Объединенный институт ядерных исследований
ЛАБОРАТОРИЯ ФИЗИКИ ВЫСОКИХ ЭНЕРГИЙ

Управление поляризацией протонов и дейтронов в коллайдере NICA

(ОИЯИ, НТЛ «Заряд», МФТИ)

Докладчик: Филатов Ю.Н.

25 июня, 2018, Дубна

Outline

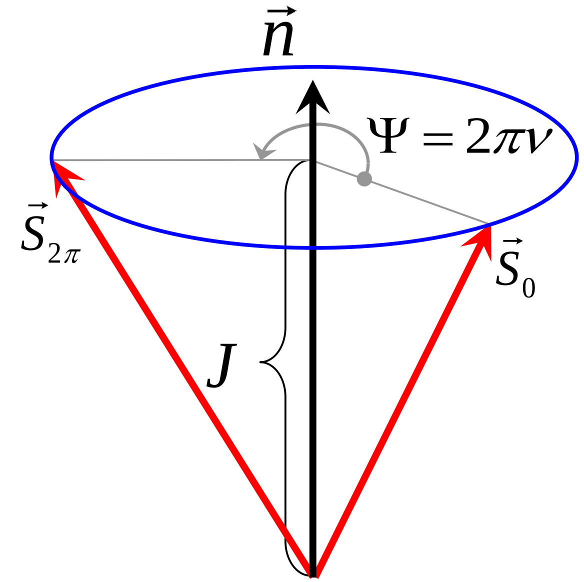
1. Spin transparency mode in the NICA collider
2. Placement of the snake solenoids in the NICA collider
3. Polarization control scheme by means of weak solenoids
4. Summary

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

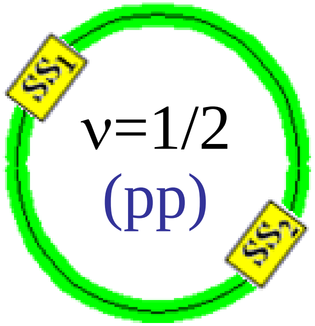
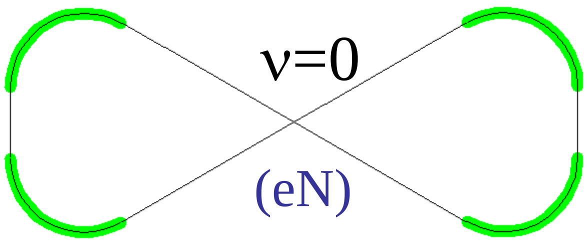
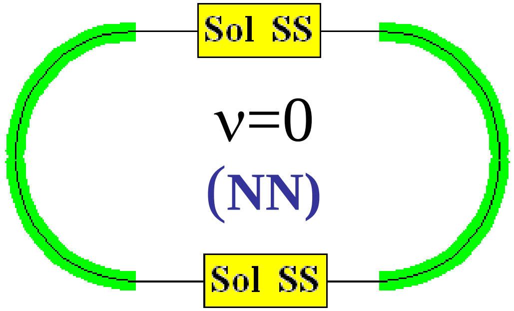
If $\vec{S}_0 \perp \vec{n} \;\Rightarrow\; \vec{S}_{2\pi} \perp \vec{n}, \;\; \angle\left(\vec{S}_0, \vec{S}_{2\pi}\right) = \Psi = 2\pi\nu$

$\nu -$ spin precession tune

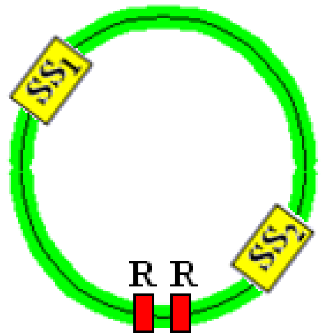
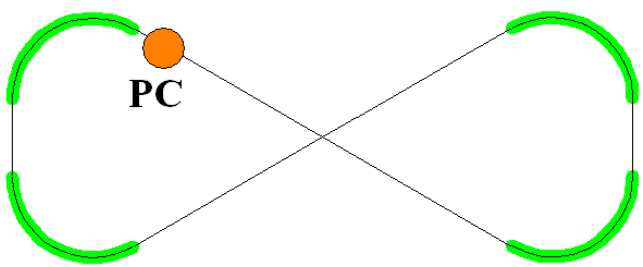
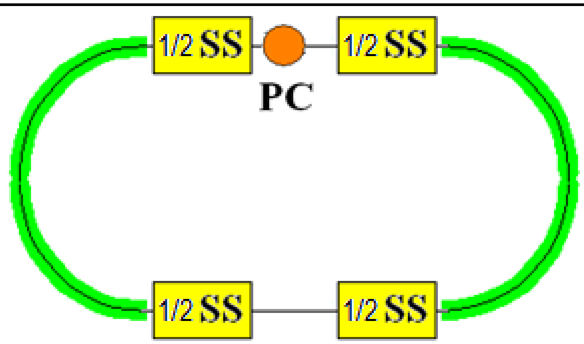
In ideal accelerator $\vec{n} = \vec{e}_z, \qquad \nu = \gamma G \qquad G = (g-2)/2 -$ gyromagnetic anomaly

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*.

Схема коллайдера		Поляризация
RHIC **(BNL)** **25÷250 GeV/*c***		Выделено единственное устойчивое направление
JLEIC **(JLAB)** **25÷100 GeV/*c***		Возможно любое направление
NICA **(JINR)** **2.5÷13.5 GeV/*c***		Возможно любое направление

Управление поляризацией пучков в коллайдерах

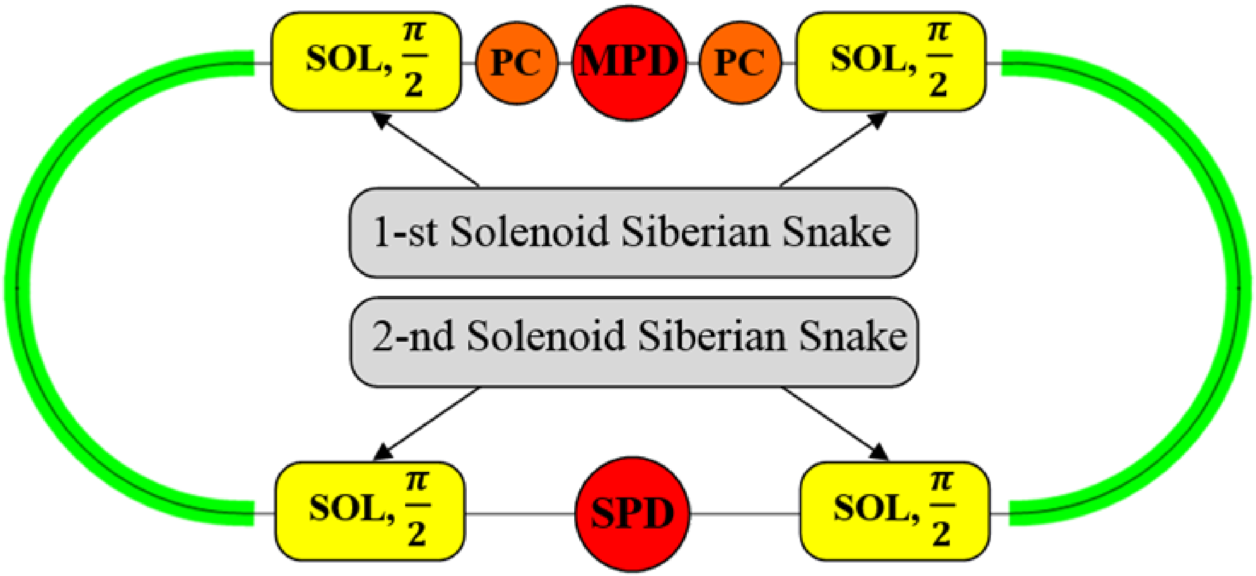
Схема коллайдера	Элементы управления	Орбитальные характеристики
RHIC $\nu=1/2$ 	Ротаторы с **сильными** полями (R)	**Изменяются при управлении**
MEIC $\nu=0$ 	Соленоиды со **слабыми** полями (PC)	**Не изменяются при управлении**
NICA $\nu=0$ 	Соленоиды со **слабыми** полями (PC)	**Не изменяются при управлении**

Ion Polarization Control

Collider	Spin Rotators based on	Polarization Direction at IP	Spin Flipping	
			Reversal Time	Orbital Parameters
RHIC (*BNL*)	‘**strong**’ magnetic fields	Transversal Longitudinal (**w/o deuterons**)	Few **min**	Change
JLEIC (*JLAB*)	‘**weak**’ solenoids	Any directions (**any particles:** ***p, d, He³***, **…**)	from **ms** up to **sec**	Do not change
NICA (*JINR*)	‘**weak**’ solenoids	Any directions (**any particles:** ***p, d, He³***, **…**)	from **ms** up to **sec**	Do not change

Spin Flipping System allows one to make spin reversal during an experiment (high precision experiments with polarized ions).

Spin Transparency Mode in NICA Collider



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*).

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 (p, d, ^3He, …);
- 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.

Zero-Integer Spin Resonance & Spin Stability Criterion

The total **zero-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: $\boldsymbol{\omega_{coh} \sim 10^{-6} \div 10^{-5}, \omega_{emitt} \sim 10^{-7} \div 10^{-6}}$

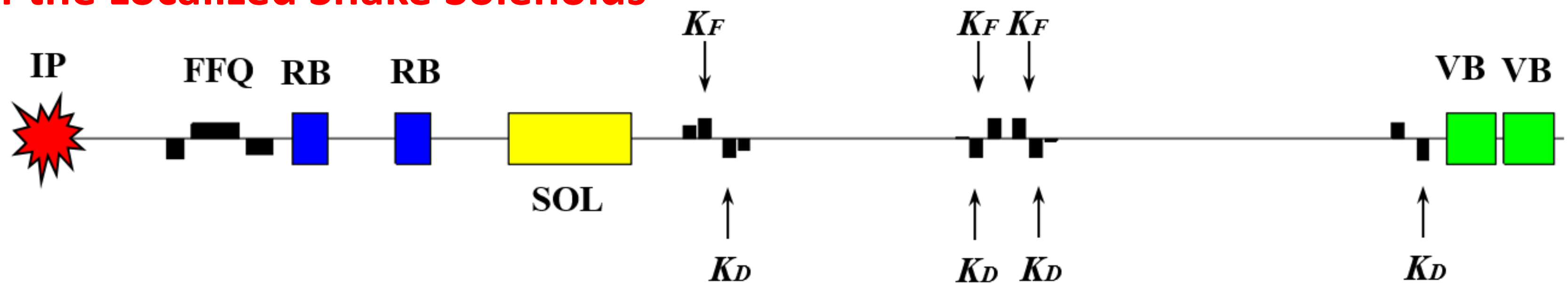
Total PC solenoids field integral about of **0.03 T· m** is sufficient for stabilization and control of deuteron polarization in NICA collider.

