ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK133

MAGNETIC FIELD TOLERANCES OF DIPOLE AND QUADRUPOLE MAGNETS FOR XiPAF SYNCHROTRON

H. J. Zeng, H. J. Yao, S. X. Zheng †, X.L. Guan, X.W. Wang, P.F. Ma, Key Laboratory of Particle & Radiation Imaging (Tsinghua University), Ministry of Education, Beijing 100084, China also at Laboratory For Advanced Radiation Sources and Application, Tsinghua University, Beijing 100084, China also at Department of Engineering Physics, Tsinghua University, Beijing 100084, China
H. Ning at Northwest Institute of Nuclear Technology, Xi'an, China

Abstract

The magnets are being constructed for Xi ' an Proton Application Facility (XiPAF) synchrotron, which is dedicated to fulfill the need of the experimental simulation of the space radiation environment. A study is started to obtain the specifications and tolerances of the magnets to avoid beam lost by the excessive magnetic field errors. The study includes the effect of field and alignment errors of the magnets on the closed orbit and beam optics. Also, a preliminary study of effect due to multipole components in dipole and quadrupole magnets on dynamic aperture has been done.The tolerances of dipole and quadrupole magnets on field errors, including multipole components, and alignment errors are described in this paper.

INTRODUCTION

A compact proton synchrotron with the ability to deliver a 230MeV proton beam carrying 30nA average current is under construction for XiPAF [1]. The purpose of the facility is to enable ground accelerated tests of space radiation effects on electronic components. In our lattice design, we use a DBFO cell as the basic component [2], where "D" and "F" represent defocusing and focusing quadrupole, "B" represents dipole, and "O" represents drift space. The optics of a DBFO cell are similar to those of a FODO cell, so it can easily be changed by tuning the strength of the quadrupoles to satisfy different requirements during the injection and extraction stages.The optical function of one cell is shown in Fig. 1.

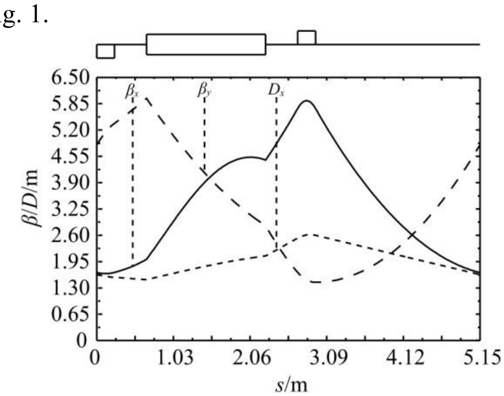

Figure 1: Lattice of one cell called DBFO.

The compact synchrotron consists of 6 DBFO cells, the circumference of which is 30.9m. The layout is shown in Fig. 2. and main parameters are given in Table 1.

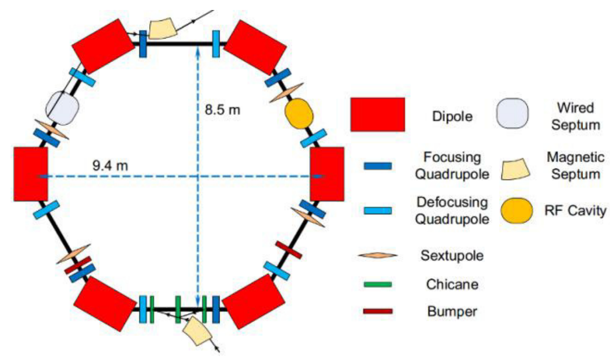

Figure 2: Layout of XiPAF synchrotron.

Table 1: Parameters of the Lattice

Parameter	Value	Unit
dipole effective length	1.6	m
dipole edge angle	60	°
injection energy, E_{inj}	7	MeV
extraction energy, E_{ext}	60~230	MeV
$\beta_x/\beta_y/D_x$ [1]	5.7/6.0/2.6	m
Tune, ν_x/ν_y	1.678/1.784	

[1] β_x and β_y are the peak value of horizontal and vertical β function, respectively. D_x is the peak value of the horizontal dispersion function.

Being a compact proton synchrotron, the performance of dipole and quadrupole magnets become a major concern here. Thus each and every parameter should be fixed repeatedly with utmost care and after a thorough study and analysis by the magnet constructor and the physical designer. The aim of this study is started to obtain the specifications and tolerances for the dipole and quadrupole magnets. To make this study more reliable, we use cross-validation to simulation by Madx and Elegant, but only Madx results are presented for more concise read. A linear error analysis is carried out to obtain the aperture, which includes the orbit distortion and beta beat due to linear errors i.e. field, gradient and alignment errors. Then a study is carried out to quantify the effect of multipole components in dipole and quadrupole magnets on the dynamic aperture. In this paper in section-2, we present

† zhengsx@tsinghua.edu.cn

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the linear analysis and in subsequent sections, nonlinear analysis, results, and conclusions are presented.

