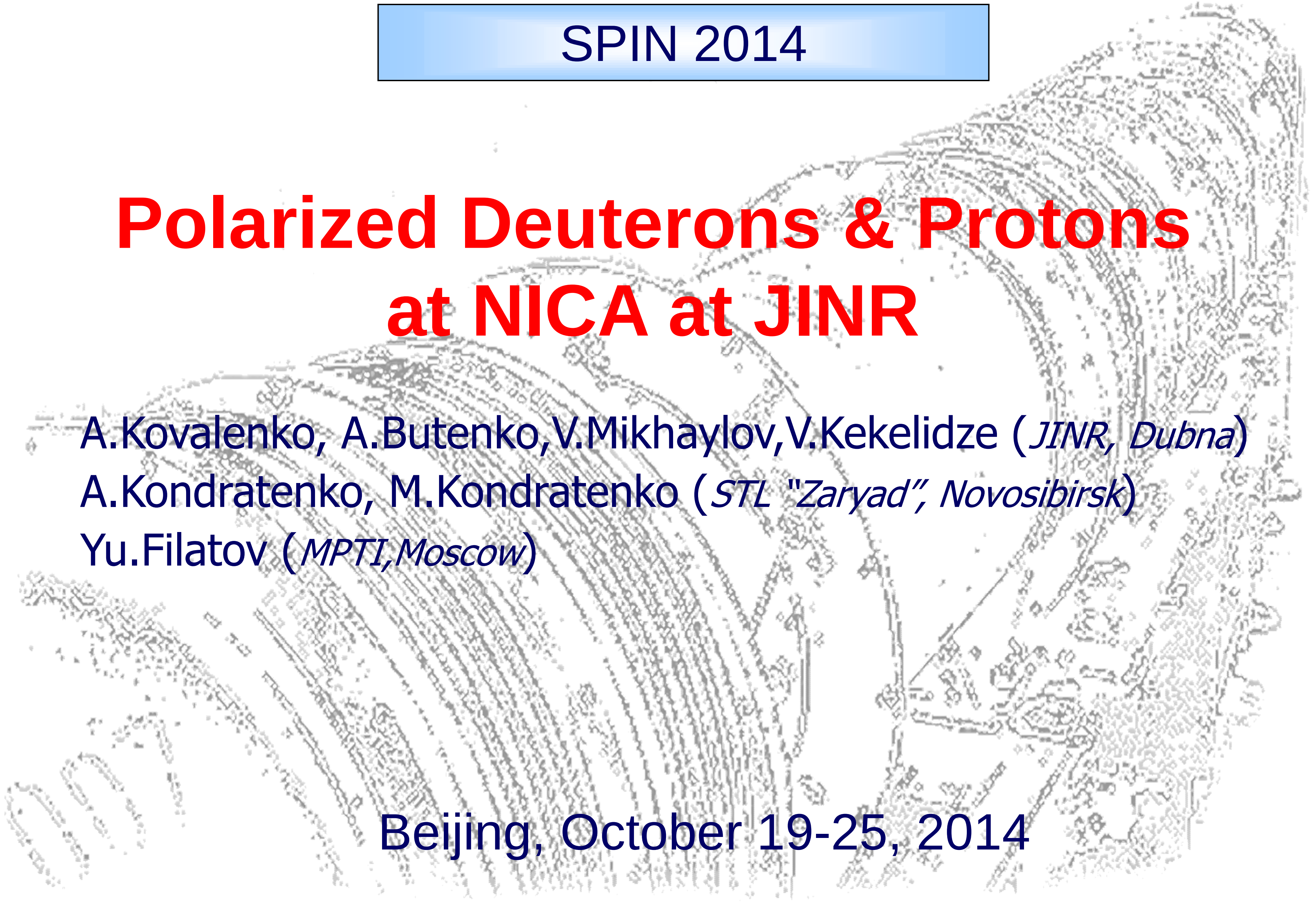
SPIN 2014



Polarized Deuterons & Protons at NICA at JINR

A.Kovalenko, A.Butenko,V.Mikhaylov,V.Kekelidze (*JINR, Dubna*)
A.Kondratenko, M.Kondratenko (*STL "Zaryad", Novosibirsk*)
Yu.Filatov (*MPTI,Moscow*)

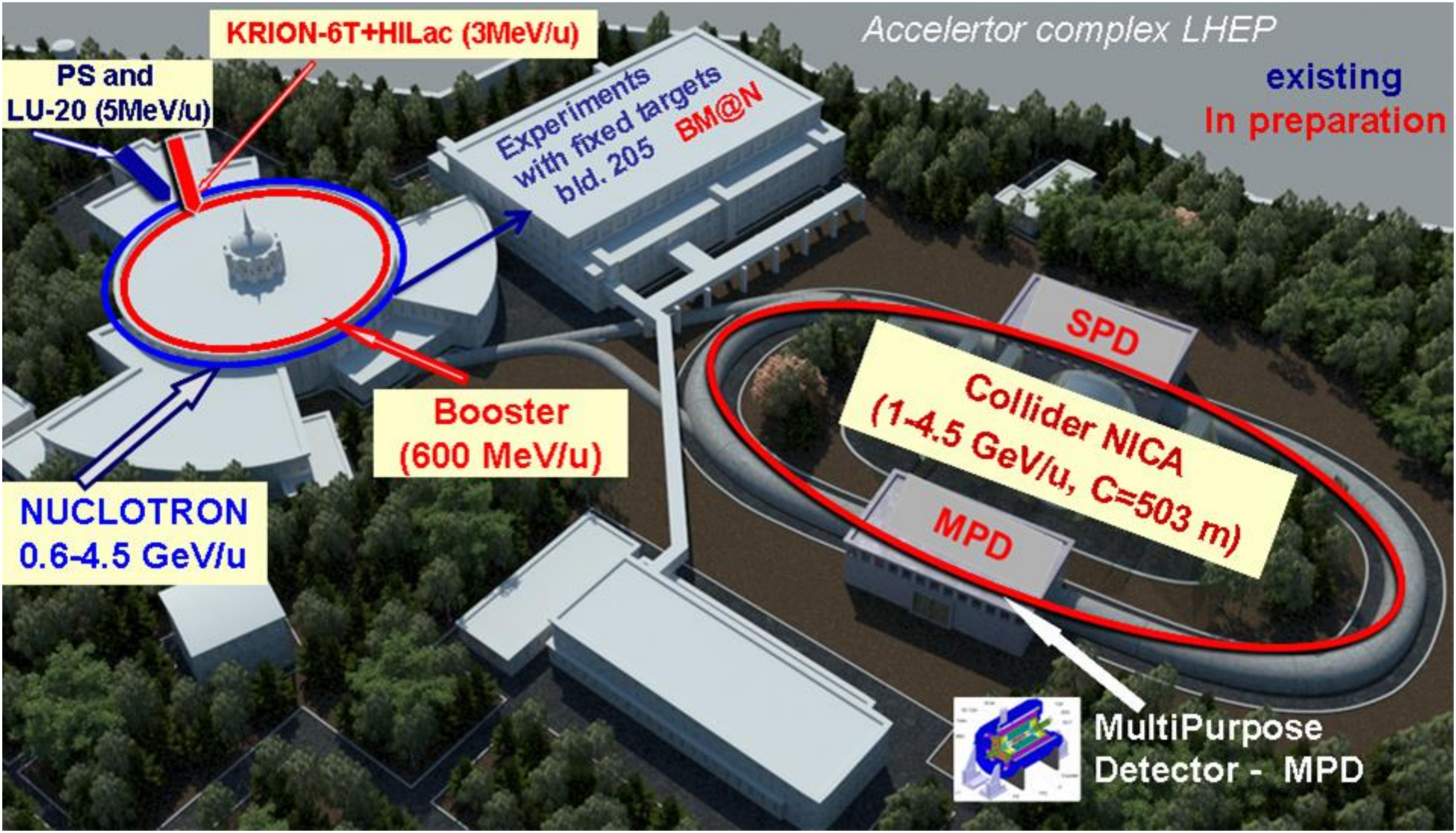
Beijing, October 19-25, 2014

OUTLINE

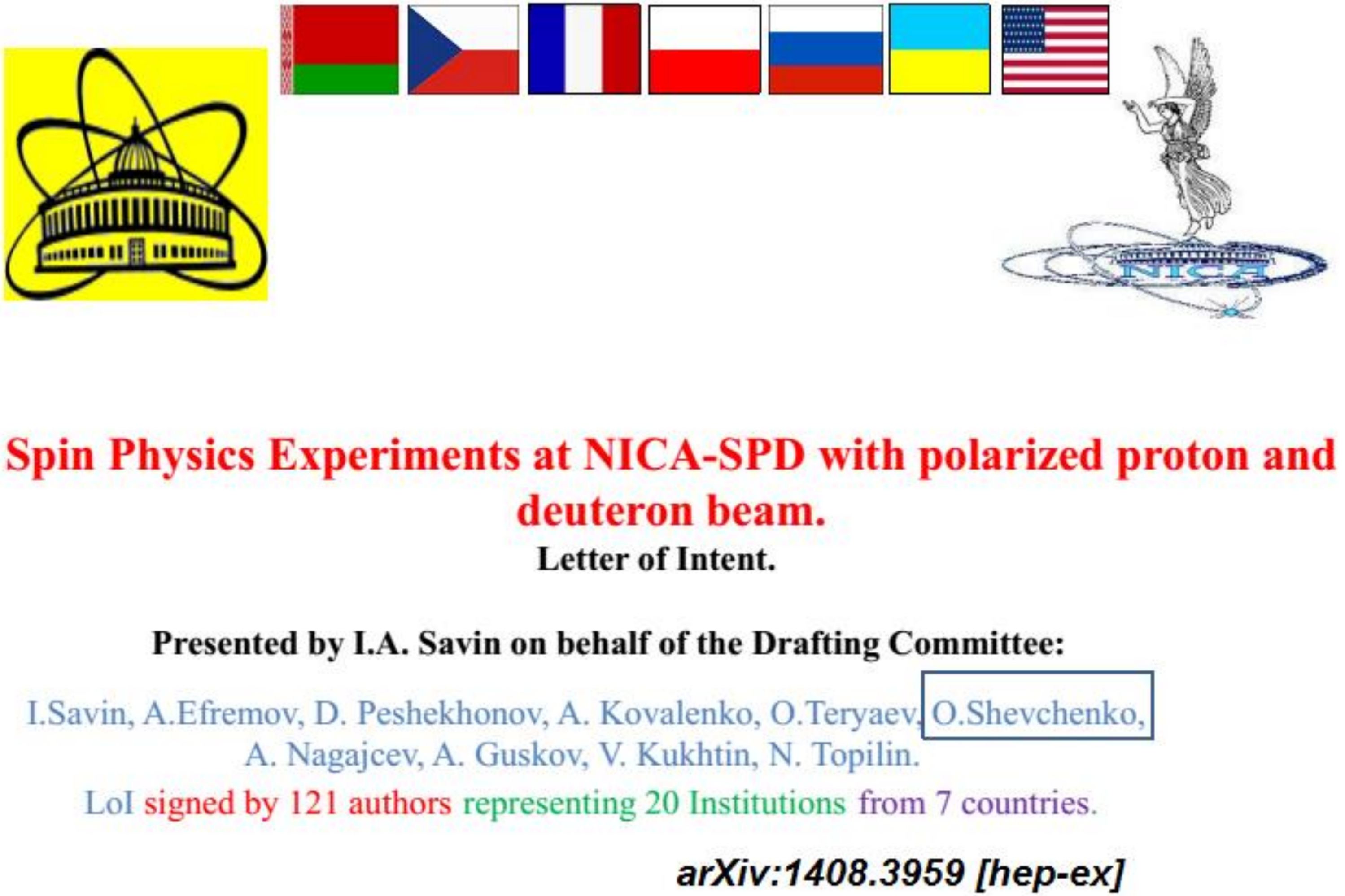
- NICA@JINR: General comments
- NICA layout in polarized mode
- Polarization control schemes
- Polarized pp: expected luminosity
- Outlook

