

Polarized deuterons in the spin transparency mode at the NICA accelerator complex

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Abstract

The specific features of spin dynamics control for polarized deuterons in the NICA accelerator complex (JINR, Dubna) are discussed. While the small deuteron G -factor simplifies the preservation of polarization during acceleration to relativistic energies, it simultaneously creates significant technical difficulties for controlling the spin orientation in the experimental area. Conventional spin-rotator methods based on strong transverse magnetic fields cannot be employed for deuterons, because they would demand unfeasibly large field integrals. As a solution, the spin transparency (ST) mode is proposed, which allows stabilizing any desired polarization direction at a given point of the orbit using spin navigators based on weak quasi-stationary magnetic fields. An analysis of deuteron polarization preservation in the Nuclotron and NICA collider rings is performed for different operating points of betatron tunes. For the NICA collider, two implementations of the ST mode are considered: at a single integer spin resonance ($\gamma G = -1$) at a momentum of 13 GeV/ c , and in a continuous energy range using two solenoidal snakes. The prospects for constructing a new figure-8 shaped injector for polarized deuterons are discussed, which provides the ST mode over the entire energy range without using snakes and also opens up opportunities for experiments with internal and external targets.

Keywords: polarized deuterons, NICA, spin transparency, spin navigators, solenoidal snakes, spin-flip

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1. Introduction

The study of spin-dependent effects in nuclear and subnucleonic interactions is one of the key directions of modern high-energy physics. A special place in this research is taken by experiments with polarized deuterons, which provide unique information about the structure of light nuclei at short internucleonic distances, as well as about the mechanisms of nucleon–nucleon (NN) interactions in the transition region from meson–nucleon to quark–gluon degrees

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of freedom. The spin-1 nature of the deuteron ensures a richness of polarization phenomena for nuclear and electromagnetic reactions involving it [1].

At the Joint Institute for Nuclear Research (JINR, Dubna) a research program with polarized deuterons has been under development for more than four decades — first at the Synchrophasotron, and then at the superconducting Nuclotron. A key milestone was the creation at the end of the 1970s of the unique cryogenic source of polarized deuterons, POLARIS [2], which in 1981 for the first time enabled the acceleration of a transversely polarized deuteron beam to relativistic energies at the Synchrophasotron. This source made it possible to launch an extensive program of measurements of polarization observables in reactions involving deuterons and secondary neutrons and protons. POLARIS was used for experiments with polarized particles at the Synchrophasotron until 2002, and from 2002 to 2005 — for experiments at the Nuclotron.

In 2016, a new source of polarized ions, SPI (Source of Polarized Ions) [3, 4], was put into operation. It was created by the JINR and INR RAS collaboration using the equipment of the CIPIOS source (IUCF) [5]. SPI provides beams of polarized deuterons and protons with a current of up to 10 mA and a polarization of up to 90%, which opens up new possibilities for spin experiments at the Nuclotron/NICA complex.

A number of polarimeters have been developed for measuring beam polarization. Measurements of the vector and tensor polarization components of the deuteron beam from POLARIS were performed at the exit of the LU-20 linear accelerator at an energy of 5 MeV/nucleon using the reactions $^4\text{He}(p, p)^4\text{He}$ [6] and $^3\text{He}(d, p)^4\text{He}$ [7], respectively. The existing polarimeter at the internal target of the Nuclotron employs the reaction of elastic deuteron–proton scattering at an energy of 270 MeV [8], where the analyzing powers A_y , A_{yy} , A_{xx} , and A_{xz} are known with high accuracy (better than 2%). The vector polarization of extracted deuteron and proton beams is measured by a polarimeter located at the F3 focus of the beam transport channel to Experimental Hall 205. The polarimeter is based on the reaction of quasi-elastic proton scattering on a polyethylene target at fast-proton scattering angles of 14° and 8° at energies up to 2.2 GeV and 3.7 GeV, respectively [9]. At present, active work is underway to upgrade the existing polarimeters and to develop the new ones capable of measuring and monitoring polarization over the entire energy range of the Nuclotron/NICA complex [10]. The detailed description of the Synchrophasotron/Nuclotron spin equipment is given in the recent review [11].

The energy range at the Synchrophasotron/Nuclotron, spanning from nonrelativistic energies of a few tens of keV to relativistic energies of several GeV, has made it possible to perform experiments in close collaboration with physicists from France (Saclay), the USA (JLab), and Japan (several centers) along two main directions: the study of the structure of the lightest nuclei, primarily the deuteron, at short internucleonic distances [12], and the traditional study of elastic NN scattering at intermediate energies with measurements of polarization observables [13].

