Development of large-current high-temperature superconducting conductors to be applied to next-generation fusion experimental devices

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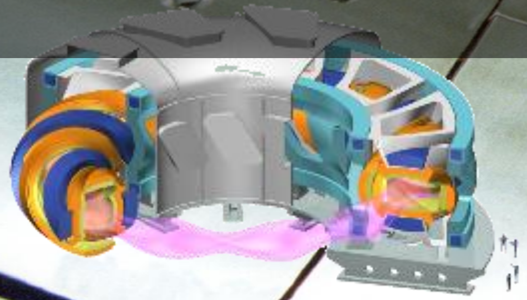
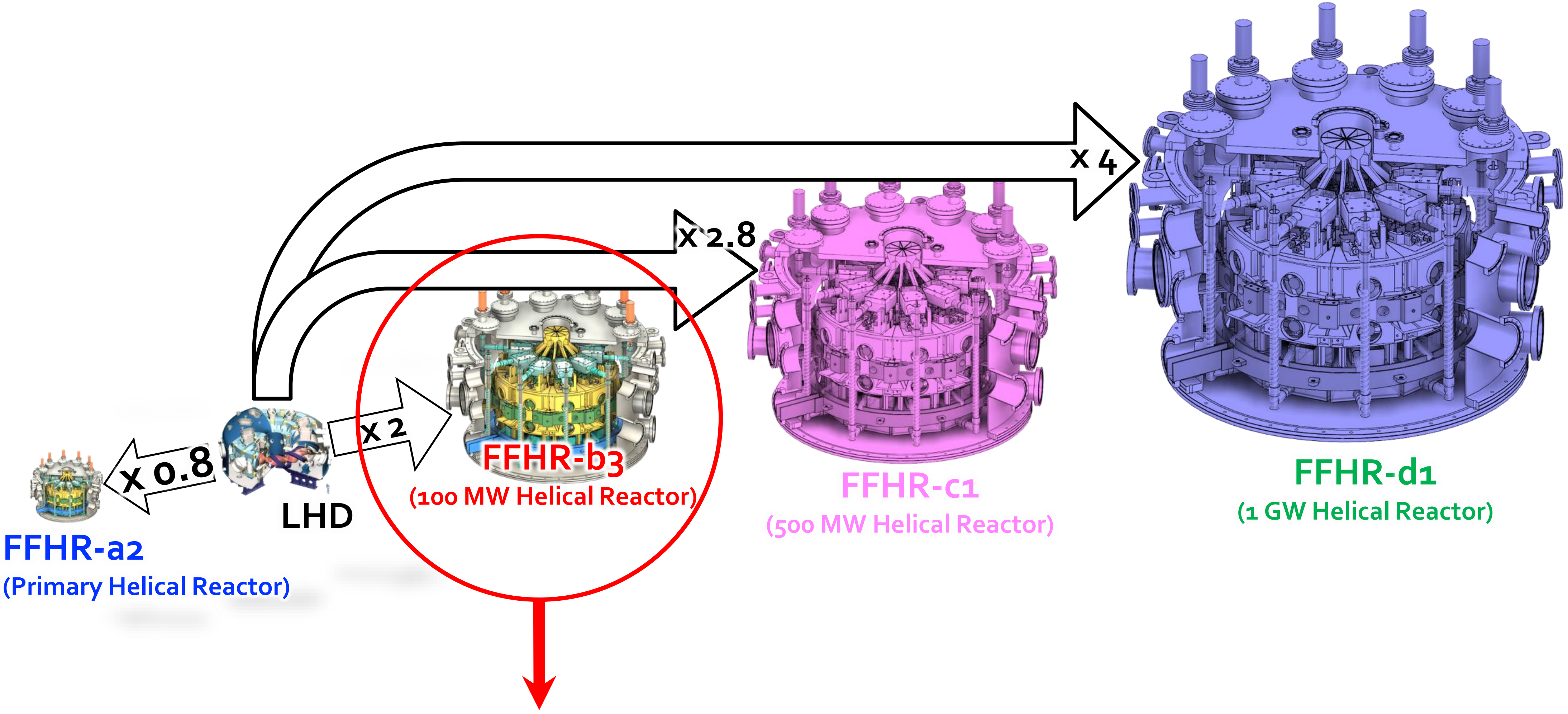


US-Japan Workshop on Fusion Reactor Design and Critical Issues of Fusion Engineering
March 28, 2022

New Strategy for Early Realization of Helical Reactor



Slight improvement of plasma confinement / Innovation for reactor engineering

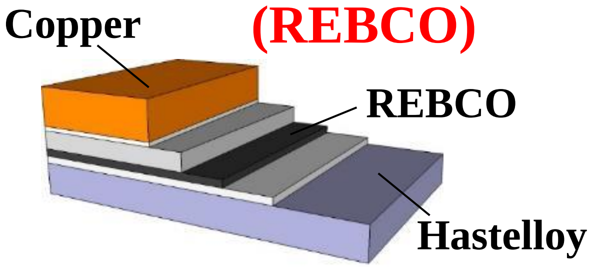
➔ Early realization of a helical reactor with

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

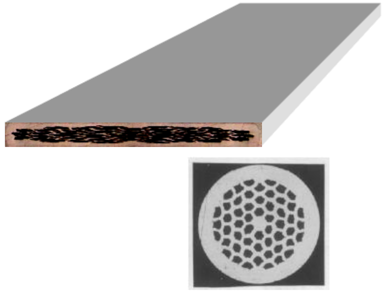
High-Temperature Superconducting Magnet Option

(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



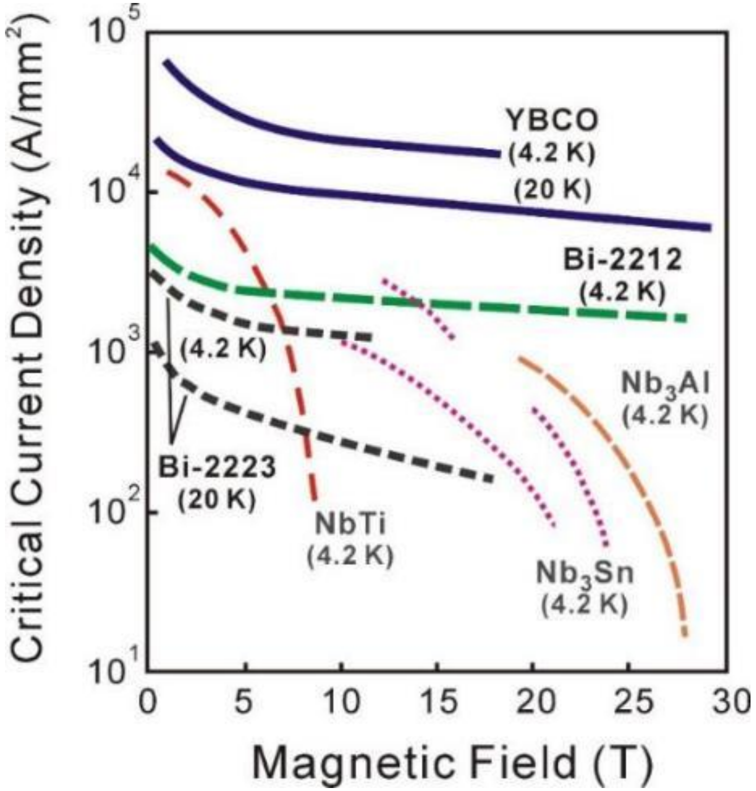
Stability Margin

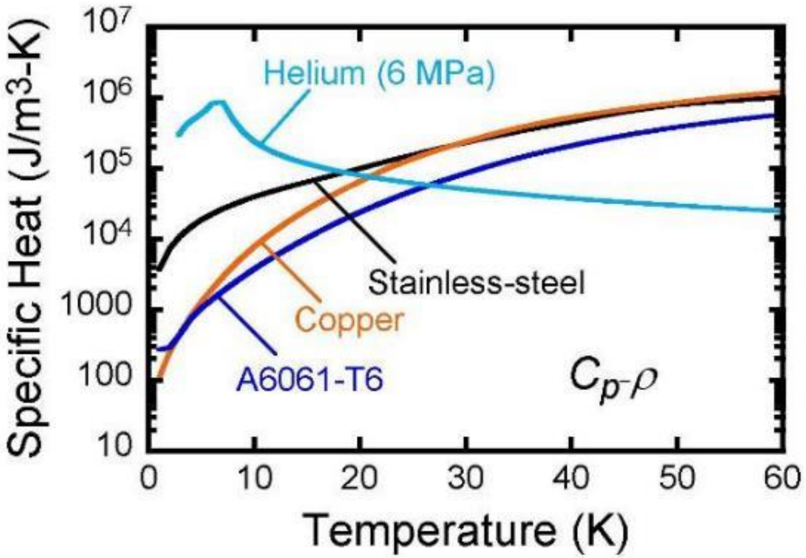
$$\Delta Q < C_p \rho \Delta T$$

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

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

Higher than CIC conductor
➔ **Low quench risk!**

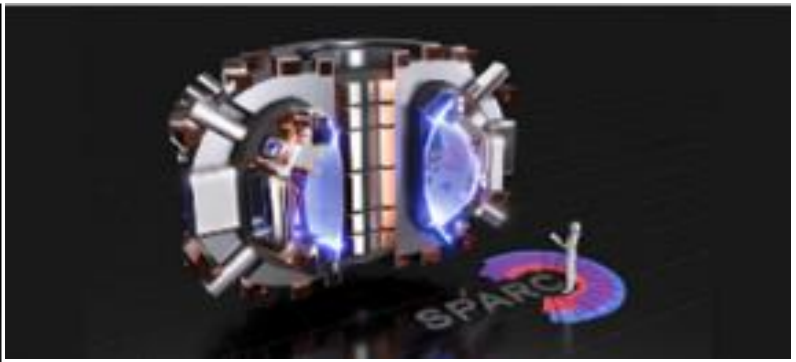




N. Yanagi, S. Ito, et al., Plasma and Fusion Research 9 (2014) 1405013

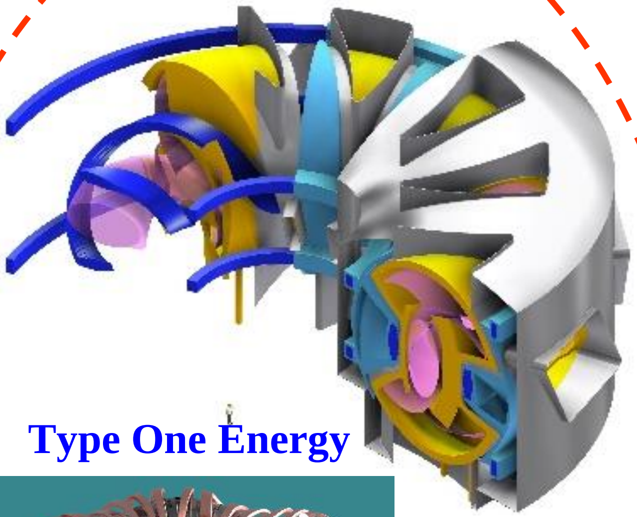
Fusion reactor designs with HTS magnet in the World

ARC & SPARC (MIT/CFS)

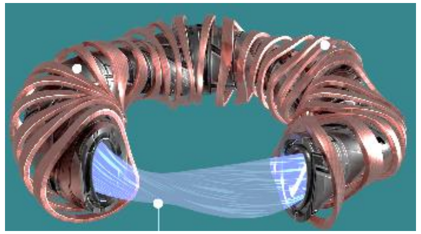


B_t = 9-12 T
B_{max} = 21-23 T

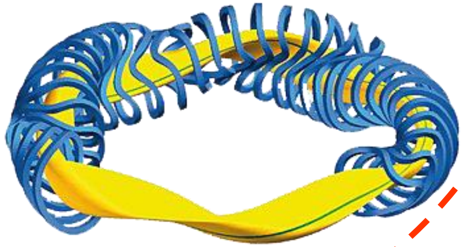
FFHR-d1 (NIFS)



