Numerical analysis of the Screening Current-Induced Magnetic Field Intensity in the HTS Insert of a 16-T Superconducting Dipole Magnet

Ze Feng[1], Chengtao Wang[1], Chunyan Li[1], Juan Wang[1], Rui Kang[1] and Qingjin Xu[1]*

中國科學院高能物理研究所 Institute of High Energy Physics Chinese Academy of Sciences

1.the Laboratory of Particle Acceleration Physics and Technology, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

1.Abstract

To obtain higher magnetic fields beyond 16 T, ReBCO high temperature superconducting (HTS) tapes are applied to the superconducting accelerator dipole magnets. The Institute of High Energy Physics (IHEP) is designing a 3-T HTS coil to be inserted into a 13-T Nb_3Sn dipole magnet at 4.2 K. In order to improve the stability, the HTS insert has been optimized with 4 double pancake coils, which are wound with the 2 mm thick and 9 mm wide multi-strand high temperature superconducting X-cables. Due to the large size of the HTS filaments, coated conductors are strongly magnetized. Therefore, superconducting accelerator magnets based on ReBCO tapes might experience a degradation of the magnetic field quality in the magnet apertures. As a consequence, T-A formulation is employed to simulate the screening current within a cable made of parallel tapes. The numerical magnet model has been built to quantify the influence of the Screening Current-Induced Field (SCIF) and the external iron yoke to the magnetic field quality at a reference radius of 10 mm. According to the results, the deviation in the dipole component from its designed value calculated with the uniform current density distribution is 0.18 T, which is about 1.1% of the designed value. At the design current (7580A), the SCIF has the largest contribution to b_3, which is about -6.1 units. While for the higher order multipole components, the drifted value caused by the SCIF are lower than ± 3 units. The contribution of the iron yoke to the a_2 exceeds that of the SCIF at 7580 A, which is around 36.08 units.

2.Simulation Method

T-A formulation

$$\boldsymbol{J} = \nabla \times \boldsymbol{T}$$
$$\boldsymbol{B} = \nabla \times \boldsymbol{A}$$
$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$
$$\nabla \times \boldsymbol{B} = \mu \ \boldsymbol{J}$$

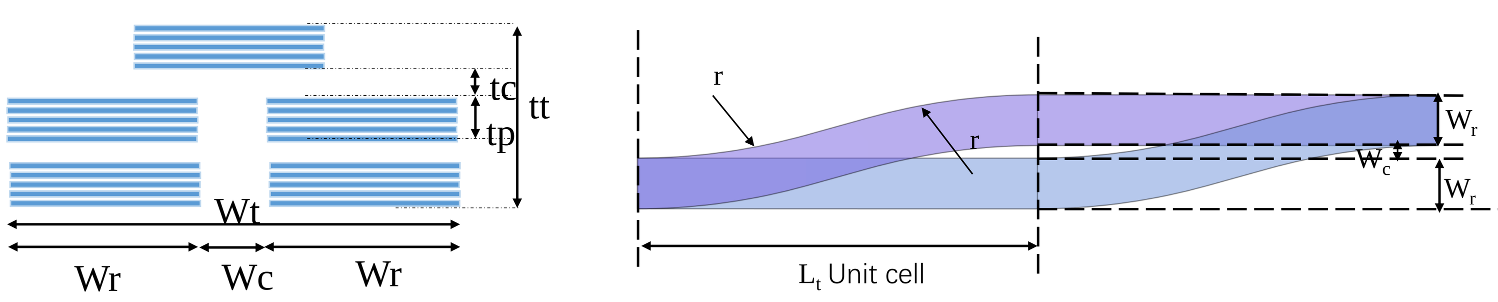
H formulation

$$\boldsymbol{J} = \nabla \times \boldsymbol{H}$$
$$\nabla \times \boldsymbol{E} = -\mu \frac{\partial \boldsymbol{H}}{\partial t}$$

