The 2014 Kyoto Workshop on HTS Magnet Technology
for High Energy Physics
(WAMHTS-2)
November 13 – 14, 2014
Kyoto, Japan

R&D of fundamental technologies of accelerator magnets using coated conductors

N. Amemiya, Z. Zhang, T. Sano, Y. Sogabe, T. Nakamura (Kyoto Univ.)
T. Ogitsu (KEK), K. Koyanagi, S. Takayama, T. Kurusu (Toshiba)
Y. Mori (KURRI), Y. Iwata, K. Noda (NIRS), M. Yoshimoto (JAEA)

This work was supported by Japan Science and Technology Agency under Strategic Promotion of Innovative Research and Development Program (S-Innovation Program).

Outline

1. Overview of the S-Innovation Project on R&D of fundamental technologies of accelerator magnets using coated conductors
2. As a topic: study on magnetization of coated conductor and field quality

Overview of the S-Innovation Project

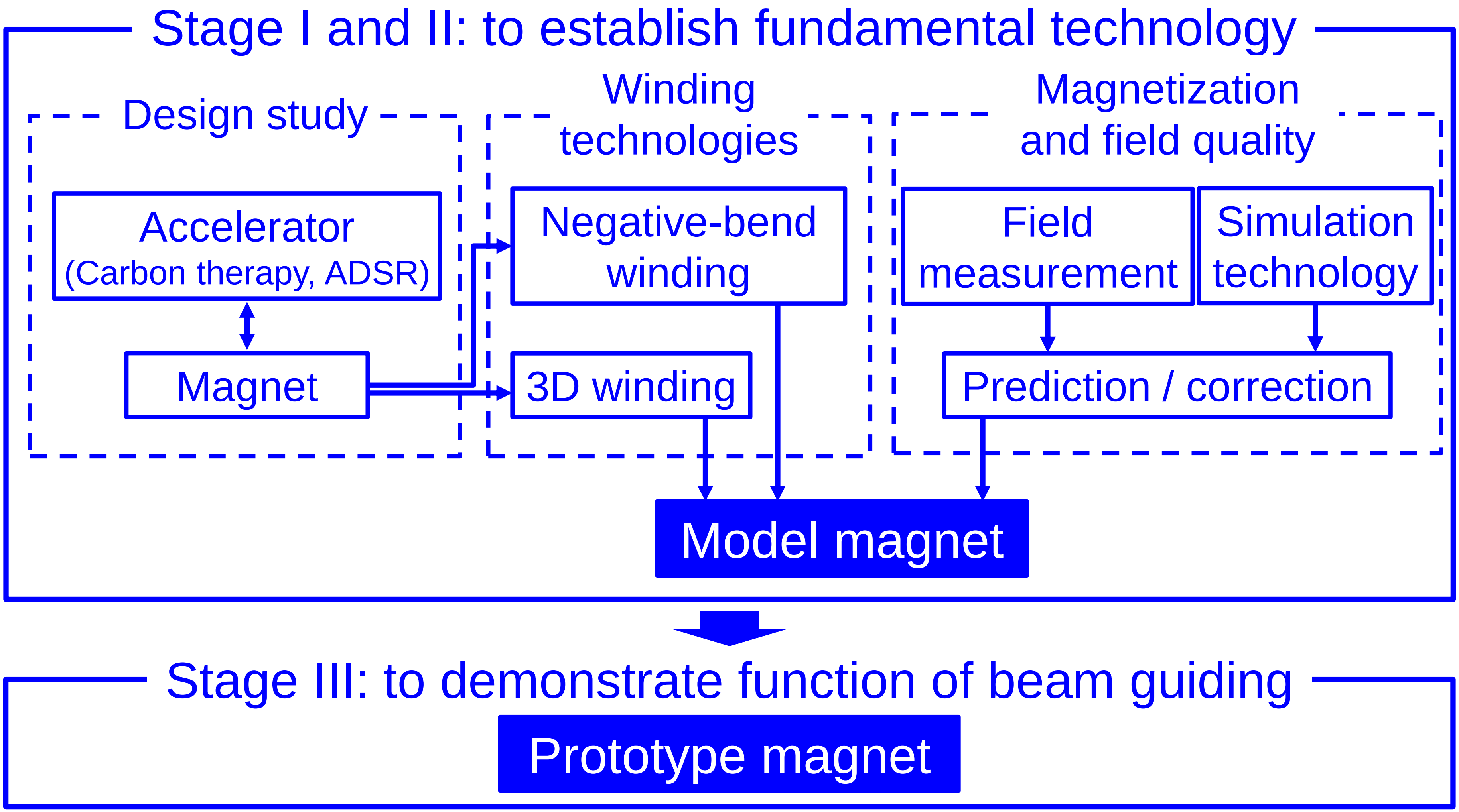
Outline the project

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, Toshiba, KEK, NIRS (National Institute of Radiological Sciences), 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 (S-Innovation) Program by JST

Key issues in R&D

- HTS magnet design which is compatible with accelerator design
- Winding technology for negative-bend coils and 3D shape coils to realize the designed magnets
- Tape magnetization which affects the field quality of magnets

