Acceleration of Polarized Protons up to 3.4 GeV/c in the Nuclotron at JINR

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Abstract. To preserve proton polarization in the Nuclotron up to 13.5 GeV/c, it is enough to use a partial solenoid snake with maximal field integral of 25 Tm that allows one to eliminate crossings of the most dangerous intrinsic and integer spin resonances. The insertion of weak field integral is sufficient to preserve the proton polarization up to 3.4 GeV/c. This momentum corresponds to the first intrinsic resonance. To preserve polarization during crossings of five integer spin resonances, it is possible to choose crossing rates that correspond to either the fast or the slow resonance crossings. Another possibility is a deliberate increasing of the resonance strength. To eliminate depolarization during protons injection into the Nuclotron, a scheme of matching of the polarization with a vertical direction is presented. During the run in February-March 2017, the three measurements of the proton polarization at kinetic energies of 0.5 GeV, 1 GeV and 2 GeV were made that allow one to obtain the integer spin resonances strengths.

1. Preservation of the proton polarization by the partial solenoidal snakes

The beam depolarization during acceleration of the protons at the Nuclotron occurs due to crossing of a large number of spin resonances. A full solenoidal snake allows one to suppress resonant depolarization of the proton beam and requires a longitudinal magnetic field integral of about 50 Tm at the maximum momentum of 13.5 GeV/c [1]. 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 by the proper choice of the betatron tunes. In the paper [2] it was shown that a solenoidal 50%-snake, which requires a field integral of 25 Tm at the maximum momentum and rotates the spin at 90 degrees around the longitudinal direction, allows one to preserve proton polarization and still leaves a lot of freedom in choosing the betatron tunes. 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 preserved without usage of solenoids with large field integrals up to the energy corresponding to the first intrinsic resonance. Spin tracking simulation had demonstrated that the 5% solenoid snake preserves proton polarization at the Nuclotron up to 3.4 GeV/c. The 5%-snake eliminates crossing of five integer spin resonances and requires the field integral of 0.65 Tm at the momentum of 3.4 GeV/c [2]. The value of the longitudinal field integral can be reduced further, but then it is necessary to take into account the synchrotron modulation of the energy. The rough estimations show that the weak solenoid with field integral of 0.06 Tm eliminates polarization losses during protons acceleration up to 3.4 GeV/c.
2. Preservation of the proton polarization without additional magnetic insertions

To preserve the polarization during protons acceleration without insertion of additional magnetic fields into the Nuclotron lattice it is sufficient to provide either the fast or the slow spin resonance crossings. To choose an appropriate field ramp rate at the moments of the crossing it requires detailed information on the values of the integer spin resonances strengths.

Such information can be obtained from the experimental data received in the run with the polarized protons (February-March 2017), when the following three proton polarizations at the Nuclotron

\[ P_1 = (34.5 \pm 2.4)\%, \quad P_2 = (12 \pm 1)\%, \quad P_3 = -(9 \pm 1)\% \]

were measured at the beam kinetic energies of 0.5 GeV, 1 GeV and 2 GeV correspondently [3,4].

Figure 1 shows the location of the polarization measurement points, as well as the location of five points of the integer spin resonances \( \gamma G = k \) (\( \gamma \) is a relativistic factor, \( G \) is a proton anomalous part of gyromagnetic ratio).

![Figure 1. Location of the polarization measurement points (red arrows) and of integer spin resonances points.](image)

Analysis of the experimental data shows that the loss of the beam polarization occurs for two reasons. The first reason is a matching of the proton polarization to vertical direction during beam injection to the Nuclotron ring (see the next section). The maximum initial polarization at the beam injection to the Nuclotron could not exceed the value of about 40% due to the polarization mismatching.

The spin resonances crossings are the second reason of the depolarization. The polarizations before and after crossing of the resonance region are connected by Froissart-Stora formula [5]

\[ P_{after} = \left[ 2 \exp \left( -\frac{\pi \omega^2}{2 |\epsilon'|} \right) - 1 \right] P_{before}. \]

Here \( \omega \) is the spin resonance strength, \( \epsilon' \) is resonance crossing rate which is proportional to the field ramp rate \( dB/dt \). In the experiments the field ramp rate was of 0.6 T/s and the corresponded resonance crossing rate was about of \( \epsilon' \approx 10^{-6} \). During fast resonance crossing (\( \epsilon' \gg \omega^2 \)) the polarization remains practically unchanged. At slow (adiabatic) resonance crossing (\( \epsilon' \ll \omega^2 \)) the polarization makes reversal and changes its sign. The polarization loss occurs at intermediate resonance crossing (\( \epsilon' \sim \omega^2 \)). The resonance strength corresponding to the intermediate crossing with a full beam depolarization is about of \( 5.7 \cdot 10^{-4} \) at the field ramp rate of 0.6 T/s.

The integer spin resonances occur due to manufacturing and alignment errors of the Nuclotron magnetic elements. The closed orbit distortion gives the main contribution to the resonance strength. Here we use a model of random quadrupole shifts. The accuracy of statistical model is determined by the number of the Nuclotron quadrupoles \( N_{quad} \) and in our calculations is about of \( 1/\sqrt{N_{quad}} \approx 10\% \).

The initial polarization \( P_{inj} \) at the Nuclotron injection and the rms deviation of the quadrupoles vertical shifts \( \sigma_{\Delta y} \) are used as the fitting parameters. The best fitting to the measured polarizations occurs when parameters are equal to \( P_{inj} \approx 39.2\% \) and \( \sigma_{\Delta y} \approx 0.86 \) mm. In this case our model gives the next results

\[ P_1^* = 34\%, \quad P_2^* = 12.2\%, \quad P_3^* = -8.3\%, \]

which are in good agreement with the measured polarizations. The integer spin resonances strengths obtained from experimental data are presented in table 1. Also table 1 shows the depolarization degree.
at crossing the resonance with $P_{\text{before}} = 100\%$ and the field ramp rates corresponding to the fast and slow crossing with 5% loss of the polarization after crossing of the resonance.

