2015 CHATS on Applied Superconductivity Workshop
September 14 – 16, 2015
Bologna, Italy
(September 15, Tuesday)

Ac Loss Calculation of a Dipole Magnet Wound with Coated Conductors

N. Amemiya, Y. Sogabe (Kyoto University)
Y. Iwata, K. Noda (NIRS)
Y. Ishii, T. Kurusu (Toshiba)

This work will be submitted to SUST: "Ac loss analyses of a cosine-theta dipole magnet wound with coated conductors for carbon rotating gantry".

This work was supported by AMED and METI in the Development of Fundamental Technologies for HTS Coils Project.

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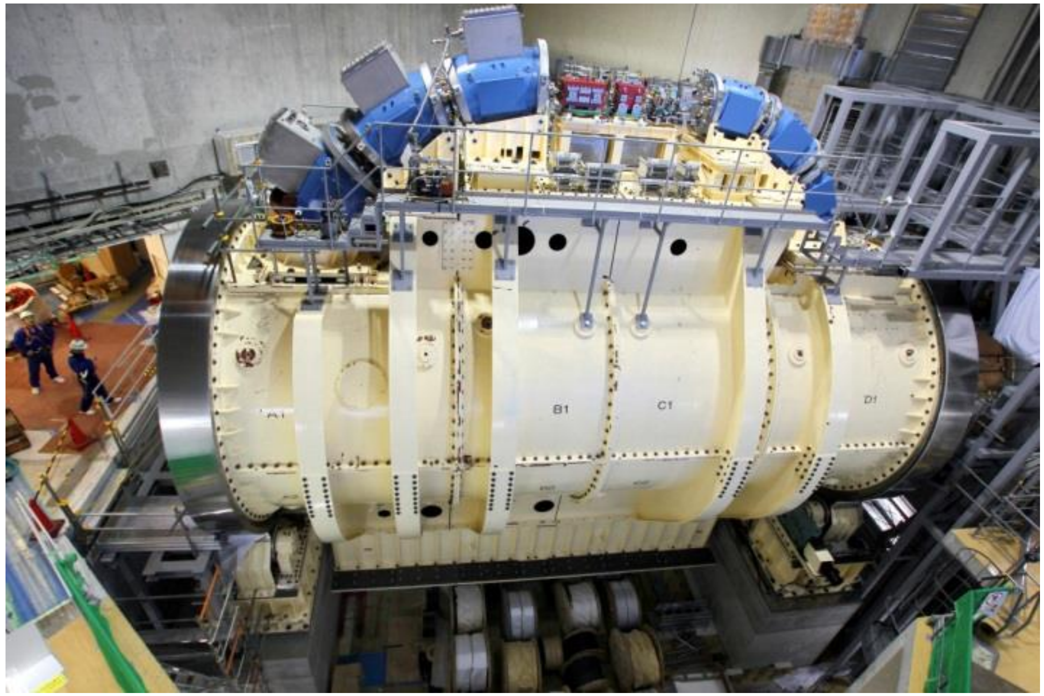
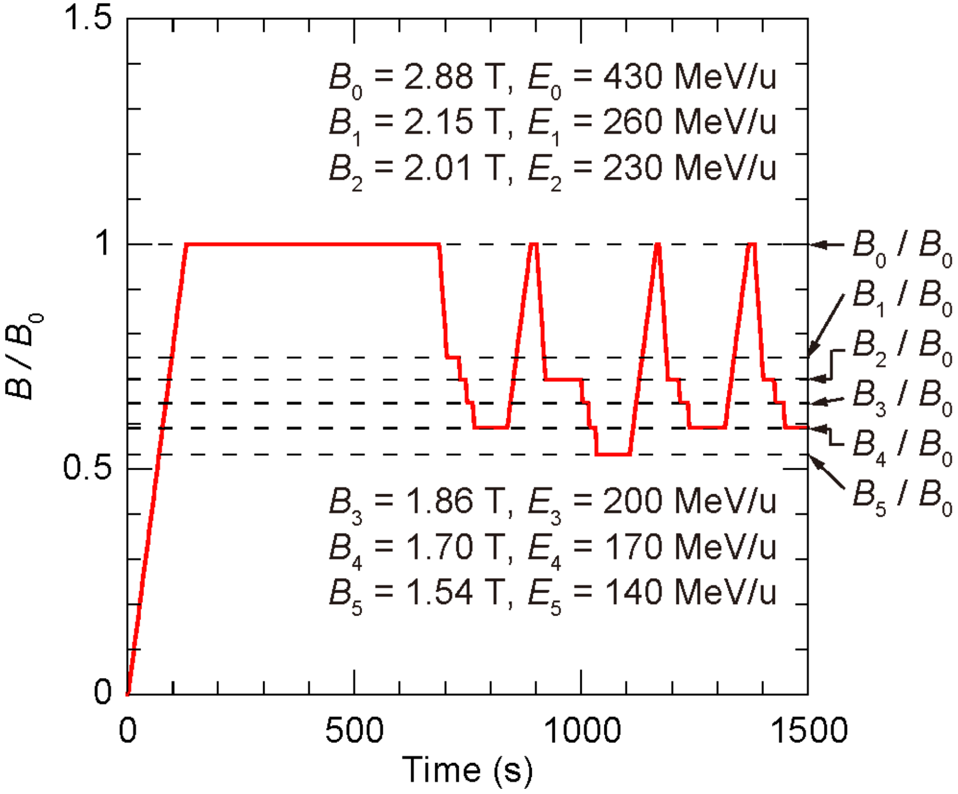
Rotating gantry for carbon therapy using SC magnet constructed at NIRS, Japan



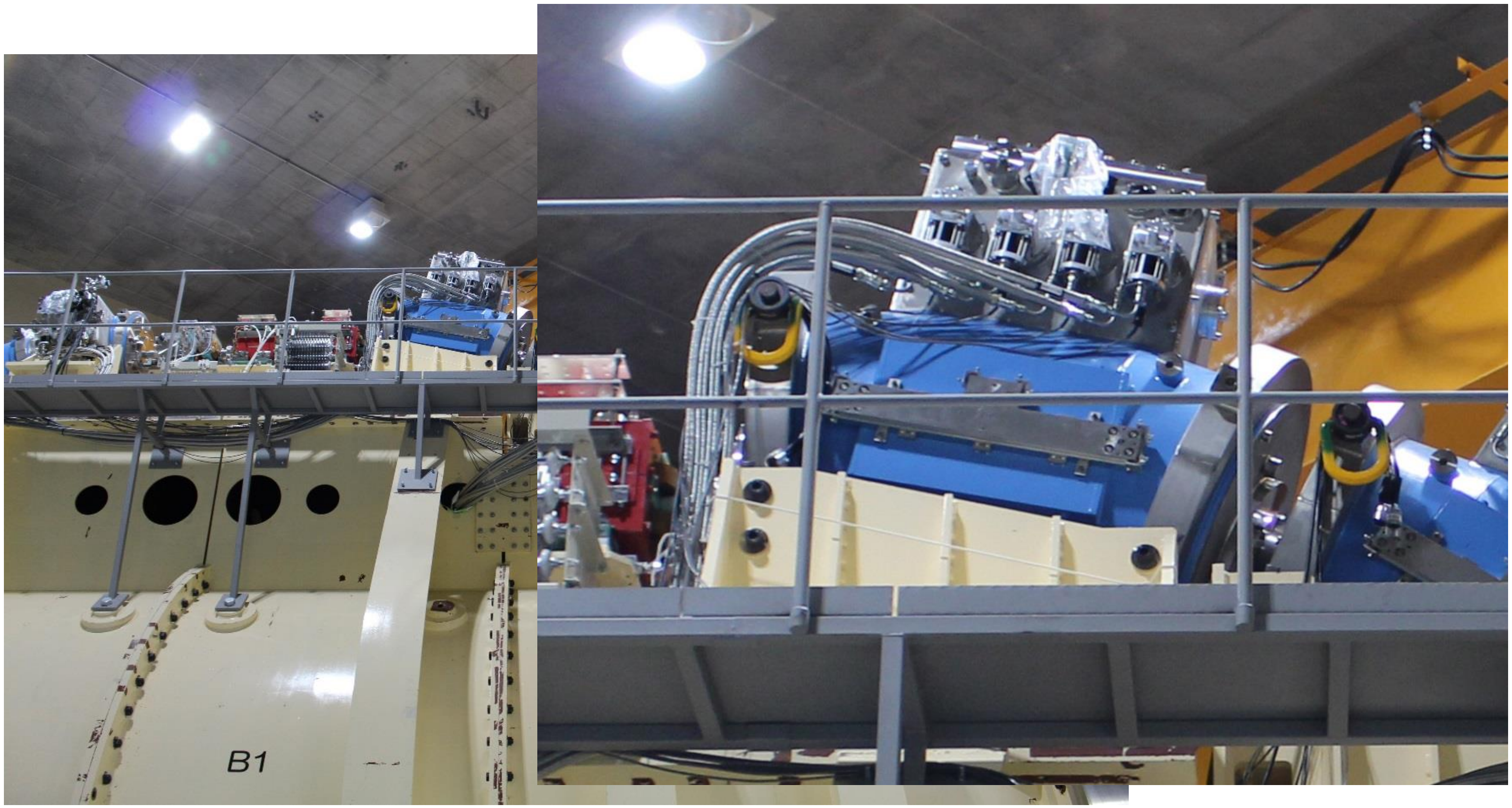
Advantage of SC magnets
- ✓ High magnetic field
- ✓ Light weight

Excitation pattern of magnets in a rotating gantry



Substantial ac losses will be generated.

