IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

TOSHIBA
Leading Innovation

2LO1-01

Manufacturing of LTS and HTS Magnets for Heavy-Ion Rotating Gantry

S. Takayama, K. Koyanagi, H. Miyazaki, S. Takami, T. Orikasa, Y. Ishii, T. Kurusu
(TOSHIBA Corporation)
Y. Iwata, K. Noda
(Department of Accelerator and National Institute of Radiological Sciences)
T. Obana
(National Institute for Fusion Science)
K. Suzuki, T. Ogitsu
(High Energy Accelerator Research Organization)
N. Amemiya
(Kyoto University)

This work is supported by the ministry of economy, trade and industry of the Japanese government, METI and the Japan agency for medical research and development, AMED.

EUCAS2017
Sept. 19, 2017

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

Outline

- Introduction
- Design and Manufacturing of First LTS gantry
- Recent Development of LTS gantry
- Future plan (HTS gantry)
- Conclusion

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

Introduction

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

Introduction

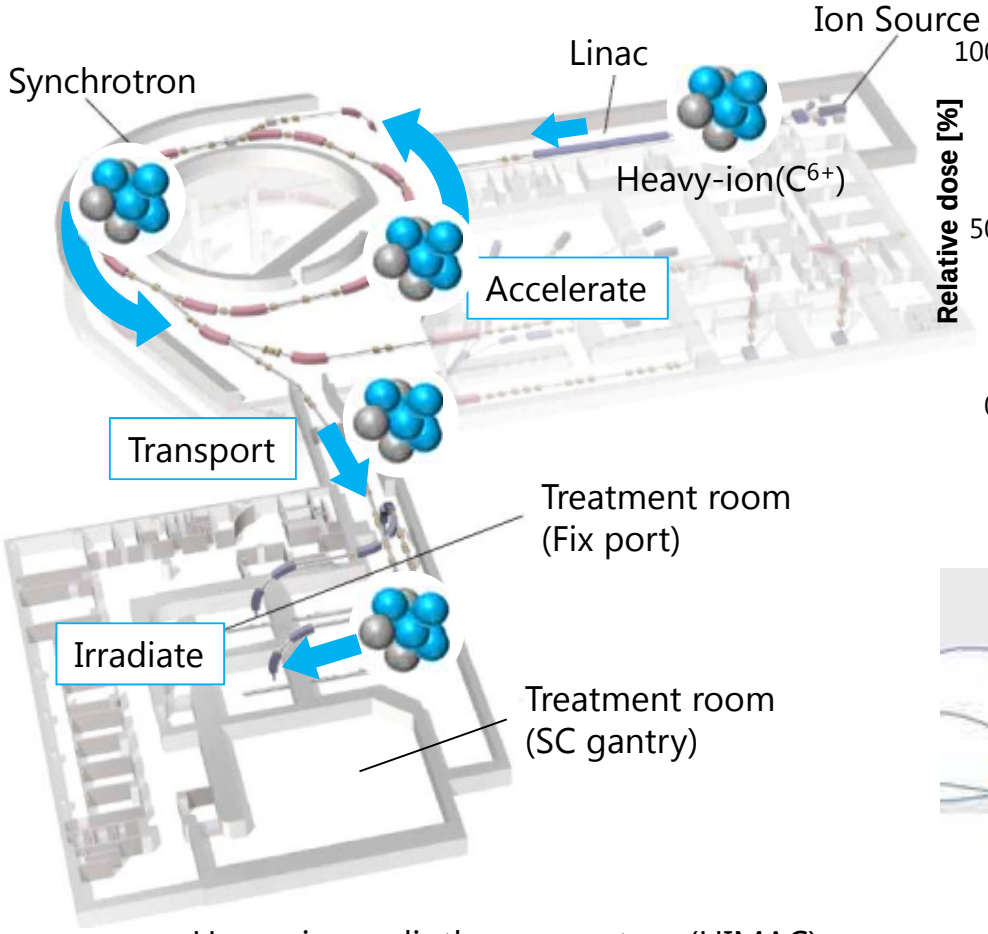
Cancer therapy

- Surgery
- Chemotherapy
- Radiotherapy
  - Photon beam
    - X-rays
    - γ-rays
  - Particle beam
    - Electron
    - Proton
    - Heavy-ion(Carbon)
    - Neutron

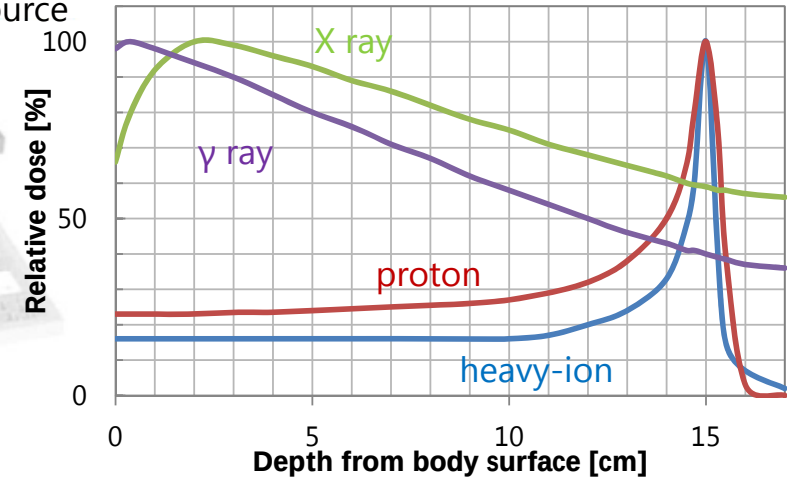
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

Introduction

Heavy-ion radiotherapy



Heavy-ion radiotherapy system (HIMAC)



Relationship of depth and relative dose

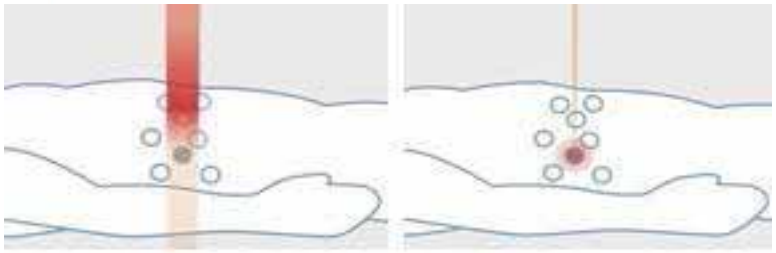
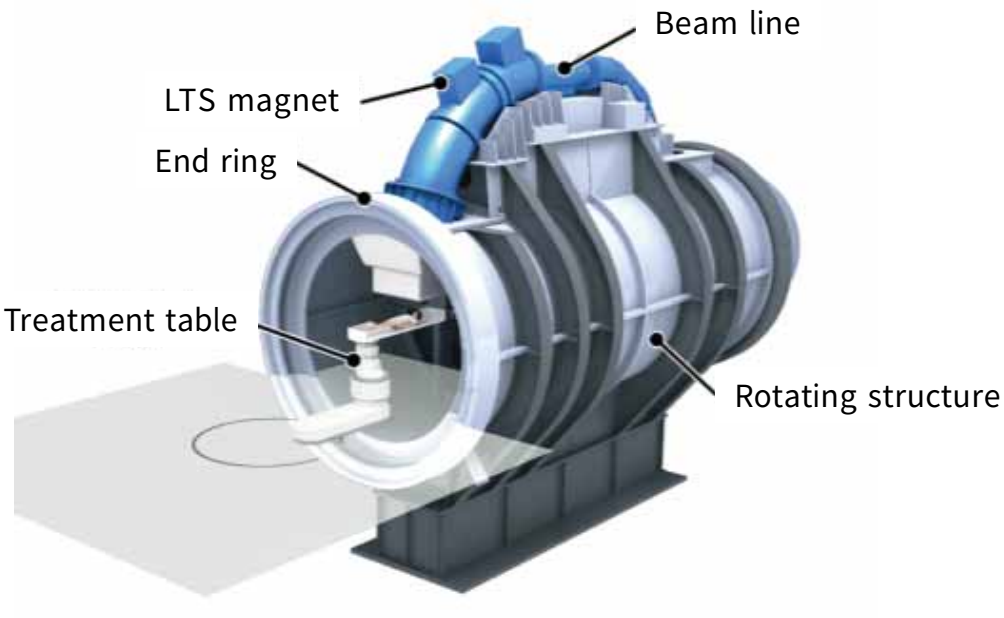


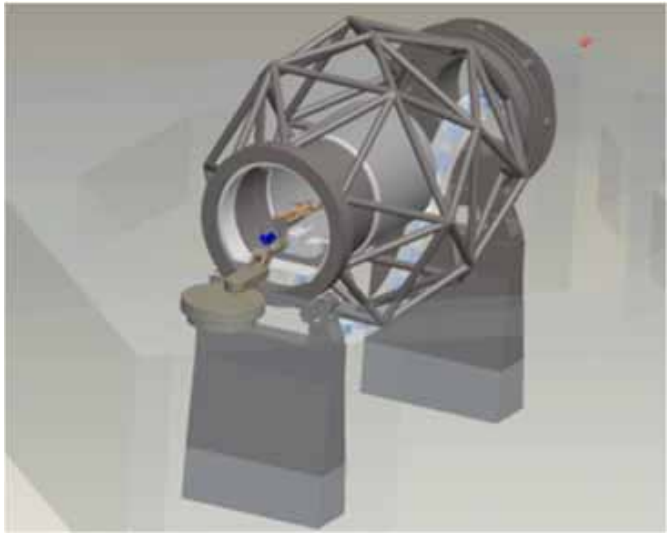
image of heavy-ion irradiation

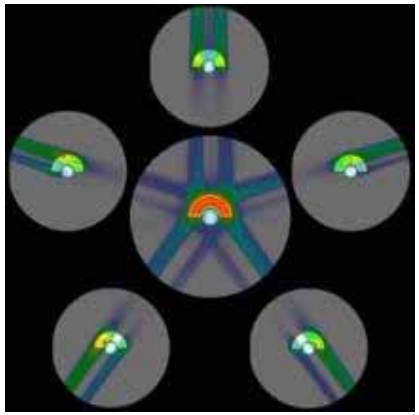
Introduction

Rotating gantry (Irradiation equipment)