Project overview and key R&D issues at stage I & II

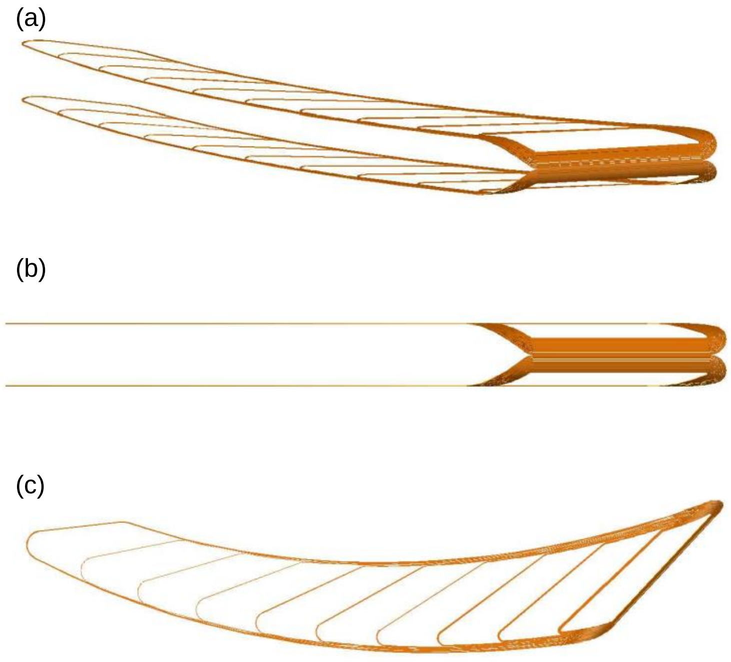


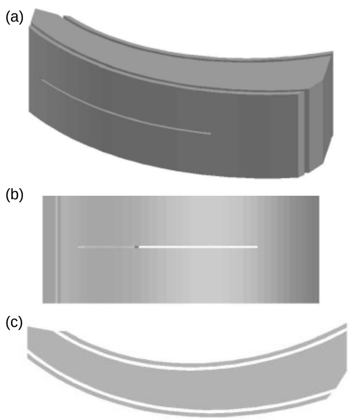
Magnet design
Spiral sector FFAG accelerator for carbon cancer therapy

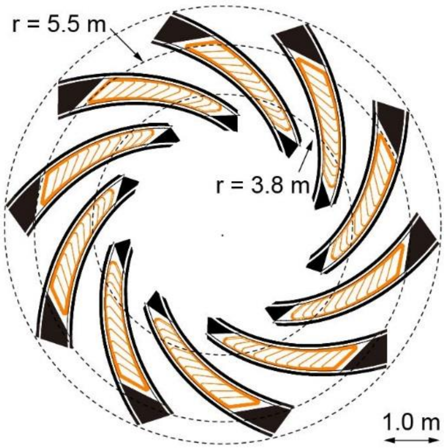
Radial magnetic field distribution $B(r) = B_0 \left(r/R_0 \right)^k$

FFAG accelerator: strong focusing with dc magnet	
Type	Spiral sector
Purpose	Carbon cancer therapy
Particle	C^{+6}
Energy	40 - 400 MeV/u
Major radius	4.65 m
Average orbit radius	3.8 – 5.5 m
Field index (k value)	5.7
Integrated field at *r* = 5.5 m	3.98 T·m
Spiral angle	58.4 deg
Number of cell	10
Packing factor	0.5

Magnet design
Spiral sector FFAG accelerator for carbon cancer therapy





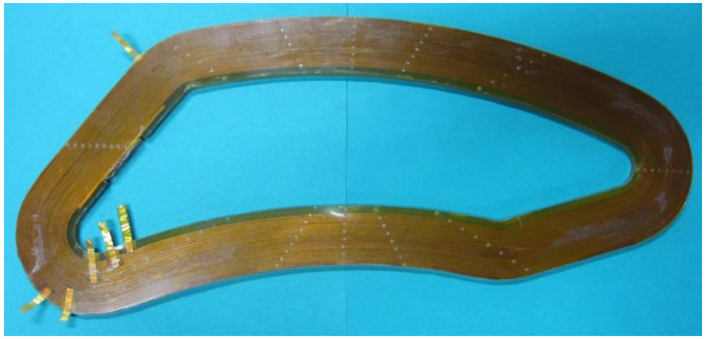


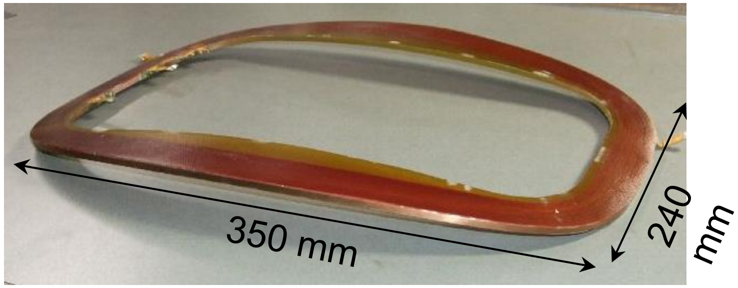
- Radial profile is provided by ladder shape coils. $B(r) = B_0 \left(r/R_0 \right)^k$
- Field with spiral angle is provided by coils with negative bend and iron.

