Preservation of the proton polarization up to 13.5 GeV/c in the Nuclotron at JINR using partial snakes based on dynamic solenoids

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Outline

1. Spin resonances in the Nuclotron.
2. Partial snakes based on a dynamic solenoid.
3. Preservation of the proton polarization in the Nuclotron by one 50% partial snake.
4. Preservation of the proton polarization in the Nuclotron by two 20% partial snakes.
5. Summary.

Spin resonances of linear approximation

Type of a resonance	*Condition of a resonance*	*Number of resonances*
Intrinsic resonances	$\nu = kN \pm \nu_y$	6
Integer resonances	$\nu = k$	25
Non-superperiod resonances	$\nu = m \pm \nu_y, m \neq kN$	44
Coupling resonances	$\nu = k \pm \nu_x$	49

An unperturbed lattice of Nuclotron can only have a series of **intrinsic resonances**.

The others resonances are associated with misalignments and manufacture errors of the Nuclotron magnetic elements (imperfection resonances).

Spin resonance crossing

The spin-tune offset-from-resonance (resonance-detune): $\varepsilon = \gamma G - \nu_k$

The normalized resonance-detune rate: $\varepsilon' = R\frac{d\varepsilon}{dz} = \frac{eGR\rho}{mc^3}\left(\frac{dB}{dt}\right),$

In the Nuclotron at $R \approx 40$ m, $\rho \approx 22$ m $\varepsilon' \approx 1.75 \cdot 10^{-6}\frac{dB\,[\mathrm{T}]}{dt\,[\mathrm{s}]}$

The vertical spin component after the crossing changes according to the Froissart-Stora equation

$$S_y^{\text{after}} = \left(-1 + 2\exp\left(-\frac{\pi\,\omega^2}{2\varepsilon'}\right)\right)S_y^{\text{befor}}$$

ω is a resonance strength

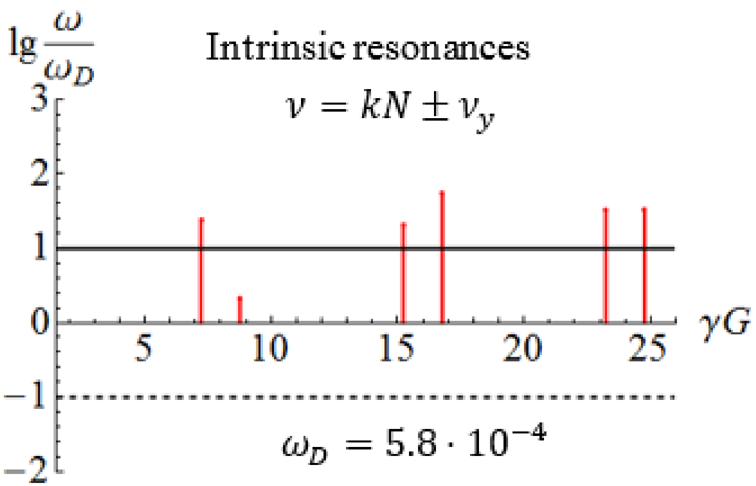
$\omega_D = \sqrt{\varepsilon'/\pi}$ is a characteristic resonance strength

$\boldsymbol{\omega \ll \omega_D}$ fast crossing, $\boldsymbol{\omega \gg \omega_D}$ adiabatic crossing,

$\boldsymbol{\omega \sim \omega_D}$ intermediate crossing (depolarization occur)

At the field ramp rate $dB/dt = 0.6$ T/s $\varepsilon' \approx 10^{-6}$, $\boldsymbol{\omega_D = 5.6 \cdot 10^{-4}}$

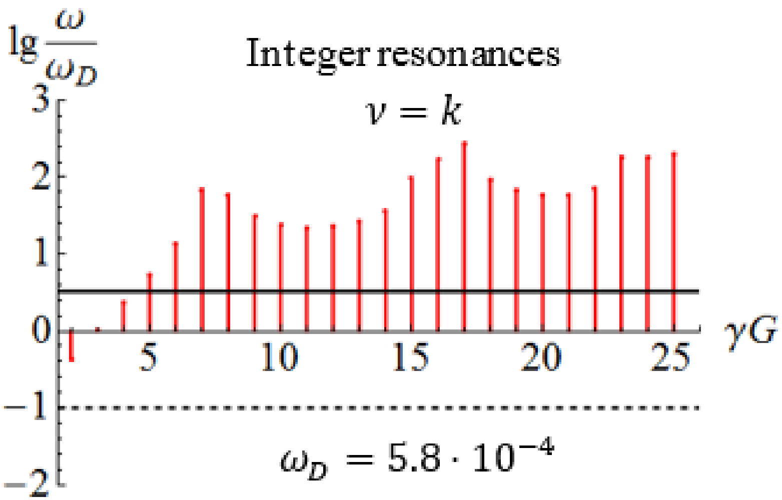
Strong spin resonances



Intrinsic resonances occur due to correlation of the spin motion with the particle betatron motion.

