大電流高温超伝導積層型導体の研究開発と核融合炉マグネットへの適用検討

Development of Large-Current High-Temperature Superconducting Stacked-Type Conductor and Its Application to Fusion Magnets

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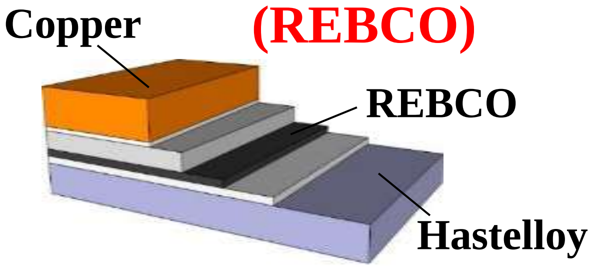
ユニット成果報告会
2024年5月9日

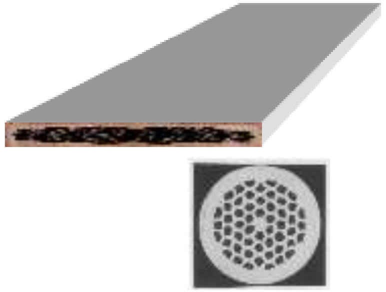
High-Temperature Superconducting Magnet Option

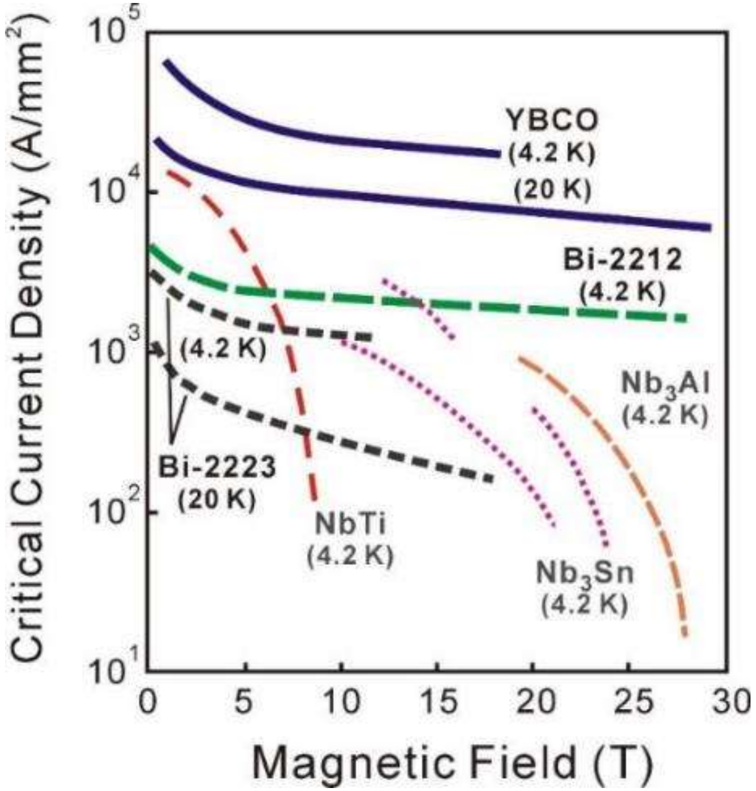
(1) High critical current to high field
(2) High cryogenic stability ➔ High current density
(3) Low cryogenic power
(4) High mechanical rigidity
(5) Industrial production of tapes
(6) Saving helium resources

Rare-Earth Barium Copper Oxide (REBCO)



Bismuth-based HTS



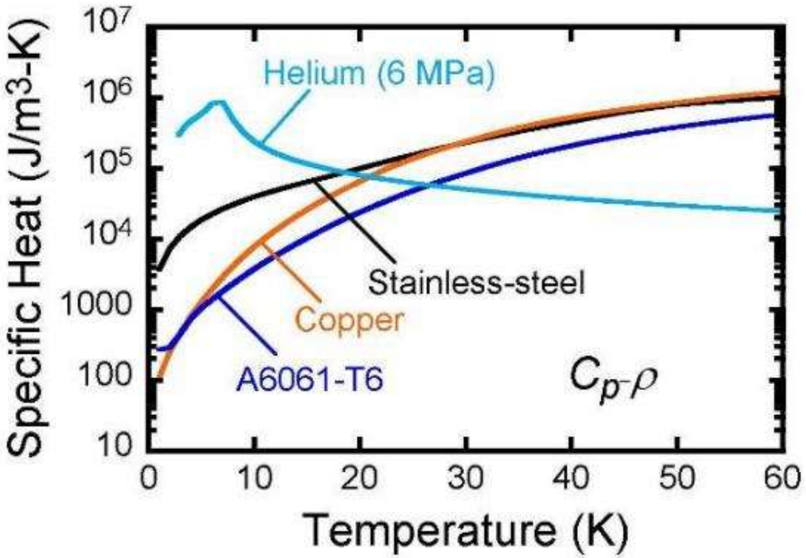


Stability Margin

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

$$C_p \rho \Delta T \approx 2\times10^5\ (\mathrm{J/m^3K})\times 10\ (\mathrm{K})$$

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

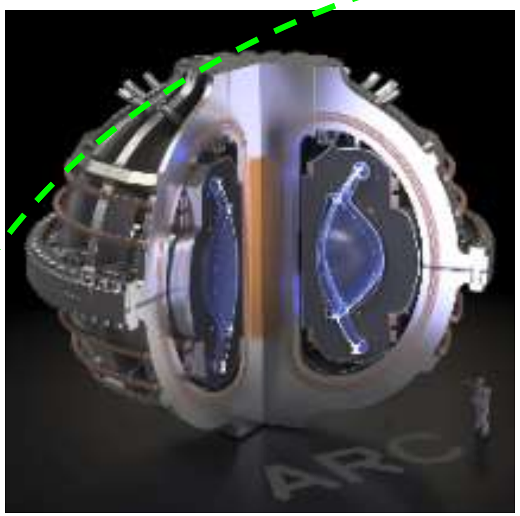


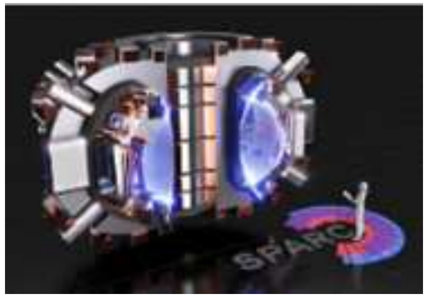
Higher than CIC conductor
➔ Low quench risk!

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

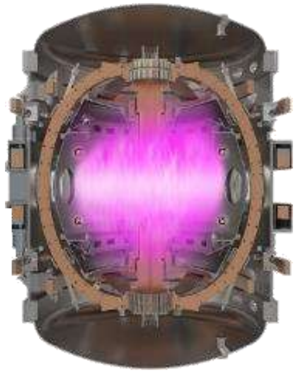
Fusion reactor designs with HTS magnet in the World

ARC & SPARC (MIT/CFS)



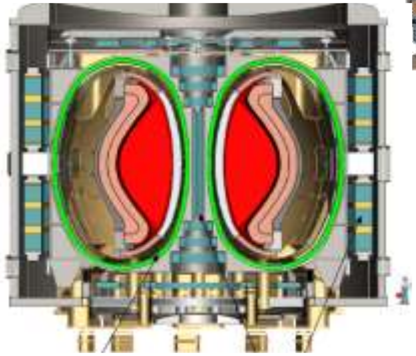


Tokamak Energy

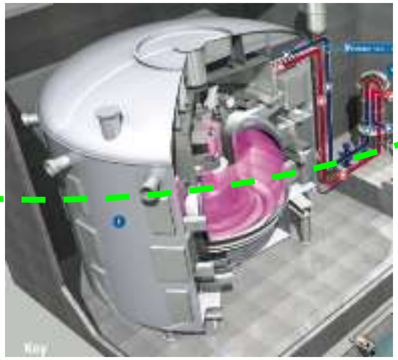


STEP (UKAEA)

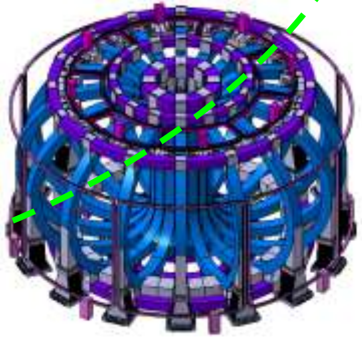
FNSF-ST (PPPL)



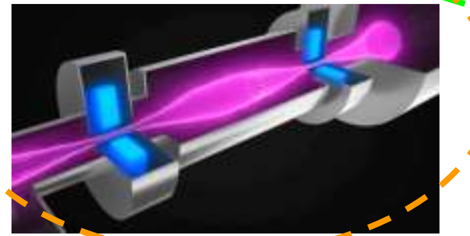
EU DEMO HTS option (EUROfusion)



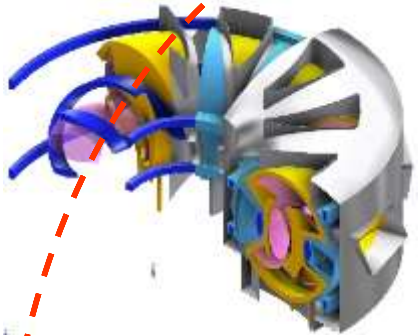
CFETR for CS coils (ASIPP)



Realta Fusion

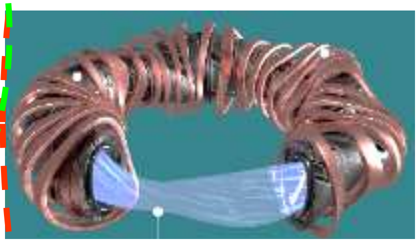


FFHR-d1 (NIFS)



