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ELEMENTARY PARTICLES AND FIELDS
Experiment

NICA Facilities for the Search for EDM Light Nuclei

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Abstract—To search for proton Electric Dipole Moments (EDM) using proton storage ring with purely electrostatic elements, the concept of frozen spin method has been proposed by Brookhaven National Laboratory. This method is based on two facts: in the equation of spin precession, the magnetic field dependence is entirely eliminated, and at the "magic" energy, the spin precession frequency coincides with the precession frequency of the particle momentum. In case of deuteron, we have to use the electrical and magnetic field simultaneously, keeping the frozen spin direction along the momentum as in the pure electrostatic ring. Later, Yu. Senichev proposed the concept of quasi-frozen spin, in which the spin oscillates around the direction of the pulse within half the value of the advanced phase of rotation in magnetic arcs, each time returning back in deflectors with an electrostatic field. Due to the low value of the anomalous magnetic moment of deuteron, an effective contribution to the expected EDM effect is reduced only by a few percent compared with frozen spin method. In this work, we consider the adapted structure of the NICA and Nuclotron synchrotrons, in which the "quasi-frozen spin" option can be implemented. The advantage of the "quasi-frozen spin" concept is the possibility of using synchrotrons already existing in the world that are not focused on studying EDM, which makes this method the only one possible for the accelerators of the NICA complex.

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1. BASIC PRINCIPLE OF EDM MEASUREMENT OF A CHARGED PARTICLE IN AN ACCELERATOR

The basic principle for measuring EDM in the storage mode of a synchrotron comes from the Thomas-Bargmann, Michel, Telegdy (T-BMT) equation. In accordance with the Ehrenfest theorem, the T-BMT equations describe the classical behavior of the spin of a charged particle, taking into account the assumed EDM:

$$\frac{d\mathbf{S}}{dt} = \mathbf{S}\times(\mathbf{\Omega}_{\text{mdm}} + \mathbf{\Omega}_{\text{edm}}),$$

$$\mathbf{\Omega}_{\text{mdm}} = \frac{e}{m\gamma}\left\{(\gamma G+1)B_\perp + (1+G)B_{\text{II}} - \left(\gamma G + \frac{\gamma}{\gamma+1}\right)\frac{\boldsymbol{\beta}\times\mathbf{E}}{c}\right\},$$

$$\mathbf{\Omega}_{\text{edm}} = \frac{e\eta}{2m}\left(\boldsymbol{\beta}\times\mathbf{B} + \frac{\mathbf{E}}{c}\right); \quad G = \frac{g-2}{2}, \quad (1)$$

where γ is the Loretz factor, $\boldsymbol{\beta}$ is the relative speed, c is the speed of light, e, m are the charge and mass of the particle, G is the magnetic moment anomaly, g is the gyromagnetic ratio, $\mathbf{\Omega}_{\text{mdm}}$ is the spin precession frequency due to the magnetic dipole moment, $\mathbf{\Omega}_{\text{edm}}$—spin precession frequency due to the electric dipole moment, η is a dimensionless coefficient determined in (1) by the relation $d = \eta e\hbar/4mc$, $\mathbf{B} = \{B_\perp, B_{\text{II}}\}$, $\mathbf{E} = \{E_\perp, E_{\text{II}}\}$—magnetic and electric fields.

In the future, since we will not use elements with a longitudinal magnetic field, we will accept $B_{\text{II}} = 0$. The longitudinal electric field $E_{\text{II}} = 0$ is also not taken into account due to the smallness of its contribution. The "frozen spin" method [1] is based on the fact that at a certain so-called "magic" energy, the spin of a particle in external fields begins to rotate with a frequency equal to the frequency of rotation of the particle's momentum in orbit $\Omega^p_{E,B} = \frac{eE}{m\gamma\beta c} + \frac{eB}{m\gamma}$. Subtracting the frequency $\Omega^p_{E,B}$ from $\mathbf{\Omega}_{\text{mdm}}$, we obtain the spin precession frequency relative to the direction of the impulse $\mathbf{\Omega}^p_{\text{mdm}}$:

$$\mathbf{\Omega}^p_{\text{mdm}} = \boldsymbol{\omega}^p_E + \boldsymbol{\omega}^p_B, \quad (2)$$

