Spin Transparency mode at the NICA accelerator complex

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on behalf SPRINT@NICA group

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Conceptual design of the Spin Physics Detector (arXiv:2102.00442)

Available species and types of collisions

The basic specification to the available polarization states and combinations is the following:

- **protons (possibly helium-3** ions at the second stage): **vector polarization, longitudinal and transverse** direction in respect to the particle velocity;
- **deuterons:** vector and tensor polarization, vertical direction of polarization, longitudinal polarization up to about a 4 GeV/c momentum, and longitudinal polarization at discrete momentum of about 13 GeV/c;
- possibility of colliding any available polarized particles: p-p with a **luminosity up to 10^{32} cm $^{-2}$ s $^{-1}$** and d-d, p-d, p-^{3}He, d-^{3}He with a luminosity of 10^{30} cm $^{-2}$ s $^{-1}$ at the collision energy equivalent to p-p collisions;
- possibility of asymmetric collisions should be considered as an option for the future development of the facility;
- for essential reduction of a systematic uncertainty, a **spin-flipping system** is implemented, which allows one **to rotate the polarization direction with a step of 90° simultaneously in all bunches** within a minimal time period.

Beam Polarization Preservation in the Nuclotron

Spin Resonances (Nuclotron)

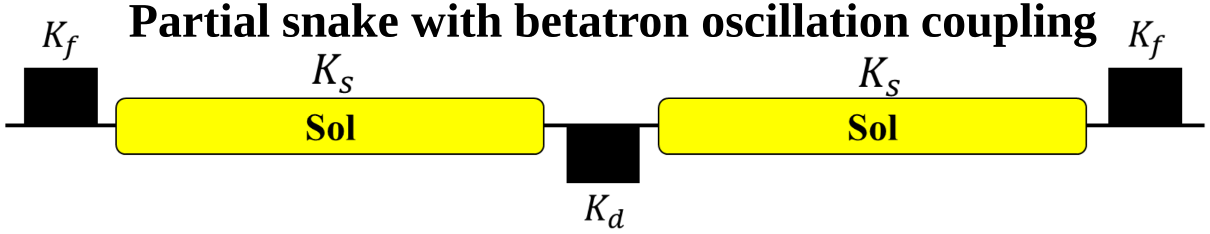
	proton	deuteron	helium-3
G-factor	1.792	-0.142	-4.191
Integer Spin Resonances	24	1	34
Intrinsic Spin Resonances	6	1	8

There are no issues with deuteron beam polarization preservation.

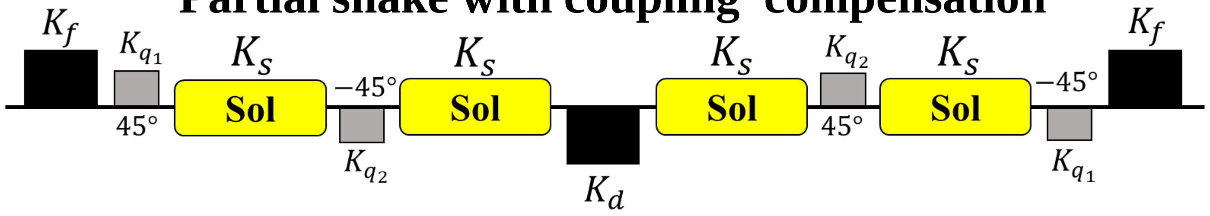
The designs of partial snakes for preserving proton polarization also make it possible to preserve the polarization of helium-3 beams.

