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Characteristics of an HTS dipole magnet

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Abstract *We fabricate a short model of the HTS dipole for the CIRT Gantry, and its characteristics is studied. In parallel, we also measure the I-V characteristics of REBCO coated conductor to collect data for the quench simulation so we can predict a quench behavior of this HTS dipole.*

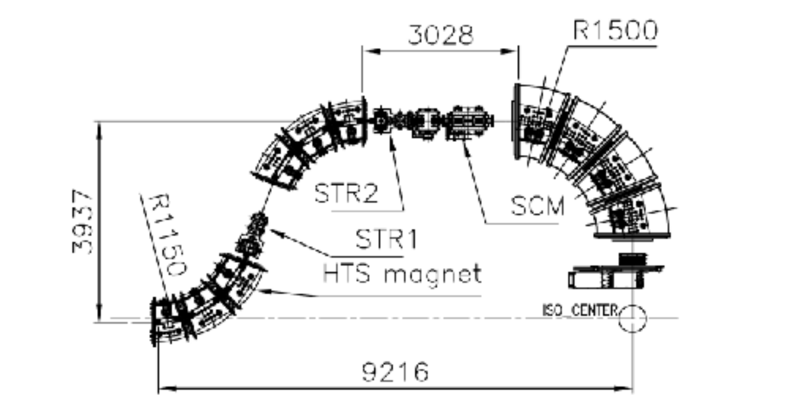
Introduction

Gantry for CIRT

There are two institutions at which carbon-ion radiotherapy (CIRT) gantries are installed :
- Heidelberg Ion-Beam Therapy Center (HIT)
  * World-first "Normal Conductor (NC)" gantry (2012~)
- National Institute of Radiological Science (NIRS)
  * World-first "Low T_c Superconductor (LTS)" gantry (2015~)

In the CIRT application, the size of gantry is a major bottleneck for construction / installation.

Solution:
→ Use "High T_c Superconductor (HTS)" for gantry magnets
→ REBCO coated conductor (CC) is a good candidate
* More affordable than other HTSs
* Its properties have been studied well over decades



HTS gantry design [1]

	Maximum dipole	Total length	Total weight
NC-based gantry (HIT)	1.8 T	25 m	600 ton
LTS-based gantry (NIRS)	2.9 T	13 m	210 ton
HTS-based gantry [1]	**5.8 T**	**9.2 m**	**177 ton**

What's challenging ?

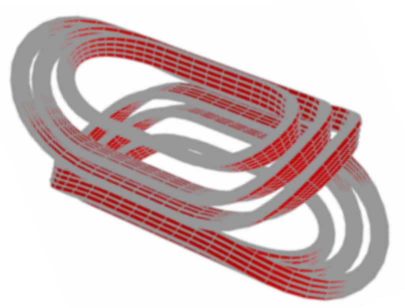
- REBCO CC has a large screening current, whose strength and time dependences are not understood well
  → Could affect the field quality of the magnet
- Mechanical stress on CC could lead to quench at worst

Our goal

Investigate the possibility of using YBCO CC for HTS gantry
- **Construct a model dipole magnet which is the shorten model of the actual design**
- **Measure the dipole field quality & Compare the measurement with results from numerical calculation**
- **Consider the quench protection system dedicated to the HTS magnet**

