The new generation of intense X-rays sources based on a low-energy electron storage ring and on the Compton scattering of an intense laser beam allows to produce hard X-rays with intensity up to $10^{12}$ photon/s. One of the main traits of a storage ring lattice for such type of generators is the use of magnetic elements with combined focusing functions such as bending magnets with quadrupole and sextupole field components. In combination with a very low bending radius and dense magnetic elements positioned along the ring circumference it leads to increasing of 3D magnetic field effects on the electron beam dynamics and can drastically decrease the generated radiation intensity. The paper is devoted to studying the 3D magnetic field effects on bending magnet edges and lattice lens interference on the electron beam dynamics and parameters of produced radiation for the NSC KIPT 225 MeV storage ring.

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### 1. INTRODUCTION

For recent few years the design of a compact X-ray generator NESTOR (New-generation Electron Storage Ring) based on the Compton scattering are being carried out in the Kharkov Institute of Physics and Technology (KIPT) [1]. It is supposed that the generator will produce the X-rays of intensity up to $2 \times 10^{12}$ photon/s. It is possible to reach such a level of generation that the electron beam size of about 50 µm in the interaction point is provided. For this purpose a lattice of the ring being achromatic in the first as well as in the second order at the interaction point has been developed. The results of numerical simulations of the electron beam dynamics in NESTOR taking into account the intrabeam scattering and Compton scattering show that the required value of the steady state electron beam size can be obtained.

All calculations were accomplished taking into account the ideal magnetic fields; meanwhile focusing conditions in the facility are very difficult. Under conditions of compactness, strong focusing and use of magnet elements with combined focusing functions the effects of 3D distribution of a magnetic field can lead to decreasing of dynamic aperture of the ring and increasing of the effective beam size. So, there are tasks to design magnetic elements of the ring in such a way to provide a minimum value of particle motion exiting, to investigate 3D effects of designed magnetic elements and to improve the ring lattice if it is needed.

This article is the first publications devoted to this subject and mainly describes efforts of the KIPT on designing magnetic elements for NESTOR with a minimum value of non-ideal magnetic field components. The estimation of the values of such components had been carried out. The preliminary results of dynamic aperture simulations are presented.

### 2. PARAMETERS OF MAGNETIC ELEMENTS OF THE NESTOR LATTICE

The lattice of the X-ray generator NESTOR with the electron beam energy up to 225 MeV are presented in [2]. The main parameters of lattice focusing elements are presented in Table. Main parameters of the magnetic elements of NESTOR

<table>
<thead>
<tr>
<th>Element type</th>
<th>Aperture, mm</th>
<th>$B_0$, T</th>
<th>$G_1$, T/m</th>
<th>$G_2$, T/m²</th>
<th>Eff. length, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole magnet</td>
<td>18</td>
<td>1.5</td>
<td>1.8</td>
<td>-</td>
<td>0.7854</td>
</tr>
<tr>
<td>Quadrupole magnet</td>
<td>18</td>
<td>-</td>
<td>20</td>
<td>-</td>
<td>0.15</td>
</tr>
<tr>
<td>Sextupole magnet</td>
<td>18</td>
<td>-</td>
<td>-</td>
<td>225</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### 3. DIPOLE MAGNET EDGE FIELD

The characteristics of the edge field depend on the following factors:

- Magnetic field topology in the regular part of the magnet;
- Shape of the magnet edge;
- Exiting coil positions;
- Positions of the next magnets.

All this factors were taken into account in calculations of the magnetic field map of the dipole magnet. The calculations have been carried out using the MERMAID code [3].

The shape of the regular part of the dipole magnet pole was calculated by the authors with method [4] and checked up with MERMAID [3] and POISSON [5] codes. The following requirements where taken into account through the calculations of a dipole pole shape:

- The operation area width of the dipole magnet is ± 0.025 m;
- Field quality are $\Delta B/B_0 < 10^{-4}$; $\Delta G/G_0 < 10^{-2}$;
- There is a flat plate on the pole for magnet gap calibration;
- The curvature of the pole sections has to provide a required magnetic field strength in the operation area without saturation of the pole;
- The pole shape has to provide a minimum value of nonlinear field components at magnetic field value equal to 1.5 T at the reference orbit.

The dipole magnet with the pole shape presented in Fig.1 provides a magnetic field as is shown in Fig.2. The magnetic field value is normalized with the table value of the magnetic field gradient of the dipole magnet (Table 1). Calculations were carried out for the cylindrical symmetry case with the radius equal to 0.5
The magnetic field value exceeds 1.8 T nowhere in the magnet gap.

To prevent saturation of the dipole magnet pole on the face sides of the magnet pole we use additional plates limiting the pole smoothly in the longitudinal direction. The cross-section of the additional plate with cylindrical surface is given in Fig.3.