↓

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

Placement of the Snake Solenoids

Case of the Localized Snake Solenoids

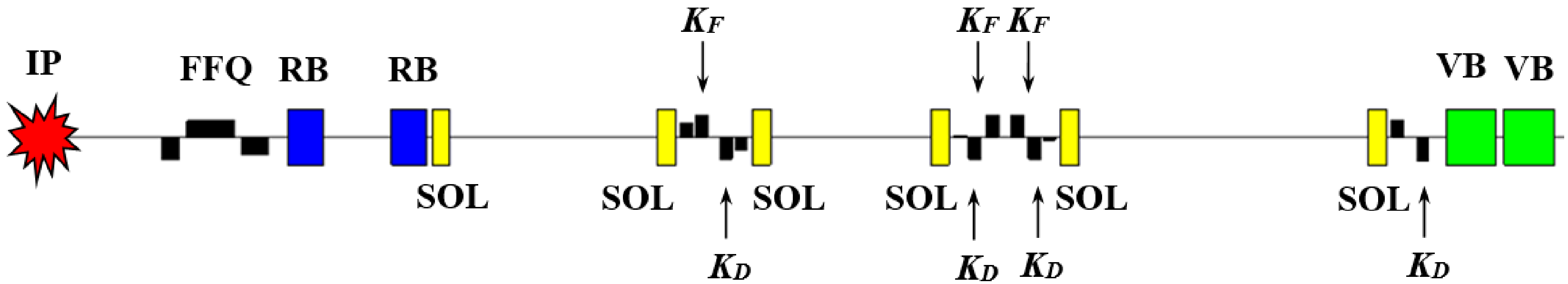


SOL – 6T Solenoid of 4.2 m (One Siberian Snake = 2×SOL)

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



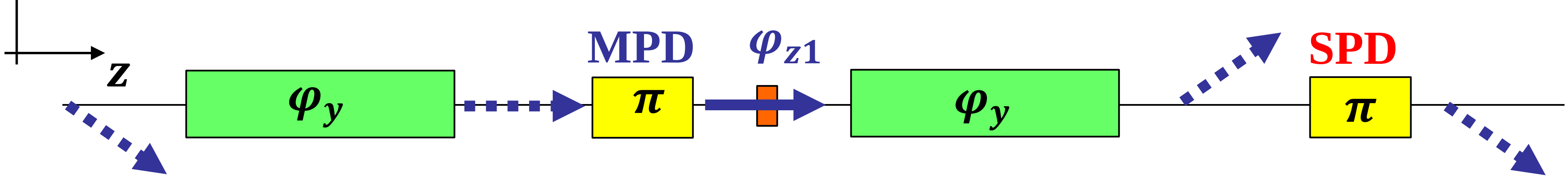
SOL – 6T Solenoid of 0.7 m (One Siberian Snake = 12×SOL)

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

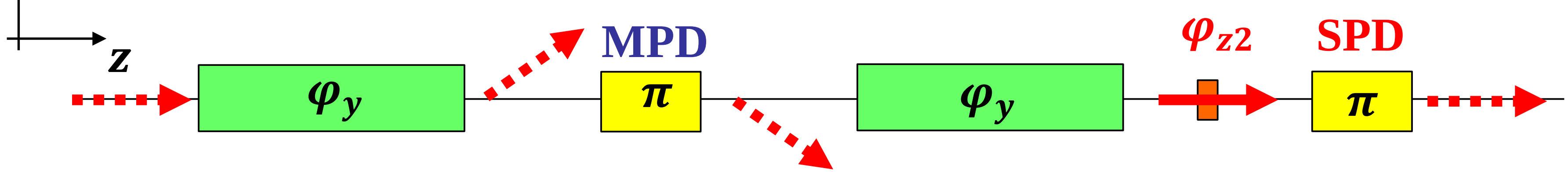
$$K_F = K_{F0} + \delta K_F\,, \qquad K_D = K_{D0} + \delta K_D, \qquad K_{F0} = 0.519\ \text{m}^{-2}, \quad K_{D0} = 0.504\ \text{m}^{-2}$$

Ion polarization control in NICA collider by means of "weak" solenoids at MPD and SPD detectors

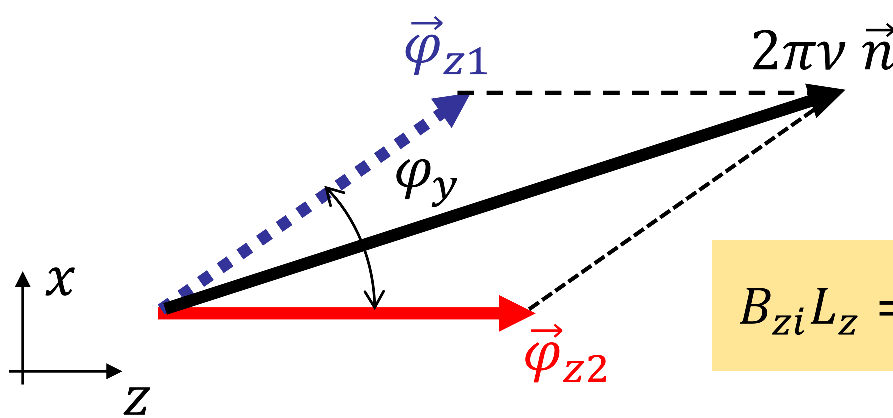
$\boldsymbol{\varphi_{z1}}$ stabilizes the longitudinal polarization at MPD detector ($\varphi_y = \gamma G \pi$)



$\boldsymbol{\varphi_{z2}}$ stabilizes the longitudinal polarization at SPD detector



Vector diagram for calculation of control solenoid field integrals



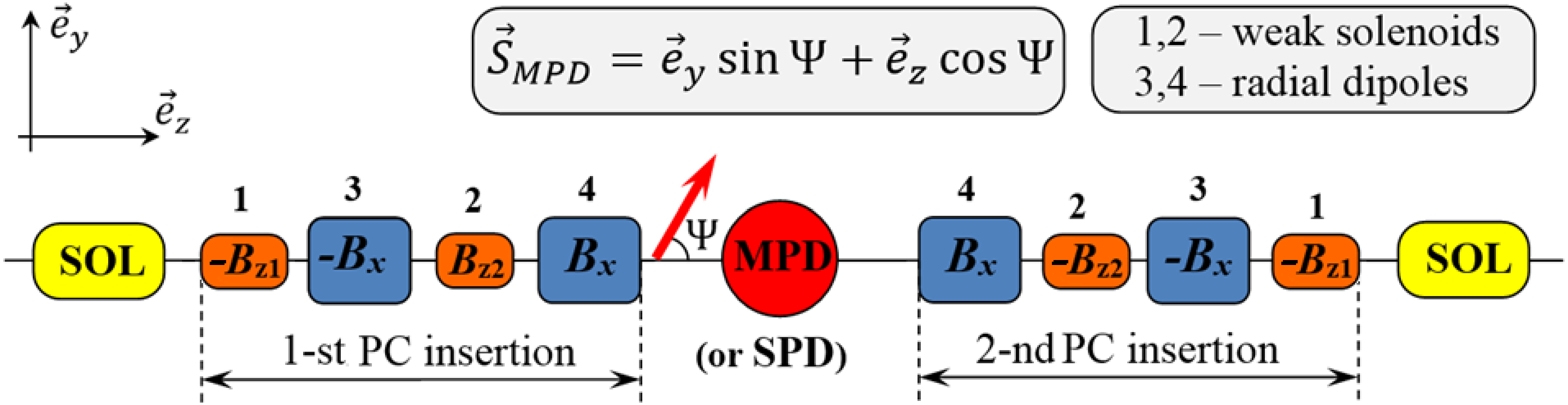
$$\varphi_{z2} = 2\pi\nu\left(n_z - \frac{n_x}{\tan\varphi_y}\right)$$

$$\delta\varphi_{z1} = 2\pi\nu\frac{n_x}{\sin\varphi_y}$$

$$B_{zi}L_z = \frac{\varphi_{zi}}{1+G}B\rho$$

$$\varphi_y = \gamma_{max} G\,\alpha_{orb} < \pi$$

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



Ψ is the angle between the polarization and velocity directions

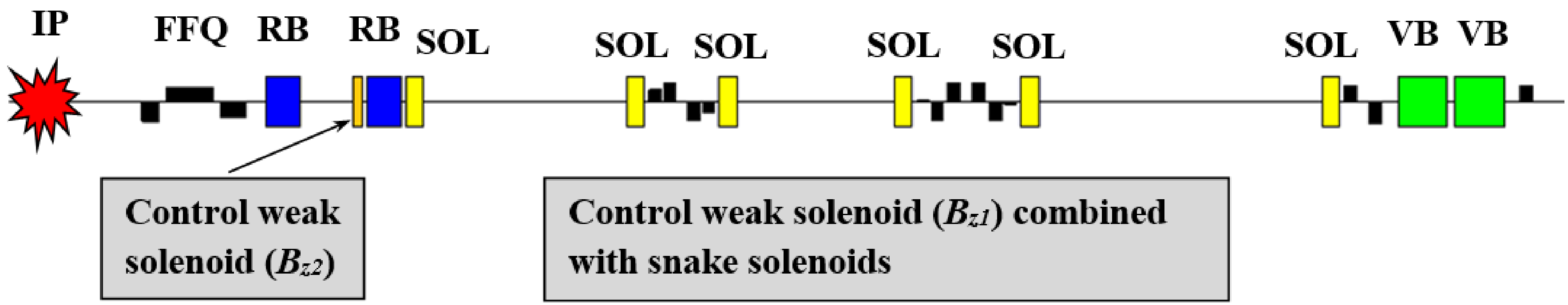
Longitudinal polarization

Ψ = 0° Ψ = 180°

Vertical polarization

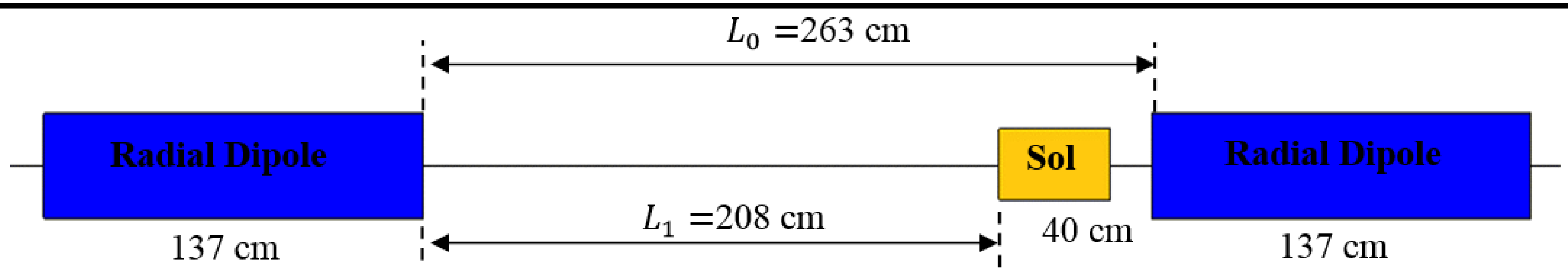
Ψ = -90° Ψ = 90°

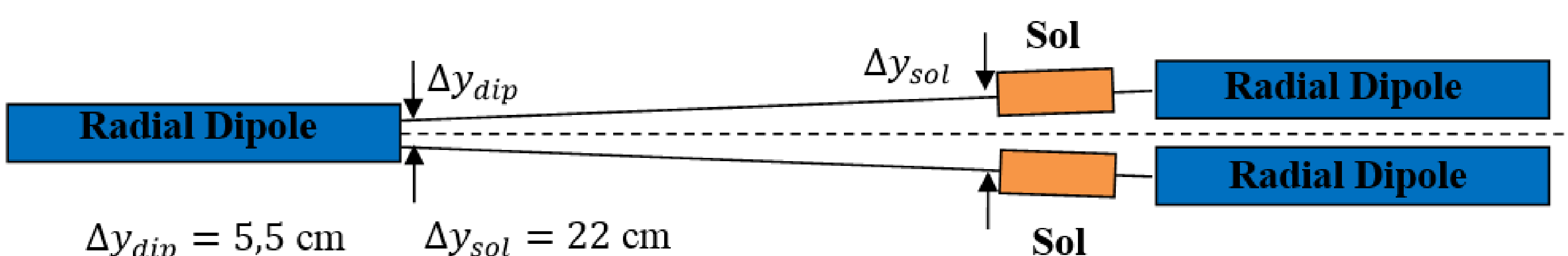
Schematic layout of the half experimental straight section



