International Workshop on Spin Physics at NICA (SPIN-Praha-2018)

July 9 –13, 2018, Charles University, Prague

Spin Transparency Mode at the NICA collider for proton and deuteron beams

Yu.N. Filatov[1,3], A.D. Kovalenko[1], A.V. Butenko[1], A.M. Kondratenko[2], M.A. Kondratenko[2] and V.A. Mikhaylov[1]

[1]Join Institute for Nuclear Research, Dubna, Russia
[2] Science and Technique Laboratory Zaryad, Novosibirsk, Russia
[3]Moscow Institute of Physics and Technology, Dolgoprydny, Russia

Outline

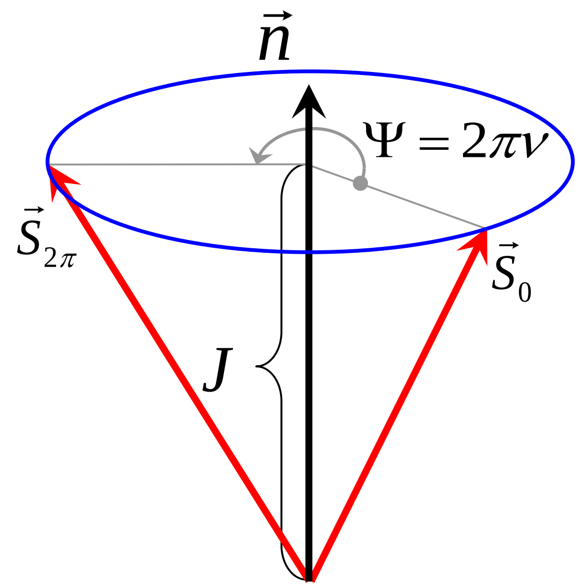
1. Proton polarization in Nuclotron
2. Spin transparency mode in the NICA collider at integer spin resonances (discrete values of energy)
3. Spin transparency mode in the NICA collider in (continuous values of energy)
4. Summary

Spin Motion at Conventional Circular Accelerator

$$\frac{d\vec{S}}{d\theta} = [\vec{W} \times \vec{S}],$$

Thomas-BMT equation

$\theta -$ particle's azimuth



The spin equilibrium closed orbit

$\vec{n}(\theta + 2\pi) = \vec{n}(\theta) -$ 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 rotate around *n*-axis:

If $\vec{S}_0 \parallel \vec{n} \;\Rightarrow\; \vec{S}_{2\pi} = \vec{S}_0$

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

$\nu -$ spin precession tune

In ideal accelerator $\vec{n} = \vec{e}_z, \qquad \nu = \gamma G \qquad G = (g-2)/2 -$ gyromagnetic anomaly

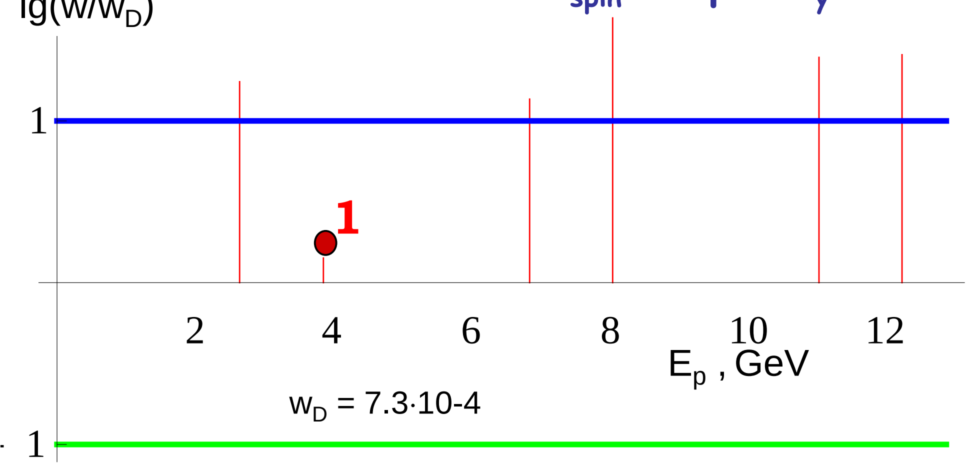
In colliders "*with preferred spin direction*", the periodic spin motion along the closed orbit is unique, i.e. the static magnetic lattice determines a single stable orientation of the beam polarization. The fractional part of *the spin tune differs from zero*.

In colliders "*transparent to the spin*", any spin direction repeats every particle turn along the closed orbit, i.e. the accelerator's magnetic lattice is transparent to the spin. The fractional part of *the spin tune is equal to zero*.

