1st Workshop on Accelerator Magnets in HTS
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Magnetization modeling and measurements

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Background …

- When using a coated conductor with wide tape shape for an accelerator magnet, its large magnetization is apparently a big concern.
- Electromagnetic field analyses, which can clarify the electromagnetic phenomena inside coated conductors, must be powerful tools to study the magnetizations of coated conductors, cables, and coils.

Today's presentation includes …

- Modeling cables and coils as well as coated conductors for electromagnetic field analyses
- Comparing numerical analyses with experiments

Outline

- Principle of modeling and formulation
- Magnetization modeling and comparison with measurements in …
  - Roebel cable: ac losses
  - Striated coated conductor: ac losses
  - Dipole magnet comprising race-track coils: field quality (temporal evolution of magnetic field harmonics)
- Recent challenge and future plan

Principle of modeling and formulation

M. Nii et al. SUST25(2013)095011

Key points when modeling and our approaches

- Superconducting property
  - Use of the extended Ohm's law using equivalent (nonlinear) conductivity or resistivity as the constitutive relation
- Three-dimensional geometry and very thin superconductor layer of coated conductor
  - Use of the thin-strip approximation, where the thin strip of superconducting layer of a coated conductor follows a curved geometry of the coated conductor in a cable or in a coil

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. $E=E_0\left(J/J_c\right)^n$

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

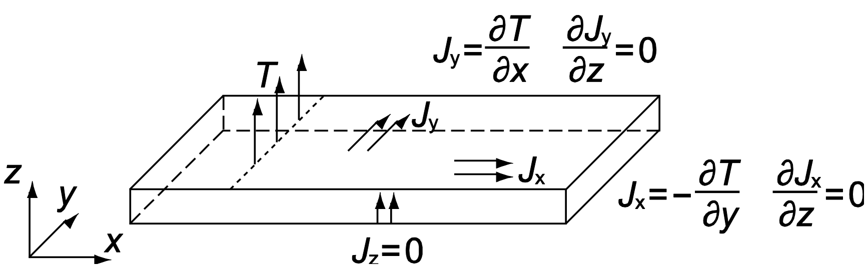
Integrate along thickness of coated-conductor

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

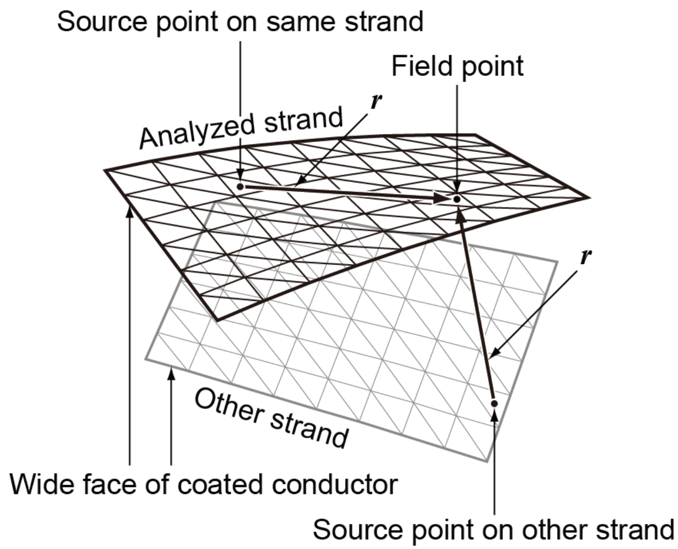
Computational cost can be reduced drastically.

Thin strip approximation

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



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

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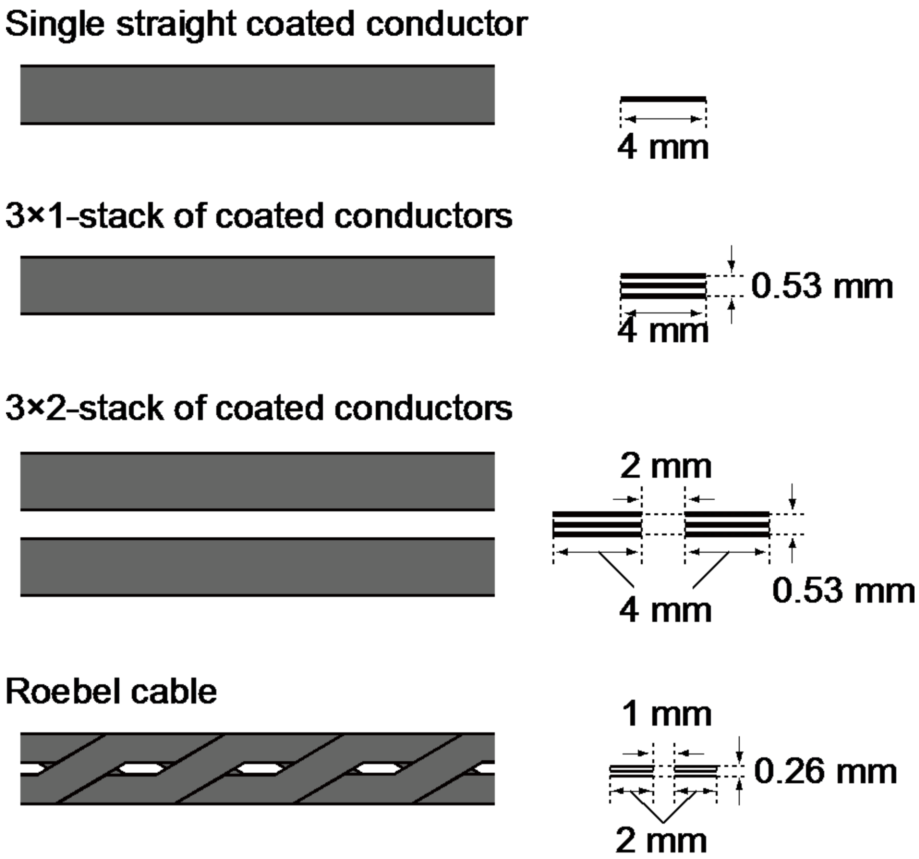
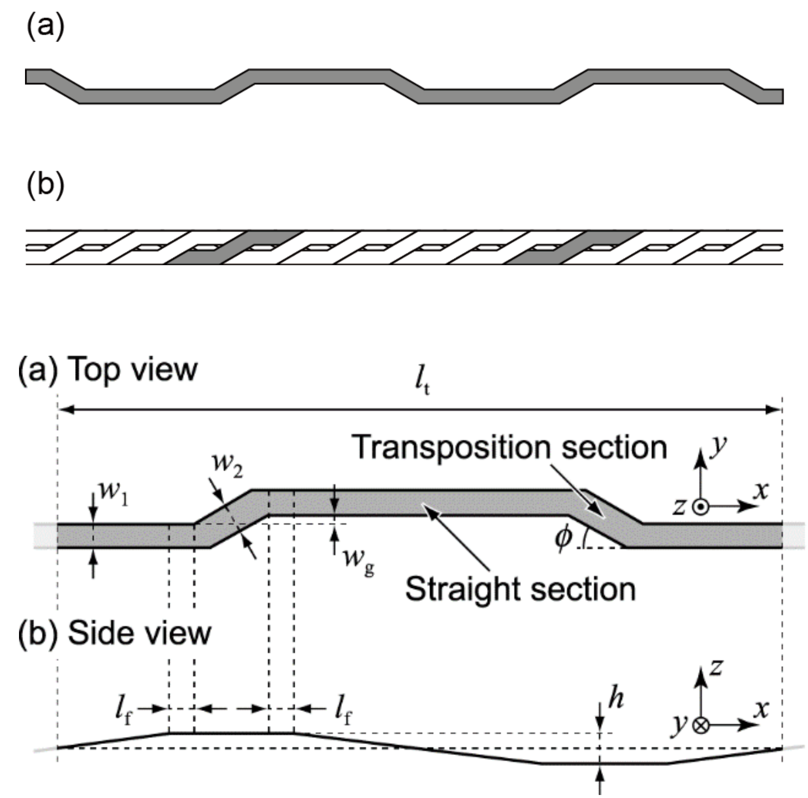
Roebel cable