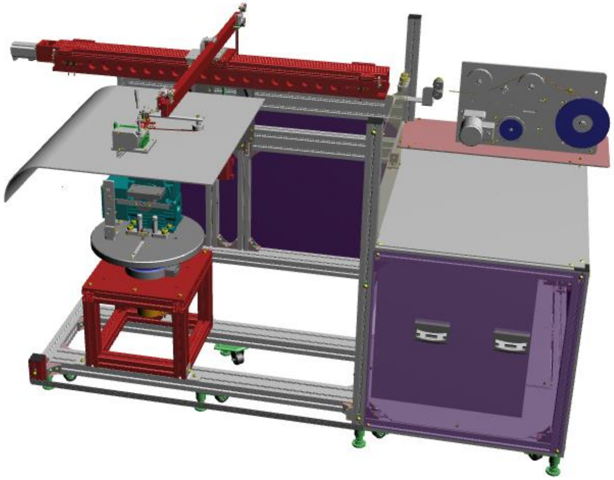
Preliminary estimation

Weight of iron ~ 60 t; stored energy ~ 2 – 3 MJ; B @ conductor ~ 7 – 8 T

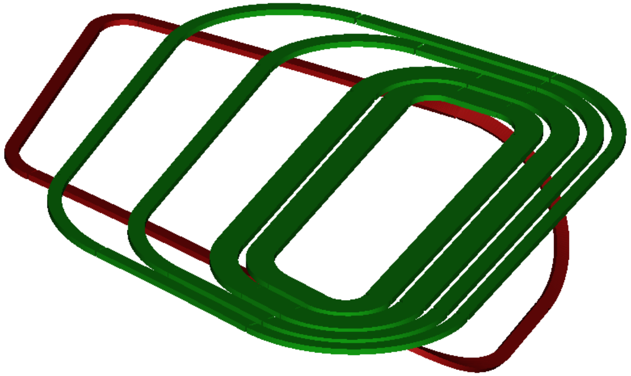
Winding technology R&D
Examples of test winding

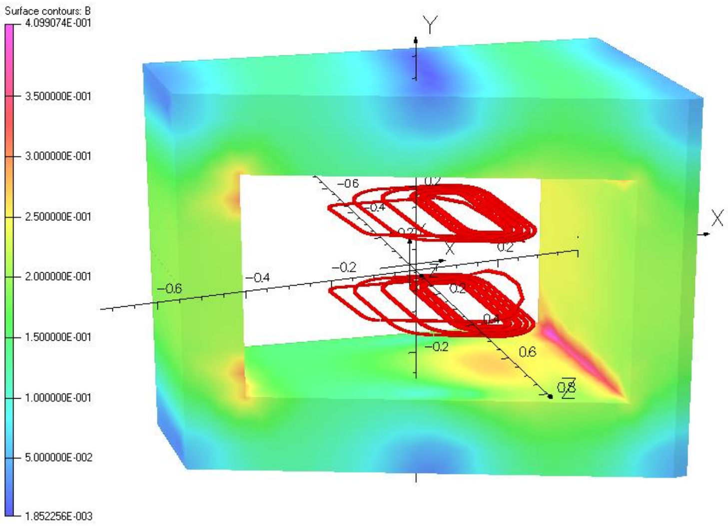






Model magnet to verify developed technologies





- Coils are put in cryostat and cooled by using GM cryo-cooler
- Iron is placed at room temperature
- Magnetic field distribution will be measured by using scanning Hall probe and rotating pick-up coils

Study on magnetization of coated conductor and field quality

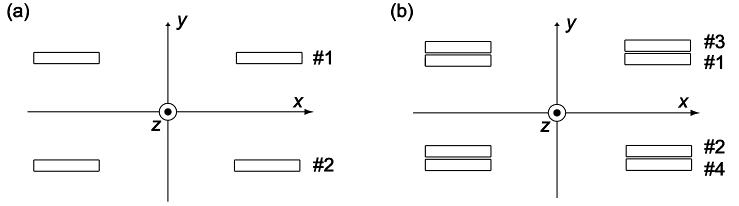
Content of this part

- Magnetic field harmonics measurements in small dipole magnets
  - Comparisons with 2D electromagnetic field analyses
- 3D model for electromagnetic field analyses to evaluate magnetic field harmonics
- Perspective: how to manage this issue

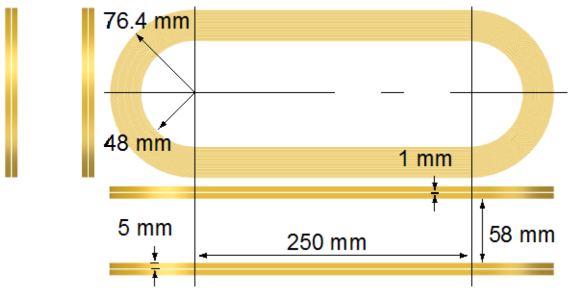
Magnetic field harmonics measurements

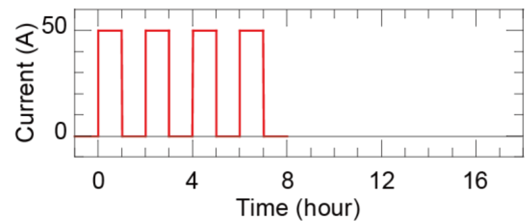
Tested magnets

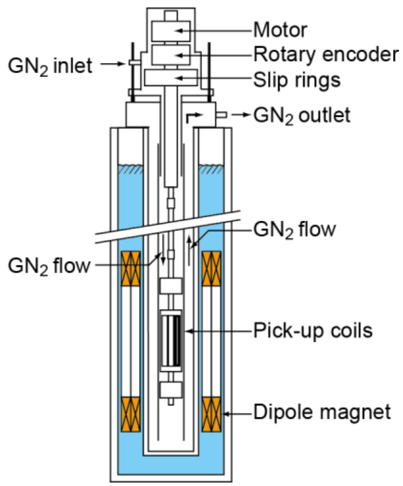
	RTC4-F	RTC2-F	RTC4-SP
Number of racetrack coils	4	2	4
Inner / outer width of racetrack	96 mm / 152.8 mm	80 mm / 132 mm	96 mm / 134 mm
Length of straight part	250 mm	250 mm	250 mm
Number of turn	83 turns/coil	76.5 turns/coil	108 turns/coil
Separation between pole	58 mm	52.8 mm	56.2 mm
Coated conductor	FYSC-SC05	FYSC-SC05	SCS4050
Cooling	LN_2	GM cryocooler	GM cryocooler
Dipole field	0.088 T @50 A		0.5 T @200 A
Conductor field	0.23 T @50 A		1.45 T @200 A

