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Effect of Screening Current Induced Field on Field Quality of an Air-Core HTS Quadruple Magnet

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Abstract

- **An air-core high-temperature superconducting (HTS) quadruple magnet has many advantages by eliminating iron-core of a conventional HTS quadruple magnet for heavy ion accelerator application. It is compact, lightweight, and free to hysteresis of the ferromagnetic material. The air-core HTS quadruple magnet was designed to achieve target field quality, such as gradient, uniformity, and effective length. It is composed of eight double-pancake racetrack coils, each wound with 4 mm wide HTS tapes. The uniform current density is assumed in the HTS tapes. However, in the HTS racetrack coils, magnetization currents are induced by the magnetic field component perpendicular to the tapes, and the magnetization currents generate so called screening current induced field (SCIF). For the quadruple magnet, the SCIF could be critical to the field quality. In this paper, the current density distribution is calculated in the HTS racetrack coils considering the magnetization current, and the effect of the SCIF is analyzed and discussed on the field quality of the magnet.**

I. Introduction

- **For heavy ion accelerator application, a quadruple magnet is exposed to a high radiation dose in the front of an in-flight projectile fragment separator, where the rare isotope beams are produced through the interaction of the primary beam with production target. Second generation (2G) high-temperature superconducting (HTS) tapes are more efficient to cool the heat load than low-temperature superconducting wire because of its higher critical temperature. Hence, a quadruple magnet made of 2G HTS tapes is indispensable for heavy ion accelerator application.**
- **There are probably two kinds of HTS quadruple magnets, iron-core and air-core. It has not been reported yet that the screening current induced field (SCIF) affects the field quality of an iron-core HTS quadruple magnet. It may be because iron-induced magnetic field dominates coil-induced field. By contrast, in the case of an air-core HTS quadruple magnet, the SCIF may lead to some problems because only coil-induced field exists.**
- **This poster is organized as follows: the designed air-core HTS quadruple magnet is modeled in 2D based on *H*-formulation and domain homogenization in Section II; 3D modeling is established using the current density distribution of the 2D simulation; all simulations are carried out by means of the commercial finite element method (FEM) software COMSOL Multiphysics; Section III analyzes the simulation results of the 2D and 3D models.**

