Manufacturing error analysis of a curved CCT magnet applied to a superconducting gantry

Chunyi Li, Wenjie Han, Bin Qin, Xu Liu
State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology

Abstract

A lightweight superconducting (SC) gantry with large momentum acceptance is under development at Huazhong University of Science and Technology (HUST). The essential component of this SC gantry is the curved alternating gradient canted-cosine-theta (AG-CCT) magnet. This paper introduces the study on coil error analysis of AG-CCT magnets. Based on single line model using Biot-Savart (B-S) law, a coil model including manufacturing error is developed, and is used to study the influence on the proton beam. A comparative study on the different error levels is carried out to determine the tolerance of manufacturing error. In addition, The beam compensation method is also discussed.

Theory

- ***The path equation of curved CCT***

- Curved CCT is constrained to the surface of the torus, see Fig.1, the path equation in cartesian coordinate system is

$$\vec{P}(\xi)=\begin{cases} a\dfrac{\sinh(\eta_0)}{k}\cos(\phi)\,\hat{x} \\ a\dfrac{\sinh(\eta_0)}{k}\sin(\phi)\,\hat{y} \\ a\dfrac{\sin(\xi)}{k}\,\hat{z} \end{cases}$$

- ***Error model***

- B-S law are often used to calculate CCT's magnetic field. When use B-S law to calculate the magnetic field of CCT, the coil is discrete into multiple linear current elements. The coil error can be added to the endpoints of the linear current elements. Fig.2 shows a current element with coil error.
- Manufacturing error has a certain influence on the magnetic field generated by CCT and the beam transmission. In general, these errors can be divided into two types: a. the error in radial direction; b. the error in binormal direction, corresponding to $\vec{r}$ and $\vec{b}$ in Fig.1.
- In the actual manufacturing process, the error does not mutate, and it tends to change linearly between the two local error extremum point. This is the main idea of error model construction in this paper

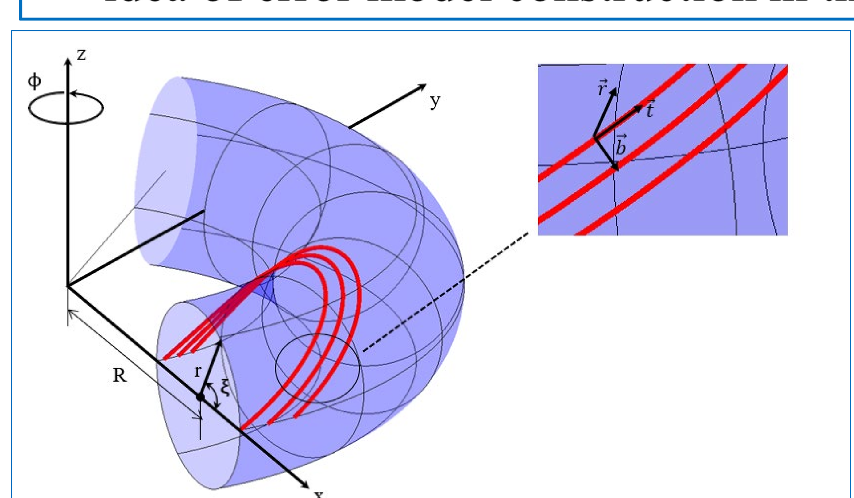

Fig.1 Schematic diagram of curved CCT distribution on torus

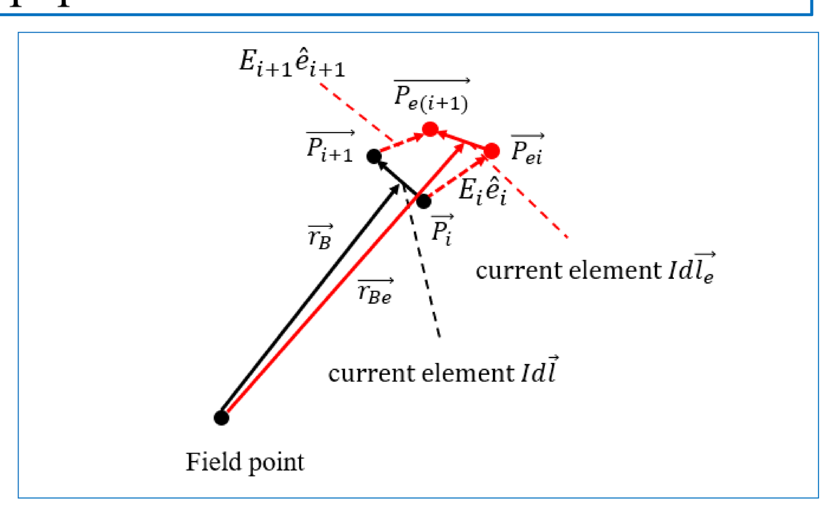

Fig.2 The position of the current element with coil error

Results

- In order to study the influence of error on the beam at the iso-center of HUST SC gantry, we introduce the error model described in theory with four error types into gantry. For the HUST SC gantry, the momentum acceptance ranges from -7% to 5%. We select the beam with three representative energies when studying the influence of errors on the beam, and their momentum dispersion is -7%, 0 and +5% respectively with center energy 215 MeV. The simulation results are below.

