INVESTIGATION AND OPTIMIZATION OF TRANSVERSE NON-LINEAR BEAM DYNAMICS IN THE HIGH-ENERGY STORAGE RING HESR

D.M. Welsch*, A. Lehrach, B. Lorentz, R. Maier, D. Prasuhn, R. Tölle
Institut für Kernphysik, Forschungszentrum Jülich, Germany

Abstract

The High-Energy Storage Ring (HESR) [1] is part of the upcoming Facility for Antiproton and Ion Research (FAIR) [2]. The HESR will provide antiprotons in the momentum range from 1.5 to 15 GeV/c for the internal target experiment PANDA [3]. The demanding requirements of PANDA in terms of beam quality and luminosity together with a limited production rate of antiprotons call for a long beam life time and a minimum of beam loss. Thus, a sufficiently large dynamic aperture of the HESR is crucial. To provide this, a chromaticity correction scheme for the HESR has been developed to reduce tune spread and thus to minimize the emittance growth caused by betatron resonances. The chromaticity correction scheme has been optimized through dynamic aperture calculations. The estimated field errors of the HESR dipole and quadrupole magnets have been included in the non-linear beam dynamics studies. The ion optical settings of the HESR have been improved using dynamic aperture calculations and frequency map analysis technique. In this presentation comprehensive beam simulations [4] are presented and predictions of long-term stability based on short-term particle tracking and orbit diffusion discussed.

HESR LATTICE

The HESR is designed as race track shaped storage ring (see Fig. 1) with a length of approximately 575 m and a beam momentum ranging from 1.5 to 15 GeV/c. The straight sections house the PANDA experiment and cooling devices as well as acceleration cavity and injection equipment. Since the PANDA experiment requires the beam size to be adjustable to the target dimensions, the beta functions can be varied in a range from 1 to 10 m. This focussing results in large beta functions of up to 300 m around the target in the adjoining quadrupole triplets which limit the geometric acceptance.

In order to optimise the stochastic cooling, the transition energy (γ_{tr}) can be varied between 6.2 and 15 GeV. This, the necessary dispersion suppresion in the straights, and the adjustment of both transverse tunes (Q_x, Q_y) are achieved by four quadrupole families in the arcs (three horiz., one vert.) together with a missing dipole concept. There are several optical settings defined where the $\gamma_{tr} = 6.2$ optics (see Fig. 2) is most important due to the PANDA flagship experiment at 8.9 GeV/c. Thus, this optical setting is considered in the following. Since the expected field errors of the main quadrupoles are highest at 15 GeV/c, all presented calculations used thosed values.

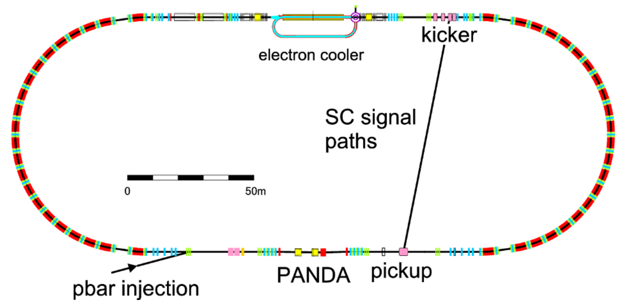

Figure 1: HESR lattice: Upper straight is housing electron cooler and stochastic kickers, lower straight contains injection, PANDA experiment with target, and stochastic pickups. The second dipole from each end of both arcs is missing for dispersion suppression in the straight sections and γ_{tr} adjustment.

