Design of a cosine-theta dipole magnet considering influence of shielding-current-induced field on field quality

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1. Background and objective

Cosine-theta dipole magnet wound with coated conductor

High magnetic field by using cryocooler
Deterioration of field quality by large shielding-current-induced field (SCIF)
Necessity of generation of time-dependent magnetic field with sufficient accuracy for everytime

3D electromagnetic field analysis

To design considering influence of SCIF on field quality, accurate evaluation of time-dependent SCIF is essential.

- **Conducting 3D electromagnetic field analysis for a cosine-theta dipole magnet**
- **Studying how to reduce the influence of SCIF on the field quality**

2. Analysis model

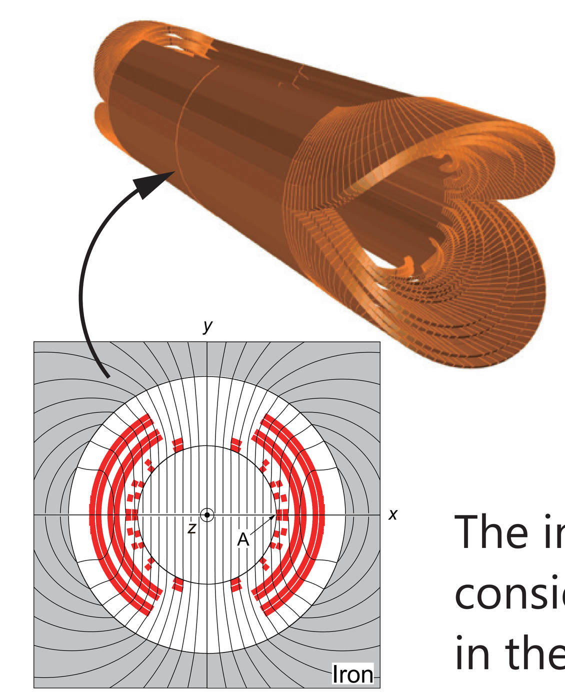
Equation to be solved in analysis model

$$\nabla \times \left(\frac{1}{\sigma}\nabla \times \boldsymbol{T}\right) + \frac{\partial}{\partial t}\frac{\mu_0}{4\pi}\int_V \frac{(\nabla \times \boldsymbol{T}')\times \boldsymbol{r}}{r^3}\mathrm{d}V + \frac{\partial \boldsymbol{B}_{\mathrm{ext}}}{\partial t} = \boldsymbol{0}.$$

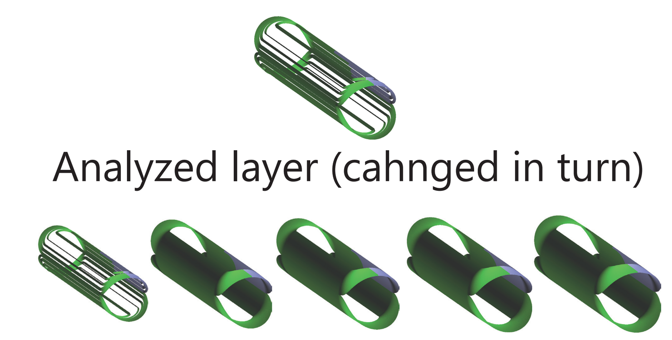
Thin strip, nested-loops, and block approximations are used in this model

Y. Sogabe, et al.: IEEE Trans. Appl. Supercond. vol. 25, no. 3 (2015) Art. No. 4900205.

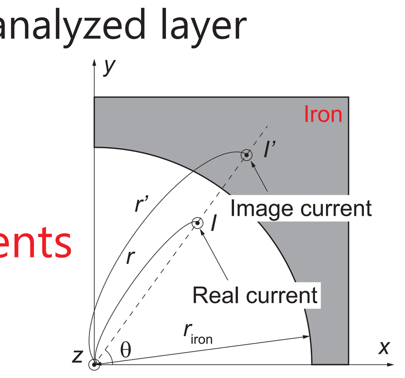
3D shape of the magnet



Layer-by-layer model

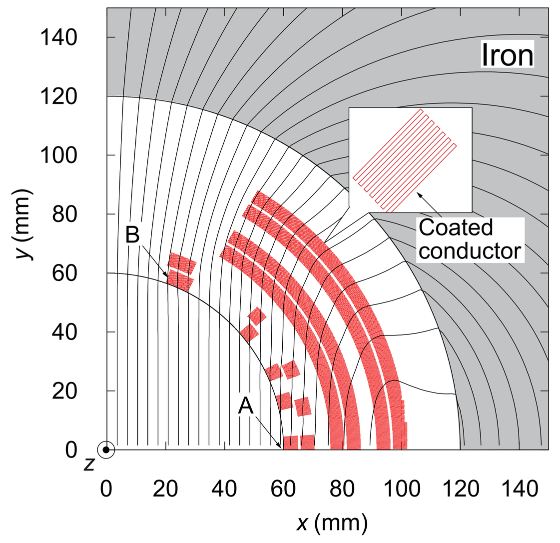


The influence of iron yoke is considered as the image currents in the iron yoke.



