Polarized Proton and Deuteron Beams at NICA – Precession Spin Approach

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Outline

1. Basic requirements from the experimental point of view.
2. Proton and deuteron spin tunes, spin resonances, energy ramping in the Nuclotron.
3. Precession spin approach. Flipper device.
4. Partial Siberian Snake approach for the proton beam.
5. Beam cooling and luminosity issues.
6. Beams separation scheme – an alternative proposal.
7. Summary.

Basic requirements from the experimental point of view

I.A. Savin et al, “Spin Physics Experiments at NICA-SPD with polarized proton and deuteron beams”, Letter of Intent, 2014.

V.D. Kekelidze et al , “Three Stages of The NICA Accelerator Complex Nuclotron-based Ion Collider fAcility”, Proc. of the LHCP2015 Conf. St. Petersburg, Russia, August 31 – September 5, 2015.

A. Kovalenko, I. Savin, “Spin Physics Experiments at NICA-SPD”, talk given at SPIN2016, Urbana-Champain, USA, 2016.

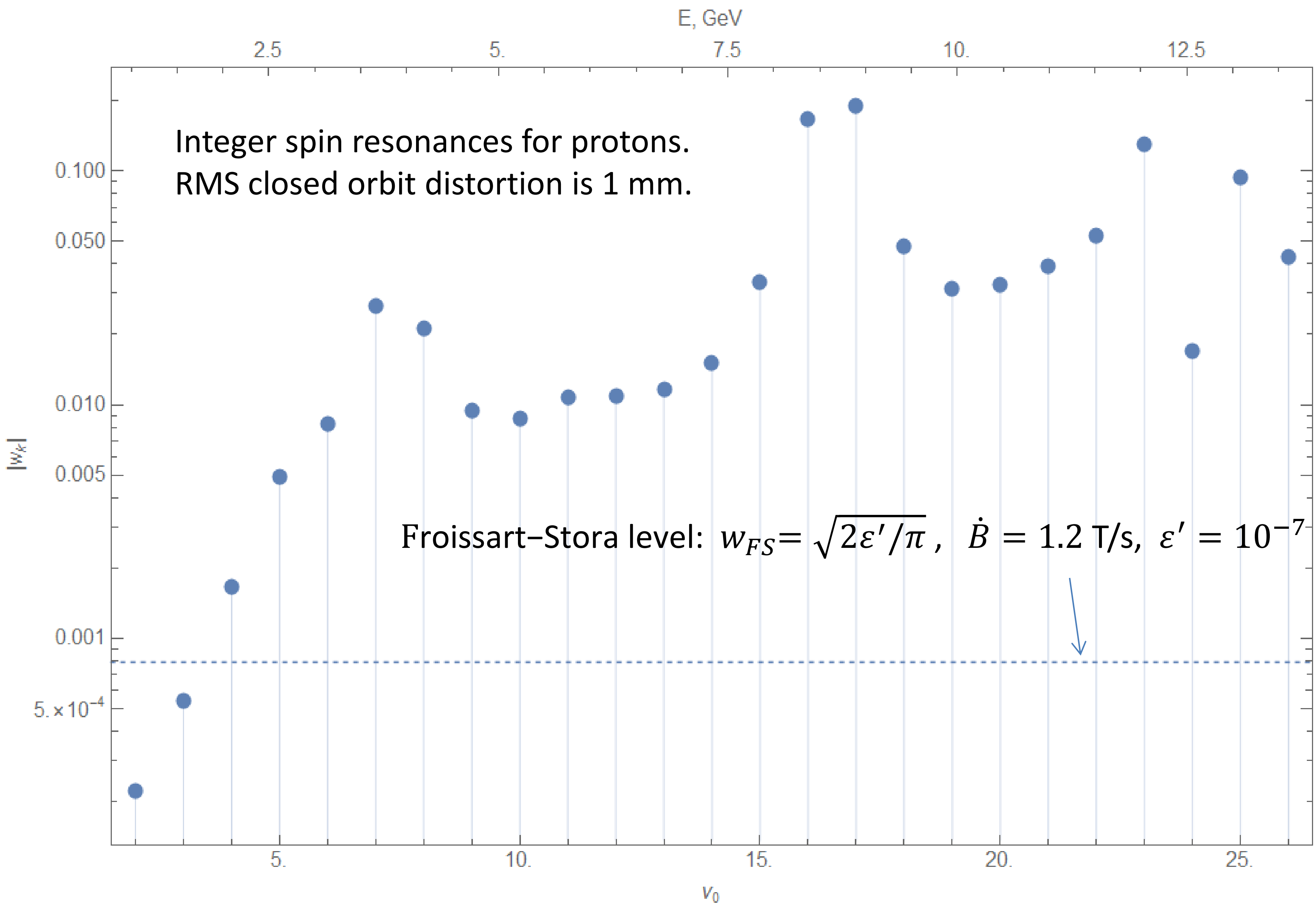
1. Both, transverse and longitudinal polarization directions: →→, ↑↑, ↑→, →↑. Proton-proton and deuteron-proton collisions.

