Kinematics of proton and deuteron beam polarization in the transparent spin mode of the NICA collider

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Abstract. For experiments with polarized protons and deuterons, the NICA collider is planned to be used in the transparent spin mode, which is provided by two solenoid snakes. The required direction of polarization in the SPD detector is set by "spin navigators", which are insertions that rotate the spins at small angles. The polarization outside the SPD detector is determined by arc dipoles and the placement of snake solenoids in the collider. The kinematics of beam polarization is calculated when vertical, longitudinal or radial polarization is set in the SPD detector for different schemes of placement of snake solenoids. The results are relevant to solve the problems of injection and polarimetry for conducting experiments with polarized beams in the spin transparency mode.

1. Transparent Spin mode in the NICA collider

Transparent Spin (TS) mode meets all the requirements for research with polarized protons and deuterons in the NICA collider [1, 2, 3], namely:

- completely eliminates resonant depolarization during beam acceleration to experimental energy,
- maintains long-term polarization during an experimental run,
- provides longitudinal and transverse polarization in SPD (Spin Physics Detector) or MPD (Multi-Purpose Detector) in the whole energy range,
- allows flexible manipulation of the polarization direction at any orbital location during the whole time of an experiment,
- allows one to organize a spin-flip system to minimize systematic errors.

The TS mode in the NICA collider is provided by two full snakes inserted in opposite straight sections of the collider. Each snake based on solenoids is divided symmetrically into two halves around SPD and MPD as shown in figure 1 [2, 3]. The required integral of the longitudinal field is proportional to the momentum and reaches the value per the half-snake of 25 T·m for protons and 80 T·m for deuterons at a maximum momentum of 13.5 GeV/c.

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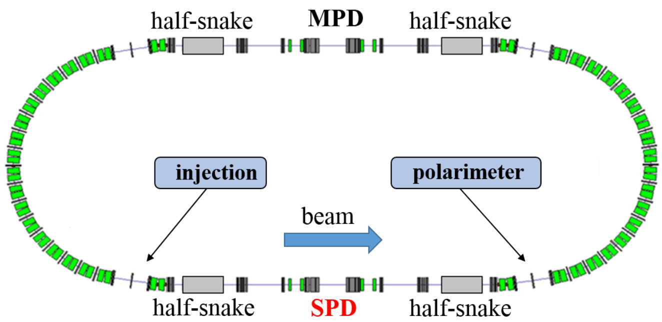

Figure 1. Placement of solenoid snakes in the NICA collider.

Figure 2 shows in more detail the placement of the solenoids in each half-snake. The elements are the following: SOL is a solenoid, FFQ is a final focus triplet, VB are structural dipole magnets, RB are bending dipoles with radial field for converging the bunches in the collision point of SPD (or MPD). In the case of 6 T solenoids the length of each solenoid of 0.7 m is sufficient to operate with protons in the whole momentum range.

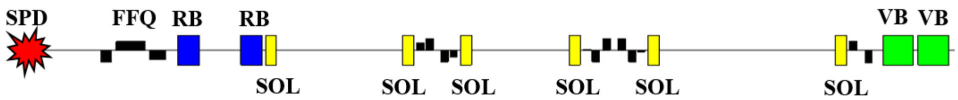

Figure 2. Placement of the half-snake's solenoids in the NICA straight section.

The TS mode can also be arranged without snakes for discrete energy values that correspond to integer spin resonances $\gamma G = k$. Here γ is a relativistic factor, G is an anomalous part of the gyromagnetic ratio. For protons the number of such energy values is of 25 with the energy step of 0.523 GeV. For deuterons there is only one point with the total energy of 13.1 GeV.

