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CHARGED PARTICLE ACCELERATORS FOR NUCLEAR TECHNOLOGY

Designing Bypass Channels in NICA Accelerator Complex for Polarized Beam Experiments for EDM Search

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Abstract—Experiments with polarized beams for electric dipole moment search in the NICA accelerator complex implies the design of additional bypass channels. Such alternative channels will make it possible to use NICA as a storage ring and collect enough statistical data.

Keywords: magneto-optical structure, bypass channels, storage ring, electric dipole moment

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INTRODUCTION

NICA (Nuclotron-based Ion Collider fAcility) is an accelerator complex located in Dubna, Russia. The main ring is designed for collision experiments with heavy ions at 4.5 GeV to study the properties of dense baryonic matter as well as for polarized proton beams at 13 GeV. For these purposes, appropriate spin polarized (SPD) and multipurpose (MPD) detectors and other necessary implements are installed on the straight sections [1].

In experiments on measuring the electric dipole moment (EDM), the main feature is to maintain a high value of spin coherence time (SCT) at about 1000 s. During this time, coherent polarized beam stores in a ring. For these needs, it is necessary to operate the main NICA ring as a storage ring, and not in a collider mode. To do this, it is proposed to install bypass channels. Thus, it is possible to create a completely new alternative regular structure in a straight section, parallel to the original one. Creating bypass channels is a big adventure that does not require significant restructuring of the complex and costs and will make it possible to engage NICA in various experiments at once.

1. PREREQUISITES FOR NICA MAIN RING MODERNIZATION

To measure the EDM, it is necessary to develop spin control methods. Spin-vector evolution is described by T-BMT equations [2]:

$$\begin{aligned}
\frac{d\mathbf{S}}{dt} &= \mathbf{S}\times(\boldsymbol{\Omega}_{\mathrm{MDM}}+\boldsymbol{\Omega}_{\mathrm{EDM}}),\\
\boldsymbol{\Omega}_{\mathrm{MDM}} &= \frac{q}{m\gamma}\left\{(\gamma G+1)\mathbf{B}_{\perp}+(G+1)\mathbf{B}_{\parallel}\right.\\
&\quad \left.-\left(\gamma G+\frac{\gamma}{\gamma+1}\right)\frac{\boldsymbol{\beta}\times\mathbf{E}}{c}\right\},\\
\boldsymbol{\Omega}_{\mathrm{EDM}} &= \frac{q\eta}{2m}\left(\boldsymbol{\beta}\times\mathbf{B}+\frac{\mathbf{E}}{c}\right),\quad G=\frac{g-2}{2}.
\end{aligned} \tag{1}$$

As can be seen from Eq. 1, the main features are the energy of the experiment and the type of particles.

The EDM research experiment does not require a special detector; only a polarimeter is necessary. The cross section on the polarimeter with a carbon target achieves the highest value for protons and deuterons at energy about 270 MeV. This requirement determines the energy of the experiment just by the needs of the polarimeter.

In addition, stable spin motion is required. The frozen spin concept is the direct consequence of the given equations [2]. This method involves zeroing the term associated with the magnetic dipole moment (MDM) during the entire time of beam retention. This method is valid for both protons and deuterons, but has significant differences. For a deuteron, the magnetic moment anomaly is negative $G_d = -0.1429$, which is an order of magnitude less than for the proton $G_p = 1.7928$. For protons at a certain energy called "magic," the MDM term takes zero value in a purely electric ring, without magnetic elements, whereas for

