INVESTIGATION OF LATTICE FOR DEUTERON EDM RING

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Abstract

The quasi-frozen spin (QFS) concept of a storage ring for deuteron EDM measurement is based on the fact that the anomalous magnetic moment has a small negative value. Due to this fact, the rotation of spin in two parts of ring with the magnetic and electric fields relative to the momentum can compensate each other. In contrast to the concept of frozen spin we have the freedom to choose the ring parameters and also greatly simplified lattice. We consider two possible options for the lattice based on QFS concept and compare them with the frozen spin lattice where the elements with the combined electric and magnetic fields proposed by BNL are used. In the first QFS option, we use completely separate electric and magnetic parts that form a structure. In the second option, we suggest using only two magnetic arcs with two straight sections having the straight elements with magnetic and electric fields. The straight elements have a horizontal electric field of 120 $\mathrm{kV/cm}$ and a vertical magnetic field of 80 mT. They provide the compensation for the spin rotation in the arc and at the same time allow having straight electric plates without the higher orders field. This scheme could be tested in the COSY ring at FZ Juelich to prove the quasi-frozen spin concept.

FROZEN AND QUASI-FROZEN SPIN CONCEPT

In the frozen spin method [1], the main objective is to maximize the EDM signal growth, which is provided by the frozen orientation of spin along the momentum, i.e. by zero spin frequency $\vec{\omega} = 0$ relative to the momentum due to the magnetic dipole moment (hereinafter called MDM precession) in $\vec{E} \times \vec{B}$ fields:

$$\vec{\omega}_G = -\frac{e}{m}\left\{ G\vec{B} + \left(\frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c} \right\}, \quad (1)$$

where $G = (g-2)/2$ is the anomalous magnetic moment and g is the gyromagnetic ratio.

However, if the spin oscillates in the horizontal plane with respect to the frozen spin direction with amplitude Φ_s, then the EDM growth decreases proportionally to the factor $J_0(\Phi_s) \approx 1 - \frac{\Phi_s^2}{4}$.

Taking into account that the deuterons anomalous magnetic moment $G = -0.142$ has a small value and the fact that the spin oscillates around the momentum direction within half value of the advanced spin phase $\pi \cdot \gamma G/2n$, each time returning back by special optics with n-periodicity, it is obvious that the effective contribution to the expected EDM effect is reduced only by a few percent. This allows us to proceed to the concept of quasi-frozen spin [2], where the spin is not frozen with respect to the momentum vector, but continually oscillates around momentum with a small amplitude.

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TWO POSSIBLE OPTIONS OF QUASI-FROZEN SPIN LATTICE

In [1], it has been shown how to implement a variable MDM spin precession in the storage ring and to provide a sufficient EDM signal growth. Due to the fact that there is an energy region, where the MDM spin oscillation in the electric field is several times faster than in the magnetic field, the idea of quasi-frozen structure can be implemented on the basis of two lattice structure options. The first option is based on two types of arcs: magnetostatic and electrostatic with inverse curvature of the later. That is, the lattice is created by two parts: two magnetic arcs with bend magnets, rotating the particle by angle $\Phi^B = (\pi + 2\alpha)$ per arc and providing the MDM spin rotation in horizontal plane relative to the momentum by an angle $\Phi_s^B = \nu_s^B \cdot \Phi^B$, where ν_s^B is spin tune in magnetic field, and two electrostatic arcs with electric deflectors of negative curvature, rotating the beam by an angle $\Phi^E = -2\alpha$ per arc and providing the MDM spin rotation in the horizontal plane relative to the momentum in opposite direction by an angle $\Phi_s^E = \nu_s^E \cdot \Phi^E$, where ν_s^E is spin tune in electric field. To realize the quasi-frozen spin concept, we have to fulfil the condition $\Phi_s^E = -\Phi_s^B$. Since in the electrostatic deflector the spin is rotated relative to the momentum with frequency that is by the factor of $K = \nu_s^E/\nu_s^B$ faster than in magnetostatic structure, we have the basic relation for two different arcs:

$$\begin{aligned} \nu_s^B \cdot (\pi + 2\alpha) &= \nu_s^E \cdot 2\alpha \\ \alpha &= \frac{0.5 \cdot \pi}{\nu_s^E/\nu_s^B - 1}. \end{aligned} \quad (2)$$

Following the principles of this idea, it is obvious that the electrostatic and magnetostatic parts have an arbitrary geometry with the single condition:

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$$\sum_i \Phi_i^E \nu_s^E = \sum_j -\Phi_j^B \nu_s^B, \tag{3}$$

where Φ_i^E, Φ_j^B are the momentum angle rotations in i-th electrostatic and j-th magnetostatic element of structure respectively. The sequence of magnetic and electrostatic elements in the ring is also arbitrary and determined by the beam dynamics. So, turn by turn, the MDM spin rotation in magnetostatic part is compensated by MDM spin rotation in electrostatic part.

