Joint Institute for Nuclear Research

VBLHEP Specialized Seminar

A.M. Baldin Relativistic nuclear physics and polarization phenomena № 778

Conceptual design of scheme of the protons and deuterons polarization control in the NICA collider

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report on work performed

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Outline

1. Polarization control scheme requirements for spin physics program at the NICA collider
2. Polarization control at SPD/MPD in the NICA collider with two solenoidal snakes
3. Spin flipping and on-line polarimetry systems
4. Preservation of the polarization during beam acceleration up to experiment energy
5. Summary

Main Requirements for the Polarization Control Scheme at NICA

Experiments with polarized beams of **protons, deuterons, and helium-3** are planned at the NICA collider to investigate various issues (Drell-Yan, J/Ψ, high p_T hadron physics, exotic states, etc) with luminosity 10^{30}-10^{32} $cm^{-2} \cdot s^{-1}$ in the momentum range from 2 to 13.5 GeV/c.

The polarization control scheme must satisfy the following requirements:

- to manipulate with longitudinal and transverse polarization at SPD/MPD
- to maintain polarization up to 90% during the lifetime of the beam
- allow to have the polarized beams in full energy range
- allow to have the polarized beams during the asymmetric mode operation
- to have Spin Flipping System with reverse time less 1 sec.

Spin Motion at Conventional Circular Accelerator

The spin equilibrium closed orbit

$\vec{n}(z+L) = \vec{n}(z)$ is a periodical axis of precession

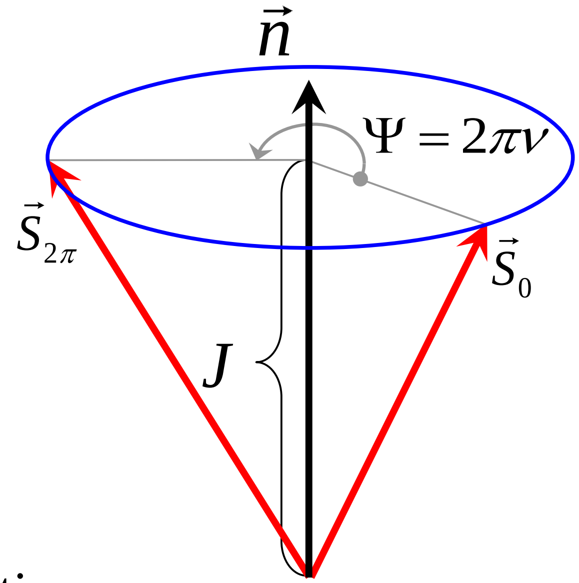
$\vec{S} = J \cdot \vec{n} + \vec{S}_\perp, \qquad J = \vec{S} \cdot \vec{n}, \qquad \vec{S}_\perp \perp \vec{n}$

Spin vector rotates around *n*-axis:

If $\vec{S}_0 \parallel \vec{n} \Rightarrow \vec{S}_0 = \vec{S}_L$

If $\vec{S}_0 \perp \vec{n} \Rightarrow \vec{S}_L \perp \vec{n}, \ \angle(\vec{S}_0, \vec{S}_L) = \Psi = 2\pi\nu$

ν is a spin precession tune

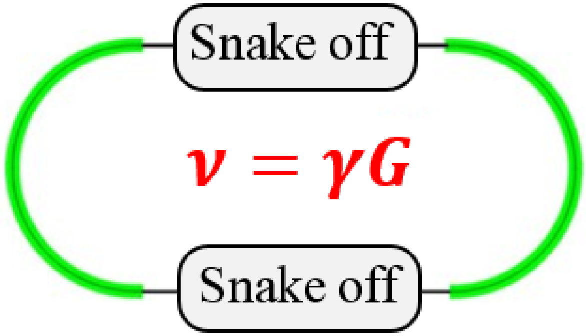
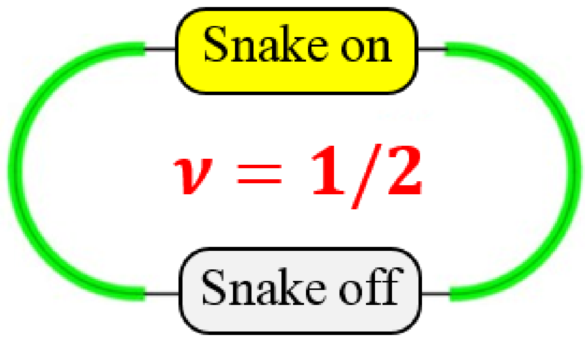
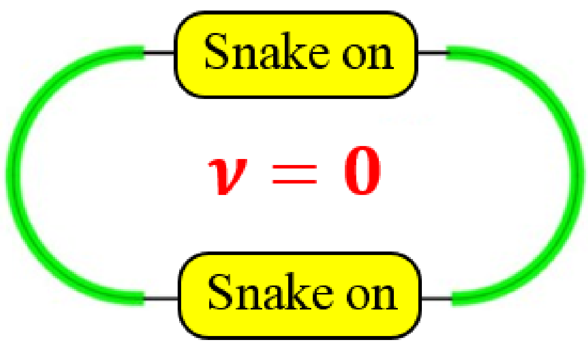


In ideal accelerator $\vec{n} = \vec{e}_y, \qquad \nu = \gamma G$

$G = (g-2)/2$ is an anomalous part of gyromagnetic ratio

Spin mode	n-axes	Spin tune	Spectrum
Preferred Spin mode **(PS mode)**	periodic spin motion along the closed orbit is **unique**	$\{\nu\} \neq 0$	spin motion tunes are added to the orbital spectrum
Spin Transparency mode **(ST mode)**	**any** spin direction repeats every particle turn	$\{\nu\} = 0$	same as the spectrum of the orbital motion

