STUDIES ON THE INFLUENCES OF LONGITUDINAL GRADIENT BENDING MAGNET FABRICATION TOLERANCES ON THE FIELD QUALITY FOR SILF STORAGE RING

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Abstract

The advanced storage ring of 4th generation synchrotron radiation facility, known as the diffraction-limited storage ring (DLSR), is based on multi-bend achromat (MBA) lattices, which enables an emittance reduction of one to two orders of magnitude pushing beyond the radiation brightness and coherence reached by the 3rd generation storage ring. The longitudinal gradient bending (LGB) magnets, with multiple magnetic field stages in beam direction, are required in the DLSR to reduce the emittance. The permanent magnet based LGB magnets are selected for the Shenzhen Innovation Light-source Facility (SILF) due to the advantages of operation economy, compactness and stability compare to the electro-magnet. In this paper, the influences of typical LGB magnet fabrication tolerances on the field qualities are presented using a dedicated parameterized finite element (FE) model, including the poles height tolerances, the pole tip inclination (in different orientations).

INTRODUCTION

Benefit from supporting the cutting-edge researches in various disciplines and industry applications, such as physics, material, bioscience, medicine, electronics, chemistry, etc., the advanced storage ring of 4th generation synchrotron radiation facility based on multi-bend achromat (MBA) lattices (also known as the diffraction-limited storage ring, DLSR) is emphasized and constructed world widely, pushing beyond the radiation brightness and coherence attained by the 3rd generation storage ring [1]. In the Institute of Advanced Science Facilities (IASF, Shenzhen, China), a storage ring of this type in Shenzhen Innovation Light-source Facility (SILF) is proposed and under preliminary design [2]. The longitudinal gradient bending (LGB) magnets, with multiple field stages in beam line direction, are required in DLSR design to reduce the electron beam emittance. Concerning the advantages of operation economy, compactness and stability compare to the electro-magnet, the permanent magnet (PM) based LGB magnets are selected and designed for SILF storage ring.

Typical structure of the LGB magnet is shown in Fig. 1. Field of five stages is first designed by adjusting the PM block number, size and easy magnetization direction in each module. The pole profile is optimized to fulfill the field quality requirements in good field region, i.e. the homogeneity of the field in transverse direction and / or the integrated field in beam direction (denoted as TFH and IFH respectively). The C-shape design has an open access to the magnet gap which simplifies the beam pipe installation and field measurements. Sm_2Co_{17} is selected as the PM material, which has small temperature coefficient and good magnetic performance. The pole, yoke, shielding plates and field tuning bolts are made of soft iron DT4. The material of the bolts for the back yoke fixation is carbon steel. The Fe-Ni alloy with high temperature coefficient (grade 1J30) is introduced at the magnet opening side to compensate the field changes result from the temperature variations. The field tuning bolts provide an additional approach to actively adjust the fields afterwards.

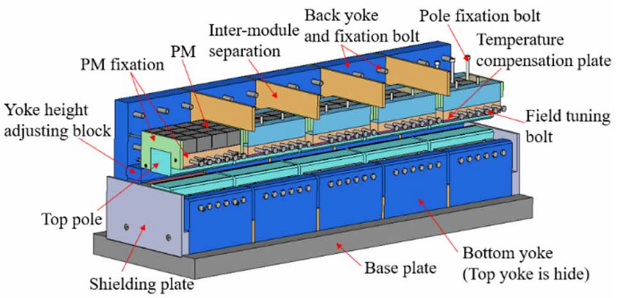

Figure 1: Typical structure of LGB magnet for SILF (5 modules assembled).

The five magnet modules have similar structures as shown in Fig. 1. Aluminium blocks fill the remain voids between the poles and yokes to support the PMs. The magnet modules are assembled separately at first and then combined as entire structure by bolting to the base plate and separated longitudinally by thin aluminium plates.

The fabrication and assembly tolerances of the LGB magnet will inevitably affect the final field quality, in order to conduct the LGB magnet manufacturing process in this regard, the influences of LGB magnet fabrication tolerances on the field quality are investigated using a dedicated parameterized finite element (FE) model, including the pole height tolerances, the pole tip inclination in transverse and longitudinal directions. The influences of the mesh sizes on field quality are firstly studied in order to find a compromise between the computation accuracy and efficiency with respect to the FE model size.

PARAMETERIZED FE MODEL

A parameterized FE model of the entire typical LGB magnet is firstly developed in Opera-3D®, however, the computation time turns out very long. We therefore reduce the model size to has only one module, i.e. the one for the highest field stage with the shielding plates at both ends, as shown in Fig. 2. The model size reduction is under the assumption that the relative change of the TFH / IFH results from a particular fabrication tolerance is the same for

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single module and entire LGB magnet. The assumption is reasonable since the change of the field / integrated field is proportional to the field / integrated field itself. As a result, the influences on the entire LGB magnet TFH / IFH could be easily deduced from the study results of single module.