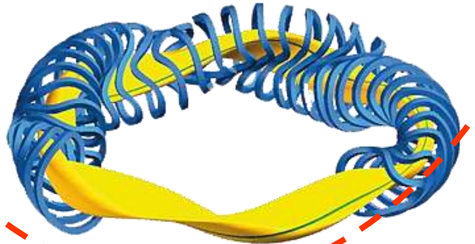
Helical Fusion

Type One Energy

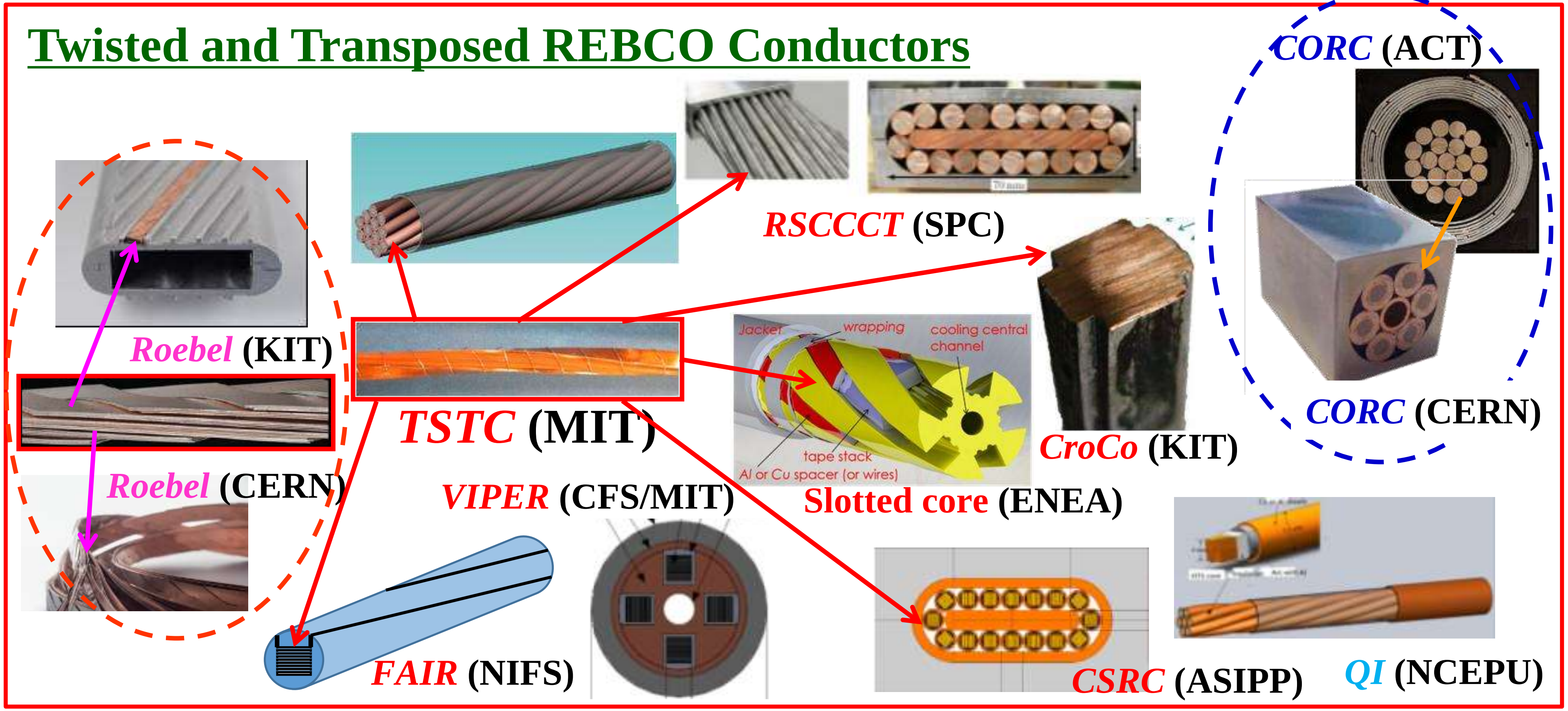


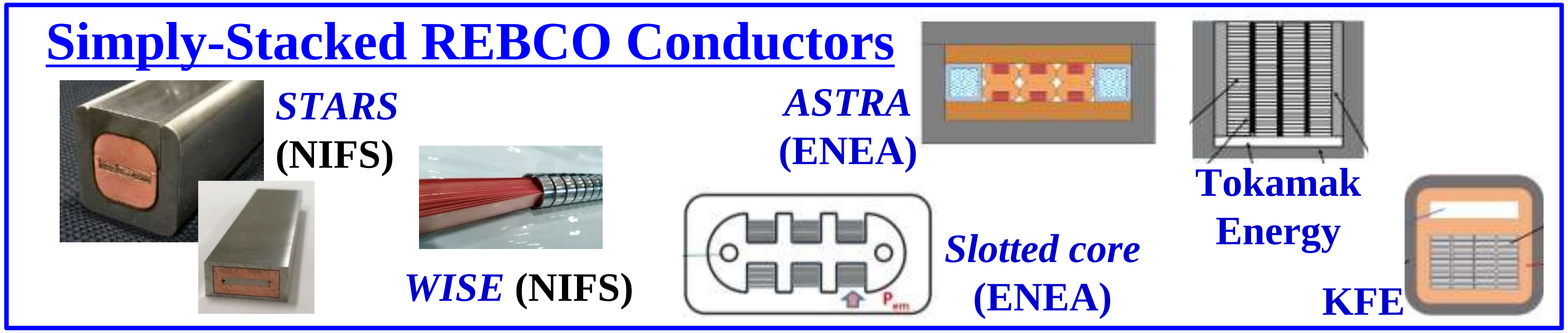
Renaissance Fusion

Proxima Fusion

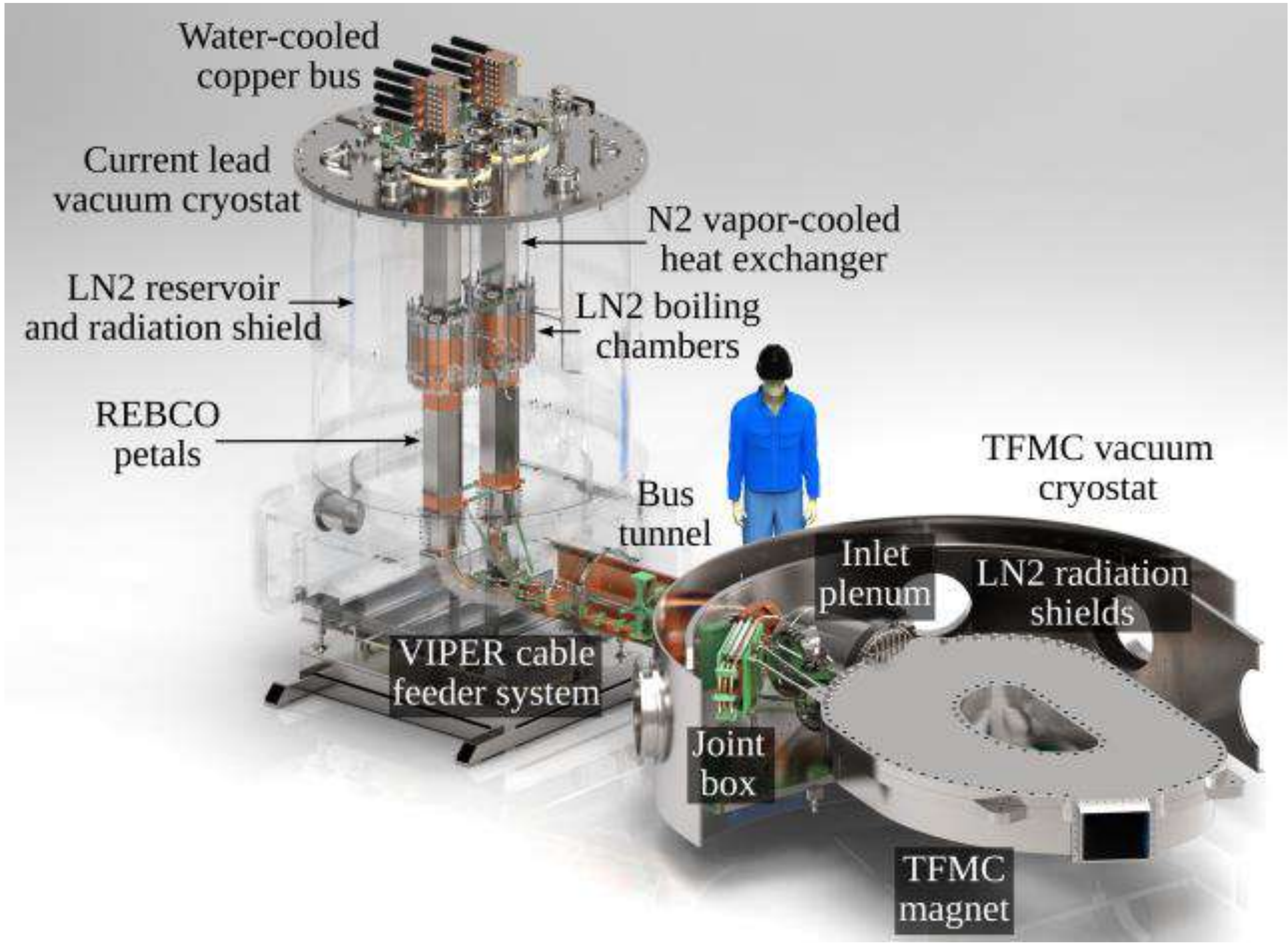


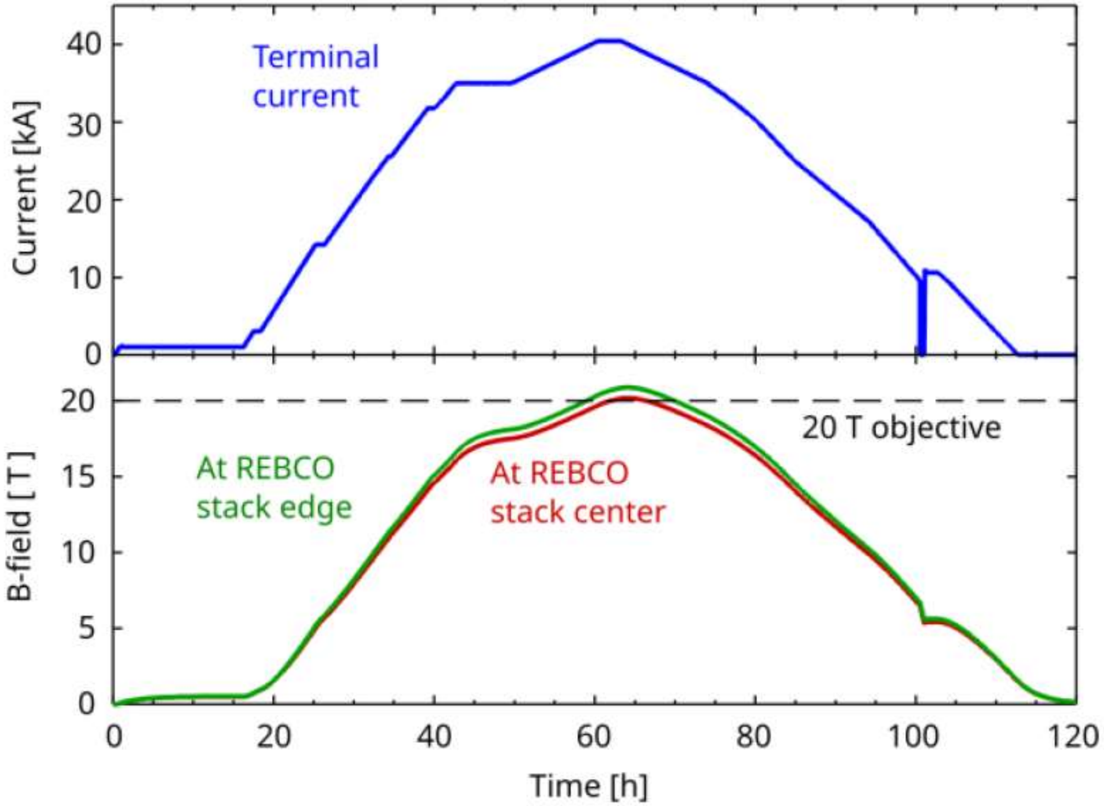
Large-current HTS conductors developed for fusion magnets