In an ideal collider lattice, the spin motion becomes degenerate: any spin direction at any orbital location repeats every particle turn. This means that the spin tune in the TS mode is zero and the particles are in a TS resonance. In such a case the spin motion is highly sensitive to small perturbations of the magnetic fields, which are associated with lattice imperfections as well as with betatron and synchrotron particle's oscillations. In a real situation, spin degeneracy is removed, since the polarization becomes stable along an unknown direction determined by the collider lattice imperfections. Polarization control is provided by spin navigators, which are devices based on weak solenoids that set the required direction of polarization at the SPD interaction point. The effect of the navigator on spin should significantly exceed the effect of the small perturbative fields [4].

Scheme of polarization control in the TS mode is presented in figure 3. Two spin navigators symmetrically placed around SPD are used to stabilize the required polarization direction at the SPD vertical plane (Ψ is the angle between polarization and particle velocity vectors) [3].

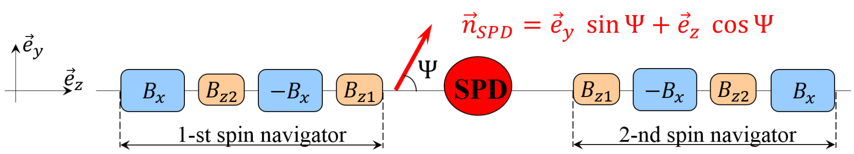

Figure 3. Schematic for control of ion polarization in the vertical plane of SPD.

In each navigator 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 SPD interaction point. The scheme provides polarization control over NICA energy range if the field integral will reach 0.6 T·m in each of four solenoids. The control solenoid length is of 40 cm if the maximum field is of 1.5 T [3].

The purpose of the navigator is to “point out” the direction of polarization in SPD. Outside of SPD, the polarization kinematics is determined by strong arc dipoles and snake solenoids. The relation between polarization directions in SPD and MPD was considered earlier in paper [5]. Here we consider an issue of where the polarization will be directed at the injection and the polarimeter places, which are indicated in figure 1, for a given direction of polarization in SPD. This information is necessary for matching the direction of polarization of the injected beam with a stable direction of polarization in the collider in order to eliminate partial or complete polarization loss due to the spin tune spread. Since the polarimeter measures the transverse component of polarization, it is important to know its value at the polarimeter place.

2. Numerical calculation of polarization dynamics in NICA

Let us consider the dynamics of polarized protons and deuterons in the NICA for the TS mode without snakes and the TS mode with two snakes.

2.1. The TS mode at integer spin resonances

Figure 4 shows the projections of the proton polarization as a function of the z coordinate along the orbit in the TS mode without snakes for energy corresponding integer spin resonance $\gamma G = 7$. The radial n_x, vertical n_y, and longitudinal n_z polarization components correspond to blue, green, and red curves. The frame origin coincides with the SPD interaction point. In the calculations, it was assumed that the magnetic fields at orbit in SPD and MPD are absent.

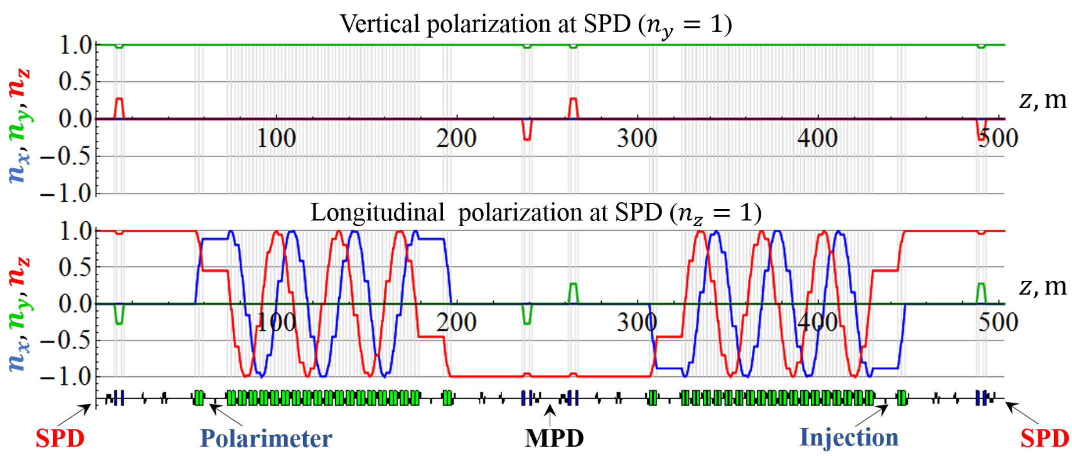

Figure 4. Dynamics of the proton polarization in the TS mode without snakes.

