Design of conduction-cooled HTS coils for a rotating gantry

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1. Introduction

Background
- Rotating gantries for carbon cancer therapy are too large and heavy for installation in general hospitals.
- An R&D project to reduce the size of a rotating gantry by applying HTS magnets is currently progress.

Objectives
- The influence of tape magnetization and manufacturing accuracy on the field quality.
- The thermal stability of the conduction-cooled HTS coils under an alternating magnetic field.
- Methods of protecting the coils from thermal runaway.

The thermal stability of conduction-cooled HTS coils is discussed.

2. Beam optics and magnet layout

Beam optics

Beam optics calculations were performed to determine the requirements for the magnets of the rotating gantry.
- **Entrance |** $\beta_H = \beta_V = 12$ m, $\alpha_H = \alpha_V = 0$, $D_H = D_V = 0$, $D'_H = D'_V = 0$
- **Isocenter |** $\beta_H = \beta_V = 5$ m, $\alpha_H = \alpha_V = 0$, $D_H = D_V = 0$, $D'_H = D'_V = 0$
- **Beam emittance |** $\varepsilon = 2\pi$ mm mrad.

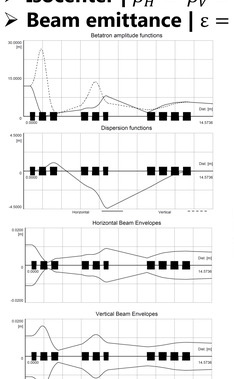

Fig. 1. Beta and dispersion function (up), and beam envelope (down) for the gantry beam line.

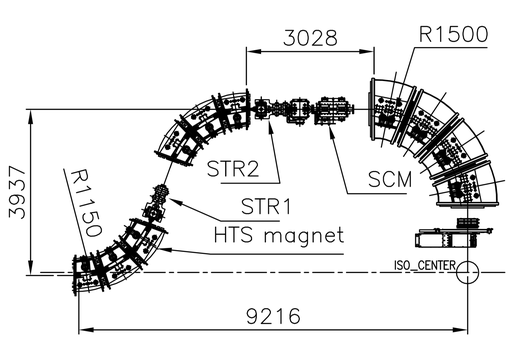

Fig. 2. Layout of rotating gantries

3. Design of superconducting coils

Coil design

The HTS coils were designed based on the required intensity, quality, and spatial size of the magnetic field.

- Dipole field | 5.8 T
- Quadrupole fields | 15.5 T/m
- Dipole magnetomotive force | 823 kA
- Quadrupole magnetomotive force | 21 kA
- Iron core thickness | 400 mm
- 4 blocks/pole with 50 turns/block
- Field quality within the reference radius of 20 mm | 2.75×10^{-4}

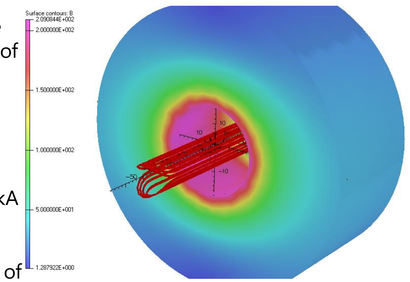

Fig. 3. Result of three-dimensional magnetic analysis

4. Thermal runaway properties

It is difficult to use coolant for the magnets mounted on the rotating gantry because they are rotating. Therefore, conduction cooling should be employed.
As a first step, the thermal stability of the conduction-cooled HTS coils under a static situation is considered.

Analysis model
- The coils were impregnated with an epoxy resin
- A aluminum conduction plate with a thickness of 0.25 mm was fixed on the entire upper side of the coil.
- 1/4 cut model was used in the analysis
- 49 mesh elements in the longitudinal direction
- 5 mesh elements in the thickness direction
- 4 mesh elements in the width direction
- Temperature in the aluminum plate of coil end is constant