N. Amemiya et al. SUST27(2014)035007

Electromagnetic field analyses and magnetization loss measurements

Roebel cable as well as reference conductors





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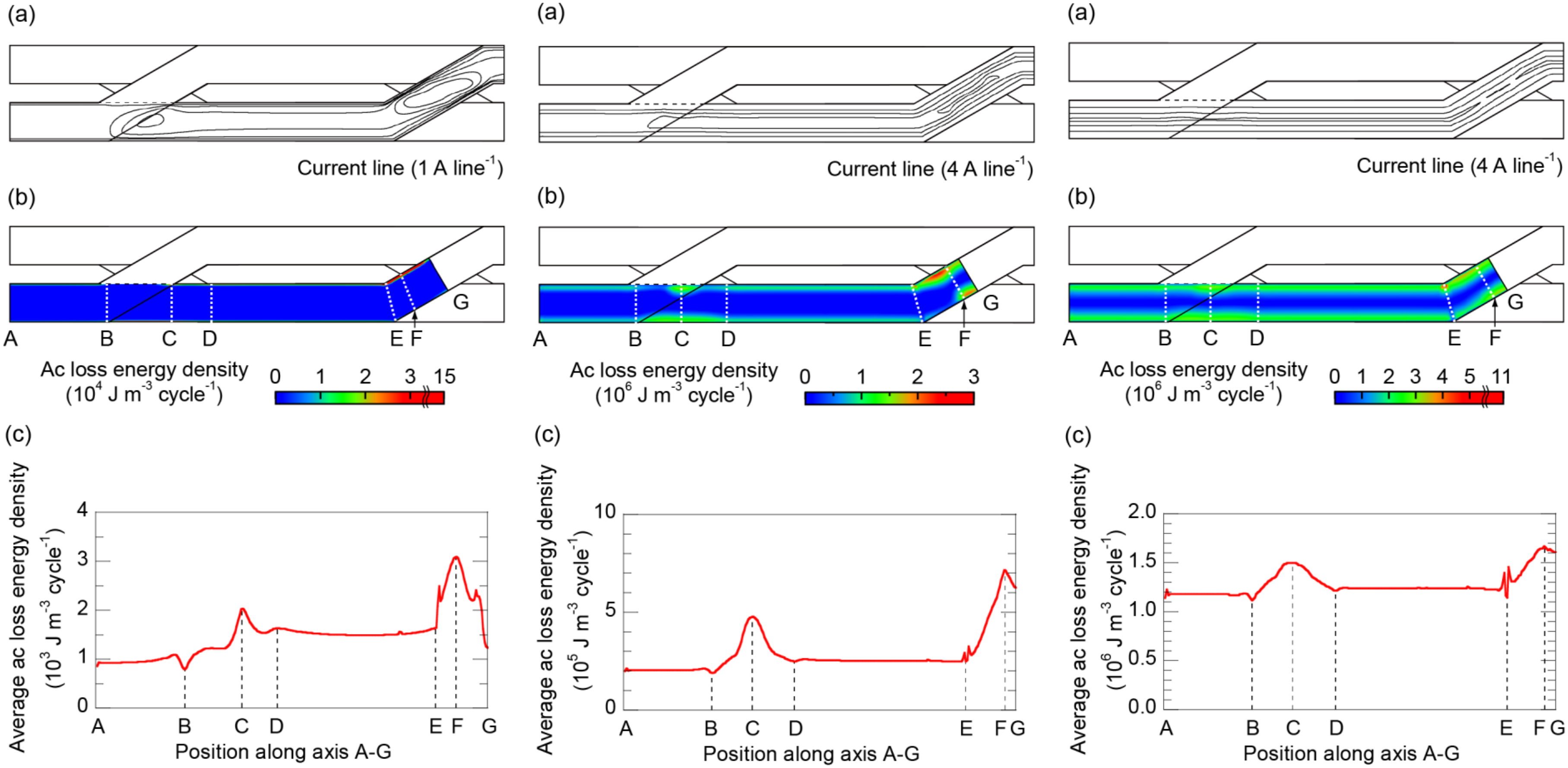
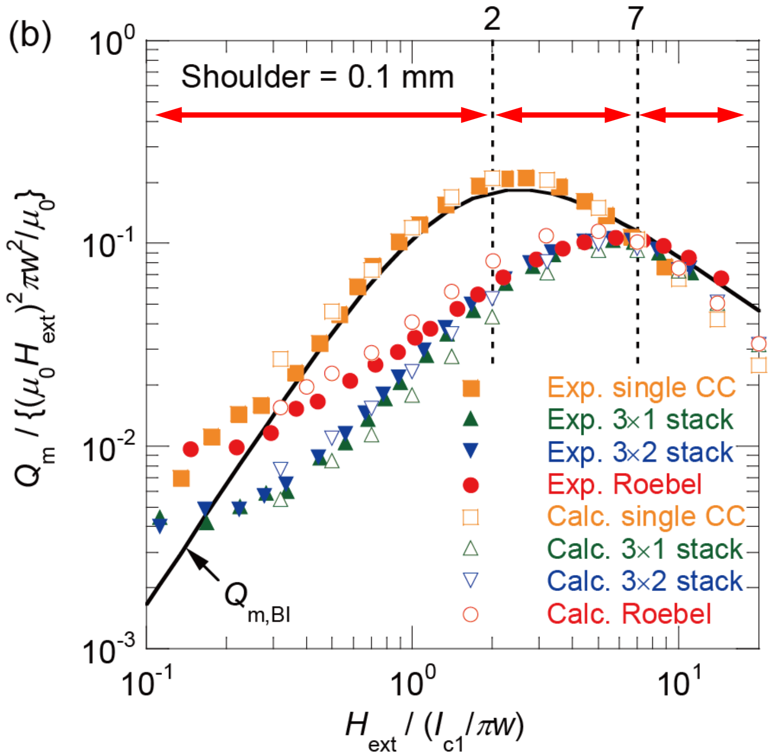
Transverse magnetic field only

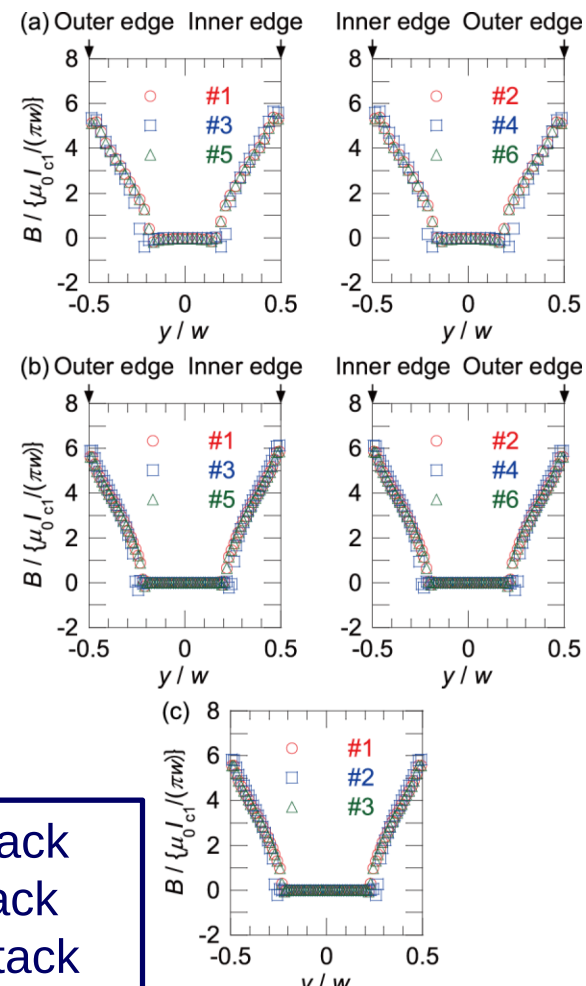


$H_e / (I_{c1} / \pi w) = 0.5$ $H_e / (I_{c1} / \pi w) = 3.2$ $H_e / (I_{c1} / \pi w) = 7$

Transverse magnetic field only

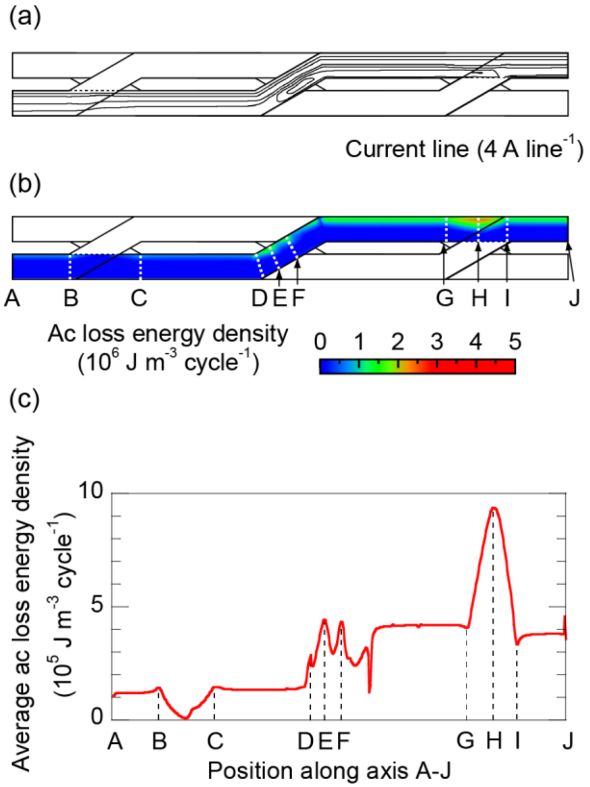


$H_e / (I_{c1} / \pi w)$
$= 3.2$



- (Low field) Single CC > Roebel cable > 3×2-stack ~ 3-stack
- (Mid field) Single CC > Roebel cable ~ 3×2-stack ~ 3-stack
- (High field) Single CC ~ Roebel cable ~ 3×2-stack ~ 3-stack

