LATTICE OF NICA COLLIDER RINGS

S.Kostromin, O.Kozlov, I.Meshkov, V.Mikhailov, A.Sidorin, JINR, Dubna, V.Lebedev, S.Nagaitsev, FNAL, Batavia, Illinois, USA; Yu.Senichev, IKP, Juelich, Germany

Abstract

The Nuclotron-based Ion Collider fAcility (NICA) [1] is a new accelerator complex being constructed at JINR. It is designed for collider experiments with ions and protons and has to provide ion-ion (Au^{79+}) and ion-proton collisions in the energy range 1÷4.5 GeV/n and collisions of polarized proton-proton and deuteron-deuteron beams.

Collider conceptions with constant γ_{tr} and with possibility of its variation are considered. The ring has the racetrack shape with two arcs and two long straight sections. Its circumference is about 450m. The straight sections are optimized to have β^*~35cm in two IPs and a possibility of final betatron tune adjustment.

INTRODUCTION

NICA collider lattice development has a number of challenges which must be overcome in the design process. The requirements set by physics goals are: changeable energy of the Au-ions collision in the range 1÷4.5 GeV/n, operation with different ion mass (Au^{79+}, deuterons and protons), the peak luminosity up to $5\bullet10^{27}$ $cm^{-2}s^{-1}$ at 4.5 GeV/n, and, additionally, the collider rings must fit into existing JINR infrastructure.

The ring lattice is based on super-ferric magnets with 2T bending field. The technology of fabrication of such magnets operating at 4.5K with hollow composite NbTi cable is well established in JINR.

The main luminosity limitation is set by the direct space charge tune shift. In this case the luminosity is proportional to the beam emittance and, consequently, to the collider acceptance. Thus, good optics for NICA implies that in addition to the standard requirement of small beta-function in IP, β^*, there is a requirement of maximizing the machine acceptance.

INTRA-BEAM SCATTERING STUDY

The intra-beam scattering (IBS) is one of the main factors which have to be taken into account in a collider ring design. For operation below transition IBS is significantly reduced if the local beam temperatures averaged over the ring are equal. In this case the emittance growth rate due to IBS is equal to zero for a perfectly smooth lattice. Beta-function and dispersion variations destroy this thermal equilibrium resulting in an emittance growth in all three planes: larger variations excite faster emittance growth.

First, the IBS rates were computed for the ideal rings (without straight sections) constructed from ODFDO - and FODO -cells [2]. For the same number of particles the beam emittances were adjusted to have the same growth rates for all planes (thermal equilibrium) and to have the same vertical space charge tune shift (bunch density). Due to"smother" optics the IBS heating rate, τ_{IBS}^{-1}, for the ring based on the triplet cells is ~5 times smaller than for the singlet cells ring with the same phase advance per cell. Therefore the ODFDO-cell ring was chosen as a reference for the collider optics.

A transition from the ideal ring to the collider optics with low-β straight sections increases β-function and dispersion variations and yields an increase of IBS rates. Finally, the collider ring lattice based on FODO-cells has only ~3.3 times larger rates: the growth time of ~400 s versus ~1350 s for the luminosity of $6\cdot10^{27}$ $cm^{-2}s^{-1}$.

Table 1: Main Parameters of the Collider Rings Optics

Beam species and energy	Au^{79+}, 4.5 GeV/n
Ring circumference	454 m
Gamma-transition, γ_{tr}	6.22
Betatron tunes	9.46 / 9.46
Particles per bunch (of 20 bunches)	$5.3\cdot10^9$
Acceptance	40 π mm mrad
Longitudinal acceptance, Δp/p	+/- 0.0125
RMS emittance, $\varepsilon_x/\varepsilon_y$	1.1/0.6 π mm mrad
Beta function at IP, β^*	35 cm
Rms bunch length	60 cm
IBS growth time	1350 s
Luminosity (for Au^{79+} 4.5 GeV/n)	$6\cdot10^{27}$ cm^{-2} s^{-1}

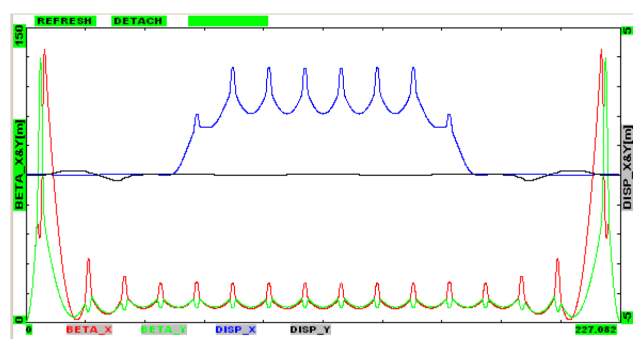

Figure 1: β-function & dispersions for half of the ring.