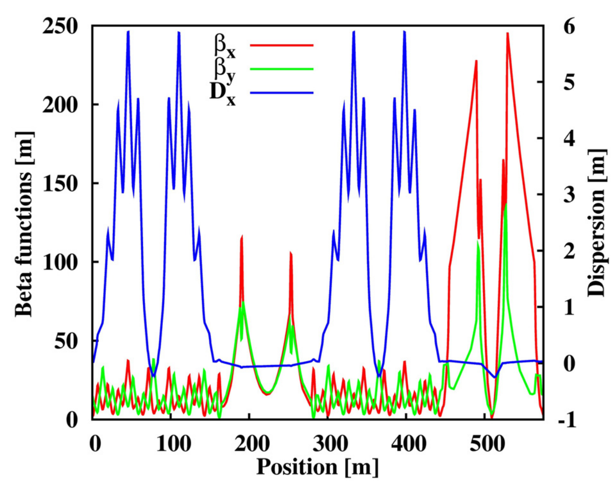

Figure 2: HESR optics for $\gamma_{tr} = 6.2$: electron cooler is located at roughly 220 m, the PANDA target at 509 m. The straight sections are nearly dispersion-free except for around the PANDA target where a kink is introduced by the PANDA chicane dipole magnets.

DYNAMIC APERTURE

The dynamic aperture is usually defined as a multi-dimensional border in phase space which encloses only particles surviving for a certain amount of time or turns. In-

* d.welsch@fz-juelich.de

vestigations have shown that the initial transverse momenta are negligible under the conditions chosen for this investigations. Therefore a dense mesh of particles' start coordinates is spanned in x-y space. The particle tracking starts from the location with the largest beta function in order to directly compare the dynamic aperture with the geometric acceptance limit. A tracing of particles for a few thousand turns is sufficient to investigate the betatron resonances and the influence of field errors on them [5]. From the x-y coordinates of the surviving particles, the emittances are calculated. Due to the restriction to round beams, the dynamic aperture is defined here as the largest circle in emittance space which encloses only surviving particles. The dynamic aperture calculations took the estimated field errors of the HESR main magnets into account including variations due to fabrication and design accuracy. They have been performed for several tens up to one hundred different sets of field errors.

TUNE SCANS

From the resonance condition of betatron resonances $(m, n, p) \rightarrow mQ_x + nQ_y = p$, the tune dependence of the dynamic aperture is very obvious. Whereas the frequency map analysis can be used to obtain information about the local resonance web, 2D tune scans varying both transverse tunes provide information about the strongest resonances over a larger area in the tune diagram. Since momentum spread and other effects can lead to coherent and incoherent tune shifts, tune scans are also used to find tune areas with enough space and large dynamic aperture.

Thus we started the investigations with 2D tune scans (see Fig. 3). That 2D tune scan shows a general tendency of the dynamic aperture to decrease from left to right toward the integer tune until no stable solution of the linear lattice can be found. That decrease can be explained by an occurring mismatch of the arcs and the straight sections leading to increase of beta functions in the triplets around the target. This translates via increase of beam size together with the field errors to stronger non-linearities affecting the dynamic aperture. The resonance lines could be identified as 1) Skew Sextupole $(2, 1, 23)$; 2) Octupole $(2, 2, 31)$; 3) Skew Octupole $(3, 1, 31)$; 4) Octupole $(4, 0, 31)$; 5) 12-pole $(4, 2, 47)$. Some resonance lines are shifted e.g. line 4) at $Q_x = 7.76$ instead of $Q_x = 7.75$. This can partly be explained by the display of the grid and its step size itself but mostly by frequency mixing which affects the resonance characteristics. Based on the 2D tune scans, 1D tune scans can be obtained e.g. with one of the tunes variable and the other one fixed. These 1D tune scans can be used for direct comparison between dynamic aperture and geometric acceptance limit and show that left of $Q_x = 7.75$, the dynamic aperture is larger than the geometric acceptance (except for the resonance lines) but becomes smaller right of it. Due to that and the mentioned mismatch, the tunes should stay in the lower left corner.