The polarization oriented vertically in the SPD remains vertical at the injection and polarimeter places, as well as in MPD for any energy. A small longitudinal component appears only in dipoles with radial fields, which deflect bunches to the SPD and MPD interaction points.

The polarization oriented longitudinally in the SPD lies in the collider plane ($n_y = 0$) almost everywhere. The angles between the directions of polarization and velocity at the injection place $\Psi_{\rm inj}$ and the polarimeter place $\Psi_{\rm pol}$ depend on the energy and are equal

$$\Psi_{\rm inj} = \gamma G\pi/20\,, \qquad \Psi_{\rm pol} = -\gamma G\pi/20\,.$$

Here $\pi/20$ is the orbit rotation angle after passing two arc dipoles. In our example, the angles Ψ_{inj} and Ψ_{pol} are equal $\pm 63°$. In MPD, polarization is directed against velocity, since the spin makes a half-integer number of turns in each arc. The maximum deviation of the polarization vector from the direction of velocity at the injection and the polarimeter places will be $\pm 234°$ for protons ($\gamma G = 26$) and $\mp 9°$ for deuterons ($\gamma G = -1$).

2.2. TS mode with four half-snakes

Figure 5 shows the projections of the deuteron polarization as a function of the z coordinate along the orbit in the TS mode with four half-snakes ($\gamma G = -0.4$).

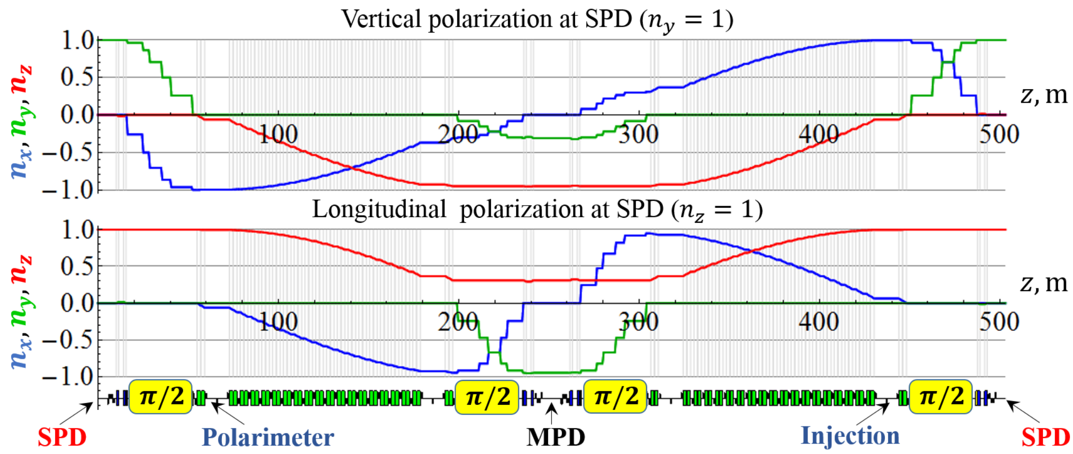

Figure 5. Dynamics of the deuteron polarization in the TS mode with four half-snakes.