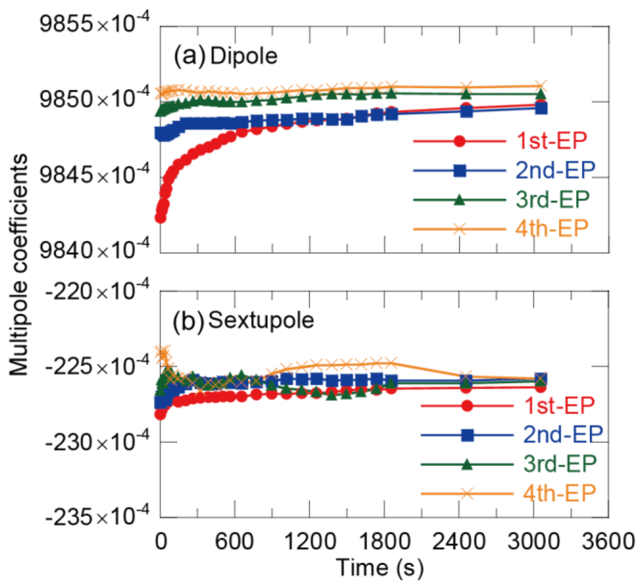


RCT-4, LN_2, experimental setup, typical data

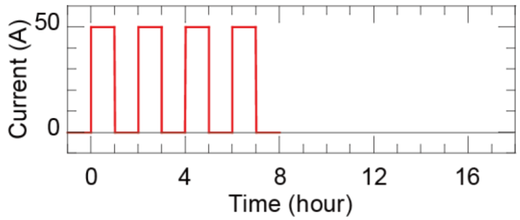


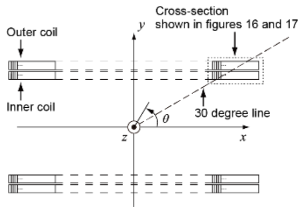


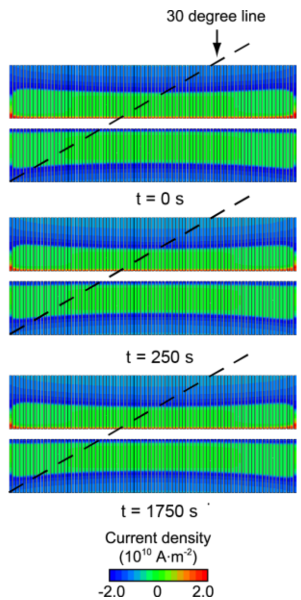


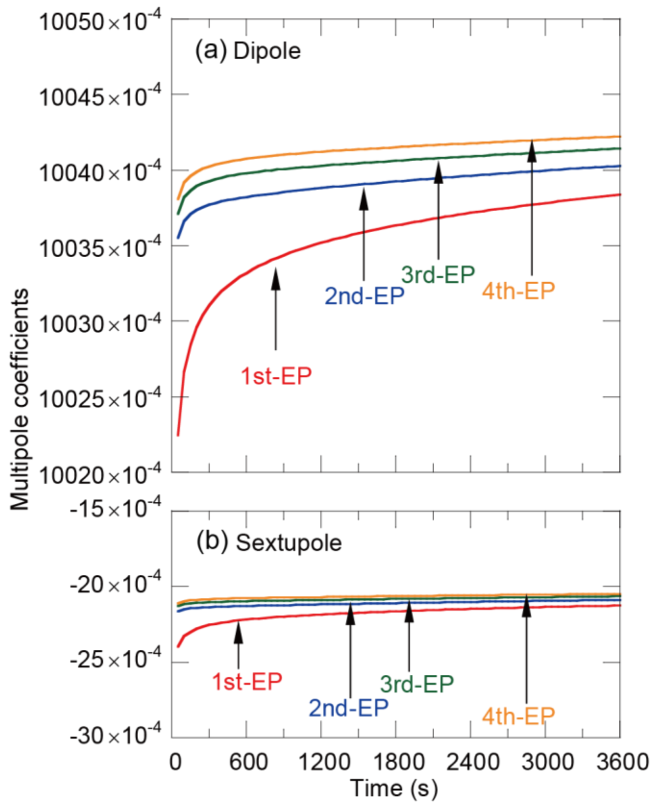


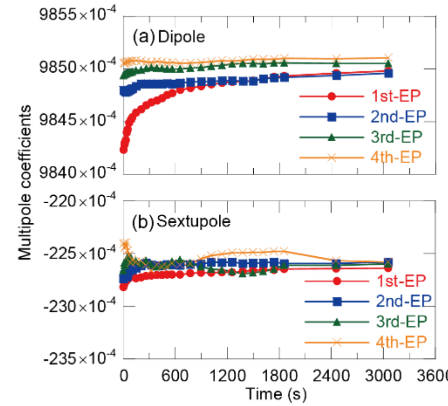
RCT-4, LN_2, 2D electromagnetic field analyses