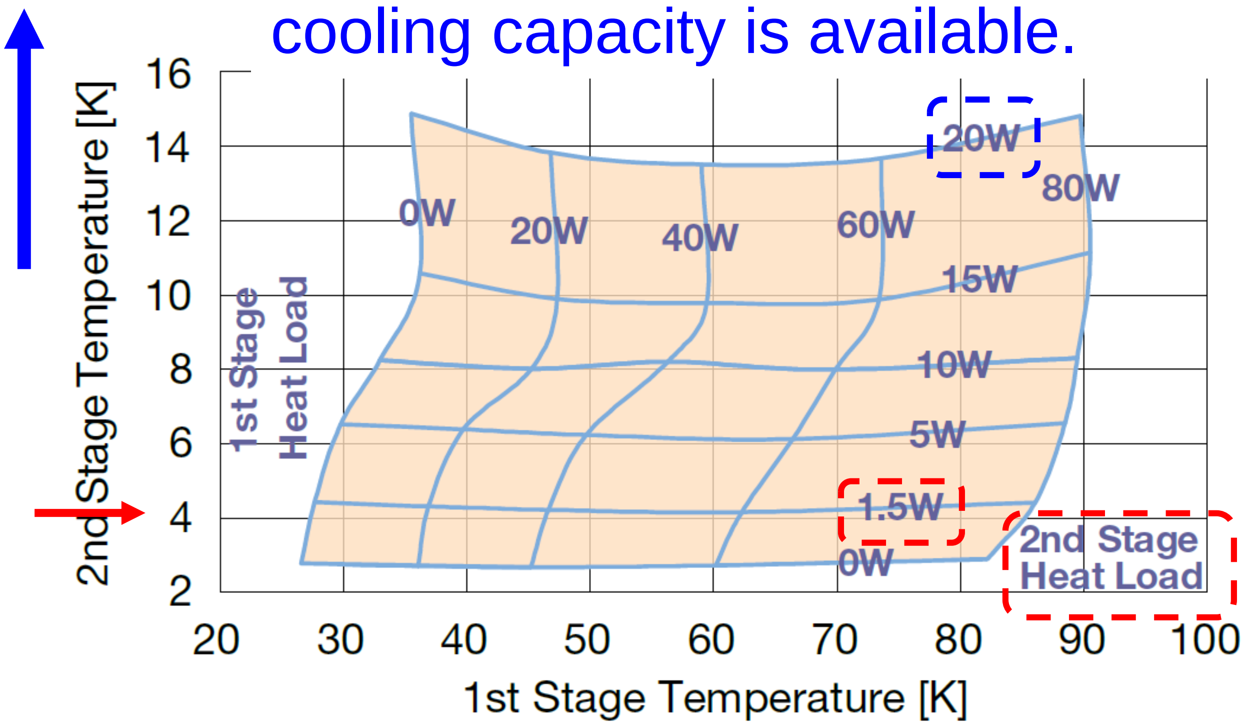
NbTi magnets cooled by GM cryocoolers used in the gantry



Their disadvantages include the small temperature margin of NbTi as well as small cooling capacity of cryocooler at ~4.2 K.

Cooling capacity of GM cryocooler

With increasing temperature, larger cooling capacity is available.



Heat leak and some unknown thermal disturbance as well as ac losses are concerns at lower temperature.

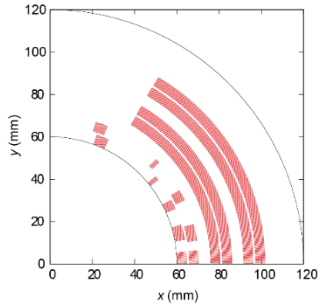
Applications of coated conductors to dipole magnets for rotating gantry

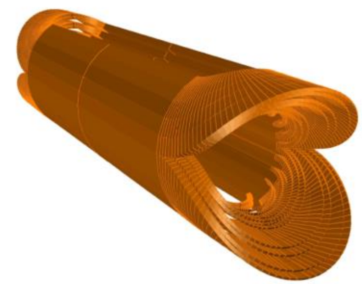
- Advantages
  - Larger temperature margin
  - Operation at higher temperature
    - Larger heat capacity of materials leading to potential better thermal stability
    - Larger cooling capacity available
- Disadvantages
  - Large ac loss caused by wide tape shape
  - Screening current deteriorating field qualities

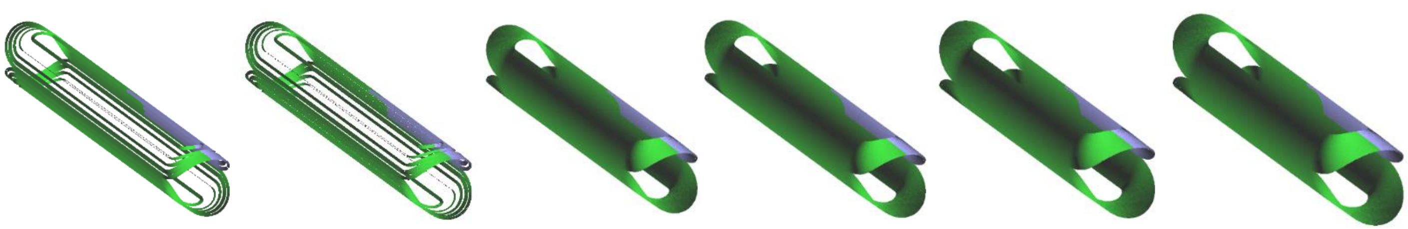
Ac loss evaluation by electromagnetic field analyses of a dipole magnet wound with coated conductors

Specifications of analyzed coil

Current per conductor	200 A
Number of turn (conductor length)	2744 (5.48 km)
Length of straight section	700 mm
Length of entire coil	1082 mm
Inner radius of coil	60 mm
Separation of turns	0.1 mm
Dipole component	2.64 Tm
higher multipole components	$< 10^{-4}$







1st layer 2nd layer 3rd layer 4th layer 5th layer 6th layer

Layer	1	2	3	4	5	6	Total
Turns / pole	82	88	263	283	319	337	1372

Governing equation and constitutive equation

〔Faraday's law〕

$$\nabla \times \boldsymbol{E} + \frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{0}$$

〔Biot-Savart's law〕

$$\boldsymbol{B} = \frac{\mu_0}{4\pi} \int_V \frac{\boldsymbol{J} \times \boldsymbol{r}}{r^3} dV$$

〔Definition of current vector potential〕

$$\boldsymbol{J} = \nabla \times \boldsymbol{T}$$

〔Extended Ohm's law〕

$$\boldsymbol{E} = \boldsymbol{J} / \sigma(J)$$

Equivalent conductivity derived from *E*-*J* characteristic: Ex. $E = E_0 (J / J_c)^n$

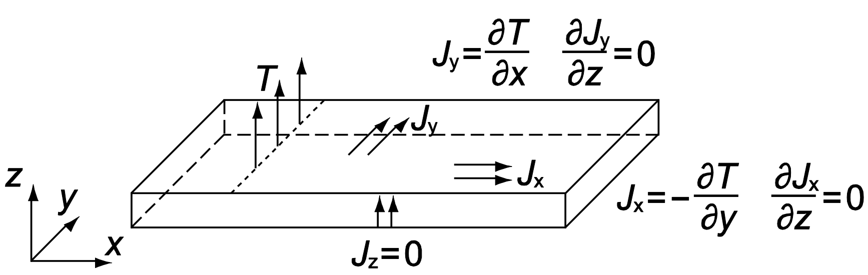
$$\nabla \times \left(\frac{1}{\sigma} \nabla \times \boldsymbol{T}_\mathrm{f} \right) + \frac{\mu_0}{4\pi} \frac{\partial}{\partial t} \int_V \frac{(\nabla \times \boldsymbol{T}_\mathrm{s}) \times \boldsymbol{r}}{r^3} dV = \boldsymbol{0}$$

Integrate along thickness of coated-conductor

$$\nabla \times \left(\frac{1}{\sigma} \nabla \times \boldsymbol{T}_\mathrm{f} \right) + \frac{\mu_0 t_\mathrm{s}}{4\pi} \frac{\partial}{\partial t} \int_S \frac{(\nabla \times \boldsymbol{T}_\mathrm{s}) \times \boldsymbol{r}}{r^3} dS = \boldsymbol{0}$$

Thin strip approximation

High cross-sectional aspect ratio of coated-conductor allows its use.



