Polarized Hadron Beams in NICA Project

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Introduction: Physics at NICA

Spin Physics at NICA

The SPD program includes the studies of
- Drell-Yan processes,
- J/Ψ production processes,
- Spin effects in elastic $p\uparrow p\uparrow$, $p\uparrow d\uparrow$
  and $d\uparrow d\uparrow$ scattering,
- Spin effects in inclusive high-pT reactions,
- Polarization effects in heavy ions collisions.

Polarized beams of protons and deuterons:
(both longitudinal and transverse polarizations)

$p\uparrow p\uparrow \sqrt{s_{pp}} = 12 \div 27$ GeV ($5 \div 12.6$ GeV kinetic energy)
$d\uparrow d\uparrow \sqrt{s_{NN}} = 4 \div 13.8$ GeV ($2 \div 5.9$ GeV/u ion kinetic energy)
$L_{\text{average}} \geq 1E30$ cm$^{-2}$s$^{-1}$ (at $\sqrt{s_{pp}} = 27$ GeV)
1. Facility Scheme and Operation Scenario

**NICA Layout**

**Fixed target experiments**

- Nuclotron beam transfer line
- Synchrophasotron yoke
- SPI & LU-20 ("Old" linac)

**Beam transfer lines & New research area**

- Collider: $C = 534 \, \text{m}$
- Spin Physics Detector (SPD)
- Booster
- Nuclotron

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1. Facility Scheme and Operation Scenario (Contnd)

Polarized proton acceleration (Contnd)

Source of Polarized Ions (SPI)

LU-20: $2 \times 10^{10}$ ions/pulse of 
$\uparrow d$ (5 MeV/u) or $\uparrow p$ 20 MeV

Collider (45 Tm)
Storage of 30 bunches by $1 \times 10^9$ $p \uparrow$ per ring at 5 - 12 GeV, No cooling!

Below 1\textsuperscript{st} dangerous resonance in the Booster ⇒ To be analyzed!

Booster (25 Tm)
1(2-3) single-turn injection, 
storage of $2 \times 10^9$ $p \uparrow$, acceleration up to 50 MeV,
electron cooling, extraction

Nuclotron (45 Tm)
injection of one bunch of $1.1 \times 10^9$ ions, 
acceleration up to 12 GeV max.

2x30 injection cycles

## Spin resonances

<table>
<thead>
<tr>
<th>Type of resonance</th>
<th>Resonance condition</th>
<th>Total number of resonances at acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Intrinsic res.</td>
<td>$\nu_{\text{spin}} = kp \pm Q_y$</td>
<td>6</td>
</tr>
<tr>
<td>2. Integer res.</td>
<td>$\nu_{\text{spin}} = k$</td>
<td>25</td>
</tr>
<tr>
<td>3. Nonsuperperiodic</td>
<td>$\nu_{\text{spin}} = m \pm Q_y$, $m \neq kp$</td>
<td>44</td>
</tr>
<tr>
<td>4. Coupling res.</td>
<td>$\nu_{\text{spin}} = m \pm Q_x$</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>$p^{\uparrow}$ 0 - 12 GeV</td>
<td>$d^{\uparrow}$ 0 - 6 GeV/u</td>
</tr>
<tr>
<td></td>
<td>$(5.6 \text{ GeV/u})$</td>
<td></td>
</tr>
</tbody>
</table>

$\nu_{\text{spin}}$ - spin precession tune, $Q_{x,y}$ - betatron tunes
$k, m$ - integers, $p$ - number of superperiods ($8$ for Nuclotron)

Power of the spin resonances: $w_{1,2} >> w_{3,4}$

Thus, no problem for $d^{\uparrow}$ acceleration in Nuclotron
2. Polarized Protons and Deuterons Acceleration in Nuclotron

**Spin resonances at Nuclotron**

- **dB/dt = 1 T/s**
- **1. Intrinsic res.** \( \nu_{\text{spin}} = kp \pm Q_y \)
- **2. Integer res.** \( \nu_{\text{spin}} = k \)

![Graph showing resonance strengths](image)

Here \( w \) is the resonance strength: \( w \sim 1/(2n_\theta) \), where \( n_\theta \) is turn number at exact resonance that is sufficient for spin overturn (at \( dB/dt = 0 \)).