3. Details of analysis conditions

Specifications of analyzed magnet	
Number of turn (conductor length)	2744 (5.48 km)
Length of straight section	700 mm
Length of entire magnet	1082 mm
Inner radius of magnet	60 mm
Separation of turns	0.1 mm
Dipole component	2.64 Tm
Higher multipole components	$< 10^{-4}$
Relative permeability of iro yoke	3000



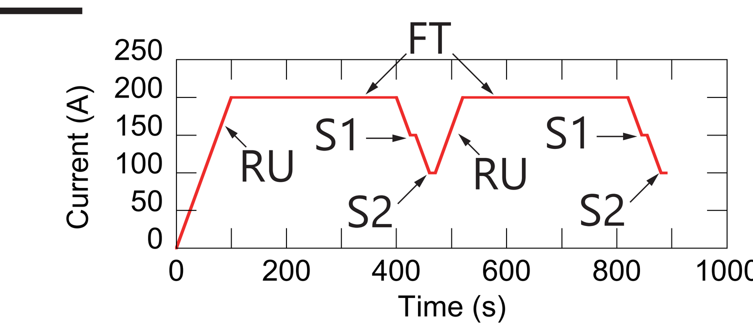
Cross-section

Parameters of coated conductor	
Width	5 mm
Thickness	0.2 mm
Superconductor layer thickness	2 μm
E_0	10^{-4} V/m
n	40
J_{c0}	1.6×10^{11} or 1.3×10^{11} A/m^2
B_0	1.0 T

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

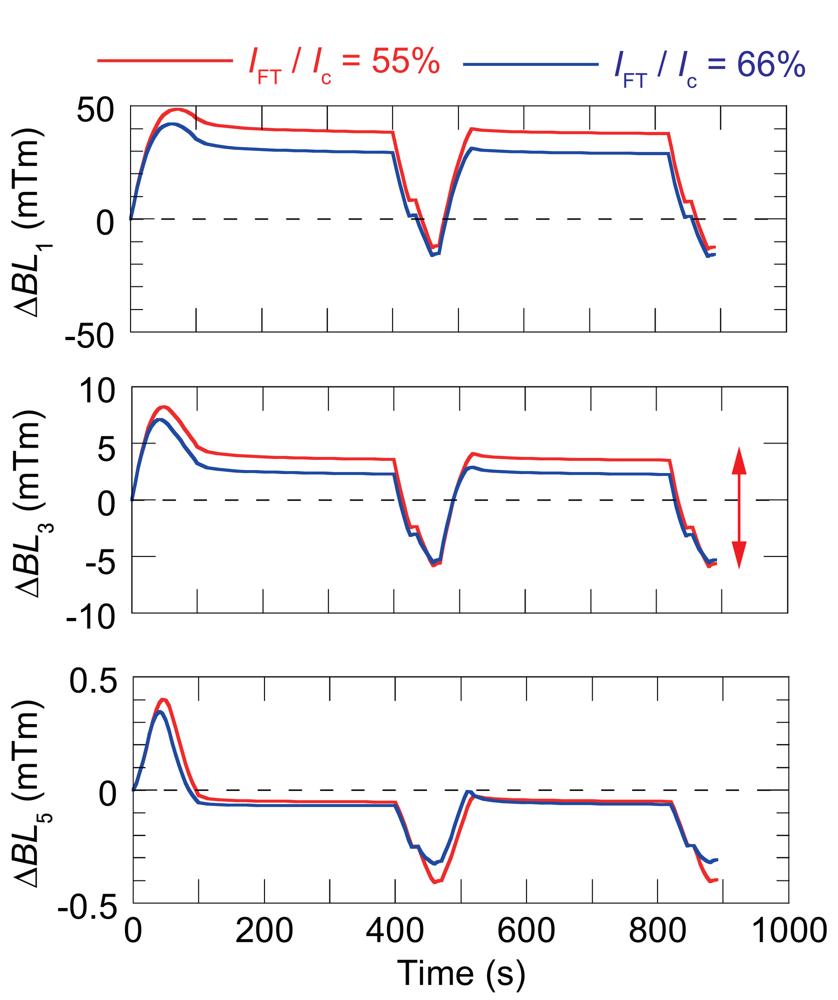
Kim model $J_c = J_{c0}\frac{B_0}{B_0 + |B_n|}$

