CORRECTION OF THE MAGNETIC FIELD IN THE NICA COLLIDER

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Abstract

The magnetic field correction systems in the optimized lattice of the NICA collider are considered. The dipole, normal and skew quadrupoles, sextupole and octupole additional windings are placed in the corrector elements to compensate separately the alignment errors, betatron tune shifts, betatron coupling, chromaticity and non-linear fields. The overall correction effect should increase the dynamic aperture and provide the required beam and luminosity lifetime of the collider.

INTRODUCTION

The Nuclotron-based Ion Collider fAcility (NICA) [1] is a new accelerator complex being constructed at JINR. Two collider rings are designed and optimized to achieve the required luminosity at two interaction points (IP). The first IP is connected with Multipurpose detector (MPD) for the ion-ion (Au^{+79}) collider experiments in the energy range of 1÷4.5 GeV/u. The second IP is aimed for the polarized proton-proton (5÷12.6 GeV) and deuteron-deuteron (2÷5.8 GeV/u) collisions. The collider lattice is based on the technology of super-ferric magnets developed in VBLHE, JINR. The collider optics is optimized to obtain the required luminosity (Table 1) with the certain effects which set constraints on the lattice parameters: luminosity lifetime limitation by intrabeam scattering in a bunch (IBS), space charge tune shift, threshold of microwave instability, slippage factor optimization for efficient stochastic cooling, maximum required RF voltage amplitude. This paper considers the $^{197}Au^{+79}$ heavy ion mode of facility operation. The possible schemes of the correction of the linear and non-linear imperfections of the magnetic fields of the structural elements of the collider are supplied to the collider optics to increase the dynamic aperture.

LATTICE OF THE RINGS

Collider lattice was developed and optimized [2] with some constraints: ring circumference, a number of the dipole magnets in an arc, convenience of the beam injection into the ring. The rings are vertically separated (32 cm between axes) and use two-aperture superconducting magnets (dipoles and quadrupoles). Rings have the racetrack shape with the bending arcs and long straight section. The principal choice for the arc structure is the FODO optics with 12 periods. Circumference of the rings corresponds exactly to two Nuclotron circumferences. The project parameters of the collider ring are presented in Table 1.

Bending arc comprises 12 FODO cells with nominal betatron phase advances of 90^0 per cell. The cells with empty dipoles are used for horizontal dispersion suppression and convenient beam injection and extraction (dumping) schemes. Periodic FODO cell consists of four rectangular dipole magnets per cell (80 magnets per ring), two quadrupoles [3], multipole correctors and beam position monitors (BPM) (Fig. 1). The maximum field in 1.94 m dipole of 1.8 T and gradient in 0.47 m quadrupoles of 23 T/m. The long straight sections matched to the arcs contain the RF stations, electron and stochastic cooling devices, BPMs, superconducting quadrupole blocks. The optics in these sections produces the betatron tune variation, vertical beam separation in the rings and conditions for colliding beams in interaction points (IP). The schematic composition of the rings is given in Fig. 2. The Twiss-functions of the ring are shown in Fig. 3.

Table 1: Project Parameters of the Collider Rings

Ring circumference, m	503.04		
Number of bunches	22		
Rms bunch length, m	0.6		
β-function in the IP, m	0.35		
Betatron tunes, Q_x/Q_y	9.44/9.44		
Chromaticity, $Q'_{x,0}/Q'_{y,0}$	-33/-28		
Acceptance π·mm·mrad	40		
Long. acceptance, Δp/p	±0.010		
Gamma-transition, γ_{tr}	7.088		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch	$2.0\cdot10^8$	$2.4\cdot10^9$	$2.3\cdot10^9$
Rms Δp/p, 10^{-3}	0.55	1.15	1.50
Rms emittance, hor./vert. (unnorm.), π·mm·mrad	1.10/ 0.95	1.10/ 0.85	1.10/ 0.75
Luminosity, $cm^{-2}s^{-1}$	$0.6\cdot10^{25}$	$1.0\cdot10^{27}$	$1.0\cdot10^{27}$
IBS growth time, s	170	470	2000
Tune shift, $\Delta Q_{SC}+2\Delta Q_{bb}$	-0.050	-0.037	-0.011

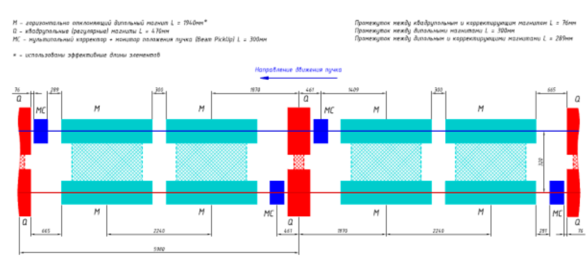

Figure 1: Periodic FODO cells for both rings.

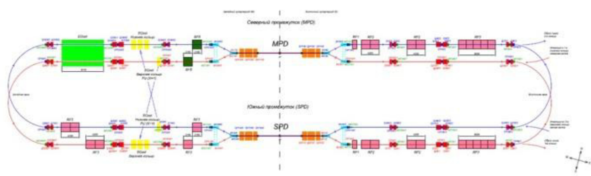

Figure 2: Collider scheme and equipment layout.