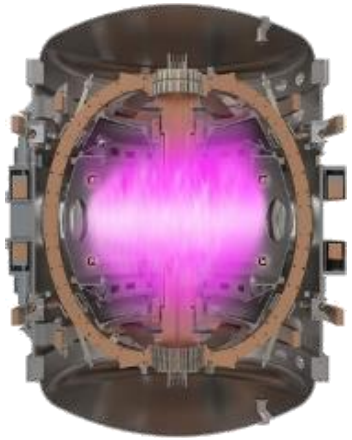
Type One Energy



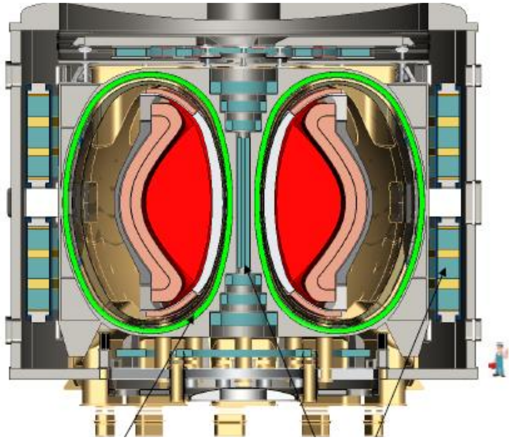
Renaissance Fusion



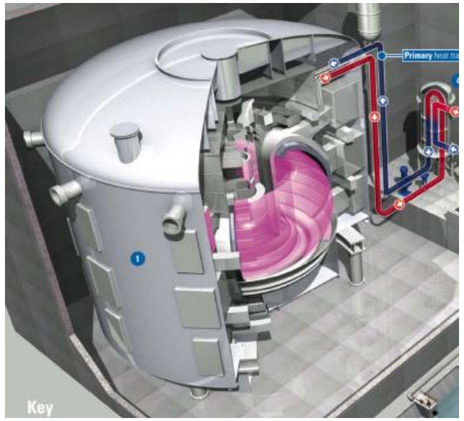
Tokamak Energy



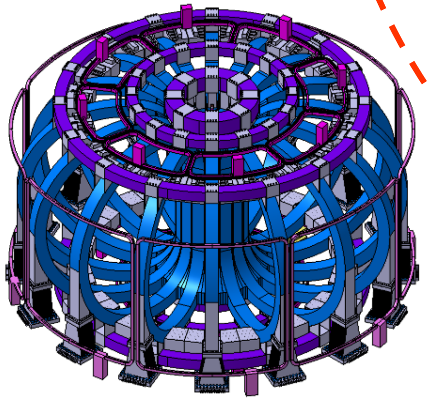
FNSF-ST (PPPL)



EU DEMO HTS option (EUROfusion)



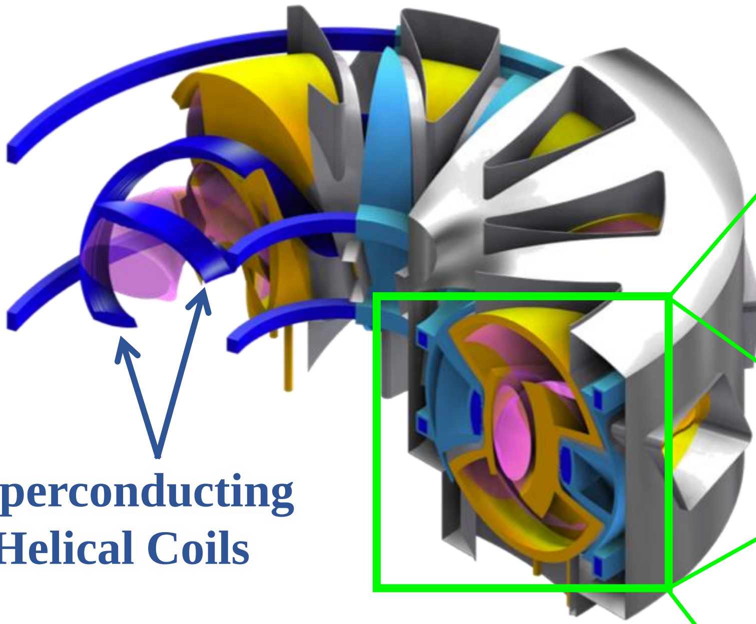
CFETR (ASIPP) for CS coils



SPARC TFMC achieved 20 T, 20 K (September 2021)

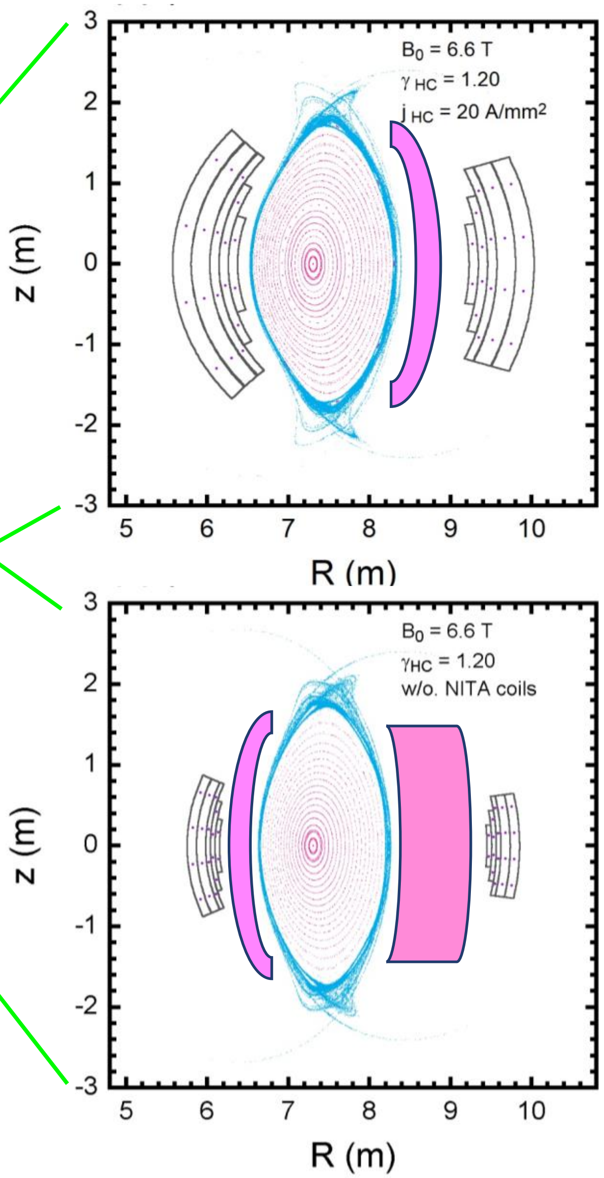
It was a moment three years in the making, based on intensive research and design work: On Sept. 5, for the first time, a large high-temperature superconducting electromagnet was ramped up to a field strength of 20 tesla, the most powerful magnetic field of its kind ever created on Earth. That successful demonstration helps resolve the greatest uncertainty in the quest to build the world's first fusion power plant that can produce more power than it consumes, according to the project's leaders at MIT and startup company Commonwealth Fusion Systems (CFS).

What is the key for selecting HTS for making a compact helical reactor?



Helical Fusion Reactor, FFHR-b3
R_0 = 7.8 m
B_0 = 6.6 m
(B_{HC} = 15-16 T ➔ not very high…)