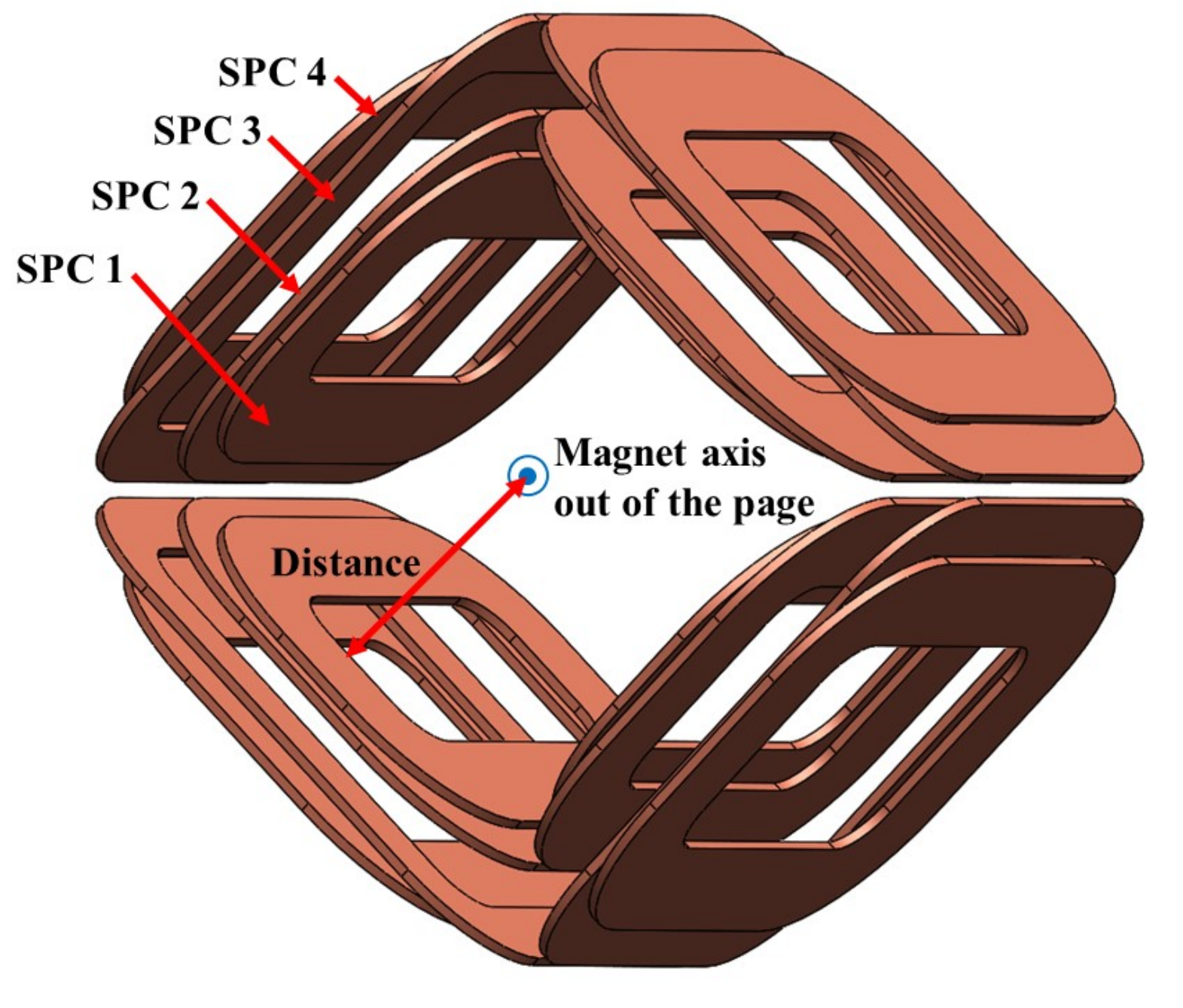

Fig. 1. The schematic of the designed air-core HTS quadruple magnet.

II. Simulation Method

A. Governing Equation

- **This work adopts *H*-formulation with domain homogenization. The main idea of domain homogenization method does not consider the actual stack of HTS tapes but its homogenized bulk. *H*-formulation can be written as follows.**

$$\vec{\nabla} \times \rho\left(\vec{\nabla} \times \vec{H}\right) = -\mu \frac{\partial \vec{H}}{\partial t}$$

- **An isotropic *E-J* relation is assumed. Thus, the resistivity of an HTS tape can be expressed as follows.**

$$\rho = \frac{E_c}{J_c}\left|\frac{\vec{J}}{J_c}\right|^{n-1}$$

- **In general, J_c and *n* of have the magnetic field dependence. However, this work ignores the *n*(B) dependence. The modified Kim model is used to describe J_c(B) dependence.**

$$J_c(\vec{B}) = \frac{J_{c0} B_{n0}}{B_{n0} + \sqrt{{B_n}^2 + k^2 {B_p}^2}}$$

- **For the homogeneous bulk model of stacked HTS tapes, J_c(B) is multiplied by the volume fraction of an HTS layer.**