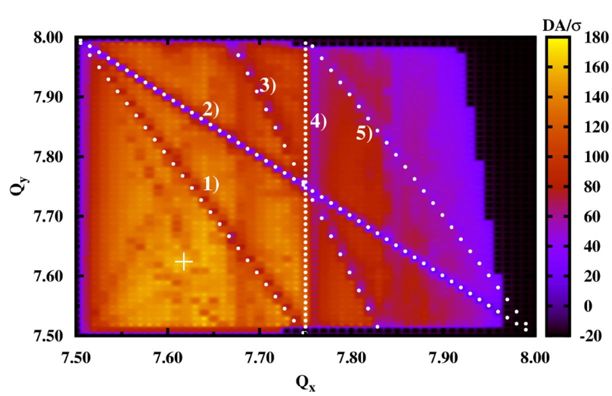

Figure 3: Tune scan for $\gamma_{tr} = 6.2$ and on-momentum particles tracked over 1000 turns. The dynamic aperture in terms of beam size DA/σ is plotted in color scale againt the transverse tunes Q_x and Q_y. The value of -20 is artificially introduced to differentiate unstable linear lattice (-20) from zero dynamic aperture. The design tunes are marked with a white cross. Enumeration of resonances is explained in text.

FREQUENCY MAP ANALYSIS

The frequency map analysis for the HESR was based on the NAFF-like code SUSSIX [6]. This code was used to determine the tunes of all surviving particles with high accuracy. The orbit diffusion coefficient D is calculated as

$$D = \log_{10}\left[\sqrt{\left(Q_x^{(2)} - Q_x^{(1)}\right)^2 + \left(Q_y^{(2)} - Q_y^{(1)}\right)^2}\,\right]$$

where the indices (1) and (2) refer to two adjacent turn intervals. Its introduction enabled long-term predictions based on short-term tracking data. In the calculations performed, the two intervals were chosen to be the first and second thousand turns. The validity of the long-term predictions was verified by the comparison with long-term tracking data for a few 10^7 turns. The frequency maps have been calculated for different optical settings at discreet momentum offsets ($\Delta p/p$) and varying tunes. The frequency map for the design tunes and on-momentum particles is shown in Fig. 4. The resonance web can easily be observed. The quadrupole coupling resonance (1,-1,0) splits the frequency map into two parts. The most serious resonances (red color) are of eighth order which is also reflected by the fact that the corresponding horizontal phase space plot shows eight hyperbolic fix points in the chaotic region. Speaking of that phase space plot, the presence of a strong 12-pole is indicated by a deformed hexagonal shape of the very same phase space plot with six corners from where particles are lost. This indication gives an additional hint for later optimizations. The use of the orbit diffusion coefficient within dynamic aperture plots reveals affecting resonances in x-y plane (see Fig. 5). The dynamic aperture marked with a black elliptic line has a size of roughly 8.5

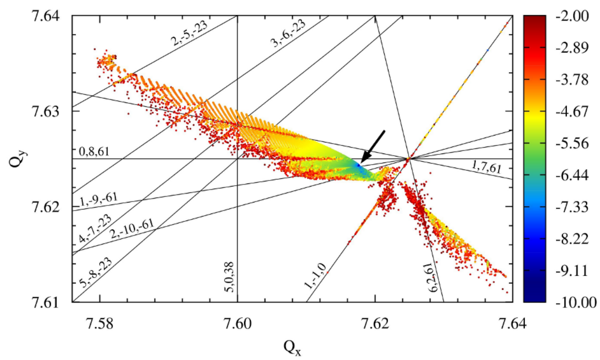

Figure 4: Frequency map for HESR design tunes at $\gamma_{tr} = 6.2$ calculated from first and second thousand turns. The identified resonances are marked by lines and the corresponding resonance condition (m,n,p). Design tunes are located at the blue spot marked by the arrow.