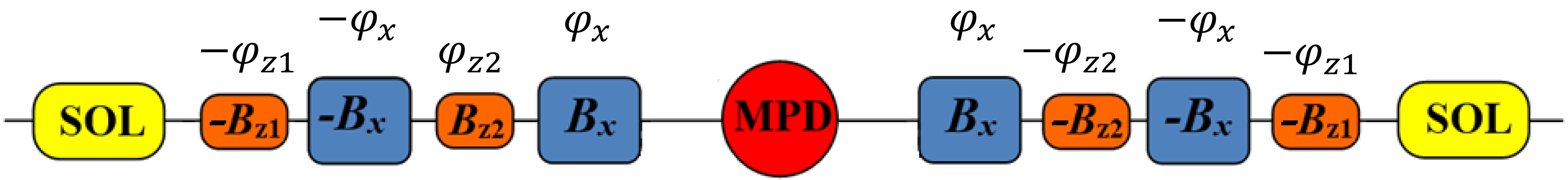
SOL – 6T Solenoid of 0.7 m (One Siberian Snake = 12×SOL)
VB – arc's Vertical-field Bending magnets,
RB – Radial-field Bending magnets , **FFQ** – Final Focus Quadrupoles

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





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



Polarization at MPD lies in the **vertical detector's plane** ($\nu \ll 1$): $\vec{S}_{MPD} = (0, n_y, n_z)$

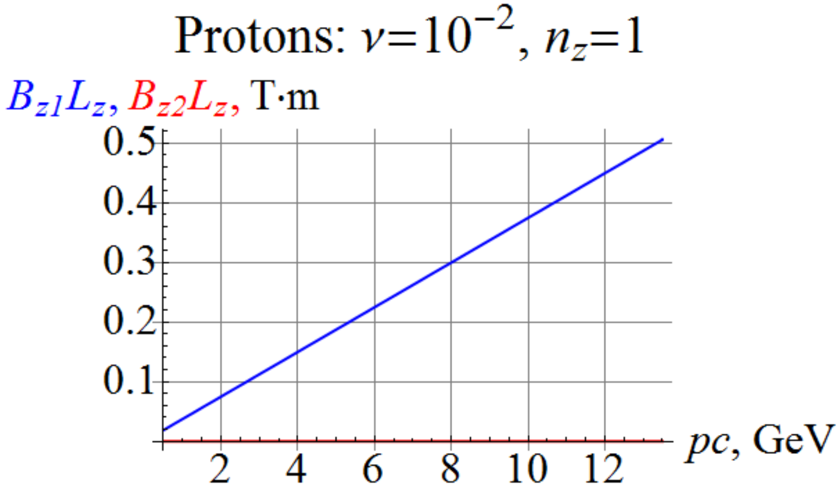
$$\varphi_{z1} = n_z\,\pi\nu, \qquad \varphi_{z2} = n_y \frac{\pi\nu}{\sin\varphi_x}, \qquad \varphi_{zi} = \frac{(1+G)B_{zi}L_z}{B\rho}, \qquad \varphi_x = \frac{\gamma G\; B_x L_x}{B\rho}.$$

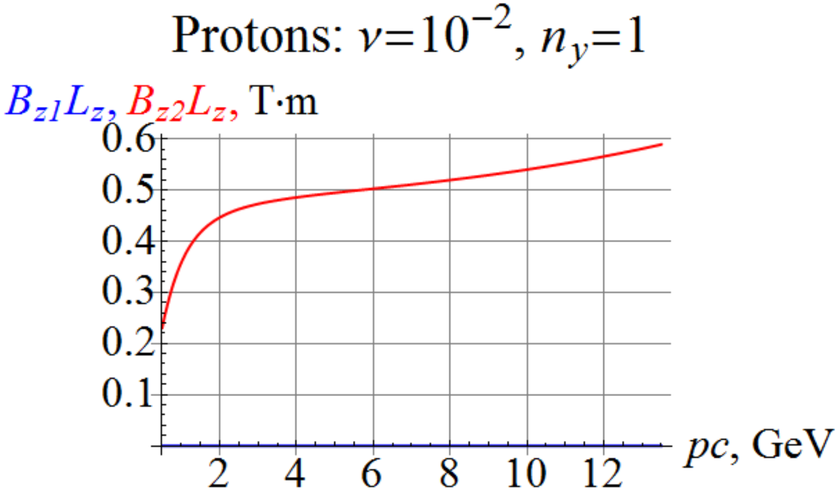
Polarization at SPD also lies in the **vertical detector's plane** and depends on spin angle in the arc $\gamma G\pi$ and signs of the shake's angles :

Snake Angle Sign		Angles between polarization and velocity direction: Ψ_{SPD} and Ψ_{MPD}
MPD	**SPD**	
+	+	$\boldsymbol{\Psi_{SPD} = \gamma G\pi - \Psi_{MPD}}$
−	−	$\Psi_{SPD} = -\gamma G\pi - \Psi_{MPD}$
+	−	$\Psi_{SPD} = -\gamma G\pi + \Psi_{MPD}$
−	+	$\Psi_{SPD} = \gamma G\pi + \Psi_{MPD}$

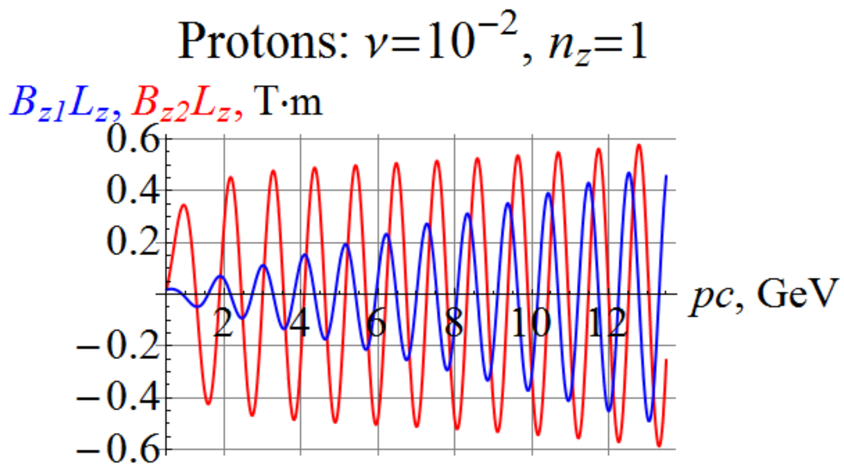
Control solenoid field integrals vs momentum (protons)

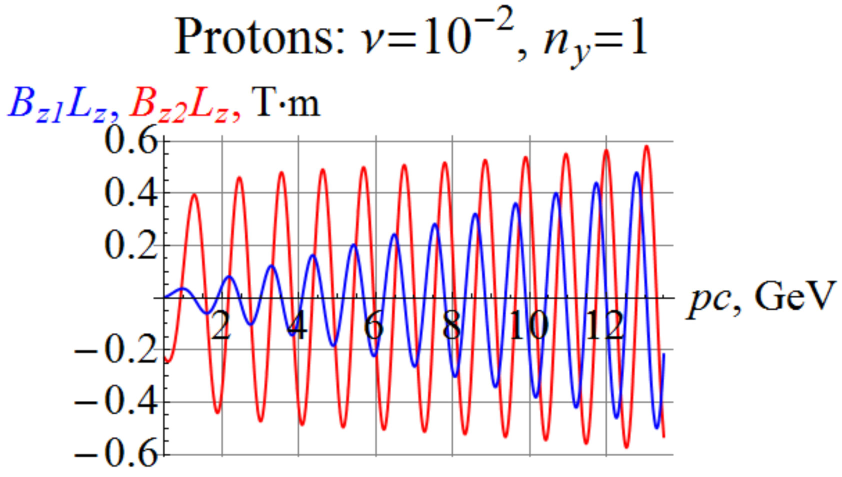
Longitudinal ($\boldsymbol{n_z = 1}$) and **vertical** ($\boldsymbol{n_y = 1}$) polarization **at MPD detector**





Longitudinal ($\boldsymbol{n_z = 1}$) and **vertical** ($\boldsymbol{n_y = 1}$) polarization **at SPD detector**





Control of the deuteron polarization by the snake solenoids

Let us introduce **small deviations $\delta\varphi_{SPD}, \delta\varphi_{MPD}$** of the snakes' spin rotation angles

$$\varphi_{SPD} = \pi - \delta\varphi_{SPD}, \qquad \varphi_{MPD} = \pi - \delta\varphi_{MPD},$$

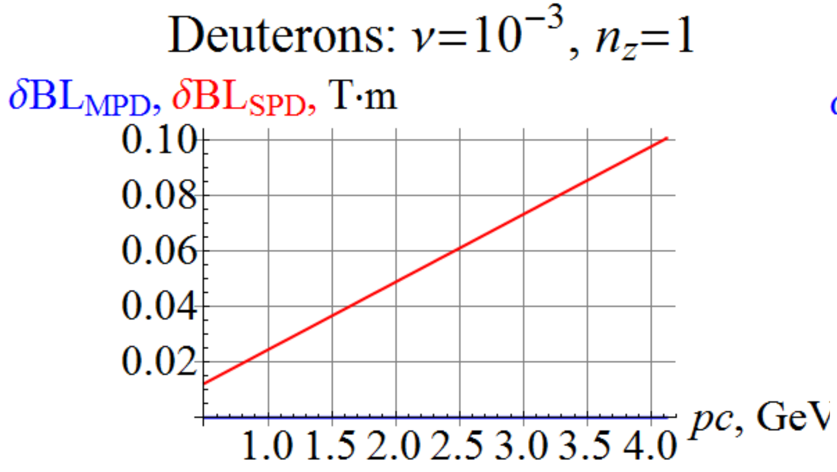
Polarization at MPD lies in the **vertical detector's plane** ($\nu \ll 1$): $\vec{S}_{MPD} = (0, n_y, n_z)$