B. Key Design Parameters of the Quadruple Magnet

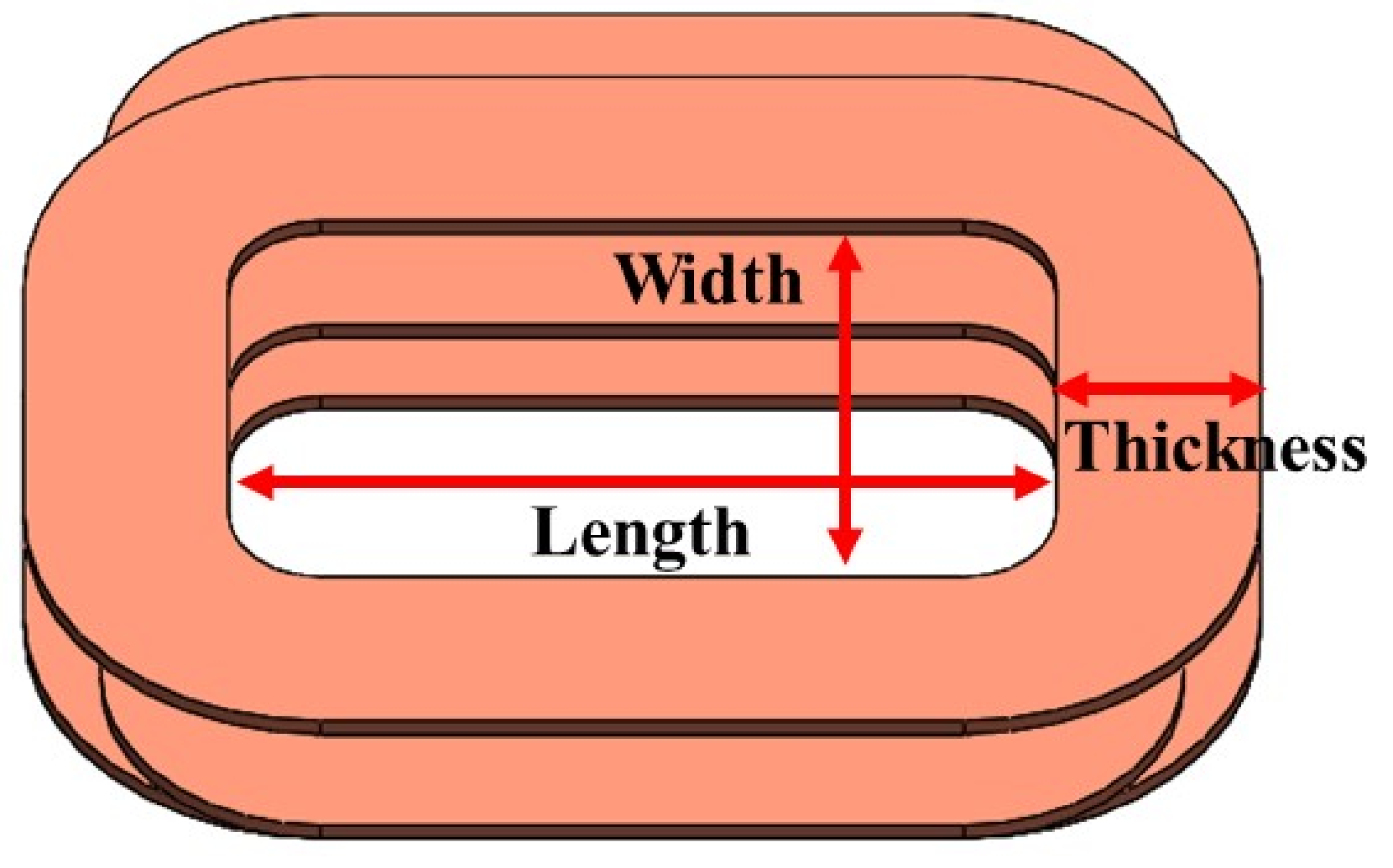

Fig. 2. Each pole of the designed air-core HTS quadruple magnet. The quadruple magnet was designed to have two double-pancake racetrack coils on each pole.

- **The 4 mm wide REBCO tapes manufactured by SuNAM Co., Inc. was employed. The operating current of the magnet is 50 A. The quadruple magnet is charged at a ramping rate of 0.05 A/s.**

TABLE I
SPECIFICATIONS OF THE DESIGNED QUADRUPLE MAGNET

Parameters	Unit	SPC 1	SPC 2	SPC 3	SPC 4
Distance	mm	96.4	102.5	128	134.1
Length	mm	179			
Width	mm	78	109	193	109
Turns		195	200	125	200
Thickness	mm	42.9	44	27.5	44
Tape width	mm	4.1			
Tape thickness	mm	0.22			
Critical current	A	237			
Index value		30			
Volume fraction		0.0057			