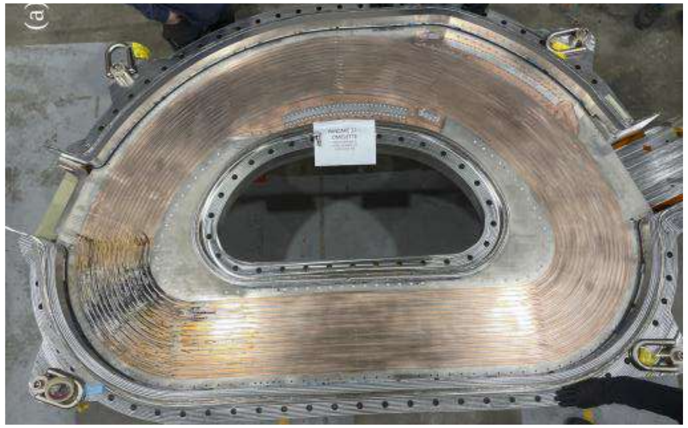




Achievement of 20 K, 20 T by SPARC TFMC (Sep. 2021) with NINT (No-Insulation No-Twist) coil (by MIT / CFS)



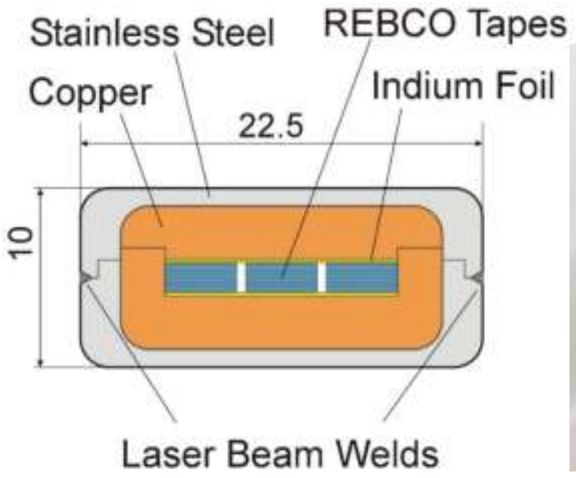




D. G. Whyte et al., "Experimental Assessment and Model Validation of the SPARC Toroidal Field Model Coil", IEEE Trans. Appl. Supercond. 2024 0600218

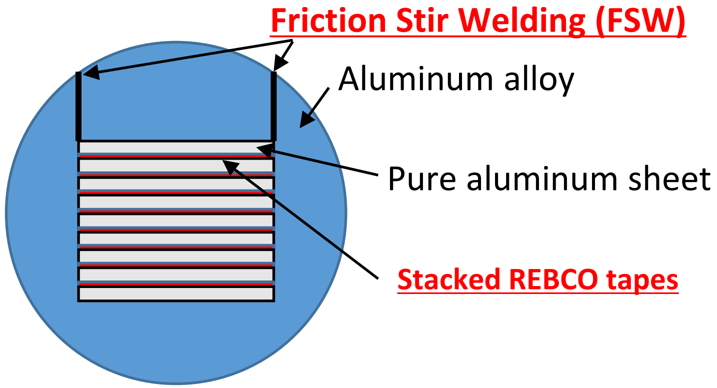
HTS conductor development at NIFS
for the next-generation fusion experimental devices

STARS
(Stacked-Tapes Assembled in Rigid Structure)



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

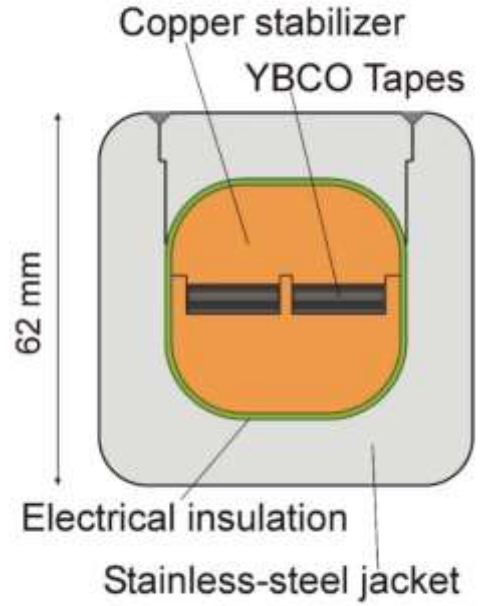
FAIR
(FSW, Al-alloy, Indirect-cooling, REBCO)



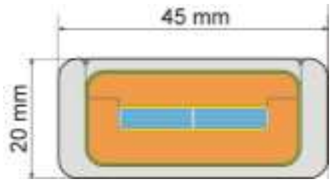
WISE
(Wound and Impregnated Stacked Elastic tapes)

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

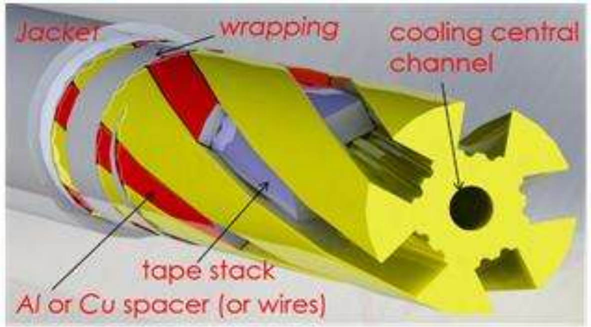
- Non-uniform current distribution may be allowed
- High mechanical strength (no void & local deformation)
- Low cost / low-resistance joint
- Development since 2007

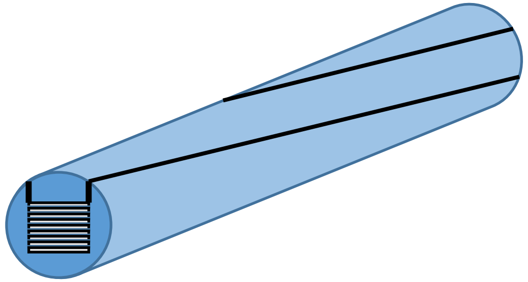
"Can we apply simple-stacking conductors to large coils?"

- **Twisting and transposition are the "iron rules" to avoid non-uniform current distribution (NUCD)**
- **NUCD makes Low-Temperature Superconducting (LTS) conductors unstable with a premature quench at a high ramp rate (Ramp-Rate Limitation)**
- **Most of the conductor designs for HTS have employed twisting and/or transposing**

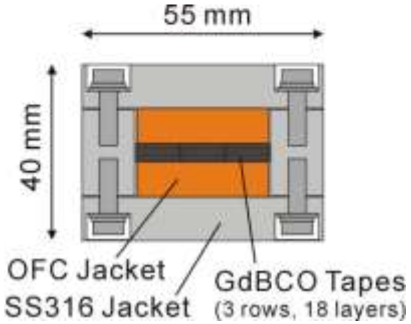
➔ **If we can employ simple stacking, we may have robust and low-cost eonductors …**

> ***"HTS has much higher cryogenic stability margin than LTS… The iron rules for LTS may not have to be followed by HTS…"***
>
> ➔ **Working hypothesis with no clear proof**

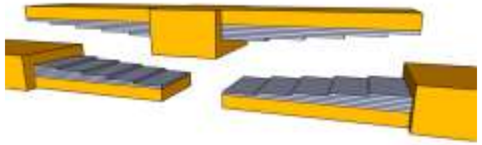


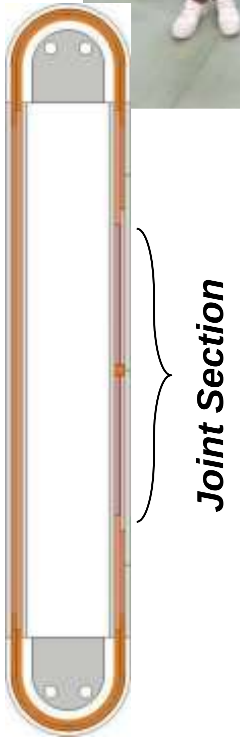


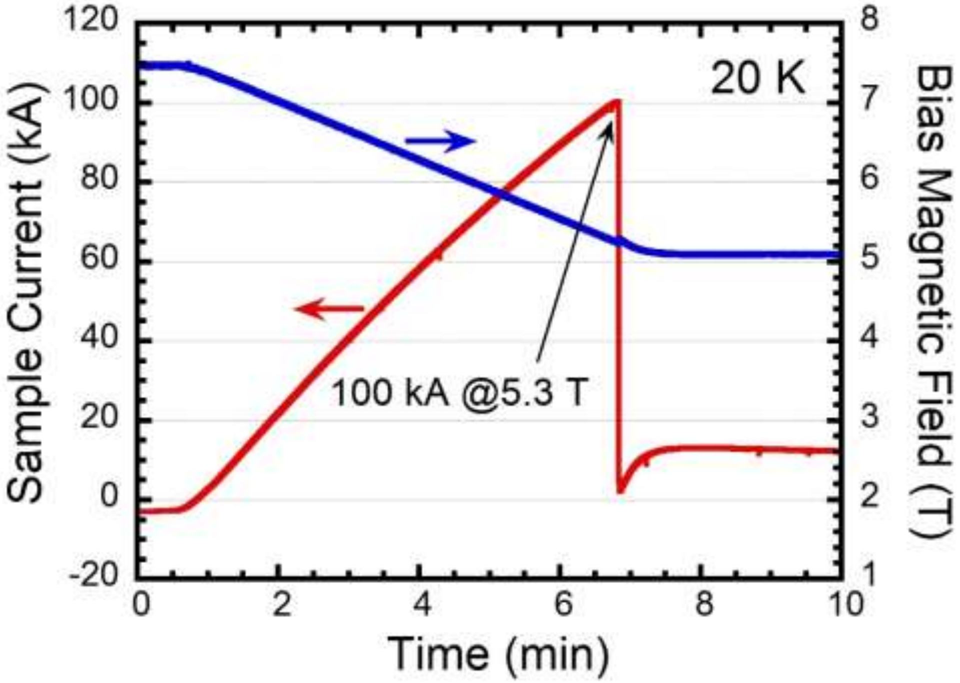
100 kA-Class Prototype STARS Conductor Test

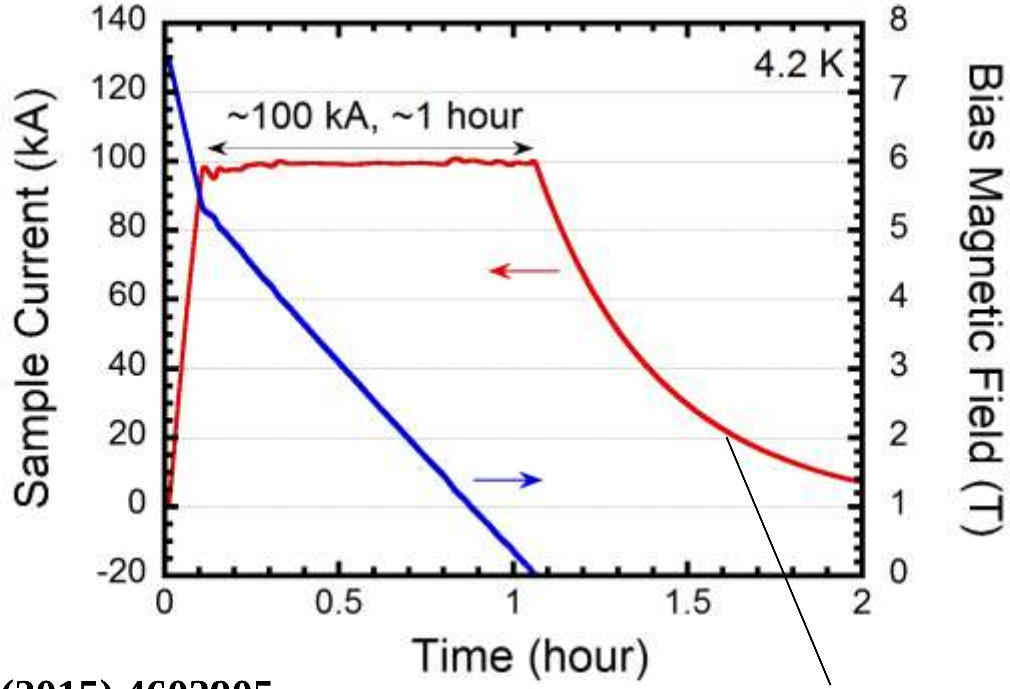


Bridge-type mechanical lap joint
"*Invisible joint*"