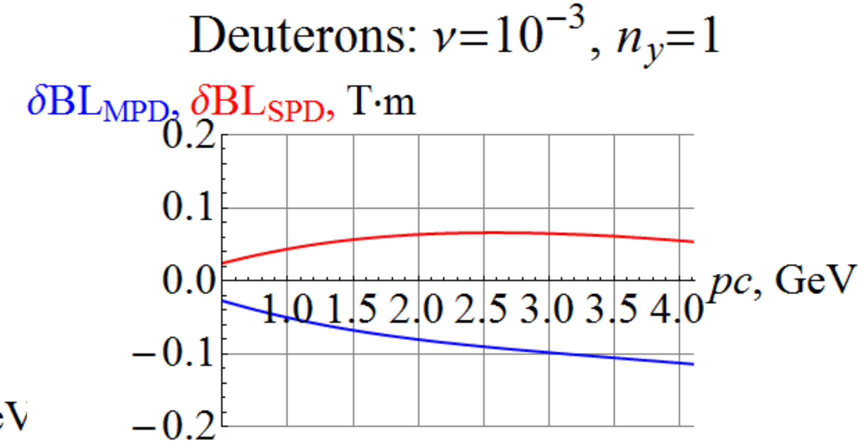
$$\delta\varphi_{MPD} = 2\pi\nu\left(n_z - \frac{n_y}{\tan\gamma G\pi}\right), \quad \delta\varphi_{SPD} = 2\pi\nu\frac{n_y}{\sin\gamma G\pi}$$

Polarization at SPD also lies in the **vertical detector's plane**

$$\delta\varphi_{MPD} = 2\pi\nu\frac{n_y}{\sin\gamma G\pi}, \qquad \delta\varphi_{SPD} = 2\pi\nu\left(n_z - \frac{n_y}{\tan\gamma G\pi}\right),$$

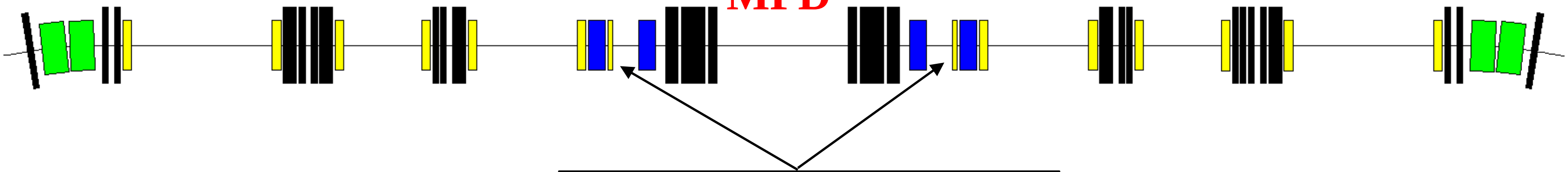
Longitudinal ($n_z = 1$) and **vertical ($n_y = 1$)** polarization **at SPD detector**





Parameters of solenoids

MPD



2×(PC SOL): 1.5 T, 0.4m

24× (SNAKE′S SOL): 6 T, 0.7m

SPD

Solenoids	B_{max}, T	L_{sol}, m	Aperture, cm	Field ramp	Total number of solenoids per ring
Snake	6	0,7	10	Few T/min	2 section ×12
Control	1,5	0,4	10	Few T/s	2

Концепция быстрой поляриметрии

Кондратенко А.М., Шиманский С.С. (семинар ОИЯИ 25.02.2016)

"Новые возможности для высокоточных поляризационных экспериментов на коллайдере NICA: система спин-флипа и быстрая относительная поляриметрия"

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

Можно взглянуть иначе на вопросы, связанные с поляриметрией пучка

1. Необходимо ***во время работы коллайдера обеспечить стабильность*** поляризации
2. Для ***измерения степени поляризации*** достаточно знать лишь направление n-оси, «измерение» направления которой ***сводится к измерению магнитных полей***.

Появляется уникальная возможность быстрой поляриметрии пучка в режиме спиновой прозрачности коллайдера NICA.

Работа на NICA со спин-флипперами

Новые режимы заполнения колец (все банчи с одной поляризацией в обоих кольцах) и работы (поочерёдное включение спин-флипперов в кольцах):

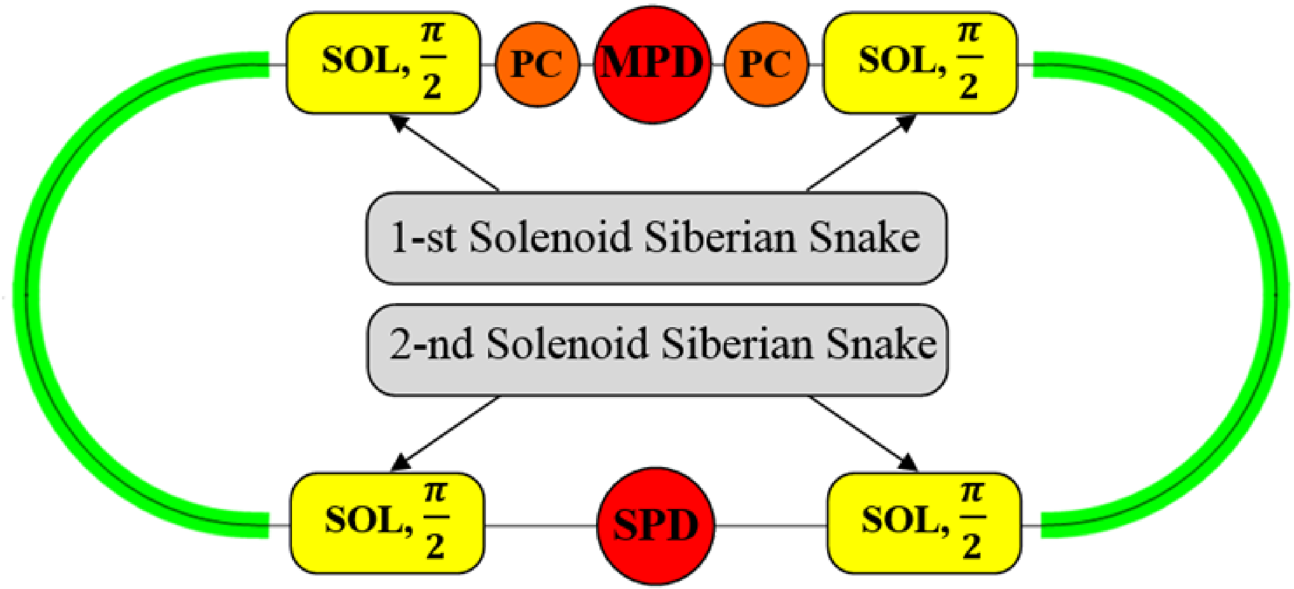
1-е кольцо	+++… |xxx| - - -… |----| - - -… |xxx| +++ |----| +++…
2-е кольцо	+++… |----| +++… |xxx| - - -… |----| - - - |xxx| +++…
	(+ +) (- +) (- -) (+ -) (+ +)

|xxx| — ротатор включён, нет набора данных

|----| — ротатор не включён, нет набора данных

- **Нет проблемы измерения межбанчивой светимости,**
- **нет проблемы с разной поляризацией в разных модах при работе источника!**

Available Spin Modes at the NICA Collider with solenoidal snakes

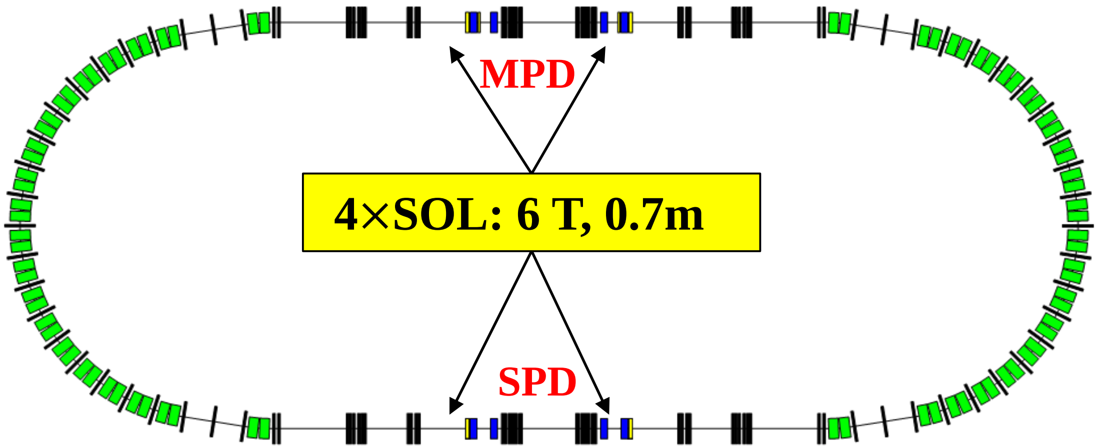


Spin Mode	Snakes		Spin tune, ν	Polarization at SPD	Polarization at MPD	Spin Flipping
	SPD	MPD				
W/O Snakes	OFF	OFF	γG	Vertical	Vertical	—
With One Snake (Preferred Spin)	ON	OFF	½	$\Psi_{SPD} = \gamma G\ \pi$	Longitudinal	—
	OFF	ON	½	Longitudinal	$\Psi_{MPD} = \gamma G\ \pi$	—
Spin Transparency	ON	ON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

Summary

- Режим спиновой прозрачности в коллайдере NICA открывает уникальные возможности
  - манипулировать поляризацией любого сорта частиц (*p*, *d*, ^3He, …) в любом месте орбиты не изменяя орбитальные характеристики пучка, в том числе обеспечивать продольную и вертикальную поляризацию пучка в MPD и SPD детекторах
  - быстро измерять поляризацию пучка во время проведения эксперимента (быстрая поляриметрия)
  - реализовать систему спин-флипа для проведения экспериментов с поляризованными пучками на новом уровне точности

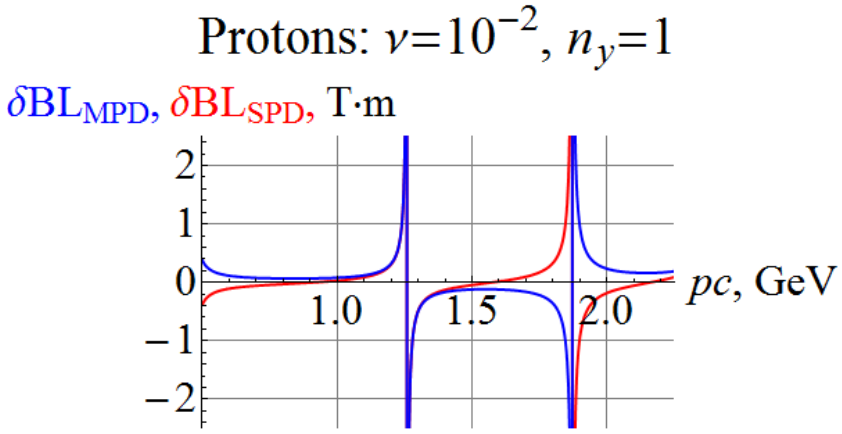
Ongoing plan on the Ion Polarization in the NICA Collider

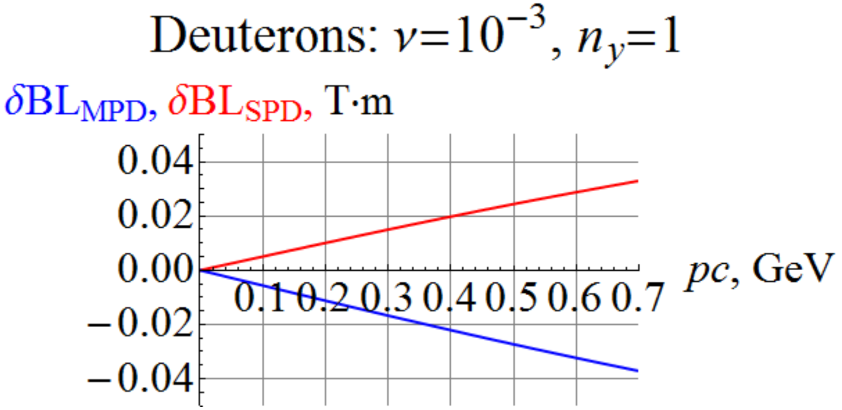


***p* up to 2.25 GeV/c**
***d* up to 0.69 GeV/c**

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

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





Ongoing plan

- Введение на первом этапе работ 4-х соленоидов (каждый 6T × 0.7m) в структуру коллайдера и одного такого же соленоида в канал инжекции коллайдера позволит
  - провести экспериментальную верификацию управления поляризацией протонов и дейтронов в режиме спиновой прозрачности
  - экспериментально изучить время жизни поляризованного пучка в коллайдере NICA без змеек, с одной змейкой и в режиме спиновой прозрачности
  - провести тестирование системы спин-флипа

Thank you for your attention!