III. Simulation Results

A. 2D Modeling and Simulation

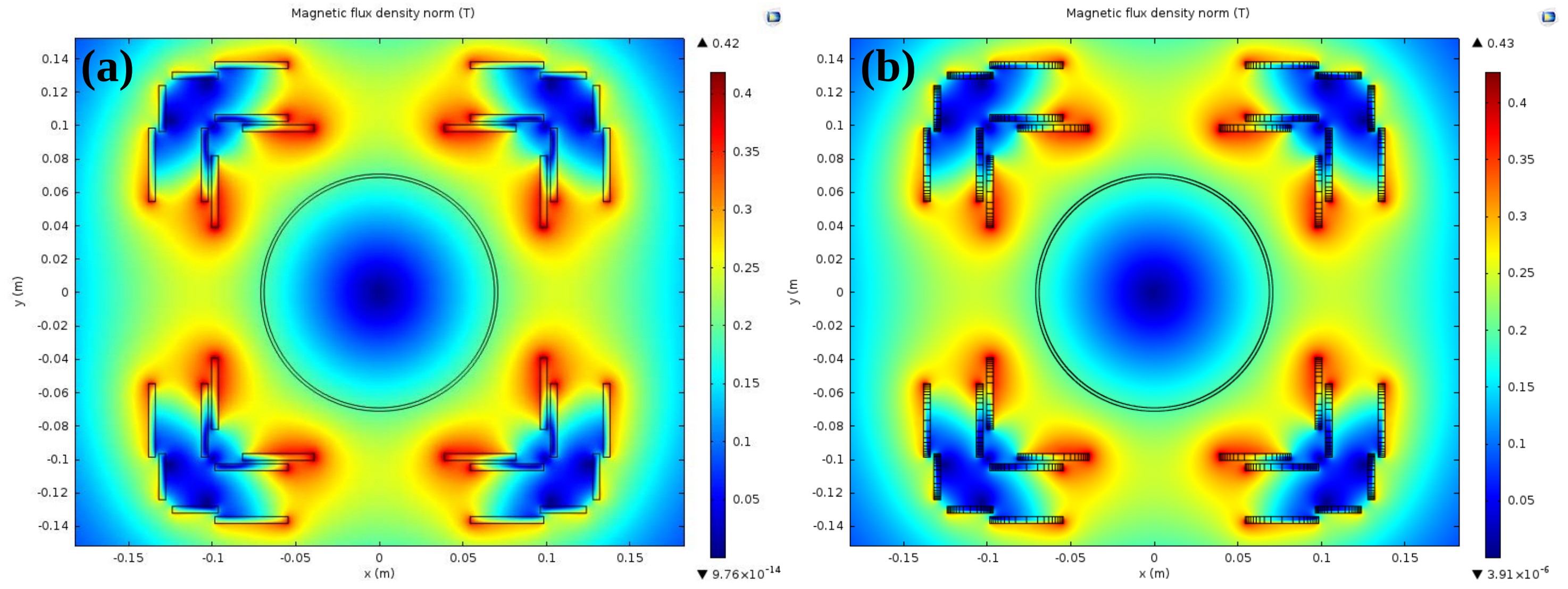

Fig. 3. The magnitude of the magnetic flux density of 2D simulation: (a) Case A and (b) Case B.