LTS rotating gantry



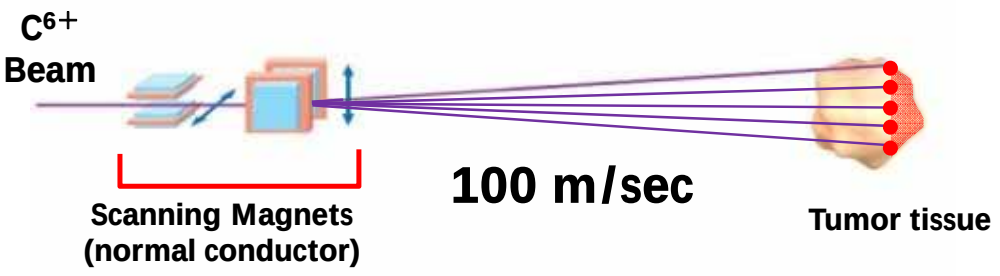


example of irradiation by rotating gantry

Introduction

Irradiation system

3D high-speed Scanning



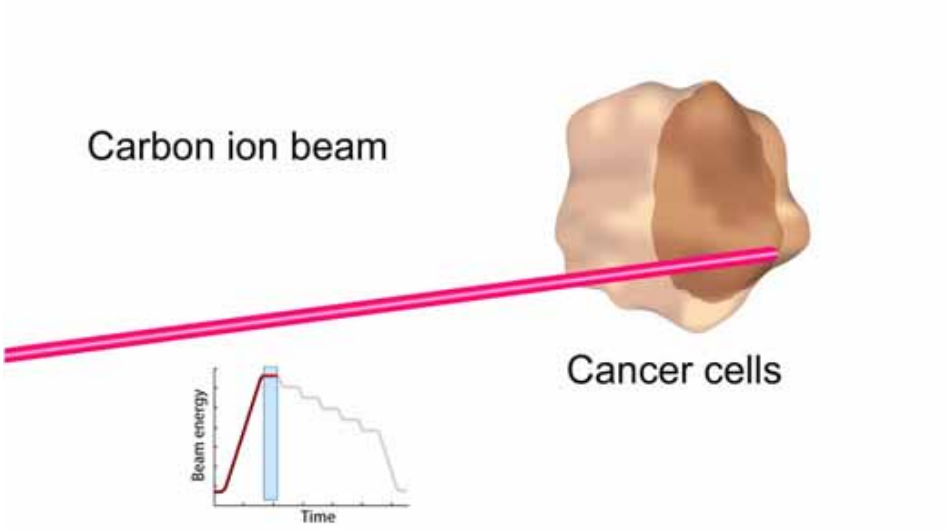


image of scanning irradiation

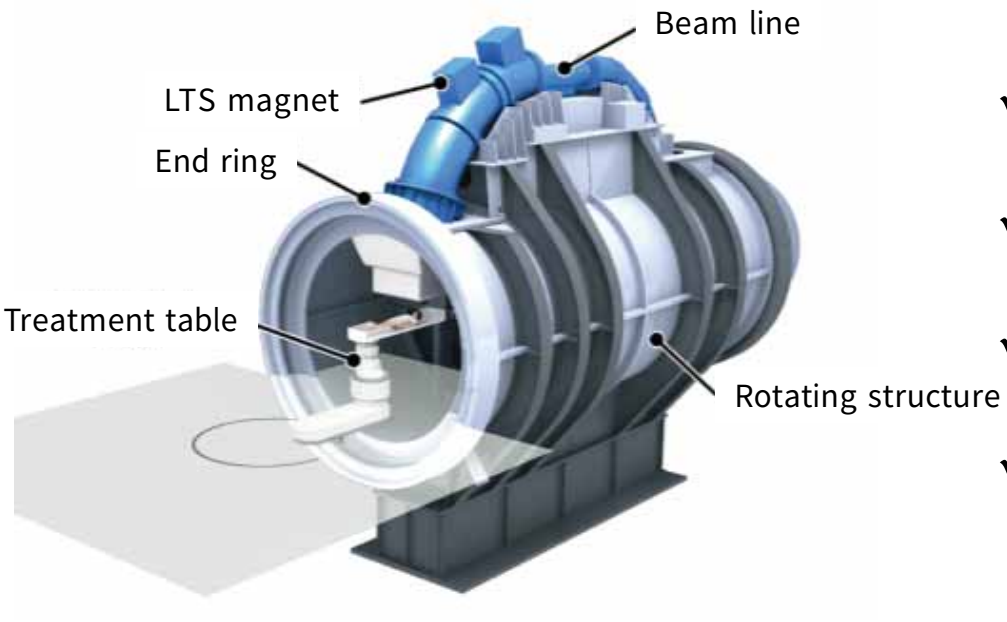
example of scanning irradiation

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

Design and Manufacturing of First LTS gantry

Design and Manufacturing of First LTS gantry

Design of first LTS gantry



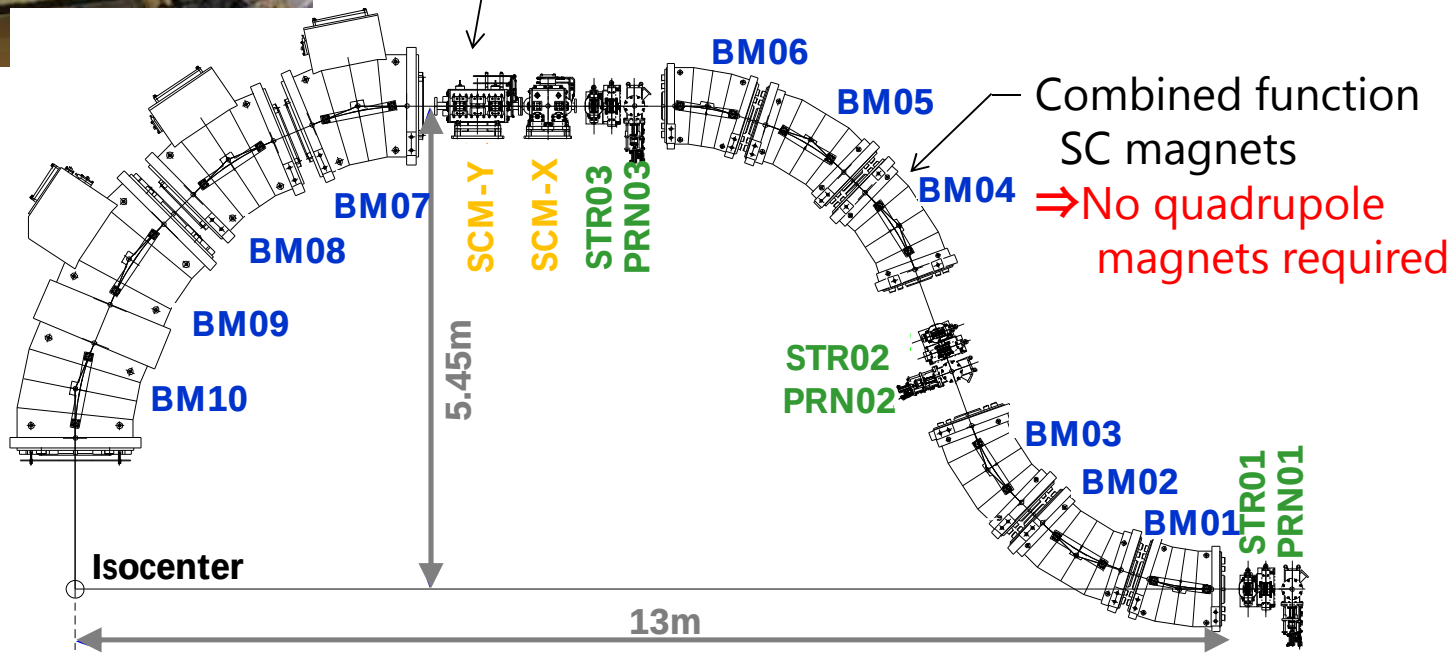
LTS rotating gantry

- ✓ Total length:
  14 m Approx.
- ✓ Rotating radius:
  5.5 m Approx.
- ✓ Diameter of end ring:
  6.5 m
- ✓ Rotating speed:
  0.38 rpm (rated speed)
- ✓ Superconducting magnets
  SC wire :Nb/Ti
- ✓ 4K GM Cryocoolers
  Q'ty 34
  (Liquid Helium free system)
- ✓ Multiple-flattop operation
  (No energy degrader)

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

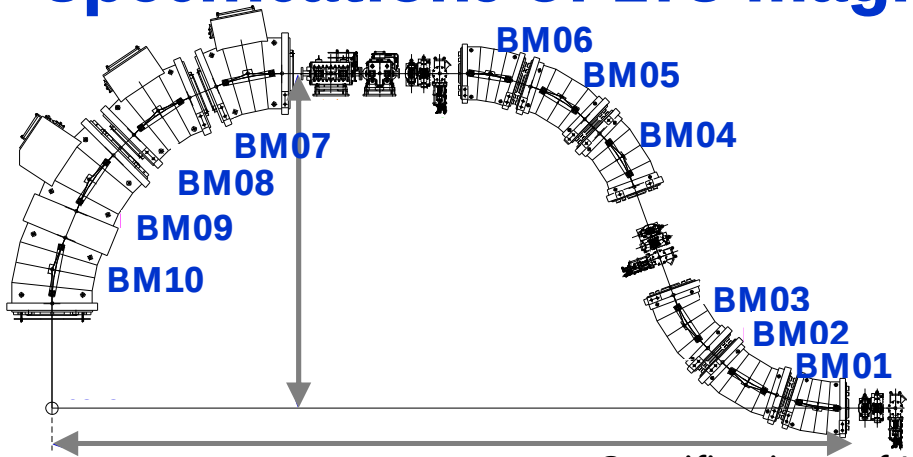
Design and Manufacturing of First LTS gantry