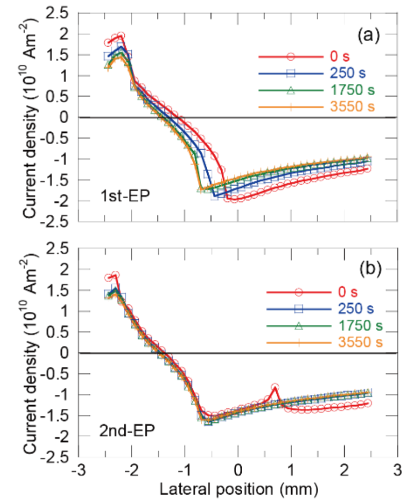




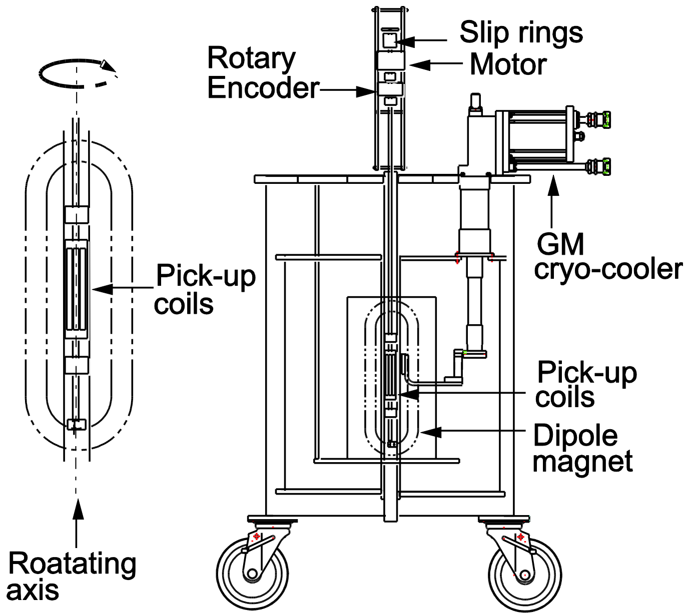




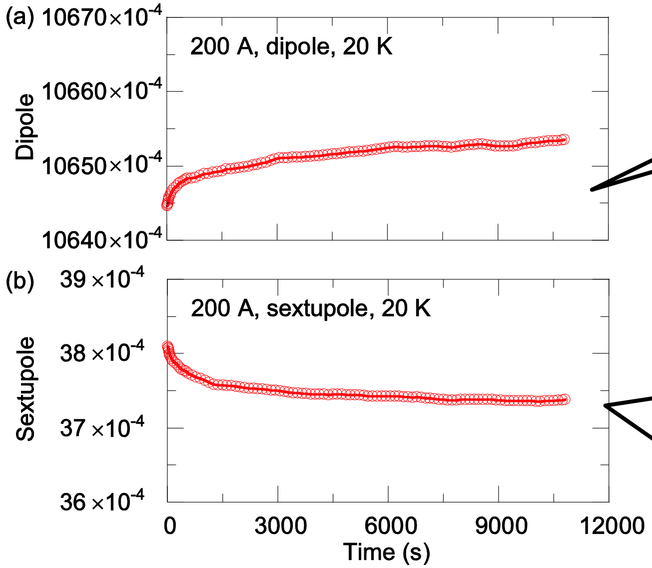




RTC4-SP, GM cryocooler, drifts in dipole and sextupole



200 A, 3 hour @20 K

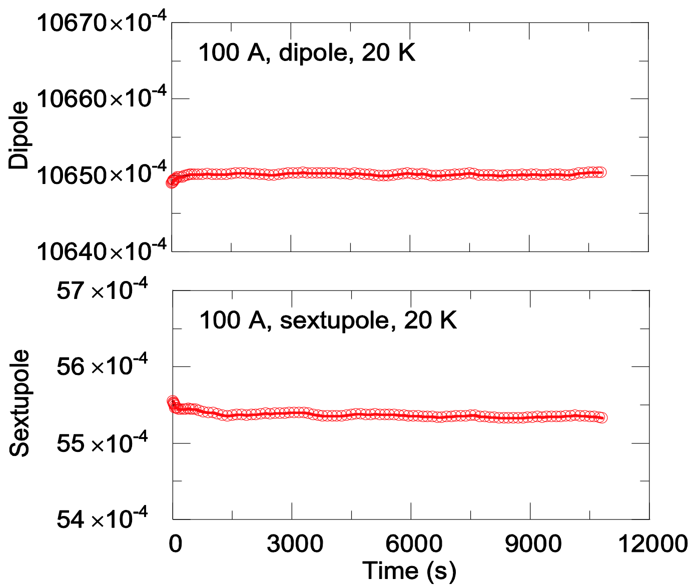


Drift in dipole
8.9×10^{-4}

Drift in sextupole
0.72×10^{-4}

RTC4-SP, GM cryocooler, temperature dependence

100 A, 3 hour @20 K

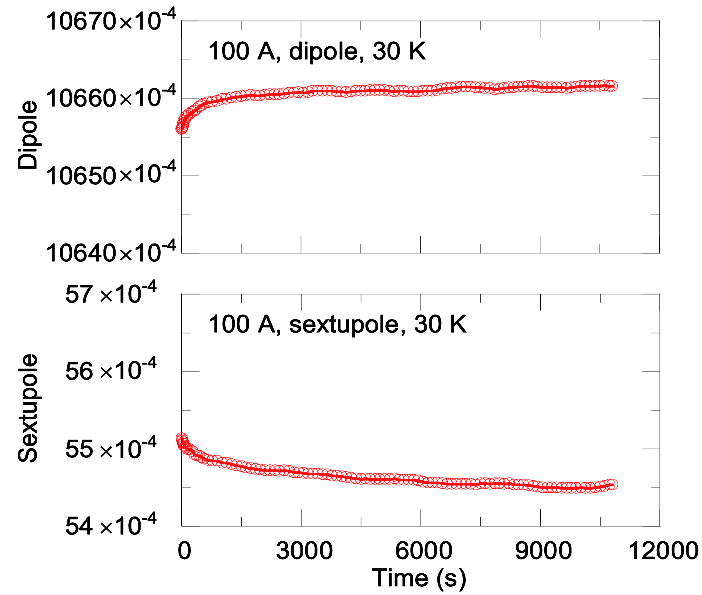


Drift in 3 hours

Dipole: 1.4×10^{-4}

Sextupole: 0.22×10^{-4}

100 A, 3 hour @30 K



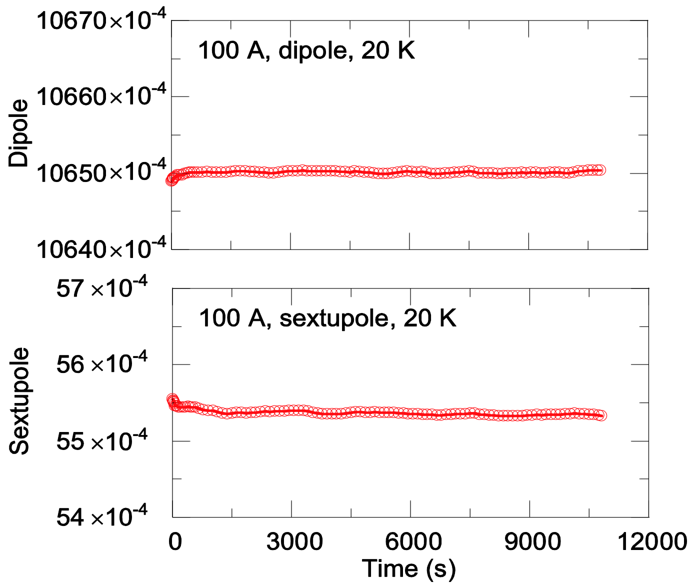
Drift in 3 hours

Dipople: 5.5×10^{-4}

