Polarized Deuterons & Protons at NICA at JINR

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• NICA@JINR: General comments
• NICA layout in polarized mode
• Polarization control schemes
• Polarized pp: expected luminosity
• Outlook
NICA place near DUBNA town
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:
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LoI signed by 121 authors representing 20 Institutions from 7 countries.

arXiv:1408.3959 [hep-ex]
NICA-SPIN program approved by JINR PAC

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

Present status: CDR preparation


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arXiv:1408.3959 [hep-ex]
Requirements to the facility in polarized mode

- polarized and non-polarized p–; d–collisions
  - \( p^{\uparrow}p^{\uparrow}(p) \) at \( \sqrt{s_{pp}} = 12 \div 27 \text{ GeV} \) (5 \( \div \) 12.6 GeV kinetic energy)
  - \( d^{\uparrow}d^{\uparrow}(d) \) at \( \sqrt{s_{NN}} = 4 \div 13 \text{ GeV} \) (2 \( \div \) 5.5 GeV/u kinetic energy)
- \( L_{\text{average}} \approx 1 \cdot 10^3 \text{ cm}^{-2}\text{s}^{-1} \) (at \( \sqrt{s_{pp}} \geq 27 \text{ GeV} \))
- 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)*

**BM@N**

- Fixed target area
- KRION-6T and HILac (3.5 MeV/u)
- SPI and LU-20 (5 MeV/u)
- Cryogenics

**SPD**

- Spin Physic Detector
- NICA Collider (1-4.5 GeV/u, C~500 m)
- Booster (3-600 MeV/u)
- Nuclotron 0.6-4.5 GeV/u

**MPD**

- Multi-Purpose Detector
- HV e-cooler

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NICA operation in Polarized Mode (1)

- Polarized $dd$ – collisions: $\text{SPI} \rightarrow \text{LU-20M} \rightarrow \text{Nuclotron} \rightarrow \text{Collider}$
- Polarized $pp$ – collisions: $\text{SPI} \rightarrow \text{LU-20M} \rightarrow \text{Nuclotron} \rightarrow \text{Collider}$
- Polarized $pd$ – collisions: no final scheme yet

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NICA operation in Polarized Mode (2)

- $d^\uparrow$ - accelerated at the Synchrophasotron in 1986; at the Nuclotron in 2002. No dangerous spin resonances up to 5.6 GeV/u.

- $p^\uparrow$ - never been accelerated at the LHEP facility.

The problem with $p^\uparrow$ (at Nuclotron or NICA booster) – numerous spin resonances.
NICA operation in Polarized Mode (2)

• $d^\uparrow$- accelerated at the Synchrophasotron in 1986; at the Nuclotron in 2002. No dangerous spin resonances up to 5.6 GeV/u.

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The problem with $p^\uparrow$ (at Nuclotron or NICA booster) – numerous spin resonances.

Solution: $p^\uparrow$ acceleration up to 5-6 GeV at Nuclotron with dynamic solenoid Siberian snake $\rightarrow$ transfer to collider rings $\rightarrow$ 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

\[ (B || L)_{\text{max}} = 21 \text{ T} \cdot \text{m} \]

\[ \alpha_y = \pi / 2 \]

\[ E_{\text{max}} = 6 \text{ GeV} \]

Partial Siberian Snake

\[ (B || L)_{\text{max}} = 10.5 \text{ T} \cdot \text{m} \]

\[ \alpha_y = \varphi_z / 2 \]

angle between polarization and vertical axis

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The Snake: Previous scheme of the insertion
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

The diagram displays the regions of \( \cos(2\pi\nu_x) \) and \( \cos(2\pi\nu_y) \) values for different normalized gradients of focusing \( K_z \) and defocusing \( K_x \) quads. The diagram consists of repeated areas of white, black, grey and red colours.

- betatron motion is stable
- on the edge of black regions the values of cosines are \( \pm 1 \), i.e., condition of the integer resonances \( \nu_z = k \) are fulfilled.
- on the edge of grey regions the values of cosines are \( \mp 1 \), i.e., condition of the half-integer resonances \( \nu_z = k \pm 1/2 \) are fulfilled.
- on the edge of red regions the values of cosines coincide, i.e., condition of the coupling resonances \( \nu_y = k \pm \nu_x \) are fulfilled.

IPAC2014, Dresden, June 2014

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Critical current of the improved Nuclotron magnets at $B = 2\, \text{T}$, $\frac{dB}{dt} = 4\, \text{T/s}$, $f = 1.0\, \text{Hz}$ exceed $8000\, \text{A}$. 
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 ($\sim 5\% @ \frac{dB}{dt} = 4 \text{T/s}$)

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

$p = (2.5 \div 13) \text{GeV/c}$

protons: $(B_{||L})_{\text{max}} = 4 \times (5 \div 25) \text{ T} \cdot \text{m}$

deuterons: $(B_{||L})_{\text{max}} = 4 \times (15 \div 80) \text{ T} \cdot \text{m}$
Polarization control in the Collider by means of small longitudinal field integrals

\[ S_{MPD} = \tilde{e}_y \sin \Psi_{MPD} + \tilde{e}_z \cos \Psi_{MPD} \]

\[ S_{SPD} = \tilde{e}_y \sin \Psi_{SPD} + \tilde{e}_z \cos \Psi_{SPD} \]

\[ \Psi_{MPD} = \gamma G \pi + \Psi_{SPD} \]