2. Energy range: up to 12.6 GeV/u for protons and 5.9 GeV/u for deuterons.

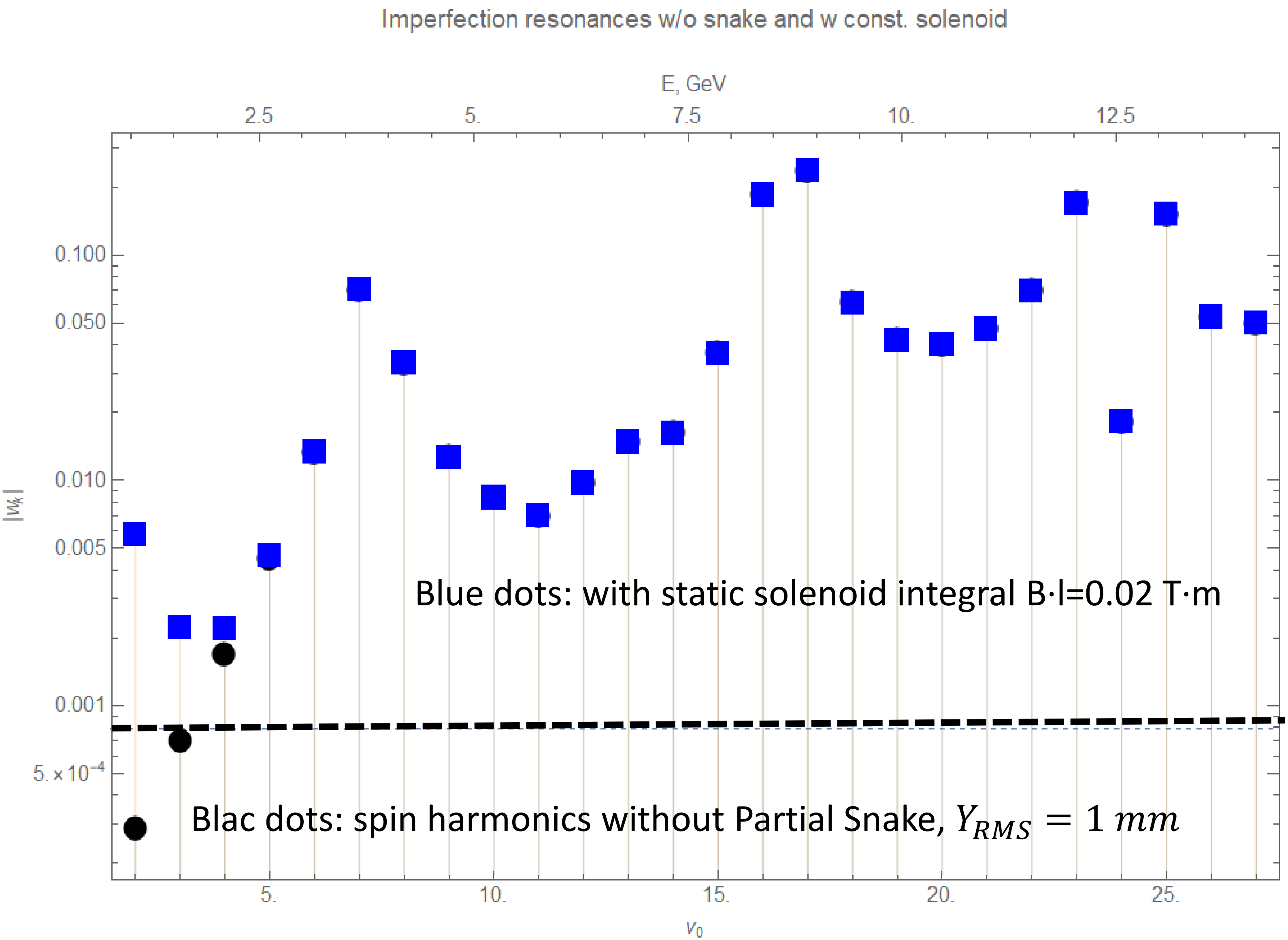
3. Spin tunes: $\gamma \leq \begin{cases} 14.4 & \text{for protons} \\ 7.2 & \text{for deuterons,} \end{cases} \quad G = \begin{cases} 1.793 \\ \text{-}0.143 \end{cases} \quad \nu_0 = \gamma\,|G| \leq \begin{cases} 25.8 & \text{for protons} \\ 1.03 & \text{for deuterons} \end{cases}$

So, 25 integers resonances for protons and only a single resonance for deuterons! A proton beam acceleration in the Nuclotron requires use of a Partial Siberian Snake (idea of Derbenev, Kondratenko developed in 70-th). For deuterons only intrinsic spin resonances with the vertical betatron oscillations present a problem. But can be crossed adiabatically with large beam emittances in the Nuclotron.

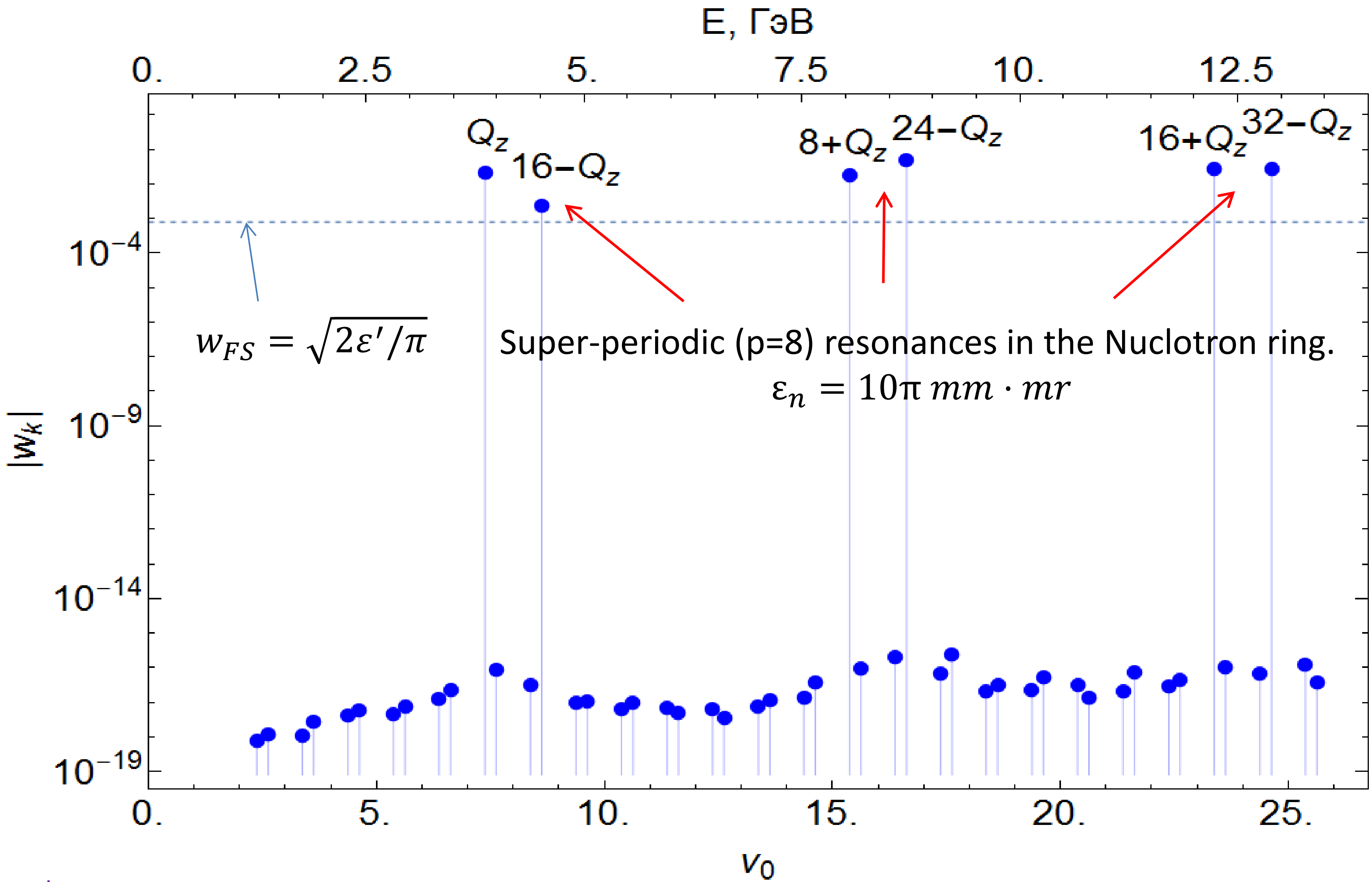
Energy ramping in the Nuclotron. Spin resonances for protons.



