Polarized hadrons beams in NICA project

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Abstract. The report is dedicated to the problem of formation and maintenance of polarized proton and deuteron colliding beams in the collider of Nuclotron-based Ion Collider fAcility (NICA). The NICA project is under development at JINR presently. The schemes of polarized proton and deuteron beams acceleration in the superconducting synchrotron Nuclotron and formation of both longitudinal and transverse particle polarization in the collider are presented. The problems of long term conservation of the beams polarization in the collider are discussed as well.

1. The spin physics at NICA
The project of the Nuclotron-based Ion Collider fAcility and Multipurpose Physics Detector (NICA/MPD) is presently under development at the Joint Institute for Nuclear Research JINR [1]. The facility consists of both, heavy ions and polarized protons and deuterons injectors, the Booster — super conducting (SC) synchrotron, SC synchrotron Nuclotron and two colliding rings. The collider has two interaction points (IP). The first is occupied by MPD, the second one by Spin Physics Detector (SPD). The last one is dedicated to spin physics program that includes [2]:

- Drell-Yan processes,
- \(J/\Psi\) 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-\(p_T\) reactions,
- Polarization effects of heavy ions collisions.

Realization of this program requires both longitudinal and transversal polarized beams of protons (\(\sqrt{s_{pp}} = 12 \div 27\) GeV) and deuterons (\(\sqrt{s_{nn}} = 4 \div 13.8\) GeV). Average collider luminosity is designed to be above \(10^{30}\) cm\(^{-2}\) s\(^{-1}\) (at \(\sqrt{s_{pp}} = 27\) GeV for protons beams). The Nuclotron is used as a booster-synchrotron for the collider. Therefore we consider first of all acceleration of polarized beams in the Nuclotron and then formation and maintenance of polarization in collider rings.

2. Polarized protons and deuterons acceleration in Nuclotron
The main destruction of the beam polarization in Nuclotron occurs at crossing of spin resonances. The linear approximation resonances are the most influencing ones on spin motion (Table 1).
| Type of resonance | Resonance condition | Number of resonances protons | Number of resonances deuterons |
|-------------------|---------------------|-----------------------------|-----------------------------|
| Intrinsic         | \( \nu_s = kN \pm Q_y \) | 6                           | -                           |
| Integer           | \( \nu_s = k \)       | 25                          | 1                           |
| Nonsuperperiodic  | \( \nu_s = k \pm Q_y \) (\( k \neq m p \)) | 44                          | 2                           |
| Coupling          | \( \nu_s = k \pm Q_x \) | 49                          | 2                           |

There \( k \) and \( m \) are integer numbers, \( N = 8 \) is super-period number of the Nuclotron lattice, \( Q_y, Q_x \) are the betatron tunes in the Nuclotron.

For deuterons number of the spin resonances is very small due to low value of \( G = -0.143 \). Only dangerous is the integer resonance with the spin tune \( \nu_s = -1 \). It can be crossed adiabatically by application of rather low longitudinal magnetic field. Therefore we consider below the problems related to polarized protons beams only.

To estimate a resonance influence on spin dynamics we use below dimensionless characteristic resonance strength \( w_d = \sqrt{\varepsilon'/\pi} \) that causes practically complete beam depolarization at crossing of resonance with the speed \( \varepsilon' \). The \( \varepsilon' \) parameter is proportional to the rate of the Nuclotron dipole field growth. At the rate of 1 T/s these parameters are equal to \( \varepsilon' = 1.7 \cdot 10^{-6}, w_d = 0.73 \cdot 10^{-3} \).

In Figure 1 the logarithms of linear resonance strengths are presented in units of characteristic resonance strength \( w_d \) versus the kinetic energy of protons \( E_k \) in Nuclotron energy range [3]. We used when calculating the normalized both horizontal and vertical emittances equal to 0.4\( \pi \) mm mrad, the errors of quadrupoles positioning of 0.1 mm and the errors of dipole magnet misalignments of 1.0 mrad. Horizontal lines divide the area of resonances in three parts depending of resonance strength: intermediate crossing of a resonance (area between solid and
dashed lines), fast ones (below dashed line) and adiabatic ones (above solid line). Resonances located in area of intermediate crossing provoke the beam depolarization.

To cross any resonance one can apply so called transparent resonance crossing (TRC) method [4]. It is based on reconstruction of the spin adiabatic invariant (spin projection on the periodic precession axes) by variation of spin tune in resonance area. This variation can be produced with additional magnets fields in the ring. Then spin tune is determined not only by particle energy but also by additional magnetic fields: \( \nu(B) = \nu_0 + \Delta \nu(B) \).

