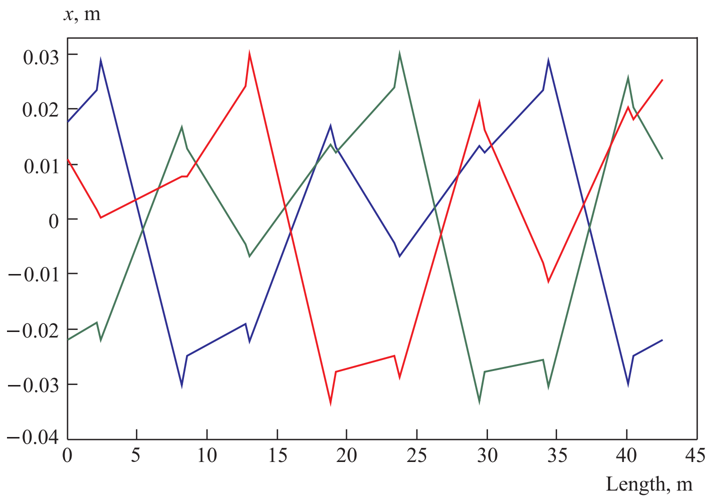

Fig. 11. The last three turns of the central particle in the ring during slow extraction

without degradation of the extraction efficiency. To this end, two sextupoles located at 12 and 23 m have been excited simultaneously. The first time the sextupole at 12 m was excited to $k_{\rm Sx} = -6$ m^{-2}, and the sextupole at 23 m to $k_{\rm Sx} = +1$ m^{-2}, while the second time sextupoles were powered vise versa. As a result, the exit angle was changed from +2 to +5 mrad, while the distance between the two last successive precession cycles is kept the same, i.e., 7 mm (Fig. 10, *b*).

Benefit of employing two sextupoles is evident, but in the USR the septum deflector will be used for both types of extraction. For fast extraction the exit angle of ions is about +100 mrad, i.e., $\sim 6°$, while during slow extraction the septum should be tilted at only +4 mrad, i.e., $\sim 0.23°$. The variation of the inclination angle of the septum entrance in the range from 0 to $+6°$ will be foreseen in the design of the USR extraction system and the use of a second sextupole might not be necessary. Also an additional 6° deflector should be installed after the septum electrodes to direct the beam into the main 30° cylindrical ES deflector during slow extraction.

The particles, having reached a position close to the septum, but that are not yet extracted, have to overcome three turns in the ring before being captured by the deflector. This condition gives the main requirement for the demanded aperture of the bending and quadrupole elements in the synchrotron. The aperture of electrostatic elements must be large enough to accommodate the last turns in the ring. To imagine the necessary aperture of the ring elements, we present the last three turns during slow extraction in Fig. 11. The span of radial oscillations exceeds 60 mm and might be limited by a narrow gap between plates in the 39° electrostatic deflectors of the USR.

CONCLUSION

In this paper, we have presented a modified layout and results of computer calculations of the USR slow- and fast-extraction modes. The main elements of both extraction systems will be combined in one straight section of the ring. The position and dimensions of the extraction elements have been checked for consistency and some modifications to the extraction scheme were proposed. Simulations of the slow-extraction process were performed for the different sextupole positions and settings.

The generous support by the Helmholtz Association of National Research Centers (HGF) under contract number VH-NG-328 and the GSI Helmholtz Centre for Heavy Ion Research GmbH is acknowledged.

