COLLIDER OF THE NICA ACCELERATOR COMPLEX: OPTICAL STRUCTURE AND BEAM DYNAMICS

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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). Providing the intense ion beam life time the space charge effects were considered. Beam accumulation scheme and scenario of collider operation in collision mode with application of electron beam or stochastic cooling methods were proposed.

INTRODUCTION

The goal of the NICA project is construction at JINR of the new accelerator facility that consist of [1]: cryogenic heavy ion source of Electron String type (ESIS), source of polarized protons and deuterons, the existing linac LU-20 of Alvaretz type, a new heavy ion linear accelerators RFQ-DTL, a new superconducting Booster-synchrotron placed inside the decommissioned Synchrophasotron yoke, the existing proton and heavy ion synchrotron Nuclotron, the new system of beam transfer channels, and two new superconducting storage rings of the collider. 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 must fit into JINR infrastructure and has a certain circumference limitation. The collider lattice is based on the technology of super-ferric magnets developed in VBLHE, JINR [3]. Such a dipole magnet with up to 2 T bending field operates with hollow composite NbTi cable at 4.5 K. The collider optics optimization includes the certain effects which set some 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.

Collider operation at fixed energy without acceleration of the injected from the Nuclotron beam is considered. Beam storage at some optimum energy and slow acceleration in the collider (at field ramp rate < 1 T/s) is presumed as a reserve option. The maximum energy of the experiment is determined by the Nuclotron maximum magnetic rigidity of 45 T·m. In this paper we discuss only the most developed heavy ion mode of facility operation and the $^{197}Au^{+79}$ ions as the reference particles.

LATTICE STRUCTURE

Together with the physical effects the another technical constraints were taken into account in lattice optimization: ring circumference, number of the dipole magnets in arc, convenience of the beam injection into the ring. The FODO optics with 12 periods is a principal choise 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 "twin aperture" superconducting magnets (dipole and quadrupoles) [2]. This lattice has a large efficiency of stochastic cooling at 4.5 GeV/amu. But the luminosity of 10^{27} cm^{-2} s^{-1} could be reached in the wide energy range. The convenient injection scheme could be realized through the arc dipole-empty cell.

Table 1: Collider Ring and Beam Parameters

Ring circumference, m	503.04		
Gamma-transition, γ_{tr}	7.091		
Betatron tunes, Q_x/Q_y	9.44/9.44		
Chromaticity, $\xi_{x,0}/\xi_{y,0}$	-33/-28		
Max. number of bunches	23		
Rms bunch length, m	0.6		
β-function in the IP, m	0.35		
FF lenses acceptance	40π mm mrad		
Long. acceptance, Δp/p	±0.010		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch	2.75e8	2.4e9	2.2e9
Rms Δp/p, 10^{-3}	0.62	1.25	1.65
Rms emittance, hor/vert, (unnorm), π·mm·mrad	1.1/ 1.01	1.1/ 0.89	1.1/ 0.76
Luminosity, cm^{-2}s^{-1}	1.1e25	1e27	1e27
IBS growth time, s	190	700	2500

FODO-cell geometry is set up with the fixed lengths of magnetic elements and spaces. In Fig. 1 the scheme of 11.96 m cell is shown. There are four rectangular dipole magnets per cell (80 magnets per ring), two quadrupoles [3], multipole correctors and BPMs. The maximum field in dipoles of 1.8 T and gradient in quadrupoles of 23 T/m are chosen to possibly avoid the saturation effects in iron yokes at higher energies. Multipole corrector includes the several types of windings – dipole (orbit correction),

ISBN 978-3-95450-125-0

quadrupole (tuning), skew quadrupole (coupling correction), sextupole (chromaticity correction).

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 vertical the beam separation and final focusing in IPs.

Ring general parameters are given in Table 1 and assembly for one of the rings is shown in Fig. 2. Two rings are separated vertically. Counter circulating beams must see the same optics to adjust the same betatron tunes ($Q_{x,1}$=$Q_{x2,}$ $Q_{y,1}$=$Q_{y,2}$). Thus 2-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. The corresponding β and dispersion functions over half of the ring are pictured in Fig. 3. In antisymmetric scheme the uncorrected vertical dispersion approximately cross zero at IPs.