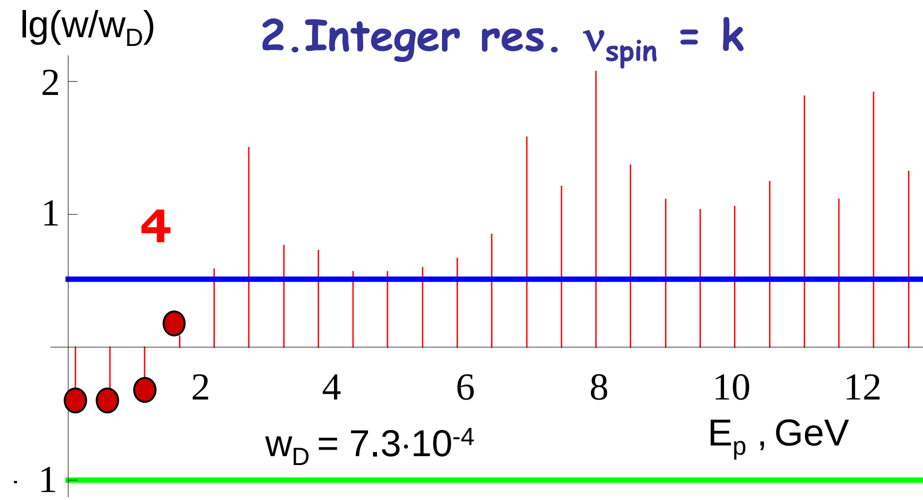
Proton's spin resonances at Nuclotron

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

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

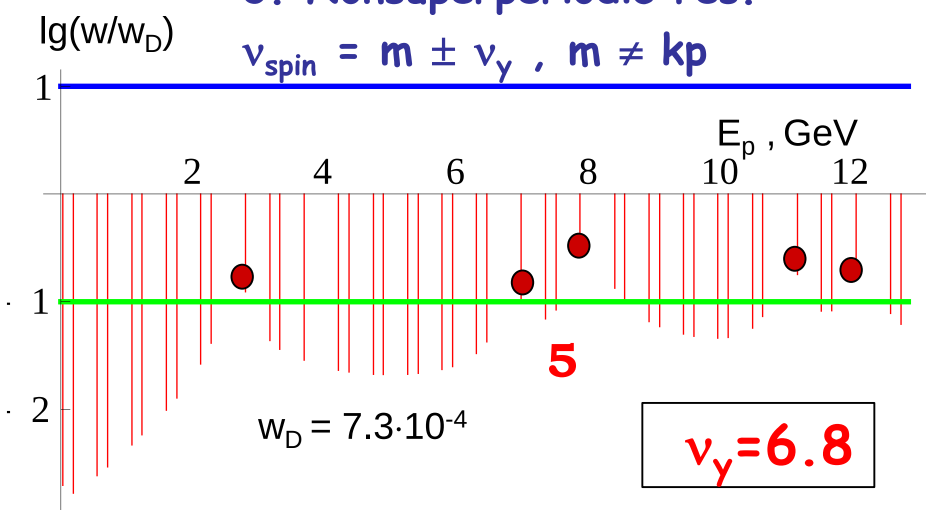


2. Integer res. $\nu_{spin} = k$



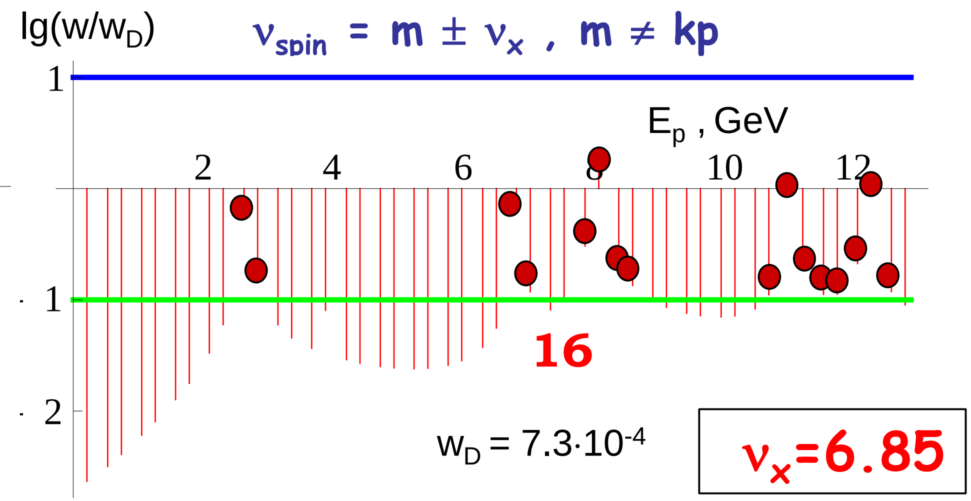
3. Nonsuperperiodic res.

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



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*

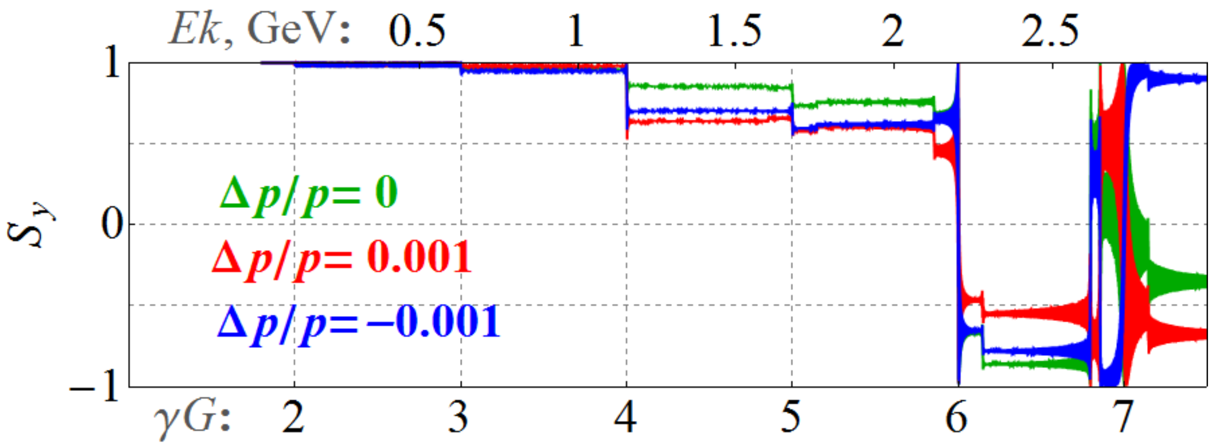
These techniques allow one only to reduce the depolarization for each resonance crossing. Thus, crossing of a large number of dangerous resonances may eventually lead to a significant polarization loss.

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**.