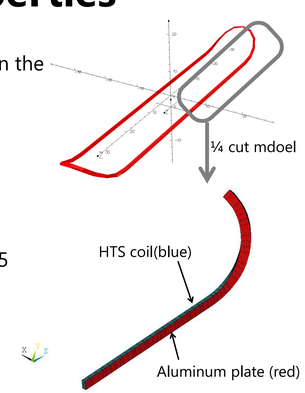

Fig. 4. Analysis model

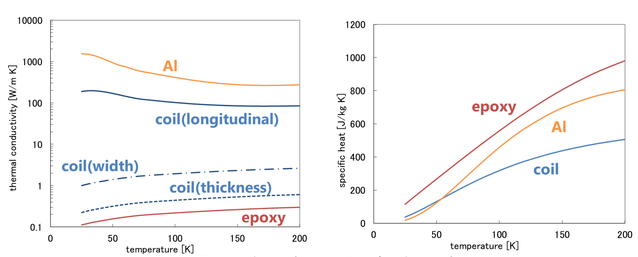

Fig. 5. Physical properties for the analysis

Thermal input
- The thermal input of the coil was considered to be Joule heating loss by flux-flow resistances generated in the superconductor or in the stabilized copper part.

$$V_{sc} = 10^{-4}\left(\frac{I_{op}}{I_c(B,T,\theta)}\right)^n d \mid V_{cu} = R_{cu}\frac{d}{S_{cu}}I_{op}$$

$$V = \begin{cases} V_{sc} & (V_{sc} < V_{cu}) \\ V_{cu} & (V_{sc} \geq V_{cu}) \end{cases} \mid q = \frac{VI_{op}}{Sd}$$

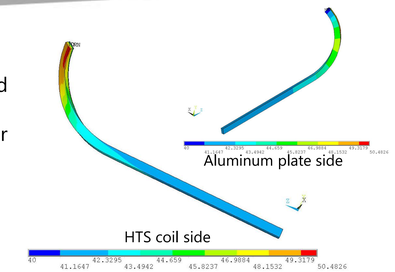

Fig. 6. Temperature distribution of the coil (coil base temperature | 40K, operating current | 293A)

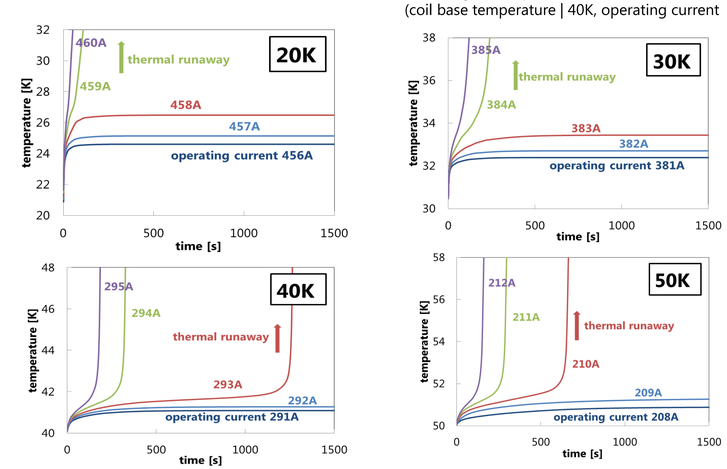

Fig. 7. Time dependence of the coil peak temperature

Results
- Thermal runaway currents are calculated in several coil temperature.
- The difference between the coil critical current and thermal runaway current was almost the same as 4.5-7.5%.
- The result is due to the high n-value of the HTS conductor.
- A high n-value causes the generation of a sudden resistance, and this results in rapid heat generation

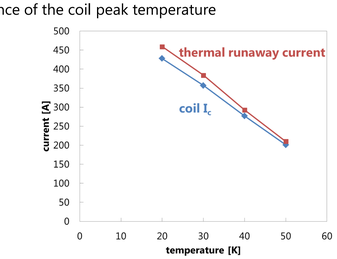

Fig. 8. Calculated result of thermal runaway current and coil Ic

5. Conclusion

- Thermal runaway analysis for the conduction-cooled HTS saddle-shaped was carried out.
- Thermal runaway currents are calculated, and the difference between the coil critical current and thermal runaway current was almost the same as 4.5-7.5%.
- It is considered that this result is due to the high n-value of the HTS conductor, and the high n-value causes the rapid heat generation.

This work is supported by the Ministry of Economy, Trade and Industry (METI), Japan

Presented at the ICEC25-ICMC2014 , 2014 Jul. 7 – 11, University of Twente, Enschede, The Netherlands; Session: Wed-Af-P2.4-17.