Partial Siberian Snake for crossing of integer spin resonances.



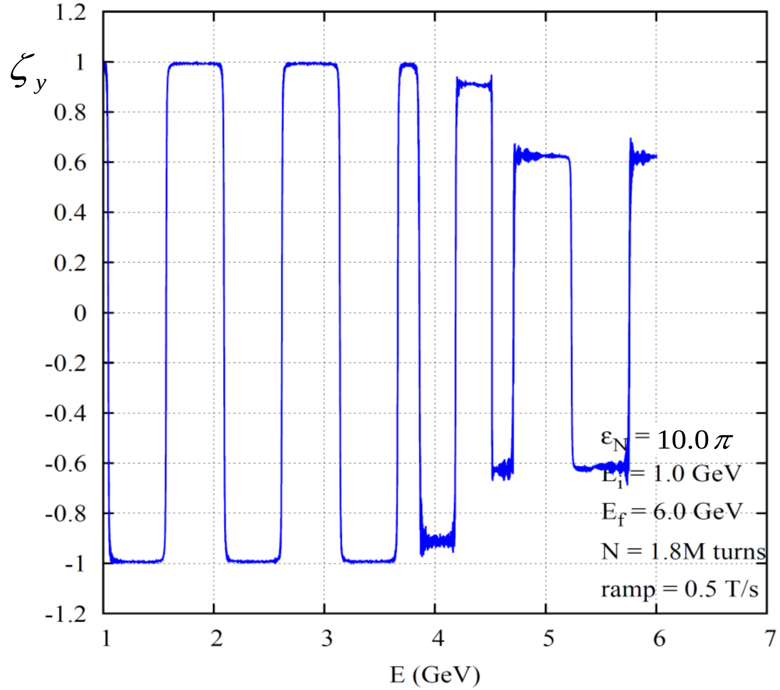
Intrinsic spin resonances for protons in Nuclotron.

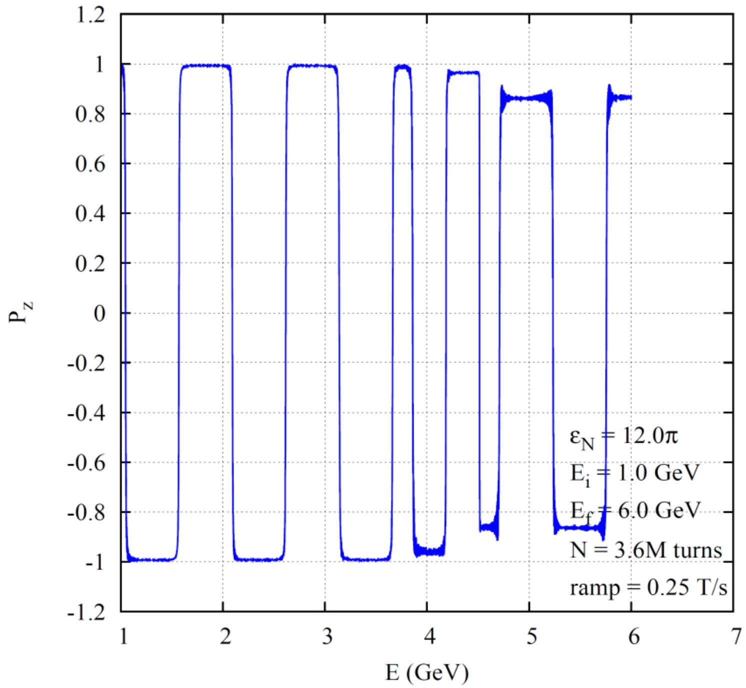


See also:

Yu.N. Filatov et al. "Acceleration of polarized proton and deuteron beams in the Nuclotron at JINR", in Proceedings of IPAC2017, Copenhagen, Denmark.

Adiabatic crossing of the integers and intrinsic resonances at different speeds.

