IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue 53, July 2023.
Presentation given at Coated Conductors for Applications Workshop, Houston, TX, USA, April 2023.

Applicability of large-current HTS STARS conductor to the next-generation fusion experimental devices

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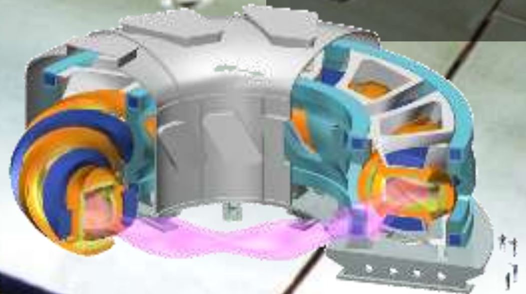
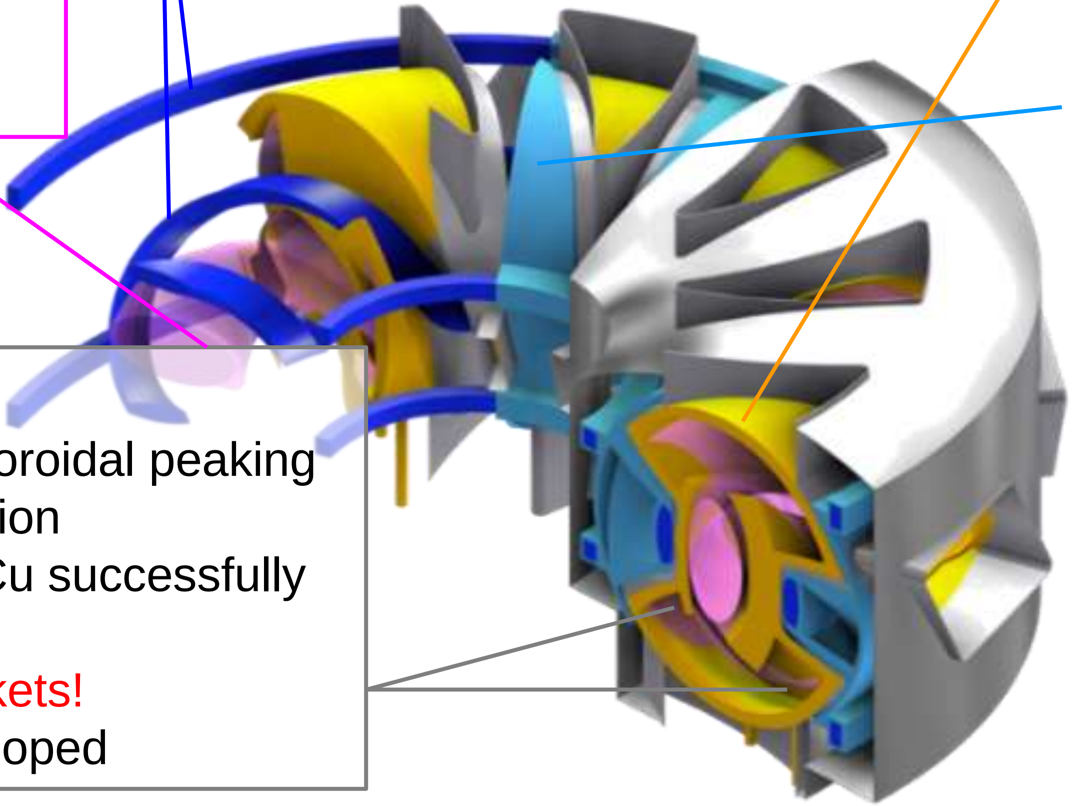
[3] Tohoku University



International Workshop on Coated Conductors for Applications (CCA2023)
April 3-6, 2023, Houston, USA

Reactor Design Studies on the LHD-type Helical Fusion Reactor, FFHR



Magnet

- Continuous helical coils = naturally wound double helix, suitable for winding HTS
- Joint-winding by HTS conductor is possible to facilitate winding

Plasma

- Steady-state w/o. plasma current
- No disruption

Blanket

- Molten-salt and/or liquid metal blankets
- RAFM and/or Vanadium alloy
- Easy maintenance through large ports
  - Cartridge-type with external handling
  - Helically-shaped with remote handling

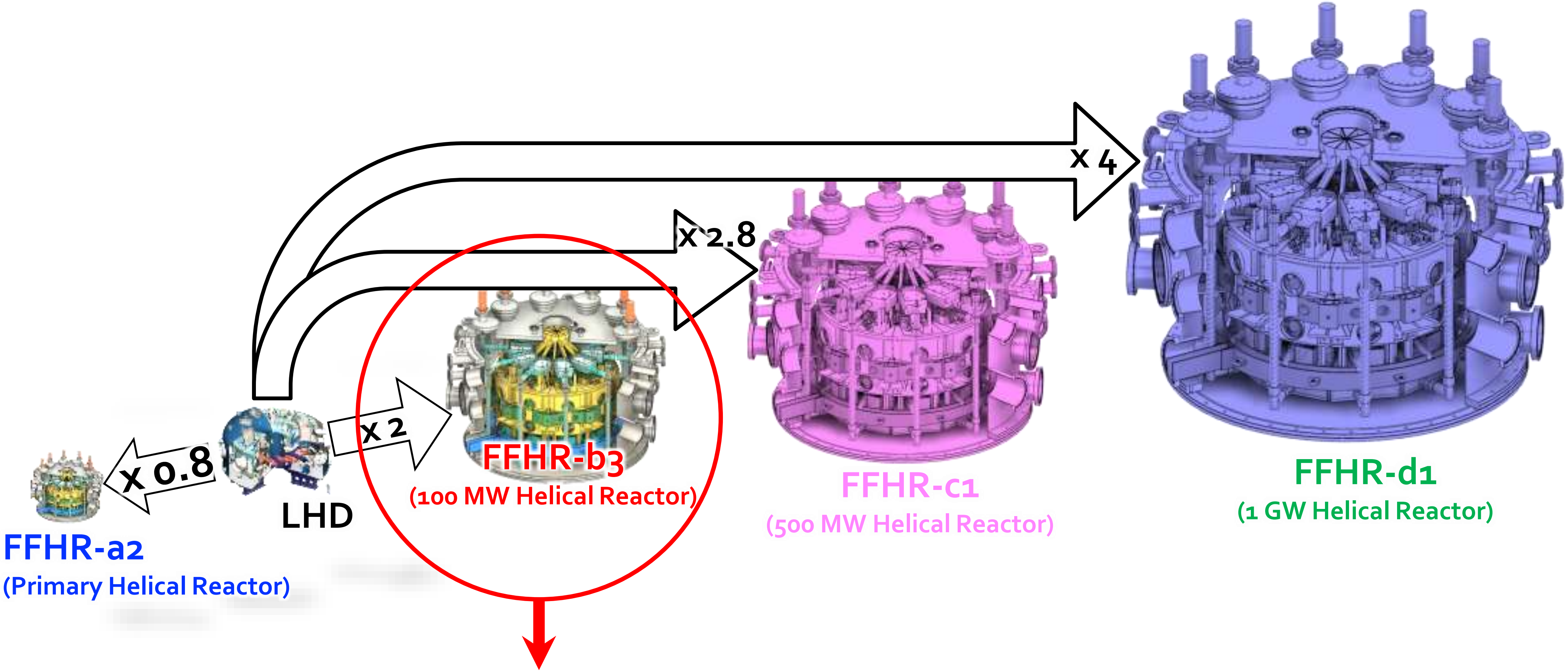
EM Support Structure

- Topology optimization reduces mass >25%

Divertor

- Large wetted area with reduced toroidal peaking <30 MW/m^2 w/o radiation dispersion
- Advanced Brazing of W & ODS-Cu successfully achieved >30 MW/m^2
- Divertors are placed behind blankets!
- Liquid divertor is also being developed

Conceptual Design Studies for Early Realization of Helical Reactor



Improvement of plasma confinement / Innovation for reactor engineering

➔ Early realization of a helical fusion reactor with

- **Double size of LHD (R = 7.8 m)**
- **100 MW net electricity production**

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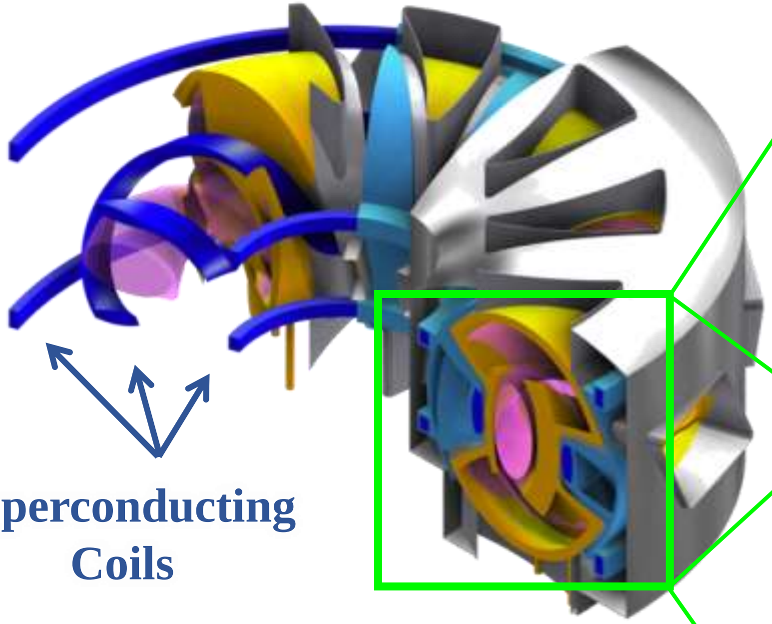
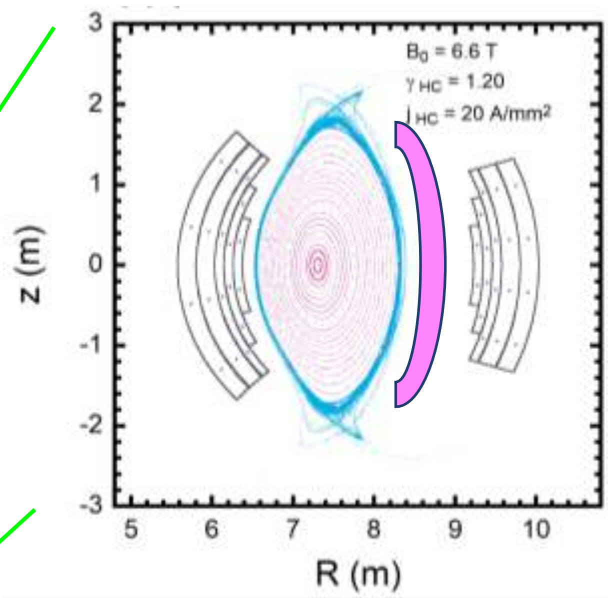
High-current density is the key for a compact helical reactor



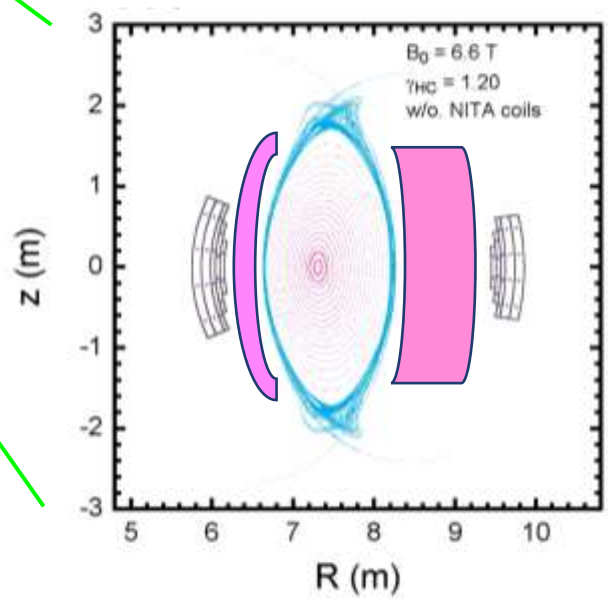
Superconducting Coils

Helical Fusion Reactor FFHR-b3

R = 7.8 m
B_{max} = 15-16 T



Low-Current Density Coil
(Low-Tc SC)
20 A/mm^2

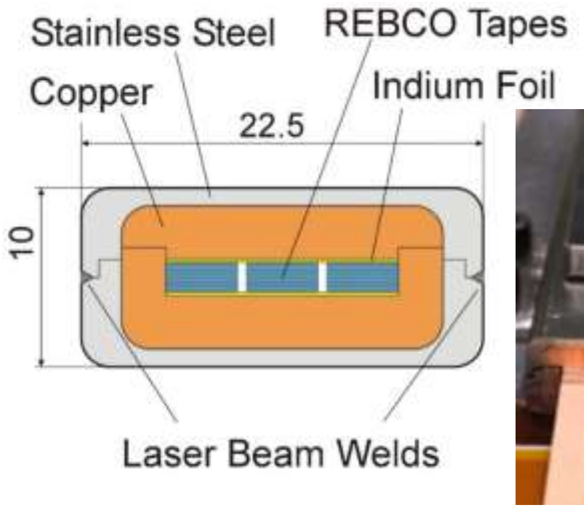


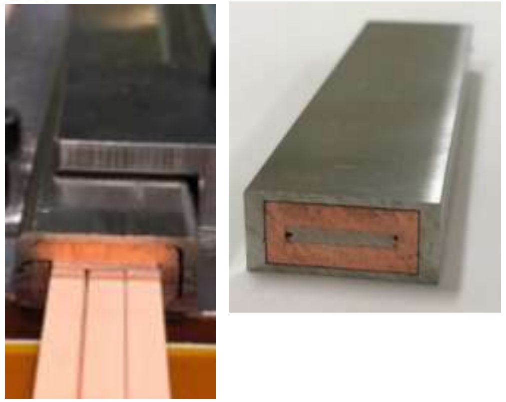
High-Current Density Coil
(High-Tc SC)
80 A/mm^2

