Polarized Deuterons & Protons at NICA Complex

A.Kovalenko

A. (*JINR, Dubna*)

NICA_MAC Meeting, Dubna, May 22-23, 2017

The contributors to the design and experiments

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I.Dobrin et al. (*Romania*)

CONTENT

- General remarks
- The facility concept in polarized mode
- Polarized deuterons & protons in 2016-17
- Near future tasks

NICA REQUEST: is based at the LoI

LoI: Spin Physics Experiments at NICA-SPD with polarized proton and deuteron beams

compiled by the Drafting Committee: I.A.Savin, A.V.Efremov, D.V.Peshekhonov, A.D.Kovalenko, O.V.Teryaev, O.Yu.Shevchenko, A.P.Nagajcev, A.V. Guskov, V.V. Kukhtin, N.D. Topilin.

presented at the JINR PAC for Particle Physics on 25–26 June 2014.

PAC Recommendations:

….The PAC regards the SPD experiment as an essential part of the NICA research program and encourages the authors of the Letter of Intent to prepare a full proposal and present it at one of the forthcoming meetings of the PAC. …

LoI: Spin Physics Experiments at NICA-SPD with polarized proton and deuteron beams

list of participants

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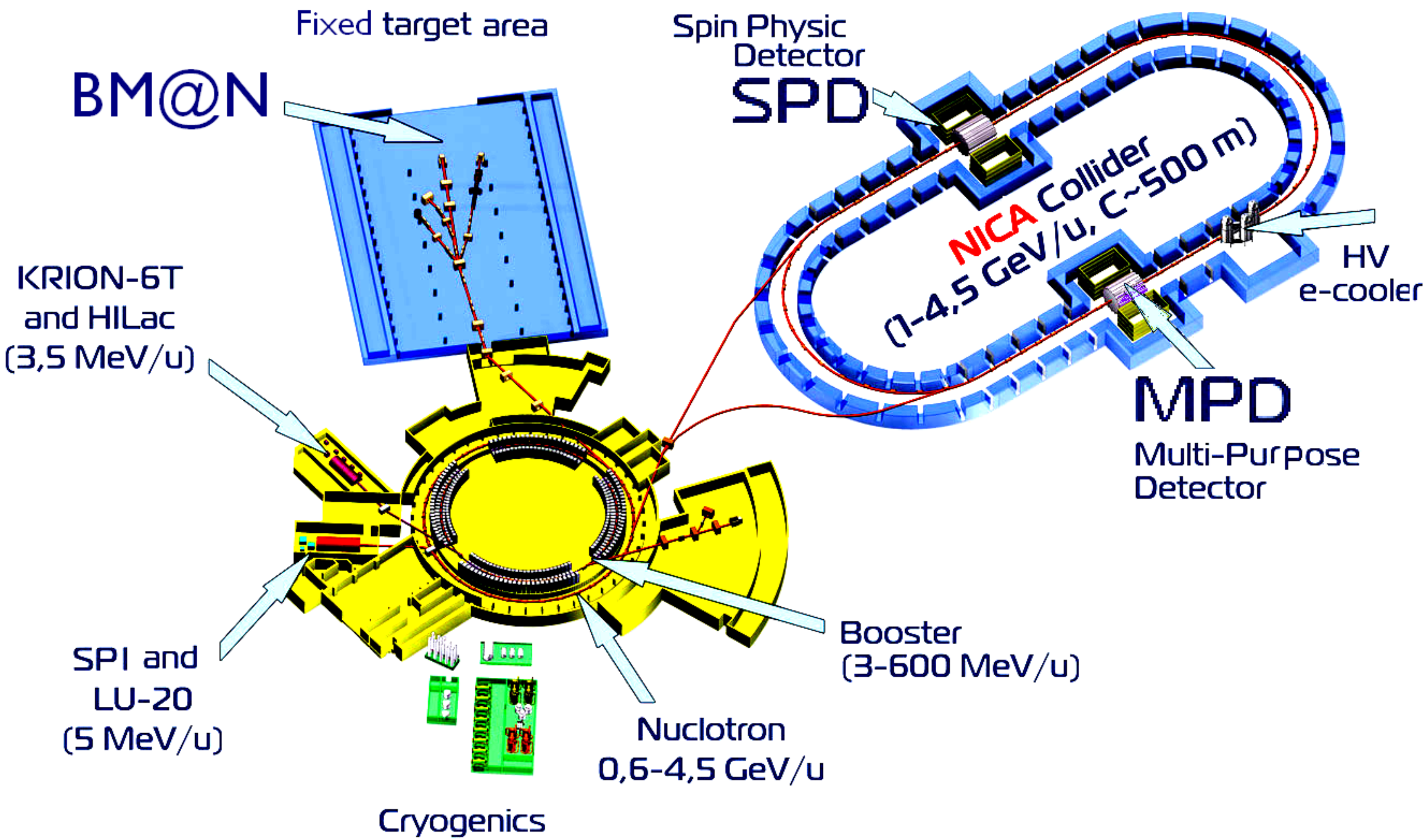
Requirements to the facility in polarized mode

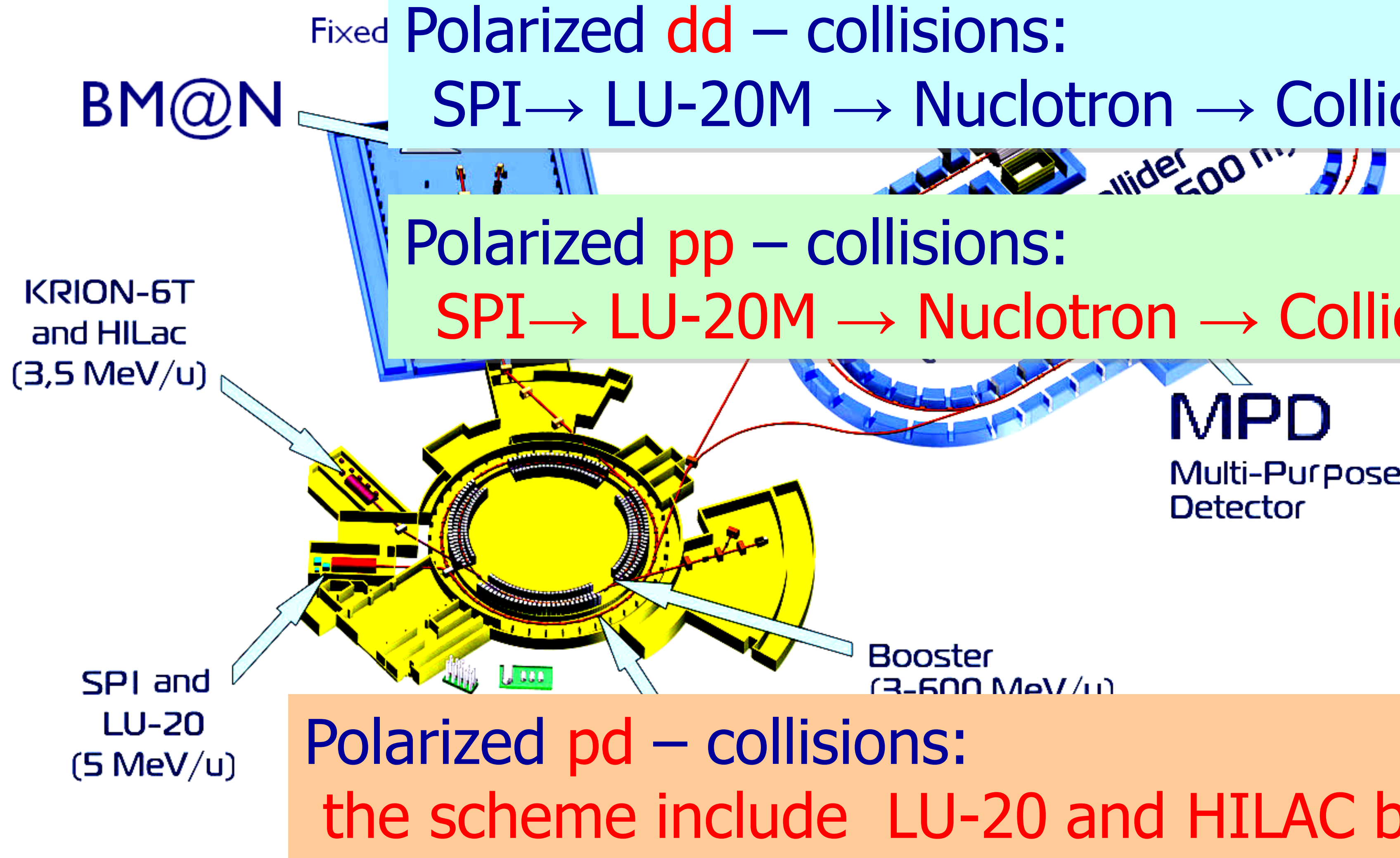
- **polarized and non-polarized p-; d–collisions**
- **p↑p↑(p)** at $\sqrt{s_{pp}}$ **= 12 ÷ 27 GeV** (5 ÷ 12.6 GeV kinetic energy)
- **d↑d↑(d)** at $\sqrt{s_{NN}}$ **= 4 ÷ 13 GeV** (2 ÷ 5.5 GeV/u kinetic energy)
- $\mathbf{L_{average}} \approx 1 \cdot 10E32\ cm^{-2}s^{-1}$ (at $\sqrt{s_{pp}} \geq 27$ GeV)
- sufficient lifetime and degree of polarization
- longitudinal and transverse polarization in MPD/SPD
- asymmetric collision mode, pd, should be possible