All the non-magnetic materials are excluded from the FE model. The defined parameters including all the geometry dimensions, mesh size of different parts, air field size, PMs number, the magnetic material properties, the pole height tolerances and the pole tip inclinations. The interested region in the magnetic gap and extended at the ends is modelled in special with refined mesh, and with as much as possible nodes aligned on the field extraction lines (to reduce the field interpolation errors).

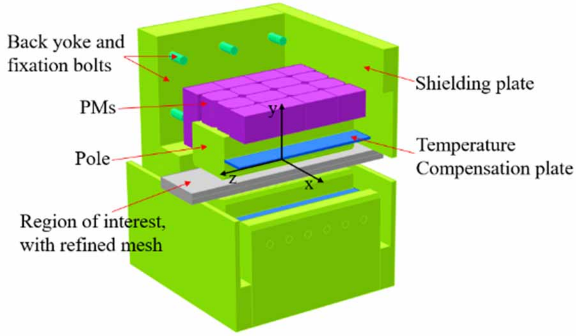

Figure 2: The parameterized FE model of single module in the typical LGB magnet.

INFLUENCES OF MESH SIZE ON FIELD QUALITY

In order to lowering the influences of mesh sizes and external air field size on the calculated field quality, a prior study is carried out to find the reasonable mesh sizes for different parts and the external air field size (ratios to the model sizes in x, y and z directions). The mesh sizes for magnetic materials, interested region in magnetic gap, external air field are defined for each run separately, as well as the external air field size. Table 1 lists the results of the studied cases. Following conclusions could be drawn from the studies:

- Further reduction of the mesh size at the interested region does not improve the accuracy significantly.
- The reduction of magnetic material mesh size reduces the TFH, and also increases the field at the middle plane of good field region (by ~10 Gauss, not listed in Table 1), but does not show strong relation to the IFH. It is reasonable since the refined mesh of magnetic materials reflects more accurately the material nonlinearity, and the integrated field is indirectly related to the fields of a certain region. However, the model size of element number is increased dramatically.
- The external air field size also affects the results of field homogeneity. Although the influences are not significant, the larger external air field is preferred to weaken the influences of the parallel magnetic flux conditions at the exterior surfaces.

INFLUENCES OF FABRICATION TOLERANCES ON FIELD QUALITY

The definition of three types of tolerances are illustrated in Fig. 3, each has separated values for top and bottom poles. If considering the coupling between different tolerances, the number of cases to be calculated will be tremendous. For example, if each tolerance has 10 different values, the number of total cases will be 10^6! In order to reduce the case number, we first verified that the field deviation ΔBy on the extraction points result from one specific tolerance is irrelevant to the values of other tolerances. The field deviation ΔBy is relative to the reference case, which has zero tolerances for all types. The extraction points are actually the points on the lines for field quality calculation, including the TFH and IFH. Moreover, taking the advantage of model symmetry (about the XZ plane), only the

Table 1: Studied Cases of the Influences of Mesh Sizes on Field Quality

Cases	**Magnetic materials mesh size** [mm]	**Interested region mesh size** [mm]	**External air field size**[1]	**Air field mesh size** [mm]	**TFH**[2] [$\times10^{-4}$]	**IFH**[3] [$\times10^{-4}$]
Case 1	3.0	1.0	4, 4, 4	20	2.05	2.10
Case 2	3.0	0.5	4, 4, 4	20	2.01	4.11
Case 3	2.0	1.0	4, 4, 4	20	1.35	1.84
Case 4	1.0	1.0	4, 4, 4	20	0.27	3.89
Case 5	2.0	1.0	3, 3, 3	20	1.06	3.29
Case 6	2.0	1.0	5, 5, 5	20	1.05	1.77
Case 7	1.0	1.0	4, 4, 4	15	0.30	3.79
Case 8	2.0	0.5	4, 4, 4	20	1.08	2.26
Case 9	2.0	1.0	6, 6, 6	20	1.04	2.93
Case 10	1.0	1.0	6, 6, 6	15	0.29	3.98

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[1] Ratios to the model size in x, y and z directions.

[2] By along the line: $y = z = 0, -10 < x < 10\ mm$.

[3] By on the plane: $y = 0, -10 < x < 10\ mm, -131 < z < 131\ mm$.

tolerances for top pole are considered in the calculation, i.e. $dy1$, $d\theta1$ and $d\varphi1$, the left ones for bottom pole are considered as equal. The calculated tolerances for each type are:

- $dy1$ from 30 to -30 µm with the interval of 5 µm, including the reference case when $dy1$ is 0 µm;
- $d\theta1$ from 0.79 to -0.79 mrad with the interval of 0.1316 mrad;
- $d\varphi1$ from 0.966 to -0.966 mrad with the interval of 0.0966 mrad.