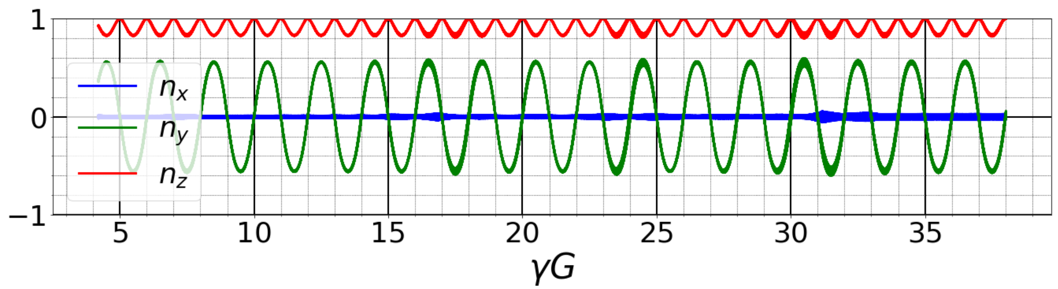
Report by E.D. Tsyplakov (7 Sept, 17:50)

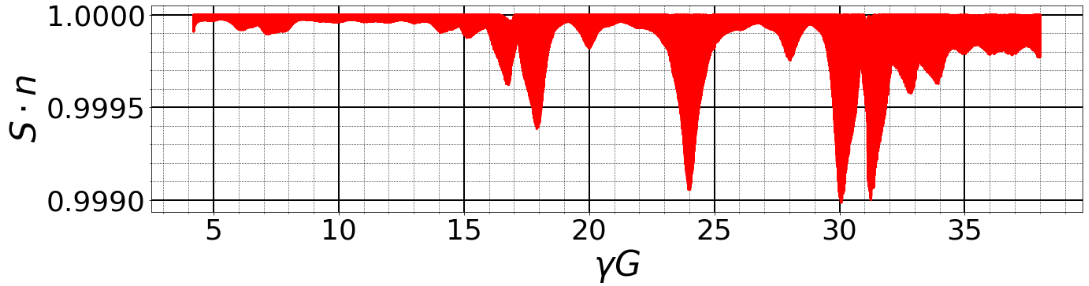
Partial snake with betatron oscillation coupling



Partial snake with coupling compensation







Polarization Direction Control

	Proton	deuteron	helium-3
G-factor	1.792	-0.142	-4.191
Solenoid snake $(BL)_{tot}$, T·m	51	165	44
Dipole snake $(BL)_{tot}$, T·m	22	550	14

Longitudinal and transverse magnetic field integrals for spin rotation by angle φ :

$$B_{||}L = \frac{\varphi}{1+G} B\rho \qquad B_{\perp}L = \frac{\varphi}{\gamma G} B\rho$$

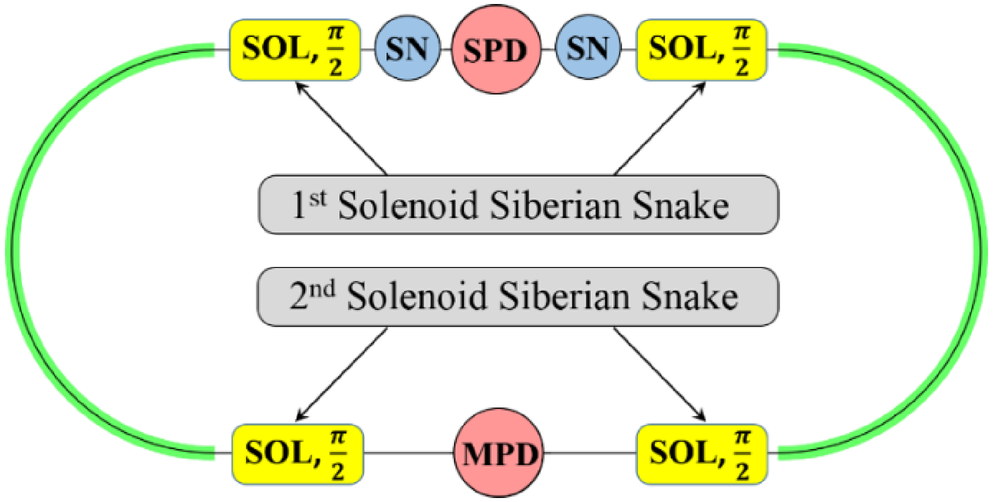
Due to the orbit restoration condition, the total spin rotation angle accumulated in the dipole snake magnets is about 4π.

