Polarized Ions in the NICA Complex

(proposal to SPD CDR)

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SPD CDR
Part 3

3 Polarized beams

3.1 Available species and types of collisions

Basic specification to available polarization states and combinations is the following:

- Protons: vector polarization, longitudinal and transverse direction in respect to a particle velocity;
- Deuterons (possibly helium-3 ions at the second stage): vector and tensor polarization, vertical direction of polarization, changing of the polarization direction at 90^o up to about 4 GeV/c momentum;
- Possibility of collisions any available polarized particles: proton-deuteron, proton-helium3, deuteron – helium3 with the luminosity of $10^{30}cm^{-2}s^{-1}$ at the collision energy equivalent to the proton-proton collisions;
- Possibility of asymmetric collisions should be considered as an option for the future development of the facility;
- For efficient estimates of systematic error it is desirable (or necessary) to realize rotation of a bunch polarization direction on 90^0 within one turn;

Technical realization of the above mentioned conditions is feasible [1].

3.2 Beam structure, intensity and luminosity

Beam structure of polarized proton and deuteron beams at the first stage will be corresponded to that was optimized for the NICA heavy ion regime. Some of the important, for the SPD, operation parameters in case of bunched beam are the following: bunch number -22, bunch length - σ = 60 cm, the collider orbit length – 503 m, bunch velocity $v \approx c = 3{\cdot}10^8\ m{\cdot}s^{-1}$, revolution time $\tau \approx 1.67{\cdot}10^{-6}$ s, bunch revolution frequency $f \approx 0.6$ MHz, time gap between bunches centers, $\Delta\tau \approx 76{,}0{\cdot}10^{-9}$ s.

The dependence of the pp-collision luminosity on the energy and number of protons is presented in Fig. 2.1.

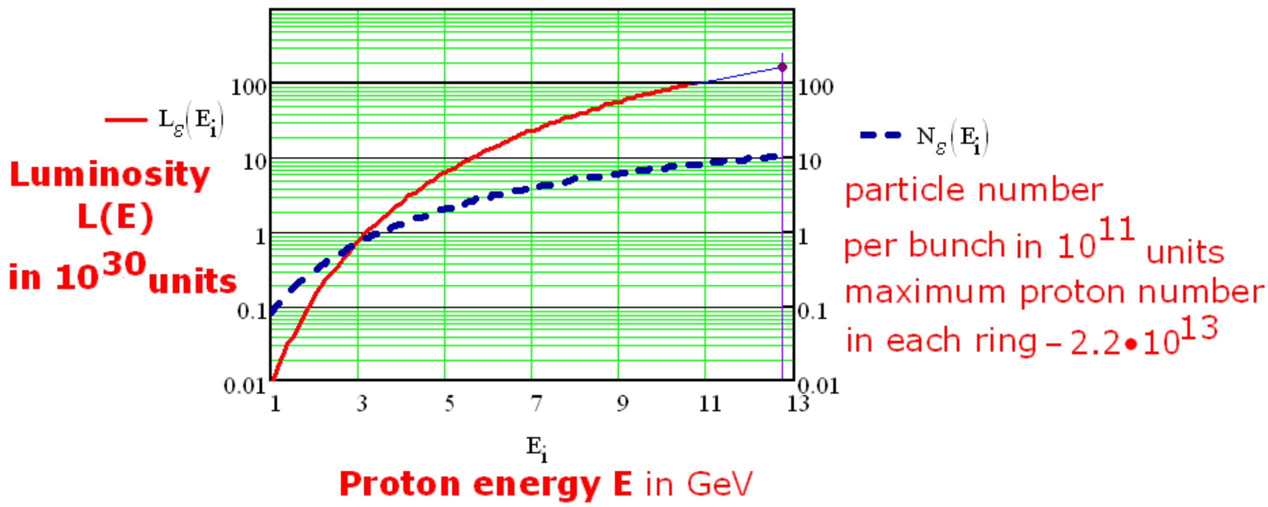

Fig. 2.1. Normalized dependence of pp-collision luminosity on proton kinetic energy.