HTS conductor development for the next-generation helical device

STARS

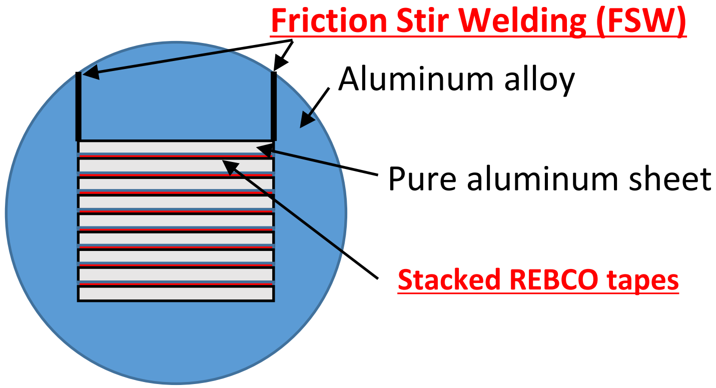
(Stacked-Tapes Assembled in Rigid Structure)





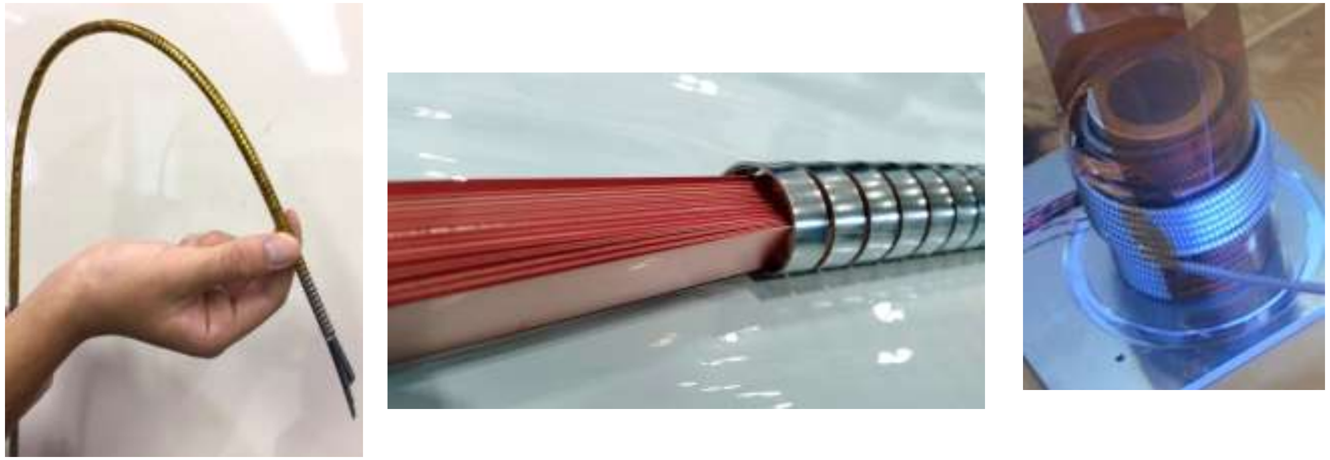
FAIR

(FSW, Al-alloy, Indirect-cooling, REBCO)



WISE

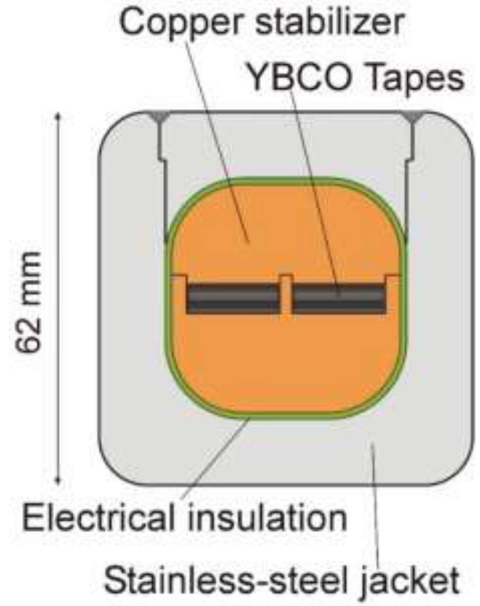
(Wound and Impregnated Stacked Elastic tapes)



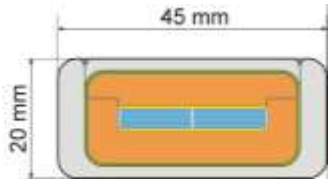
- Current capacity: 10-20 kA @ 8 T, 20 K
- Current density: 80 A/mm^2

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

Operation current	94 kA @12 T
Operation temperature	20 K
Conductor size	62 mm × 62 mm
Current density	24.5 A/mm^2
Number of tapes	40
Cabling method	Simple Stacking
Stabilizer	OFC
Outer jacket	Stainless Steel
Electrical insulation	Organic or Inorganic
Cooling method	GHe / LH_2
Superconductor	REBCO



STARS
for FFHR-d1
94 kA, 25 A/mm^2



STARS
for FFHR-b3
66 kA, 80 A/mm^2

Simply-stacked HTS conductor for DC helical coils

- Non-uniform current distribution may be allowed
- High mechanical strength (no void & local deformation)
- Low cost / low-resistance joint

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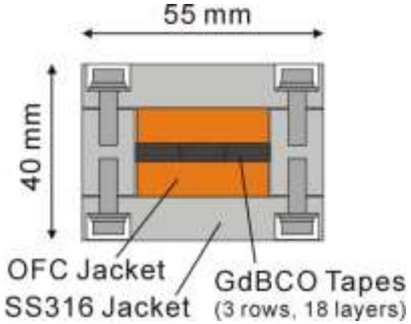
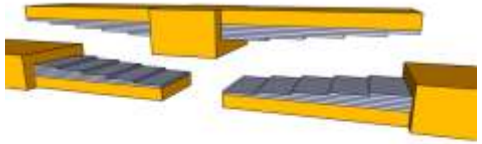
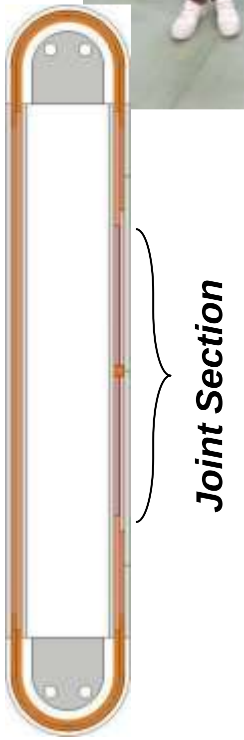
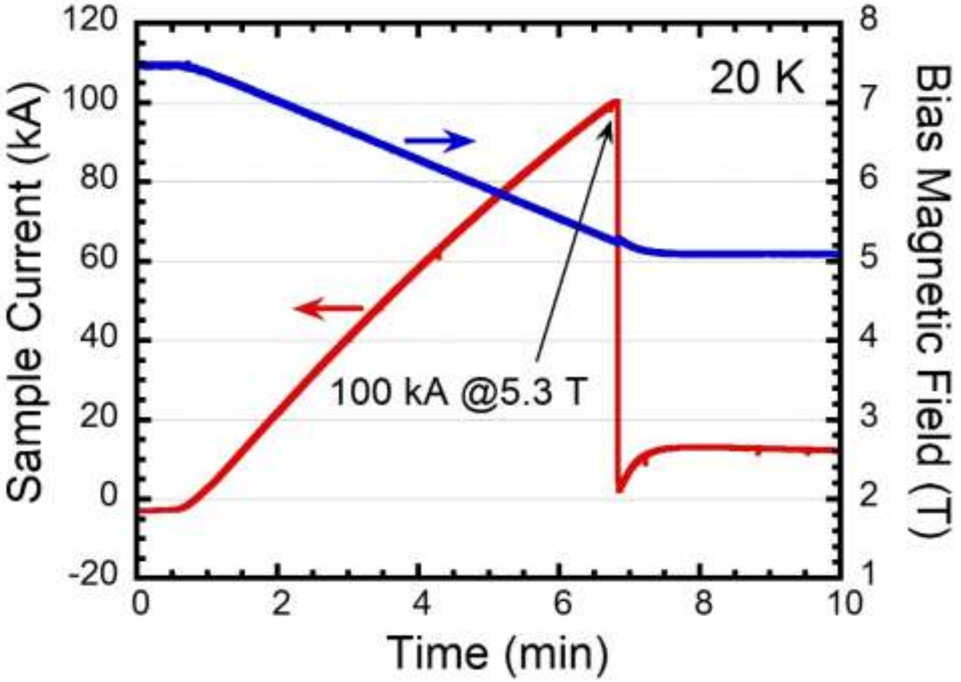
100 kA-Class Prototype STARS Conductor Test

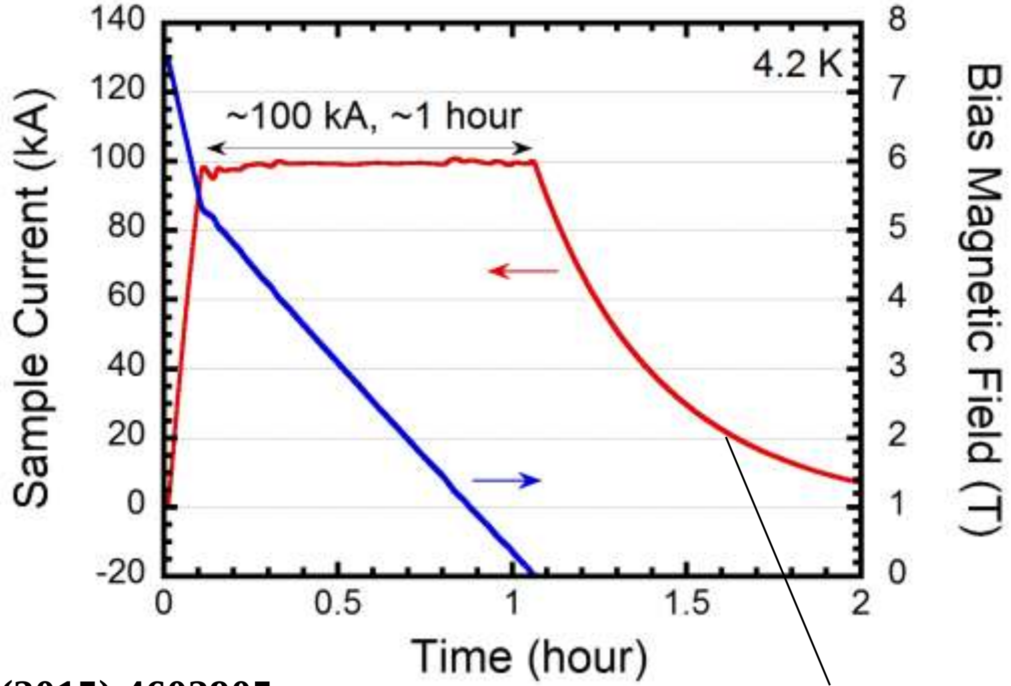


Bridge-type mechanical lap joint
"*Invisible joint*"









Joint resistance
~1.8 nΩ

N. Yanagi et al., Nucl. Fusion 55 (2015) 053021
Y. Terazaki et al., IEEE Trans. Appl. Supercond. 25 (2015) 4602905
S. Ito et al., IEEE Trans. Appl. Supercond. 25 (2015) 4201205