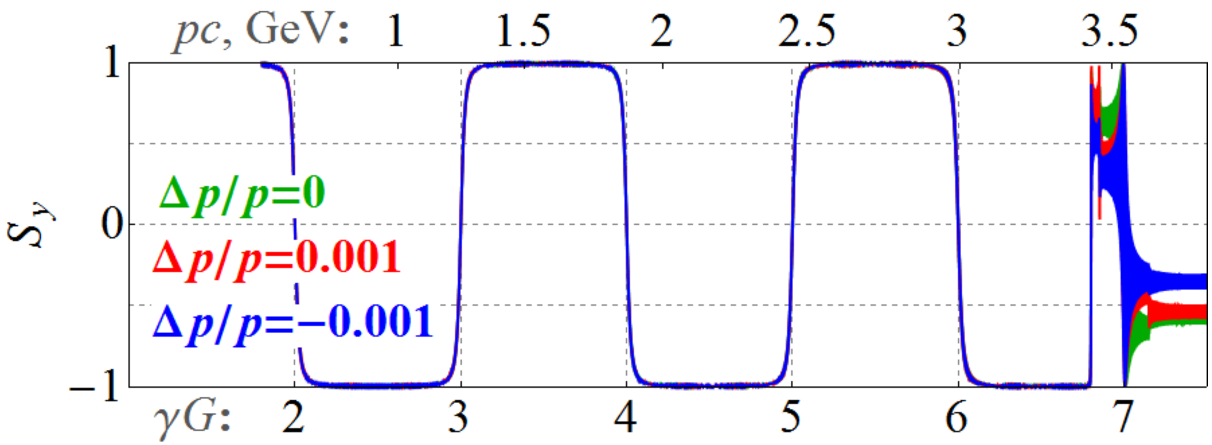
Acceleration of Polarized Proton up to 3.4 GeV/c



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

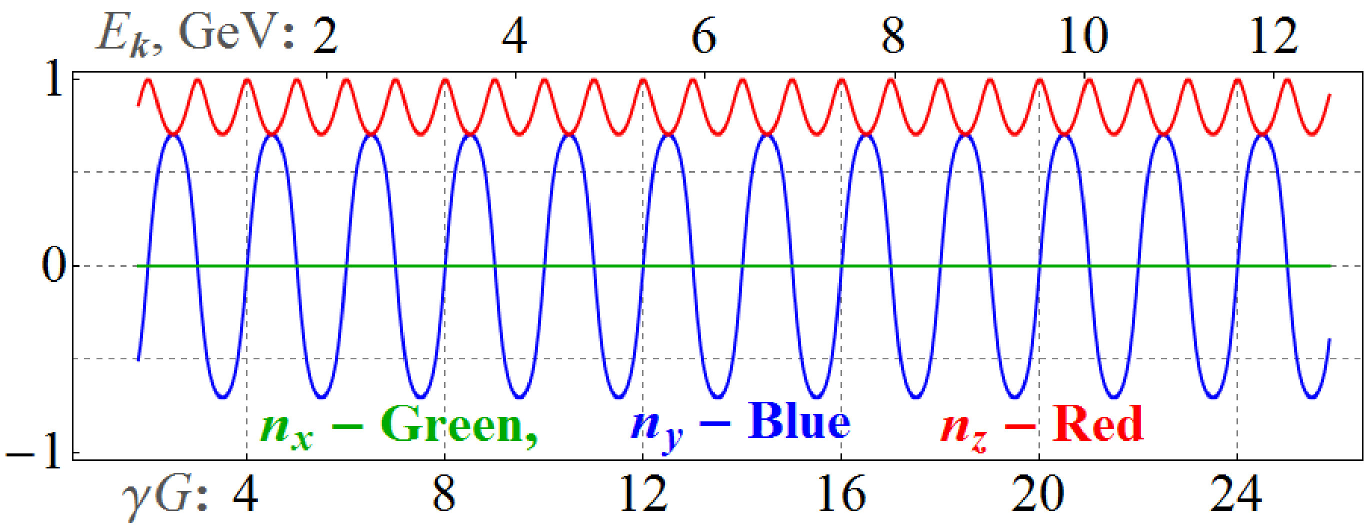
Synchrotron oscillations have strong influence on the proton spin dynamics

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

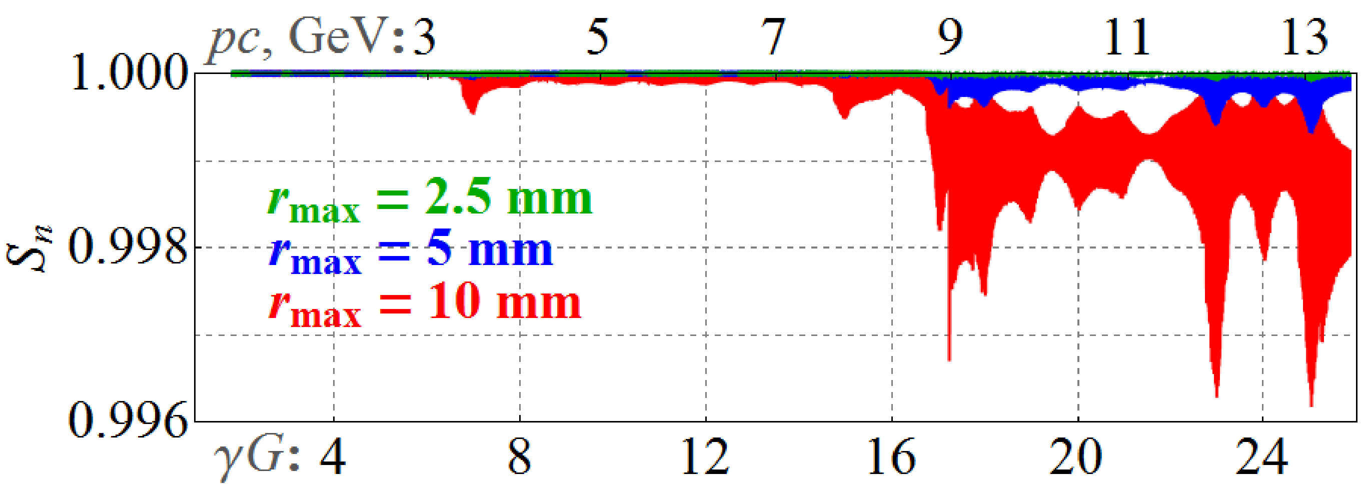


The 5% solenoid snake is required the solenoid field integral of **0.65 T·m** at the momentum of **3.4 GeV/c**.

