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ION OPTICS OF THE HESR STORAGE RING AT FAIR FOR OPERATION WITH HEAVY IONS*

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Abstract

The High Energy Storage Ring (HESR) of the FAIR project is primarily designed for internal target experiments with stored and cooled antiprotons, which is the main objective of the PANDA collaboration. However, the HESR storage ring also appears to have remarkable properties to carry out physics experiments with heavy ions [1].

In this paper a new ion optical design allowing the heavy ion operation mode of the HESR is presented. The main goal was to provide an optics which meets the requirements of the future experiments with heavy ion beams. Closed orbit correction, dynamic aperture as well as other characteristics of beam dynamics of the ion optical setup are under analysis in this study.

INTRODUCTION

The HESR is a storage ring with a racetrack design and a circumference around 575 m (Fig. 1). A special attribute of the ring is the 6D phase space cooling of the particle beam by means of both electron and stochastic cooling. A barrier bucket RF system together with longitudinal cooling will be used to accumulate the beam [2].

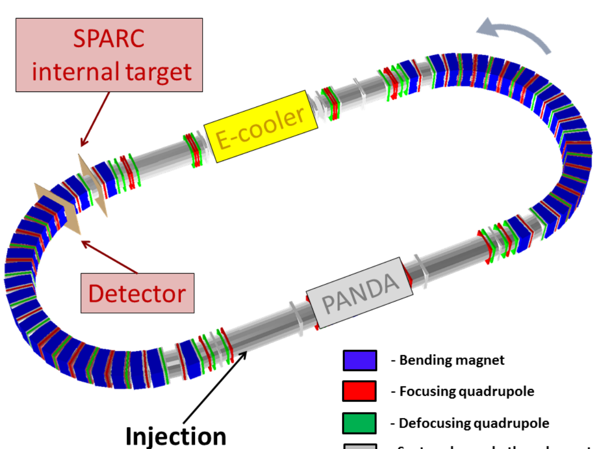

Figure 1: The HESR layout with the positions of the main experiments and the electron cooler. The arrow shows the direction of the beam circulation.

Besides the PANDA experiments with antiprotons the HESR will also be utilized for heavy ion research in the framework of the SPARC collaboration.

In this connection a new ion optical design is proposed specifically for the HESR operating in the heavy ion mode. The results of the numerical simulations as well as the possibility of experiments with an internal gas jet target (SPARC target) are discussed.

LINEAR ION OPTICS FOR HEAVY ION OPERATION

Based on the HESR main ion optics for PANDA experiment (from now on referenced as "antiproton mode"), where γ_{tr} = 6.23, the optimized ion optics for heavy ion beams is proposed (see Fig. 2). In Fig. 2 the calculated Twiss functions are shown. The quadrupoles in the electron cooler zero-dispersion straight allowed to reach the desired betatron amplitudes without changing the transition energy, whose value is crucial for stochastic cooling.

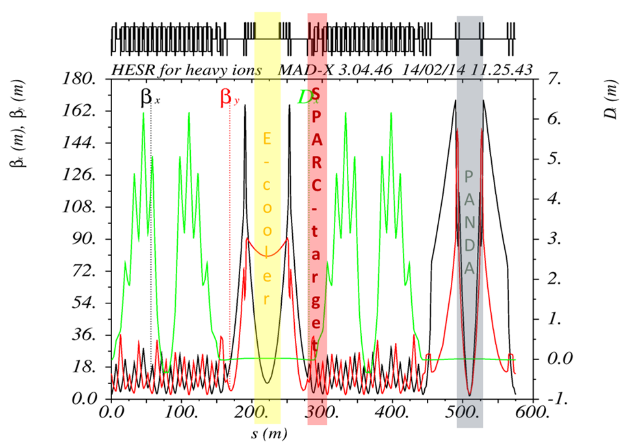

Figure 2: Twiss functions of the HESR in the operation mode with heavy ions

The betatron tunes for the calculated "heavy ion mode" optics are $Q_{x,y}$ = (7.629, 7.602), the transition energy γ_{tr} = 6.23 is the same as for antiproton mode.

The ion optics for heavy ions has special features comparing to the antiproton mode optics. The beta amplitudes in the place of PANDA experiment are more relaxed since there is no need of strong focusing at the PANDA target. The maximum value of the horizontal amplitude function β_x in the new optics is decreased from 230 m to 170 m. In the vertical plane the maximum β_y value is decreased not that significantly: from 175 m to 150 m. Under these conditions the ring acceptance becomes larger. Another advantage of the new optics is that the transition energy has

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the same value for which stochastic cooling of heavy ions is optimized (see [3]).