As it clear from the calculation the luminosity level of $1{\cdot}10^{30}\ cm^{-2}s^{-1}$ is reached at a bunch intensity of 10^{11} polarized protons, whereas to reach the level of $1{\cdot}10^{32}\ cm^{-2}s^{-1}$ multi-bunch storage mode and the beam cooling should be used. [2]

3.3 Polarization control and monitoring

3.3.1. Transportation of polarized ions in the complex

Polarized protons and deuterons from the source SPI are accelerated first in the linac LU-20M and after that are injected and accelerated in the Nuclotron to the specified energy and extracted to the collider via long transfer line.

The maim tasks at this stage are the following: 1) preservation of the ion polarization during acceleration in the Nuclotron (and in the collider also) and 2) the polarization control in the collider mode. Moreover, it is necessary to adjust the polarization direction at the beam transfer between the Complex elements.

3.3.2. Operation modes of the NICA collider at polarized ions

From the spin dynamics point of view, NICA collider can operate in two regimes (modes), namely: in a Preferred Spin mode (PS-regime) and in the Spin Transparency mode (ST-regime)

In the PS - regime periodic motion of the spin along the particle orbit is the only possible, i.e. – stationary magnetic structure select the only one stable direction of the polarization vector in any point of the particle orbit, non-integer part of the spin tune is not equal to zero, whereas in the ST – regime the direction of the spin vector is reproduced in any point at every turn, i.e. magnetic structure of the accelerator (or storage ring) is transparent for the spin – non-integer part of the spin tune is equal to zero.

The main difference between the PS- and ST- regimes is occurred at the manipulations of the spin direction during physics data taken. In the ST- regime the spin motion is very sensitive to the magnetic field changes, because particles are moved in the vicinity of the integer resonance In this case the use of additional "weak" magnetic field, rotating spin at small angles $\Psi \ll 1$, provides the needed polarization direction at any specified point of the collider. It is possible to use a pair of solenoids with the field integral of 1 Т·м, introduced negligible distortions of the particle closed orbit, to produce necessary variation of the spin angle in the NICA collider over the momentum range up to 13,5 GeV/c.

In the case PS regime similar procedure will require spin rotators base on a strong fields, rotating the spins at the angles of $\Psi{\sim}1$. Thus, in the case of the changing the polarization direction from the longitudinal to the transverse one, it would be necessary to apply the transverse field with the total integral of 20-30 T·m, which would be resulted in a strong distortions of the particle close orbit. The amplitude of the distortions can reach of tens of centimeters at low energies. Thus, efficient polarization control of ions, deuterons especially, by means of quasi-stationary weak fields is possible the only if the ST- regime is used.

3.3.3. Specifications to the polarized beams in the collider

Different experiments are planning with polarized proton, deuteron and helium-3 (in the future) particles to identify and study different observables for different physics tasks: Drell-Yan, J/Psi, high p_T hadron physics, exotic states etc. The polarization control system should be satisfied to the following main conditions:

- To obtain both longitudinal and transverse polarization in the MPD and SPD detectors with the polarization degree not less 70% and the polarization lifetime not less than the beam lifetime;
- To provide the collision luminosity of ~10^{30}-10^{32} cm^{-2}·c^{-1} over the particle momentum range from 2 to 13.5 GeV/c;
- To provide the particle energy scan with a step of 1.0 GeV (Drell-Yan, J/Psi) and 0.3 MeV (high p_T hadron physics, exotic states);
- To adopt operation in asymmetric on the particle momentum mode;
- Make simultaneous spin-flips for all bunches in Spin Flipping experiments (SF system).

3.3.4 Spin Flipping system

The SF system makes it possible to carry out the spin physics experiments at much higher level of the accuracy [3]. Being equipped by such system the SPD set-up will have real privileges, in particular:

- revers of the polarization direction at the polarized ion source is not necessary;
- no necessity of a bunch-to-bunch luminosity measurements and bunch monitoring system;
- the possibility of comparison collisions of bunches with any directions of the particle spin (vertical-longitudinal, vertical – radial, radial – longitudinal, etc.).