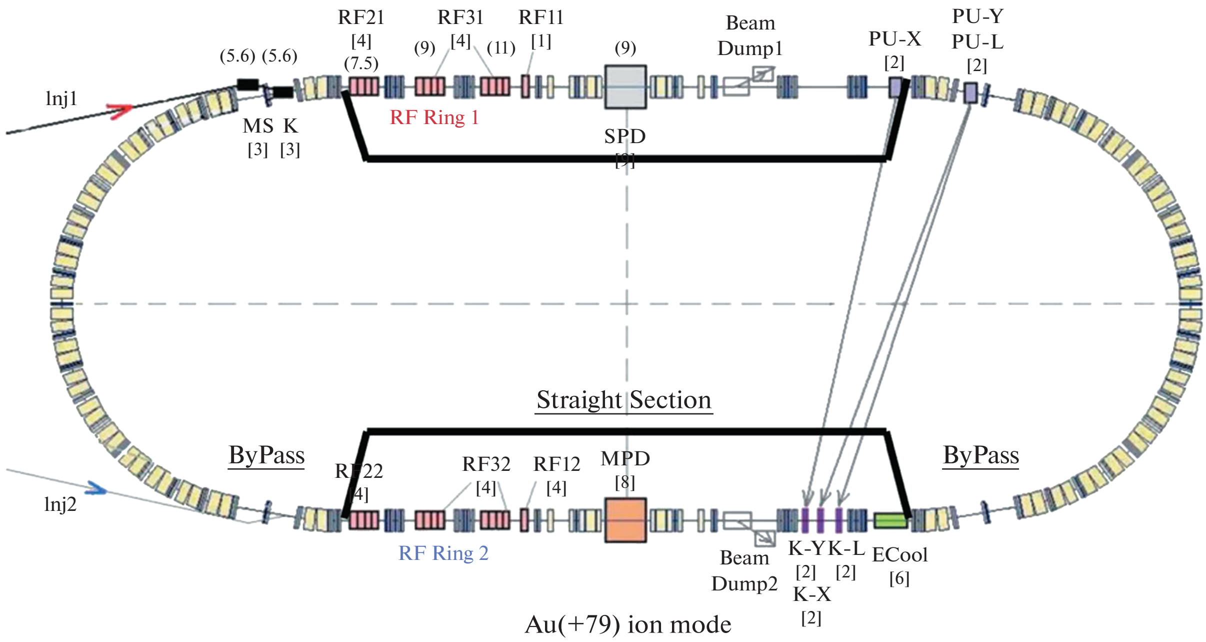

Fig. 1. Schematic diagram of bypass channels in the existing NICA complex.

deuterons, because of the negative value of the magnetic anomaly, the necessary magneto-optical structure involves the use of deflectors with both electric and magnetic fields. In this case, spin rotation in a magnetic field is compensated by an electric one in each element. Thus, the rotation retains its orientation during the entire rotation time in the ring. However, the dipoles in the arcs of the NICA main ring have only a magnetic field component. Thus, the implementation of the "frozen spin" concept in the NICA ring is impossible without a corresponding significant modernization and reconstruction.

To carry out an experiment on search for EDM, it becomes necessary to use an alternative spin control method—the concept of "quasi-frozen spin" (QFS) [3]. Unlike the "frozen spin" method, here the spin does not retain orientation throughout the entire period of circulation, but restores orientation on a straight section. This is possible by using elements with both electric and magnetic fields, which are called Wien filters. The rotation of the spin in the arc by a certain angle is compensated by the corresponding rotation in the Wien filter. Also, fields can be chosen to create zero Lorentz force and not disturb orbit. For this reason, a polarimeter can be installed on straight sections. Thus, polarimeters located after Wien filters will detect the same orientation of the spin vector and for them it will be "frozen."

Table 1. Main parameters of the structure and experiment

Magnetic field of dipoles	0.132 T
Magnetic rigidity $B\rho$	3.252 T m
Full length of the accelerator	503.04 m
Energy of the experiment	240 MeV

There are two main reasons for modernization of the magneto-optical structure. Firstly, there is a lack of space for Wien filters in already existing straight sections. Secondly, the available magneto-optics assumes the NICA ring in the collider mode. But EDM search experiments involve long-term retention and preservation of a polarized coherent beam at a time about $T_{SC} \approx 1000$ s. Therefore, the modernization by introduction of bypass channels was proposed to create an alternative straight section parallel to the original one (Fig. 1). Thus, NICA can be used as a storage ring. Such rings can carry out EDM experiments with polarized deuterons and axion search in the QFS regime.

2. MAGNETO-OPTICAL STRUCTURE WITH BYPASS CHANNELS

The features given in the previous chapter are crucial for choosing the energy of the experiment and type of particles. In the future, all proposed magneto-optics will be considered for deuterons at energy of 240 MeV. It is worth noting that the calculations show the main parameters of the dipole magnetic field $B_{dip} = 0.132$ T, as well as magnetic rigidity $B\rho$ = 3.252 T m (Table 1).