Obviously, this oscillation should lead to EDM signal reduction. However, due to the small amplitudes of Φ_s^E and Φ_s^B, the growth of EDM signal is reduced in comparison to the fixed spin direction case by the factor:

$$J_0(\Phi_s^{E,B}) \approx 1 - \frac{(\Phi_s^{E,B})^2}{4}, \tag{4}$$

which is ~ 0.98 in our case.

Figure 1 shows a visual appearance example of the first option of the ring for the deuteron energy 270 MeV based on QFS concept.

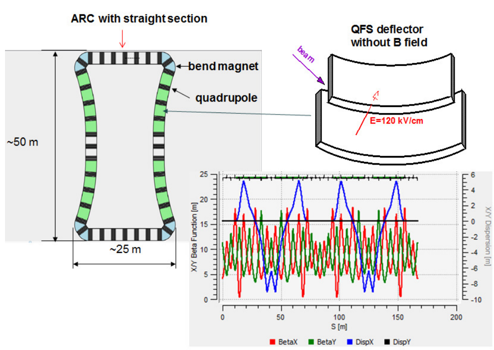

Figure 1: First option of ring lattice based on QFS concept with TWISS.

The free dispersion straight sections are placed between the magnetic arcs and are necessary to accommodate the polarimeter, the beam extraction and injection systems and RF cavity. The separation of bend elements on the magnetic and electrostatic components simplifies the common construction and allows adjusting them separately.

However, this concept inherits one drawback of cylindrical electrodes, namely the whole set of high-order nonlinearities. Therefore, we introduced a magnetic field of small value ~ 80 mT, compensating the Lorentz force of the electric field. Thus, in the second option of lattice, we use the straight elements placed on the straight sections with incorporated E and B fields to recover MDM spin rotation in the magnetic arcs. The lattice consists of two magnetic arcs and two straight sections with the straight $\vec{E} \times \vec{B}$ elements, where Lorentz force equals to zero, and the total length of these elements is defined by the required spin recovery condition.

Figure 2 shows second option of the ring for the deuteron energy 270 MeV based on this concept.

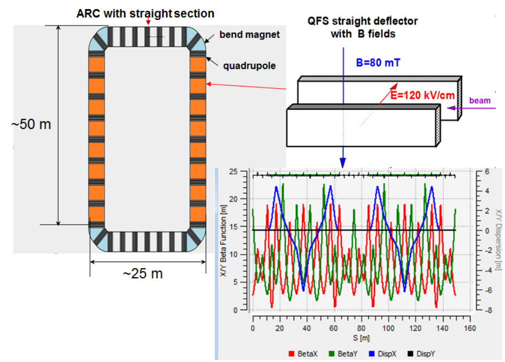

Figure 2: Second option of ring lattice based on QFS concept with TWISS.

As in the previous option, the lattice includes the straight sections with zero dispersion in the middle of magnetic arcs for the polarimeter, the beam extraction and injection systems, and the RF cavity. Thus, in the magnetic arc, the particles are rotated by the angle Φ_{arc}^B, with simultaneous MDM spin rotation in horizontal plane relative to momentum by the angle $\Phi_s^{arc} = \gamma G \cdot \Phi_{arc}^B$. On the straight section, the straight elements with E and B fields provide MDM spin rotation in the horizontal plane in the opposite direction relative to the momentum in E field by an angle $\Phi_s^E = -\left(\gamma G + \frac{\gamma}{\gamma+1}\right)\beta^2 \cdot \Phi_{ss}^E$, where Φ_{ss}^E is momentum rotation in electric field, and in B field by an angle $\Phi_s^B = (\gamma G + 1)\Phi_{ss}^B$, where Φ_{ss}^B is momentum rotation in magnetic field. Since the Lorenz force is zero, the angles $\Phi_{ss}^E = \Phi_{ss}^B$ are equal to each other. Therefore, they could be defined through one of them, for instance through magnetic field $\Phi_{ss}^B = \frac{eB_{ss}}{m\gamma v} \cdot L_{ss}$, where B_{ss}, L_{ss} are the magnetic field and length of the straight element. To realize the quasi-frozen spin concept, we have to fulfil the condition $\Phi_{ss}^B - \Phi_{ss}^E = \Phi_{arc}^B$, i.e.