β-functions in the NICA collider without snakes

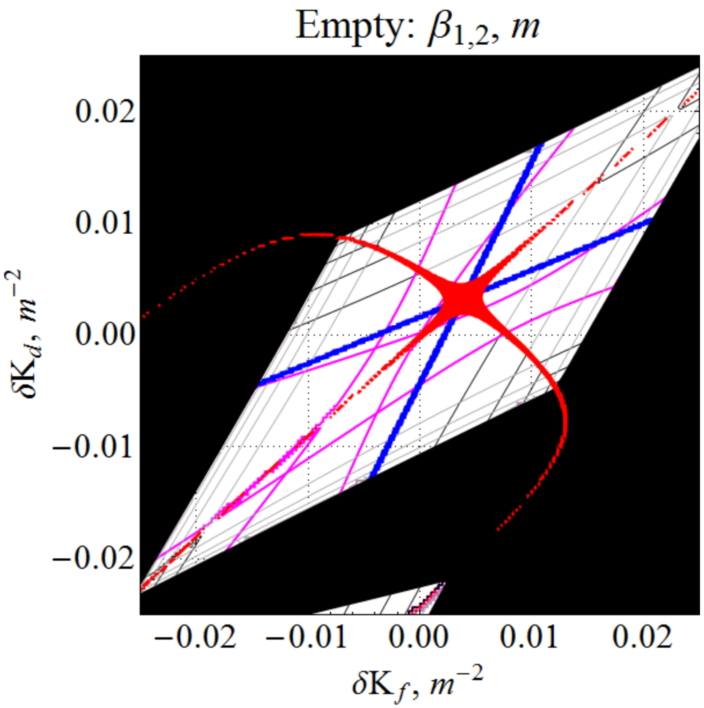
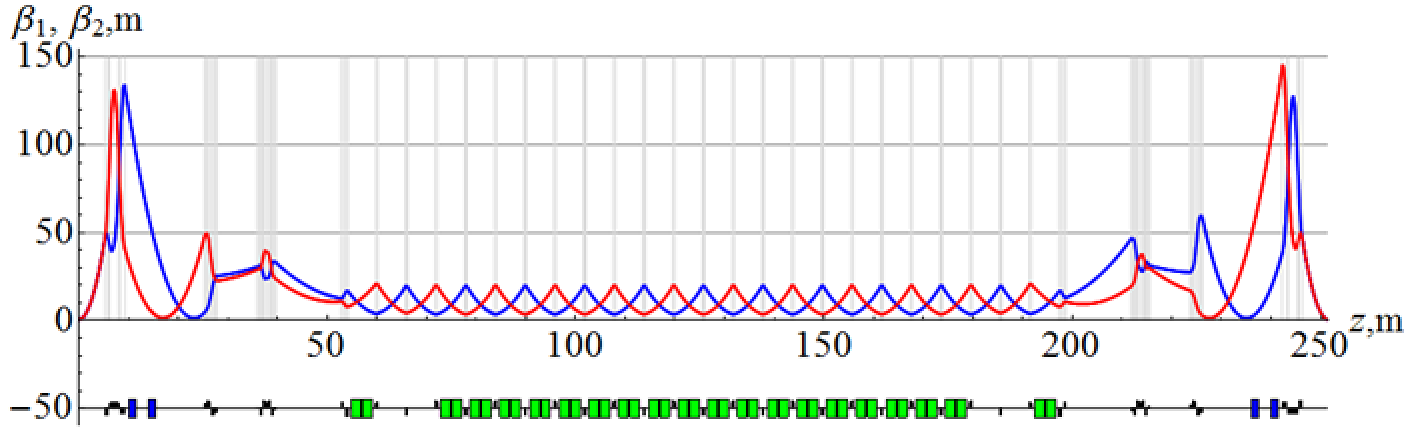


Diagram of Betatron Motion Stability

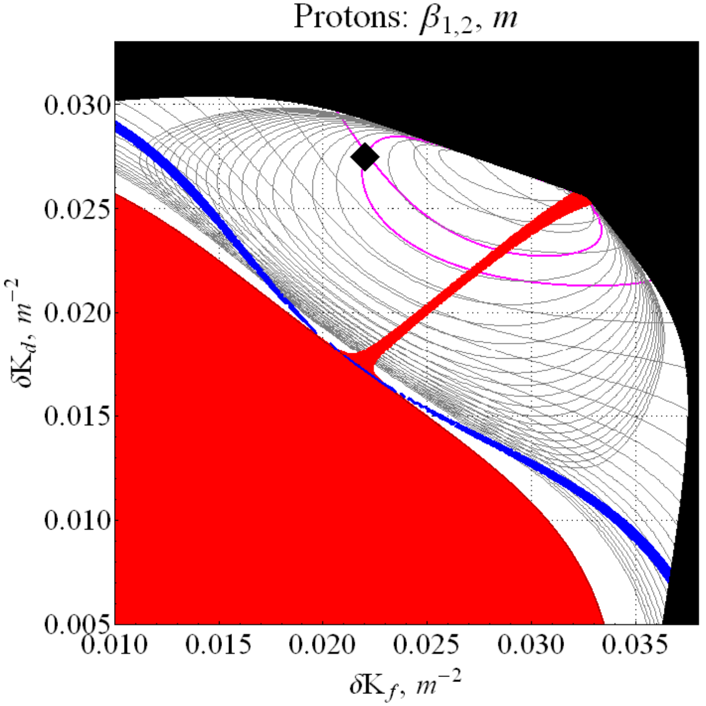
- (white) is a stable motion
- (black) (blue) (red) are unstable motion

- (black) *integer resonances* $\nu_{1,2}=k$
- (blue) *half-integer resonances* $\nu_{1,2}=k+1/2$
- (red) *coupling resonances* $\nu_1=k\pm\nu_2$

Magenta curves correspond to $\beta_{1,2}=0.6$ m



β-functions in the NICA collider with snakes (protons)



Case of the Localized Snake Solenoids

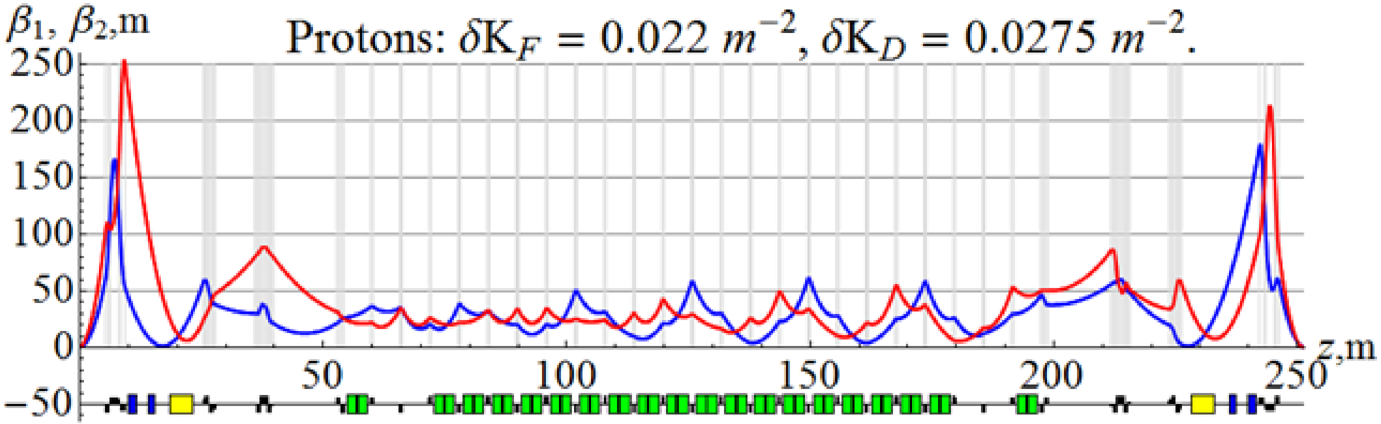
Magenta curves correspond to $\beta_{1,2} = 0.6$ m

◆ Dimond corresponds to the point

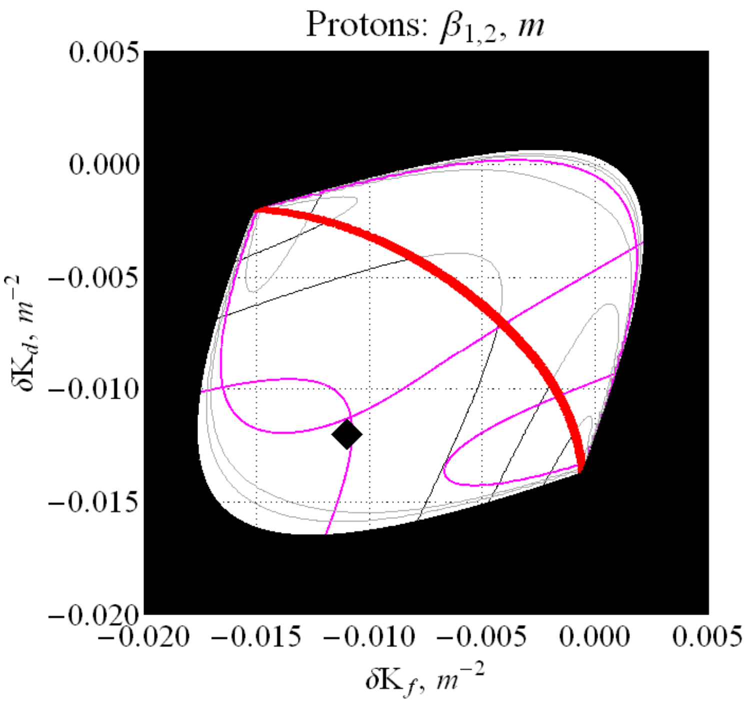
$(\delta K_F = 0.022,\ \delta K_D = 0.0275)$

with β-function values of

$\beta_1 = 0.6\, m, \quad \beta_2 = 0.6\, m.$



β-functions in the NICA collider with snakes (protons)



