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SIMULATION STUDY OF THE FRINGE FIELD EFFECTS IN THE HEPS STORAGE RING*

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Abstract

The High Energy Photon Source (HEPS) is a 6 GeV, 1.3 km storage ring light source being built in Beijing, China. To get an ultralow emittance, high-gradient quadrupoles, combined-function magnets and longitudinal gradient dipoles (BLG) are adopted in the design of the storage ring. The impact of fringe field effects is of interest. To this end, several methods based on one-dimensional and three-dimensional magnetic fields are used to model different kinds of magnets of the HEPS storage ring. In this paper, we will introduce detailed modeling methods and the impact of fringe field effects on the HEPS storage ring.

INTRODUCTION

The High Energy Photon Source (HEPS), a 6 GeV synchrotron radiation facility with ultralow emittance, is being built in Beijing, China. A hybrid 7BA design for the HEPS, with a natural emittance of ~35 pm·rad and circumference of about 1.3 km, has been made [1-3].

To get an ultralow emittance, high-gradient quadrupoles, combined-function dipoles and longitudinal gradient dipoles are adopted in the design of the storage ring. Usually, the lattice design of accelerator is based on the hard-edge model of all the magnets. In fact, the magnetic field distribution is different from the hard-edge model. To achieve the expected performance, one important issue is to study the lattice and beam dynamics with realistic field models of magnets. This paper will use several methods to study the fringe field effects of different kinds of magnets and evaluate the impacts of fringe field effects on the linear optics and chromaticity.

FRINGE FIELD EFFECTS OF QUADRUPOLES

There are 14 quadrupoles in every 7BA cell. To study the fringe effects of quadrupoles, three one-dimensional (1D) magnetic field methods and two three-dimensional (3D) magnetic field methods are used to model the quadrupoles.

Slicing method is a general way to study the fringe field effects of magnets, we tried this method using AT [4]. For slicing method, the quadrupole is divided into many slices and each one is regarded as a quadrupole with constant strength. The central region of quadrupole where K(z)/max(K)>=0.999 is regarded as one slice and the left and right parts are divided into the same number of slices of the same length. The number of slices is scanned to reach a good balance between the accuracy of model and calculation time. As shown in Fig. 1, we can see that when the number of slices (for left part or right part) exceeds 200, the tunes converge, so the total number of slices 401 is chosen in the slicing method of quadrupoles.

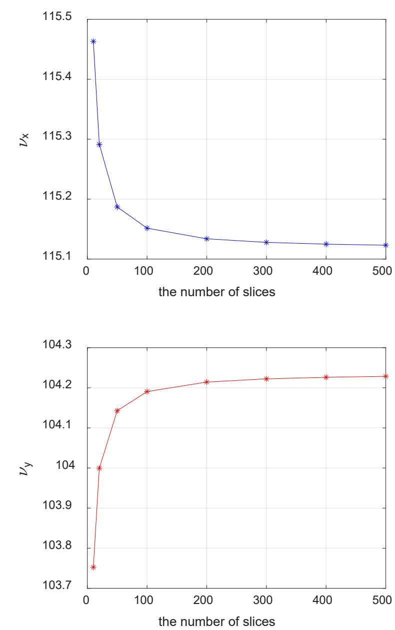

Figure 1: The tune with respect to the number of slices (for left part or right part): horizontal (top), vertical (bottom).

Trapezoidal model is a common and simple method to model the fringe field of quadrupoles. The quantities F_1 and L_{eff} are the fringe field integral parameter and effective length of quadrupole, respectively. These two parameters are used to characterize the slope of the fringe field [5]. F_1 is calculated for the entrance in the range of $(-\infty, 0]$ and for the exit in the range of $[0, +\infty)$. This method is implemented in AT.

Integral parameter method is based on the KQUAD element in ELEGANT [6]. The fringe field can be characterized by 10 integral parameters given in [7, 8]. It is to make a fringe field nonlinear modification calculating in Lie algebra to the hard-edge model.