The E-J relationship of HTS materials can be modeled by the power law

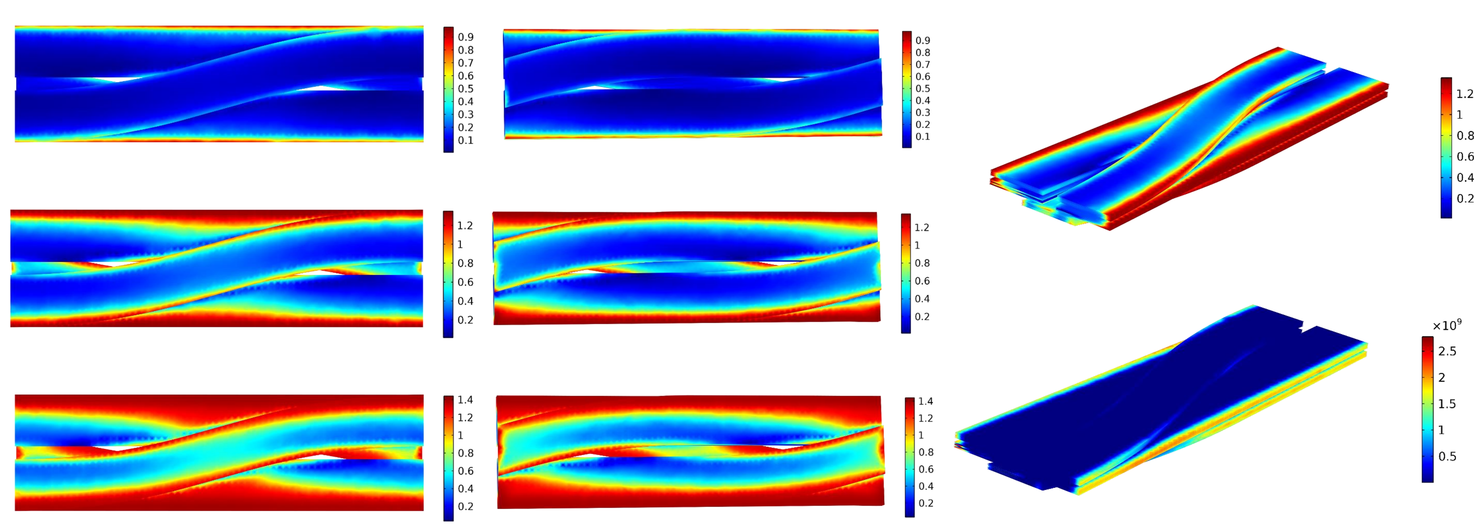
$$E = E_0 \left(\frac{J}{J_c}\right)^n$$