The SF system based on quasi-stationary fields is naturally realized in the ST collider regime. The pair of “weak” controlled solenoids provides simultaneous influence on the polarization direction and the spin tune. Thus, possibility of the spin tune stabilization during the spin flipping is occurred, preventing both as the zero spin tune and higher order spin resonances crossing. The polarization degree will be kept with an exponential accuracy, if the field of “weak” controlled solenoids will be changed slowly.
For realization of SF system in the collider operating in a PS regime it would be necessary to introduce in the lattice RF-field of a MHz’s range and the field total integral of 1 Tm, that’s not so easy technical task.

3.3.5. On-line control of the polarization in the collider

The unique possibility of the on-line polarization control is occurred if the collider operates in the ST-regime. Because the field ramp in a “weak” solenoids ($t_{изм}$ ~ 0.2 c) is much larger of the spin precession period around the induced spin field ($t_{об} \sim 10^{-4}$ c), any manipulations with the spin direction at spin tune will be occurred adiabatically and the polarization degree during the experiment time will be supported constant with the exponent accuracy. The direction of polarization vector will be a function of the weak solenoids field and can be defined by mean of the field measurements.
The comparison of the ST- and PS- regimes in the NICA collider is presented in Table 1.
Table 1.

Possibility of realization	PS regime	ST regime
Stationary longitudinal/transverse polarization in the detectors	yes	yes
Polarization control in any point of the orbit	no	yes
Spin Flipping systems based on quasi- static fields	no	yes
on-line polarization control	no	yes

Thus, the ST-regime makes it possible to carry out the experiments at the NICA collider at the new level of the accuracy.

3.3.6. Polarization control in the collider NICA in ST regime
Use of integer spin resonances in ST-regimes

Stable polarization direction in the NICA collider is vertical (orthogonal to the particle orbit), whereas the spin tune is proportional to the particle energy: $\nu = \gamma\, G$, where G — is anomalous part of the gyromagnetic ratio. The collider is operated in the PS- regime practically over the total energy range because $\gamma \neq k/G$, где k — integer. The ST regime is realized at discrete energy points corresponding to integer spin resonances: $\gamma = k/G$. Для протонов The number of points corresponding to ST- regime is 25 starting from minimal energy $E_{kin}^{min} = 108$ МэВ with the step of $\Delta E = 523$ МэВ. There is only one point $E_{kin} = 5.63$ ГэВ/u, corresponding to the momentum $pc = 13$ ГэВ i.e. the ST-regime for deuterons in the Nuclotron/NICA complex.

Possible scheme of ion polarization control in the collider at the integer spin resonances is presented in Fig.1. Two PC-insertions (marked with orange circles in Fig.1) placed near MPD are used to stabilize the needed polarization direction at any point of the collider ring, including the collision points, at injection, etc. Detail scheme of the PC's is presented in Fig.2. Weak solenoids (

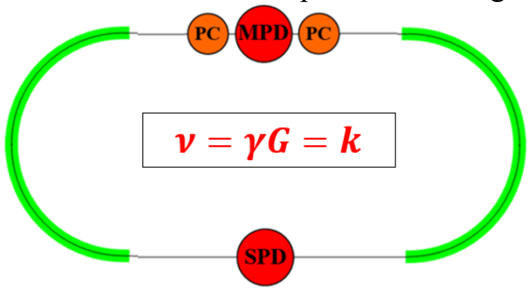

Fig. 1. General scheme of the polarization control at integer spin resonance points.

B_{z1} and $B_{z2)}$ generated longitudinal magnetic field $\pm B_{z2}$ are placed between the collider structural magnets, generated radial field $\pm B_x$ (marked as 3 and 4), providing deflection the beams to the collision plane of the MPD.