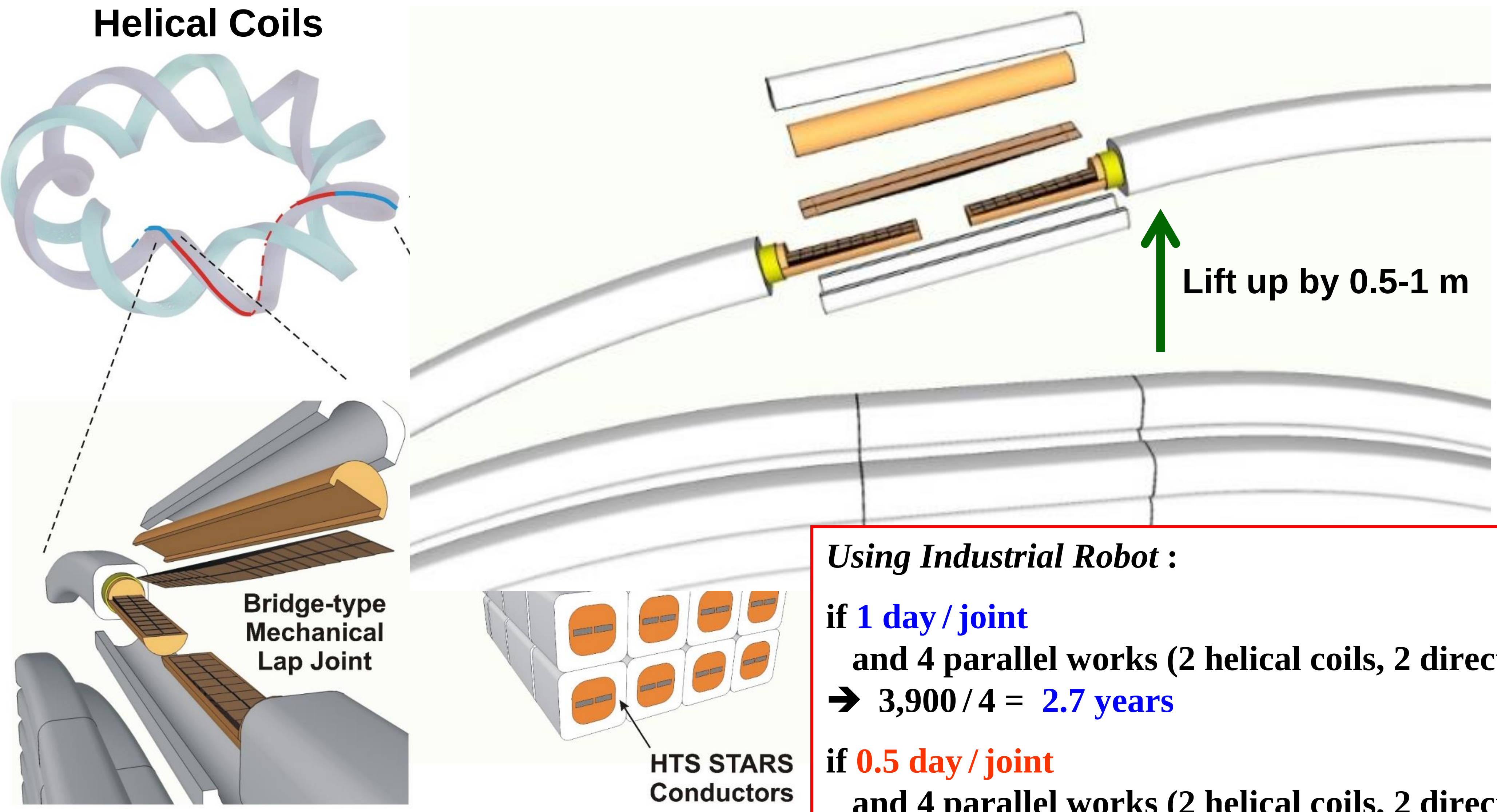
High-current density is the key



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

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

“Joint-Winding” of Helical Coils



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

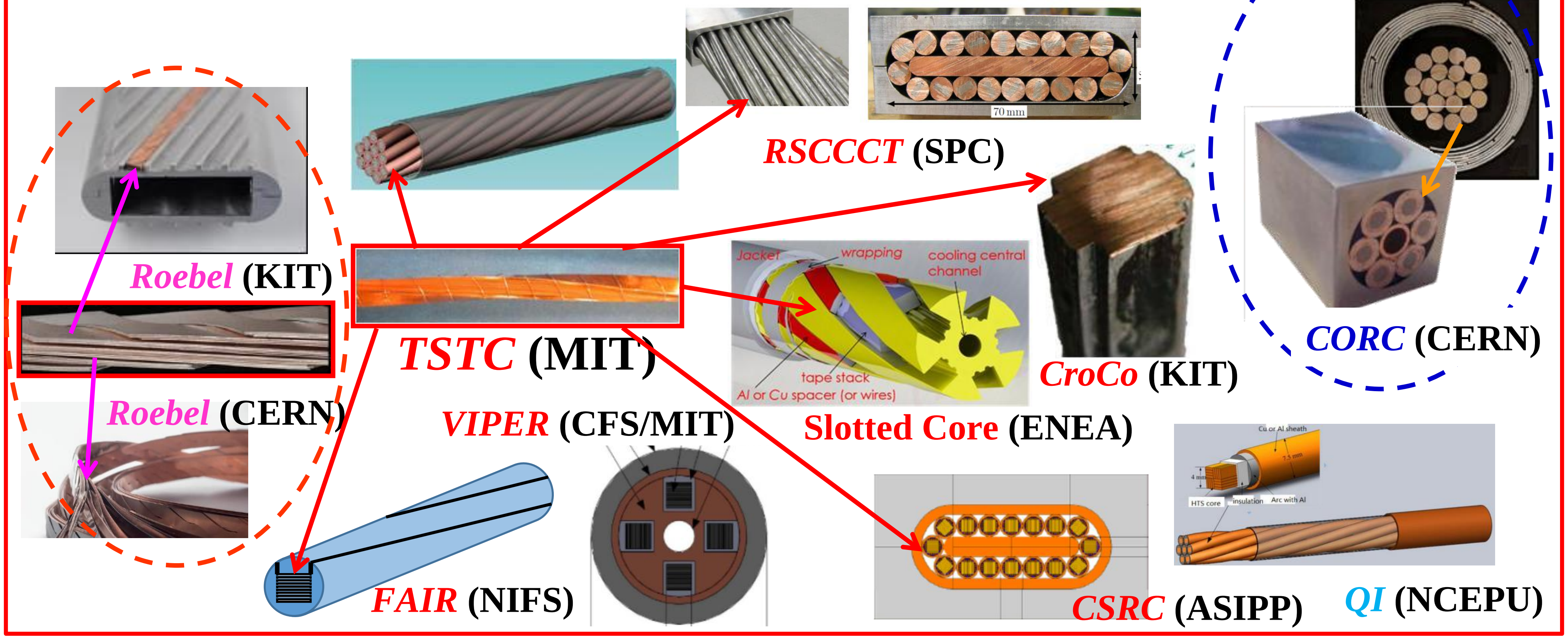
Using Industrial Robot :

if 1 day / joint
and 4 parallel works (2 helical coils, 2 directions)
➔ 3,900 / 4 = 2.7 years

if 0.5 day / joint
and 4 parallel works (2 helical coils, 2 directions)
➔ 3,900 / 2 / 4 = 1.3 years

Large-current HTS conductors developed for fusion magnets

Twisted and Transposed REBCO Conductors

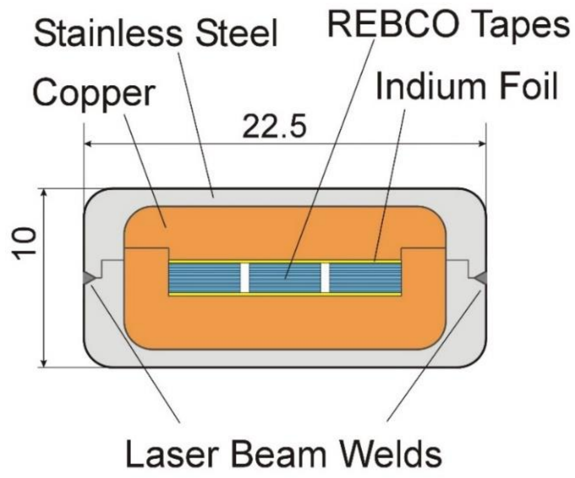


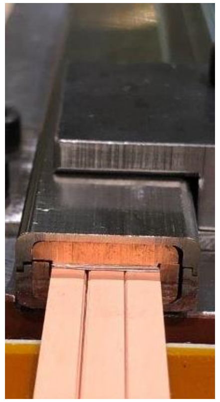
Simply-Stacked REBCO Conductors

Bi-2212 CIC Conductors

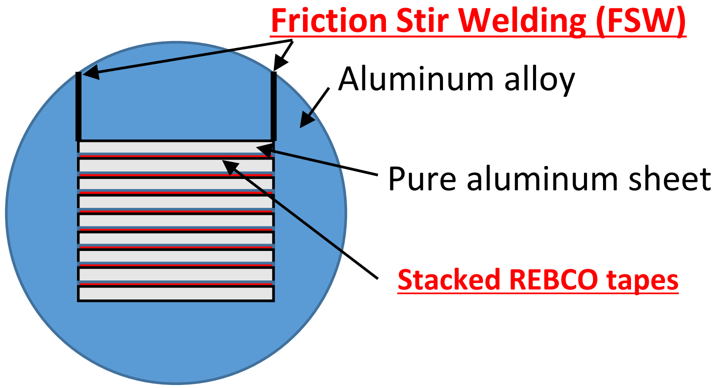
Practical HTS conductor development for the next-generation helical device

STARS
(Stacked-Tapes Assembled in Rigid Structure)

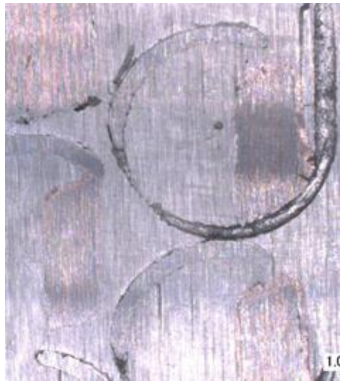




FAIR
(FSW, Al-alloy, Indirect-cooling, REBCO)



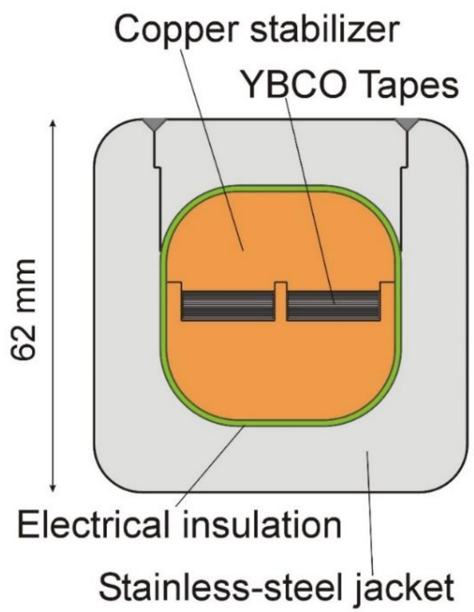
WISE
(Wound and Impregnated Stacked Elastic tapes)



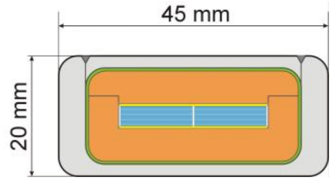
- **Current capacity: 10-20 kA @ 8 T, 20 K**
- **Current density: 80 A/mm^2**

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 & no local deformation)
- Low cost / low-resistance joint

History of HTS STARS Conductor Development at NIFS

2003-2006 — **LTS / HTS hybrid conductor sample**
NbTi + Bi-2223 tapes + Cu (soldered)

2006-2007 — **10-kA-class HTS STARS conductor sample**
Bi-2223 tapes + Cu (soldered)

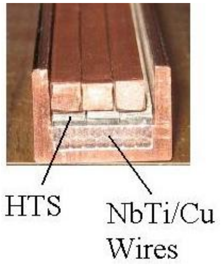
2007-2008 — **15-kA-class HTS STARS conductor sample**
YBCO / GdBCO tapes + Cu (soldered)

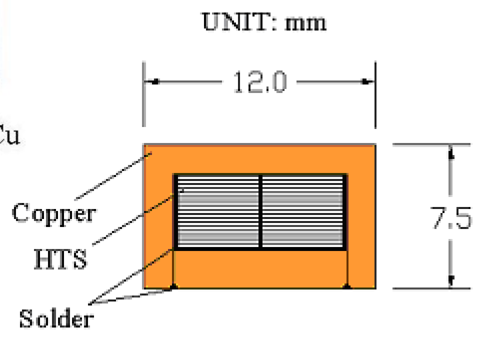
2012-2013 — **30-kA-class HTS STARS conductor sample**
GdBCO tapes + Cu + SS (bolted)

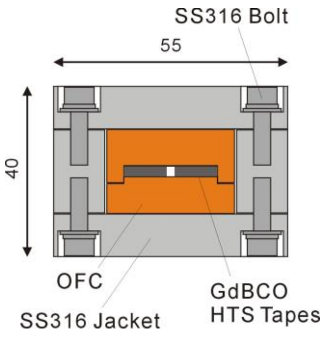
2013-2014 — **100-kA-class HTS STARS conductor sample**
GdBCO tapes + Cu + SS (bolted)

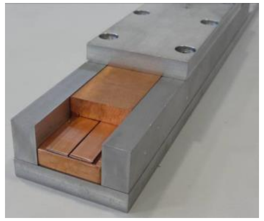
2019-2020 — **20-kA-class HTS STARS conductor sample**
EuBCO + Cu + SS (welded)

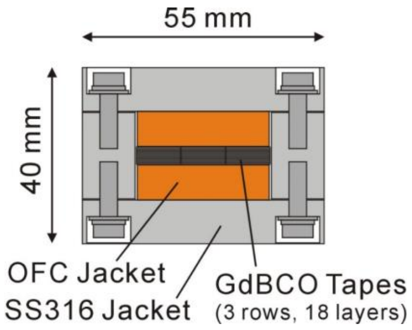
2020-2021 — **20-kA-class HTS STARS conductor sample**
GdBCO + Cu + Kapton + SS (welded)

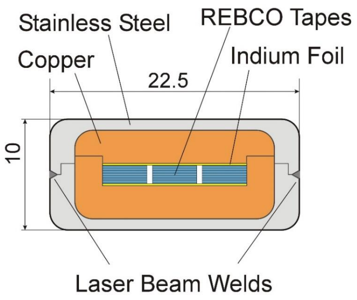


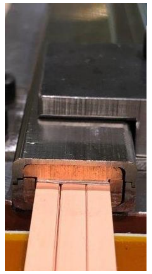


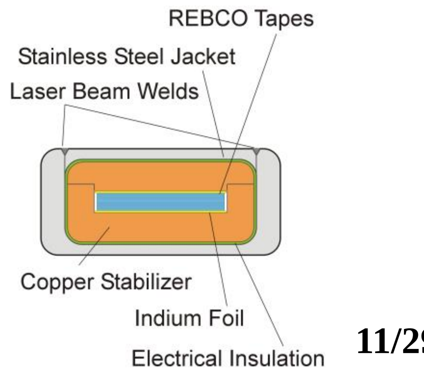




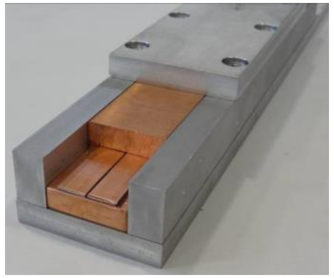


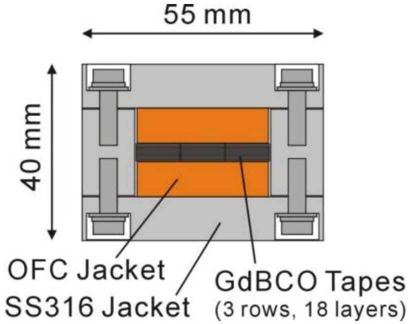




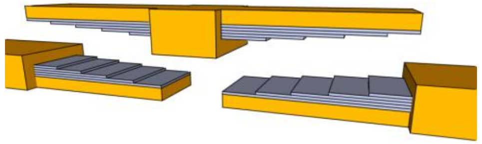


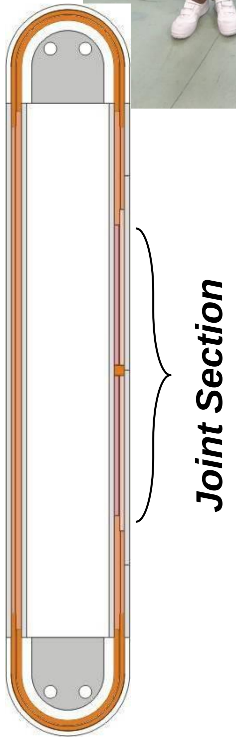
100 kA-Class Prototype STARS Conductor Test

