HESR LATTICE WITH NON-SIMILAR ARCS FOR STOCHASTIC COOLING

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Abstract

The advanced HESR lattice with two arcs having the identical layout and the different slip factors are developed. The conception of arcs with three families of quadrupole allows easy adjusting the imaginary transition energy in one arc and the real transition energy in another arc with the absolute value close to the beam energy in whole required region from 3.0 GeV to 14 GeV. The arcs have the special feature, when the high order non-linearities are fully compensated inside of each arc, and therefore the dynamic aperture of the whole machine is conserved. We consider and compare two lattices with the same absolute value of transition energy: the current lattice with the negative momentum compaction factor in both arcs and the lattice having the negative and positive momentum compaction factors in different arcs correspondingly. Simultaneously we analyzed the 4 and 6 fold symmetry arcs machine. It allows making the conclusion that the 4 fold symmetry lattice is more suitable to get the required slip factors. At the lowest energy 3 GeV, it is $\eta_{imag}/\eta_{real} \approx 4 \div 5$ in the imaginary and the real arc correspondingly. For the higher beam energy this ratio is much bigger.

INTRODUCTION

To intensify the stochastic cooling process it is desirable to have the mixing factor between the pick-up and kicker as much as possible, and on the contrary, in the case of mixing between the kicker and pick-up we should try to make it smaller. This option can be realized, if the lattice has the different local optical features between the pick-up – the kicker and the kicker – the pick-up.

First the idea with different slip factors was proposed by Möhl [1,2]. Later many authors try to design such lattice, for instance [3, 4]. However, it makes more complicate lattice with large number of quadrupole and sextupole families and the need to have different optical settings at different energy. In result the dynamic aperture in such lattices usually is unacceptably small, and it has very difficult tuning. Therefore the compromise was to scarify some of the desired re-randomisation in order to avoid too much unwanted mixing. In the classical lattice the slip factors between pick-up and kicker η_{pk}, kicker and pick-up η_{kp} are similar, and by Möhl definition [2] the mixing factors are approximately equal. In papers [5] the comprehensive analysis of the stochastic cooling has been done in the HESR lattice with similar arcs and the negative momentum compaction factor ($\gamma_{tr} = 6.5i$) [6]. In this paper we consider the advanced HESR lattice with the different slip factors η_{pk}, η_{kp} in two arcs.

ARCS WITH DIFFERENT SLIP FACTOR

The HESR lattice consists of two arcs and two straight sections for the target and cooling facilities with circumference ~500÷600 m. The arcs have 6-fold (or 4-fold) symmetry with super-periodicity S =6 (or 4). The phase advance per arc is $\nu_{x,y} = 5.0$ (or $\nu_{x,y} = 3.0$) in both planes. Each super period consists of three FODO cells with 4 superconducting bending magnets (B=3.6T) and superconducting quadrupoles with G<60T/m (see fig. 1).

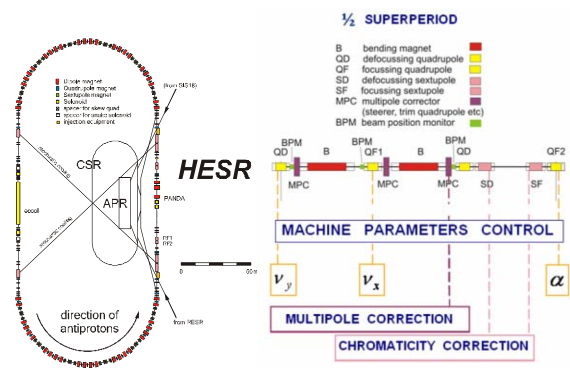

Figure 1: HESR layout and half super-period

The momentum compaction factor is one of the most important characteristics of any accelerator, which defines its transition energy. The slip factor, $\eta = 1/\gamma^2 - 1/\gamma_{tr}^2$ determined by transition γ_{tr} and current γ energy should be as high as possible in order to increase the micro-wave stability threshold.

The most successful solution for the control of the momentum compaction factor has been done in [7] by simultaneously correlated curvature and gradient modulations. This lattice was taken in projects: the Moscow Kaon Factory, the TRIUMF Kaon Factory, the SSC Low Energy Booster, the CERN Neutrino Factory and in the under construction being main ring of the Japan Proton Accelerator Research Complex facility [8]. In the HESR lattice the same idea was taken [6]. Now in the advanced HESR lattice for the stochastic cooling we propose modifying the conception to provide the different slip factor in two arcs, but with conservation of sequence of all bending, focusing elements and drift between them.

The proposed lattices meet the next requirements:

- momentum compaction factor is about $1/\nu^2$ in one arc (the slip factor close to zero, isochronous structure) and it is negative in another arc -$1/\nu^2$; the total slip factor is enough high to provide a minimum spread in incoherent frequencies for the longitudinal motion stability requirements;

- dispersion free straight sections;
- convenient method to correct the chromaticity by the sextupoles;
- sufficiently large dynamic aperture after chromaticity correction.