The spin structure of two- and three-nucleon short-range correlations (SRCs) has been extensively investigated at the Synchrophasotron/Nuclotron complex in hadronic reactions using polarized deuteron beams. Unique results were obtained for the tensor analyzing power T_{20} and the vector polarization transfer κ_0 in deuteron breakup reactions [14–17] and deuteron–proton elastic scattering at 180° in the center-of-mass system [18, 19], which demonstrated sensitivity to the spin structure of isoscalar SRCs down to internucleonic distances of about 0.2 fm. Similar measurements were performed at SATURNE-2 (Saclay, France) [20–23] at lower energies. Measurements of the tensor analyzing power A_{yy} in the deuteron breakup reaction at large transverse momenta of the outgoing proton [24–27] revealed a dependence of the relativistic spin structure of SRCs on two internal variables. Data obtained on tensor analyzing powers in cumu-

relative pion production [28–30] exhibit a strong dependence on the transverse momentum of the emitted pion and a possible contribution from non-nucleonic degrees of freedom in the deuteron. Measurements of the vector A_y and tensor A_{yy} and A_{xx} analyzing powers in deuteron–proton elastic scattering at various energies on the internal target of the Nuclotron [31–33] performed by JINR–RIKEN(Japan) collaboration show a strong sensitivity to isoscalar SRCs and reaction mechanisms. These measurements were the natural continuation of the studies performed at lower energies at RIKEN and RCNP in Japan [34–36].

An important direction of spin research at the Synchrophasotron/Nuclotron complex is to perform the experiments using secondary beams of polarized neutrons and protons obtained by the breakup of vector-polarized deuterons. The energy dependence of the total cross-section difference for neutron–proton scattering with longitudinally polarized particles, $\Delta\sigma_L(np)$ [37–39], was measured using a beam of quasi-monochromatic polarized neutrons and a polarized proton target. The results obtained showed a decrease in the magnitude of $-\Delta\sigma_L(np)$ with increasing energy. These results significantly extended the energy range of the $-\Delta\sigma_L(np)$ measured previously at SATURNE-2 [40]. The study of the electromagnetic form factors of nucleons at large Q^2 requires the development of focal-plane (2π) polarimetry for high-energy neutrons and protons [41]. The analyzing powers of inclusive reactions of proton [42] and neutron [43] interactions with polyethylene and nuclear targets were measured using secondary beams of polarized nucleons at the Synchrophasotron/Nuclotron complex. The analyzing powers measurements [42, 43] provided significant contribution to the preparation of the experiments on the studies of the nucleons electromagnetic form factors at large Q^2 at JLab (USA).

The effect of birefringence of particles, in particular, the tensor polarization appearance in nonpolarized deuteron beam moving in nonpolarized matter (so-called dichroism) has been described in the recent review [44]. The experimental confirmation of the dichroism effect in relativistic deuteron–carbon interactions at 5 GeV/c has been obtained at the Nuclotron extracted beam [45, 46].

At present, further development of the polarized-beam research program is planned at NICA with the SPD detector, aimed at studying the gluon structure of the proton and deuteron [47] and other spin and polarization phenomena [48]. The implementation of this program requires high-intensity beams of polarized protons and deuterons with a polarization degree of no less than 70% [49, 50]. In addition to transverse beam polarization in the detector, longitudinal polarization is also required. Furthermore, to suppress systematic errors in the experiment, it is necessary to organize a system of multiple spin reversals (a spin-flip system) with a reversal time of about 1 s.

Thus, the ongoing and planned spin experiments at the Nuclotron/NICA complex require the use of a high-intensity deuteron beam with vector and/or tensor polarization, as well as the ability to control the deuteron spin direction to provide longitudinal vector or in-plane tensor polarization components.

Because of the small anomalous part of the gyromagnetic ratio, controlling the orientation of deuteron spins represents a major technological challenge. The application of existing methods for proton spin control using spin rotators based on transverse magnetic fields, such as those employed at the RHIC collider (BNL), is not acceptable for deuterons due to the large field integrals required.

The polarization research program can be implemented for both protons and deuterons using a new polarization control mode — the spin transparency (ST) mode — developed jointly by MIPT and JINR, which makes it possible to preserve polarization during acceleration and to flexibly control its direction by means of spin navigators based on weak magnetic fields. The

spin navigators being developed at JINR, which form the basis for spin flipping [51, 52], online monitoring, and compensation of lattice imperfections [53], will ultimately make the NICA complex a facility for conducting high-precision experiments with polarized beams. Besides EDM search experiments in the quasi-frozen spin mode [54–57], experiments in the ST mode will also become feasible, such as searches for axion-like particles [58], CP violation studies [59, 60], measurements of the deuteron G -factor, and others.

Before examining the main features of spin dynamics when operating with deuterons in the ST mode, let us discuss the issues of polarization preservation during the acceleration of a deuteron beam in the NICA complex.

2. Preservation of deuteron polarization in the NICA complex

The Nuclotron and the NICA collider are conventional synchrotrons with a vertical guiding field. In such accelerators, the normalized spin tune in units of the revolution frequency $\nu = \gamma G$ (where γ is the relativistic factor and $G = g \frac{A}{2Z} - 1$, g being the gyromagnetic ratio, A — the atomic mass number, and Z — the nuclear charge number) is proportional to the energy, and the stable polarization (n -axis) is directed vertically in almost the entire energy range. The exceptions are the energies corresponding to spin resonances:

$$\gamma G = k + k_x \nu_x + k_y \nu_y, \quad (1)$$

where k, k_x, k_y are integers, and ν_x, ν_y are the radial and vertical betatron oscillation tunes. Beam depolarization can occur when crossing spin resonances and depends significantly on the crossing rate and the resonance strength.

The strongest resonances are those of the linear approximation ($|k_x| + |k_y| < 2$), which include intrinsic resonances $\gamma G = mN \pm \nu_y$ ($N = 8$ is the number of superperiods) associated with vertical betatron oscillations and imperfection resonances related to inaccuracies in the manufacturing and misalignment of the magnetic elements of the synchrotron. The latter include integer resonances $\gamma G = k$, non-superperiodic resonances $\gamma G = k \pm \nu_y$ ($k \neq mN$), and coupling resonances $\gamma G = k \pm \nu_x$.

