2LO3-05

Stability Analysis of the 100 kA-class HTS STARS Conductor

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National Institute for Fusion Science
Tohoku University

Helical fusion reactor FFHR-d1

LHD-type Helical Fusion Reactor FFHR-d1

Major radius of Helical coil : 15.6 m
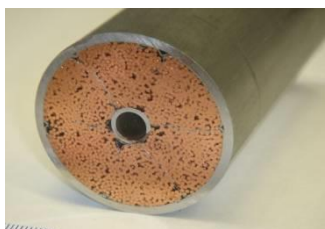Center Magnetic Field of HC : 4.7 T
Maximum Magnetic Field : 12 T
Operating Current : 94 kA
Stored Magnetic Energy : ~160 GJ

LTS option

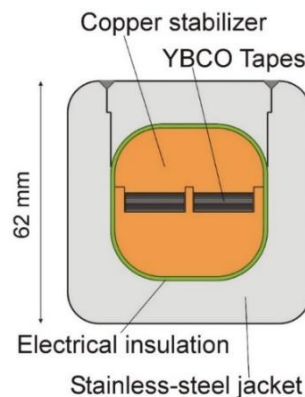Force-cooled Cable-in-conduit conductor

Indirect-cooled LTS conductor

HTS option

Helium gas cooled HTS conductor

Copper stabilizer
YBCO Tapes
62 mm
Electrical insulation
Stainless-steel jacket

Major Specifications

Operation current	94 kA @12 T
Operation temp.	20 K
Conductor size	62 mm × 62 mm
Current density	24.5 A/mm^2
Number of tapes	40
Cabling method	Simple Stacking

HTS option for FFHR-d1
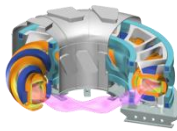
- Magnets of helical fusion reactor is basically DC operation.
- Specific heat at elevated temperature (~20 K) is larger than that of 4 K.
- HTS has high cryogenic stability.

Simply-Stacked HTS Conductor

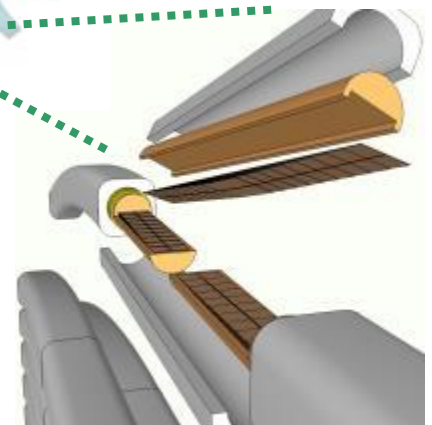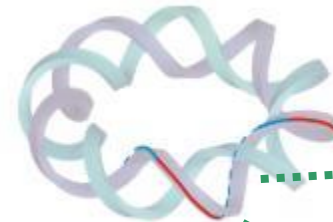Stacked Tapes Assembled in Rigid Structure (STARS) Conductor

➢ Conductor with a simple stacking of HTS tapes imbedded in a stabilizing copper jackets and rigid stainless steel jacket

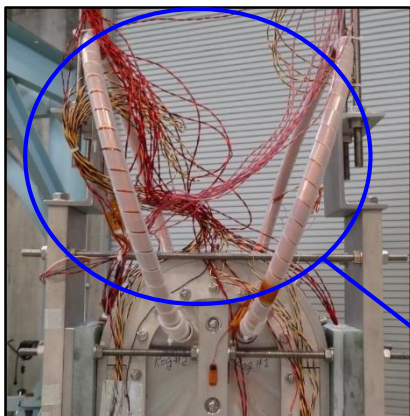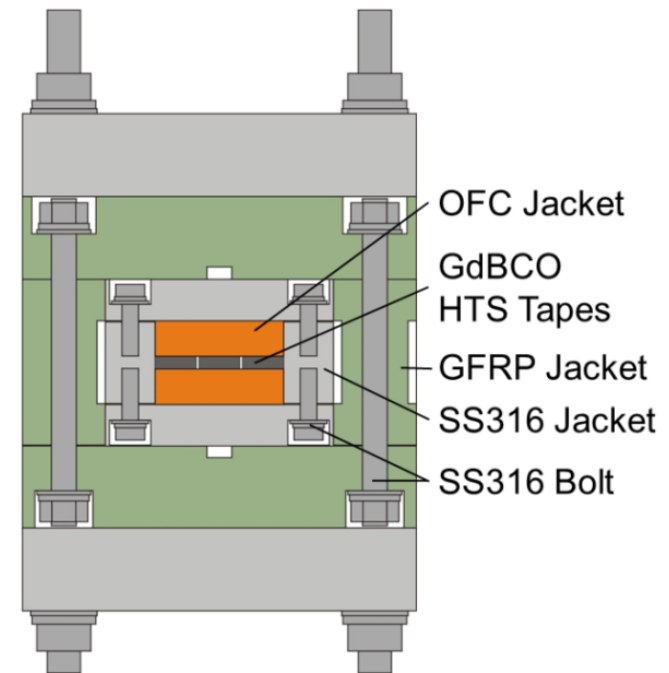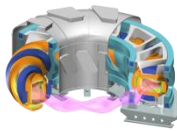10 kA-class conductor   100 kA-class conductor for FFHR-d1

✓ AC loss is not big problem at steady-state operation.
✓ Coils are constructed by connecting segmented conductors.
✓ Conductor has a rigid structure. (No voids)
✓ Refrigeration power is low at elevated temperature.
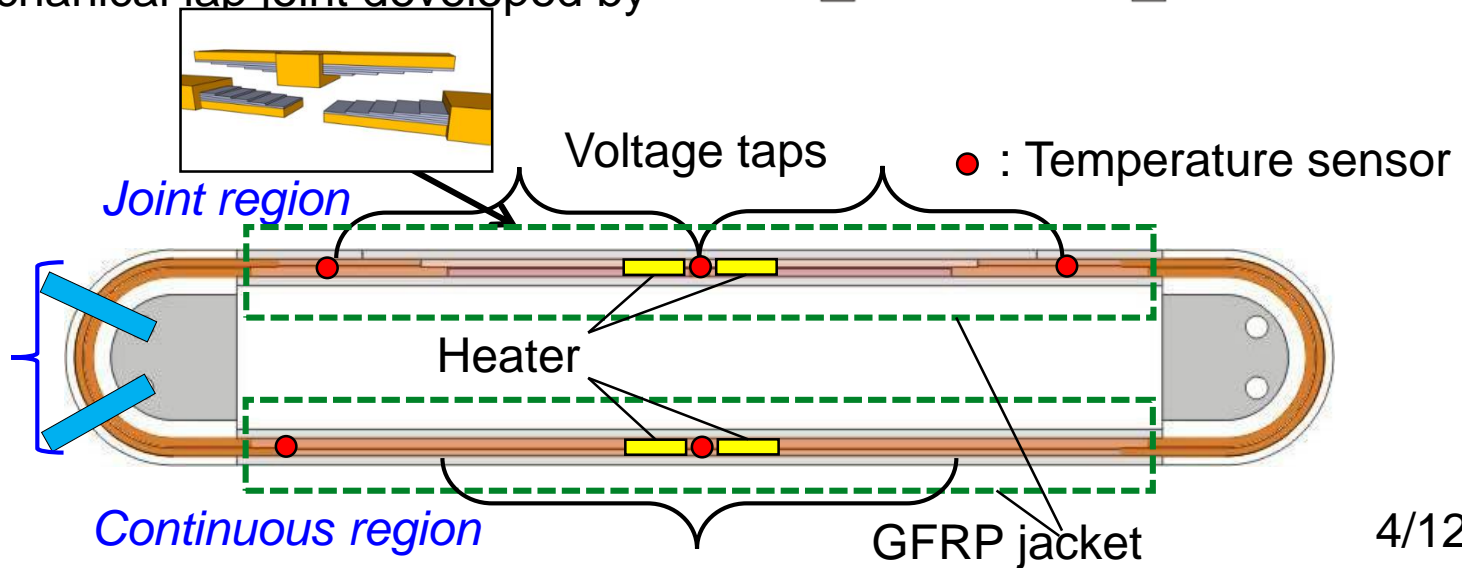✓ Non-uniform current distribution may be allowed by high cryogenic stability and current transfer among tapes

Joint-winding method

Large Current STARS conductor sample

- 54 (or 20) GdBCO tapes（manufactured by Fujikura Ltd., $I_C \sim 600A@77K$, s.f.）simply stacked in a copper jacket in 100-kA (or 30-kA) sample
- The copper jacket installed in a stainless-steel jacket by bolts
- Temperature sensors, heaters and voltage taps attached on the stainless-steel jacket
- GFRP blocks around the conductor for thermal insulation
- Short-circuit sample having the joint region
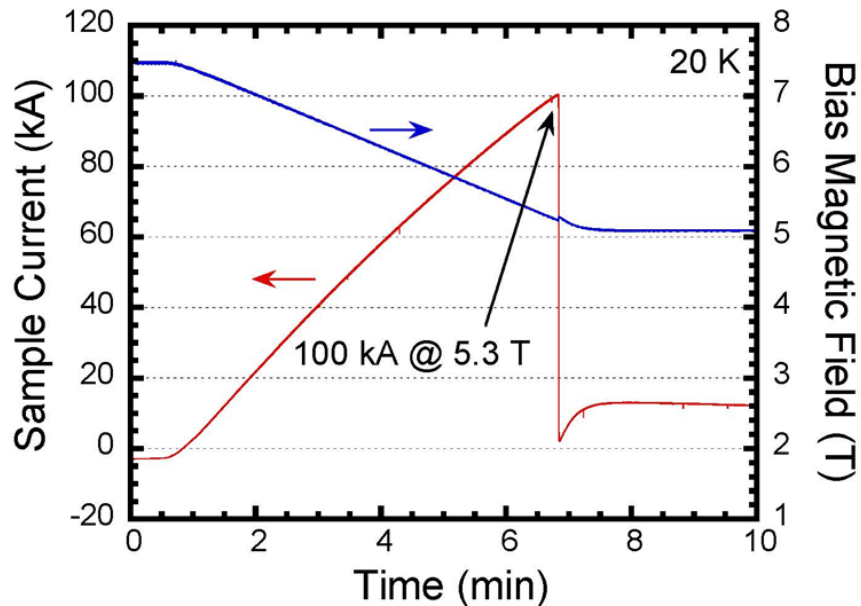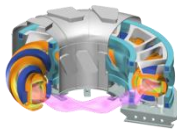- Bridge-type mechanical lap joint developed by Tohoku Univ.

