

# 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 crossing of spin resonances. For deuterons, the vertical polarization 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 T·m 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 T·m 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  $\gamma$  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  $\nu = k N \pm \nu_y$ . 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.

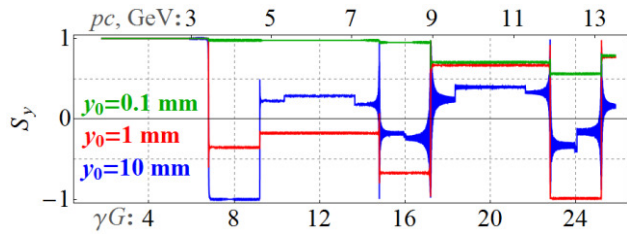


Figure 1: Changes of the proton vertical spin projections at the crossing of the intrinsic spin resonances.

### Integer Resonances

Random vertical quadrupole shifts give rise to a series of integer resonances  $\nu = k$ . 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  $\gamma G = 4$  with an intermediate crossing rate is the most dangerous.

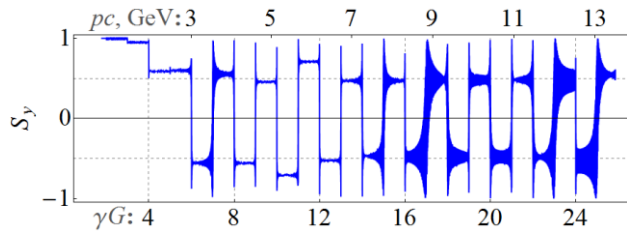


Figure 2: Change of the proton vertical spin projection at the crossing of the integer spin resonances.

### Coupling and Non-Super-Periodic Resonances

Random changes in quadrupole gradients give rise to a series of non-super-periodic resonances  $\nu = k \pm \nu_y$  ( $k \neq mN$ ). Random quadrupole rolls give rise to a series of coupling resonances  $\nu = k \pm \nu_x$ . 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  $G_D \approx -0.143$  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  $\Delta p/p = 0$  (the green curve),  $\Delta p/p = 10^{-3}$  (the red curve) and  $\Delta p/p = -10^{-3}$  (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  $\gamma G = -1$  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.

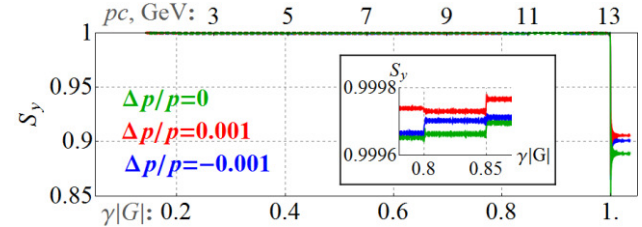


Figure 3: Change of the deuteron vertical spin projection at the crossing of the spin resonances in the Nuclotron.

## NUCLOTRON WITH A PARTIAL SNAKE

To preserve proton polarization over the total momentum 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].

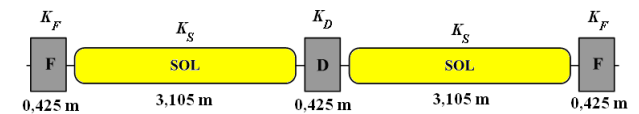


Figure 4: Layout of a 50% solenoidal snake without compensating quadrupoles.

For a partial snake the spin tune is determined by the equation:

$$\cos(\pi\nu) = \cos(\Psi/2) \cos(\pi\gamma G). \quad (1)$$

Variable  $\Psi$  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:

$$\cos(2\pi\nu_{x,y}) > \cos \Psi. \quad (2)$$

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.

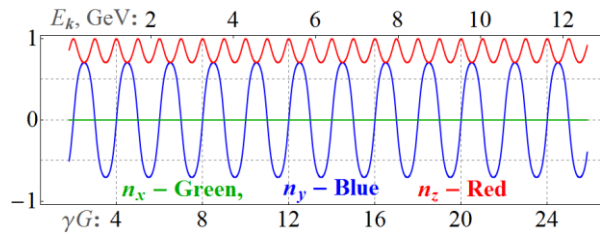


Figure 5: The  $\vec{n}$ -axis components at acceleration in the Nuclotron with the 50% solenoidal snake.

The spin projection  $S_n$  at  $\vec{n}$ -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/s. Thus, the spin, oriented originally along  $\vec{n}$ -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 Eq. (2), the betatron tunes are chosen  $\nu_x \approx 6.78$ ,  $\nu_y \approx 6.9$ . 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  $\vec{n}$ -axis.

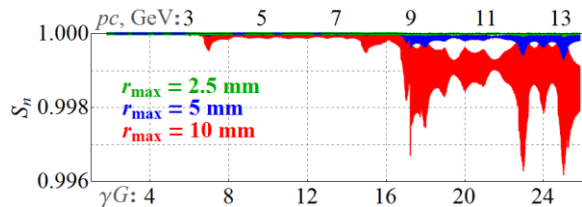


Figure 6: The  $S_n$  projections at acceleration of 3 protons in the Nuclotron with the 50% solenoidal snake.

The calculation confirms that proton spins practically do not deviate from the  $\vec{n}$ -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 7 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  $\gamma G = \nu_y = 6.8$  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  $\gamma G = 4$ , the depolarization loss is about 40%. The adiabatic spin flip occurs at the resonance  $\gamma G = 6$ . Figure 8 shows the vertical proton spin components during acceleration of three protons with different momenta in the Nuclotron with a 5% solenoid snake, which is re-

quired the solenoid field integral of 0.65 T·m at the momentum of 3.5 GeV/c.

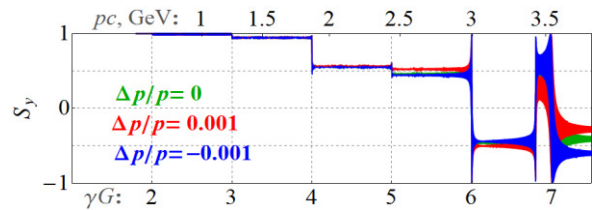


Figure 7: Vertical spin components at acceleration of protons with different momenta up to 3.5 GeV/c.

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.

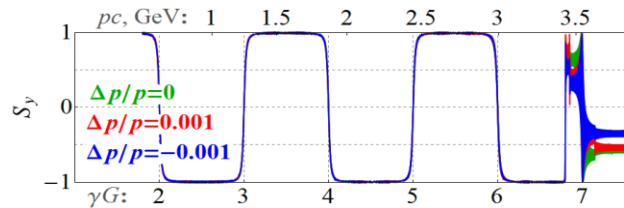


Figure 8: Vertical spin components at acceleration of protons in the Nuclotron with the 5% snake up to 3.5 GeV/c.

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  $\gamma G = 2$  was crossed without essential polarization loss. The intermediate crossing of the resonance  $\gamma G = 3$  leads to polarization loss about 75%. Crossing of the resonance  $\gamma G = 4$  flips the polarization. After measuring strengths of the integer resonances, it is possible to choose crossing rates that correspond to either the fast or the slow resonance crossings. The polarization of protons can be preserved without additional inserts up to 3.4 GeV/c.

## CONCLUSION

The presented calculations demonstrate the possibility of using the Nuclotron without additional magnetic inserts as an injector of polarized protons in the NICA collider 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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