During beam acceleration, the crossing of intrinsic resonances is particularly dangerous. Unlike imperfection resonances, intrinsic resonances exist even in a lattice with perfectly manufactured and aligned magnetic elements. Furthermore, the strength of an intrinsic resonance is proportional to the betatron oscillation amplitude. If the resonance crossing rate is not high enough to ensure fast crossing for all particles, then particles undergoing fast, intermediate, and slow crossing may simultaneously be present in the beam (polarization profile) [61]. Fast crossing, where the vertical spin projection does not undergo essential change upon crossing, occurs for small amplitudes. Slow crossing with adiabatic spin-flip occurs for sufficiently large amplitudes. The remaining particles will undergo intermediate crossing with a significant deviation of the spins from the vertical direction, which leads to beam depolarization.

The relation between the vertical spin projection before (S_y^-) and after (S_y^+) crossing an isolated spin resonance at a constant rate ε' is given by the Froissart–Stora formula:

$$S_y^+ = S_y^- (-1 + 2e^{-\frac{\pi\omega^2}{2\varepsilon'}}), \quad (2)$$

where ω is the resonance strength, which has the following physical meaning: if a particle is exactly in the spin resonance, a vertically oriented spin will flip in $1/(2\omega)$ revolutions. The dimensionless resonance crossing rate ε' is determined by the ramp rate of the arc dipole field:

$$\varepsilon' = \frac{eG\rho L}{2\pi mc^3} \frac{dB}{dt}, \quad (3)$$

where L is the synchrotron length, ρ is the orbital bending radius in the arc dipole, mc^2 is the rest energy of the particle. The crossing rate defines the characteristic resonance strength:

$$\omega_D = \sqrt{\frac{\varepsilon'}{\pi}}, \quad (4)$$

at which the significant deviation of the spins from the vertical direction occurs after crossing the resonance. Depending on the resonance strength, the following types of spin resonance crossing are distinguished: $\omega \ll \omega_D$ — fast crossing; $\omega \gg \omega_D$ — slow crossing; $\omega \sim \omega_D$ — intermediate crossing. Figure 1 illustrates how the vertical spin projection S_y behaves for the different types of isolated resonance crossing with the constant rate ε' . Here $\theta = z/R$ is the longitudinal coordinate of the particle z in units of the radius R . The green curve represents fast crossing, in which the spin projection remains essentially unchanged. The blue curve represents slow crossing, in which the spin projection flips after the crossing. The red curve represents intermediate crossing, in which the spin deviates significantly from the vertical after the crossing, ultimately leading to beam depolarization.

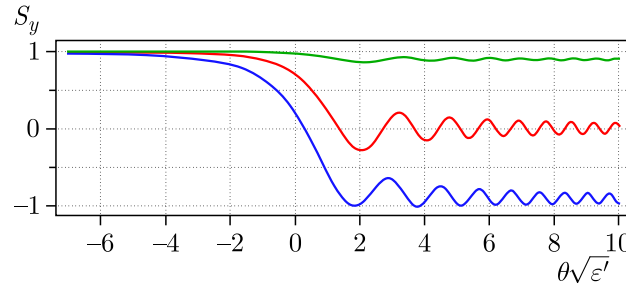


Figure 1. Fast, intermediate, and slow Froissart–Stora crossing of an isolated spin resonance.

For spin resonances, a strength equal to $0.1\omega_D$ corresponds to a 1% polarization loss in fast crossing. In slow crossing, a 1% polarization loss corresponds to a resonance strength equal to $10\omega_D$ for spin–betatron resonances and a strength equal to $3.2\omega_D$ for integer resonances.

The strength of intrinsic resonances significantly exceeds the strength of non-superperiodic resonances and coupling resonances. In practice, integer resonances driven by closed-orbit distortion and perturbing longitudinal fields on the orbit can be quite strong.

2.1. Nuclotron

The Nuclotron is a superconducting synchrotron with a superperiodicity $N = 8$, designed for a maximum magnetic rigidity of $B\rho = 45 \text{ T} \cdot \text{m}$, which allows accelerating protons and deuterons up to a maximum momentum of $13.5 \text{ GeV}/c$. The absolute value of the deuteron spin tune within this momentum range varies over

$$0.143 < \gamma|G| < 1.04, \quad (5)$$

within which, depending on the chosen betatron tunes, there can be from three to five spin resonances. The crossing rate at an arc dipole field ramp rate of $dB/dt = 0.6 \text{ T/s}$ and the corresponding characteristic depolarizing resonance strength ω_D are equal to

$$\varepsilon' \approx 4.1 \cdot 10^{-8}, \quad \omega_D \approx 1.14 \cdot 10^{-4}. \quad (6)$$

A distinctive feature of the Nuclotron is its large superperiodicity, which, when choosing a vertical betatron tune $\nu_y < 7.14$, makes it possible to exclude the intrinsic resonance $\gamma G = \nu_y - 8$

