NICA COLLIDER LATTICE OPTIMIZATION

O. Kozlov, A. Butenko, H. Khodzhibagiyan, S. Kostromin, I. Meshkov, A. Sidorin, E. Syresin, G.Trubnikov, JINR, Dubna, Russia

Abstract

The Nuclotron-based Ion Collider fAcility (NICA) [1] is a new accelerator complex being constructed at JINR. It is aimed to collider experiments with ions and protons and has to provide the ion-ion (Au^{+79}) and ion-proton collision in the energy range of 1÷4.5 GeV/u and also polarized proton-proton (5÷12.6 GeV) and deuteron-deuteron (2÷5.8 GeV/u) collisions. Two collider rings are designed and optimized to achieve the required luminosity at two interaction points (IP). Taking into account space charge effects of the intense ion beam the application of electron beam or stochastic cooling methods were proposed to provide beam or luminosity lifetime. This paper is considering one of the most challenging problems of accelerator physics that is finding the dynamic aperture (DA) of the collider ring.

INTRODUCTION

NICA collider lattice development [2] has many necessary aspects of the design. The collider should operate in the energy range for Au-ions of 1÷4.5 GeV/u, with the average luminosity about $1{\cdot}10^{27}$ cm^{-2} s^{-1}. The ring should work with the different particle species (Au^{+79}, protons and deuterons). Collider has a certain circumference limitation. The collider lattice is based on the technology of super-ferric magnets developed in VBLHE, JINR [3]. The collider optics optimization includes 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. The maximum energy of the experiment is determined by the Nuclotron maximum magnetic rigidity of 45 T·m. This paper considers only the most developed heavy ion mode of facility operation and the $^{197}Au^{+79}$ ions as the reference particles.

LATTICE STRUCTURE

Technical constraints were taken into account in lattice optimization: ring circumference, a number of the dipole magnets in an arc, convenience of the beam injection into the ring. The FODO optics with 12 periods is a principal choice for arc structure. Two arcs and two long straight section form the collider racetrack shape and correspond exactly to two Nuclotron circumferences. The rings are vertically separated (32 cm between axes) and use two-aperture superconducting magnets (dipoles and quadrupoles) [3]. This lattice has a large efficiency of stochastic cooling at 4.5 GeV/u. The luminosity of 10^{27} cm^{-2} s^{-1} could be reached in the wide energy range.

Table 1: Collider Ring and Beam Parameters

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, $\xi_{x,0}/\xi_{y,0}$	-33/-28		
Ring acceptance	40 π·mm·mrad		
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	2.0e8	2.4e9	2.3e9
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}	0.6e25	1e27	1e27
IBS growth time, s	170	470	1900

The convenient injection scheme could be realized through the arc dipole-empty cell.

FODO periodic cell (12 m length) consists of four rectangular dipole magnets per cell (80 magnets per ring), two quadrupoles [3], multipole correctors and BPMs. The maximum field in 1.94 m dipole of 1.8 T and gradient in 0.47 m quadrupoles of 23 T/m are chosen to avoid the saturation effects in iron yokes at higher energies. Multipole corrector includes the several types of windings – dipole (orbit correction), quadrupole (tuning), skew quadrupole (coupling correction), sextupole (chromaticity correction) and octupole.

Arc comprises 12 FODO cells (90^0 phase advance per cell). The last 1.5 cells realize the horizontal dispersion suppressor (the effective quadrupole gradient (3 families) tuned by the nearby quadrupole corrector).

Long straight sections are matched to the arcs, contain the insertion devices, produce the betatron tune variation and the vertical beam separation and final focusing in IPs.

Collider ring general parameters are given in Table 1 and Twiss-functions for the ring are shown in Fig. 1. Two rings are separated vertically. In this scheme, two-aperture quadrupoles should have the opposite connections for upper and bottom rings in arcs and long straights, but the final focus triplets should have the antisymmetric connections with respect to IPs providing the same horizontal and vertical betatron tunes for counter circulating beams.