Transport current + transverse magnetic field

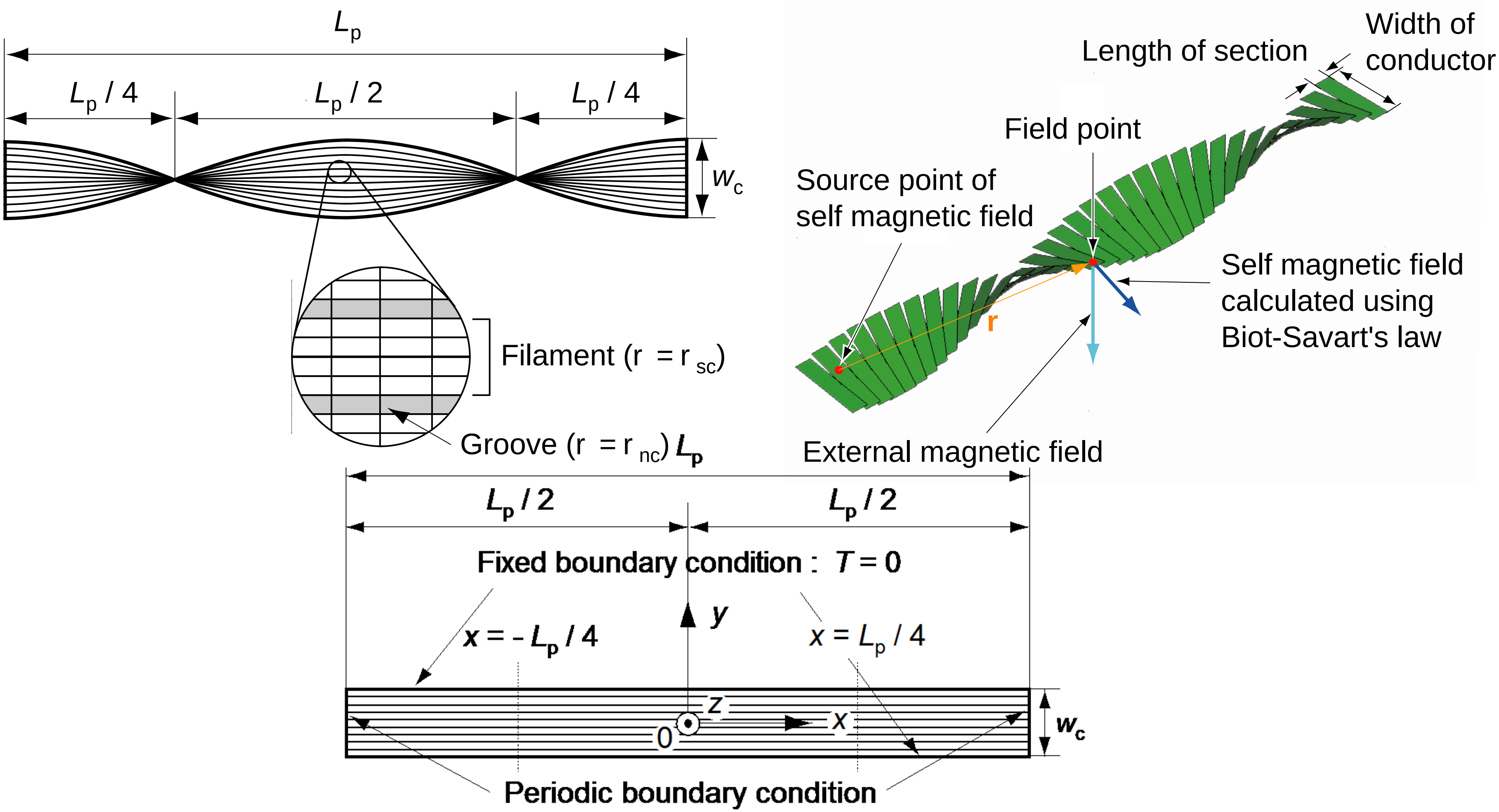


$$I_t \,/\, I_{c1} = 0.6,\ H_e \,/\, (I_{c1} \,/\, \pi w) = 2$$

Striated coated conductor

N. Amemiya et al. SUST17(2004)1464
N. Amemiya et al. IEEE-TAS15(2005)1637

Model of striated-and-twisted coated conductors



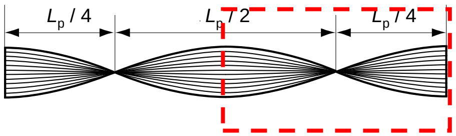
Actual 2D analysis region untwisted on a flat plane

Specifications of conductors for analysis

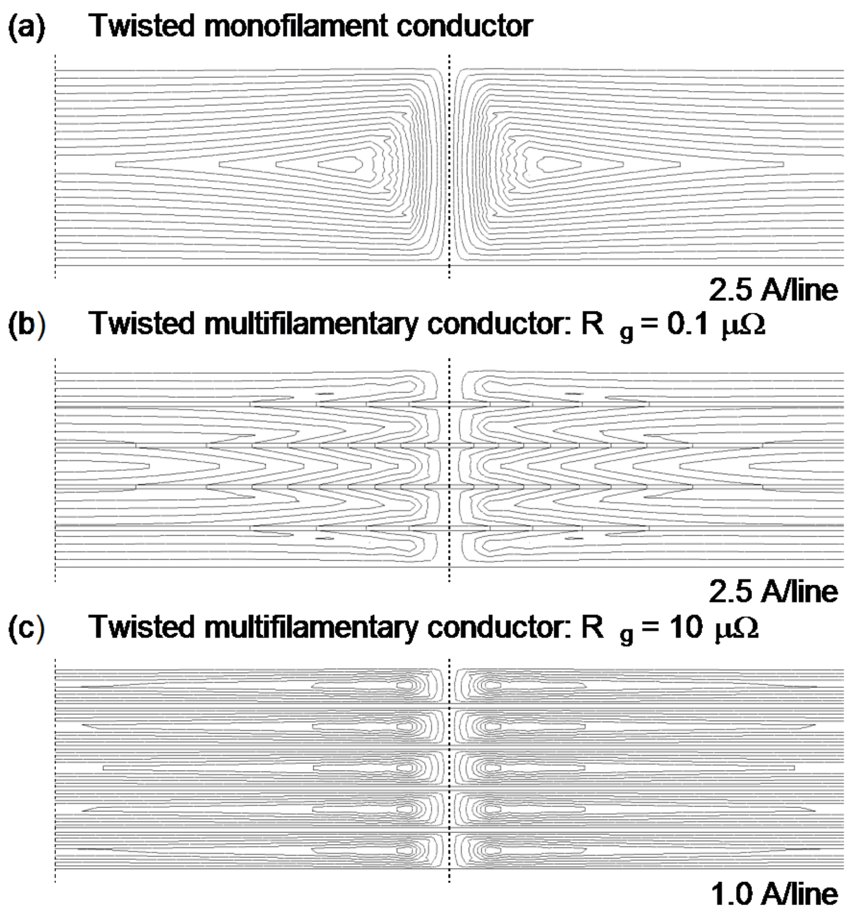
Width of conductor	4.9 mm
Width of filament	900 μm
Width of groove between filaments	100 μm
Number of filaments	5
Twist pitch	200 mm
Thickness of YBCO layer	1 μm
Critical current density	2×10^{10} A/m^2
n value	20
Transverse resistance between filaments for one meter	Varied

Frequency of transport current and applied magnetic field is fixed at 50 Hz.

