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**SPIN COHERENCE AND BETATRON CHROMATICITY OF DEUTERON BEAM IN «QUASI-FROZEN» SPIN REGIME**

**S. Kolokolchikov*a, b\*,* A. Aksentiev*a, b*, A. Melnikov*a*, *b*, c, Yu. Senichev*a, b***

*a Institute for nuclear research RAS, Moscow, Russia*

*b Moscow Institute of Physics and Technology, Dolgoprudny, Russia*

*c Institute for Theoretical Physics LD Landau, Chernogolovka, Russia*

*\*E-mail: sergey.bell13@gmail.com*

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A distinctive feature of the "Quasi-Frozen" spin mode in the synchrotron is the installation of special elements with crossed magnetic and electric fields in straight sections that compensate the spin rotation from the MDM components on the arcs. Moreover, due to the presence of the longitudinal length and the momentum spread inside the beam, spin rotation may occur incoherently. In order to suppress this effect, sextupoles are installed, which also affect chromaticity suppression.

*Keywords*: spin coherence, betatron chromaticity, Quasi-Frozen Spin, electric dipole moment

# INTRODUCTION

The possibility of spin control for Electric Dipole Moment (EDM) experiment can be done by setting Wien Filters in straight ByPass sections, which ensure that the particles spin retains mean direction in accordance with «Quasi-Frozen Spin» mode. However, the spin of different particles, due to their different motion in 3D space, rotates with slightly different frequencies around the invariant axis. Thus, violates spin coherence. To ensure spin coherence, nonlinear elements, sextupoles, with a special non-zero dispersion placement on arcs must be used. Since sextupoles simultaneously affect the betatron chromaticity, we consider this complicated case.

«QUASI-FROZEN SPIN» REGIME

T-BMT equations describe the evolution of spin-vector over time in particle rest frame in electrical and magnetic fields in laboratory frame:

# As it can be seen from Eq. 1 for EDM search it is necessary to lower the impaction from magnetic dipole moment (MDM). But NICA has purely magnetic arcs. Thus, it cannot be used «Frozen Spin» method [1]. Wien Filters implemented in the straight section compensate rotation via MDM in arc and realize a «Quasi-Frozen Spin» condition for deuterons [2]. For this purpose, NICA needs a modernization to operate as a storage ring with alternative straight sections by using ByPass channels [3].

# Spin decoherence

If we follow T-BMT Eq. 1 spin-tunes in electric and magnetic fields are given by the expressions:

*An Equilibrium Level Energy Shift*

Different particles have different momentum, and there is a need to use effective energy:

The equilibrium momentum spread due to the betatron motion and non-zero second order momentum compaction factor based on synchronous principle [4] and define by:

for betatron orbit lengthening term

where index means synchronous particle, , – emittances, , – tunes, – relative momentum deviation, , – two first orders of momentum compaction factor. Equation (2) together with Eqs. 3–5 shows that spin-tune spread depends on the equilibrium energy level of the particle.

*Orbit Lengthening and Betatron Chromaticity*

More formal theory implies the interaction of external (sextupole) field. Taking into account the expression for total orbit lengthening from [5]:

where , – chromaticities. If we compare Equation (6) with (4) and (5), it can be noticed that orbit length is closely connected with equilibrium energy level.

# SEXTUPOLE CORRECTION

As a result, Eqs. (4), (6) show that using sextupoles can influence spin tune precession and finally don’t allow to get spin coherence. Such experiments were made at COSY, Yulich, Germany to get SCT at the level of 1000 s [6]. Sextupoles located in non-zero dispersion regions at arcs. In minimum and maximum of dispersion-function и beta-function make the most impact and are physically located next to quadrupole lenses. Twiss-functions of NICA arc are regular and can be seen at Fig. 1 [7]. Dispersion is suppressed with «Missing Magnets» at the edges.

*Betatron Chromaticity*

For betatron chromaticity correction used only 2 families of sextupoles: one near focusing, other - defocusing quadrupoles. Natural chromaticity of ByPass NICA Storage Ring is . After optimization, can monitor spin-tune at Figure 2: red line shows natural chromaticity, blue one – corrected to about zero. For this case also made spin tracking during turns for particles with different initial deviation in x, y, d coordinates with and initial spin orientation at an angle of 45 degrees in y-z plane, shown on Figure 3 [8].

*Spin Coherence*

To get spin coherence, considered pure spin-tune. COSY Infinity [8] cannot operate near zero-value of spin-tune. It can cause an error due to resonant denominators, thus let the spin precess with . But require to do it synchronously – coherent.

Main parameter is the spin-tune which in generally depend on coordinates and energy. It can be seen that the dominant component is quadratic term in the expansion of the spin-tune on Fig. 2 for non-corrected cases, both: natural and correct chromaticity. For this reason, sextupoles can be selected in other way, just to get spin coherence.

As we can see, from Eqs. 4, 6, it is not enough to use 2 families, thus 3d family used to influence energy coordinate. But, in regular structures beta и dispersion functions – don't allow to use 3 linear independent families. Figure 1 shows sextupole arrangement of families: SF1, SF2, SD. In this method we don't influence chromaticity, just monitor the main value . It is not enough for stable orbital motion. For this case, it can be seen that spin coherence achieved – there is no dependance of coordinates/energy (Figure 2: green line). Tracking results confirm this. On Figure 4, the spin-tune switched up to the , and considered turns or 3 seconds. Particles with different initial deviation precess with the same spin-tune. But in this case maximum of sextupole coefficient is huge and can cause non-linear effects (Table 1).