Normalized betatron emittances

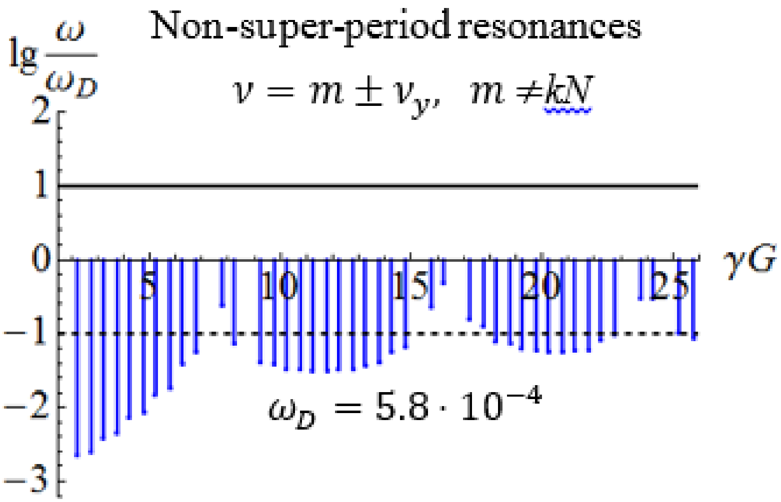
$$\epsilon_{x,y} = 5\pi \cdot \text{mm mrad}$$



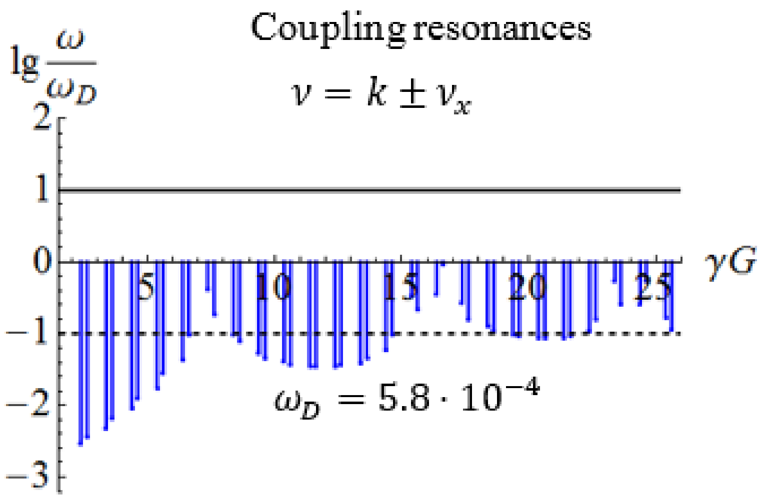
Random vertical quadrupole shifts give rise to a series of integer resonances.

(closed orbit distortions ~ 10 mm)

Weak spin resonances



Random changes in quadrupole gradients give rise to a series of non-super-periodic resonances.
Relative error of the quadrupole gradients: $\sigma_g/g = 10^{-3}$



Random quadrupole rolls give rise to a series of coupling resonances.
Error of quadrupole rolls : $\sigma_\alpha = 1\text{mrad}$

The resonance strengths of these resonances are much less than the strengths of intrinsic and integer resonances.

Intrinsic resonances ($\nu = k\,N \pm \nu_y$)