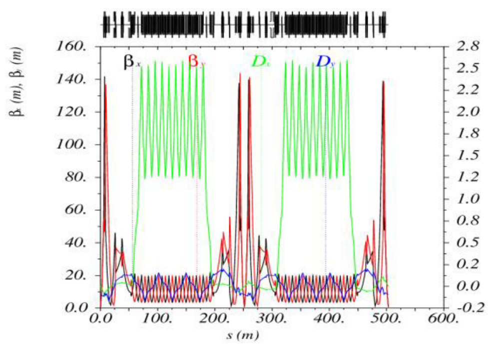

Figure 3: Collider Twiss-functions, β^* =0.60 m.

CORRECTION OF MAGNETIC FIELD

For the stable circulation of the ion beam in the collider the definite magnetic field correction systems should be provided in the collider optical structure. The following required set of correcting circuits are considered for the collider rings: correction of the closed orbit distortions, linear betatron tune shift correction, correction of the transversal betatron oscillations coupling, compensation of the vertical dispersion, correction of the chromaticity of the betatron tunes, higher order non-linear effects compensation including fringe field effect. Multipole corrector element is designed for these purposes. It has the length of 0.3 m and up to the four layers of the "cosine-type" superconducting windings. The multipole correctors are located next to the superconducting quadrupoles in the arcs and in the straight section. The required maximal number and maximal strength of the correcting winding are obtained from the beam dynamics calculation.

Dipole closed orbit correction parameters are defined from the numerical statistical experiment by the calculation the number of the random closed orbits caused by the following sources of distortions (r.m.s. values): $\sigma_{\Delta B/B} = 5\cdot10^{-4}$, $\sigma_{\Delta s} = 0.5$ mm, $\sigma_{\Delta y} = 0.5$ mm, $\sigma_{\Delta\varphi} = 0.5$ mrad – spread of the guiding field, longitudinal shift, vertical shift, roll angle in dipole magnets; $\sigma_{\Delta x/\Delta x} = 0.1$ mm – transversal shifts of the quadrupole axes. Then the maximal excursions of the 100 closed orbits are obtained. The correction algorithm (MICADO [3]) is applied for each orbit with the additional requirements for residual orbit ($\sigma_{x/y}$ =0.1 mm), maximal number of the used corrector ($n_{corr} = 30\div50$) and the maximal correction angle kick ($\theta_{corr} \approx 0.01\cdot\theta_{dip}$). As a result of these calculations: for the $n_{corr} = 30$ horizontal and vertical dipole correctors with the maximal strength of $\theta_{corr} \leq 0.5$ mrad and located in the ring more or less uniformly, the orbit distortions could be minimized to the required values taking to the account the technically realized tolerances for dipole guiding field and quadrupole alignment. The excursions of the uncorrected closed orbits are shown in Fig. 4 and the required corrector kicks distributions are shown in Fig. 5.

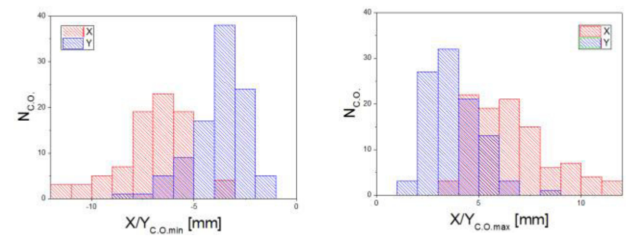

Figure 4: Closed orbit distortion statistics for 100 random orbits. Maximal/minimal pick-up reading before correction.

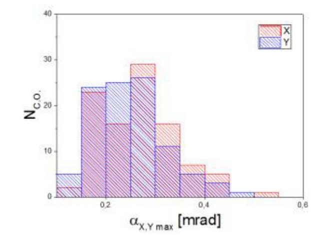

Figure 5: Maximal values of horizontal/vertical dipole corrector strength for the required residual orbit of $\sigma_{x/y} = 0.1$mm. n_{corr} =30, $\theta_{corr,max}$=0.5 mrad, $B_{corr,max}$=0.15 T.

The correction of the linear betatron tunes $Q_{x,y}$ is produced by the structural quadrupole lenses. For example, the move from the first working point $Q_{x,y}$=9.44/9.44 (Fig. 6) to the second one $Q_{x,y}$=9.10/9.10 is produced by current correction -300 A in all quadrupole, except final focus quadrupoles, and +9 A in QD arc quadrupoles.

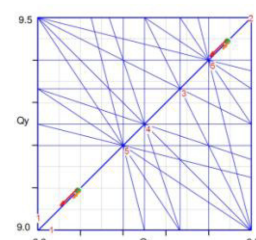

Figure 6: Resonance diagram up to 5[th] order. Collider working points of betatron tunes. Space charge tune shifts at 1 and 4.5 GeV/u.