OFC Jacket
GdBCO HTS Tapes
GFRP Jacket
SS316 Jacket
SS316 Bolt

Rogowski coil

Joint region

Voltage taps

● : Temperature sensor

Heater

Continuous region

GFRP jacket

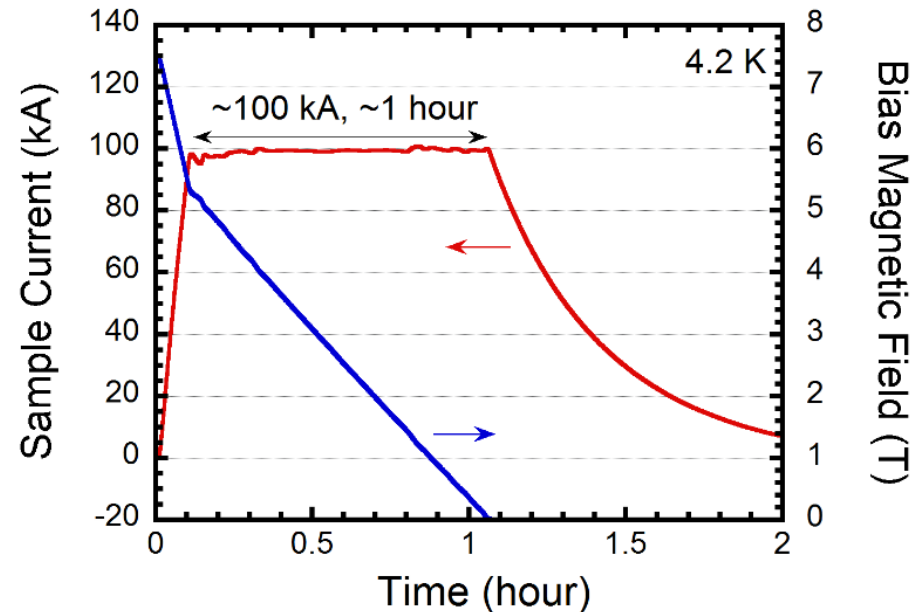# Results of 100 kA sample test
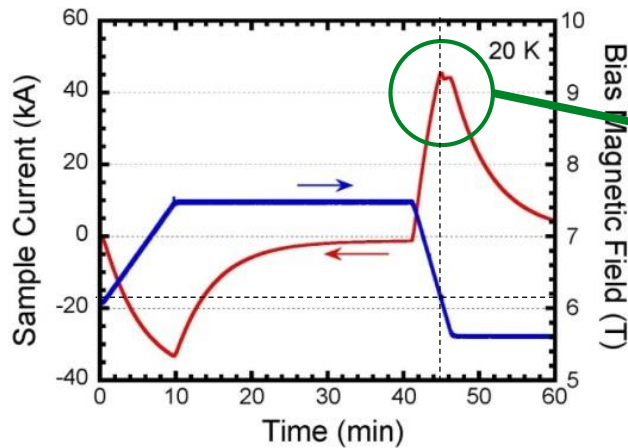
- **Sample current reached 100 kA @ 20 K, 5.3 T.**

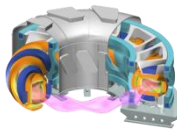- **100 kA for 1 hour**

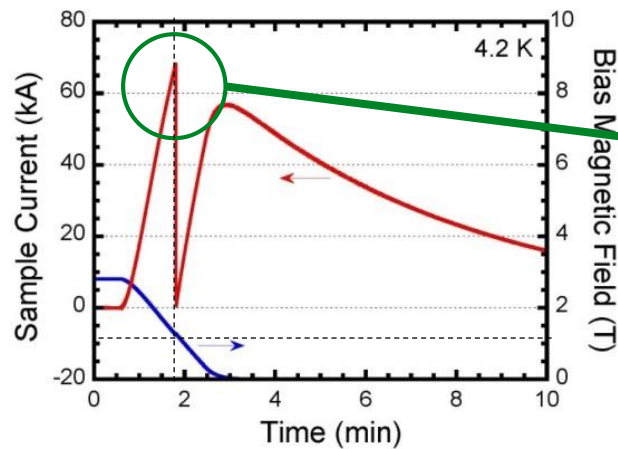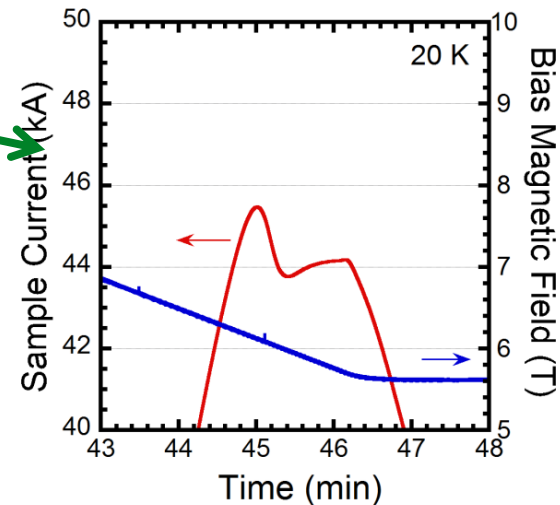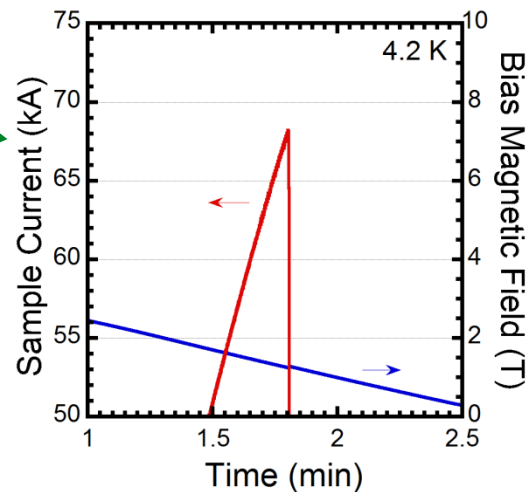 Control of the sweep rate of the external magnetic field

Quench didn't occur.
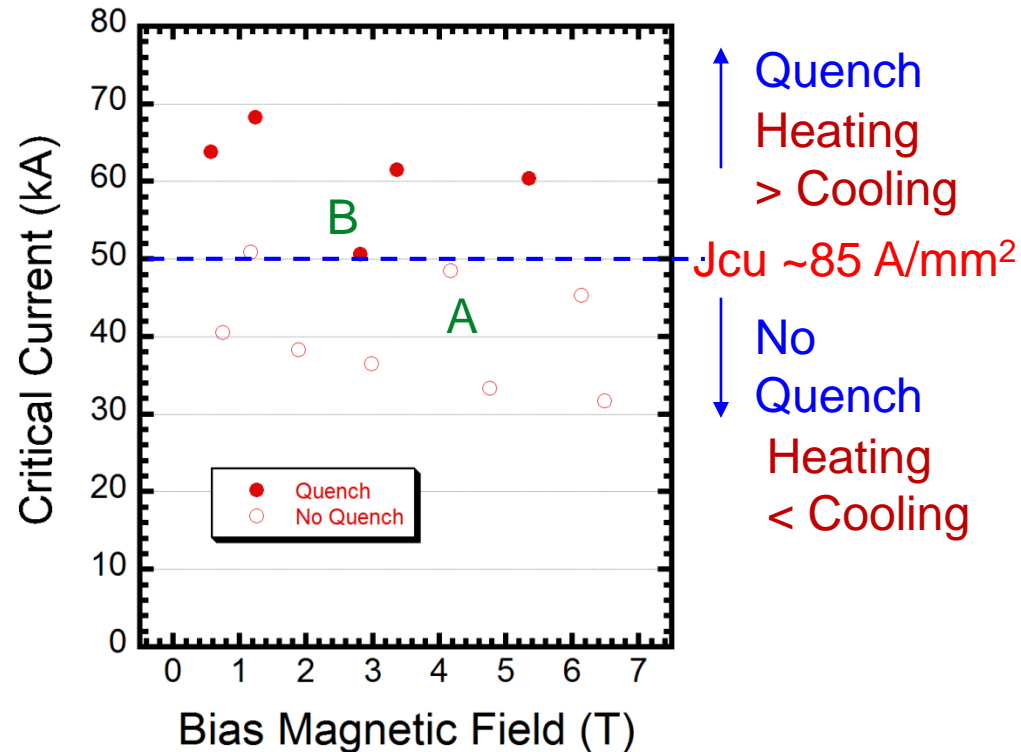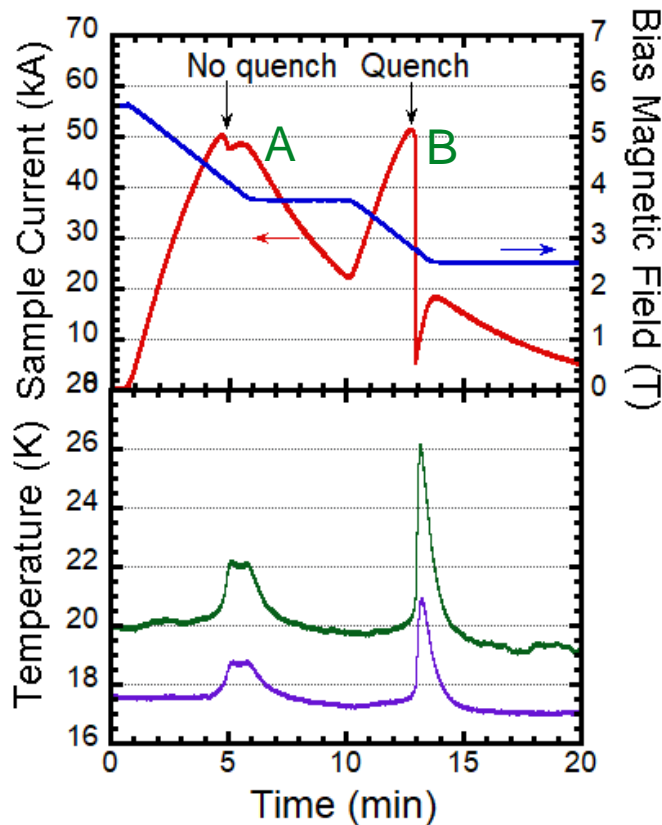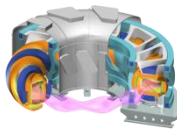
Quench occurred.