ST and PS modes at the NICA collider with two snakes

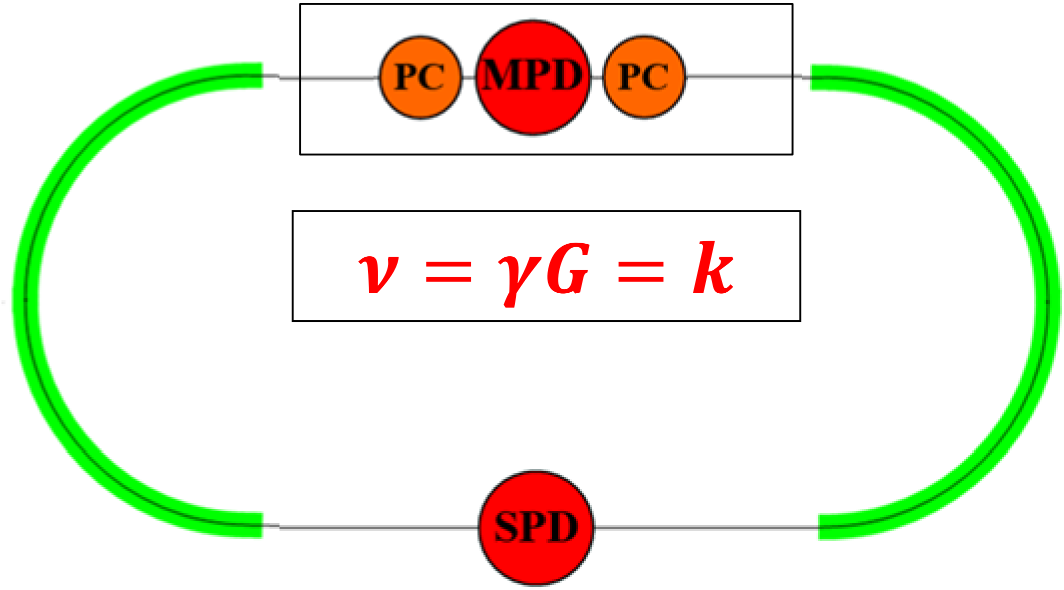
Collider's configuration		Spin mode
Without snakes		($\gamma G \neq k$) Preferred Spin (unique spin direction) ($\gamma G = k$) Spin Transparency (any spin direction)
With one snakes		Preferred Spin mode (unique spin direction)
With two snakes		Spin Transparency mode (any spin direction)

Possible directions of the polarization at the SPD/MPD

Collider's configuration	Spin tune	Spin mode	Polarization at the SPD/MPD
Without snake	$\gamma G \neq k$	**PS**	**Vertical direction** at SPD and MPD
Without snake	$\gamma G = k$	**ST**	**Any direction** at SPD or MPD
With one snake (SPD)	1/2	**PS**	**Longitudinal direction** at MPD
With one snake (MPD)	1/2	**PS**	**Longitudinal direction** at SPD
With two snakes	0	**ST**	**Any direction** at SPD or MPD

PS is "Preferred Spin" mode,
ST is "Spin Transparency" mode

Spin Transparency Mode in NICA Collider at integer spin resonances (discrete values of energy).



$$\nu = \gamma G = k$$

Polarized beam is injected from Nuclotron to the NICA collider at energy which correspond to integer spin resonance

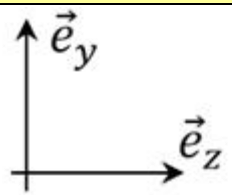
Polarization control insertion based on "weak" solenoids with maximum field integral ***BL* < 0.6 T·m** (***protons, deuterons***)

Polarization direction in **SPD** or **MPD** — **any** direction **in vertical plane** (*z*-*y*)

Protons: $E_{kin}^{min} = 108\text{ MeV}, \;\; \Delta E = 523\text{ MeV}$ (25 energy points)

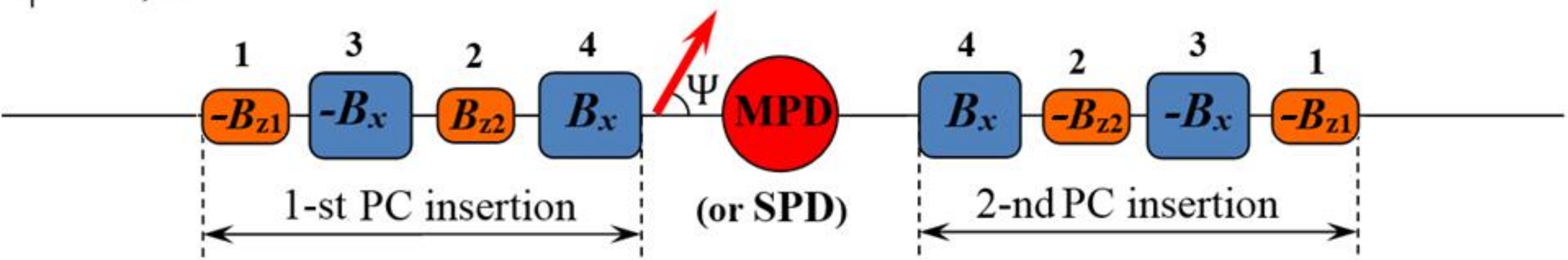
Deuterons: $E_{kin} = 5.63\text{ GeV/u}, \;\; pc = 13\text{ GeV}$ (1 energy point)

Ion polarization control in NICA collider by means of "weak" solenoids

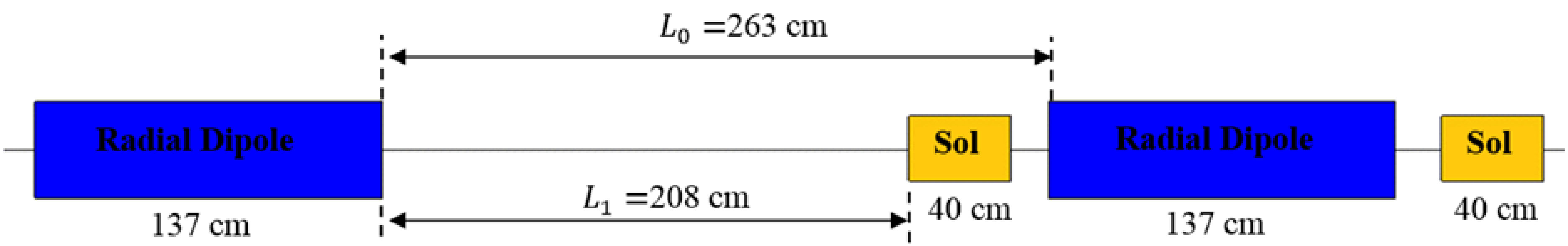


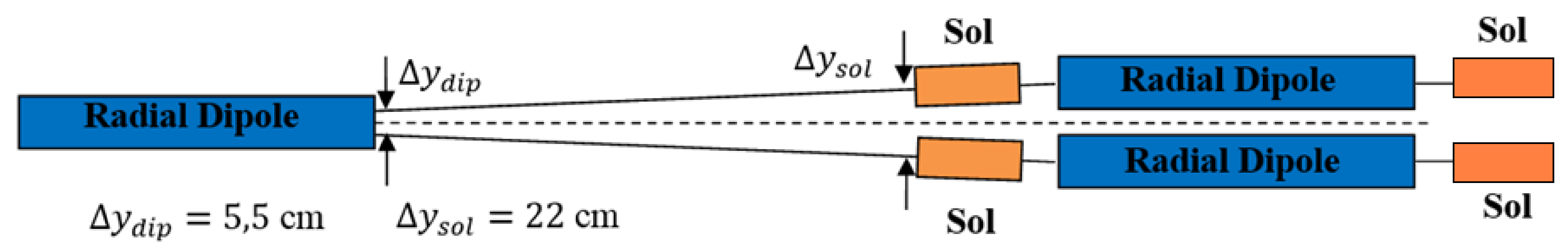
$$\vec{S}_{MPD} = \vec{e}_y \sin\Psi + \vec{e}_z \cos\Psi$$