NICA place near DUBNA town

NICA complex at Laboratory site



NICA-SPIN program approved by JINR PAC



Spin Physics Experiments at NICA-SPD with polarized proton and deuteron beam.

Letter of Intent.

Presented by I.A. Savin on behalf of the Drafting Committee:

I.Savin, A.Efremov, D. Peshekhonov, A. Kovalenko, O.Teryaev, O.Shevchenko,
A. Nagajcev, A. Guskov, V. Kukhtin, N. Topilin.

LoI signed by 121 authors representing 20 Institutions from 7 countries.

arXiv:1408.3959 [hep-ex]

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Spin Physics Experiments at NICA-SPD with polarized proton and deuteron beam.

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arXiv:1408.3959 [hep-ex]

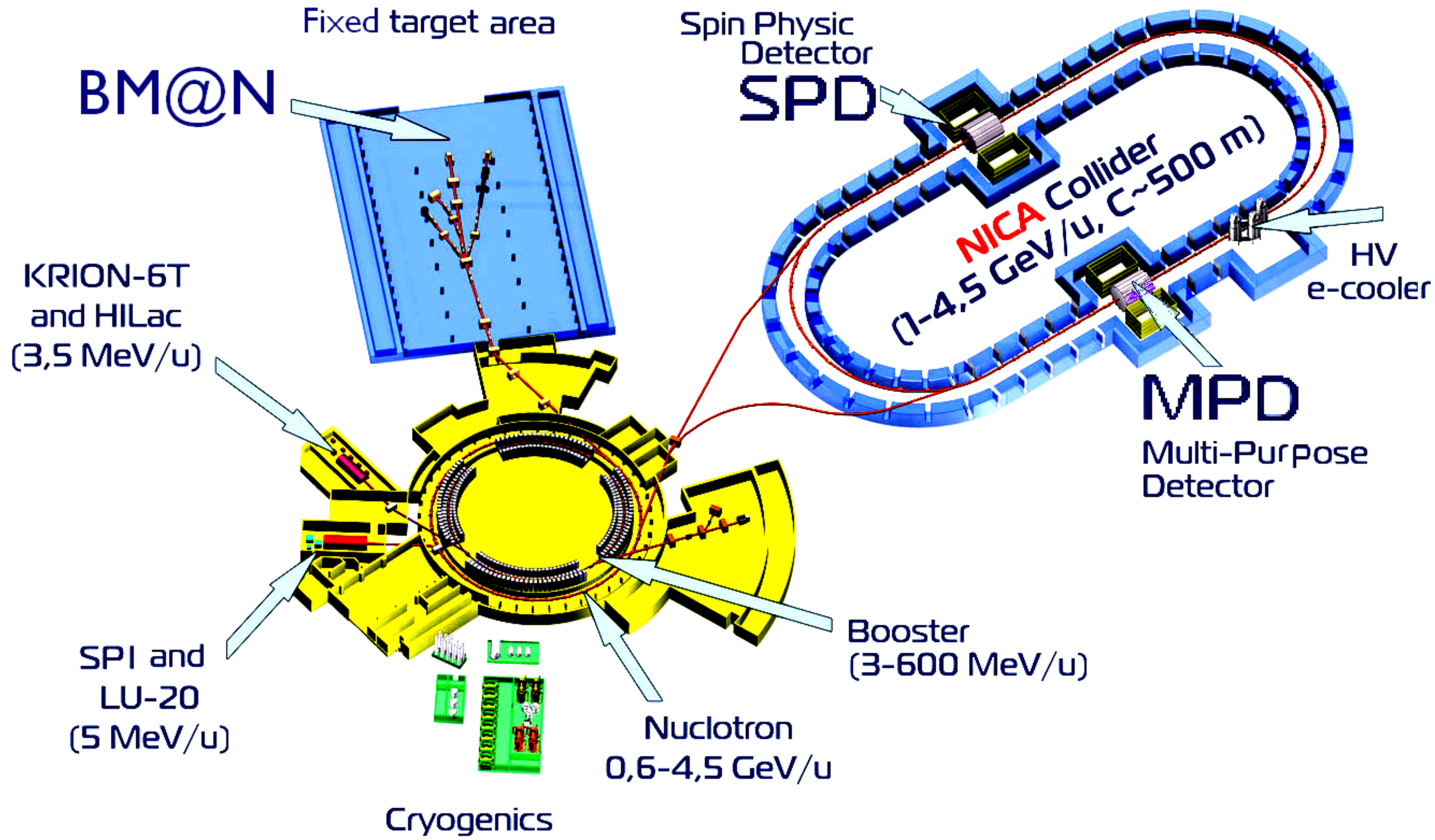
Present status: CDR preparation

Requirements to the facility in polarized mode

- ☐ **polarized and non-polarized p-; d–collisions**
- ☐ **p↑p↑(p)** at $\sqrt{s_{pp}}$ **= 12 ÷ 27 GeV** (5 ÷ 12.6 GeV kinetic energy)
- ☐ **d↑d↑(d)** at $\sqrt{s_{NN}}$ **= 4 ÷ 13 GeV** (2 ÷ 5.5 GeV/u kinetic energy)
- ☐ $\mathbf{L_{average}} \approx 1\cdot10E32\ cm^{-2}s^{-1}$ (at $\sqrt{s_{pp}} \geq 27$ GeV)
- ☐ sufficient lifetime and degree of polarization
- ☐ longitudinal and transverse polarization in MPD/SPD
- ☐ asymmetric collision mode, pd, should be possible

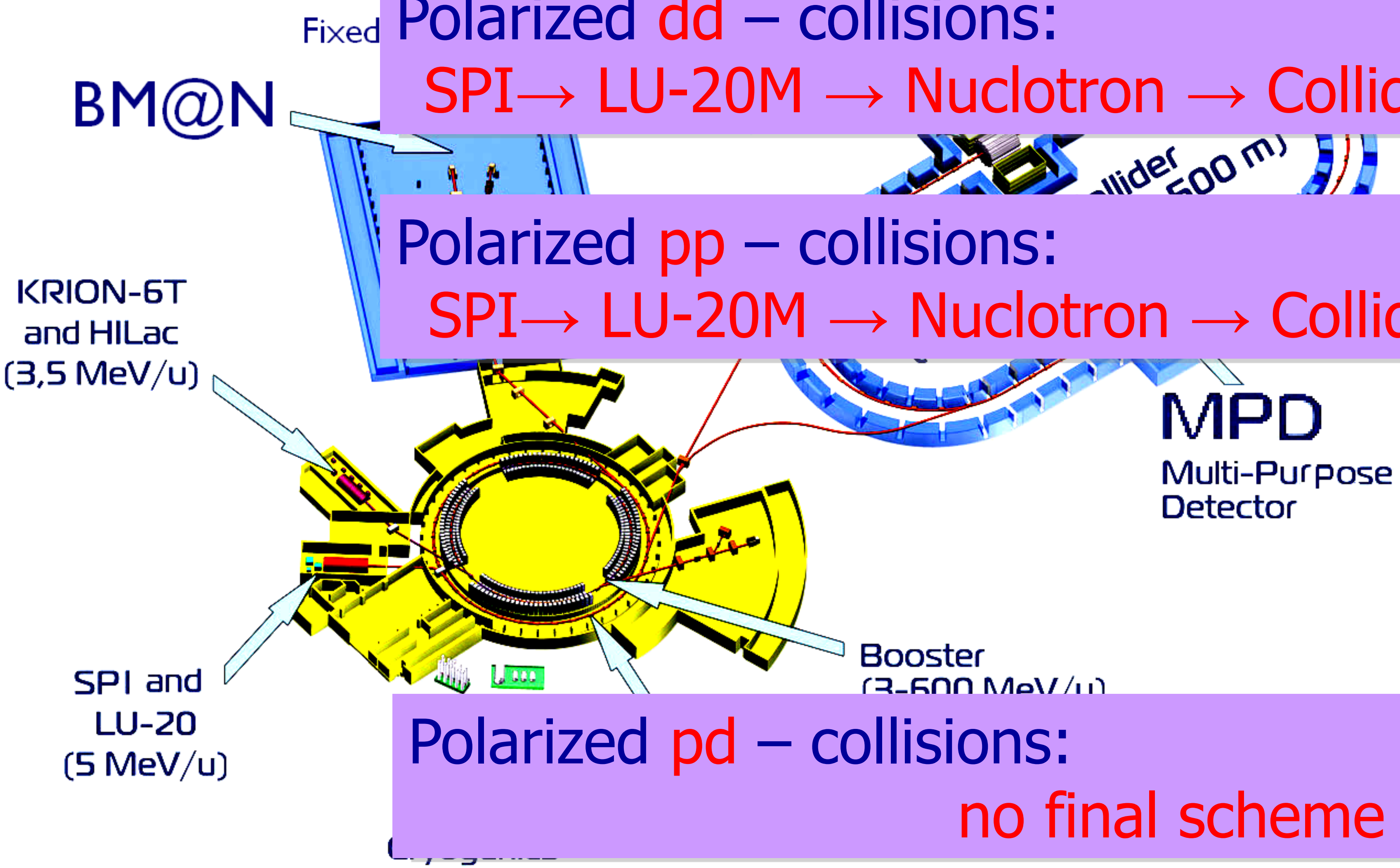
Superconducting accelerator complex NICA