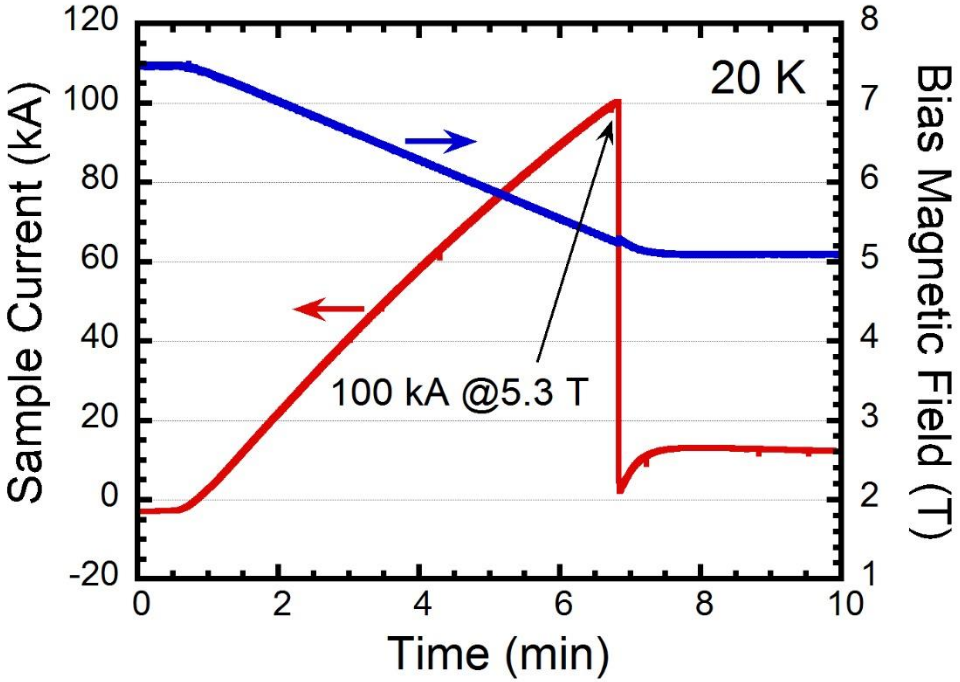


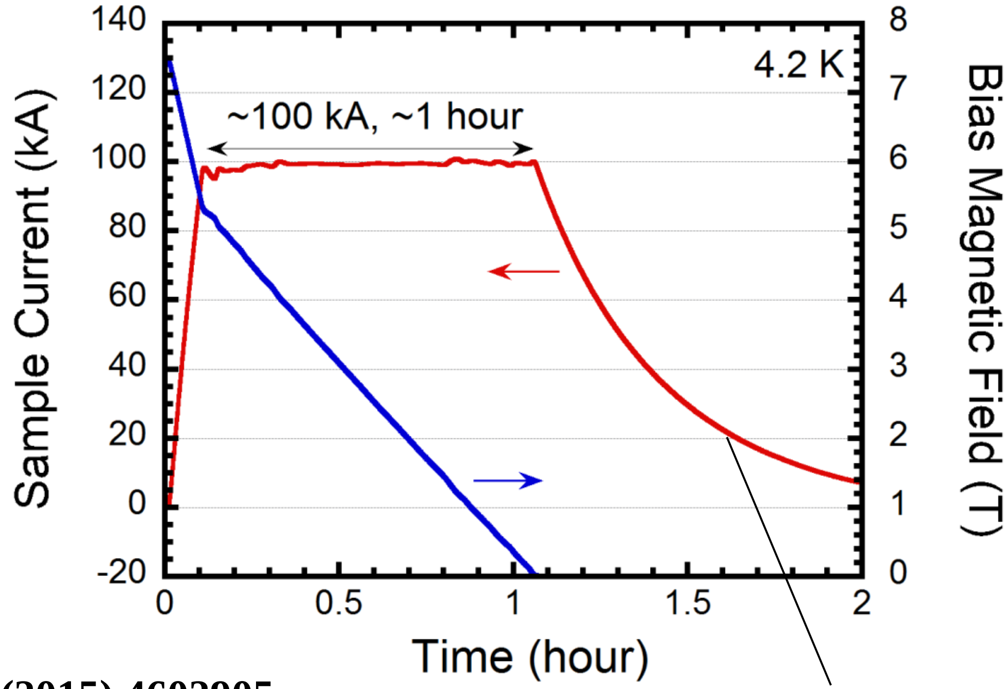


Bridge-type mechanical lap joint
“*Invisible joint*”









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

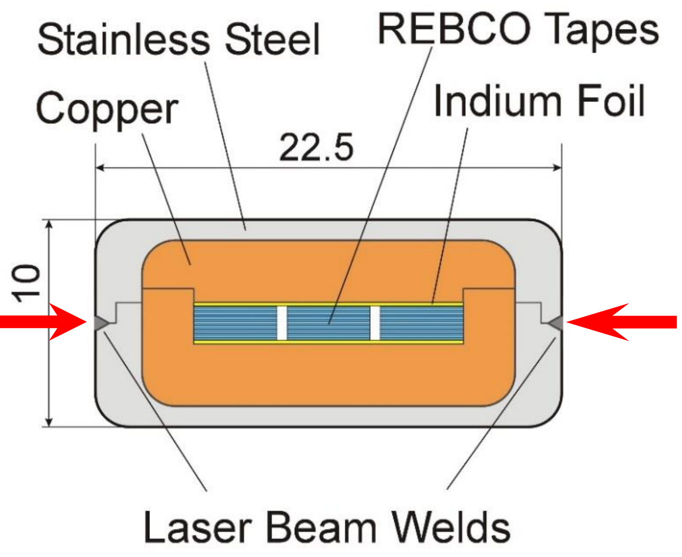
20 kA-class STARS Conductor

- 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/mm² is a big target (former achievement: 25 A/mm²)
- 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



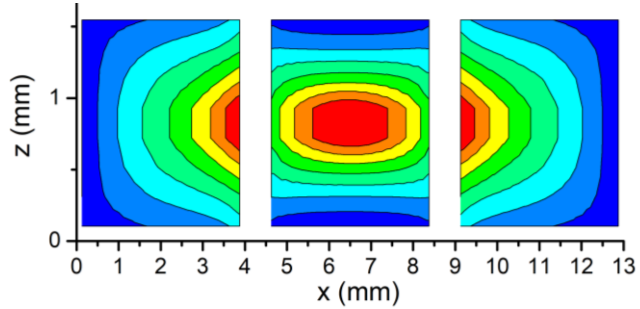
Temperature at the inner wall of Cu stabilizer was
44 °C << 200 °C（allowable limit for REBCO tapes)

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

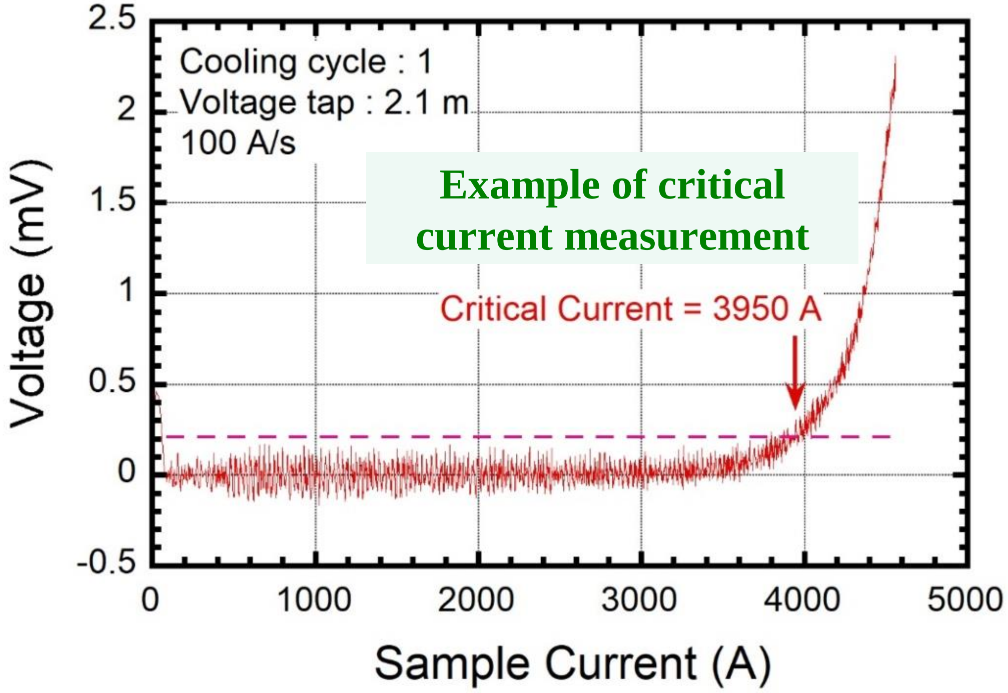
  Verified by numerical simulation with current density and magnetic field distribution, extrapolation to 20 kA at 20 K and 10 T
- Tolerable reduction (~1%) of critical current by cooling cycle
- Further reduction (~2%) with 3000 mm bending radius
- Recovery by releasing (straightening)

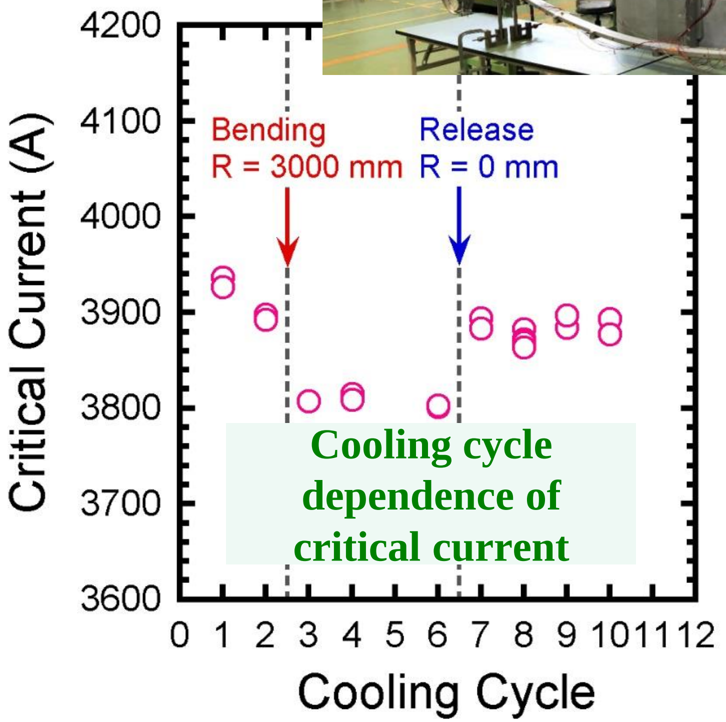
◆ Test in 4-50 K by helium cooling and <9 T magnetic field is planned



