BEAM TEST OF SLOW EXTRACTION FROM THE ESR

A. Dolinskii, C. Dimopoulou, O. Gorda, S. Litvinov, F. Nolden, M. Steck,
GSI, Darmstadt, D-64291 Germany

Abstract

In the frame of a dedicated ESR machine development the conventional third order resonant slow extraction was theoretically investigated and experimentally tested. This was a demonstration of the possibility to extract a beam from the ESR by preparing a resonant closed orbit, which has strong nonlinear characteristics. A third-integer resonant slow extraction has been adopted for a 100 MeV/u Ar beam.

INTRODUCTION

The Experimental Storage Ring (ESR) is operated since 1990 [1]. The nominal operating parameters are summarized in Table 1. The ESR employs heavy ion beams of many different ion species at beam energies ranging from 0.004 to 1 GeV/nucleon. The slow extraction is required in order to deliver a continuous stream of highly charged low energy particles to a fixed target behind the ring. In this report we present results of simulations and first experimental measurements of slow extraction for the ESR. The conventional third integer resonant extraction process employs a single thin electrostatic septum and a thick septum magnet, with the resonance created by re-configuring 8 of the main horizontal chromaticity sextupoles. The expected extraction efficiency is about 85 %, based on the thin septum thickness and the predicted particle jumping (step size of the resonant beam) at the septum. The maximum kinetic energy of the extracted beams is limited by the maximum ESR rigidity of 10 Tm. Fully stripped ions are injected to the ESR from the synchrotron SIS18 at intensities of up to 10^9 per pulse. In the ESR these ions can be decelerated to the required energy.

After several ion-optical manipulations with the beam the extraction from the ESR is performed. In order to find out which manipulations are needed for a slow extraction, the ion optical calculations with the MIRKO and PTRACK [2] codes have been done.

Table 1: The ESR machine parameters

Circumference, C, m	108.4
Max. rigidity , Tm	10
Transition energy, $\gamma_{tr,}$	2.7
Tunes Q_x / Q_y	2.27 / 2.23
Trans. acceptance (mm mrad)	300 / 100
Mom. acceptance	3%
Num. superperiods	2
Lattice type	Doublet, Triplet
Vacuum chambers h/v (mm)	220 / 70 (dipole) 300 / 320 (quad)

The first slow extraction of the beam from the ESR took place in January 2009. At that time it was demonstrated that we could manipulate the beam in tune and horizontal phase space with little or no beam loss and then extract it. By tuning the ring ion optics into resonance with quadrupole magnets the extraction starts.

SIMULATION OF THE SLOW EXTRACTION SCHEME

The ESR ring has a two-fold symmetry lattice with two 20 m long straight sections. The characteristics of the ESR from the slow extraction point of view are the following. The path length from the Electrostatic Septum (ES) to the Magnetic Septum (MS) is 39.1 m. The ES is placed in the arc, where the dispersion function is close to the maximum value of 5.5 m. The MS is placed in the dispersion free long straight section. The beam optics functions β_x and α_x at the entrance of the ES are 23.5 m and 3.49 m respectively. The ES wires are positioned so that x=-70 mm at the entrance. The ES length is 0.8 m length, the wire thickness is 0.1 mm. The betatron phase advance between the ES and the SM is 225 degrees, which makes a separation of 25 mm between the kicked and not kicked particles at the ES. The arrangement of the magnets between ES and MS is shown in Fig.1. The Injection Septum Magnet (ISM) is placed upstream of the ES, between them the electron cooler is positioned. The ISM restricts the acceptance of the beam line from the ES to MS within which the particles kicked by the ES have to be transferred to the MS gap.