The polarization oriented vertically in SPD is rotated by the first half-snake to the radial direction ($n_x = -1$), and then rotates in the collider plane ($n_y = 0$). Before MPD, polarization from the collider plane is transferred to the vertical MPD plane by the second half-snake. The angle between the directions of polarization and velocity in MPD depends on the energy

$$\Psi_{\text{MPD}} = \gamma G\pi - \pi/2\,.$$

After MPD, polarization from the vertical plane (yz) is again transferred to the collider plane (xz) by the third half-snake, then it rotates in the second arc ($n_y = 0$) and finally restores its vertical direction after passing through the fourth half-snake. The polarizations at the injection and the polarimeter places lie in the collider plane and have angles with the velocity given by Polarization oriented longitudinally in SPD performs a similar motion along the orbit, rotating in the collider plane in the arcs. The half-snakes of the MPD straight section transfer the polarization from the collider plane into the vertical MPD plane and return it back to the collider plane. The corresponding polarization angles with speed will be equal to

$$\Psi_{\text{inj}} = -\gamma G\pi/20 + \pi/2\,, \qquad \Psi_{\text{pol}} = \gamma G\pi/20 - \pi/2\,.$$

Polarization oriented longitudinally in SPD performs a similar motion along the orbit, rotating in the collider plane in the arcs. The half-snakes of the MPD straight section transfer the polarization from the collider plane into the vertical MPD plane and return it back to the collider plane. The corresponding polarization angles are equal to

$$\Psi_{\text{inj}} = -\gamma G\pi/20\,, \qquad \Psi_{\text{pol}} = \gamma G\pi/20\,, \qquad \Psi_{\text{MPD}} = \gamma G\pi\,.$$

Thus, in the TS mode with four half-snakes in the existing polarization control scheme (see figure 3), which allows one to set any direction of polarization in the SPD vertical plane, the polarization directions in MPD and the injection and polarimeter places depend on energy. However, if the spin navigator allows one to set the radial polarization in SPD, then these directions will no longer depend on energy (see figure 6). In this case, the polarization in the arcs will be directed along the vertical direction ($n_y = \pm 1$), and in MPD it will change its direction to the opposite one ($n_x = -1$).

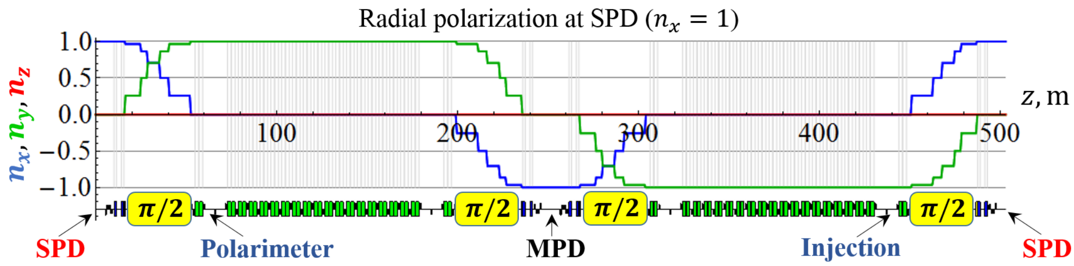

Figure 6. Dynamics of the deuteron polarization in the TS mode with four half-snakes.

2.3. TS mode with two full snakes

It is possible to provide independence on energy of the directions of polarization at places of MPD, injection and polarimeter in the existing polarization control scheme. It's enough to distribute the required longitudinal field integral for the full snake on one side of the detectors. Figure 7 shows the projections of the proton polarization as a function of the z coordinate along the orbit in the TS mode with two full snakes ($\gamma G = 6.2$).