The skew quadrupole correctors are used in collider optics for two reasons: correction of betatron coupling and local correction of the vertical dispersion. The first problem supposes four families (independent current supplies) placed in straight sections. Taking into account the main sources of coupling in the collider rings, MPD detector solenoid (5.8 m long, $B_{s,max}$=0.5 T), electron cooler solenoid (6 m long, $B_{s,max}$=0.2 T), the required maximal gradient of the skew quadrupole winding is about 2.5 T/m in the worst case of one direction of the solenoid fields. Due to the vertical separation of the beams there is the small uncorrected vertical dispersion in

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the collider rings. The local suppression of the vertical dispersion D_y requires two additional skew quadrupole families located in the bending arcs next to D_x maximum.

The correction of the chromaticity of betatron tunes is the principal task in the collider because the large natural chromaticities of $Q'_{x,y} \approx -30$ due to the large variation of the β-functions in the ring especially in the beam separation and interaction regions. System of the chromaticity correction includes 4 families of sextupole correctors (focusing and defocusing) placed near focusing and defocusing quadrupoles in the arcs. Sextupoles in each family are sit apart in 180^0 betatron phase advance for the compensation of their nonlinear influence on the dynamic aperture (DA). The dependence of the collider tune on $\Delta p/p$ is shown in Fig. 7 before and after chromaticity correction (maximum sextupole strength of 150 T/m^2 at the maximum energy of 4.5 GeV/u). The value of the sextupole harmonics of the dipole field expected from the magnetic measurements is about $b_3=5\cdot10^{-4}$ (r=30 mm) at the highest energy of E_k=4.5 GeV/u. This nonlinear component of the field changes the chromaticities and increase the maximal corrector strength of the defocusing family up to the 175 T/m^2.

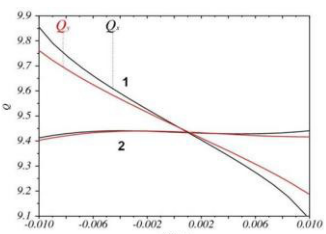

Figure 7: Tune spread over the momentum acceptance before (1) and after (2) chromaticity correction.

The collider dynamic aperture (DA) calculations [2] were carried out with the possible nonlinearities of the magnetic field. The proper harmonics of the structural dipole and quadrupole magnets introduce the small influence on DA. The chromaticity correction operates anytime of particle tracking. The fringe fields of the magnetic elements, in particular, the final focus quadrupoles, show the most severe effect on the collider DA. Following the dependence of the fringe field kick in quadrupole $\Delta\theta/\theta \sim \beta^2\cdot k^2\cdot d\cdot\varepsilon$, this effect could be reduced by the decreasing the beta-function β in quadrupole, quadrupole strength k and length d, and also the beam emittance ε. In the case of the final focus quadrupoles increasing the β^* in IP decreases the maximal value of β-function in quadrupole and decreases the fringe field effect. The DA calculations by MAD-X [3] include the fringe field in all magnetic elements. The correction of this influence on DA by the linear arrangement of the collider optics is shown in Fig. 8, where the stable DAs in the terms of beam amplitude are given for the β^*=0.35 m and β^*=0.60 m. Optics with the β^*=0.60 m in IP provides the double excess of DA over the geometrical acceptance. This optics needs the beam intensity increase due to 25% drop of luminosity.

The DA increase by introduction of the octupole nonlinearities is carried out. The additional octupole windings near final focus quadrupoles (two families with gradients of 60 and 150 T/m^3) could improve the situation (Fig. 9).

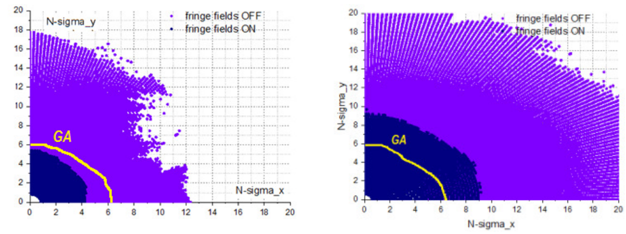

Figure 8: Collider DA in terms of beam amplitude. $q_{x,y}$=0.44, β^*=0.35m (left), 0.6m (right). GA – geometrical acceptance.

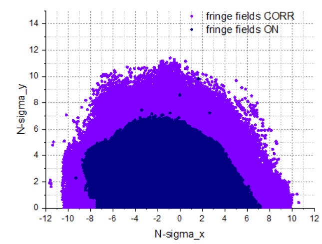

Figure 9: Collider DA with fringe field switch-on and octupole correction effect.

Figure 10: Multipole correctors setup (half-ring). b_n – normal, a_n – skew windings.

CONCLUSION

The structure and parameters of the magnetic correction systems of the collider are optimized and determined. The multipole correctors setup is shown in Fig. 10 for half of the ring. The general correction effect should enlarge the linear and nonlinear dynamic acceptance for the particle motion.

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[2] O.S. Kozlov et al., "NICA Collider lattice optimization", Proc. of Russian Particle Accelerator Conf. (RuPAC 2016), St. Petersburg, Russia, 2016, pp. 166-168.

[3] MAD – Methodical Accelerator Design, http://madx.web.cern.ch/madx/.

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