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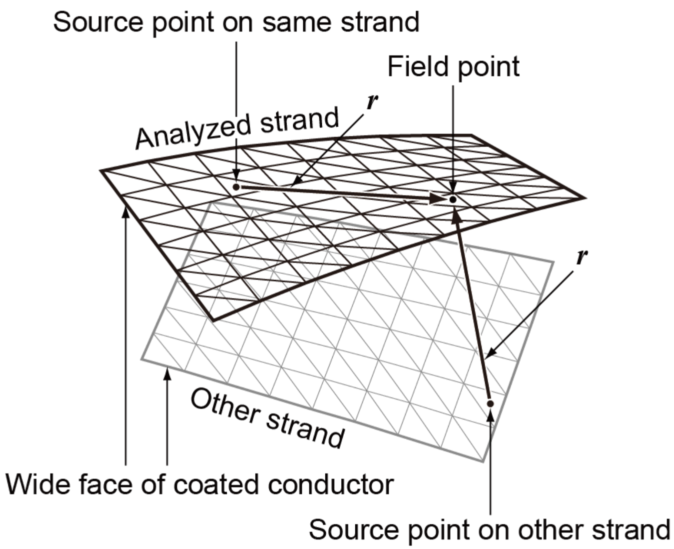
Consideration of three-dimensionally-curved coated conductors

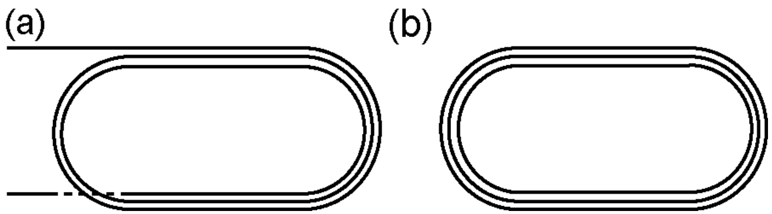


$$\nabla\times\left(\frac{1}{\sigma}\nabla\times\boldsymbol{n}T\right)\cdot\boldsymbol{n}+\frac{\partial}{\partial t}\left(\frac{\mu_0 t_s}{4\pi}\int_{S'}\frac{\left(\nabla\times\boldsymbol{n}'T'\right)\times\boldsymbol{r}\cdot\boldsymbol{n}}{r^3}\mathrm{d}S'+\boldsymbol{B}_{\mathrm{ext}}\cdot\boldsymbol{n}\right)=0$$

This term representing ***B*** in Faraday's law is calculated by Biot-Savart's law based on currents on arbitrary 3D-shaped conductors

Nested-loops approximation and block approximation

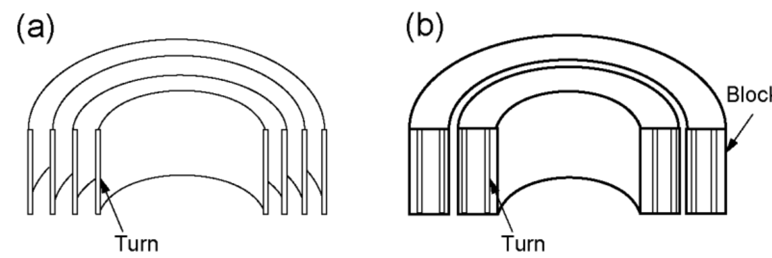
Nested-loops approximation



A continuous piece of coated conductor wound spirally in a coil is replaced with the nested-loops of coated conductor.

Y. Sogabe, T. Tsukamoto, T. Mifune, T. Nakamura, and N. Amemiya IEEE-TAS **25**(2015) 4900205

Block approximation



A coil is divided by blocks; the current distributions in coated conductors in a block are assumed to be identical.

Calculated for the turn representing each block

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

Calculated for all turns

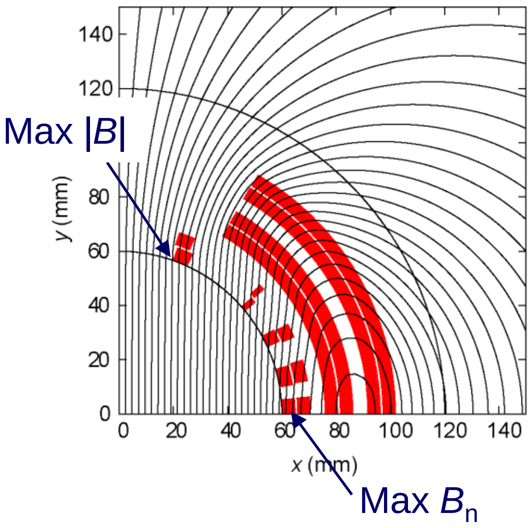
Superconductor

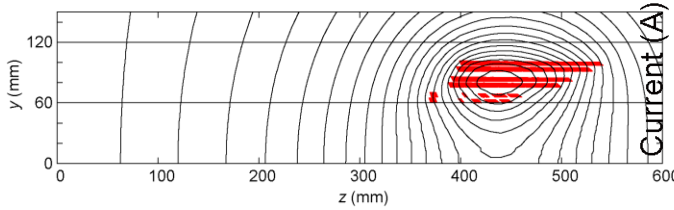
Width	5 mm
Thickness	0.2 mm
Superconductor thickness	2 μm
n value	30
Critical current density at zero magnetic field J_{c0}	1.2×10^{11} A·m^{-2}
Constant of Kim's model B_0	1.0 T

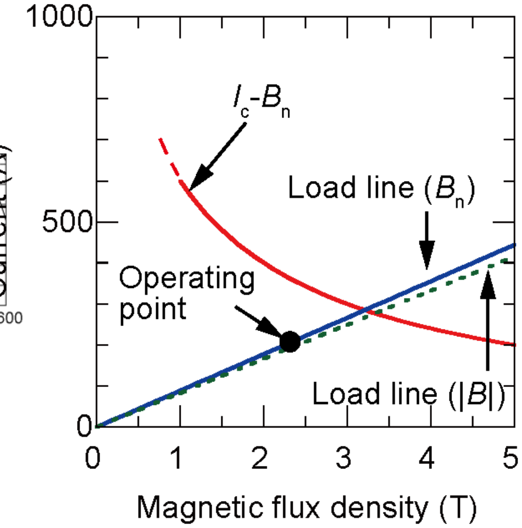
$$E = E_{\mathrm{c}} \left(\frac{J}{J_{\mathrm{c}}} \right)^n$$

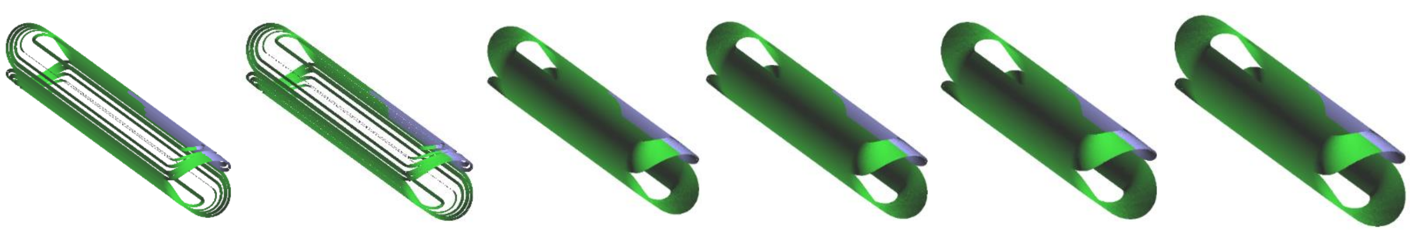
$$J_{\mathrm{c}}(B_{\mathrm{n}}) = J_{\mathrm{c0}} \frac{B_0}{B_0 + |B_{\mathrm{n}}|}$$

Mmagnetic field distribution, load lines, I_c – B curve



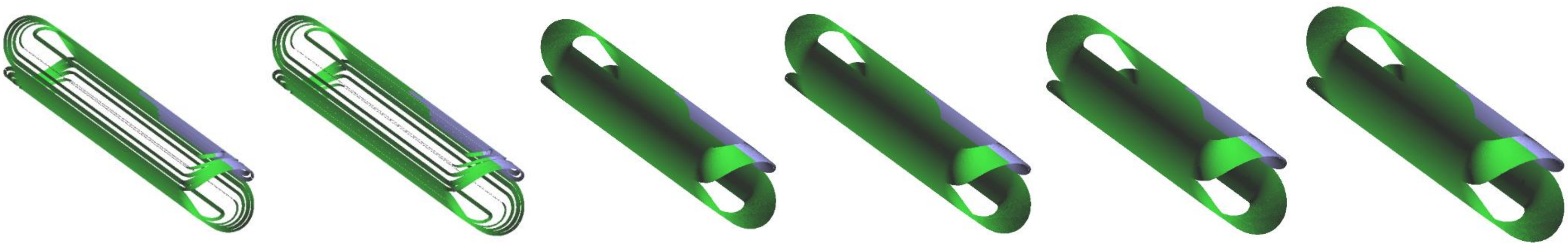






1st layer 2nd layer 3rd layer 4th layer 5th layer 6th layer

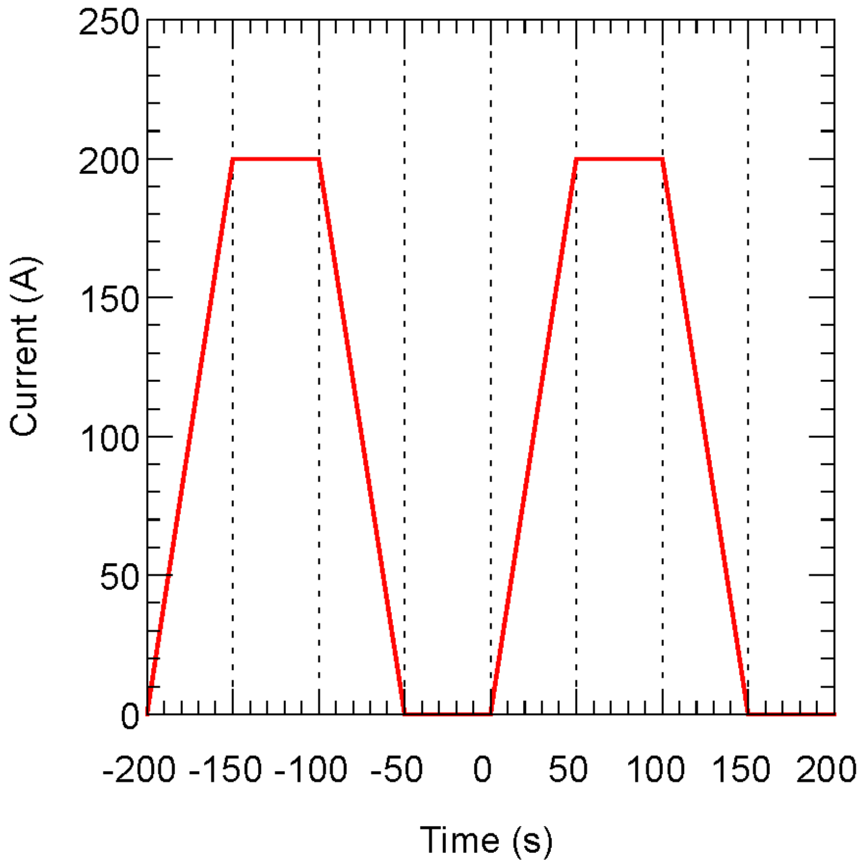
Layer-by-layer analyses



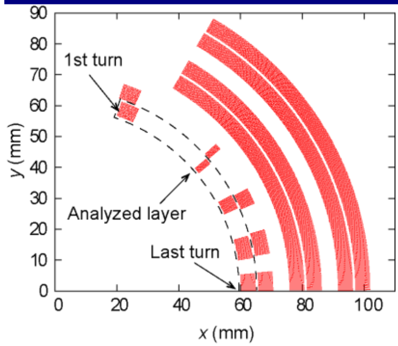
1st layer　2nd layer　3rd layer　4th layer　5th layer　6th layer