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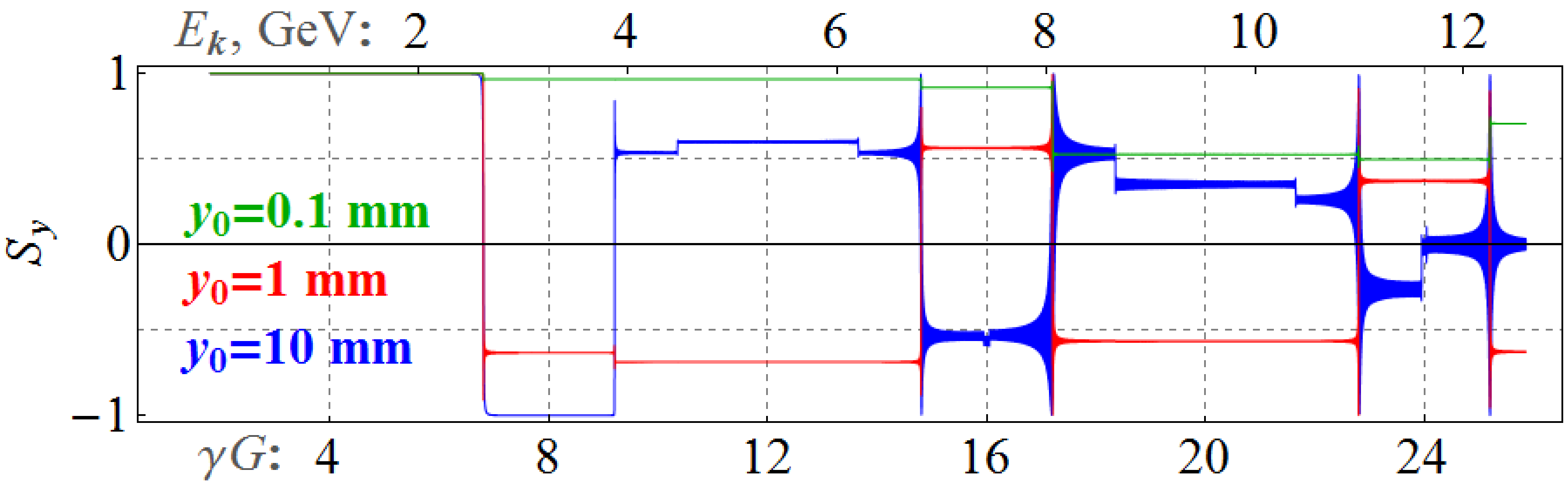
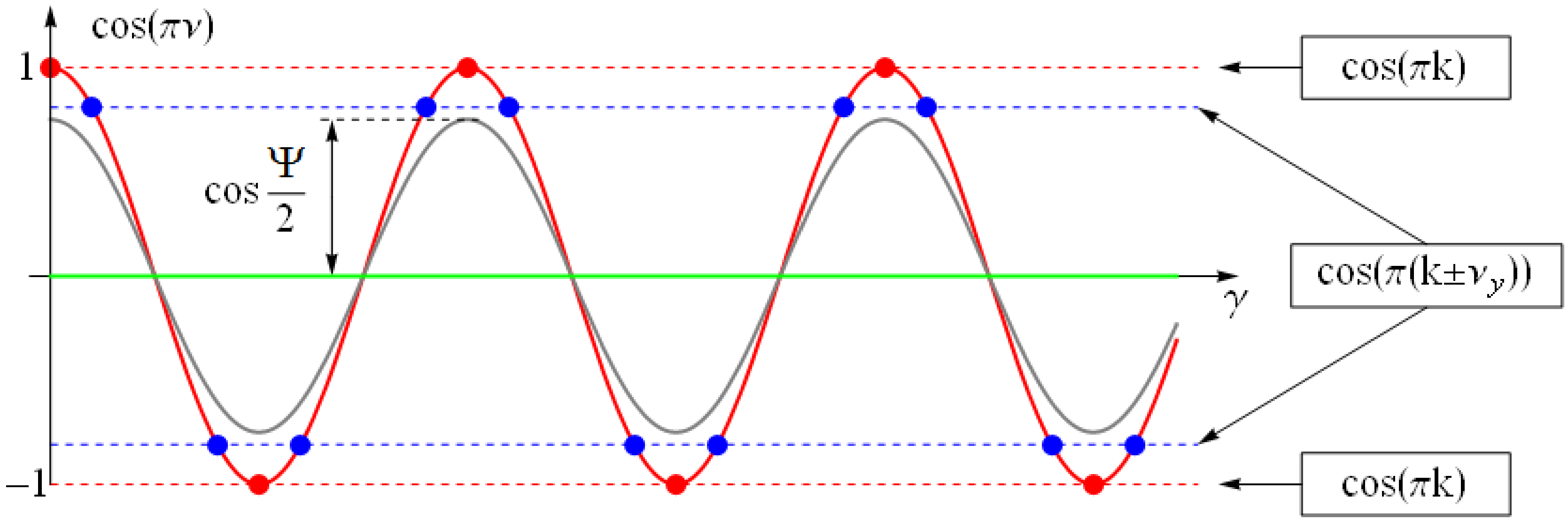
Initial conditions :
y_0**=0.1 mm**, y_0**=1 mm**, y_0**=10 mm**, **dB/dt=0.6 T/s**



Intrinsic resonances belong to the category of incoherent resonances. The strength of an intrinsic resonance is proportional to the amplitude of betatron oscillations and, therefore, during a slow crossing of the resonance, there could simultaneously be present particles with intermediate and fast crossing rates.

Partial Snake

$$\cos(\pi\nu) = \cos(\pi\gamma G)\cos\frac{\Psi}{2}, \qquad \Psi = (1+G)\frac{B_{\parallel}L}{B\rho}$$



Integer resonances are excluded if

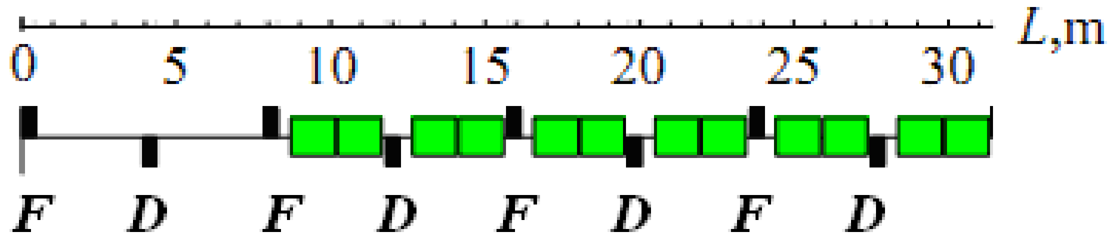
$$\cos\Psi < \cos 2\pi w_k$$

Intrinsic resonances are excluded if

$$\cos\Psi < \cos 2\pi\nu_{1,2}$$

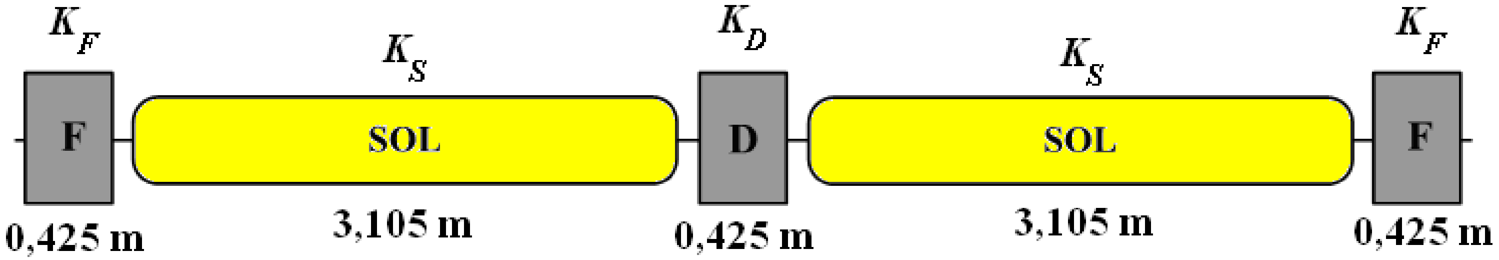
The full snake eliminates all spin resonances : $\Psi = \pi$

Scheme of the Nuclotron superperiod



Betatron tunes are determined by two families of focusing and defocusing quadrupoles F and D

Layout of the solenoidal snake



Here K_F , K_D are the gradients of the focusing and defocusing quadrupoles in units of $B\rho$, K_S is the solenoid field in units of $B\rho$.