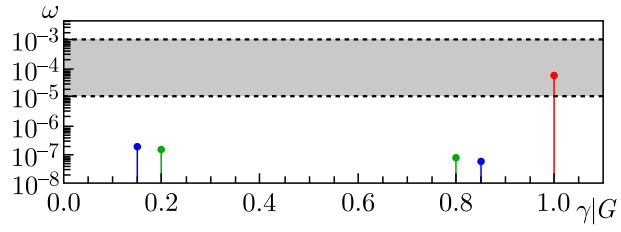


Figure 2. Spin resonance strength for deuterons in the Nuclotron at $\nu_x = 6.8$ and $\nu_y = 6.85$.

from the Nuclotron momentum range. Figure 2 shows the linear-approximation resonances for deuterons in the Nuclotron when choosing the radial and vertical betatron tunes as $\nu_x = 6.8$ and $\nu_y = 6.85$, respectively. The calculations assumed that misalignments of magnetic elements disturb the closed orbit of about 1 cm, the rolling error of the quadrupole and dipole magnets with respect to the longitudinal axis is of 10^{-3} , and the normalized emittances of the radial and vertical betatron oscillations are $4.5\pi \text{ mm} \cdot \text{mrad}$.

Non-superperiodic resonances are shown in blue, coupling resonances — in green, and the integer resonance — in red; their characteristics are given in Table 1.

Table 1. Linear-approximation resonances for deuterons in the Nuclotron ($\nu_x = 6.8$ and $\nu_y = 6.85$).

Resonance condition	γG	Beam momentum, GeV/c	Resonance strength
$\gamma G = \nu_y - 7$	-0.15	0.61	$2.0 \cdot 10^{-7}$
$\gamma G = \nu_x - 7$	-0.2	1.85	$1.6 \cdot 10^{-7}$
$\gamma G = -\nu_x + 6$	-0.8	10.4	$7.9 \cdot 10^{-8}$
$\gamma G = -\nu_y - 6$	-0.85	11.0	$5.9 \cdot 10^{-8}$
$\gamma G = -1$	-1.0	13.0	$5.9 \cdot 10^{-5}$

The gray shaded area in Figure 2 indicates the dangerous zone for resonance strengths $0.1\omega_D < \omega < 10\omega_D$, in which substantial beam depolarization occurs at a field ramp rate of 0.6 T/s. In the given example, crossing the integer resonance is dangerous. The depolarizing effect of the integer resonance can be suppressed with a weak solenoid, which ensures its adiabatic crossing. Note that, under real conditions, the maximum beam momentum in the Nuclotron is limited by the characteristics of the regular superconducting dipoles to approximately 12 GeV/c, making the integer resonance unreachable for deuterons. Thus, if the intrinsic resonance is excluded by choosing the vertical betatron tune, no difficulties arise in preserving deuteron polarization in the Nuclotron.

Other situation occurs when the vertical betatron tune is chosen in the range of $\nu_y > 7.14$. In this case, the intrinsic resonance $\gamma G = \nu_y - 8$ is crossed, which can lead to a loss of polarization.

Figure 3 and Table 2 show the result of calculations for the linear-approximation deuteron resonance strengths in the Nuclotron with the radial and vertical betatron tunes as $\nu_x = 7.35$ and $\nu_y = 7.4$, respectively. The calculations assumed that the beam parameters and magnet element misalignments are the same as in the case with betatron tunes of $\nu_x = 6.8$, $\nu_y = 6.85$.

Figure 3 shows that, in addition to the integer resonance (red line), the intrinsic resonance (orange line) also enters the dangerous gray zone. Although the integer resonance for deuterons is not reachable under real conditions in the Nuclotron, accelerating the beam to momenta exceeding 7.67 GeV/c at a betatron tune of $\nu_y = 7.4$ will result in a polarization loss of up to several percents.

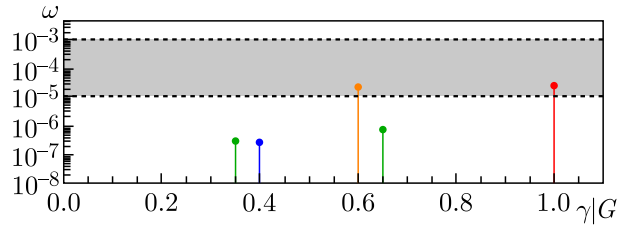


Figure 3. Spin resonance strength for deuterons in the Nuclotron at $\nu_x = 7.35$ and $\nu_y = 7.4$.

Table 2. Linear-approximation resonances for deuterons in the Nuclotron ($\nu_x = 7.35$ and $\nu_y = 7.4$).

Resonance condition	γG	Beam momentum, GeV/c	Resonance strength
$\gamma G = -\nu_x + 7$	-0.35	0.61	$3.0 \cdot 10^{-7}$
$\gamma G = -\nu_y + 7$	-0.4	1.85	$2.6 \cdot 10^{-7}$
$\gamma G = \nu_y - 8$	-0.6	10.4	$2.5 \cdot 10^{-5}$
$\gamma G = \nu_x - 8$	-0.65	11.0	$7.6 \cdot 10^{-7}$
$\gamma G = -1$	-1.0	13.0	$2.6 \cdot 10^{-5}$

2.2. NICA collider

The maximum momentum of deuterons in the NICA collider, as in the Nuclotron, is of 13.5 GeV/c, and the absolute value of the deuteron spin tune does not exceed $\gamma|G| < 1.04$. The betatron tunes in the radial and vertical directions are equal, with $\nu_x \approx \nu_y \approx 9.44$. The number of superperiods in the NICA collider is $N = 2$, and an intrinsic resonance is always present within the momentum range.

