
# Control of the polarization of protons and deuterons in the NICA complex in the spin transparency mode

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# Outline

1. Experimental verification of the Spin Transparency (**ST**) mode in Nuclotron
2. High precision experiments with deuterons in the NICA ST mode at $\gamma G = -1$
3. ST mode in the NICA collider with two solenoid snakes. Ultra-high precision experiments with deuterons
4. ST mode in the NICA collider at integer spin resonances for protons at high energies
5. Conclusion

# Spin Transparence mode in the NICA complex

**The ST mode in NICA allows one to:**

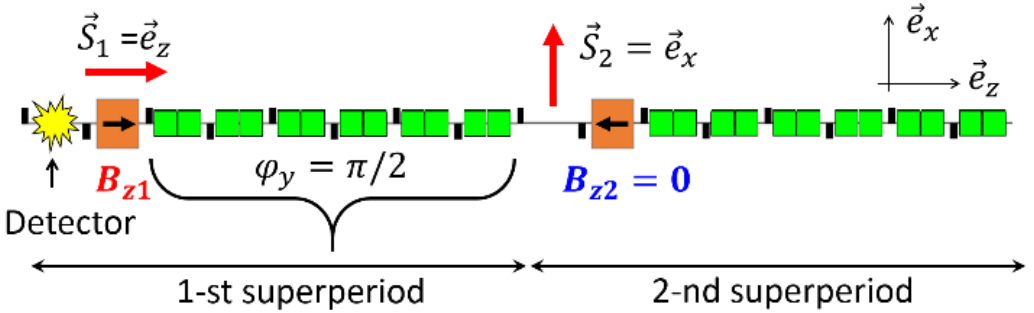
- Manipulate with longitudinal and transverse polarization at SPD/MPD by weak magnetic fields (**spin navigator**) not affecting the orbital dynamics
- Set any required polarization direction at any orbital location in NICA
- Accelerate the beam without polarization loss
- Maintain stable polarization during an experiment
- Change the polarization direction during an experiment
- Monitor the polarization on-line during an experiment
- Do frequent coherent spin flips of the beam to reduce experiment's systematic errors
- Carry out high-precision experiments with polarized beams

| **ST mode at an integer spin resonance** | **ST mode with two solenoid snakes** |
|---|---|
| $\nu = \gamma G = k$ | $\nu = 0$ |
| **discrete** values of energy | **continuous** values of energy |
| **Nuclotron, the NICA collider** | **the NICA collider** |

# ST mode at an integer spin resonance in Nuclotron

***Hadron polarization control at integer spin resonances in synchrotrons using a spin navigator*** (2021) Physical Review Accelerators and Beams, 24 (6), 061001

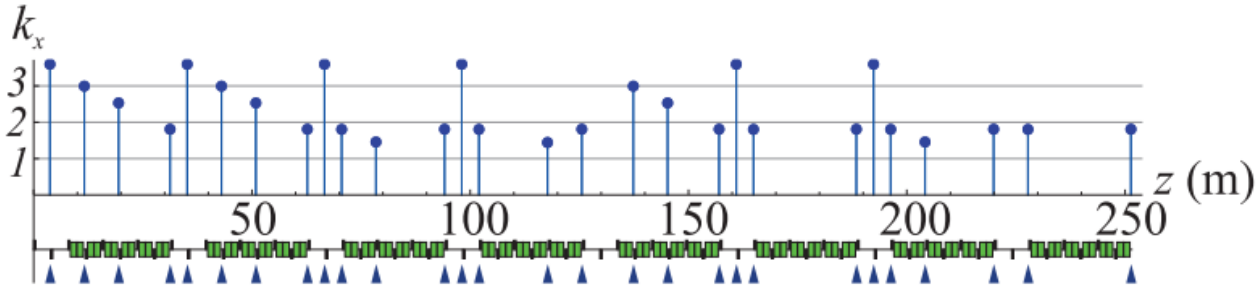
***Numerical modeling of a proton spin-flipping system in the spin transparency mode at an integer spin resonance in JINR's Nuclotron***, (2021) JINST, 16 (12), P12039