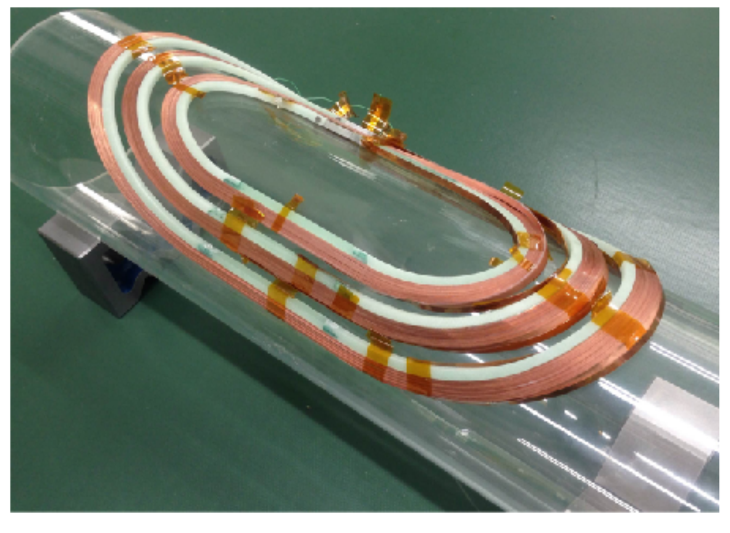
Model magnet fabrication

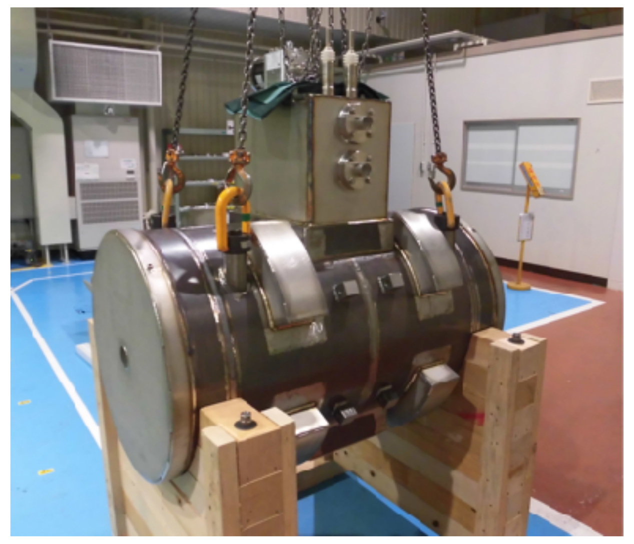
- Coil design : saddle shape [2]
- Each coil is wound by REBCO CC which is produced by SuperPower Inc.
  - Width: 4mm / Thickness: 0.1mm
- 32 different coils in total, 16 each sits on one side of the poles
- 4 layer structure and 4-blocks design : cosθ-current distribution (dipole)
- **1/3 of the short model was fabricated for checking its feasibility**



Main parameter of the model magnet	
Dipole field strength	3 T
Rated current	366 A
Bore radius	30 mm
Inner radius of iron yoke	95 mm
Outer radius of iron yoke	205 mm
Num. of HTS coils	24
Num. of turn for each coil	50
Magnet mechanical length	1200 mm
Coil mechanical length	340 mm
Coil inductance	288.9 mH
Sum of Lorentz force per quadrant	
Horizontal (ΣF_x)	349.4 kN/m
Vertical (ΣF_y)	-74.7 kN/m

Coil type	Inner Radius (mm)	Aperture angle (degree): Actual & Four blocks	Aperture angle (degree): Three blocks
A1	60	7.33	-
A2		21.58	17.42
A3		36.71	32.55
A4		60.11	55.95
B1	65	7.33	-
B2		21.58	17.42
B3		36.71	32.55
B4		60.11	55.95
C1	70	7.33	-
C2		21.58	17.42
C3		36.71	32.55
C4		60.11	55.95
D1	75	7.33	-
D2		21.58	17.42
D3		36.71	32.55
D4		60.11	55.95