\( w_D \) is the resonance strength that produces full depolarization at “free” crossing of the resonance at given crossing speed at given \( dB/dt \) (or \( d\gamma/dt \)).

(In other words: one has to choose a crossing speed and calculate \( w_D \) for it; then to compare actual resonance strength \( w \) with \( w_D \)).
Spin resonances at Nuclotron


\[ \nu_{\text{spin}} = m \pm Q_y, \ m \neq kp \]

4. Coupling res.

\[ \nu_{\text{spin}} = m \pm Q_x, \ m \neq kp \]

Not any resonance is dangerous!

There are three Types of Spin resonances at Nuclotron:

- above blue line - strong resonance: particle crosses it without polarization loss (regime of adiabatic crossing, see further),
- below green line - a weak resonance, particle crosses it “free”,
- between both lines - intermediate (see further).
Not any resonance is dangerous!

Dangerous resonances are marked with red caps.

1. Intrinsic res. $\nu_{\text{spin}} = kp \pm Q_y$

2. Integer res. $\nu_{\text{spin}} = k$

3. Nonsuperperiodic res. $\nu_{\text{spin}} = m \pm Q_y$, $m \neq kp$

4. Coupling res. $\nu_{\text{spin}} = m \pm Q_x$, $m \neq kp$

2. Polarized Protons and Deuterons Acceleration in Nuclotron (Contnd)

Polarized proton acceleration in Nuclotron: Transparent Crossing of spin resonances

\[ J_{\text{after}} = \mp J_{\text{before}} \]

\( J \) is a Spin Adiabatic Invariant, i.e. projection to the periodical \( n \)-axis
2. Polarized Protons and Deuterons Acceleration in Nuclotron (Contnd)

Polarized proton acceleration in Nuclotron:
Transparent Crossing of spin resonances

Spin Tune Control System (STCS)

Dynamics of the Spin Orbit Vector (SOV) $\vec{n}$

$\Delta \nu_{\text{Spin}} = \frac{\varphi_x \cdot \varphi_y}{2\pi}$ per 1 turn, $\varphi_x, \varphi_y << 1$

Closed orbit distortion less than 0.5 cm
### Polarized proton acceleration in Nuclotron (Contnd)

#### 2. Polarized Protons and Deuterons Acceleration in Nuclotron (Cont'd)

**STCS parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dipole</th>
<th>Solenoid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements</td>
<td>$1 \times 1 + 2 \times 0.5$</td>
<td>$2 \times 1 + 2 \times 0.5$</td>
</tr>
<tr>
<td>Regime</td>
<td>Pulsed mode</td>
<td>Cycling mode</td>
</tr>
<tr>
<td>Winding type</td>
<td>Normal</td>
<td>Superconductive</td>
</tr>
<tr>
<td>Pulse duration (period)</td>
<td>$\sim 320 \mu \text{sec}$</td>
<td>$\sim 4 \text{ sec}$</td>
</tr>
<tr>
<td>Repetition rate, $s^{-1}$</td>
<td>$\sim 5.0$</td>
<td>0.25</td>
</tr>
<tr>
<td>Length, mm</td>
<td>575</td>
<td></td>
</tr>
<tr>
<td>Aperture, mm</td>
<td>hor. 108</td>
<td>hor. 108</td>
</tr>
<tr>
<td></td>
<td>ver. 56</td>
<td>ver. 108</td>
</tr>
<tr>
<td>Magn. field, T</td>
<td>0.59</td>
<td>5.0</td>
</tr>
<tr>
<td>Max. current, kA</td>
<td>26.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Max. voltage</td>
<td>5.75 kV</td>
<td>35.0 V (SC)</td>
</tr>
</tbody>
</table>

$L_{\text{total}} \approx 3.5 \text{ m}$

2. Polarized Protons and Deuterons Acceleration in Nuclotron (Contnd)

Polarized proton acceleration in Nuclotron (Contnd)

Proton Energy Spread Limitation at Transparent Crossing of a Resonance

The condition to be met:

If \( \frac{\Delta \gamma}{\gamma} < \frac{w_D}{\gamma} \) when \( D<0,1 \ D_0 \)  

If \( \frac{\Delta \gamma}{\gamma} < \frac{w_D}{2\gamma} \) when \( D<0,01 \ D_0 \)

\( D, D_0 \) - the beam depolarization at the transparent resonance crossing with STCS application and without it, correspondingly.