Numerical simulation of J and B distribution

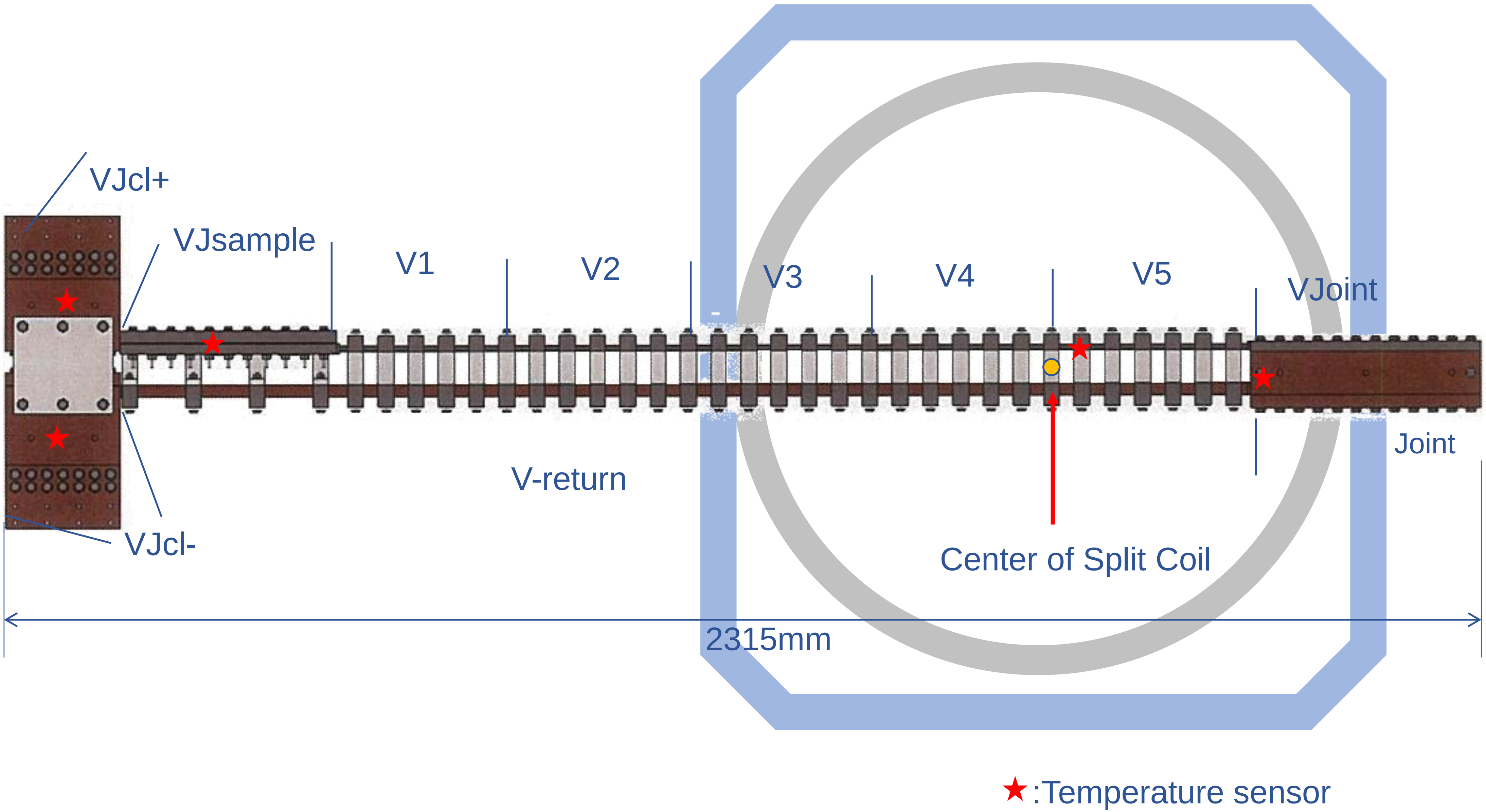
Y. Terazaki





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

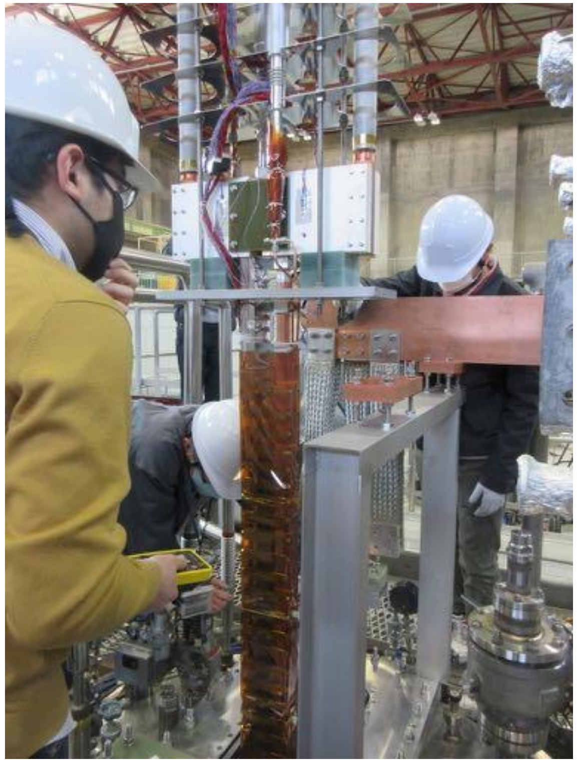
< 9 T, 20-50 K, <20 kA (for the present setup)