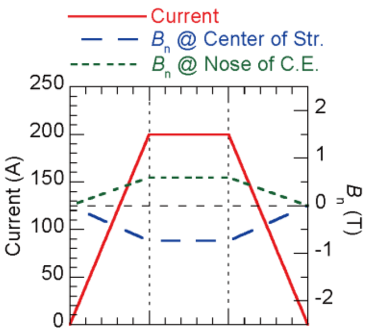
- Coated conductors in one layer are analyzed, while the currents in other layer provide the time-dependent “external magnetic fields” to the analyzed layer.
- The nested-loops approximation and the block approximation (20 blocks per each layer) are applied to the analyzed layer.

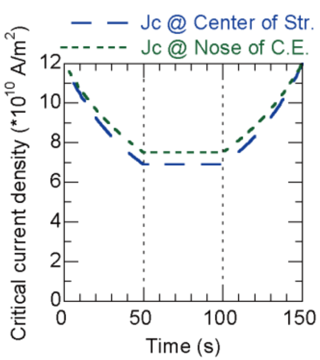
Temporal profile of magnet current



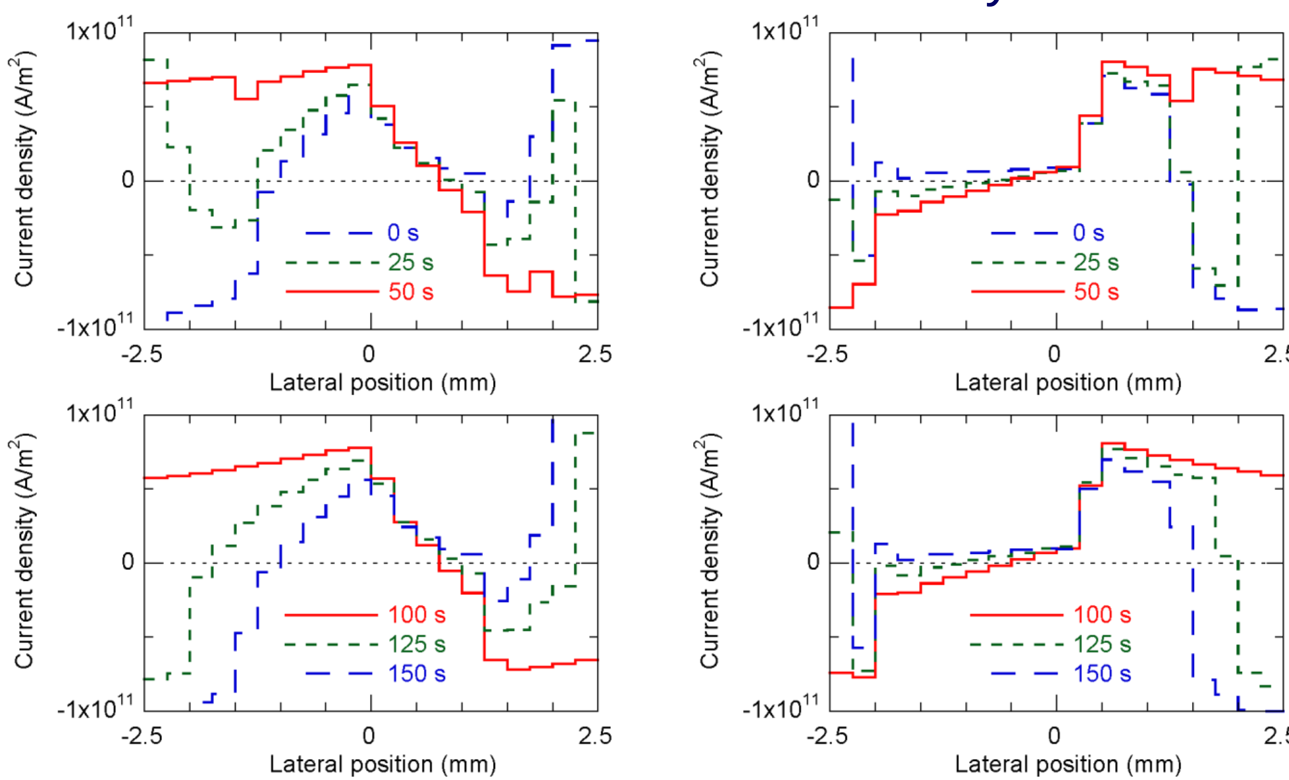
Current distribution at the 1st turn in the 1st layer







The 1st turn in the 1st layer



Center of straight part

Nose of coil end

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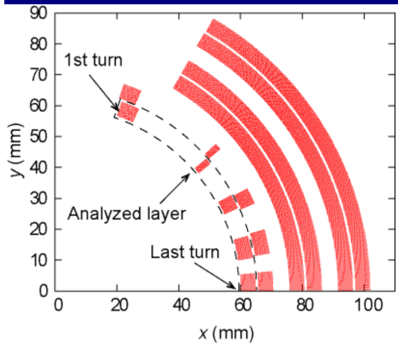
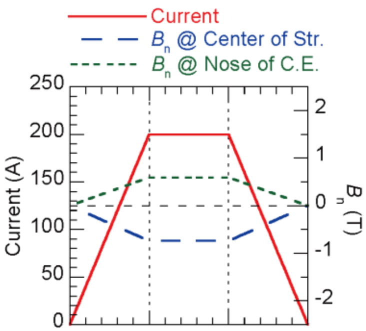
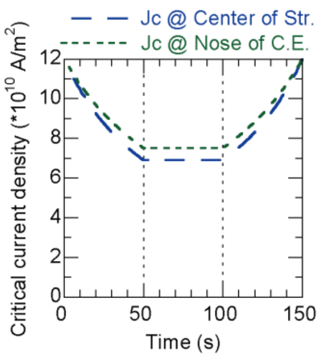
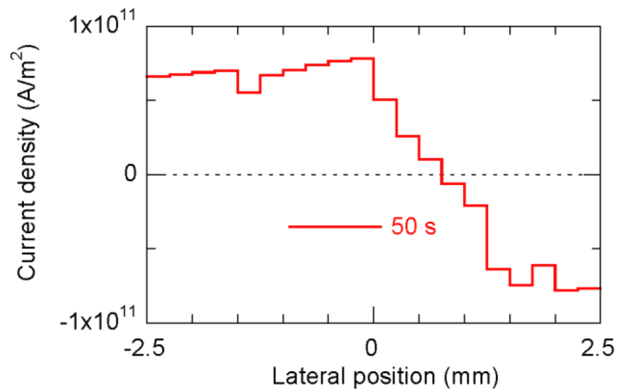
Current distribution at the 1st turn in the 1st layer



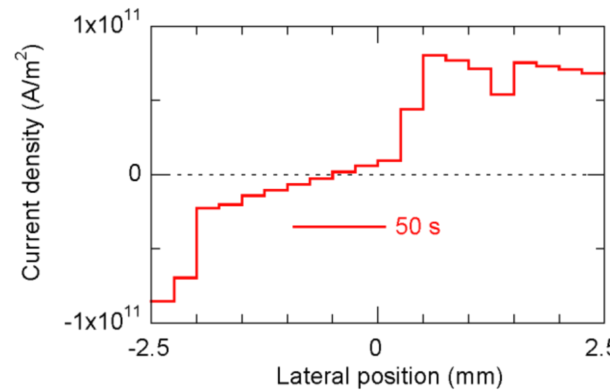




The 1st turn in the 1st layer

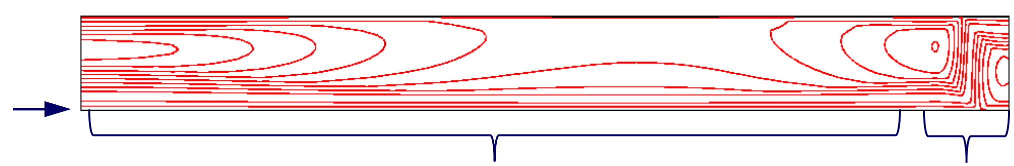


Center of straight part



Nose of coil end

Edge near magnet axis (negative lateral edge)