CLOSED ORBIT CORRECTION

Because of the magnet misalignments and field errors one should expect orbit deviations which leads to the acceptance reduction. The COD calculations and its correction have been performed for the HESR ring in the heavy ion operation mode. Among the main causes of orbit distortions are:

- Linear magnetic field errors
- Dipole rolls
- Quadrupole misalignments

All errors and misalignments were assumed to satisfy the 3σ-truncated Gaussian distribution. Afterwards the correction procedure was applied. The whole process consisted of the following steps:

- Random misalignments (rms value = 0.2 mm) and random tilts (rms value = 0.5 mrad) are assigned to the lattice elements.
- Systematic as well as random magnet field errors are generated in bending and quadrupole magnets.
- Closed orbit with the above mentioned misalignments and errors is calculated.
- MAD-X Singular Value Decomposition (SVD) algorithm [4] applied to correct the closed orbit and to find the desired dipole correctors strengths.

Statistical computation was performed with 500 random seeds for different error sets generation.

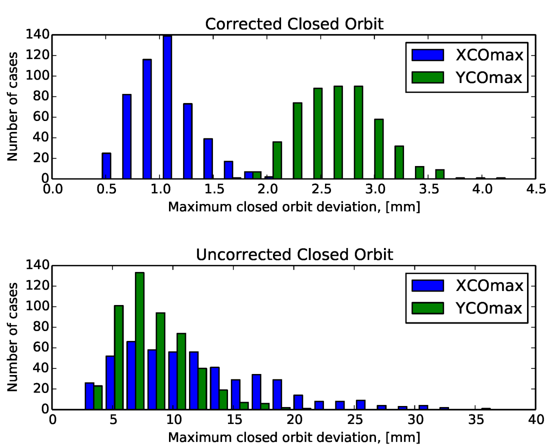

Figure 3: Corrected (top) and uncorrected (bottom) closed orbits' maximal deviations in both planes.

From Fig. 3 one can obtain the most probable values for the maximum closed orbit deviation after correction. In vertical plane the desired value is about 2.7 mm whereas in horizontal plane it is close to 1 mm.

Additionally, the possibility of creating a local closed orbit bump at the location of the SPARC internal target was checked. It was proved that with the present setup of BPMs and dipole correctors it is possible to have a bump in both planes in the ±5 mm tolerance interval. It will allow to have the best possible beam-target overlap.

DYNAMIC APERTURE CALCULATIONS

Depending on the type of the experiment, the heavy ion beam may circulate in the HESR for tenths of minutes which corresponds to hundredths million turns. During such period of time the magnetic field errors can bring a particle to the unstable region.

The dynamic aperture (DA), which indicates the border of the beam stability, together with tune map were calculated. The sextupole correction is applied to compensate the natural chromaticities $\xi_{x,y} \approx -14$.

4D particle tracking and FFT analysis were performed using the computing power of the GSI computing grid. Every time the magnetic field errors as well as misalignments distributions were generated. Then the linear optics with the errors was loaded to MAD-X PTC accelerator code [4] for 2048 turns tracking. The tracking started at the entrance of the north arc of the HESR in the direction of beam propagation. The spatial coordinates (x, y) were traced inside a half circle of a radius large enough to embrace the DA area. The slope coordinates were kept constant $x' = y' = 0$. Afterwards, in order to provide mapping from initial coordinates to tune space, for each (x, y) pair after each 1024 turns period a fine frequency search was applied. It means that after 2048 turns two frequencies were obtained which were used for diffusion coefficient [5] calculation:

$$D = \log_{10} \sqrt{((Q_{x,2} - Q_{x,1})^2 - (Q_{y,2} - Q_{y,1}))} \quad (1)$$

where $Q_{(x,y),1}$, $Q_{(x,y),2}$ are the frequencies computed after the first and the second halves of the sample (each half consists of 1024 turns) correspondingly.

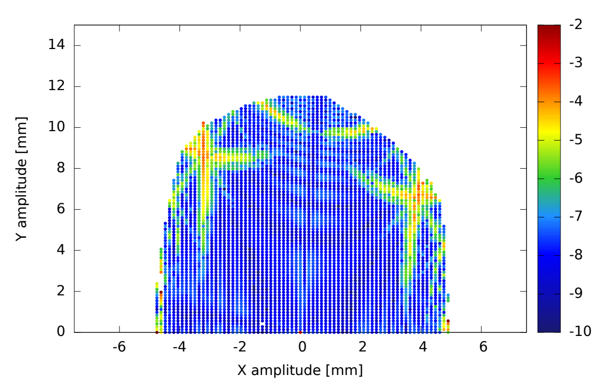

Figure 4: Dynamic aperture for Δp/p = 0. The palette bar to the right represents diffusion coefficient, i.e. a measure of chaoticity of particle with given initial coordinates. The dark-blue represents most stable particle orbits whereas the red indicates high chaoticity and diffusion.