(Nuclotron based Ion Collider fAcility)



A.D.Kovalenko et al

NICA operation in Polarized Mode (1)



Polarized dd – collisions:
SPI→ LU-20M → Nuclotron → Collider

Polarized pp – collisions:
SPI→ LU-20M → Nuclotron → Collider

Polarized pd – collisions:
no final scheme yet

NICA operation in Polarized Mode (2)

- d↑- accelerated at the Synchrophasotron in 1986; at the Nuclotron in 2002. No dangerous spin resonances up to 5.6 GeV/u.
- p↑- never been accelerated at the LHEP facility.

The problem with p↑ (at Nuclotron or NICA booster) – numerous spin resonances.

NICA operation in Polarized Mode (2)

- d↑- accelerated at the Synchrophasotron in 1986; at the Nuclotron in 2002. No dangerous spin resonances up to 5.6 GeV/u.
- p↑- never been accelerated at the LHEP facility.

The problem with p↑ (at Nuclotron or NICA booster) – numerous spin resonances.

Solution: p↑ acceleration up to 5-6 GeV at Nuclotron with dynamic solenoid Siberian snake → transfer to collider rings → storage, stochastic cooling and further acceleration up to 13.5 GeV in the collider rings.

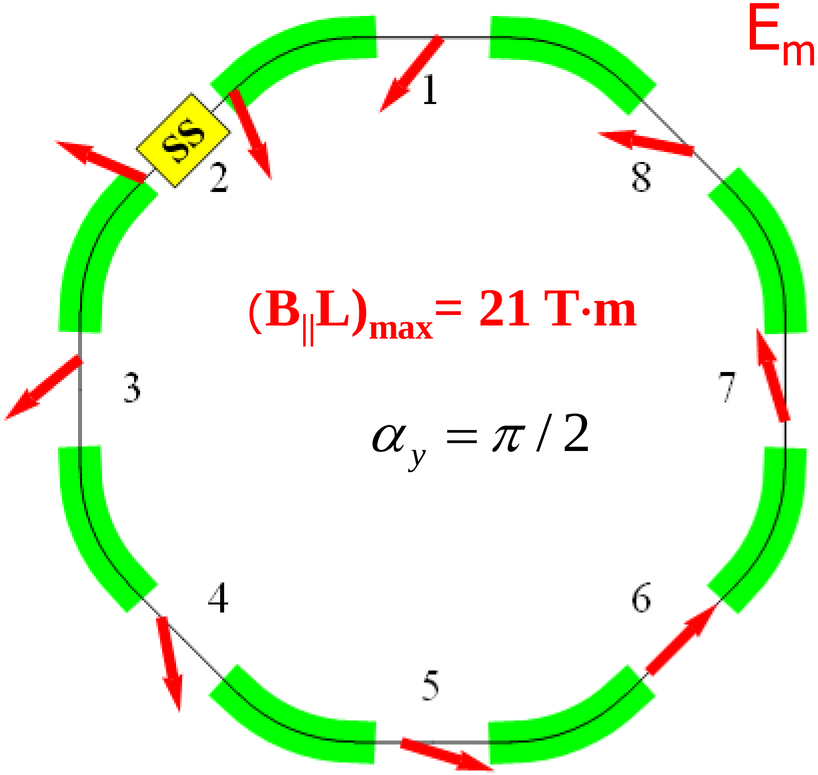
Polarized Protons in Nuclotron (1)

Dynamic Solenoid Siberian Snake

Full Siberian Snake

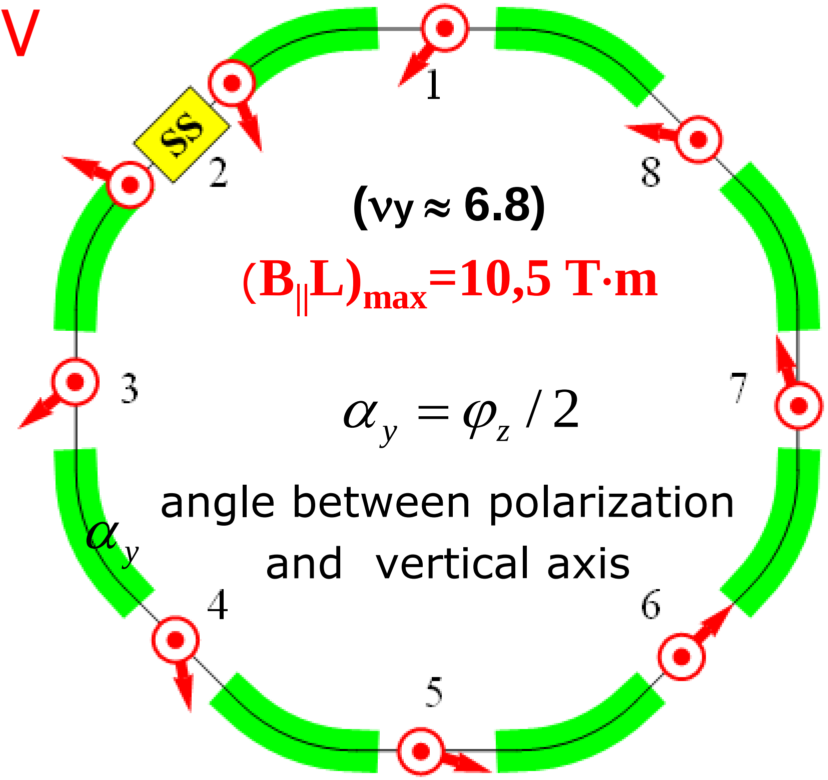
Partial Siberian Snake

$E_{max} = 6$ GeV



$(B_{||}L)_{max} = 21$ T·m

$$\alpha_y = \pi / 2$$



($\nu_y \approx 6.8$)

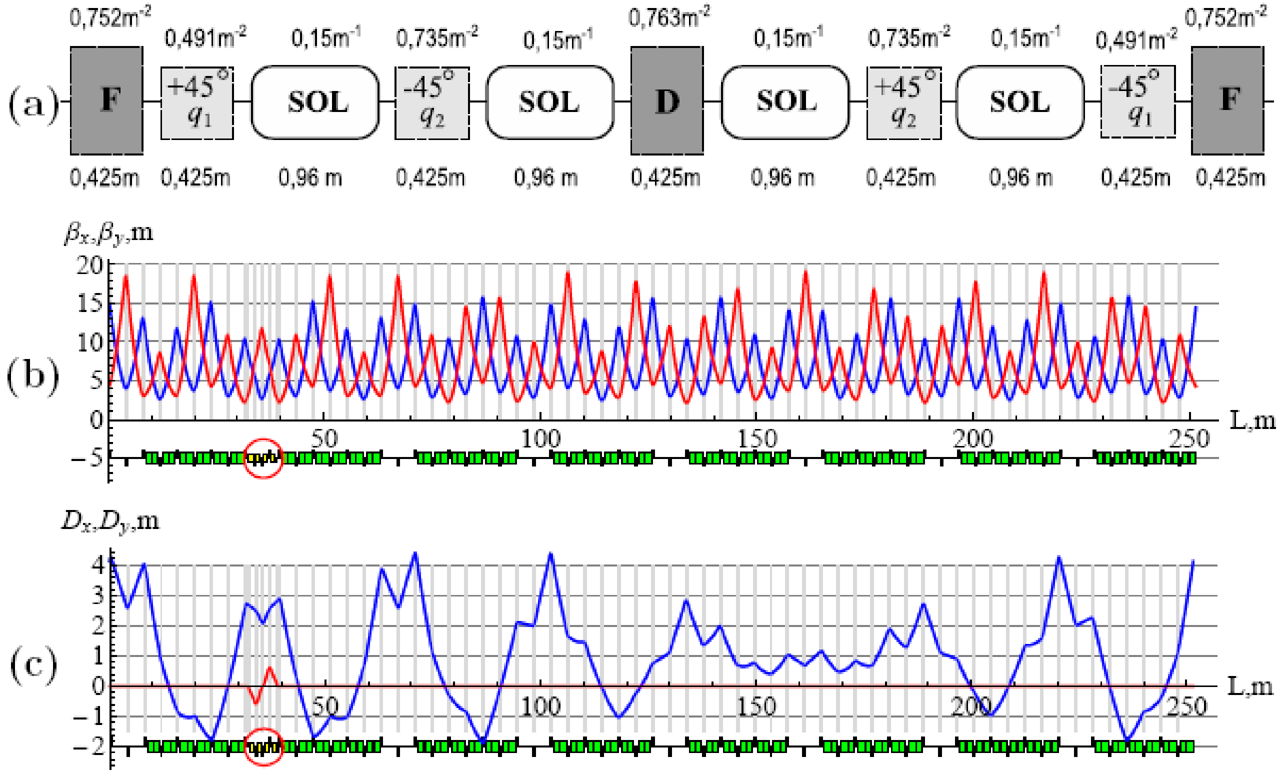
$(B_{||}L)_{max} = 10{,}5$ T·m

$$\alpha_y = \varphi_z / 2$$

angle between polarization and vertical axis

Polarized Protons in Nuclotron (2)

