Spin Transparency Mode in the NICA Collider with Solenoid Siberian Snakes for Proton and Deuteron Beam

A D Kovalenko¹, A V Butenko¹, V A Mikhaylov¹, M A Kondratenko², A M Kondratenko², and Yu N Filatov¹,³

¹Joint Institute for Nuclear Research, 141980, Dubna, Russia
²Science and Technique Laboratory “Zaryad”, 630090, Novosibirsk, Russia
³Moscow Institute of Physics and Technology, 141700, Dolgoprudny, Russia

¹kovalen@dubna.ru

Abstract. Two solenoid Siberian Snakes are required to obtain ion polarization in spin transparency mode of the NICA collider. The snake solenoids with a total field integral of 2×50 T⋅m are placed into the straight sections of the NICA collider. It allows one to control polarization of protons and deuterons up to 13.5 GeV/c and 4 GeV/c respectively. The snakes introduce a strong betatron oscillation coupling. The calculations of orbital parameters of proton and deuteron beams in the NICA collider with solenoid Snakes are presented.

1. Ion colliders in the “Spin transparency” mode

The NICA (Nuclotron-based Ion Collider fAcility) collider at the Joint Institute for Nuclear Research (Dubna, Russia) is designed to provide high polarization of both protons and deuterons colliding beams. To control ion polarization the NICA collider is set up in a “spin transparency” mode [1]. “Spin transparency” means that total effect of all magnetic fields along design orbit on the spin is reduced to zero. Thus, any spin direction repeats after a particle turn. Particles are in the region of a zero-integer spin resonance and the spin tune is zero. Colliders transparent to the spin offer a unique opportunity to efficiently control the ion polarization using small quasi-stationary magnetic field.

The natural example of a collider transparent to the spin is the Jefferson Lab Electron Ion Collider (JLEIC) with figure-8 shaped rings [2]. The conventional NICA collider becomes “transparent to the spin” due to introduction of two identical solenoidal snakes into its opposite straight sections.

Let us demonstrate the main features of the ion polarization control in the “spin transparency” mode comparing the JLEIC and NICA colliders with the RICH collider [3]. Table 1 shows a general information and ability to use these colliders in the “spin transparency” mode. The spin tune at RHIC is equal to one half and does not depend on energy as well, but there is no “spin transparency”.

| Collider      | Momentum range, GeV/c | Colliding particles | Spin Tune | Spin Transparency |
|---------------|------------------------|---------------------|-----------|-------------------|
| RHIC (BNL)    | 25-250                 | pp                  | 1/2       | –                 |
| JLEIC (JLAB) (figure-8) | 8-100              | eN                  | 0         | +                 |
| NICA (JINR)   | 2.5-13.5               | NN                  | 0         | +                 |

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The independence of the spin tune on the beam energy solves a problem of the polarization preservation during beam acceleration. In colliders, a crucial task is not only preservation of the polarization during the energy ramp but also its control at the interaction points during experiments. Table 2 shows information about ion polarization control at the considering colliders.

**Table 2. Ion Polarization Control.**

| Collider  | Spin Rotators based on | Polarization Direction at IP | Spin Flipping          |
|-----------|------------------------|------------------------------|------------------------|
| RHIC (BNL) | ‘strong’ magnetic fields | Any directions *without deuterons* | A few min Change       |
| JLEIC (JLAB) | ‘weak’ solenoids   | Any directions *any particles: p, d, He* | A few ms Do not change |
| NICA (JINR)  | ‘weak’ solenoids   | Any directions *any particles: p, d, He* | A few ms Do not change |

At RHIC polarization is controlled using a pair of spin rotators with “strong” fields, which provide the required spin orientation at an interaction point and then return the spin to its original direction. This process changes not only the polarization direction but the trajectories of the beam particles as well. This causes a change in the orbital characteristics of the beam. There are betatron tune shifts, changes in dispersion, beta-functions, luminosity, etc. Accounting for the changes in the beam orbital characteristics becomes a problem when doing experiments with polarized beams in colliders.

In colliders with spin transparency, any small perturbation has a strong effect on the beam polarization. To stabilize the spin direction, one must introduce spin rotators based on “weak” fields into the collider’s lattice, which “shift” the spin tune by a small value (\(\nu \ll 1\)) and set the necessary orientation of the polarization. The required “weak” field integrals are significantly lower than the field integrals used in the RHIC spin rotators and are limited by the strength of the zero-integer spin resonance \(w_0\): \(\nu \gg w_0\). What especially stands out is the possibility of using weak solenoids, which do not impact the closed orbit at all. Spin rotators based on “weak” solenoids have essentially no effect on the beam’s orbital characteristics during adjustment of the beam polarization direction.