*Spin navigator based on **two weak solenoids**:*

$$\gamma G = 2$$

***Спиновый навигатор на базе корректирующих диполей Нуклотрона/ОИЯИ*** (2022) Письма в ЖЭТФ, том. 116, вып. 7, с. 411

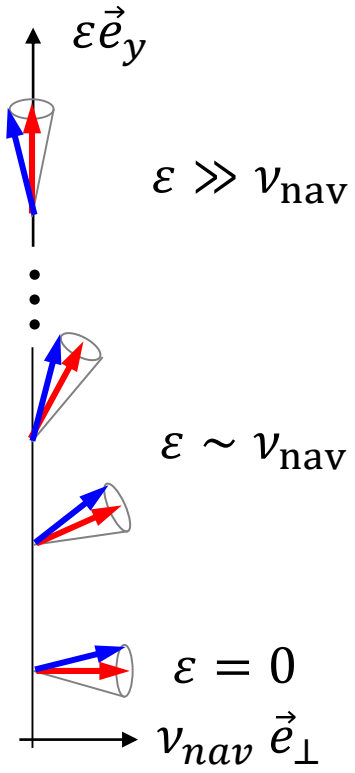



*Spin navigator based on **correcting dipoles**:*

$$\gamma G = 6$$

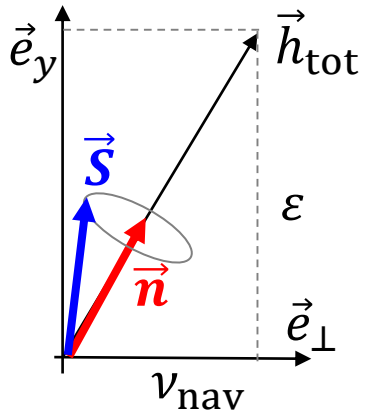
Experimental verification of the ST mode in JINR's Nuclotron

# Adiabatic capture of polarization by a spin navigator




Spin precession axis (n-axis)

$$\vec{n} = \frac{\vec{h}_{tot}}{h_{tot}} = \frac{\varepsilon\, \vec{e}_y + \nu_{\text{nav}}\ \vec{e}_\perp}{\sqrt{\varepsilon^2 + \nu_{\text{nav}}^2}}$$




Spin adiabatic invariant

$$J = \vec{S} \cdot \vec{n}$$

**The resonance system** rotates around the vertical direction with a resonance tune $\nu_k = \gamma_k G = k$.

Spin rotates in the field: $\vec{h}_{\text{tot}} = \varepsilon\, \vec{e}_y + \nu_{nav}\ \vec{e}_\perp$.

$\boldsymbol{\varepsilon = \gamma G - k}$ is a resonance detuning

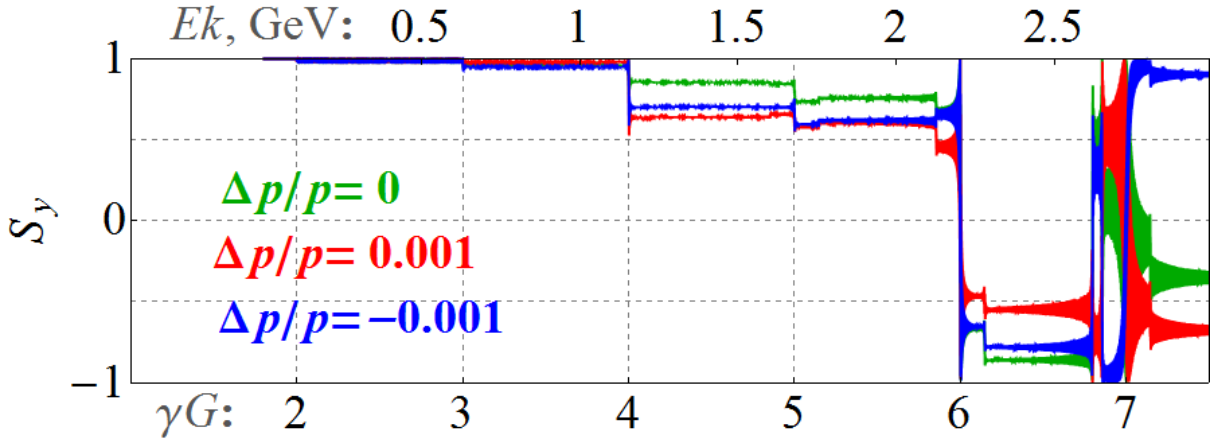
$\vec{h}_{\text{nav}} = \boldsymbol{\nu}_{\text{nav}}\, \vec{e}_\perp$ is a spin navigator field