Magnet layout of the gantry



Design and Manufacturing of First LTS gantry

Specifications of LTS magnet



5 types of 10 magnets were employed

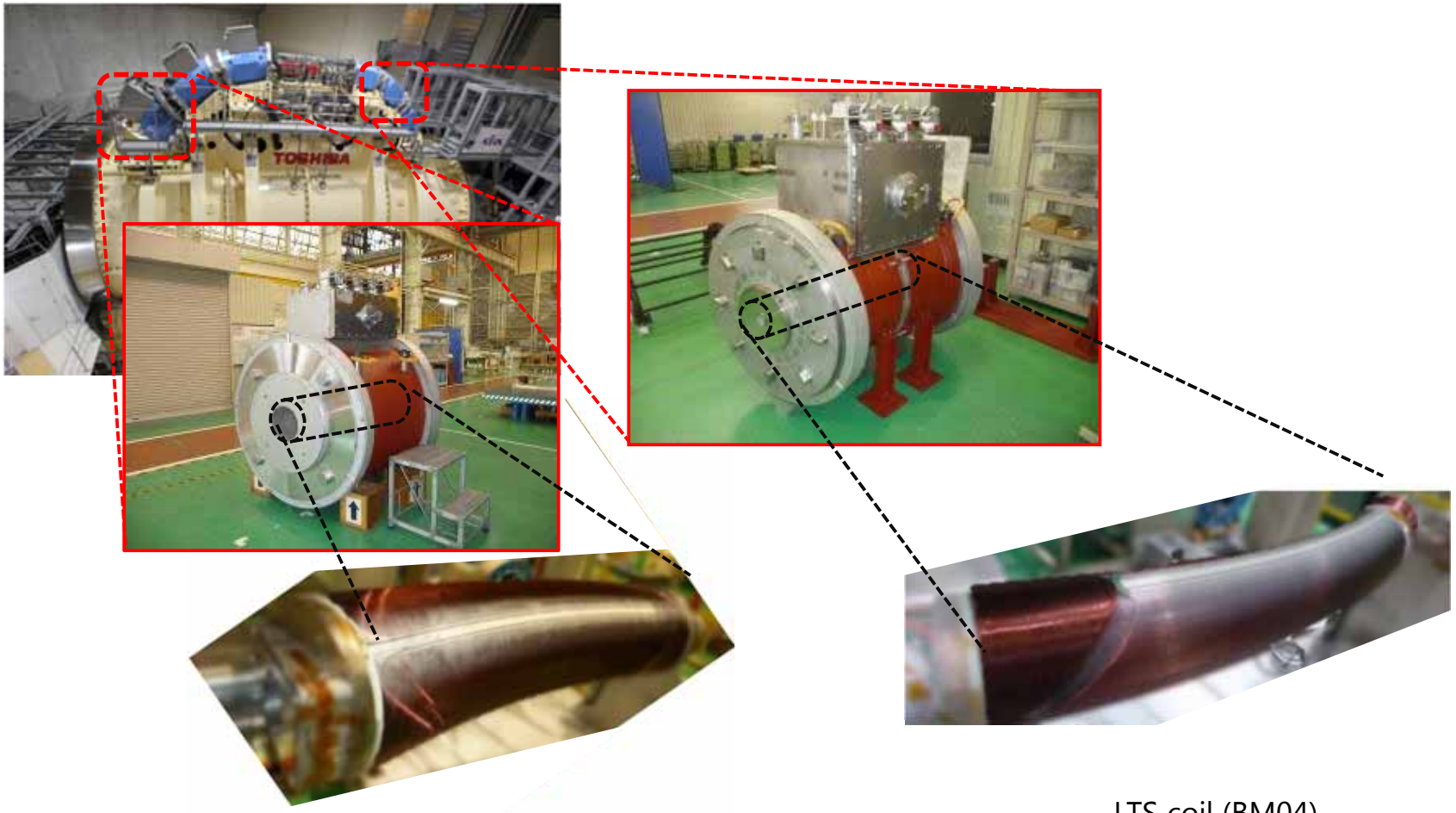
Specifications of LTS magnets

parameter	unit	BM01/BM06	BM02～BM05	BM07	BM08	BM09/BM10
Bending angle	deg.	18	26	22.5	22.5	22.5
Bending radius	m	2.3	2.3	2.8	2.8	2.8
Max. field (dipole)	T	2.88	2.88	2.3	2.3	2.3
Max. current (dipole)	A	136	136	227	225	231
Max. field (quad.)	T/m	9.0	9.0	-	-	1.3
Max. current (quad.)	A	130	130	-	-	200
Num. of Cryocooler	-	3	3	4	4	4
Total weight	tons	2.9	3.4	6.0	8.1	9.3

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

Design and Manufacturing of First LTS gantry

Photograph of manufactured LTS magnet



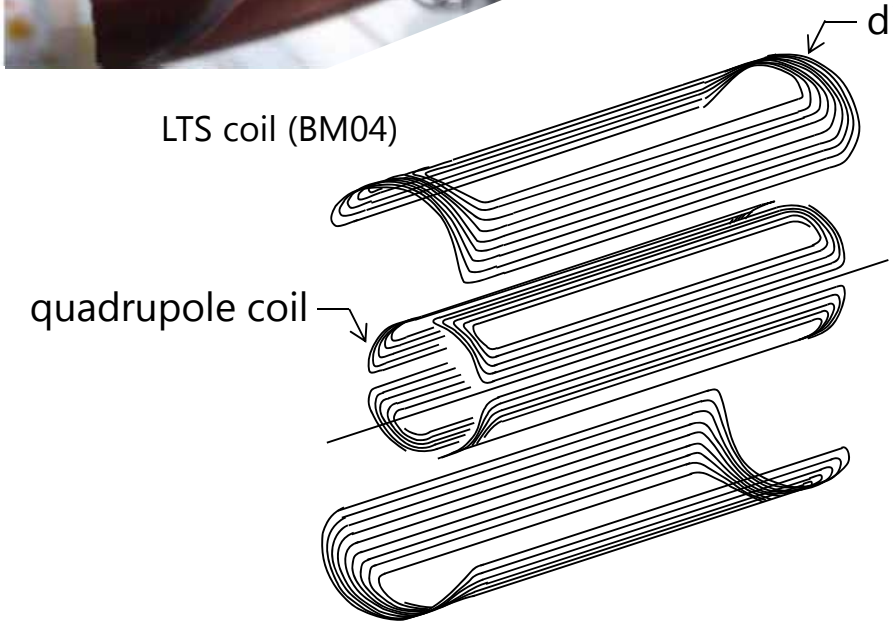
LTS coil (BM10)

LTS coil (BM04)

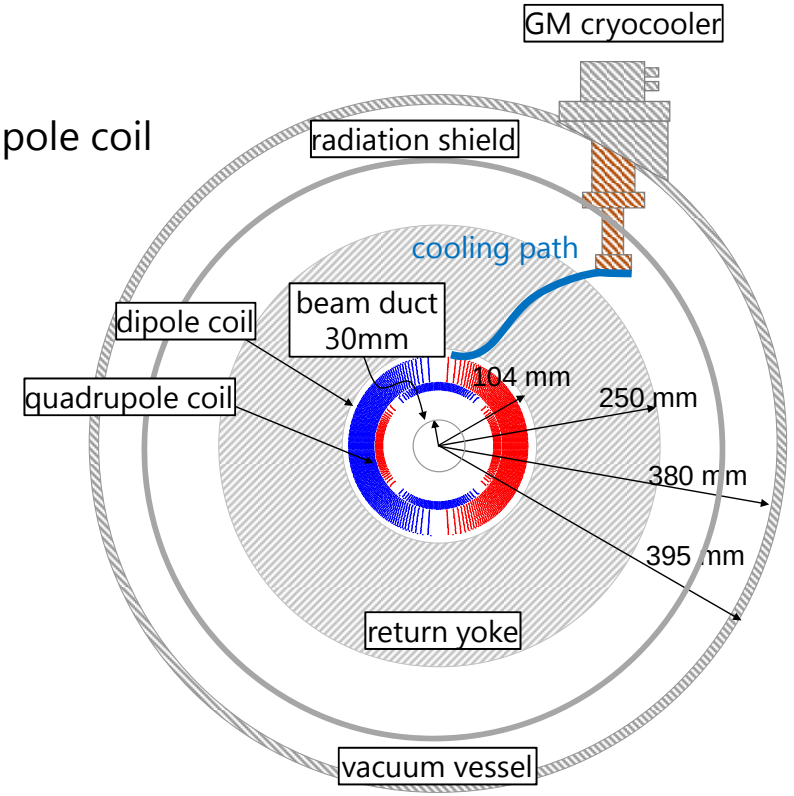
Design and Manufacturing of First LTS gantry

Combined functional and conduction-cooling magnet

LTS coil (BM04)



developed figure of LTS coil

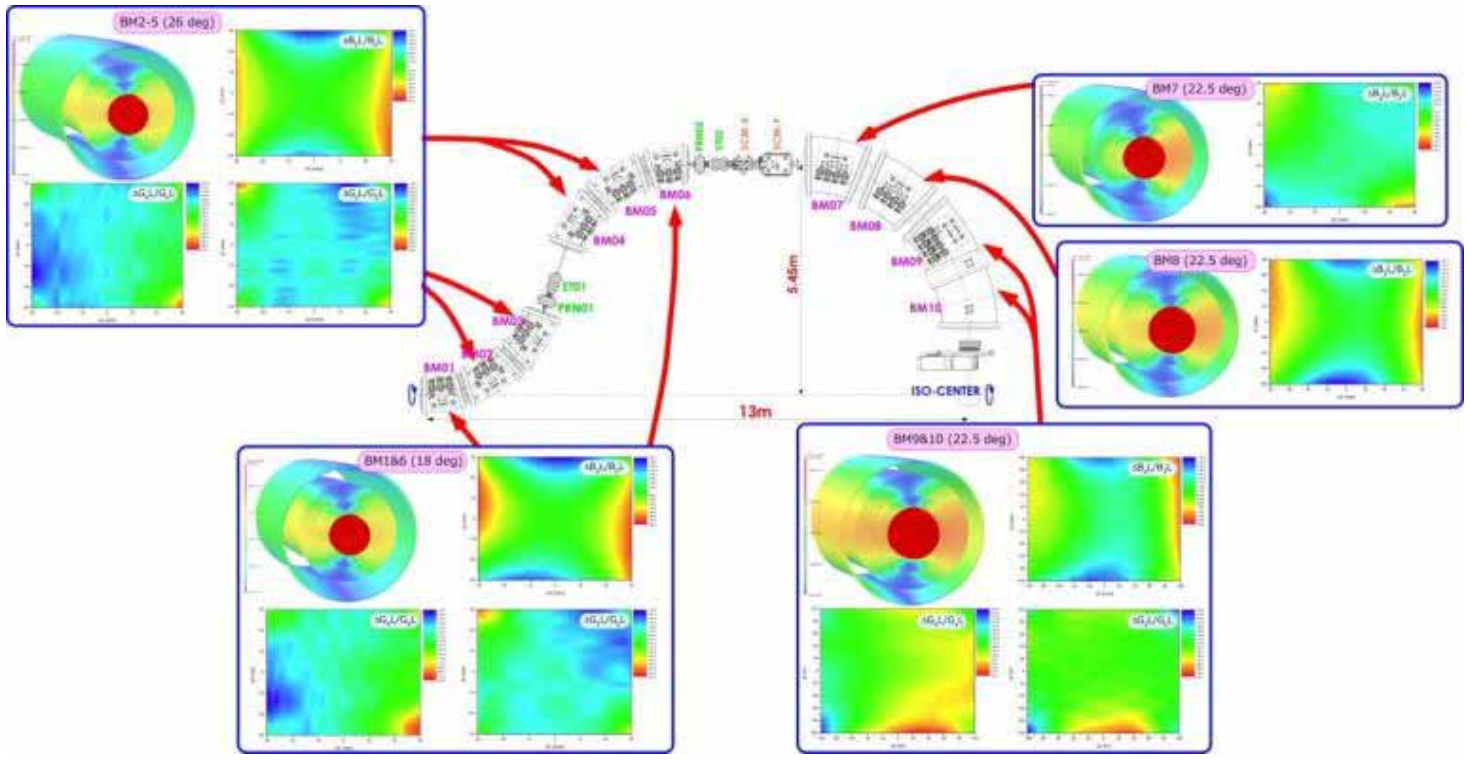


cross section of LTS magnet

Design and Manufacturing of First LTS gantry

Design of magnetic field

The magnet was designed so that the integral dipole and quadrupole field were uniform.