Since the orbit length of the NICA collider is twice that of the Nuclotron, the crossing rate and the corresponding characteristic depolarizing resonance strength ω_D for the field ramp rate $dB/dt = 0.6$ T/s are

$$\varepsilon' \approx 8.0 \cdot 10^{-8}, \quad \omega_D \approx 1.6 \cdot 10^{-4}. \quad (7)$$

Figure 4 and Table 3 show the linear-approximation resonances of deuterons in the NICA collider for the betatron tunes $\nu_x \approx \nu_y \approx 9.44$. The calculations assumed that magnetic element

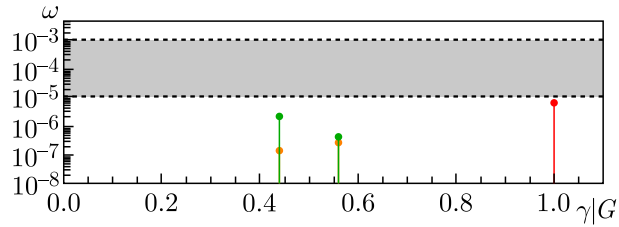


Figure 4. Spin resonance strengths for deuterons in the NICA collider at $\nu_x \approx \nu_y \approx 9.44$.

Table 3. Linear-approximation resonances for deuterons in the NICA ($\nu_x = 9.44$ and $\nu_y = 9.44$).

Resonance condition	γG	Beam momentum, GeV/c	Resonance strength
$\gamma G = -\nu_x + 9$	-0.44	5.47	$3.0 \cdot 10^{-6}$
$\gamma G = -\nu_y + 9$	-0.44	5.47	$1.9 \cdot 10^{-7}$
$\gamma G = \nu_y - 10$	-0.56	7.12	$5.6 \cdot 10^{-7}$
$\gamma G = \nu_x - 10$	-0.56	7.12	$3.6 \cdot 10^{-7}$
$\gamma G = -1$	-1.0	13.0	$8.9 \cdot 10^{-6}$

misalignments disturb the closed orbit at the level of 2 mm, the rolling error of the quadrupole and dipole magnet angles relative to the longitudinal axis is 10^{-3} , and the normalized emittances of the radial and vertical oscillations are $1\pi \text{ mm} \cdot \text{mrad}$.

It should be noted that none of the spin resonances enters the dangerous gray zone. Due to the smaller normalized betatron emittances and the small number of superperiods, the strength of the intrinsic resonances in the collider is significantly weaker than in the Nuclotron. Thus, there is no problem in preserving the deuteron polarization at a field ramp rate of 0.6 T/s for the betatron tunes under consideration.

3. Longitudinal polarization of deuterons in the NICA complex

The smallness of the deuteron G -factor considerably eases the challenge of preserving vertical polarization as the beam is accelerated to the experimental energy. At the same time, this very smallness makes it substantially more difficult to achieve longitudinal polarization at the experimental location, be it for an extracted beam or an internal target. The conventional scheme employs a pair of spin rotators: the first rotates the polarization from the vertical to the longitudinal direction before the detector, and the second one returns the polarization back to the vertical direction. The scheme is not feasible in practice, since it would require very large magnetic field integrals (up to several hundreds T · m). To obtain a longitudinal polarization component in the Nuclotron, one can employ the schemes based on a spin resonance, in which the periodic n -axis lies in the plane of the Nuclotron.

3.1. Precessing polarization of deuterons

To control the polarization of deuterons at COSY (Jülich, Germany), radio-frequency transverse or longitudinal fields [62, 63] were used, which induced an RF spin resonance:

$$\gamma G = k \pm \nu_{\text{RF}}, \quad (8)$$

where k is an integer, ν_{RF} is the RF-tune (dimensionless frequency of RF field in units of the beam revolution frequency). The RF-tune depends on the beam energy in the experiment. Thus, when operating in the low-energy region of the Nuclotron, the RF field frequency will be about 150 kHz. In the middle of the Nuclotron energy range, the RF fields with a frequency of about 500 kHz will be required. As one approaches the integer resonance $\gamma G = -1$, which corresponds approximately to the maximum beam energy, the field frequency will decrease down to zero at the point of the integer spin resonance.

Far from the resonance, the polarization (n -axis) is directed vertically. Upon a slow approach to the resonance, the polarization will be “captured” by the RF field and will lie in the plane of the synchrotron in the resonance. In this case, the stable polarization at the observation point will precess around the vertical axis, rotating by an angle of $2\pi\nu_{\text{RF}}$ with each particle revolution:

$$\vec{n}_{\text{res}}(N_i) = \cos(2\pi\nu_{\text{RF}}N_i + \Phi_0)\vec{e}_z + \sin(2\pi\nu_{\text{RF}}N_i + \Phi_0)\vec{e}_x, \quad (9)$$

where $\vec{e}_z, \vec{e}_x$ are the accelerator unit vectors in the longitudinal and radial directions, N_i is the particle revolution number, and Φ_0 is the initial phase.