Acceleration of Polarized Proton up to 13.5 GeV/c



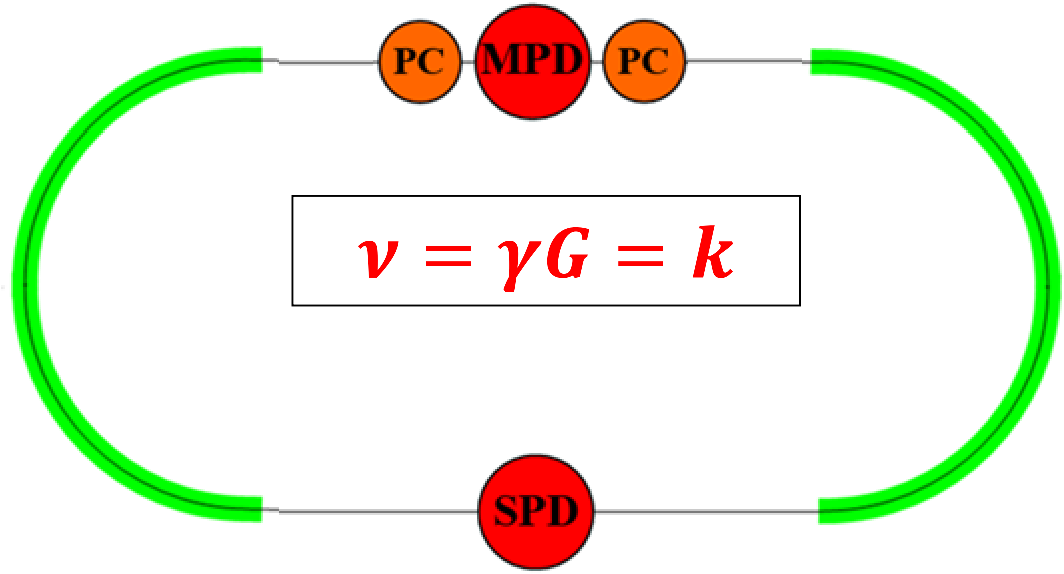
The $\vec{n}$-axis components at acceleration with the 50% solenoidal snake



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**

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



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

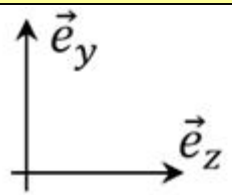
Polarization control insertion based on "weak" solenoids with maximum field integral $BL < 0.6$ T·m (***protons, deuterons***)

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

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

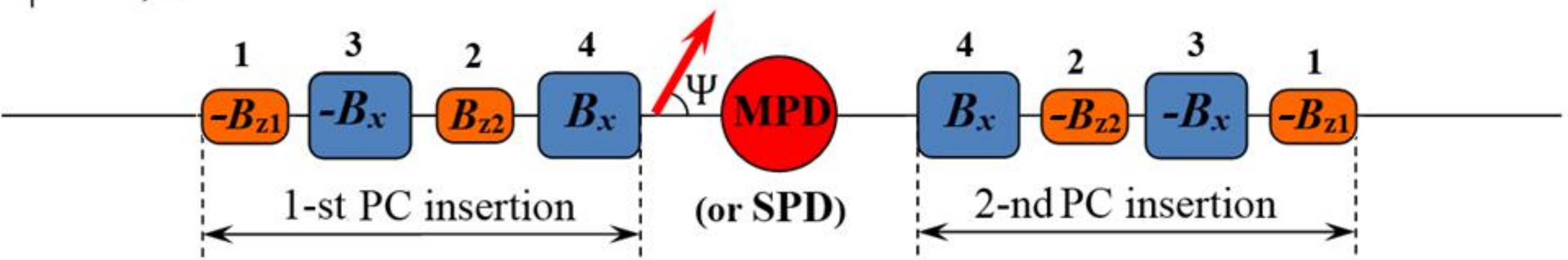
Deuterons: $E_{kin} = 5.63$ GeV/u, $pc = 13$ GeV (1 energy point)

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

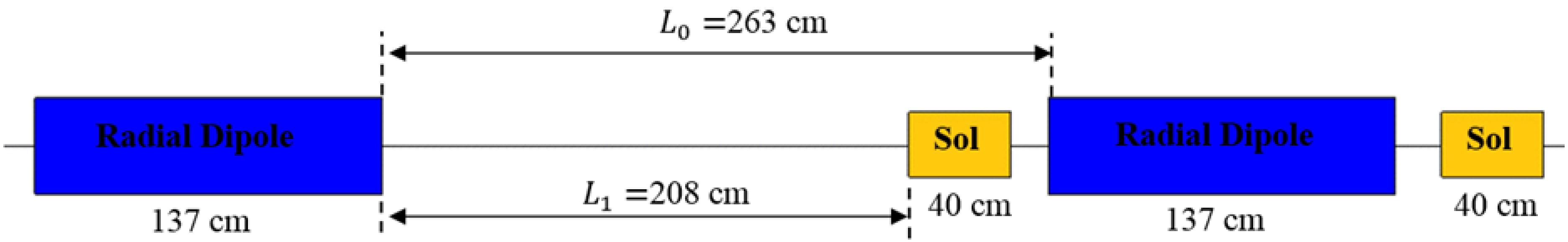


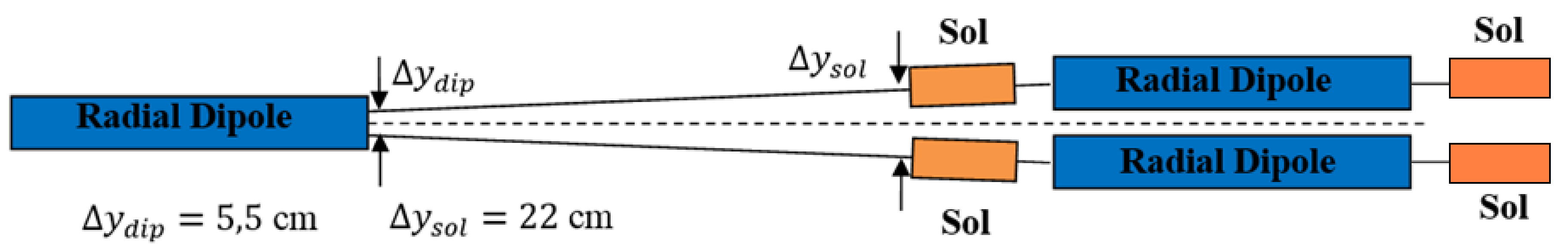
$$\vec{S}_{MPD} = \vec{e}_y \sin\Psi + \vec{e}_z \cos\Psi$$