LINEAR ERROR ANALYSIS

Detailed studies of the sensitivity of the chosen lattice are carried out against to the linear errors in dipole and quadrupole field as well as alignment error. These studies include the effect on closed orbit and optics due to dipole field error in the dipole magnets, alignment error in quadrupole magnets and quadrupole gradient errors in the quadrupole magnets. At this compact synchrotron, all dipole magnets are driven by the same power supply and thus correction in power supply will bring the field at the same baseline level for all the magnets of the family. Thus we emphasized the study under the random errors.

Effect On Orbit

The expression of the closed orbit distortion (COD) due to any perturbation, which is dipole in nature, is given by

$$u_{s\to 0} = \frac{\theta\sqrt{\beta_s\beta_0}}{2\sin(\pi\upsilon)}\cos\left(\pi\upsilon - \left|\varphi_s - \varphi_0\right|\right). \quad (1)$$

where (β_s, φ_s) and (β_0, φ_0) are the beta function and phase advance at the place of measure and perturbation, ν is the tune, θ is the equivalent kick strengths of the perturbation. The major contribution to COD comes from two sources, namely the alignment error of dipoles and quadrupoles and random field error in the dipole magnets, and then individually the effects of these errors on orbit are studied. The results show that all kinds of errors have a significant effect on the closed orbit in one direction, either horizontal or vertical. For dipole magnets, the field errors are particular keys, which generate horizontal COD. In addition, by the significant effect on the edge angle focusing the displacement of vertical and the rotation around longitudinal direction generate COD at vertical. For quadrupole magnets, the displacement of the horizontal and vertical introduce corresponding dipole errors, which result in COD at orthogonal directions. We assigned gaussian random errors to these dipole and quadrupole magnets, which are shown in Table 2.

Table 2: Various Errors in the Field and Alignment

Type	Random error
Field error in the dipoles	<±5E-4(3σ)
Gradient error in quadrupoles	<±1.5E-3(3σ)
Displacement error in all magnets	0.2mm(1σ)
Rotation error in all magnets	0.2mrad(1σ)

Different 500 random seeds are chosen for studies. The max COD with and without correction plot in the Fig. 3. There are a few mm COD at either horizontal or vertical, and thus the correction is needed. After correction, COD reduce below 1mm at horizontal and vertical, which is less than 1/10 beam size at injection energy. The max kick strength of the correctors is shown in Fig. 3. All the kicks at either horizontal or vertical less than the 1 mrad limited corresponding to the max current of the corrector power supply, which can be acceptable.

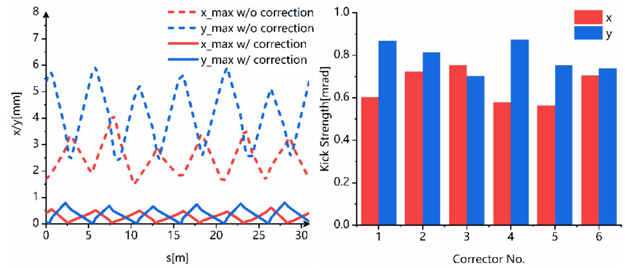

Figure 3: COD (left)and max kick strength (right).

Effect On Optics

The gradient errors in the quadrupole generate tune shift, beta beat and also breaks the symmetry of the lattice. The effect on the working point and beta function is presented in this section. Symmetry breaking causes shrinkage in the dynamic aperture, which is presented in the next section. The change in beta i.e. beta beat due to gradient errors is given by

$$\Delta\beta_{u_{s\to 0}} = \frac{\Delta K\beta_s\beta_0}{2\sin(2\pi\upsilon)}\cos\left(2\left(\pi\upsilon - \left|\varphi_s - \varphi_0\right|\right)\right). \quad (2)$$

where (β_s, φ_s) and (β_0, φ_0) are the beta function and phase advance at the place of measure and errors, ν is the tune, ΔK is the equivalent kick strengths of the gradient errors. The tune shift due to these errors is given by

$$\Delta Q_u = -\frac{1}{4\pi}\beta\Delta K\Delta s \cdot \quad (3)$$

Where ΔK is the equivalent kick strengths of the gradient errors, β is the average beta function in the quadrupole, Δs is the length of the quadrupole. A 500 random gaussian distribution of gradient errors, which also can be see in Table 2, are generated for the simulation, the results shown in Fig. 4.