Case of the Distributed Snake Solenoids

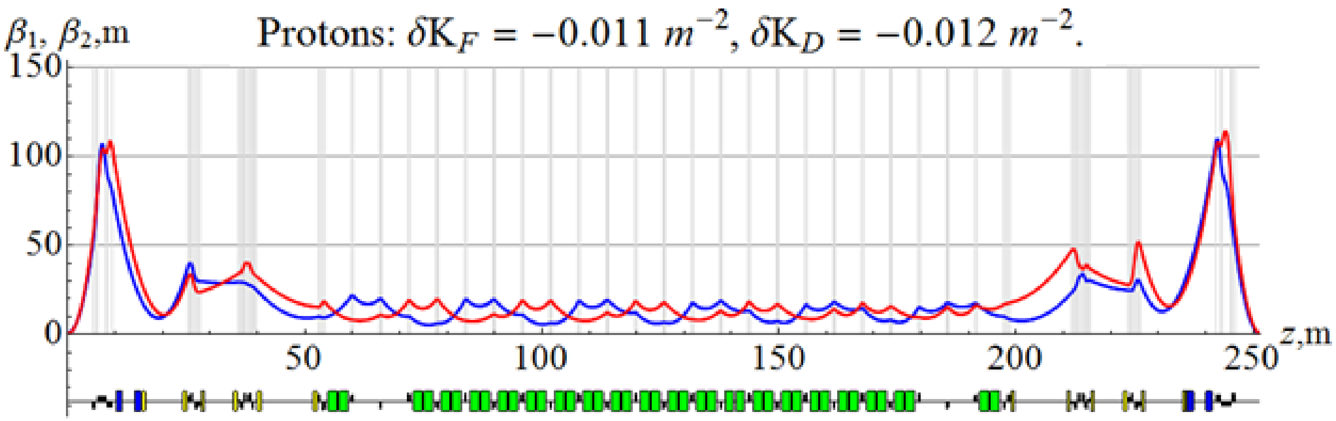
Magenta curves correspond to $\beta_{1,2} = 0.6$ m

◆ Dimond corresponds to the point

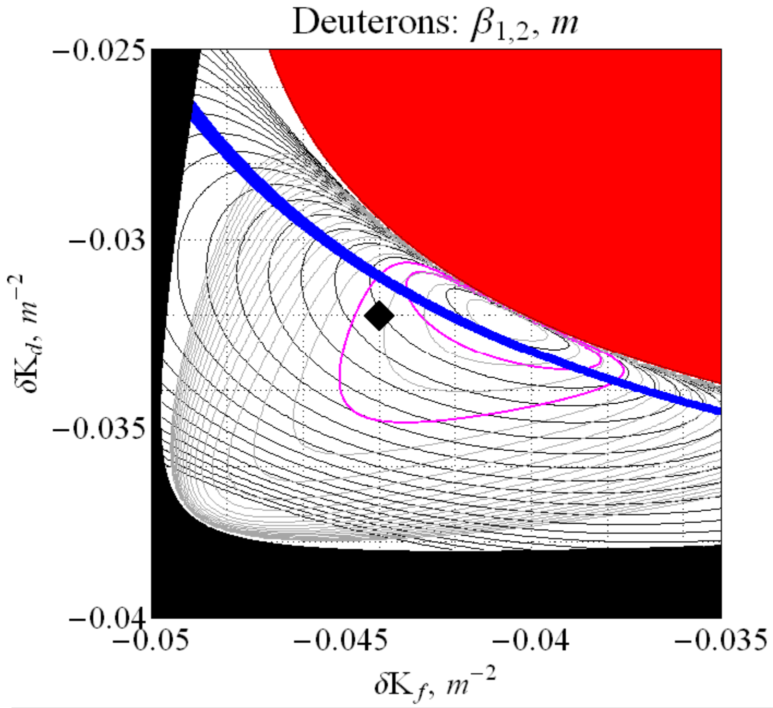
$$(\delta K_F = -0.011,\ \delta K_D = -0.012)$$

with β-function values of

$$\beta_1 \approx 0.6\, m, \quad \beta_2 \approx 0.6\, m.$$



β-functions in the NICA collider with snakes (deuterons)



Case of the Distributed Snake Solenoids

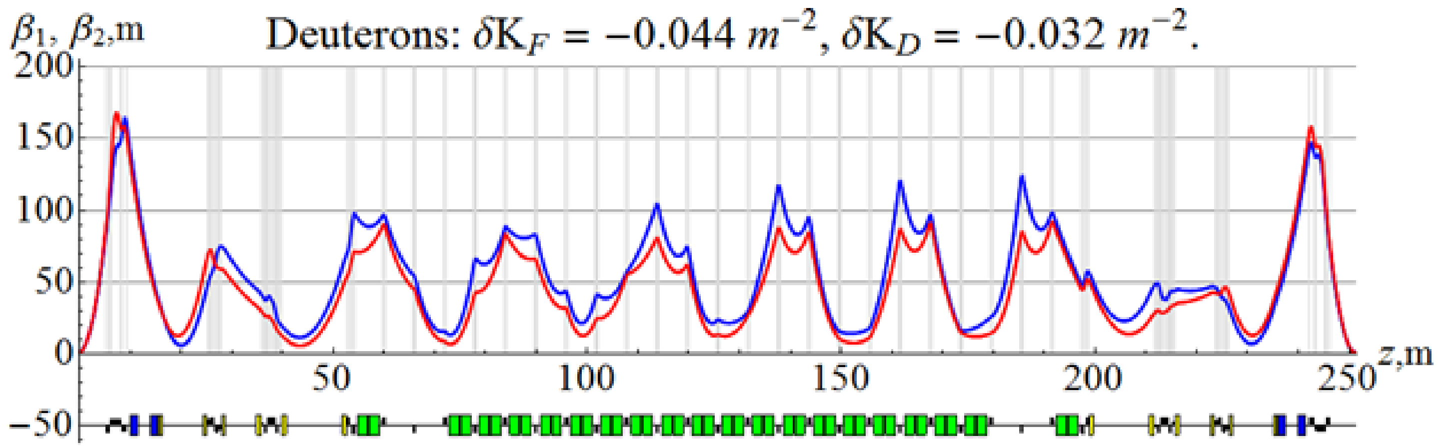
Magenta curves correspond to $\beta_{1,2} = 0.6$ m

◆ Dimond corresponds to the point

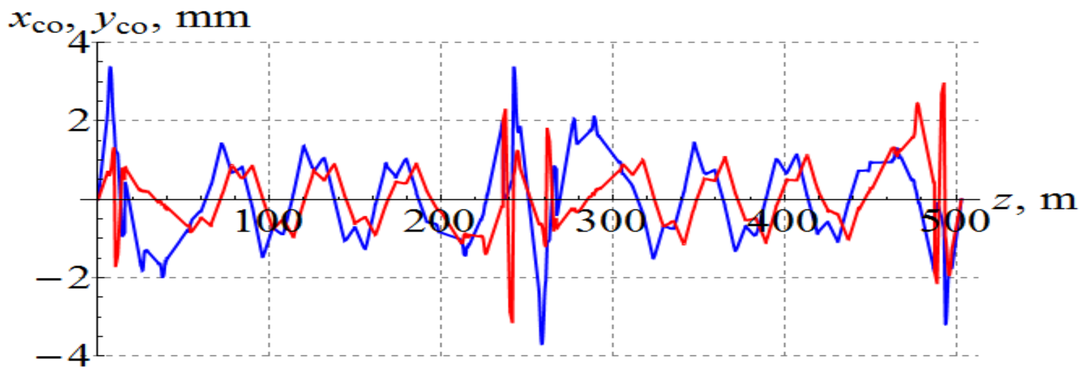
$$(\delta K_F = -0.044,\ \delta K_F = -0.032)$$

with β-function values of

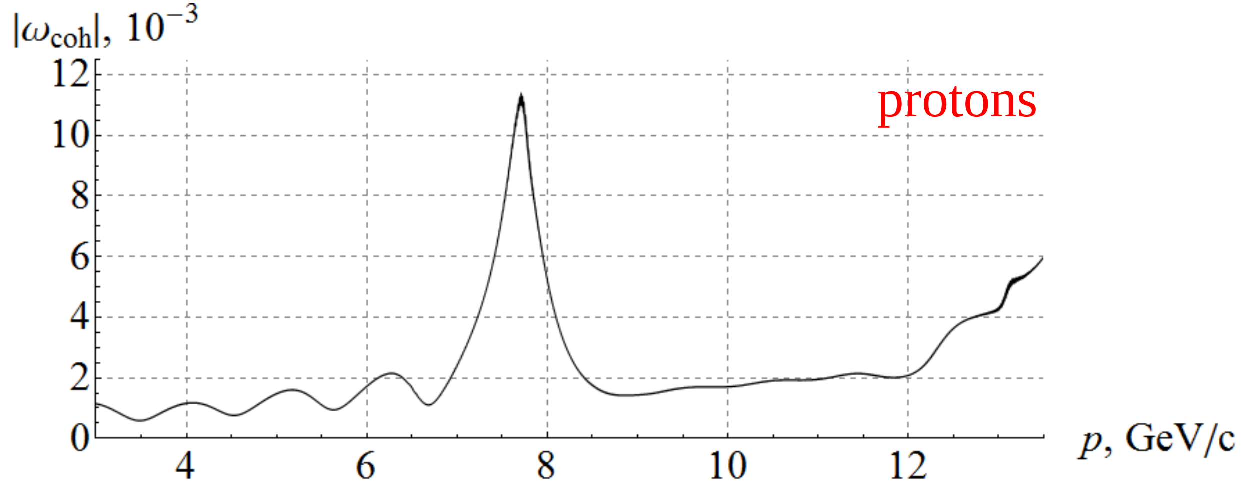
$$\beta_1 \approx 0.5\, m, \quad \beta_2 \approx 0.7\, m.$$



Coherent Part of the Spin Resonance Strength

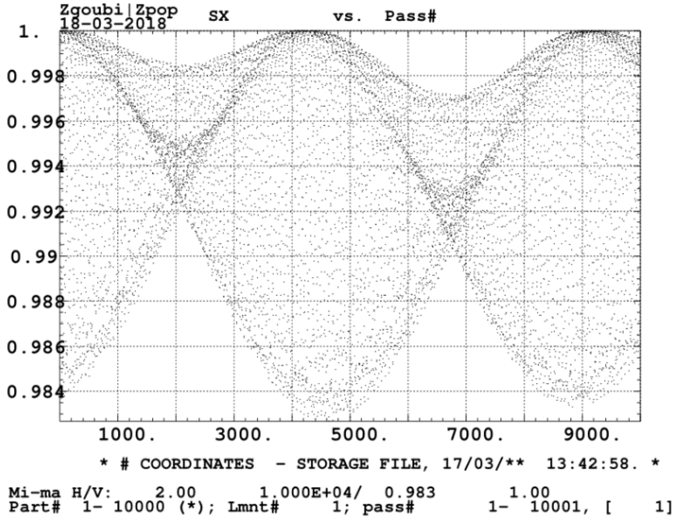


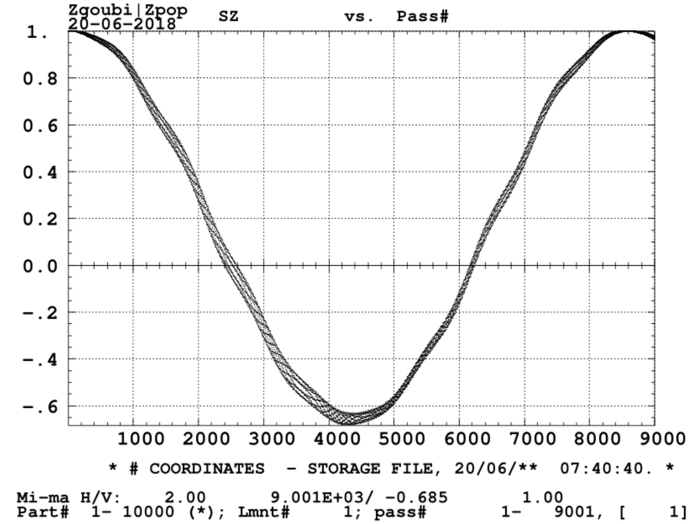
Искажение замкнутой орбиты при случайных сдвигах квадруполей.
Среднеквадратичный сдвиг квадруполей 25 мкм