In designing the NICA storage ring with bypass sections, the geometry of arcs is planned to remain unchanged. It is possible to change fields in already

Table 2. Lengths and parameters of the considered magneto-optical structures

Structure	Full length, m	Straight section length, m	Bypass channel length, m	Matching section length, m	Working point
NICA	503.04	109.6	–	–	9.44/9.44
3 Quadrupoles	503.46	83.97	6.41	3.198	13.8/11.8
5 Quadrupoles	510.0	83.97	9.35	2.548	13.44/11.44
Real	503.5	80.70	9.35	2.548	12.8/11.8

installed elements, so that it is possible to use NICA for various experiments.

In the NICA ring, the arc is a place with a nonzero dispersion. At the edges, both dispersion and its derivative suppressed to zero. The straight section has zero dispersion throughout.

The total length of original NICA ring $L_{\text{acc}} = 503.04$ m. Each arc length is $L_{\text{arc}} = 142.15$ m. So, there is $(L_{\text{acc}} - 2L_{\text{arc}})/2 = 109.6$ m available.

Bypass is a channel for beam deflection into an alternative straight section. Dipole magnets are chosen to make a deviation by angle $\alpha = 9°$. Dipole strength $B_{\text{BP}} = 1$ T with length $L_{\text{dip}}^{\text{BP}} = 50$ cm. The alternative straight section is at a distance of 1 m from the original one, so bypass section length $L_{\text{BP}} = 1\ \text{m}/\sin\alpha \approx 6.4$ m. A schematic diagram of bypass channels is shown in Fig. 1.

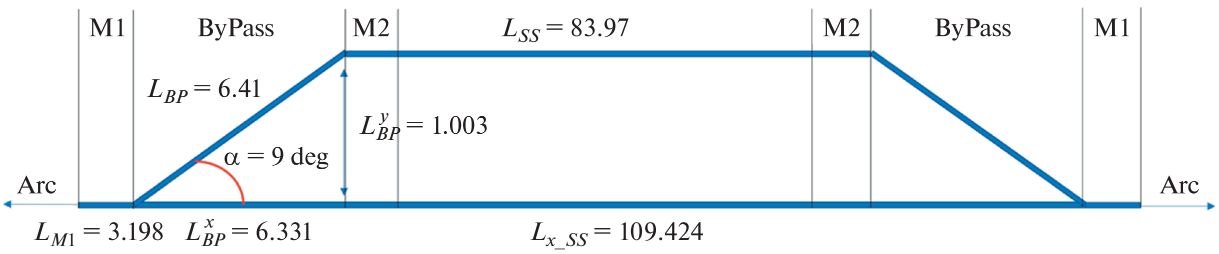

Fig. 2. Schematic diagram of bypass with three quadrupoles.