We concentrate design efforts at the pp-mode that need extremely high the peak and average luminosity

Superconducting accelerator complex NICA
(Nuclotron based Ion Collider fAcility)



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:
the scheme include LU-20 and HILAC both

NICA operation in Polarized Mode (2)

- **d↑-** was accelerated at the Synchrophasotron in 1986; at the Nuclotron in 2002. No dangerous spin resonances up to 5.6 GeV/u.

- **p↑-** was not accelerated at the facility up to 2017. The first test was performed at Nuclotron after more detailed analysis of the problem of spin resonances at real operation conditions of the accelerator.

(see Addendum 1. Yu. Filatov et al. IPAC2017.)

NICA operation in Polarized Mode (3)

- To control the polarization direction world famous technology of "Siberian snake" *(Y. S. Derbenev and A. M. Kondratenko, 10th Int. Conf. on High Energy Accel. v.2, p.70 ,Protvino, 1977)* was proposed to be used for the Nuclotron/NICA complex

- The analysed of different "snake" structures of a (dipole, spiral dipole, solenoid) have shown that solenoidal structure is optimal in the NICA energy range

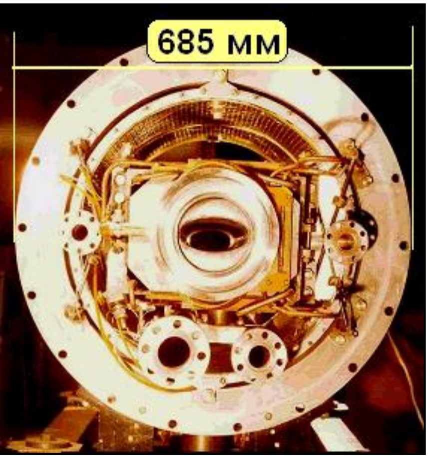
NICA operation in Polarized Mode (4)

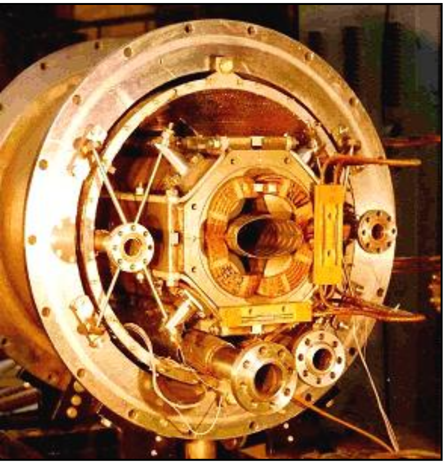
<u>First solution:</u> p↑ acceleration up to 5-6 GeV at Nuclotron with dynamic solenoid Siberian snake → transfer to collider rings → storage, stochastic cooling and further acceleration up to 13.5 GeV in the collider rings.

<u>Recent solution:</u> p↑ acceleration up to 1.5 - 2 GeV at Nuclotron without snake → formation and stochastic cooling of a bunch → bunch transfer to collider ring → storage, acceleration up to the needed energy (max. 13.5 GeV) in the collider rings, final optimization to reach peak luminosity.

Polarized Protons at Nuclotron (1)

Necessary solenoid can be manufactured base on a hollow Nuclotron-type SC cable and the new SC wire.





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

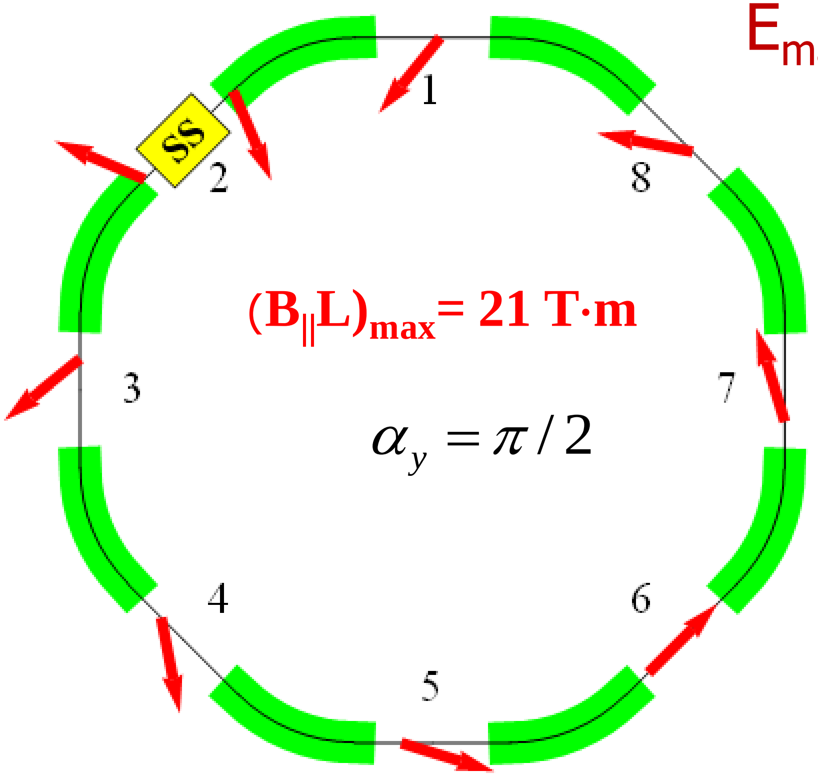
Suitable NbTi wire was designed by the Bochvar company for **6 T, 1 T/s** magnet of SIS300 R&D program.

Polarized Protons at Nuclotron (2)

