LATTICE DESIGN STUDY FOR HESR

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Abstract

The High Energy Storage Ring (HESR) of the future GSI FAIR project is an antiproton storage ring in the energy range from $0.45 \div 14.5$ GeV. It has to provide small momentum spread down to 10^{-5} and intensities up to $5*10^{11}$. In this paper a lattice with flexible momentum compaction is presented able to fulfil these requirements and leading to ~ 500 m total circumference. Impedance limits for the cooled HESR beam have to be determined.

INTRODUCTION

To meet to all requirements of HESR project [1] the lattice has to provide special features:

- small momentum spread $10^{-4} \div 10^{-5}$
- flexible adjustment of momentum compaction factor in region $\alpha \approx 0 \div -0.2$
- wide energy range $0.45 \div 14.5$ GeV
- dispersion free straight sections
- sufficiently large dynamic aperture after sextupole correction
- corrected chromaticity by arc's sextupoles
- minimum influence of non-linear tune shift in target point

The most critical point to reach is low momentum spread. The only solution is a negative momentum compaction factor $\alpha = 1/\gamma_t^2 < 0$ with imaginary transition energy γ_t, since higher slip factor, $\eta = 1/\gamma_t^2 - 1/\gamma^2$, provides higher Keil-Schnell threshold $Z_{KS} \approx B_f \dfrac{mc^2\beta^2\gamma}{eI_c} \cdot |\eta| \cdot \left(\dfrac{\delta p}{p}\right)^2$. In a lattice with a low or negative momentum compaction factor (MCF) we must have $\alpha = \dfrac{1}{c}\int^{C} \dfrac{D(\tau)}{\rho(\tau)} d\tau \le 0$, where C is the circumference of the orbit, $D(\tau)$ the dispersion function and $\rho(\tau)$ the radius of curvature of the closed-orbit. The last two values are associated with each other through

$$\mathrm{D''} + \mathrm{K}(\tau)\mathrm{D} = \frac{1}{\rho(\tau)}, \qquad (1)$$

where $K(\tau) = \dfrac{eG(\tau)}{p}$, $G(\tau)$ is the gradient of the quadrupole and $p = m_0\gamma v$ is the momentum of the particle. When the curvature is modulated with some frequency S as $1/\rho(\tau) \sim Be^{iS\tau} + 1/\overline{R}$ and $\overline{R} = \langle\rho(\tau)\rangle$ the common solution of (1) is:

$$D(\tau) \sim Ae^{i\nu_x\tau} + \frac{B}{\nu_x^2 - S^2}e^{iS\tau} + \frac{1}{\overline{R}} \qquad (2)$$

In a lattice with super periodicity close to the eigen frequency $S - \nu_x << S, \nu_x$ the dispersion is determined by the second term of (2) and the momentum compaction factor is:

$$\alpha \sim \frac{B^2}{\nu^2 - S^2} + \frac{1}{\nu_x^2} \qquad (3)$$

The idea how to get the negative momentum compaction factor was qualitatively shown in reference [2] first. Later many authors tried to realize this idea in different lattices, and most successful solution has been reached in [3] by correlated curvature and gradient modulations. Later this lattice was taken as reference in projects like the TRIUMF Kaon Factory, SSC LEB, CERN Neutrino Factory and the main ring of the JPARC facility presently under construction [4].

ARCS

In order to minimize the preparation procedure for each experiment the HESR lattice has to have decoupled functions responsible for global parameters of the machine like transition energy, zero chromaticity, dispersion suppressing and local parameters like beam luminosity on target, optimum parameters for cooling, injection system etc. The lattice consists of two arcs and two straight sections for target and cooling facilities with circumference approx. 500 m. The arcs play the most important role for global parameters. We considered two types of lattice, both with a racetrack shape. In the first option the arc has a four-fold symmetry with four super periods. In the second option the arc has a six-fold symmetry with six super periods. The phase advance per arc is chosen 3.0 and 5.0 in first and second options correspondingly. To suppress the dispersion function in the straight sections the arc has to be a second order achromat: the phase advance is integer and the chromaticity is corrected to zero in the arc. Each super period consists of three FODO cells with 4 super conducting bending magnets (B_{max}=3.5T) and super conducting quadrupoles (G<75T/m) (see fig.1).