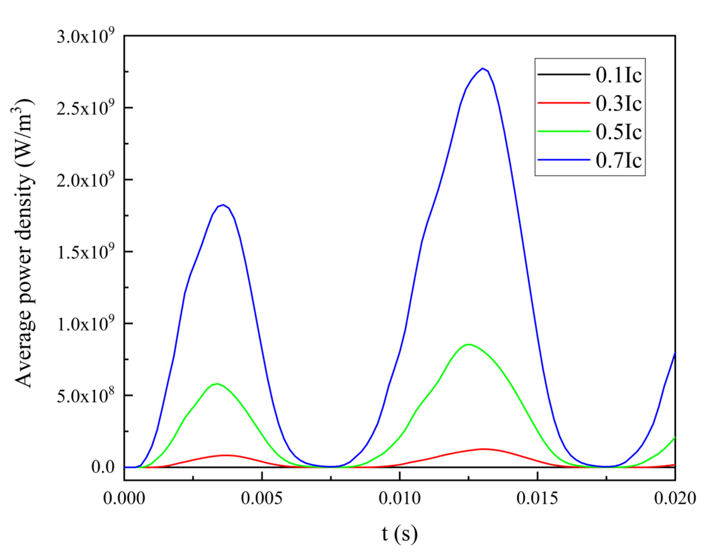
3.Geometry of 25 strands X-cables

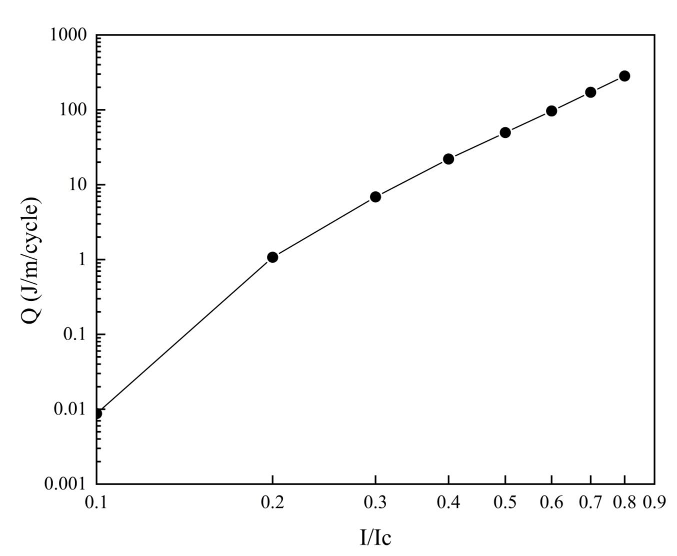


Symbol	Unit	Xcable	Description
Ns	n.a.	25	Number of tapes
ds	μm	80	Tape thickness
di	mm	0.1	Insulation thickness
Wr	mm	4	Strand width
Wc	mm	1	Channel width
Wt	mm	9	Cable width
Lt	mm	155	Transposition pitch
r	mm	50	radius