$$(\gamma G + 1) \cdot \Phi_{ss}^B - \left(\gamma G + \frac{\gamma}{\gamma + 1}\right)\beta^2 \cdot \Phi_{ss}^E = \gamma G \cdot \pi. \tag{5}$$

Carrying out simple transformations, we obtain the basic relation for the straight element parameters:

$$\begin{aligned} L_{\sum} E_{ss} &= \frac{G}{G+1} \cdot \frac{mc^2}{e} \cdot \pi\beta^2\gamma^3 \\ B_{ss} &= -\frac{E_{ss}}{c\beta}, \end{aligned} \tag{6}$$

where $L_{\sum}$ is the total length of straight elements in one straight section.

Thus, taking maximum electric field at level 120 kV/cm requires a magnetic field below 80 mT.

It opens prospects for simplifying the general construction. In particular, a permanent magnet or an air core electric coil may be used.

Finally for comparison, we have designed lattice based on the BNL deflector on arc with incorporated E and B fields (see Fig. 3).

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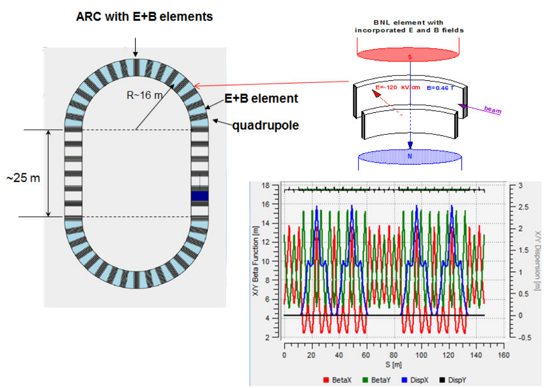

Figure 3: Option of lattice based on BNL element with TWISS functions.

Despite the difference in the concepts, the basic parameters, namely the size of the rings, the length of the straight sections, the number of focusing periods, and the number of deflecting and focusing elements and sextupoles all remain approximately the same.

As a special role is given to sextupoles, all structures have at least 6 families of sextupoles for a flexible control of spin coherence time and chromaticity in all coordinates, and each family carries out its own functions. Besides, since sextupoles are non-linear elements and, in addition to useful functions, distort phase trajectories and may induce nonlinearity in the dependence of orbit lengthening versus particle coordinates, we have studied all families from the point of view of spin coherence time correction and phase trajectories.

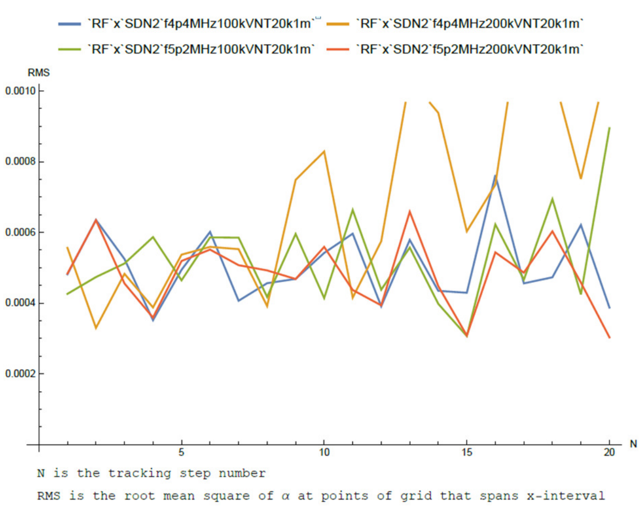

Figure 4: RMS spin deviation vs turn number

Figure 4 shows an example of how the rms spin deviation over whole bunch changes with turn number (up to one million turns). For some families, deviation remains practically at the same level. More details of these studies are given in [3].

CONCLUSION

The proposed quasi-frozen spin method could simplify the lattice and would allow diagnosis of the presumably existing EDM signal. The structures based on QFS concept are much easier and cheaper. The QFS lattice meets to all requirements of EDM search. This scheme can be applied in any existing ring with energy of at least 270 MeV and with deuteron polarized sources. To confirm the feasibility of the structure, we have done a numerical simulation of 3D spin-orbital motion using two codes, COSY-Infinity [4] and MODE [5].

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