1,2 – weak solenoids
3,4 – radial dipoles



Ψ is the angle between the polarization and velocity directions





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Integer Spin Resonance strength & Spin Stability Criterion

The total **integer spin resonance** strength

$$\omega = \omega_{coh} + \omega_{emitt}, \qquad \omega_{emitt} \ll \omega_{coh}$$

is composed of

- coherent part ω_{coh} due to closed orbit excursions
- incoherent part ω_{emitt} due to transverse and longitudinal emittances

After compensation of the ω_{coh} **the collider with errors** becomes equivalent to **the ideal collider without errors**

Spin stability criterion

the spin tune induced by the PC solenoids must significantly exceed the strength of the zero-integer spin resonance

$$\nu \gg \omega_{emitt}$$

- for proton beam $\nu = 10^{-2}$
- for deuteron beam $\nu = 10^{-4}$

Coherent and incoherent parts of zero-integer resonance strength

Protons: $\boldsymbol{\omega_{coh} \sim 10^{-3} \div 10^{-2}, \omega_{emitt} \sim 10^{-4} \div 10^{-3}}$

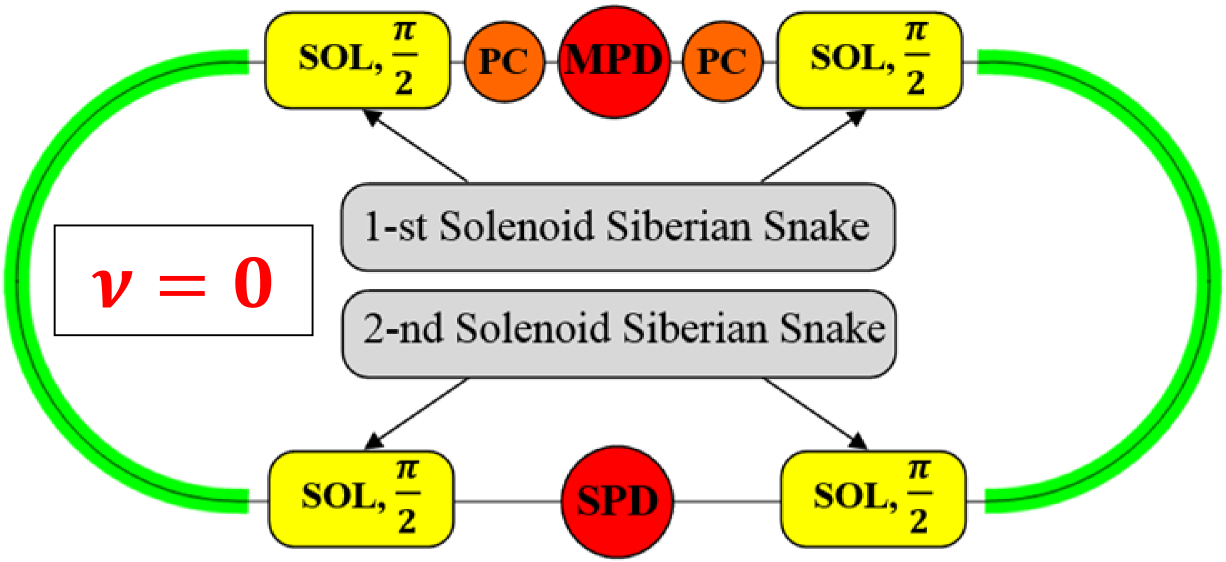
Total PC solenoids field integral about of **1 T· m** is sufficient for stabilization and control of proton polarization in NICA collider.

Deuterons: $\boldsymbol{\omega_{coh} \sim 10^{-6} \div 10^{-5}, \omega_{emitt} \sim 10^{-7} \div 10^{-6}}$

Total PC solenoids field integral about of **0.03 T· m** is sufficient for stabilization and control of deuteron polarization in NICA collider.

It allows one to carry out ultra-high precision experiments with polarized deuteron beams

Spin Transparency Mode in NICA Collider at zero-spin tune (continuous values of energy).



Solenoids for spin transparency mode:

BL = 1÷25 T·m (***protons***), BL = 3÷80 T·m (***deuterons***)

Orbital parameters do not depend on the beam energy

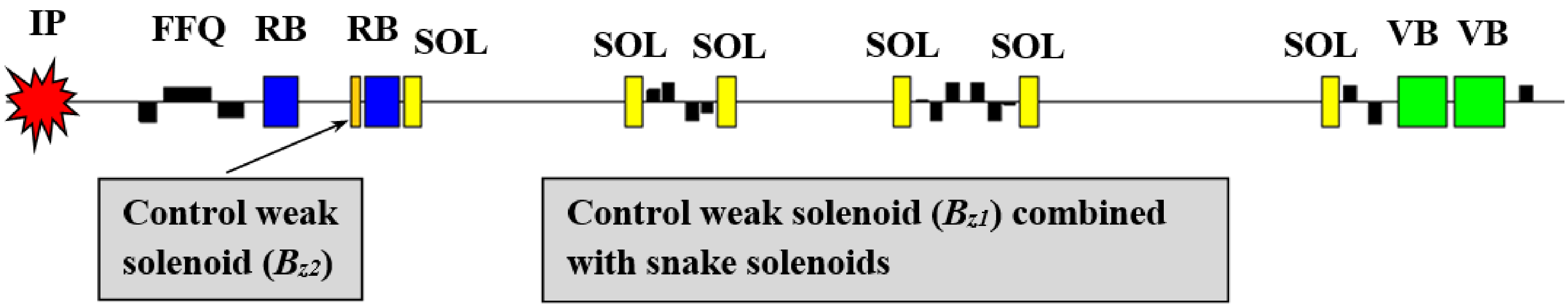
Polarization control insertion based on "weak" solenoids with maximum field integral BL < 0.6 T·m (***protons, deuterons***)

Polarization direction (***p, d, ³He, …***) **:**

in **SPD** or **MPD** — **any** direction **in vertical plane** (*z-y*);

in **arcs** — **any** direction **in orbit plane** (*z-x*).