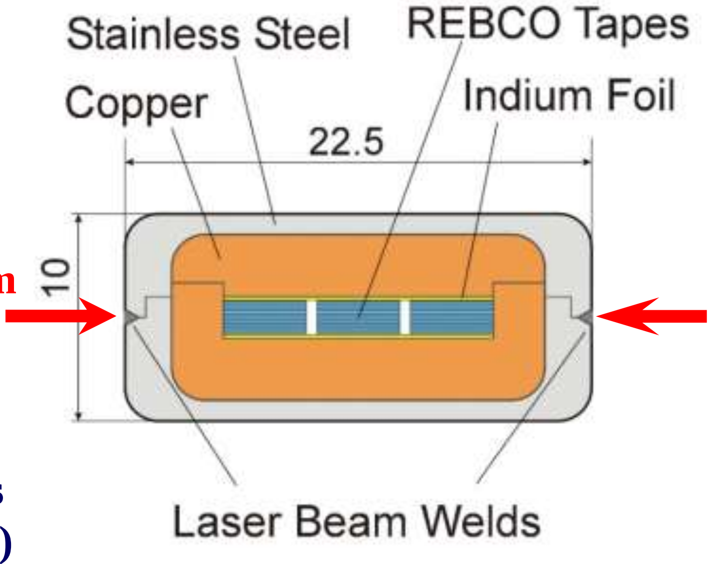
20 kA-class STARS Conductor

- **HTS (REBCO) tapes (simply stacked) + Copper stabilizer + Stainless steel jacket**
  - ➢ **Suitable for DC magnet, high mechanical strength, low hot-spot temperature, simple joint**
- **Development since 2005 for the helical fusion reactor FFHR**
- **10-kA class ➔ 15-kA class ➔ 30-kA class ➔ 100-kA class (prototype samples)**

100 kA@5.3 T, 20 K achieved (total length: 3 m, tested region: 0.3 m, bolted jacket)

- **Next phase development of 20-kA-class conductor with long length to be applied to the next generation helical device**
  - ➢ **High current density of 80 A/mm^2 is a big target (former achievement: 25 A/mm^2)**
- **A 3-m-long conductor sample**
  - ➢ **Fabricated by HITACHI Ltd.**
  - ➢ **45 REBCO tapes (Fujikura FESC-SCH04)**
  - ➢ **Laser beam welding of SS jacket**

Laser Beam Welding



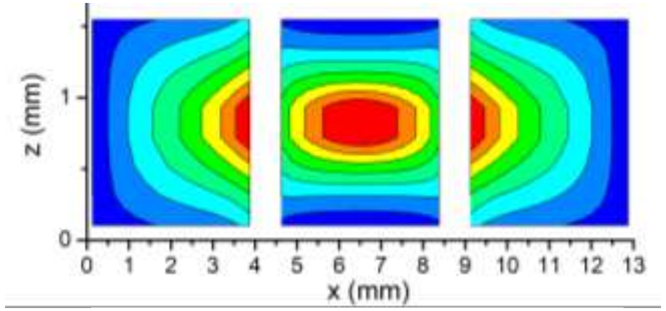
Temperature at the inner wall of Cu stabilizer was 44 °C << 200 °C（allowable limit for REBCO tapes)

20 kA-class STARS conductor test in liquid nitrogen

- Short sample test in liquid nitrogen (77 K) and no magnetic field
- Critical current of 3,950 A confirmed

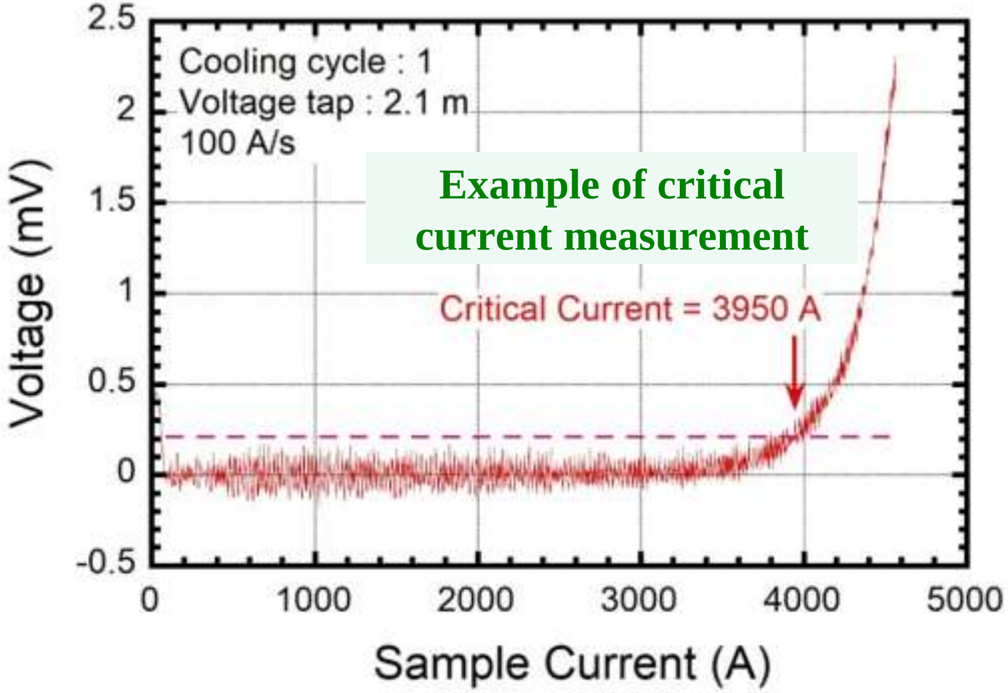
  Verified by numerical simulation with current density and magnetic field distribution, extrapolation to 20 kA at 20 K and 10 T
- Tolerable reduction (~1%) of critical current by cooling cycle
- Further reduction (~2%) with 3000 mm bending radius
- Recovery by releasing (straightening)