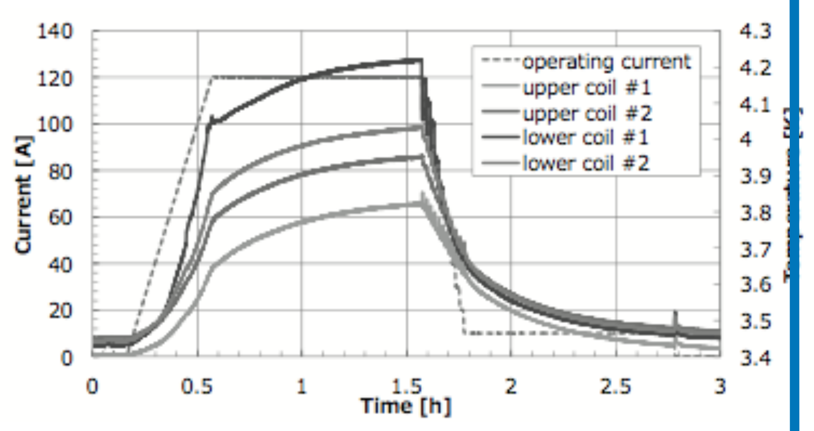




HTS dipole measurement

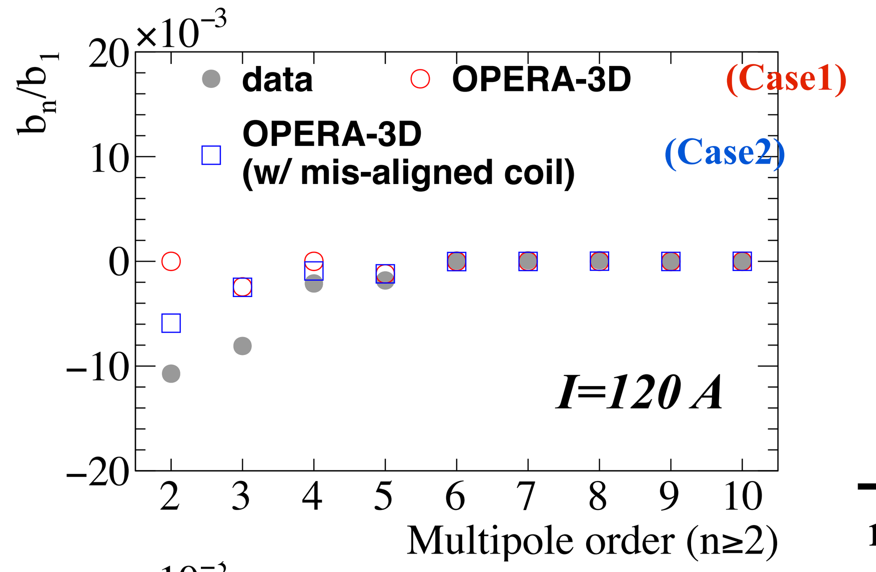
Temperature stability during operation

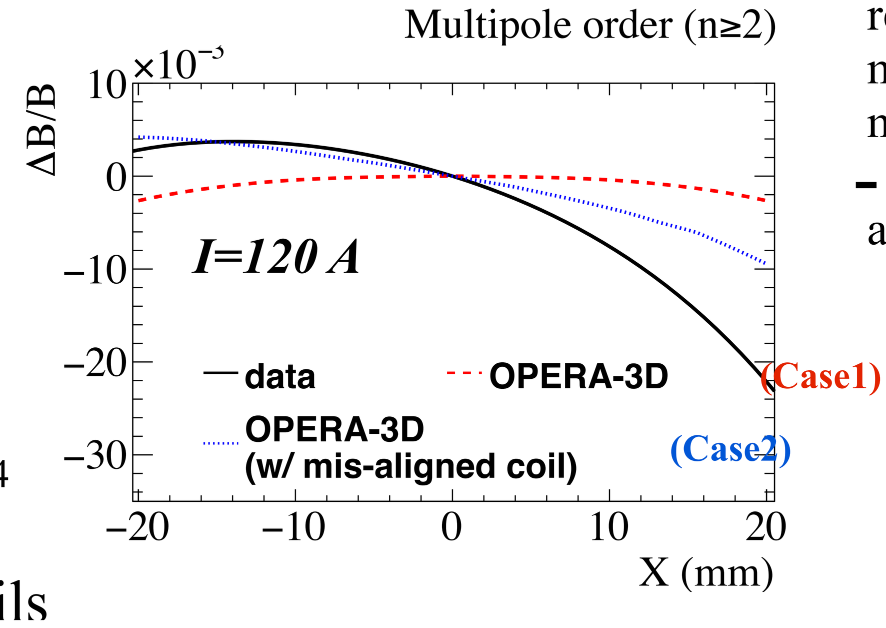
- Maximum current was limited at 150A since a gradual temperature increase was observed
- At 120A operation, which corresponds to B=1T, increase of the magnet temperature was less than 0.7 K



