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PARTICLE COLLIMATION IN THE NICA COLLIDER

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Abstract

The system of particles collimation developed for the NICA collider is considered. The main collimation goal is the beam halo cleaning to minimize the background for experiment. The main mechanisms of particle losses, including the ion recombination in electron cooler, are also reviewed.

INTRODUCTION

The Nuclotron-based Ion Collider fAcility (NICA) [1] is a new accelerator complex being constructed at JINR. Two collider rings are designed to achieve the required luminosity up to 10^{27} $cm^{-2}s^{-1}$ 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 and deuteron-deuteron collisions. The collider must obtain the required luminosity taking into account the certain conditions: 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 article considers the $^{197}Au^{+79}$ ion mode of the facility operation.

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 beam axes) and use two-aperture superconducting magnets (dipoles and quadrupoles). Rings have the racetrack shape with the bending arcs and long straight section. Bending arc comprises 12 FODO cells. The cells with empty dipoles are used for horizontal dispersion suppression and convenient beam injection and extraction (dumping) schemes. The long straight sections matched to the arcs contain the RF stations, electron and stochastic cooling devices, BPMs, superconducting quadrupole blocks and collimation elements as well. 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 project parameters of the collider ring are presented in Table 1. The placement of collimation system elements in both collider rings is possible only in the western superperiod (Fig. 1). The eastern part of the collider is designed to accommodate the modules of the acceleration system.

Table 1: Main Parameters of the Collider Rings

Ring circumference	503.04 m	
Number of bunches	22	
Rms bunch length	0.6 m	
β-function in the IP	0.35 m	
Betatron tunes, Q_x/Q_y	9.44/9.44	
Chromaticity, $Q'_{x,0}/Q'_{y,0}$	-33/-28	
Acceptance	40 π·mm·mrad	
Long. acceptance, Δp/p	±0.010	
Gamma-transition, γ_{tr}	7.088	
	Dipole	Quadrupole
Number of magnets	80+8(vert.)	86+12(fin.foc)
Max. magnetic field	1.8 T	23 T/m
Effective length	1.94 m	0.47 m
Beam pipe (h/v)	120mm/70mm	

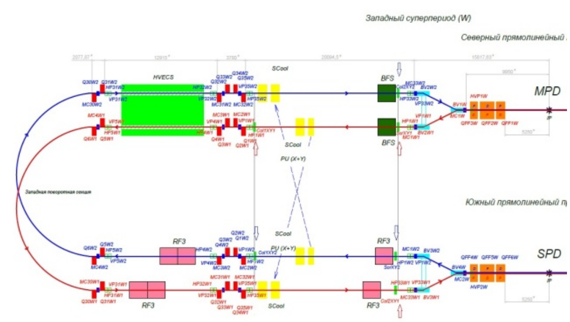

Figure 1: Positioning of the collimation elements in the collider lattice (shown by thick arrows).

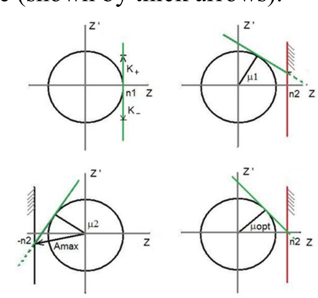

Figure 2: Principle of two-stage collimation in transversal phase space.

STATUS OF THE SYSTEM OF PARTICLE COLLIMATION

The collimation system is designed to clean the beam halo [3], the particles that have get maximum amplitudes (comparable to acceptance) due to intrabeam scattering or nonlinearities of the magnetic field, to reduce it interaction with the walls of the vacuum chamber and, especially, to protect the detector from additional background.

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A two-stage particle collimation scheme is considered, consisting of a scraper and two interceptors or collimators of scattered particles for each ring (Fig. 2). The arrangement of the collimators corresponds to the optimal betatron phase advance between these devices. The separate device contains horizontal and vertical movable elements limiting the beam aperture. Scraper - a thin foil (for example, W) is located at the acceptance border (6σ). Halo particles passing through it obtain an additional transverse angle due to multiple Coulomb scattering. For example, the characteristic W foil thickness of 0.1÷1 mm is required for the scattering angle of 0.5÷1 mrad. Collimators (interceptors) - extended devices located outside the acceptance limits, provide the absorption of the energy of scattered particles. The process of particle scattering is considered depending on the foil material and particle energy. The chosen scheme of collimation is the relatively dependent on of the scrappers and collimators locations (Fig. 3). The scattered particles envelopes were traced (Fig. 4) and the possible locations of the thick collimators were determined. The required longitudinal lengths of the devices for ion stopping were calculated. The characteristic longitudinal length for the absorber plates (Fe, W, Inconel) reserved for the collimator design is less than 10 cm.