Specifications of current profile	
FT	200 A, 300 s
S1	150 A, 10 s
S2	100 A, 10 s
Ramp up/down rate	2 A/s



4. Influence of load ratio on SCIF

When J_{c0} = 1.6 x 10^{11} A/m^2, magnet I_c = 360 A and I_{FT} / I_c = 55%
When J_{c0} = 1.3 x 10^{11} A/m^2, magnet I_c = 300 A and I_{FT} / I_c = 66%

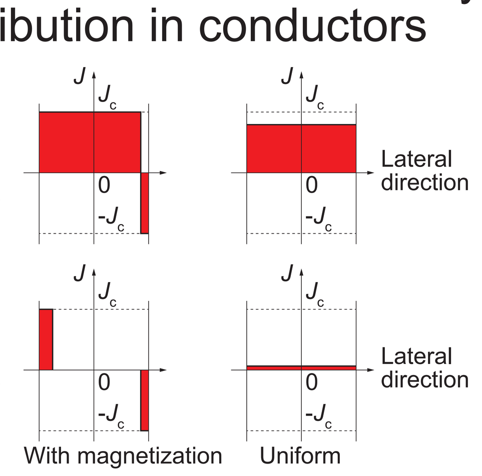


$\Delta BL_n = BL_n(t) - BL_{n,\mathrm{uniform}}(t)$

BL means the integrated B along the beam direction

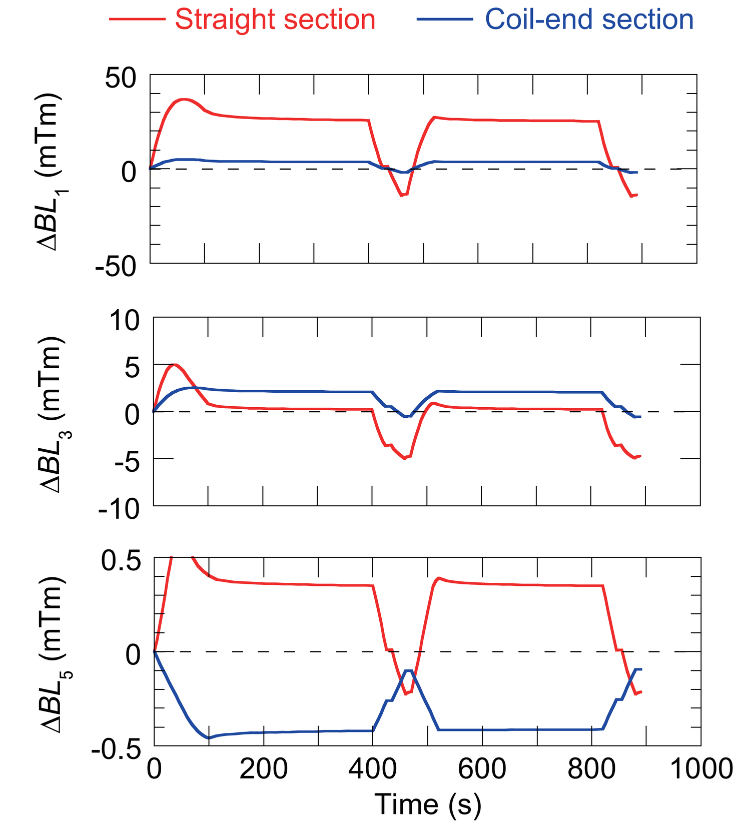
BL_n: Analysis result of 2n-pole component of BL
$BL_{n,\mathrm{uniform}}$: 2n-pole component of BL with uniform current distribution

Higher load ratio (I_{FT} / I_c) resulted in smaller SCIF because of small non-uniformity of J distribution in conductors