To reach the required momentum compaction factor we make a correlated modulation of the gradients in the quadrupoles and orbit curvature [3]. The MCF is determined by the nS-th harmonic nearest to eigen frequency ν_x:

$$\alpha = \frac{1}{\nu_x^2}\left(1 - \frac{1}{4\left(\dfrac{nS}{\nu_x} - 1\right)} \cdot \left(\frac{g_n}{1 - \left(\dfrac{nS}{\nu_x} - 1\right)^2} - \frac{r_n}{r_0}\right)^2\right), \qquad (4)$$

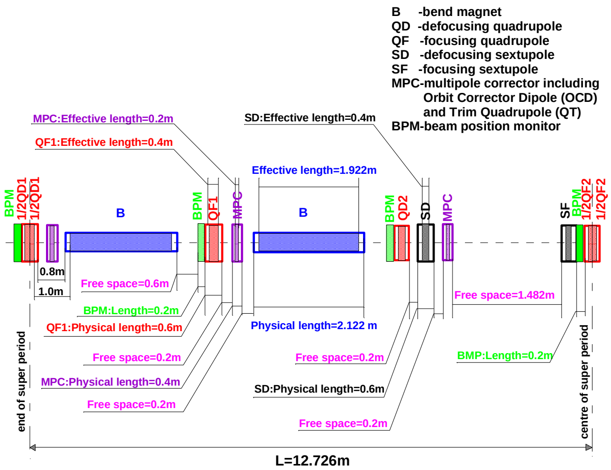

Figure 1: Half super period of an arc

where g_n and r_n are amplitudes of Fourier harmonics. In this lattice the gradient and the curvature modulation amplifies each by other, if they have opposite signs. Optimised ratio between g_n and r_n is determined, when next inequalities reach maximum:

$$\begin{aligned}
&\frac{\partial\alpha}{\partial G_{QF2}} > \frac{\partial\alpha}{\partial G_{QD2}} >> \frac{\partial\alpha}{\partial G_{QF1}} \approx \frac{\partial\alpha}{\partial G_{QD1}} \\
&\frac{\partial\nu_x}{\partial G_{QF1}} > \frac{\partial\nu_x}{\partial G_{QF2}} >> \frac{\partial\nu_x}{\partial G_{QD1}} \approx \frac{\partial\nu_x}{\partial G_{QD2}} \\
&\frac{\partial\nu_y}{\partial G_{QD1}} \approx \frac{\partial\nu_y}{\partial G_{QD2}} >> \frac{\partial\nu_y}{\partial G_{QF1}} \approx \frac{\partial\nu_y}{\partial G_{QF2}}
\end{aligned} \tag{5}$$

Thus, we have separated internal arc functions:

- MCF is controlled by central focusing quadrupole QF2,
- horizontal tune is controlled by focusing quadrupole QF1,
- vertical tune is controlled by defocusing quadrupoles QD1 or/and QD2.

Since derivatives $\frac{\partial\nu_y}{\partial G_{QD1}}$ and $\frac{\partial\nu_y}{\partial G_{QD2}}$ have approximately equal values, we use one family of defocusing quadrupoles only. Of course modulating of gradient functions causes changes of TWISS parameters. Figure 2 shows the dependence of TWISS parameters on the momentum compaction factor.

Two families of sextupoles are used for the chromaticity correction: two focusing and defocusing ones (see figure 1). If the super period number S is even and the arc tunes $\nu_{x,y}$ are odd then the phase advance between similar sextupoles of $i-th$ and $\left(i+\frac{S}{2}\right)-th$ super periods equals $\frac{\nu}{S}\cdot\frac{S}{2}=\frac{\nu}{2}$. This means that we have an exact condition for compensating each sextuplet's non-linear action by another one. Besides, we have a convenient place in the super period for chromaticity correcting.