➢ Thermal balance between Joule heating in the conductor and cooling by thermal conduction along to the conductor
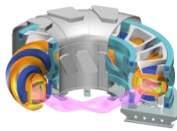
When reaching the critical current, a slight difference in current leads to a quench or a no-quench.

A coupled analysis of heat and electromagnetic transfers is carried out for reproducing the current transport characteristics of the HTS STARS conductor.

One-dimensional thermal conduction equation

$$\mathrm{d}c(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\lambda(T)\frac{\partial T}{\partial x} + Q$$

$$Q = \frac{R_{sc}(T)I_{sc}^{2} + R_{m}(T)I_{m}^{2}}{S}$$

T : Temperature (K)

t : time (s)

x : Longitudinal position (m)

λ : Thermal conduction (W/m/K)

Q : Dissipation density (W/m^3)

d : Conductor density (kg/m^3)
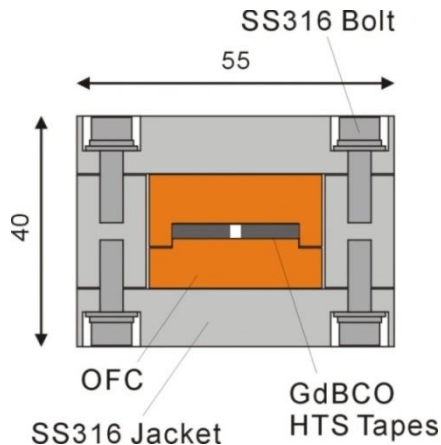
c : Specific heat (J/kg/K)

R_{sc} : Resistivity of superconductor (Ω/m)
（Percolation model）

R_{m} : Resistivity of matrix (Ω/m)
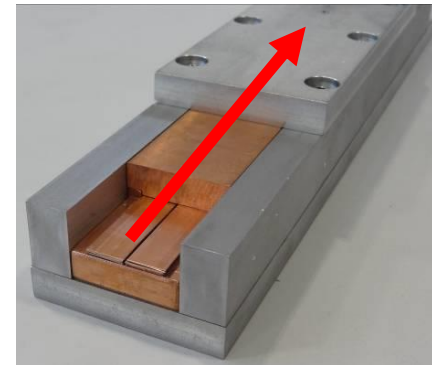
I_{sc} : Current in superconductor (A)

I_{m} : Current in matrix (A)

S : Cross-sectional area (m^2)

Cross-sectional image of 30 kA sample

Longitudinal direction
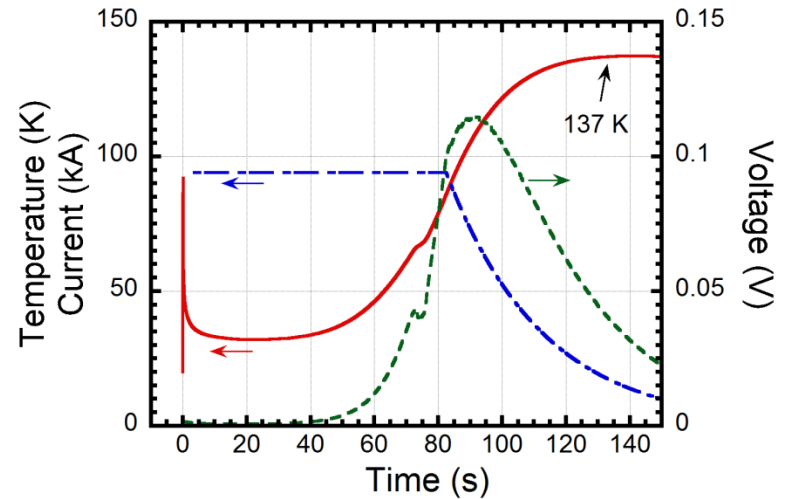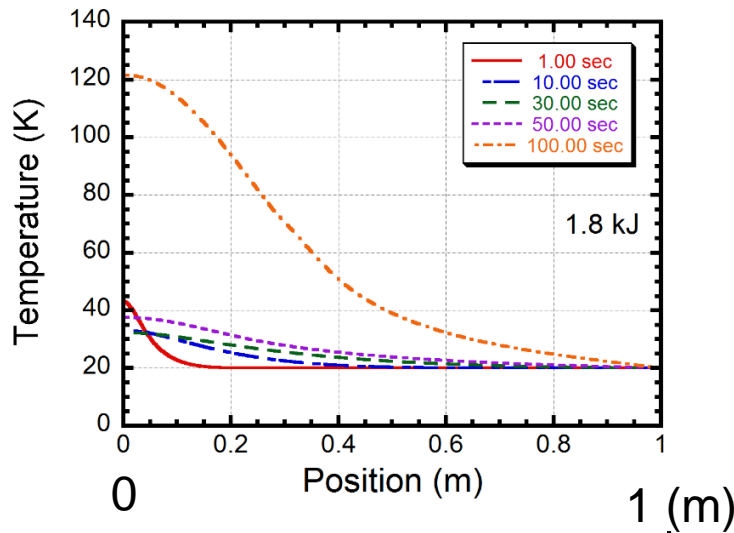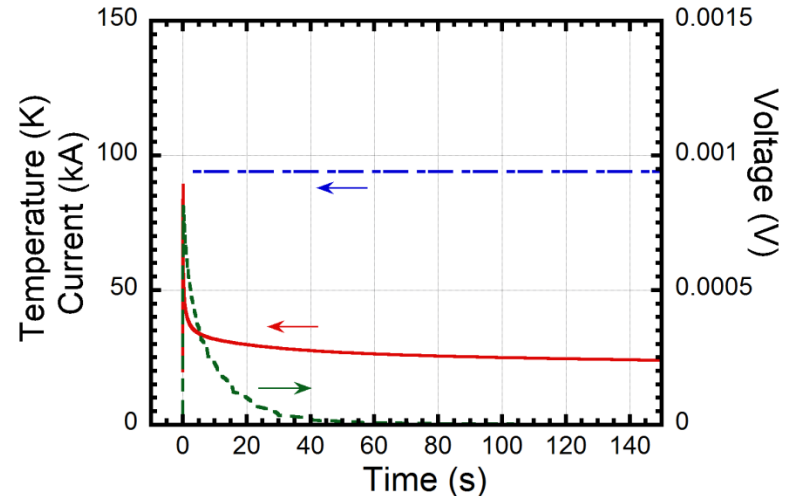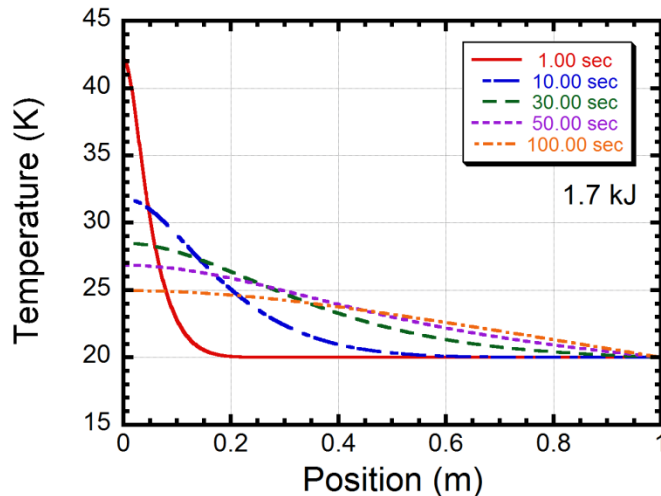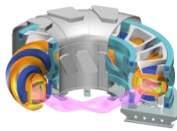
Hotspot temperature analysis for FFHR-d1

- Hotspot temperature was examined for the FFHR-d1 HTS option using the thermal analysis part of the simulation code before carrying out the cryogenic stability analysis.

- Initial current of 94 kA, Initial magnetic field of 12 T, Initial temperature of 20 K (The critical current of 120 kA@12 T, 20 K)
- Calculation region of 1 m
- The left side of the region (x = 0 m) is an adiabatic boundary condition, the other side (x = 1 m) is a fixed boundary condition.
- Heat flux is applied to the left side for 0.1 s to initiate a normal state in the conductor.
- When the voltage exceeds 0.1 V, the current is exponentially decreased with a time constant of 30 s.

0   1 (m)
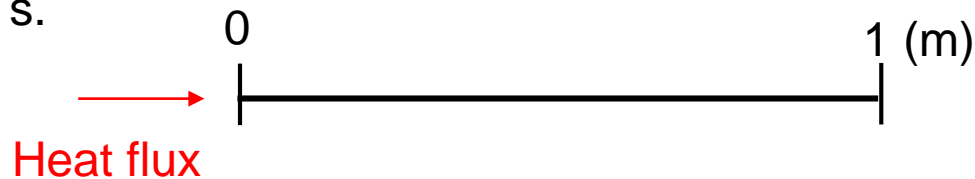
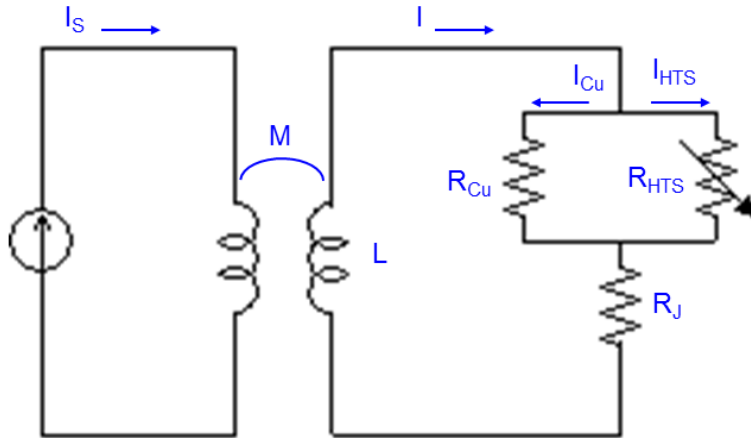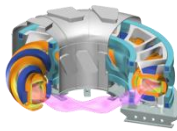Heat flux

Longitudinal direction

Results of hotspot analysis

Normal state does not expand with heat flux of 1.7 kJ, but expands with that of 1.8 kJ.