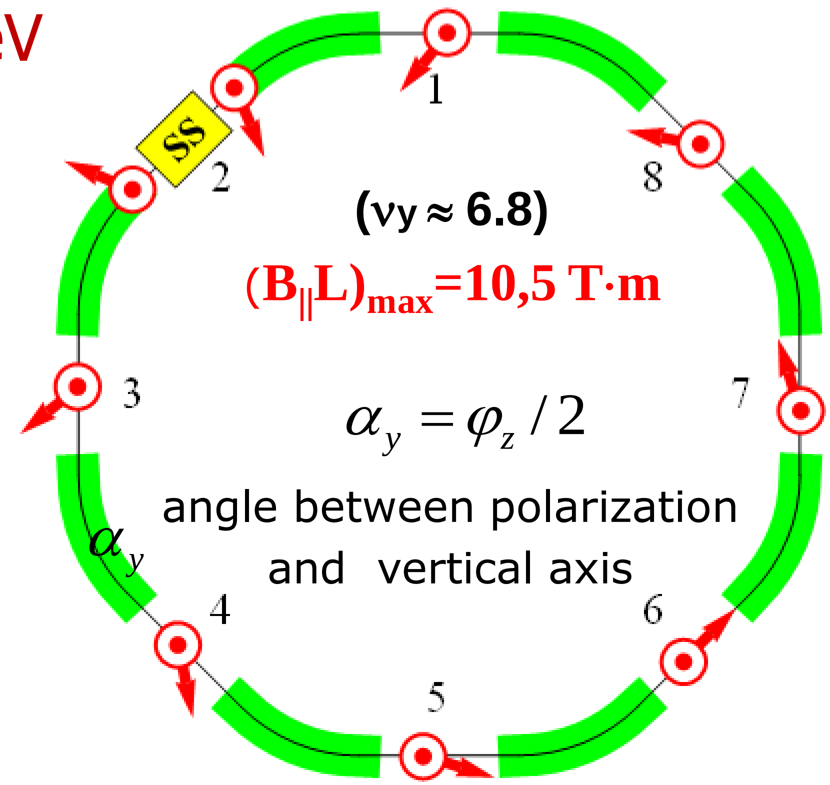
Dynamic Solenoid Siberian Snake

E_{max}= 6 GeV

Full Siberian Snake



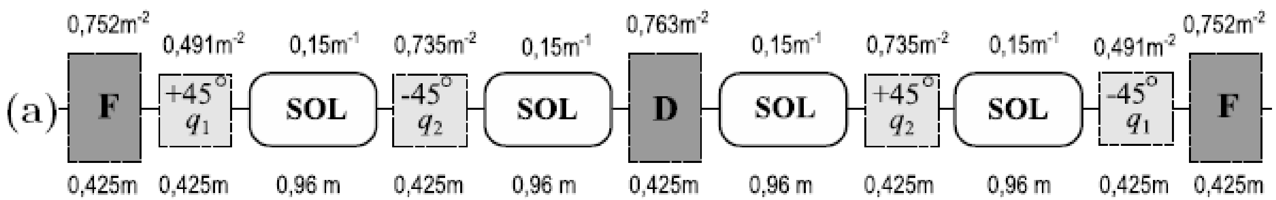
Partial Siberian Snake



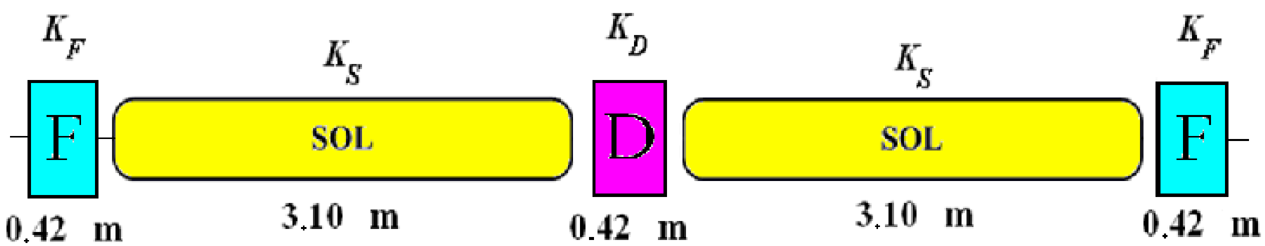
Polarized Protons at Nuclotron (3)

The Snake structure:

a) Scheme with compensating skew quadrupoles



b) Scheme without skew quadrupoles

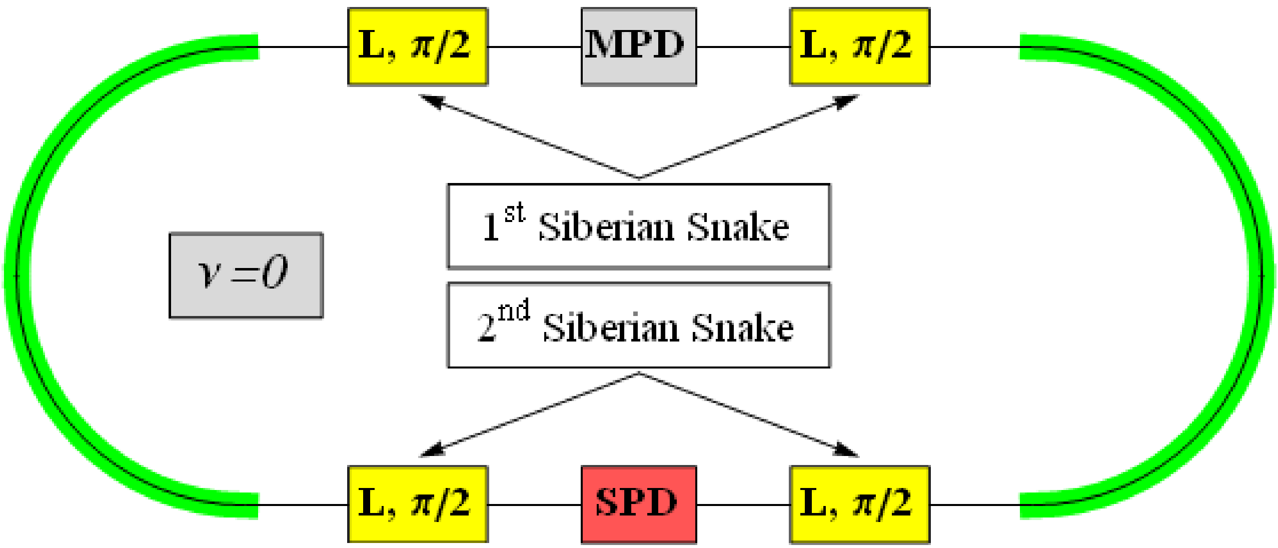


- Magnetic field (specified) – 3.387 T (full snake); 1.694 T (half snake)
- Maximum supply current, – 12.0 kA 6.0 kA
- Stored energy per section – 278 kJ 69.6 kJ

Polarization control in the Collider at $\nu_s = 0$ (1)

Solenoidal Snake at particle momentum:

$p=(2.5\div13)$GeV/c



Necessary integral of the magnetic field

protons:

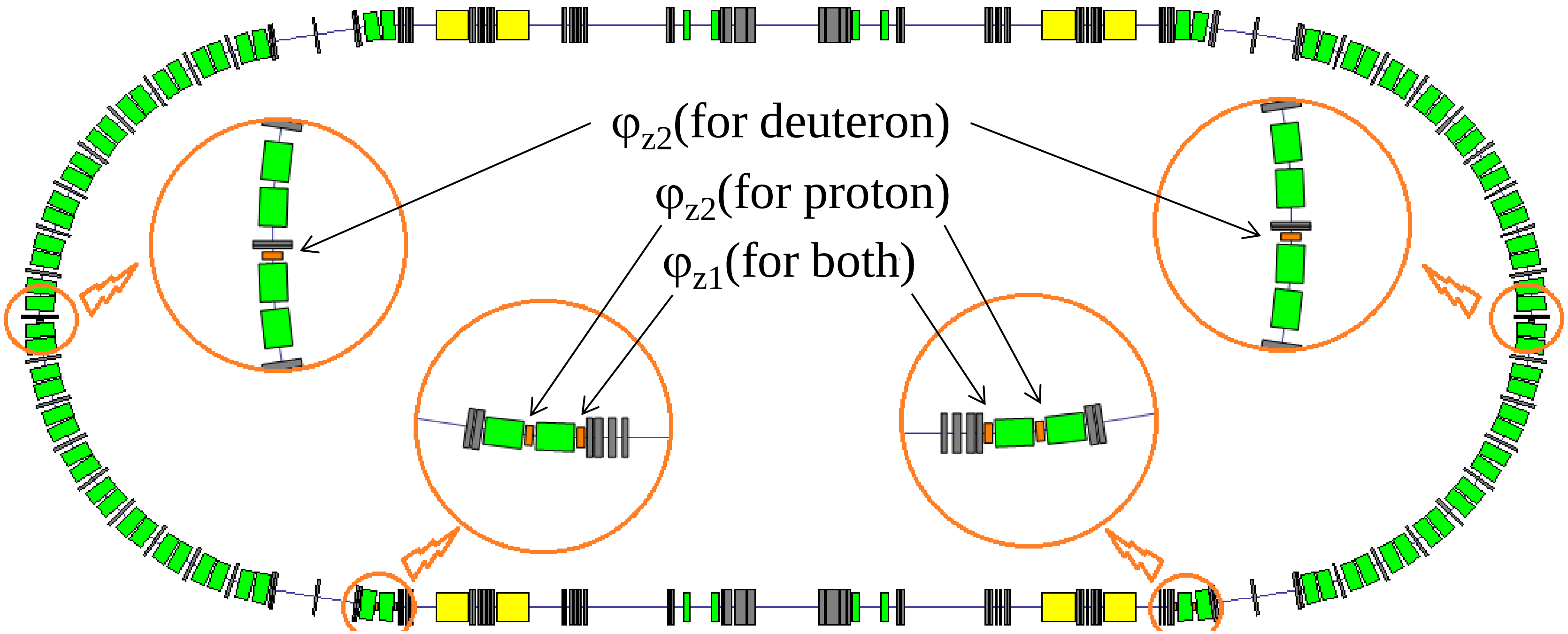
$(B_{||}L)_{max}=4\times(5\div25)$ T·m

deuterons:

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

Polarization control in the Collider at $\nu_s = 0$ (2)

Ideal scheme:



	number	B_{max}, T	Leff, m	BL, T·m
Main tune shift solenoids	8	6.0	2.08	20 -100
Weak solenoids for polarization control (red)	6	1,5	0,4	0÷0,6

Polarization control in the Collider at $\nu_s = 0$ (3)

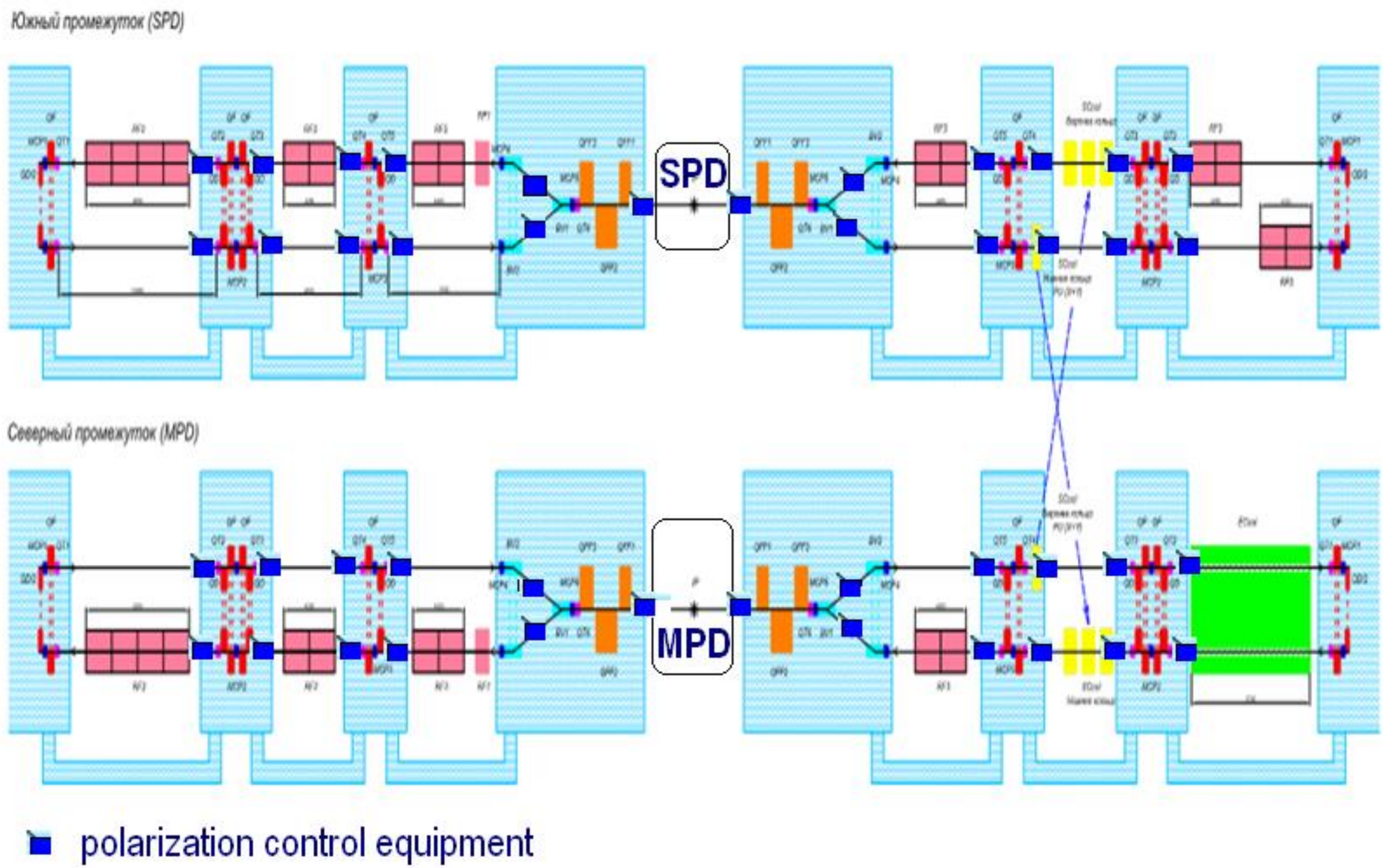
- The proposed scheme is suitable for any type of the particles.

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

Limitations: 1 – available space at the ring; 2 – deuteron momentum ≤ 30% of max. if the polarization direction should be changed at 90 degree.

Polarization control in the Collider at $\nu_s = 0$ (4)

option 1: combination of the solenoids and RF

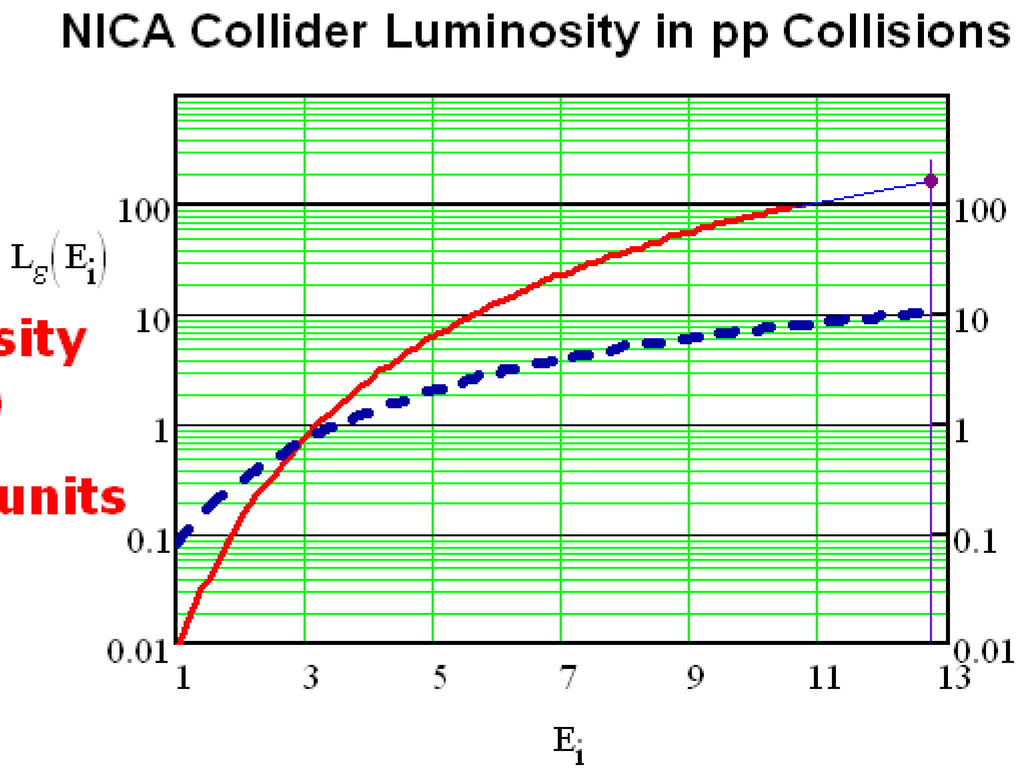


Polarization control in the Collider at $\nu_s = 0$ (5)

option 2: the solenoids instead of some RF modules

Start option could be: the solenoids instead of SPD (provide the experiments at MPD with polarized beams)

NICA pp-collisions peak luminosity (1)



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

Proton energy E in GeV

Lpeak ≈ $1.8 \cdot 10^{32}$ cm-2·s-1

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

NICA pp-collisions peak luminosity (2)

Main problems and limitations:

1. Proper beam intensity from the ion source and Nuclotron (**~10E11 per cycle**)
2. Maximum possible pulse repetition rate (**0.2 Hz**)

Necessary stored particle number in the collider is reached after 220 injection pulses and will take not more than ½ hour to fill the ring with 1.5-2.0 GeV polarized protons in this case.

3. Storage in the collider ring (bunched or coasting beam?), acceleration from ***~2 to 12.7 GeV (or to the experiment energy), formation of bunch parameters corresponding to the maximum luminosity.***

Other problems: transition energy, polarization degradation, microwave instabilities, beam-beam effects, etc.

The further tasks towards realization of polarization research program at Nuclotron/NICA

- Improvement of the polarized ion source;
- The RFQ pre-injector and LU-20 front end upgrade;
- Upgrade of polarimeters: linak output; circulating beam; extracted beam; test the new approach to proton polarization measurements above 6 GeV;
- Design and tests of the 6 T SC-solenoid module;
- Further simulations of polarized beam dynamics in the Nuclotron and NICA collider especially at long circulation time scale, 10E4 s, simulation of the storage process, analysis of instabilities.