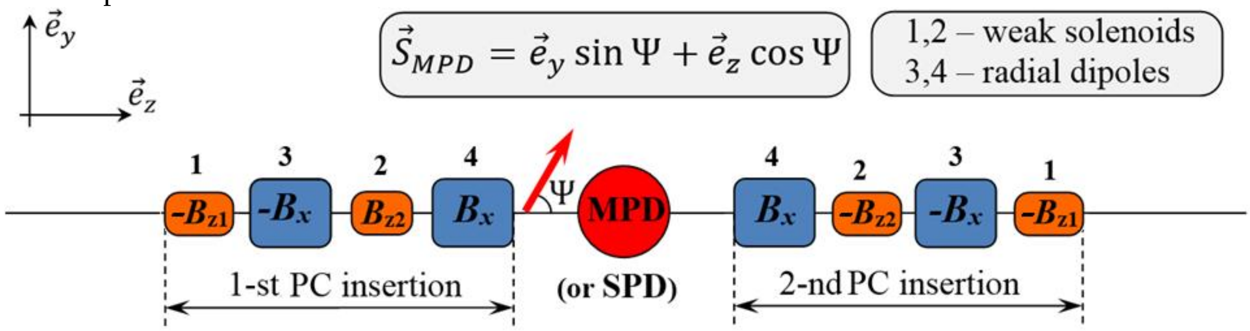

Fig. 2. Detail scheme of the PC's insertions in the collider in the ST regime.

The scheme make it possible the ion polarization control in vertical plane (*yz*) in the MPD (or SPD) (Ψ — angle between polarization and particle velocity vectors). The scheme provides necessary spin rotation for all discrete points over NICA energy range if integral magnetic field will reach 0.6 T·m in each of four solenoids. If we limit the field maximum to 1.5 T, the magnetic length of the solenoid unit of 40 cm. Real relative scale of the control solenoid (40 cm long), radial dipole and distances between them is shown in Fig. 3.

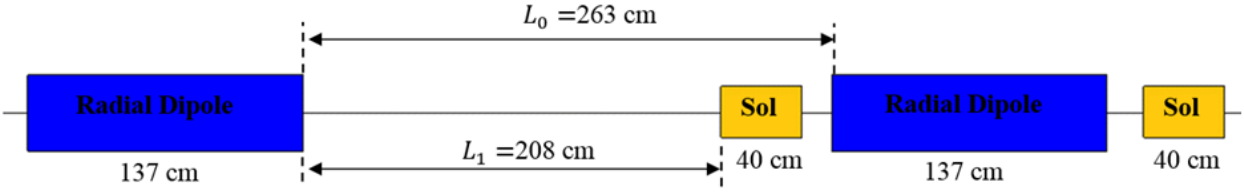

Fig. 3. Placement of weak control solenoids in horizontal plane.

The scheme of installation weak control solenoids in vertical plane together with the collider lattice elements is presented in Fig. 4. The beam convergence angle in vertical plane, defined by the dipoles with transverse to the beam axis magnetic fields is: $\alpha_x = 0{,}04$ rad. The distance between the collider rings in vertical is 32 cm. The distances in vertical plane between the particle closed orbits are $\Delta y_{dip} = L_x\alpha \approx 5{,}5$ cm. and $\Delta y_{sol} = \Delta y_{dip} + 2L_1\alpha \approx 22$ cm. at the output of common radial dipole and at the exits of control solenoids respectively.

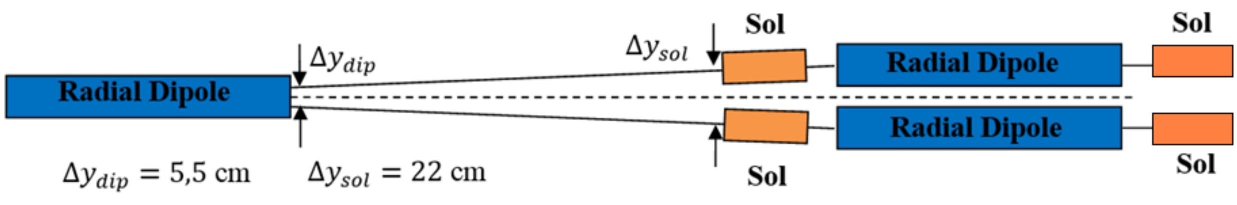

Fig. 4. Placement of weak control solenoids in vertical plane together with radial dipoles.

3.3.7 Ion polarization control in ST regime by means of two snakes

Two solenoidal snakes installed symmetrically in respect to both MPD and SPD set-ups will provide ST regime in NICA collider (Fig.5).