Before the particle extraction starts, one has to prepare resonance conditions. For this, two resonance sextupole magnets are activated in order to excite the 3^{rd} - order resonance. The other 6 sextupole magnets are used to restrain the chromaticity to small values on the extraction orbit. The chromaticity is corrected from ξ =-7.2 in both planes to about ξ =-3. This needs excitation of 6 sextupole magnets as it is done at the normal operation mode of the ESR. The values of the resonance sextupoles are calculated to have a particle jump (step size) of 9 mm after every 3 turns at the position of the electrostatic septum (ES). Fig.2 shows the calculated separatrix in the horizontal phase space at the position of the ES. One can see that whole separatrix is shifted by -44 mm on the inner side of the ring. This is needed in order to increase the acceptance of the beam line from the ES to MS only for particles, which deflected by the ES. The separatrix shift shown in Fig.2 is produced by creation of a resonance condition on the equilibrium orbit corresponding to the momentum deviation of -0.8%.

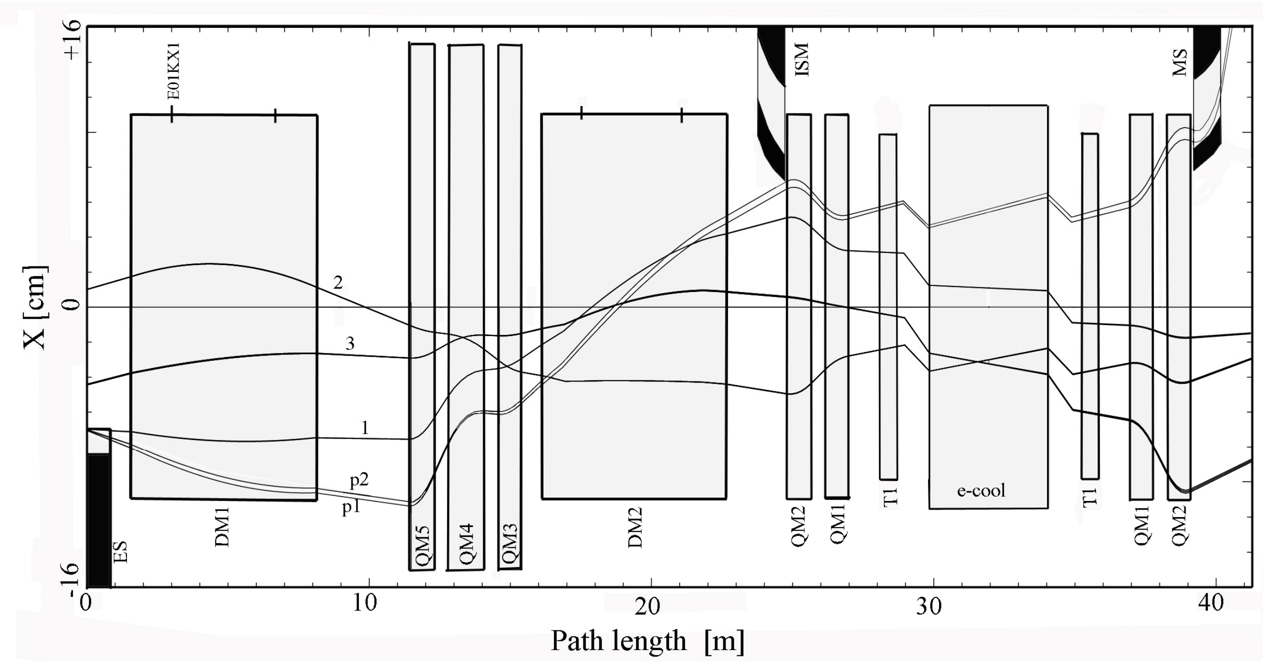

Figure 1: Particle trajectories in the region from the Electrostatic Septum (ES) to the Magnetic Septum (MS). ISM – Injection Septum Magnet, e-cool –electron cooler, DM–Dipole Magnet, QM–Quadrupole Magnet, E01KX1 – corrector magnet. Boxes show the limit of beam survival with real aperture limitations. Numbers 1,2,3 correspond to the last three turns in the ring; p1,p2 – trajectories of the kicked particles by the ES with the initial angle $\Delta x_1'$ and $\Delta x_2'$ (Fig.2).