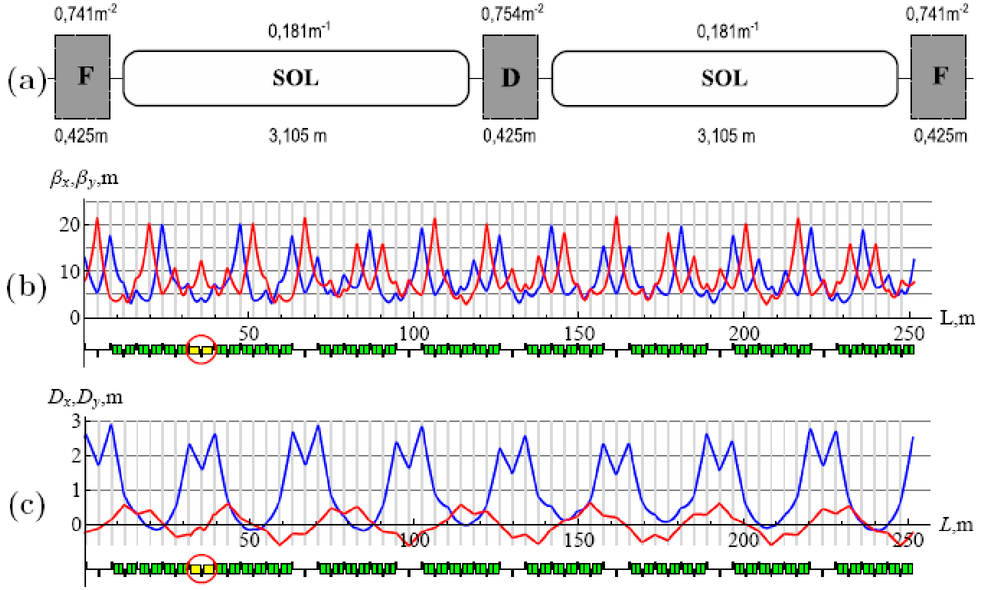
The Snake: *Previous scheme of the insertion*



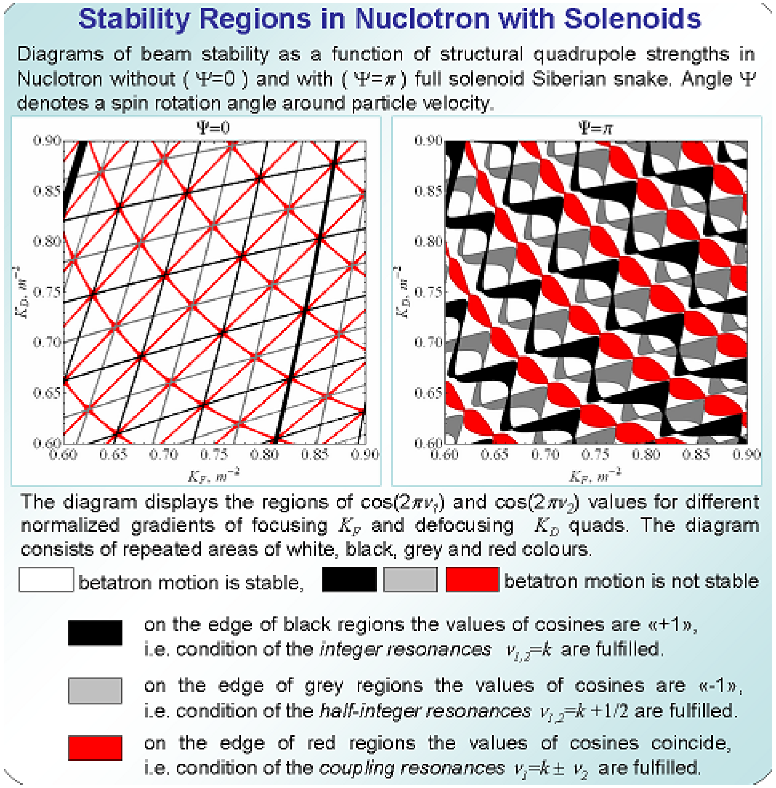
DSPIN, 2013, Dubna, October 2013

Polarized Protons in Nuclotron (3)

The Snake: *insertion without compensation of the betatron tunes couplings*



Stable motion can be provided by proper choice of the tunes



Stability Regions in Nuclotron with Solenoids

Diagrams of beam stability as a function of structural quadrupole strengths in Nuclotron without (Ψ=0) and with ($\Psi=\pi$) full solenoid Siberian snake. Angle Ψ denotes a spin rotation angle around particle velocity.

The diagram displays the regions of cos($2\pi\nu_1$) and cos($2\pi\nu_2$) values for different normalized gradients of focusing K_F and defocusing K_D quads. The diagram consists of repeated areas of white, black, grey and red colours.

⬜ betatron motion is stable, ⬛ ▨ 🟥 betatron motion is not stable

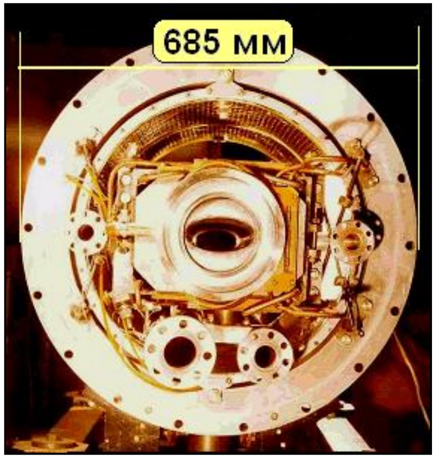
⬛ on the edge of black regions the values of cosines are «+1», i.e. condition of the *integer resonances* $\nu_{1,2}=k$ are fulfilled.

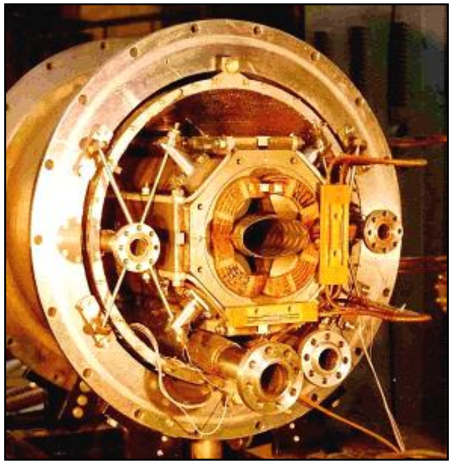
▨ on the edge of grey regions the values of cosines are «-1», i.e. condition of the *half-integer resonances* $\nu_{1,2}=k+1/2$ are fulfilled.

🟥 on the edge of red regions the values of cosines coincide, i.e. condition of the *coupling resonances* $\nu_1=k\pm\nu_2$ are fulfilled.

IPAC2014 , Dresden, June 2014

Polarized Protons in Nuclotron (5)



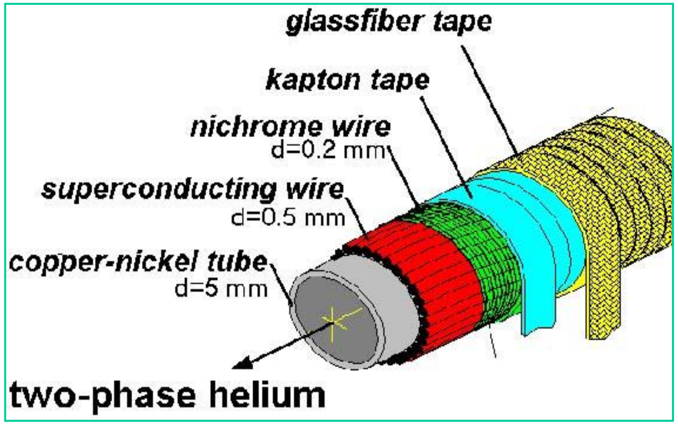


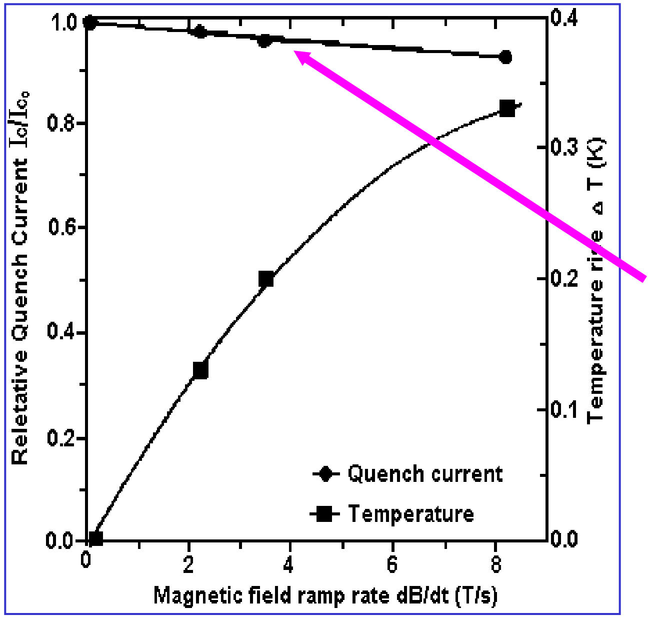
Critical current of the improved Nuclotron magnets at B = 2 T, dB/dt = 4 T/s, f = 1.0 Hz exceed 8000 A.

Polarized Protons in Nuclotron (6)

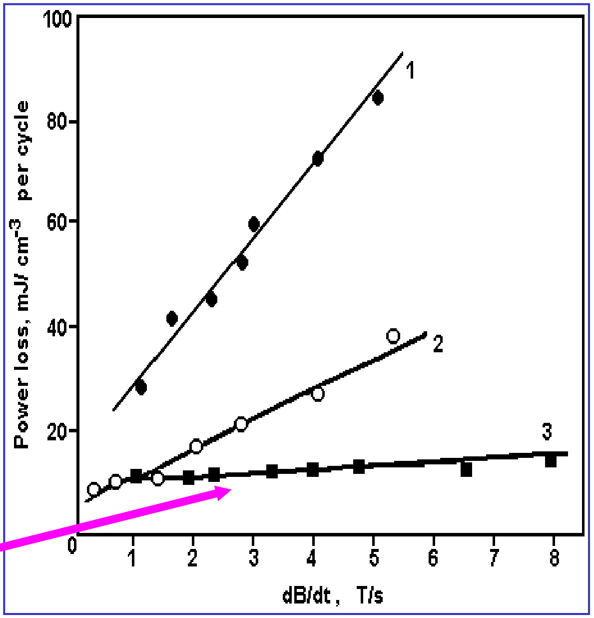
The Dubna hollow SC cable:

the strands don’t soldered to the tube but pressed with NiCr wire wound.