Вывод: Для управления поляризаций протонов достаточно использовать слабые соленоиды каждый с интегралом поля 0.6 T m ($\nu = 10^{-2}$)

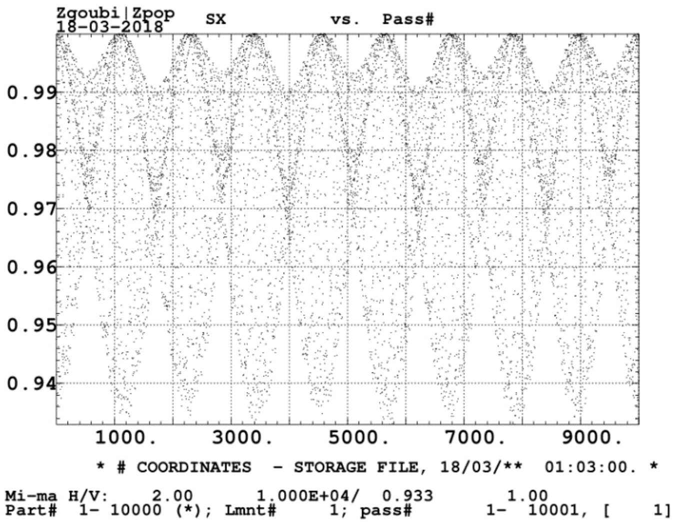
Incoherent Part of the Spin Resonance Strength





protons

Частица запущена с нормализованными эмиттансами 5 mm mrad. $\Rightarrow \omega_{emitt} \approx 10^{-4}$

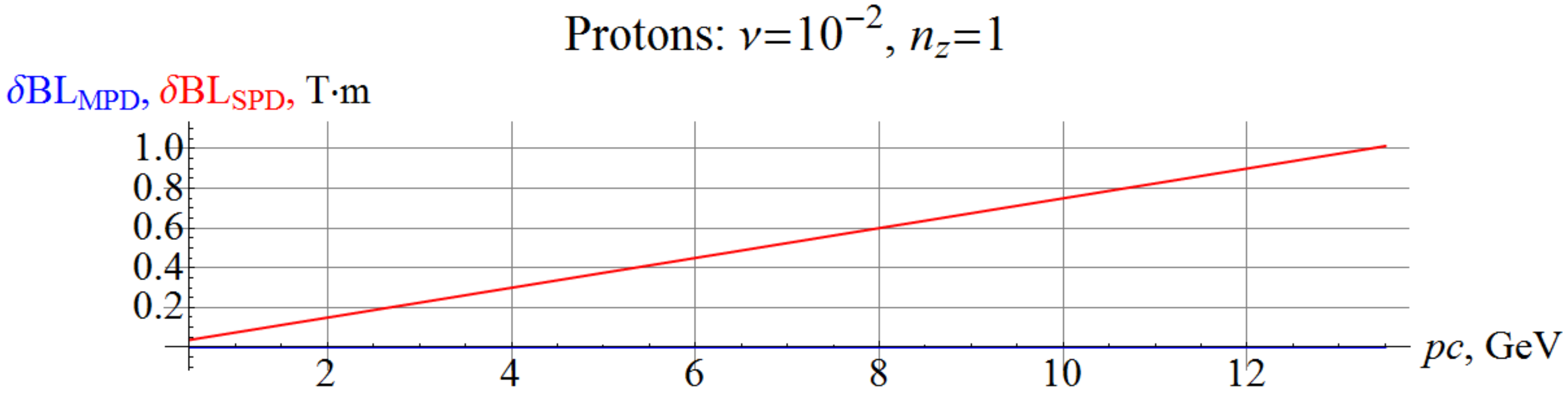


Расчет некогерентной части мощности резонанса. Частица запущена с удвоенными размерами в месте встречи. Полученное значение ω_{emitt} в 4 раза больше $\Rightarrow \omega_{emitt} \propto \varepsilon$

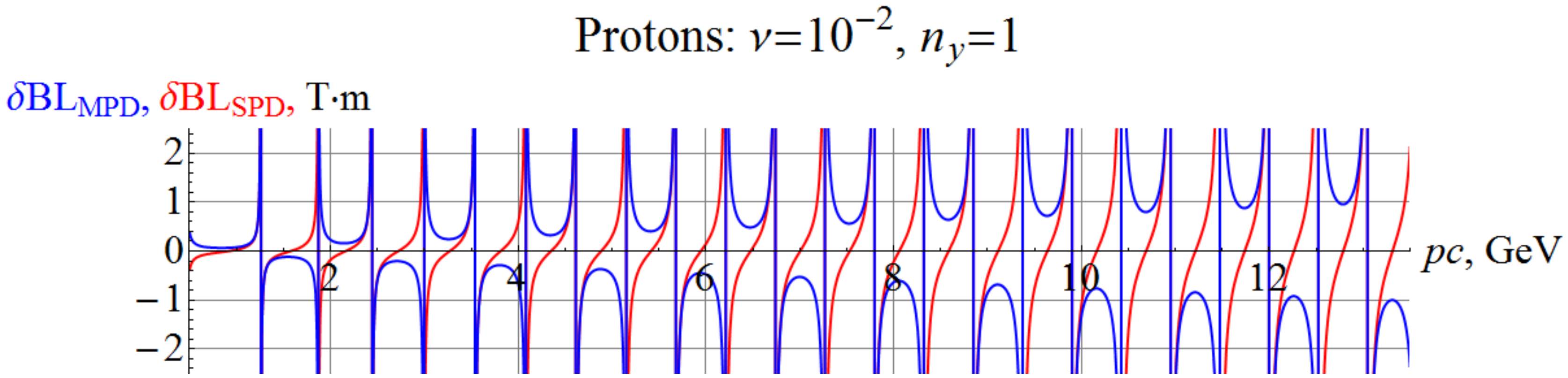
$$\omega_{emitt} \ll \omega_{coh}$$

Control of the proton polarization by the snake solenoids

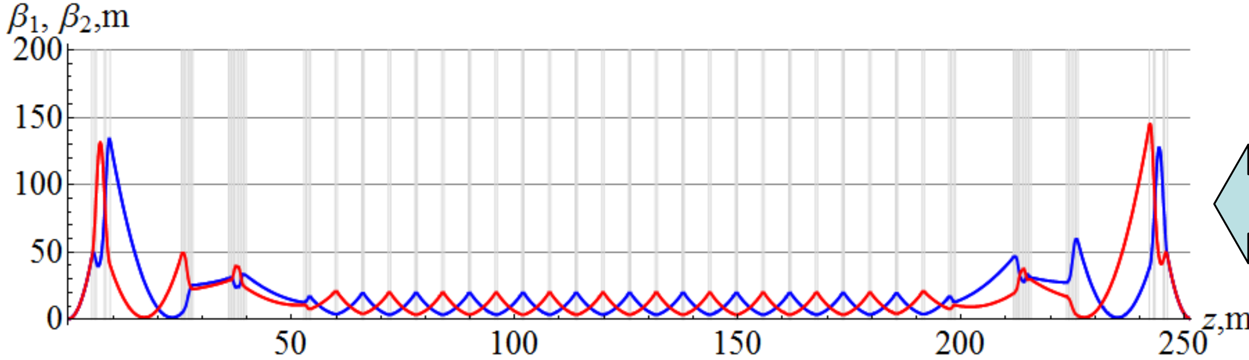
Longitudinal polarization **at SPD detector** $\delta\varphi_{MPD} = 0, \quad \delta\varphi_{SPD} = 2\pi\nu.$



Vertical polarization **at SPD detector** $\delta\varphi_{MPD} = \frac{2\pi\nu}{\sin\gamma G\pi}, \quad \delta\varphi_{SPD} = -\frac{2\pi\nu}{\tan\gamma G\pi}.$

