Studies on the Influences of Longitudinal Gradient Bending Magnet Fabrication Tolerances on the Field Quality for SILF Storage Ring

J. Zhu[1]*, M. Zhang[1]*, C. Wang[1], D. Liang[1], Y. Shi[1]

[1]Institute of Advanced Science Facilities, Shenzhen, China

Introduction

- A 4th generation storage ring for Shenzhen Innovation Light-source Facility (SILF) in IASF is proposed and under preliminary design[1-2];
- The longitudinal gradient bending (LGB) magnets are required to reduce the electron beam emittance, and the permanent magnet (PM) based LGB magnets are selected;
- The design of a typical LGB magnet is introduced at first, followed by the study on the influence of mesh size on the calculated field quality;
- The influences of LGB magnet fabrication tolerances on field quality are investigated using a dedicated FE model;
- In addition, the influence of the magnetic forces induced yoke deformation on field quality is also studied.

Typical structure of LGB magnet

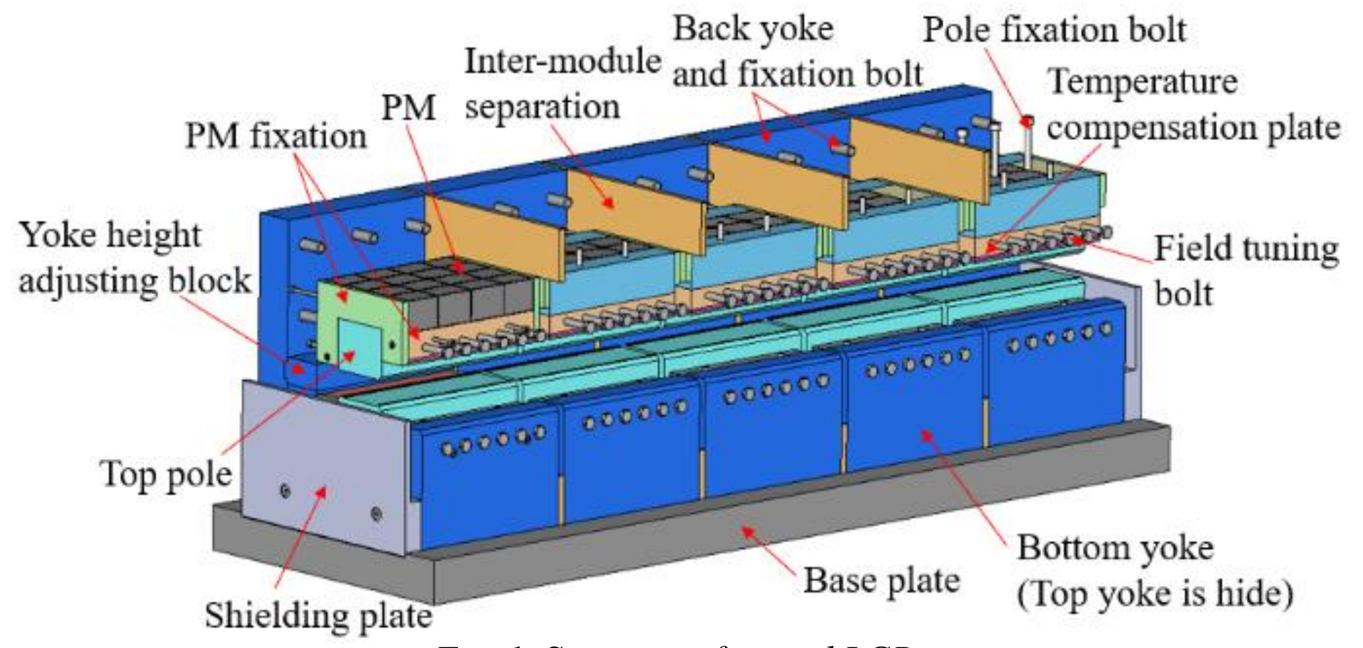

Fig. 1. Structure of typical LGB magnet

- Five magnet modules for different field stages;
- Sm_2Co_{17} is selected for PM, the pole, yoke, shielding plates and field tuning bolts are made of DT4;
- Fe-Ni alloy is introduced to compensate the field changes due to the temperature variations;
- Field tuning bolts provide an additional approach to adjust the fields afterwards;
- AL blocks fill the remain voids between the poles and yokes to support the PMs.