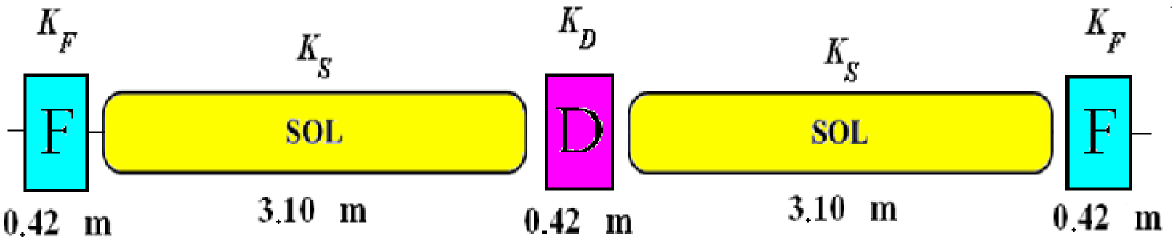


Weak degradation of critical current at fast ramp (~ 5 % @ dB/dt = 4 T/s)



Weak dependence of the eddy current loss on the magnetic field ramp (3)

Polarized Protons in Nuclotron (4)



Snake solenoid parameters:

- Cable outer diam.(with insulations) – 9 mm
- Number of turns per meter – 111
- Solenoid inner diameter – 100 mm
- Number of layers - 2

- Magnetic field (specified) – 3.387 T (full snake); 1.694 T (half snake)
- Maximum supply current, – 12.0 kA 6.0 kA
- Stored energy per section – 278 kJ 69.6 kJ

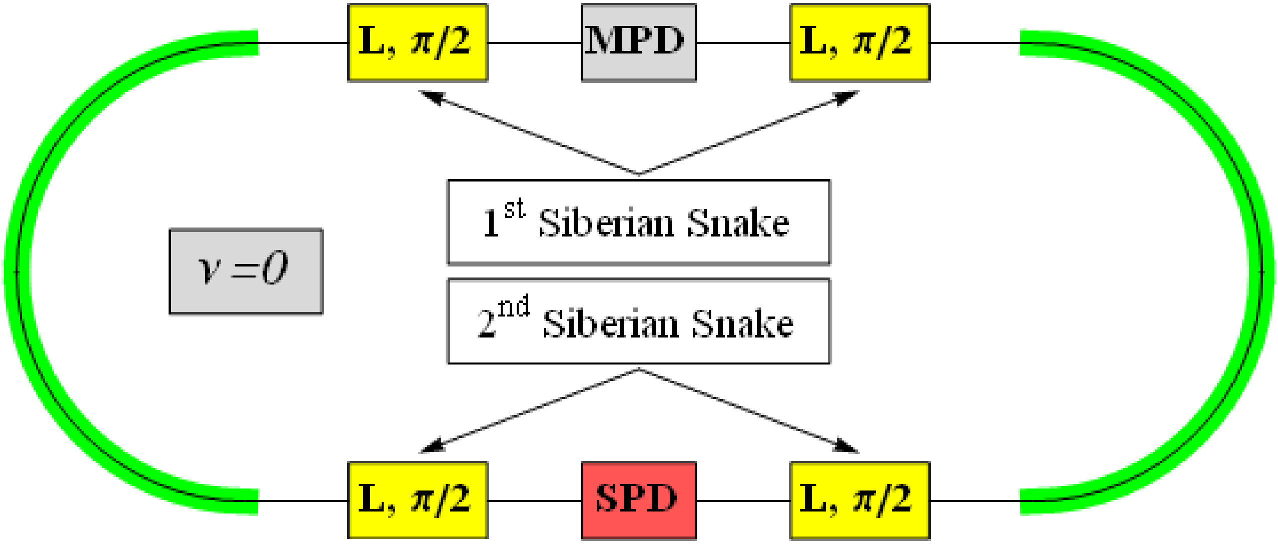
Polarized Protons in Nuclotron (7)

- Technical design of the solenoid model will be started in 2015.

- The further steps – in accordance with general NICA-SPIN program.

Polarization control scheme in the Collider with spin tune $\nu = 0$

Solenoid-based Siberian Snake at particle momentum:



p=(2.5÷13)GeV/c

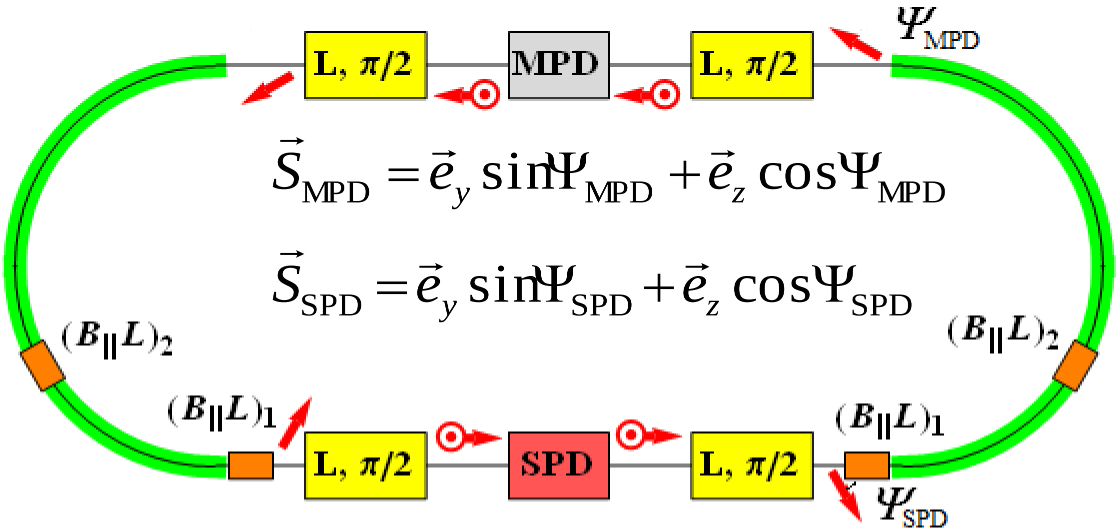
protons:

$(B_{||}L)_{max} = 4\times(5\div25)$ T·m

deuterons:

$(B_{||}L)_{max} = 4\times(15\div80)$ T·m

Polarization control in the Collider by means of small longitudinal field integrals



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

$$\vec{S}_{SPD} = \vec{e}_y \sin\Psi_{SPD} + \vec{e}_z \cos\Psi_{SPD}$$

$$\varphi_{z1} = \pi\nu \frac{\sin(\varphi_y - \Psi_{SPD})}{\sin\varphi_y}$$

$$\varphi_{z2} = \pi\nu \frac{\sin\Psi_{SPD}}{\sin\varphi_y}$$

$$\Psi_{MPD} = \gamma G\pi + \Psi_{SPD}$$

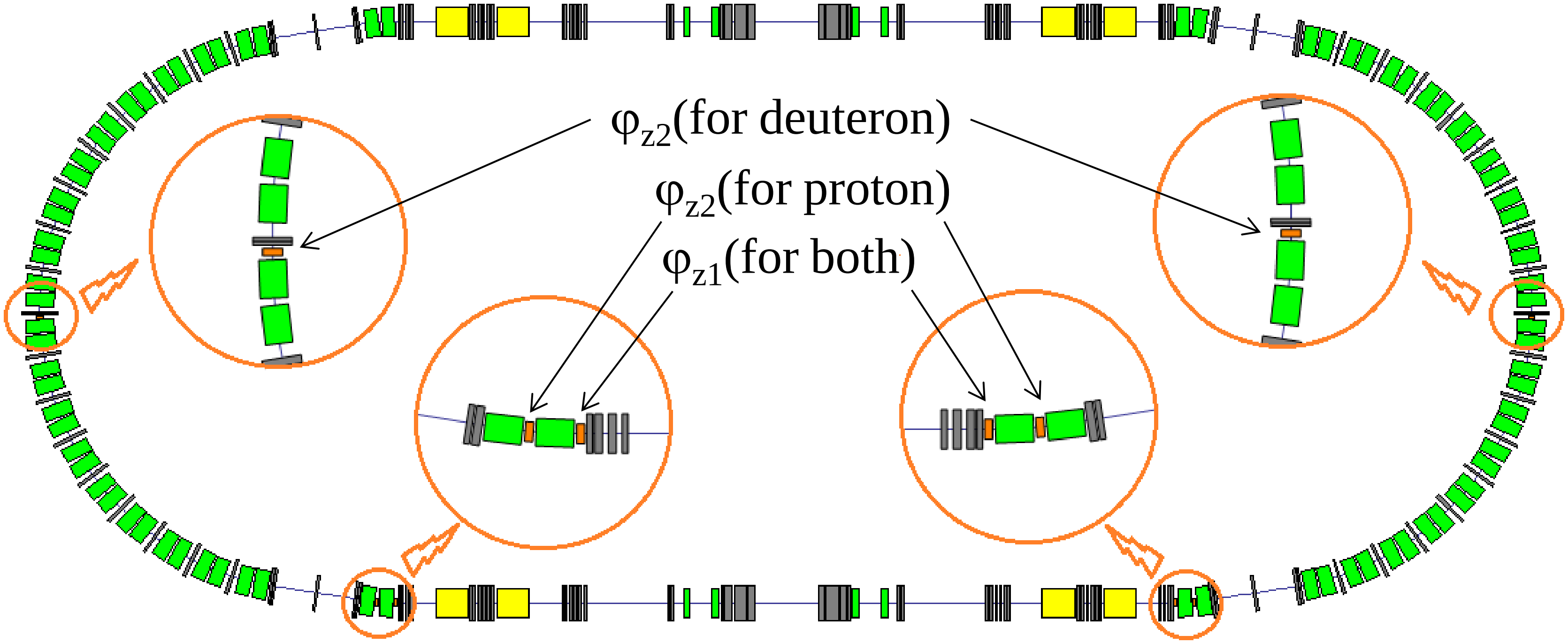
$\varphi_{zi} = (1+G)(B_{||}L)_i / B\rho$ - the spin rotation angles in the solenoids