Schematic layout of the half experimental straight section



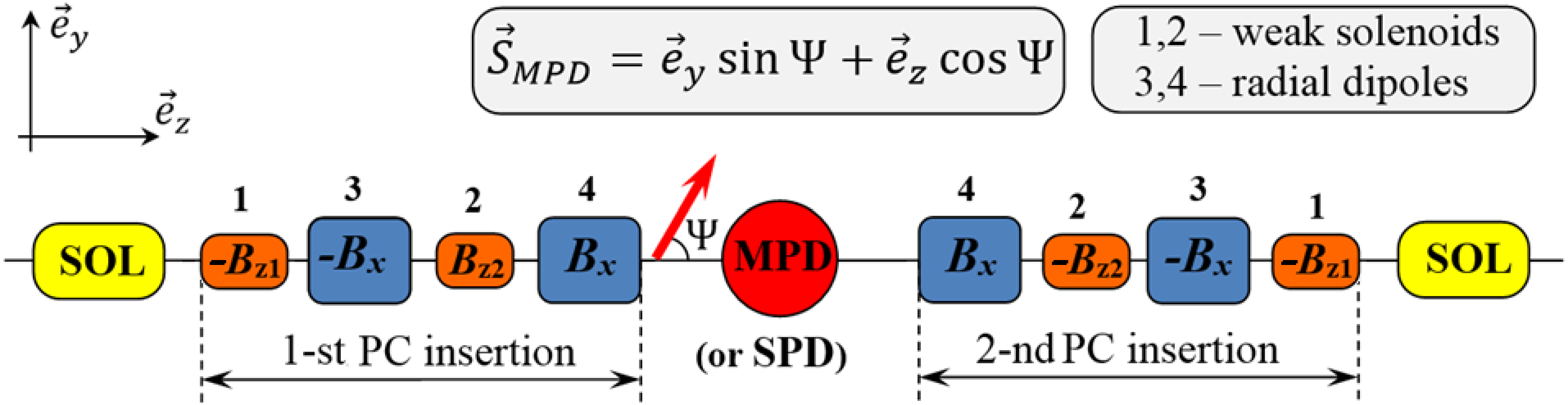
SOL – **6T Solenoid of 0.7 m** (One Siberian Snake = 12×SOL)
VB – arc's Vertical-field Bending magnets,
RB – Radial-field Bending magnets ,
FFQ – Final Focus Quadrupoles

p **up to momentum of 13.5 GeV/c**
d **up to momentum of 4.12 GeV/c**

Ion polarization control in NICA collider by means of "weak" solenoids

$$\vec{S}_{MPD} = \vec{e}_y \sin\Psi + \vec{e}_z \cos\Psi$$

1,2 – weak solenoids
3,4 – radial dipoles



Ψ is the angle between the polarization and velocity directions

Longitudinal polarization

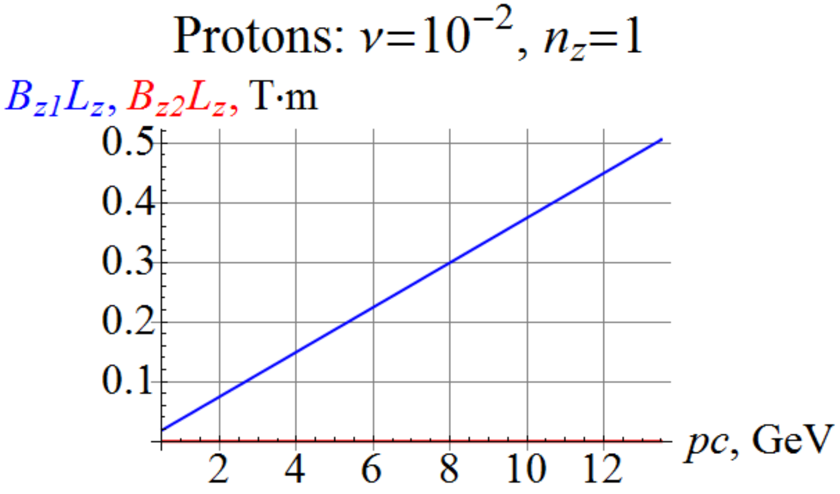
Ψ = 0° Ψ = 180°

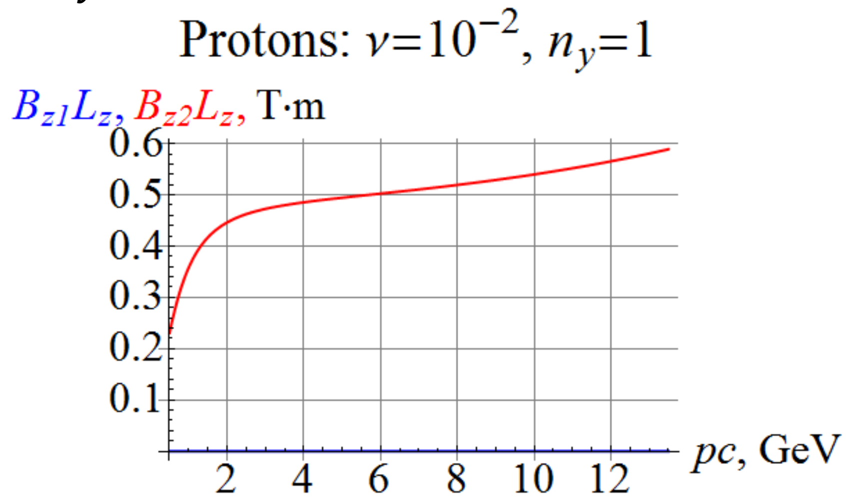
Vertical polarization

Ψ = -90° Ψ = 90°

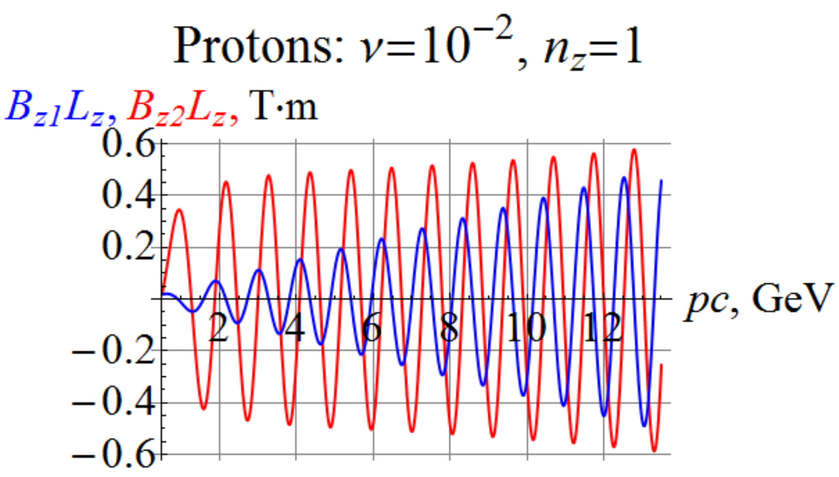
Control solenoid field integrals vs momentum (protons)