Field quality measurement (Ref.[3])

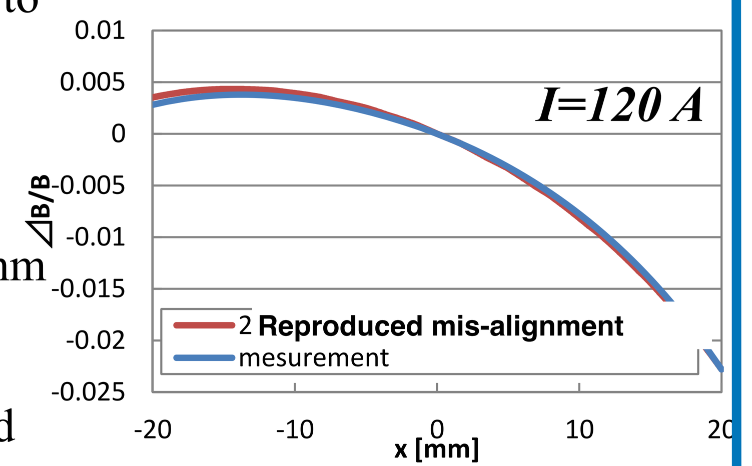
- Field harmonics were measured at reference radius of 20mm
  * Operating current was fixed at 120A
- Larger contributions were observed especially from quadrupole (b_2) and sextupole (b_3)
- OPERA-3D was used for comparison
  * Two cases were considered in the calculation:
    1.) w/ perfect aligned coils,
    2.) w/ mis-aligned coils **based on survey**
- Case 1.) doesn't indicate large contaminations of b_2
- Case 2.) shows large shifts in b_2 and b_4
  * These two large terms could be explained by mis-alignments of the coils





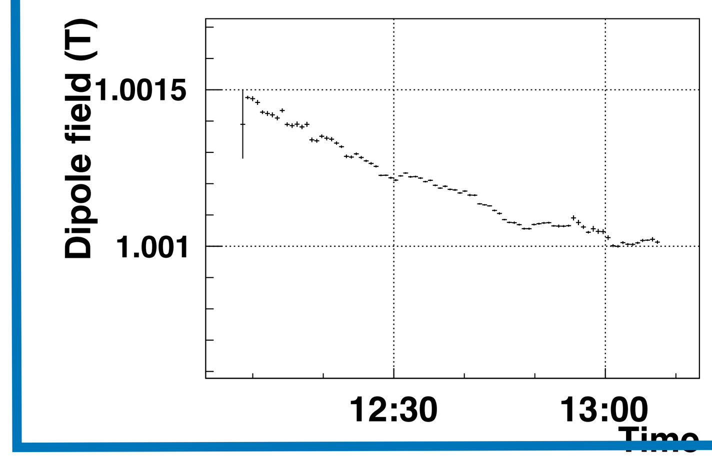
Further Investigation for the coil mis-alignment

- Mis-alignment of the coils was reproduced in the simulation to match field profile with the measured one
- Find one possible mis-alignment in which:
  - All the coils shift in 0.5 mm in the X dir.
  - The top and bottom coils both move by 4 mm toward their pole directions
  - One of the coils (B2) rotates by 2 deg. wrt the beam axis