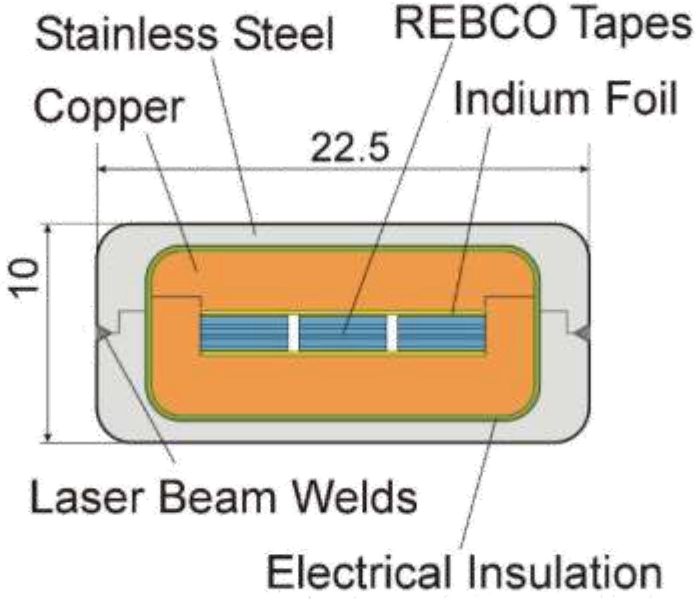


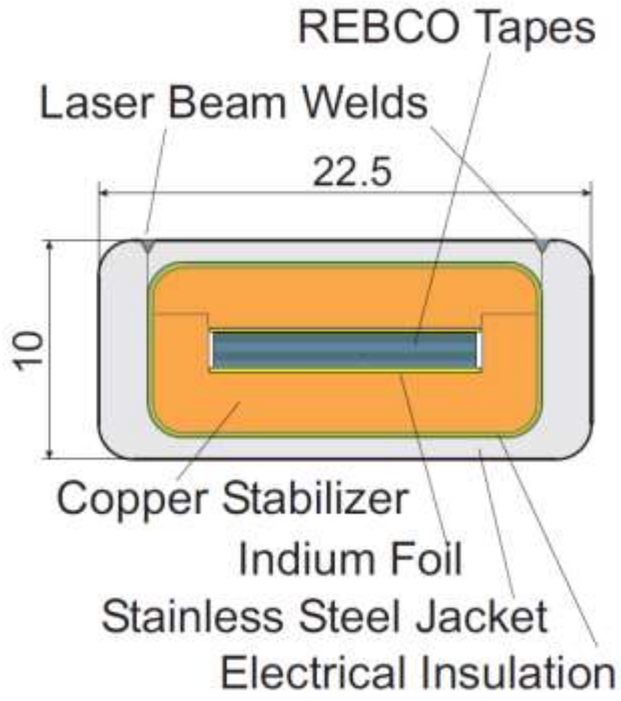


Joint resistance ~1.8 nΩ

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

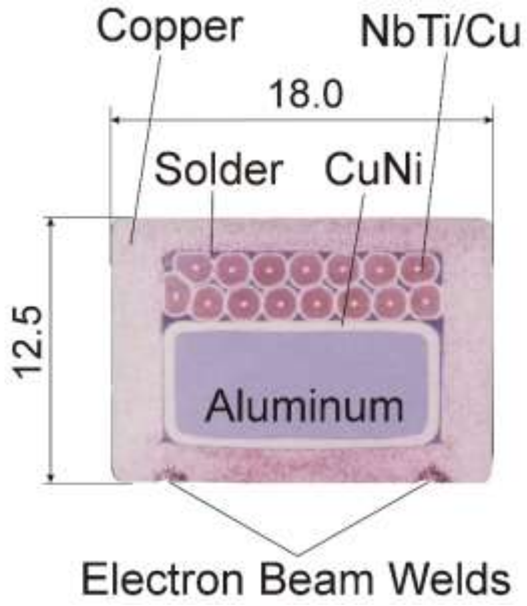
20 kA-class STARS conductor with internal electrical insulation





HTS Conductor

REBCO + Cu + SS
18 kA@15 T
80 A/mm^2



LTS Conductor for LHD helical coils

NbTi/Cu + Al + Cu
13 kA@6.9 T
57.8 A/mm^2

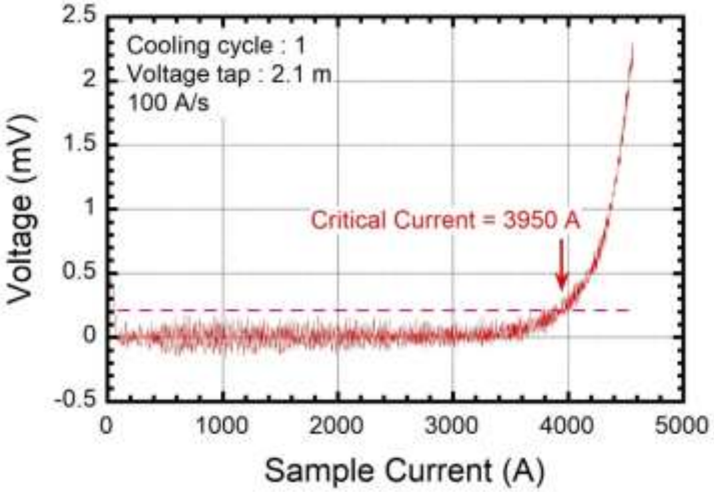
- **In FY2020, new conductor samples (1-m and 3-m length) with internal electrical insulation were fabricated at Metal Technology Co. Ltd. (Toki factory)**
- **The same ~4 kA critical current was observed in liquid nitrogen, as was observed for the former sample without electrical insulation**

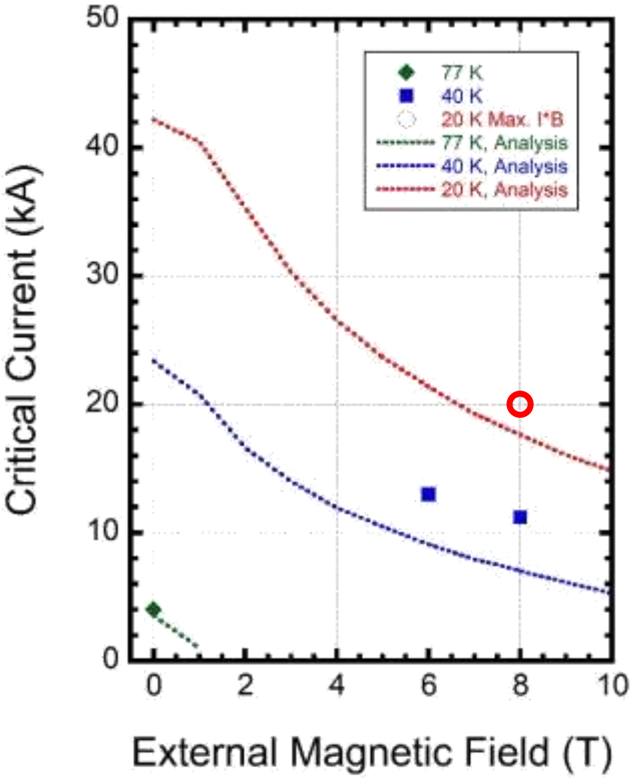
20 kA-class STARS Conductor

- Next phase development of 20-kA-class conductor with long length to be applied to the next generation fusion experimental devices
  - High current density of 80 A/mm² is a big target
- A 3-m-long conductor sample
  - Fabricated by HITACHI Ltd.
  - 45 REBCO tapes (Fujikura FESC-SCH04)
  - Laser beam welding of SS jacket

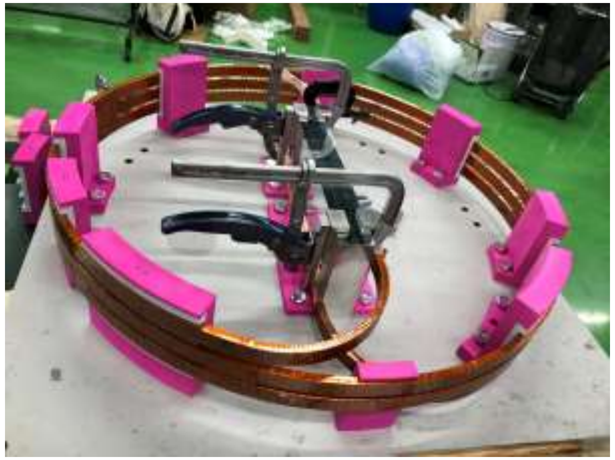
Laser Beam Welding

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

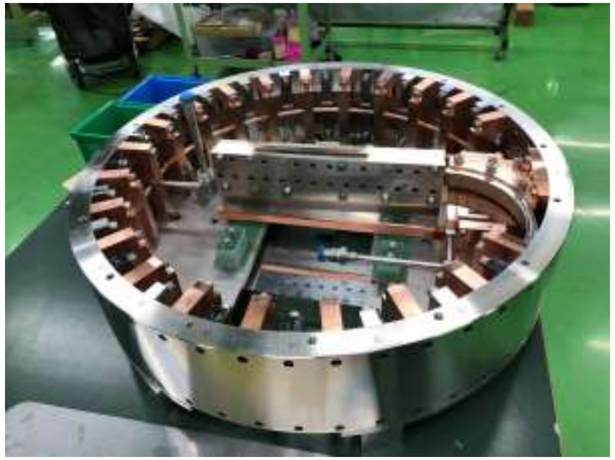
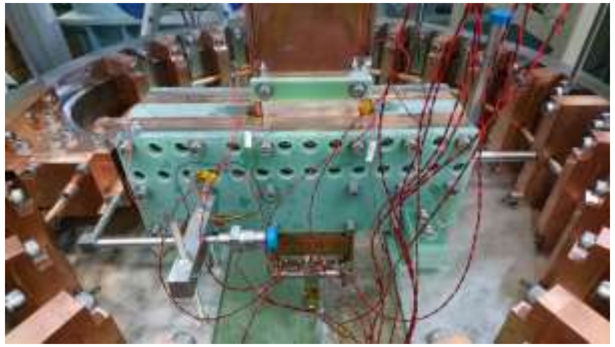