We hope for the MAC support of the proposals

NICA results were reported and discussed by the community

Regular SPIN@FERMI/NICA Teleconferences (monthly during the past five years)

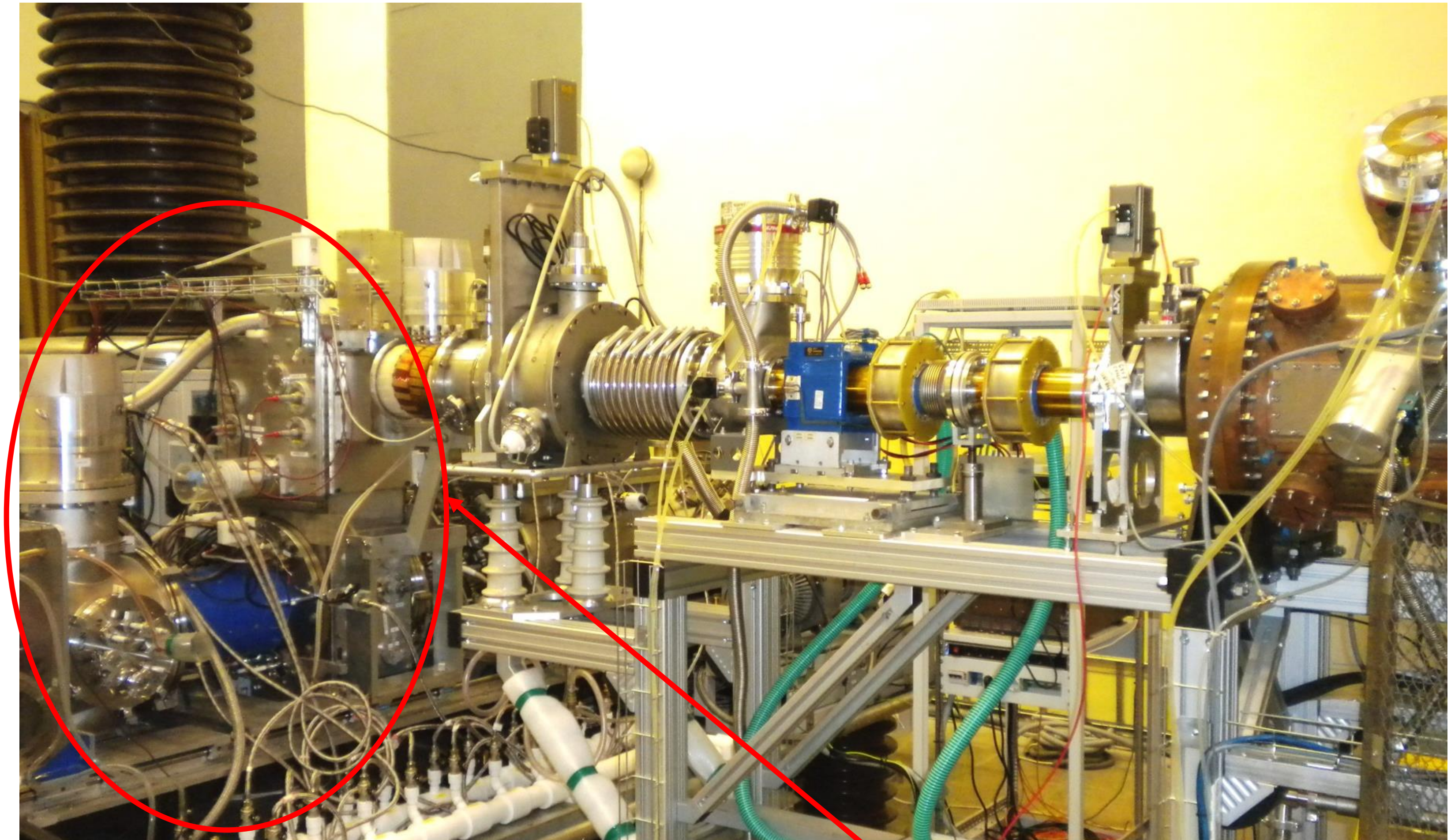
1. A D Krisch *(Michigan)*
2. Alex Chao
3. Alexander Belov
4. Alexander Dutton
5. Alexander. Kovalenko
6. Anatoly Kondratenko
7. Austin Tai
8. Chris Quigg
9. Christine Aidala
10. Dennis W Sivers
11. Man Hung
12. Donald Crabb
13. Ernest Courant
14. Erik Ljungman
15. Foivos Antoulinakis
16. Francisco Kulyckyj
17. Giuseppe Fidecaro
18. Greg Bock
19. Herman B White Jr
20. Hikaru Sato
21. Igor Savin
22. Ioanis Kourbanis
23. J D Bjorken
24. Jacob A Askari
25. Jessica K Thompson
26. John Peoples
27. John R O'Fallon
28. Karl Slifer
29. Katsuya Yonehara
30. Lawrence Jones
31. Marc L Kaducak
32. Maria Fidecaro
33. Mei Bai
34. Mike Syphe
35. Mikhail Ukhanov
36. Milorad Popovic
37. Paul Reimer
38. Pier J Oddone
39. Richard Raymond
40. Rolland Johnson
41. Sergey Troshin
42. Spencer Haupert
43. Steve Holmes
44. Steven Geer
45. Stuart D Henderson
46. Thomas Roser
47. Vasiliy Morozov
48. Victor K. Wong
49. Vladimir A Anferov
50. W T H vanOers

THANK YOU

FOR YOUR ATTENTION

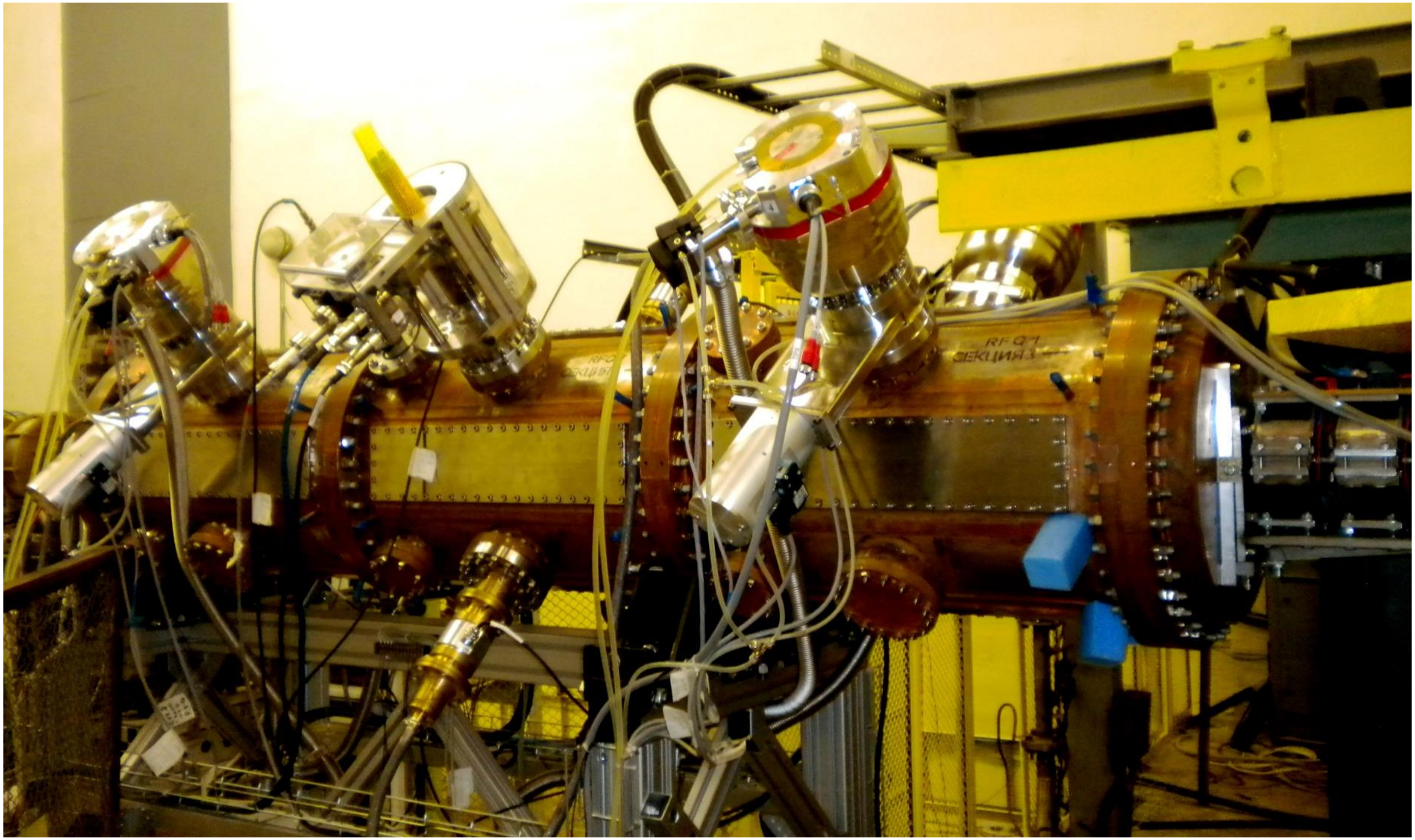
SOME ILLUSTRATIONS

Implementation of polarized beam program (1)