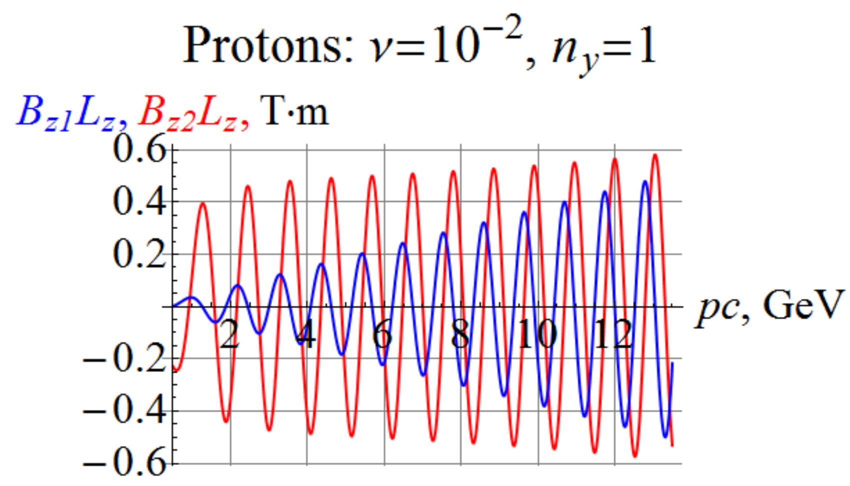
Longitudinal ($n_z = 1$) and **vertical** ($n_y = 1$) polarization **at MPD detector**



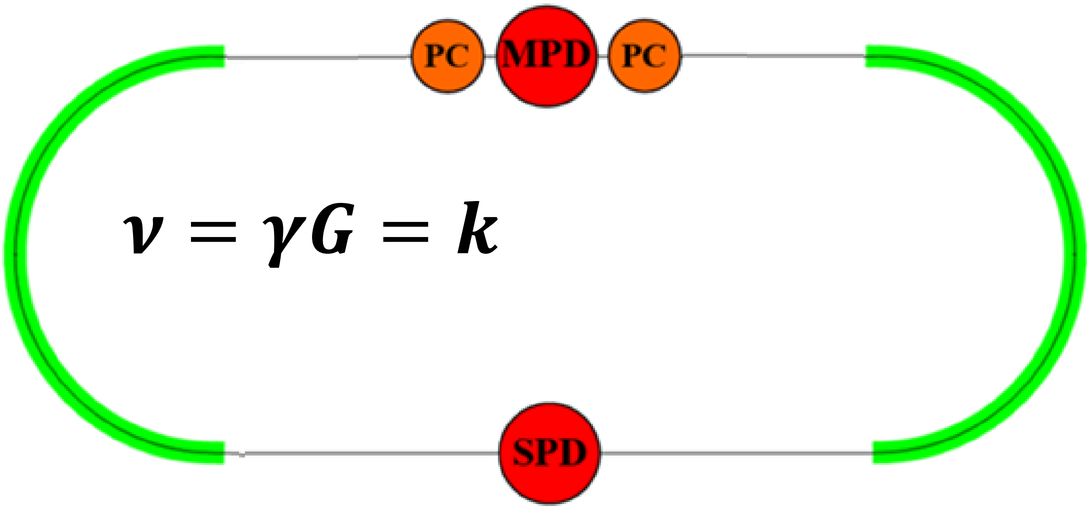


Longitudinal ($n_z = 1$) and **vertical** ($n_y = 1$) polarization **at SPD detector**

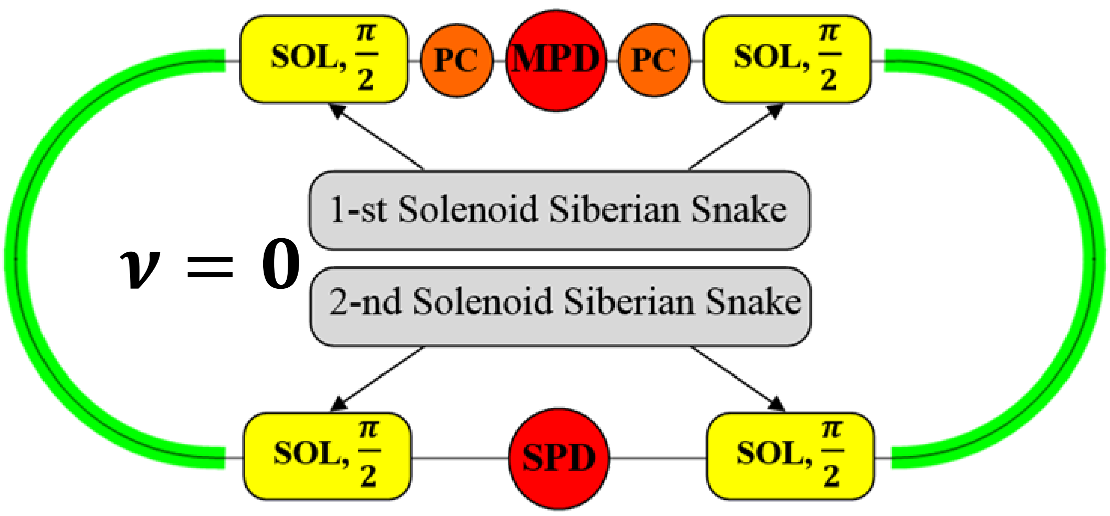




Polarization at the Spin Transparency Modes



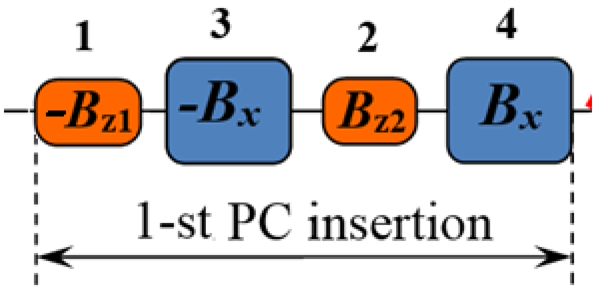
Spin transparency mode at zero-spin tune gives advantage even at energies which corresponds to the integer spin resonances $\gamma G = k$.



In the case of $\nu = 0$ two **solenoidal snakes eliminate impact of synchrotron oscillations** on polarization which allow to significantly improve quality of polarized beam and increase lifetime of the polarization by factor of $\sim \boldsymbol{\gamma G}$.

On-line spin direction control and Spin Flipping System

$$\vec{n} = \vec{n}(B_{z1}, B_{z2}), \qquad \nu = \nu(B_{z1}, B_{z2})$$



During spin manipulation one can keep the value of spin tune constant. It eliminates crossings of high order spin resonances and provides the stability of the SF system.

New concept of the on-line polarization control at the NICA collider

1. It is necessary to provide the stability of polarization ***during the operation*** of the collider.
2. To measure the degree of polarization, it is sufficient to know only the direction of the n-axis, which "measurement" reduces to measuring the control solenoid fields.

There is a unique possibility of the on-line polarization control in the spin-transparency mode of the NICA collider.