COLLIDER RING OPTICS STRUCTURE

Two main options of the NICA optics were considered.

Triplet Based Racetrack with γ_{tr}=6.22

This option was considered in Ref. [3] (see Fig.1). The objectives for the optics design are: (1) small β*, (2) an operation near thermal equilibrium where IBS rates can be minimized, (3) large transverse and momentum acceptances, (4) small circumference, (5) optimal location of collider tune and (6) two IPs. That determined the following design choices: (1) mirror symmetric racetrack with IP in each straight section, (2) triplet focusing through the entire machine (including IPs), (3) phase

This work is supported by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy.

advance of 90° per cell, (4) dispersion zeroing in the straight sections by a half-dipole without changing phase advance per cell, and (5) vertical beam separation at IPs with two-step vertical elevation for zeroing the vertical dispersion in IPs. The ring parameters are listed in Table 1.

Important to note, that a relative smoothness of the optics resulted in a 3.5 times difference between the heating of all degrees of freedom and the temperature exchange time between different planes ($\tau_{exchange} \approx 380$ s).

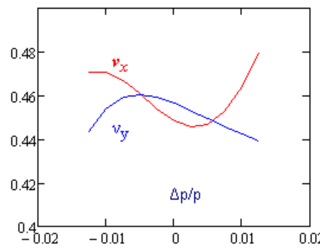

Figure 2: Tune dependence on the momentum offset.

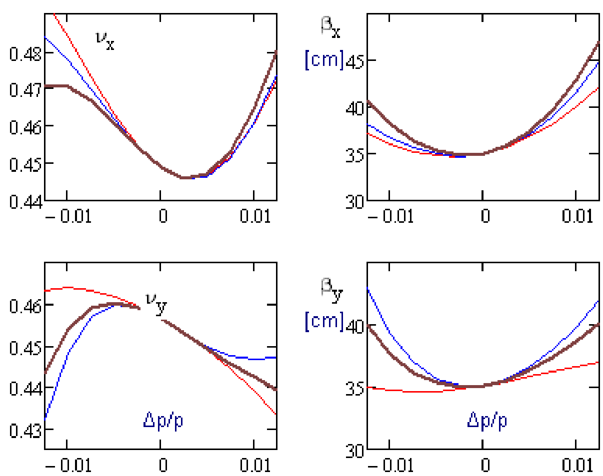

Figure 3: Dependence of the tune and β^* on $\Delta p/p$ with different sextupoles strength.

A chromaticity correction includes 4 families of sextupoles (2 focusing and 2 defocusing ones). It allows one to correct both the tune chromaticity and the beta-function chromaticity excited by IP quadrupoles. Sextupoles of each family are located with 180° betatron phase advances for their nonlinearity compensation. The dependence of the collider tune on $\Delta p/p$ is shown in Fig. 2. It is very nonlinear due to large β^* which excites large tune and β-function chromaticity. The natural chromaticity of the ring are: ξ_x=-27.1, ξ_y=-23.2 ($\Delta\xi_{x,y} \sim -17$ from two IPs). Corrected chromaticities are: $\xi_x = -1.54$, $\xi_y = -1.50$. The sextupole strength is ~0.35 kG/cm^2. A non-linear dependence of tunes and β-functions on $\Delta p/p$ and the optics smoothness requirement do not allow the perfect chromaticity correction. However sextupole settings making reasonably good compensation were found (see Fig. 3). That allowed us to avoid adding octupoles. Note also that the nonlinearity of tunes is actually profitable. It allows us to have large tune chromaticity required for transverse instabilities suppression with moderate tune variation across the momentum aperture.