Y. Iwata et al., Proc. of PAC2013, Pasadena, CA USA, FRXB1

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

Design and Manufacturing of First LTS gantry

Rotating test

Rotation over +/- 180 degrees
- Appling maximum coil current
  ⇒No quench and no temperature rise observed
- Long term rotating test (33,000 times position changing)
  ⇒ No change in the coil temperature

photographs of rotating test (prototype magnet)

Y. Iwata et al., Proc. of PAC2013, Pasadena, CA USA, FRXB1

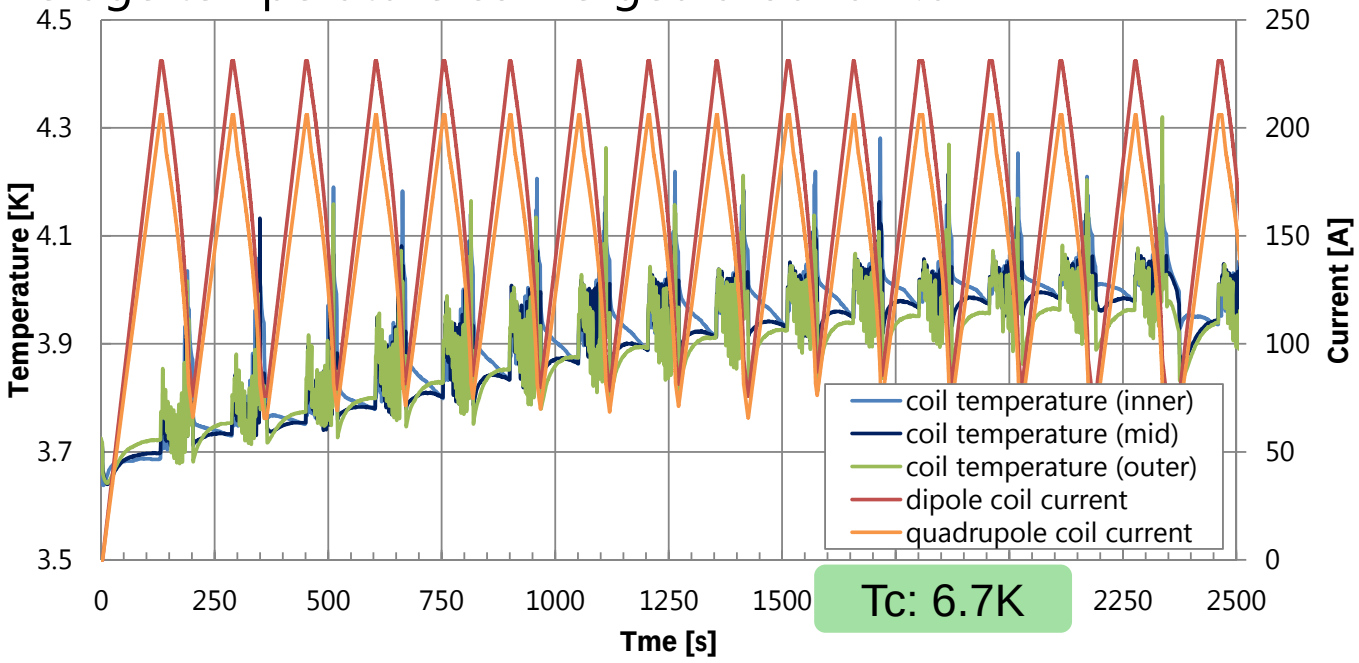
Design and Manufacturing of First LTS gantry

Pattern excitation

Operated SC Magnet simulating 201-flattop pattern (BM10). Each flattop was 300ms.

⇒No quench observed

⇒Average temperature converged around 4.0K



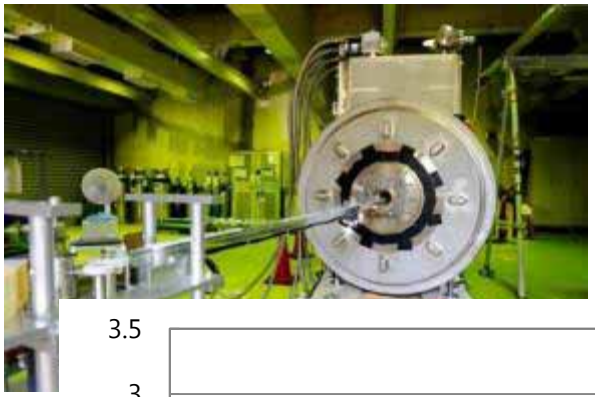
Coil temperature profile in pattern excitation (BM10)

Y. Iwata et al., Proc. of PAC2013, Pasadena, CA USA, FRXB1

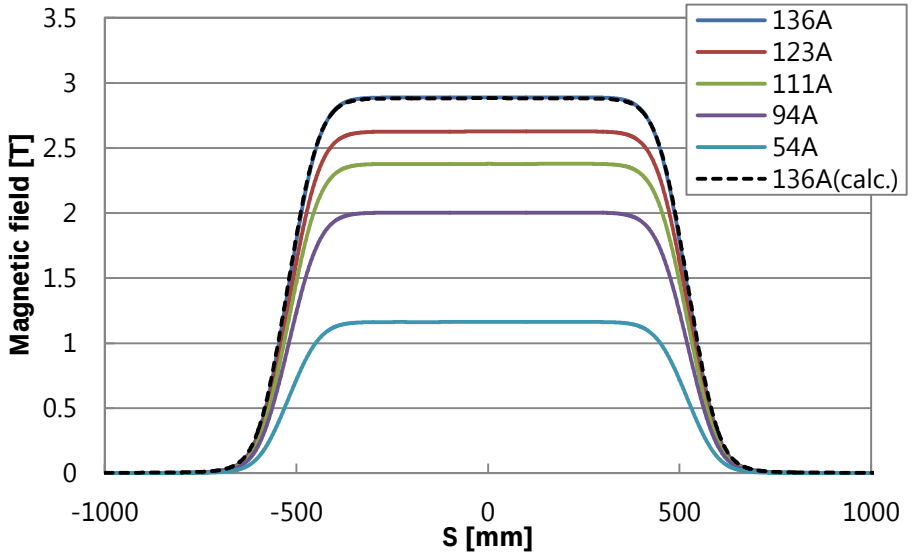
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

Design and Manufacturing of First LTS gantry

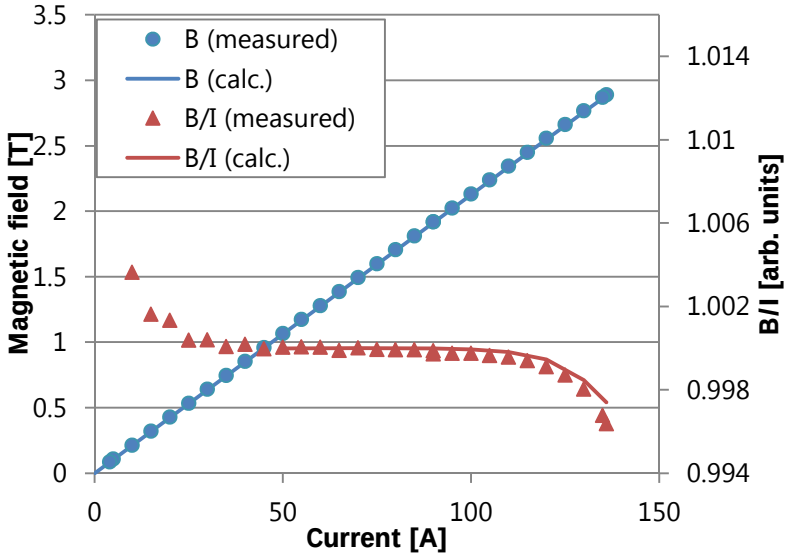
Measurement of magnetic field



The magnetic field of all manufactured LTS magnets were measured.



magnetic field profile (BM2)



B/I characteristics (BM2)