There is a possibility to implement a spin flipping system based on the spin rotators. Spin flipping system allows one to make spin reversal during. At RHIC spin reversal time is determined by the time of strong field variation and is about of few minutes. At JLEIC and NICA in spin transparency mode spin reversal time is about few milliseconds. Due to orbital parameters become unchanged during spin manipulation in spin transparency mode the luminosity of colliding bunches does not change at JLEIC and NICA. Thus, spin transparency mode allow one to carry out high precision experiments with polarized ions.

Let us emphasize that the ion polarization control scheme in spin transparency mode is universal for all particle species including both protons and deuterons, while obtaining longitudinal deuteron polarization at RHIC presents a serious problem.

2. The NICA collider in spin transparency mode

The scheme of polarization control is based on the use of two types of solenoids, namely, strong-field solenoids and weak-field solenoids (see figure 1). The strong-field solenoids are used for Siberian snakes, which create the “spin transparency” mode in the NICA collider. Two solenoidal snakes are inserted in the opposite straight sections of the racetrack-shaped collider. The snakes are divided symmetrically onto two parts by MPD and SPD setups. Such snake design allows one to control the beam polarization in vertical plane of SPD and MPD detectors while the polarization lies in the plane of the collider in the NICA arcs.
Figure 1. Polarization control scheme at the NICA collider in spin transparency mode.

The weak-field solenoids with small integral of the longitudinal field are used directly for the control of the beam polarization of any particle species ($p$, $d$, $^3$He, …) in any orbit place by means of polarization control insertions (PC insertions) [4]. For example, it is possible to arrange both vertical and longitudinal directions of the beam polarization in MPD and SPD detectors. One can obtain any spin direction in the collider arcs, which is necessary for the matching of the polarizations during the beam injection from Nuclotron. One can provide the spin reversals in the detectors during an experiment (spin flipping systems) [5].

3. Orbit matching of the snake solenoids to the NICA collider lattice
The PC insertions weak solenoids do not influence on the collider orbital characteristics. On the contrary, the snake solenoids introduce a strong coupling of the betatron oscillations. The snake solenoid fields are proportional to the momentum and the collider optics remains unchanged during the beam acceleration.

The total solenoid field integral required for the snake can be obtained in parts by inserting solenoids into available spaces of the NICA straight section. We choose design of the one snake which consist of eight solenoids of 1.2 m length each. At maximum momentum of 13.5 GeV/c the solenoid field is 6 T. It allows one to control polarization in the total momentum range for protons and up to 4 GeV/c for deuterons. Figure 2 shows placement of the snake and PC insertion solenoids into the collider half straight section. Here SOL are snake solenoids, PC are polarization control solenoids, FFQ are final focus quadrupoles, VB are arc’s vertical-field bending magnets and RB are radial-field bending magnets, which provide beams collisions at interaction point IP.

Figure 2. Placement of the snake solenoids in the NICA half straight.

Two families of focusing $K_F$ and defocusing $K_D$ quadrupoles are used for matching the snake solenoids to the collider optics. Additional quadrupoles for compensation of the coupling of the betatron oscillations are not used in our matching scheme [6].

Let us give an example of the snake solenoids matching, when the values of the $\beta$- functions at interact points of MPD and SPD detectors remain the same as for the case of NICA without snakes. The $\beta$-functions for NICA with proton and deuteron snakes are shown in figures 3. The deviation $\delta K_F$ and $\delta K_D$ of gradients $K_F$ and $K_D$ in unit of the magnetic rigidity are indicted on the graphs. Proton snakes practically do not change beam’s orbital parameters. Deuteron snakes increase values of $\beta$-functions in the collider arcs which can be compensated by optimization of the collider straights sections lattice.
Conclusion
The spin transparency mode in the NICA collider opens wide opportunities to carry out high quality experiments with polarized proton and deuteron beams. The presented examples of the snake solenoids matching to the NICA collider lattice without compensation of betatron oscillations coupling demonstrate that the spin transparency mode in the NICA collider looks feasible for proton and deuteron beams in the real collider lattice.

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