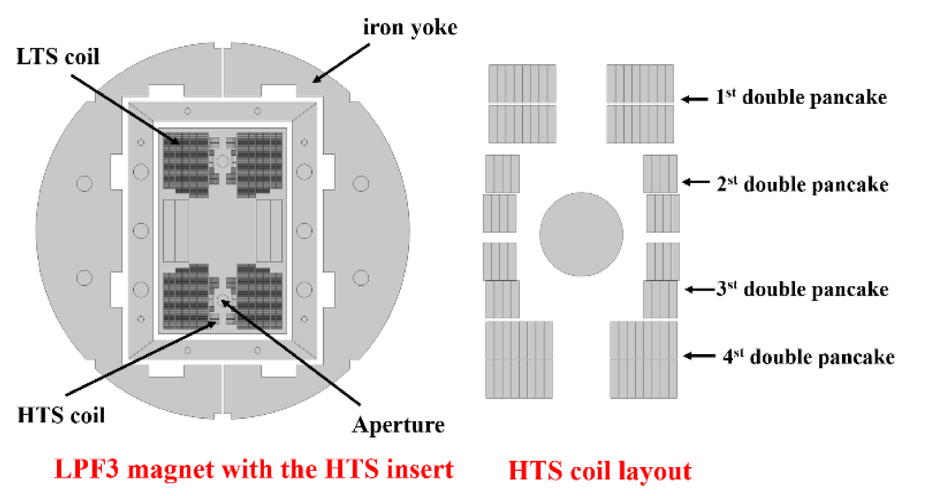
4.Ac loss

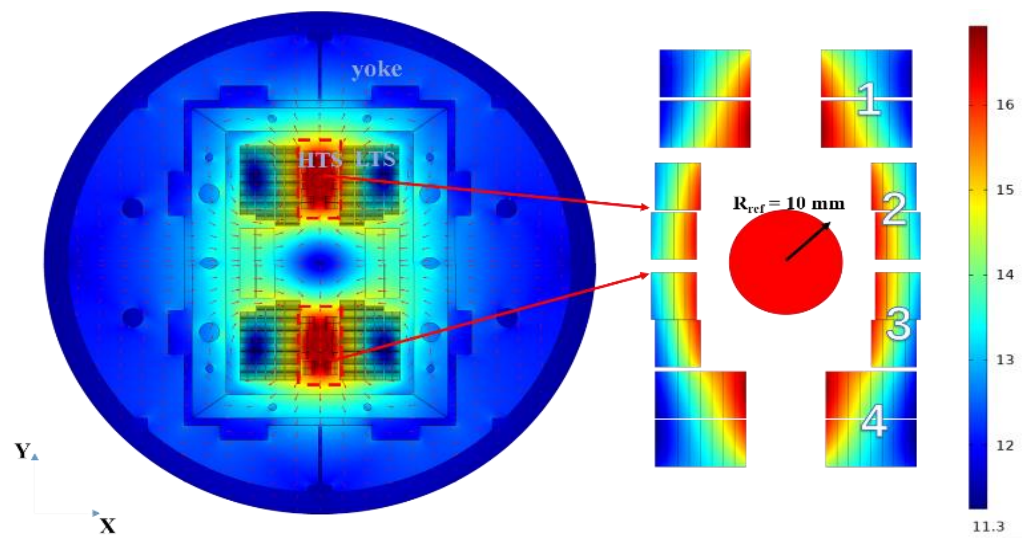




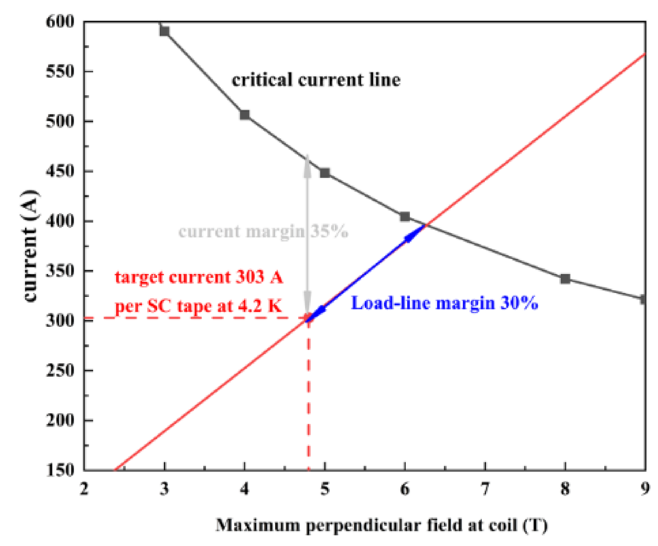


5.Geometry of LPF3 magnet

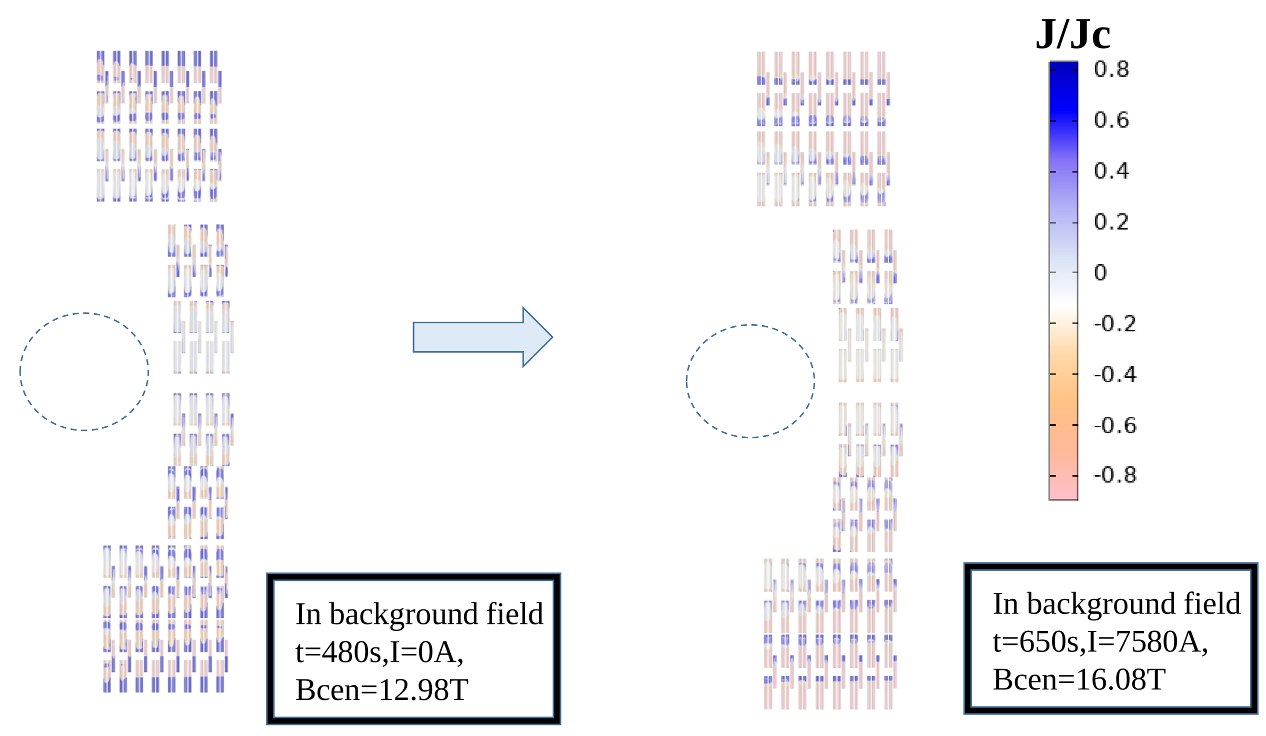


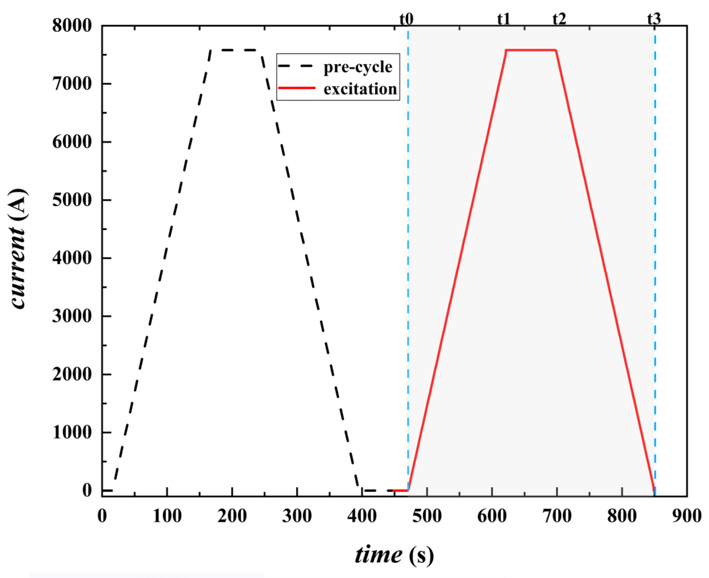


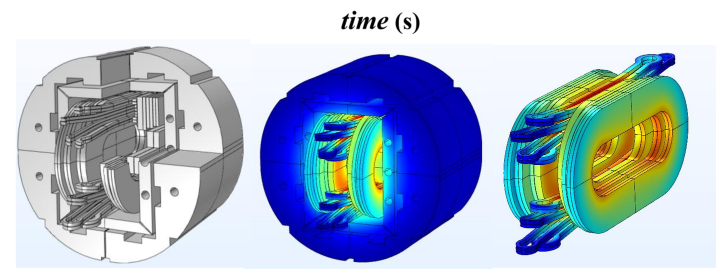
The critical current of the superconducting tape is influenced by the magnitude and the direction of the magnetic field. With the maximum external parallel field below 17 T at 4.2 K[1,2], the critical current is dominated by the perpendicular field. For simplicity, only the perpendicular field is considered when calculating the load-line. As can be seen from the Fig. 3, the margin in current is around 35%, and the operating margin in the insert is around 30%.