a.Fig. 3 shows the change of beam at iso-center when the constant deviation of the four types of errors is 1mm respectively.

b.Fig. 4 shows the change of beam phase ellipse at the iso-center with the error of uniform distribution.

c.In order to realize the error levels of CCT magnet manufacturing, several simulation studies were carried out under different error levels. The beam size change and center drift are obtained as Fig. 5~ Fig. 8 (the radius of the error bar corresponds to one sigma value)

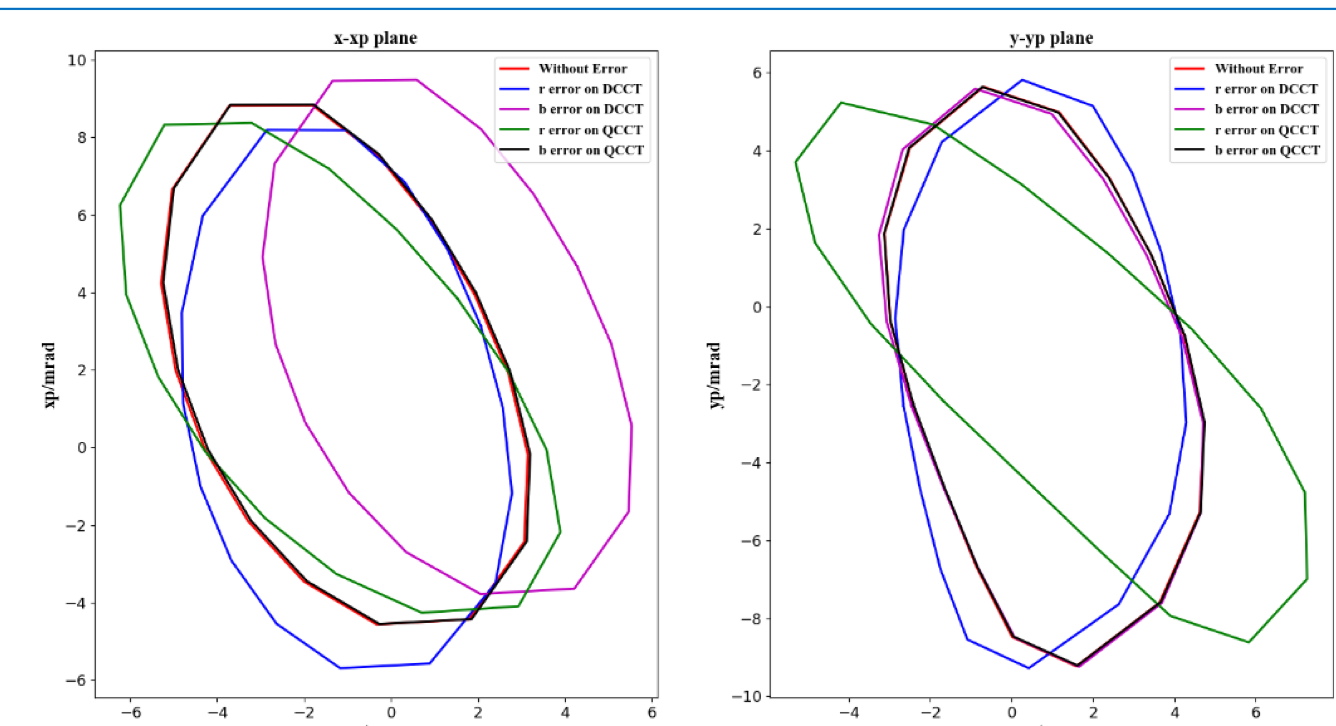

Fig.3 The phase ellipse changes at the iso-center point of the four different error types when the constant deviation is 1mm respectively