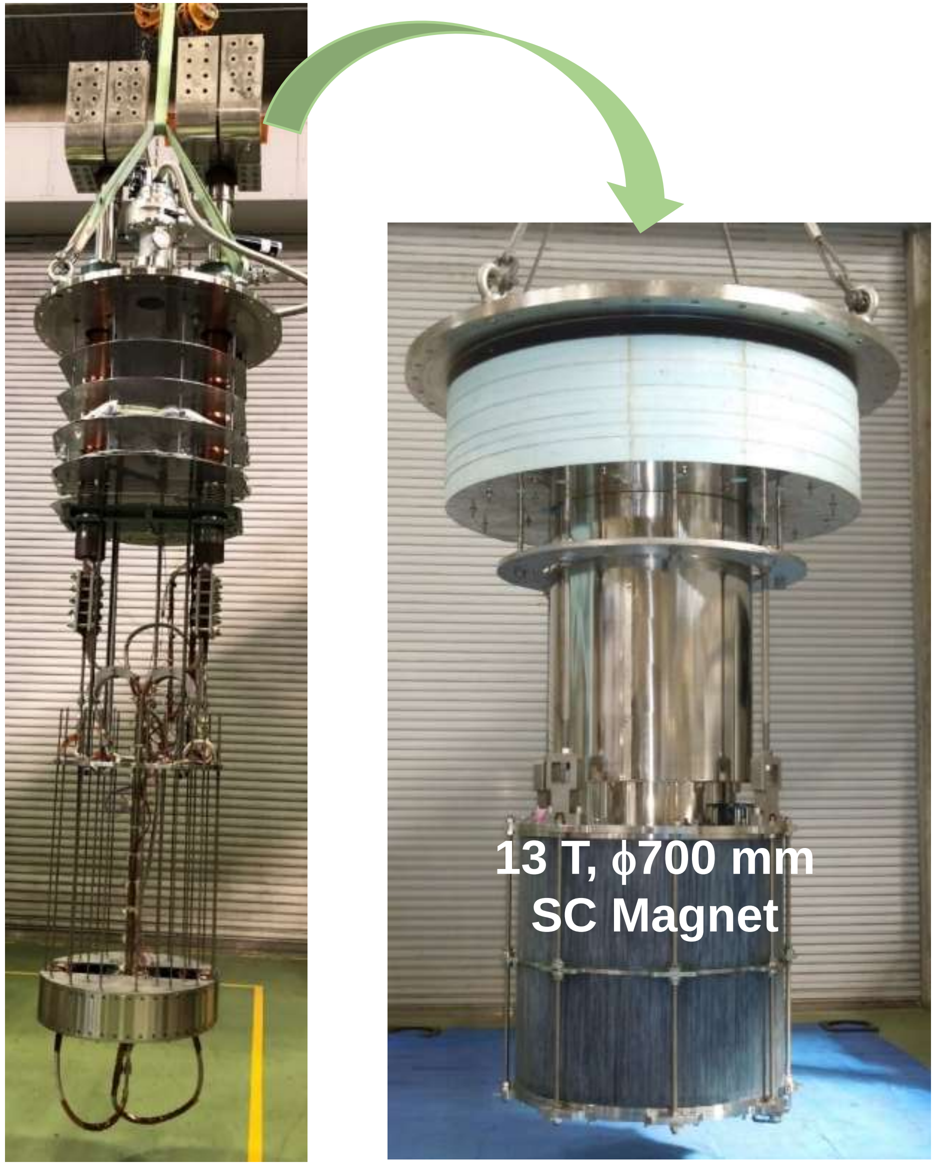
Fabrication of 20-kA-class STARS conductor, 6-m sample