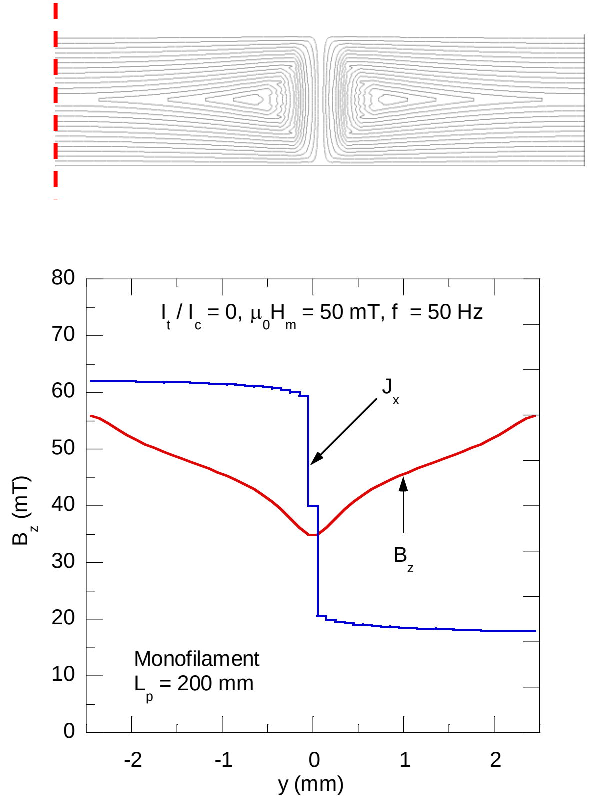
Calculated current lines



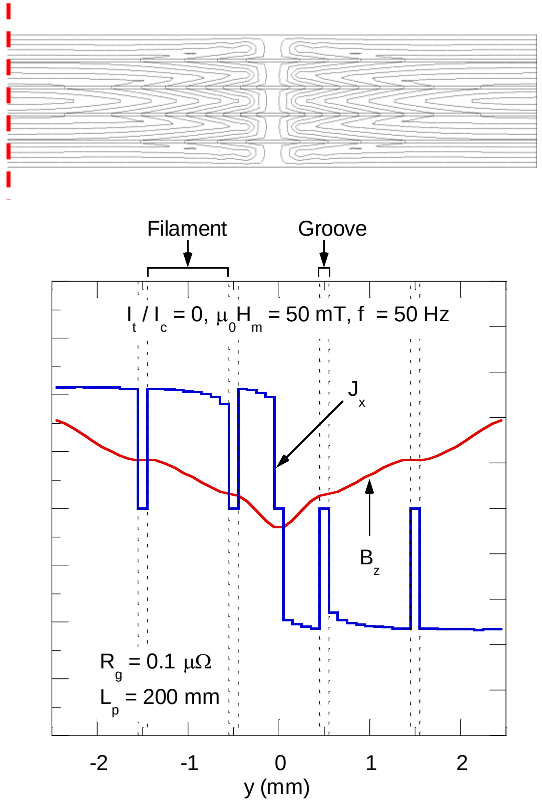
$I_t/I_c = 0$



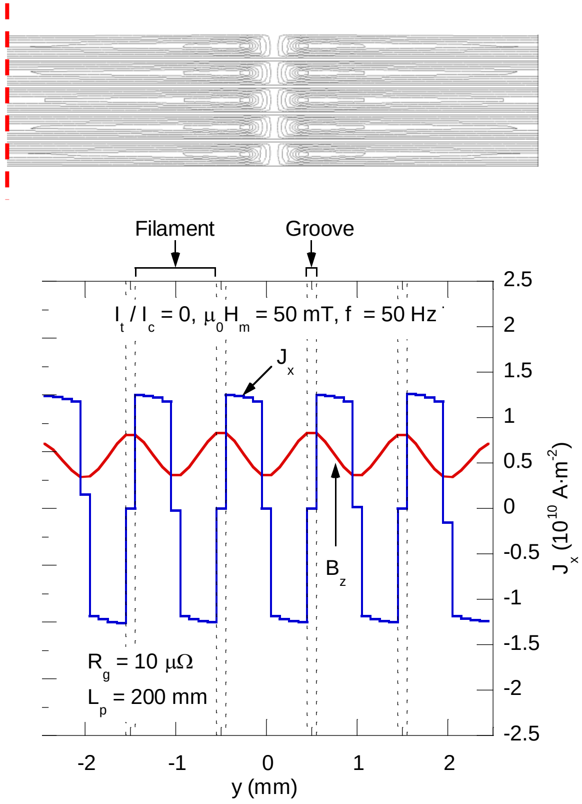
Current distribution in monofilament conductor and multifilamentary conductors carrying no transport current



Monofilament



Multifilament
R_g = 0.1 μΩ



Multifilament
R_g = 10 μΩ

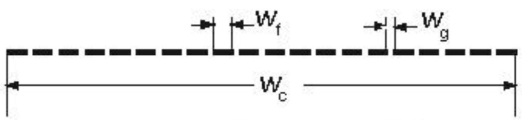
Specification of measured multifilamentary sample

Width of conductor	10 mm
Length of conductor Non twisted but finite length	ST40L: 100 mm ST40M: 50 mm ST40S: 25 mm
Width of filament	200 μm
Width of groove between filaments	50 μm
Number of filaments	40
Thickness of YBCO layer	1.4 μm
Thickness of silver protective layer	5.1 μm
Buffer layer	Non-conducting (primarily YSZ)
Substrate	Hastelloy
Critical current at 77 K, self-field	100 A
n value at 77 K, self-field	23

1D model and 2D model

One-dimensional FEM model

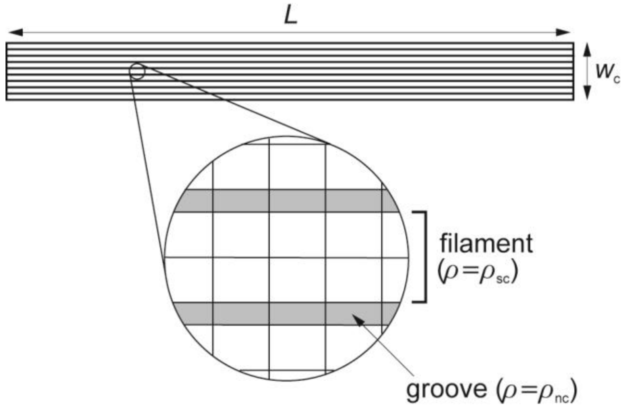
Enabling us to calculate the current distribution in a cross section of an infinitely-long *completely* decoupled conductor



AC loss reduced to the ideal level in completely decoupled conductor can be calculated.

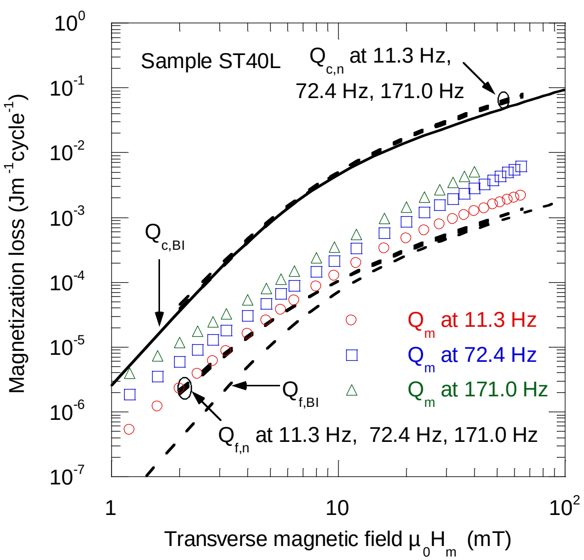
Two-dimensional FEM model

Enabling us to calculate the current distribution in a wide face of an finite-length conductor at partially decoupled state

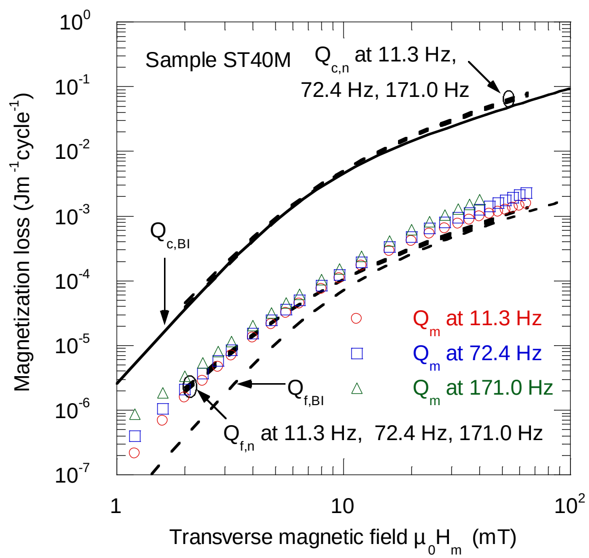


Coupling loss can be studied.