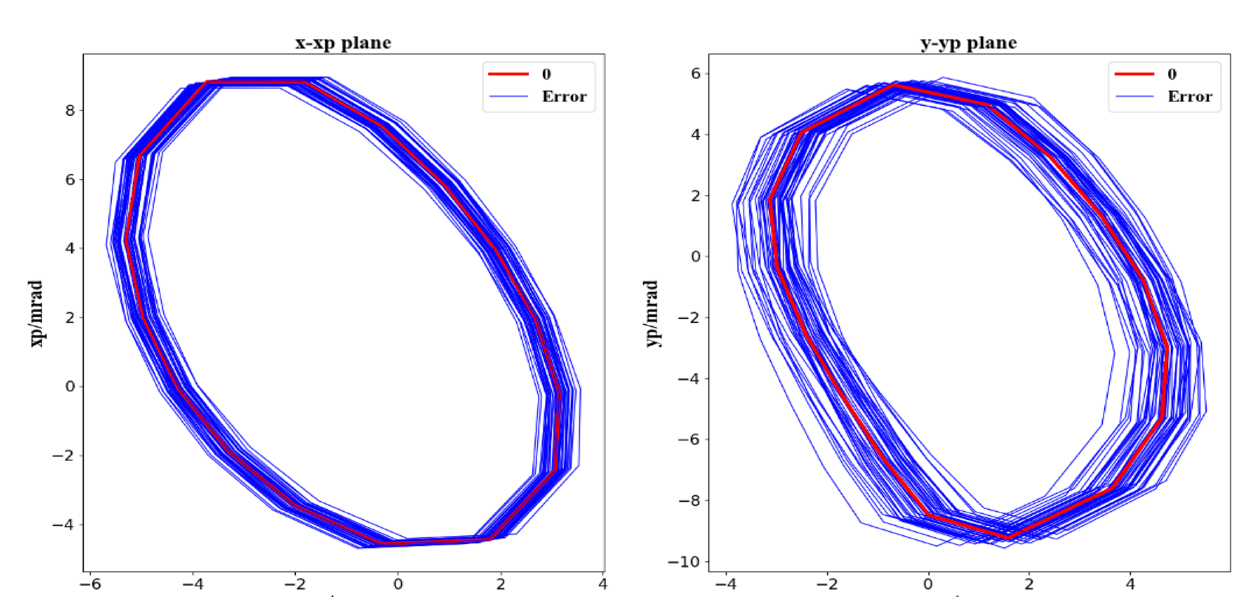

Fig.4 The influence of uniform distribution on phase ellipse at iso-center

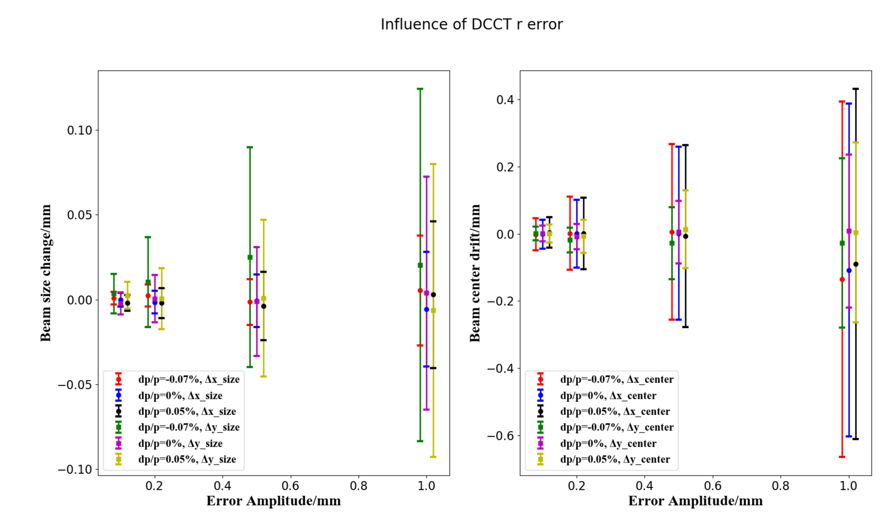

Fig.5 Sensitivity of the beam spot size and center drift related to r error on DCCT

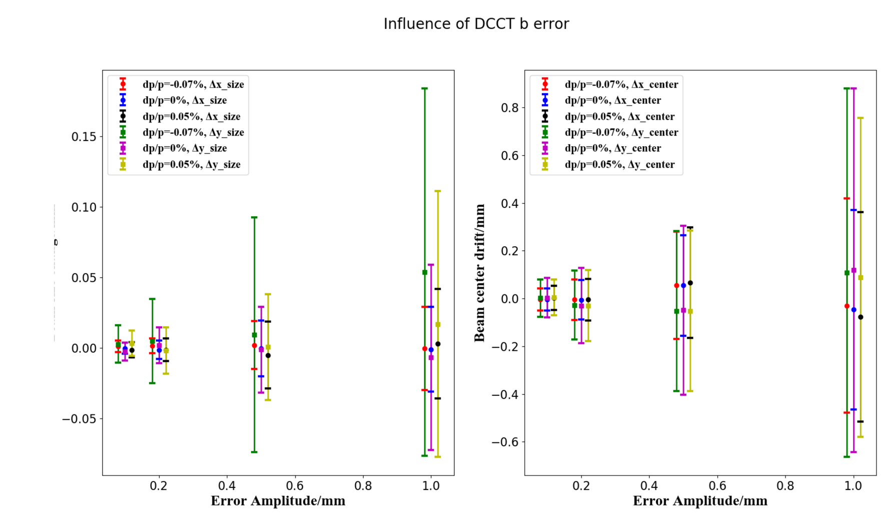

Fig.6 Sensitivity of the beam spot size and center drift related to b error on DCCT

