Mitigation of shielding-current-induced field of a dipole magnet wound with coated conductors during pattern-operation and evaluation of beam orbit

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***Abstract*—We have been developing large-scale electromagnetic field analysis model of magnets composed of coated conductors to predict their field quality. We applied the model to a dipole magnet wound with coated conductors and calculated shielding-current-induced field during pattern-operation. Moreover, to mitigate the influence of the shielding-current-induced field on the field quality of the dipole magnet, we suggested two solutions: current control for dipole component and combination of the dipole magnet and corrections coils for sextupole component. Also, we conducted beam orbit simulations and particle distribution estimation with/without the mitigation methods.**

Keywords—coated conductor, electromagnetic field analysis, shielding-current-induced fields, mitigation

I. Introduction

The precise prediction of shielding-current-induced fields (SCIFs) of magnets wound with coated conductors by electromagnetic field analyses is quite important to optimize their design and operation [1]–[5]. However, the modelling of the magnets wound with coated conductors is quite difficult and complicated due to the strong nonlinear electric property of the coated conductors and very high aspect ratio of the cross-section of superconductor layer in the coated conductors. In addition, the influence of the shielding-current-induced fields on the beam characteristics

We developed large-scale electromagnetic field analysis model to visualize electromagnetic phenomena in the magnets wound with the coated conductors. We apply the developed model to a dipole magnet wound with coated conductors which is designed and operated based on specifications of magnets in a rotating gantry for carbon cancer therapy. To discuss the influence of the SCIF, stability and reproducibility of the integrated magnetic field along beam axis are evaluated by using time-evolution of multipole components of the magnetic field. Then, mitigation methods of dipole and sextupole components of the magnetic filed are discussed. In addition, because the distribution of multipole components of the magnetic field along beam axis can be cause of beam loss and undesired change of beam shape, we conducted beam orbit simulations with and without mitigation methods by using WinAGILE. In the simulations, the distribution of magnetic field along beam axis is considered.

II. Electromagnetic field analysis

The equation in the electromagnetic field analyses is derived from Faraday's law, Biot-Savart's law, Ohm's law, and definition of current vector potential. And also, the thin-strip approximation is applied to the model. The equation to be solved in the analyses is as follows [1], [2]:

$$\nabla \times \left(\frac{1}{\sigma} \nabla \times \boldsymbol{n} T \right) \cdot \boldsymbol{n} + \frac{\partial}{\partial t} \frac{\mu_0 t_s}{4\pi} \cdot \left(\int_{S'} \left[\left\{ \left(\nabla \times \boldsymbol{n}' T' \right) \times \boldsymbol{r} \cdot \boldsymbol{n} \right\} / r^3 \right] \mathrm{d}S' + \boldsymbol{B}_{\mathrm{ext}} \cdot \boldsymbol{n} \right) = \boldsymbol{0}. \quad (1)$$

In our software, a preconditioning method based on the AMG method is applied to the BiCGSTAB method to improve the convergence property of the linear solver. Furthermore, to address the huge required memory consumption and computation time due to dense matrix *B*, we applied hierarchical matrices.

III. Analysis results of a dipole magnet wound with coated conductors

We apply the developed model to a dipole magnet wound with coated conductors shown in Fig. 1, whose design and operation pattern shown in Fig. 2 are decided from actual magnets in a rotating gantry in HIMAC (Heavy Ion Medical Accelerator in Chiba). The numbers of degree of freedoms of the model is more than 1.5 million; the memory consumption by hierarchical matrices is 177 GB, while that by a dense matrix had been 16.7 TB.

The time-evolution of the multipole components of SCIF is shown in Fig. 2. Here, the relative multipole components of SCIF Δbln (n = 1, 3, 5, ...) against designed dipole components are plotted against time.

The calculated time-changing SCIF help optimization of magnet design and its operation. the influence of SCIF on the dipole and sextupole components need to be mitigated for application because their change during operation is more than required field quality which is less than 1×10^{-3}. Therefore,. we need to consider mitigation methods of them numerically by the developed model.