Sextupole: 0.60×10^{-4}

RTC4-SP, GM cryocooler, field (current) dependence

100 A (0.725 T @conductor)
3 hour @20 K

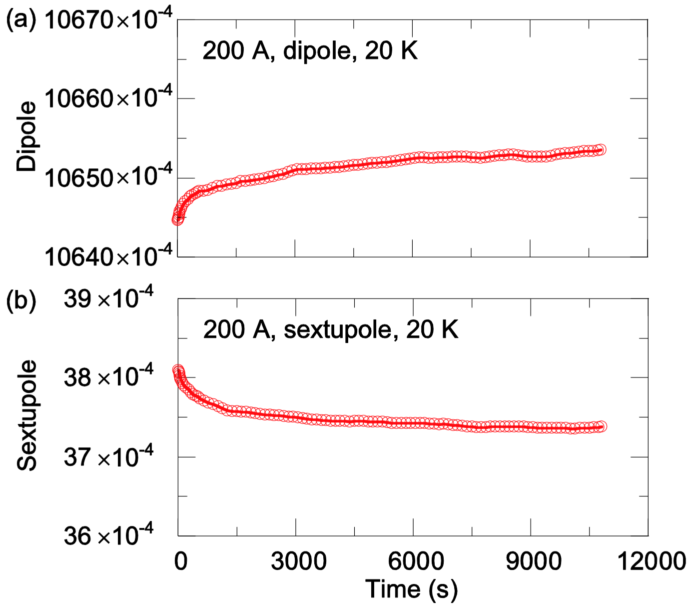


Drift in 3 hours

Dipole: 1.4×10^{-4}

Sextupole: 0.22×10^{-4}

200 A (1.45 T @conductor)
3 hour @20 K



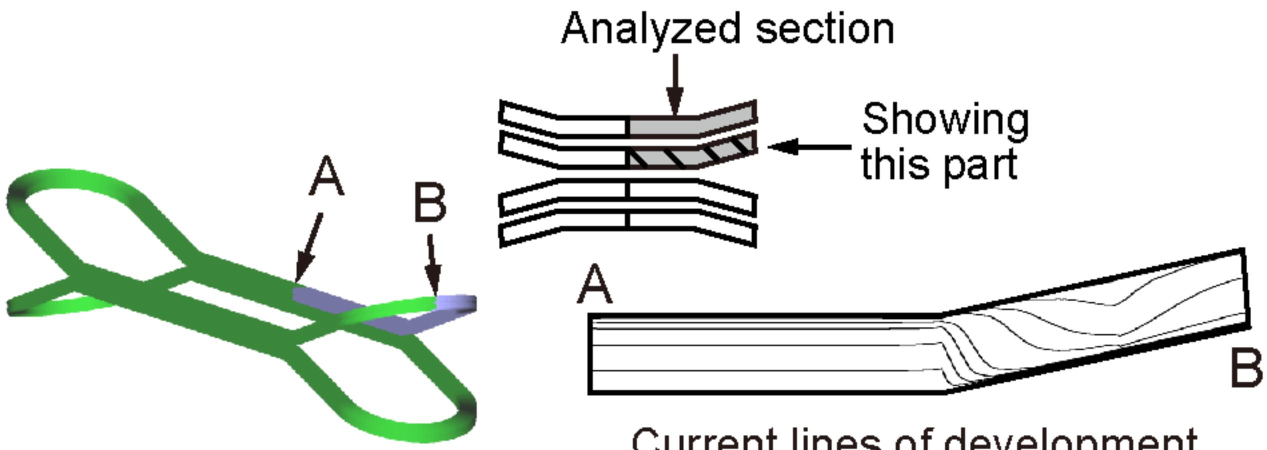
Drift in 3 hours

Dipople: 8.9×10^{-4}

Sextupole: 0.72×10^{-4}

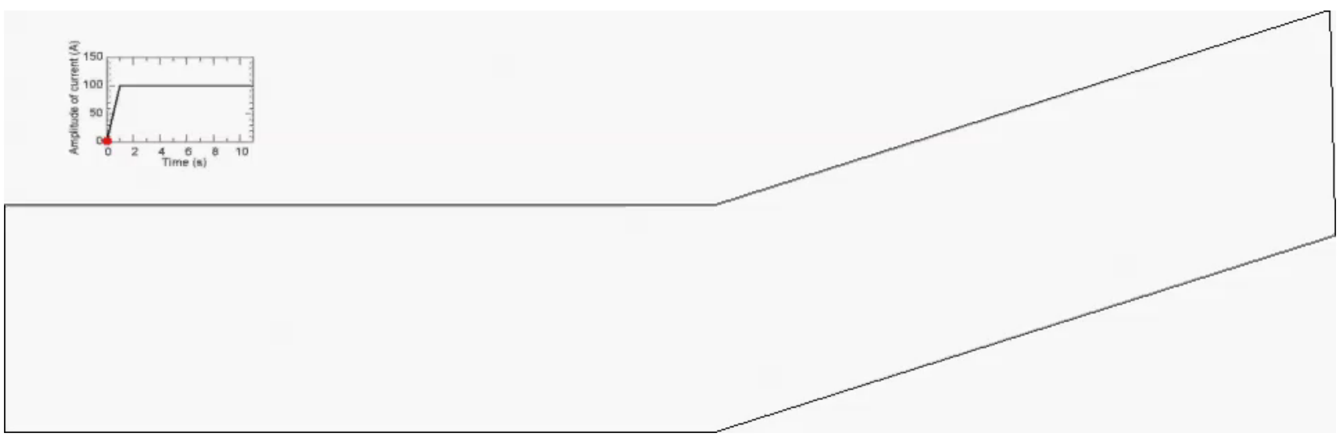
3D model for electromagnetic field analyses to evaluate magnetic field harmonics

Flared-end racetrack coils



Flared racetrack coil

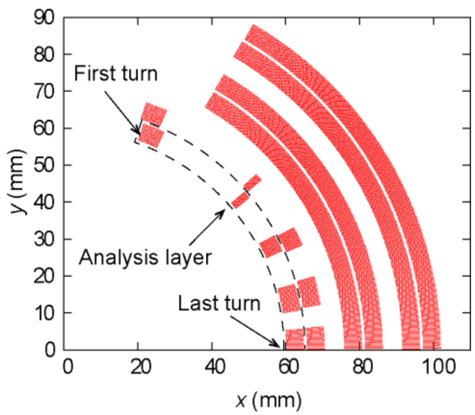