Therefore, there are totally 45 cases calculated, for each of them, the field deviation ΔBy is calculated and saved for the extraction points. The field By (on extraction points) for the different combinations of tolerances could be handled now by adding the corresponding field deviations (result from different tolerances), as well as the reference fields. In this way, the field homogeneity of all different combinations of tolerances could be calculated.

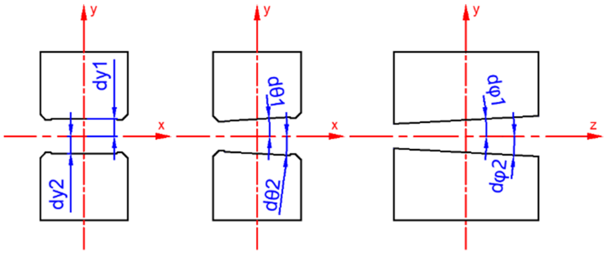

Figure 3: The defined pole tolerances for the field quality study.

In order to convert further the results into the desired requirements on the fabrication tolerances, we assume that the requirements of the same type of tolerance for both top and bottom poles are the same, i.e. the requirements for tolerances $dy1$ and $dy2$ are the same, etc. The three types of tolerance requirements are denoted as Ry, $R\theta$ and $R\varphi$. Since the corresponding field homogeneity are related to all Ry, $R\theta$ and $R\varphi$, we define all the possible combinations of these requirements. For each of the combinations, the result data are filtered and the worst homogeneities are found out as the corresponding requirements of field homogeneity. As an example, in case the tolerance requirement is defined as Ry =10 µm, $R\theta$ =0.2632 mrad, $R\varphi$=0.1932 mrad (all are positive values). The cases not satisfy the following conditions are filtered out:

- $-10\ \mu m \leq dy1, dy2 \leq 10\ \mu m$,
- $-0.2632\ mrad \leq d\theta1, d\theta2 \leq 0.2632\ mrad$,
- $-0.1932\ mrad \leq d\varphi1, d\varphi2 \leq 0.1932\ mrad$.

Then, the worst field homogeneities are found as the corresponding requirements.

Table 2 lists the results of some of the tolerance requirements combinations. The change of field homogeneities relative to the reference case are also listed, which will be used when extend the results to the entire five modules LGB as explained at the beginning of Section 2. According to the results, following conclusions could be drawn:

- The TFH is more sensitive to $R\theta$ than other two types of tolerance requirements.
- The IFH is sensitive to all types of tolerance requirements, however, the dependence on $R\varphi$ becomes minor when beyond the first interval of 0.1 mrad. The reason is that the IFH shows strong nonlinearity to the tolerances.
- The combination of different tolerance requirements worsen the IFH, especially when both $R\theta$ and $R\varphi$ are existed.

Table 2: Study Results of Some of the Fabrication Tolerance Combinations

Ry [µm]	$R\theta$ [mrad]	$R\varphi$ [mrad]	**TFH**[1] [10^{-4}]	**IFH**[1] [10^{-4}]
0.0	0.0	0.0	1.04/0.0	2.9/0.0
5.0	0.0	0.0	1.08/0.04	3.67/0.77
10.0	0.0	0.0	1.08/0.04	5.17/2.27
0.0	0.13	0.0	1.3/0.26	4.16/1.26
0.0	0.26	0.0	1.83/0.79	5.32/2.42
0.0	0.0	0.1	0.6/0.07	3.26/1.81
0.0	0.0	0.2	0.65/0.12	3.26/1.81
5.0	0.13	0.0	0.7/0.17	4.07/2.62
0.0	0.13	0.1	0.75/0.22	5.36/3.91
5.0	0.0	0.1	0.61/0.08	4.89/3.44
5.0	0.13	0.1	0.77/0.24	6.77/5.32

CONCLUSION

To compromise between the computation accuracy and efficiency, the influence of mesh size on the field quality is firstly studied with a dedicated parameterized FE model for LGB magnet, and the mesh size of moderate model size and accuracy is selected. The influences of LGB fabrication tolerances on TFH and IFH are then studied. The tolerances including the pole tip height, and inclinations in transverse and longitudinal directions for both top and bottom poles. The situation of different combinations of these tolerances is considered under the assumption that the coupling among them is minor. Finally, the requirements (in terms of the worst field homogeneities) for different fabrication tolerance combinations are given, and the results indicate that the TFH is more sensitive to transverse inclination, while the IFH shows strong nonlinearity to all the tolerances.

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[2] Tao He, Zhenbiao Sun, *et al.*, “Physics design of the Shenzhen innovation light source storage ring”, *J. Instrum.*, vol. 18, p. P05037, May, 2023. `doi: 10.1088/1748-0221/18/05/P05037`

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[1] homogeneity and the change of homogeneity relative to reference case.