In common case the momentum compaction factor is determined from the integral $\alpha = \frac{1}{\gamma_t^2} = \frac{1}{2\pi}\int_0^{2\pi}\frac{D(\phi)}{\rho(\phi)}d\phi$, where $D(s)$ is dispersion function and $\rho(s)$ is radius of curvature of equilibrium trajectory. To reach the required momentum compaction factor we make a correlated modulation of the quadrupoles gradients $\varepsilon \cdot k(\phi) = \sum_{k=0}^{\infty} g_k \cos\, k\phi$ and the orbit curvature $\frac{1}{\rho(\phi)} = \frac{1}{\overline{R}}\left(1 + \sum_{k=1}^{\infty} r_k \cos k\phi\right)$ with superperiodicity S_{arc}.

The radius curvature modulation r_n is provided by the missing magnet and it is done once and then is fixed. But the gradient modulation is variable parameter. Due to the FODO structure with mirror symmetry we realize $\frac{\partial\alpha}{\partial G_{QF2}} >> \frac{\partial\alpha}{\partial G_{QF1}} \approx \frac{\partial\alpha}{\partial G_{QD}}$, $\frac{\partial\nu_x}{\partial G_{QF1}} > \frac{\partial\nu_x}{\partial G_{QF2}} >> \frac{\partial\nu_x}{\partial G_{QD}}$ and $\frac{\partial\nu_y}{\partial G_{QD}} >> \frac{\partial\nu_y}{\partial G_{QF1}} \approx \frac{\partial\nu_y}{\partial G_{QF2}}$, and the lattice provides independent control of $\alpha, \nu_{x,y}$ by gradients of quadrupoles QF2, QF1 and QD correspondingly.

In paper [7] the dispersion equation has been solved for case of both the quadrupoles gradients and the orbit curvature modulation:

$$\alpha_s = \frac{1}{\nu^2}\left\{1 + \frac{1}{4\cdot(1-kS/\nu)}\cdot\left[\left(\frac{\overline{R}}{\nu}\right)^2\frac{g_k}{[1-(1-kS/\nu)^2]} - r_k\right]^2\right\}$$

where $\overline{R}$ is average radius of machine, and ν is horizontal tune. We can see that the sign of the momentum compaction factor depends on the term $1-kS/\nu$. The negative momentum compaction factor is reached in lattice with super-periodicity S and ν, when $1-kS/\nu < 0$ and it is determined by the kS-th harmonic.

You can see this lattice has the remarkable feature: the gradient and the curvature modulation amplify each by other if they have opposite signs $g_k \cdot r_k < 0$, and on the contrary they can compensate each other when they have the same sign. We use just this feature to make arcs with the different slip factors. Hereinafter we will call the arc between the pick-up and the kicker in the line of beam as the real arc $\alpha = 1/\gamma_t^2 > 0$. Correspondingly the arc between the kicker and the pick-up will be called as the imaginary arc $\alpha = 1/\gamma_t^2 < 0$, because the transition energy is imaginary.

First of all in both arcs we create the resonant curvature modulation by the usual method of the "missing magnet" in the center of the super-period. Then the quadrupole gradient is modulated with the opposite sign and the value determined by the gradient modulation when the ratio between them is $|r_k| \le \left(\frac{\overline{R}}{\nu}\right)^2\left|\frac{g_k}{1-(1-kS)^2}\right|$.

In principle the curvature modulation can be done much higher, but since in the real arc we need full compensation of the curvature modulation by the gradient modulation, and we would like to have the identical sequence of magneto-optic elements in both arcs, it is no desirable to increase the first of them. In the same time the gradient modulation is restricted by the parametric resonance of the envelope, when the second harmonic $kS/\nu = 2$.

Therefore from this point of view it is desirable to get such g_k when the ratio has a value:

$$\frac{1}{4(kS/\nu - 1)}\cdot\left(\frac{g_k}{[1-(1-kS/\nu)^2]} - r_k\right)^2 \approx 2$$

Then the momentum compaction factor in the imaginary arc takes a meaning $\alpha_{kp} \approx -1/\nu^2$, and the momentum compaction in the real arc is $\alpha_{pk} \approx 1/\nu^2$. Thus, in such lattice we can make two arcs with the different slip factors: $\eta_{pk} = 1/\gamma^2 - 1/\gamma_{tr}^2$; $\eta_{kp} = 1/\gamma^2 + 1/\gamma_{tr}^2$. In case $\gamma \approx \nu$ one of the arc is isochronous when the slip factor is $\eta_{pk} \approx 0$, and another slip factor is $\eta_{kp} \approx 2/\nu^2$.