Table 1. The integer spin resonances strengths obtained from the experimental data.

| $\gamma_G$ | 2  | 3  | 4  | 5  | 6  |
|------------|----|----|----|----|----|
| $E_{\text{kin}}$, GeV | 0.108 | 0.632 | 1.155 | 1.679 | 2.202 |
| $\omega$, $10^{-4}$ | 2.09 | 4.96 | 10.8 | 23.6 | 57.5 |
| $D$, % | 13 | 63 | 33 | $\approx 0$ | $\approx 0$ |
| $(dB/dt)_{\text{fast}}$, T/s | 1.6 | 9.1 | 43 | 206 | 1220 |
| $(dB/dt)_{\text{slow}}$, T/s | 0.01 | 0.06 | 0.29 | 1.39 | 8.28 |

From table 1 it follows that the first resonance $\gamma_G = 2$ is crossed rather fast with 13% polarization loss relative to the initial value of the polarization $P_{\text{inj}}$. The main depolarization occurs at crossing of $\gamma_G = 3$ and $\gamma_G = 4$ resonances. The spin resonances $\gamma_G = 5$ and $\gamma_G = 6$ are crossed adiabatically without polarization losses. During each adiabatic crossing the polarization is flipped.

The decreasing field ramp rate by half provides the adiabatic crossing of the $\gamma_G = 4$ resonance with a 5% relative depolarization.

To reduce polarization losses down to 5% at the each $\gamma_G = 2$ and $\gamma_G = 3$ resonances it sufficient to increase the field ramp rate in the resonance regions up to 1.6 T/s and 9.1 T/s correspondently. The time of crossing the resonance region is about of a few milliseconds. Another possibility to reduce polarization losses is the decreasing the field ramp rate down to 0.01 T/s and 0.06 T/s. But at such a significant decrease of field ramp rate it is necessary to take into account the high order spin resonances and the synchrotron modulation of the energy.

The usage of combined spin resonance crossing techniques can be very efficient. A deliberate increase of the integer resonance strengths by means of the correcting dipoles allows one to reduce requirement on decreasing of the field ramp rate. In principal, it is possible to efficiently increase the resonances strength by correcting dipoles leaving acceptable closed orbit distortion. The influence of correcting dipoles on spin dynamics increases with increasing the beam energy. It becomes real to provide adiabatic crossing of all integer spin resonances by using correcting dipoles.

3. Matching the polarization direction at the injection of protons to the Nuclotron ring

The scheme of the beam polarization transportation from Source of Polarized Ions (SPI) [6] to the Nuclotron is shown in figure 2. At the SPI exit the polarization is directed vertically and keeps its orientation after passing the LU-20 linac. After passing the injection channel the polarization changes vertical direction. The proton polarization after beam injection to the Nuclotron ring is determined by the angle $\alpha$ between the polarization and vertical direction and equals to $\cos \alpha$ at the 100% polarization from SPI.

![Figure 2](image)

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The injection channel consists of three dipole magnets with different field directions (see table 2 and figure 3). The change of polarization direction after passing the injection channel occurs due to rotations around magnet’s field directions. Calculation shows that the initial polarization $P_{\text{inj}}$ at protons injection to the Nuclotron is of 39.2% if the polarization is directed vertically at the SPI exit. Additional rotation of the polarization could take place in the SPI solenoid, which is placed at the SPI exit. In this case calculation shows that the value of $P_{\text{inj}}$ could not exceed of 44.2%.
Table 2. Dipole magnet in the injection channel.

| Dipole      | \( K_{x1} \) (radial) | \( K_y \) (vertical) | \( K_{x2} \) (radial) |
|-------------|------------------------|-----------------------|-----------------------|
| Length, m   | 1.0                    | 2.4                   | 0.425                 |
| Orbital angle, rad | 0.272               | 0.944                 | -0.158                |

To match proton polarization with vertical direction at the injection to the Nuclotron it is sufficient to insert two solenoids into the injection channel as shown in figure 3.

![Figure 3. Placement of two solenoids into the injection channel for the polarization matching.](image)

Table 3 shows values of the solenoidal field’s integrals to obtain the proton polarization directed either upward or downward the vertical. Thus, the presented matching scheme allows one to make spin reversal during the beam injection into the Nuclotron.

Table 3. The vertical up and down polarization directions at proton injection to the Nuclotron.

| \((S_y)\) | \((B_{sol} L)\), T\cdot m | \((B_{sol} L)\), T\cdot m |
|----------|--------------------------|--------------------------|
| +1       | 0.249                    | -0.207                   |
| -1       | 0.115                    | 0.259                    |

Conclusion

Let us briefly summarize the main results:

- the weak solenoid with field integral of 0.06 T\cdot m eliminates polarization losses during protons acceleration up to 3.4 GeV/c,
- the information on the spin resonance strengths obtained from the experimental data allows one to accelerate protons up to 3.4 GeV/c with the polarization loss less than 15% without insertion of additional magnetic fields into the Nuclotron lattice.

Analysis of the measured polarizations allows one to draw the following conclusions:

- essential depolarization about of 60% occurs at injection protons into the Nuclotron ring,
- the proton polarization at the exit of the source of polarized ions (SPI) was about \((90 \pm 10)\%\),
- rms deviation of random quadrupole vertical shifts \(\sigma_{\Delta y}\) of about 1 mm causes the closed orbit distortion with maximum deviation is about \(\pm 2\) cm,
- measurements of polarization give valuable information on the orbital and spin parameters.

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