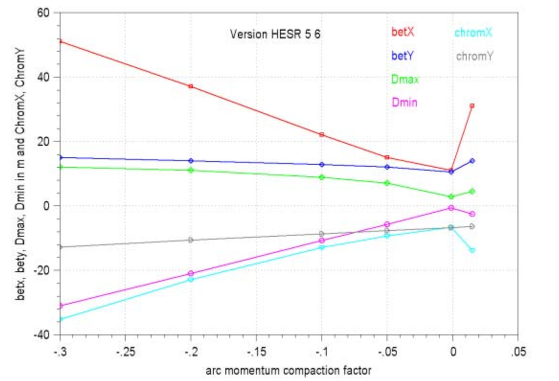

Figure 2: TWISS parameters vs momentum compaction factor

sextupoles: the central drift space, where the dispersion function has a maximum value (figure 3). For higher efficiency the sextupoles are desirable to be placed as near to quadrupoles as possible in order to have weaker gradient.

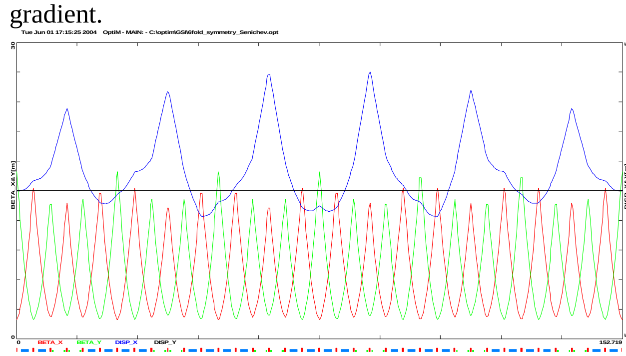

Figure 3: β - functions and dispersion in one arc

To correct the dipole, quadrupole, sextupole and octupole components of transverse motion, the multi-pole correctors are placed near maximum beta-function (see figures 1 and 3). For diagnostics the beam position monitors are installed in each $40^0 \div 50^0$ phase advance in both transverse planes with maximum field approx. 0.1 T and effective length 0.2 m. BPMs are placed near each quadrupole and provide maximum residual orbit distortion approx. 5 mm.

STRAIGHT SECTIONS

The HESR has two straight sections for cooling and target facilities. Both straight sections are based on split triplet optics, when the central quadrupole is divided on two even parts with long drift space between them. The main requirement to the optics of the cooling section is the adjustable $\beta_{x,y}$ -functions in the range 100-250 m in the solenoid installed for electron cooling. Figure 4 shows TWISS parameters of the cooling straight section.

The main function of the target straight section is to provide the required size of beam on the target. The $\beta_{x,y}$ -function has to be adjusted in the region 0.5-1.5m (see figure 5). On both straight sections the extreme three quadrupoles serve as tuning corrector in transverse planes. In order to get small β-function on target we must blow it up somewhere, which causes essential contribution to the total chromaticity.

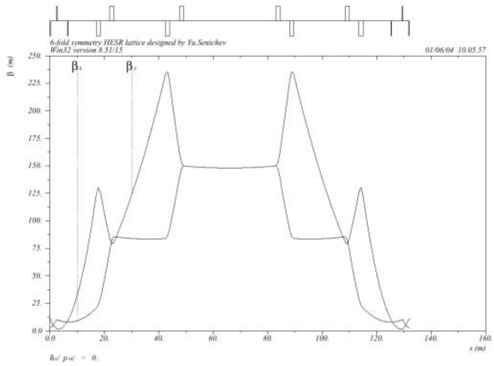

Figure 4: The cooling straight section

For instance in case of $\beta_{x,y}$ =1.5m the target chromaticity induces up 20% and 40% of the total horizontal and vertical chromaticity respectively. In order to focus the beam to $\beta_{x,y}$ =1.0 m these values are increasing to 30%, 50% or even to 50% and 70% for $\beta_{x,y}$ =0.5.