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



Ψ is the angle between the polarization and velocity directions





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

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

On-line spin direction control at the NICA collider

A.M. Kondratenko and S.S. Shimanskii (JINR seminar, 25.02.2016)

"New possibilities for high-precision experiments with polarized proton and deuteron beams at the NICA collider: spin-flipping system and on-line spin direction control"

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

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):

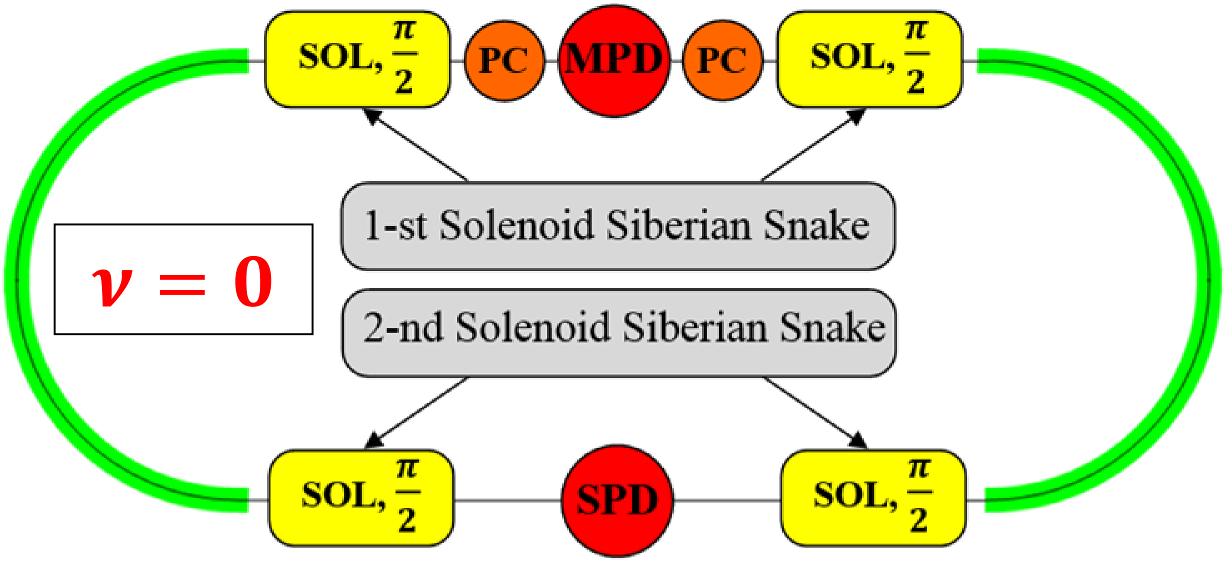
1-st ring	+++…	|xxx|	- - -…	|----|	- - -…	|xxx|	+++	|----|	+++…	
2-nd ring	+++…	|----|	+++…	|xxx|	- - -…	|----|	- - -	|xxx|	+++…	
	(+ +)		(- +)		(- -)		(+ -)		(+ +)	

|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**

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

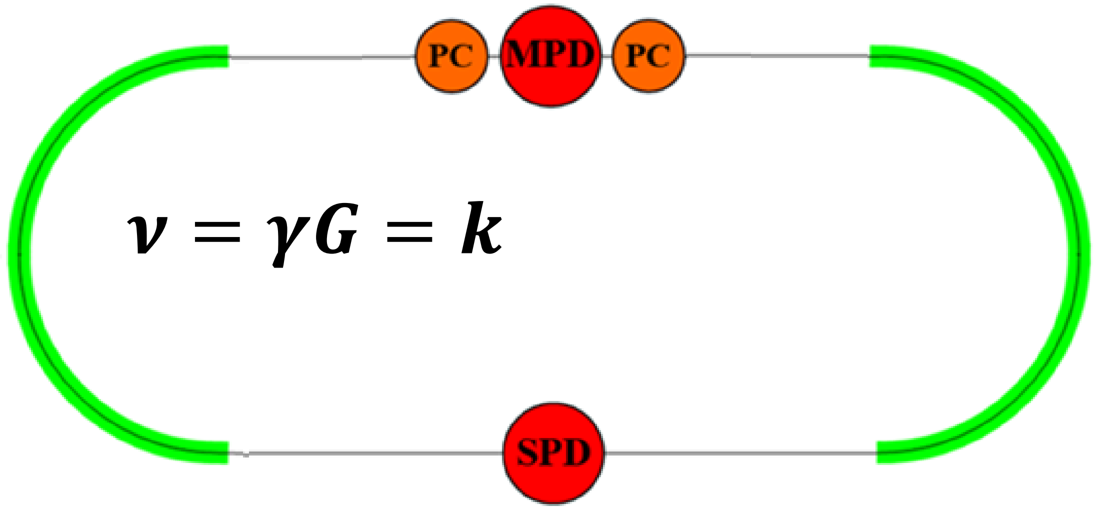
Polarization control insertion based on “weak” solenoids with maximum field integral $BL < 0.6$ T·m (***protons, deuterons***)