ISBN 978-3-95450-181-6

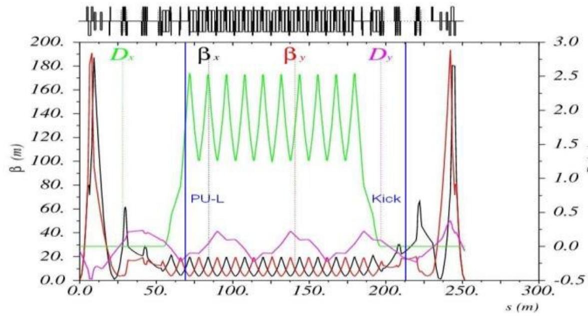

Figure 1: β-functions and dispersions for half a ring.

DYNAMIC APERTURE

In the design of a cyclic accelerator, one of the main tasks is to calculate or estimate the effect of nonlinear forces on the motion of a charged particle. One can introduce the concept of a maximum initial amplitude of particle oscillation assuming the absence of real geometrical aperture limitations or a vector in the space of transverse invariants, $E_{x,y}(s)$, so that the particle remains stably circulating in the accelerator ring within the required time or number of turns N_{turn}. The value of $E_{x,y}$ in a certain position along the accelerator ring is called the dynamic aperture (DA). The DA in an optimally designed accelerator must satisfy the condition $E_{x,y}(s) \geq A_{x,y}(s)$, where $A_{x,y}(s)$ is the acceptance of the ring at a given azimuth. In our optimizations of the collider DA we have aimed for the reasonable reserve for DA as $E_{x,y}(s) = 2 \cdot A_{x,y}(s)$. The following nonlinear fields were taken into account in DA estimations:

Nonlinear harmonics of the dipoles and quadrupoles, systematic and random, expected values are obtained from the magnetostatic calculations [3].

System of the chromaticity correction, which includes 4 families of sextupole correctors (focusing and defocusing). Sextupoles in each family are located 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 Δp/p is shown in Fig. 2 before and after chromaticity correction (maximum sextupole strength of 150 T/m^2 at the maximum energy of 4.5 GeV/u).

Fringe fields of the dipole and quadrupole magnet, in particular, the quadrupoles of the final focusing in IP.

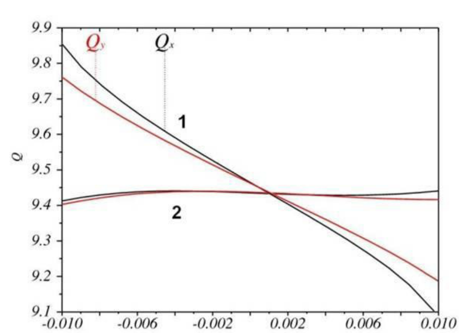

Figure 2: Tune spread over the momentum acceptance before (1) and after (2) chromaticity correction.

DA CALCULATION

The DA is calculated by the accelerator design program MAD-X [4]. Two methods for numerical integration of charged particle motion in external fields are implemented in MAD-X. One method, the thin lens model, transforms each magnet into a sequence of thin elements (slices) or, by default, one element of zero length placed in the center of the "thick" element. The other method, the Polymorphic Tracking Code (PTC) [4], is the same attempt of symplectic integration of particle motion, i.e., the motion with conservation of phase space. In this method, the ring elements are described symplectically to a certain extent, which depends on the user and the computer speed.

The collider DA calculations were carried out with and without nonlinearities of the magnetic field. The proper harmonics of the structural dipole and quadrupole magnets introduce the small influence on DA. The sextupole correction system of tune chromaticity operates anytime of particle tracking. The fringe fields of the magnetic elements show the most severe effect on the collider DA. The option of switching-on or switching-off of the fringe fields of all elements along the collider ring is realized in PTC tracking code. The particle dynamics was checked for the $N_{turn}=10^3$ number of turns in the collider ring.