50 A/line

Straight part

Coil end

***t* = 50 s**

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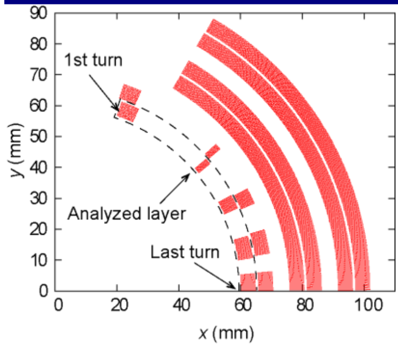
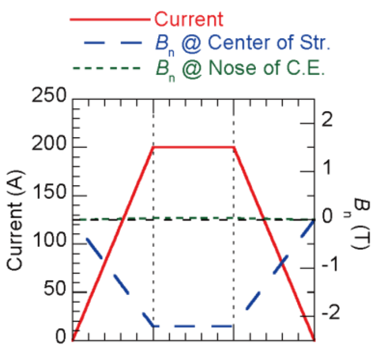
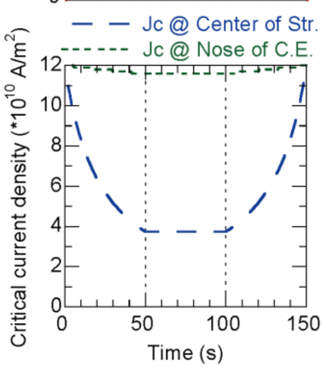
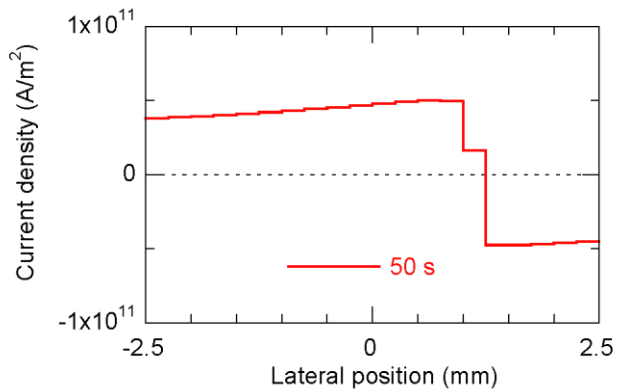
Current distribution at the last turn in the 1st layer



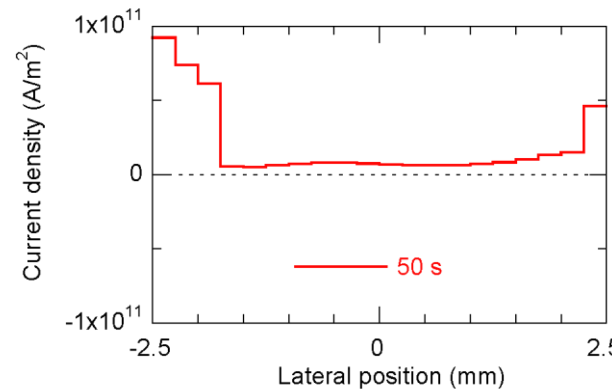




The last turn in the 1st layer

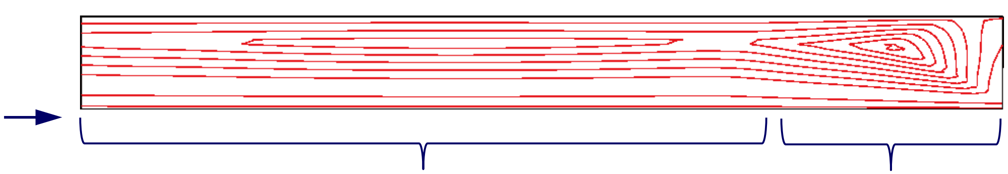


Center of straight part



Nose of coil end

Edge near magnet axis (negative lateral edge)



50 A/line

Straight part

Coil end

***t* = 50 s**

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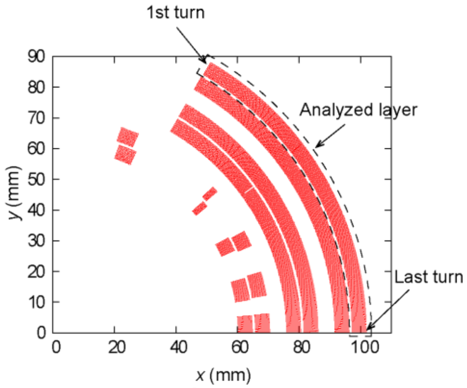
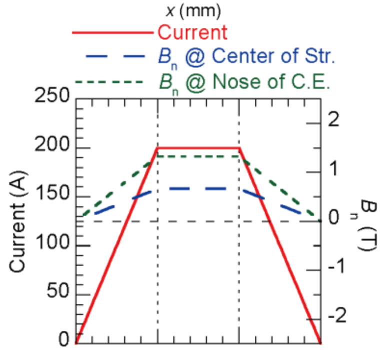
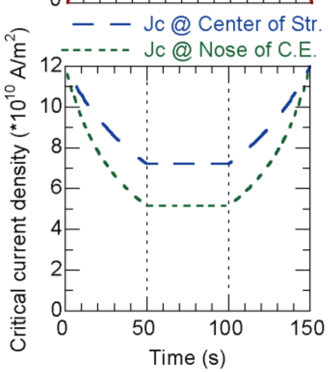
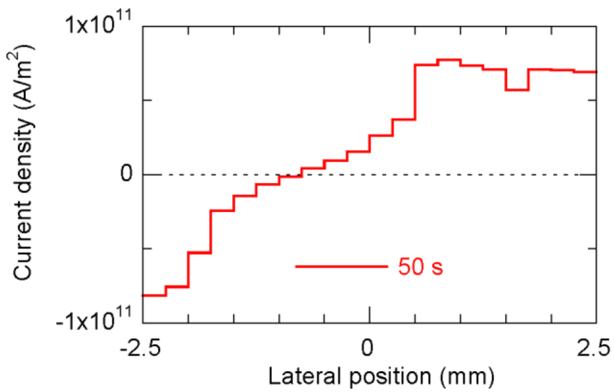
Current distribution at the 1st turn in the 6th layer



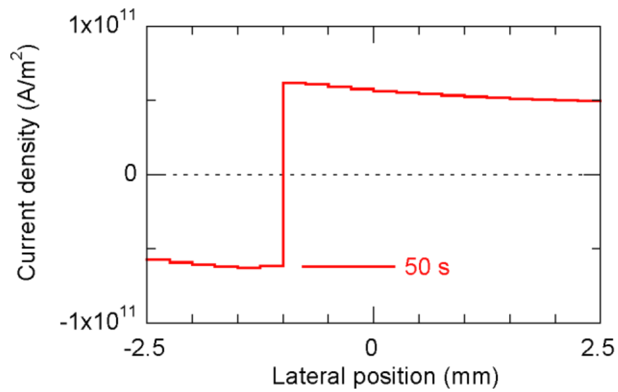




The 1st turn in the 6th layer

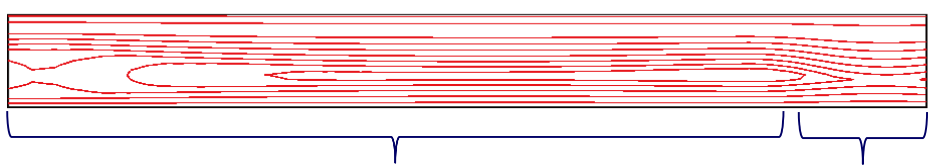


Center of straight part



Nose of coil end

Edge near magnet axis (negative lateral edge)



20 A/line

Straight part

Coil end

***t* = 50 s**

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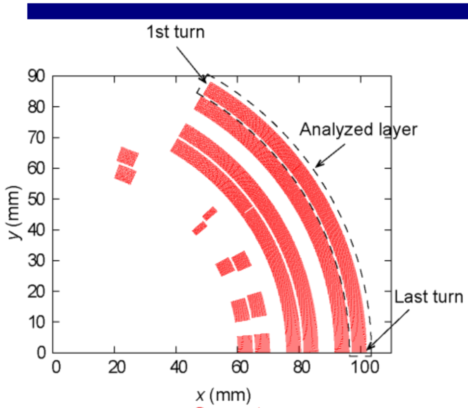
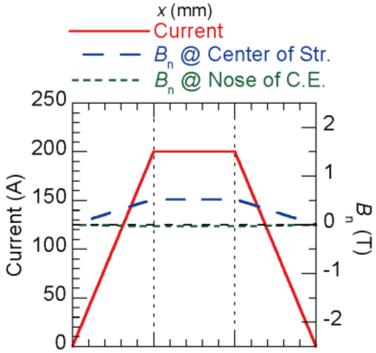
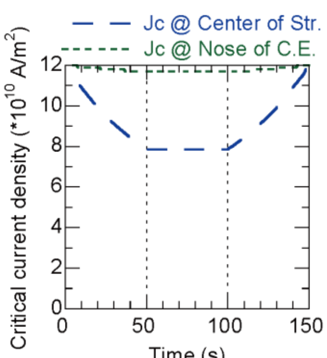
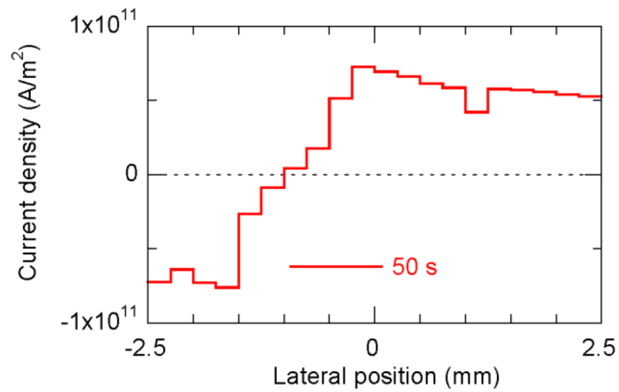
Current distribution at the last turn in the 6th layer