◆ Test in 4-50 K by helium cooling and <9 T magnetic field is planned

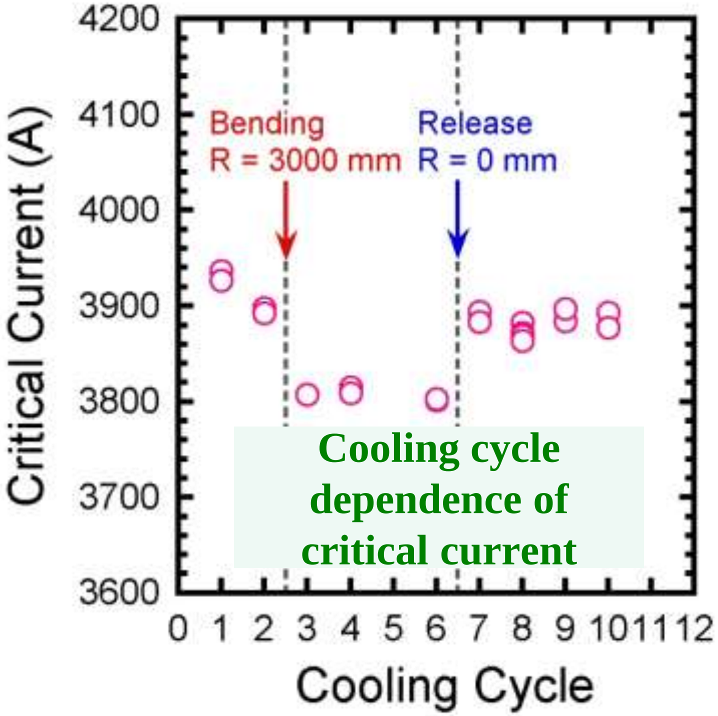


Numerical simulation of J and B distribution

Y. Terazaki

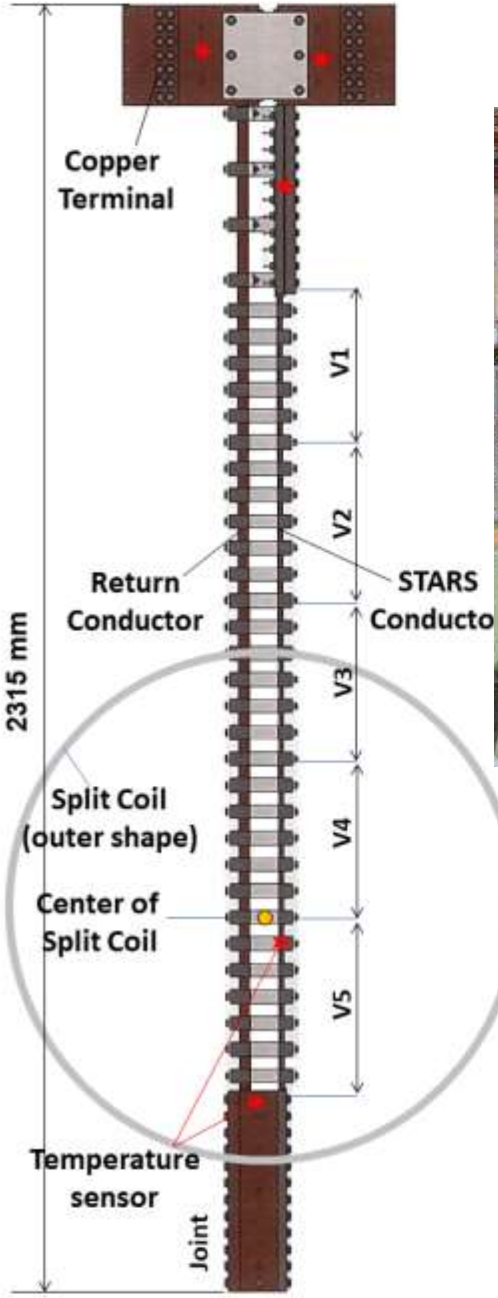


Example of critical current measurement

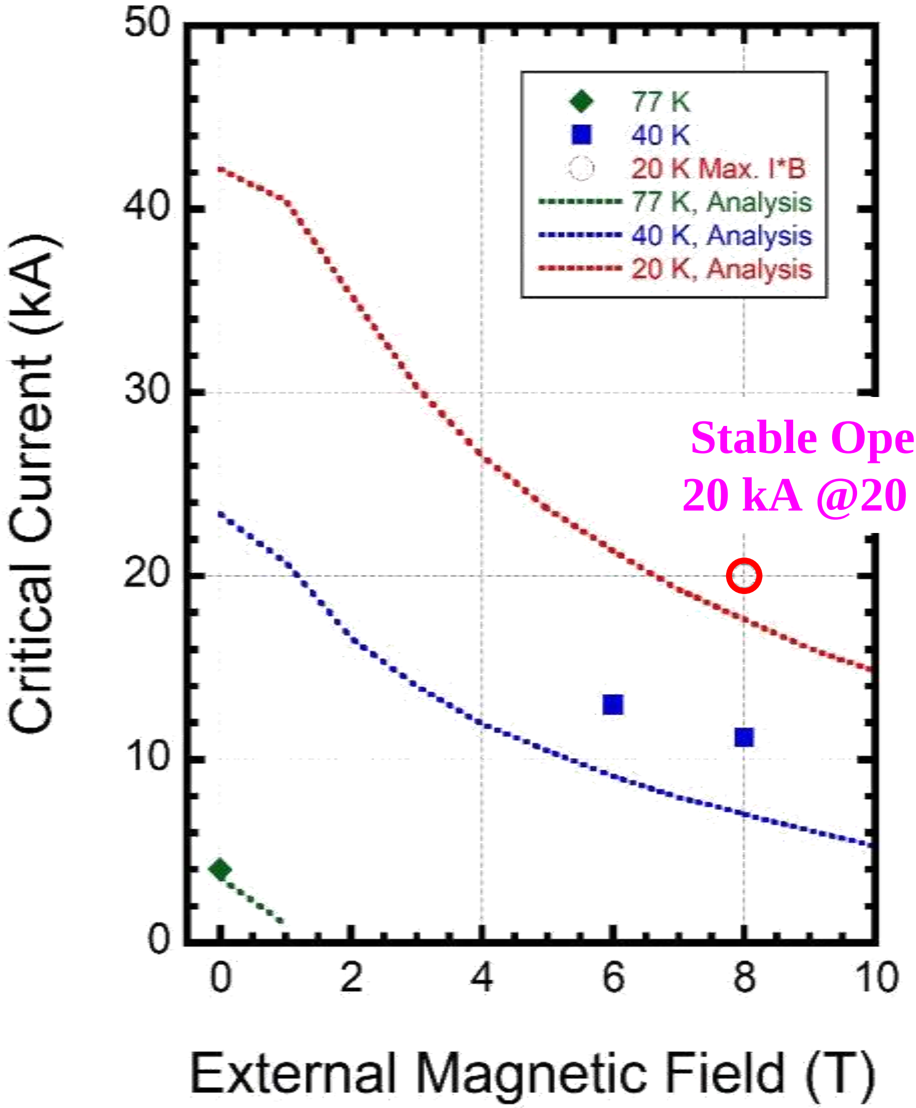


Cooling cycle dependence of critical current

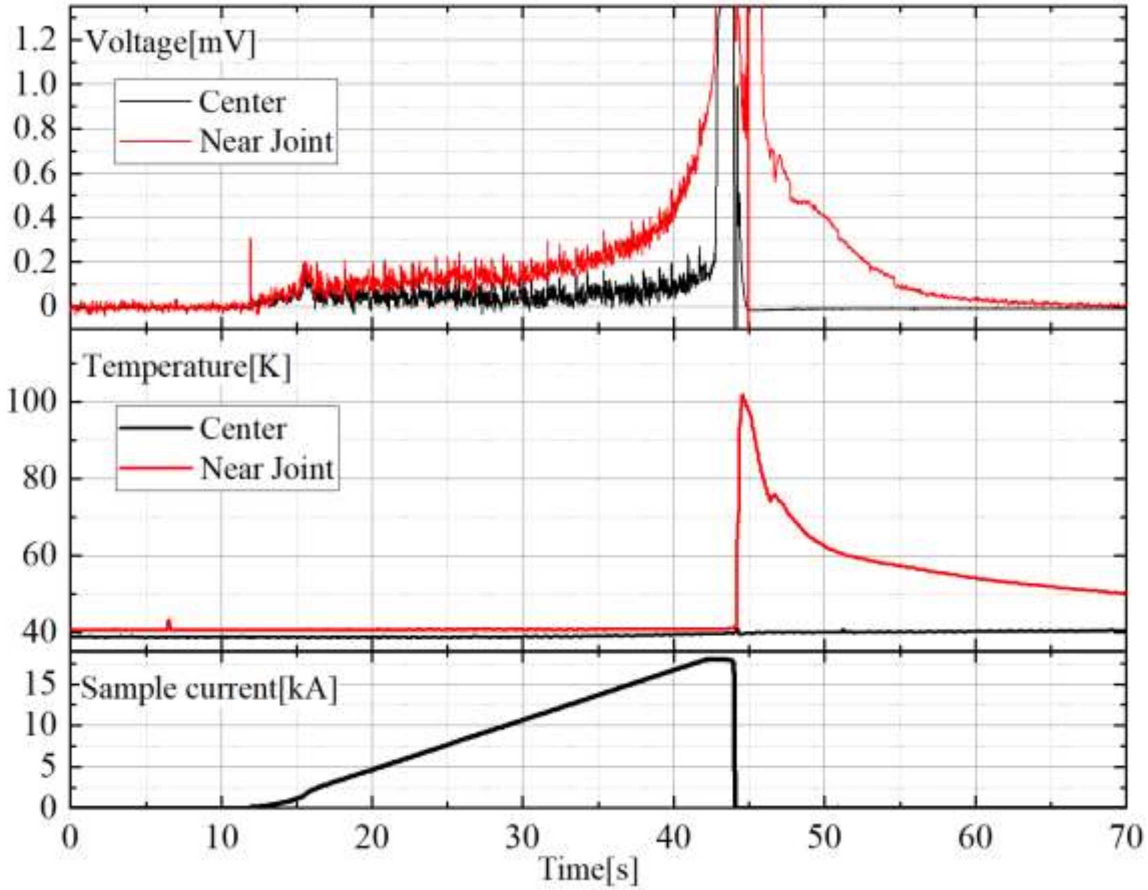
20 kA-class STARS conductor test in large-superconductor testing facility



20 kA-class STARS conductor test in 20-40 K, <8 T



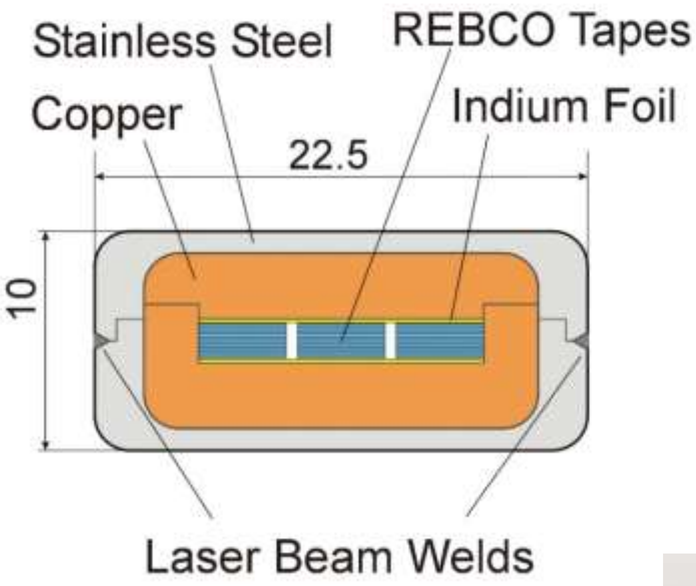
Stable Operation
20 kA @20 K, 8 T

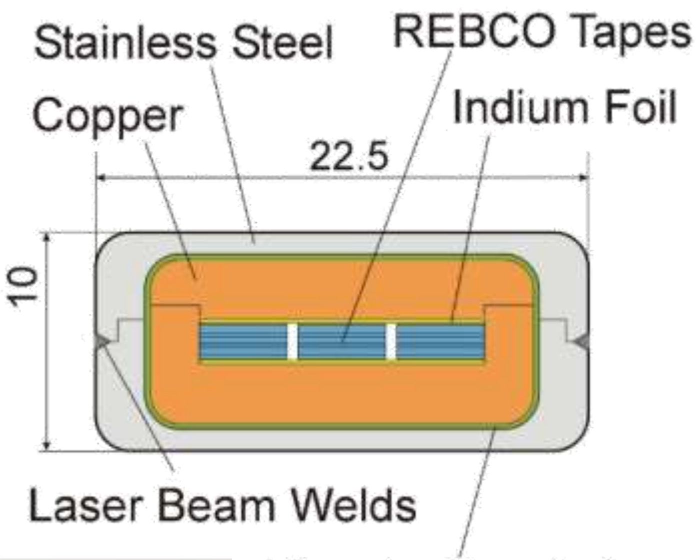


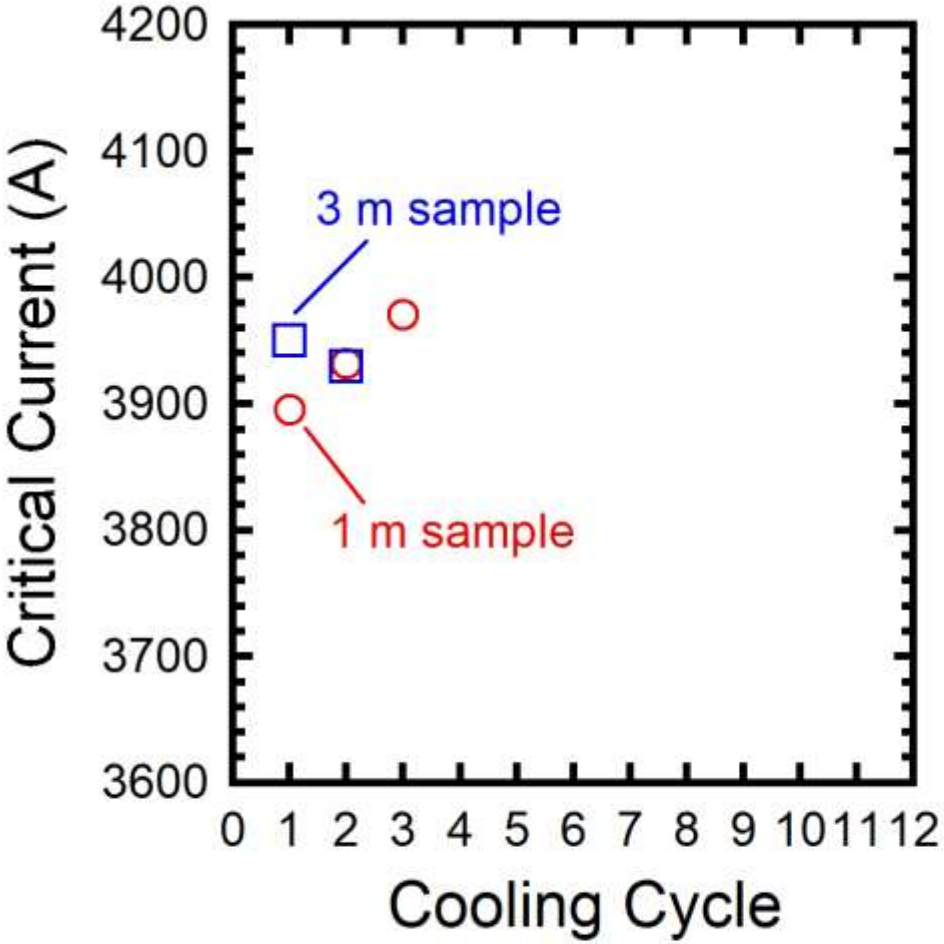
Mistake in quench detection
➔ sample melted locally

Critical current was observed at 11.2 kA@40 K, 8 T and 13.0 kA@40 K, 6 T

20 kA-class STARS conductor with internal electrical insulation

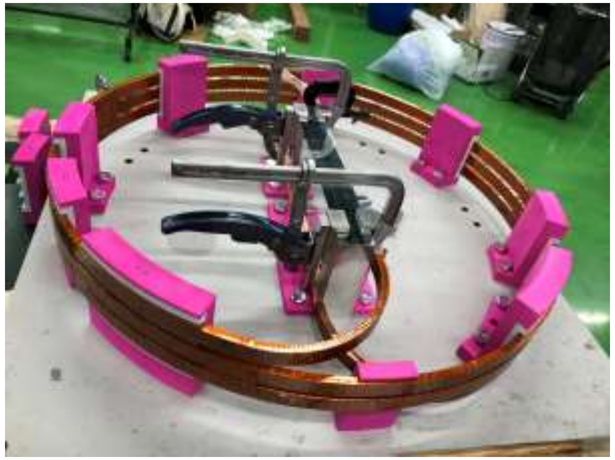




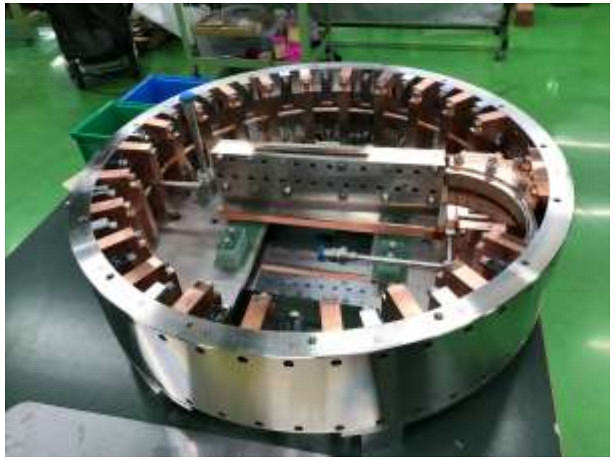
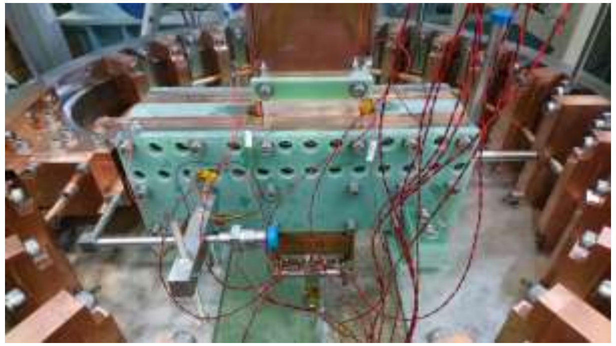


- In FY2020, new conductor samples (1-m and 3-m length) with internal electrical insulation were fabricated at Metal Technology Co. Ltd. (Toki factory)
- The same ~4 kA critical current was observed in liquid nitrogen, as was observed for the former sample without electrical insulation