Longitudinal polarization can be provided, for example, at the location of the RF solenoid ($\Phi_0 = 0$), if the RF-tune is chosen as a rational fraction: $\nu_{\text{RF}} = k_1/k_2$, where k_1 and k_2 are integers. Then, every k_2 revolutions, the polarization will return to the longitudinal direction. In the remaining cases, the polarization will have both longitudinal and radial components, which are a given function of the particle revolution number.

The limiting factors of the method are the influence of synchrotron energy modulation and the choice of betatron tunes. Synchrotron oscillations lead to the splitting of the main resonance into a series of satellite resonances. For deuterons, unlike protons, the influence of the side satellite resonances on the polarization is small compared to the influence of the central resonance. To stabilize the precessing polarization, the strength of the RF resonance, which is proportional to the RF field integral, must significantly exceed the strength of high-order spin resonances with betatron tunes located in the vicinity of the RF resonance. For example, when using an RF solenoid in the Nuclotron as in the COSY experiments [64] with a maximum RF field integral of $\sim 0.6 \text{ mT} \cdot \text{m}$, when operating at energies of several hundreds MeV, spin resonances with strengths on the order of 10^{-4} must be taken into account, and when operating at energies of $\sim 10 \text{ GeV}$, spin resonances with strengths on the order of 10^{-6} must be considered.

Experiments in the rings of the NICA collider using an RF solenoid (RF flipper) were proposed to detect violation of P -parity in interactions of a polarized proton or deuteron beam with an unpolarized target [59].

3.2. Stabilization of longitudinal polarization at an integer resonance

As noted above, when operating with an RF field in the “precessing” polarization mode near an integer resonance, the RF-tune tends to zero. It follows from formula (2) that at the point of the integer spin resonance, a stationary longitudinal field stabilizes the longitudinal polarization direction at the solenoid location. In this case, the polarization becomes a periodic function of the particle revolution number, and the longitudinal direction will repeat with each particle revolution.

The only integer resonance for deuterons, $\gamma G = -1$, occurs at a momentum of approximately $13 \text{ GeV}/c$, which corresponds to practically the maximum beam energy of the NICA collider. For the Nuclotron, as noted above, the integer resonance $\gamma G = -1$ is not attainable.

The use of a weak solenoid with a stationary field for stabilizing longitudinal polarization in the interaction regions of the SPD or MPD detectors at integer resonances for protons and deuterons in the NICA collider was proposed in [48]. However, with such a placement of the solenoids, transverse beam polarization becomes unattainable at integer resonances.

4. ST mode for deuterons in the NICA complex

The spin transparency (ST) mode opens up broad opportunities for conducting experiments with polarized beams, where not only stabilization of the polarization direction is required, but also controlled change of its direction during the experiment [65–67]. Of particular importance is the possibility of implementing a system of multiple spin reversals of the entire bunch — a spin-flip system — which allows a substantial reduction of the systematic errors of the experiment.

Below, we consider the main features of operation with polarized deuterons in the ST mode in the NICA collider, and also discuss the possibility of using the ST mode in a new synchrotron, which could be employed for injecting polarized beams and conducting experiments with polarized deuterons.

4.1. NICA collider

4.1.1. ST mode at an integer spin resonance

In the NICA collider rings, the vertical guide field of the arc dipoles determines a unique stable spin direction for deuterons, which is oriented vertically across nearly the entire energy range. The distinct nature of the n -axis lies in the periodicity of the spin motion directed along

this axis, which ensures the stability of the spin dynamics for polarization oriented along the n -axis [51]. Spins directed transversely to the n -axis will rotate around it with the spin tune $\nu = \gamma G$, and due to the spread of the spin tune, the transverse polarization relative to the n -axis will be smeared out.

At the point of the integer spin resonance $\gamma G = -1$, when the deuteron completes one revolution in the opposite direction around the vertical axis, the distinct nature of the n -axis disappears, since any spin direction repeats with each particle revolution [68]. In other words, at the spin resonance point, when a particle moves through an ideal lattice along a closed orbit, the integral effect of the arc dipole magnets over one revolution is compensated — the structure becomes transparent to spin motion. The spin dynamics in the ST structure is unstable: any small perturbing magnetic field strongly affects the direction of the n -axis. Stability of the spin dynamics in the ST mode is ensured by spin navigators (SN) based on weak quasi-stationary magnetic fields. While for deuterons a scheme with spin rotators requiring hundreds of T · m of magnetic field is not feasible in practice, the required magnetic field integrals of a spin navigator for stabilizing the spin direction do not exceed 1 T · m. For deuterons, the ST mode is the only possibility to provide the required polarization direction at a given location of the orbit.

In the momentum range of the NICA collider, spin navigators are more effectively implemented using weak solenoids. Figure 5, *a* shows the locations of the navigator solenoids in the NICA collider, which are symmetrically arranged around the SPD detector in the regions where dipoles with radial fields are located, providing the merging of the counter-propagating deuteron beams at the SPD detector [49]. Also, Figure 5, *b* shows a detailed layout of the navigator solenoids with a field integral of ~ 0.5 T · m each, marked in green, inside the SN insertion among the dipoles with radial fields, marked in blue.