Influences of fabrication tolerances on field quality

- In order to reduce the case number, we neglect the weak coupling between different tolerance types;
- Due to the symmetry, only the tolerances for top tole are considered in the calculation, i.e. *dy1*, *dθ1* and *dφ1*, 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,
  - *dθ1* from 0.79 to -0.79 mrad with the interval of 0.1316 mrad,
  - *dφ1* from 0.966 to -0.966 mrad with the interval of 0.0966 mrad;
- For each case, the field deviation ΔBy relative to the reference case is calculated and saved for the extraction points;
- The field on extraction points for the different combinations of tolerances could be obtained by adding the corresponding field deviations and the reference case field, there are 12595401 cases in total!
- The tolerance requirements are defined as *Ry*, *Rθ* and *Rφ*, for each combination of them, the above results are filtered and the worst field homogeneity is found out as the corresponding field homogeneity requirement.

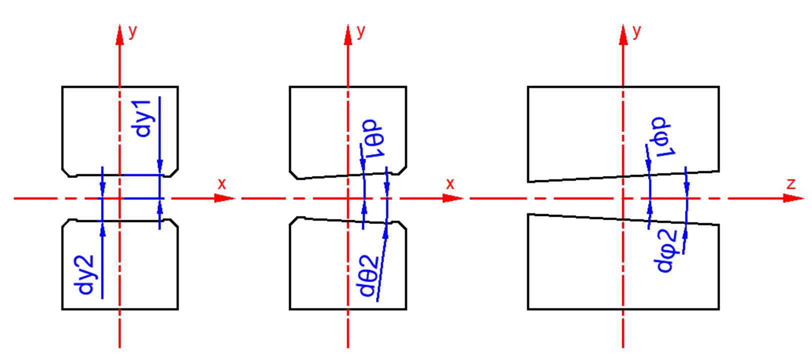

Fig. 3. The defined pole tolerances

Table 2. Study results of some of the fabrication tolerance combinations

Ry, μm	*Rθ*, mrad	*Rφ*, mrad	TFH, 10^{-4}	IFH, 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