The stochastic cooling system is assumed to be used in the collider. The slip-factor was chosen for optimal cooling at 4.5 GeV/n. The cooling time is ~200 s which is significantly smaller than the IBS heating time. The slip factor is increasing fast with beam energy decrease. For fixed momentum spread and bunch length it would result in an unacceptably high RF voltage. However, the beam thermal equilibrium yields a momentum spread decrease with energy decrease as the beam emittance is determined by the ring acceptance and stays constant. That results in that the maximum RF voltage of 0.9 MV is achieved at 2.5 GeV/n. This is only 2 times larger than at 4.5 GeV/n – the energy where optics was optimized.

FODO-cell Based Racetrack with Changeable γ_{tr}

To meet the NICA requirements of operation with different magnetic rigidity beams, Au-ions in range 1÷4.5 GeV/u and with proton 6÷13 GeV, we consider a lattice with changeable transition energy. Such lattice has to be capable to support operation with the minimum IBS heating for Au-ions and increased transition energy for operation with protons.

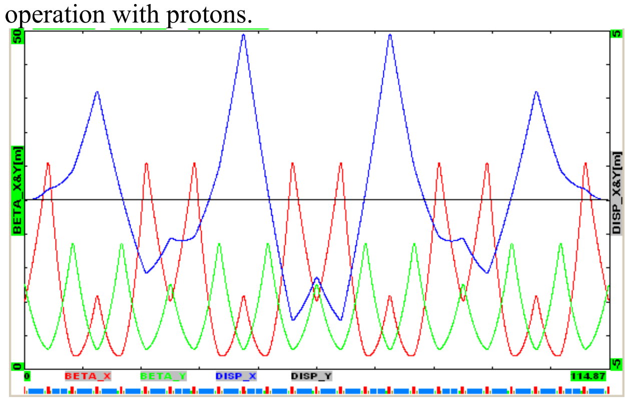

Figure 4: β-function & dispersion on arc, protons beam (12.6 GeV -kinetic energy) - γ_{tr}=37

In the proton mode the number of cells in one superperiod N_{cell} and the number of superperiods S_{arc} per arc are dictated by the required betatron phase advance in the horizontal plane. Following the theory of resonant lattices [4], we construct a lattice with the horizontal betatron phase advance in the arc ν_{arc} as close to the number of superperiods S_{arc} as possible keeping them both being integers. This means that the phase advance in one superperiod should be $2\pi\nu_{arc}/S_{arc}$, and the phase advance of radial oscillations between the cells located in different superperiods and separated by $S_{arc}/2$ superperiods is $2\pi \cdot \frac{\nu_{arc}}{S_{arc}} \cdot \frac{S_{arc}}{2} = 2\pi \cdot \frac{\nu_{arc}}{2} = \pi + 2\pi n$.

It corresponds to the condition of first-order compensation for the nonlinear effects of sextupoles in the arcs. In the Au option any modulation of gradient leads to the IBS heating. Therefore considering all implications we choose the arc with 12 FODO cells. They are grouped into 4 superperiods by gradient modulation in the case of proton mode (see fig. 4) and remain a regular periodic structure (no modulation) for Au-ions (see Fig.5). A transition from one option to another is done by gradient change in two focusing quadrupole families in the arcs and then by optics match to the straight sections.

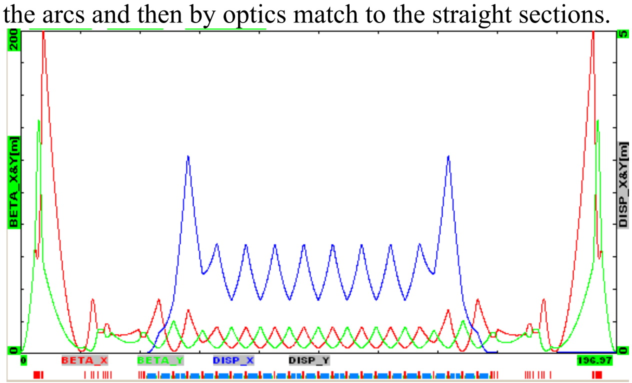

Figure 5: β-function & dispersion on half of the ring, Au^{79+} beam (4.5 GeV/n -kinetic energy) - γ_{tr}=7.13

In the proton mode the dispersion in the straight sections is suppressed due to the 2π integer betatron phase advance in the arc. It works for Au option as well, but the super-periodic dispersion modulation provokes additional IBS heating and should be excluded.