As we can see, pure betatron chromaticity correction did not allow us to get zero spin-tune spread. Simultaneously, getting spin coherence by suppressing quadratic term of spin-tune expansion did not suppress chromaticity. This brings us back at Equation 6. Term can be averaged using RF for mixing . Thus, to make a zero orbit lengthening, chromaticities must be correct together with to zero value. It is also possible using 3 sextupole families. But still did not allow to get spin coherence. Fig. 2 (violet line) shows the non-zero spin-tune dependance from coordinates. Same occurs if we follow Equation 4 and suppress together with chromaticity correction (Figure 2). Moreover, maximum of sextupole filed is too strong and cannot be realized (Table 1).

CONCLUSION

As a result, considered the phenomenon of spin decoherence simultaneously with betatron chromaticity at the ByPass NICA Storage Ring. It operates in "Quasi-Frozen Spin" mode and can be used for dEDM experiments.

Different cases of sextupoles optimization were considered. Quadratic terms of spin-tune expansion are the most valuable and represent the dependence on coordinates. All the main parameters that were monitored are shown on Table 1. The research shows that it is not possible to use 3 sextupoles families in regular structure to achieve both betatron chromaticities and get spin coherence. Moreover, maximum value of sextupole coefficient not satisfactory and can cause non-linear instabilities. It is worth noted that regular dispersion function on the arc did not allow to locate 3 linear independent families, as they are placed in the same minimum/maximum of – functions. But it can be possible to modulate dispersion function in such way to get 3 linear independent sextupole families. Also, one of the possible problem decisions is using cooled beam at the level of . This can help to minimize effective and finally get spin coherence simultaneously with corrected betatron chromaticity.

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CONFLICT OF INTEREST

The authors confirm that they have no conflict of interest.

# LIST OF LETERATURE

1. F. J. M. Farley et al., “New Method of Measuring Electric Dipole Moments in Storage Rings”, Phys. Rev. Lett., vol. 93, no. 5, Jul. 2004. doi:10.1103/physrevlett.93.052001

2. Y. Senichev et al., “Quasi-Frozen Spin Concept of Magneto-Optical Structure of NICA Adapted to Study the Electric Dipole Moment of the Deuteron and to Search for the Axion”, in Proc. IPAC’22, Bangkok, Thailand, Jun. 2022, pp. 492–495. doi:10.18429/JACoW-IPAC2022-MOPOTK024. <https://doi.org/10.18429/JACoW-IPAC2022-MOPOTK024>

3. S. Kolokolchikov, A. Melnikov, A. Aksentyev, E. Syresin, V. Ladygin, and Y. Senichev, “ByPass optics design in NICA storage ring for experiment with polarized beams for EDM search”, IPAC’23, Venice, Italy, May 2023, paper MOPA072. <https://doi.org/10.18429/JACoW-IPAC-23-MOPA072>

4. Y. Senichev, R. Maier, D. Zyuzin, and N. V. Kulabukhova, “Spin Tune Decoherence Effects in Electro- and Magnetostatic Structures”, in Proc. IPAC’13, Shanghai, China, May 2013, paper WEPEA036, pp. 2579–2581.

5. Y. Senichev, A. Aksentyev, and A. Melnikov, “Spin Chromaticity of Beam: Orbit Lengthening and Betatron Chromaticity”, Phys. At. Nucl., vol. 84, no. 12, pp. 2014–2017, Dec. 2021. doi:10.1134/S1063778821100367

6. G. Guidoboni et al., “How to Reach a Thousand-Second in- Plane Polarization Lifetime with 0.97-GeV/c Deuterons in a Storage Ring.”, Phys. Rev. Lett., vol. 117, no.5, 2016, 054801. doi:https://doi.org/10.1103/PhysRevLett. 117.054801

7. V. Lebedev, OptiM code, Private communication url:www-bdnew.fnal.gov/pbar/organizationalchart/lebedev/OptiM/optim.htm

8. COSY INFINITY. <url:www.bmtdynamics.org>

TABLES

**Table 1**. Basic parameters of the structure and experiment.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Optimization | w/o Optimization | Chromaticity | Spin Coherence | Chromaticity | Chromaticity |
| Betatron tune (working point) |  |  |  |  |  |
| Coefficient | 0.2 | -0.4 |  |  | -0.85 |
| Coefficient |  |  |  |  |  |
| Coefficient |  |  |  |  |  |
| Coefficient |  |  |  |  |  |
| # sextupole families | w/o sextupoles | 2 | 3 | 3 | 3 |
| Max. sextupoles field, | - | 2.7 | 19.4 | 4.9 | 104.2 |

FIGURE CAPTIONS

**Fig. 1.** ByPass NICA Twiss-parameters for deuteron mode in OptiM. The arrangement of sextuple families is also shown.

**Fig. 2.** Dependence of the spin tune precession on the coordinates x, y, d for various optimization cases. NC – natural chromaticity (red line); BC – zero (betatron) chromaticity (blue dotted line); SC – spin coherence (green line); BC\_α – zero chromaticity and (purple line); BC\_η – zero chromaticity and zero (light blue line).

**Fig. 3.** Spin tracking of particles with different initial deviation in coordinates x, y, d using 2 families of sextupoles to obtain zero betatronic chromaticity.

**Fig. 4.** Spin tracking of particles with different initial deviation in coordinates x, y, d using 3 families of sextupoles to obtain spin coherence.