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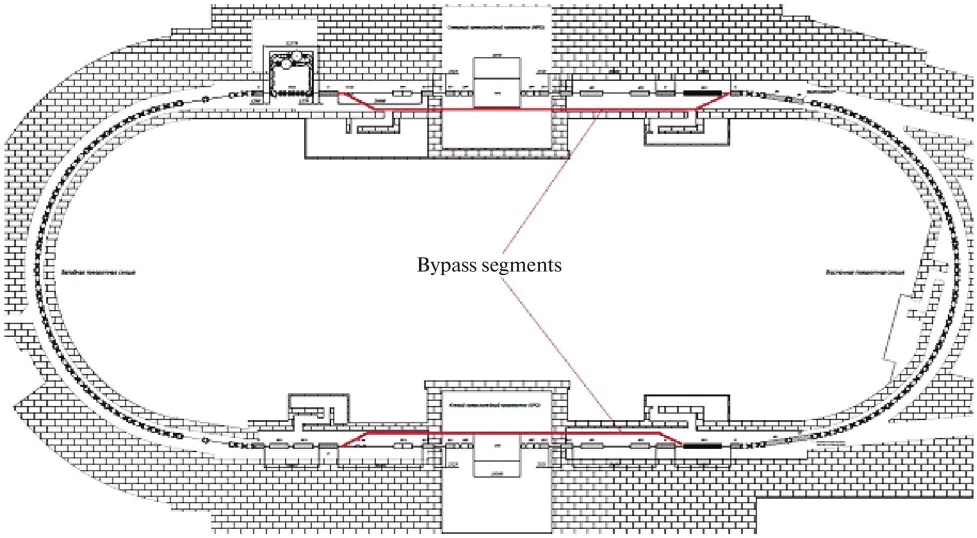

Fig. 1. Modernized NICA structure with bypass sections for EDM search.

where $\boldsymbol{\omega}_E^p = \frac{e}{m}\left(G - \frac{1}{\gamma^2-1}\right)\frac{\mathbf{E}\times\boldsymbol{\beta}}{c}$ is the spin precession frequency relative to the momentum in the electric field and $\boldsymbol{\omega}_B^p = \frac{e}{m}G \cdot B_\perp$—respectively in a magnetic field. The condition for "frozen spin" in a completely electrostatic ring $\mathbf{B} = 0$ is the equality to zero $\boldsymbol{\omega}_E^p = 0$, which is satisfied at "magic" energy:

$$G - \frac{1}{\gamma_{\rm mag}^2 - 1} = 0. \quad (3)$$

In a ring with magnetic and electric elements, the frozen spin condition is satisfied under the same condition $\boldsymbol{\Omega}_{\rm mdm}^p = \boldsymbol{\omega}_E^p + \boldsymbol{\omega}_B^p = 0$, which is satisfied with a balance between the radial electric field E_r and the leading vertical magnetic field B_v in the ratio:

$$E_r = \frac{GBc\beta\gamma^2}{1 - G\beta^2\gamma^2} \approx GB_v c\beta\gamma^2. \quad (4)$$

A hybrid ring with electric and magnetic fields is used for the case of deuterons, since for them the G-factor has a negative value $G = -0.14$ and condition (3) is not satisfied. For further consideration, we introduce the definition of "spin tune", the value of which determines the number of spin oscillations per revolution in the accelerator. Spin tune in an electrostatic ring ν_s^E, defined as the normalized frequency of spin precession to the orbital frequency of the particle $\nu_s^E = \omega_E^p/\Omega_E^p$, is determined by the formula

$$\nu_s^E = \left(G - \frac{1}{\gamma^2 - 1}\right)\gamma\beta^2. \quad (5)$$

Similarly, we find the spin tune $\nu_s^B = \omega_B^p/\Omega_B^p$ in a magnetic field relative to momentum:

$$\nu_s^B = \gamma^G. \quad (6)$$

Thus, for both protons and deuterons there is a general idea of how to build a ring, but this is implemented using different types of deflectors.