For optimal stochastic cooling operation it is desirable to have the partial pickup-to-kicker slip factor being sufficiently small. In the case of pickup and kicker located symmetrically relative to the ring center it can be achieved by operation near γ_{tr} in the entire energy range. It requires γ_{tr} being adjustable in the range 7 to ~3. In the lattice design it is done by the decreasing tune in the arcs. For the Au mode the dispersion is suppressed by adjustments of two focusing quads at the arc exterior. It results in zero dispersion in the straight sections for different phase advances per cell and, consequently, different γ_{tr}.

Main parameters of the lattice are presented in Table 2.

Straight sections were designed to provide β*~35 cm, to bring minimum chromaticity into the ring, to ensure total ring tune adjustment, and to have space for non-structural equipment positioning.

Nevertheless due to two IP the NICA has sufficiently high normalised chromaticity value $\xi_{x,y}/\nu_{x,y}$~3.5, and use of quite strong sextupole magnets for chromaticity correction sharply restricts the dynamic aperture.

For proton in the "resonant" lattice sextupoles are placed in the maximum dispersion coinciding with the minimum beta function. Due the higher dispersion the sextupole strength is less; and due to smaller beta function the non-linear kick weaker. Besides as we said already the sextupoles are self compensated in the first approach. Overall DA for the proton lattice is sufficient.

In the Au-option we introduce irregularities through suppressors, which partly destroy the sextupole compensation. Therefore if only two families of sextupoles are used, the horizontal dynamic aperture does not exceed 30 π mm·mrad.

To correct the sextupoles scheme we switched off sextupoles in the suppressors and doubled their strength in the central part. Then, the dynamic aperture became quite symmetric and grew up to ~70 π mm·mrad..

Table 2: Main Parameters of the Collider Rings Optics.

Beam	Au^{79+}, 1÷4.5 GeV/n
Ring circumference	400 m
Gamma-transition	3÷7 for Au^{79+} ; 13÷37 for p
Betatron tunes	9.44/10.45
Particles per bunch (20 bunches in the ring)	$1 \cdot 10^9$
Acceptance	70 π mm mrad
Longitudinal acceptance, Δp/p	+/- 0.010
RMS emittance, $\varepsilon_x/\varepsilon_y$	0.4/0.4 π mm mrad (32 bunches per ring)
Beta function at IP	35 cm
Bunch length (6σ)	60 cm
IBS growth time	380 s
Luminosity (for Au^{79+} 4.5 GeV/n)	$1 \cdot 10^{27}$ cm^{-2} s^{-1}

Similarly to the triplet option we investigated the tune versus momentum (Fig.6). At such non-linearities

$$\nu_x = \nu_0 - 0.43 \cdot \frac{dp}{p} + 240 \cdot \left(\frac{dp}{p}\right)^2 + 12000\left(\frac{dp}{p}\right)^3 + ... \text{ and}$$

$$\nu_y = \nu_0 - 0.55 \cdot \frac{dp}{p} + 660 \cdot \left(\frac{dp}{p}\right)^2 + 73000\left(\frac{dp}{p}\right)^3 + ...$$

the dynamic aperture practically remain to be unchanged in whole beam momentum spread Δp/p≈±0.005.

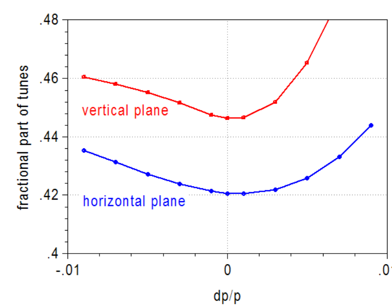

Figure 6: Tune dependence on momentum spread.

REFERENCES

[1] G. Trubnikov et al., "Project of the Nuclotron-based Ion Collider fAcility (NICA) at JINR, Proceedings of RuPAC 2008, Zvenigorod, Russia.

[2] S. Nagaitsev, "Intrabeam scattering formulas for fast numerical evaluations", Physical Review Special Topics – Accelerators and Beams, 8, 064403, (2005) and V. Lebedev, OptiM - Computer code for linear and non-linear optics calculations, 2009.

[3] V. Lebedev, "NICA: Conceptual proposal for collider", MAC2010, January, 2010.

[4] Yu. Senichev and A. Chechenin, Theory of "Resonant" Lattices for Synchrotrons with Negative Momentum Compaction Factor, Journal of Experimental and Theoretical Physics, December 2007, vol. 105, No. 5, pp. 1127–1137.