ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB041

SPIN RESONANCE STRENGTH IN THE TRANSPARENT SPIN MODE OF THE NICA COLLIDER

Yu. N. Filatov, S. V. Vinogradov, MIPT, Dolgoprudniy, Moscow Region, Russia
A. M. Kondratenko, M. A. Kondratenko, STL "Zaryad", Novosibirsk, Russia
A. D. Kovalenko, JINR, Dubna, Russia

Abstract

To implement the polarization program at the NICA complex (Dubna, Russia) the novel mode of ion polarization control — the transparent spin mode — is planned to use. To set up the transparent spin mode in the NICA collider two solenoidal snakes will be placed in straights of the Multi Purpose Detector (MPD) and the Spin Physics Detector (SPD). The beam polarization at SPD will be controlled by means of "weak" solenoids. The main characteristic of the transparent spin mode is the spin resonance strength, which consists of two parts: a coherent part arising due to additional transverse and longitudinal fields on the beam trajectory deviating from the design orbit and an incoherent part associated with the particles' betatron and synchrotron oscillations (beam emittances). The resonance strength allows one to formulate requirements on the magnitudes of the control solenoids' fields. The theoretical analysis, calculation and spin tracking simulation of the spin resonance strength in the whole momentum range of the NICA collider are presented.

INTRODUCTION

Different experiments are planning with polarized proton, deuteron and helium-3 (in the future) to identify and study different observables for different physics tasks at the SPD set-up. The polarization control system should provide the followings: 1) longitudinal and transverse polarization at the MPD and SPD interaction points with the polarization degree not less 70% and the polarization lifetime comparable to the beam lifetime; 2) the collision luminosity of $10^{30} - 10^{32}$ cm^{-2}·c^{-1} over the particle momentum range from 2 to 13.5 GeV/c; 3) the collision energy scan with specified step (from 1.0 GeV to 0.3 MeV). Operation in asymmetric (for example *pd*–collision) mode is foreseen also [1].

DISTINCT SPIN MODE AT RHIC

At the present time, RHIC is the only facility that operate in polarized proton mode [2]. To provide long-term stability of polarization (a few tens of hours) two helical snakes, which eliminate the influence of synchrotron oscillations on the spin, are inserted in opposite straights of the collider. The snakes rotate the spins over 180° about their axes oriented at +45° and −45° with respect to the beam direction (the snakes' axes are perpendicular). The collider operates in the "Distinct Spin" (DS) mode, the magnetic lattice determines a single stable orientation of the beam polarization. The dynamics of the stable polarization direction along the ring is as follows: first, the spin initially directed vertically saves this orientation in the first arc, then the spin is flipped by the first helical snake and after that it keeps the flipped vertical direction in the second arc and, finally, restores its initial vertical orientation after the flipping by the second snake. Any polarization in the arc lying in the collider plane after one particle turn on the design orbit changes its direction to the opposite, which means that the spin tune is 1/2. To obtain longitudinal polarization, two spin rotators located directly in front of and after the detector are used [3]. The total integral of the transverse field in spin rotators and snakes is about 100 T·m. The RHIC polarization control scheme is not suitable for deuterons.

TRANSPARENT SPIN MODE AT NICA

In the "Transparent Spin" (TS) mode, any polarization direction is repeated after particle's each turn, i.e. the magnetic lattice of the collider is transparent to the spin [4, 5], and the spin tune is equal to zero. Two solenoidal snakes symmetrically located around the SPD and MPD setups provide a long-term polarization stability (see Fig. 1). The axes of the snakes are parallel that keeps the zero spin tune over the total energy range.

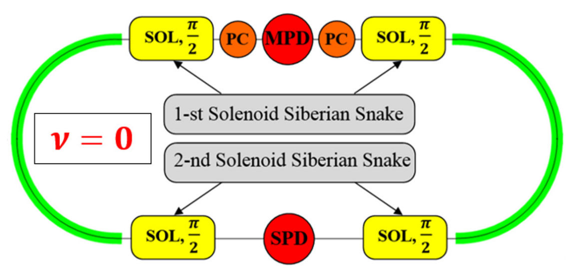

Figure 1: Polarization control at the NICA's TS mode.

