CLOSED ORBIT CORRECTION AND SEXTUPOLE COMPENSATION SCHEMES FOR NORMAL-CONDUCTING HESR*

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Abstract

The High Energy Storage Ring (HESR) [1] will be part of the future Facility for Antiproton and Ion Research (FAIR) [2] located at GSI in Darmstadt, Germany. The HESR will be operated with antiprotons in the momentum range from 1.5 to 15 GeV/c, which makes a long beam life time and a minimum of particle losses crucial. This and the demanding requirements of the PANDA experiment [3] lead to the necessity of a good orbit correction and an effective multipole compensation. We developed a closed orbit correction scheme and tested it with Monte Carlo simulations. We assigned different sets of angular and spatial errors to all elements (magnets, beam position monitors, etc.) within the lattice of the HESR. For correction we applied the orbit response matrix method. We carried out investigations concerning higher-order multipoles and created a scheme for chromaticity correction and compensation of arising resonances utilising analytic formulae and dynamic aperture calculations. In this presentation we give an overview of the correction and compensation schemes and of the corresponding results.

HESR LATTICE

The HESR has a length of roughly 575 m and a magnetic rigidity of $50\ Tm$. It consists of two similar arcs and two straights (see Fig. 1).

The straights are designed in a way that beta functions can be adjusted at the target from 1 to $10\ m$ and at the electron cooler from 25 to $200\ m$. The arcs contain four different quadrupole families (three horiz., one vert.). These provide adjustment of both tunes (Q_x, Q_y) and transition energy (γ_{tr}) as well as suppression of dispersion in both straight sections. The latter is a requirement from the PANDA experiment whereas the adjustment of transition energy is important for stochastic cooling.

There exist four defined optical settings by now: Injection, $\gamma_{tr} = 6.2$ (see Fig. 2), $\gamma_{tr} = 13.4$, $\gamma_{tr} = 33.2$. Their tunes are in the vicinity of 7.62 and their natural chromaticy is ranging in X from -12 to -17 and in Y from -10 to -13.

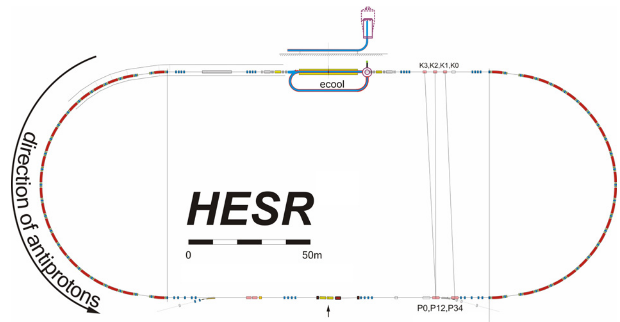

Figure 1: HESR lattice: Upper straight is housing electron cooler and stochastic kickers, lower straight contains injection, PANDA experiment with target (arrow), and stochastic pickups. The second dipole from each end of both arcs is missing for dispersion suppression in the straight sections.

In the arcs, there are 96 positions available for sextupoles, beam position monitors, and orbit correction dipoles. Because of this limitation all beam position monitors will be included inside sextupoles.

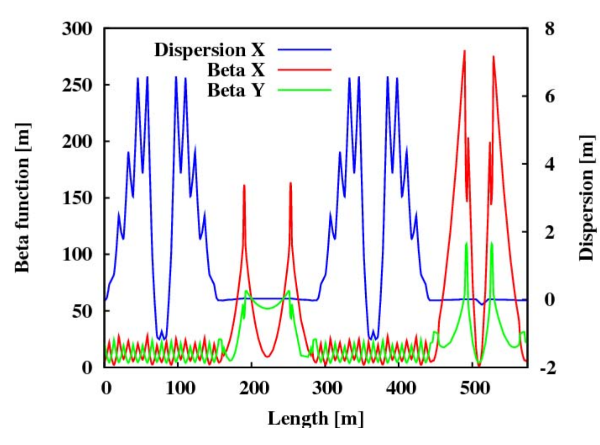

Figure 2: Optical functions of $\gamma_{tr} = 6.2$ lattice. Target is located at $s = 509\ m$ where a kink in the dispersion function can be seen (PANDA chicane). The electron cooler is located at $s = 222\ m$.

CLOSED ORBIT CORRECTION

The most serious cause for orbit distortions is angular and spatial displacements of magnets. Alignment and measurement errors of beam position monitors also contribute

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to orbit distortions. Both types of errors have been included in the simulations.

The goal of the closed orbit correction scheme is to reduce closed orbit deviations to below $5\ mm$ while not exceeding $1\ mrad$ of correction strength.