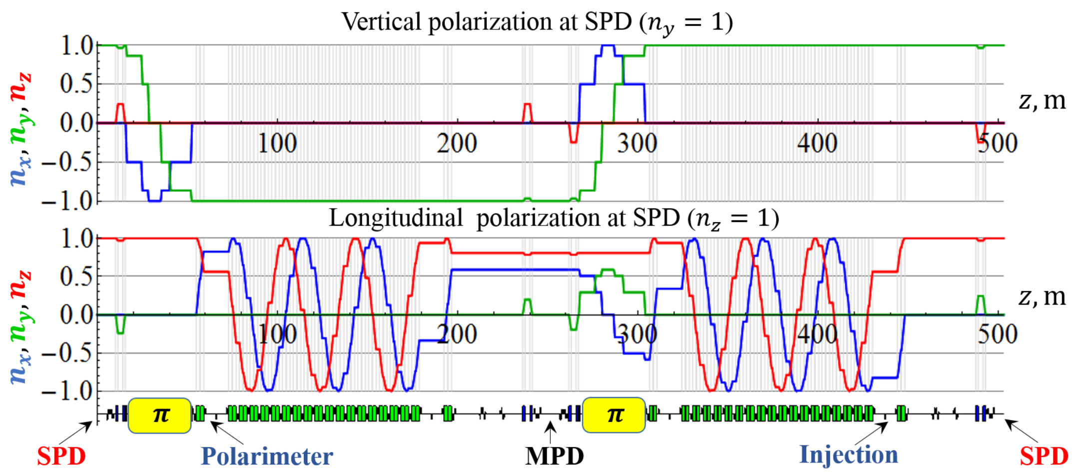

Figure 7. Dynamics of the proton polarization in the TS mode with two full snakes.

In this example, the polarization directed vertically at SPD remains vertical for any energy at places of MPD, injection and polarimeter. It should be noted that in the existing configuration of snake solenoids (see figures 1 and 2) the allowed momentum range in the TS mode with two full snakes will be reduced by half compared to the TS mode with four half-snakes. Table 1 shows the allowed momentum ranges to operate with protons and deuterons in the TS modes of the NICA collider, when the maximum field integral on each side of the detectors is 25 T·m.

Table 1. The allowed momentum range in the TS mode for protons and deuterons.

TS-mode configuration	**Momentum range**, GeV/c protons	deuterons
with four half-snakes	≤ 13.5	≤ 4.14
with two full snakes	≤ 6.75	≤ 2.07

Conclusion

Let us present a summary table 2 for protons and deuterons in the TS mode, which shows the directions of polarization at places of MPD, injection and polarimeter for a given initial polarization at SPD. Here $\vec{e}_x$, $\vec{e}_y$, $\vec{e}_z$ correspond to the radial, vertical and longitudinal polarizations, (xz) denotes the collider plane, and (yz) denotes the MPD vertical plane.

Table 2. Polarization direction at places of MPD, injection and polarimeter for a given polarization at SPD for protons and deuterons in the TS mode.

TS-mode scheme	**SPD**	**MPD**	**Injection** proton	deuteron	**Polarimeter** proton	deuteron
without snakes	$\vec{e}_x$	$\pm\vec{e}_x$	(xz)	$\approx \vec{e}_x$	(xz)	$\approx \vec{e}_x$
	$\vec{e}_y$	$\vec{e}_y$	$\vec{e}_y$	$\vec{e}_y$	$\vec{e}_y$	$\vec{e}_y$
	$\vec{e}_z$	$\pm\vec{e}_z$	(xz)	$\approx \vec{e}_z$	(xz)	$\approx \vec{e}_z$
with four half-snakes	$\vec{e}_x$	$-\vec{e}_x$	$-\vec{e}_y$	$-\vec{e}_y$	$\vec{e}_y$	$\vec{e}_y$
	$\vec{e}_y$	(yz)	(xz)	$\approx \vec{e}_x$	(xz)	$\approx -\vec{e}_x$
	$\vec{e}_z$	(yz)	(xz)	$\approx \vec{e}_z$	(xz)	$\approx \vec{e}_z$
with two full snakes	$\vec{e}_x$	(xz)	(xz)	$\approx -\vec{e}_x$	(xz)	$\approx \vec{e}_x$
	$\vec{e}_y$	$-\vec{e}_y$	$\vec{e}_y$	$\vec{e}_y$	$-\vec{e}_y$	$-\vec{e}_y$
	$\vec{e}_z$	(xz)	(xz)	$\approx \vec{e}_z$	(xz)	$\approx \vec{e}_z$

The presented data are relevant for solving the task of matching the direction of polarization during beam injection into the collider, as well as for developing methods for measuring polarization during experiments with polarized protons and deuterons in the NICA collider.

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