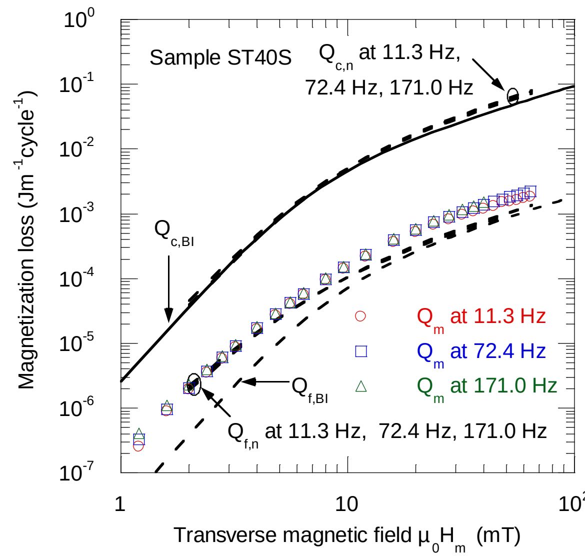
Measured losses in samples with various length



ST40L (100 mm)



ST40M (50 mm)

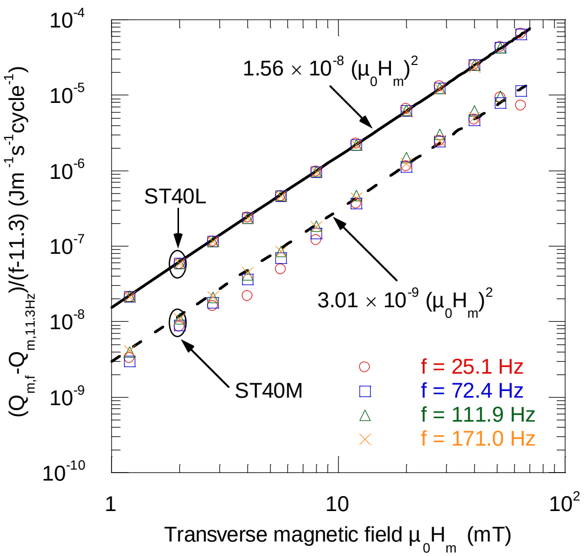


ST40S (25 mm)

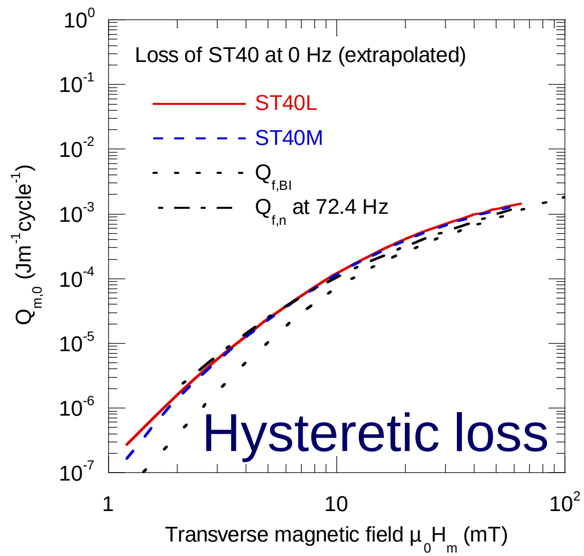
Frequency dependence in measured loss disappears with decreasing sample length.

Coupling loss and hystresis loss components

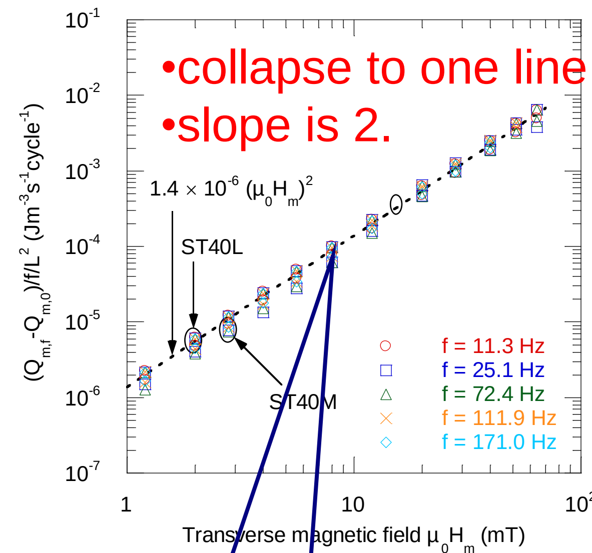
$(Q_{m,f}-Q_{m,11.3Hz})/(f-11.3)$ vs. $\mu_0 H_m$



$Q_{m,0}$: extrapolated loss at 0 Hz



$(Q_{m,f}-Q_{m,0})/(fL^2)$



$$1.4\times10^{-6}(\mu_0 H_m)^2$$

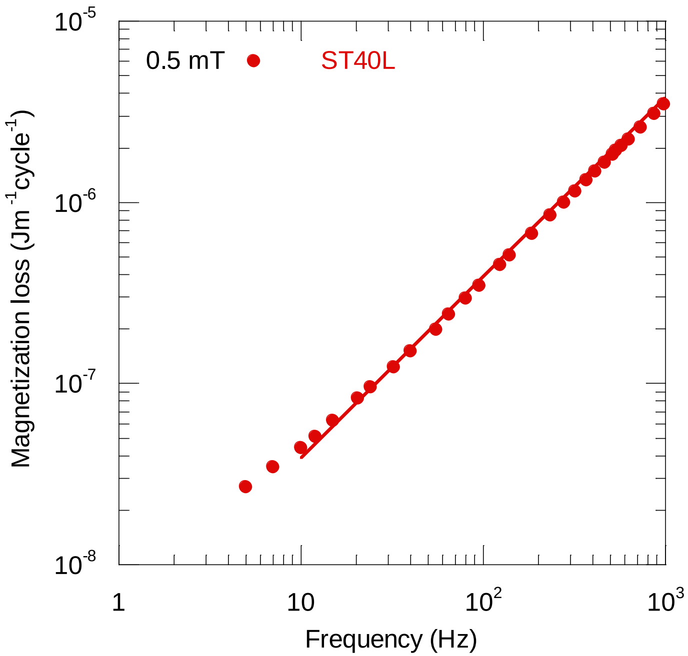
- Data for each samples collapse to one line.
- Slope is 2: Proportional to $(\mu_0 H_m)^2$

$$Q_{m,f} = 1.56\times10^{-8}(\mu_0 H_m)^2 (f-11.3) + Q_{m,11.3Hz}$$

$$Q_{m,f} = 3.01\times10^{-9}(\mu_0 H_m)^2 (f-11.3) + Q_{m,11.3Hz}$$

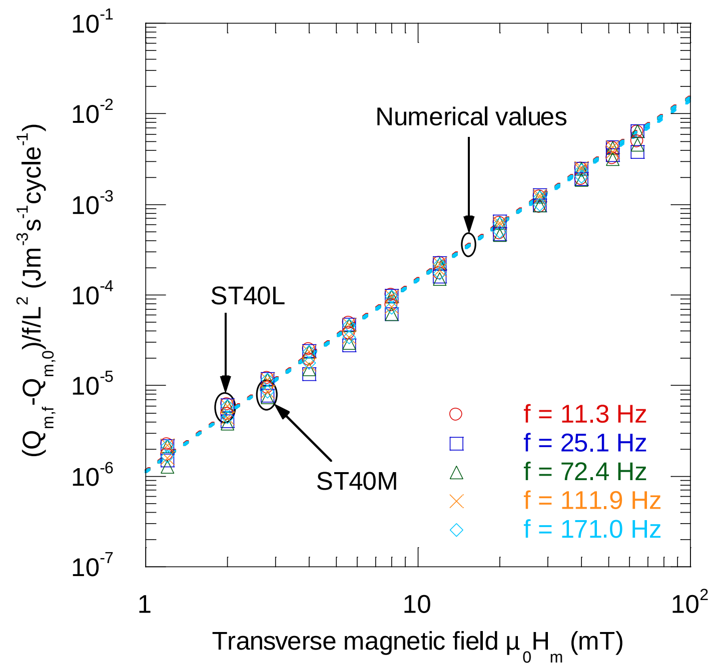
$$Q_{m,es}(L, f, \mu_0 H_m) = 1.4\times10^{-6} L^2 f (\mu_0 H_m)^2 + Q_{m,0}(\mu_0 H_m),$$

Measured and calculated coupling loss



At 0.5 mT, 10-1k Hz, the measured loss and calculated loss is compared to determined the transverse resistance between filaments.