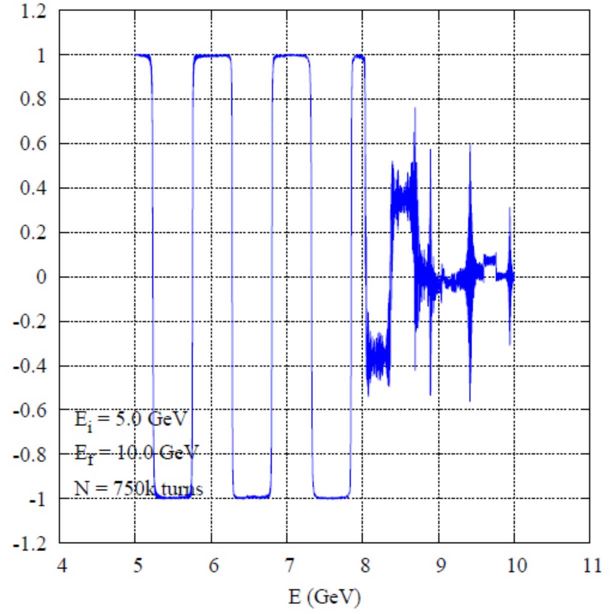




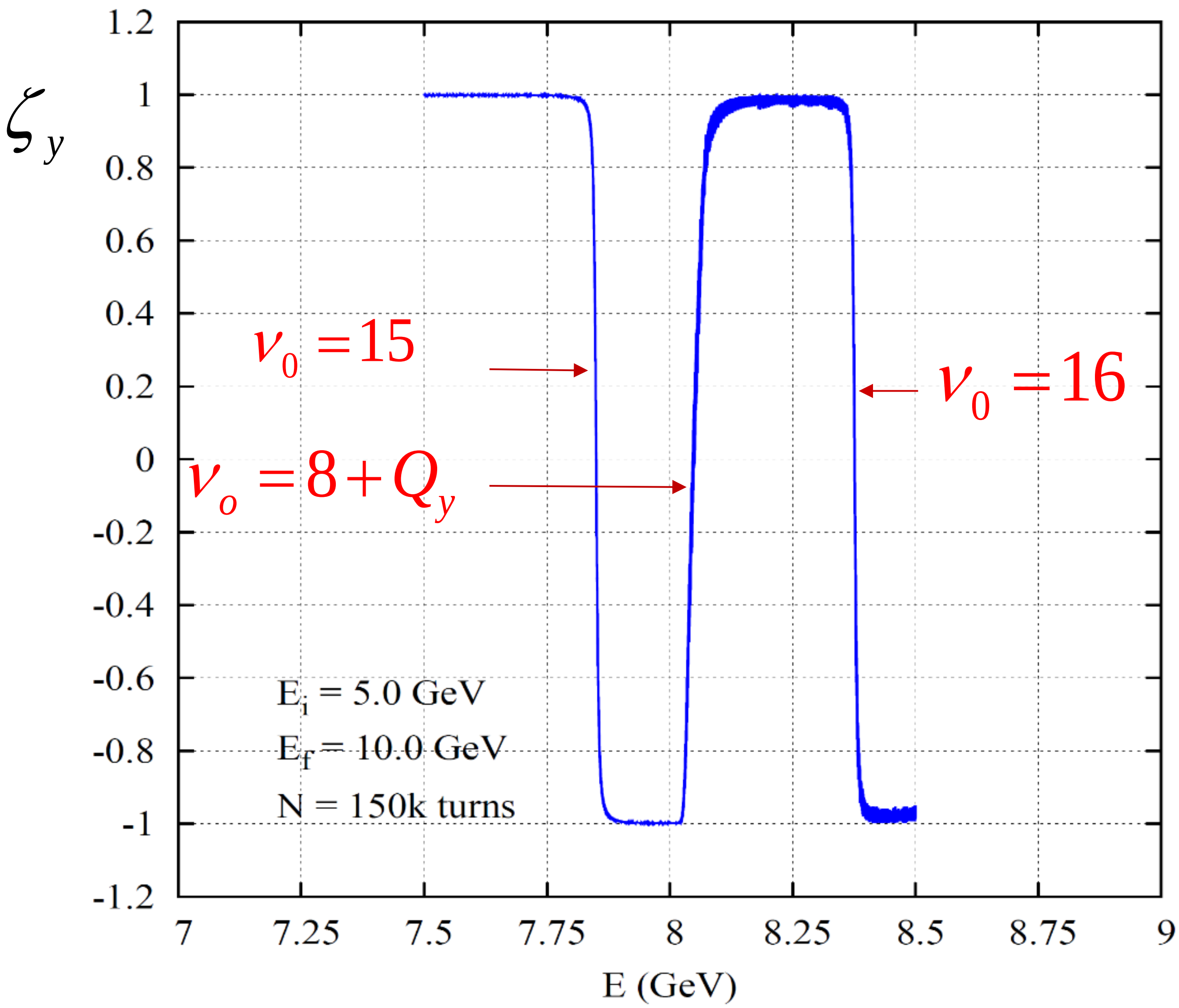
Decreasing of the ramping speed we improve fulfilment of the adiabaticity condition. As a result - polarization loss at E=4.5 GeV is 10%, only.

Acceleration above E=8 GeV meets a problem with crossing of the resonance $\nu_0 = 8 + Q_y$, see lower plot.

Excitation of coherent vertical oscillations helps to overcome this difficulty, see next slide.