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

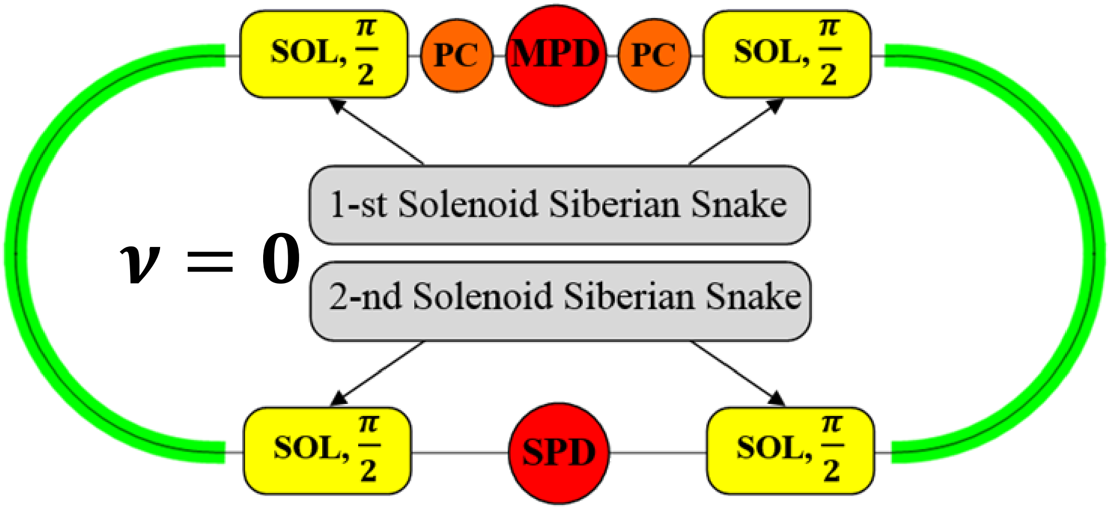
in **SPD** or **MPD** — **any** direction **in vertical plane** (*z*-*y*);

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

Polarization at the Spin Transparency Modes



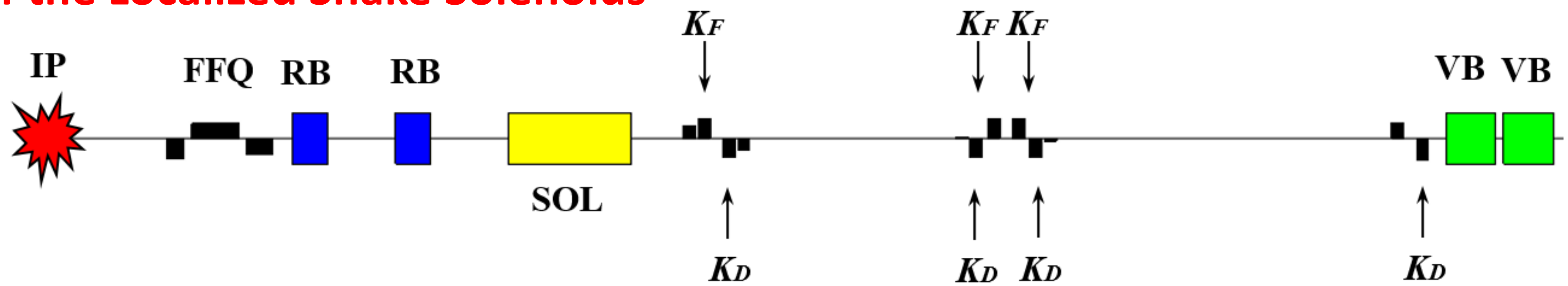
Spin transparency mode at zero-spin tune gives advantage even at energies which corresponds to the integer spin resonances $\gamma G = k$.



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.

Placement of the Snake Solenoids

Case of the Localized Snake Solenoids

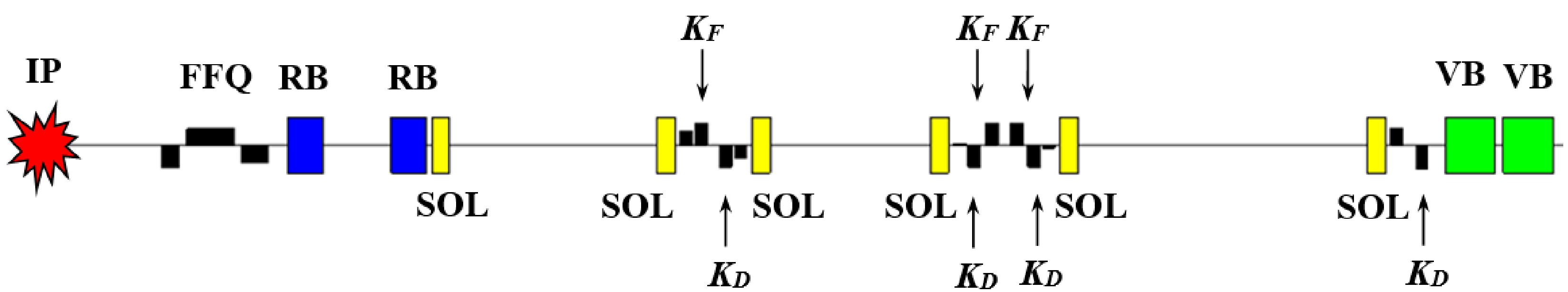


SOL – **6T Solenoid of 4.2 m** (One Siberian Snake = 2×SOL)