Two 3D magnetic field methods based on ELEGANT are also tried to study the fringe field effects of quadrupoles. One is the BMXYZ element for straight element only which simulates transport through a 3D magnetic field specified as a field map, the other is the BGGEXP element for straight and bending magnet, it is a magnetic field element using generalized gradient expansion [9].

The impacts of the fringe field effects on the main parameters of the lattice based on different models are listed in Table1. The tune shifts of each family of quadrupoles

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due to the fringe field effects are shown in Fig. 2. We can see that the tune shifts based on different models are almost identical.

Table 1: The Impacts of Quadrupoles Fringe Field Effects on the Lattice Main Parameters

Method	$\Delta\nu_x$	$\Delta\nu_y$	$\Delta\varepsilon$ (pm·rad)
Slicing method	-0.390	-0.563	0.6
Trapezoidal model	-0.428	-0.613	0.7
Integral parameter method	-0.422	-0.599	0.7
3D BMXYZ model	-0.378	-0.563	0.6
3D BGGEXP model	-0.372	-0.552	0.7

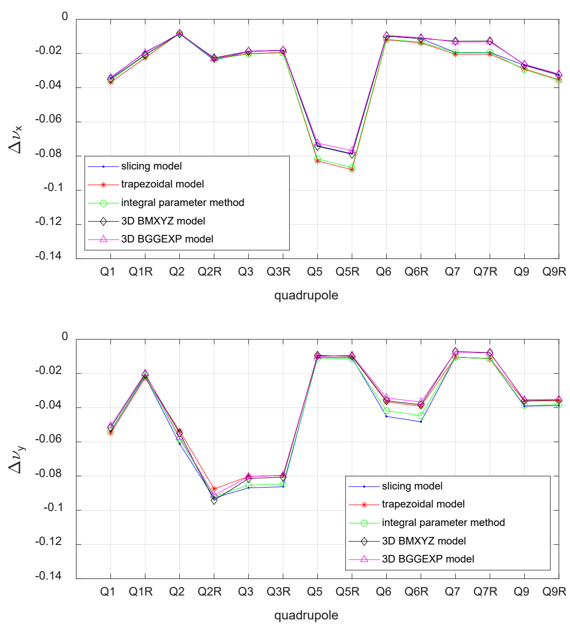

Figure 2: Tune shifts due to the fringe field effects of each family of quadrupoles.

FRINGE FIELD EFFECTS OF BLGS

There are five BLGs in every 7BA and each one has five segments. For the BLG, the magnetic field not only extend at the end, but also changes gradually between the segments. Figure 3 shows the magnetic field distribution of BLG3 (the third BLG in one 7BA) with hard-edge model and data simulated by the software OPERA. BLG modelling likewise begin with slicing method based on AT. The linear length of each slice is 1mm and the bending angle and path length of each slice change according to the field strength.

Similarly, two three-dimensional magnetic field methods based on ELEGANT are used to model BLGs. One is BGGEXP, the other is BRAT element which is for bending element only. It is worth mentioning that the 3D magnetic field method applied on the bending element does not allow to calculate the emittance through the radiation integrals.

The impacts of the fringe field effects of all the BLGs on the main parameters of lattice based on different methods are shown in Table 2. For the slicing method, the fringe field effects of BLGs mainly change the vertical tune. But the results based on 3D method are obviously different from that based on slicing method. After analysis, it is found that this is mainly because the one-dimensional magnetic field method cannot reflect the homogeneity of the fringe field in the horizontal direction.

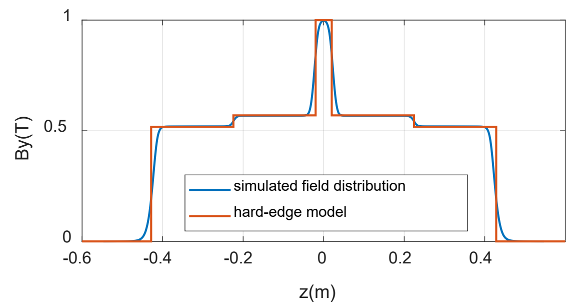

Figure 3: Simulated magnetic field distribution of BLG3.