Simulation of the adiabatic crossing of the integers and intrinsic resonances



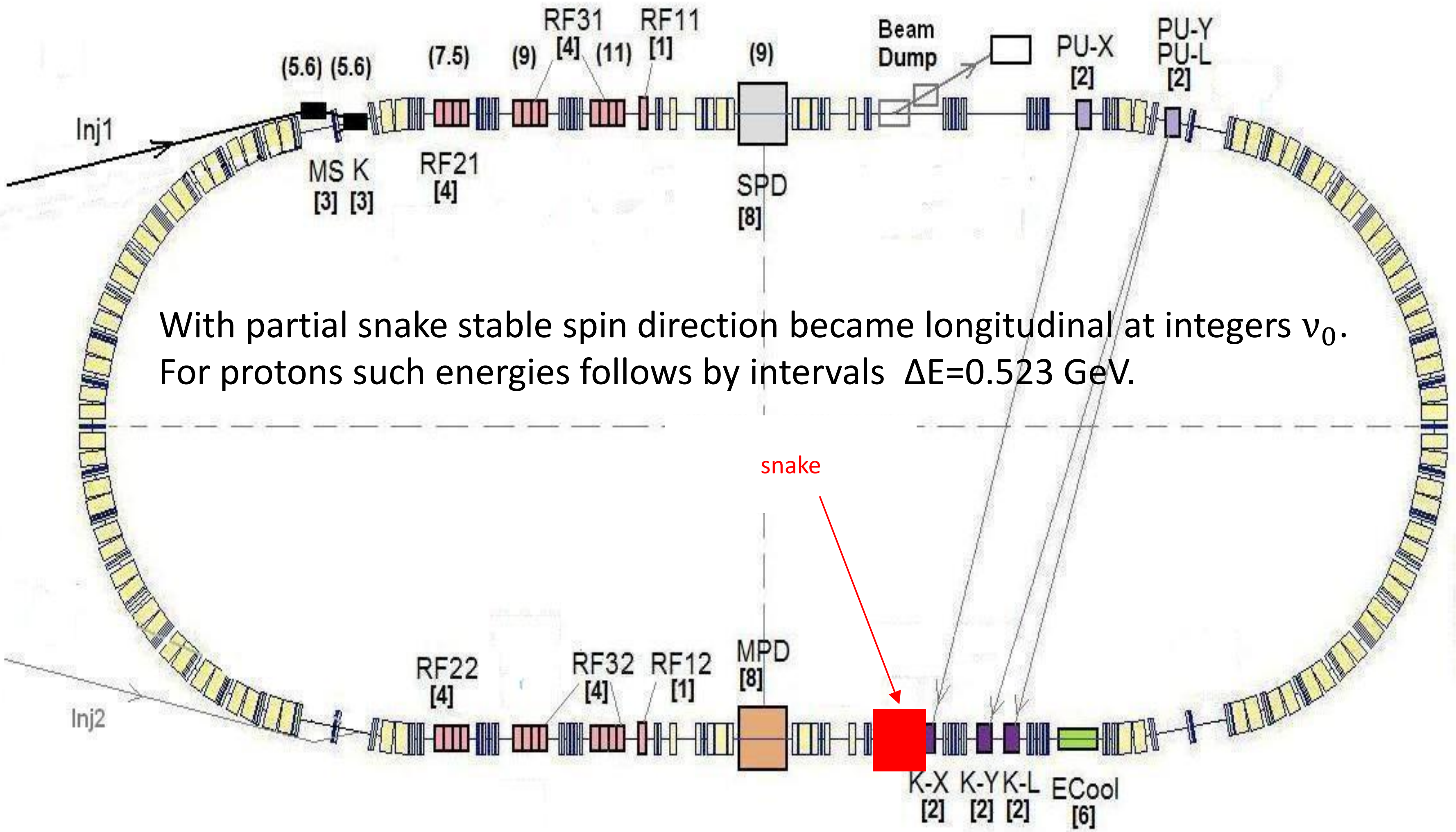
Spin tracking code EILMS written by S. Mane. Here it simulates energy ramp from 5 to 10 GeV in N=150 000 turns.

Coherent vertical oscillations are excited to produce the needed magnitude of the spin harmonic.

To cross the resonance $\nu_0 = 16 - Q_y$ we propose Q-jump: ΔQ_y=0.1

Partial Siberian Snake for creation of longitudinal polarization of protons in NICA

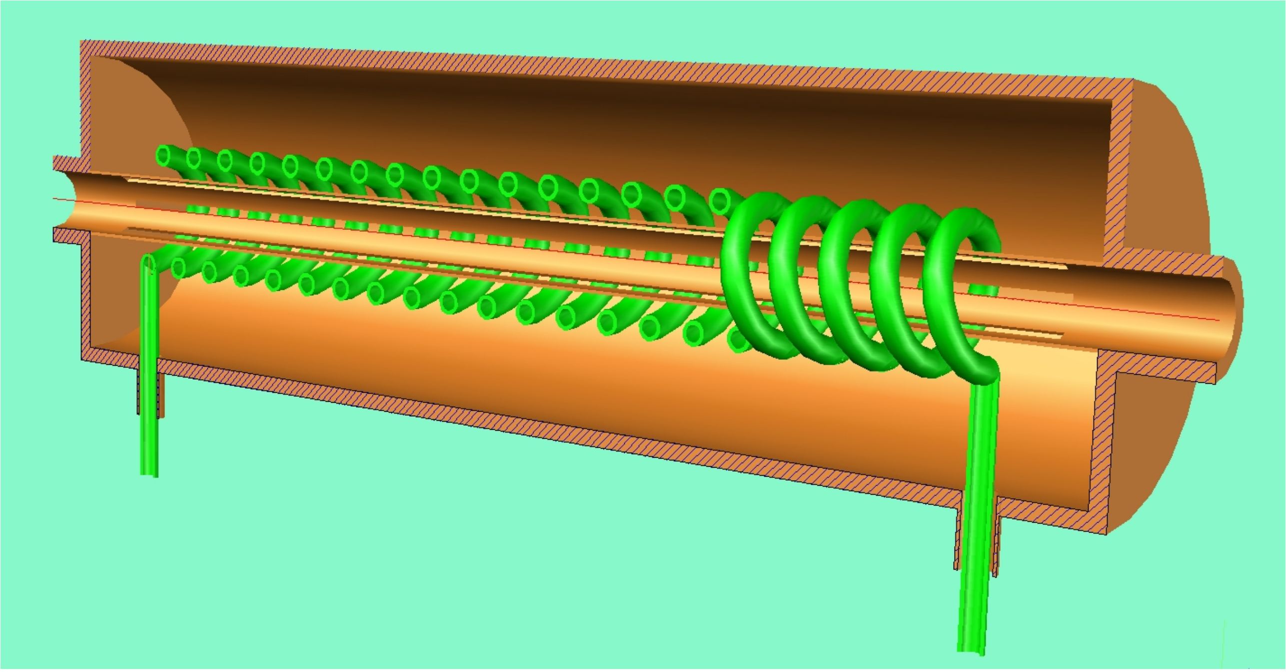
With partial snake stable spin direction became longitudinal at integers ν_0.
For protons such energies follows by intervals ΔE=0.523 GeV.



Au(+79) ion mode

Precession spin approach. Flipper device.