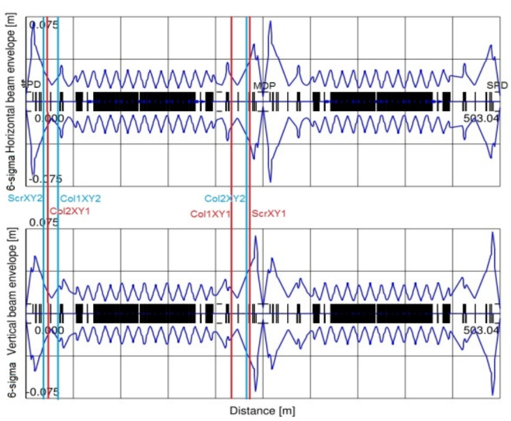

Figure 3: Locations of the collimation elements and acceptances of the rings in horizontal and vertical planes.

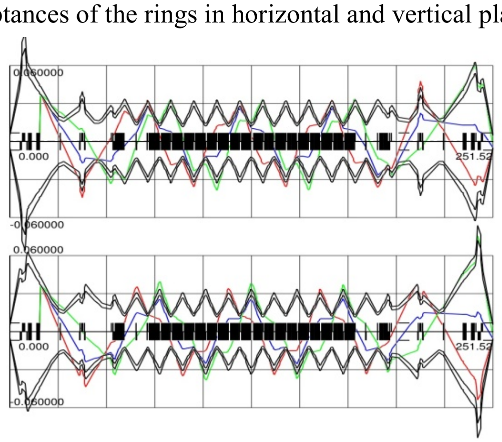

Figure 4: Scattered particles envelopes tracking. Beam envelopes (6σ and 7σ, black curves) are shown in horizontal (top) and vertical (bottom) planes.

An extensive study of the interaction of high-energy ions with matter was carried out (angles of multiple Coulomb scattering in the foil, ion energy losses in the collimator material). The Fig. 5 shows examples of energy loss by an ion in a thick collimator.

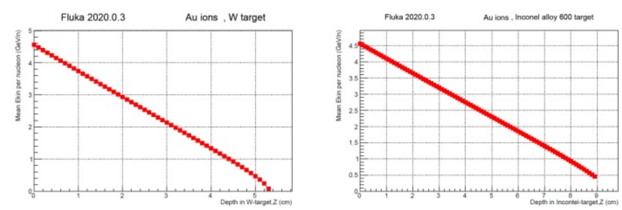

Figure 5: The average energy of Au^{+79} ions in absorber (W and Inconel) depth. The initial ion energy is E_k=4.5 GeV/n.

The designs of the scraper and collimator for the collider have been developed. The Fig. 6 shows the design of a combined device that allows to control the movement of horizontal and vertical plates (or foil in scraper). The device combines collimator functions for both rings.

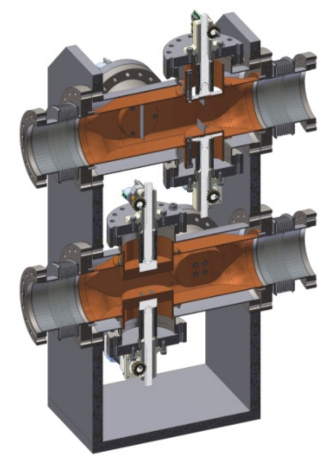

Figure 6: Horizontal and vertical collimator design for two-level collider rings.

CHARGE EXCHANGE EFFECTS IN THE COLLIDER

Losses of ions in the rings of the collider can occur due to the change in the charge state by the ion, the capture of an electron. Three relevant effects were estimated for the collider: charge exchange due to residual gas, bounded-free pair production and recombination in electron cooler.

The rate of recombination of the ions Au^{+79}→Au^{+78} in the section of the electron cooling system was calculated by the well-known approach.