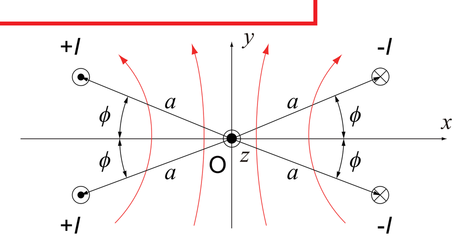


5. Discussion about ΔBL_n by each section

I_{FT} / I_c = 66%

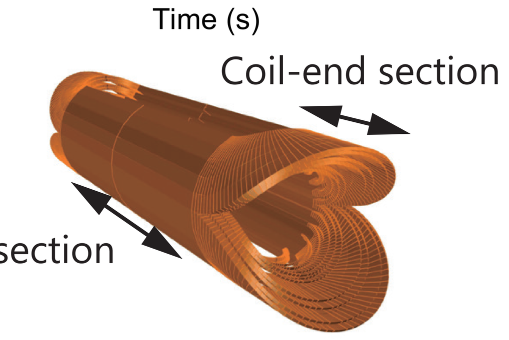


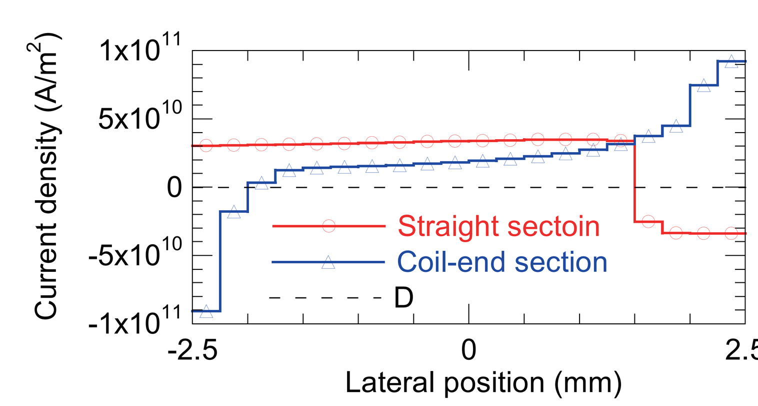
$$B_n = \frac{2\mu_0 I r_0^{n-1}}{\pi a^n}\cos n\phi \quad ; n \in \text{odd}.$$



- ΔBL_n relate with condcutors arrangement in cross-sections normal to beam direction

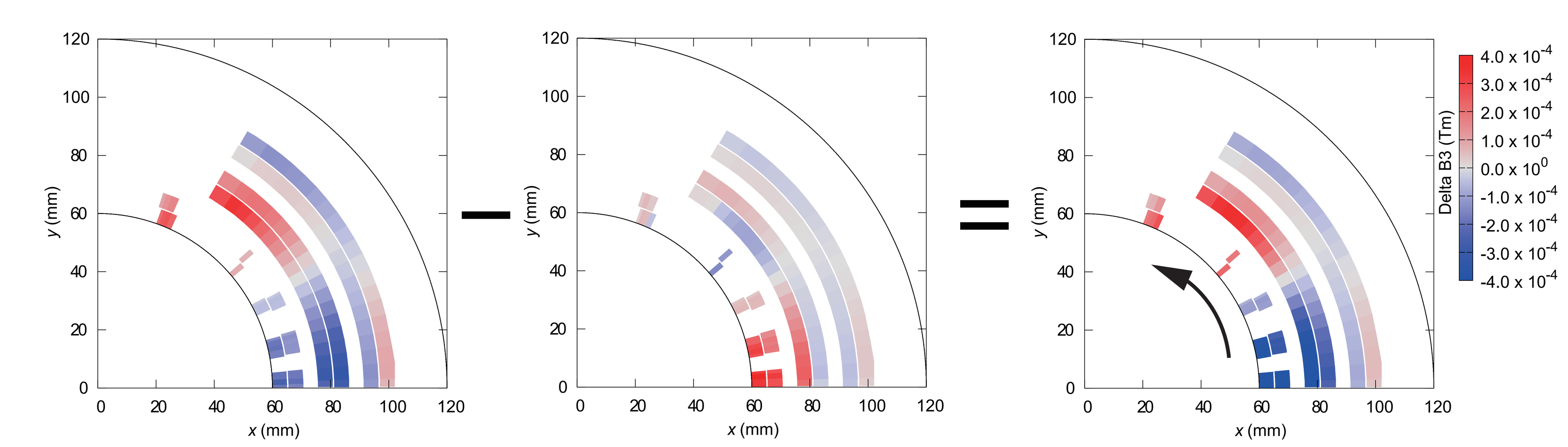
In the cross-section in coil-end, J distributions in conductors are different from those in the cross-section in straight section.





6. Design strategy to reduce SCIF influence

- Dipole component can be compensated by minute correction of operating current.
- ΔBL_n (n>3) are sufficiently small for magnet in beam-line or rotating gantry → can be ignored



By transposition of some conductors to larger ϕ, large change of ΔBL_3 in operating cycle can be cancelled

We are looking for 3D design based on this strategy!

Acknowledgement
This work was supported in part by JSPS KAKENHI Grant Number 16H02326.