Fabrication of 20-kA-class STARS conductor, 6-m sample



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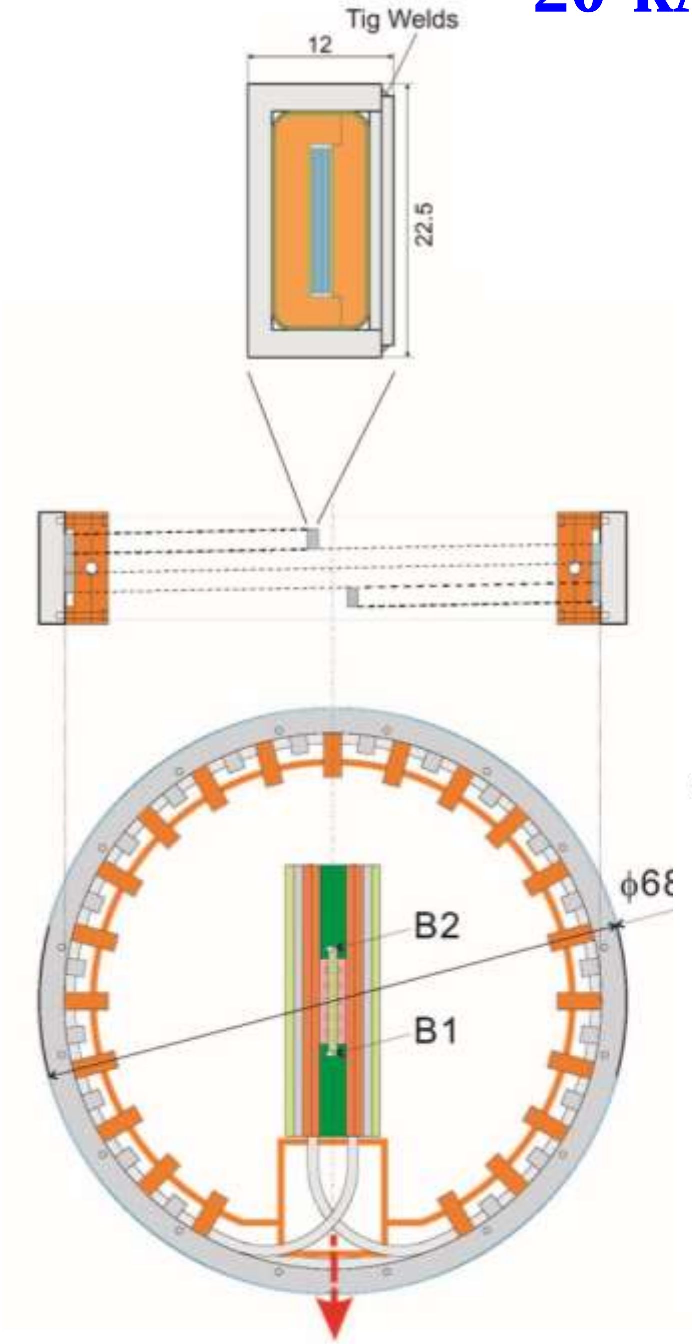
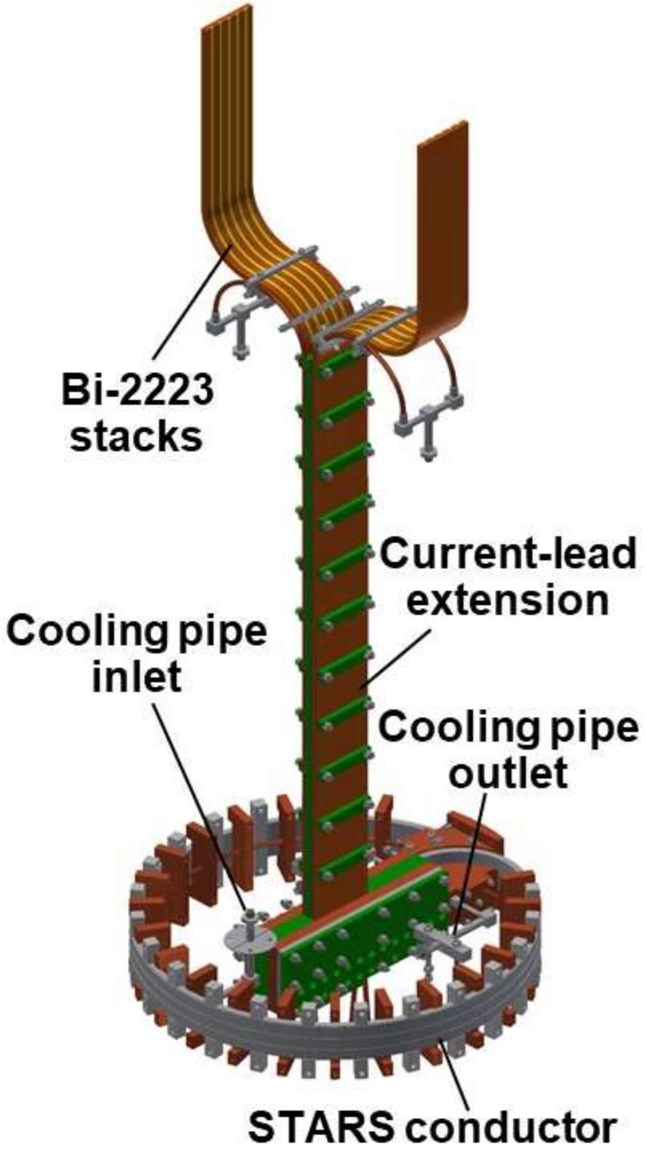
20-kA-class STARS conductor, 6-m sample