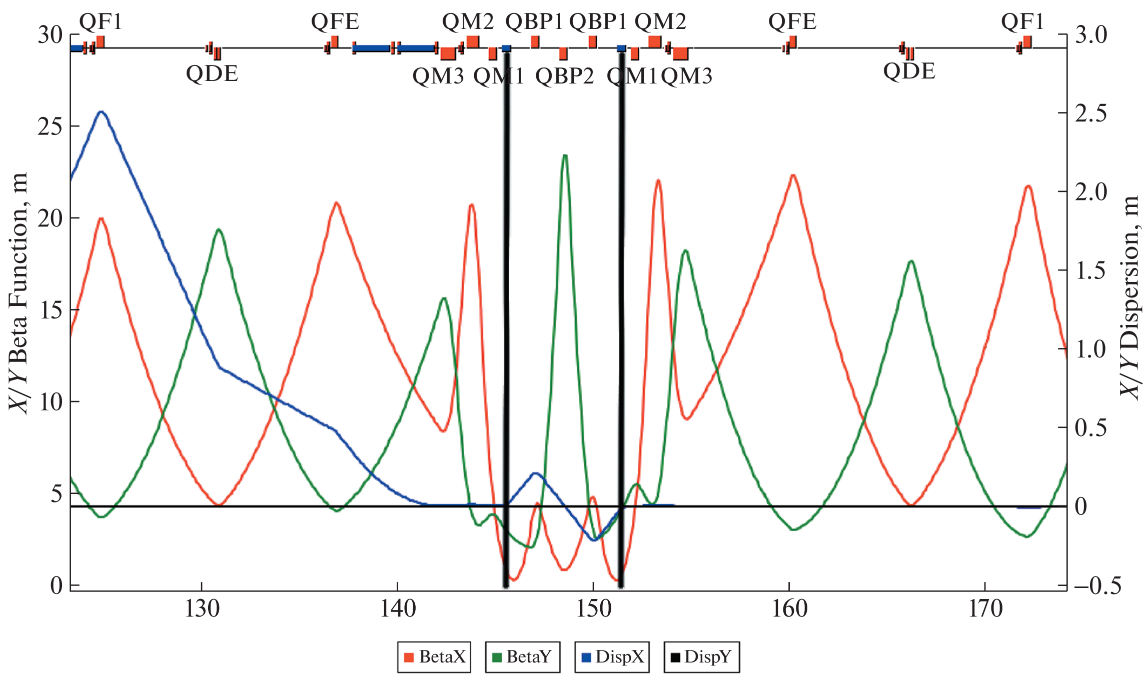

Fig. 3. Twiss parameters for bypass with three quadrupoles. The black lines show the location of the deflectors.

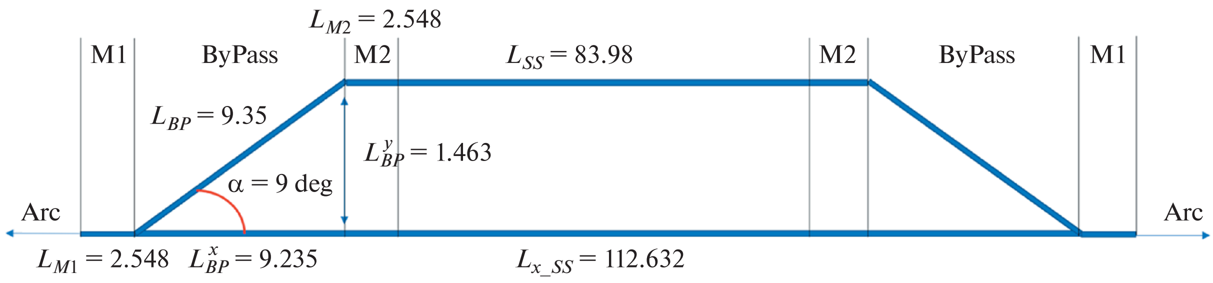

Fig. 4. Schematic diagram of bypass with five quadrupoles.