➢ Hotspot temperature：137 K

Electrical circuit analysis

Equivalent electrical circuit of the sample tests

Sample Current

Time (s)

$$M \frac{\mathrm{d}I_{\mathrm{ex}}}{\mathrm{d}t} = L \frac{\mathrm{d}I}{\mathrm{d}t} + R_{\mathrm{j}}I + R_{SC}I_{\mathrm{SC}}$$

$$R_{\mathrm{SC}}I_{\mathrm{SC}} = R_{\mathrm{Cu}}I_{\mathrm{Cu}}$$

$$I = I_{\mathrm{HTS}} + I_{\mathrm{Cu}}$$

M : Mutual Inductance (H)

L : Self Inductance of sample (H)

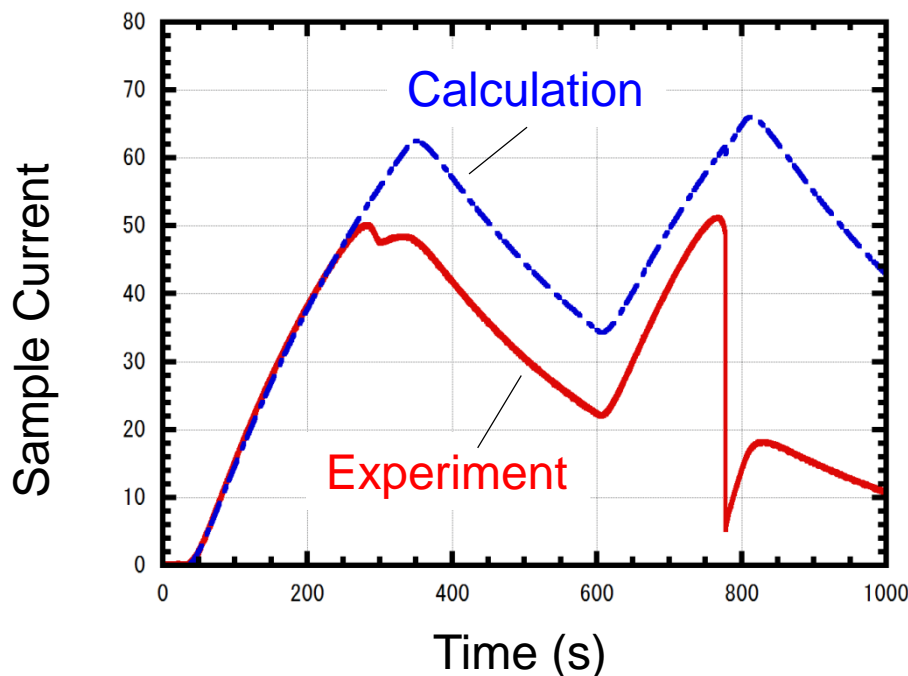R_{sc} : Resistivity of superconductor (Ω/m)
（Percolation model）

R_{Cu} : Resistivity of copper jacket (Ω/m)

I : Current of sample (A)

I_{ex} : Current of external field coil (A)

I_{sc} : Current in superconductor (A)

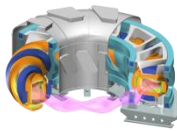I_{Cu} : Current in copper jakect (A)

Experimental results were partially reproduced.
→A coupled analysis is in progress.
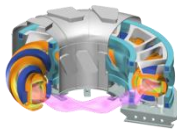
Summary and Future tasks

- HTS STARS conductor is developing for the helical fusion reactor.
  - ➤ Large current (100 kA and 30 kA) conductor tests were carried out.
  - ✓ 100 kA@20 K, 5.3 T was reached and 100 kA was kept for 1 hour.
  - ✓ Quench didn't occur below the current density in copper of 85 A/mm^2.

- A coupled analysis of heat and electromagnetic transfers is carried out for reproducing the current transport characteristics of the HTS STARS conductor.
  - ✓ Heat transfer analysis was applied to the hotspot analysis for FFHR-d1
    - ➤ Hotspot temperature : 137 K (Optimistic condition)
  - ✓ The equivalent electrical circuit model partially reproduced the experimental result.
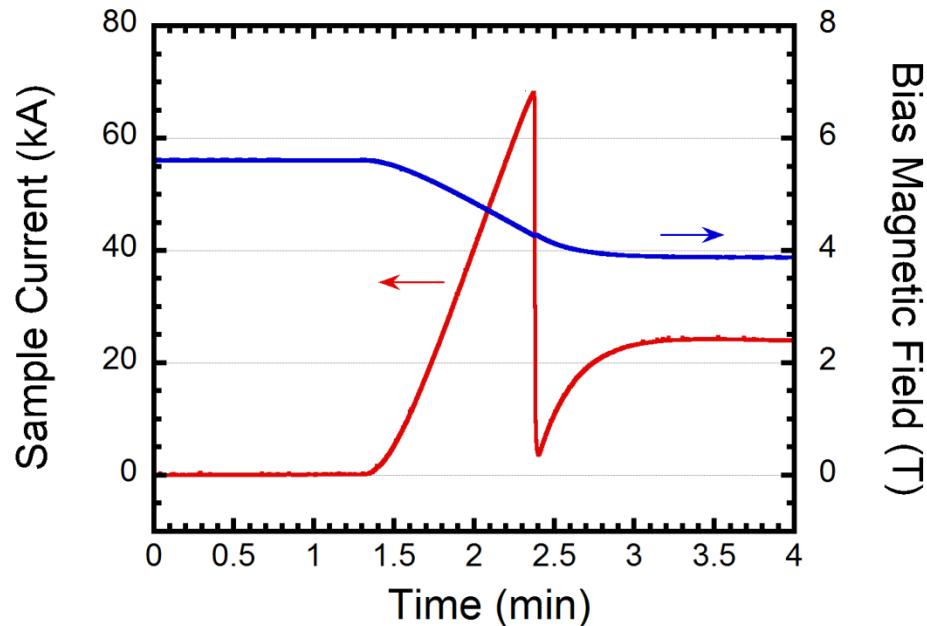
Future tasks

☐ Coupled analysis will be carried out.

☐ Design of helical coils will be proceed using the coupled analysis code.

- I_C measurement

Voltage-current characteristic

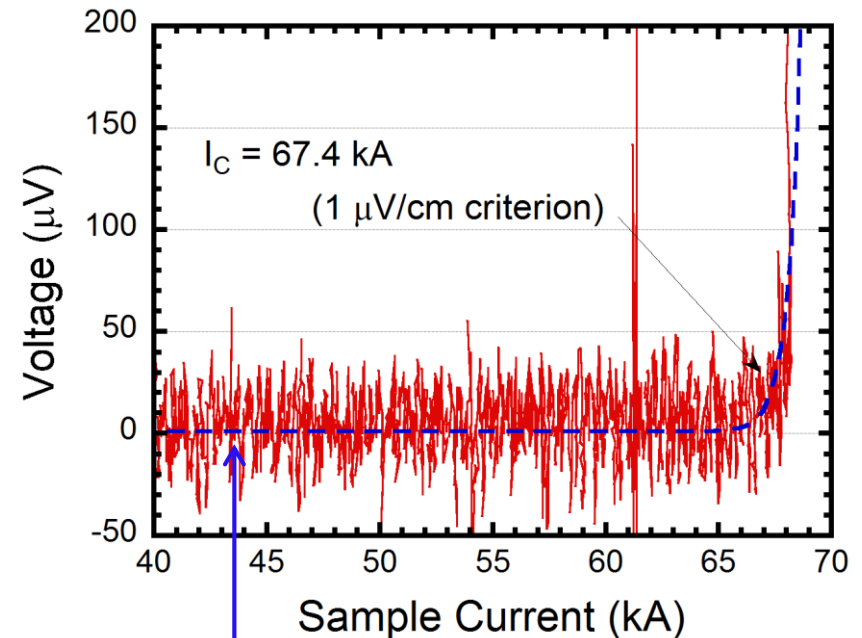Sweep rate ~ 1 kA/s

- I_C = 67.4 kA@"45 K", 4.3 T
- I_C = 72.6 kA@"45 K", 2.8 T

  (*) temperature on the stainless-steel jacket
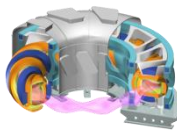
I_C = 67.4 kA

(1 μV/cm criterion)

$$V = V_C \left(\frac{I}{I_C} \right)^{n}$$

Voltage criterion, V_C = 20 μV
(Electric field criterion, E_C = 1 μV/cm
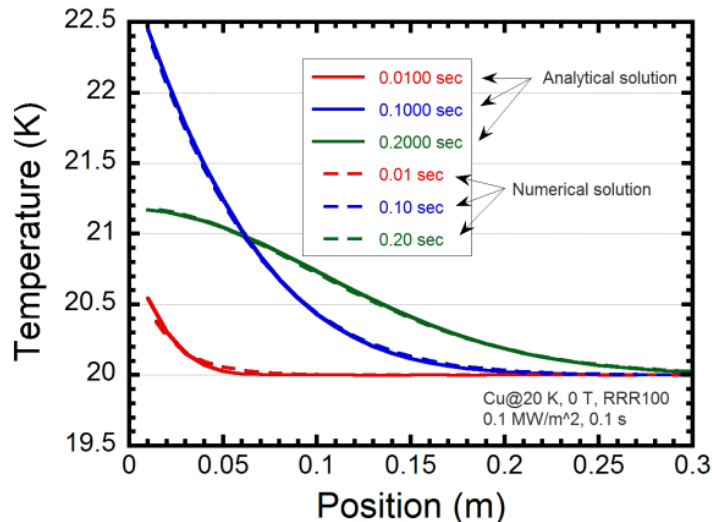distance of the voltage taps = 20 cm)