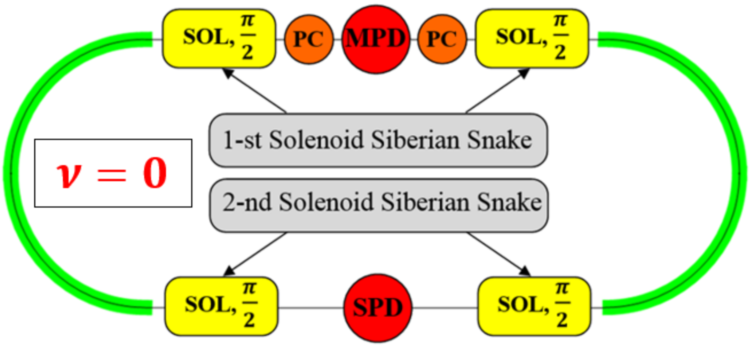

Fig. 5. Scheme of realization ST regime in NICA Collider.

The configuration make it possible to turn the spin in vertical plane (*yz*) of MPD or SPD detector, whereas in the collider magnet arcs the polarization vector is moving in the median plane (*xz*) [4]. From the spin dynamics point of view our system is equivalent to the "figure 8" electron-ion collider LEIC that is designed at the Jefferson Lab (USA).

The ST scheme with two snakes provides the zero spin tune at any point of the particle energy. It is very important for optimization of the NICA effective operation at the highest possible luminosity of pp – collisions, due to necessity of the particle store at an energy level that gives proper conditions for electron cooling of stored beam. Only in this case it is possible to form particle bunches with high number of particles and high degree of the polarization at low energy (about 1.5-2.4 GeV) with further acceleration up to the experiment energy.

The total integral of longitudinal solenoidal field should reach 4x25 Tm per ring at the proton momentum of 13.5 GeV/c and 4x80 Tm for deuterons respectively. The distributed system consisting of a short solenoids is possible, i.e. In the case of 6T solenoids the total length of 4.2 m is sufficient to form a half-length snake.

It is possible to adopt the collider lattice structure optimized for heavy ion beam for the case of ST regime at the protons mode over the total energy range. Weak control solenoids don't disturb practically orbital motion in the collider whereas, strong solenoids of the snakes led to a strong betatron tunes coupling. Because longitudinal field of the snakes is changed proportionally to the particle momentum, the collider magnetic optics will stay adequate to the polarized particle stable motion during the beam acceleration phase.

Matching of the solenoids with the collider structure is provided by means of proper choice of the work point by means of structural *KF* (focusing) and *KD* (defocusing) quadrupole lenses.

Possible scheme of the distributed snake (one half) based on short 6T superconducting solenoids (SC) is shown in Fig. 6. The elements are the following: SOL – SC solenoid, FFQ - final focus triplet of the collider, VB – structural dipole magnets; RB - bending dipoles with transverse field for converging the bunches in the collision point IP.

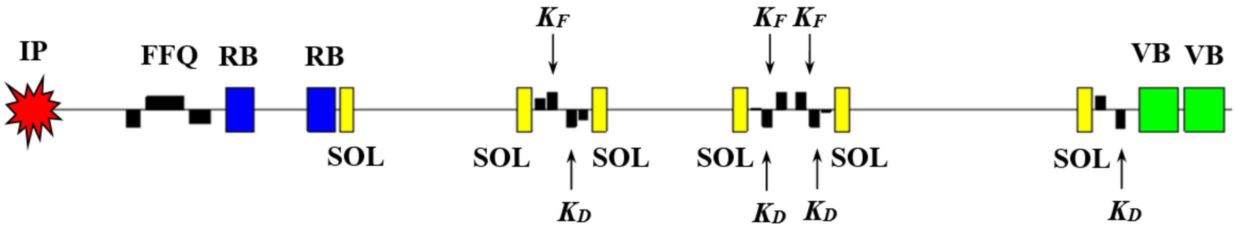

Fig.6. Distributed snake (one half) based on short 6T SC solenoids.

3.3.8. Stability of spin motion

In the ST regime precession of the polarization vector is caused by the field of solenoids, by the field imperfections of the collider lattice elements, by a finite beam emittance and depends on a power of zero spin tune resonance. To stabilize the polarization during acceleration process or during control the polarization direction in the ST regime it will be necessary to provide spin tune level caused by the control solenoids much higher of a power of zero spin tune resonance: $\nu \gg \omega$. The calculations have showed that the level of 10^{-2} for protons and 10^{-4} for deuterons would be sufficient. These values put limitations on the minimum field integral in each of weak control solenoids – 0.6 T·m.