By strong enough RF-solenoid beam polarization could be brought adiabatically from the initial vertical orientation into the horizontal plane. For this trick the frequency of a "Flipper" is slowly swiped to a resonance, starting, say, at 10 bands from the resonance value.
As a result, we can lock the spin precession phase to a Flipper phase. Realization of the Flipper idea was successfully demonstrated in our Experiment-1987 for comparison of anomalous magnetic moments of positrons and electrons (I.B.Vasserman et al, Phys.Lett.B, v.198, n2, 1987,p.302-306).
For deuterons the longitudinal magnetic field integral is needed about: $Bl = 0.066\ \mathrm{T \cdot m}$. This corresponds to the resonance harmonic strength: $w_k = 10^{-4}$.
Strip line RF-dipole can be used instead of RF-solenoid, but then beam oscillates vertically.



The synchrotron modulation index $\xi = \nu_0 \sigma_\delta / Q_s$ is small for deuteron beam: ξ_d=0.5 and too high for protons: ξ_p=8.4. Therefore, only for deuterons the Flipper approach works.
For protons 10 times lower value of the energy spread is wanted. Electron cooling may provide $\sigma_\delta = 2 \cdot 10^{-4}$?

General scenario for experiments with polarized beams

1. Electron or/and stochastic cooling shall be used to get high enough luminosity.

2. Bunched operation assumes equal beams velocities.

3. Foreseen for NICA two coolers have maximal kinetic electrons energy 2.5 MeV. Then available maximal gamma-factors are: $\gamma_{max} = 5.9$.

4. Proton and deuteron beams with equal velocities have very different momenta and, so, cannot have the common final focus triplets. Bending fields for them differs by factor 2.

5. Beam separation scheme shall be modified in such a way that orbit splitting magnets are placed between triplets, not too far from the IP. Total separation angle of 75 mr seems is adequate for this.

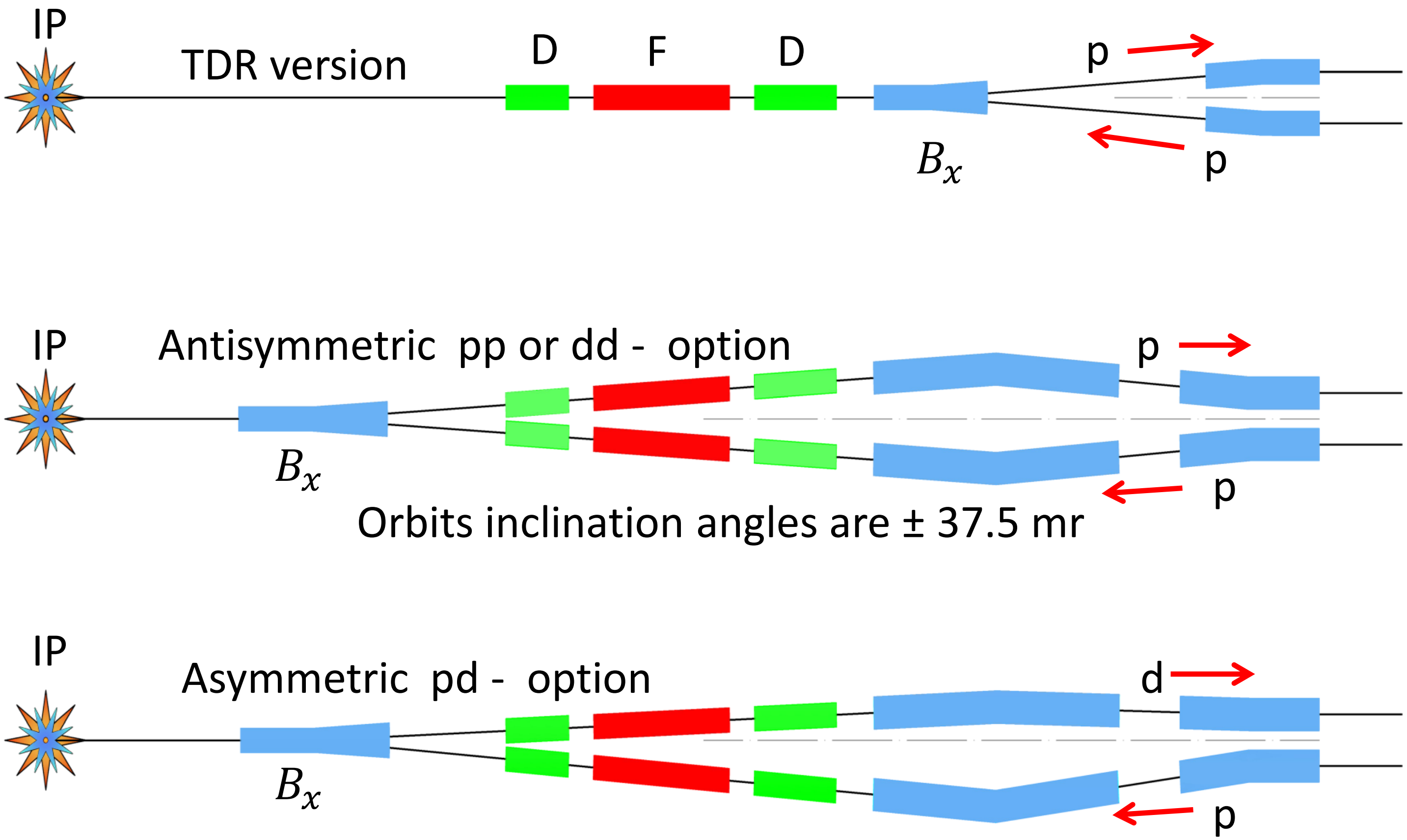
6. Screening of the detector solenoid field should be foreseen.