➢ 計算コードの検証1

$$dc\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\lambda\frac{\partial T}{\partial x}$$
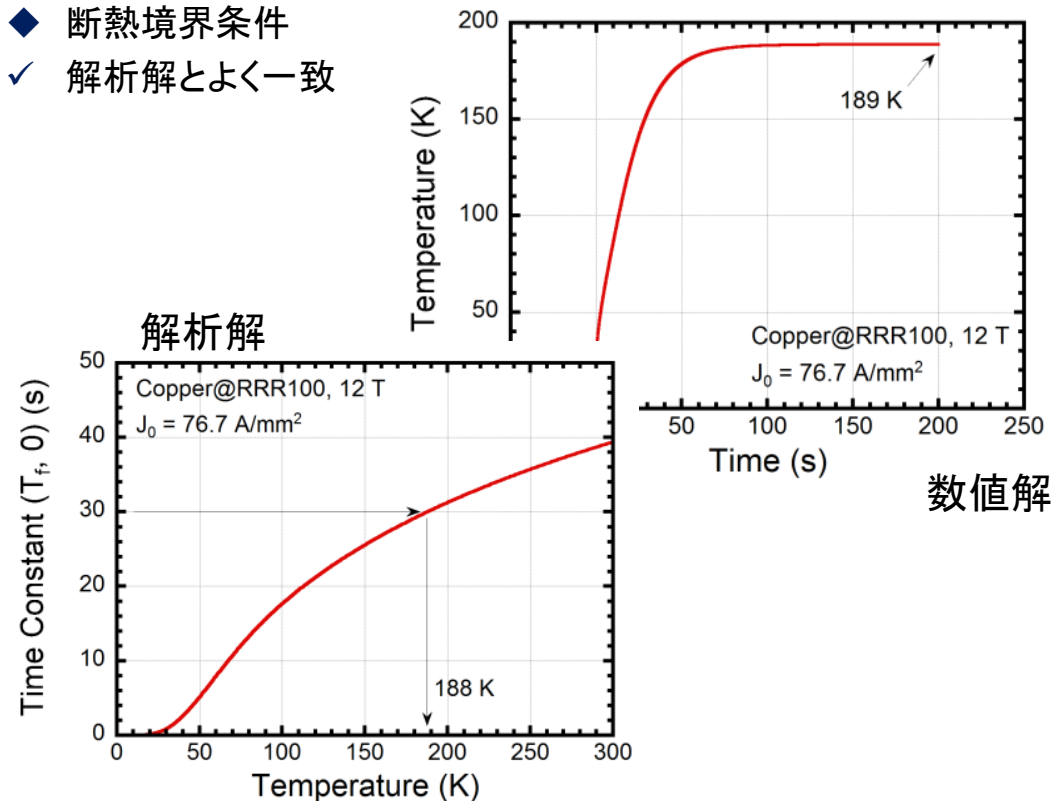
◆ 解析解（線形非定常解）と比較
◆ 無限平板で厚さ1 mの銅（20 K, 0 T, RRR100）にx = 0 mから熱流束0.1 MW/m²を0.1秒間入熱
◆ 断熱境界条件
◆ 内部発熱は無し
✓ 解析解とよく一致
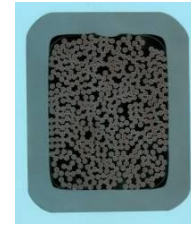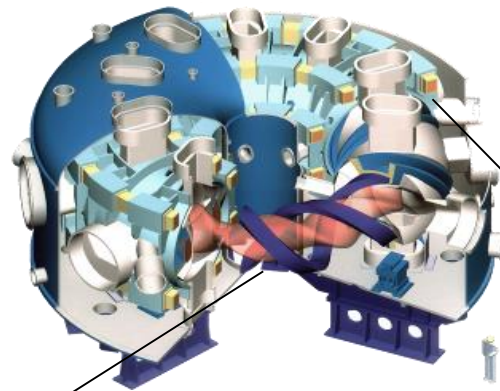
➢ 計算コードの検証2

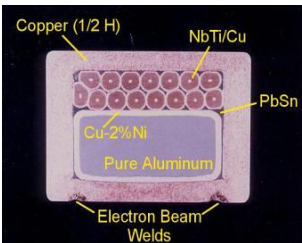$$dc(T)\frac{\partial T}{\partial t} = \rho(T)j^2, \quad j = j_0 e^{-t/\tau}$$

◆ 0次元ホットスポット解析（非線形定常解）
◆ 電流密度 76.7 A/mm² で銅（12 T, RRR100）に流れる電流を時刻 t = 0 sから時定数30秒で外部抵抗によって遮断したときの銅の温度上昇
◆ 断熱境界条件
✓ 解析解とよく一致

解析解

数値解

From LHD *to* FFHR

Poloidal Coils
NbTi-CICC (world first)

Helical Coils
NbTi
pool-boiling

Construction : 1990-1998
Operation : 1998-

What kind of superconductor should be used?

SC Material Selection

1. LTS ➜ Nb_3Al, Nb_3Sn
2. HTS ➜ YBCO

Conductor Selection

1. Force-cooled LTS-CIC conductor
2. Indirectly-cooled LTS conductor
3. Gas-cooled HTS conductor

A. Sagara et al., Fusion Engineering and Design 89 (2014) 2114

High-Temperature Superconductor (HTS)

(1) High critical current up to high field

(2) High cryogenic stability

(3) Low cryogenic power

(4) High mechanical rigidity

(5) Industrial production for electrical and medical applications

(6) Low consumption of helium resources

Rare-Earth Barium Copper Oxide (REBCO)

Copper

REBCO

Hastelloy

Fujikura
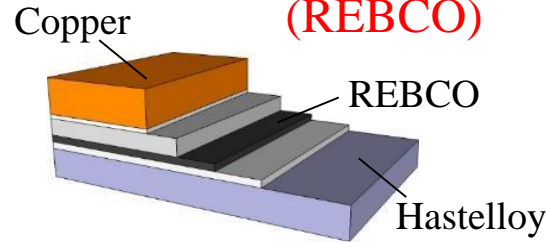
Stability Margin

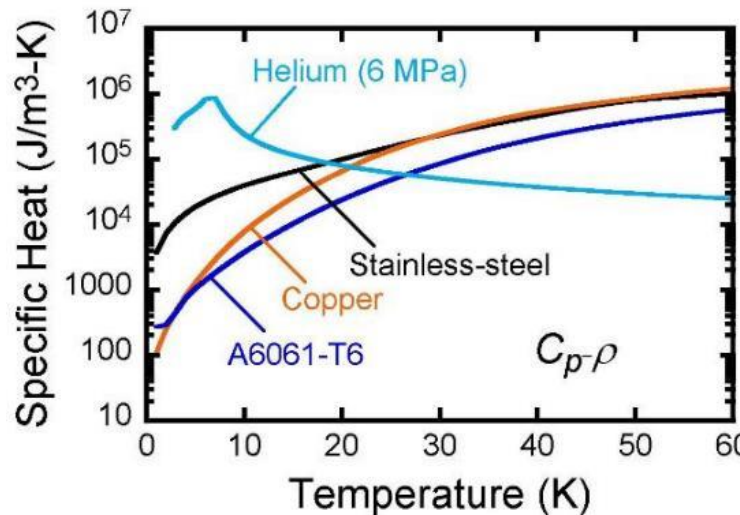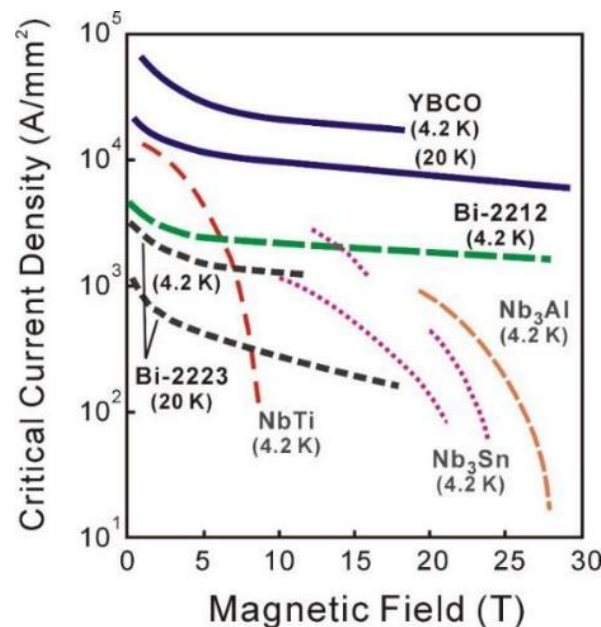$$\Delta Q < C_p \rho \Delta T$$

$$C_p \rho \Delta T \approx 2 \times 10^5 \ (\text{J/m}^3\text{K}) \times 10 \ (\text{K})$$

$$\approx 2 \ (\text{J/cc})$$

Higher than CIC conductor
➔ Low quench risk!

**N. Yanagi,** S. Ito, et al., Plasma and Fusion Research 9 (2014) 1405013

100 kA-class HTS Conductor for FFHR-d1
STARS (Stacked Tapes Assembled in Rigid Structure)

Operation current 94 kA	
Maximum field	12 T
Operation temperature	20 K
Conductor size	62 mm × 62 mm
Current density	24.5 A/mm^2
Number of HTS tapes	40
Cabling method	Simple-stacking
Stabilizer OFC	
Outer jacket	Stainless-steel
Insulation	Internal (ceramic?)
Cooling method	Helium gas
Superconductor	YBCO (width 15 mm)
Critical current	>900 A/cm @77 K, s.f.

