Numerical calculation of ion polarization in the NICA collider

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Abstract. The NICA Collider with two solenoid Siberian snakes is “transparent” to the spin. The collider transparent to the spin provides a unique capability to control any polarization direction of protons and deuterons using additional weak solenoids without affecting orbital parameters of the beam. The spin tune induced by the control solenoids must significantly exceed the strength of the zero-integer spin resonance, which contains a coherent part associated with errors in the collider’s magnetic structure and an incoherent part associated with the beam emittances. We present calculations of the coherent part of the resonance strength in the NICA collider for proton and deuteron beams.

1. Introduction

The NICA collider is setup in the “spin transparency” mode using two solenoidal snakes inserted in its opposite straights (see figure 1) [1]. The spin transparency mode means that the influence of the fields generated by the two solenoidal snakes and the collider’s arcs does not change the spin direction from turn to turn, i.e. the magnetic system is transparent for the spin. The NICA collider with two solenoidal snakes becomes similar to the figure-8 collider project at JLAB [2].

![Figure 1. Polarization control scheme in the NICA spin transparency mode.](image-url)

The control of the beam polarization is provided by means of polarization control insertions (PC insertions) based on the weak-field solenoids [3, 4].
• to provide polarization control of any ion species ($p$, $d$, $^3He$, ...),
• to provide any direction of polarization in the vertical plane of SPD and MPD detectors,
• to solve the problems of spin matching at injection in the NICA collider and polarization measurement as well,
• to eliminate resonant beam depolarization during acceleration,
• to realize spin-flipping system,
• to control polarization at SPD and MPD detectors without any change of beam orbital characteristics.

The required weak field integrals are limited by the strength of the zero-integer spin resonance $\omega$. For stability of the beam polarization, the spin tune $\nu$ induced by the PC solenoids must significantly exceed the strength of the zero-integer spin resonance: $\nu \gg \omega$.

Let us calculate the spin resonance strength to estimate required weak field integrals of PC solenoids for proton and deuteron beams.

2. Strength of the zero-integer spin resonance in the NICA collider

The resonance strength is the value of the average spin field, which is determined by deviation of the trajectory from the ideal design orbit. The resonance strength consists of two parts: a coherent part arising due to additional dipole and longitudinal fields on a trajectory deviating from the design orbit and an incoherent part associated with betatron and synchrotron oscillations of ions (beam emittances). The coherent part of the resonance strength is determined by the linear approximation in orbit deviations and lies in the orbit plane. The incoherent part of the resonance strength is determined by the second approximation in orbit deviations and is significantly less than the coherent part.

The coherent part of zero-integer spin resonance induced by perturbing radial field $h_x$ can be calculated using periodical response function $F(z)$ ($z$ is a particle coordinate along the orbit):

$$\omega_{\text{coherent}} = \gamma G \langle h_x(z) F(z) \rangle .$$

The response function is only determined by the design collider lattice. Perturbing radial fields arise, for example, due to dipole roll errors, vertical quadrupole misalignments, etc.

Figure 2 shows graphs of the response functions in the NICA collider at momentum of 13.5 GeV/c for proton and deuteron beams, respectively. The lattices of the NICA collider with proton and deuteron solenoidal snakes are presented in paper [5].

Let us calculate the coherent part of the spin resonance strength using a statistical model of quadrupole misalignments in vertical direction. Figure 3 shows calculated dependence of the resonance strength $\omega_{\text{coherent}}$ on the proton and deuteron momenta, respectively, when the orbit
For protons in the presented examples, the coherent part of the resonance strength does not exceed $\sim 10^{-3}$ almost in all momentum range, except for two ranges near of 8 and 13 GeV/c with peak values of $3.5 \cdot 10^{-3}$ and $6 \cdot 10^{-3}$. It is due to that the response function depends on the collider lattice and the spin rotation angle in each arc’s dipole. One can suppress the peak values down to $10^{-4} \div 10^{-3}$ by means of collider lattice optimization. Besides, it is useful to minimize the response function in the experimental straights to reduce their contribution to the resonance strength, which is about 85% in the considered example (see figure 2). Thus, one can use PC solenoids with integral field of $1 \times 0.6$ m for the protons polarization control. Such PC solenoids can provide the spin tune value of $10^{-2}$ in the all collider energy range.

Let us pay attention to the control of deuteron beam polarization. The coherent part of the resonance strength for deuterons does not exceed $\sim 10^{-6}$ in the all collider momentum range and is approximately three orders of magnitude lower than for protons. Thus, the spin tune value of $10^{-4}$ is surely sufficient for the deuteron polarization control. The field of the one PC solenoid is only 0.03 T at length of 0.6 m. The ramp field time of such a solenoid can be a few milliseconds. There is unique opportunity to arrange fast spin reversals in the detector for all bunches simultaneously during the experiment. The fast spin-flipping system would cardinaly solve the problem of experimental systematic errors related to the uncertainty of a relative bunch-by-bunch luminosity.

3. The NICA collider for high precision experiments with polarized proton and deuteron beams

There is additional option for improvement of a polarized beam quality by the compensation of the coherent part of the zero-integer spin resonance strength. It is sufficient to use the existing collider control PC insertions (see figure 5). The first PC insertions located in the straight containing the interaction point directly control the polarization. The second PC insertions with constant solenoid fields are located in the other straight and are used to compensate the coherent part of resonance strength.
Conclusion
In summary, one can draw the following conclusions:

• for stability of ion polarization at the NICA collider in spin transparency mode, the spin tune induced by the PC solenoids must significantly exceed the strength of the zero-integer spin resonance,
• PC solenoids with 0.03 T field are sufficient for stabilization and control of deuteron polarization in NICA collider,
• such PC solenoids fields allow one to realize spin-flipping system with reversal time of a few seconds for protons and a few milliseconds for deuterons,
• the NICA collider in spin transparency mode allows one to carry out ultra-high precision experiments with polarized beams.

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