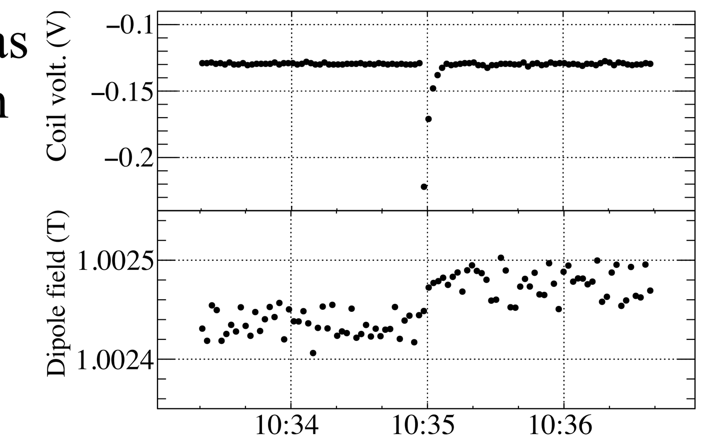
Field non-uniformtiy along the X direction

Temporal behavior in the dipole field



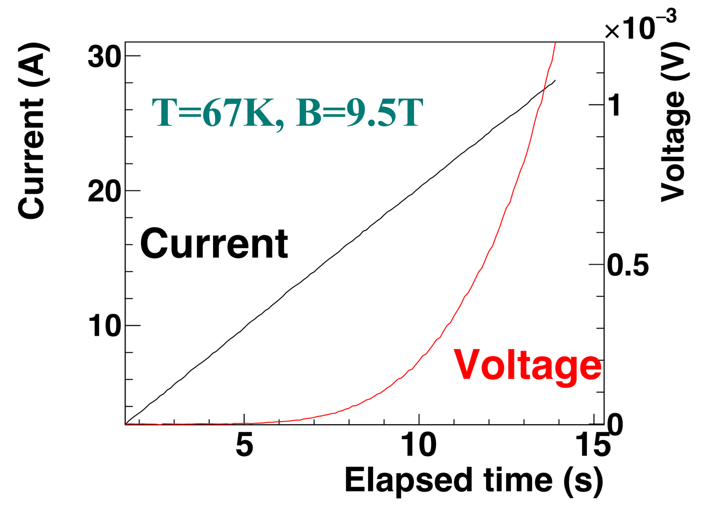
- Creep down in the dipole field was observed after reaching 120A even at stable current operation
- Effect from the magnetization?
- Further study with numerical simulation could reveal cause of this temporal behavior