The optimization of the collider optics is carried out from the viewpoint of the large DA in the limits of the designed collider geometry and concept of the 12 FODO cell bending arcs. The regulations of Q_x, Q_y betatron tunes and beta-functions $\beta^*_{x,y}$ in IPs are realized by both the trim quadrupoles in the long straight section (small regulation $\Delta Q_{x,y}=\pm 0.1$, small correction current $I_{t,max}=1$ kA) and arc quadrupoles (strong change of tunes in the range $Q_{x,y}=8.1\div 9.5$, $I_{q,max}=11$ kA). In Fig. 3 the resonance diagram and possible betatron working points of the collider ring are shown. The nominal tunes of q=0.42÷0.44 are preferable for the stochastic cooling method in the energy range of $E_k=3\div 4.5$ GeV/u, but the tunes around q=0.1 could be used for electron beam cooling technique at the lower energies.

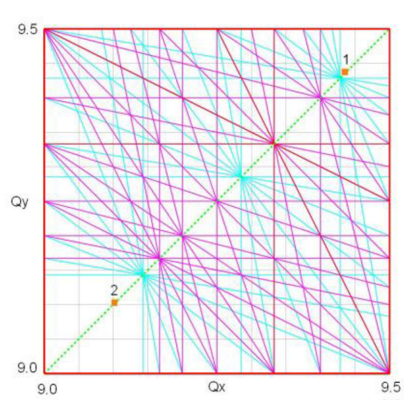

Figure 3: Resonance diagram up to 7^{th} order. Collider working points of betatron tunes.

ISBN 978-3-95450-181-6

The PTC DA calculation value for the nominal parameters of the collider (Table 1, Fig. 1) ($Q_{x,y}$=9.44, $\beta^*_{x,y}$=0.35 m) gives the averaged value of E=160 π·mm·mrad when the fringe field is off, chromaticity correction is on. The fringe fields reduce the DA below the ring's geometrical acceptance. Obviously, the increase the beta-function β^* in IPs leads to decrease the maximal beta-function β_{max} in final focusing quadrupoles and, consequently, to decrease the fringe field effect. The optics with $Q_{x,y}$=9.44, $\beta^*_{x,y}$=1.0 m provides the E=400 π·mm·mrad (no fringe field), E=100 π·mm·mrad (fringe field) and the considerable luminosity reduction as well. The next studies of the collider DA were carried out around the working point Q_x=8.44, Q_y =9.44, which is tuned by arc quadrupoles. The large number of the arc quadrupoles requires the small change in gradient. Thus, one can build the collider optics and provide the optimal chromaticity correction control (Fig. 4).

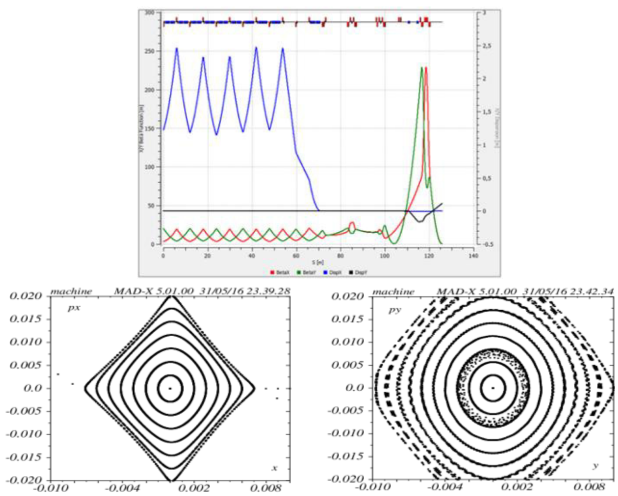

Figure 4: Collider optics, quarter of the ring, symmetric version. Phase portraits in IP (hor./vert.) with chromaticity correction.