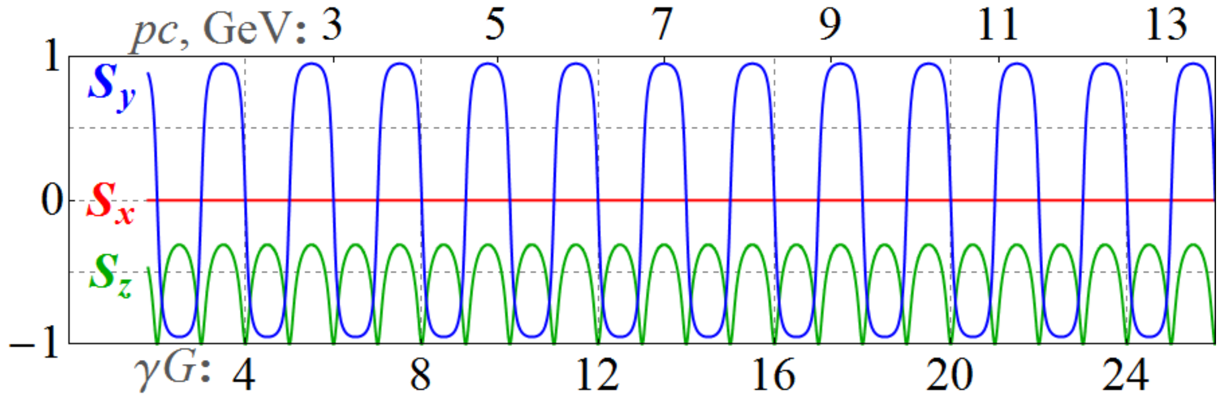
20% snake: $B_{sol} L$ = 10 T·m, B_{sol} =1.6 T at beam momentum of 13.5 GeV/c
50% snake: $B_{sol} L$ = 25 T·m, B_{sol} = 4 T at beam momentum of 13.5 GeV/c

Stable polarization in the Nuclotron with partial snake

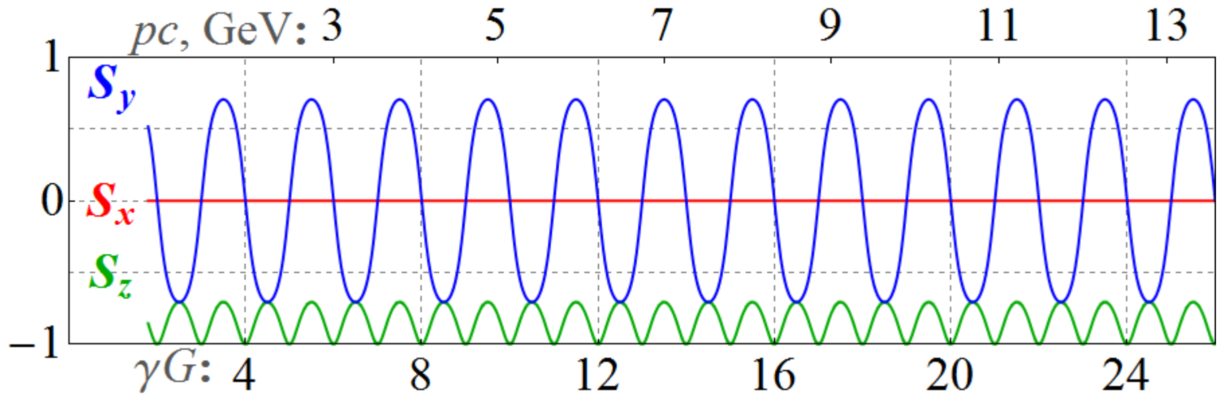
In opposite to the snake straight, the stable spin precession $\vec{n}$-axis is:

$$\vec{n} = \frac{\sin(\Psi/2)\,\vec{e}_z + \cos(\Psi/2)\sin(\pi\gamma G)\ \vec{e}_y}{\sqrt{1-\cos^2(\Psi/2)\cos^2(\pi\gamma G)}} \,.$$