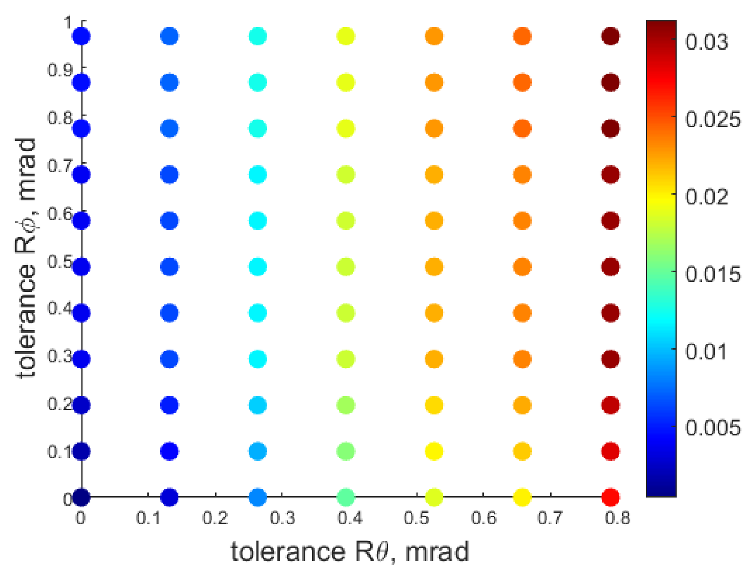

Fig. 4. The change of TFH relative to reference case, Ry=5 μm, unit in %

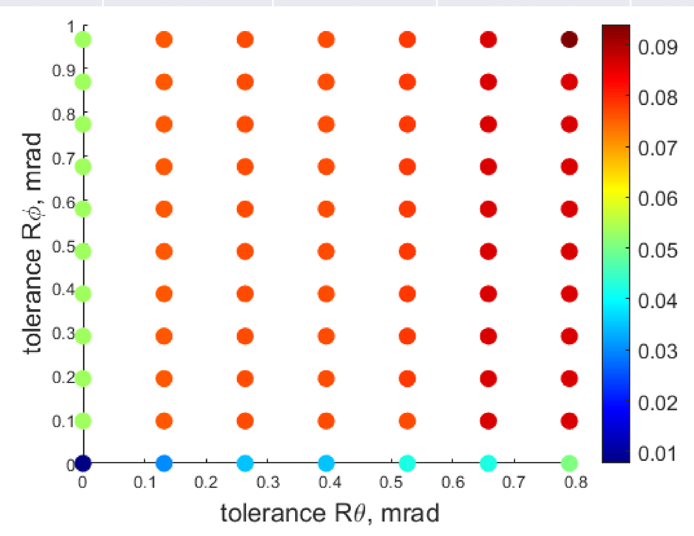

Fig. 5. The change of IFH relative to reference case, Ry=5 μm, unit in %

Parameterized FE model

- The module of the highest field stage is modeled with shielding plates at the ends;
- Model size reduction is under the assumption that the relative change of field homogeneity result from a particular fabrication tolerance is the same for single module and entire LGB magnet;
- All the magnetic materials are included in the FE model;
- The defined parameters including all the geometry dimensions, mesh sizes, air field size, PMs number, the pole height tolerances, the pole tip inclinations, etc.

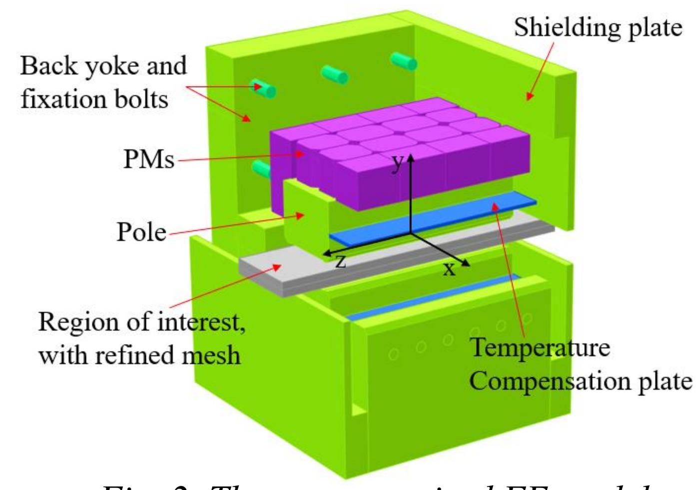

Fig. 2. The parameterized FE model

Influences of mesh size on field quality

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], [×10^{-4}]	IFH[3], [×10^{-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

1. Ratios to the model size in x, y and z directions.
2. Transverse field homogeneity, By along the line: y=z=0, -10<x<10 mm
3. Integral field homogeneity, By on the plane: y=0, -10<x<10 mm, -131<z<131 mm

- Further reduction of the mesh size at the interested region does not improve the accuracy significantly, see Cases 1, 2, 3 and 8;
- The reduction of magnetic material mesh size reduces the TFH, but does not show strong relation to IFH, see Cases 1, 3, 4, 2 and 8;
- The external air field size also affects the results, but not significant;
- The air field mesh size plays minor role on the results;
- We select the mesh size and external air field size of Case 9 for the subsequent studies.