However together with this advantage of two different arcs for the stochastic cooling we lose the lattice mirror symmetry, which one makes the probability of the structure resonances excitation higher. Since any order resonance strength is determined by the integral

$$\left\langle h_{k_x,k_y,p}\right\rangle \propto \int_0^C \beta_x^{k_x/2}\beta_y^{k_y/2}\frac{\partial^{(k_x+k_y-1)}B_{y,x}}{\partial(x,y)^{(k_x+k_y-1)}}(s)\exp i(k_x\mu_x + k_y\mu_y)ds$$

and, as we can see, the $\beta_{x,y}$-functions are the multipliers of field errors in the under integral expression, the resonance excitation probability is determined by the difference of $\beta_{x,y}$-function behaviour in the arcs. However, the developed lattice has the fundamental feature, since the equipments of both arcs are placed

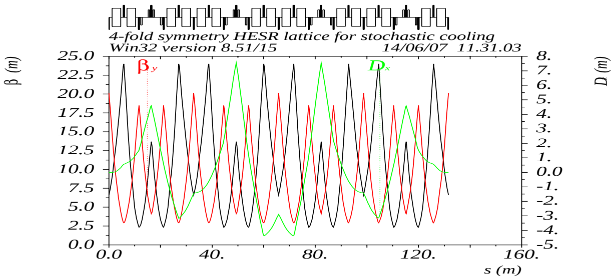

Figure 2: Imaginary arc

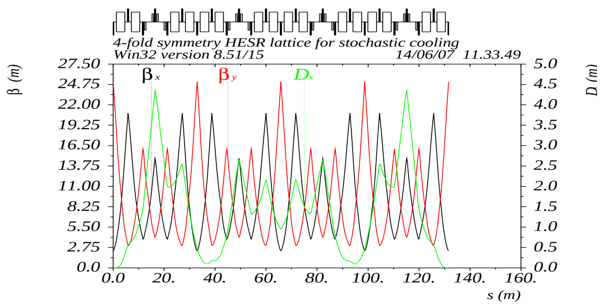

Figure 3: Real arc

absolutely identically. Figures 2 and 3 shows the $\beta_{x,y}, D_x$ functions for the real and imaginary 4 fold symmetry arcs. In both arcs the dispersion is suppressed to have the zero-dispersion straight sections. We can see from these figures the different momentum compaction factors are reached mainly due to the dispersion function change, and the β-function itself changes insignificantly.

Two families of sextupoles are used for the chromaticity correction (see fig. 1). To provide in the first approach the sextupoles self-compensating we have to have the even number of the arc super-periods S_{arc} and as consequence the nearest to S_{arc} the arc tune $\nu_{arc} = S_{arc} - 1$. Then the phase advance between similar sextupoles of $i-th$ and $(i + S_{arc}/2) - th$ super periods equals $\nu_{arc}/2$. It means we have an exact condition for compensating each sextuplet's non-linear action by another one. Thus, there are combinations: $\{S_{arc}, \nu_{arc}\} = \{4{,}3;\ 6{,}5;\ 8{,}7;\ldots\}$.

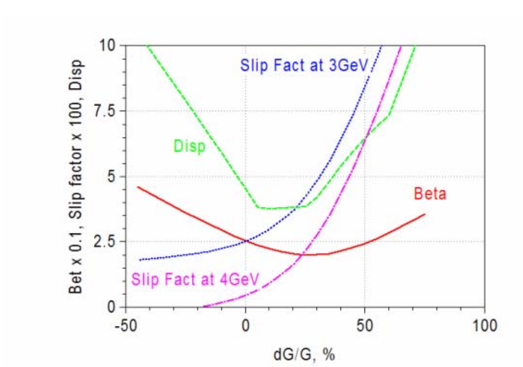

Figure 4: β_x, D_x, η vs. gradient modulation

The optimum set for our case should be around a value $\nu = 2\nu_{arc} \approx \gamma$ and depends on the lowest energy. For instance, for energy E=3 GeV ($\gamma \approx 4.2$) the 4 fold arc with tune of arc $\nu_{arc} = 3$ gives the best fit. Figure 4 shows Twiss parameters together with slip factor dependence on the gradient modulation. We can see for energy 3 GeV at acceptable Twiss parameters behavior the maximum ratio is $\eta_{imag}/\eta_{real} \approx 4 \div 5$, while at 4 GeV this ratio can be significantly higher.

DYNAMIC APERTURE

To the end of this paper we will discuss the numerical calculation results. Since the indicator of any structure is the dynamic aperture, we have done the tracking simulation in the lattice with non-similar arcs and compare with the lattice where the arcs are similar. Of course due to loss of the mirror symmetry in the whole ring lattice the dynamic aperture becomes smaller. But the significant reserve of the dynamic aperture allows having still the large appropriated value in the horizontal plane ~270 mm mrad and in the vertical plane ~500 mm mrad. Both values very well satisfy to the required ratio between the dynamic and physical apertures.

CONCLUSION

We developed the advanced lattice for the stochastic cooling. The lattice has two similar arcs having the different mixing factors due to the different slip factors with conservation of the optic geometry. Each arc has two families of focusing quadrupoles and one family of defocusing quadrupole. The transition energy is adjusted by the quadrupole gradient modulation. The natural chromaticity is corrected by one family of focusing and defocusing sextupole. After the chromaticity correction the dynamic aperture remains to be very large. The straight section allows making the stochastic and electron cooling simultaneously.

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