2. UPGRADED MAGNETO-OPTICAL STRUCTURES OF THE NICA FACILITIES FOR SEARCHING FOR EDM

In the case of the "quasi-frozen" structure, there are two options [2]. In the first QFS version the magnetic and electric fields are completely spatially separated: the former is found in the magnetic arcs and the latter in the straight sections, which are realized in the form of negative-curvature "reverse electric" arcs, respectively. In the second version of the QFS lattice, we introduced a small magnetic field ~100 mT into the spin-aligning $(E + B)$ elements, which compensates for the Lorentz force of the electric field and allows us to make them straight. In this case, element $E + B$ becomes Wien filter.

The second option is most suitable for the NICA ring with introduced bypass sections, while for the Nuclotron, due to the limited space for placing equipment, the first option is considered as a working one.

To implement the quasi-frozen concept in NICA collider, we propose to introduce two bypass sections. Both direct bypass sections (see Fig. 1) do not include meeting points in the MPD and SPD detectors and are free to accommodate Wien filter elements.

Channels with Wien filters are transparent to beam dynamics due to the zero Lorentz force and rotate the spin in the direction opposite to the rotation in the arcs, thereby realizing the concept of "quasi-frozen spin". Without meeting points, we have two uncrossed rings with the possibility of doubling the speed of statistics collection. In Figs. 2 and 3a, 3b

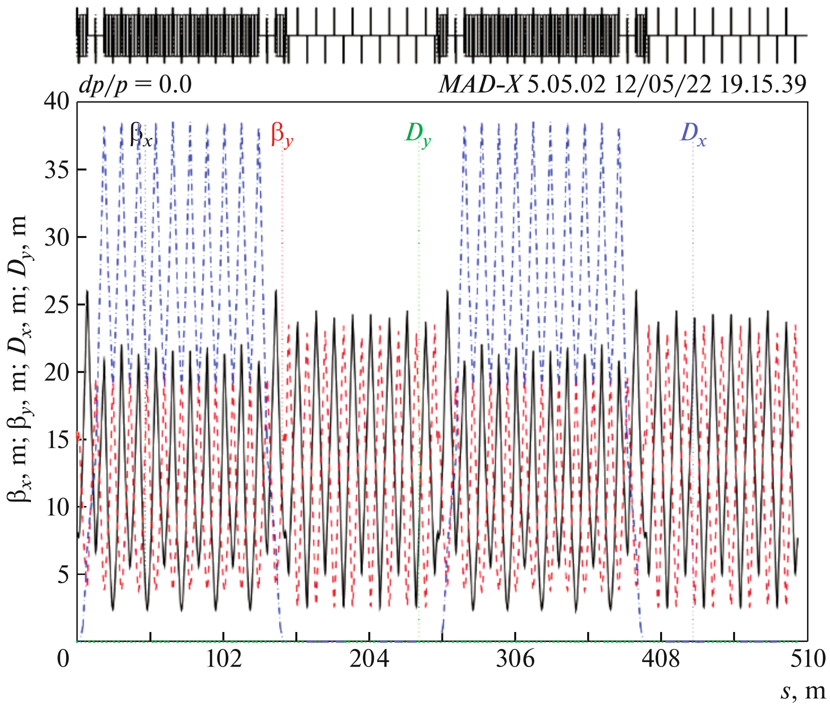

Fig. 2. Twiss functions of the NICA collider with bypass sections.