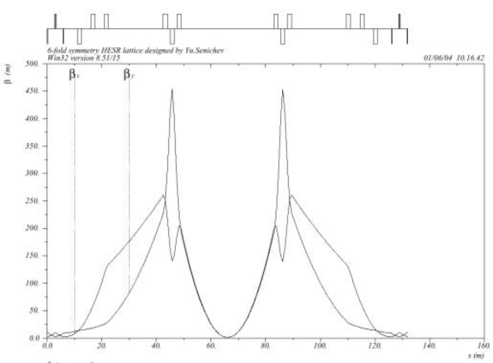

Figure 5: The target straight section

In this respect we consider two options: sextupoles correcting the arc's chromaticity only utilizing the arc as a pure second order achromat, or sextupoles correcting the chromaticity of the whole machine operating the arc as pseudo second order achromat.

We analysed the dynamic aperture in the whole range of momentum spread. Due to a suitable sextupole correction scheme and appropriate choice of the tune working point the dynamic aperture for $\Delta p/p = \pm 5\cdot 10^{-3}$ change its range in horizontal plane $DA_x \approx 350 \div 450$ mm mrad and in vertical plane $DA_y \approx 100 \div 200$ mm mrad.

LATTICE ADJUSTING TO DIFFERENT MODES OF HESR

The beam is injected in the HESR with $\delta W = 1$ MeV (rms) independent from the injection energy. In order to satisfy to Keil-Schnell criteria for up to N=5*10^{11} particles in bunch and injection energy W_{inj} >6 GeV the momentum compaction factor has to be adjusted from zero to -0.03. This is easy provided by gradient modulation (see figure 2).

The HESR is supposed to work in two modes: the high-luminosity mode with $L = 2*10^{32}\,cm^{-2}\sec^{-1}$ and momentum spread $(\delta p/p) \sim 10^{-4}$, and the high-resolution mode with momentum spread $(\delta p/p) \sim 10^{-5}$ and luminosity of $10^{31}\,cm^{-2}\sec^{-1}$. In both modes two bunches are formed after injection in two separatrixes with a total number of particles between 5*10^{11} and 5*10^{10} correspondingly. In the high luminosity mode, when $\langle \delta p/p \rangle \geq 2\cdot 10^{-4}$ the lattice with $\alpha \approx 0$ satisfies to Keil-Schnell criteria in whole energy range. To have stability at $(\delta p/p) \approx 10^{-4}$ the momentum compaction factor has to be changed from zero to –0.03. Although we should mention that in the region from 0.45 GeV to 0.9 GeV the Keil-Schnell criteria is not fulfilled due space charge impedance, which is even increased during transverse beam cooling.

Figure 6 shows similar estimation for the high-resolution mode. For almost all range of energy the lattice with $\alpha \approx -0.012$ satisfies the Keil-Schnell criteria for a beam with $(\delta p/p) = 5\cdot 10^{-5}$, and for $(\delta p/p) = 2\cdot 10^{-5}$. In the region $10 \div 14.5$ GeV we have to adjust $\alpha \approx -0.12$.

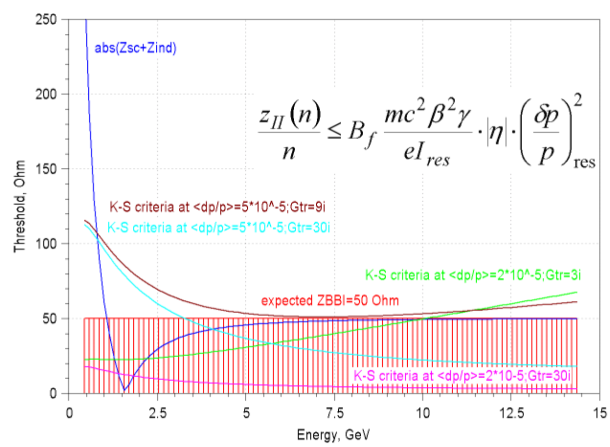

Figure 6: Z_{KS} and Z_{BBI} (broad band impedance) for high-resolution mode

The authors thank to Dr. A. Dolinskii for his fruitful discussion of HESR lattice.

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