To bring particles to the outer side of the separatrix (from stable to unstable region) the horizontal betatron tune Q_x was approached from below the resonance 7/3 to the resonance by ramping 4 focusing quadrupole magnets placed in the straight sections. The particles reaching the ES (x=70 mm from ring axis, fig.2) still have to overcome last 3 turns in the ring before they were extracted. Fig.1 shows the last three turns of the particles in the region from the ES to the MS before they are bent by the MS.

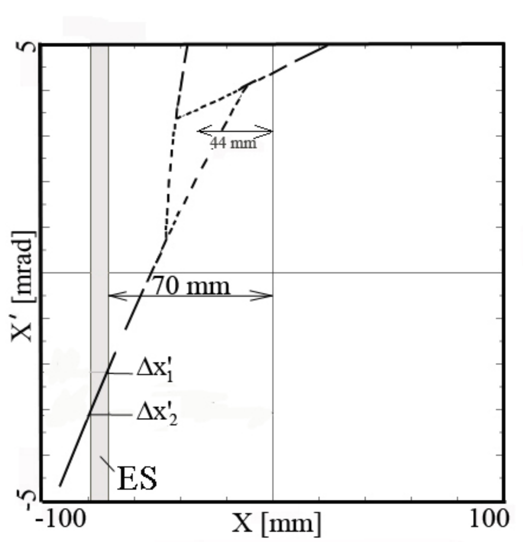

Figure 2: The phase space at the entrance of the ES. $\Delta x_1'$ and $\Delta x_2'$ are the initial angles of particles before they are kicked by ES and directed to MS as shown in Fig.1.

The orbits for these last three turns require an aperture of the magnets up to ±150 mm In principle the ESR magnets have such an aperture. After three turns the particles jump into the ES having initial angles in the range [-2.1, -3.1] mrad ($\Delta x_1'$ and $\Delta x_2'$ shown in Fig.2). According to the simulations the ES should provide an inward kick angle of about -2 mrad (20 kV) in order to direct the particles to the MS. In the path length from the ES to MS the ISM restricts the required aperture for these particles. At the position of the ISM the aperture is restricted from the outside by +70 mm and from the inner side by -100 mm that limits the acceptance for extracted particles. To avoid collisions of a kicked particle with the ISM one has to disturb the shape of the closed orbit by the corrector magnet E01KX1, which is located in the dipole magnet DM1. The kick angle of the corrector must be -1 mrad.

Summarizing the numerical simulations the following manipulations must be done step by step in order to extract beam slowly from the ring:

- the injected beam is shifted to the equilibrium orbit corresponding to the momentum deviation of - 0.8 %.
- the closed orbit of the ring is deformed by the corrector magnet, which is set to a kick angle of -1 mrad.
- 2 out of 8 sextupole magnets are activated in order to excite the 3rd order resonance. The other 6 sextupole magnets are used to restrain the chromaticity to small values.
- the ion optics of the ESR is adjusted to have the operating betatron tune close to the resonance $Q_x = 7/3$.
- running into the resonance with 4 quadrupole magnets the slow extraction starts.

TEST RUN

In the test run the Ar^{18+} beam was injected into the ESR on the injection orbit at the energy of 100 MeV/u. The injection orbit of the ESR corresponds to the momentum deviation of +1% with respect to the reference orbit (or central orbit of the ring). The beam was moved from the injection orbit to the extraction one (-0.8%) by ramping the magnets of the whole ESR machine without energy changing. With this procedure the beam with the energy of 100 MeV/u is moved automatically to the orbit with $\Delta p/p$=-0.8%. The resonance sextupole magnets are activated and then the betatron tunes are adjusted to Q_x=2.325, Q_y=2.24.

To begin extraction the beam was moved into the resonance by slowly increasing the field of the four ESR quadrupole magnets. This causes the tune of the beam to shift slowly into the resonance and particles enter into the region of a non-linear betatron amplitude growth. As the step size increases over many turns the particles eventually either hit the thin septum and are lost or step across it and are deflected across the MS and then bent out of the ESR into the extraction beam line. To direct particles to the MS we adjust the ES kick angle to the -0.8 mrad instead of -2 mrad that was predicted by calculations. Fig.3 shows the beam current decreasing during slow extraction. Fig.4 shows the beam as seen on an illumination screen in the extraction beam line for a time step of 2 sec after the start of extraction.