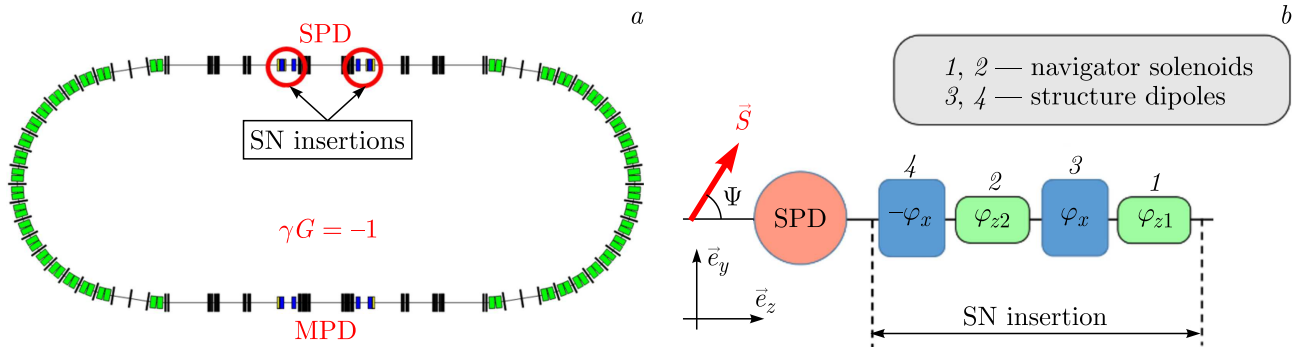


Figure 5. Layout of the spin navigator based on weak solenoids in the NICA collider: *a*) general layout; *b*) detailed placement of the navigator solenoids among the radial-field dipoles.

The presented navigator based on weak solenoids allows stabilization of any polarization direction in the vertical plane of the SPD detector. Moreover, such a navigator enables spin-flips of deuterons during the experiment while maintaining a stable spin frequency during the reorientation of the polarization direction, thereby eliminating resonant depolarization of the beam during spin-flips.

The navigator defines the direction in the SPD detector. As the particle moves along the orbit, the subsequent kinematics of the spins will be determined by the arc dipoles [69]. Thus, if in the vertical plane of the SPD detector a spin direction is stabilized that makes an angle Ψ with the velocity direction, then in the MPD detector the polarization will also lie in the vertical plane and will make an angle $(\pi - \Psi)$ with the velocity direction. If the polarization is vertical

in the SPD detector, it will remain vertical in the MPD detector as well. If the polarization is longitudinal in the SPD detector, it will also be longitudinal in the MPD detector, but of the opposite sign.

4.1.2. ST mode with solenoidal snakes

The ST mode at the integer resonance $\gamma G = -1$ considered above is realized at a beam momentum of 13 GeV/c. The introduction of two solenoidal snakes into opposite straight sections of the NICA collider, as shown in Figure 6, provides the ST mode for any deuteron beam energy [70]. Each snake is divided into two parts symmetrically arranged around the SPD and MPD detectors. Stabilization of the spin direction in the SPD detector is accomplished by the same navigator solenoids as in the case of the ST mode at the integer resonance (see Figure 5, b).

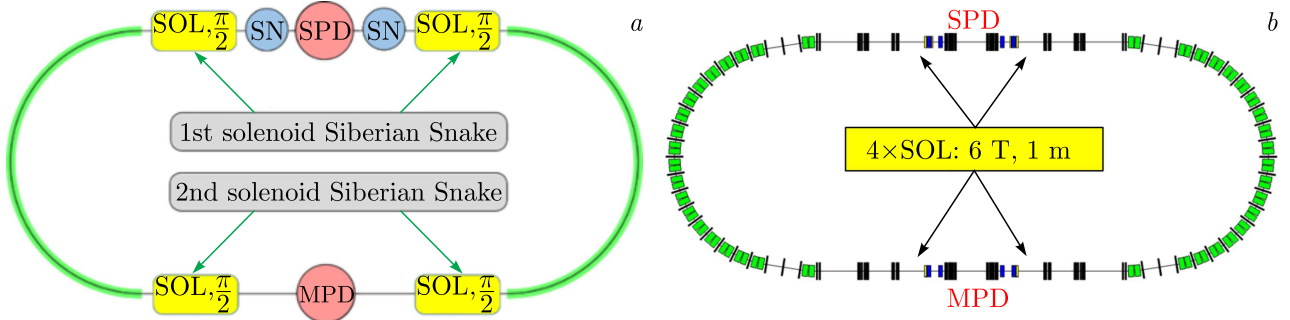


Figure 6. ST mode in the NICA collider in the continuous momentum range: a) layout of the solenoidal snakes; b) placement of the 6 T solenoids in the NICA collider.

Let us trace how the solenoidal snakes change the polarization direction as the particle moves from the SPD to the MPD detector. Consider the case of co-directed snake solenoids, when the navigator stabilizes the deuteron polarization making an angle Ψ with the velocity direction in the vertical plane of the SPD detector. The first half of the snake will rotate the polarization into the plane of the collider. Then, the arc dipoles will rotate the polarization around the vertical direction by an angle $\pi\gamma G$. After that, the first half of the snake in the MPD straight section will return the polarization to the vertical plane of the MPD detector, making an angle $(\pi\gamma G - \Psi)$ with the velocity direction. In general, unlike the integer resonance case, when vertical or longitudinal polarization is stabilized in the SPD, both polarization components (longitudinal and vertical) will be present in the MPD.