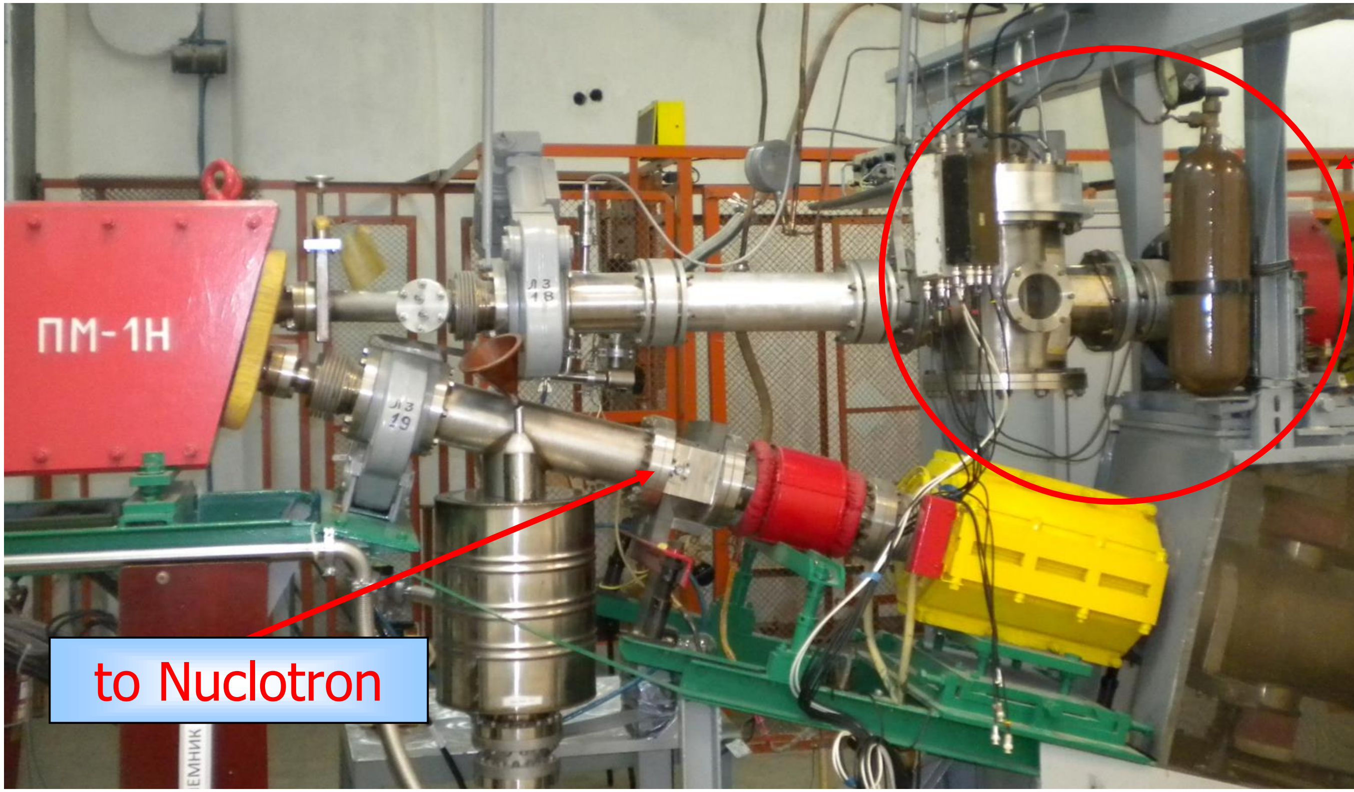
Equipment of new polarized ion source SPI and LEBT part of beam channel to RFQ section

Implementation of polarized beam program (2)



New RFQ section – pre-injector LU-20

Implementation of polarized beam program (3)

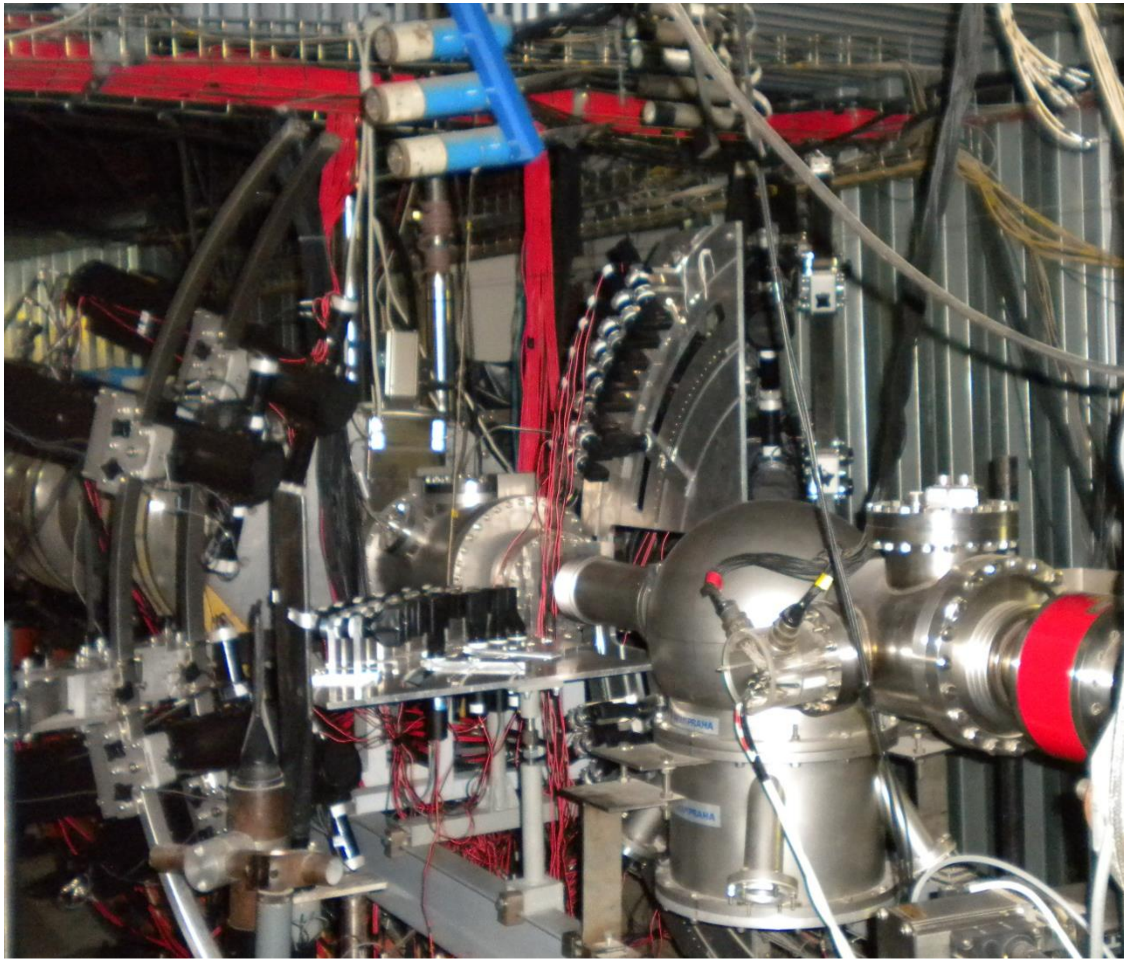


polarimeter

D.Krivenkov
L.Zolin,
V.Nikitin,
V.Avdeichikov
M.Aver'yanov
et al.