When slowly approaching the ST-resonance **adiabatic invariant is preserved**

**Away from the ST resonance**, the polarization vector is approximately directed **along the vertical direction**

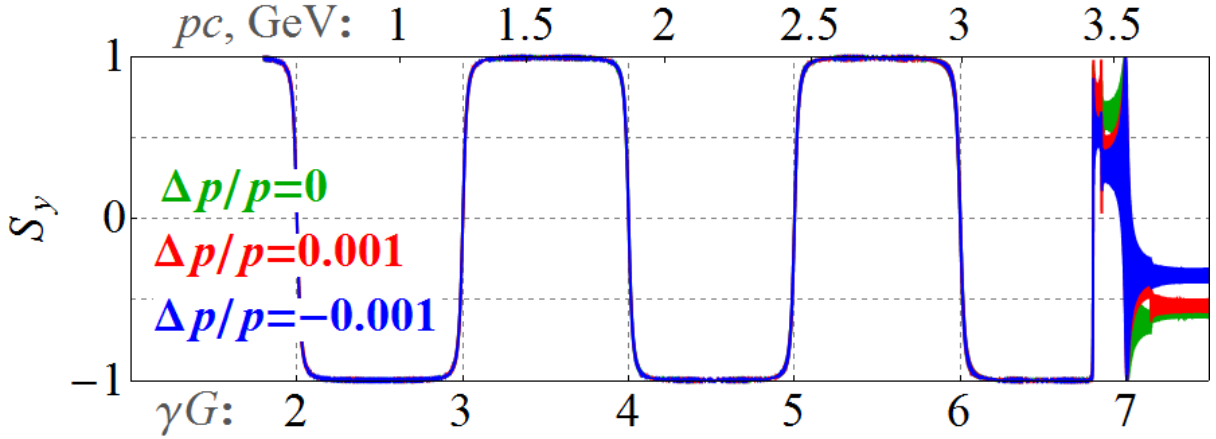
**In ST-resonance** the polarization is oriented **along the navigator axis** lying in the Nuclotron plane

# Acceleration of Polarized Proton up to 3.4 GeV/c




The vertical proton spin components during acceleration of three protons with different momenta in the Nuclotron **without partial snake**

**To eliminate a series of integer resonances**, it is sufficient to use a partial snake with a **small field integral**




The **5% solenoid snake** is required the solenoid field integral of **0.65 T·m** at the momentum of **3.4 GeV/c**.

**Correcting dipoles** can be used **instead of 5% solenoid snake** to preserve polarization

# Experimental verification of the ST mode in Nuclotron

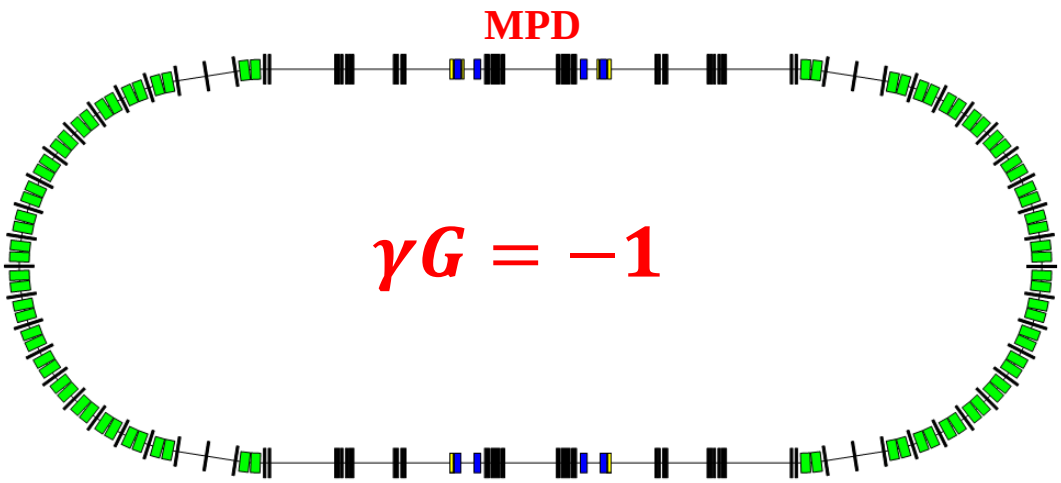
The proton **navigator based on correcting dipoles** allows to perform a series of unique experiments on Spin Transparency in **Nuclotron**, which include **verification** of:

- **adiabatic capture** of spins by the navigator in the ST resonance region
- **spin navigator** operation
- **spin-flip system** based on the navigator

The experiments **require polarimeters** to measure the **vertical and radial** polarization of protons

After verification of the ST mode it will be possible to carry out experiments with polarized protons on internal and external targets. **The results are relevant for the NICA collider**

# ST mode for deuterons in NICA at $\gamma G = -1$




**Deuterons**

$pc \approx 13$ GeV

The **same magnetic lattice as for heavy ions** is used to carry out experiments with deuterons

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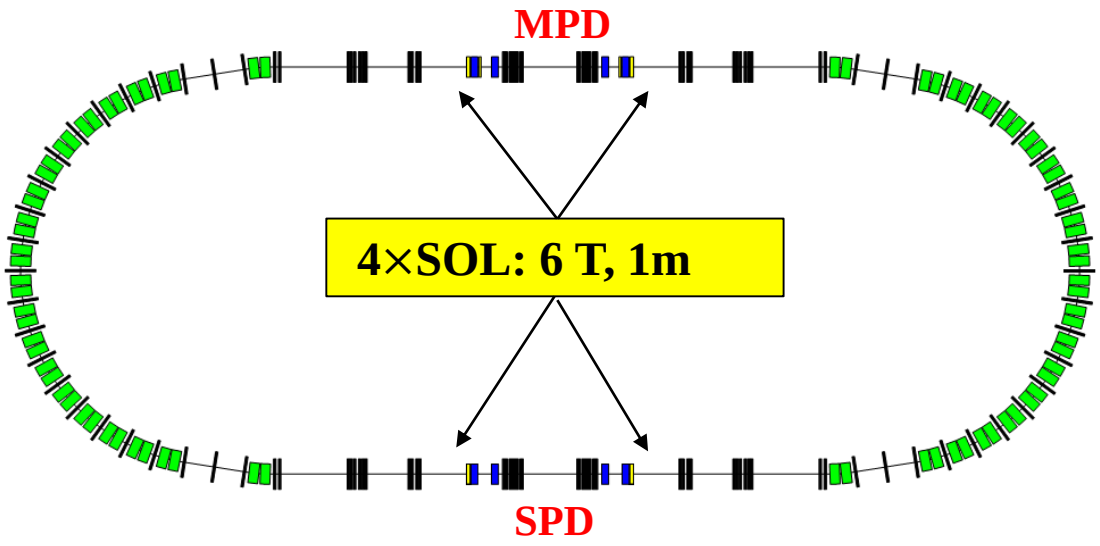
**Unique experiments** with deuterons on Spin Transparency in **NICA**:

- Adiabatic capture of spins by the navigator
- Spin navigator operation
- Spin-flip system
- **High-precision measurement of the G-factor of deuterons**
- **High-precision experiments for searching of EDM deuterons**

# ST mode in NICA with two solenoidal snakes




*ST mode with four 6T-solenoid*

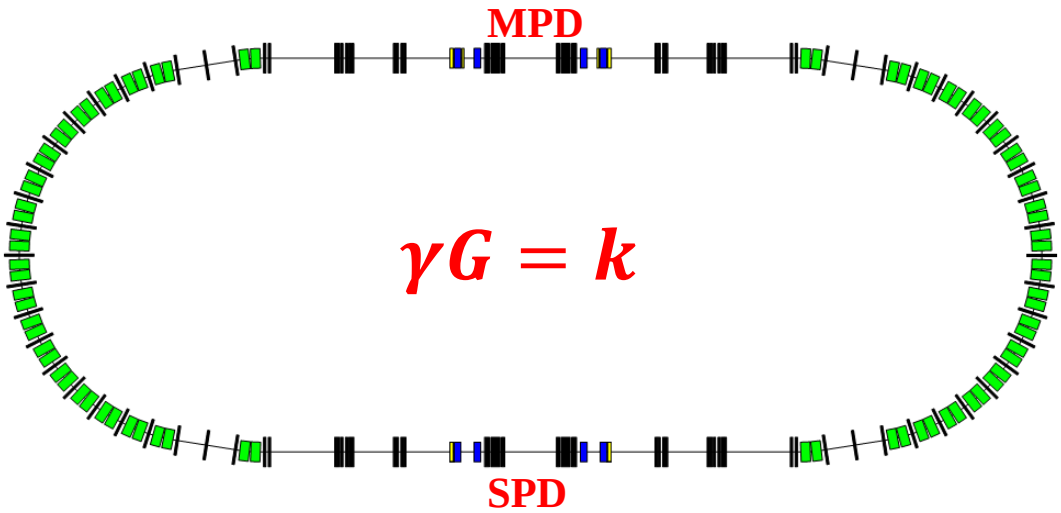
| | |
|---|---|
| *p* | up to 3.20 GeV/c |
| *d* | up to 0.98 GeV/c |
| $He^3$ | up to 7.32 GeV/c |