Y. Iwata et al., Proc. of PAC2013, Pasadena, CA USA, FRXB1

Design and Manufacturing of First LTS gantry

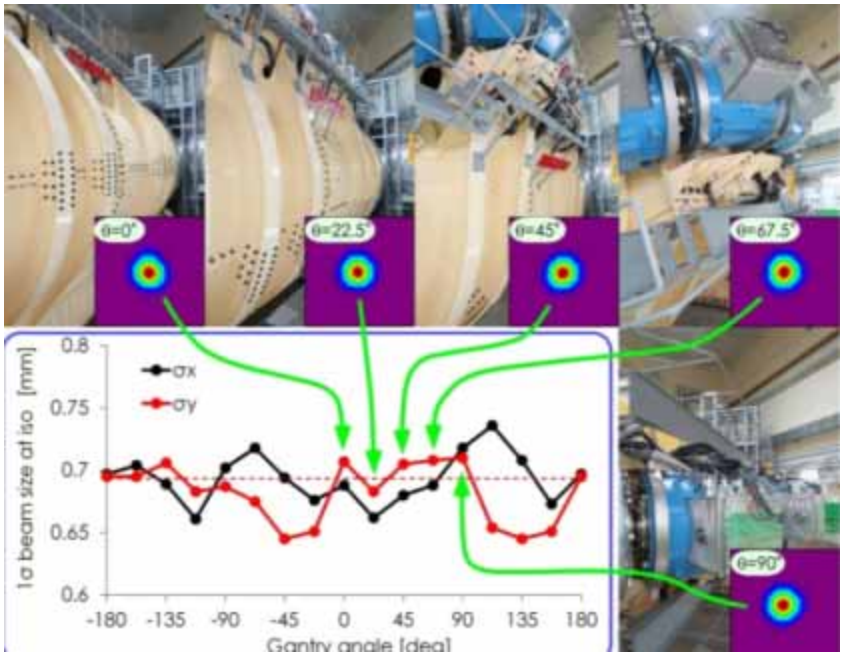
Construction of first LTS gantry

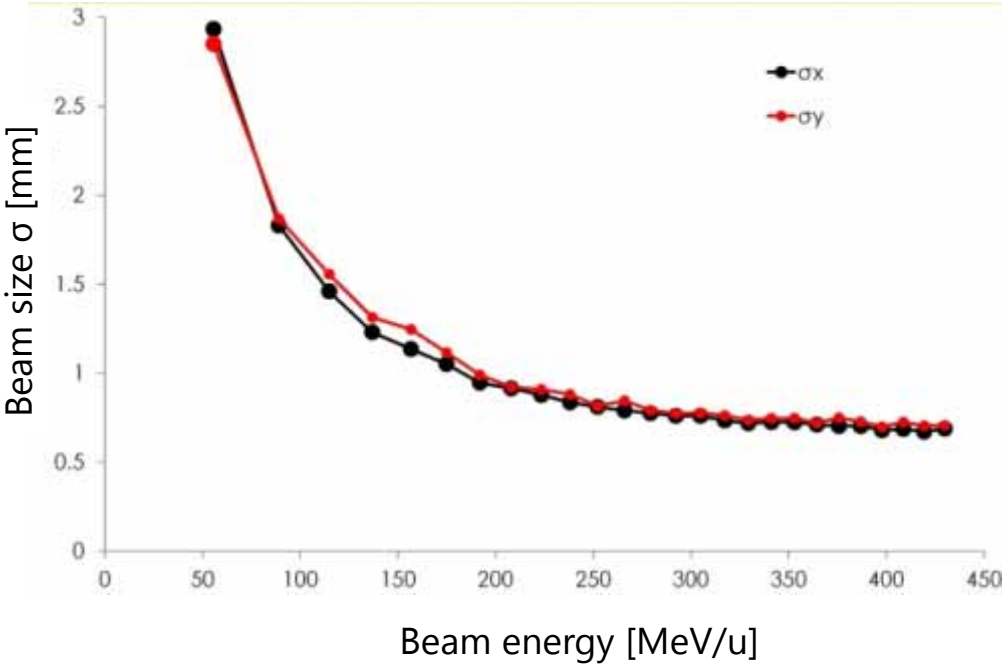
(By Courtesy of QST/NIRS)

Design and Manufacturing of First LTS gantry

Beam commissioning

Beam commissioning was complied successfully.
Treatment already started from 9th May 2017.





Y. Iwata et al., Proc. of the 13th PASJ, WEOL13.
Y. Iwata et al., Nucl. Instrum. and Meth. in Phys. Res. A834(2016)71.

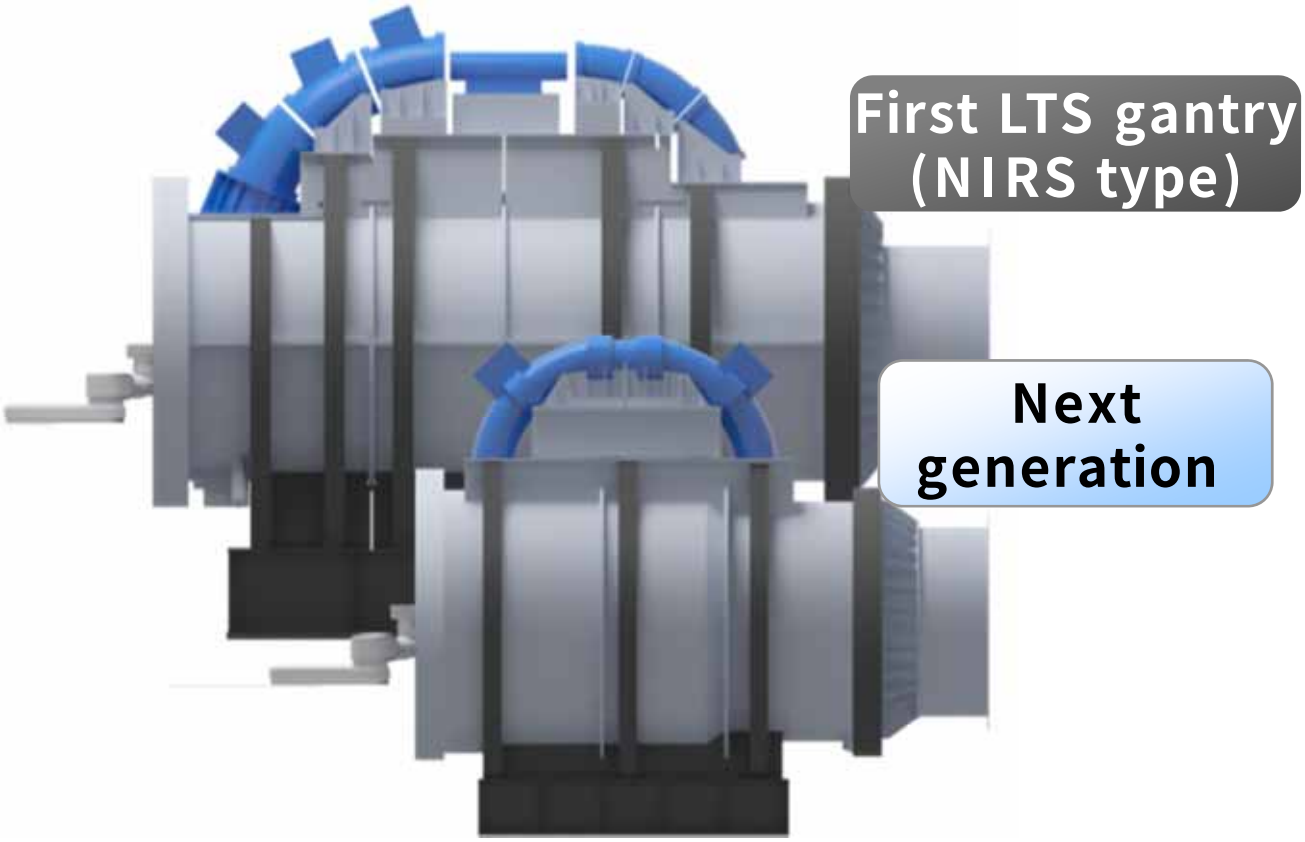
2013-2016 : R&D and Construction
2016-2017 : Commissioning