The dependencies of the collider DA on beta-function in IP at the chosen working point are shown in Fig. 5, where the aperture presented in terms of beam amplitude and emittance. It seems the optics for β^*=0.6÷0.7 m and Q_x=8.44, Q_y=9.44 looks optimal and provide the double acceptance of the collider ring. The dominant influence of the final focusing quadrupoles fringe field on the DA could be demonstrated through the particle tracking over the system of quadrupole lens triplets having symmetric or antisymmetric connection with respect to IPs. The transverse phase space distortion appears at large amplitudes as it has shown in Fig. 6 for horizontal plane and symmetric connection. The pictures are similar for horizontal and vertical plane, symmetric and antisymmetric schemes.

CONCLUSION

The collider lattice concept – 503 m circumference with 12 cell FODO structure in the arcs has been chosen. The

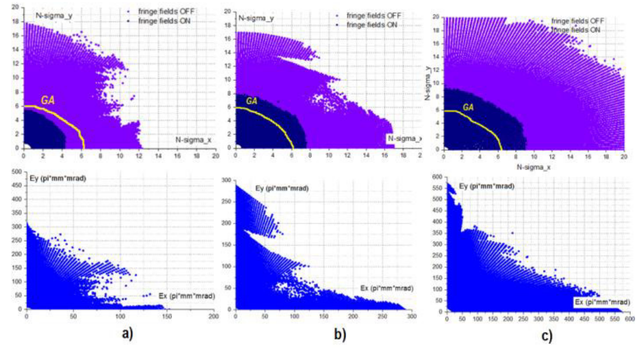

Figure 5: Collider DA in terms of beam amplitude and emittance. Q_x=8.44, Q_y =9.44, β^*=0.35 m (a), 0.5 m (b), 0.7 m (c). GA – geometrical acceptance.

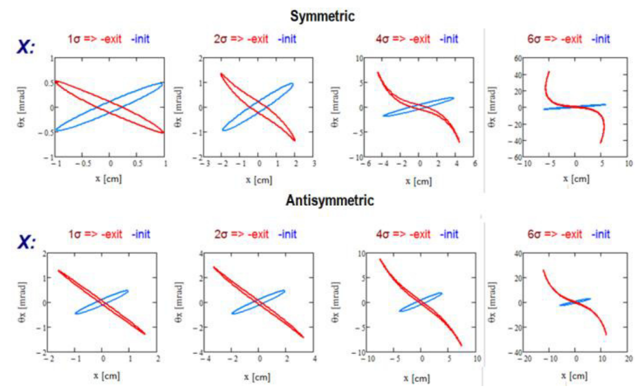

Figure 6: Particles tracking over the system of final focusing quadrupoles. Horizontal plane. Initial beam – blue, exit beam – red.

optical properties of this lattice have been optimized for the larger dynamic aperture of the ring. The variation of the betatron tunes together with the value of the beta-function in the interaction point by the arc and trim quadrupoles allows to find the new settings for the working point Q_x=8.44, Q_y =9.44, β^*=0.6 m where the DA is about the twice of ring geometrical acceptance. The some luminosity decrease is compensated by the small raise of beams intensity.

REFERENCES

[1] G.V. Trubnikov et al., "Status of NICA Project at JINR", Proc. of International Particle Accelerator Conf. (IPAC 2014), Dresden, Germany, 2014, pp. 1003-1005.

[2] O.S. Kozlov et al., "Collider of the NICA accelerator complex: optical structure and beam dynamics", Proc. of Russian Particle Accelerator Conf. (RuPAC 2012), St. Petersburg, Russia, 2012, pp. 278-280.

[3] H.G. Khodzhibagiyan et al., "Status of the design and test of superconducting magnets for the NICA project", Proc. of Russian Particle Accelerator Conf. (RuPAC 2012), St. Petersburg, Russia, pp. 149-151.

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

ISBN 978-3-95450-181-6