$\varphi_y = \gamma\, G\alpha$ - the spin rotation angle between weak solenoids

α - the orbit rotation angle between the weak solenoids

Ψ_{SPD}, Ψ_{MPD} - the angles between the polarization and velocity directions in SPD and MPD detectors

Polarization control scheme for p and d in NICA collider (1)



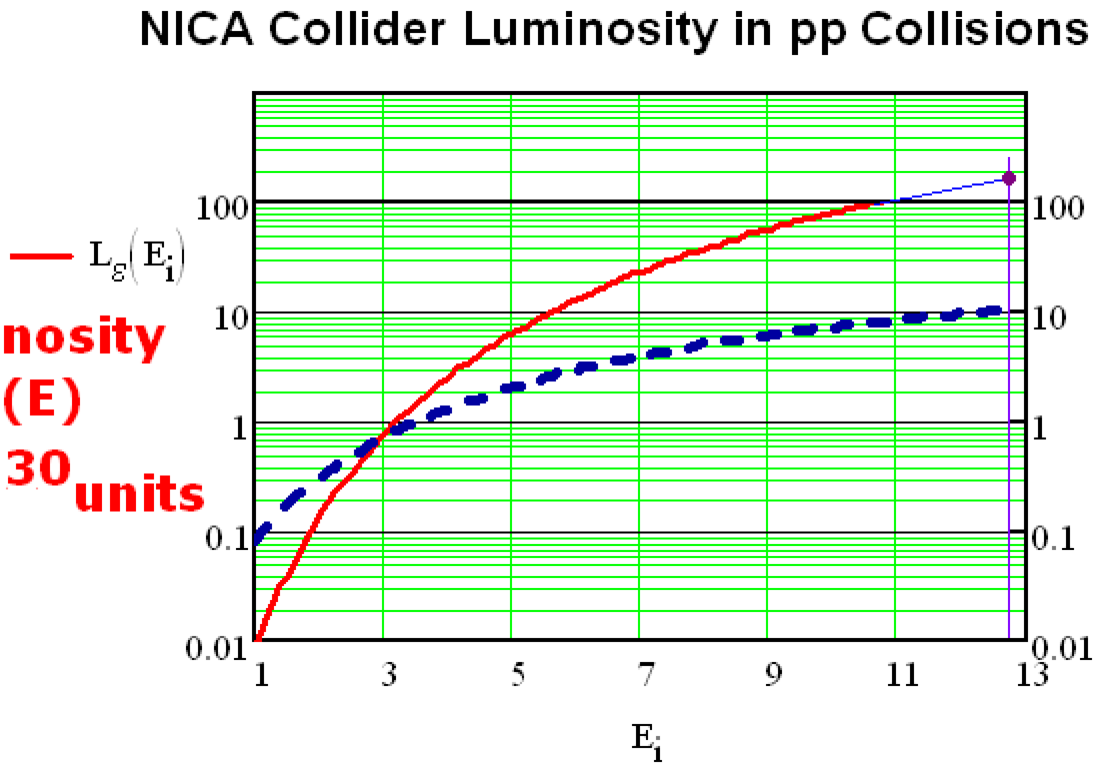
	number	B_{max}, T	L, m	BL, T·m
Main tune shifts solenoid	8	7,3	5,5	0÷40
Weak solenoid for polarization control (red)	6	1,5	0,4	0÷0,6

Polarization control scheme for p and d in NICA collider (2)

- The proposed scheme is suitable for any type of the particles. Necessary manipulations are provided without re-installations of the equipment at the magnetic system.

- The scheme provides the desired polarization direction in the both IP's (MPD and SPD detectors), and gives also a possibility of simple decision the problems of polarization matching at injection and polarimetery

NICA pp-collisions peak luminosity



Luminosity L(E) in 10^{30} units

Proton energy E in GeV

Lpeak ≈

1.8·10^{32} cm-2·s-1

$N_\varepsilon(E_i)$

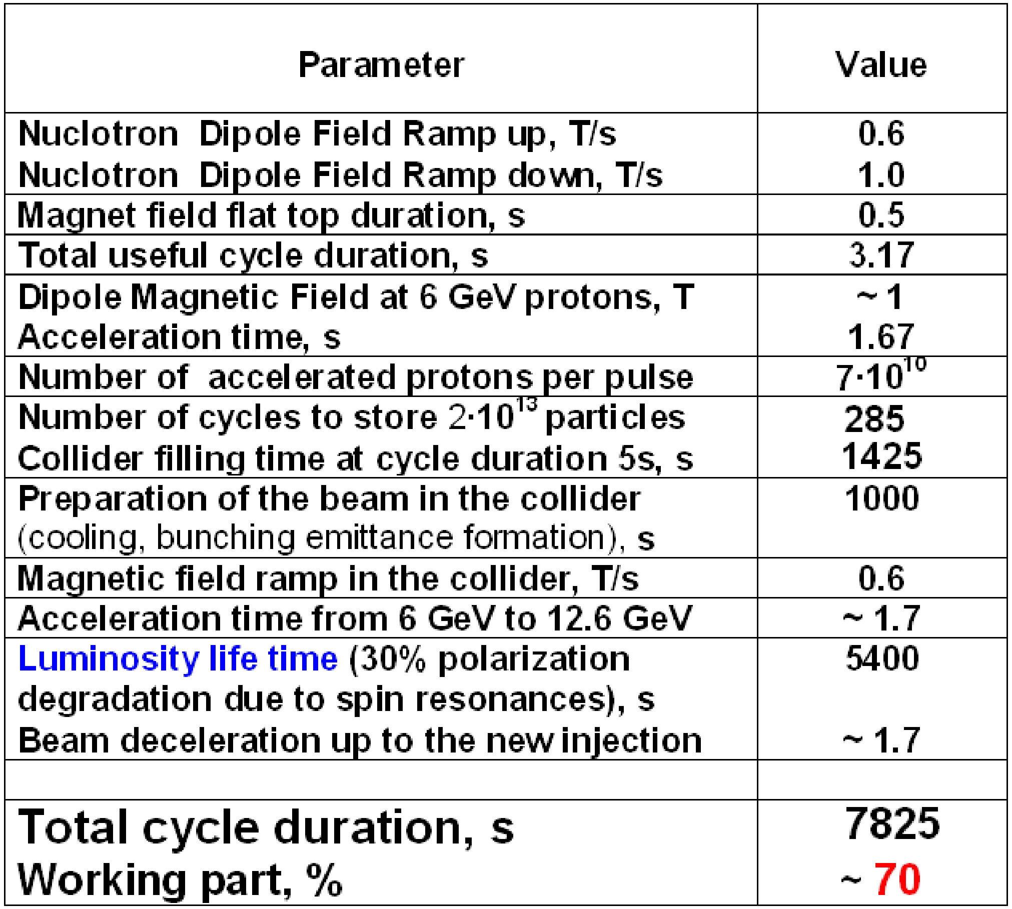
particle number per bunch in 10^{11} units

maximum proton number in each ring – $2.2 \bullet 10^{13}$

❑ IP parameters: **β** = 35 cm, bunch length **σ** = 60 cm (not optimized), **bunch number** – 22, collider perimeter **C** = 503 m