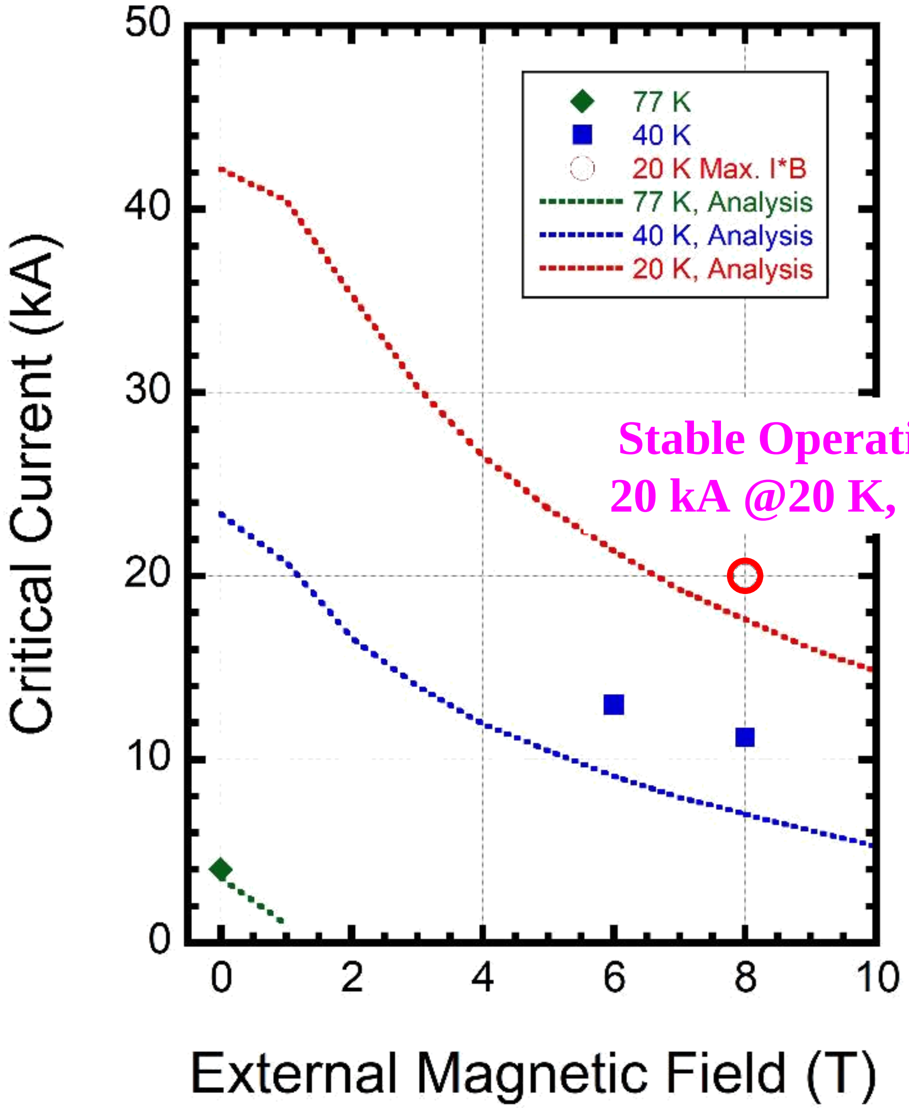




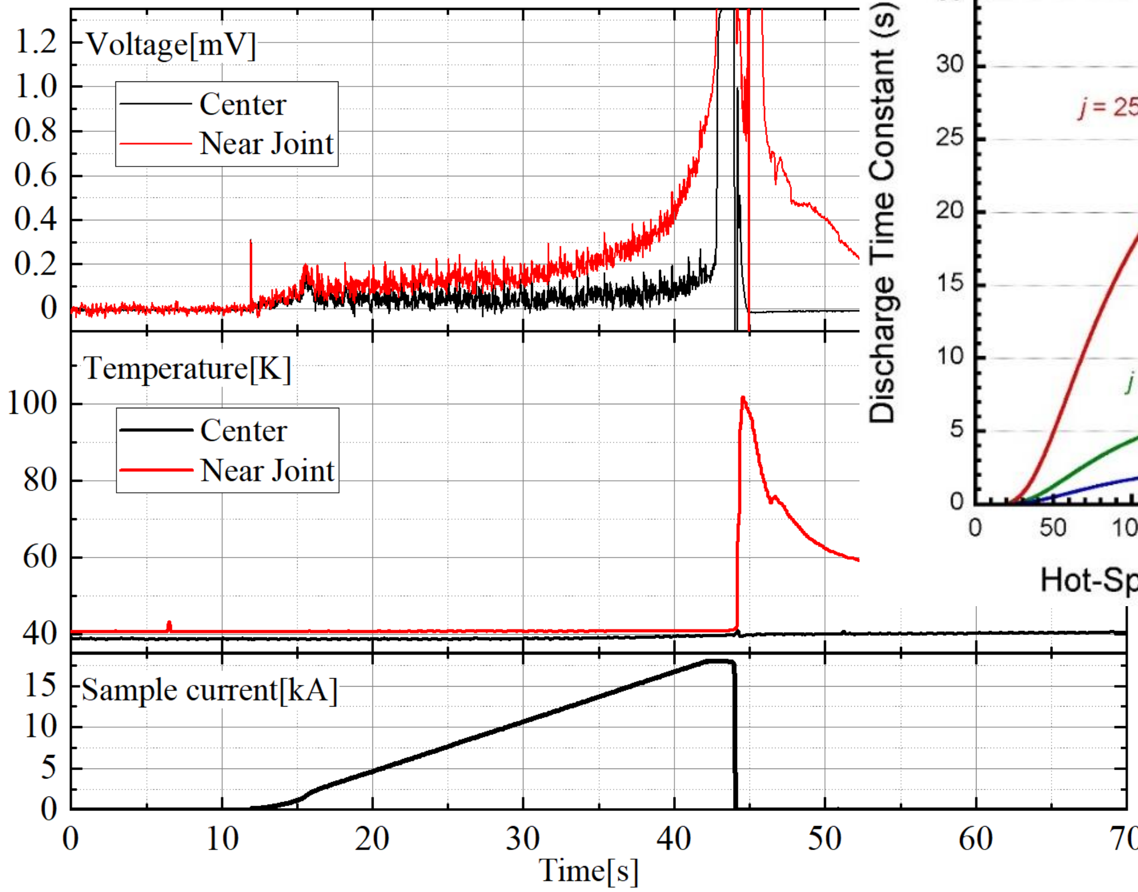


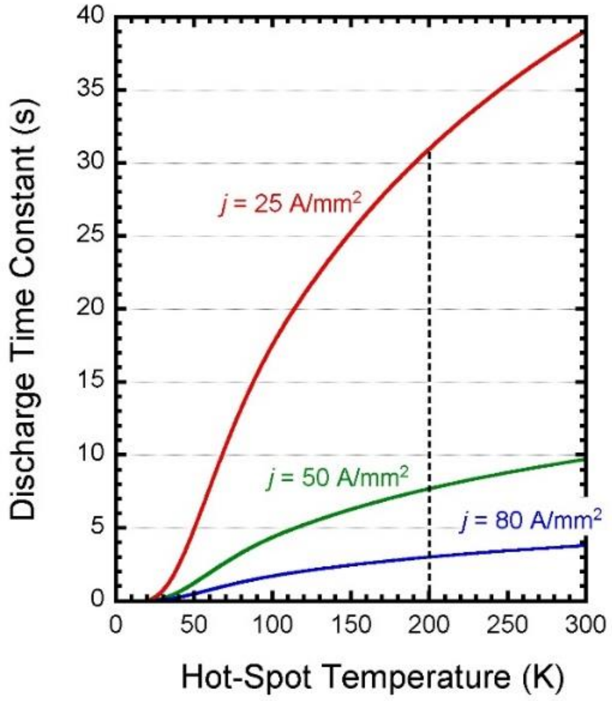



20 kA-class STARS conductor test in 20-40 K, <8 T



Stable Operation
20 kA @20 K, 8 T

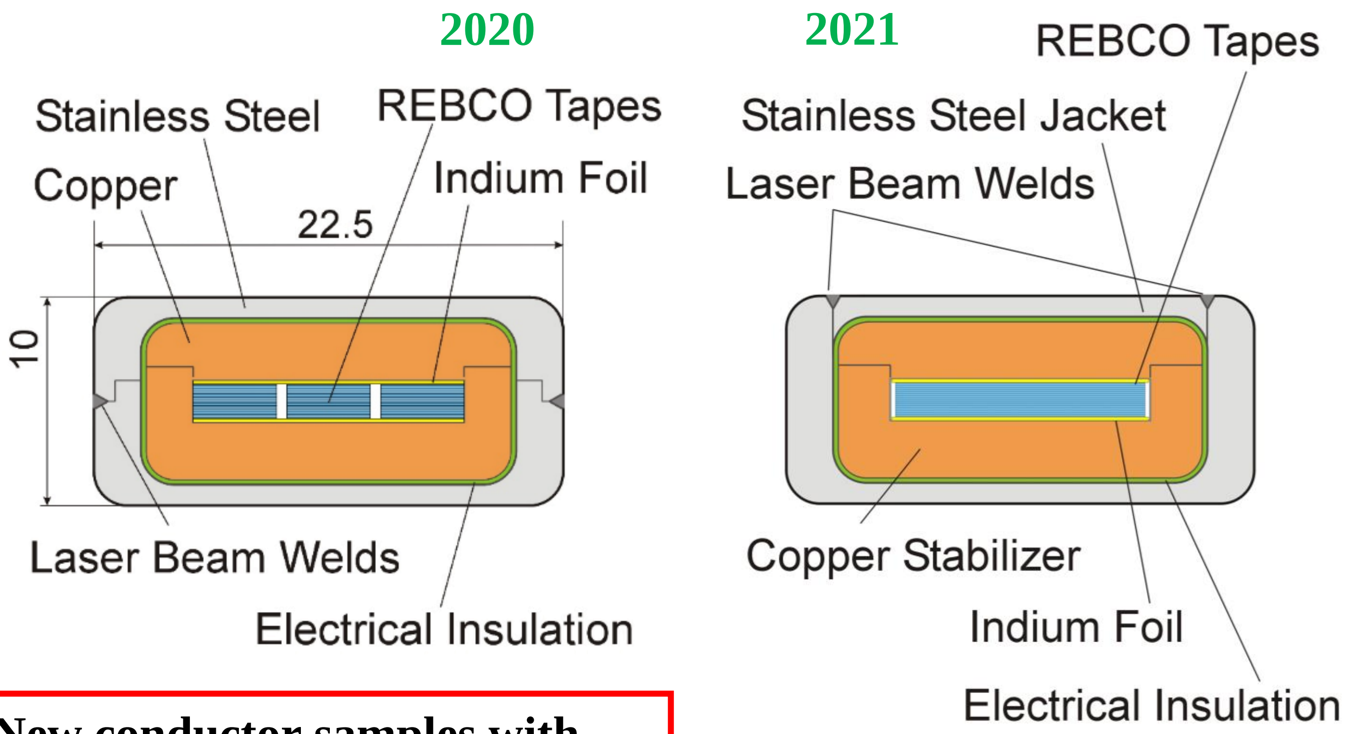


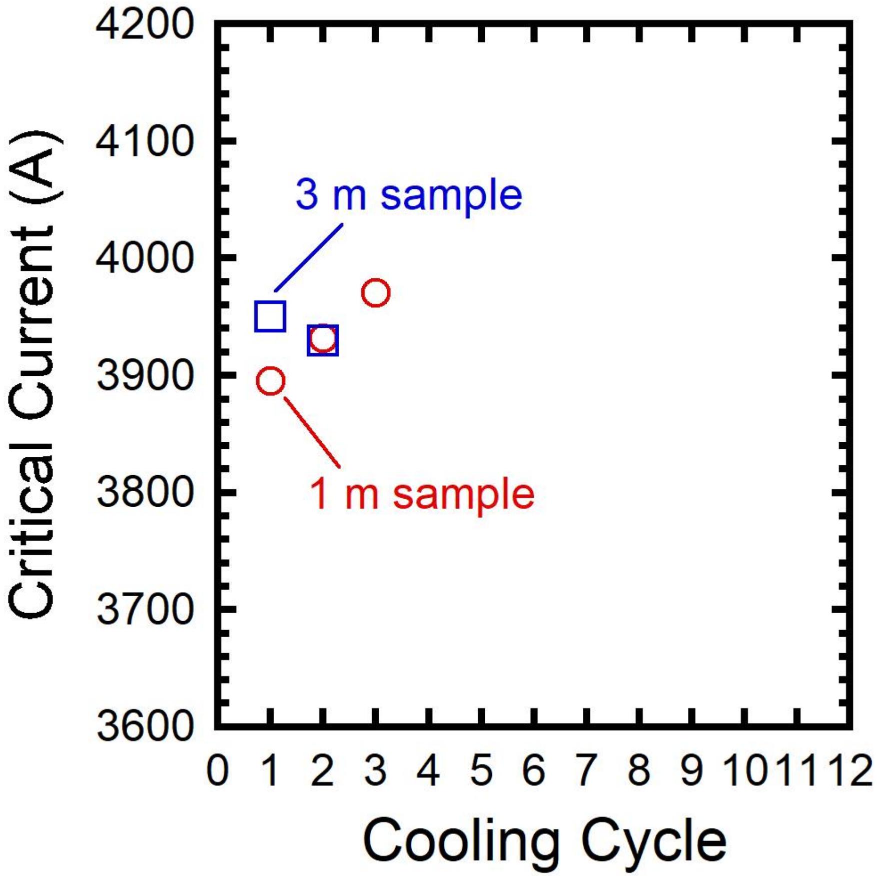


Mistake in quench detection
➔ sample melted locally

Critical current was observed at 11.2 kA@40 K, 8 T and 13 kA@40 K, 6 T

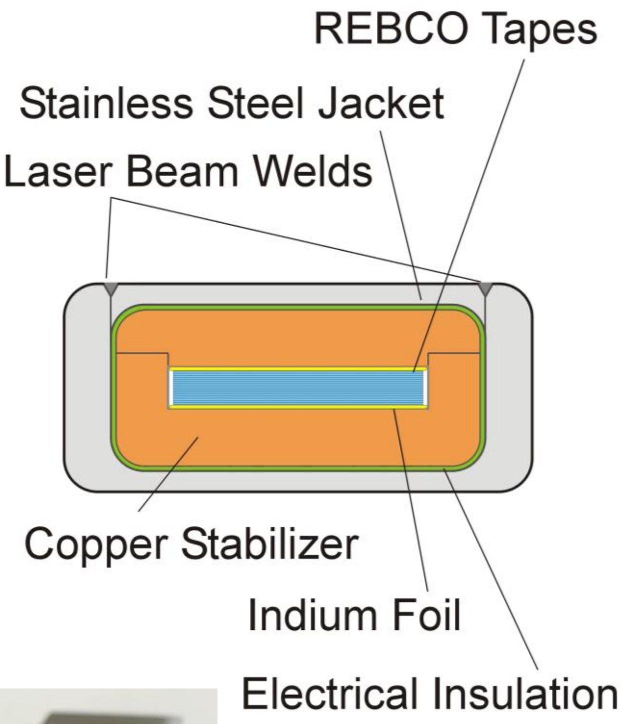
20 kA-class STARS conductor with internal electrical insulation

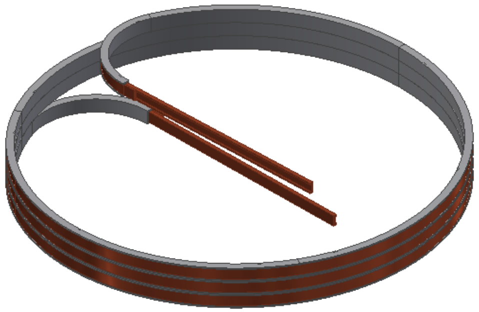


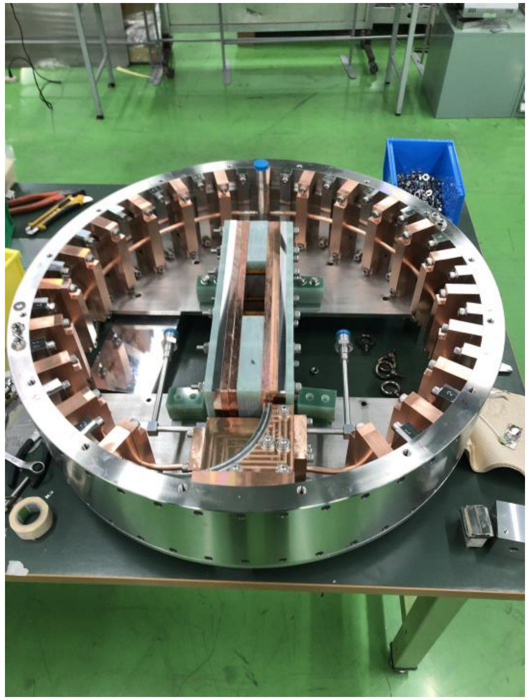


- **New conductor samples with internal electrical insulation were fabricated (by MTC, Toki factory)**
- **Critical current was measured at ~4,000 A at 77 K, self-field = within 1-2% of the previous sample**