Current lines of development of innermost turn



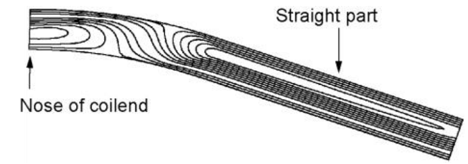
TOSHIBA
Leading Innovation >>>
NIRS
JAEA

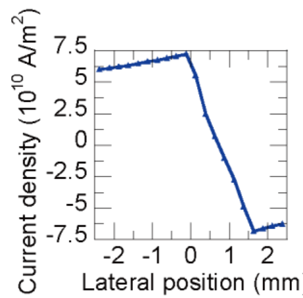
A cosine-theta dipole magnet for rotating gantry for carbon cancer therapy

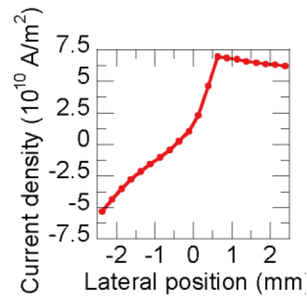
Analysis of 1st layer only



1st turn in 1st layer







Multi-pole coefficients	Analyzed value (with magnetization)	Uniform current	contribution of magnetization
6 pole	100.124	91.504	8.620
10 pole	9.611	7.277	2.334
14 pole	1.064	1.013	0.051

Perspective

How to manage this issue?