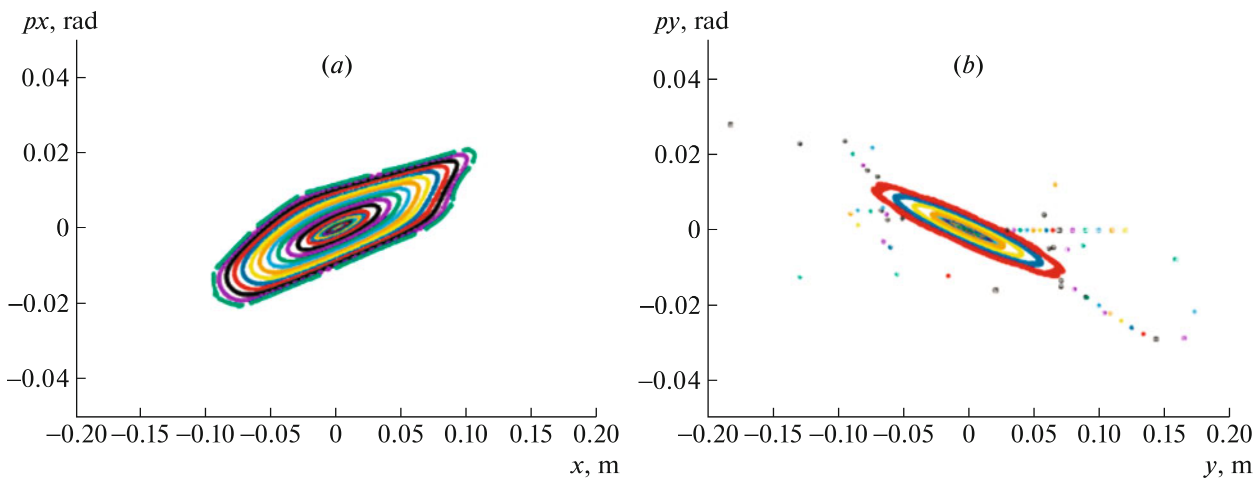

Fig. 3. Dynamic aperture in the horizontal and vertical planes of the NICA collider with bypass sections.

show the Twiss functions and dynamic aperture for both transverse planes.

As can be seen, the linear part of the dynamic aperture ∼2000 mm mrad significantly exceeds the required value in both planes. Taking into account the limiting values of the electric field ∼100 kV/cm and using the obtained expressions for the parameters of Wien filters, we calculate their required net length of ∼25–30 meters for one bypass section, which is 30% of the total length of the bypass section. The result of spin-orbit simulation for three spin projections shows that the rotation changes direction relative to the momentum within ±7.5 degrees (see Fig. 4). Despite the change in spin direction, the polarization asymmetry remains constant at the location of the polarimeter.

Another accelerator of the NICA complex, which can be considered as a candidate for search for EDM, may be the Nuclotron. The task of adapting the Nuclotron structure to the requirements for the structure for measuring the electric dipole moment of the deuteron can be determined by a set of problems: increasing the straight sections length, suppressing the dispersion in the straight sections, and maintaining the direction of the spin along the momentum. The first problem, increasing straight sections to the required length, is solved by increasing the maximum magnetic field in the bending magnets to a value of

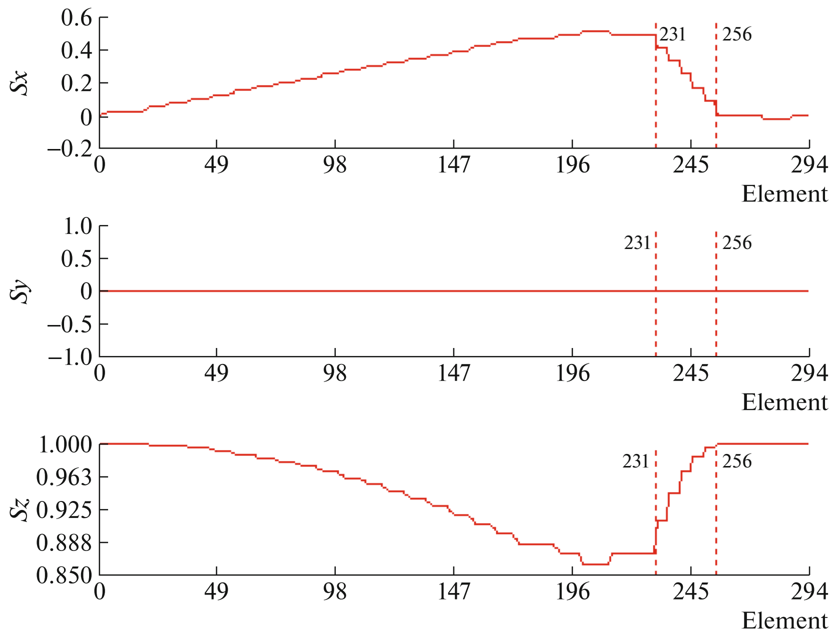

Fig. 4. Spin-orbit simulation on half of the synchrotron "arc + bypass section".