Output beam channels from linac LU-20

Implementation of polarization program (4)



V.Ladygin
et al.

Proton and deuteron polarimeter at Nuclotron ring

Implementation of polarization program (5)

N.Piskunov
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A.Livanov

et al.

Proton and deuteron polarimeter at Nuclotron extracted beam (focus F3 point)

Addendum 1

ACCELERATION OF POLARIZED PROTON AND DEUTERON BEAMS IN THE NUCLOTRON AT JINR

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Abstract
The superconducting synchrotron Nuclotron allows one to accelerate proton and deuteron beams up to 13.5 GeV/c. The beam depolarization occurs at the cross-ing of spin resonances. For deuterons, the vertical polari-zation is preserved almost to the maximum momentum. Tens of spin resonances are crossing during the proton acceleration. The proton polarization will be preserved by a solenoidal 5% snake up to 3.4 GeV/c at the field ramp rate of 1 T/s. It is planned to use a partial 50% snake to eliminate the resonant depolarization of the proton beam in the total momentum range of the accelerator. The results of simulations and experimental data are presented.

INTRODUCTION

A set of papers [1-7] has been published devoted to the problem of polarization preservation of protons and deuterons at acceleration in the Nuclotron at JINR (Dubna). At the present, the Nuclotron is planned as an injector of polarized protons and deuterons for the NICA collider [5]. An analysis of depolarizing effects in the Nuclotron has shown that the vertical polarization of deuterons is preserved during beam acceleration practically through the total momentum range, whereas the proton polarization is lost due to crossing of a large number of dangerous spin resonances. To preserve the proton polarization both as conventional methods (deliberate increase of spin resonance strength and the betatron tune jump methods) and the new method of the spin tune jump were studied [3]. The considered methods did not eliminate, but only reduced the resonant depolarization of a proton beam. A totally new method of transparent spin resonance crossing, which eliminated the loss of polarization after resonance crossing, was proposed in [4]. However, beams with a sufficiently low momentum spread are required to implement it at the Nuclotron [2]. Significant progress in the case of protons was achieved after a proposal to install a solenoidal Siberian snake to suppress resonant depolarization of the beam [5,6]. Feasibility of the proposal was increased after development of the snake scheme without compensation the betatron oscillation coupling induced by the solenoids. A full snake requires a longitudinal magnetic field integral of about 50 Tm at the momentum of 13.5 GeV/c. To preserve proton polarization, it is enough to use a partial snake that allows one to eliminate crossings of the most dangerous intrinsic and integer spin resonances due to the proper choice of the betatron tunes. A solenoidal 50%-snake, which rotates the spin at 90 degrees around the longitudinal direction, still leaves a lot of freedom in choosing the tunes. The field integral of 25 Tm is sufficient at the maximum momentum.
The presented calculations are obtained by the spin tracking code Zgoubi [8].

THE LATTICE WITHOUT A SNAKE

In this case the stable polarization points along the vertical axis ($\vec{n}$-axis of spin precession) and the spin tune is proportional to the beam energy: $\nu=\gamma G$, where γ is a relativistic factor and G is anomalous part of gyromagnetic ratio. This unavoidably leads to crossing of the spin resonances during acceleration and, as a consequence, to resonant depolarization of the beam. At the beam acceleration, the polarization can significantly deviate from the vertical axis in the regions of the spin resonances. Polarization after spin resonance crossing is determined by the spin resonance strength and the field ramp rate. A fast crossing keeps the spin aligned with the vertical field. A slow resonance crossing flips the spin direction along the field. In an intermediate situation, the spin orientation significantly deviates from the field direction. The resonances with intermediate crossing rate are the most dangerous.
The calculations of spin dynamics were performed at $\nu_x=6.85$ and $\nu_y=6.8$ horizontal and vertical betatron tunes respectively and at the field ramp rate of 1 T/s.

Intrinsic Spin Resonances

An unperturbed lattice of the Nuclotron can only have a series of intrinsic resonances $\nu=kN\pm\nu_y$. Intrinsic resonances occur due to correlation of the spin motion with the particle betatron motion. Here N=8 is a Nuclotron superperiod and k is an integer number. Intrinsic resonances, similar to all resonances involving betatron tunes, belong to the incoherent resonances. The strength of an intrinsic resonance is proportional to the amplitude of betatron oscillations and, therefore, during a slow crossing, there could simultaneously be present particles with both intermediate and fast crossing rates. The fraction of such particles determines the polarization loss. **Figure 1** demonstrates the crossings of the intrinsic resonances at acceleration of protons with three different initial betatron amplitudes. All particle spins are oriented initially along the vertical axis. As we can see, with a small initial offset $y_0=0.1$ mm (the green curve), the spin practically does not change, i.e. all resonances are crossed quickly. With an initial offset of $y_0=10$ mm (the blue curve), the spin flips practically at each crossing of the intrinsic resonance, i.e. the crossings are slow. An initial offset $y_0=1$ mm (the red curve) corresponds to the intermediate-rate crossings of the intrinsic resonances.

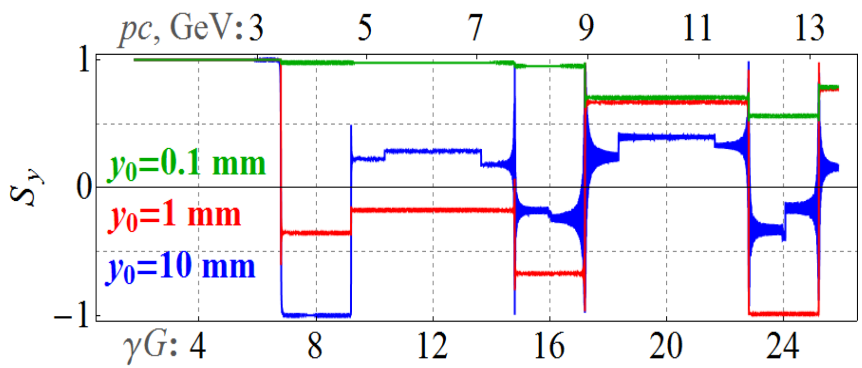


Figure 1: Changes of the proton vertical spin projections at the crossing of the intrinsic spin resonances.

Integer Resonances

Random vertical quadrupole shifts give rise to a series of integer resonances ν=k. Integer resonances belong to the coherent resonances, i.e. they are crossed identically for all particles with different betatron amplitudes. Figure 2 shows the crossings of the integer resonances at acceleration of a protons at a random quadrupole shifts with rms deviation equal to 0.25 mm. Such shifts distort the closed orbit to about 1 cm. The proton was launched with a vertical spin along the distorted closed orbit. In this example, the resonance γG=4 with an intermediate crossing rate is the most dangerous.

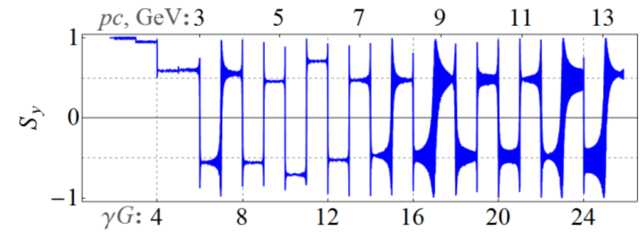


Figure 2: Change of the proton vertical spin projection at the crossing of the integer spin resonances.

Coupling and Non-Super - Periodic Resonances

Random changes in quadrupole gradients give rise to a series of non-super-periodic resonances ν=k±νy + (k≠mN). Random quadrupole rolls give rise to a series of coupling resonances ν=k±νx. The resonance strengths of these resonances are much less than the strengths of intrinsic and integer resonances. During proton acceleration at the field ramp rate of 1 T/s, the coupling resonances and the non-super-period resonances are crossed quickly. The presented data demonstrates the difficulties arising with preservation of the proton polarization.

Acceleration of Polarized Deuterons

Due to a small value of G_D≈-0.143 for deuterons, there are only five spin resonances: two coupling resonances, two non-super-periodic and one integer resonance. Figure 3 shows the vertical spin components in the Nuclotron during acceleration of deuterons with Δp/p=0 (the green curve), Δp/p= 〚10〛 ^(-3) (the red curve) and Δp/p= 〚-10〛 ^(-3) (the blue curve). Three types of errors in the setup and manufacturing of the Nuclotron lattice elements (lattice imperfections) were taken into account in the calculations, namely: random quadrupole shifts with rms value of 0.25 mm, random quadrupole rolls with rms value of 1 mrad, and random changes in quadrupole gradients of 0.1%. The main deuteron depolarization about of 10% occurs at the crossing of the integer spin resonance γG=-1 at the end of the acceleration cycle. In addition, a fragment of the crossings of the non-super-periodic and coupling resonances, which are crossed quickly, is shown in Fig. 3. The calculations show that energy modulation in synchrotron leads to an incoherent mixing of the spins.