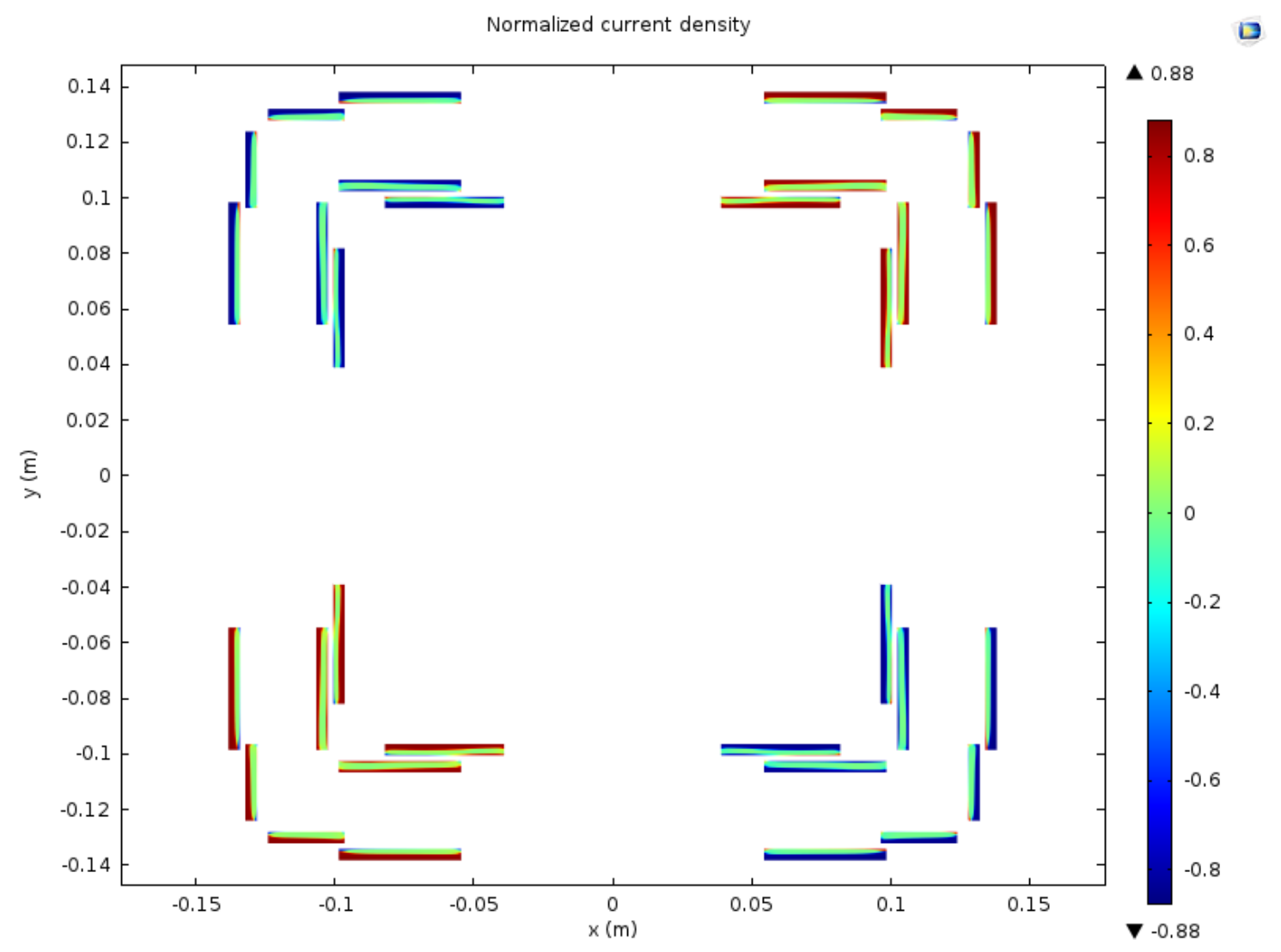

Fig. 4. The normalized current density for Case B.