A chromaticity correction 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. 4 before and after chromaticity correction. At the slightly negative corrected chromaticity $\xi_{x,y}$=–1.5 sextupole setting (maximum strength of 130 T/m^2) the corresponding estimated DAs (for several 1000 turns) are pictured in Fig.5 for the maximum energy 4.5 GeV/u without and with expected nonlinearities in dipoles [3]. In these cases they are large enough compare to the ring acceptance. But DA studies require more detailed and sophisticated simulation in 3D with the beam space charge for the very large turn numbers.

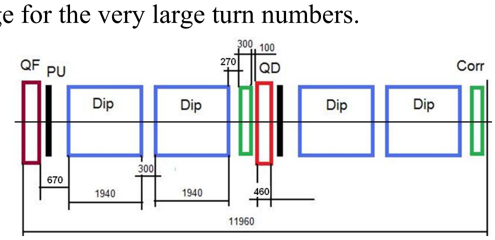

Figure 1: Arc periodic cell.

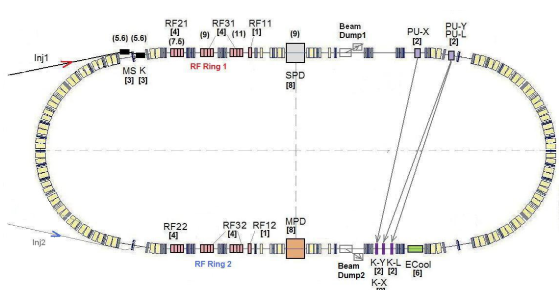

Figure 2: Ring assembly. Stochastic cooling system location for one ring, electron cooling and RF systems location for both rings are shown.

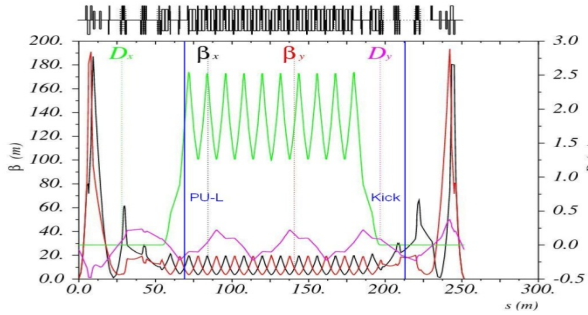

Figure 3: β-functions and dispersions for half a ring.

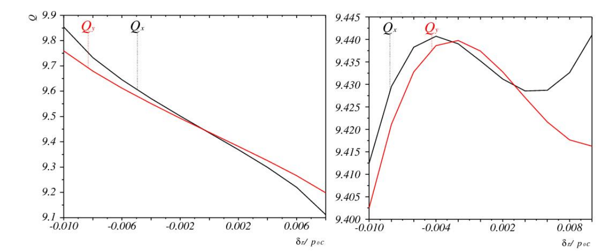

Figure 4: Tune dependence on momentum offset before and after chromaticity correction.

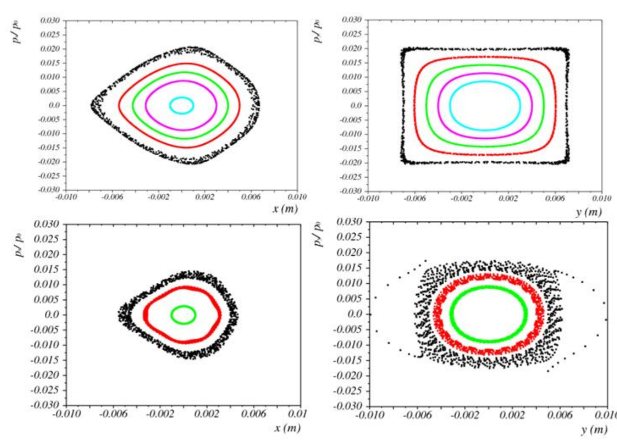

Figure 5: Horizontal and vertical DAs at IP, 4.5 GeV/u: top – chromaticity correction, bottom – chromaticity correction and b_2 dipole errors.

LONGITUDINAL DYNAMICS

To achieve desirable bunch parameters for collision, three RF systems are needed in the collider: one broadband type for ion accumulation and two narrow-band systems for the bunch formation [6].