Other studied issues

- The deformation results from the attractive forces between the top and bottom poles is analyzed,
- Few iterations of the coupled structural and electromagnetic analysis are performed to determine the yoke dimensions,
- The module of the highest field stage is taken, and the attractive force between the poles is about 2.6 kN,
- The influence on the TFH in good field region is 0.0045% at maximum, which is considered as acceptable,
- the actual influence on TFH depends on the profile of transverse field, as illustrated in Fig. 7.

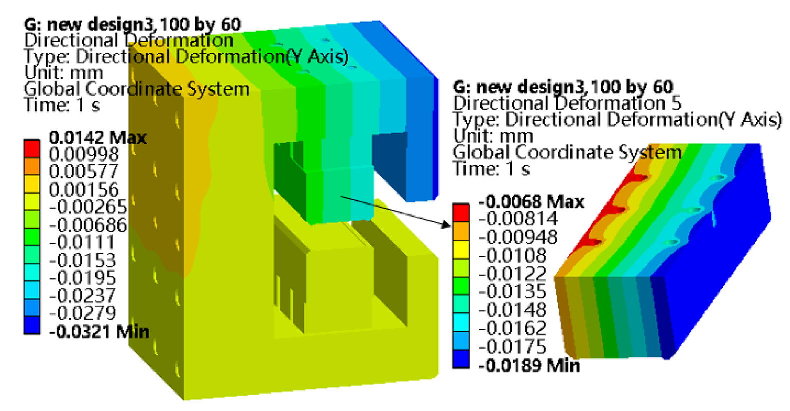
Fig. 6. The deformation of the LGB magnet yoke and top pole in Y direction

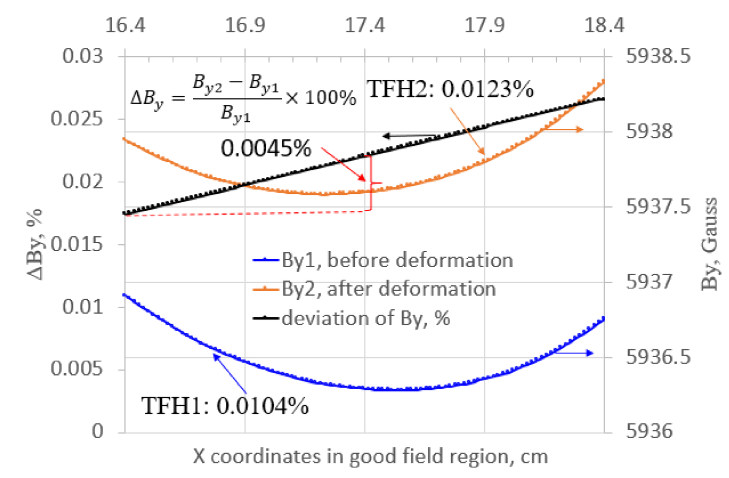

Fig. 7. Calculation of the influence of force induced yoke de-formation on the TFH, TFH1 and TFH2 are the values before and after deformation.

Conclusions

- To compromise the computation accuracy and efficiency, the influence of mesh size on the field quality is firstly studied with a dedicated parameterized FE model,
- The influences of LGB fabrication tolerances on TFH and IFH are then studied, including the pole tip height, and inclinations in transverse and longitudinal directions,
- The requirements for different fabrication tolerance combinations are given, the TFH is more sensitive to transverse inclination, while the IFH shows strong nonlinearity to all tolerance types,
- The influence of the magnetic forces induced yoke deformation on the field quality are also studied and presented,
- The study result provides important guidance in the design and fabrication of different types of LGB magnets for SILF storage ring.

[1] Seunghwan Shin, "New era of synchrotron radiation: fourth-generation storage ring", AAPPS Bull. Aug. 2021, vol. 31, no. 21, pp. 57-59.

[2] Tao He, Zhenbiao Sun, et al., "Physics design of the Shen-zhen innovation light source storage ring", Journal of In-strumentation, May 2023, vol. 18.

*Corresponding author: zhujiawu@mail.iasf.ac.cn; zhangmiao@mail.iasf.ac.cn

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