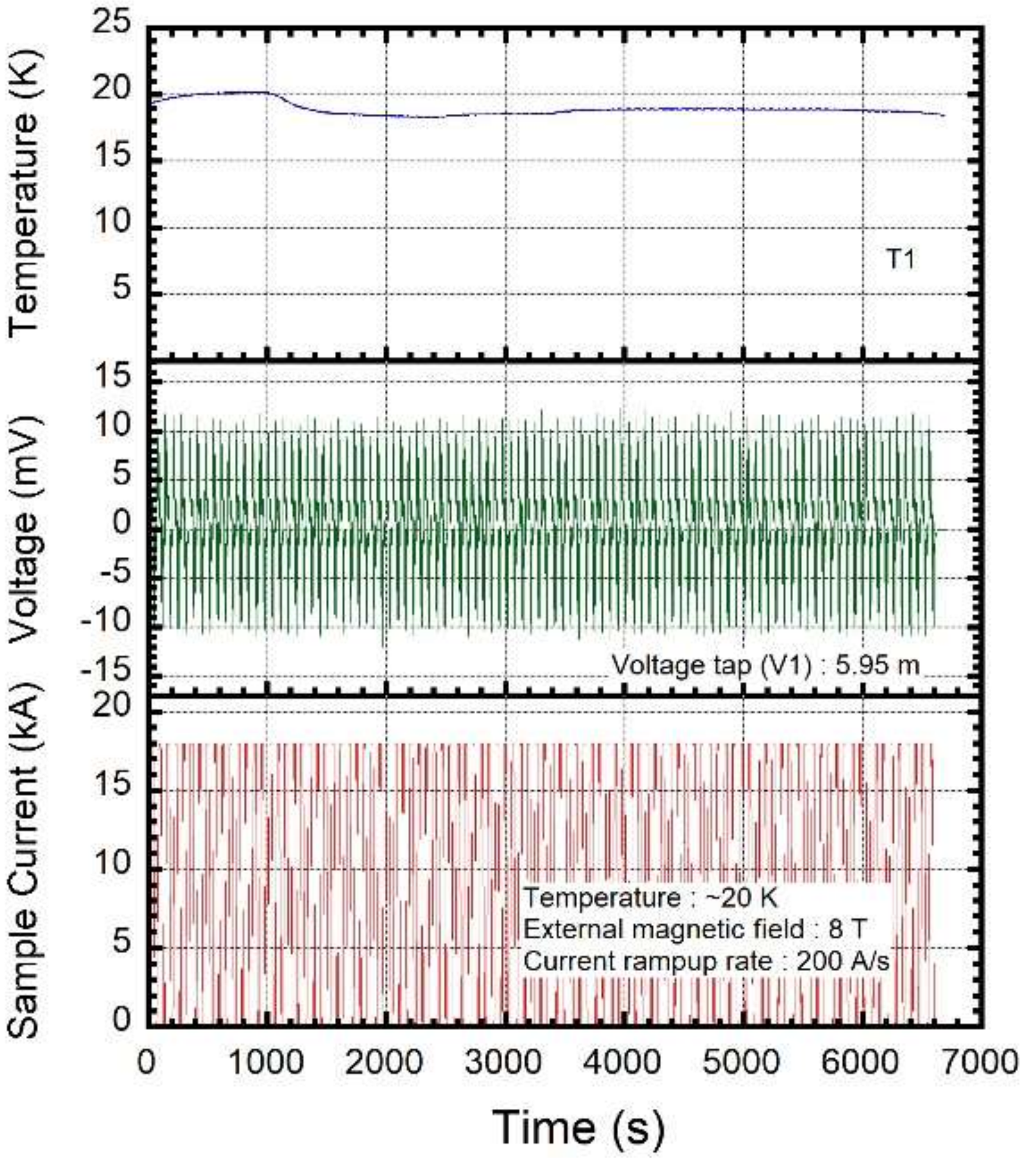


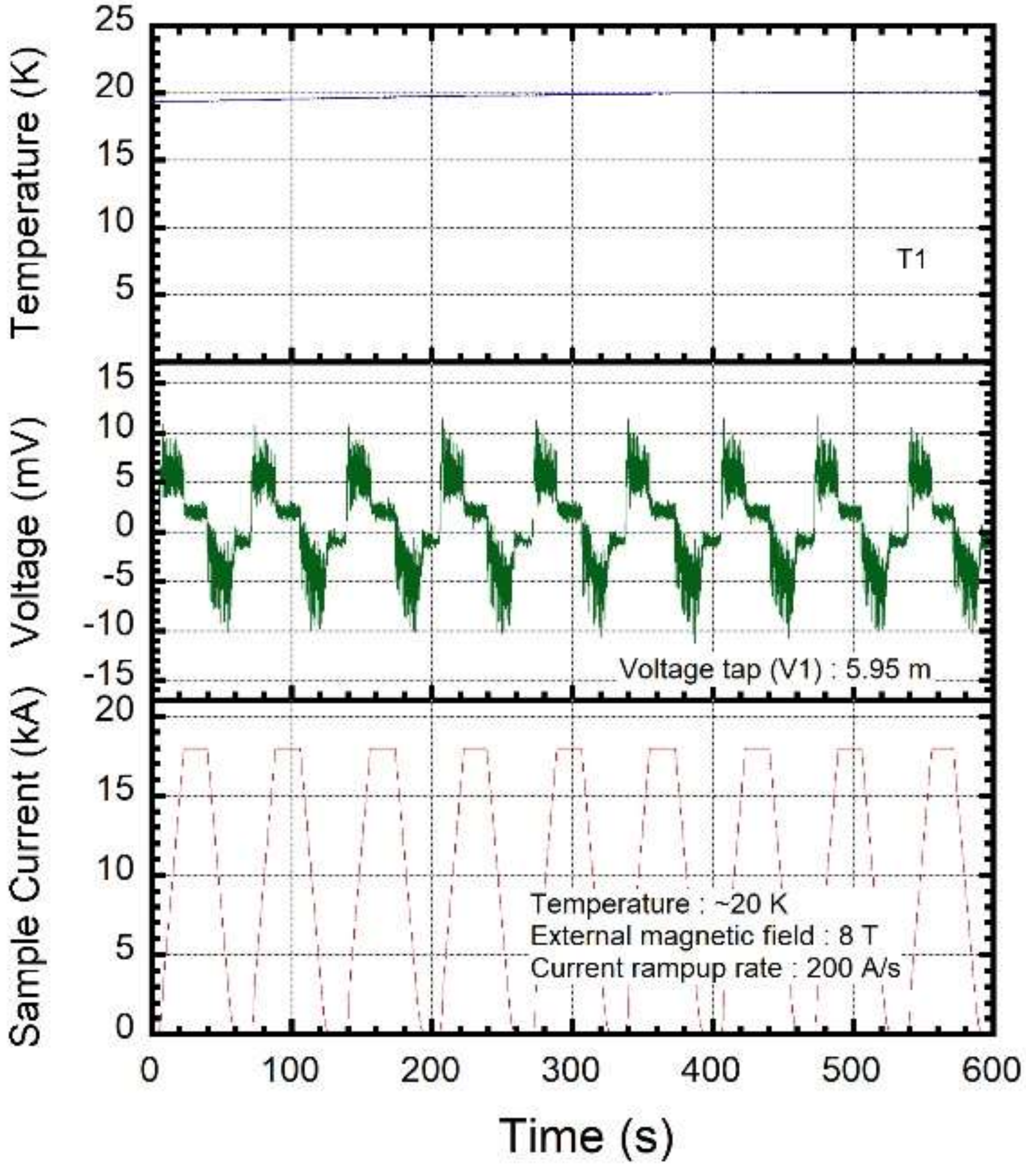



20-kA-class STARS conductor, 6-m sample experiment



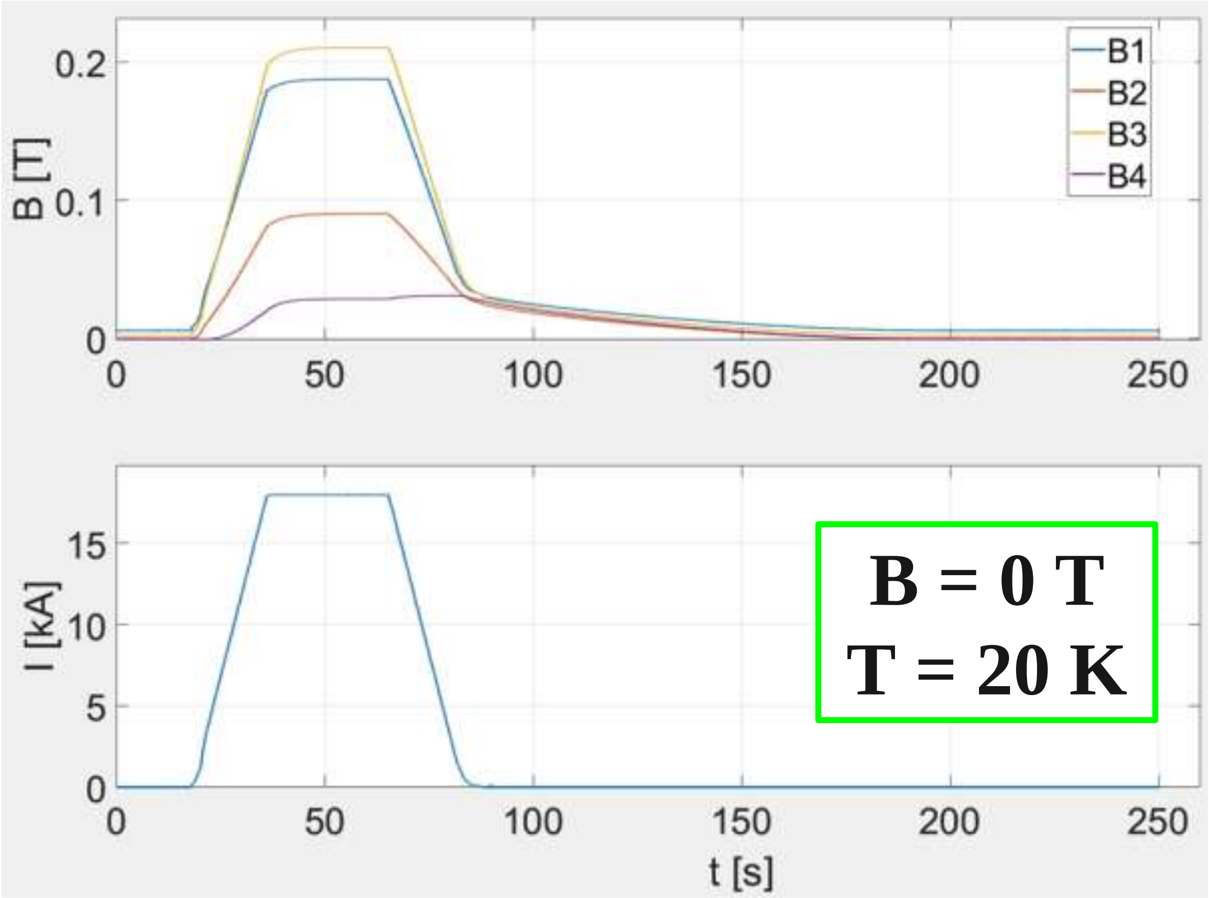
Repetitive excitations with fast ramp rate

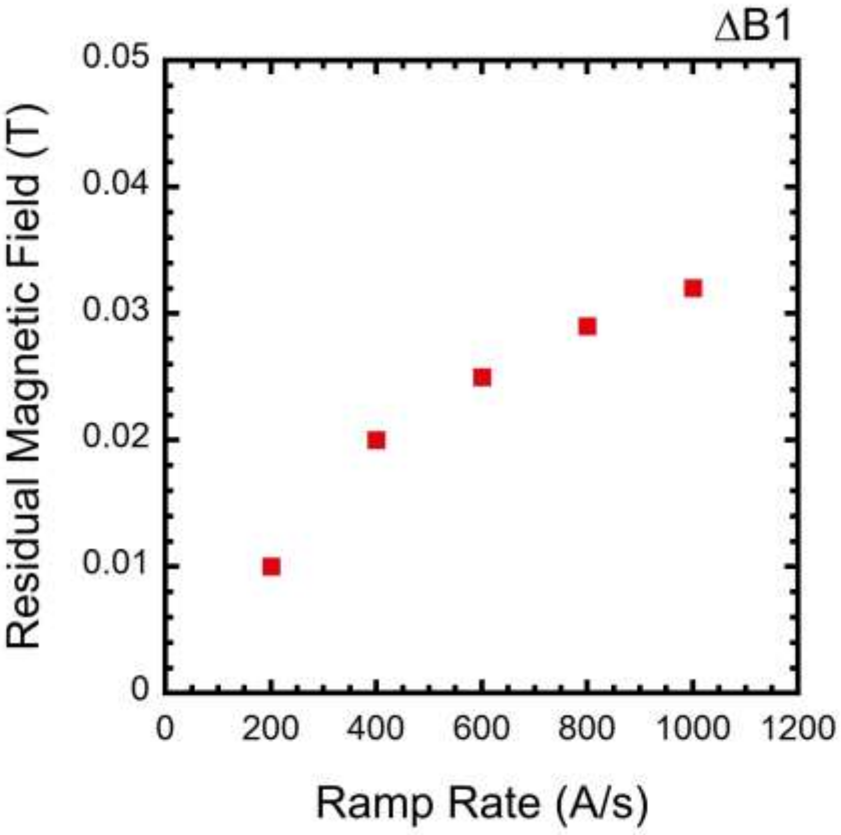


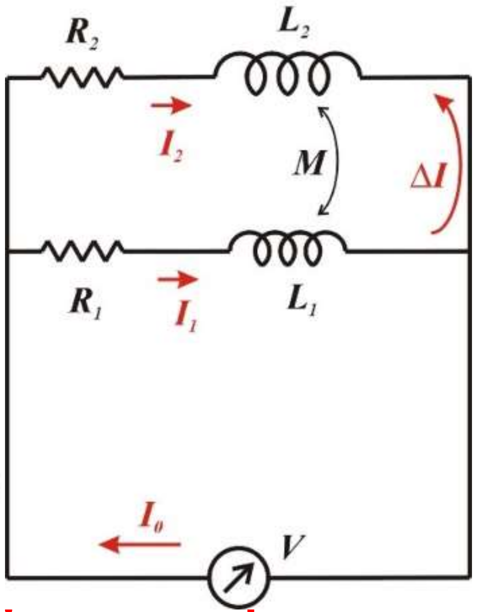


100 times of repetitive excitations up to 18 kA @20 K, 8 T with a fast ramp rate of 1 kA/s

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







For a two-tape system, the circulation current becomes

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

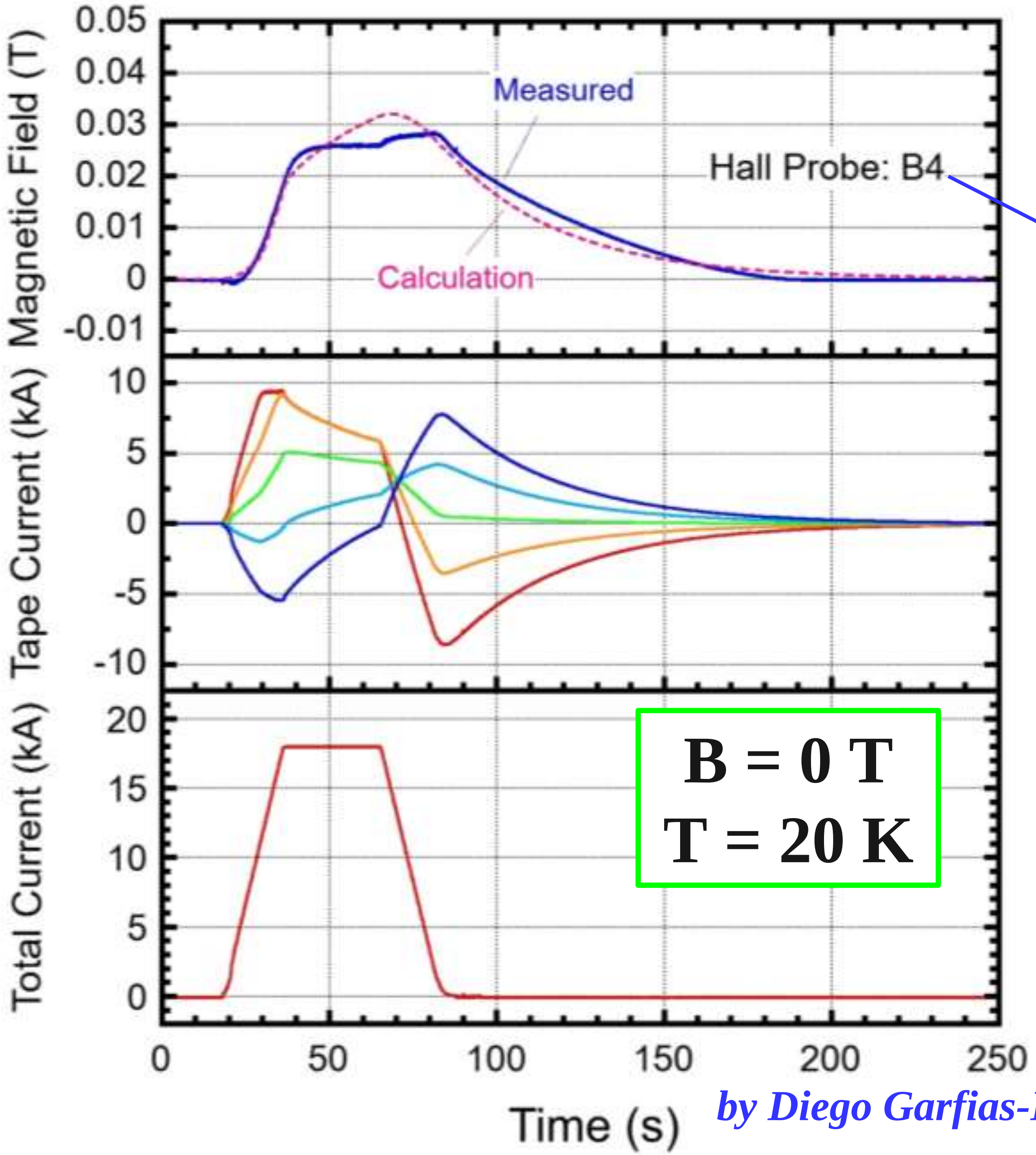
- **Residual magnetic field was measured in the second experiment at 0 T, 3 T, 6 T, and 8 T**
- **At 0 T, the decay time constant was much longer than that at 8 T (in the 1st experiment) due to lower joint resistance**
- **Residual magnetic field saturates with a fast ramp rate, by reaching the critical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

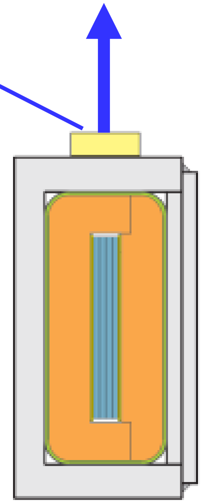
Non-uniform current distribution in STARS