Copper stabilizer
YBCO Tapes
62 mm
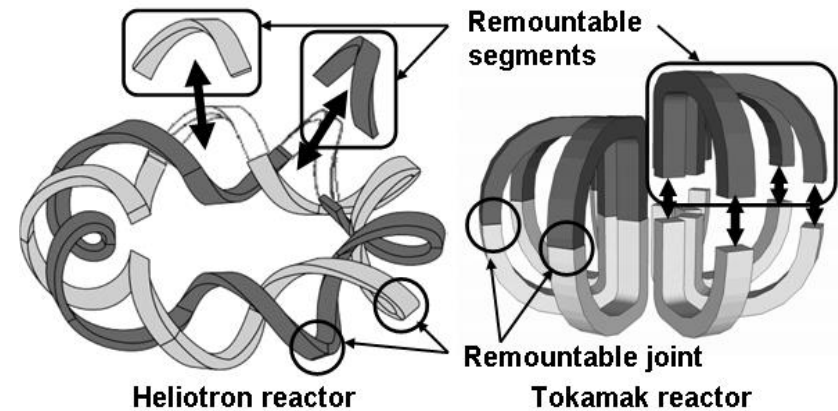Electrical insulation
Stainless-steel jacket
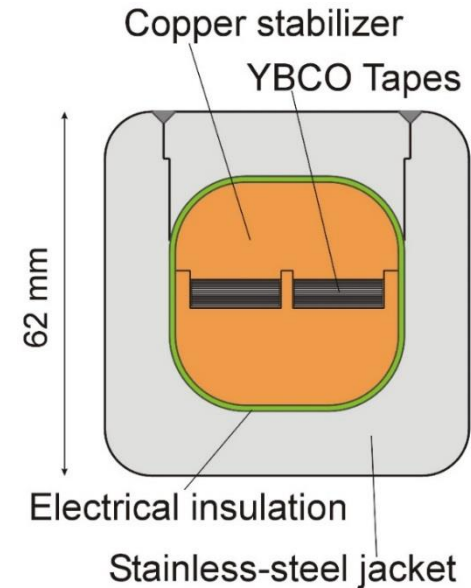
Concept of Segmented Fabrication of Helical Coils
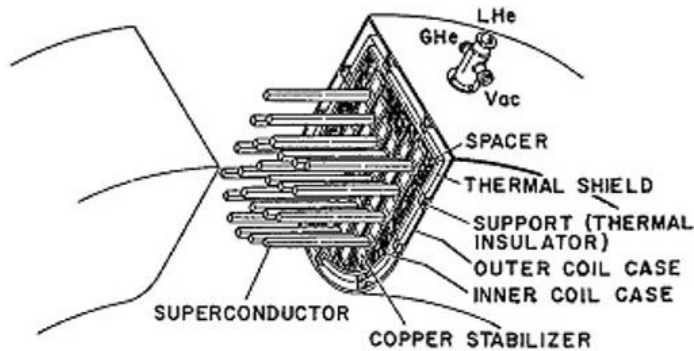
K. Uo (1985)
Demountable helical coils with LTS

H. Hashizume (2000)
Demountable TF and helical coils with HTS

A. Sagara (2001.6)
Excavation of the idea for FFHR design

H. Hashizume, A. Sagara (2001.12)
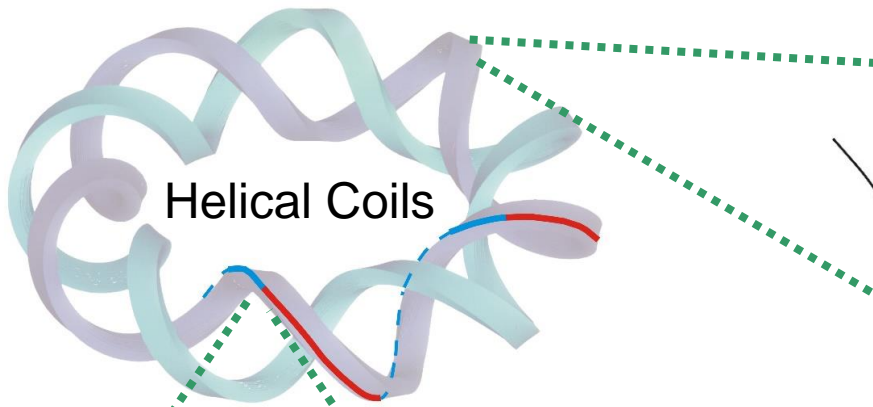*Demountable helical coils with HTS*

N. Yanagi
Once-through joint of HTS coils (2006)
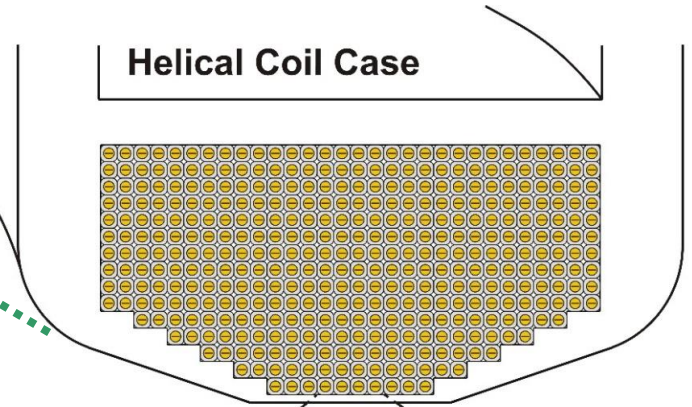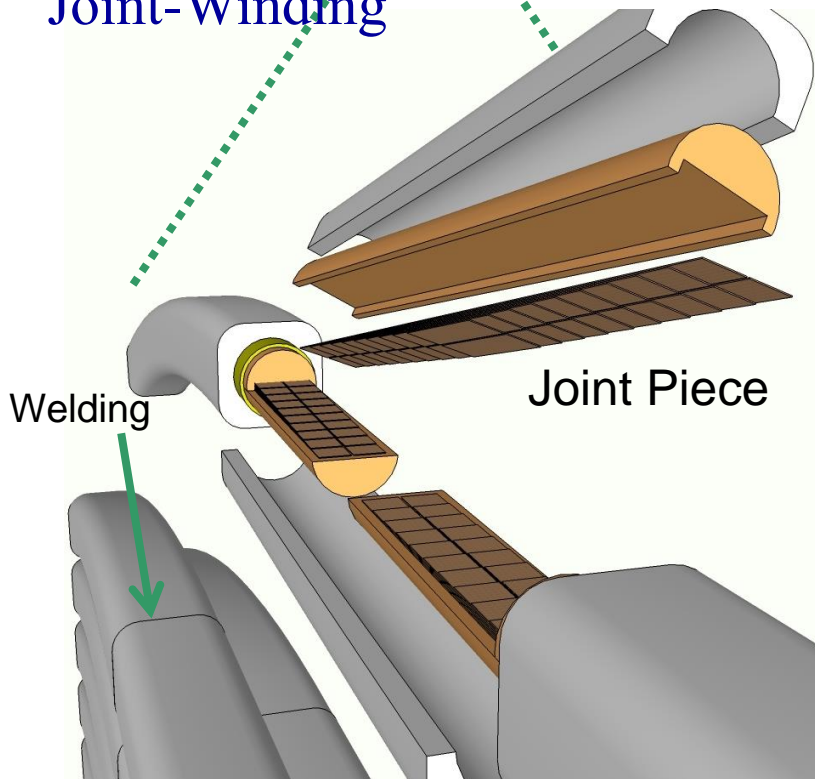*"Joint-winding" of HTS conductors* (2010)

H. Hashizume, S. Ito
*"Remountable" (demountable) HTS coils
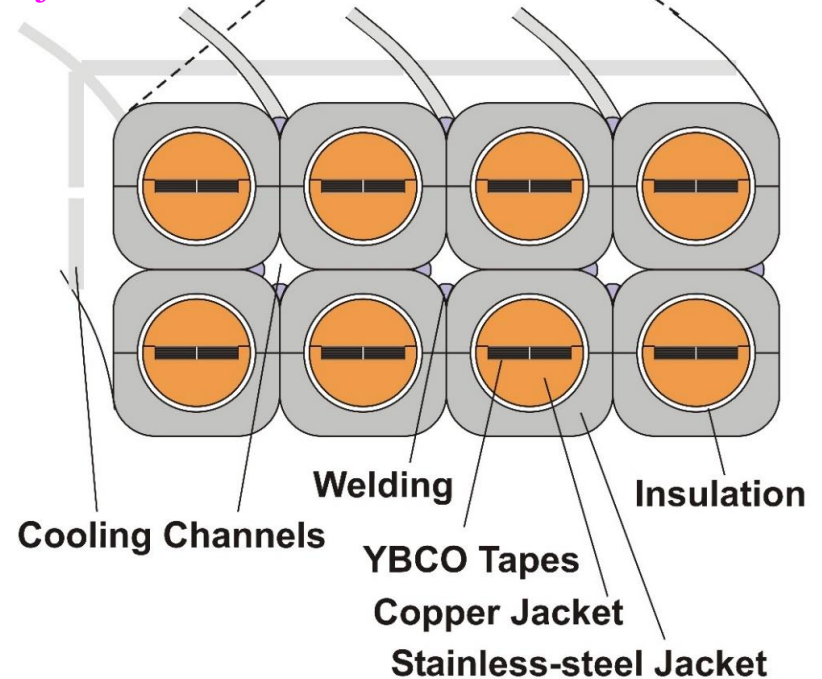   for advanced option of helical coils
   for advanced TF coils*

"Joint-Winding" of Helical Coils

Helical Coils

Helical Coil Case

"Joint-Winding"

390 turns × 5 segments × 2 coils
➜ 3,900 joints

Welding

Joint Piece

Cooling Channels

YBCO Tapes
Copper Jacket
Stainless-steel Jacket

Welding

Insulation

Discussion for Simple Stacking

	Conductor Sample	1 Block of FFHR Coil
Length	~3 m	~4800 m
L (self-inductance)	~2 μH	~30 mH (excluding mutual inductance with other blocks)
Joint Resistance	1 / 2 nΩ @1 joint	160 nΩ @160 joints
L dI/dt for 1 m	~0.7 mV @1 kA/s	~0.06 mV @10 A/s ~0.03 mV @5 A/s
RI for 1 m	~0.07 mV @100 kA	~0.003 mV @100 kA
Ratio between *L dI/dt* & *RI*	~10 @1 kA/s	~20 @10 A/s (2.8 h excitation) ~10 @5 A/s (5.6 h excitation)