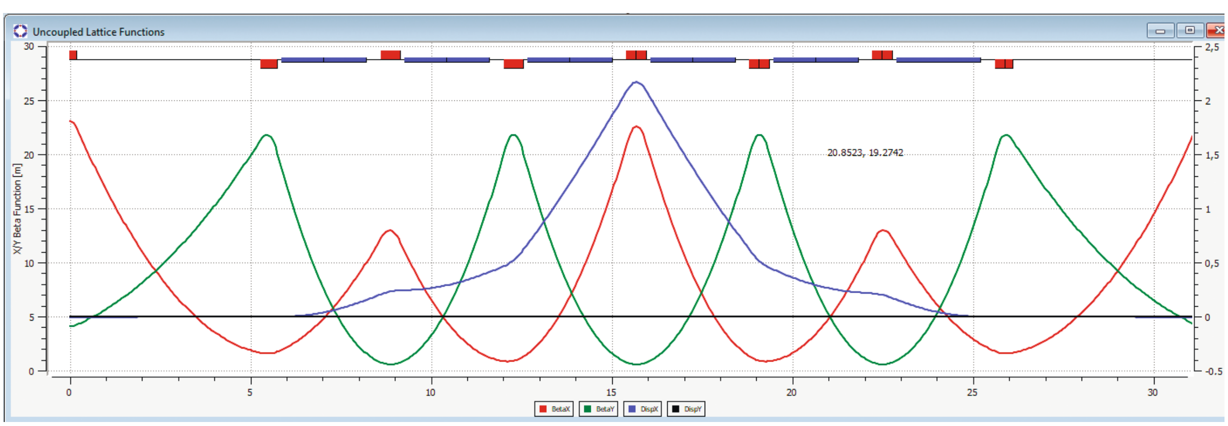

Fig. 5. TWISS functions of one superperiod of the modernized Nuclotron.

1.8 Tesla. Simultaneously with the first problem, the problem of suppressing dispersion is solved by choosing of the advanced phase of radial oscillations on the arcs. The proposed modernized structure of one super period of the Nuclotron is shown in Fig. 5.

Thanks to an increase in the magnetic field to 1.8 Tesla in the bending magnets, the length of the straight section in each super period is increased from 7.3 to 10.5 m. The third problem of maintaining the direction of the spin relative to the momentum, necessary for diagnosing the EDM signal, is solved by introducing electrostatic deflectors with negative curvature at each super period of the structure (see Fig. 6). This allows the average direction of spin to be maintained along the momentum across the entire ring within the concept of "quasi-frozen spin" in the accelerator.

Nuclotron, with the "quasi-frozen" structure should consist of two different parts: magnetic arcs with bend magnets that change the direction of particle motion on each arch by an angle $\Phi^B = (\pi/N + 2\alpha)$ and provide rotation of the spin with the tune ν_s^B in the horizontal plane relative to the momentum by an angle $\Phi_s^B = \nu_s^B \cdot \Phi^B$, and electrostatic arcs with the negative curvature, rotating the beam on each arc by an angle $\Phi^E = -2\alpha$ and ensuring rotation of the spin with the tune ν_s^E in the horizontal plane relative to the momentum in the opposite direction by an angle $\Phi_s^E = \nu_s^E \cdot \Phi^E$. To implement the concept of quasi-frozen spin, it is necessary to provide $\Phi_s^E = -\Phi_s^B$. Since in an electrostatic deflector the spin rotates relative to the momentum with a frequency many times greater than in a magnetostatic structure, we have a basic