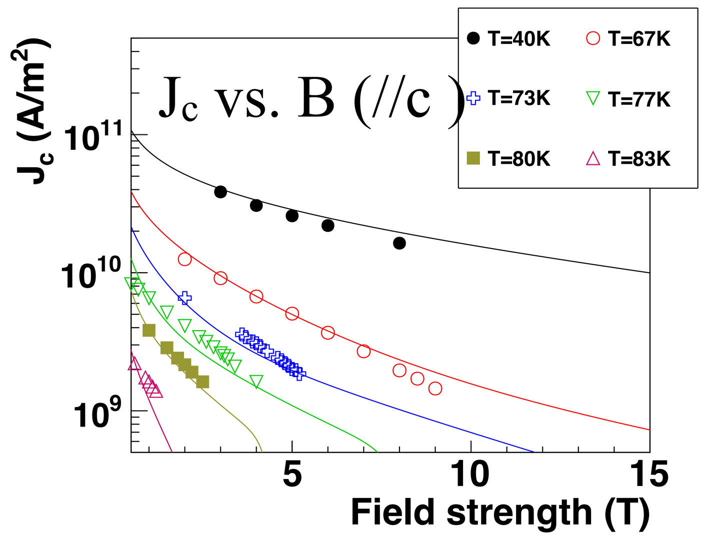
Observation of flux jump(?) event



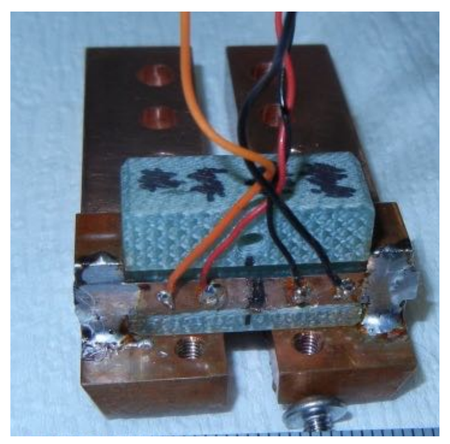
- Flux jump (?) events were observed during flattop operation at I=120kA
- Small variation was observed in the dipole field, which corresponds to ~100ppm.
- As past studies indicated (e.g. Ref [4]), increasing temperature is one of the solutions to avoid this phenomena

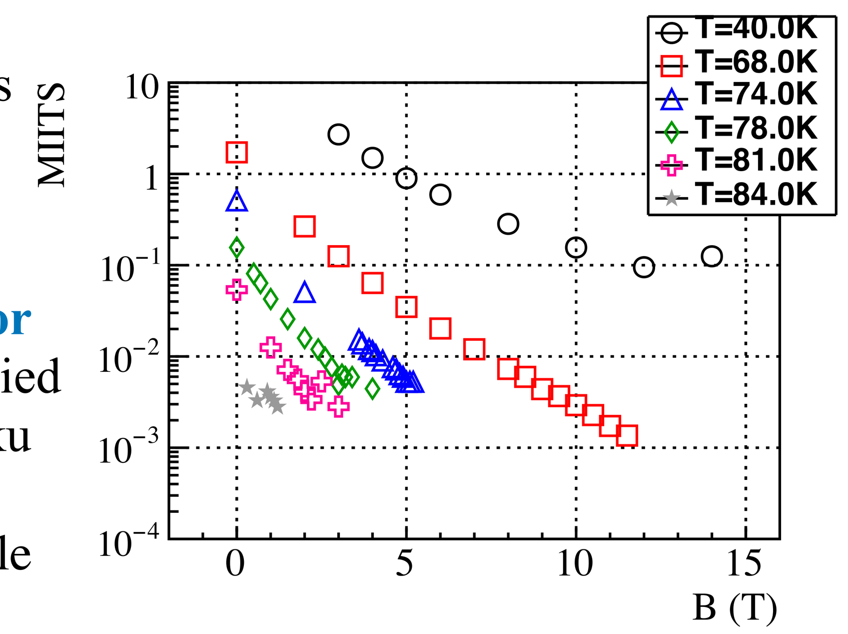
R&D on the quench protection for the HTS dipole





- One of the major concerns in operation of the HTS magnet is 'quench', and its protection system should be considered
- In addition, possibility in the higher temperature operation should be investigated to avoid 'flux jump '
- **→ Quench simulation should be developed to predict the quench behavior**
- IV characteristics of REBCO coated conductor (~1cm short sample) was carried out at the International Research Center for Nuclear Material Science of Tohoku Univ.
- Sample was cooled by means of the conduction-cooling method with a variable temperature insert, and exposed to the magnetic field that the superconducting solenoid generates.





- Sample, however, burned out when the applied field and the temperature were set to 3T, and 40K, respectively.
- Corresponding MIITs was computed using the following Eq.

$$MIITs = \int_{t=0}^{t_{end}} I^2 dt$$

→ 2.71 for (B,T)=(3T, 40K)

Plan: Further study on the quench protection system with:
- a quench simulation and ,
- hot spot temperature analysis using the MIITs result above.

Future plan

- Establish quench protection system
- Continuous operation for the HT dipole

Reference [1] S. Takayam *et al.*, Phys. Proc. vol76, 2015, p879-884 [2] K. Koyanagi *et al.*, IEEE Trans. Appl. Supercond., vol23, 2013, 4100404, [3] K. Suzuki *et al.*, IEEE Trans. Appl. Supercond., vol27, 2017,7748449 [4] K. Chen *et al.*, Appl. Phys. Lett., vol56, 1990, p2675-2677