One can use the spin tune control structure (STCS) with longitudinal and radial magnetic fields (Figure 2), which has the first and second integrals along the trajectory equal to zero. Such a scheme does not provoke a coupling among vertical and radial betatron oscillations as well.

\[
\begin{align*}
-\varphi_s/2 & \quad \varphi_s/2 & \quad \varphi_s & \quad -\varphi_s & \quad -\varphi_s & \quad \varphi_s/2 & \quad \varphi_s/2 \\
L_s/2 & \quad L_s/2 & \quad L_s & \quad L_s & \quad L_s/2 & \quad L_s/2 & \quad L_s/2
\end{align*}
\]

**Figure 2.** The spin tune control system (STCS); S-solenoid, H- fast cycling dipole.

In approximation of small angles of the spin rotations (\( \varphi_x, \varphi_s \ll 1 \)) the polarization remains vertical after STCS crossing, but spin tune shift becomes equal to \( \Delta \nu = \varphi_x \varphi_s / (2\pi) \).

For TRC one can apply, for instance, sinusoidal dependence of the spin tune shift on time (Figure 3). During resonance crossing one can keep solenoid magnetic field constant. Then dipole magnetic field has to be varied proportionally to spin tune shift. At Nuclotron magnetic field rate of 1 T/s the period of variation of STCS fast dipole fields is of the order of 270 \( \mu \)s at any particle energy. The STCS elements have the following lengths: solenoids — \( L_s = 33.3 \) cm, dipoles — \( L_x = 50 \) cm, and total length of the STCS (including technical gaps) is of \( L_{\text{tot}} = 3.2 \) m. Maximum displacement of the particle equilibrium orbit in vertical plane is of the order of 0.5 cm. Maximum fast dipole field \( B_x \text{ max} \) depends both on particle energy and on maximum solenoid field, \( B_s \text{ max} \). For instance if \( B_s \text{ max} = 5 \) T and \( \gamma = 14 \) the dipole field \( B_x \text{ max} \approx 720 \) G.

At application of TRC method there are limitations related to the particle momentum (energy) spread over the beam. In the example with sinusoidal STCS field shown above the allowed proton energy spread can be estimated as follows:

\[
\frac{\Delta \gamma}{\gamma} < \begin{cases} 
\frac{w_d}{\gamma} & \text{then } D < 0.1D_0 \\
\frac{w_d}{(2\gamma)} & \text{then } D < 0.01D_0
\end{cases}
\]

Here \( D_0 \) is beam depolarization degree without TRC method application, \( D \) — when TRC method is applied. Let’s consider a numerical example of resonance crossing, which has such a strength that a beam after crossing is completely depolarized: \( D_0 = 100\% \). At field ramping rate of 1 T/s we find \( \Delta \gamma / \gamma < 7 \cdot 10^{-4} / \gamma \Rightarrow D < 10\% \), but at \( \Delta \gamma / \gamma < 3.5 \cdot 10^{-4} / \gamma \Rightarrow D < 1\% \). That demonstrates a necessity of a beam cooling application to have a high efficiency of TRC method.
3. **Longitudinal and transverse beam polarization in the NICA collider**

For longitudinal polarization of the proton beam we assume to use Siberian Snake that rotates spin vector by 180 degrees around longitudinal axis [5]. Figure 4 demonstrates the vector polarization dynamics (dark black arrows) in the collider ring.

\[
\Gamma = 6, \quad B = 5T, \quad L = 31cm, \quad \delta L = 20cm, \quad L_{tot} = 7m
\]

**Figure 4.** The scheme of longitudinal and transverse polarization control in the collider. Dark black arrows — longitudinal polarization, light-gray arrows — transverse ones.

Such a Snake can be constructed with dipole magnets of alternative transverse field directions. Full Siberian Snake consists of two parts by 7 m each one (Figure 4). The dipoles have equal lengths. Each part is placed in a free space of the MPD straight section in the ring. One can insert a few quadrupole lenses between two parts of the Siberian Snake. The displacement of particle equilibrium orbit inside Siberian Snake does not exceed of 2 cm (Figure 5). Dipole magnetic field integral over full Siberian Snake is equal to \((|B_{L}|L)_{tot} = 30.9 \, T \cdot m\).

\[
\Delta y, \Delta x, cm
\]

**Figure 5.** The proton orbit displacement in the 1\textsuperscript{st} part of the Siberian Snake. Here H indicates radial dipoles, V — vertical ones; the 2\textsuperscript{nd} part of the Siberian Snake is mirror-symmetric to the 1\textsuperscript{st} one, besides radial dipoles have opposite field direction.

The control of transverse (radial) polarization is provided with by four \(\pi/4\)-rotators around...
vertical direction. Two of them are installed in the SPD straight section — before and behind the detector. Two others are placed in the short straight section of the collider arcs (Figure 4, dashed arrows). Such a design allows us to use free spaces available in the short straight sections of the rings. The total length of the $\pi/4$-rotator is of 4.4 m. The maximum displacement does not exceed 18 mm (Figure 6).

$$\Delta y, \text{ cm}$$

![Diagram](image)

**Figure 6.** The proton orbit displacement in the $\pi/4$-rotator. Here S indicates solenoids, H — radial dipoles; $k_x = 0.45$, $k_s = 0.42$.

The proposed scheme of formation of the longitudinal and transverse polarization does work over all energy range of the Collider because Siberian Snake allows one to shift out all dangerous spin resonances (of linear approximation).

4. Conclusion
The presented spin control scheme in the collider is an interim version to be optimized when collider lattice is fixed finally. 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.

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