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

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

\[ \varphi_{zi} = \left(1 + G\right) (B_{\parallel}L)_i / B \rho \]

- the spin rotation angles in the solenoids

\[ \varphi_y = \gamma G \alpha \]

- the spin rotation angle between weak solenoids

\[ \alpha \]

- the orbit rotation angle between the weak solenoids

\[ \Psi_{SPD}, \Psi_{MPD} \]

- the angles between the polarization and velocity directions in SPD and MPD detectors
Polarization control scheme for $p$ and $d$ in NICA collider (1)

<table>
<thead>
<tr>
<th></th>
<th>number</th>
<th>$B_{\text{max}}, T$</th>
<th>$L, m$</th>
<th>$BL, T \cdot m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main tune shifts solenoid</td>
<td>8</td>
<td>7,3</td>
<td>5,5</td>
<td>0÷40</td>
</tr>
<tr>
<td>Weak solenoid for polarization control (red)</td>
<td>6</td>
<td>1,5</td>
<td>0,4</td>
<td>0÷0,6</td>
</tr>
</tbody>
</table>
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 polarimetry.
NICA pp-collisions peak luminosity

\[ L_{\text{peak}} \approx 1.8 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \]

Particle number per bunch in \(10^{11}\) units maximum proton number in each ring - \(2.2 \times 10^{13}\)

**IP parameters:** \( \beta = 35 \text{ cm},\) bunch length \( \sigma = 60 \text{ cm} \) (not optimized), **bunch number** - 22, collider perimeter \(C = 503 \text{ m}\)

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Polarized pp-collisions: average luminosity

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

\[ L \approx 0.7 \quad L_{\text{peak}} \approx 1.26 \times 10^{32} \text{ cm}^{-2}\cdot\text{s}^{-1} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclotron Dipole Field Ramp up, T/s</td>
<td>0.6</td>
</tr>
<tr>
<td>Nuclotron Dipole Field Ramp down, T/s</td>
<td>1.0</td>
</tr>
<tr>
<td>Magnet field flat top duration, s</td>
<td>0.5</td>
</tr>
<tr>
<td>Total useful cycle duration, s</td>
<td>3.17</td>
</tr>
<tr>
<td>Dipole Magnetic Field at 6 GeV protons, T</td>
<td>( \sim 1 )</td>
</tr>
<tr>
<td>Acceleration time, s</td>
<td>1.67</td>
</tr>
<tr>
<td>Number of accelerated protons per pulse</td>
<td>( 7 \times 10^{10} )</td>
</tr>
<tr>
<td>Number of cycles to store ( 2 \times 10^{13} ) particles</td>
<td>285</td>
</tr>
<tr>
<td>Collider filling time at cycle duration 5s, s</td>
<td>1425</td>
</tr>
<tr>
<td>Preparation of the beam in the collider (cooling, bunching emittance formation), s</td>
<td>1000</td>
</tr>
<tr>
<td>Magnetic field ramp in the collider, T/s</td>
<td>0.6</td>
</tr>
<tr>
<td>Acceleration time from 6 GeV to 12.6 GeV</td>
<td>( \sim 1.7 )</td>
</tr>
<tr>
<td>Luminosity life time (30% polarization degradation due to spin resonances), s</td>
<td>5400</td>
</tr>
<tr>
<td>Beam deceleration up to the new injection</td>
<td>( \sim 1.7 )</td>
</tr>
<tr>
<td>Total cycle duration, s</td>
<td>7825</td>
</tr>
<tr>
<td>Working part, %</td>
<td>( \sim 70 )</td>
</tr>
</tbody>
</table>
The first round of Russian state expertise have been passed;
Goal for 2014: start area construction works for NICA collider looks feasible.
• 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
A possibility to use Nucleotron as a polarized proton source in NICA collider for polarized target of 6 GeV was discussed since 2011. To preserve the polarization in the Nucleotron II was proposed a solenoid Siberian snake. Solenoid impact on spin very efficiently, but beam focusing is determined mainly by quadrupoles. The condition of beam coupling compensation does not required to maintain a stable coherent motion. The beam stability of the NICA collider is not as critical as the requirement of coherent motion. The influence of the solenoid on the coherent motion has been analyzed in the framework of the model of solenoidal interaction of the beam and magnetic field, which takes into account the non-linear dependence of the magnetic field in the solenoid on the magnetic field in the solenoid. The model of the solenoidal interaction of the beam and magnetic field, which takes into account the non-linear dependence of the magnetic field in the solenoid on the magnetic field in the solenoid, has been developed. The model allows to the calculation of the beam interaction with the magnetic field in the solenoid. The calculation results show that the solenoid has a significant impact on the beam stability and can be used as a polarized proton source in the NICA collider.