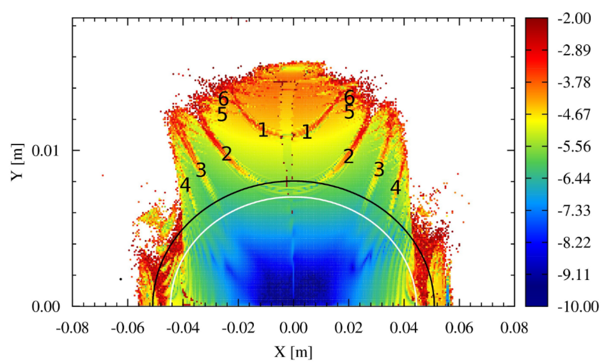

Figure 5: Dynamic aperture for HESR design tunes at $\gamma_{tr} = 6.2$ including orbit diffusion coefficient on color scale. The smaller the orbit diffusion coefficient the more stable the particle motion is. The most serious resonances are identified from Fig. 4 as 1) (1,7,61); 2) (0,8,61); 3) (1,-9,-61); 4) (2,-10,-61); 5) (5,-8,-23); 6) (4,-7,-23)

mm mrad and is slightly larger than the geometric acceptance limit (approx. 6.5 mm mrad) marked in white.

OPTIMIZATION

Two basic concepts of dynamic aperture optimization have been investigated: variation of the tunes and reduction of multipole errors.

Investigations of the dynamic aperture concerning the tunes were carried out. Based on the tune scans, a suitable tune area has been found. The 2D tune scans have been repeated with a finer grid and being limited to the suitable tune area. By picking the best tune settings found, the dynamic aperture could be increased by roughly 18% to approximately 10 mm mrad.

Another investigation was dedicated to the estimated field errors of the main HESR magnets. Especially, the field errors of the quadrupole magnets have shown a strong influence to the dynamic aperture. The most serious field errors could be identified to be the allowed 12- and especially 20-pole field components. A reasonable reduction by a factor 4 to 5 of both field components resulted in an increase of the dynamic aperture to almost 11.5 mm mrad.

The combination of both optimization methods, the choice of new tunes and the multipole reduction, lead to a dynamic aperture of more than 16 mm mrad (see Fig. 6) which is almost twice as large as the unoptimized dynamic aperture. Even the inner area of the dynamic aperture with long-term stable particles increased significantly.

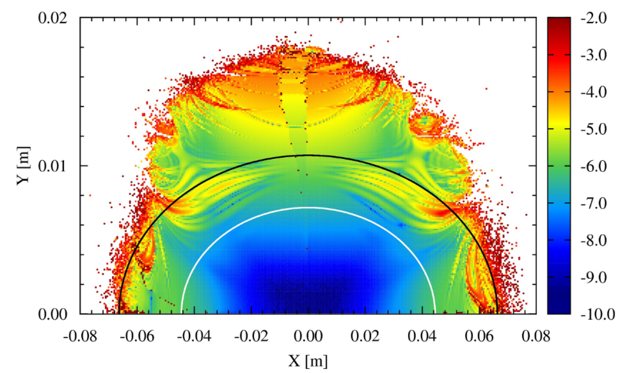

Figure 6: Dynamic aperture for HESR design tunes at $\gamma_{tr} = 6.2$ including orbit diffusion coefficient on color scale. The smaller the orbit diffusion coefficient the more stable the particle motion is.

OUTLOOK

After finalization of the magnet design a comprehensive multipole correction scheme has to be investigated. Other effects like space charge forces or the non-linear forces created by the electron cooler beam should be taken into account. Since these effects act on other time scales, the long-term dynamic aperture has to be investigated together with its dependence on the number of turns.

REFERENCES

[1] Baseline Technical Report Vol. 2, http://www.gsi.de/fair/reports/btr.html

[2] Conceptional Design Report, http://www.gsi.de/GSI-Future/cdr/

[3] The PANDA experiment, http://www-panda.gsi.de/

[4] D.M. Welsch, Investigation and Optimization of Transverse Non-Linear Beam Dynamics in the High-Energy Storage Ring HESR, Doctoral thesis, Univ. Bonn, Germany, 2010

[5] J. Bengtsson, The Sextupole Scheme for the Swiss Light Source (SLS): An Analytic Approach, SLS Note 9/97, Paul Scherer Institut, Switzerland, 1997

[6] R. Bartollini and F. Schmidt, A Computer Code for Frequency Analysis of Non-Linear Betatron Motion, SL-NOTE-98-017-AP, CERN, 1998