from I.N.Meshkov
29/11/2012

Polarized pp-collisions: average luminosity



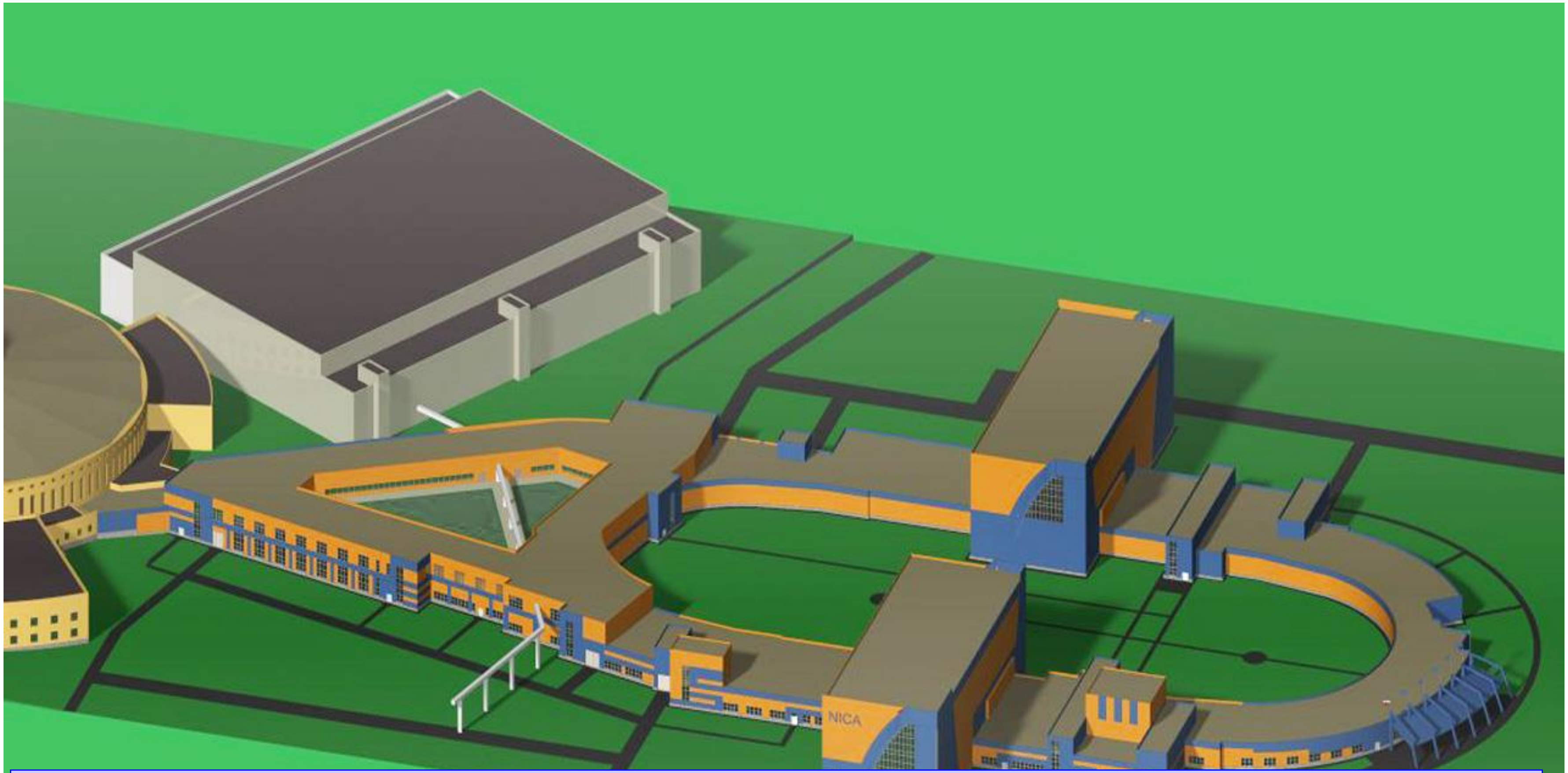
Parameter	Value
Nuclotron Dipole Field Ramp up, T/s Nuclotron Dipole Field Ramp down, T/s	0.6 1.0
Magnet field flat top duration, s	0.5
Total useful cycle duration, s	3.17
Dipole Magnetic Field at 6 GeV protons, T Acceleration time, s	~ 1 1.67
Number of accelerated protons per pulse	$7\cdot10^{10}$
Number of cycles to store $2\cdot10^{13}$ particles Collider filling time at cycle duration 5s, s	285 1425
Preparation of the beam in the collider (cooling, bunching emittance formation), s	1000
Magnetic field ramp in the collider, T/s	0.6
Acceleration time from 6 GeV to 12.6 GeV	~ 1.7
Luminosity life time (30% polarization degradation due to spin resonances), s Beam deceleration up to the new injection	5400 ~ 1.7
Total cycle duration, s **Working part, %**	**7825** **~ 70**

The time budget of the collider operation cycle presented in the Table make it possible to estimate average luminosity:

$L \approx 0.7\ L_{peak} \approx$

$1.26\cdot10^{32}$ cm-2·s-1

Status of the collider construction



- The first round of Russian state expertise have been passed;
- Goal for 2014: start area construction works for NICA collider looks feasible.

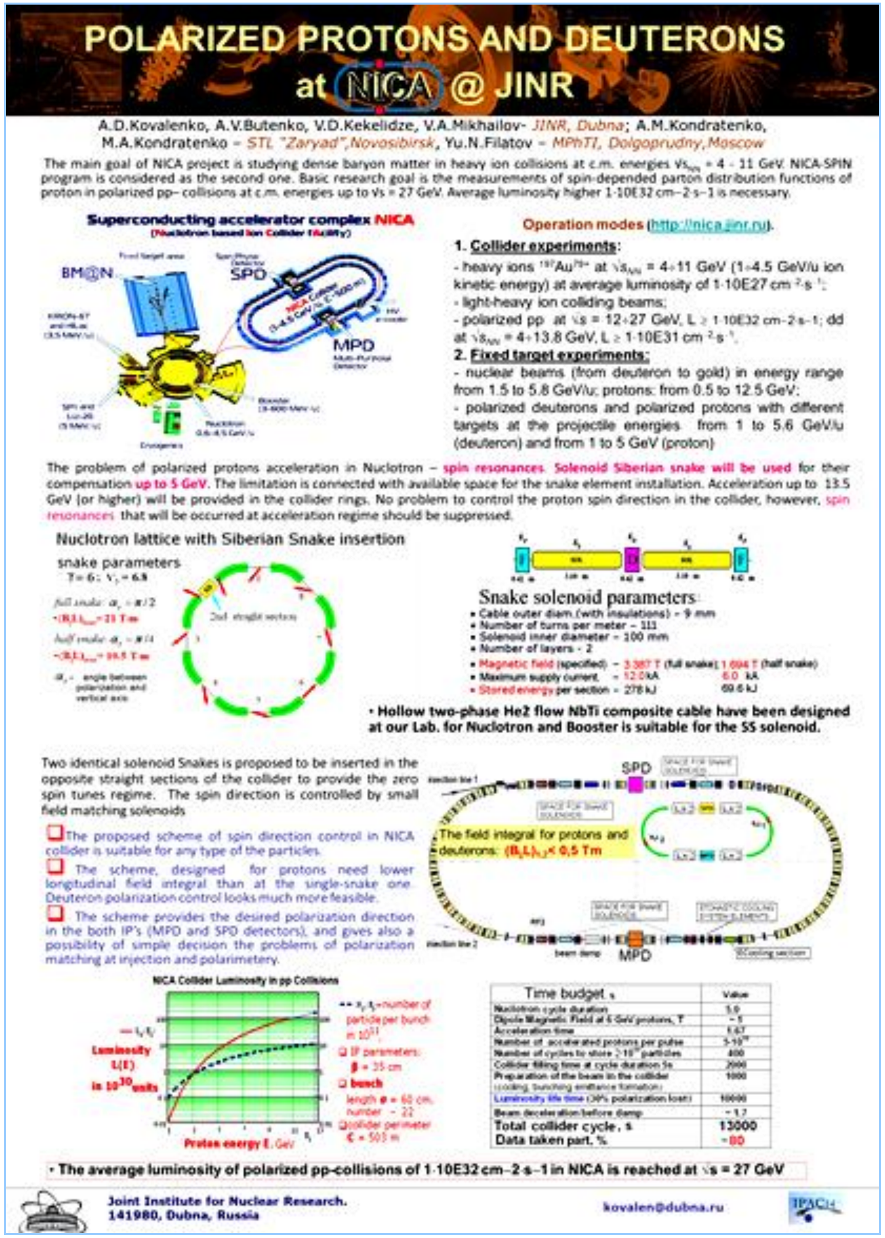
OUTLOOK

- The design concept of NICA complex operation in polarized proton and deuteron modes is worked out;

- More detailed calculations and modelling will be performed at the CDR preparation stage.

THANK YOU

FOR YOUR ATTENTION



POLARIZED PROTONS AND DEUTERONS at NICA @ JINR

A.D.Kovalenko, A.V.Butenko, V.D.Kekelidze, V.A.Mikhailov- *JINR, Dubna*; A.M.Kondratenko,
M.A.Kondratenko – *STL "Zaryad",Novosibirsk*, Yu.N.Filatov – *MPhTI, Dolgoprudny,Moscow*

The main goal of NICA project is studying dense baryon matter in heavy ion collisions at c.m. energies $\sqrt{s_{NN}}$ = 4 - 11 GeV. NICA-SPIN program is considered as the second one. Basic research goal is the measurements of spin-depended parton distribution functions of proton in polarized pp– collisions at c.m. energies up to $\sqrt{s}$ = 27 GeV. Average luminosity higher 1·10E32 cm–2·s–1 is necessary.

Superconducting accelerator complex NICA

(Nuclotron based Ion Collider fAcility)

Operation modes (http://nica.jinr.ru).

1. **Collider experiments**:
- heavy ions $^{197}Au^{79+}$ at $\sqrt{s_{NN}}$ = 4÷11 GeV (1÷4.5 GeV/u ion kinetic energy) at average luminosity of 1·10E27 cm^{-2}·s^{-1};
- light-heavy ion colliding beams;
- polarized pp at $\sqrt{s}$ = 12÷27 GeV, L ≥ 1·10E32 cm–2·s–1; dd at $\sqrt{s_{NN}}$ = 4÷13.8 GeV, L ≥ 1·10E31 cm^{-2}·s^{-1}.

2. **Fixed target experiments:**
- nuclear beams (from deuteron to gold) in energy range from 1.5 to 5.8 GeV/u; protons: from 0.5 to 12.5 GeV;
- polarized deuterons and polarized protons with different targets at the projectile energies from 1 to 5.6 GeV/u (deuteron) and from 1 to 5 GeV (proton)

The problem of polarized protons acceleration in Nuclotron – **spin resonances**. **Solenoid Siberian snake will be used** for their compensation **up to 5 GeV**. The limitation is connected with available space for the snake element installation. Acceleration up to 13.5 GeV (or higher) will be provided in the collider rings. No problem to control the proton spin direction in the collider, however, spin resonances that will be occurred at acceleration regime should be suppressed.

Nuclotron lattice with Siberian Snake insertion

snake parameters
$\gamma = 6;\ \nu_y = 6.8$

full snake: $\alpha_y = \pi/2$
$\sim(B_{\parallel}L)_{max} = 21$ T·m
half snake: $\alpha_y = \pi/4$
$\sim(B_{\parallel}L)_{max} = 10.5$ T·m
α_y – angle between polarization and vertical axis

Snake solenoid parameters

- Cable outer diam.(with insulations) – 9 mm
- Number of turns per meter – 111
- Solenoid inner diameter – 100 mm
- Number of layers – 2
- Magnetic field (specified) – 3.387 T (full snake) 1.694 T (half snake)
- Maximum supply current – 12.0 kA 6.0 kA
- Stored energy per section – 278 kJ 69.6 kJ

- **Hollow two-phase He2 flow NbTi composite cable have been designed at our Lab. for Nuclotron and Booster is suitable for the SS solenoid.**

Two identical solenoid Snakes is proposed to be inserted in the opposite straight sections of the collider to provide the zero spin tunes regime. The spin direction is controlled by small field matching solenoids

- ☐ The proposed scheme of spin direction control in NICA collider is suitable for any type of the particles.
- ☐ The scheme, designed for protons need lower longitudinal field integral than at the single-snake one. Deuteron polarization control looks much more feasible.
- ☐ The scheme provides the desired polarization direction in the both IP's (MPD and SPD detectors), and gives also a possibility of simple decision the problems of polarization matching at injection and polarimetery.