20% snake

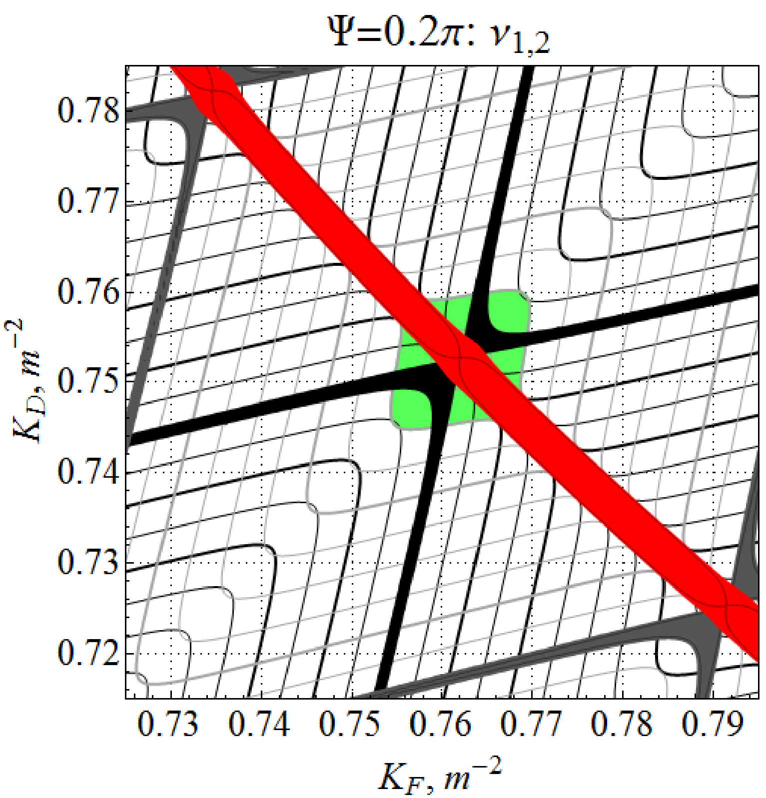


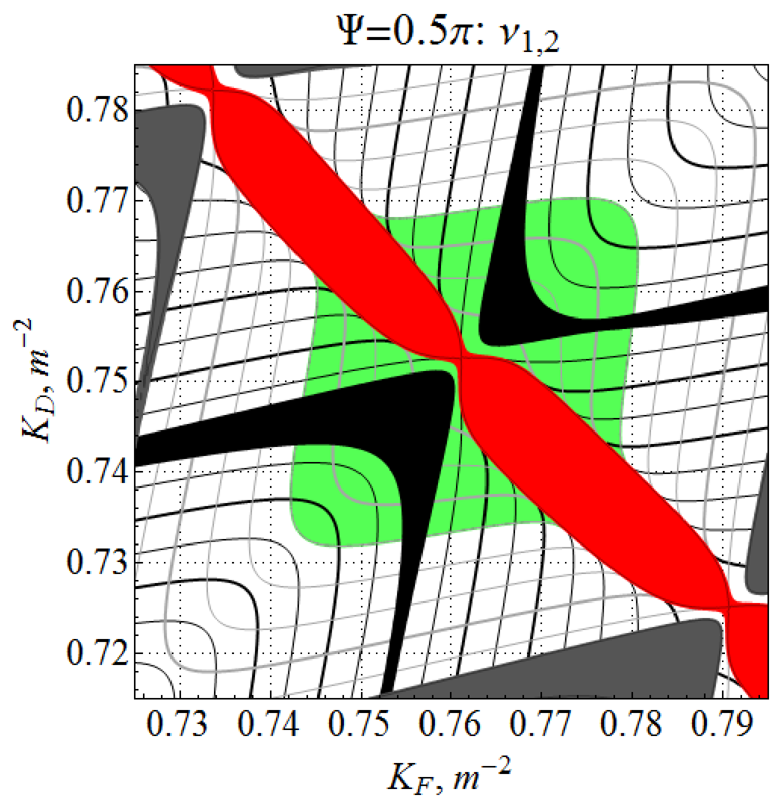
50% snake



Stability diagram of betatron oscillations

Lines of betatron tunes levels with step 0.05





Stable motion — unstable motion

On the edge of the colored areas :

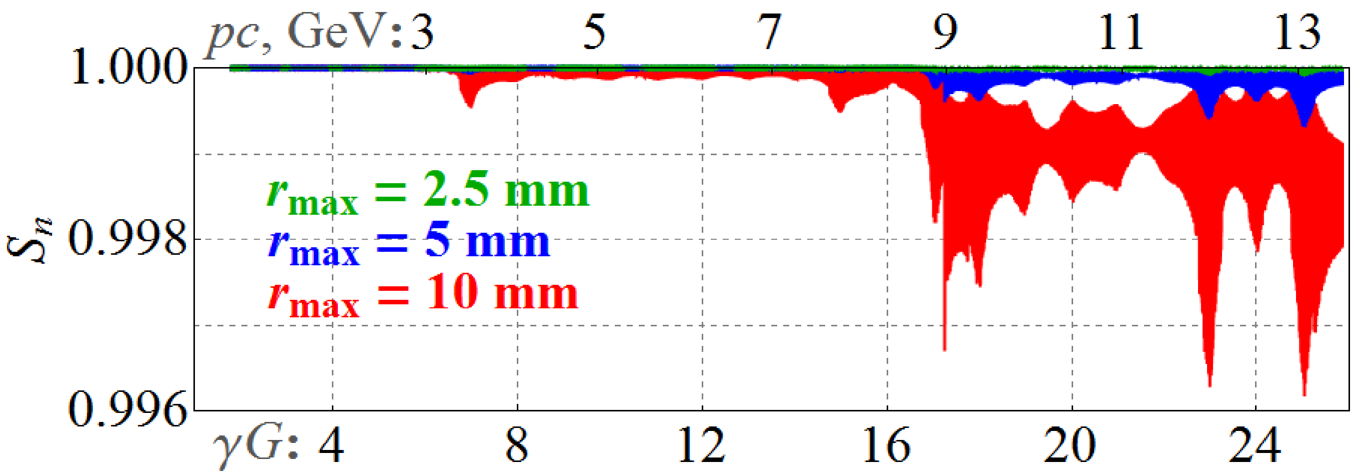
integer resonances $\nu_{1,2}=k$

half-integer resonances $\nu_{1,2}=k+1/2$

coupling resonances $\nu_1=k\pm\nu_2$

The proton polarization preservation by 50% snake

When using superconducting magnets acceleration happens adiabatically, which means that, in a characteristic time of change in the $\vec{n}$-axis, the spin makes a large number of turns. During adiabatic acceleration, the spin follows the $\vec{n}$-axis direction