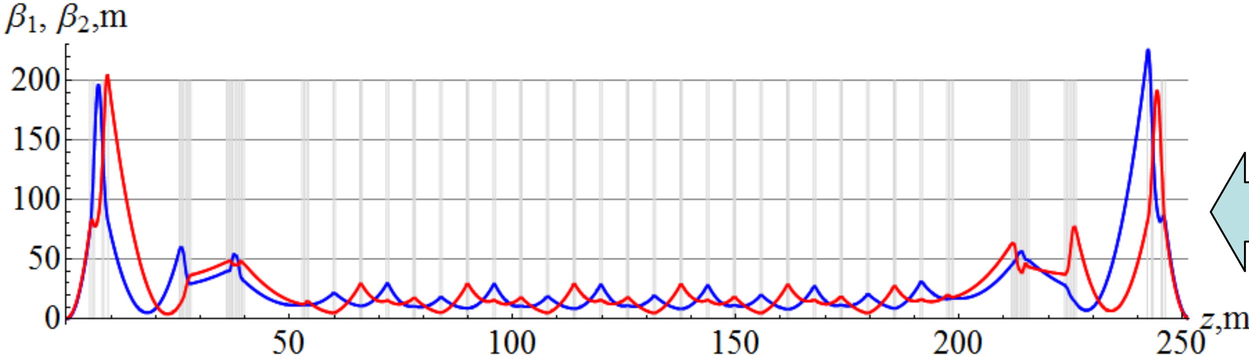


β - functions in the NICA collider



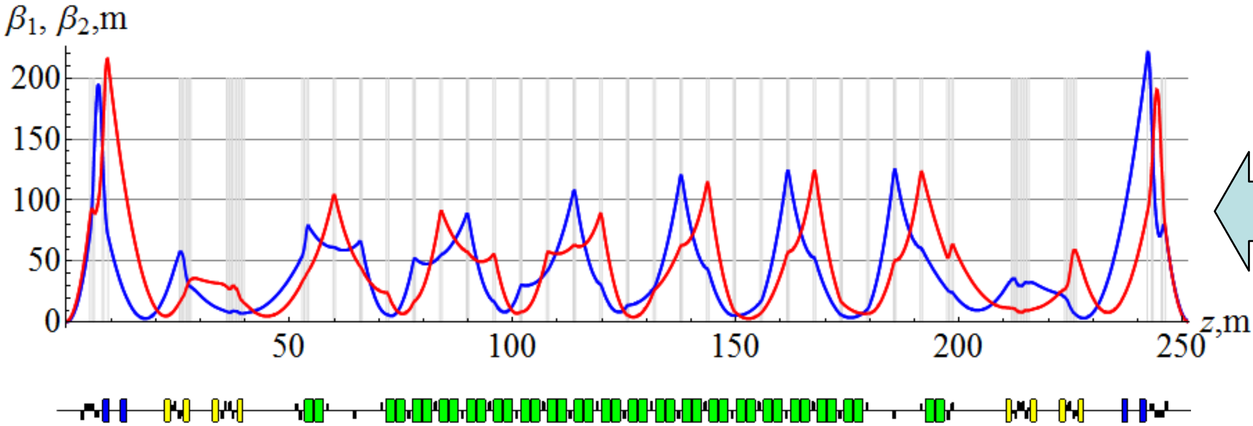
without Siberian Snakes

δK_F, m^{-2}	δK_D, m^{-2}	K_S, m^{-1}
0	0	0



with Siberian Snakes for Proton Beam

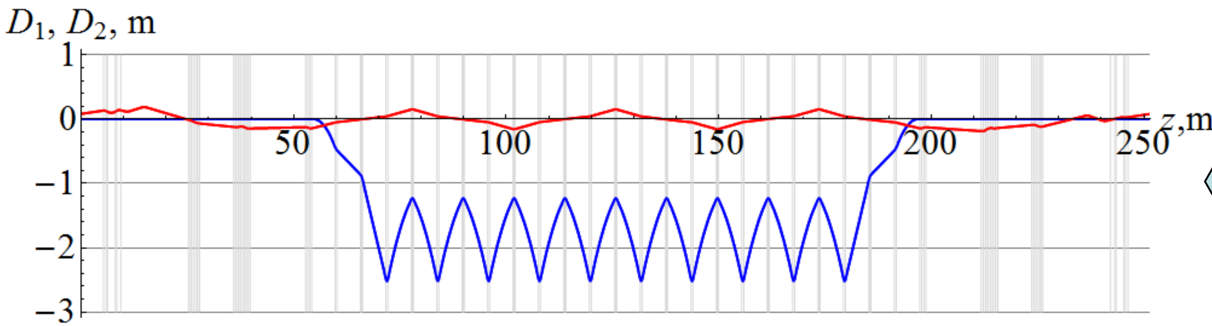
δK_F, m^{-2}	δK_D, m^{-2}	K_S, m^{-1}
0.0064	0.0045	0.117



with Siberian Snakes for Deuteron Beam

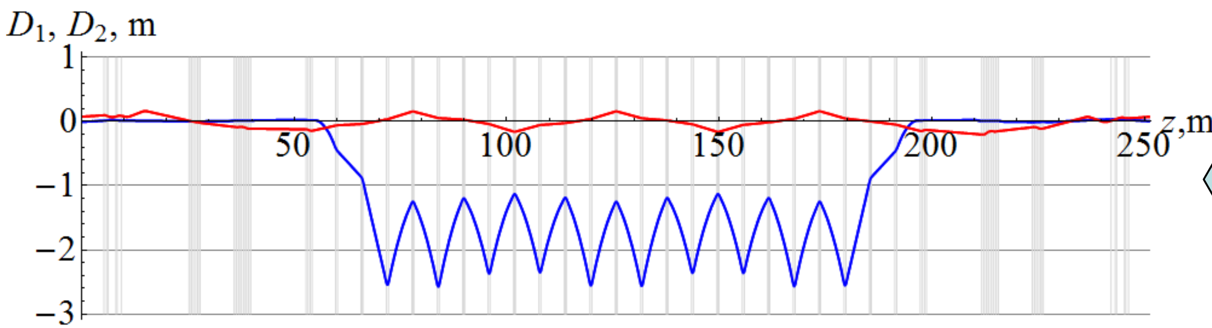
δK_F, m^{-2}	δK_D, m^{-2}	K_S, m^{-1}
- 0.0365	-0.0287	0.382

Dispersion functions in the NICA collider



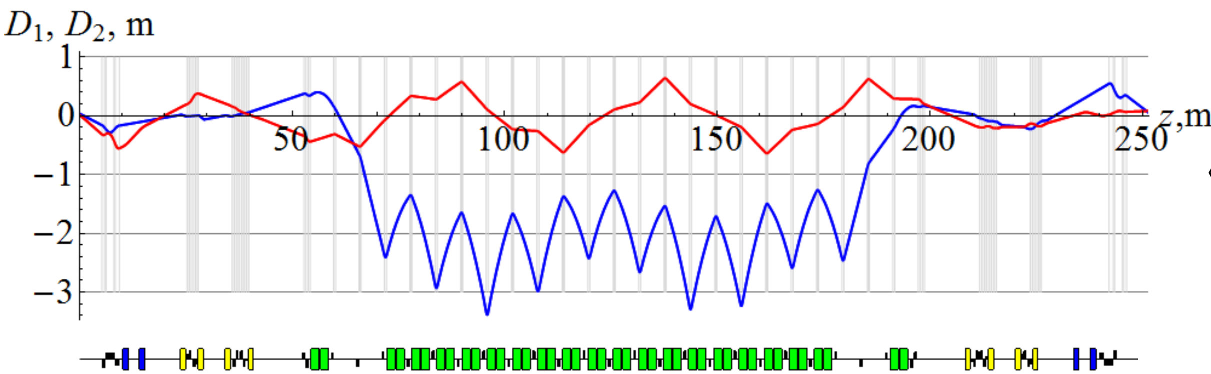
without Siberian Snakes

δK_F, m^{-2}	δK_D, m^{-2}	K_S, m^{-1}
0	0	0



with Siberian Snakes for Proton Beam

δK_F, m^{-2}	δK_D, m^{-2}	K_S, m^{-1}
0.0064	0.0045	0.117



with Siberian Snakes for Deuteron Beam

δK_F, m^{-2}	δK_D, m^{-2}	K_S, m^{-1}
- 0.0365	-0.0287	0.382

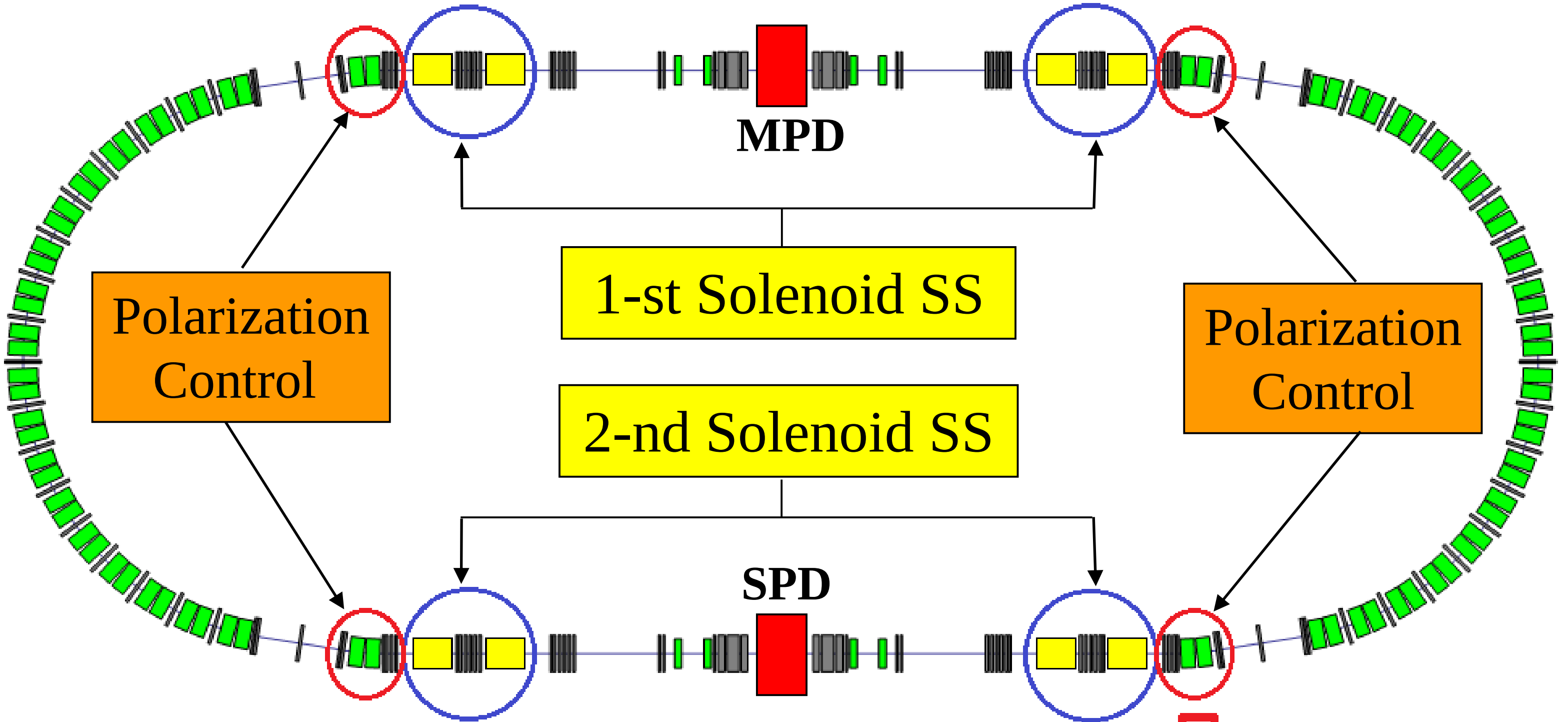
Optical Parameters at the Interaction Point

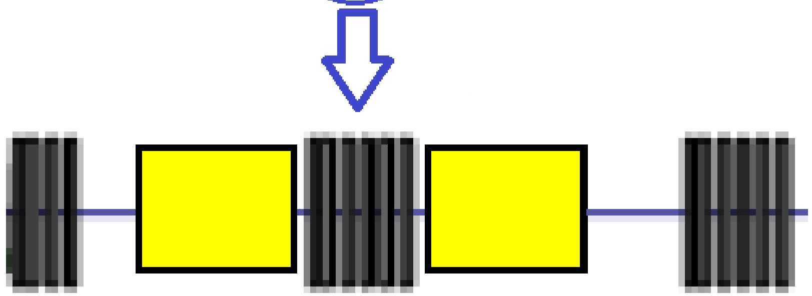
Mode	β_1^*, cm	β_2^*, cm	D_1^*, cm	D_2^*, cm
Without Snakes	60	60	0	8.4
Proton's Snakes	60	60	-0.6	7.5
Deuteron's Snakes	60	60	3.8	1.6

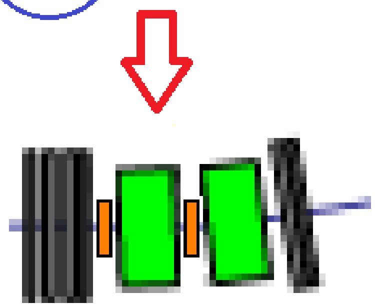
β_1^*, β_2^* are β-functions at IP
D_1^*, D_2^* are dispersion functions at IP

The presented example of matching snake solenoids in the NICA collider lattice demonstrate feasibility of spin transparency mode in NICA. Further optimization of orbital parameters are required.

Схема управления поляризацией в коллайдере NICA







protons $(B_{\|}L)_{max}$=8× (2.5÷12.5) T·m

deuterons $(B_{\|}L)_{max}$=8×(7.5÷40) T·m

Small control solenoids

$(B_{\|}L)_{max}$=8×0.25 T·m