Solenoidal snakes do not change the design orbit. Since the field integral in the snake changes proportionally to the particle momentum, the lattice functions of the orbital motion also remain constant. At the maximum momentum, the total integrals of the longitudinal field for snakes per one ring are approximately of 100 T·m for protons and of 360 T·m for deuterons. One can distribute short solenoids along the experimental straights to form the snakes [4, 6]. In the case of 6 T solenoids the total length of proton half-snake is of 4.2 m (see Fig. 2).

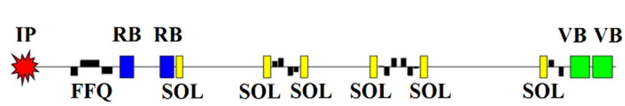

Figure 2: Distributed solenoidal snake (one half).

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB041

The elements are the following: *SOL* are the solenoids, *FFQ* is final focus triplet of the collider, *VB* are structural dipole magnets, *RB* are bending dipoles with transverse field for converging the bunches in the collision point *IP*.

In the TS mode polarization is controlled by "weak" solenoids, which require significantly smaller field integrals than in the spin rotators of the DS mode. Two polarization control (PC) insertions based on "weak" solenoids (marked as orange circles on Fig. 1) are placed symmetrically around MPD. The PC insertions allow to stabilize the required polarization direction at any place of the collider ring, including the interaction points, injection points, etc. In each PC insertion two weak solenoids with longitudinal field B_{z1} and B_{z2} are placed around the structural dipoles with radial field B_x, providing deflection the beams to the collision plane of the MPD (see Fig. 3).

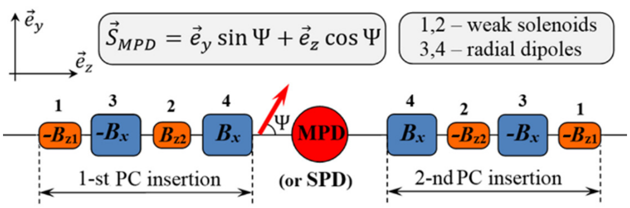

Figure 3: Scheme of the polarization control (PC) insertions in the NICA collider's TS mode.

The scheme makes it possible the ion polarization control in the vertical plane (yz) in MPD or SPD (Ψ is the angle between polarization and particle velocity vectors). The presented scheme is optimal for protons. It can also be used for deuterons, however, the efficiency of control will be reduced by an order of magnitude. For optimal control of the deuteron polarization, arc dipoles can be used by inserting two additional solenoids in the middle part of the arcs [5].

The value of the control weak solenoids is limited by polarization stability condition: one must ensure that the spin tune induced by the solenoids significantly exceeds the strength of the TS-resonance, determined by the orbital emittances and by imperfections of the collider lattice (construction and alignment errors). To determine the required minimum values of the field integrals of the control solenoids, the resonance strength was analyzed over the total energy range.

TS-RESONANCE STRENGTH

The resonance strength over the whole NICA energy range was calculated in paper [7]. In this paper only radial perturbing fields were taken into account, which make the main contribution to the resonance strength in the absence of the betatron oscillations coupling. However, in the presence of a strong coupling, the vertical disturbing fields can also make a contribution comparable to the radial fields. The paper [8] presents the development of the response functions method in the TS mode, which allows one to calculate the contribution to the resonance strength of all components of the disturbing fields in any optical lattice, including the presence of a strong coupling of betatron oscillations. The influence of periodic perturbing fields ΔB_x,ΔB_y, ΔB_z on the spin is described by three periodic vector response functions, namely: radial $\vec{F}_x$, vertical $\vec{F}_y$ and longitudinal $\vec{F}_z$, which are determined by the design collider lattice

$$\vec{\omega} = \frac{1}{2\pi}\int_0^L \left(\frac{\Delta B_x}{B\rho}\vec{F}_x + \frac{\Delta B_y}{B\rho}\vec{F}_y + \frac{\Delta B_z}{B\rho}\vec{F}_z\right) dz\,,$$

where $B\rho$ is a magnetic rigidity, L is the orbit's length.

In the spin reference frame, related with the spins dynamics when particle moves along the design orbit, the polarization rotates around the averaged spin field $\vec{\omega}$, whose magnitude is equal to the TS-resonance strength: $\omega = |\vec{\omega}|$.