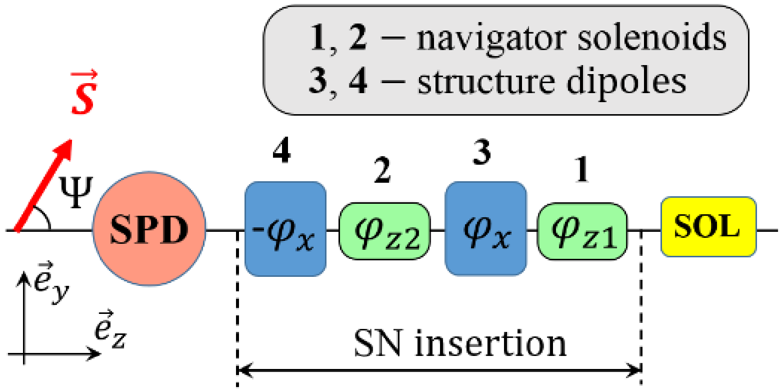
Conventional transverse-field rotators and snakes are **not feasible** for use with a **deuteron** beam.

Large closed-orbit deviations at low energies make conventional rotators and snakes for **proton and helium-3** polarization control a **serious technical challenge**.

For polarization control of ***p*, *d*** and ***^{3}He*** in the NICA range, **longitudinal fields are appropriate**.

Spin transparency mode at NICA





- Two solenoid snakes provide a spin tune of $\nu = 0$ at any energy
- There is no stable preferred direction of polarization: any spin direction repeats after each revolution of the particle
- To stabilize any required polarization direction, spin navigators based on weak solenoids with a field integral of < 0.6 T·m are used for protons, heliums-3 and deuterons
- The effect of the navigator on the spins must significantly exceed the depolarizing influence caused by lattice imperfections, as well as by betatron and synchrotron oscillations of the beam
- The field integral per half of a solenoid snake is up to 25 T·m for protons, 22 T·m for heliums-3 and up to 80 T·m for deuterons

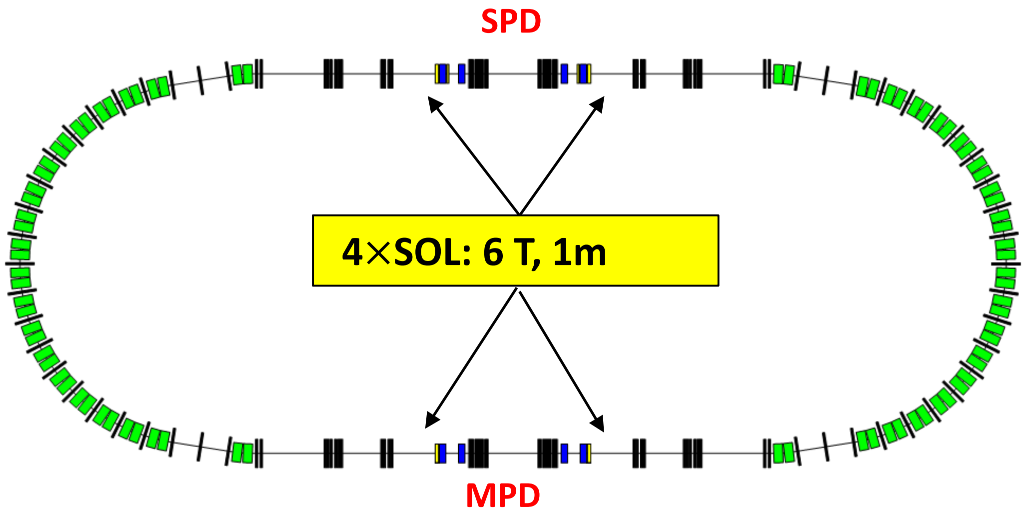
Capabilities of the ST mode for polarized beams