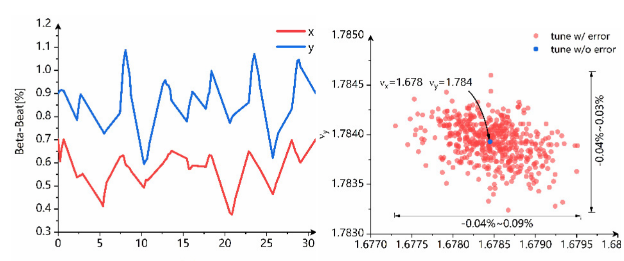

Figure 4: Beta-beat and tune shift on gradient errors.

From Fig. 4, the gradient errors generate a very small change in the tune shift and meanwhile the beta beat is less than 1.2%.

NONLINEAR ERROR ANALYSIS

Above linear analysis provides the required physical aperture, allowed dipole errors in the dipole magnets and allowed alignment errors in the dipole and quadrupole magnets. The analysis does not give a clear picture of required tolerances in the gradient errors, which breaks the symmetry of the lattice. It also does not give an indication of the effect of the main dominating multipole

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error in dipole and quadrupole magnets. The relative multipole errors for a combined dipole and quadrupole magnets respectively are [3]:

$$\frac{\Delta B}{B_0} = \frac{b_n x^n}{B_0} (n = 0,1,2,\dots) \tag{4}$$

$$\frac{\Delta B}{B_1} = \frac{b_n x^{n\text{-}1}}{B_1} (n = 1,2,3,\dots) \tag{5}$$

where

$$b_n = \frac{1}{n!}\left(\frac{\partial^n B_y}{\partial x^n}\right).$$

n=0,1 correspond to dipole, quadrupole respectively. So for obtaining the allowed multipole errors in the dipole magnets, a preliminary study of magnetic field nonlinear is carried out by Opera3D [4] code in magnet design report from Sigmaphi [5], and thus the systematic errors at multipole components see in Table 3 from the polynomial fitting of simulation data.

Table 3: Tolerance on Multipole Component for Magnets

Multipole errors	Dipole n=0		Quadrupole n=1	
	Sys	Ran	Sys	Ran
B_1/B_n	-1.50E-4	<±3E-4		<±1.5E-3
B_2/B_n	2.55E-4	<±3E-4		<±1.5E-3
B_3/B_n	3.45E-4	<±3E-4	0.24E-4	<±1.5E-3
B_4/B_n	3.15E-4	<±3E-4		<±1.5E-3
B_5/B_n			2.52E-4	<±1.5E-3

*The reference radii at dipole and quadrupole magnet are 50mm and 45mm respectively.

But the variation in construction from magnet to magnet leads to multipole components that are unique for each magnet. At the present time, it is not known precisely how large the random errors are likely to be, so we assign random errors by the experiences of magnet construction also in Table 3.

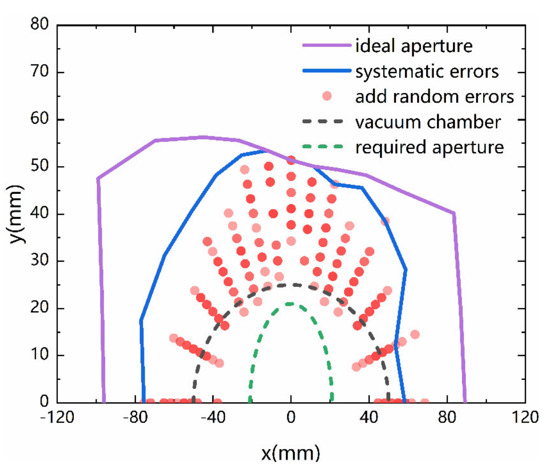

Figure 5: Dynamic aperture on multipole components.

The results on dynamic aperture with no error, with systematic errors only, with systematic and different 20 random errors at injection energy, are shown in Fig. 5. Max beam size at injection energy is plot in Fig. 5 as required aperture. The dynamic aperture with systematic error is bigger than vacuum chamber and significantly shrink into the vacuum chamber by adding random errors. But it is safe that the dynamic aperture is also bigger than required aperture.

CONCLUSION

Linear and nonlinear studies have been done for the compact proton synchrotron for the tolerances of dipole and quadrupole magnets. Significant reduction in dynamic aperture observed here gives an indication that the dynamic aperture is sensitivity against to the multipole components at the dipole magnets. The difference in the manufacture of magnets is inevitable, and further works need to be carried out to fix the multipole errors to arrive at the tolerances by means of collaboration among magnet construction, measurement, and physical design.

ACKNOWLEDGEMENT

The authors would like to thank Prof. Shyh-Yuan Lee of Indiana University and Guangrui Li of Nanjing Research Institute of Electronics Technology for their advice on dynamic aperture simulation.

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