VB – arc's Vertical-field Bending magnets, **RB** – Radial-field Bending magnets

FFQ – Final Focus Quadrupoles, K_F, K_D – quadrupoles gradients

Case of the Distributed Snake Solenoids

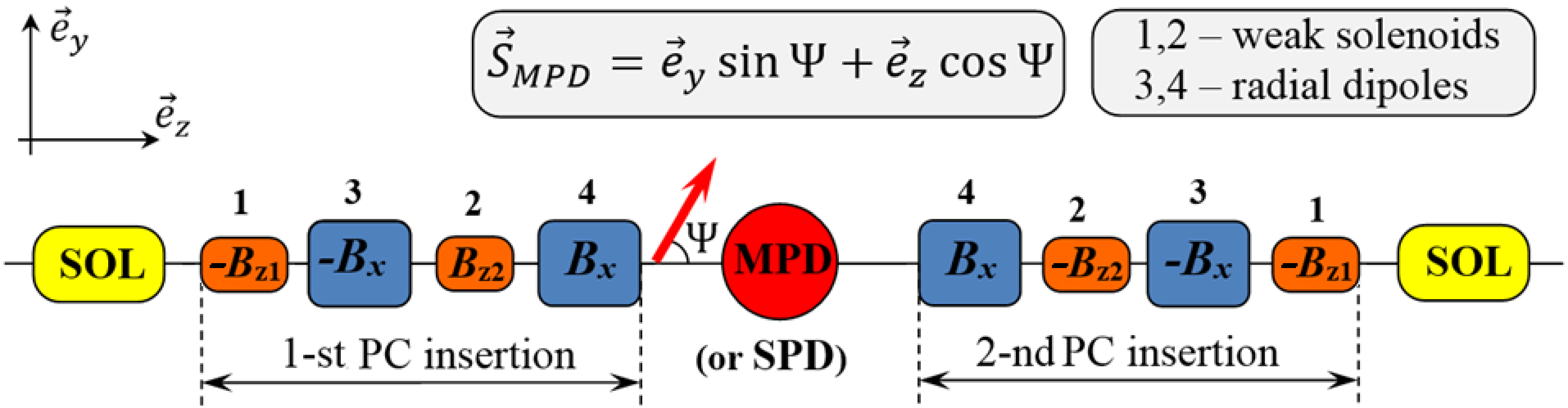


SOL – **6T Solenoid of 0.7 m** (One Siberian Snake = 12×SOL)

δK_F, δK_D – deviation of the quadrupoles gradients for snake matching

$$K_F = K_{F0} + \delta K_F, \qquad K_D = K_{D0} + \delta K_D, \qquad K_{F0} = 0.519\ \text{m}^{-2}, \quad K_{D0} = 0.504\ \text{m}^{-2}$$

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



Ψ is the angle between the polarization and velocity directions

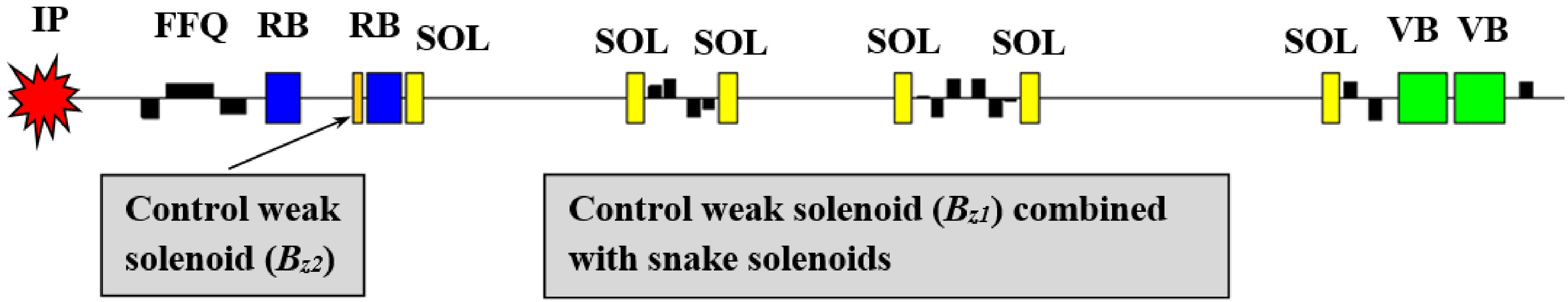
Longitudinal polarization

Ψ = 0° Ψ = 180°

Vertical polarization

Ψ = -90° Ψ = 90°

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**

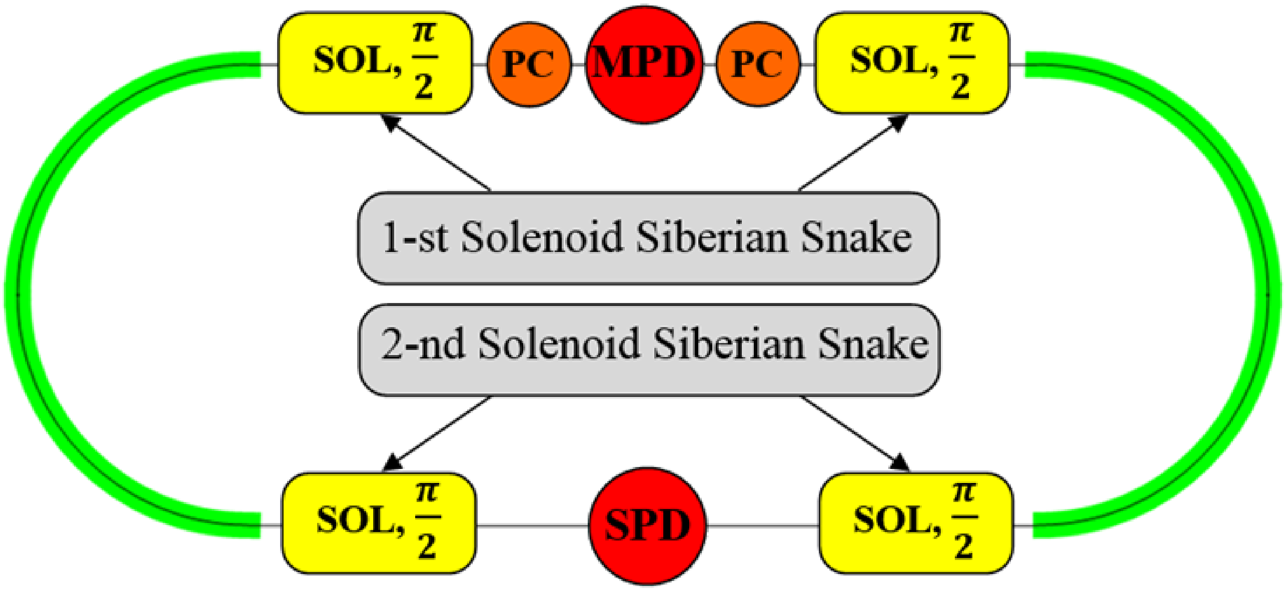
d **up to momentum of 4.12 GeV/c**

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

Polarization control system in the NICA complex makes it possible:

- to provide polarization control of different particles;
- to provide any direction of polarization in the vertical plane SPD and MPD detectors;
- to solve the problems of spin matching at injection in the NICA collider and polarization measurement as well;
- to eliminate resonance depolarization during acceleration;
- to realize Spin Flipping System;
- to control polarization in SPD and MPD detectors without any change of beam orbital characteristics.