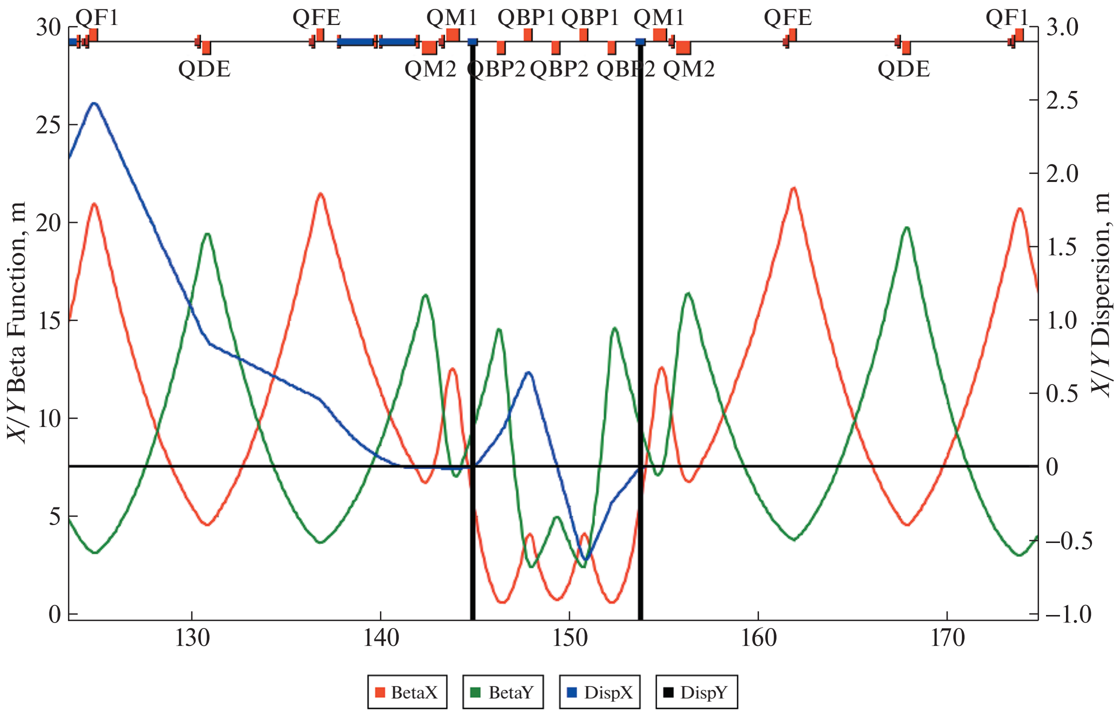

Fig. 5. Twiss parameters for bypass with five quadrupoles. The black lines show the location of the deflectors.

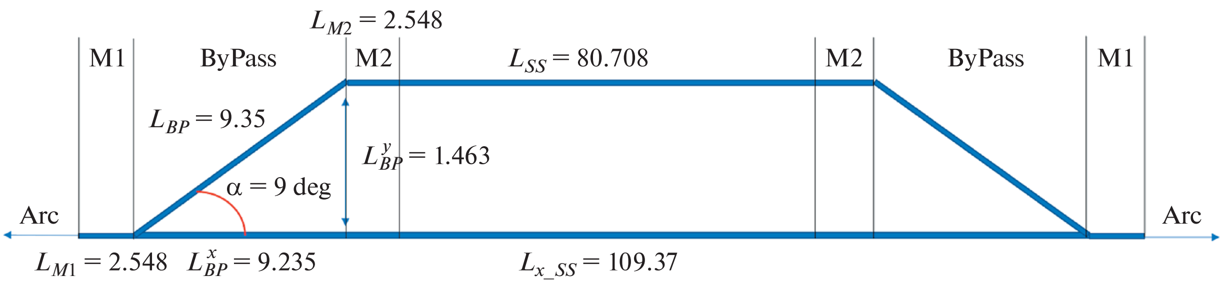

Fig. 6. Schematic diagram of a real bypass.

Deflector magnets distort the dispersion function. Thus, it is necessary to use at least two focusing quadrupoles on the bypass channel to suppress dispersion at the end. This will help to provide zero dispersion throughout the straight section. To ensure periodicity and symmetry of beta functions, one can use one or three defocusing quadrupoles at bypass.

Two cases will be considered; adopted straight sections are fully identical to arcs but without magnets. This is done for simplicity and ideal regular modeling.