3.3.9. Polarized beams dynamics in Nuclotron

Stable polarization direction in the Nuclotron is vertical, and the spin tune is proportional to the beam energy: $\nu = \gamma G$ (G — anomaly part of the gyromagnetic ratio of the particle, γ – Lorentz factor) that definitely lead to crossing of spin resonances during the particle acceleration and, as consequence, to resonance depolarization of the beam. There is no problem with deuterons: the only one integer spin resonance can be excluded by means of weak solenoid (~ 0.1 Tm) inserted into the accelerator lattice. The number of different spin resonances in the proton mode is much larger. Logarithmic graphs of linear spin resonances power scaled to the specific power w_D corresponding to complete depolarization of the beam are presented in Fig.7 [5,6]. The proton energy range E_p corresponds to the available at Nuclotron. Each graph is divided onto three areas that correspond to intermediate crossing (between horizontal lines), fast crossing (below green line) and adiabatic crossing (upper blue line). The lines of a fast and adiabatic crossing are corresponding to 1% loose of the polarization degree.

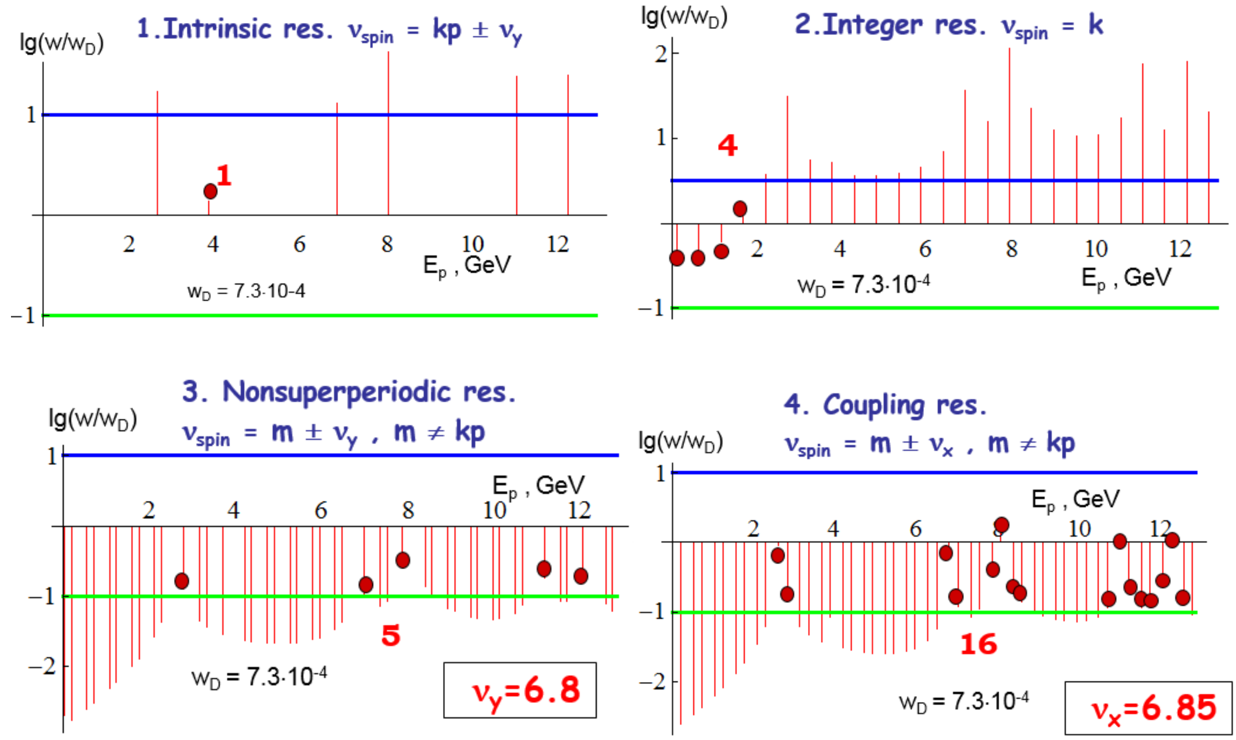

Fig. 7. Linear spin resonances in the Nuclotron at polarized proton mode.