- Five tapes are assumed for the actual 15 tapes (in 2 mm thickness)
- Inductance variations in each tape are evaluated by the geometry of the sample (total self-inductance: ~10.8 μH)
- Contact resistance is assumed as 1 nΩ for each tape (estimated from the joint resistance across the current feeders)

↓

- Significant non-uniform current distribution is observed
- Maximum current in the innermost tape is limited by the critical current
- Fairly good agreement with the observed magnetic field waveform (Hall probe attached directly to the conductor)
- No quench in experiment

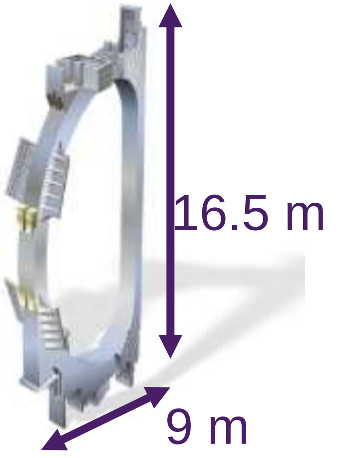


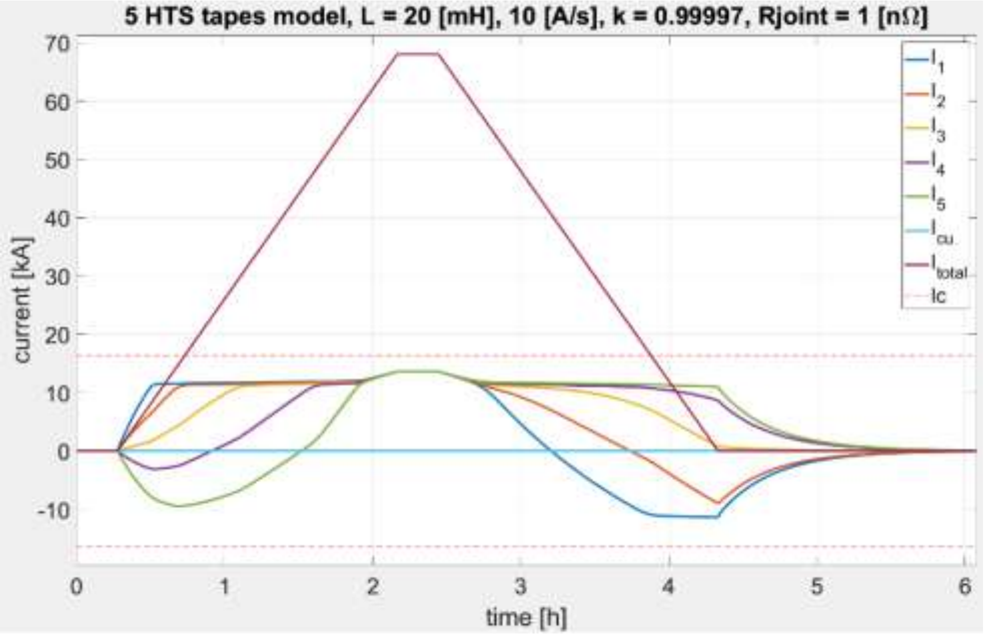


by Diego Garfias-Dávalos

Discussion on the applicability to large-scale fusion magnets

	STARS Sample	1 DP of ITER-TF
Conductor length	~6 m	~4800 m
L (self-inductance)	~10 μH	~20 mH
ΔL (inductance difference)	~1×10^{-4} μH	~1×10^{-3} μH
Joint Resistance	~1 nΩ	~1 nΩ
dI/dt	~1 kA/s	~10 A/s
Ratio *ΔL dI/dt* vs. *R*	~10	~1



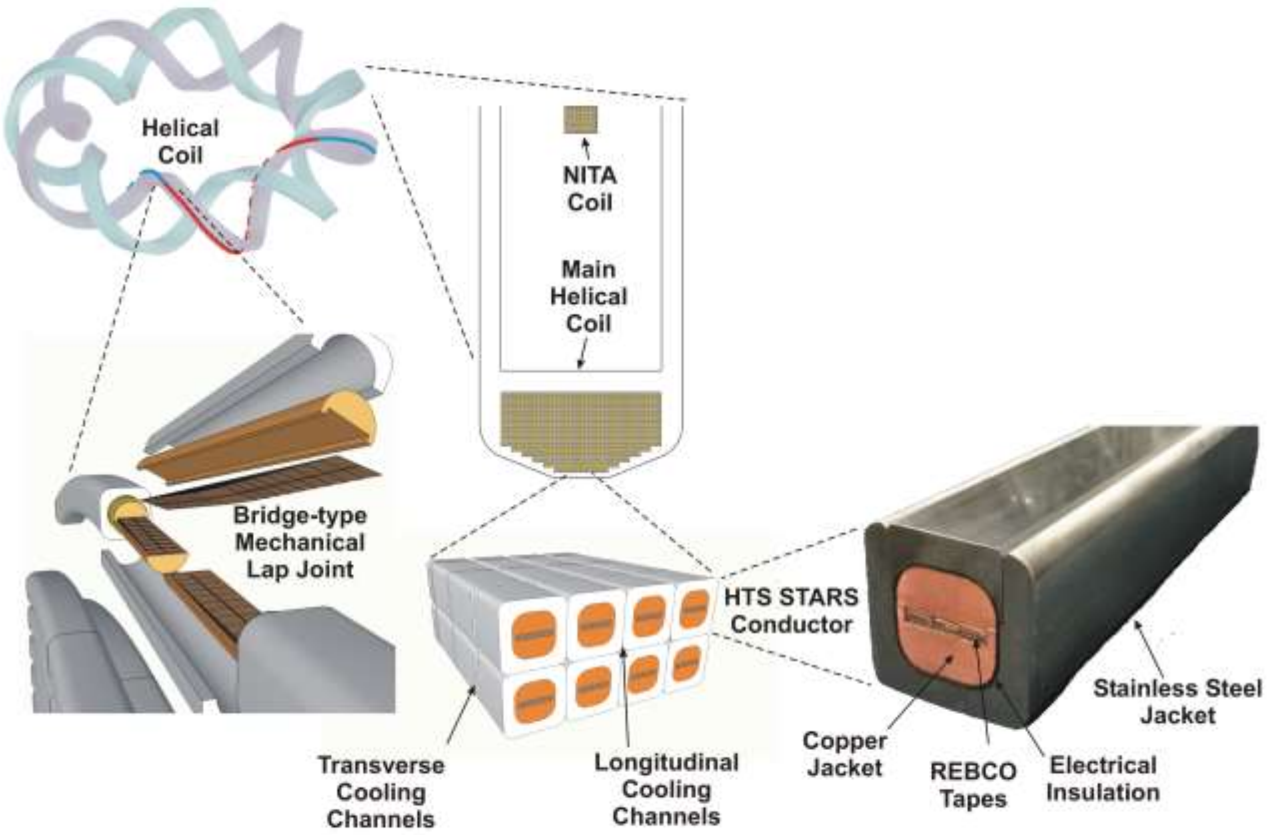


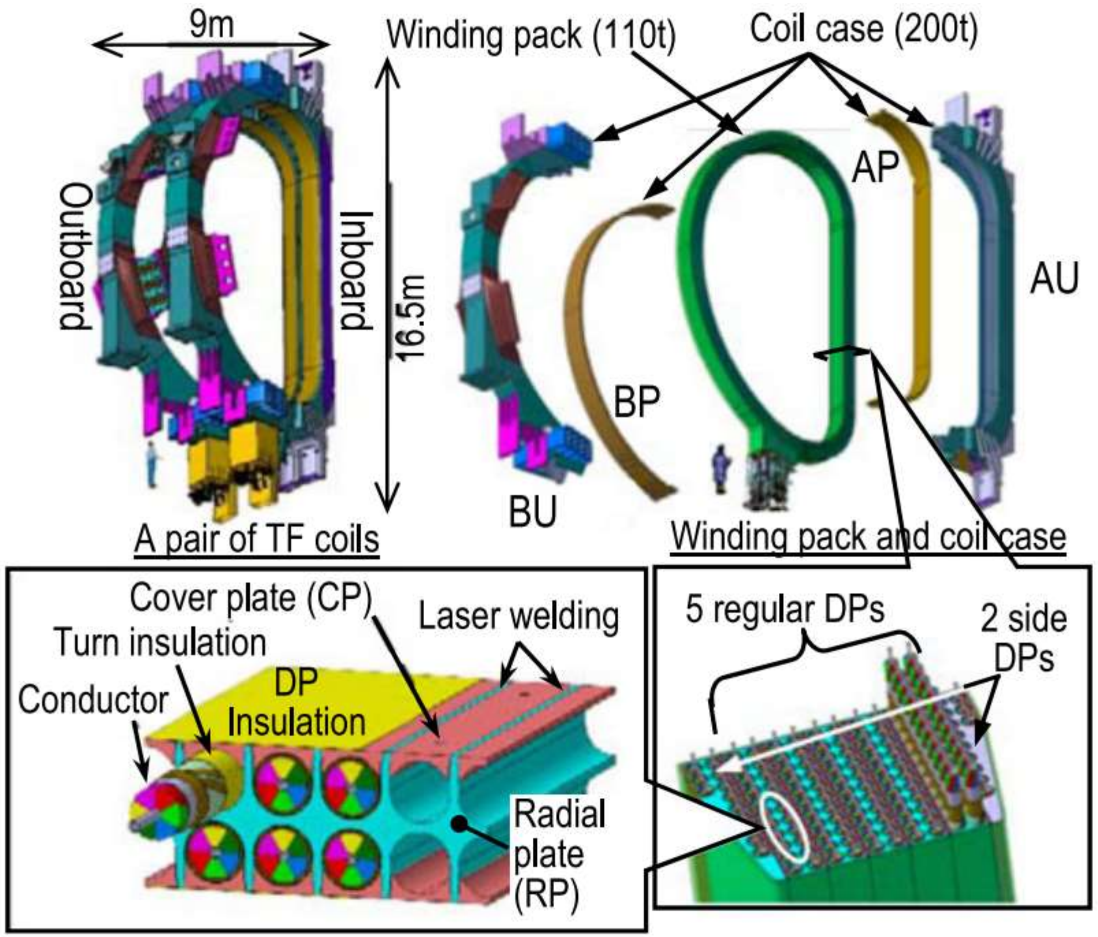
10 A/s

- At high ramp rate, significant non-uniform current distribution (NUCD) is observed
- Maximum current in the inner tapes is limited by the critical current
- A stable operation might be possible even at ~4 kA/s
- We may allow NUCD within the thin HTS area
- Further examination will have to be done to determine the stability limit by combining thermal calculation