Available Spin Modes at the NICA Collider with solenoidal snakes

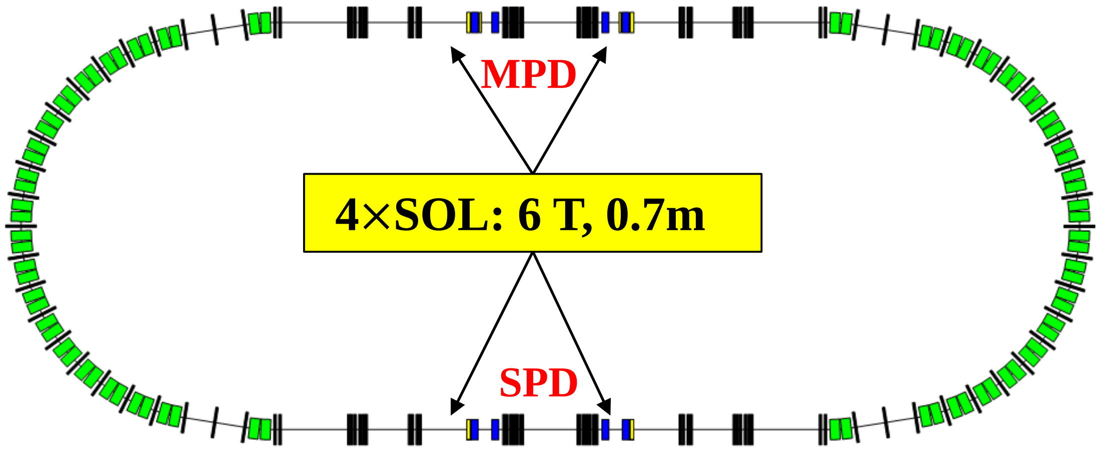


Spin Mode	Snakes		Spin tune, ν	Polarization at SPD	Polarization at MPD	Spin Flipping
	SPD	MPD				
W/O Snakes	**OFF**	**OFF**	γG	Vertical	Vertical	—
With One Snake (Preferred Spin)	**ON**	**OFF**	½	$\Psi_{SPD} = \gamma G\, \pi$	Longitudinal	—
	OFF	**ON**	½	Longitudinal	$\Psi_{MPD} = \gamma G\, \pi$	—
Spin Transparency	**ON**	**ON**	0	Any direction	Any direction	+

Summary

- Spin transparency mode at the NICA collider makes it possible
  - to manipulate the polarization of any particle type (*p*, *d*, ^3He, …) at any orbital location without changing the orbital characteristics of the beam, including to provide longitudinal and vertical beam polarization in MPD and SPD detectors
  - to organize on-line spin direction control during the experiment (fast polarimetry)
  - to realize spin flipping system for carrying out experiments with polarized beams at a new precision level

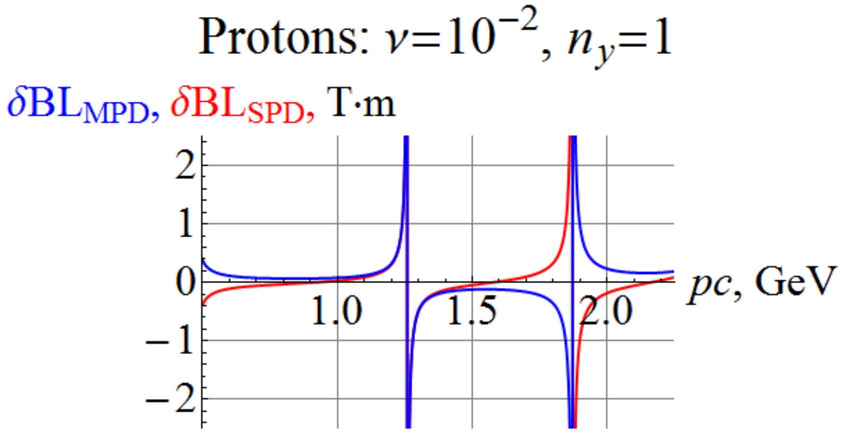
Ongoing plan on the Ion Polarization in the NICA Collider

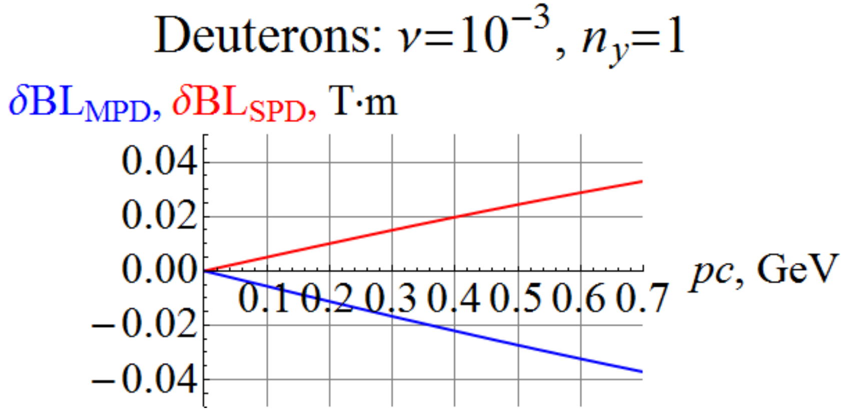


***p* up to 2.25 GeV/c**
***d* up to 0.69 GeV/c**

Longitudinal polarization **at SPD (MPD) detector** $\delta BL < 0.15\ T \cdot m$

Vertical polarization **at SPD (MPD) detector**





Ongoing plan

- Four 6T solenoids of 0,7 m, placed into the collider lattice, allow one to
  - carry out an experimental verification of the polarization control scheme at the NICA collider in the spin transparency mode for proton and deuteron beams
  - experimentally investigate the lifetime of a polarized beam in the NICA collider without snakes, with one snake and in the spin transparency modes
  - test spin-flipping system

Thank you for your attention!