Collision energy limitation by the electron coolers energy

	pp	dd	pd	
E-Cooler Energy: T_e	2.5			*MeV*
Lorentz Factors: β, γ	β=0.98549386 γ=5.89236791			
Ion Kinetic Energies: T_1, T_2	4.59 , 4.59	9.18, 9.18	4.59, 9.18	*GeV*
Collision Energy: $\sqrt{s}$	11.06	22.10	15.66	*GeV*
Beam Rigidities: HR_1, HR_2	18.174, 18.174	36.33, 36.33	18.174, 36.33	*T·m*
Orbit Separation Angles	± 37.5	± 37.5	- 50, + 25	*mr*
Space-Charge limited Luminosity (Δν=0.1, ξ=0.01, N=$2.2\cdot10^{12}$, ε=$1\cdot10^{-5}$cm·r)	$8.5\cdot10^{30}$	$1.7\cdot10^{31}$	$8.5\cdot10^{30}$	$cm^{-2}s^{-1}$

Proposed new vertical separation scheme for different ions

Individual triplets of the final focus lenses open possibility to collide ions with different magnetic rigidity. In particular, protons and deuterons with equal gamma-factors!



In the asymmetric pd-option the horizontal field bends deuterons and protons by + 25 and - 50 mr, correspondingly. So, full block of two triplets is rotated in the clockwise direction by 12.5 mr relative to the symmetric setup.

Deuteron beam depolarization by δ-electrons

$\Delta\vec{n}=\gamma\frac{d\vec{n}}{d\gamma}\cdot\delta$ - jump $\vec{n}$ due to scattering on an electron

$$\frac{dP}{dt}=-\left\langle\dot{N}\cdot\frac{1}{2}(\Delta\vec{n})^2\right\rangle=-\left\langle\dot{N}\cdot\frac{1}{2}\left(\gamma\frac{d\vec{n}}{d\gamma}\right)^2\cdot\frac{d\delta^2}{dt}\right\rangle$$

$$\left|\gamma\frac{d\vec{n}}{d\gamma}\right|=\frac{\nu_0}{w}$$

$\tau^{-1}=4\pi c\rho Z r_d r_e\frac{m_e}{M_d}\frac{{\nu_0}^2}{w^2}$ $\rho=\rho_0\frac{p}{p_0}$ - residual gas density

For gas pressure $p=10^{-10}$ mbar $\tau=4\cdot10^5$ s

Space-Charge and Beam-Beam limited luminosity

For bunched beams, assuming $\beta^* = \sigma_s$ (β^* is beta-function at IP):

$$\Delta\nu = \frac{Z^2}{A}\frac{r_p}{\varepsilon}\frac{N_b}{4\pi\gamma^3\beta^2}\frac{\sqrt{2\pi}R}{\sigma_s} \qquad \xi = \frac{Z^2}{A}\frac{r_p N_b}{4\pi\gamma\beta\varepsilon}$$

$$L_{SC} = \Delta\nu\frac{A}{Z^2}n_b N_b\frac{\gamma^3\beta^2}{\sqrt{2\pi}R r_p}f_0 \qquad L_{BB} = \xi\frac{A}{Z^2}n_b N_b\frac{\gamma\beta}{r_p\sigma_s}f_0$$

Here SC denotes Space-Charge, and BB denotes – Beam-Beam

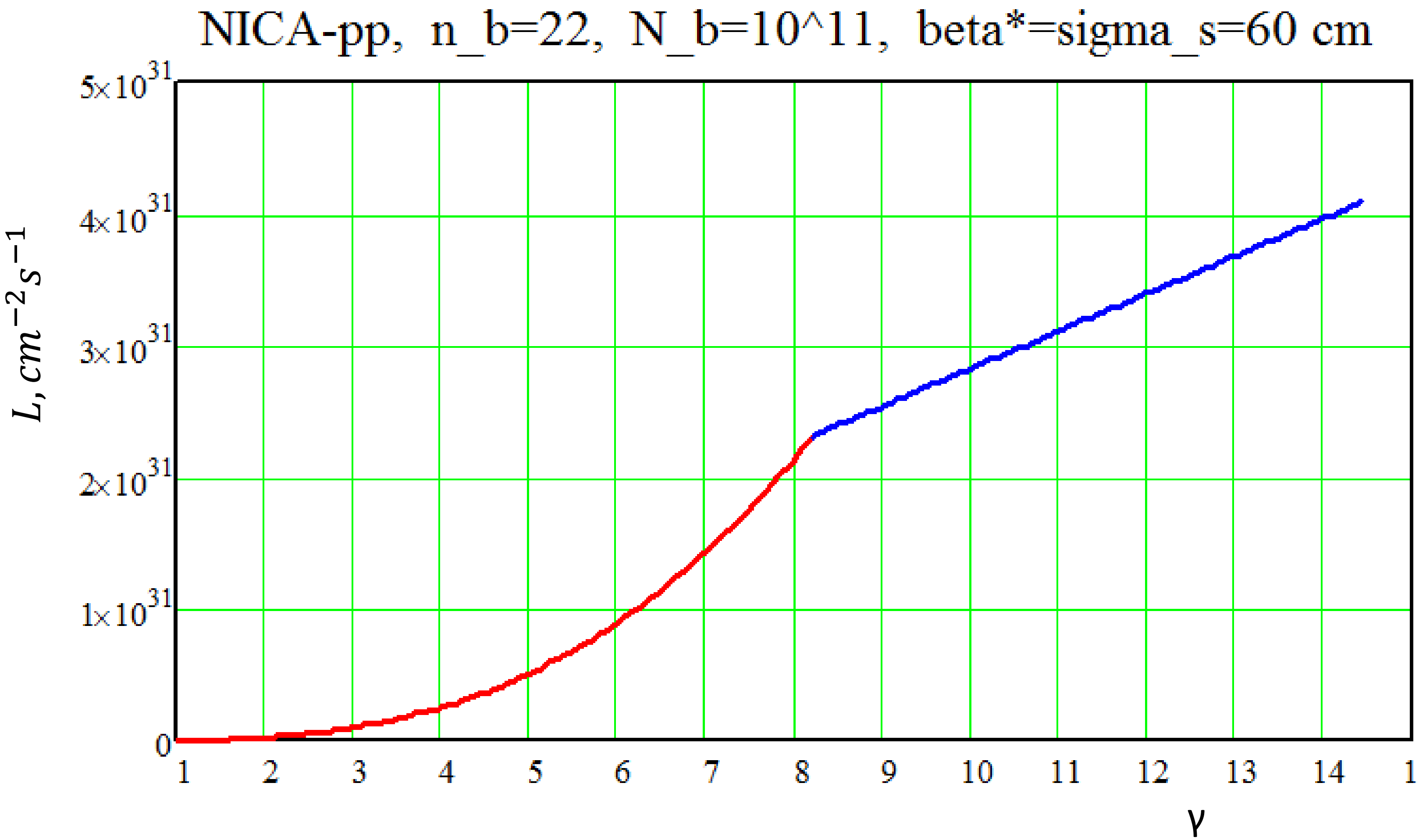
$$\varepsilon = \frac{\sigma^2}{\beta} \quad - \quad \text{Horizontal/ Vertical Emittance}$$

Strong energy dependence of space-charge limited luminosity $L_{SC} \sim \gamma^3\beta^2$ dictates operation at the highest attainable beam energy!