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

Recent Development of LTS gantry

Recent Development of LTS gantry

Next generation LTS gantry

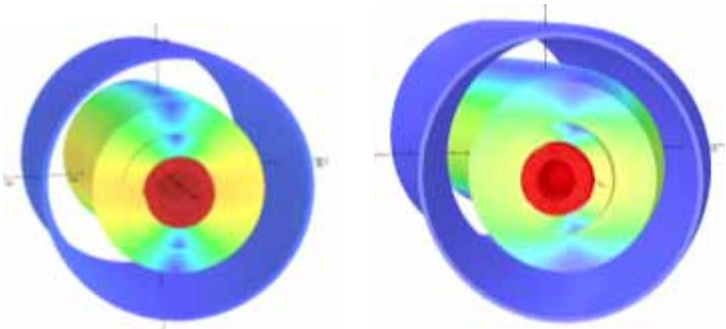


40% volume reduction

Recent Development of LTS gantry

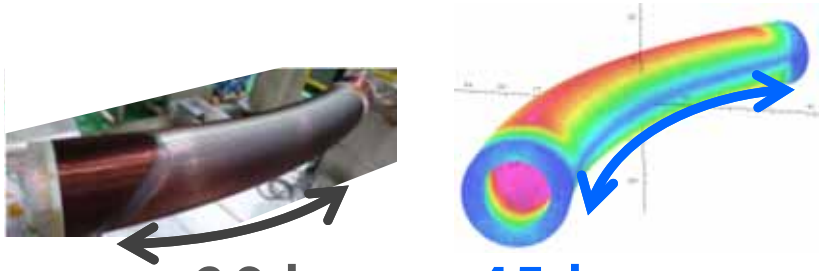
Point of downsizing

- High magnetic field



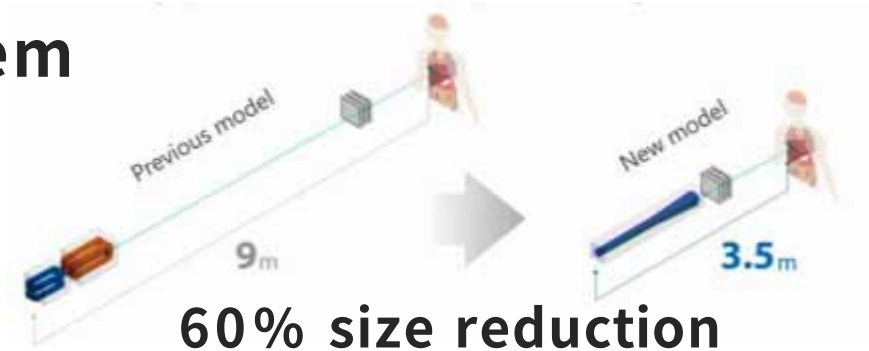
2.88T → 3T over at beam line

- Long length of SC coil



26deg. → 45deg.
large bending angle

- Short scanning system

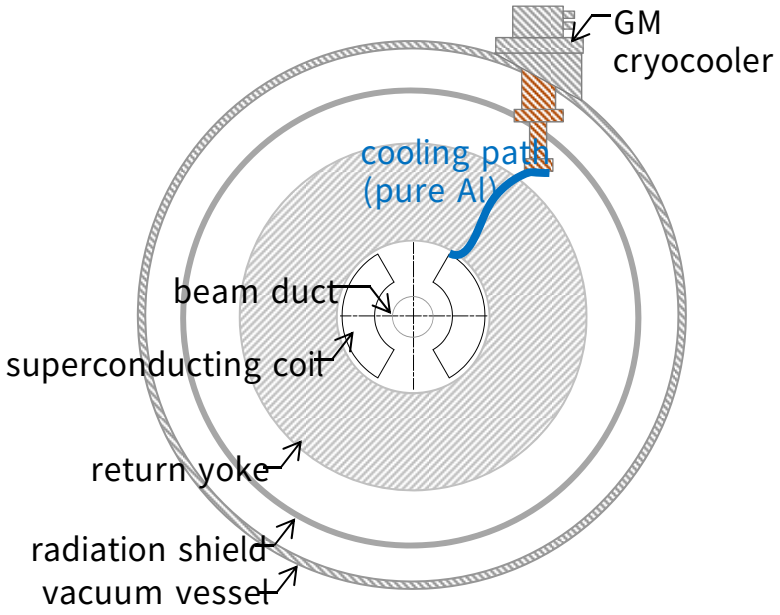


60% size reduction

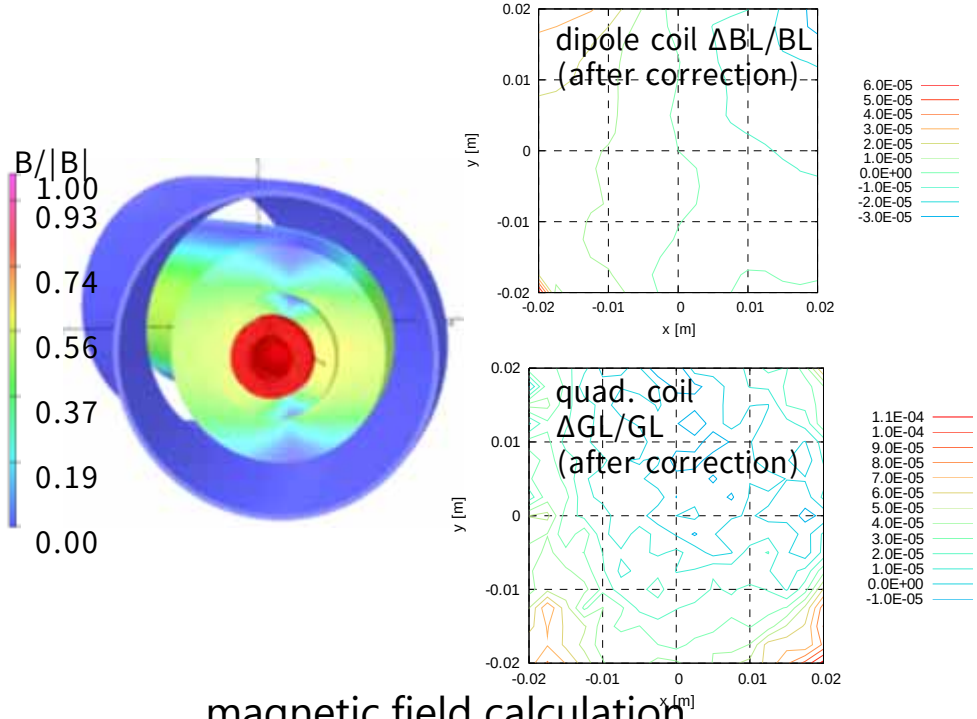
Recent Development of LTS gantry

Design of LTS magnet

The magnet was designed based on the conventional one so that the integral dipole and quadrupole field were uniform.



cross section of LTS magnet



magnetic field calculation

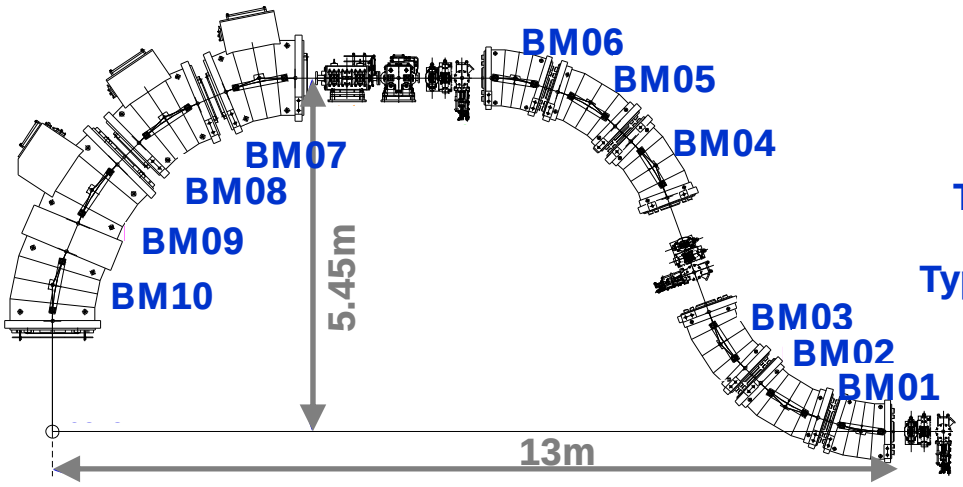
Fabrication of this LTS magnet is on-going

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

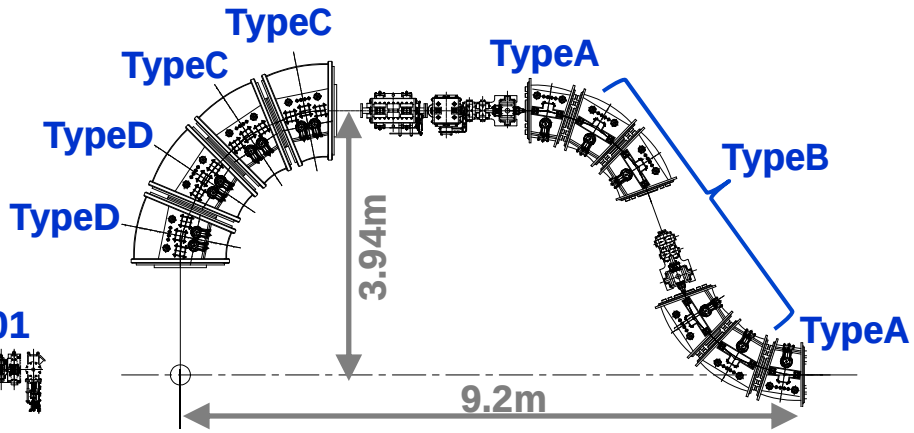
Future plan (HTS gantry)

Future plan (HTS gantry)

Magnet layout of HTS rotating gantry



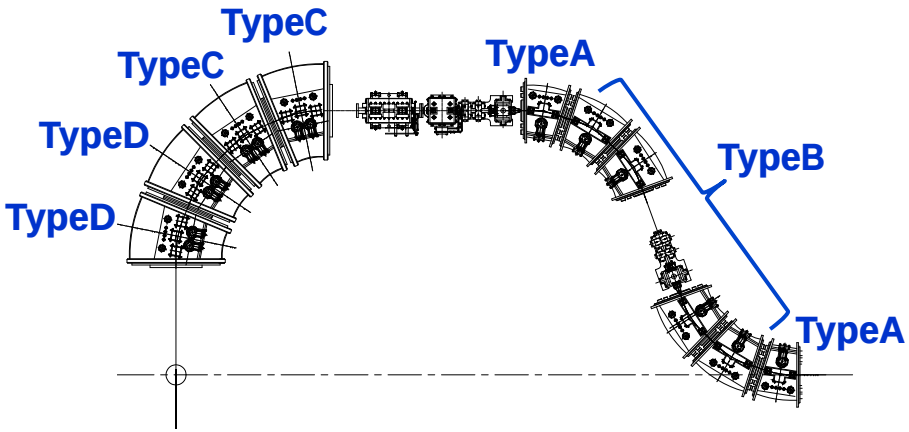
LTS rotating gantry



HTS rotating gantry

Layout of HTS gantry

Magnet layout of HTS rotating gantry



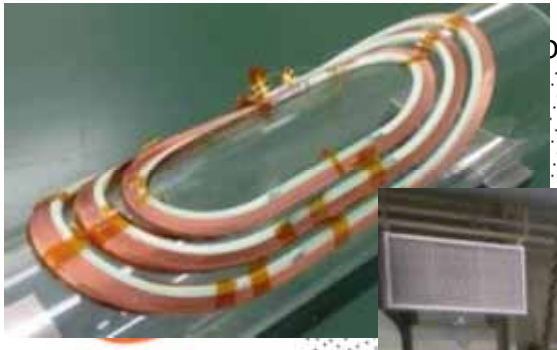
4 types of 10 magnets were employed

Specifications of HTS magnets

parameter	unit	Type A	Type B	Type C	Type D
Bending angle	deg.	18	26	22.5	22.5
Bending radius	m	1.15	1.15	1.5	1.5
Max. field (dipole)	T	5.8	5.8	4.5	4.5
Max. field (quad.)	T/m	15.5	33	-	1.7
Field uniformity (dipole)	-	$\leq 1\times10^{-3}$			
Field uniformity (quad.)	-	$\leq 1\times10^{-3}$			