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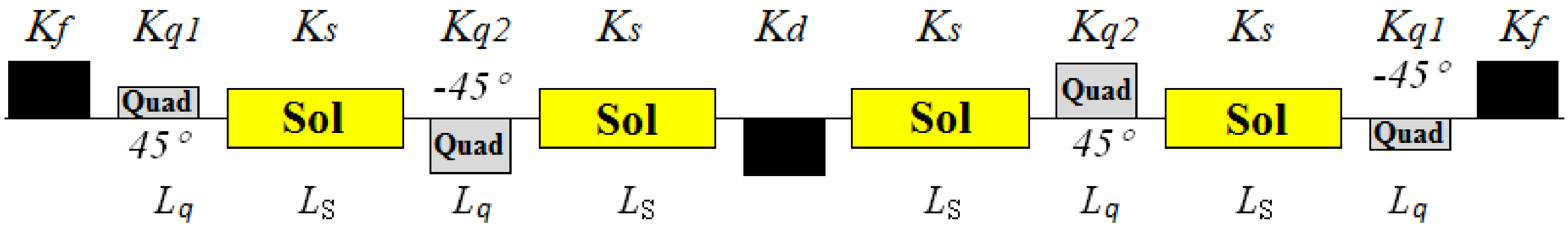
The spin projections S_n during acceleration of protons with three different betatron amplitudes ($\nu_x \approx 6.78$, $\nu_y \approx 6.9$).

The spins are initially directed along the $\vec{n}$-axis.

Snake with a betatron coupling compensation



20%-snake without betatron coupling

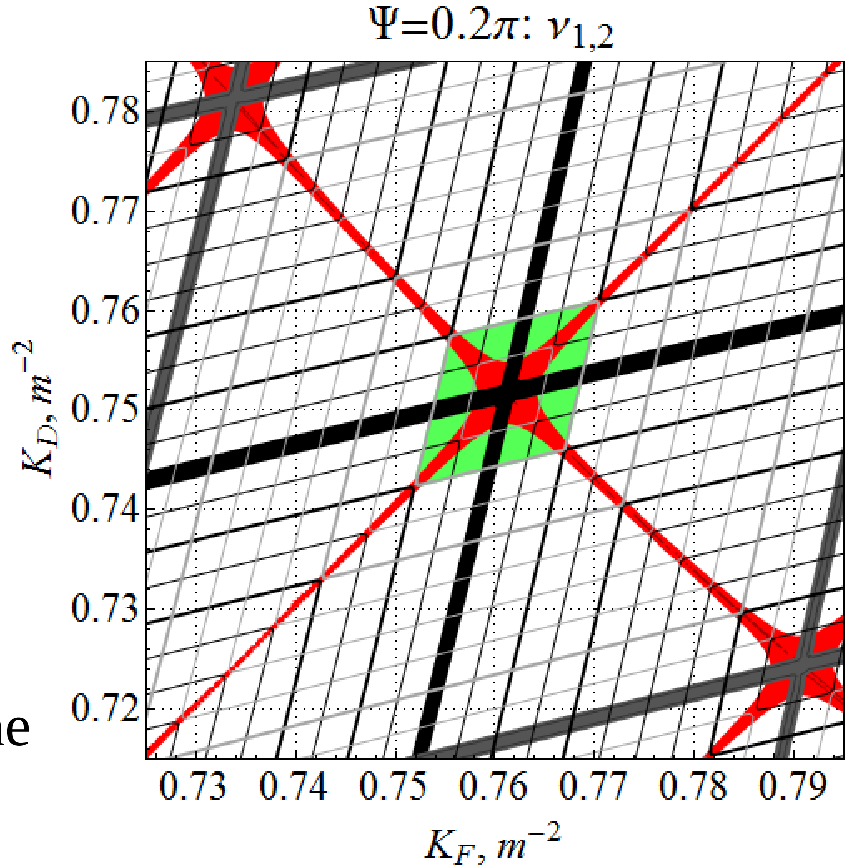
$L_s = 100$ cm (solenoid length)
$L_q = 43.9$ cm (regular Nuclotron quad)