The transverse response functions change proportionally γG, therefore, transverse field perturbations have the main influence on the proton polarization at high energies. The longitudinal response function does not grow with increasing energy. Figure 4 shows dependence of absolute values of transverse response functions on distance along the design orbit z for protons at maximum momentum of 13.5 GeV/c.

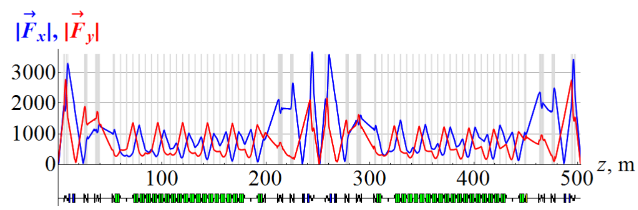

Figure 4: Radial $|\vec{F}_x|$ and vertical $|\vec{F}_y|$ response functions for protons at 13.5 GeV/c.

The rms value of the ST-resonance strength in the statistical model is calculated as follows:

$$\omega^2 = \sum_{\text{elem}} \frac{\left(\langle\Delta B_x^2\rangle|F_x|^2 + \langle\Delta B_y^2\rangle|F_y|^2 + \langle\Delta B_z^2\rangle|F_z|^2\right) L_{el}^2}{4\pi(B\rho)^2}\,.$$

Here $\langle\Delta B_x^2\rangle^{1/2}$, $\langle\Delta B_y^2\rangle^{1/2}$, $\langle\Delta B_z^2\rangle^{1/2}$ are the rms errors of the radial, vertical and longitudinal magnetic fields in an element of the lattice, and L_{el} is the element's length.

Random quadrupole shifts in vertical and radial directions give the main contribution to the TS-resonance strength in the NICA collider. Figure 5 shows the proton TS-resonance strength as a function of momentum in NICA with random quadrupole misalignments. The rms of the closed orbit deviation ρ_{rms} from the design orbit is about of 1 mm (see Fig. 6). The TS-resonance strength does not exceed the value of $2 \cdot 10^{-3}$ practically over the whole proton momentum range. The resonance strength has two interference peaks in the momentum regions of 8 and 13.5 GeV/c. The spin tune about of 10^{-2} is sufficient to stabilize the proton polarization by weak PC-solenoids. The maximum field integral per one solenoid in the scheme presented in Fig. 3 is of 0.6 T·m.

Figure 7 shows a graph of the deuteron TS-resonance strength calculated using the statistical model of random

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB041

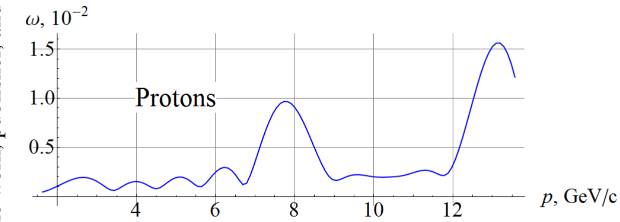

Figure 5: The TS-resonance strength for proton beam.

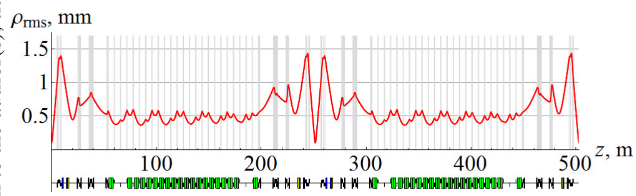

Figure 6: The rms closed orbit deviation.

quadrupole misalignments. The spin tune about of of $2 \cdot 10^{-3}$ is sufficient to stabilize the deuteron polarization, which require the maximum field integral about of 0.15 T·m per one weak solenoid inserted in the middle of the arcs.

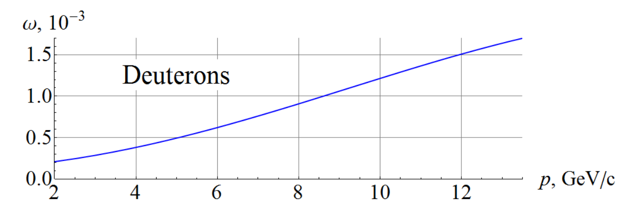

Figure 7: The TS-resonance strength for deuteron beam.

SPIN TRACKING SIMULATION

To demonstrate the influence of random quadrupoles' shifts on polarization, let us present calculations of the spin dynamics during acceleration of a proton in NICA made using a spin tracking code Zgoubi [9]. In the calculations, the closed orbit excursions caused by random quadrupole shifts are shown in Fig. 8.