Table 2: The Impacts of BLGs Fringe Field Effects on the Lattice Main Parameters

Method	$\Delta\nu_x$	$\Delta\nu_y$	$\Delta\varepsilon$ (pm·rad)
Slicing method	2E-4	-1.3E-3	-0.32
BRAT method	0.043	0.052	----
GGE method	0.045	0.057	----

FRINGE FIELD EFFECTS OF COMBINED-FUNCTION DIPOLES

Two types of combined-function dipoles are adopted in the storage ring lattice, one is the dipole with horizontal defocusing (BD), the other is anti-bend with horizontal focusing (ABF). In the process of lattice design, the curvilinear magnet with constant dipole field and gradient is used to model combined-function dipole, in the actual magnet design, combined-function dipole is quadrupole with transverse offset. Previous studied have shown that these two models have very little effect on the parameters of storage ring[10], so the model of quadrupole with transverse offset is used to study the fringe field effects.

The same three methods are tried as BLG. The impacts of the fringe field effects of all the combined-function dipoles on the main parameters of lattice are shown in Table 3. The results from different methods are very close.

Table 3: The Impacts of Combined-Function Dipoles Fringe Field Effects on the Lattice Main Parameters

Method	$\Delta\nu_x$	$\Delta\nu_y$	$\Delta\varepsilon$ (pm·rad)
Slicing method	0.828	0.460	-0.34
BRAT method	0.805	0.468	----
GGE method	0.820	0.458	----

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Table 4: The Impacts of Fringe Field Effects on the Lattice Main Parameters

Parameter	Δcir(μm)	Δε(pm·rad)	$\Delta\nu_x$	$\Delta\nu_y$	$\Delta\xi_x$	$\Delta\xi_y$
Value	158	0.6	0.339	-0.177	0.63	5.49

THE EFFECTS OF FRINGE FIELD

After the above study on fringe field effect of each type of magnet, we can see that the effects of quadrupoles and combined-function dipoles are dominant and the effects of BLGs are much less than that of other two types of magnets. Additionally, considering that all the three methods to model BLGs are very time-consuming, so the fringe field effects of BLGs are ignored and the hard-edge model are still adopted in the lattice. Taking into account the accuracy and simplicity of modeling, the trapezoidal model and slicing model are adopted to model the quadrupoles and combined-function dipoles respectively in the storage ring. The total impacts of fringe field effect on the main parameters of lattice are listed in Table 4. Fig.4 shows the optics distortions of one period introduced by the fringe field effects. The beta-beating is as large as 7.7% in the horizontal direction and 17.9% in the vertical direction.

SUMMARY

As described above, we have tried several methods to study the fringe field of quadrupoles and dipoles in the HEPS storage ring. The simulated results show that the effects of quadrupoles and combined-function dipoles are dominant and the total impacts of fringe field are not negligible.

For HEPS storage ring, the lattice is very compact and the cross-talk between adjacent magnets is also an issue worth studying, and the related studies are under way.

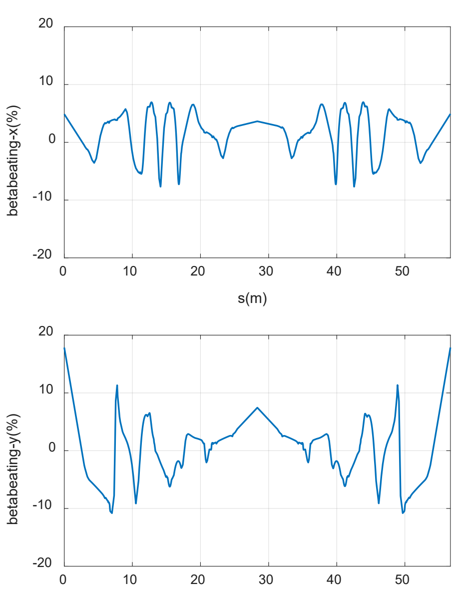

Figure 4: Beta-beating induced by the fringe field effects of one period.

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