This gives at \( dB/dt = 1 \ T/s \) at \( 2 \ T \) dipole field

\[
\begin{align*}
D<0,1 \ D_0 & \text{ if } \frac{\Delta \gamma}{\gamma} < 7,3 \times 10^{-4} \text{ or } \frac{\Delta \gamma}{\gamma} < 1,2 \times 10^{-4} \ (E=5\text{GeV}), \quad \frac{\Delta \gamma}{\gamma} < 5 \times 10^{-5} \ (E=12\text{GeV}) \\
D<0,1 \ D_0 & \text{ if } \frac{\Delta \gamma}{\gamma} < 7,3 \times 10^{-4} \text{ or } \frac{\Delta \gamma}{\gamma} < 6 \times 10^{-5} \ (E=5\text{GeV}), \quad \frac{\Delta \gamma}{\gamma} < 2,5 \times 10^{-5} \ (E=12\text{GeV})
\end{align*}
\]

However, such a low \( \Delta p/p \) requires \textit{e-cooling} application (!) that is available at The Booster.

An option: acceleration up to 5 GeV and extraction into collider for further acceleration (revolution frequency variation ≤ 1.3%) up to 12 GeV max. Depolarization at acceleration in the collider is suppressed by Siberian Snake (see further).

Then depolarization after transparent crossing of all 8 resonances is < 5%.
3. Polarized Particle Dynamics in NICA Collider

Longitudinal and transverse polarization formation

- Second part of Siberian Snake with longitudinal axis
- First part of Siberian Snake with longitudinal axis
- Spin rotators around vertical direction by $\pi/4$
- Spin rotators around vertical direction by $-\pi/4$

Injection channels
3. Polarized Particle Dynamics in NICA Collider (Contnd)

Longitudinal Polarization Formation: Dipole Siberian Snake (Contnd)

First part of Siberian Snake with longitudinal axis

1st half of the Snake: protons, 5.4 GeV ($\gamma = 6$),
14 dipoles x 0.31+0.1 m, $B_{\text{max}} = 5$ T, $L_{\text{total}} = 5.64$ m

3. Polarized Particle Dynamics in NICA Collider (Contnd)

Longitudinal Polarization Formation: Dipole Siberian Snake (Contnd)

Second part of Siberian Snake with longitudinal axis

Second half of the Snake: protons, 5.4 GeV (γ = 6),
14 dipoles x 0.31+0.1 m, B_{max} = 5 T, L_{total} = 5.64 m
3. Polarized Particle Dynamics in NICA Collider

Transverse Polarization Formation: Radial Polarization

The scheme of vertical spin rotator by \( \pi/4 \)

\[ \gamma = 14, \ B_x = 5T, \ L_x = 49\text{cm}, \ B_z = 10T, \ L_z = 62\text{cm}, \ \delta L = 10\text{cm}, \ L_{\text{tot}} = 4.398\text{m}. \]

Total length of vertical spin rotator by \( \pi/2 \) is 2x4.4m
Longitudinal polarization $\Rightarrow$ injection scheme

$$\alpha_\perp(\gamma) = \frac{(BL)_{dipole}}{(B\rho)_{ion}} \cdot (1 + \gamma a)$$

4. Luminosity of $p^+p^+$ colliding beams

Parameters of polarized proton beams in collider

<table>
<thead>
<tr>
<th></th>
<th>5</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proton number per bunch</td>
<td>6E10</td>
<td>1.5E10</td>
</tr>
<tr>
<td>Rms relative momentum spread</td>
<td>10E-3</td>
<td>10E-3</td>
</tr>
<tr>
<td>Rms bunch length, m</td>
<td>1.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Rms (unnormalized) emittance, $\pi\cdot$mm$\cdot$mrad</td>
<td>0.24</td>
<td>0.027</td>
</tr>
<tr>
<td>Beta-function in the IP, m</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Lasslet tune shift</td>
<td>0.0074</td>
<td>0.0033</td>
</tr>
<tr>
<td>Beam-beam parameter</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Luminosity, cm$^{-2}\cdot$s$^{-1}$</td>
<td>1.1E30</td>
<td>1.1E30</td>
</tr>
</tbody>
</table>
Conclusion:

Realization of polarized beam program at Nuclotron and Collider looks feasible. Its development will bring experimental studies in spin physics at JINR to a new level.

Thank you for your attention!