R_t = 4.8 μΩ for 1 m



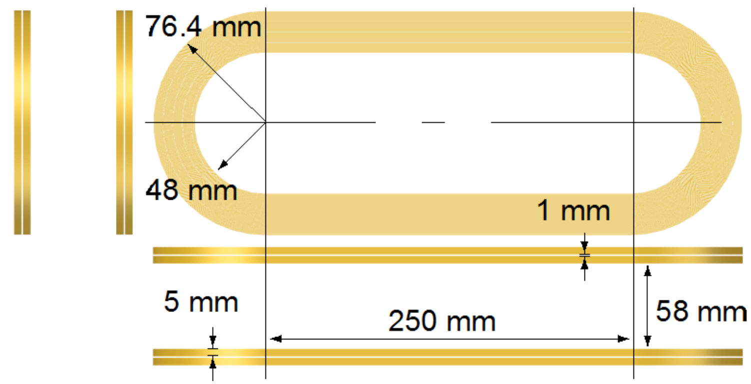
1. Using this R_t, numerical calculations were made for f = 11.3 Hz, 72.4 Hz & 171.0 Hz, and L = 50 mm & 100 mm.
2. Calculated coupling losses reasonably agree with experimental values.

Dipole magnet

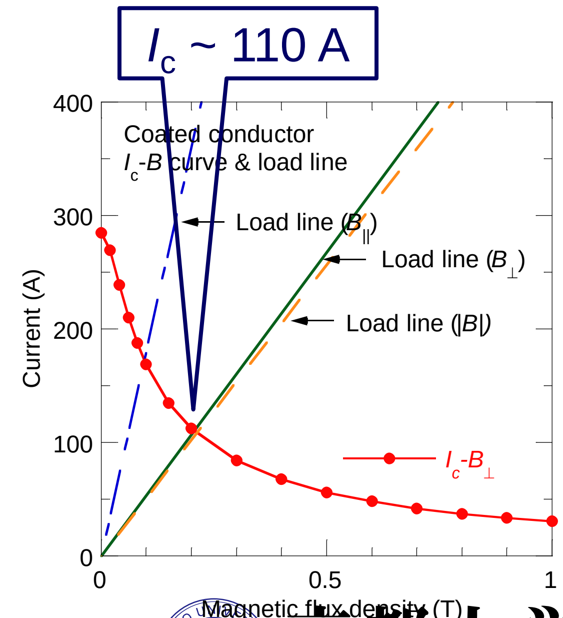
N. Amemiya et al. to be submitted to SUST?

Dipole magnet RTC4-F comprising race-track coils

Coated conductor	Fujikura (FYSC-SC05)
Superconductor	GdBCO
Width × thickness	5 mm × 0.2 mm
Stabilizer	0.1 mm – thick copper
Critical current	270 A – 298 A



Shape of coils	Single pancake race-track
Number of coils	4
Length of straight section	250 mm
Inner radius at coil end	48 mm
Outer radius at coil end	76.4 mm
Coil separation	58 mm
Number of turns	83 turn/coil
Length of conductor	74 m/coil



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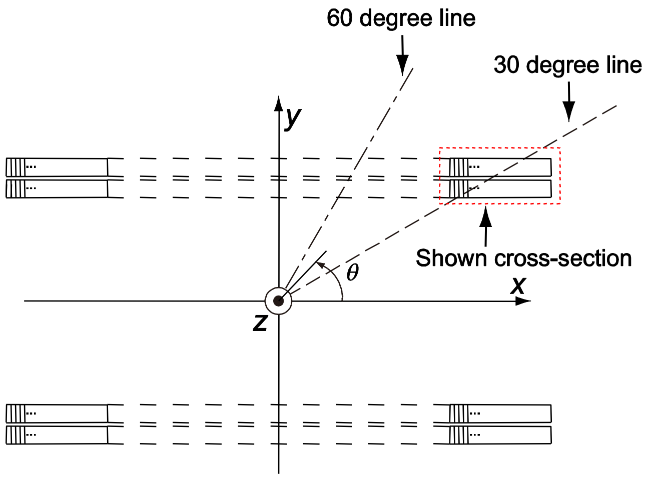
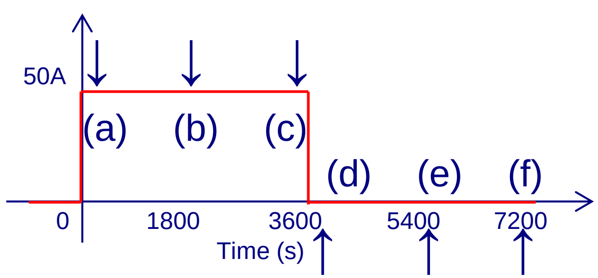
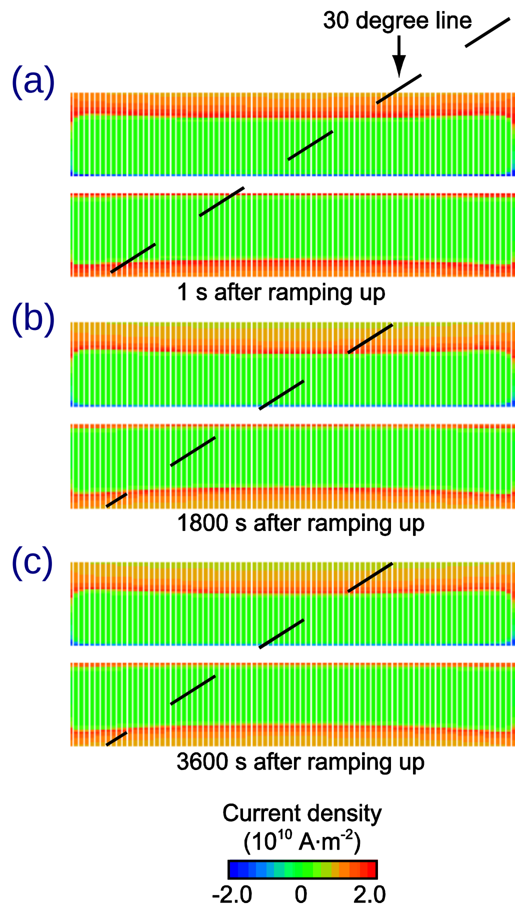
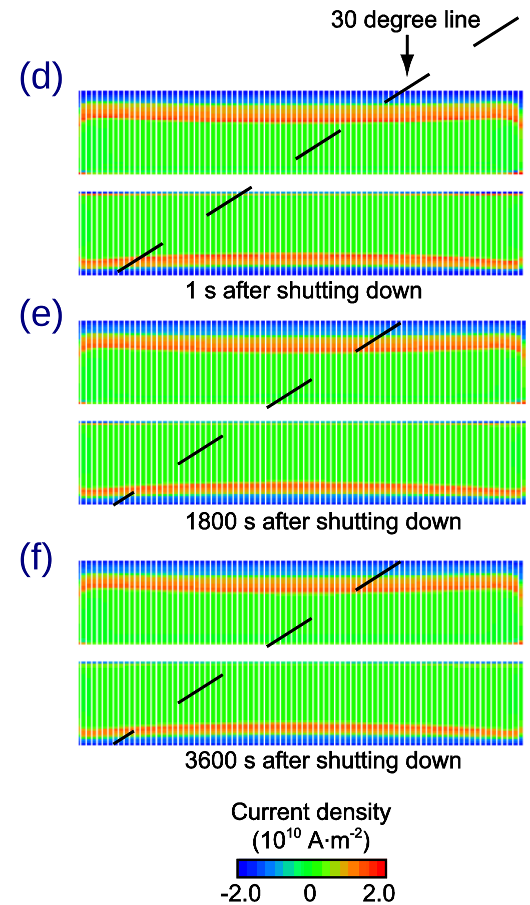
Temporal evolutions of current distribution