$K_f = 0.758\ \mathrm{m}^{-2}$, $K_d = 0.753\ \mathrm{m}^{-2}$

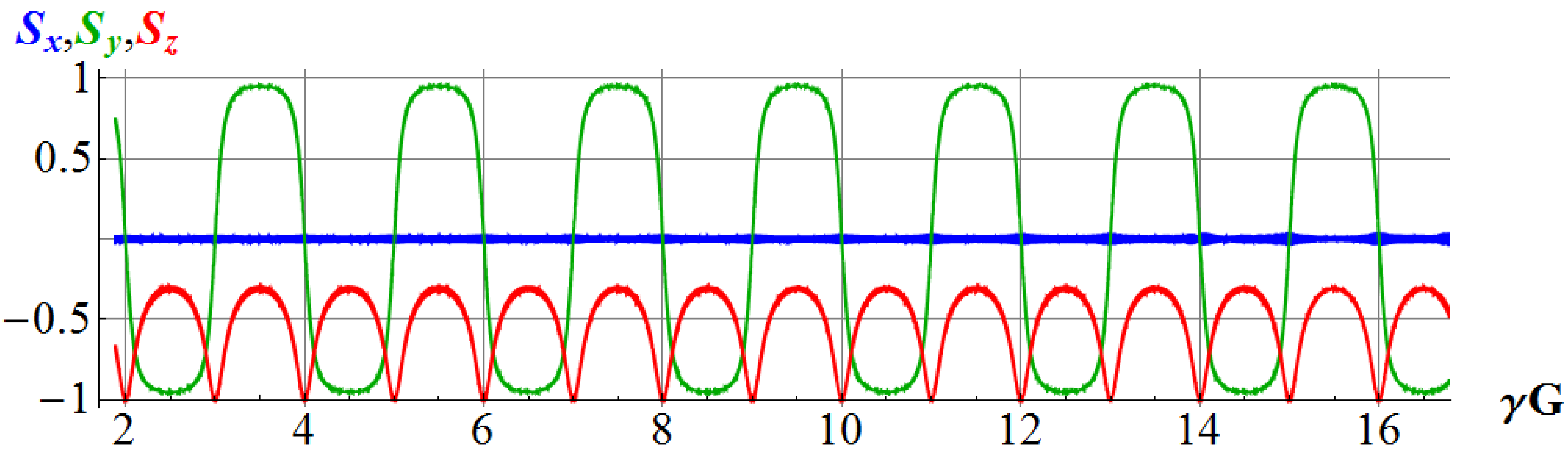
Skewed quadrupoles:
$K_{q1} = 0.140\ \ \mathrm{m}^{-2}$, $K_{q2} = 0.277\ \ \mathrm{m}^{-2}$

$\Delta\nu_{x,y} = \pm 0.01$ (betatron tune shifts)

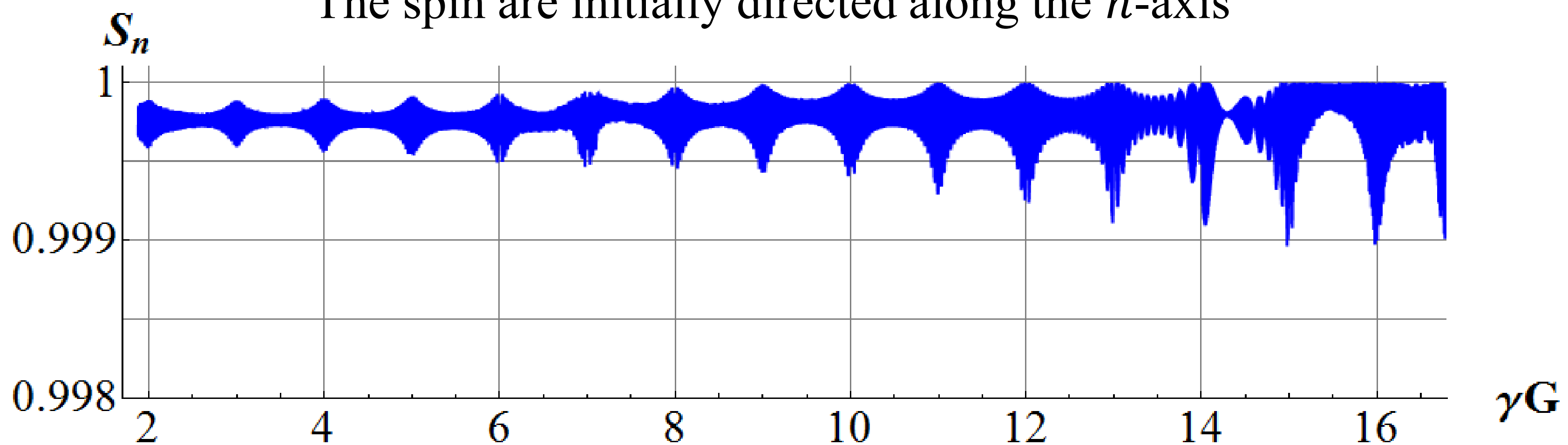
The diagram of betatron motion stability practically identical to the diagram for the empty Nuclotron (all $\nu_{x,y}$ are available.)