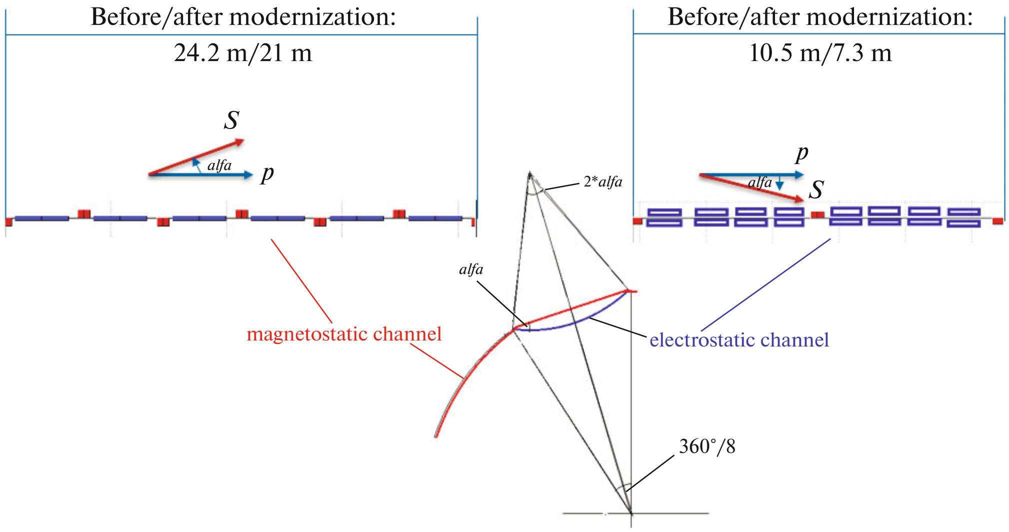

Fig. 6. Electrostatic insertion to compensate for spin rotation in a magnetostatic arc.

relationship for two different structural arcs:

$$\nu_s^B\left(\frac{\pi}{N}+2\alpha\right)=\nu_s^E\cdot 2\alpha$$

$$\text{and}\quad \alpha=\frac{1}{\nu_s^E/\nu_s^B-1}\frac{\pi}{N}. \qquad (7)$$

At the optimum energy for polarimeter $W = 270$ MeV the angle $\alpha = 0.026\pi$ and the required length of the electrostatic channel equals 7.3 m. In this case, the magnitude of the EDM signal in the "quasi-frozen" structure compared to the "frozen" option $S_{\text{EDM}}^{\text{QFS}}/S_{\text{EDM}}^{\text{FS}} = 1-\alpha^2/4 \approx 0.998$ decreases by 0.2%.

In addition to this option, we considered a structure with a double number of super periods 16. Due to the separation of the double bend magnets into individual magnets, the number of FODO periods at each super period was doubled, which made it possible to obtain dispersion suppression on every second straight section due to a phase advance of 60 degrees on each FODO cell. In this version of the structure, the rotation angle becomes $\alpha = 0.013\pi$, and the magnitude of the EDM signal for the "quasi-frozen" structure compared to the "frozen" structure decreases $S_{\text{EDM}}^{\text{QFS}}/S_{\text{EDM}}^{\text{FS}} = 1-\alpha^2/4 \approx 0.9996$ by 0.04%, which makes it practically similar the last one. This fact makes it possible to use this structure to study the EDM of the proton, since the spin rotation angle for proton on the magnetic arcs becomes only 30 degrees.

3. CONCLUSIONS

The proposed modernization of NICA and Nuclotron will make it possible to adapt the structures for conducting studies of the electric dipole moment of the deuteron. The next step in optimizing the Nuclotron structure for studying the EDM of a deuteron polarized beam is the transition to super periodicity twice as large as $N = 16$, which will allow the "quasi-frozen" structure to be brought closer in its properties to the "frozen" structure by reducing the angle α by half. At the same time, at such angles for deuterons, the possibility of studying the proton EDM can be considered with a deeper modernization of the Nuclotron.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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