The parameters taken for calculation of the resonances power were the following: the magnetic field ramp — 1 T/s; beam emittance (horizontal and vertical) at the injection energy - 45 π mm·mrad; quadrupole misalignment errors – 0.1 mm; errors of angular alignment of structural dipole and quadrupole magnets - 0,01 rad; and the relative error of the quadrupole gradients - 0,001.
The resonances marked with red circles are dangerous and lead to the beam depolarization after their crossing. To keep the polarization of proton beam at proper level, partial Siberian snake based at a solenoid will be used. Two options have been considered: 1). The use of a weak 5% snake with the field integral of 0.65 T·m, which can save the proton beam polarization up to 3.4 GeV/c and 2). The use of 25% snake (~ 12 T·m). The first one is efficient if the collider operates in the ST regime with two snakes and injection of the beam is provided at low energy (around 1 GeV), whereas strong enough snake that is used in option 2 could save the polarization over the total energy range in the Nuclotron and is suitable to the operation at integer resonances. The choice of energy points is limited to the points of integer resonances.

3.3.10. Operation modes of the NICA collider at polarized beams

Collider NICA with two solenoidal snakes will make it possible the following operation configurations (see Table 2) [7]

Table 2. Polarization in the SPD and MPD detectors in PS and ST regimes

Snake SPD	Snake MPD	Spin tune	Control regime	Polarization in SPD	Polarization in MPD
off	off	$\gamma G \neq k$	PS	vertical	vertical
off	off	$\gamma G = k$	ST	any	any
off	on	½	PS	longitudinal	in the collider median plane, direction angle depends on energy
on	off	½	PS	in the collider median plane, direction angle depends on energy	longitudinal
on	on	0	ST	any	any

If the snakes installed in SPD and MPD sections are switched off, the PS regime with vertical polarization at any point of the collider orbit is occurred. Some narrow energy gaps which the ST regime at integer resonances is exists in, gives possibility to have any direction of the polarization in the both detectors. After switching one of the snakes on, the collider will operate in PS regime with the spin tune ½. The snake transform completely spin motion providing stable longitudinal direction of the polarization in opposite respect to the snake section of the collider orbit.
If two dynamic solenoid snakes are switching on, the unique spin transparency (ST) regime is realized. The spin tune don't depend on particle energy and equal to zero that's gives possibility to obtain any direction of the polarization at any point of the collider orbit. The features of the collider operation in polarized modes are shown in Table 3.

Table 3.

Snake SPD	Snake MPD	Spin tune	Polarization control regime	SF система	On-line контроль поляризацией	Possibility of acceleration regime in the collider	Influence of RF modulation on the polarization lifetime
off	off	$\gamma G \neq k$	PS	no	no	no	reduce
off	off	$\gamma G = k$	ST	yes	yes	no	reduce
off	off	½	PS	no	no	yes	no influence
on	off	½	PS	no	no	yes	no influence
on	on	0	ST	yes	yes	yes	no influence

It is very important to realize the possibility of polarized beam acceleration in the NICA collider without loose the polarization degree. The problem of reaching the highest possible luminosity of polarized proton collisions is connected with the particle multi-bunch storage in the collider and electron cooling of the stored beam during the process. The optimal proton beam kinetic energy at the beam injection into the collider is about 1 GeV [8,9].

3.3.11. Conclusion and outlook

The proposed scheme of ion polarization control in NICA collider is adopted easily to the collider magnetic optics at any regimes of the polarization control. Important advantages could be obtained with the applying spin transparency regime. Polarization degree of about 70% is provided at the collision points. The polarization life time is expected to be at the level of hours comparable with the beam life time. We didn't describe some specific measurement and monitoring systems should be designed at the stage of preparation technical project. In particular: precise measurement of the luminosity (bunch-to-bunch?), absolute polarimeter based on a gas jet, targeting stations etc.

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