REFERENCES

1. *Welsch C. P. et al.* An Ultra-low-Energy Storage Ring at FLAIR // Nucl. Instr. Meth. A. 2005. V. 546. P. 405–417.
2. *Welsch C. P. et al.* Layout of the USR at FLAIR // Proc. of Eur. Part. Acc. Conf. «EPAC-2006», Edinburgh, Scotland, 2006. P. 1636–1638.
3. http://www.oeaw.ac.at/smi/flair/ TechnicalProposal/TP.htm
4. *Welsch C. P. et al.* Exploring Sub-femtosecond Correlated Dynamics with an Ultra-low Energy Electrostatic Storage Ring // AIP Conf. Proc. 2005. V. 796. P. 266–271.
5. *Fischer D. et al.* GSI Scientific Report. Darmstadt, 2006. 208 p.
6. *Welsch C. P., Ullrich J.* FLAIR — A Facility for Low-Energy Antiproton and Ion Research at GSI // Hyp. Int. 2007. V. 172(1–3). P. 71–80.
7. *Welsch C. P.* Ultra-low Energy Antiprotons at FLAIR // Proc. of Eur. Part. Acc. Conf. «EPAC-2004», Lucerne, Switzerland, 2004. P. 1240–1242.
8. *Welsch C. P. et al.* An Electrostatic Quadrupole Doublet with an Integrated Steerer // Ibid. P. 1234–1236.
9. *Smirnov A. V., Welsch C. P.* Cooling Rates of the USR as Calculated with BETACOOL // AIP Conf. Proc. 2006. V. 821. P. 397–401.
10. *Welsch C. P. et al.* Preliminary Design of Highly Flexible Extraction Scheme for the USR // Proc. of Eur. Part. Acc. Conf. «EPAC-2008», Genova, Italy, 2008. P. 3407–3409.
11. *Papash A. I., Welsch C. P.* On the Possibility of Realizing Shortest Bunches in Low-Energy Storage Rings // Part. Nucl., Lett. 2009. V. 6, No. 3(152). P. 216–226.
12. *Papash A. I. et al.* On the Possibility of Realizing Shortest Bunches in Low-Energy Storage Rings // Proc. of Eur. Part. Acc. Conf. «EPAC-2008», Genova, Italy, 2008. P. 334–336.
13. http://www.cern.ch/mad
14. *Papash A. I., Welsch C. P.* Investigations into the USR «Short Pulse Operation» Mode // Part. Acc. Conf. «PAC-2009», Vancouver, Canada, 2009.
15. *Welsch C. P., Papash A. I.* An Update of the USR Lattice: Towards a True Multi-user Experimental Facility // Ibid.
16. *Welsch C. P., Papash A. I., Schmid P.* Preliminary Design Studies of an Extraction of the USR // Hyp. Int. LEAP-08. Wien, 2008.

17. *Welsch C. P. et al.* Development at the Interface between Accelerator Science and Atomic Physics within the QUASAR Group. GSI Scientific Report 2009. Atomic Physics-29. P. 308–310.

18. *Karamysheva G. A., Papash A. I.* Optimization of the Extraction System in the USR: Part 1. Fast Extraction Simulations. www.quasar-group.org. 2009. 10 p.

19. *Karamysheva G. A., Papash A. I.* Optimization of the Extraction System in the USR: Part 2. Slow Extraction Simulations. www.quasar-group.org. 2009. 9 p.

20. SIMION — Industry Standard Charged Particle Optics Simulation Software. Scientific Instrument Services, Inc. http://www.simion.com

21. OPERA3d User Guide. Vector Fields OPERA-3d, Version 12. 2008. 578 p.

22. *Karamysheva G. A. et al.* Beam Dynamic Simulations in Cyclotrons in the Frame of Matlab Software Package. JINR Commun. P9-2008-52. Dubna, 2008. 6 p.

23. «COMSOL Multiphysics».

24. *Onischenko L. M. et al.* Cyclotron CYTRACK for the Membrane Production // Proc. of XVII Intern. Conf. on Cyclotrons and Their Applications, Tokyo, 2004. P. 96–99.

25. *Jongen Y. et al.* Center Region Design of the Cyclotron C400 for Hadron Therapy // Proc. of XVIII Intern. Conf. on Cyclotrons and Their Applications, Catania, Italy, 2007. P. 394–396.

26. *Strolin P.* Third-Order Resonance Slow Extraction from Alternating Gradient Synchrotrons. CERN/PS/OP 80-10 Report. 1980.

27. *Van der Meer S.* Stochastic Extraction, a Low Ripple Version of Resonance Extraction. CERN/PS//AA 78-6 Report. 1978.

Received on April 21, 2010.