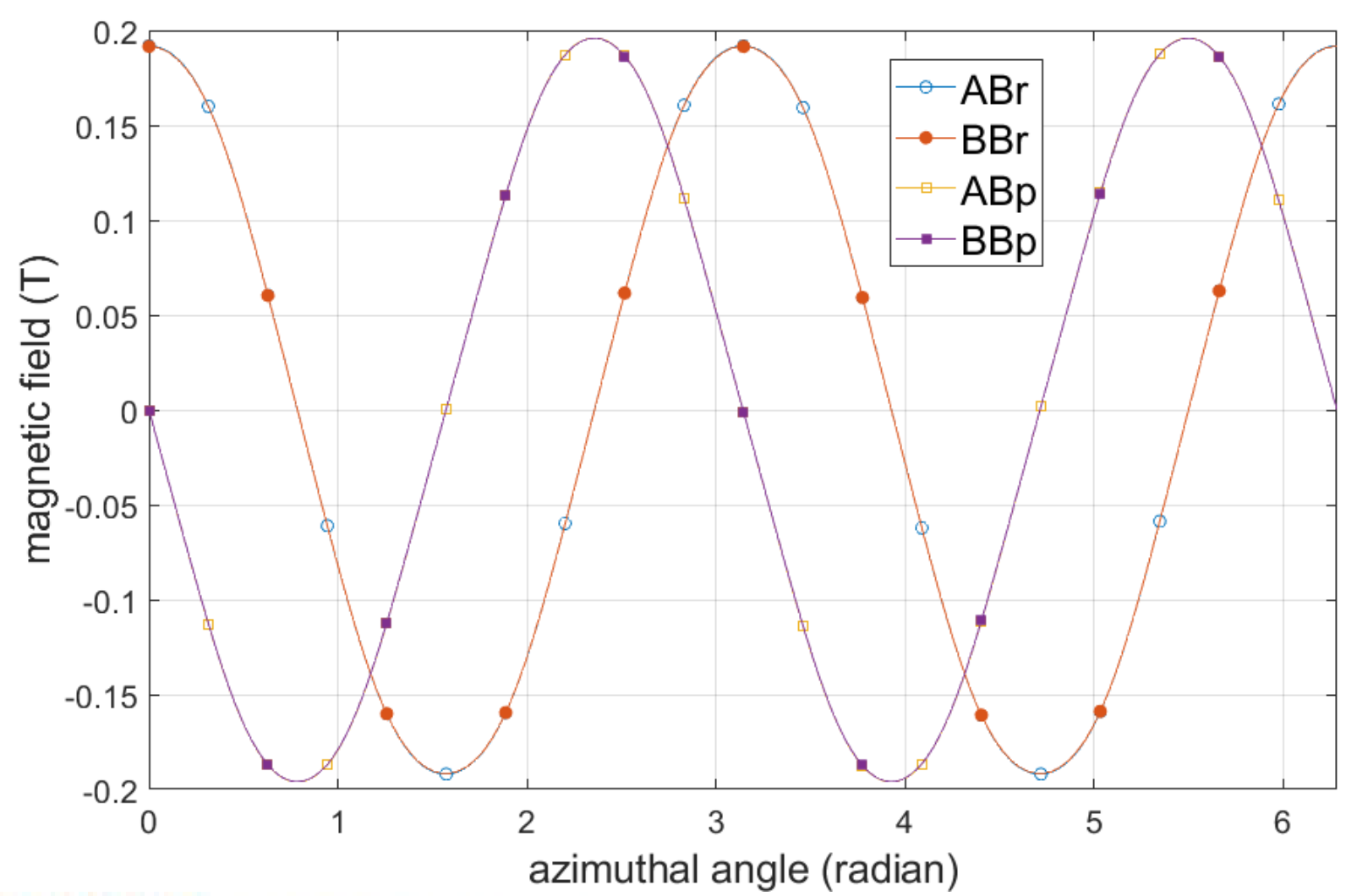

Fig. 5. The radial and azimuthal magnetic fields of 2D simulation.

TABLE II
FIELD QUALITY OF 2D AND 3D SIMULATIONS

Parameters	Unit	2D		3D	
		Case A	Case B	Case A	Case B
Gradient	T/m	2.7912	2.7880	3.0456	3.0420
Uniformity	%	1.1175	1.1621	0.1613	0.1741
Effective length	mm			207.0787	207.1625

- **Two cases are simulated to provide a comparison: Case A is that uniform current density is assumed in HTS racetrack coils, while Case B considers the induced screening current.**
- **The magnetic flux density norm for Cases A and B is presented in Fig. 3. Both results are almost identical except for the superconducting region. That is because one of physical properties of the superconductor expels the magnetic field.**
- **The high normalized current density, J/J_c, is localized in the inner region of SPC 1 and the outer region of the remaining SPCs. This is associated with the high magnetic field regions and the J_c(B) dependence, as shown in Fig. 3(b).**
- **The fields in the radial and azimuthal directions are obtained at the reference radius of 70 mm. The maximum differences of the radial and azimuthal fields are 3 G and 2 G, respectively. The SCIF causes the discrepancy between Cases A and B. It is important to note that the induced screening current flips the original magnetic polarity of the designed magnet and then reduces the target magnetic flux density.**