Spin Flipping System at the NICA collider

New regimes of filling the rings: all bunches with the same polarization in both rings. New modes of operation (spin-flippers are turned on by turns):

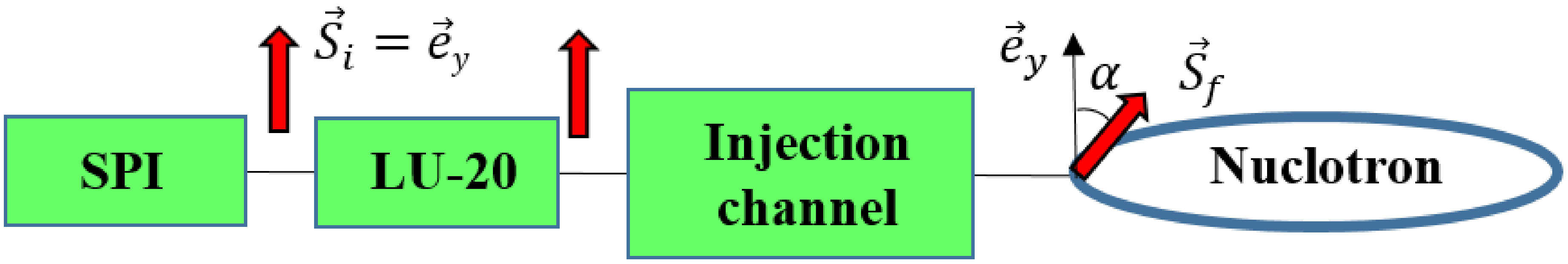
1-st ring	+++… |xxx| - - -… |----| - - -… |xxx| +++ |----| +++…
2-nd ring	+++… |----| +++… |xxx| - - -… |----| - - - |xxx| +++…
	(+ +) (- +) (- -) (+ -) (+ +)

|xxx| — spin-flipper is turned on. There is no data collection.

|----| — spin-flipper is not turned on. There is no data collection.

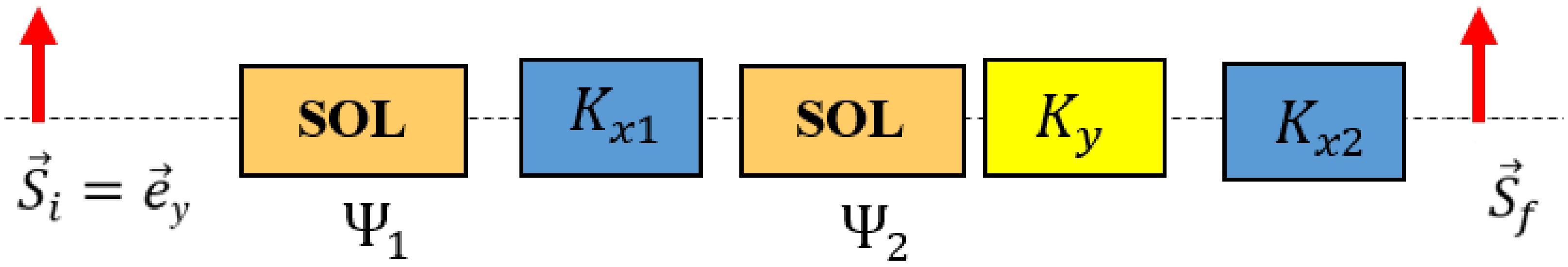
- **The measurement of the luminosity between the bunches is resolved**
- **Operation with the same polarized ion mode in all bunches during the filling ring**

Proton Polarization at injection to Nuclotron



Initial polarization in Nuclotron $P_{\text{inj}} = \cos\alpha \; P_{SPI}$

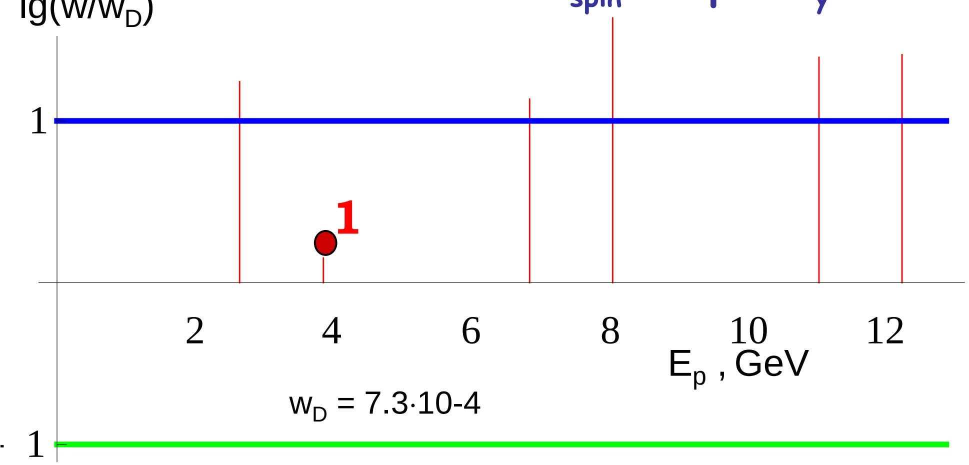
Matching of Polarization to the Vertical Direction in Nuclotron



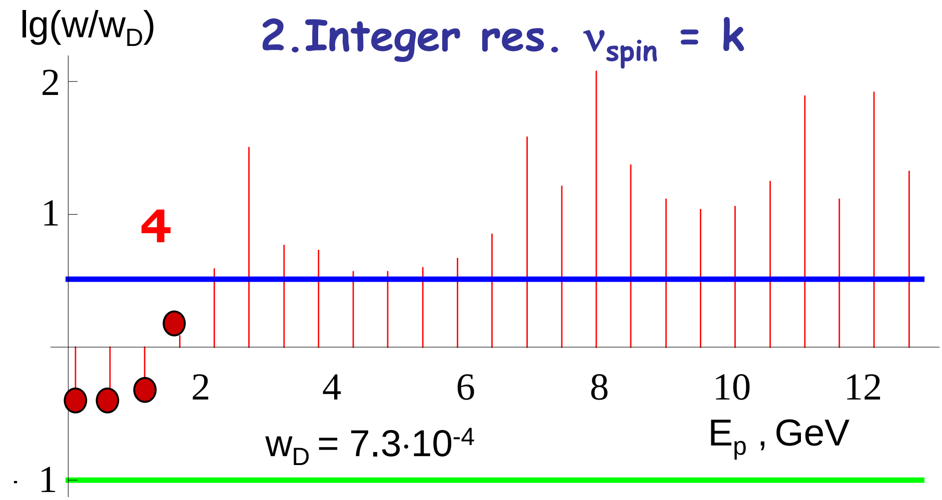
Proton's spin resonances at Nuclotron

Dangerous resonances are marked with red caps ● (dB/dt = 1 T/s)