**Snakes eliminate** both **resonant depolarization** during beam acceleration and the **influence of synchrotron oscillations** on the spin dynamics in the ST mode

**Snakes** together with navigators **allow to compensate** the coherent influence on spins of the NICA magnetic **lattice imperfections**

It becomes possible to carry out **ultrahigh-precision** experiments, such as **measurement of the G-factors of deuterons and protons**

# ST mode at an integer spin resonance in NICA



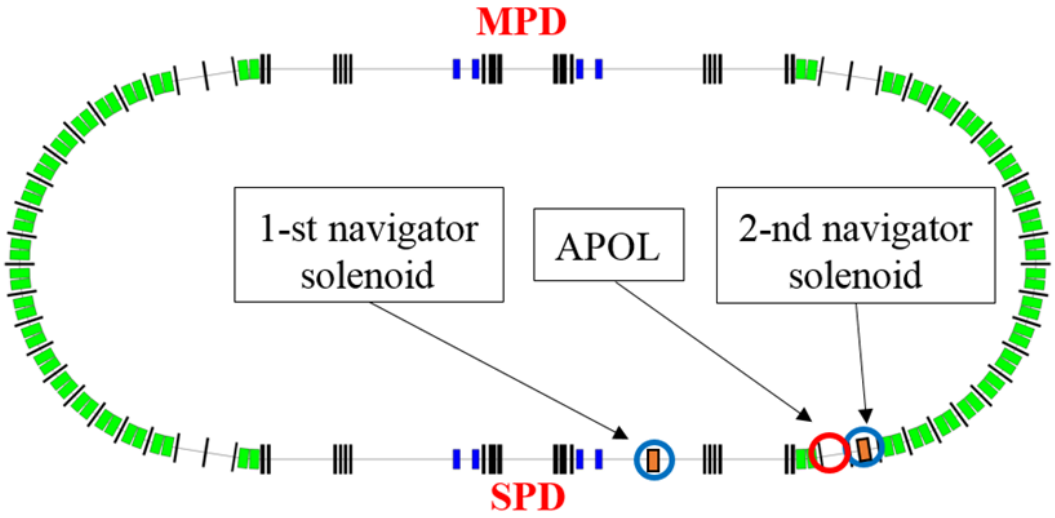

Protons

$$pc > 3.2\ \text{GeV}$$

Energy step

$$\Delta E \approx 523\ \text{MeV}$$

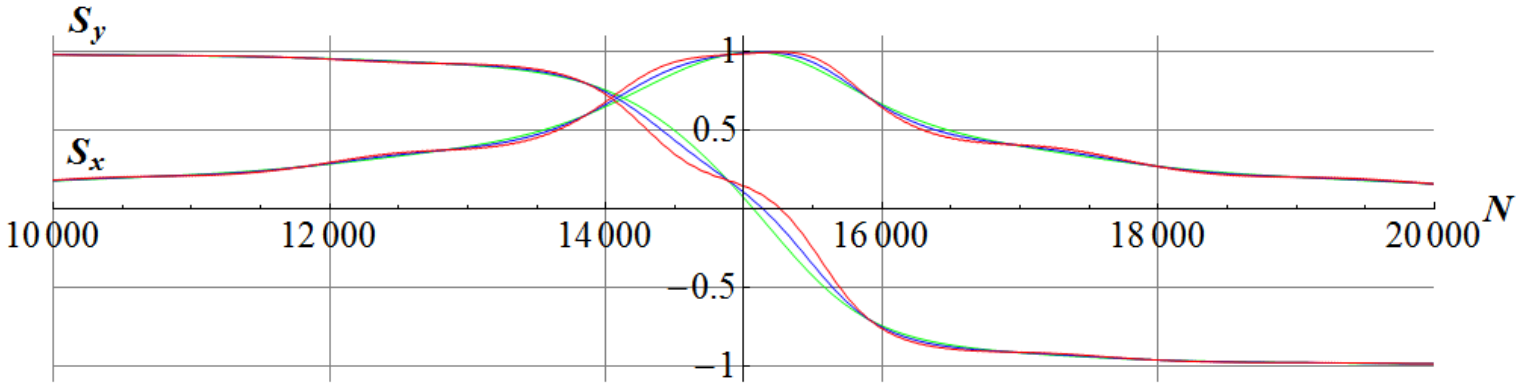
The possibility of **using 6T solenoids to preserve proton polarization** during acceleration in the NICA collider should be considered