B. 3D Modeling and Simulation

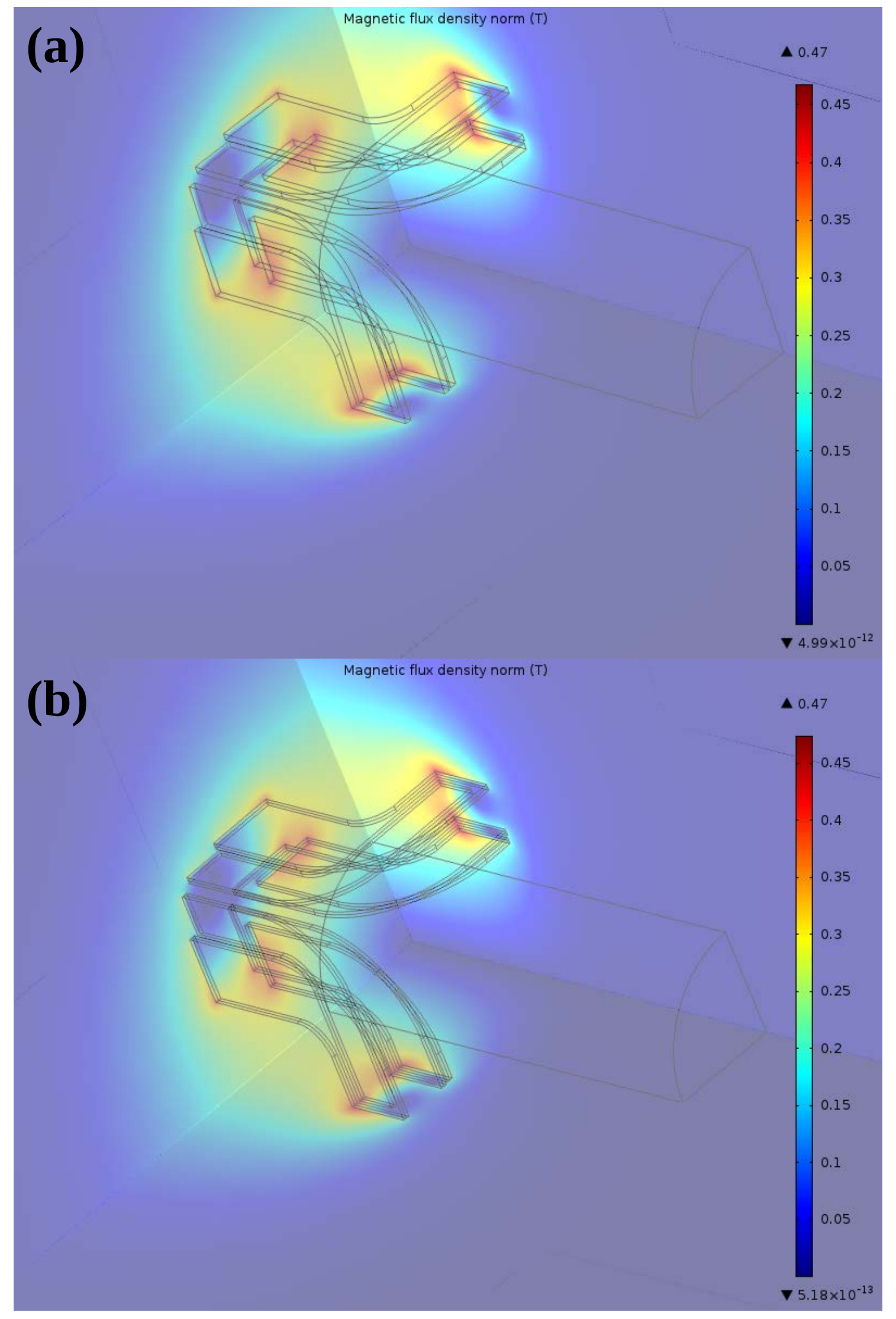

Fig. 6. The magnitude of the magnetic flux density of 3D simulation: (a) Case A and (b) Case B.