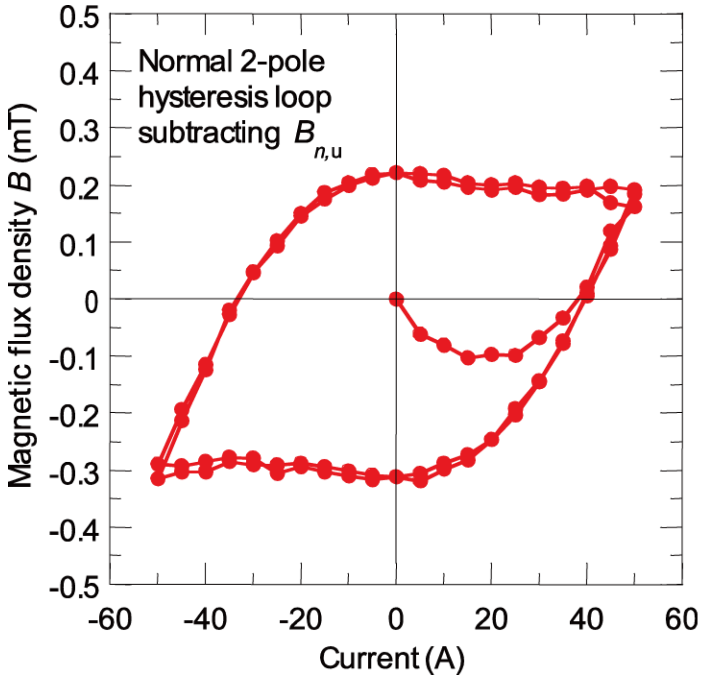
Excited



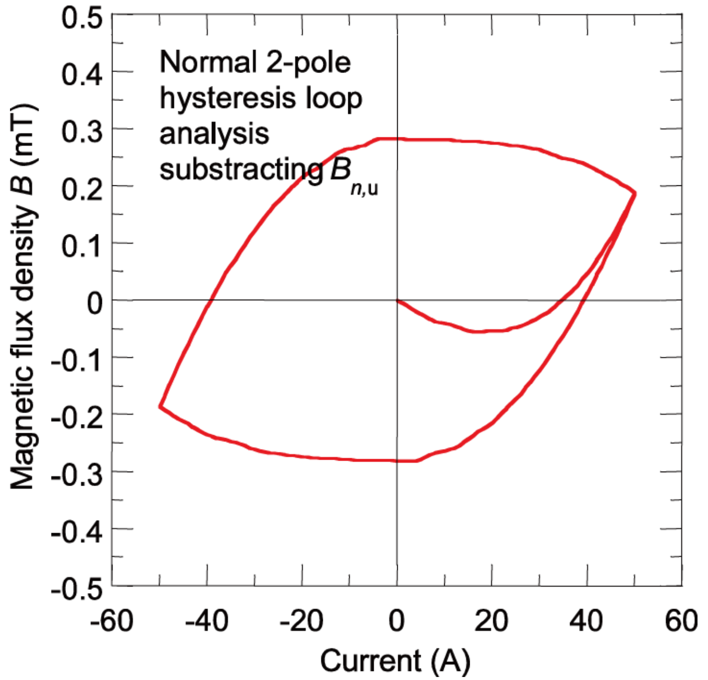
Shut down

Comparison between experiment and calculation

Hysteresis loop



Experiment

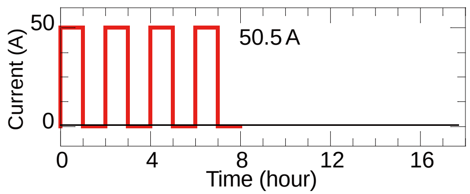


Calculation

Designed value without magnetization substituted

Comparison between experiment and calculation

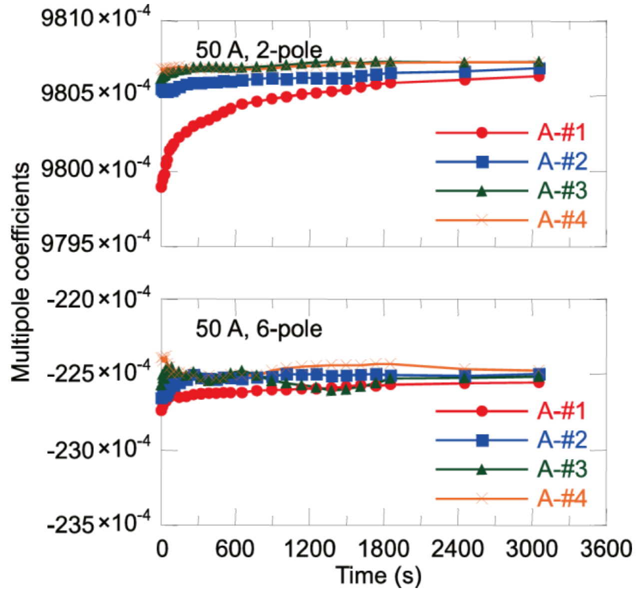
Repeated (50 A, 1 h) – excitations

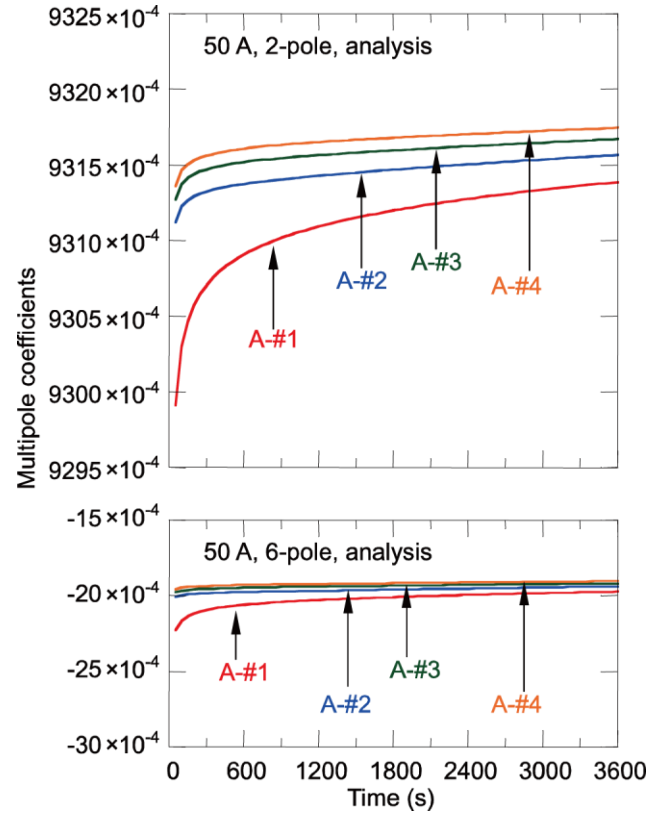


Excited

2-pole

6-pole



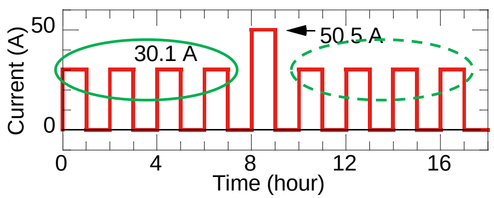


Experiment

Calculation

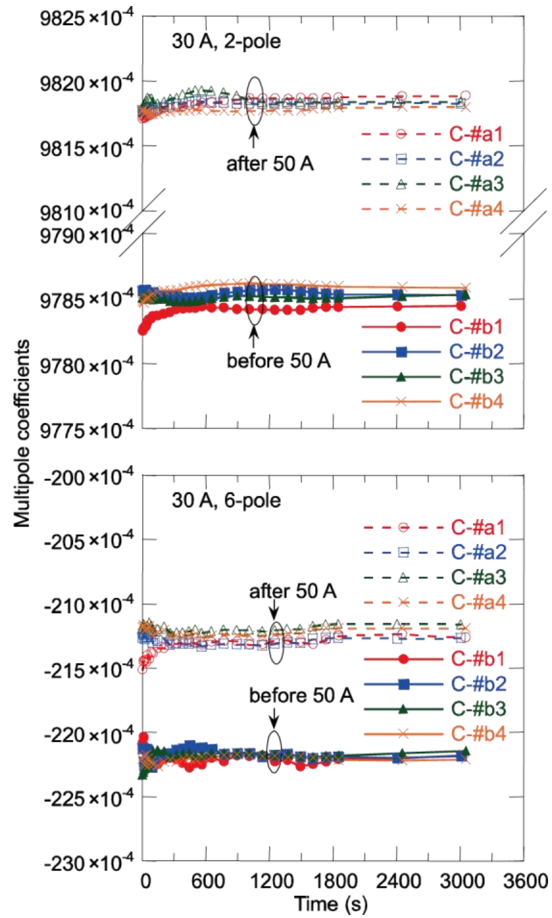
Comparison between experiment and calculation