RF1 – the first collider RF system of Barrier Bucket type serves for ion accumulation. Rectangular pulses at 5 kV of amplitude and phase duration π/6 are able to accept particles with relative momentum deviation of ±0.01. Phase distance between the pulses is π. The accumulation length is the half of the collider perimeter, one perimeter of Nuclotron. After accumulation of a required ion number the barrier voltage is switched off and the beam becomes coasting. *RF2* provides the required number of bunches in the collision mode. In presence of cooling the emittance and bunch length continue to decrease. It will be switch on until the bunch length reduces enough to fit

ISBN 978-3-95450-125-0

the RF3 acceptance. The maximum RF2 voltage amplitude of 100 kV has some reserve for operation. *RF3* is the principal system of the collider. It keeps the collision regime. The bunch momentum spread is the result of equilibrium of two processes – intra beam scattering and cooling and varies with energy as shown in Fig. 6. At harmonic number 69 the bucket size is still large enough ($\pm 6\sigma_s$ in length and $\pm 4\sigma_p$ in height) and maximum voltage is still at reasonable value (Fig. 6).

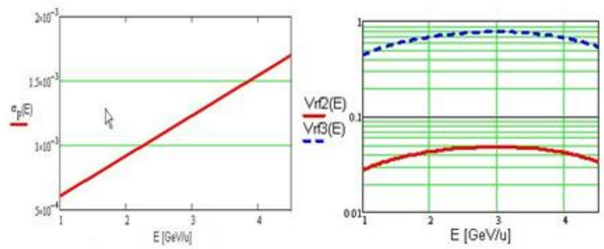

Figure 6: R.m.s. momentum spread (σ_s=0.6m), and RF2 and RF3 amplitude (in MV) vs ion collision energy.

COLLIDER LUMINOSITY AND REGIMES

The collider design has to provide the project luminosity (beam life time) and its maintenance during long time of experiment performance. Beam intensity is limited by beam space charge effects, which can be estimated by "tune shift criteria" [6]: the total tune shift $\Delta Q_{total}=\Delta Q_{Las}+2\xi$ (Laslett and 2 beam-beam) that could not exceed the limit of 0.05. The main problem of the NICA collider is suppression of intrabeam scattering (IBS) in the intense ion beam. For this purpose both electron beam and stochastic cooling methods are proposed. The first situation is the achievement the equilibrium between the cooling and space charge when the space charge reaches the resonant value ΔQ_{total} = 0.05. This is called "Space Charge dominated regime". At this regime the maximum luminosity is obtained with the maximum beam emittance. For some reasons the luminosity can be limited, for example by the value $1\cdot10^{27}$ cm^{-2} s^{-1}. In that case one can reoptimized beam intensity and emittance to keep ΔQ_{total} below the limit. It also decreases the cooling force providing the equality between IBS and cooling rates. The corresponding regime of the collider operation is called "IBS dominated regime".

For NICA parameters IBS dominated regime can be used at energies above 3 GeV/u where ΔQ_{total} <0.05. At that energy range the stochastic cooling is proposed to use. The choosing stochastic cooling system bandwidth from 3 to 6 GHz provides the cooling time two-three times shorter than IBS times. At lower energies below 3 GeV/u the application of electron cooling is preferable.

CONCLUSION

The collider lattice concept – "2 Nuclotrons" circumference with 12 cell FODO structure in the arcs has been chosen. The ring meets the requirements of tunes adjustment in the dispersion free sections, large transversal and momentum acceptances, location of number of the insertions, vertical beam separation in interaction region, maximum total voltage of RF stations (≤1MV).

The collider rings of the NICA accelerator complex have the particular operating features described in this report: SC and IBS dominated regimes. The application of the cooling methods is only way to realize the required collider luminosity parameters. The proposed cooling scenario includes: electron beam cooling in the energy range from 1 to 3 GeV/u can provide short cooling times at the SC dominated regime; the stochastic cooling technique is more preferable in the range 3÷4.5 GeV/u where luminosity $1\cdot10^{27}$ cm^{-2} s^{-1} can be obtained in IBS dominated regime (Fig. 7).

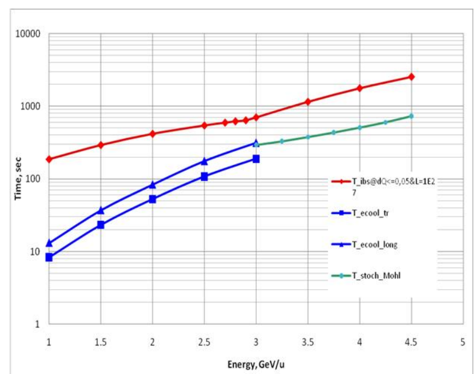

Figure 7: IBS growth times in the IBS dominated regime, electron cooling times (<3 GeV/u) and stochastic cooling time (≥3 GeV/u).

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ISBN 978-3-95450-125-0