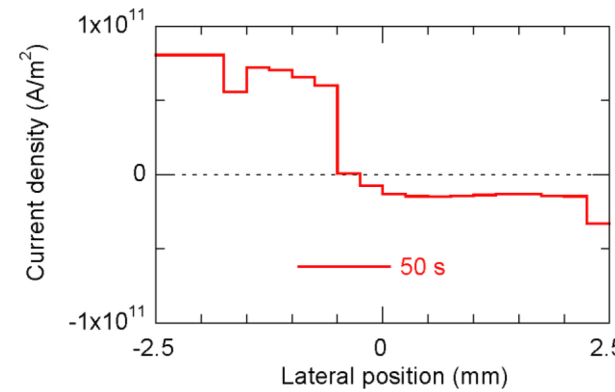




The last turn in the 6th layer

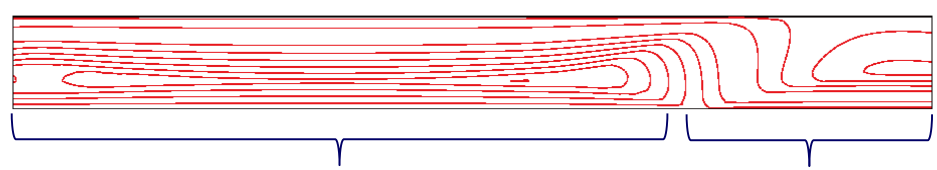


Center of straight part



Nose of coil end

Edge near magnet axis (negative lateral edge)



50 A/line

Straight part

Coil end

***t* = 50 s**

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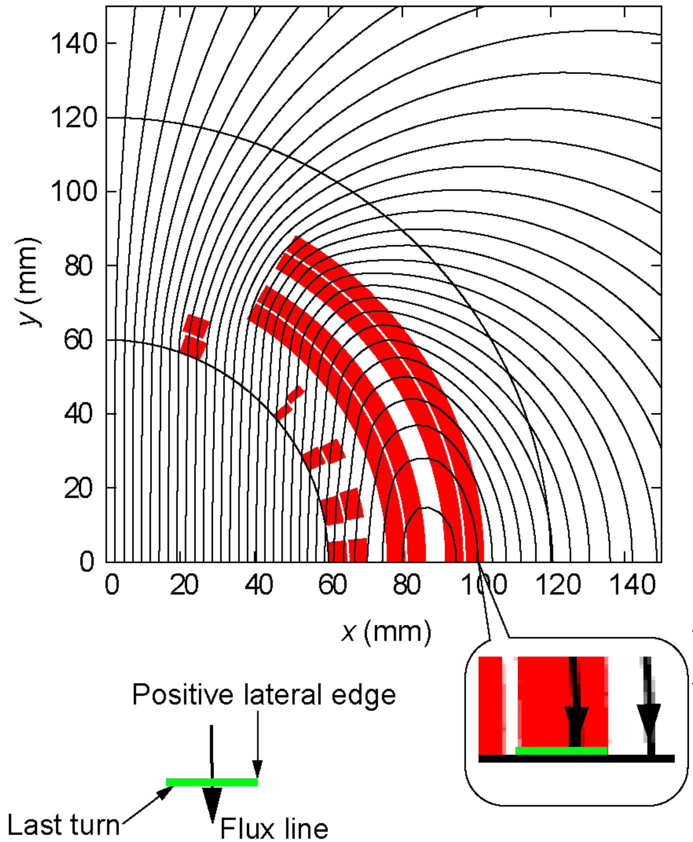
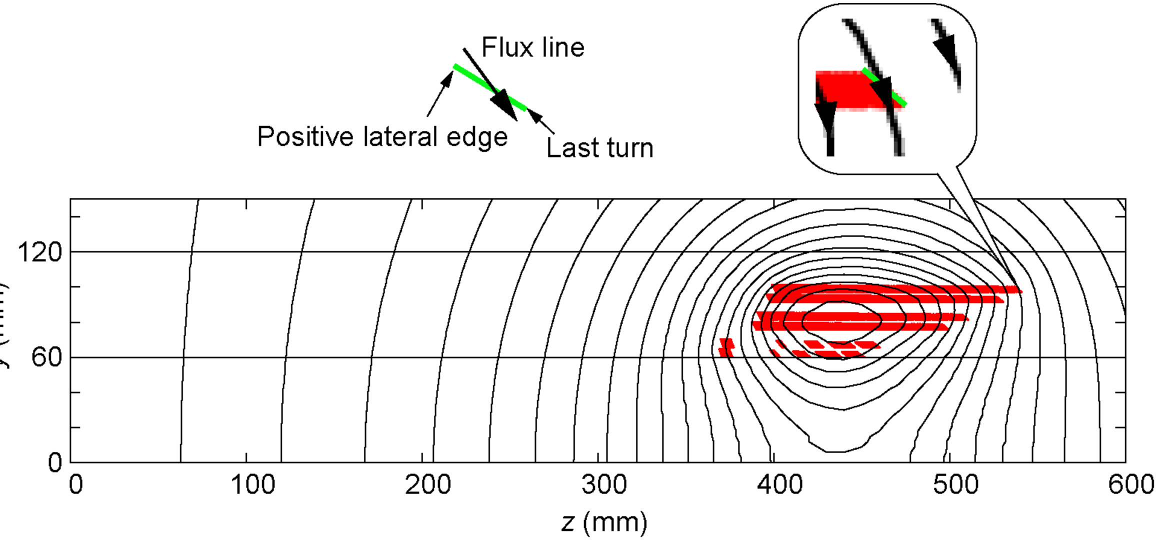
Magnetic flux line at the last turn in the 6th layer

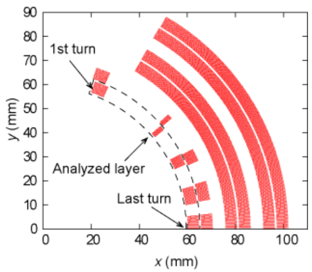
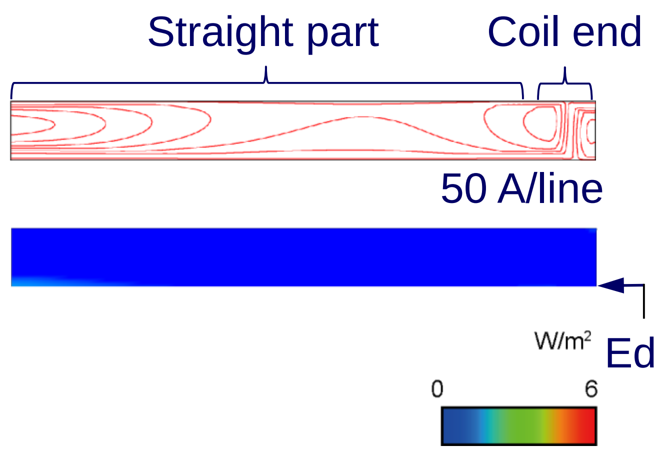
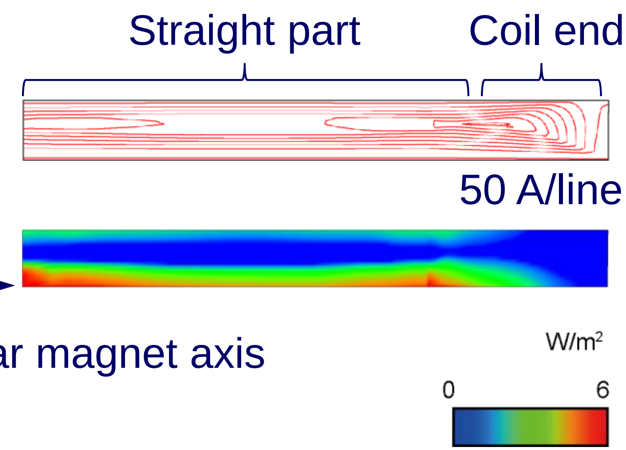
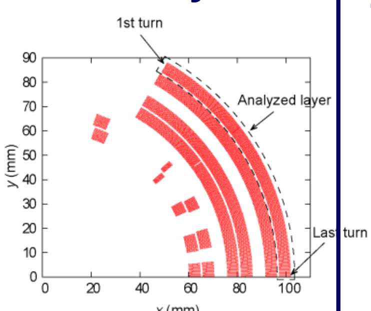
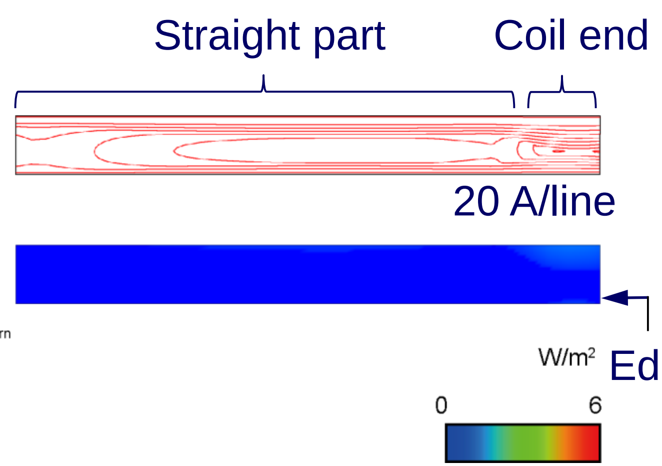
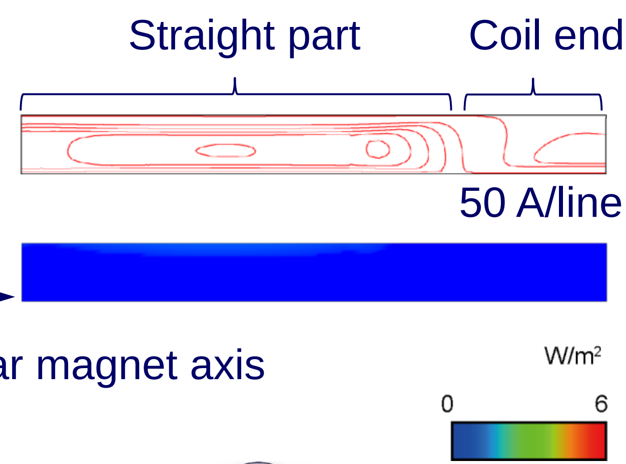
Assuming uniform current distribution in each coated conductor