Bi-2223 stacks

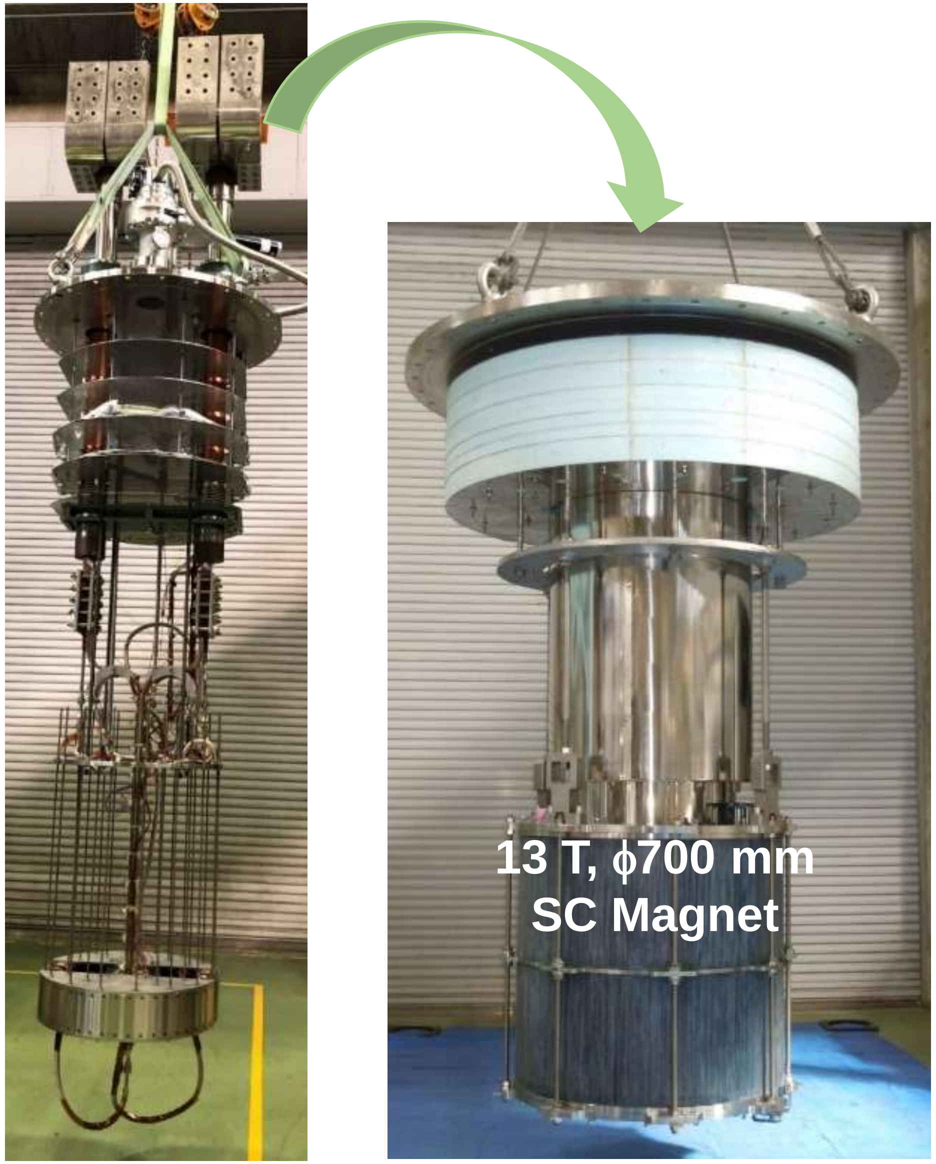
Current-lead extension

Cooling pipe inlet

Cooling pipe outlet

STARS conductor

20-kA-class STARS conductor, 6-m sample experiment



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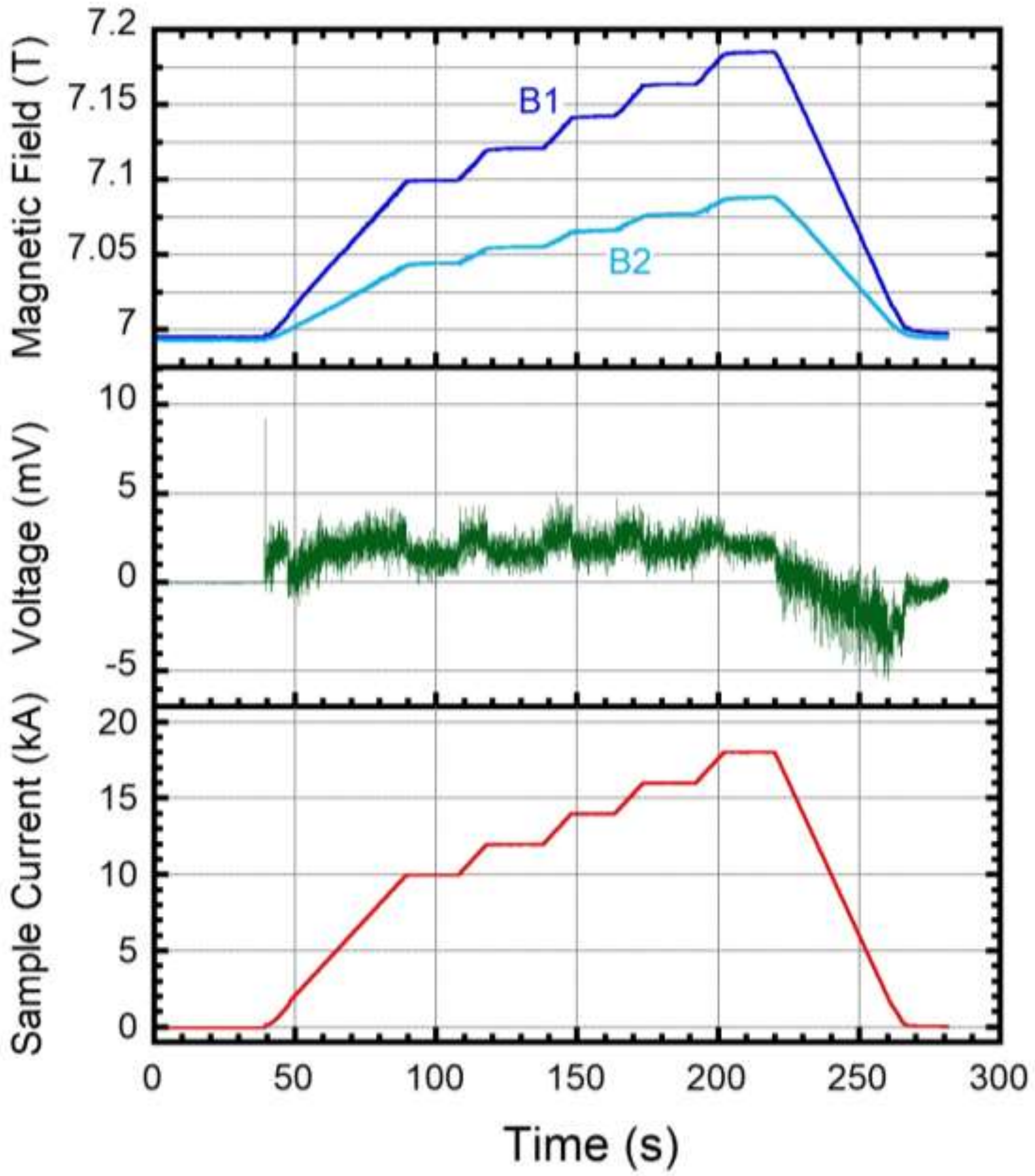
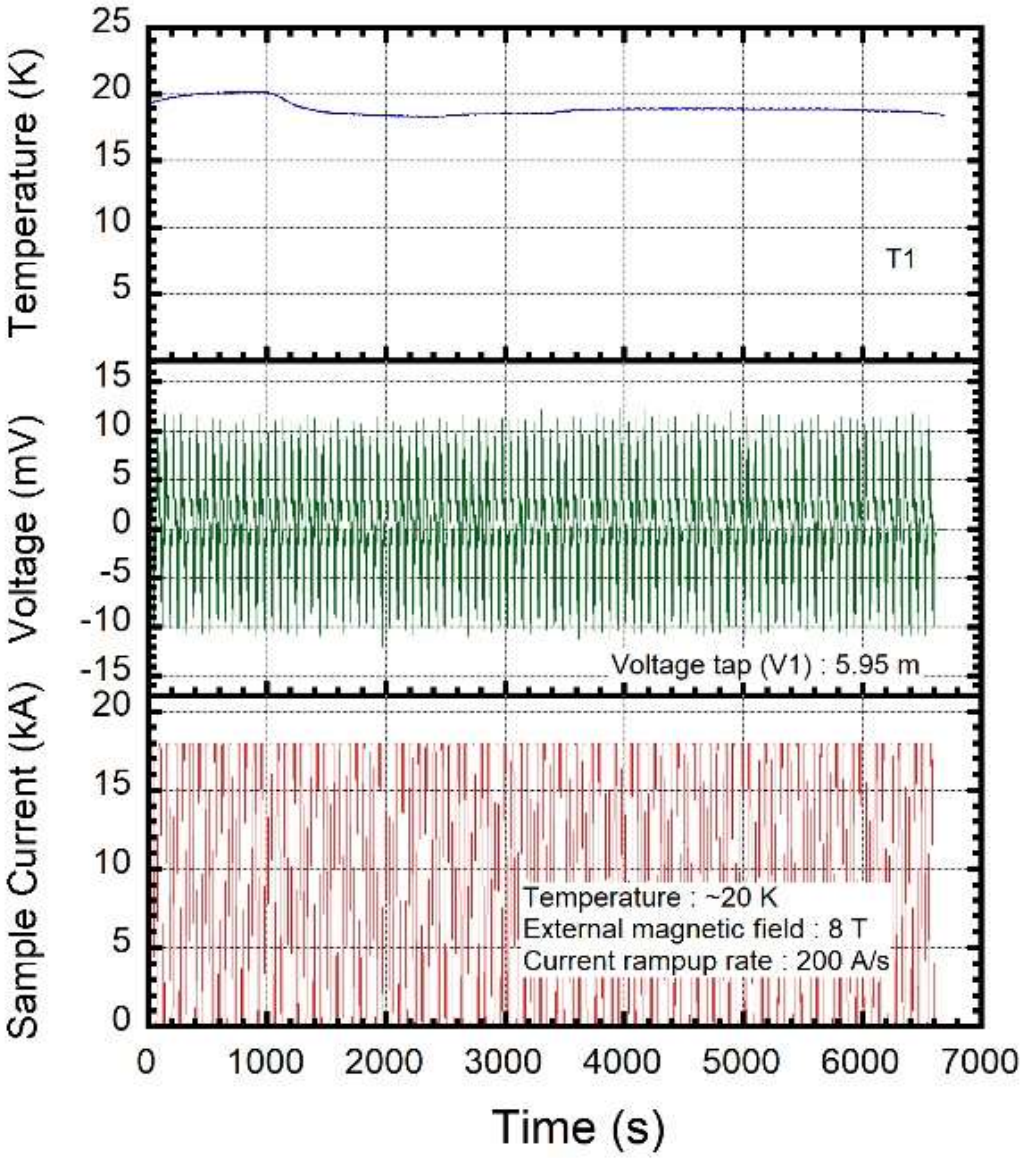
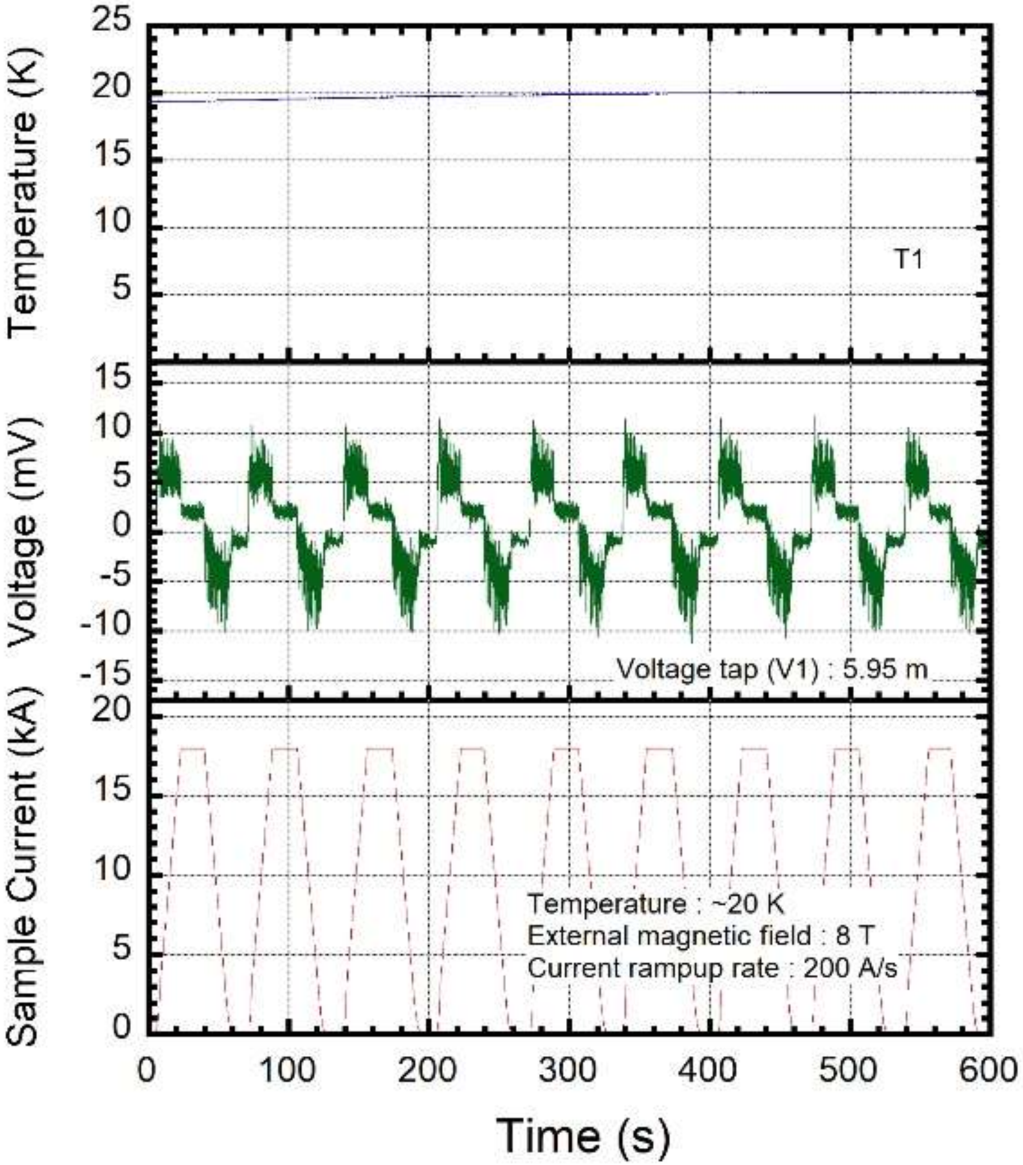
20-kA-class STARS conductor, 6-m sample experiment



Stable operation was confirmed at 18 kA@20 K, 8 T

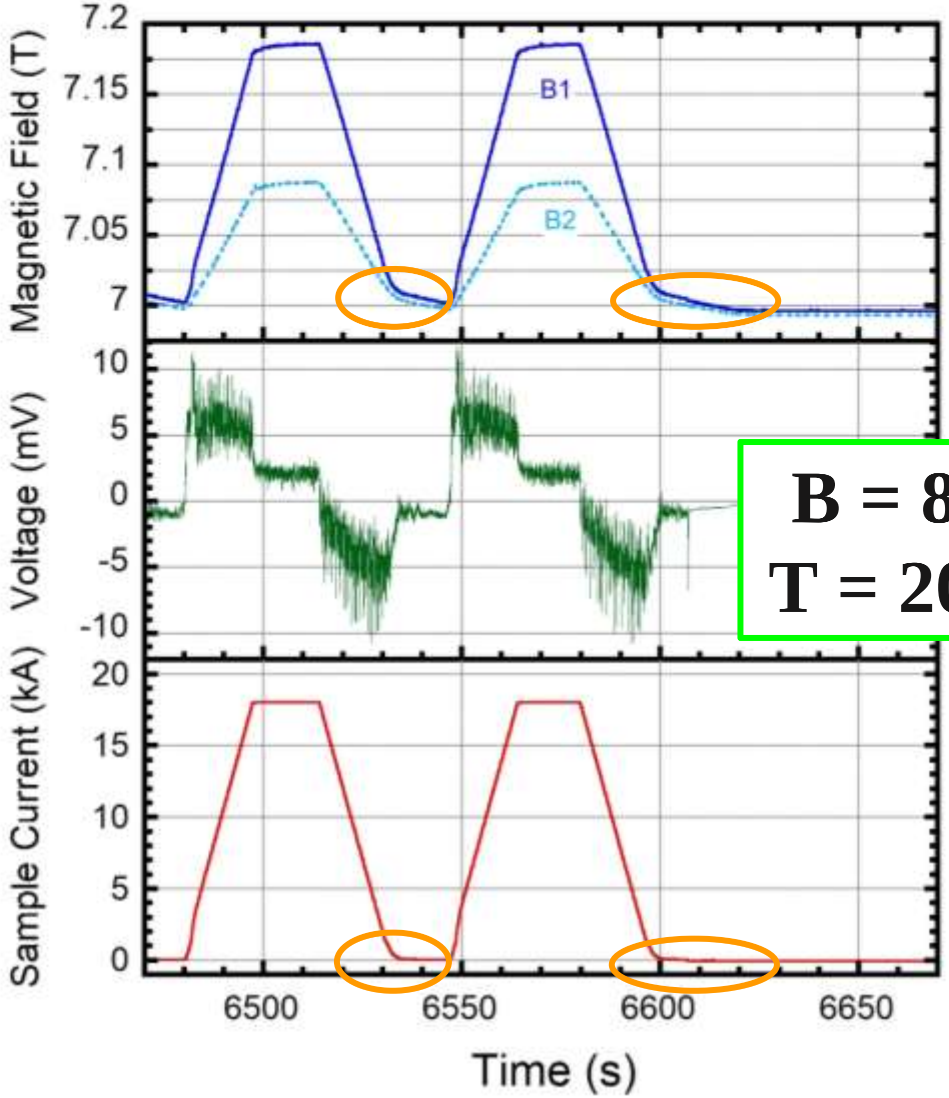
Repetitive excitations with fast ramp rate



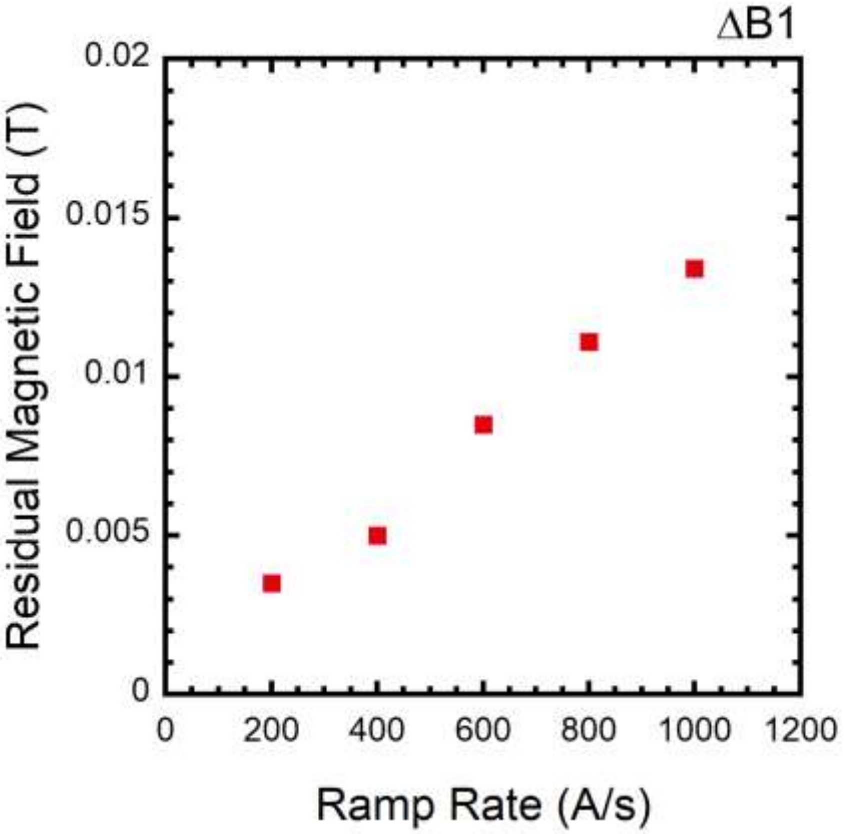


100 times of repetitive excitations up to 18 kA @20 K, 8 T with a fast ramp rate of 1 kA/s

Residual magnetic field after ramp-down



B = 8 T
T = 20 K



For a simplified two-tape system, the circulation current is given as:

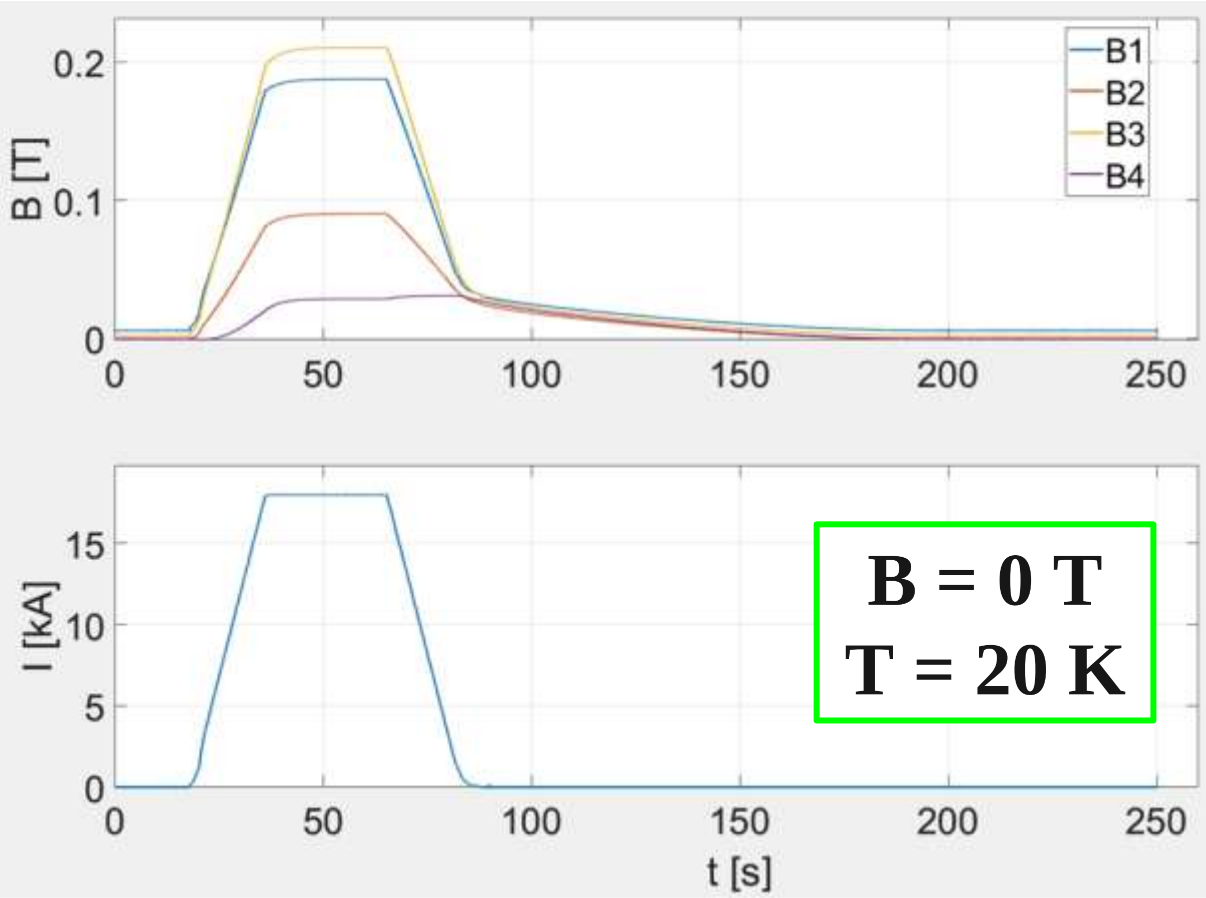
$$\Delta I = \frac{L_2 - L_1}{4R}\frac{dI_0}{dt}\exp\left(-\frac{2R}{L_2 + L_1 - 2M}t\right)$$

◆ **Residual magnetic field decays after the transport current becomes zero**

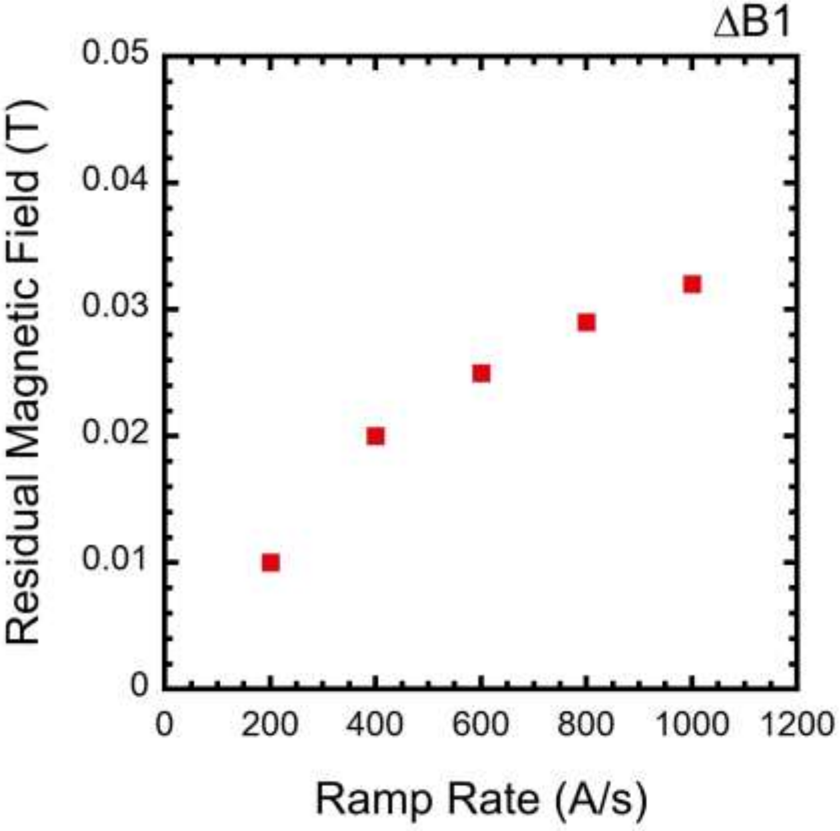
◆ **Residual magnetic field is proportional to the ramp-down rate**

◆ **Might be caused by circulation currents across stacked tapes (equivalent to the non-uniform current distribution)**

Residual magnetic field after ramp-down in the 2nd experiment



B = 0 T
T = 20 K

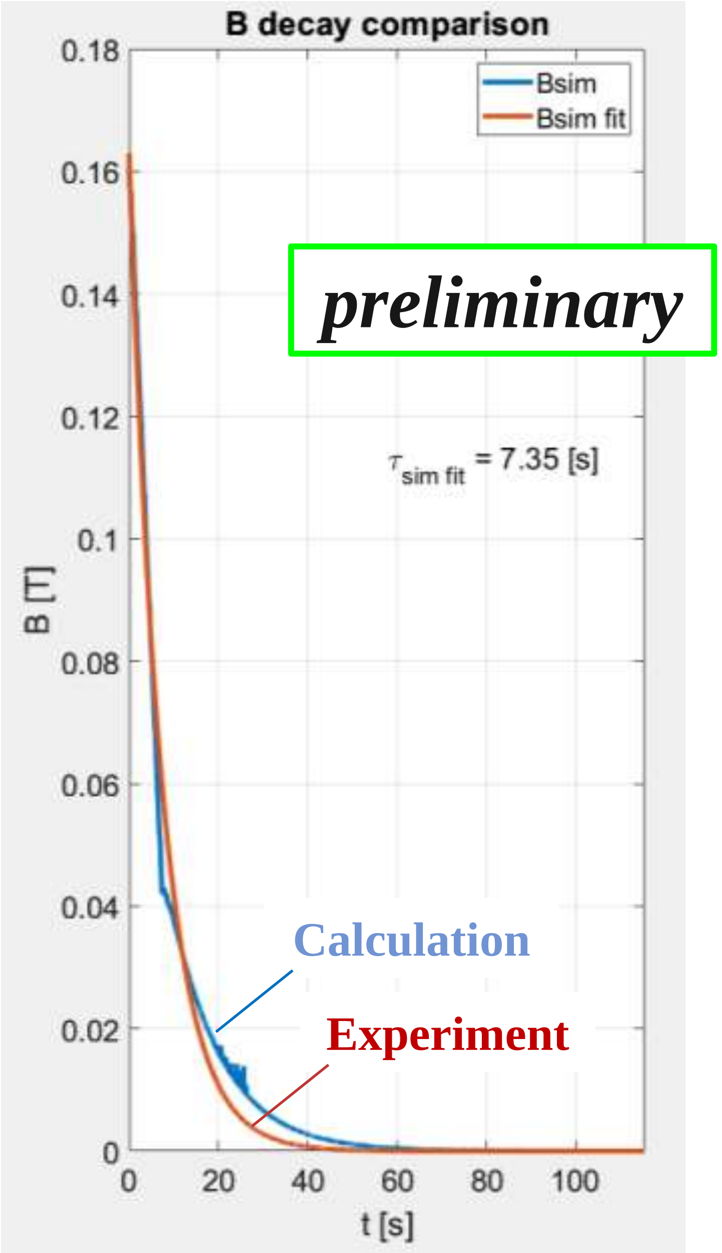


- **Residual magnetic field was measured in the second experiment at 0 T, 3 T, 6 T, and 8 T**
- **At 0 T, the decay time constant was much longer than that observed at 8 T (in the 1st experiment)**
- **It seems the residual magnetic field saturates with a fast ramp rate (by reaching the critical current?)**

➔ ***(This is wrong…)***

The ramp-down time was much shorter than the decay time constant for the circulation current to saturate…

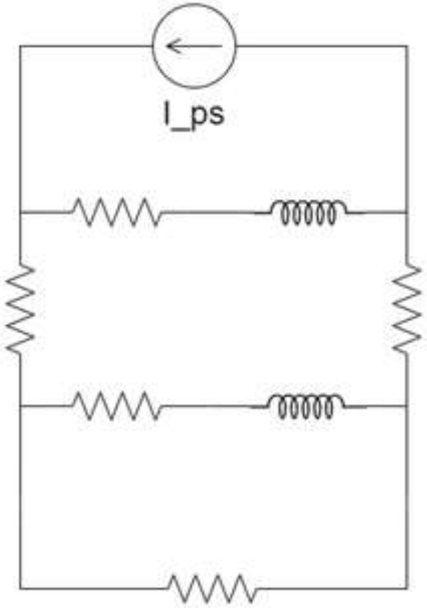
Numerical simulation of the residual magnetic field by circulation current with inductance variations among REBCO tapes