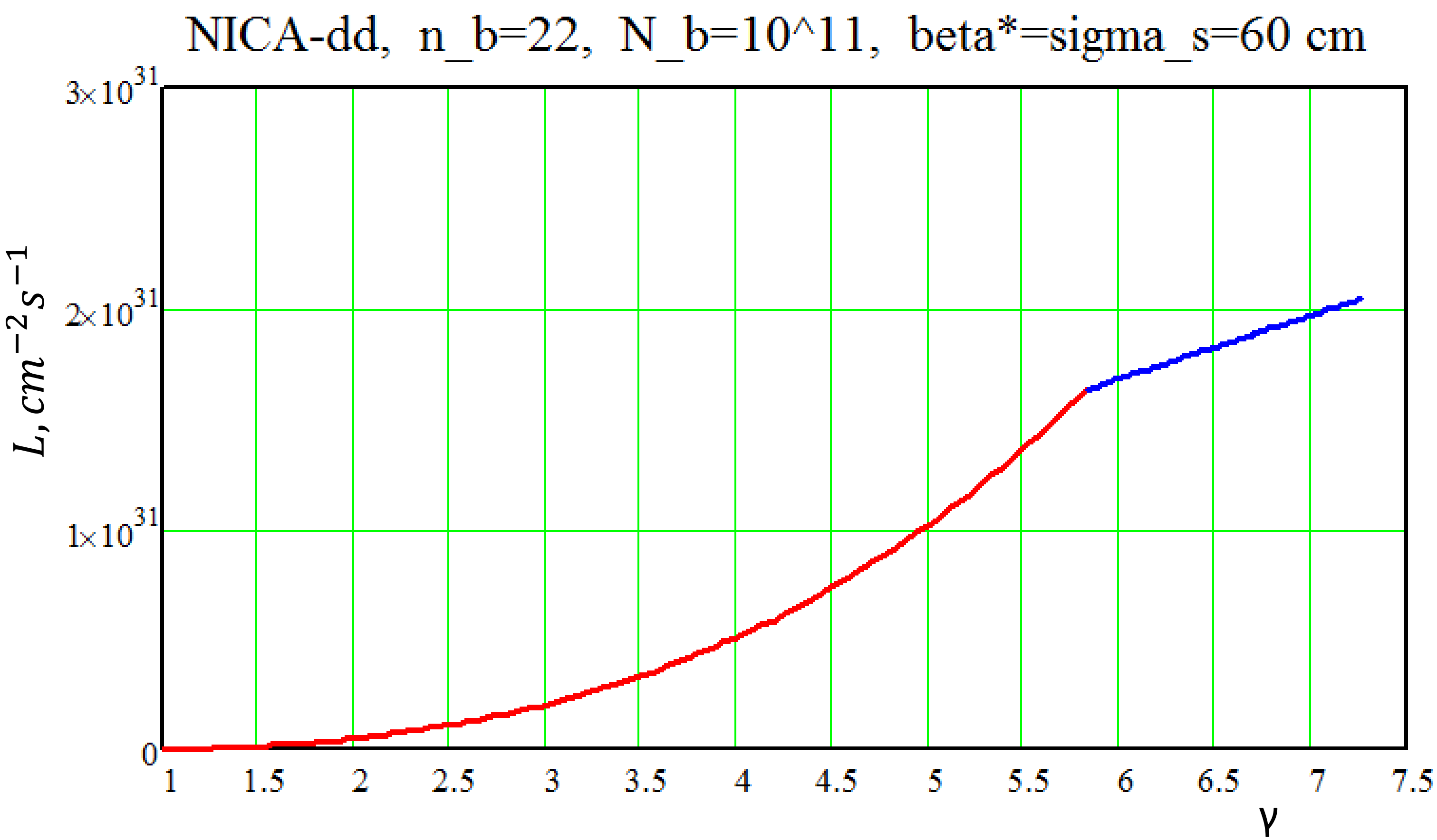
Another remarkable feature: luminosity is proportional to full number of particles in n_b bunches independently of what is the population N_b in a bunch: $\mathrm{L} \sim n_b N_b$.

For beam energies limited by the planned electron cooling system the SC and the BB limitations are more or less equal, see next slides.

Space-Charge and Beam-Beam limited pp-luminosity



Space-Charge and Beam-Beam limited dd-luminosity



Conclusions

1. Polarized proton and deuterons beams will be injected into the NICA rings being vertically polarized.
2. The zero longitudinal field integral should be provided. In both detectors !
3. The longitudinal polarization for protons will be provided by switching on of the weak Partial Snake (3-6 T·m) at magic energies, which are spaced by 0.523 GeV/beam.
4. The longitudinal polarization for deuterons will be provided by switching on of the RF-flipper operated on the resonance with the free spin precession frequency. Such forced spin precession is stable during many hours for the field integral of a flipper about 0.05 T·m.
5. Our estimations show that the needed RF-power is about 10 kW.
6. Spin precession mode of operation helps very much to cancel many systematic effects.
7. The Partial Snake and the Flipper device don't need too large space in NICA rings and are relatively cheap.
8. If energy spread of the proton beam could be brought down below the level $\sigma=4\cdot10^{-4}$, then the precession mode could be implemented also for protons similar to deuterons.