20 kA-class STARS conductor with internal electrical insulation





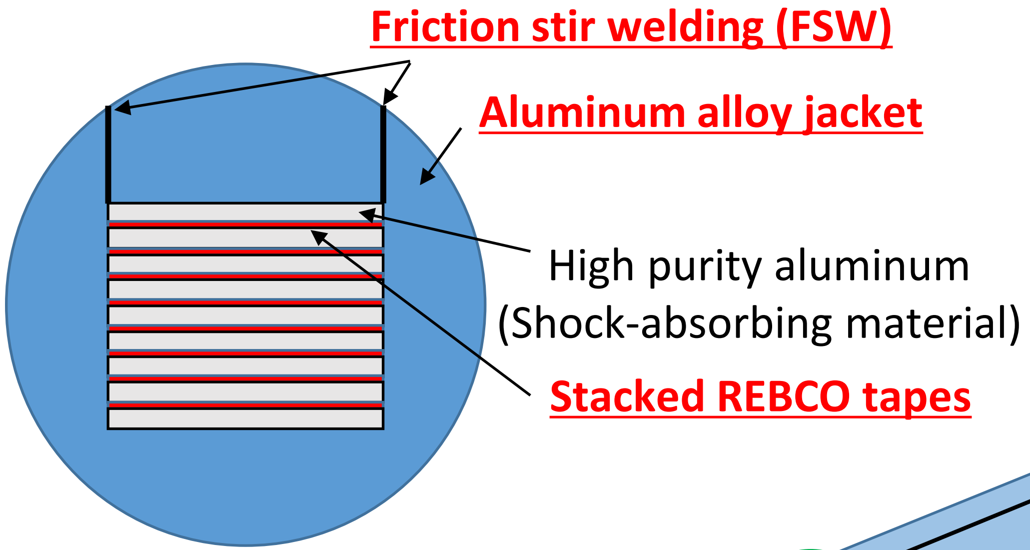


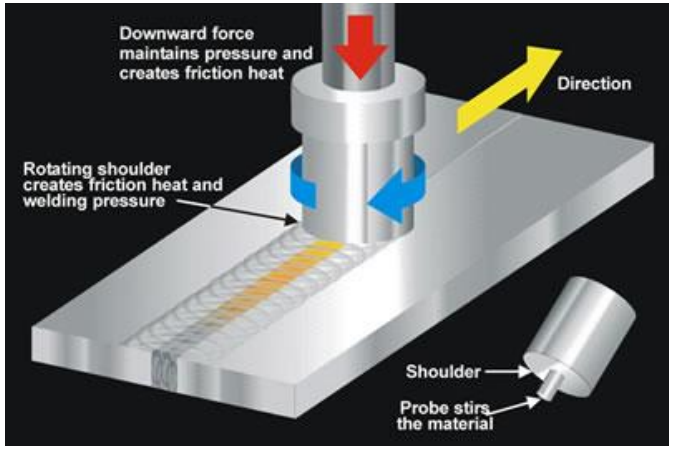
- **A 6-m conductor sample with a 3-turn coiled shape has been fabricated and will be tested in <10 T, 20 K soon (March 28 – April 1)**

FAIR Conductor

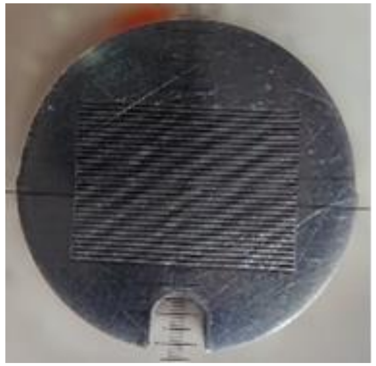
T. Mito, Y. Onodera, N. Hirano

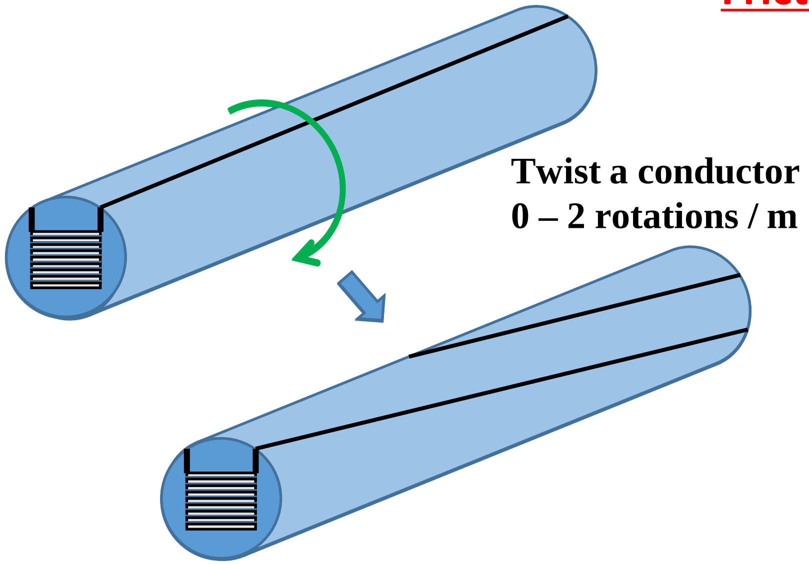
Friction stir welding, Aluminum alloy jacket, Indirect cooling, REBCO (FAIR) conductor





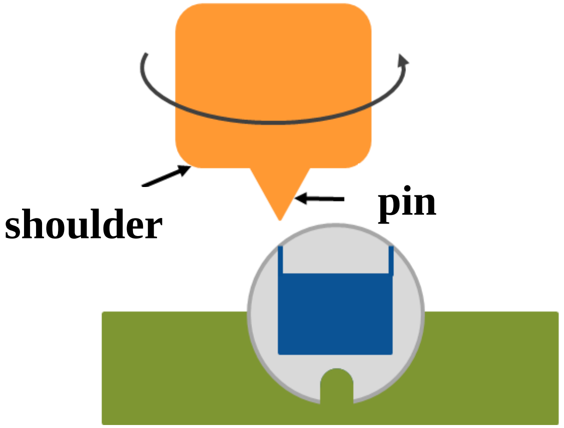
Friction stir welding (FSW)