The field integral of the solenoidal snake grows proportionally to the momentum, and for one half of the snake at the maximum deuteron beam momentum of 13.5 GeV/c it amounts to approximately 80 T·m. When using magnets with a maximum field of 6 T, the total length of the solenoids for one half of the snake will be approximately 13.5 m. At present, such free space for placing the snakes is not foreseen. At the first stage, it is planned to install four one-meter solenoids in the NICA collider, which will make it possible to provide the ST mode in a continuous momentum range up to 1 GeV/c for the deuteron beam. The layout of the 6 T solenoids is shown in Figure 6, b. The status of work on manufacturing solenoids with such parameters is presented in [71].

4.2. New injector of polarized deuterons in a figure-8 configuration

The Nuclotron has already been in operation for more than 30 years and requires substantial modernization or even complete replacement. In this regard, the development of new types

of synchrotrons capable of effectively preserving the degree of polarization during beam acceleration and providing efficient control of the spin direction is an important task. In [72], an injector of polarized nuclei for the NICA collider was proposed, configured in a figure-8 shape, the layout of which is shown in Figure 7. The ring configuration bypasses the structures of the SPD and MPD detectors, and the arcs of the injector with 2 T dipoles are located above the arcs of the collider. The critical energy value lies outside the operating momentum range, which eliminates the problem of crossing it during beam acceleration.

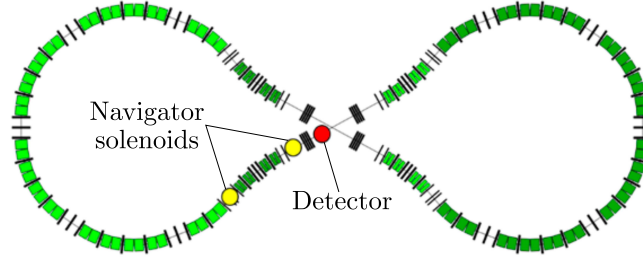


Figure 7. Figure-8 injector of polarized nuclei for the NICA collider.

The figure-8 configuration of the injector offers a number of unique properties. Such a synchrotron configuration provides the ST mode for any particle species, including deuterons, over the entire momentum range of the injector: the spin rotation in the first arc is fully compensated by the reverse rotation in the second arc. In such a structure, the spin tune is automatically zero regardless of the beam energy, which eliminates the problem of crossing spin resonances during beam acceleration. In fact, the beam is always in the region of zero spin resonance, and its stability is ensured by a spin navigator based on weak magnetic fields. Figure 7 shows the locations of two weak solenoids, separated by dipoles with a vertical field, on the basis of which a spin navigator is implemented, allowing stabilization of any spin direction in the detector in the plane of the injector.

An important advantage of the figure-8 injector is that the influence of synchrotron energy modulation on the spins is suppressed in it. The possibility of implementing, based on navigator solenoids, a system for compensating errors in the construction and misalignment of the magnetic elements of the injector lattice, as well as a system of multiple spin-flips, will allow conducting precision experiments both on an internal target of the injector and with extracted beams on external targets.

5. Conclusion

The NICA accelerator complex is a unique platform allowing experiments with deuterons with any polarization directions. The main feature of operating with polarized deuterons, related to the smallness of their G -factor, is in the simplicity of preserving the degree of polarization during deuteron acceleration to the experimental energy and the difficulty of controlling the spin orientation in the detector or at the external targets. When using the regular dipoles with a field ramp rate above 0.6 T/s, no difficulties in preserving deuteron polarization in the NICA collider arise. In the Nuclotron at the same dipole field ramp rates, when operating with the vertical betatron tune in the range $\nu_y < 7.14$, there are also no problems with polarization preservation. Depolarization at the level of a few percents could occur at crossing the intrinsic resonance ($\gamma G = \nu_y - 8$) in the Nuclotron when operating with tunes in the range of $\nu_y > 7.14$.

Control of the deuteron polarization direction in the NICA complex can be implemented in the precessing polarization mode and in the spin transparency mode. In the first mode,

the precessing polarization direction in the plane of the synchrotron is provided by an RF solenoid, which ensures a rotation of the polarization by an angle $\Psi_{\text{RF}} = 2\pi\nu_{\text{RF}}$ at each particle revolution in the detector or at the beam extraction point from the synchrotron. The value of the polarization rotation angle Ψ_{RF} determines discrete energy values from the resonance condition ($\gamma G = k \pm \nu_{\text{RF}}$). In the ST mode, spin navigators based on weak quasi-stationary fields stabilize the required polarization direction, repeating with each particle revolution, at a given orbit location. The ST mode in the collider with two solenoidal snakes, whose field integral grows proportionally to the beam momentum, is available in a continuous energy range. The ST mode for deuterons in the collider can be provided without snakes at the single integer spin resonance ($\gamma G = -1$) at 13 GeV/c.

Replacing the Nuclotron with a new figure-8 injector of polarized nuclei into the NICA collider will make it possible to provide the ST mode over the entire energy range without using solenoidal snakes. Experiments on internal targets in the injector will also become available, as well as those with extracted beams on external targets. This will extend the spin research program beyond SPD.

The use of spin navigators for compensating lattice imperfections and performing repeated spin-flips during data taking will bring precision experiments with polarized deuterons at NICA to a new level of accuracy.

Conflicts of interest

The authors declare no conflicts of interest.

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