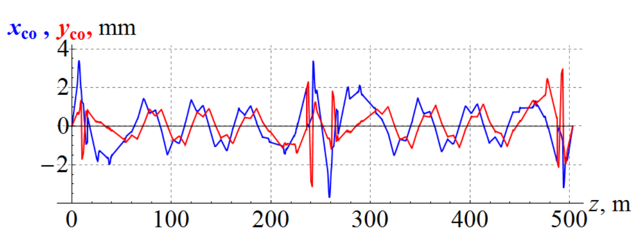

Figure 8: Radial and vertical orbit excursions with random misalignments of all quadrupoles in NICA (Zgoubi).

Figure 9 shows the spin components in NICA with quadrupole shifts during acceleration of a proton when particle moves along the closed orbit.

The spin dynamics during acceleration in NICA is a precession about the spin field $\vec{h}$, which consists of the field induced by the stabilizing solenoids and the resonance strength. The spin tune induced by weak solenoids during acceleration is 10^{-2}. The weak solenoids stabilize the longitudinal

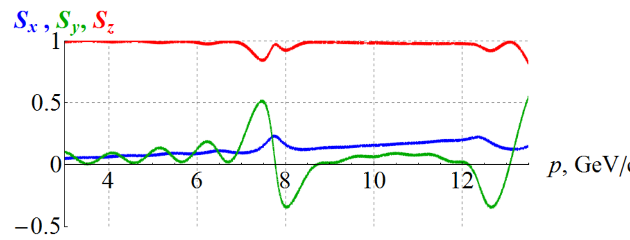

Figure 9: Proton spin components in NICA with the quadrupole misalignments during acceleration (Zgoubi).

polarization direction in the detector. During adiabatic acceleration, the spin follows the $\vec{h}$ field direction. As we can see, the spin practically does not deviate from longitudinal direction over the whole momentum range except two regions which correspond the locations of the interference peaks of the the resonance strength (see Fig. 5). Since the vertical spin component in the regions of the interference peaks deviates about of 0.5, the resonance strength in these peaks is comparable to the induced spin tune and is about of 10^{-2}. Thus, the spin tracking results are in good agreement with the analytical calculations.

CONCLUSION

The ST-resonance strength is calculated by means of spin response functions in NICA with a strong coupling of betatron oscillations. The calculations allow one to formulate the requirements for the field integrals of "weak" solenoids for the polarization control of protons and deuterons in the whole energy range in the ST mode of NICA.

REFERENCES

[1] A.D. Kovalenko *et al.*, "NICA Facility in Polarized Proton and Deuteron Mode", *Int. J. Mod. Phys.Conf. Ser.*, vol. 40, no. 01, p. 1660096, 2016, doi:10.1142/S201019451660096X

[2] M. Harrison, S. Peggs, and T. Roser, "The RHIC accelerator", *Ann. Rev. Nucl. Part. Sci.*, vol. 52, no. 1, pp. 425–469, 2002.

[3] V.I. Ptitsin, and Yu.M. Shatunov, "Helical spin rotators and snakes", *Nucl. Instr. Meth. A*, vol. 398, pp. 126–130, 1997.

[4] Yu.N. Filatov *et al.*, "Spin transparency mode in the NICA collider", *EPJ Web Conf.*, vol. 204, p. 10014, 2019.

[5] A. D. Kovalenko *et al.*, "Ion Polarization Control in the MPD and SPD Detectors of the NICA Collider", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 2031–2033.

[6] A.D. Kovalenko *et al.*, "Orbital parameters of proton and deuteron beams in the NICA collider with solenoid Siberian snakes ", *J. Phys.: Conf. Ser.*, vol. 678, p. 012022, 2016.

[7] A.D. Kovalenko *et al.*, "Numerical calculation of ion polarization in the NICA collider ", *J. Phys.: Conf. Ser.*, vol. 678, p. 012023, 2016, doi:10.1088/1742-6596/678/1/012023

[8] Yu.N. Filatov *et al.*, "Response function formalism for the transparent spin mode", to be published.

[9] F. Méot, "The Ray-Tracing Code Zgoubi ", *Nucl. Instr. Meth A*, vol. 427, pp. 353-356, 1999.