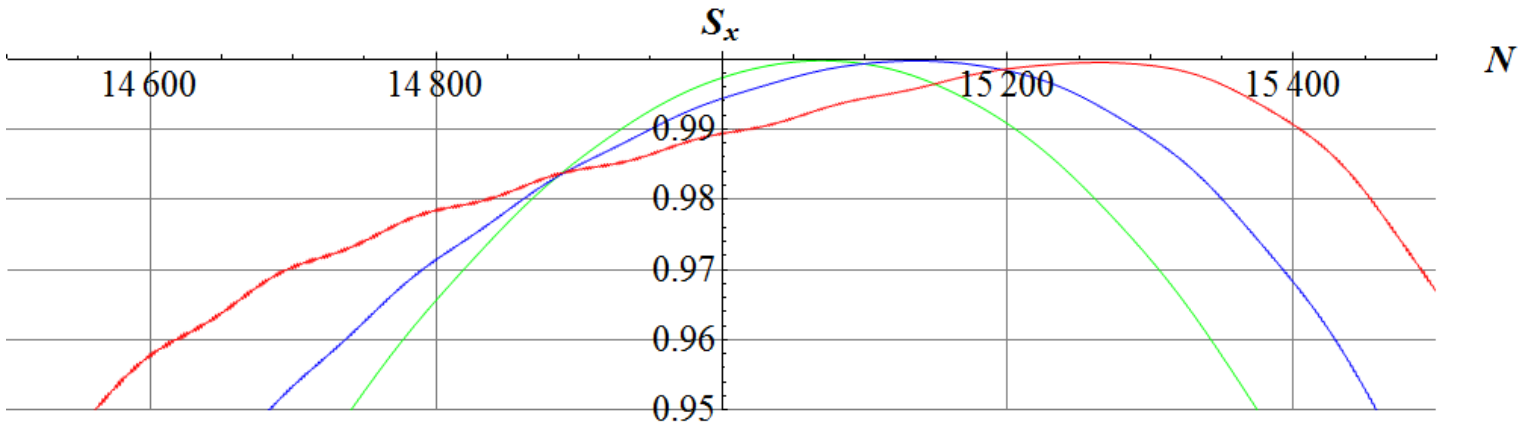



**Spin navigator based on two weak solenoids**

polarization control in the collider plane (radial and longitudinal polarization)

# Adiabatic capture of proton polarization in NICA by a spin navigator at $\gamma G = 25$ (numerical simulation)




$\nu_{nav} = 1.6 \cdot 10^{-2}$, $\nu_s = 5 \cdot 10^{-4}$ $\frac{\Delta p}{p} = 10^{-5};\ 5 \cdot 10^{-5};\ 10^{-4}$

# Spin navigators based on solenoids and dipoles

| **Navigator fields** | **additional solenoids** | **existing correcting dipoles** |
|---|---|---|
| **Polarization control** | 2D-navigator | 3D-navigator |
| **Distortion of the closed orbit** | No | Yes |
| **Momentum dependence** | $(BL)_{nav}$ is proportional to the beam momentum | $(BL)_{nav}$ is weakly dependent on the beam momentum |
| $\nu_{nav} = 0.01$ **at 13.5 GeV/c** | $(BL)_{nav} \sim 1$ T·m | $(BL)_{nav} \sim 0.01$ T·m |
| **Compensation of the ST-resonance strength** | partial compensation | complete compensation |

# Conclusion

- Possibilities for the first experiments in ST mode in the NICA acceleration complex were discussed
- It now possible to carry out pioneering experiments to verify the ST mode at Nuclotron
- Experiments with polarized deuterons at the integer spin resonance $\gamma G = -1$ are realistic as soon as the collider is commissioned
- These experiments **require measurements of both vertical and radial** beam polarization

The **spin transparency** mode makes the NICA complex a **unique facility for high-precision experiments** with polarized protons and deuterons

**Thank you for your attention!**