Layout of HTS gantry

Model magnet fabrication



1/3 scale model magnet

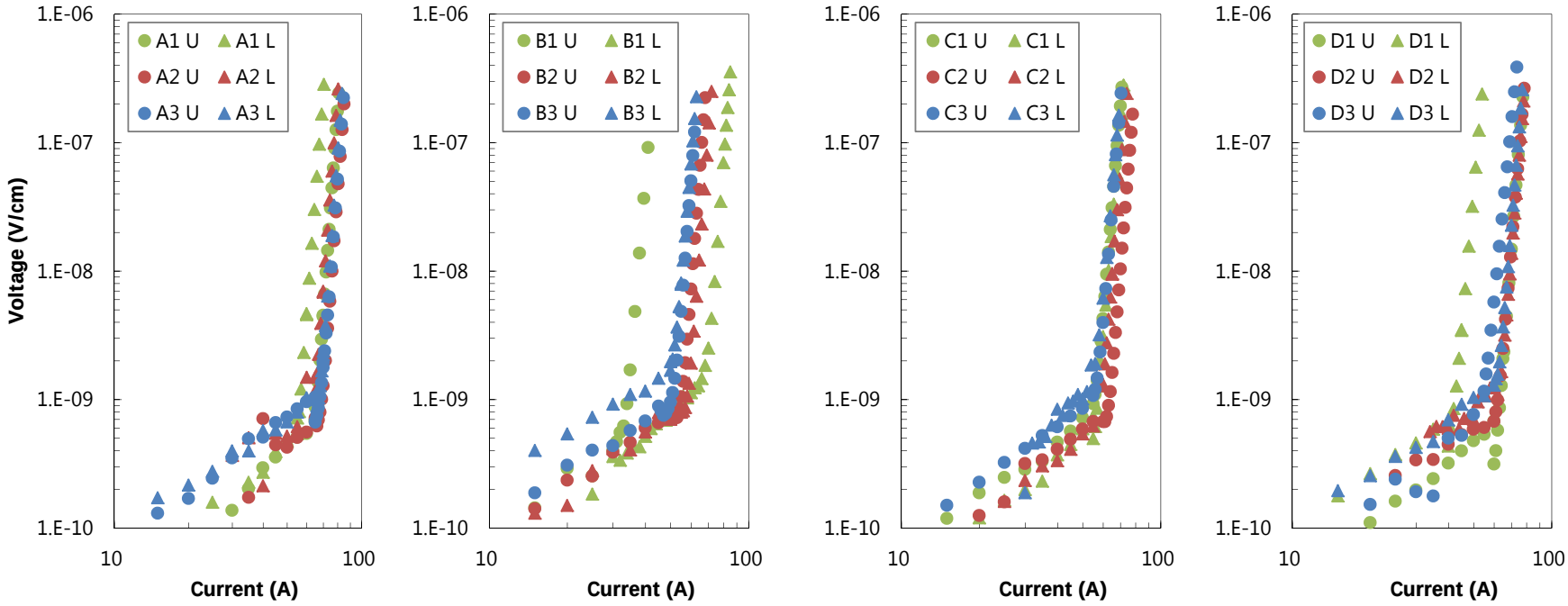
1/3 scale model magnet specifications

Magnet size	680 mm×1200 mm
Bore dia.	Φ60 mm
Central magnetic field	1.2T @ 150A
Wire length	820 m
Num. of REBCO coils	24
Num. of turn for each coil	50
Coil length	340 mm
Coil inductance	288.9 mH

Design and test results of HTS magnets

Degradation-free saddle-shaped HTS coil

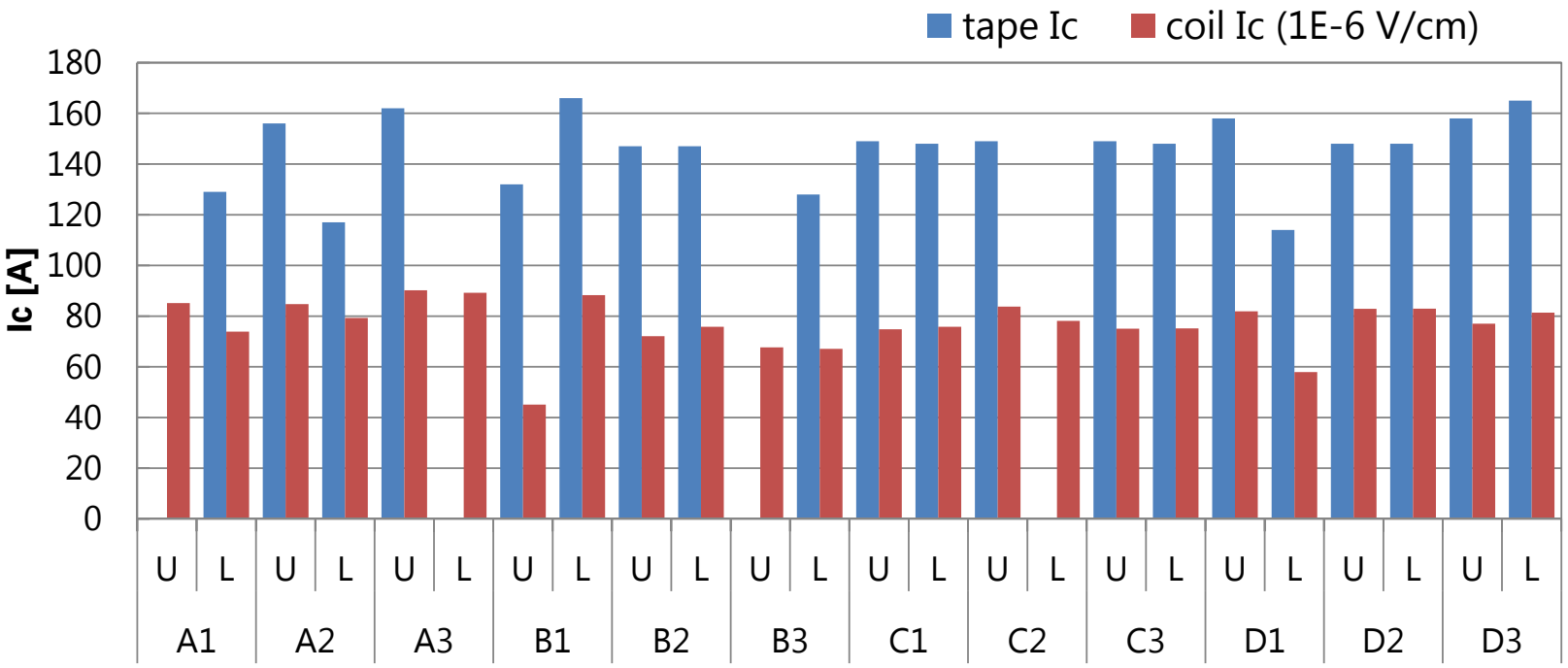
The superconducting properties of all saddle-shaped HTS coil were measured under a LN2 environment.



Design and test results of HTS magnets

Degradation-free saddle-shaped HTS coil

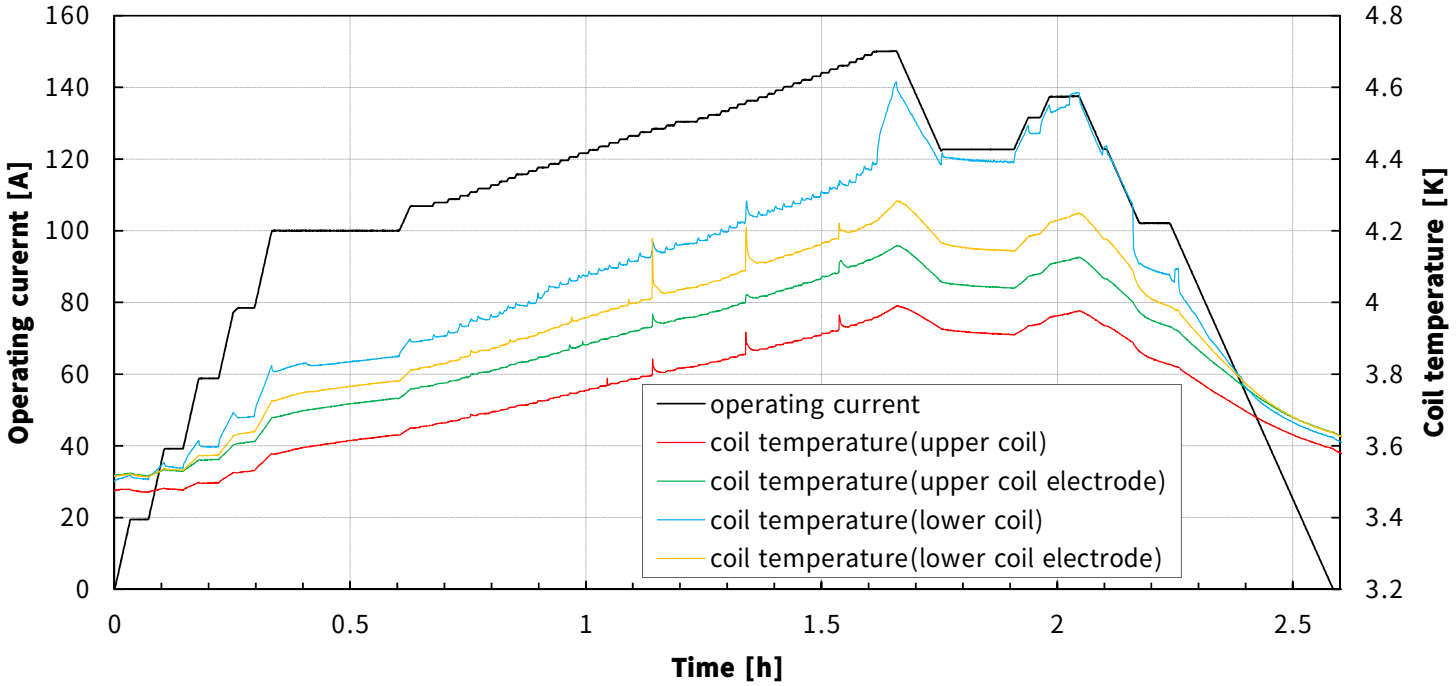
The superconducting properties of all saddle-shaped HTS coil were measured under a LN2 environment.



Design and test results of HTS magnets

Excitation test

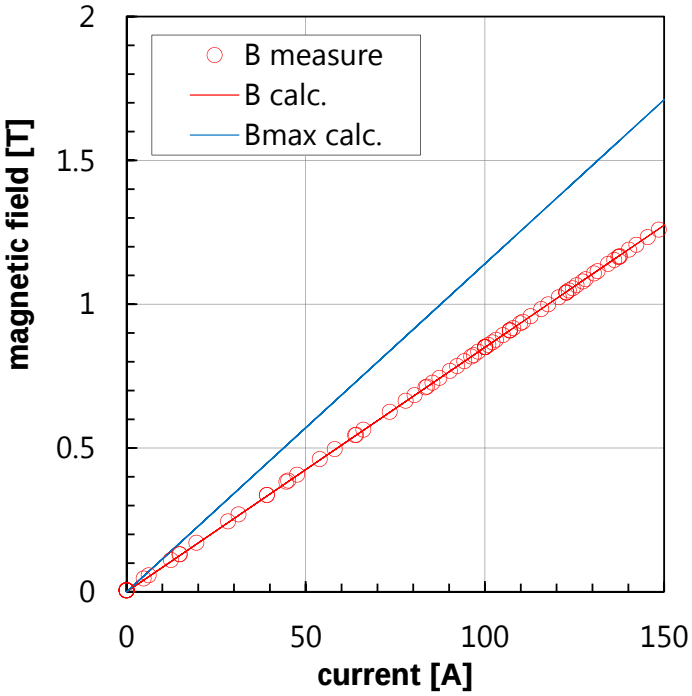
After assembly of the model magnet, excitation test were carried out.
Operating current was increased up to 153 A.