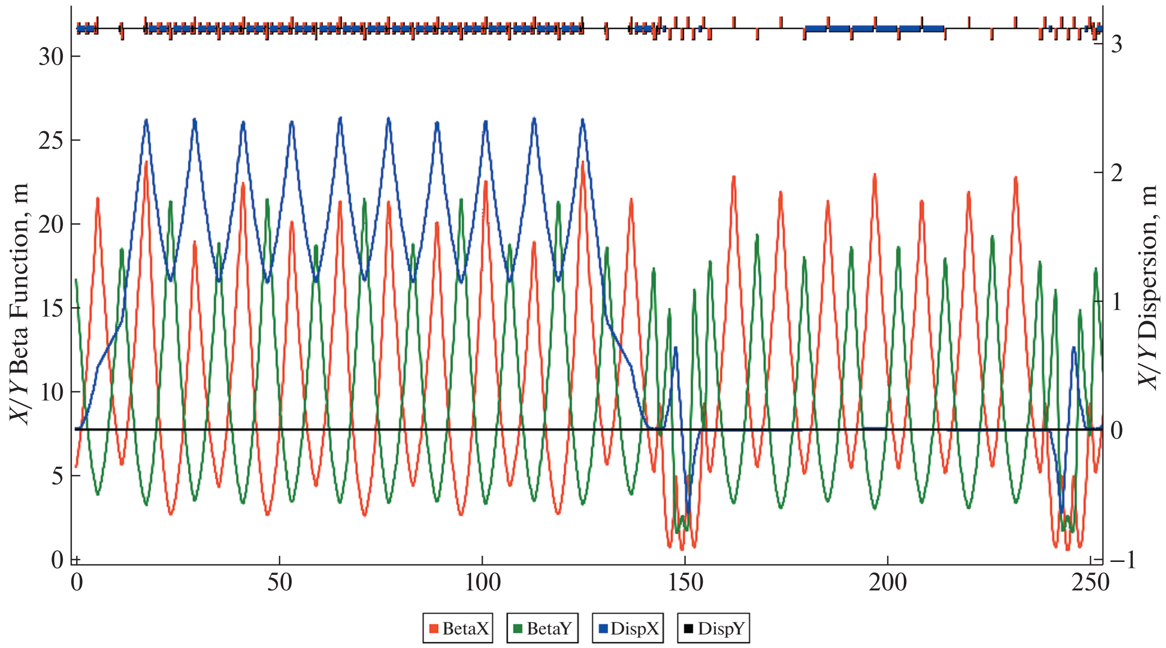

Fig. 7. Twiss functions for half of the NICA bypass ring. Wien filters located on a straight section.

Lastly, we consider a real case of magneto-optical structure with fully regular FODO straight section.

3. QUADRUPOLE BYPASS SCHEME

In this case, the bypass consists of the minimum possible three quadrupoles (Fig. 2). The matching of the arc with the bypass is provided by three quadrupoles QM1, QM2, and QM3 (M1 section). And the matching of the bypass with a straight section (M2) is identical by virtue of symmetry and consists of three quadrupoles QM1, QM2, and QM3 to ensure beta-function periodicity (Fig. 3). The total length of the whole accelerator is then $L^{\mathrm{acc}}_{\mathrm{3quad}} = 503.46$ m.

Figure 3 shows the Twiss functions; the black lines indicate the boundaries of the bypass channel. Beta-function maximum β_y is located in the center of the bypass channel. And it may take a more significant value, compared to β_x. For this reason, we can consider the case with five quadrupoles in the bypass channel.

4. QUADRUPOLE BYPASS SCHEME

Compared to the previous case, the bypass channel consists of five quadrupoles, which are represented by 2 families: focusing QBP1 and defocusing QBP2. It becomes longer $L^{\mathrm{BP}}_{\mathrm{5quad}} = 9.35$ m and is deflected by 1.46 m (Fig. 4). Now, matching sections M1 and M2 are still identical, but they are represented by two quadrupoles QM1 and QM2 to ensure the regularity of Twiss functions. However, the full length of the accelerator becomes longer, NICA $L^{\mathrm{acc}}_{\mathrm{5quad}} = 510.02$ m. Figure 5 shows that the maximum β_y becomes smaller in the center. It is worth noting that the maximum of the dispersion function has increased from $D_x^{\mathrm{3quad}} \sim 0.2$ m to $D_x^{\mathrm{5quad}} \sim 0.5$ m. Thus, this case should be adapted to the real one.

Real Case Scheme

On the basis of the cases considered, we can finally get the structure closely adapted to reality. Now, the straight section is fully regular and becomes shorter $L^{\mathrm{BP}}_{\mathrm{SS}} = 80.71$ m (Fig. 6). The bypass consists of five quadrupoles and deflects the beam by 1.46 m. But for matching, different sections M1 and M2 were used to compensate asymmetry between the arc and straight section. Finally, the Twiss function of half of the NICA bypass is presented in Fig. 7. Wien filters are located at the center of the straight section.

All calculations of Twiss functions were performed with OptiM [4] and COSY Infinity [5].

3. CONCLUSIONS

For EDM experiments it is necessary to use NICA as a storage ring. For this reason, modernization was considered by creation of alternative straight sections parallel to the original ones by using bypass channels. Also, on the straight sections, there is the ability to place special elements—Wien filters to compensate spin rotation in the arcs. As arcs remain unchanged, this makes it possible to use NICA in various experiments.

Two principal schemes of a bypass channel were considered. And finally, we obtained the most realistic case, where the straight section is fully regular. The final structure satisfies all necessary requirements for magneto-optics. Spin-tracking research with optimized Wien filters and simulations show that spin restores the orientation at the straight sections. The "quasi-frozen spin" method can be implemented in the bypass of NICA.

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CONFLICT OF INTEREST

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

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