➢ Conductor sample experiment seems to validate the feasibility
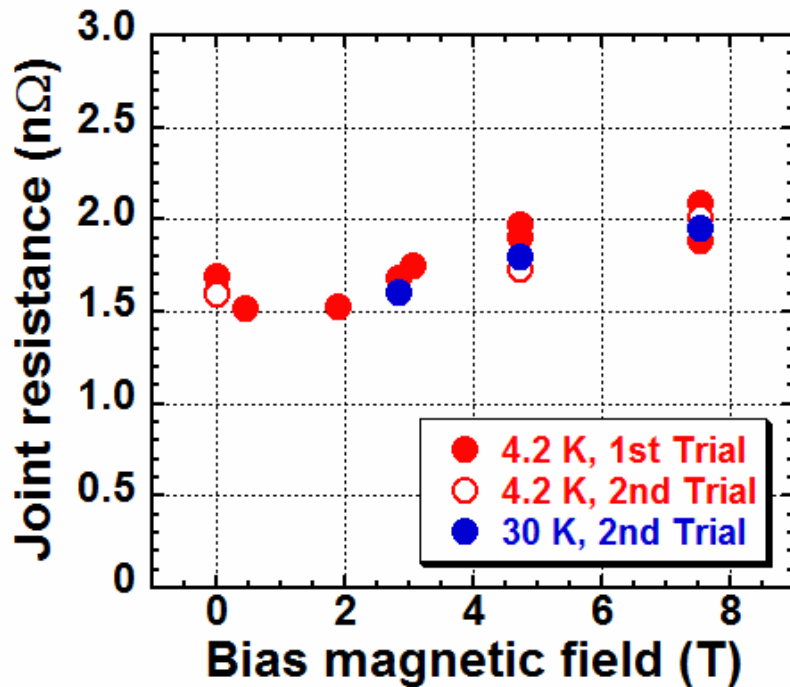➢ Detailed analysis will be carried out…

Evaluation of Joint Resistance

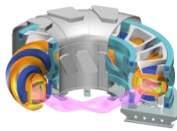Bridge-type mechanical lap joint
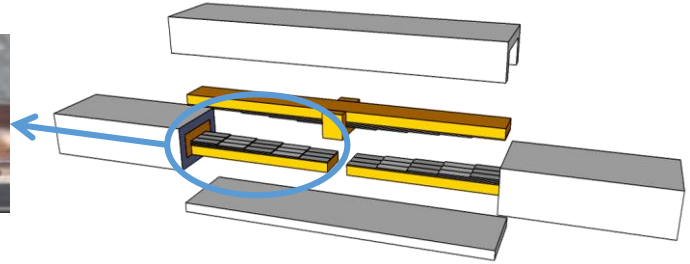
S. Ito (Tohoku Univ.)
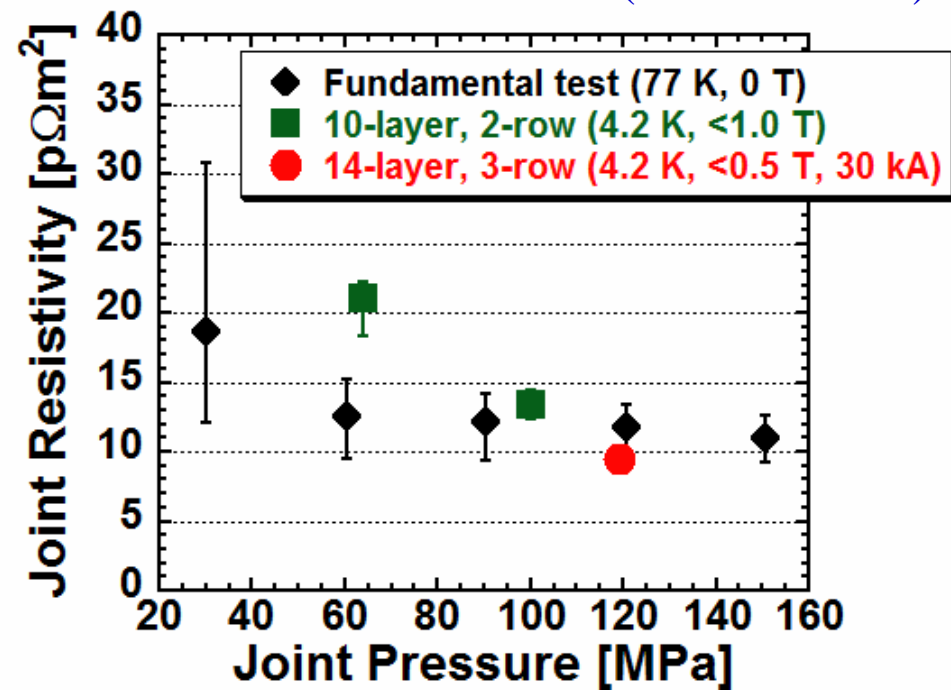
Joint resistance : ~2 nΩ ➡ Joint resistivity : ~10 pΩm^2 ➡ *Could be further reduced*

Required electrical power of the cryoplant at R.T. < 2.5 MW (for 3,900 joints)
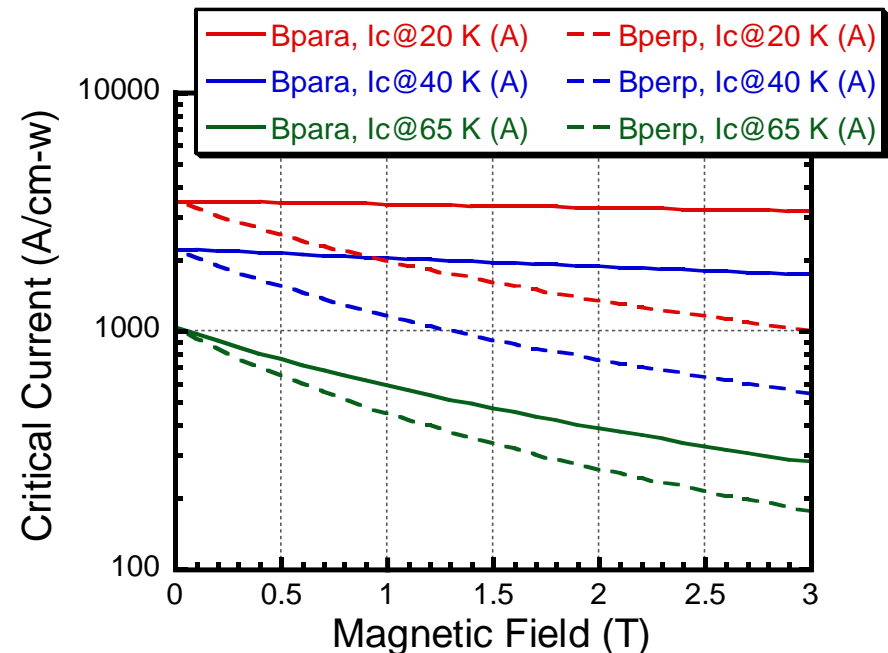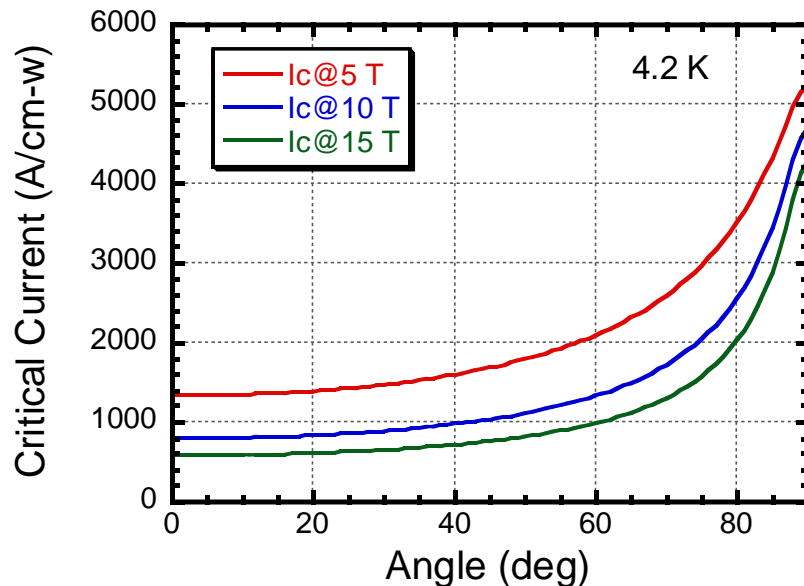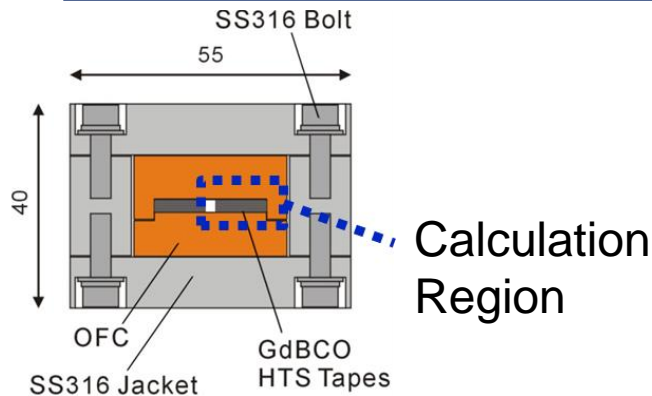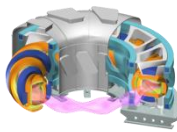
Critical current characteristics of tapes

Evaluation formula of the I_C [1] （J_{C0}, B_C, *b and k* are parameters）

$$J_C(B_\parallel, B_\perp) = \frac{J_{C0}}{\left(1 + \sqrt{(kB_\parallel)^2 + B_\perp^2}\middle/B_C\right)^b}$$

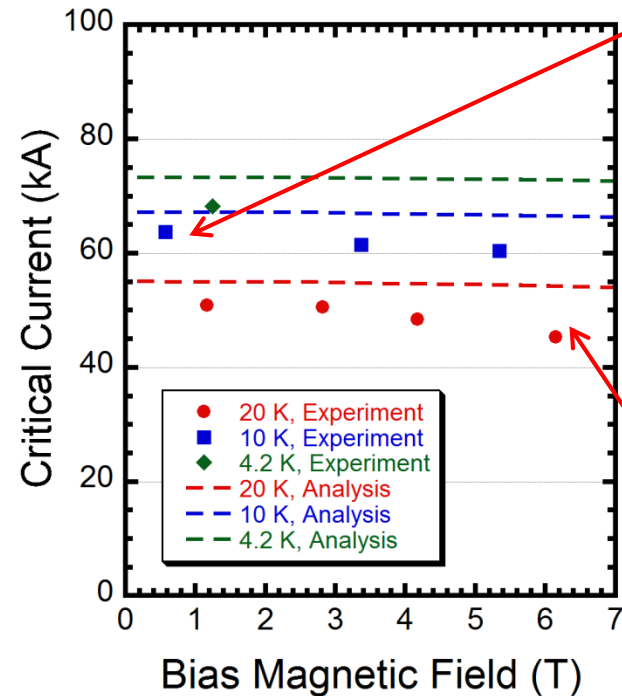[1] F. Grilli et al., IEEE Trans. Appl. Supercond., **24** (2014) 8000508