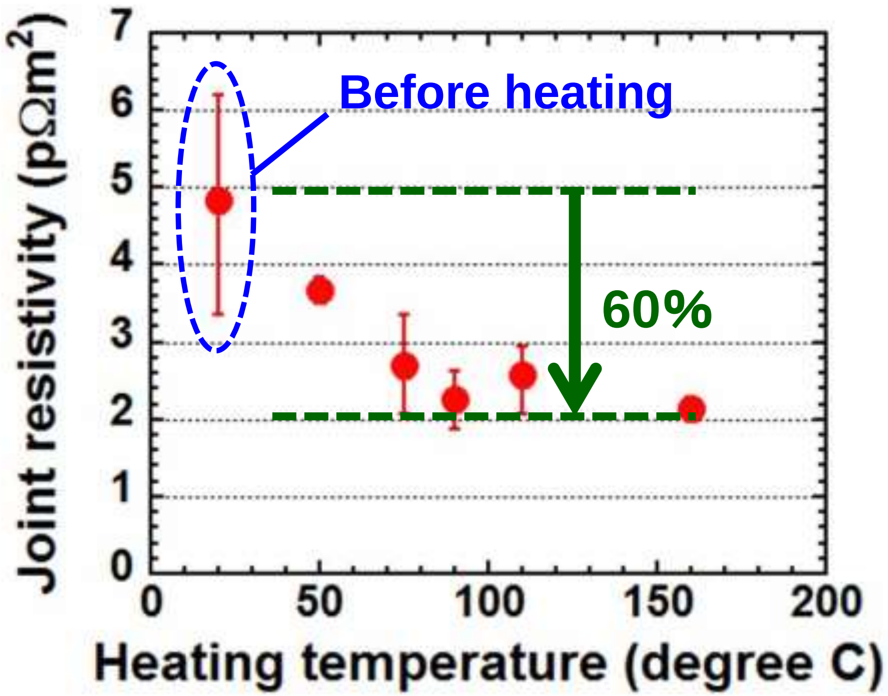
Three innovations with STARS conductor

- Simple stacking of REBCO tapes ➔ High-strength conductor (electromagnetic stress resistance)
- Internal electrical insulation ➔ High-strength coil (equivalent to radial plate after winding)
- Fabrication by joint-winding with robot ➔ High-speed winding, applicable to 3D and large coils



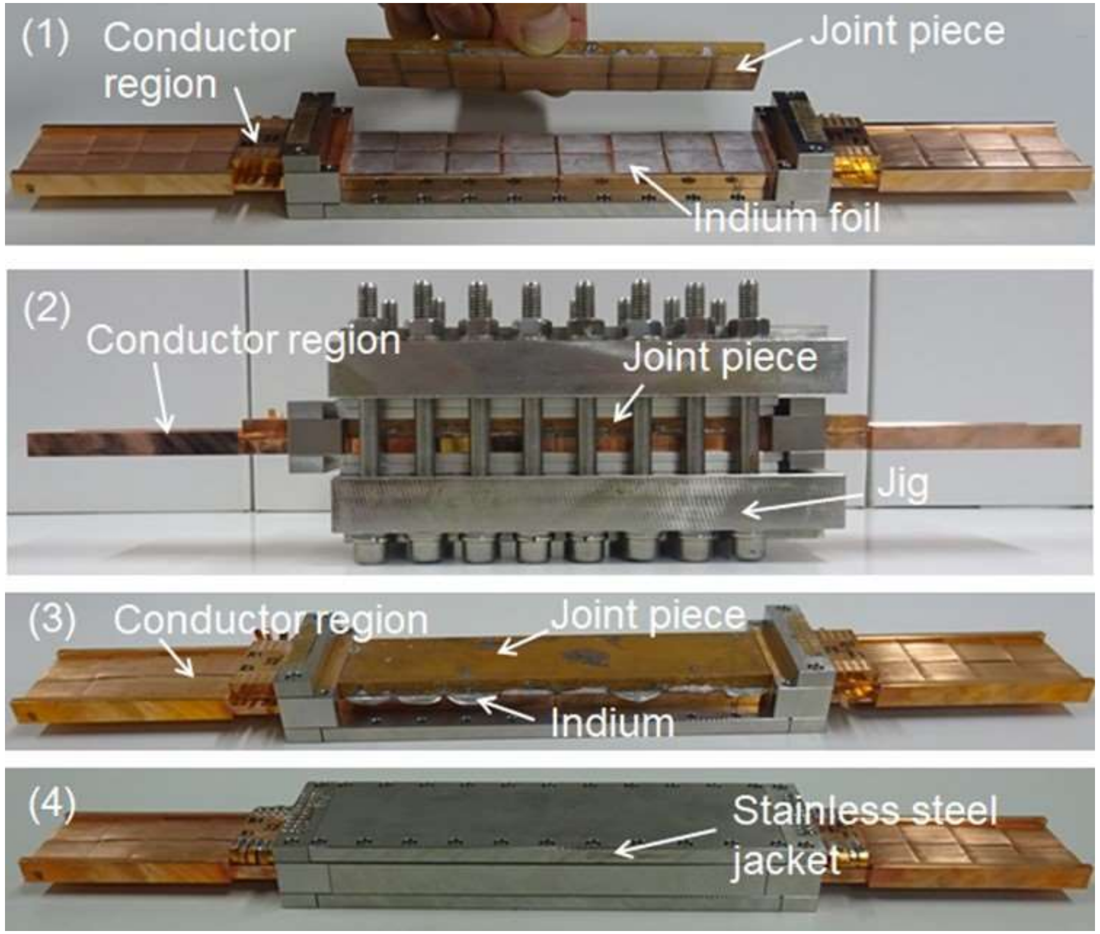


Improvement of Mechanical Lap Joint



- ✓ Joint resistivity was reduced by 60%
- ✓ Variation of resistance was reduced
- ✓ Not need for oxygen annealing

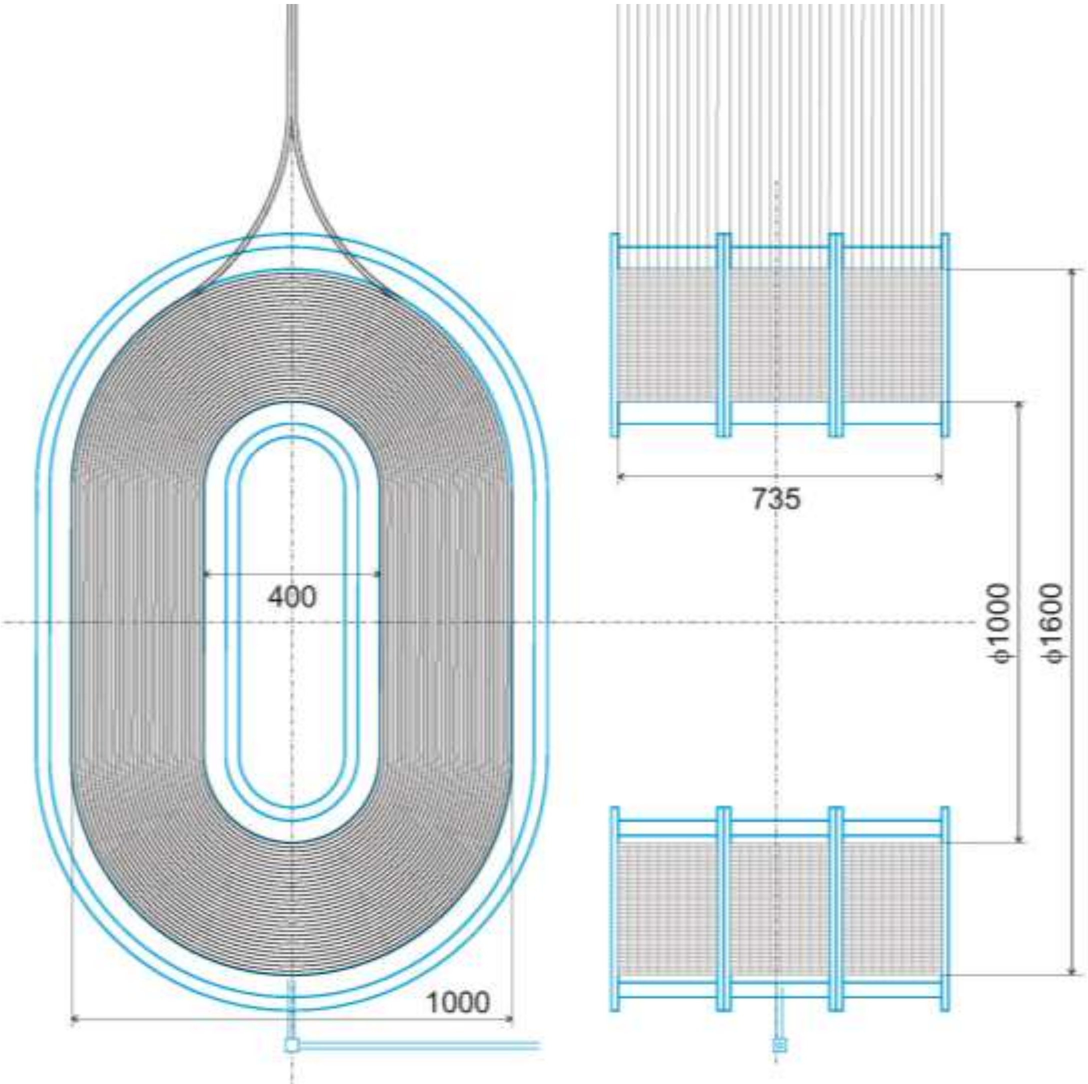
S. Ito, et al. (Tohoku Univ.)



T. Nishio et al., IEEE Trans. Appl. Supercond. 27 (2017) 4603305

S. Ito et al., Fusion Eng. Des. 146 (2019) 590

Demonstration of 9-H HTS magnet with a model coil



- Racetrack shape
- 15 (12) Double pancakes, 30 layers each
- 3 coils in total
- First, fabricate, test, and evaluate the central one coil
- Then proceed to add the remaining 2 coils
- The bottom of each double pancake is edge-connected
- Several (or all) mechanical bridge connections at straight sections of the layers in the middle (applied by industrial robots)
- Plan to use the NIFS variable temperature cryogenic facility for cooling and excitation tests

R&D coils for subcooled tests using NbTi/Cu/Al conductors for LHD helical coils (2002-2005)

Comparison with SPARC TF Model Coil

	STARS R&D	SPARC TFMC
Rated Current	18 kA	40 kA
No. of turns	900	256
Inner radius	300 mm	530 mm
Outer radius	1100 × 1800 mm	1890 × 2890 mm
Total current	16.2 MA	10.24 MA
Current density	80 A/mm^2	153 A/mm^2
Maximum Field	20.3 T	20.1 T
Operation Temp.	20 K	20 K
Coolant	Helium gas	Supercritical helium
REBCO tape length	47 km	270 km
Inductance	650 mH	140 mH
Stored energy	105 MJ	110 MJ
Winding method	STARS conductor with long-length winding / joint winding	Spiral-grooved, stacked-plate tape winding with solder impregnation
Electrical insulation	Internal insulation	No-insulation

Summary

- **Three types of large-current HTS conductors are being developed at NIFS for the next-generation fusion experimental devices and future fusion reactors with a high current density of 80 A/mm^2.**
- **For the simply-stacked STARS conductor, stable operation has been confirmed with a 6-m, ϕ600-mm, 3-turn solenoid sample with high ramp-rate excitations of 1 kA/s over 200 repetitions.**
- **Simple stacking of HTS tapes generates non-uniform current distribution (NUCD), having a long decay time constant, but the conductor is operated stably, which was successfully simulated based on the inductance variation model.**
- **The simulation is extended to a large-scale continuously-wound coil, such as ITER-TF double-pancake coil, and the result suggests that a stable operation is available even with NUCD formation.**
- **Feasibility that a simply-stacked HTS conductor may be used in large-scale magnets is suggested, which will be proven by a large-scale R&D coil in our future plan.**