The ST mode in the NICA collider makes it possible to:

- Control ion polarization using weak solenoids without affecting the orbital characteristics of the beam
- Accelerate the beam without polarization loss
- Maintain stable polarization throughout the entire experiment
- Set any desired polarization direction at any point of the collider orbit
- Change the polarization direction using spin navigators during the experiment
- Provide on-line polarization monitoring during the experiment
- Perform frequent coherent spin flips of the entire beam to reduce systematic errors of the experiment
- Carry out high-precision experiments with polarized beams

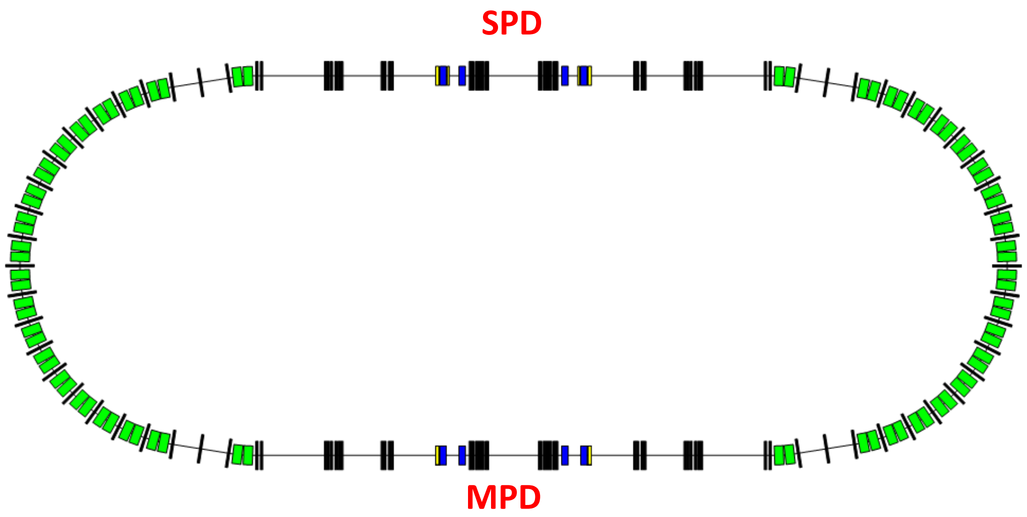
The first stage of operation in the ST mode at the NICA collider

ST mode with two solenoidal snakes



- Operation in a continuous momentum range up to **3.20 GeV/c for protons**, up to **7.04 GeV/c for helium-3** and up to **0.98 GeV/c for deuterons**.
- The snakes suppress the depolarizing effect of synchrotron energy modulation.