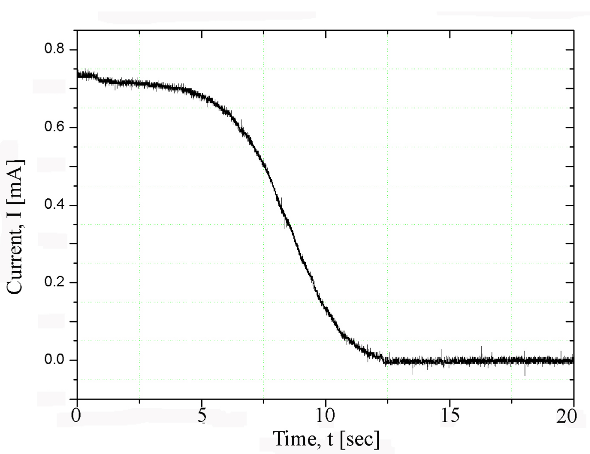

Figure 3: The beam current in the ring during moving of the horizontal tune to the resonance 7/3.

DISCUSSION

In the test run it was shown that to slowly extract beam the kick angle of the ES must be smaller by factor of about 2 compare to the calculations. The explanation of such a discrepancy can be done by consideration of the field errors in the main dipole magnets. One should note that in the ESR there are 6 dipole magnets with 60 degree bending angle, a bending radius of 6.25 m, an effective

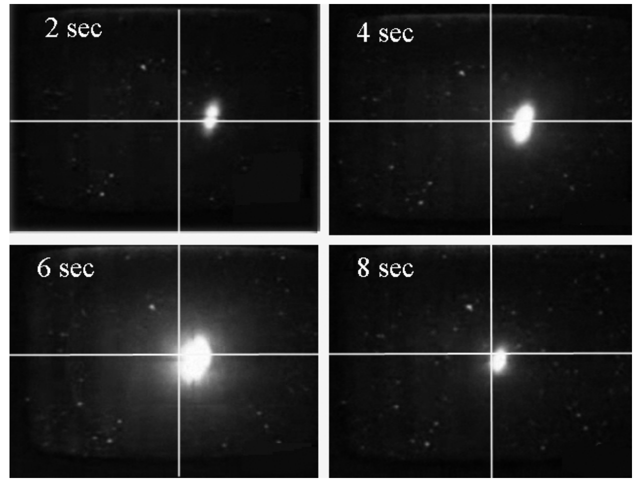

Figure 4: The extracted beam is seen on the illumination screen with a time step of 2 seconds.

length of 6.55 m. The usable apertures of the magnets are 360 mm in the horizontal and 70 mm in vertical planes.

Taking into account sextupole components of the dipole magnets the slope of the separatrix is larger by $\delta x'$=1.2 mrad at the position of the ES as shown in Fig.5. This means to direct the particles to the MS the ES should have a kick angle smaller than it was calculated in linear optic approximation. In this case we can note that the sextupole component of the dipole magnets helps the ES to bend the particles and instead of the predicted value of -2 mrad one needs -0.8 mrad kick angle of the ES as it was demonstrated in the test run.

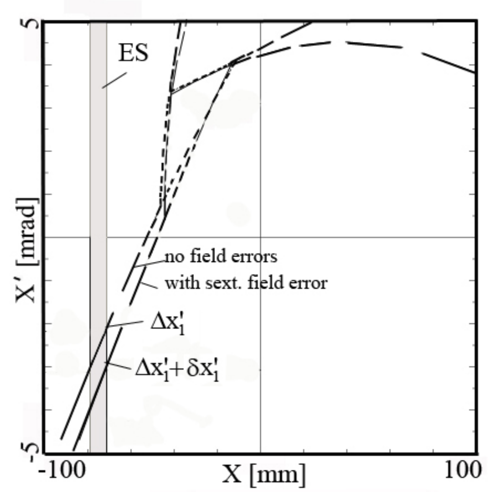

Figure 5: The separatrix at the position of the ES.

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