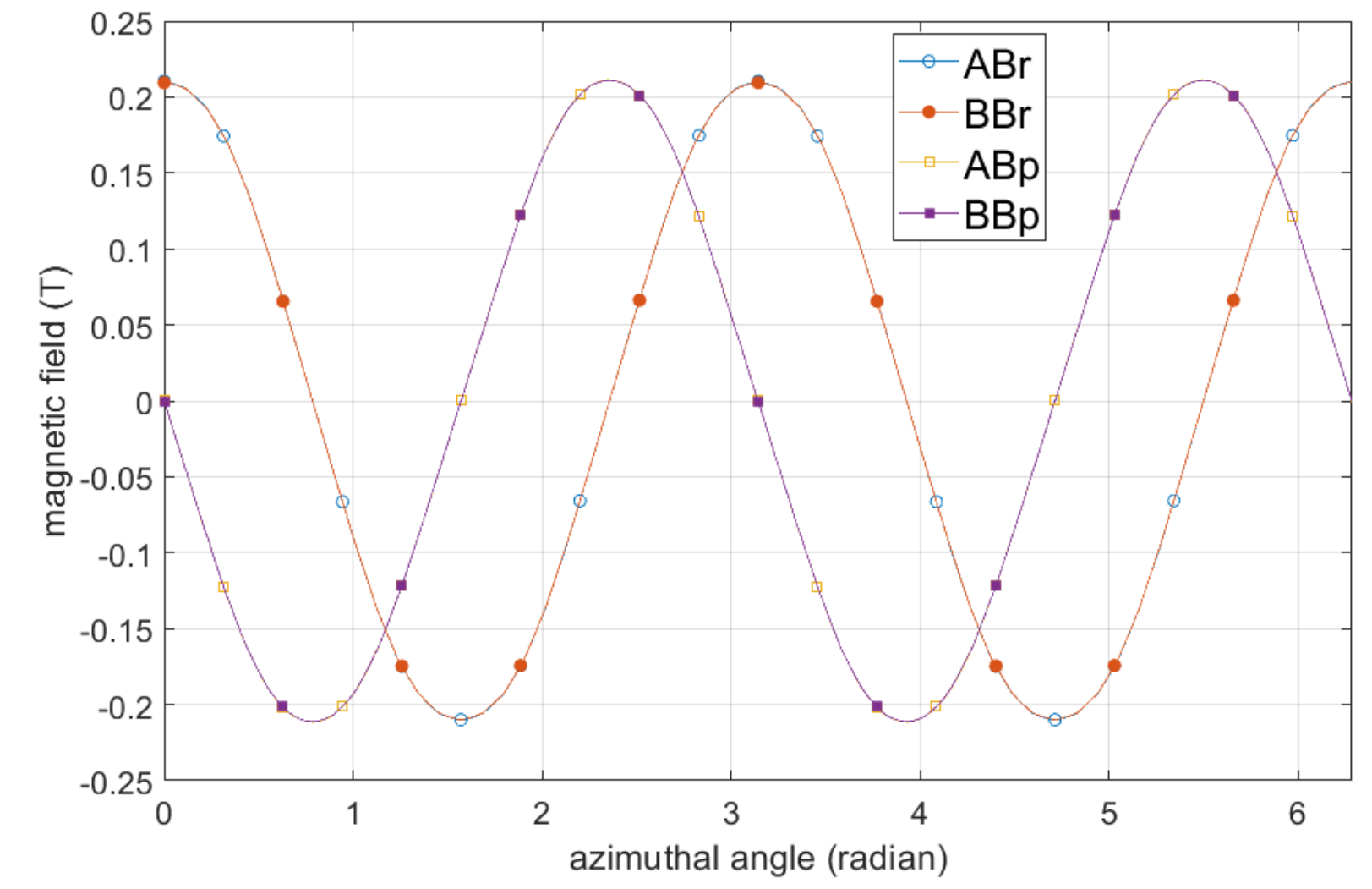

Fig. 7. The radial and azimuthal magnetic fields of 3D simulation.

- **3D modeling of the designed air-core HTS quadruple magnet is based on 2D simulation result: the current density distribution of Fig. 4 is assumed to be constant across all cross sections in all racetrack coils; each cross section is divided into two domains, each of which has area of *Thickness*×*Tapewidth*/2; the current density distribution is averaged in each domain; in 3D simulation, Cases A and B consider the uniform current density and averaged current density, respectively.**
- **The SCIF has been infamous for an HTS NMR magnet. However, in the case of the air-core HTS quadruple magnet, the SCIF has a minor effect on the field quality.**

IV. Conclusion

- **The air-core HTS quadruple magnet was designed assuming the uniform current density in all the racetrack coils. To analyze the effect of the SCIF on the field quality of the quadruple magnet, 2D *H*-formulation with domain homogenization is used. 3D modeling is established based on 2D simulation result. The SCIF slightly reduces the gradient and aggravates the uniformity. However, in the case of an HTS quadruple magnet of a relatively high gradient, the influence of the SCIF may be important. Further study will be pursued on full 3D modeling of the air-core HTS quadruple magnet to accurately calculate the electromagnetic behavior.**