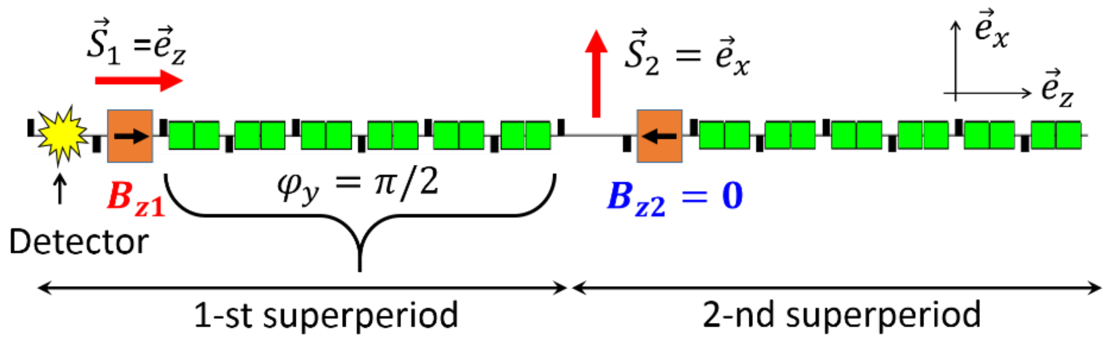
ST mode at integer spin resonances



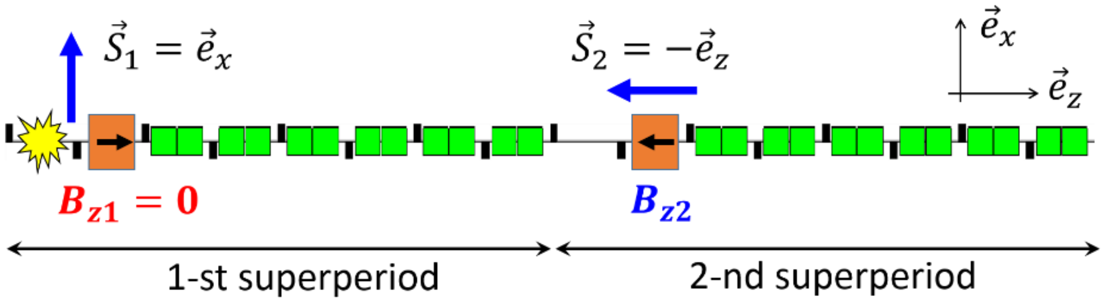
- Operation at discrete energies with a step of **523 MeV for protons** and **672 MeV for helium-3**.
- For **deuterons**, there is a single integer resonance at a momentum of **13 GeV/c**.

Experimental verification of the ST mode at the Nuclotron

A navigator based on two weak solenoids ($\gamma G = 2$)



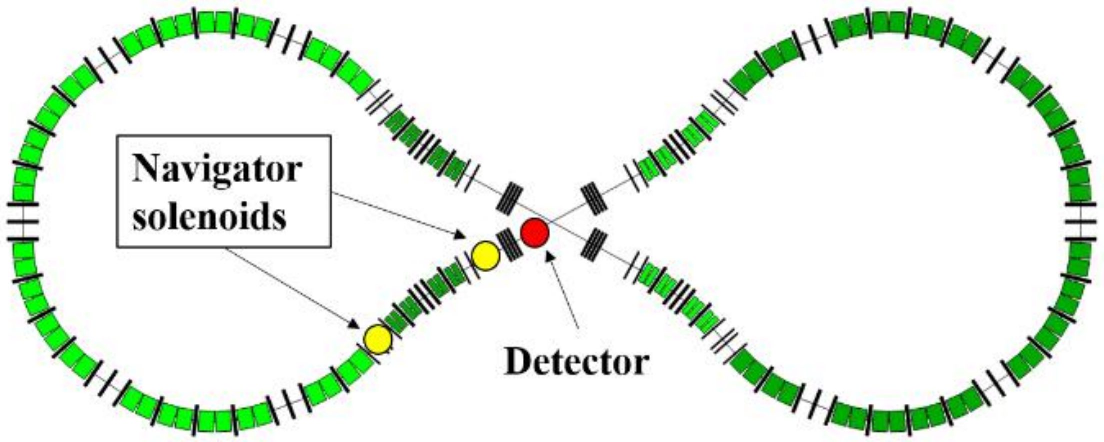
obtaining longitudinal polarization



obtaining radial polarization

- In the momentum range up to 3.5 GeV/c, there are no intrinsic spin resonances, and polarization can be preserved using a weak solenoid.
- Spin navigators (SN) based on weak solenoids have been proposed, which are optimal for γG = 2 and γG = 3 (RFBR No. 20-02-00808).
- Spin navigators based on regular dipole correctors have been proposed, which are optimal for γG = 6 and γG = 7 (RSF No. 22-42-04419).
- Adiabatic capture of polarization by the navigator when approaching the region of an integer spin resonance.
- Vertical polarization can be measured by polarimeters on the internal target and on the extracted beam.
- Upgrade of the polarimeters is required so that they can also measure the radial polarization of protons.