Comparison of results of 30 kA-class sample test
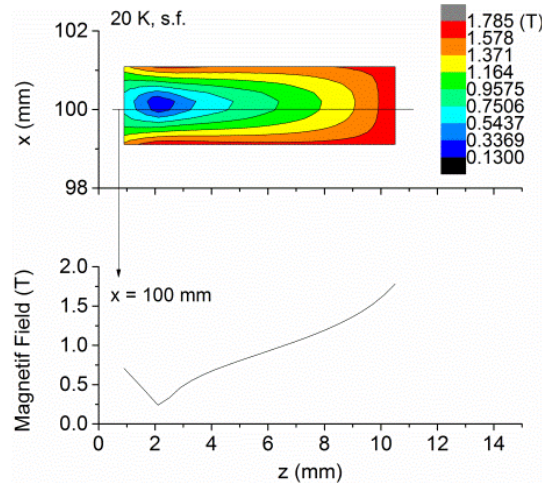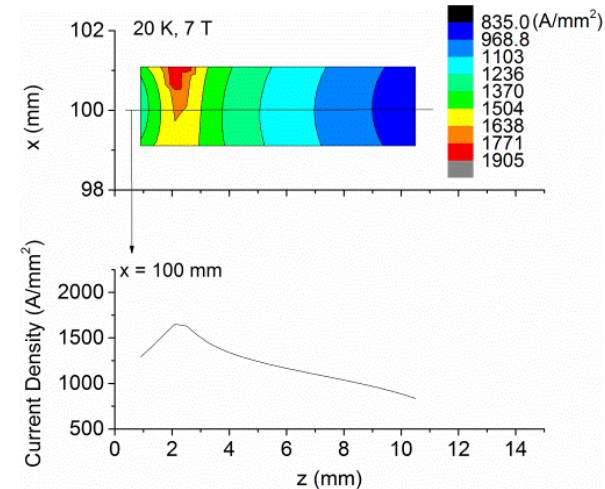
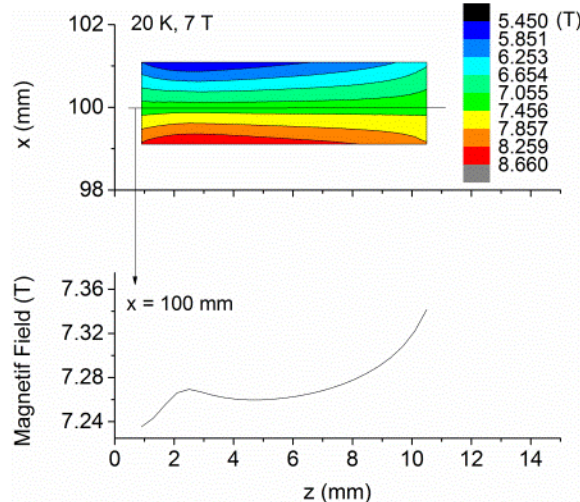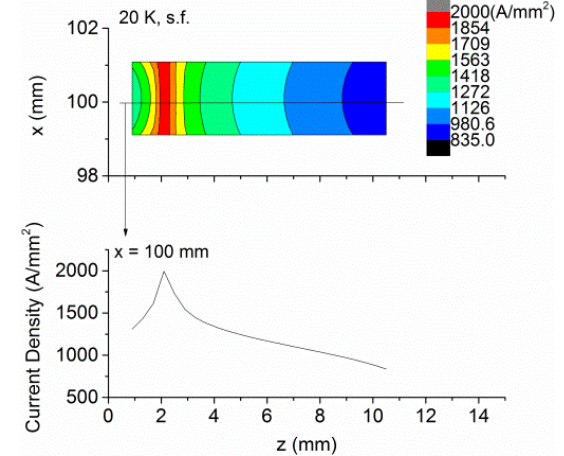

Calculation Region

Magnetic field

Current density

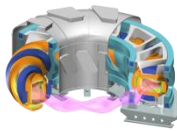Experimental results agree with computation results at low field region.

Model of critical current analysis

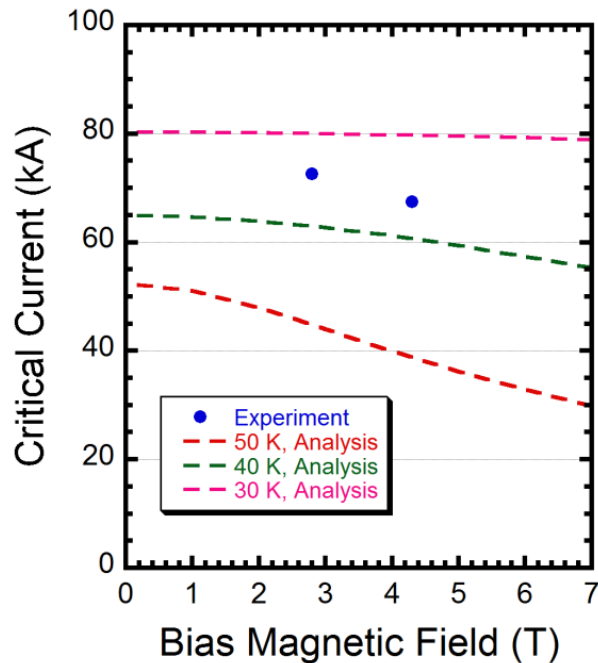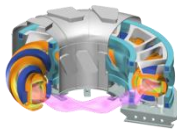Conductor I_C = Sum of local I_C in conductor

The local I_C is determined by the local magnetic field and its orientation.

➔ The current density and the magnetic field distribution in the conductor were solved self-consistently.

External magnetic field distribution

Cross-section of the sample

GdBCO
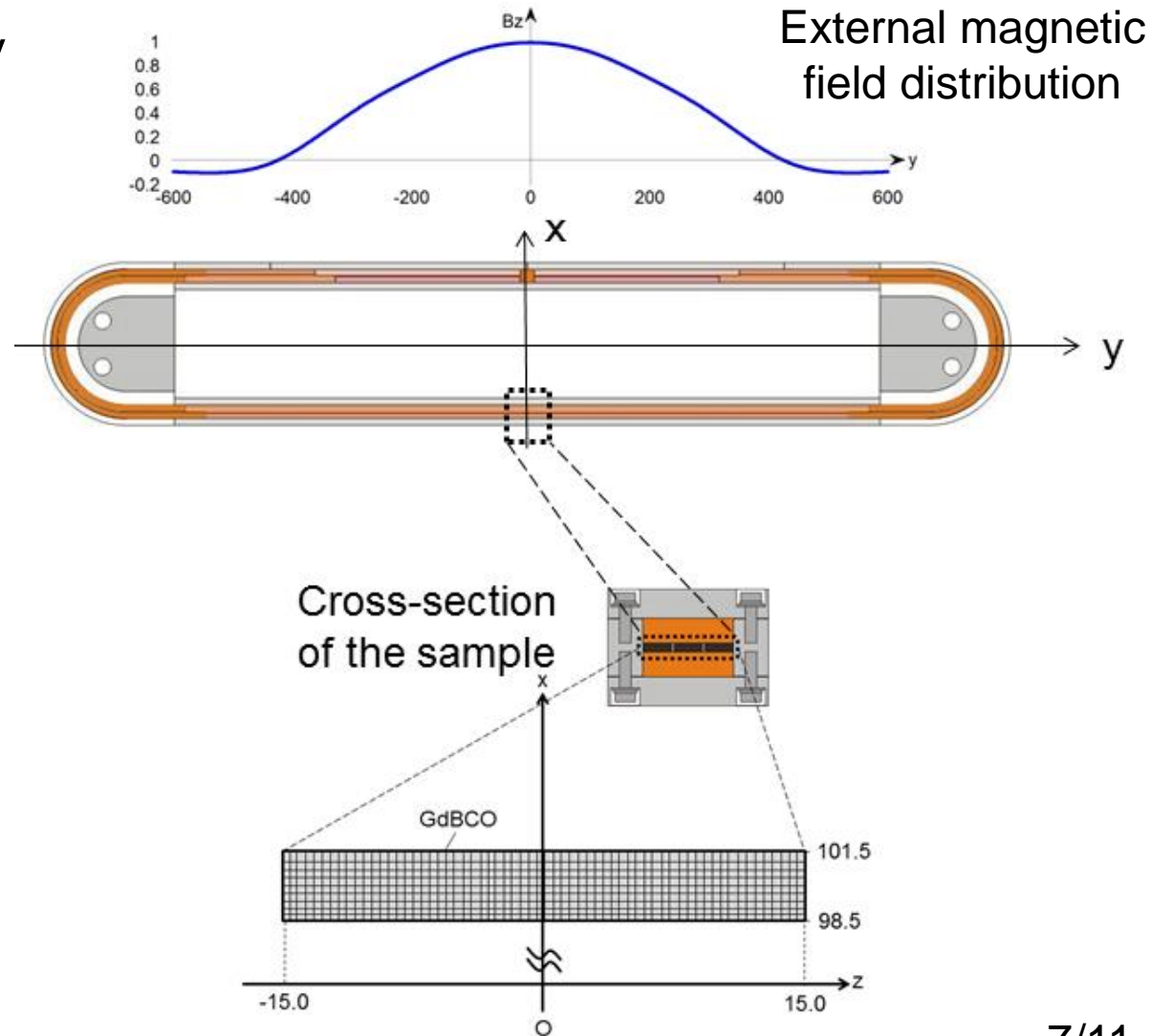
Results of 100 kA-class sample test

- I_C = 67.4 kA@"45 K", 4.3 T
- I_C = 72.6 kA@"45 K", 2.8 T

Experimental values are located between computation values of 30 K and 40 K.

➔ Temperature of the tape in the conductor is less than the temperature showed by sensors attached on the stainless-steel jacket because the conductor was heated only one-side.

The temperature of the tape was evaluated ~38 K by the finite element method analysis.

➔ It supports the result of the critical current measurement.