1. Intrinsic res. $\nu_{spin} = kp \pm \nu_y$

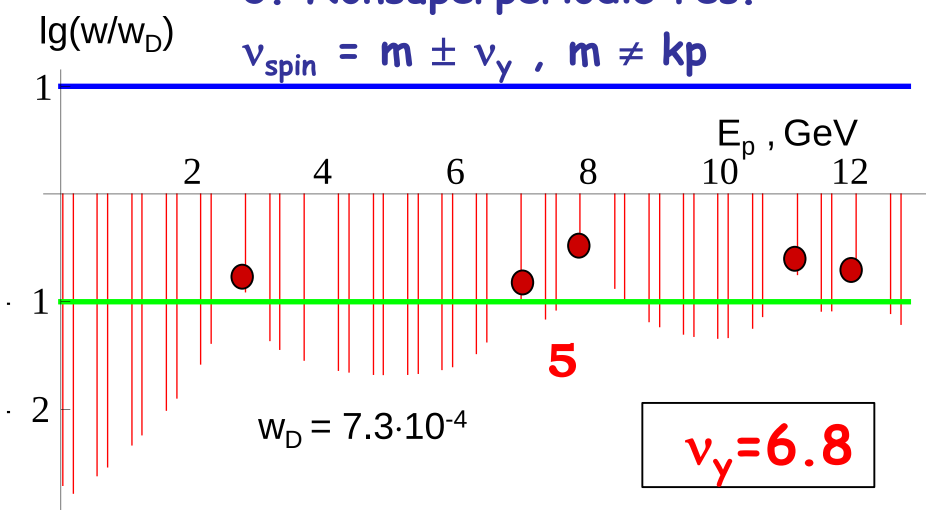


2. Integer res. $\nu_{spin} = k$



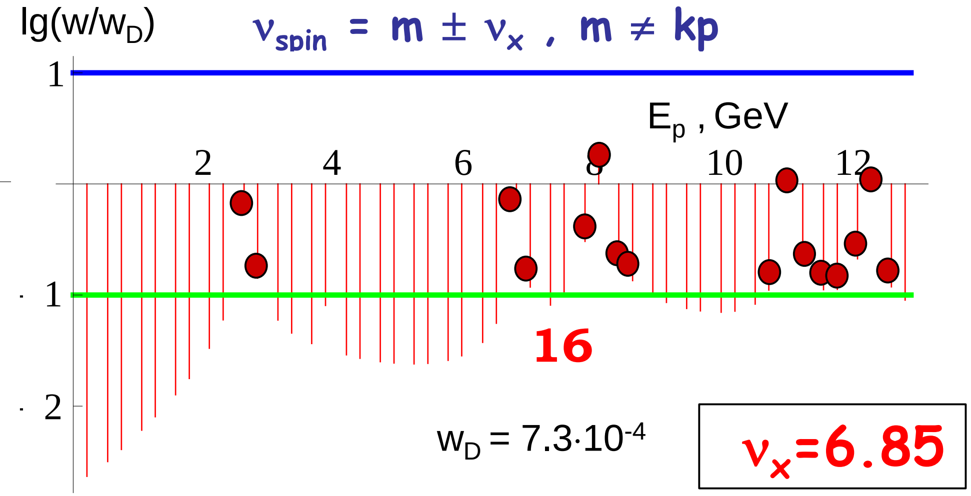
3. Nonsuperperiodic res.

$\nu_{spin} = m \pm \nu_y$, $m \neq kp$



4. Coupling res.

$\nu_{spin} = m \pm \nu_x$, $m \neq kp$



Techniques for crossing of spin resonances at Nuclotron

We had analyzed various **techniques for crossing of spin resonances**:

- *resonance strength compensation*
- *intentional enhancement of the spin resonance strength*
- *betatron tune jump*
- *spin tune jump*

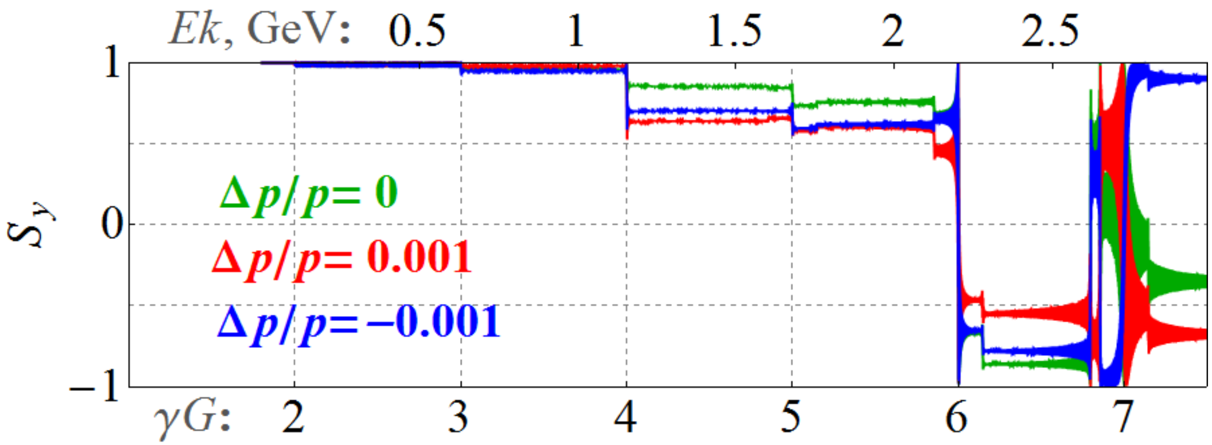
These techniques allow one only to reduce the depolarization for each resonance crossing. Thus, crossing of a large number of dangerous resonances may eventually lead to a significant polarization loss.

A transparent crossing technique was proposed and experimentally tested, which, in principle, allows one to eliminate polarization loss during a crossing.

The **limiting factors** for the transparent and fast resonance crossings are effects of the **spin and betatron tune spreads in the beam**.

For **slow resonance crossings**, preservation of the polarization is a complex task that requires consideration of the **synchrotron energy oscillations** of the beam particles and **higher-order resonances**.

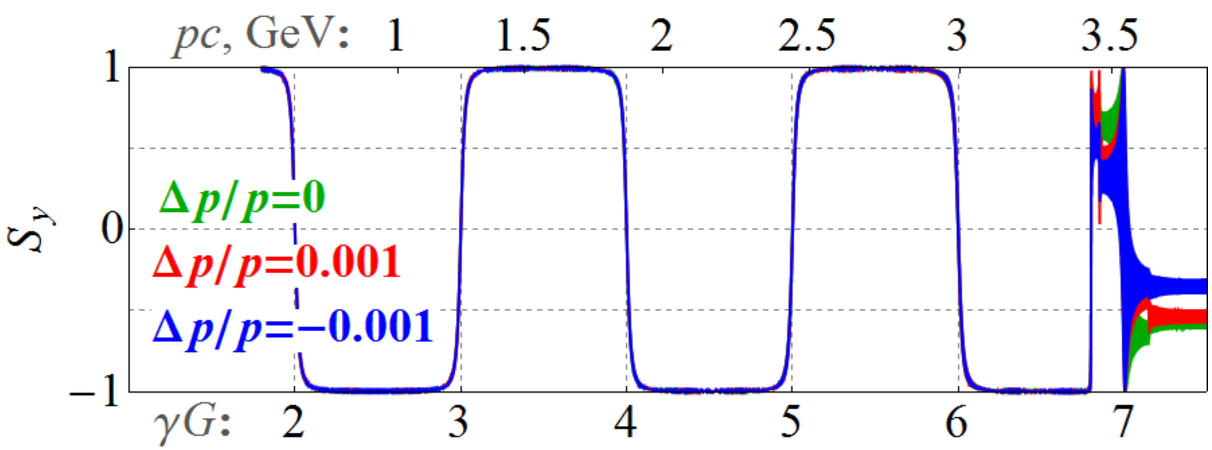
Acceleration of Polarized Proton up to 3.4 GeV/c