The last turn in the 6th layer



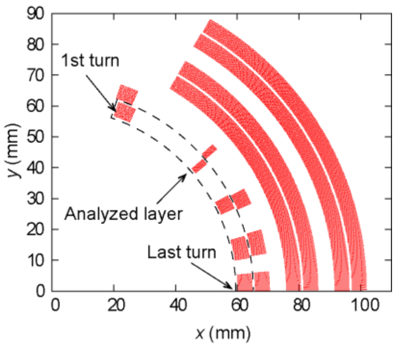
Current and ac loss distributions (t = 30 s)

	1st turn	Last turn
1st layer 		
6th layer 		

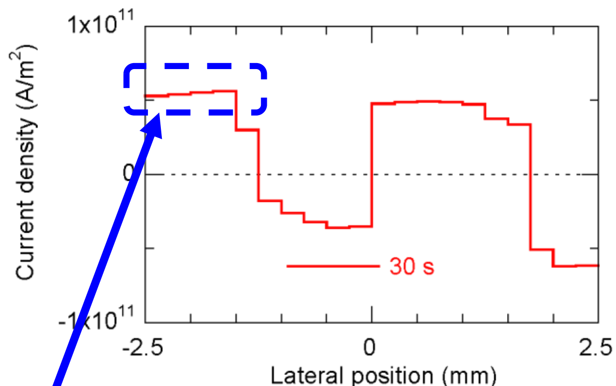
Edge near magnet axis

Edge near magnet axis

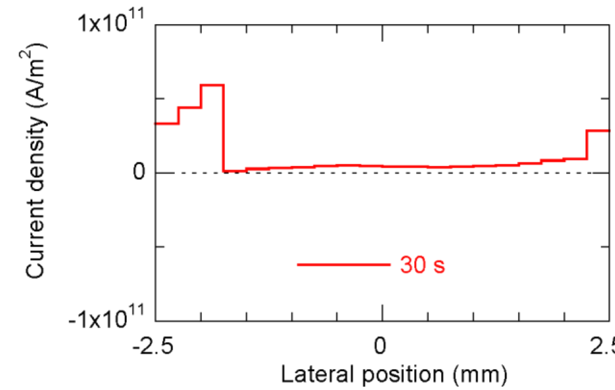
Current and ac loss distribution at the last turn in the 1st layer (t = 30 s)



The last turn in the 1st layer

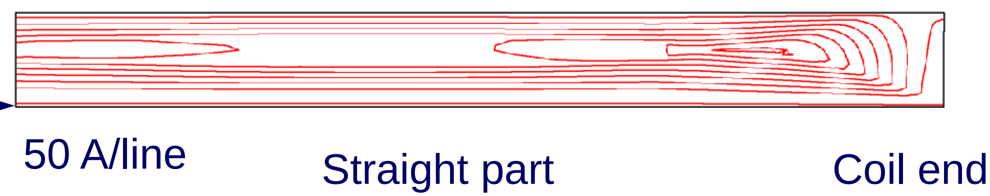


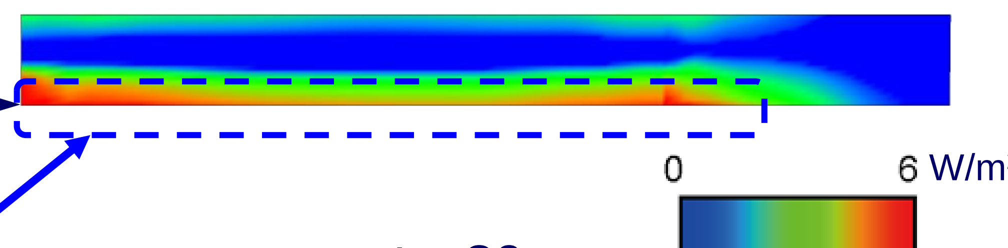
Center of straight part



Nose of coil end

Edge near magnet axis (negative lateral edge)





t = 30 s

Ac loss is generated by the penetration of magnetic flux.

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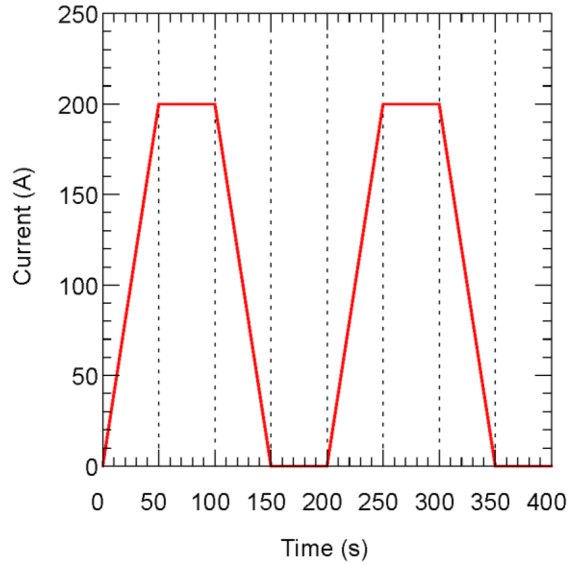
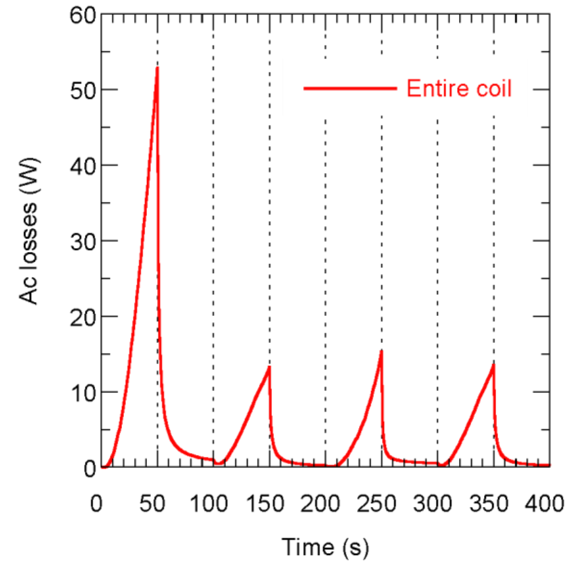
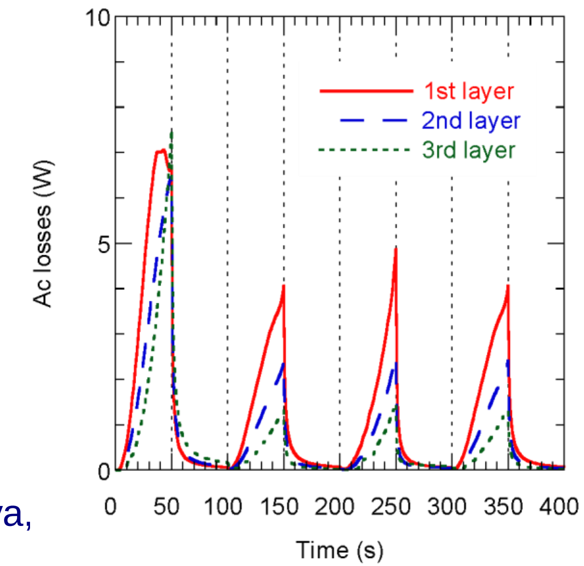
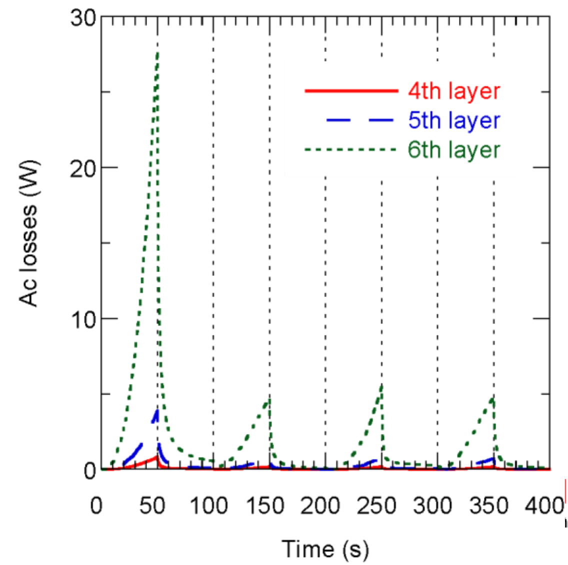
Temporal evolution of ac loss power









Ac loss energies in ramp down and ramp up

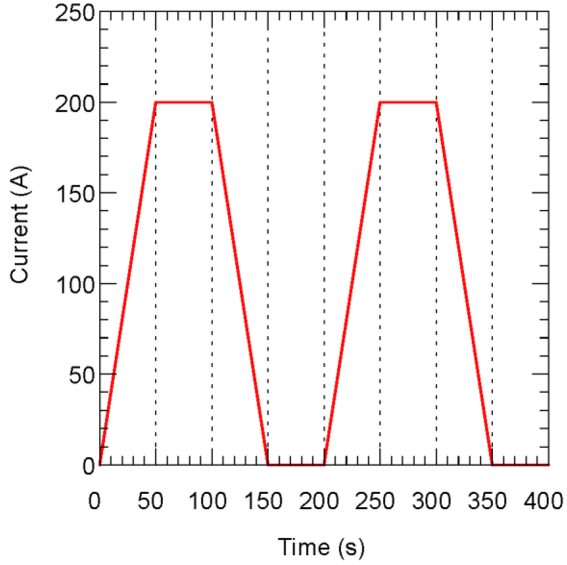
Ac loss energies in each layer and entire magnet