The field integral for protons and deuterons: $(B_{\parallel}L)_{1,2} < 0{,}5$ Tm

NICA Collider Luminosity in pp Collisions

- $N_1 N_2$ – number of particle per bunch in 10^{11}
- ☐ IP parameters: β = 35 cm
- ☐ bunch length σ = 60 cm, number – 22
- ☐ collider perimeter C = 503 m

Time budget, s	Value
Nuclotron cycle duration	5.0
Dipole Magnetic Field at 6 GeV protons, T	~1
Acceleration time	1.67
Number of accelerated protons per pulse	5·10 [illegible]
Number of cycles to store 2·10 [illegible] particles	400
Collider filling time at cycle duration 5s	2000
Preparation of the beam in the collider (cooling, bunching emittance formation)	1000
Luminosity life time (30% polarization lost)	10000
Beam deceleration before damp	~1.7
Total collider cycle, s	**13000**
Data taken part, %	**~80**

- **The average luminosity of polarized pp-collisions of 1·10E32 cm–2·s–1 in NICA is reached at $\sqrt{s}$ = 27 GeV**

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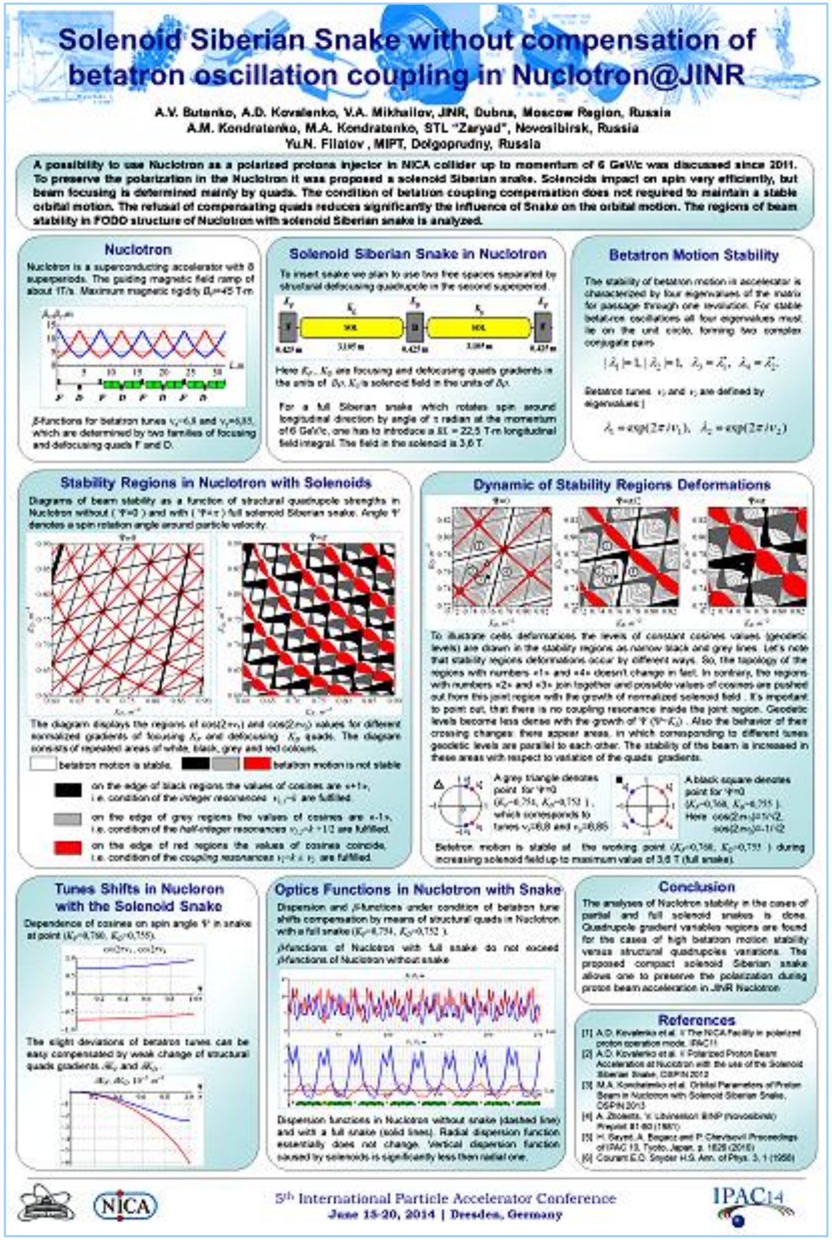

Solenoid Siberian Snake without compensation of betatron oscillation coupling in Nuclotron@JINR

A.V. Butenko, A.D. Kovalenko, V.A. Mikhailov, JINR, Dubna, Moscow Region, Russia
A.M. Kondratenko, M.A. Kondratenko, STL "Zaryad", Novosibirsk, Russia
Yu.N. Filatov , MIPT, Dolgoprudny, Russia

A possibility to use Nuclotron as a polarized protons injector in NICA collider up to momentum of 6 GeV/c was discussed since 2011. To preserve the polarization in the Nuclotron it was proposed a solenoid Siberian snake. Solenoids impact on spin very efficiently, but beam focusing is determined mainly by quads. The condition of betatron coupling compensation does not required to maintain a stable orbital motion. The refusal of compensating quads reduces significantly the influence of Snake on the orbital motion. The regions of beam stability in FODO structure of Nuclotron with solenoid Siberian snake is analyzed.

Nuclotron

Nuclotron is a superconducting accelerator with 8 superperiods. The guiding magnetic field ramp of about 1T/s. Maximum magnetic rigidity $B\rho$=45 T·m.

β-functions for betatron tunes ν_x=6,8 and ν_y=6,85, which are determined by two families of focusing and defocusing quads F and D.

Solenoid Siberian Snake in Nuclotron

To insert snake we plan to use two free spaces separated by structural defocusing quadrupole in the second superperiod.

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

For a full Siberian snake which rotates spin around longitudinal direction by angle of π radian at the momentum of 6 GeV/c, one has to introduce a BL = 22,5 T·m longitudinal field integral. The field in the solenoid is 3,6 T.

Betatron Motion Stability

The stability of betatron motion in accelerator is characterized by four eigenvalues of the matrix for passage through one revolution. For stable betatron oscillations all four eigenvalues must lie on the unit circle, forming two complex conjugate pairs

$$|\lambda_1| = 1,\ |\lambda_2| = 1,\ \lambda_3 = \bar{\lambda}_1,\ \lambda_4 = \bar{\lambda}_2.$$

Betatron tunes ν_1 and ν_2 are defined by eigenvalues:

$$\lambda_1 = \exp(2\pi i\nu_1),\ \ \lambda_2 = \exp(2\pi i\nu_2)$$

Stability Regions in Nuclotron with Solenoids

Diagrams of beam stability as a function of structural quadrupole strengths in Nuclotron without (Ψ=0) and with (Ψ=π) full solenoid Siberian snake. Angle Ψ denotes a spin rotation angle around particle velocity.

The diagram displays the regions of $\cos(2\pi\nu_1)$ and $\cos(2\pi\nu_2)$ values for different normalized gradients of focusing K_F and defocusing K_D quads. The diagram consists of repeated areas of white, black, grey and red colours.

☐ betatron motion is stable. ■ ▨ 🟥 betatron motion is not stable

- ■ on the edge of black regions the values of cosines are «+1», i.e. condition of the *integer resonances* $\nu_{1,2}$=k are fulfilled.
- ▨ on the edge of grey regions the values of cosines are «-1», i.e. condition of the *half-integer resonances* $\nu_{1,2}$=k+1/2 are fulfilled.
- 🟥 on the edge of red regions the values of cosines coincide, i.e. condition of the *coupling resonances* ν_1=k ± ν_2 are fulfilled.

Dynamic of Stability Regions Deformations

To illustrate cells deformations the levels of constant cosines values (geodetic levels) are drawn in the stability regions as narrow black and grey lines. Let's note that stability regions deformations occur by different ways. So, the topology of the regions with numbers «1» and «4» doesn't change in fact. In contrary, the regions with numbers «2» and «3» join together and possible values of cosines are pushed out from this joint region with the growth of normalized solenoid field. It's important to point out, that there is no coupling resonance inside the joint region. Geodetic levels become less dense with the growth of Ψ (Ψ~K_s). Also the behavior of their crossing changes: there appear areas, in which corresponding to different tunes geodetic levels are parallel to each other. The stability of the beam is increased in these areas with respect to variation of the quads gradients.

A grey triangle denotes point for Ψ=0 (K_F=0,794, K_D=0,752), which corresponds to tunes ν_x=6,8 and ν_y=6,85

A black square denotes point for Ψ=0 (K_F=0,768, K_D=0,755). Here $\cos(2\pi\nu_1)$=1/√2, $\cos(2\pi\nu_2)$=-1/√2

Betatron motion is stable at the working point (K_F=0,768, K_D=0,755) during increasing solenoid field up to maximum value of 3,6 T (full snake).

Tunes Shifts in Nucloron with the Solenoid Snake

Dependence of cosines on spin angle Ψ in snake at point (K_F=0,768, K_D=0,755).

The slight deviations of betatron tunes can be easy compensated by weak change of structural quads gradients δK_F and δK_D.

Optics Functions in Nuclotron with Snake

Dispersion and β-functions under condition of betatron tune shifts compensation by means of structural quads in Nuclotron with a full snake (K_F=0,794, K_D=0,752).

β-functions of Nuclotron with full snake do not exceed β-functions of Nuclotron without snake.

Dispersion functions in Nuclotron without snake (dashed line) and with a full snake (solid lines). Radial dispersion function essentially does not change. Vertical dispersion function caused by solenoids is significantly less then radial one.

Conclusion

The analyses of Nuclotron stability in the cases of partial and full solenoid snakes is done. Quadrupole gradient variables regions are found for the cases of high betatron motion stability versus structural quadrupoles variations. The proposed compact solenoid Siberian snake allows one to preserve the polarization during proton beam acceleration in JINR Nuclotron.

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