Influence of 50 A – excitation between 30 A - excitations

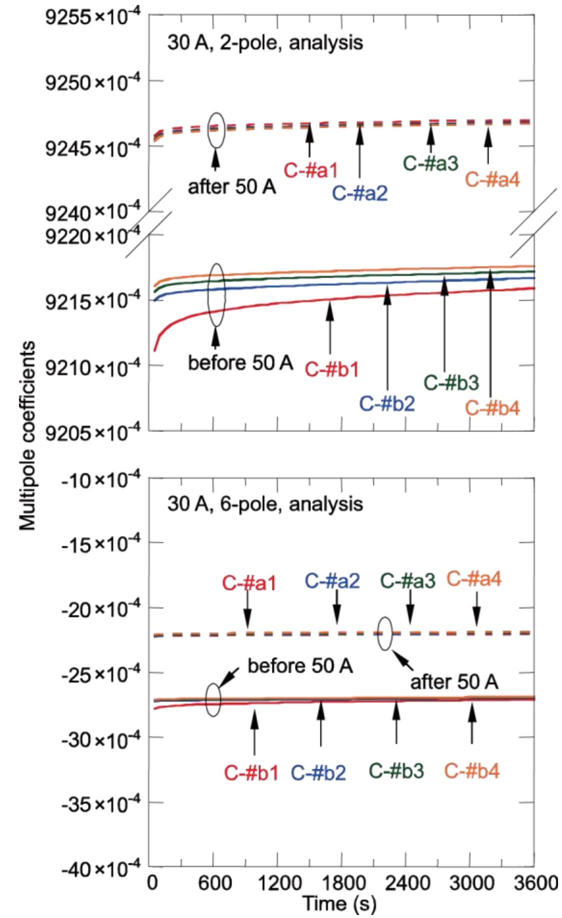


2-pole

6-pole



Experiment



Calculation

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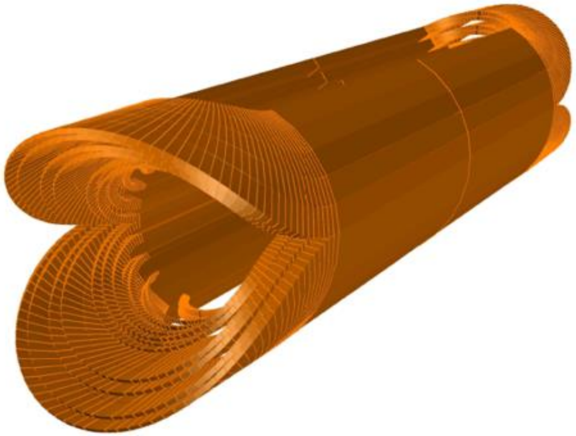
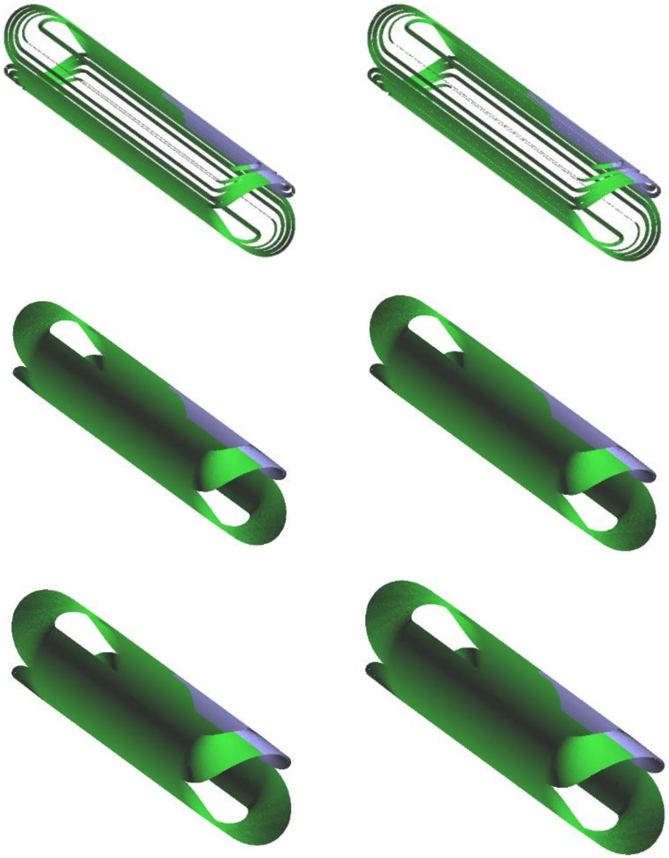
Recent challenge and future plan

3D analyses of cosine-theta magnet

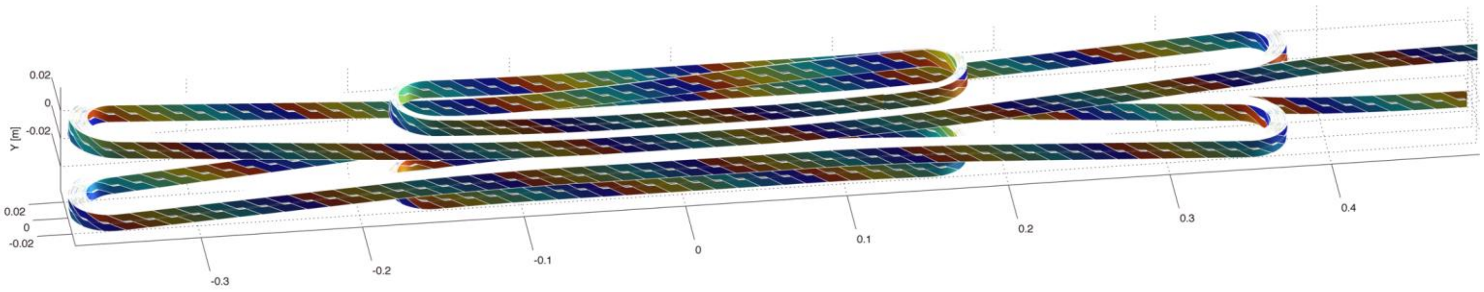
Dipole magnet for rotary gantry for carbon cancer therapy

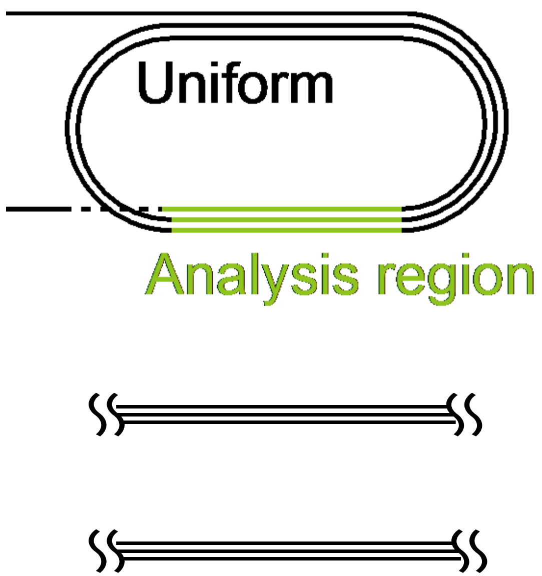


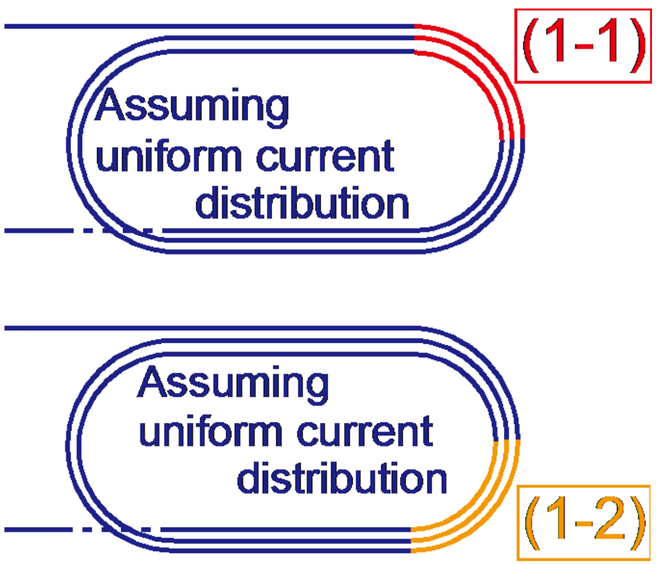
Current	200 A
BL	2.64 Tm
Higher harmonics / dipole	$< 10^{-4}$
Entire length	1084 mm
Number of turn	2844



Coil wound with Roebel cable







Summary

- We have been developing models for numerical electromagnetic field analyses of cables and coils consisting of coated conductors.
- They have been applied successfully to
  - HTS Roebel cables
  - Twisted striated coated conductors
  - Dipole magnets (2D)

  and compared with measurements.
- Applications to CORC cables as well as twisted stacked-tape cables are possible in principle.
- Recent challenge and future plan
  - 3D analyses of cosine-theta magnet
  - Coil wound with Roebel cable

Overview of S-Innovation project

Name of project	Challenge to functional, efficient, and compact accelerator system using high T_c superconductors
Objective	•R&D of fundamental technologies for accelerator magnets using coated conductors •Constructing and testing prototype magnet
Future applications	•Carbon caner therapy •Accelerator-driven subcritical reactor
Participating institutions	Kyoto University (PM: Amemiya), Toshiba, KEK, NIRS, JAEA
Period	Stage I: 01/2010 – 03/2012 Stage II: 04/2012 – 03/2016 Stage III: 04/2016 – 03/2019
Funding program	Strategic Promotion of Innovative Research and Development Program by JST