The proton polarization preservation by 20% snake



The spin are initially directed along the $\vec{n}$-axis

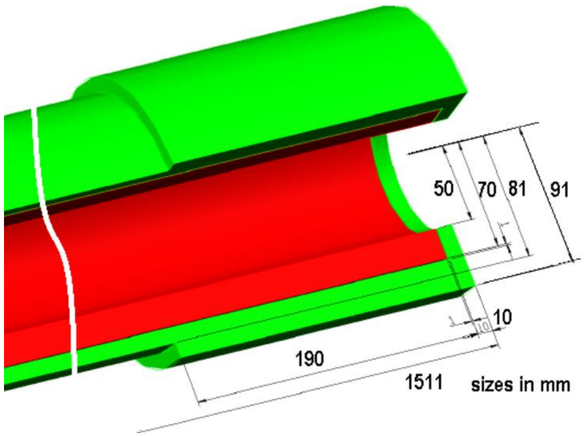


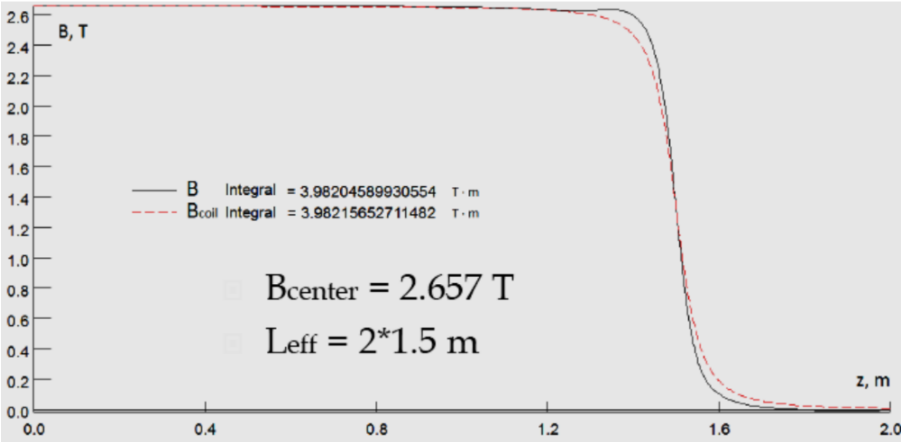
The spin projections S_n during acceleration of a proton

($\nu_x \approx 6.95$, $\nu_y \approx 7.03$, $\gamma_{\mathrm{tr}} = 9.63$, $\epsilon_{x,y} = 2.5\pi$ mm · mrad, dB/dt=1.8 T/s)

Dynamic solenoid based on NbTi/Cu hollow composite cable

A prototype of dynamic solenoids with a field ramp rate of ~1 T/s based on hollow two-phase helium flow NbTi/Cu hollow composite cable developed at JINR was proposed at EUCAS2015 (*A.D. Kovalenko et al.*)



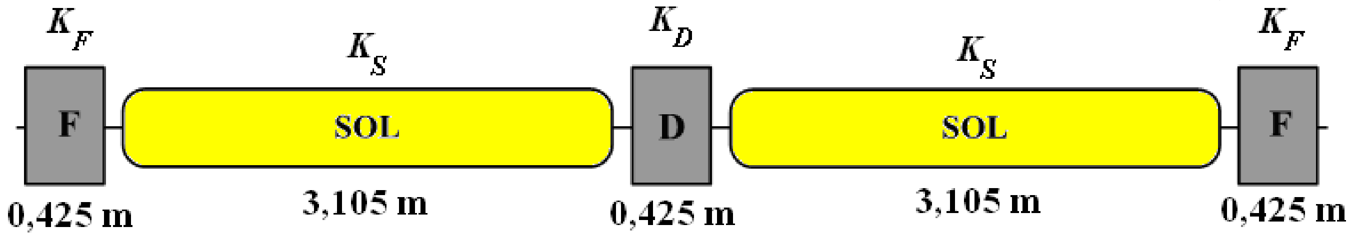


The cable outer diameter – 9 mm (with insulation, cooling channel diameter – 4 mm, coil inner diameter – 100 mm, number of turns per meter – 111, number of the coil layers – 2.

The maximum field is about 2.5 T at the solenoid length of 3 m.

Partial solenoid snakes in the Nuclotron

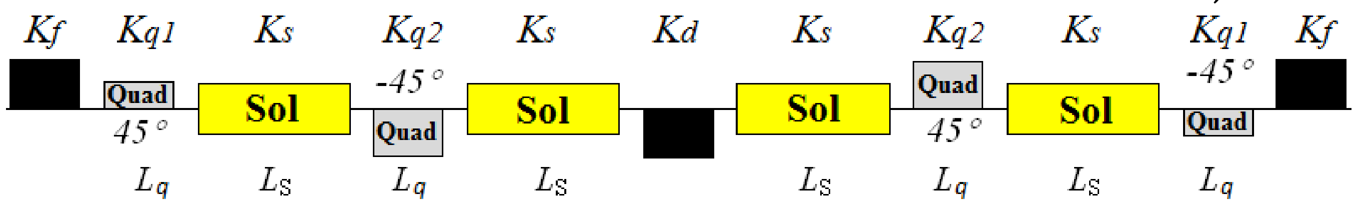
Snake **with** betatron coupling (solenoid $L_{tot} = 6.2$ m, $B_{s,\max} = 2.5$ T)



30% snake at 13.5 GeV/c

40% snake at 10 GeV/c

Snake **without** betatron coupling (solenoid $L_{tot} = 4$ m, $B_{s,\max} = 2.5$ T)



20%-snake at 13.5 GeV/c

27%-snake at 10 GeV/c

After shortening the skew quads length solenoid $L_{tot} = 4$ m

24%-snake at 13.5 GeV/c

33%-snake at 10 GeV/c

Summary

A successful preservation of polarization of protons with a momentum up to 13.5 GeV/c by solenoid partial snakes enables one to carry out experiments at external targets as well as to use the Nuclotron as a rapid-cycling injector of polarized protons into the collider in the entire momentum range of NICA.

It will become possible to inject protons into the NICA collider directly at energies corresponding to the spin transparency regime at integer spin resonances (the NICA ST regime without two full solenoid snakes).

Thank you for your attention!