Figure-8 injector



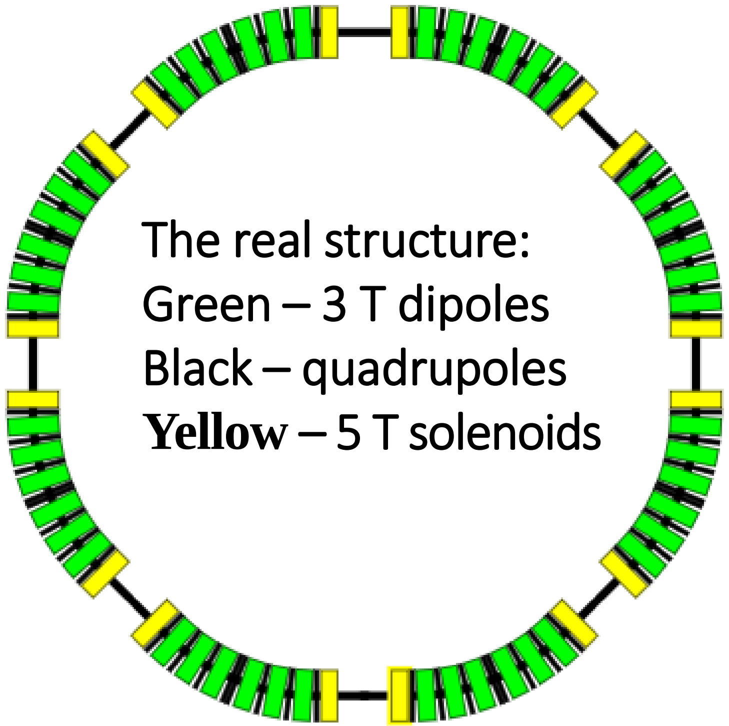
- The arcs of the figure-8 injector are located above the arcs of the NICA collider.
- The arcs use 2 T dipoles with dB/dt ~ 1 T/s.
- It is a rapid-cycling injector of polarized beams, which is a key factor in the formation of high-intensity beams in the collider rings.

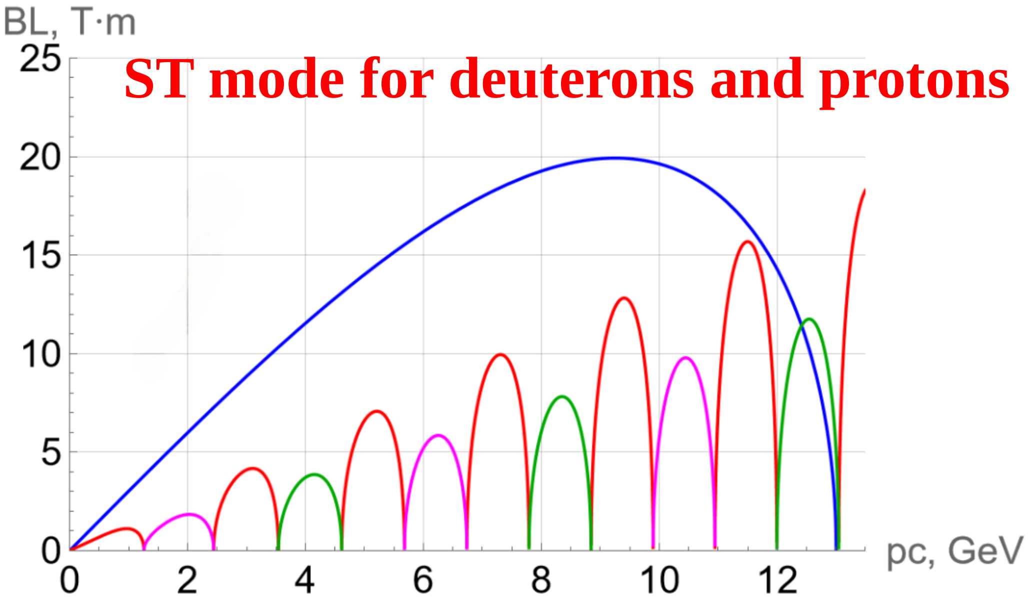
Advantages of the figure-8 injector design:

- The ST mode is achieved automatically over the entire energy range for any particle species, including deuterons.
- A universal polarization control scheme for any particle species using spin navigators based on weak solenoids.
- Simplicity of matching the polarization direction during beam injection into the figure-8 and beam extraction to the NICA rings.
- Possibility of injecting particles directly at the experimental energy — eliminating the need for further acceleration of polarized beams in the collider rings (requires electron cooling at the experimental energy).
- Possibility of conducting experiments with polarized beams of any particle species in the injector's storage mode and on extracted targets.

JINR Nuclotron Upgrade for Deuteron and Proton Polarization Control in Spin Transparency Mode

Report by E.A. Butenko (9 Sept, 18:50)





Solenoid field integral per straight section

Combinations of solenoid field signs:

deuterons:	+	+	+	+	+	+	+	+
protons:	+	+	-	-	+	+	-	-
protons:	+	+	+	+	+	+	+	+
protons:	+	-	+	-	+	-	+	-

A longitudinal field integral of up to **160 T·m is sufficient** for the deuteron ST mode — **two times smaller** than for the ST mode at NICA with two solenoid snakes

Precision experiments in the ST mode

Spin-flip system

- The spin navigator (SN) allows simultaneous control of both the polarization direction and the spin tune value.
- Adiabatic adjustment of the polarization direction at a fixed spin tune value.
- Coherent spin flip of all bunches simultaneously during the experiment.
- Reduction of systematic errors in experiments with polarized beams.

Compensation of the depolarizing effect of lattice imperfections

- Measurement of the coherent "spin field" induced by misalignment and manufacturing errors of magnetic elements, and its compensation using the spin navigator.
- A real synchrotron with lattice imperfections becomes equivalent to a synchrotron with a perfectly aligned magnetic elements.

Real-time polarization monitoring

- During adiabatic change of the spin direction, the degree of polarization does not change.
- Polarization is indirectly measured from the magnetic field values of the spin navigators.

Report by A.M. Kondratenko (9 Sept, 15:45)

Conclusion

- The ST mode in the NICA collider makes it possible to meet all the necessary requirements for carrying out the spin physics program at the SPD detector, namely: to obtain transverse and longitudinal polarization of high-intensity proton, helium-3 and deuteron beams with a polarization degree of ~80%, as well as to implement a spin-flip system with a polarization reversal time of about one second.
- The possibility of conducting a pilot experiment to verify the ST mode for protons at integer resonances at the Nuclotron will ultimately allow experiments with extracted proton beams with transverse and longitudinal polarization at discrete energies spaced by about 0.5 GeV.
- The implementation of the new figure-8 injector within the NICA complex will make it possible to accelerate particles of any species (p, d, He-3, etc.) without beam polarization loss. Moreover, in the figure-8, the ST mode is automatically realized at any energies without the use of solenoidal snakes, including for deuterons, which will allow expanding the spin research program beyond the SPD detector.
- Upgrading the Nuclotron with solenoids distributed around the ring makes it possible to implement the ST mode for protons, deuterons, and helium-3. The required longitudinal field integral for deuterons is a factor of two smaller than that for the NICA configuration with two snakes.
- The spin navigators being developed at JINR, which form the basis for spin flipping, online monitoring, and compensation of lattice imperfections, will ultimately make the NICA complex a unique facility for conducting high-precision experiments with polarized beams.