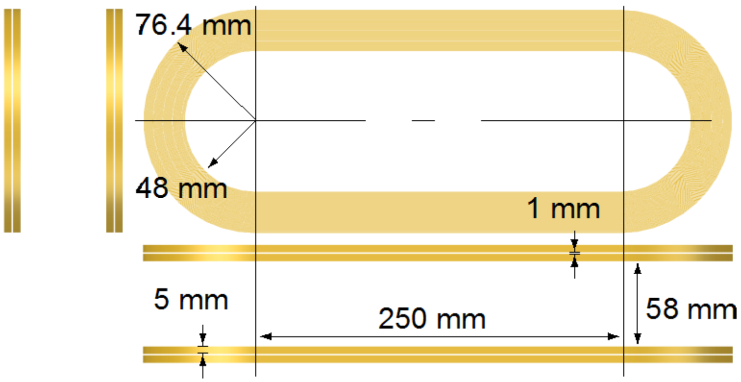
1. We have to accept the existence of the large magnetization in coated conductors.
2. A good news: reproducible magnetization
3. 3D modeling will enable us the magnetic field design considering the magnetization: at least if the magnetization current is stable and hardly decays, we can design a coil which can generate the required magnetic field, not assuming uniform current but considering the calculated not uniform current distribution with magnetization current.
4. Drift in harmonics caused by the decay of magnetization must be a more serious issue.
5. Another good news:
   - Not very large drift*:* at the order of unit, most possibly less than 10 units
   - Dipole drifting more but higher harmonics drifting less
   - Less drifts at lower temperature

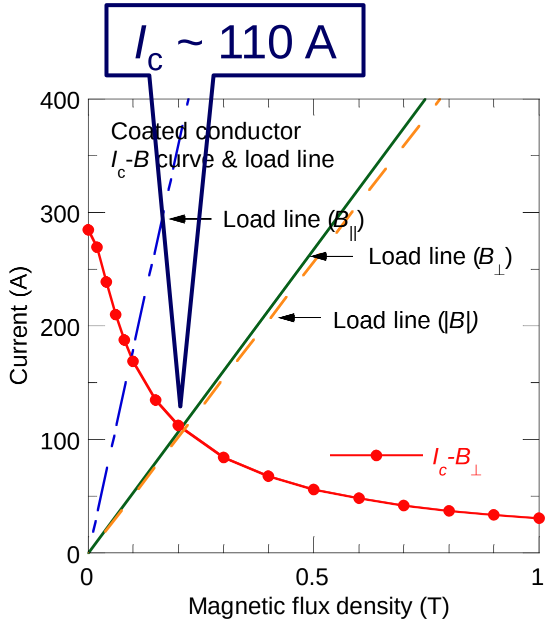
Back-up slides

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





Equation for analyses

〔Faraday's law〕

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

〔Biot-Savart's law〕

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

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

Equivalent conductivity derived from power law characteristic $E = E_0 (J / J_c)^n$

〔Definitional of current vector potential〕

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

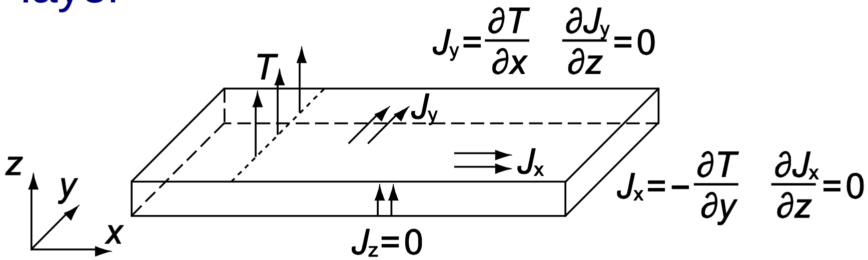
$$\nabla \times \left(\frac{1}{\sigma} \nabla \times \boldsymbol{T}_{\mathrm{f}} \right) + \frac{\mu_0}{4\pi} \frac{\partial}{\partial t} \int_V \frac{(\nabla \times \boldsymbol{T}_{\mathrm{s}}) \times \boldsymbol{r}}{r^3} dV = \boldsymbol{0}$$

Transformed to 2D problem

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

Thin strip approximation

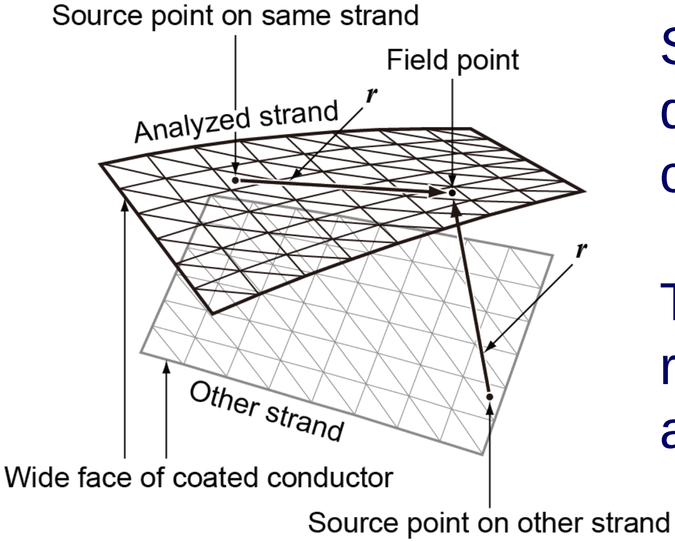
Neglecting current density component normal to SC layer / magnetic flux density component tangential to SC layer



Consideration of three-dimensional geometry of coated conductors in a coil

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

r : vector from the source point where the current resides to the field point where the potential is calculated.



Superconductor layers are mathematically two-dimensional (no thickness), but follow the curved geometry of coated conductors in a coil.

The three-dimensional geometry of the coil is retained in the modeling, while region of analysis is mathematically two-dimensional.