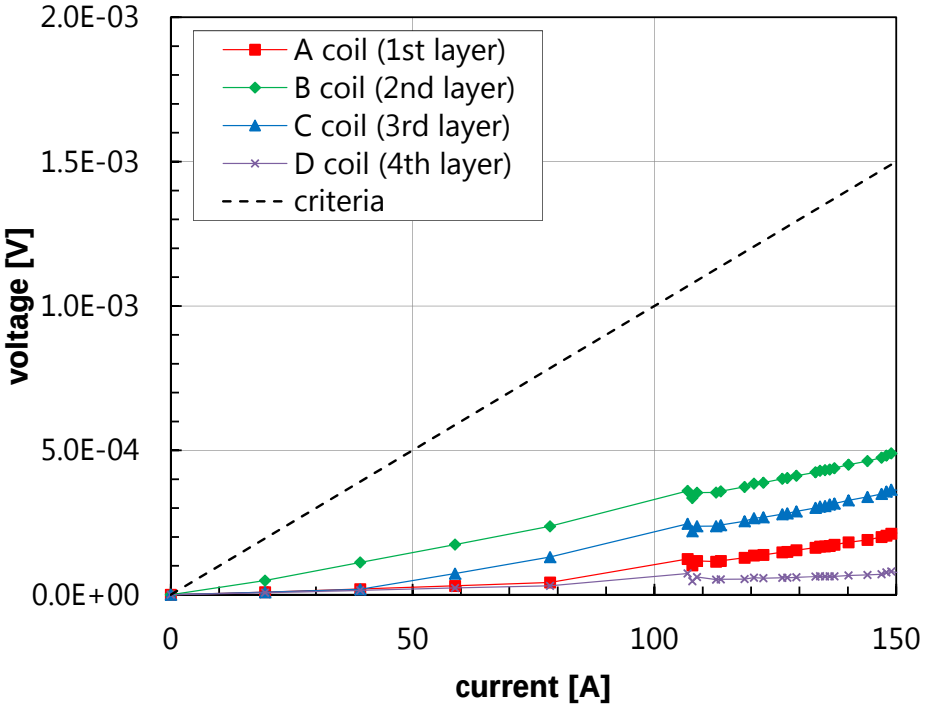


Design and test results of HTS magnets

Excitation test

The generated magnetic field at the center of the beam duct was 1.2 T.

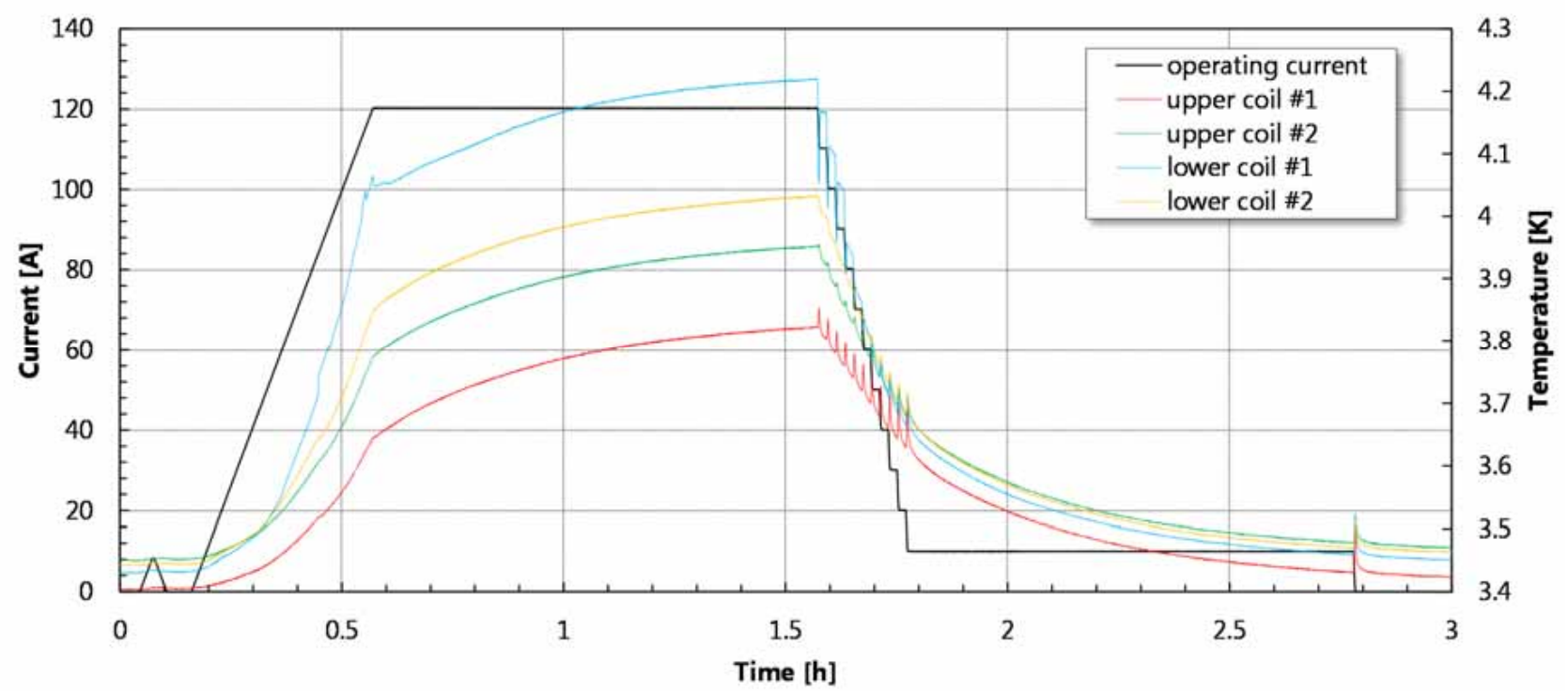




Design and test results of HTS magnets

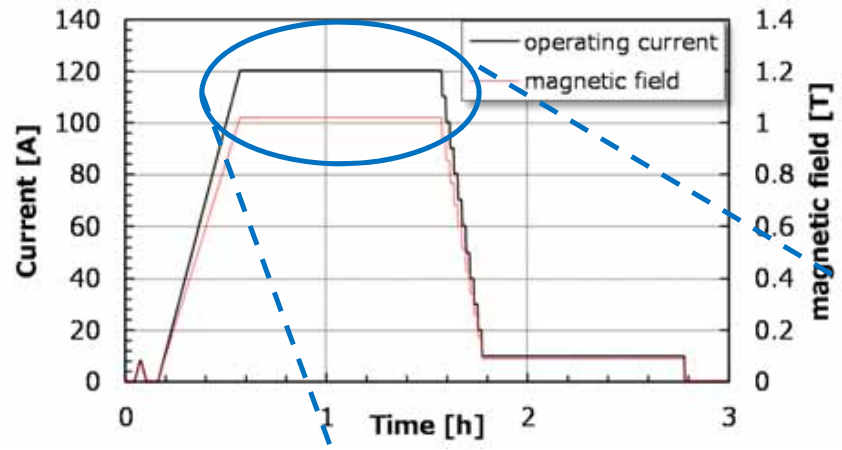
Pattern excitation test

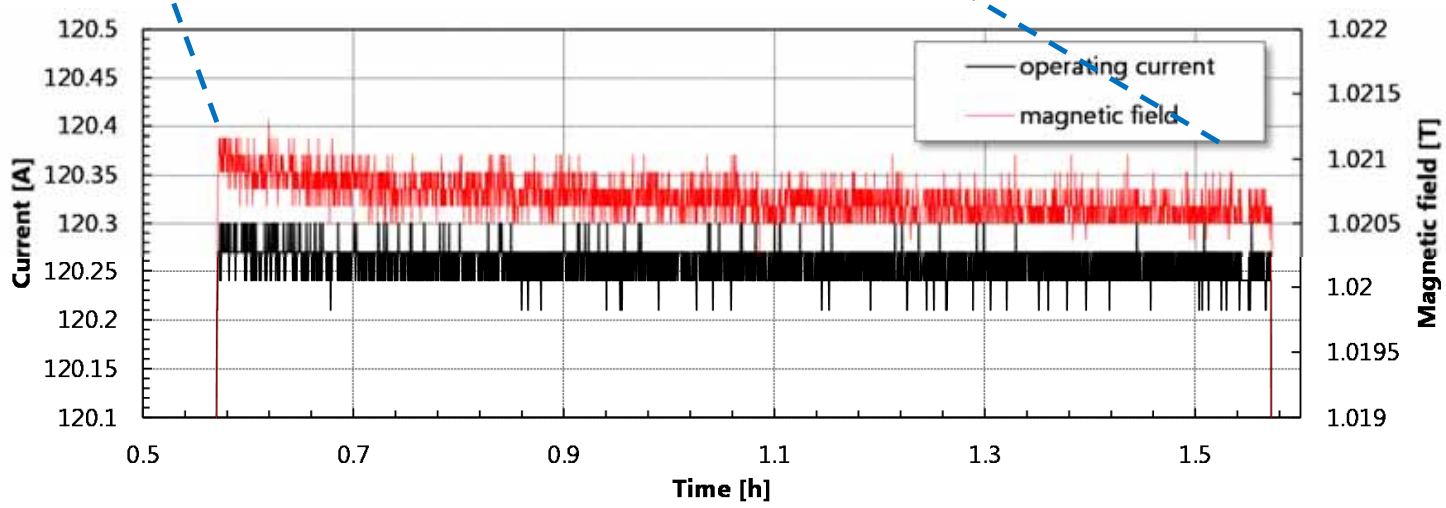
Current was increased up to 120A and kept it for an hour.
Current was decreased in 10 steps, maintaining the last step for another hour



Design and test results of HTS magnets

Pattern excitation test





magnetic field declined.
Although the decline was less than 0.1 %, it was a significant decrease compared to the operation current.
magnetization?

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

Conclusion

To reduce the size of the rotating gantry for heavy-ion radiotherapy, we have been developing LTS magnets and HTS magnets.

LTS gantry

- The first LTS gantry was successfully manufactured, and therapeutic irradiation as a clinical trial is on-going.
- For the purpose of further downsizing of the gantry, We are developing new LTS magnet and scanning system, and the fabrication is on-going

HTS gantry

- For the future technology, saddle- shaped HTS coils and model magnet was fabricated.
- The model magnet could generate a magnetic field of 1.2 T at the center of the beam duct.
- The results of pattern excitation test were positive.
- Further investigation of the model magnet is on-going.

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation 2LO1-01 given at EUCAS 17-21 September 2017, Geneva, Switzerland.