**Fig.1. The cross section of the regular part of the dipole magnet pole. Specific parts of the pole are marked with circles. A1-A2, A4-A5 are left and right shims. A2-A3 is the calibrating section. A3-A4 is the section determining the magnetic field quality.**

![Fig 1 Cross Section of Dipole Magnet Pole](image1)

The plate is made of iron and is fixed on the pole edge under the angle equal to 0.088 rad relatively to radius that is drown from the geometrical center of the dipole magnet to the point at the reference orbit with angle coordinate equal to 0.676864 rad as is shown in Fig.4. At any cross section, at any longitudinal coordinate the plate shape is parallel to the dipole magnet pole shape.

Such a solution was chosen for the following reasons. According with the dipole magnet field map the numerical simulation of the reference particle motion was carried out and the distribution of dipole magnetic field and its gradients were obtained for various dipole magnet edge shapes. Figs.5-8 show these dependences for the final version of the pole shape. Through the simulations an angle of pole (1 in Fig.4) and iron plate (2 in Fig.4) jointing was chosen to make an effective length of the quadrupole and sextupole components of the field equal to each other. It was found that the effective boundary of the dipole magnet field is away from the iron edge of the magnet at a distance equal to 0.0233 m. While geometric edge of the sector with the angle of 90° and the center coinciding with the design orbit center is as far away as 0.0247 m from this one. In such way the position of the real dipole magnet center was specified.

The higher derivatives of the magnetic field depend on the angle joining of iron plate to the magnet pole very weakly. The values of the sextupole and octupole components of the magnetic field in the dipole magnet of NESTOR equal to:

- Sextupole component: \( G_s / B_0 = 1.414 \) [m⁻¹], where \( G_s \) is sextupole gradient of the magnetic field.
- Octupole component: \( G_o / B_0 = 7.1 \) [m⁻²], where \( G_o \) is octupole gradient of the magnetic field.

**Fig.2. The magnetic field gradient distribution along the transversal coordinate in the regular part of the pole. The magnetic field value at the reference orbit equals to 1.5 T**

![Fig 2 Magnetic Field Gradient Distribution](image2)

**Fig.3. The cross section of pole of the dipole magnet with cylindrical surface which involves electron beam reference orbit. The values of parameters are in cm**

![Fig 3 Cross Section of Dipole Magnet](image3)

**Fig.4. Face part of the NESTOR dipole magnet: 1 is dipole magnet face; 2 is magnet pole; 3 is excitation coil**

![Fig 4 Face Part of Dipole Magnet](image4)

**Fig.5. Longitudinal distribution of the magnetic field in the NESTOR dipole magnet**

![Fig 5 Magnetic Field Distribution](image5)

**Fig.6. Longitudinal distribution of the quadrupole gradient of the magnetic field in the NESTOR dipole magnet**

![Fig 6 Quadrupole Gradient Distribution](image6)
4. MUTUAL EFFECTS OF RING MAGNETIC ELEMENTS

The calculations were carried out for lens couples: quadrupole – sextupole, quadrupole – quadrupole, sextupole – sextupole with parameters according to Table 1. The integral harmonic composition of the magnetic field for lens couples mentioned above was determined with MERMAID code [3]. According to calculation results the mutual lenses effects lead to weak decreasing (of about 3%) of the strength of the main harmonic. Appearance of higher harmonics was observed only in the case of significant increase of the geometrical aperture of lenses.

5. DYNAMIC APERTURE NUMERICAL SIMULATIONS RESULTS

Assuming that the quadrupole component of the magnetic field due to 3D magnetic field distribution can be suppressed by the choice of an angle of an additional plate fixation the simulation of the dynamic aperture value had been carried out taking into account the obtained value of sextupole and octupole components of the field due to 3D field distributions in bending magnet. The calculation results show that these components do not restrict the boundaries of motion stable area. The value of the dynamic aperture at the interaction point is equal to 3x3 mm. On the other hand, the growth of the steady state beam size was observed.

REFERENCES


Fig. 7. Longitudinal distribution of the sextupole gradient of the magnetic field in the NESTOR dipole magnet

Fig. 8. Longitudinal distribution of the octupole gradient of the magnetic field in the NESTOR dipole magnet

CONCLUSIONS

The results of numerical simulations showed that the 3D magnetic field distribution of the dipole magnet developed in the NSC KIPT does not restrict the dynamic aperture of the X-ray generator NESTOR. The mutual effects of magnetic lenses in the ring are weak and do not lead to the effects that can be observed. To complete the investigations of the 3D magnetic field effects it is needed to calculate magnetic field distribution in the quadrupole lenses. In order to concern investigations of 3D magnetic field effects on reference electron beam size in the interaction point the simulation code is under developing in KIPT.