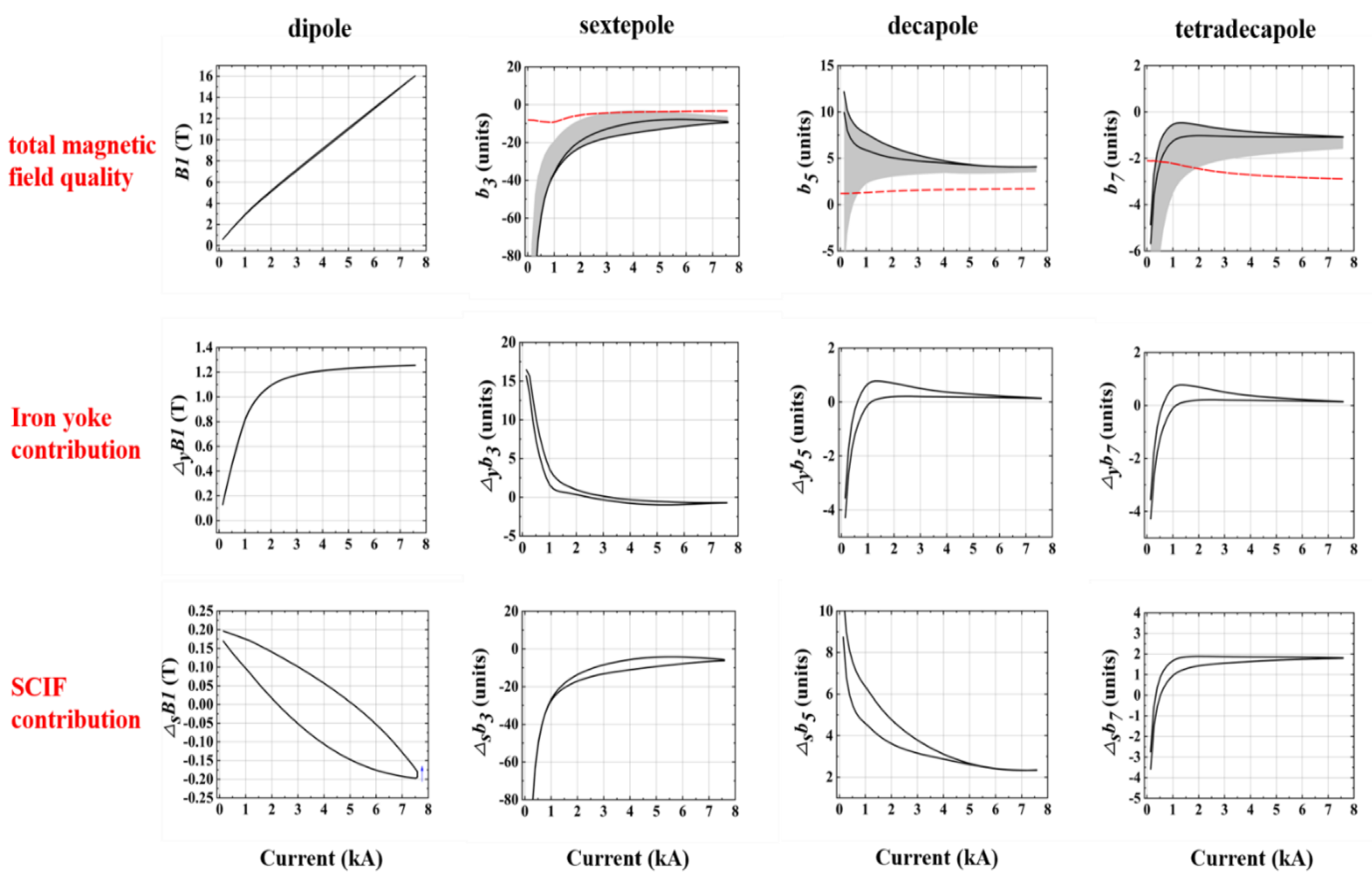


6.Simulation Results









	Current (A)	B1 (T)	b_3 (units)	b_5 (units)	b_7 (units)	a_2 (units)	a_4 (units)	a_6 (units)
homogenous	7580	16.22	-3.29	1.73	-2.9	2.5	2.9	1.4
Total magnetic field quality	500	1.69	-57.87	6.66	-2.13	52.4	-8.29	1.67
	7580	16.04	-9.41	4.10	-1.09	4.14	1.81	0.81
Iron yoke contribution	500	0.48	9.96	-1.18	2.06	140	-8.39	0.42
	7580	1.26	-0.71	-0.13	0.37	36.08	-0.45	0.8
SCIF contribution	500	0.19	-49	5.43	0.01	-86.5	-8.67	0.6
	7580	-0.18	-6.1	2.35	1.8	1.63	-1.06	-0.63

7.Conculsion

For the main dipole field B1, due to the SCIF, the central magnetic field is reduced by 0.18 T, which is approximately 1.1% of the designed maximum dipole component. It can be compensated by slightly adjusting the current in the magnet itself (around 1.1% of the maximum current). The iron yoke improves 1.26 T at 7580 A. At low current (500A), the contribution of the SCIF to the b_3, b_5, a_2, a_4 is about 8, 2, 40, and 8 times of those at the design current (7580A), respectively. At 7580 A, the contribution of SCIF to b_3, b_5, and b_7 far exceeds that of the iron yoke. it's the opposite for a_2.

[1]Y. Yan, Y. Li, and T. Qu, "Screening current induced magnetic field and stress in ultra-high-field magnets using REBCO coated conductors," *Superconductor Science and Technology*, vol. 35, no. 1, 2021, doi: 10.1088/1361-6668/ac392b.
[2]S. Awaji, R. Ishihara, K. Watanabe, K. Shikimachi, N. Hirano, and S. Nagaya, "Anisotropy of the Critical Current Density and Intrinsic Pinning Behaviors of YBa2Cu3OyCoated Conductors," *Applied Physics Express*, vol. 4, no. 1, 2011, doi: 10.1143/apex.4.013101.