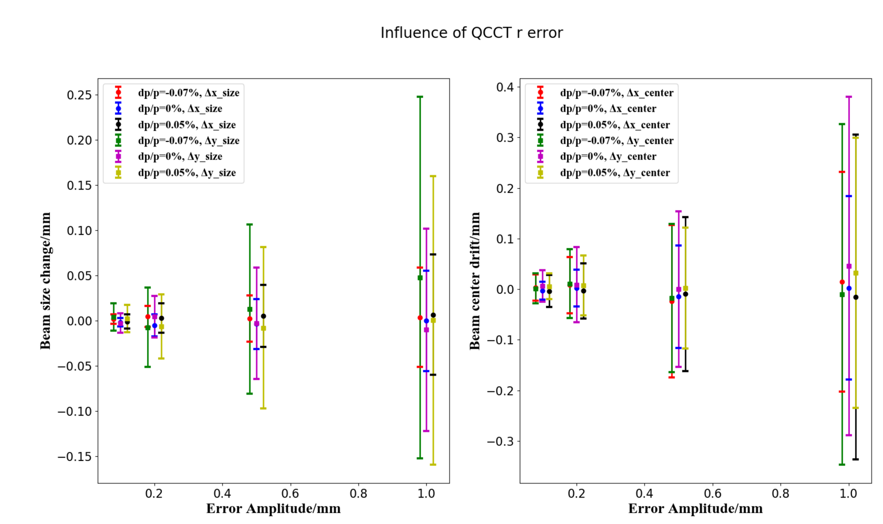

Fig.7 Sensitivity of the beam spot size and center drift related to r error on QCCT

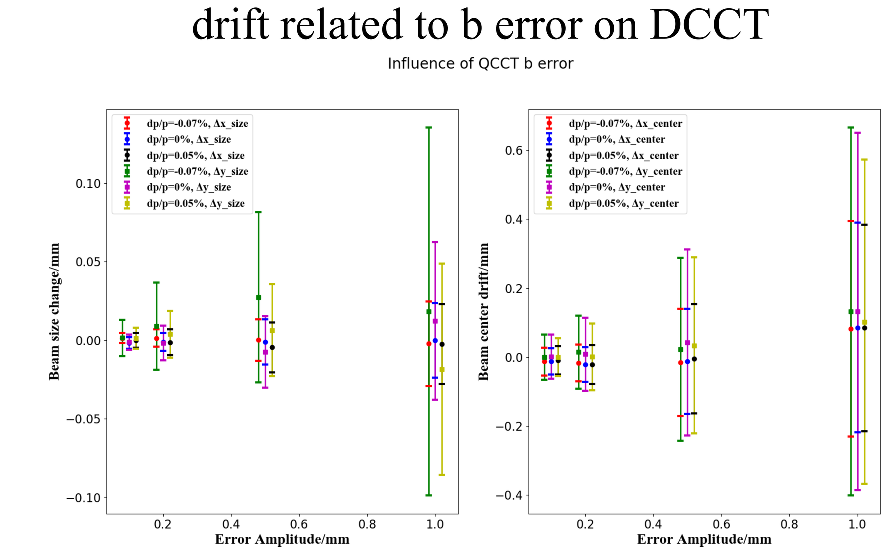

Fig.8 Sensitivity of the beam spot size and center drift related to b error on QCCT

- From Fig.3 can see, when the error distribution is constant deviation, b error on DCCT will cause the beam drift in the x direction, r error on DCCT and r error on QCCT will change the beam size.
- From Fig.4 can see , the results show that the error causes the phase ellipse to oscillate near the design value.
- From Fig. 5~ Fig. 8 can see, in order to keep the beam size and center drift within 0.5mm, we need to control manufacturing error within ±0.6mm.

The error compensation method

- Compensation for constant deviation is realized by change the AGCCT's excitation current.
- Compensation for random error and magnet installation error is realized by combining correction magnet and variable ratio of QS magnets, which will be reflected in the next research.

Conclusion

This paper established an error model to analysis the influence of the manufacturing error of AG-CCT in HUST SC gantry on beam which is transported by gantry. The analysis results show that control the manufacturing error within ±0.6mm will keep the beam state within the acceptance range. In view of the influence of manufacturing error on beam, the corresponding compensation method is also proposed.