The time constant (lifetime) of recombination is represented as

$$\tau_{rec} = \frac{\gamma^2}{\alpha_{rec} n_e \eta}, \qquad (1)$$

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where γ is the gamma factor of the ion, n_e is the density of the electron beam in the laboratory coordinate system, $\eta=C_{cool}/C_{ring}$ is the ratio of the electron cooler length to the collider perimeter, and the coefficient is written as [4]:

$$\alpha_{rec}=1.92\times10^{-13}\frac{Z_i^2}{\sqrt{T_e}}\left[\ln\left(\frac{5.66Z_i}{\sqrt{T_e}}\right)+0.196\left(\frac{T_e}{Z_i^2}\right)^{1/3}\right]. \qquad (2)$$

Calculations using the above formulas for the corresponding parameters of the ion beam of the collider and the electron beam are given in Table 2 for maximal ion kinetic energy of E_i=4.5 GeV/n, the number of bunches in the ring of n_b=22 , the electron energy of E_e=2.5 MeV, electron beam current of I_e=1 A, the electron beam diameter of d_e=1 cm, where N_i is the intensity of the ion beam, T_e is the transverse electron temperature.

Table 2: Time Constants and Recombination Rates of Au^{+79} Ions

N_i	T_e,eV	α_{rec}, cm^3/s	τ_{rec}, s / τ_{cool},s	$\Delta N=n_bN_i/\tau_{rec}$, ions/s
$2.3\cdot10^9$	100	$5.36\cdot10^{-10}$	3383 / 35	$1.50\cdot10^7$
$2.3\cdot10^9$	10	$1.98\cdot10^{-9}$	910 / 25	$5.56\cdot10^7$

For the expected parameters of the electron beam at T_e=100 eV, the estimated lifetime is 1 hour. The corresponding flow of recombined ions is $1.5\cdot 10^7$ ions per second. With a practically attainable parameter T_e=10 eV, this flux will be about $6\cdot10^7$ ions per second. The characteristic cooling times are rather weakly dependent on T_e. Without additional collimation the recombined ions will be lost in the very specific places in the bending arcs of both rings of the collider. The power will be dissipated in vacuum chamber, superconducting coil and yoke. The values of the dissipated power of the order of 0.01÷0.05 W corresponding to the typical parameters of electron cooler (Table 2) are rather acceptable for the superconducting wire operation.

To estimate the charge exchange of an ions on residual gas molecules in the NICA collider, one were used the theoretical calculations of radiactive electron capture in reactions of heavy nuclei with light target atoms, scaling law of the radiactive electron capture cross sections as a function of the atomic numbers of the incident ion and the target, the relationship between the parameters of the residual gas (partial pressures) and the parameters of the circulating beam [5]:

$$P_i=3.3\cdot10^{-21}\,\alpha T/(\mu_i\,\sigma_{i,tot}(E_k, Z)\beta)\cdot1/\tau, \qquad (3)$$

where P_i is the partial pressure of the i-th component of the gas (nTorr), μ_i is the number of atoms in a gas molecule, $\sigma_{i,tot}$ is the total cross section for charge exchange, T is the absolute temperature, E_k, β are the beam parameters, α is the permissible losses during charge exchange, τ is the beam circulation time. Using the above relation, the pressure in the beam pipe (hydrogen) during, for example, 2 hours circulation of Au^{+79} ions (E_k=4.5 GeV/n), with an acceptable loss of intensity of 5% should be no worse than P_i=0.2 nTorr.

The effect, bounded-free pair production [6], observed at colliders was also evaluated. Theoretical estimates are used for the reaction cross sections at the collider interaction point: $Z_1+Z_2\rightarrow Z_1+e^++(Z_2+e^-)_{1s1/2}$, ($Z_1=Z_2$=79). The rate of generation of $Au^{+79}\rightarrow Au^{+78}$ in the reaction of beams collision at the project luminosity of 10^{27} $cm^{-2}s^{-1}$ is rather negligible due to small total cross-sections of the reaction (<50 mb) for the collider energy range.

CONCLUSION

The scheme of a beam halo collimation system in the collider is described. The system must ensure the elimination of unnecessary particle background during the physical experiment. Other sources of losses in the collider associated with ion charge exchange processes are also considered. In particular, the effect of ion recombination in the section of electron cooling was estimated.

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