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

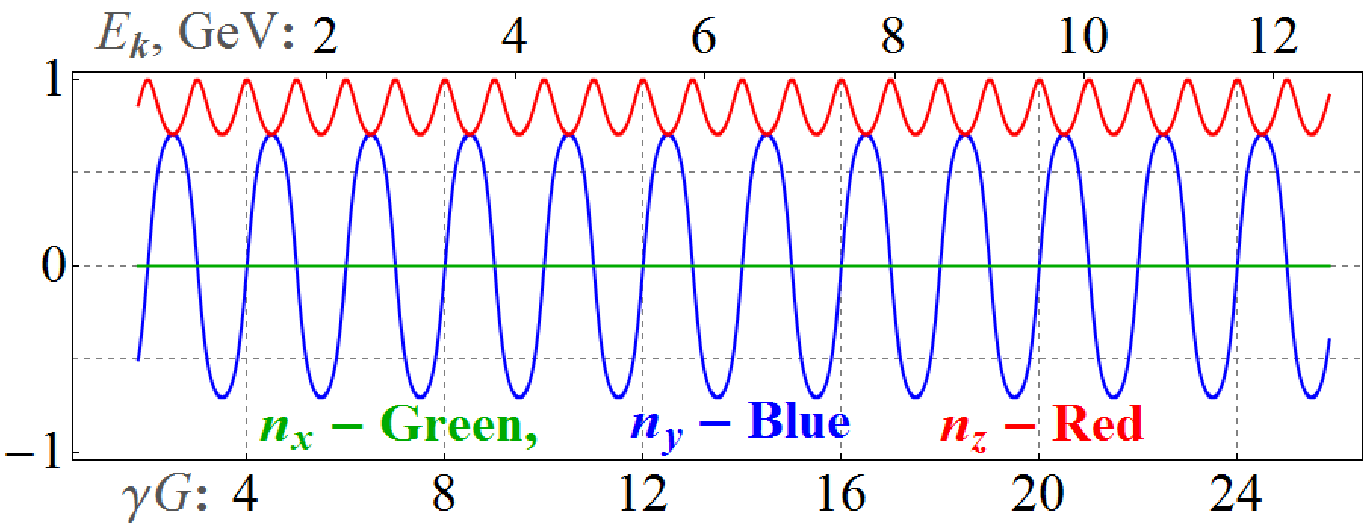
Synchrotron oscillations have strong influence on the proton spin dynamics

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

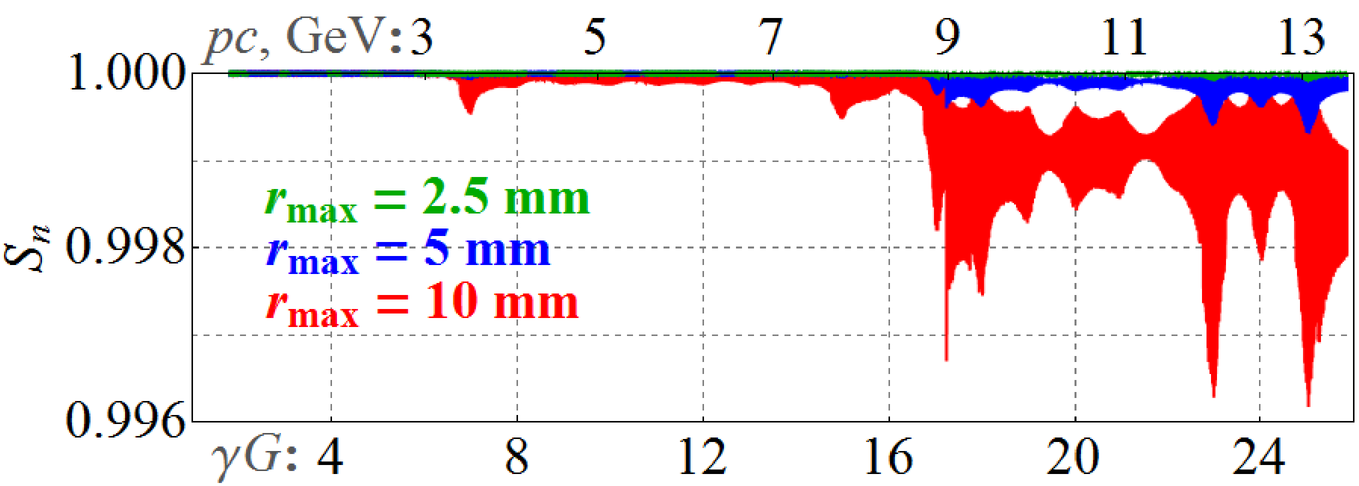


The 5% solenoid snake is required the solenoid field integral of **0.65 T·m** at the momentum of **3.4 GeV/c**.

Acceleration of Polarized Proton up to 13.5 GeV/c



The $\vec{n}$-axis components at acceleration with the 50% solenoidal snake



The $S_n = \vec{S} \cdot \vec{n}$ projections at acceleration of three protons with the 50% solenoidal snake

The requirement solenoid field integrals are of
25 Tm for the **50% snake** and **12.5 Tm** for the **25% snake**

Possibilities at the operation with polarized protons and deuterons in NICA

Collider's configuration	Spin mode	SF system	On-line polarimetry	Scanning of energy	Impact synchrotron oscillations on spin
without snakes	PS	No	No	No	Impact
without snakes	ST	Yes	Yes	No	Impact
with one snake	PS	No	No	Yes	Doesn't impact
with two snakes	ST	Yes	Yes	Yes	Doesn't impact

PS is "Preferred Spin" mode,
ST is "Spin Transparency" mode

Summary

- The configuration of the NICA collider with solenoid snakes significantly expands the possibilities of carrying out experiments with polarized protons and deuterons, and allows one **to compare experimentally different polarization control modes**
- Using of **solenoid snakes provides the independence of the orbital and spin characteristics** of the collider during the energy change
- To perform the spin physics program at JINR, it is **necessary to use the spin transparency mode** in the NICA collider with two snakes, which allows one to apply a **completely new approach** to carry out experiments with polarized ions at the **high precision level**
- The presented **universal scheme of polarization control** in ST mode allows to operate with the polarization of **any particle species**, including deuterons

Thank you for your attention!