Layer	1	2	3	4	5	6	all
Number of turns	82	88	263	283	319	337	1372
Ac losses in the 2nd ramp up	75.0 J	40.7 J	21.3 J	2.5 J	11.3 J	79.8 J	231 J
Ac losses in the 2nd ramp down	91.2 J	49.4 J	24.8 J	2.8 J	12.8 J	95.2 J	276 J

Ac loss energies per unit length of conductor in each layer and entire magnet

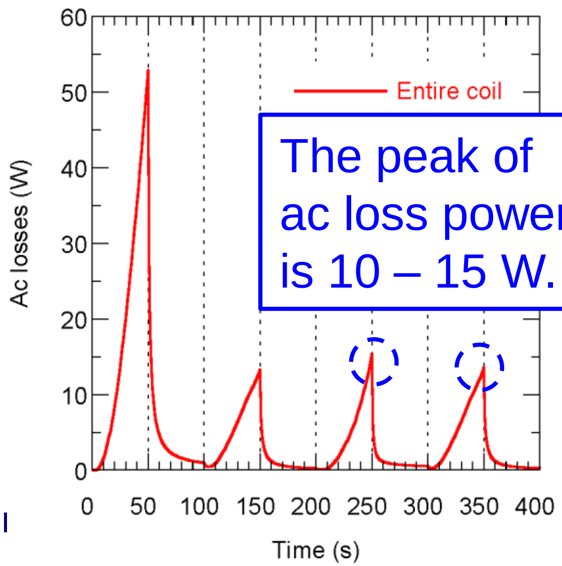
Layer	1	2	3	4	5	6	all
Ac losses in the 2nd ramp up	252 mJ/m	124 mJ/m	21 mJ/m	2 mJ/m	9 mJ/m	57 mJ/m	42 mJ/m
Ac losses in the 2nd ramp down	307 mJ/m	151 mJ/m	24 mJ/m	2.5 mJ/m	10 mJ/m	68 mJ/m	50 mJ/m

Ac losses and cooling capacity of a GM cryocooler

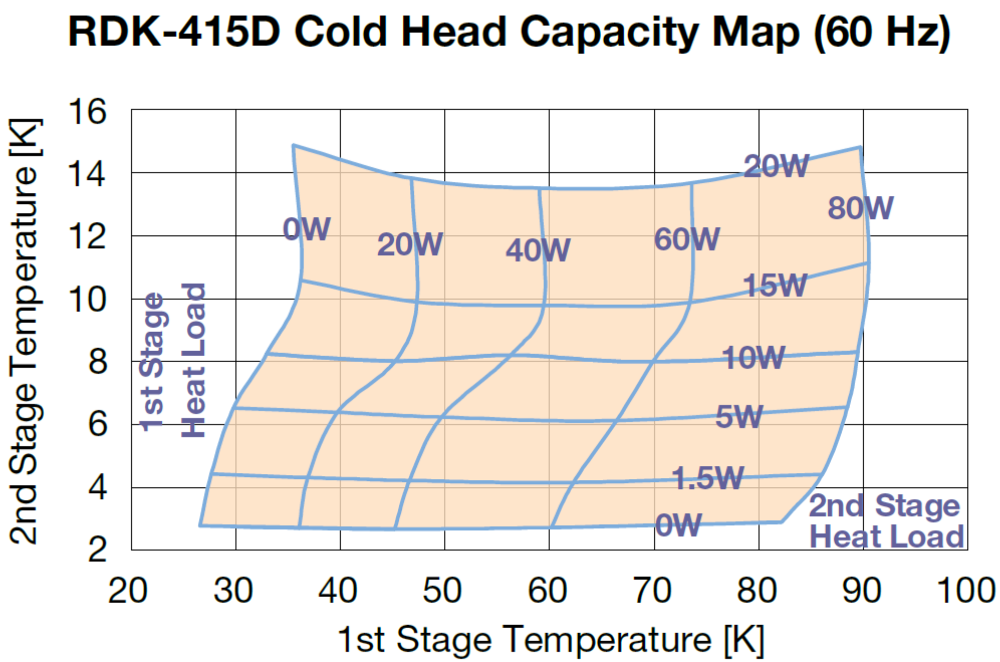


Ac losses in entire magnet	
In the 2nd ramp up	231 J in 50 s
In the 2nd ramp down	276 J in 50 s

The average ac loss power is ~5 W.



The peak of ac loss power is 10 – 15 W.

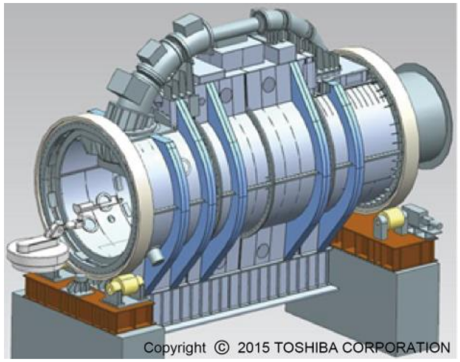


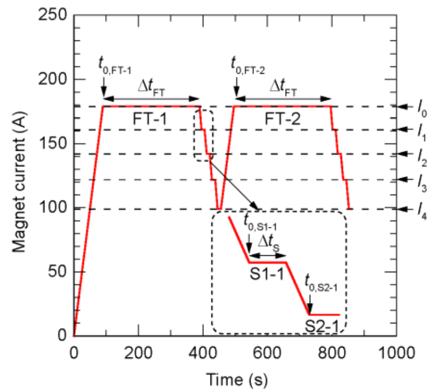
Summary

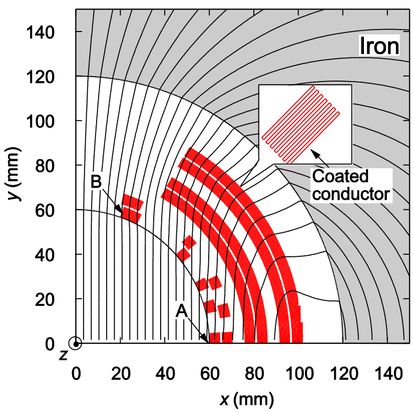
- We carried out the electromagnetic field analyses of a dipole magnet wound with coated conductors using a 3D model.
- Ac losses and field harmonics can be calculated from the results of analyses.
- Calculated ac losses are small enough to be cooled by GM-cryocooler at 20 K.

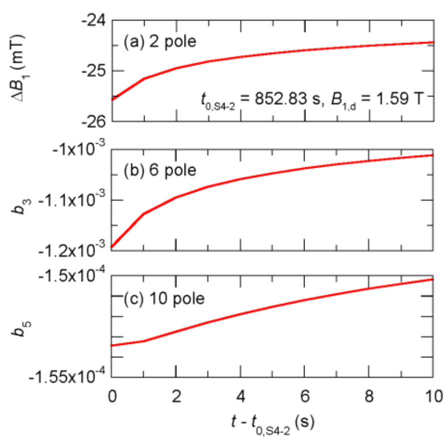
Field error (SUST)

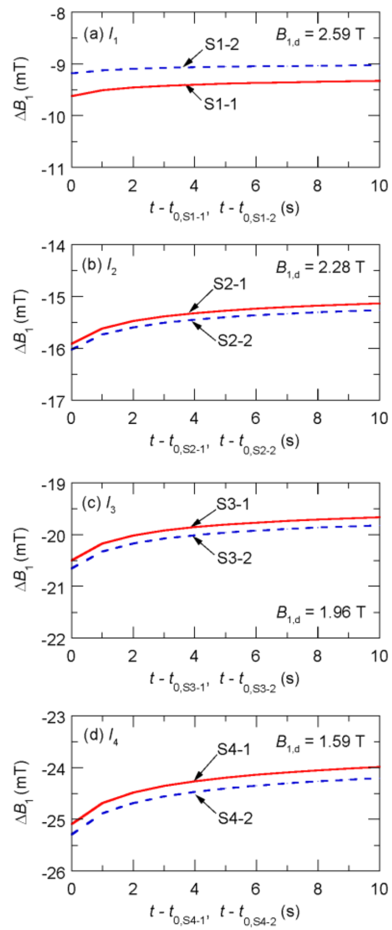
Reproducibility and stability in a magnet for rotating gantry for carbon cancer therapy (submitted to SUST)

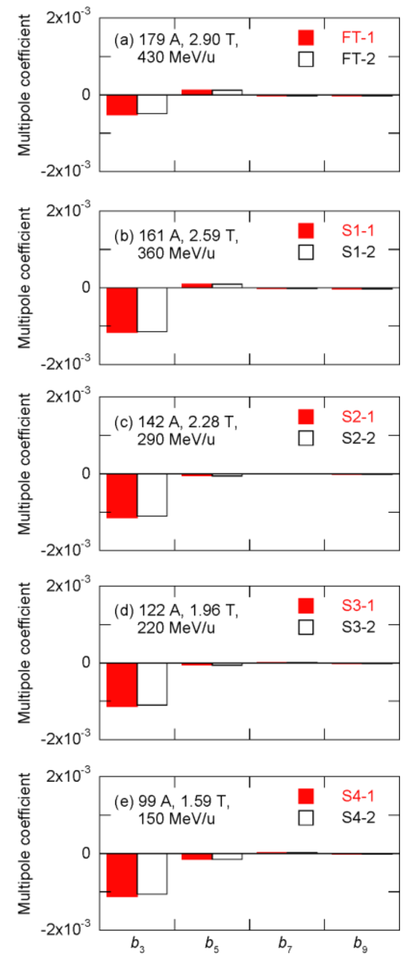












- Reproducible
- Harmonics less than 10 units
- Drifts of harmonics less than 1 unit