The NAFF algorithm [6] was used to compute the frequency. The technique consists of Fourier Transform with

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Hanning windowing combined with bisection searching method.

It is also worth noting that because of the tiny value of the tune spread after electron cooling (±0.05%) [7] the dynamic aperture due to momentum deviation changes, as numerical simulations showed, only in the range of few percents. Thus in this study only the results with on-momentum calculations are presented.

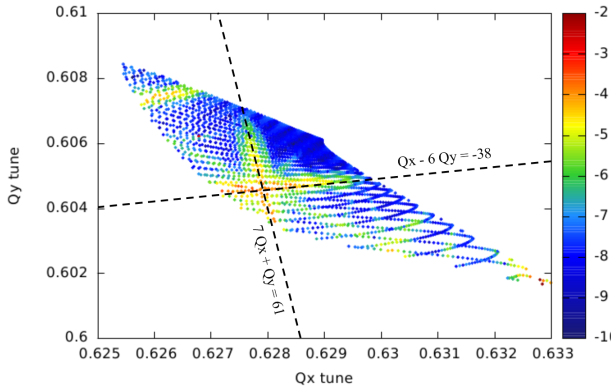

Figure 5: Tune map with fractional horizontal and vertical tunes. The blue line is 7th-order resonance Q_x - $6Q_y$ = -38, red line is 8th-order resonance $7Q_x + Q_y = 61$.

Figure 4 shows two dangerous chaotic regions created by the overlap of the resonances. From the tune resonance map (Fig. 5) it is easy to identify 7th and 8th order resonances. Despite their seemingly too high order, it is their intersection spot that may give dangerous rise to strong instabilities in the long term. Therefore in the long term dynamics the overlap of the two resonance layers in Fig. 4 can lead to strong diffusion process and a beam loss as a result [6]. The multipole errors, which drive these resonances, should be investigated in detail as well as their possible elimination. Also the possibility of another working point might be considered.

FIXED INTERNAL TARGET EXPERIMENTS

One of the most attractive features of the HESR in the framework of SPARC will be internal target experiments with cooled relativistic heavy ion beams. A gas jet target will be installed in the drift in the south arc (see Fig. 1).

A range of experiments will require detection and separation of the charge exchange reaction products from the interaction of the primary beam with the target.

Figure 6 shows a simulation [8] of the propagation of bare uranium U^{92+} beam as a primary one. Charge exchange reaction products U^{91+} and U^{90+} are created as a result of interaction the main beam with the target and their trajectories in the beam pipe are calculated.

From Fig. 6 one can clearly see the possibility of horizontal separation of the bare, H-like and He-like uranium ions. Note that with 2-σ beam the particles don't hit the aperture before detection. The rms emittances were taken

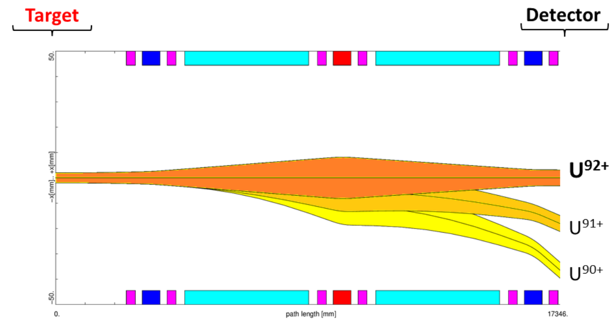

Figure 6: Propagation of different uranium ion species U^{92+} (orange), U^{91+} (light-orange) and U^{90+} (yellow) in horizontal plane after interaction of the main beam U^{92+} with the target. Among the magnet elements there are dipoles (cyan), quadrupoles (red and blue for focusing and defocusing quadrupoles correspondingly) and sextupoles (pink).

after electron cooling and are equal $(\epsilon_x, \epsilon_y) = (0.25, 0.15)\,\pi$ mm mrad [7]. The half-aperture of the magnets is 44.5 mm.

The simulations are done for the 740 MeV injection energy. When accelerated the separation of the charge exchange reaction products will be even better due to adiabatic damping.

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