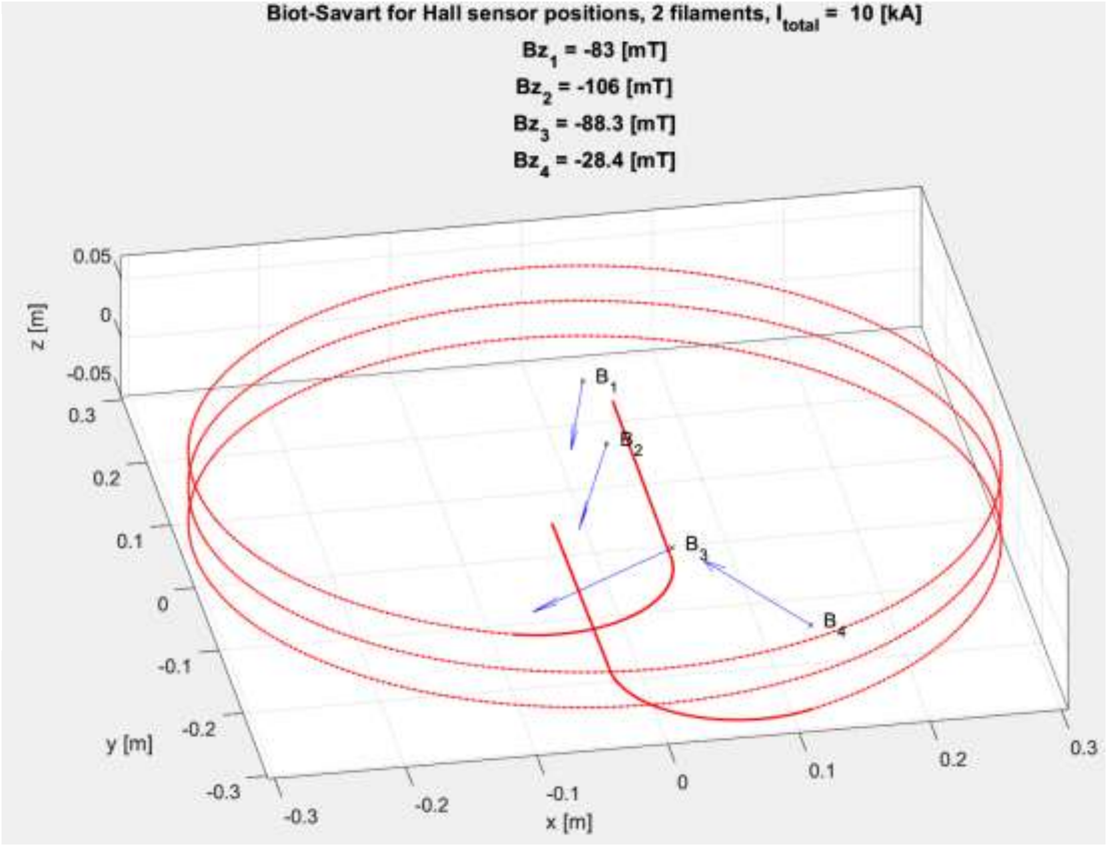


preliminary

Calculation

Experiment





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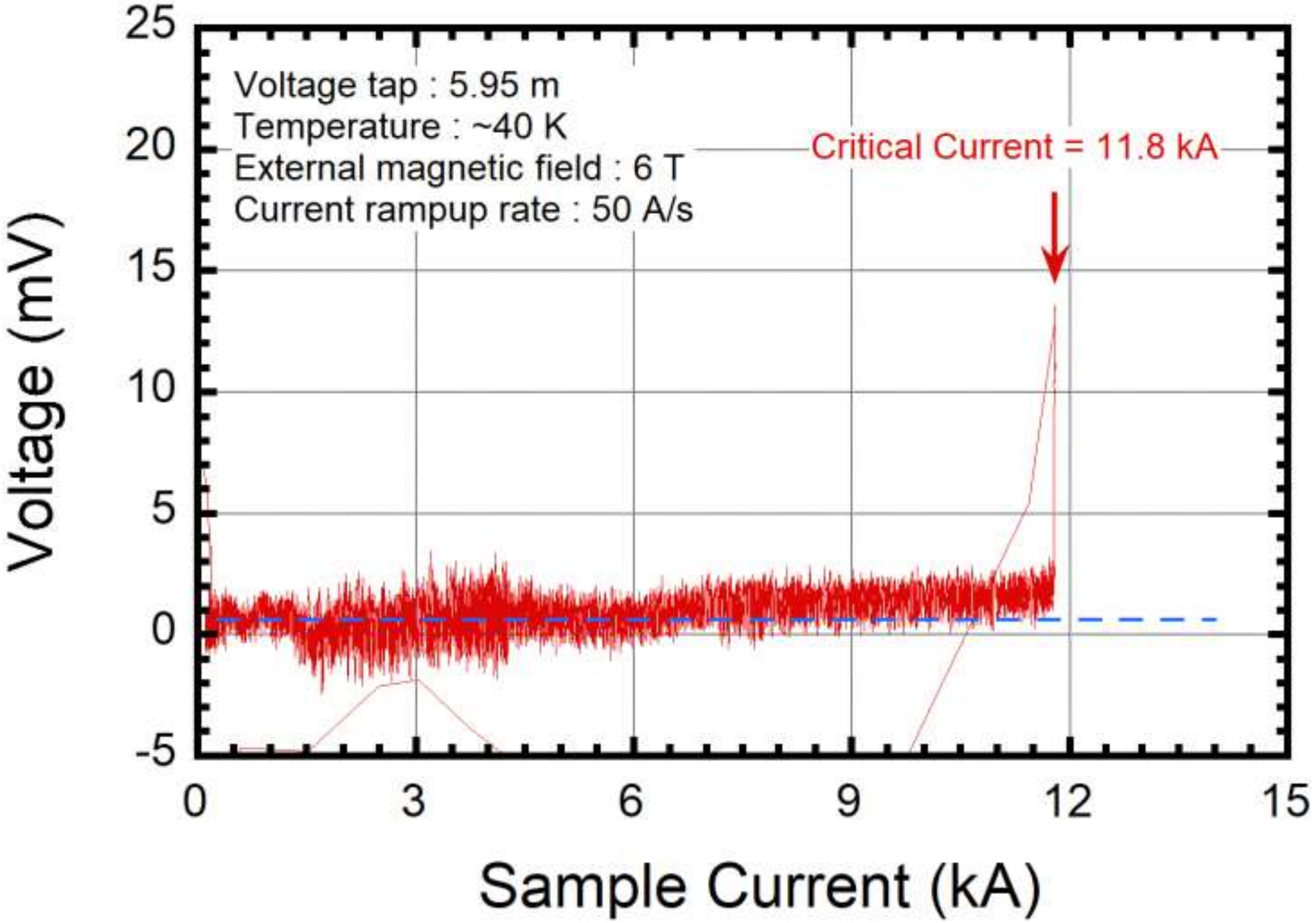
Critical current measurement in the 1st experiment



Inlet Temp.: ~40 K
Outlet Temp.: ~45 K

Vacuum pres.: ~1.3 Pa

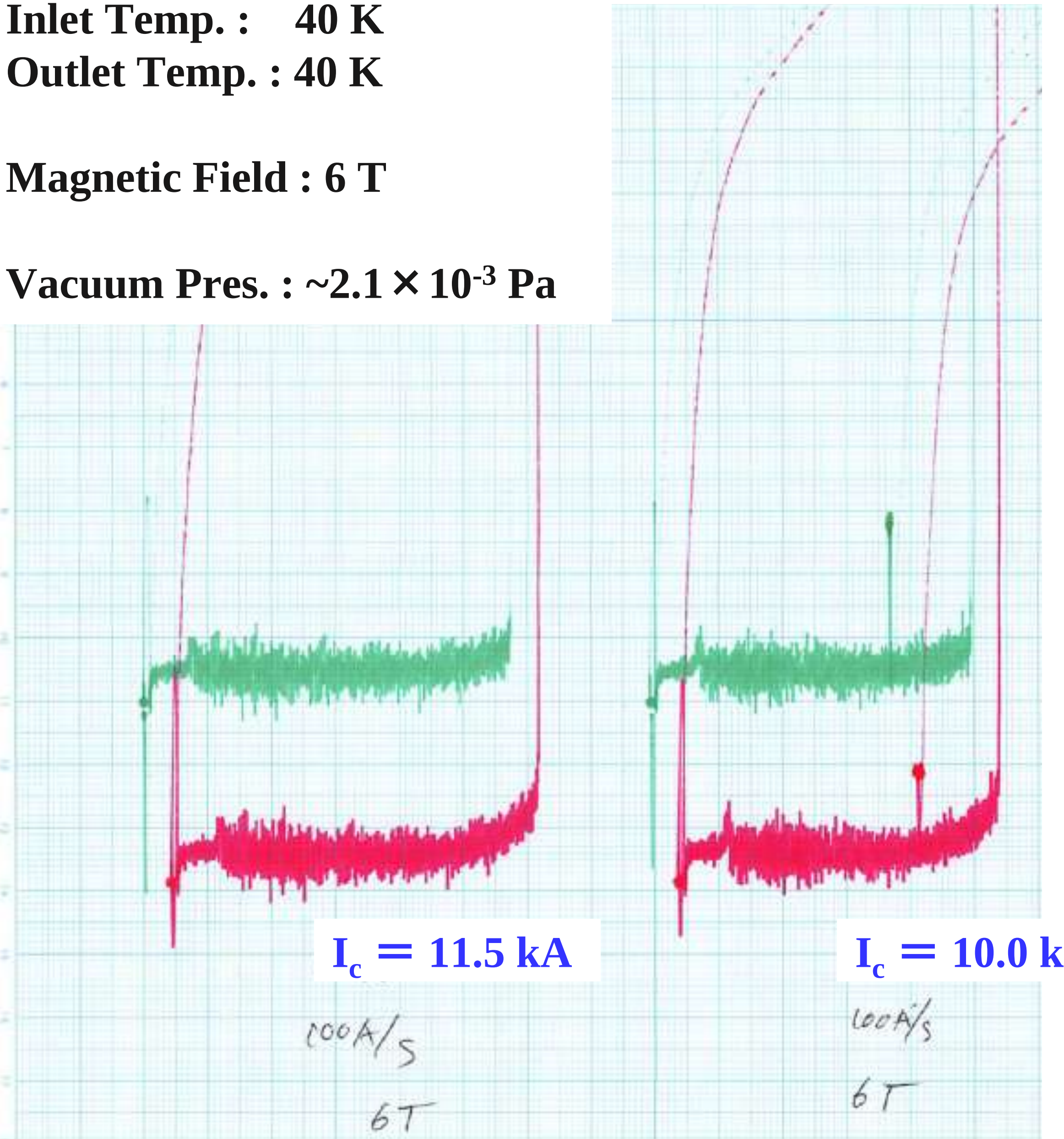
Critical current was observed at 11.8 kA@40 K, 6 T
➔ lower than that measured for the previous conductor (w/o. internal insulation) tested in the split coil (13.0 kA)

Critical current measurement in the 2nd experiment

Inlet Temp. : 40 K
Outlet Temp. : 40 K

Magnetic Field : 6 T

Vacuum Pres. : ~2.1×10^{-3} Pa



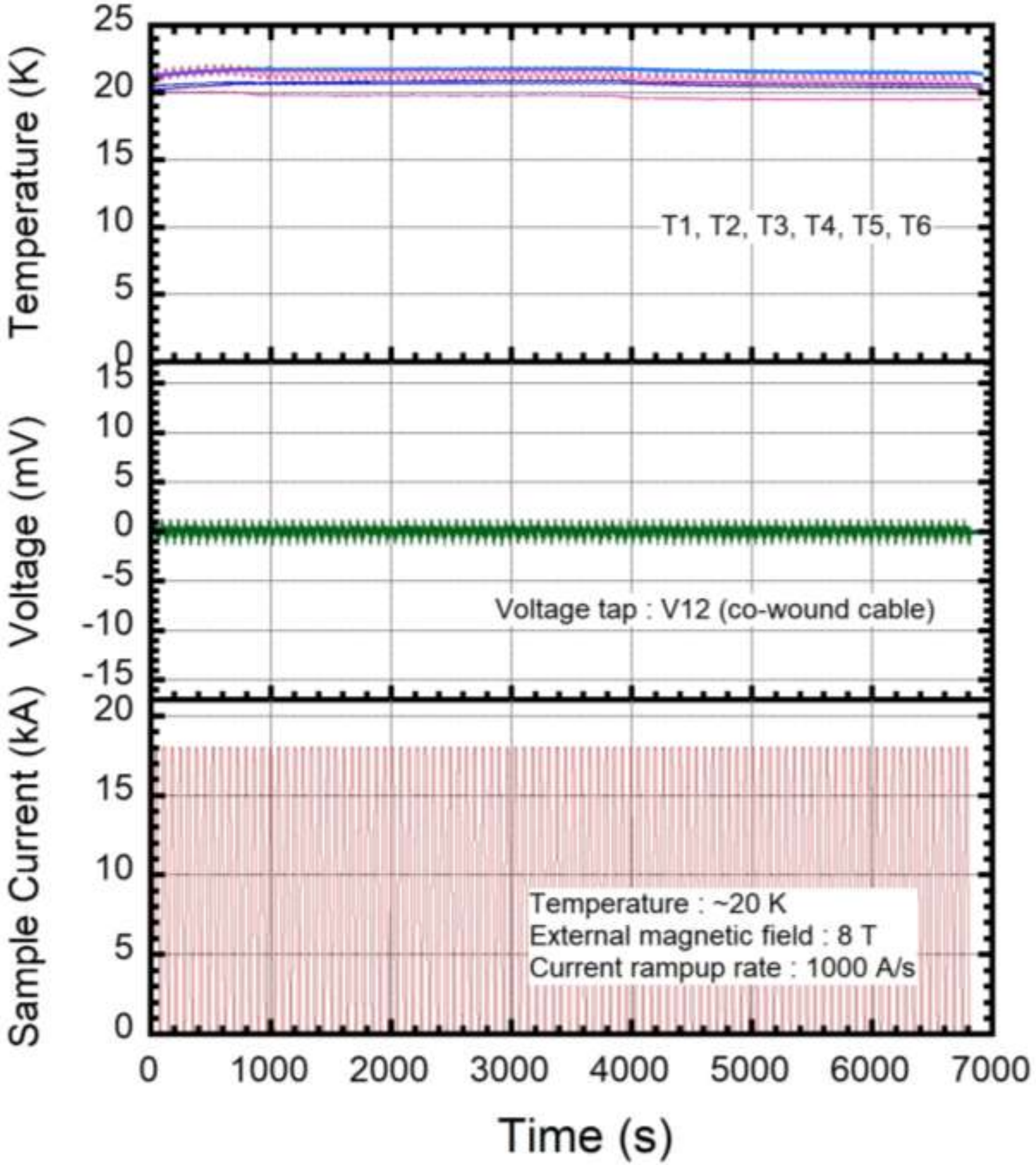
Lower critical current observed

- **Though with a uniform temperature (40 K)**
- **Degradation due to previous quenches?**
- **Degradation due to fabrication (weak point)?**

Further degradation after quench

- **Quench detection : 100 mV × 100 ms**
- **➔ Overheating may have occurred?**
- **➔ About half of tapes may have been lost…**

Quench detection
100 mV × 100 ms
➔
10 mV × 10 ms ?



20 K, 8 T, 18 kA 100 times repetition
➔ still successful!

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Summary

- **Conceptual design studies on the helical fusion reactor FFHR-b3 is aiming at 100 MW electricity production with double size of LHD and configuration optimization**
- **Three types of HTS conductors are being developed for the next-generation helical and other fusion experimental devices with a high current density of 80 A/mm^2**

STARS conductor

20 kA conductor is developed with a simple stacking of REBCO tapes and laser welding of SS jacket
Experiments in 8 T, 20 K for a 6-m solenoid sample confirmed stable operation
Fast ramp rate (1 kA/s), 100-times repetition excitations showed no degradation
Residual magnetic field suggests circulation current among stacked tapes, simulated by calculation
Degradation due to overheating after quench suggests lower detection condition

Future Works

- **Clarification of the simple-stacking concept of REBCO tapes**
  - **Application limit from the viewpoint of formation of non-uniform current distribution**
  - **Evaluation of circulation current and its effect on stability**
- **Establishment of the most suitable, reliable, and practical quench protection**