Orbit Response Matrix

The sensitivity of the orbit at a beam position monitor at location i to strength variations of an orbit correction dipole at location j is given by the orbit response matrix:

$$R_{ij} = \sqrt{\beta_i \beta_j} \frac{\cos(\frac{\mu}{2} - \phi_{ij})}{2 \sin \frac{\mu}{2}},$$

where $\mu = 2\pi \cdot Q$ denotes the phase advance of the whole ring and ϕ_{ij} the phase difference of both locations. The orbit response matrix can be derived from asn dipole error ansatz [4]. We used the inverted orbit response matrix to obtain the necessary corrector strengths. We chose singular value decomposition as inversion method because it can handle non-squared matrices as in our case.

Closed Orbit Correction Scheme

The correction scheme consists of 64 beam position monitors and 36 closed orbit correction dipoles.

There are 26 beam position monitors used per arc of which 12 are positioned at a large beta function in X and 14 at a large beta function in Y. This amount of beam position monitors just reflects the amount of chromatic sextupoles (see below) and is sufficient for the closed orbit correction. The amount of closed orbit correction dipoles is six per transverse direction and per arc.

There are six beam position monitors and also six closed orbit correction dipoles used per straight. Whereas in the arcs the orbit correction dipoles are planned to be unidirectional (because of beta functions), in the straights combined ones can be used for both transverse directions. Beam position monitors will be designed to measure always in X and Y.

Verification

In order to verify the closed orbit correction scheme, Monte-Carlo methods have been utilised [5]. We applied more than 1000 different sets of displacement and measurement errors. For all defined optical settings, we could demonstrate the effectiveness of the developed closed orbit correction scheme. Ten samples of corrected closed orbits in X are shown in Fig. 3.

Toroid Compensation

Additionally, the influence of the electron cooler toroids had to be investigated. Toroids are used in beam guiding systems of electron coolers to overlap the electron beam with the circulating beam. Since antiprotons are much heavier than electrons, the deflection of the antiprotons by the toroids is much smaller. This deflection is different for both transverse directions. To compensate the deflection, four additional correction dipoles have to be included in the HESR lattice around the electron cooler. The inner ones should be placed very close to the toroids to keep orbit deviations as small as possible. The strength of these correction dipoles has to be at maximum cooler energy or rather momentum ($\bar{\mathrm{p}}$: $8\ GeV/c$; e^-: $4.5\ MeV/c$): $\approx 3\ mrad$ and $< 0.5\ mrad$ for the inner correction dipoles and $< 0.2\ mrad$ and $< 0.1\ mrad$ for the outer ones.

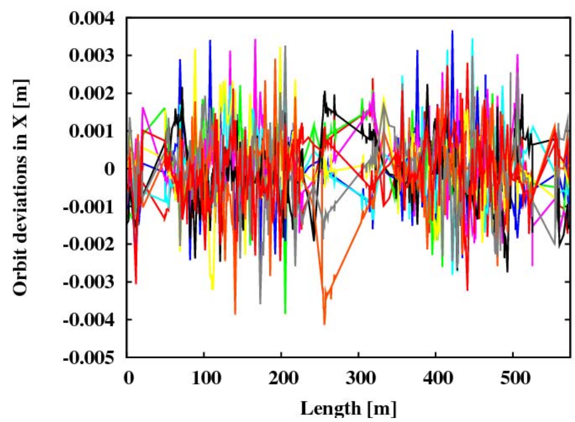

Figure 3: Shown are ten samples of corrected closed orbits in X. Max. closed orbit is reduced to below $5\ mm$. Plots for Y look similar.

Orbit Bumps

There are a few positions in the straights where orbit bumps have to be used, e.g. at the target. Therefore, all closed orbit correction dipoles in the straights are planned to provide an additional deflection strength of $1\ mrad$. Our investigations have shown that this is sufficient to set angle and position of the circulating beam in the desired ranges.

CHROMATICITY CORRECTION AND SEXTUPOLE COMPENSATION

Since the natural chromaticity ranges down to -17, there is no possibility to avoid its correction. Despite correcting chromaticity, sextupoles drive different resonances and will affect the stability of the circulating antiproton beam.

Chromaticity Correction

The natural chromaticity is corrected with sextupoles in the arcs. For a simple chromaticity correction, all sextupoles have been split into four different families (two horiz. and two vert.). This is caused by the variation of the horizontal dispersion function in the different optical settings. Due to space restrictions in the arcs, sextupoles have a design length of 0.3 m. Restricting the maximum normalised strength to $K_2 = 0.85\ m^{-3}$, the correction scheme contains 24 horizontal and 28 vertical sextupoles distributed evenly among both arcs.