In addition, we conducted beam orbit simulations on single magnet and series of the magnets to compose the

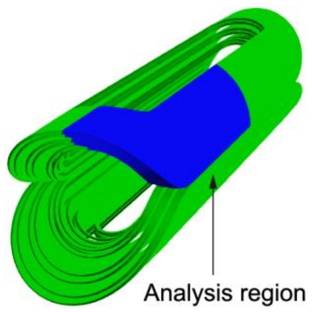

Fig. 2. Saddle-shaped coil of a cosine-theta dipole magnet for a rotating gantry for carbon cancer therapy [2].

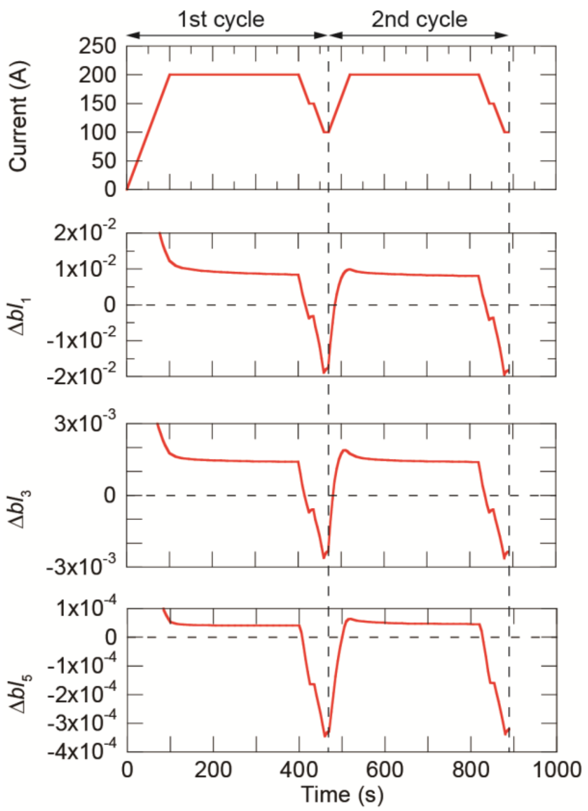

Fig. 3. Current profile in the analysis and calculated influence of the SCIF on the dipole, sextupole, and decapole components.

rotating gantry considering the distribution of magnetic field including the SCIF to evaluate the influence of the SCIFs on beam characteristics such as beam orbits and distribution of particles.

IV. Mitigation of Influence of Shielding-Current-Induced Field on Field Quality

The mitigation method for the integrated dipole component is current control. Because the dipole magnet is designed to generated only dipole component of magnetic field, control of transport current can change generated dipole component of magnetic field directly. Note that the dipole magnetic field is not linear to the transport current due to influence of shielding-current-induced field. Therefore, we conduct electromagnetic field analyses several times with

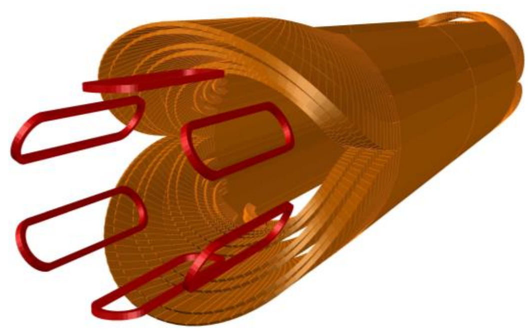

Fig. 1. Combination of the dipole magnet and the correctoin coils for mitigation of sextupole component of the SCIF.

controlled transport current until we obtain enough stability of dipole component during operation.

The integrated sextupole component of the magnetic field cannot be mitigated by current control because the cause of sextupole component is not transport current but three-dimensional distribution of shielding current in the magnet. Therefore, we need to change magnet design to mitigate the influence of SCIF on the sextupole component. To mitigate the sextupole component of the SCIF, we investigated the design of the correction coils. We designed sextupole correction coils wound with coated conductors into racetrack geometry. The correction coils are wound with same coated conductor as the dipole coil and placed at the end of the dipole magnet as shown in Fig. 3. The operation pattern of the correction coils are decided from Fig. 2.

And also, we conducted beam orbit simulations on single dipole magnet with HTS sextupole correction coils and series of the magnets with the correction coils to compose the rotating gantry considering the distribution of magnetic field including the SCIF to evaluate the influence of the SCIFs on beam characteristics. We discuss the influence of local strong sextupole component of the magnetic field by the correction coils on the beam characteristics.

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