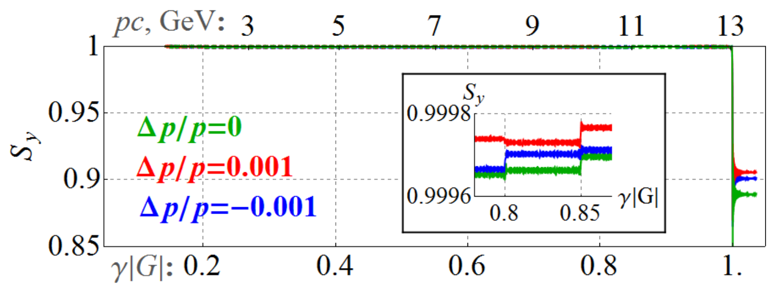


Figure 3: Change of the deuteron vertical spin projection at the crossing of the spin resonances in the Nuclotron.

NUCLOTRON WITH A PARTIAL SNAKE

To preserve proton polarization over the total momen-tum range of the Nuclotron, a 50% solenoidal snake can be used. The placement of snake solenoids in the 2nd straight of the Nuclotron lattice is shown in Fig. 4. We keep strong coupling of the betatron oscillations in the synchrotron. This allows the solenoids to occupy all free spaces between the structural quadrupoles F and D [5-6].

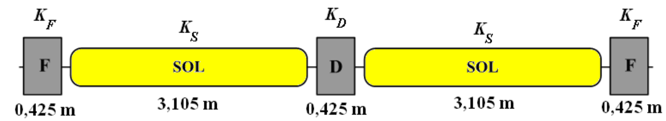


Figure 4: Layout of a 50% solenoidal snake without compensating quadruoles.

For a partial snake the spin tune is determined by the equation: $\cos(\pi\nu) = \cos(\Psi/2)\cos(\pi\gamma G)$.(1) Variable Ψ is an angle of the spin rotation in the snake.

To eliminate a series of intrinsic resonances during beam acceleration, a restriction on the possible values of the betatron tunes is the following: $\cos(2\pi\nu_{x,y}) > \cos\Psi$.(2) Stable spin precession $\vec{n}$-axis lies in the vertical plane:

$$\vec{n} = \frac{\sin(\Psi/2)\,\vec{e}_z + \cos(\Psi/2)\sin(\pi\gamma G)\,\vec{e}_y}{\sqrt{1-\cos^2(\Psi/2)\cos^2(\pi\gamma G)}}. \quad (3)$$

In contrast to the case without a snake, the $\vec{n}$-axis significantly deviates from the vertical $\vec{e}_y$ axis, periodically aligning along the longitudinal $\vec{e}_z$ axis at the energy values corresponding to the integer resonances $\gamma G = k$. Figure 5 shows the $\vec{n}$-axis components during acceleration in the Nuclotron with the 50% solenoidal snake.

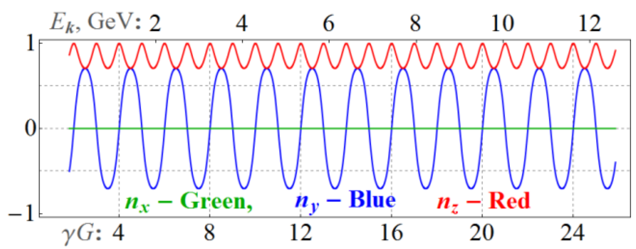
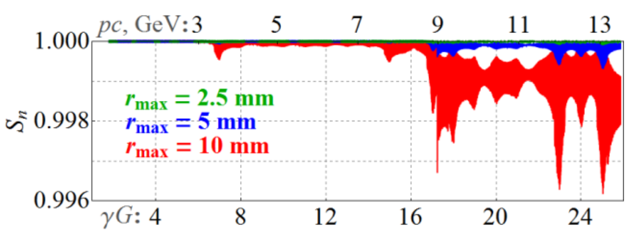


Figure 5: The n $^{\to}$-axis components at acceleration in the Nuclotron with the 50% solenoidal snake.



The spin projection Sn at n $^{\to}$-axis is adiabatic invariant, i.e. it will be preserved in the case of adiabatic change of the particle energy. The mentioned condition is fulfilled automatically at the magnetic field ramp of 1 T/c. Thus, the spin, oriented originally along n $^{\to}$-axis, will follow to that direction at the particle acceleration in the Nuclotron. .Figure 6 shows the spin projections S_n during acceleration of protons with three different betatron amplitudes in the Nuclotron with the 50% solenoidal snake. To satisfy to the condition (2), the betatron tunes are chosen v_x≈6.78, vy≈6.9. The maximum betatron beam sizes r_max are 10 mm (the red curve), 5 mm (the blue curve) and 2.5 mm (the green curve). The spins are initially directed along the n $^{\to}$-axis.

Figure 6: The Sn projections at acceleration of 3 protons in the Nuclotron with the 50% solenoidal snake.

The calculation confirms that proton spins practically do not deviate from the n $^{\to}$-axis during acceleration, i.e. a 50% snake eliminates crossings of intrinsic resonances.

Acceleration of Polarized Protons up to 3.4 GeV/c

To eliminate a series of integer resonances, it is sufficient to use a partial snake with a small field integral. Thus, the proton polarization can be conserved without usage of solenoids with large field integrals up to the energy corresponding to the first intrinsic resonance. Figure 6 shows the vertical spin components during acceleration of three protons with different momenta in the Nuclotron without a snake containing the same quadrupoles errors as in the deuteron case. The crossing of the intrinsic resonance γG=v_y=6.8 at the momentum about of 3.4 GeV/c leads to an incoherent mixing of the spins due to synchrotron energy modulation, i.e. to partial beam depolarization. After crossing of the coherent resonance γG=4, the depolarization loss is about 40%. The adiabatic spin flip occurs at the resonance γG=6. Figure 7 shows the vertical proton spin components during acceleration of three protons with different momenta in the Nuclotron with a 5% solenoid snake, which is required the solenoid field integral of 0.65 Tm at the momentum of 3.5 GeV/c.

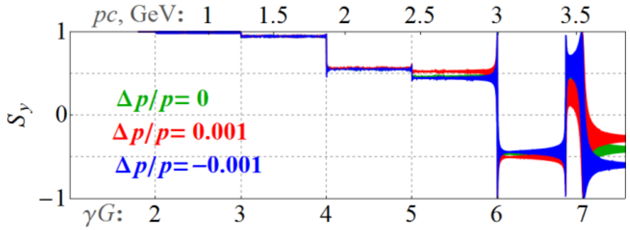


Figure 6: Vertical spin components at acceleration of protons with 3 different momenta up to 3.5 GeV/c.

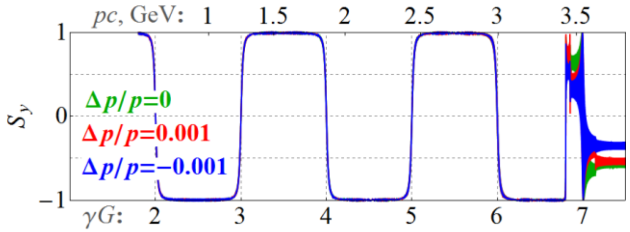


Figure 7: Vertical spin components at acceleration of 3 protons in the Nuclotron with the 5% snake up to 3.5 GeV/c

Although the quadrupoles errors were the same, the 5% snake preserves the polarization up to 3.4 GeV/c. As one can see, the proton spins are flipped at the integer resonances keeping the vertical orientation between them.

During the last run in February-March 2017, polarized protons were successfully accelerated in the Nuclotron up to 2.8 GeV/c. The experiment shows that the integer resonance γG = 2 is crossed without the polarization loss. The intermediate crossing of the resonance γG =3 leads to polarization loss of about 75%. Crossing of the resonance γG = 4 flips the polarization.

CONCLUSION

The presented calculations demonstrate the possibility of using the Nuclotron without additional magnetic in-serts as an injector of polarized protons in the NICA col-lider at the beam momentum up to about 3.4 GeV/c. The 50% snake provides polarized protons over the total momentum range.

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