Sextupole Effects in First Order

Sextupoles affect ten different lattice properties in first order [6]: Chromaticity (horiz. and vert.), second order dispersion, synchro-betatron resonances (horiz. and vert.), and five resonance driving terms. The analytic formulae describing these resonance driving terms are:

$$\begin{aligned}
h_{21000} &= -\frac{1}{8}\sum_{i=1}^{N}(b_{3i}L)\beta_{xi}^{3/2}e^{i\mu_{xi}} \\
h_{30000} &= -\frac{1}{24}\sum_{i=1}^{N}(b_{3i}L)\beta_{xi}^{3/2}e^{i3\mu_{xi}} \\
h_{10110} &= \frac{1}{4}\sum_{i=1}^{N}(b_{3i}L)\beta_{xi}^{1/2}\beta_{yi}e^{i\mu_{xi}} \\
h_{10200} &= \frac{1}{8}\sum_{i=1}^{N}(b_{3i}L)\beta_{xi}^{1/2}\beta_{yi}e^{i\mu_{xi}+2\mu_{yi}} \\
h_{10020} &= \frac{1}{8}\sum_{i=1}^{N}(b_{3i}L)\beta_{xi}^{1/2}\beta_{yi}e^{i\mu_{xi}-2\mu_{yi}},
\end{aligned}$$

where $b_{3i}L$ denotes the integrated sextupole strength and μ the phase advance. These formulae provide some guidelines for sextupole compensation: Ideally, pairs of sextupoles will compensate their contribution to driving terms if strength and beta functions are identical and the phase difference is $180°$ in both transverse directions.

Stability Optimisation

Although ten sextupole families and proper phase differences would simultaneously provide sextupole compensation and all degrees of freedom, it cannot be accomplished in the HESR. This is simply because all possible sextupole positions are predefined and do typically not have this phase difference of $180°$. Therefore, different sets of sextupole arrangements have to be evaluated by dynamic aperture calculations [7].

Up to now, no solenoids and no tune spread have been considered. This is done firstly for simplicity and secondly to observe stability changes solely due to chromaticity correction. This reduces dynamic aperture calculation to two-dimensional tracking. Other effects like field errors and kicks from electron cooler are neglected so far. Thus, the dynamic aperture is just an indicator for stability improvement and something like an upper boundary of stable phase space area. An example of such a dynamic aperture calculation is shown in Fig. 4.

Resulting Compensation Scheme

The number of sextupoles is as stated above: (24 horiz. and 28 vert.). The number of families has been increased from four to six, three horizontally and three vertically. The

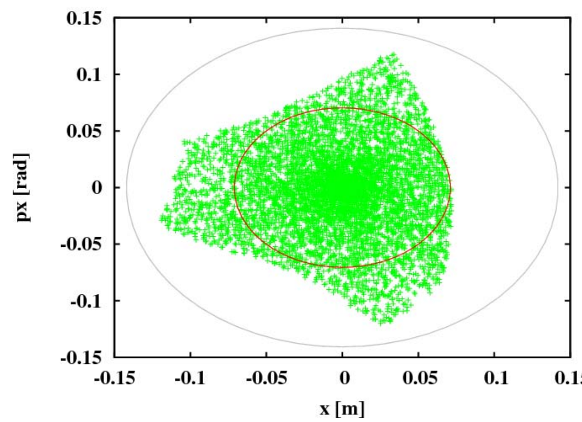

Figure 4: Example of tracking 10^4 particles 10^4 turns. Shown are the starting emittance ($2 \cdot 10^4\,\pi\ mm \cdot mrad$, grey), stable particles (green), and the biggest emittance fitting in stable area ($\approx 5000\,\pi\ mm \cdot mrad$, red).

initial stable phase space area in X-PX could be improved by a factor of ≈ 5.7. In Y-PY plane the improvement was rather small: ≈ 1.3. Since compensation is dependent on phase advances and beta functions, tune scans will be necessary for further improvement.

OUTLOOK

Optimisation of the chromaticity correction for all other defined optical settings is under way. Tune scans are necessary and investigations of the sensitivity of sextupole compensation on tune changes will be carried out soon. To get a more general insight into the dynamical behaviour of the HESR, other effects which affect stability will be taken into accout, including field errors of magnets, kicks of electron cooler, and space charge. These together with coupling will require full six-dimensional tracking.

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] R. Talman, Single particle motion, Frontiers of Particle Beams; Observation, Diagnosis and Correction, Lecture Notes in Physics, Vol. 343, Springer Verlag, New York, 1988

[5] D.M. Welsch, Auslegung eines Orbitkorrektursystems für den Hochenergie Speicherring HESR im Projekt FAIR, Diploma thesis, Jül-4241, Forschungszentrum Jülich, Germany, 2007

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

[7] G. Franchetti, private communication