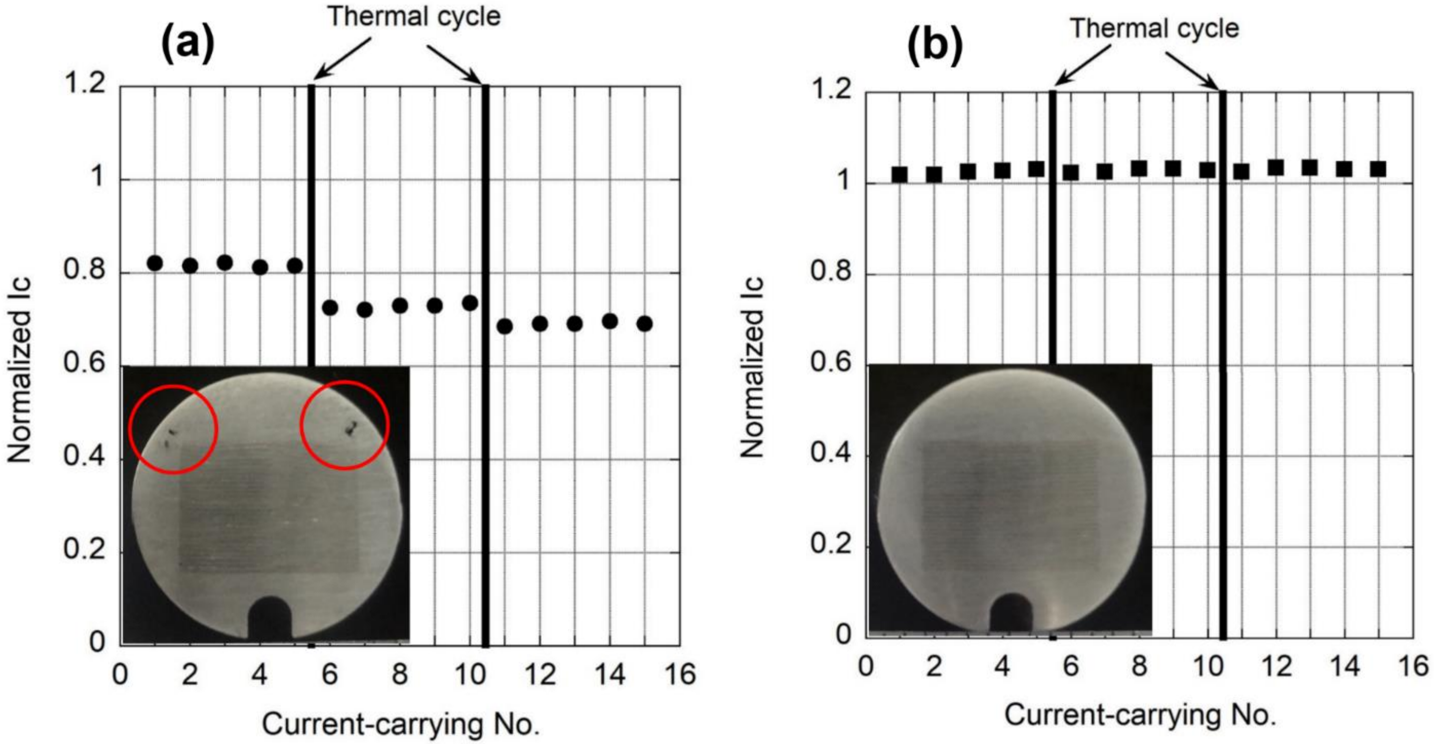


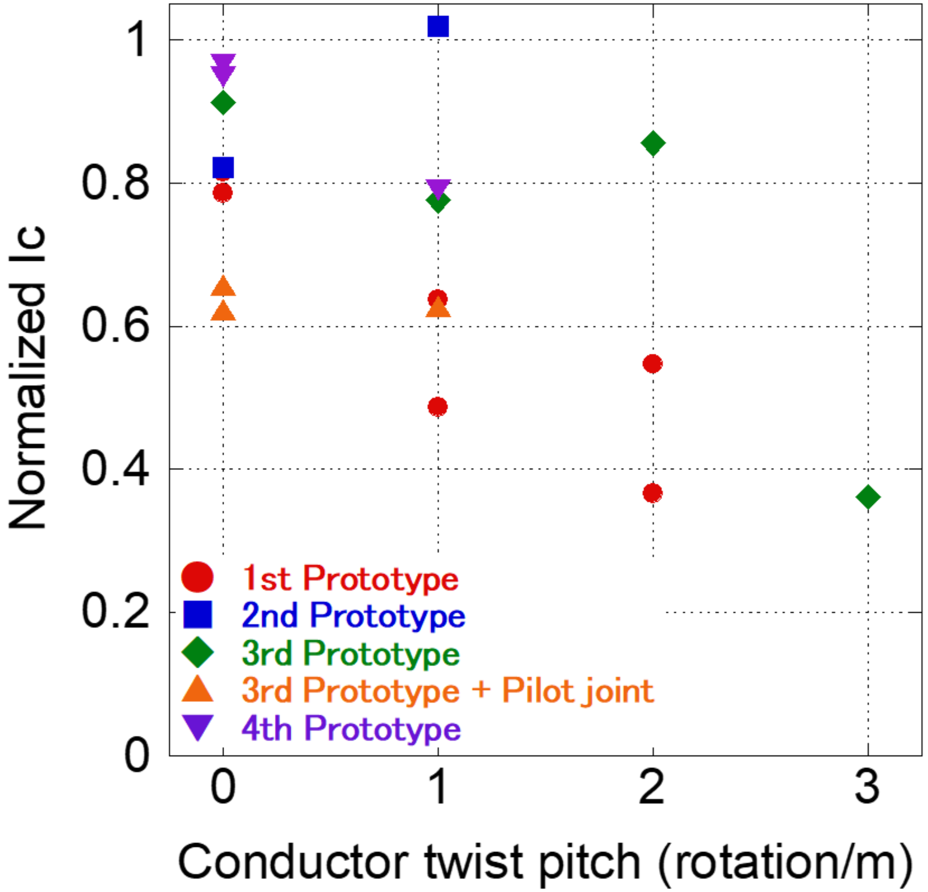


T. Mito et al., J. Phys. Commun. 4 (2020) 035009

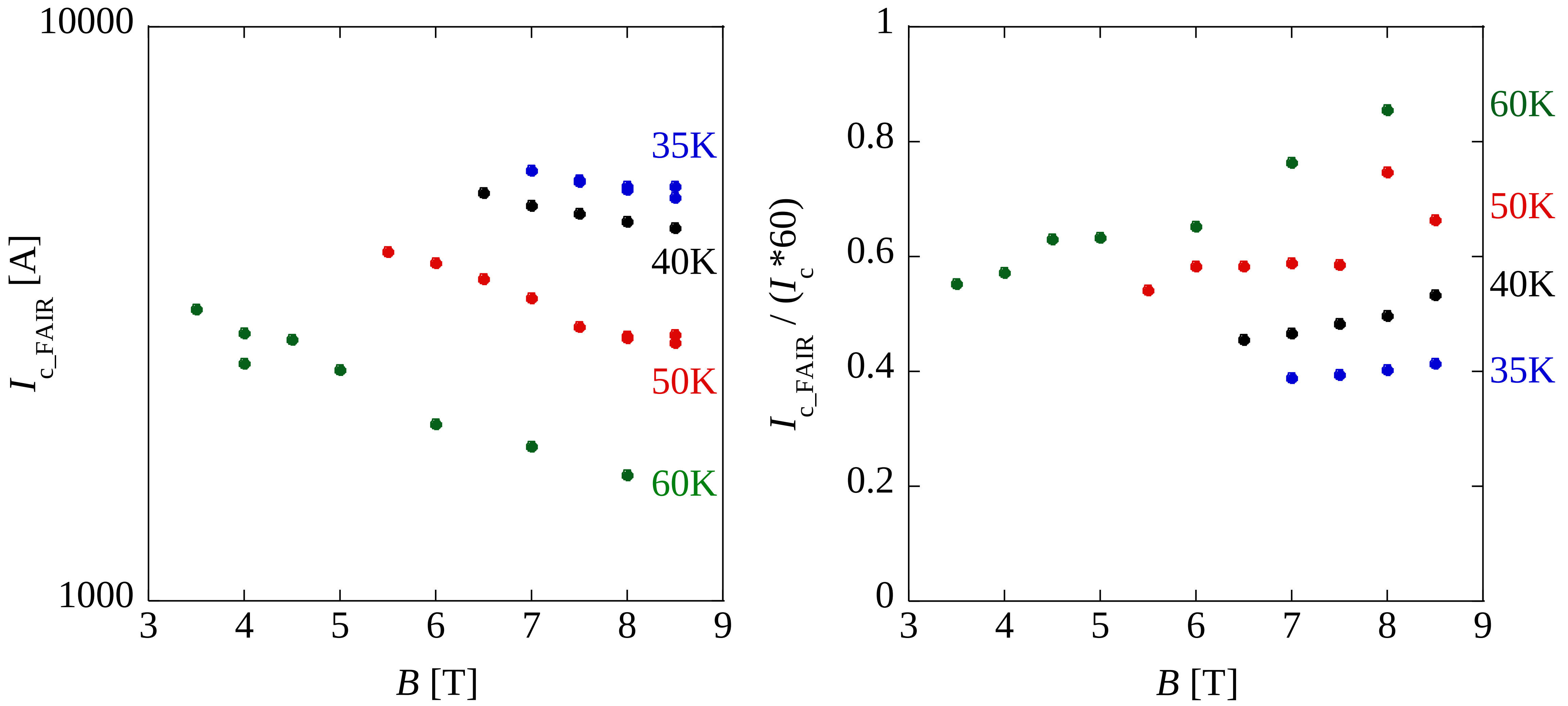
Improvement of FAIR conductor by optimizing FSW process







FAIR conductor test in large-superconductor testing facility (20-60 K, <8.5 T)



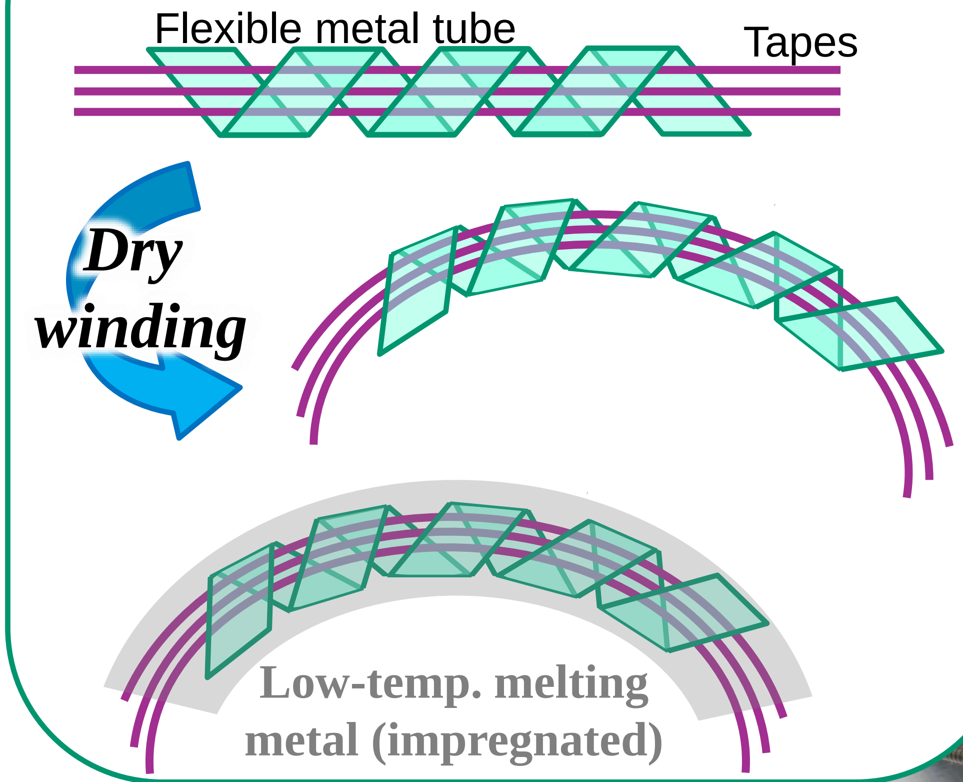
- **Mechanical failure due to insufficient EM support prevented maximum current**
- **Observed critical currents were lower than expected; furhter improvement being planned**

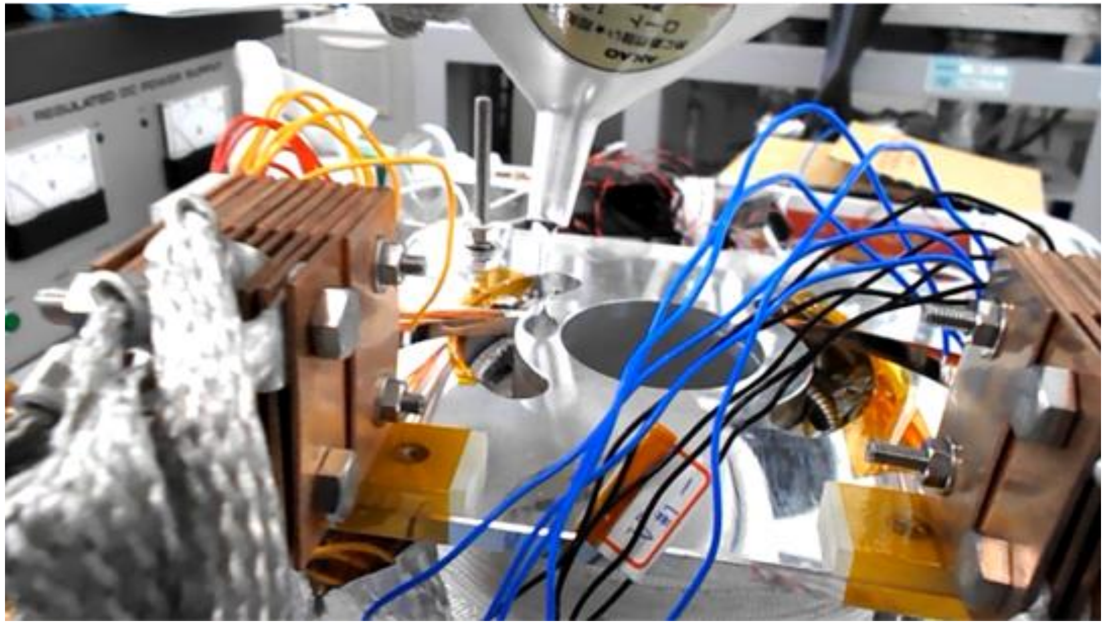
WISE Conductors and Coils

Y. Narushima, et al. 24P-5F-10

J. Miyazawa, Y. Narushima, S. Matsunaga

Wound and Impregnated Stacked Elastic tapes (WISE) concept

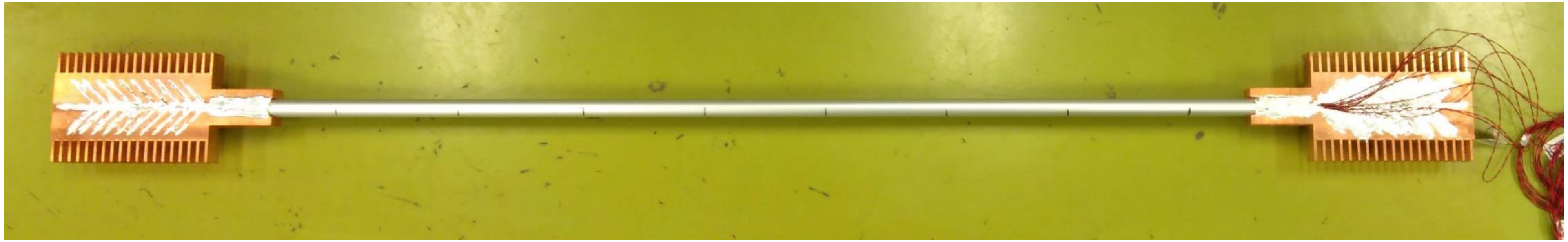




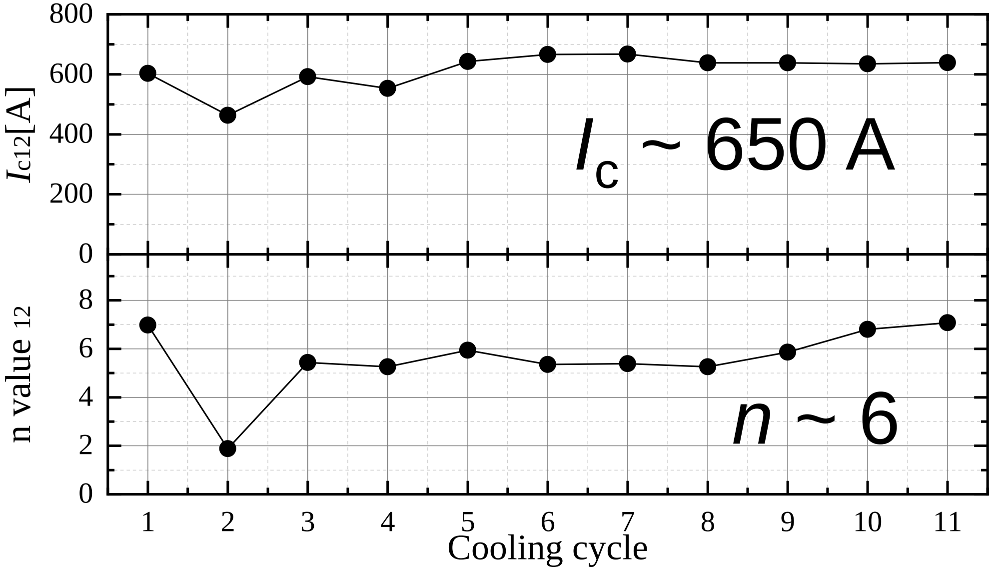
S. Matsunaga et al., IEEE Trans. Appl. Supercond. 30 (2020) 4601405

Development of WISE conductor

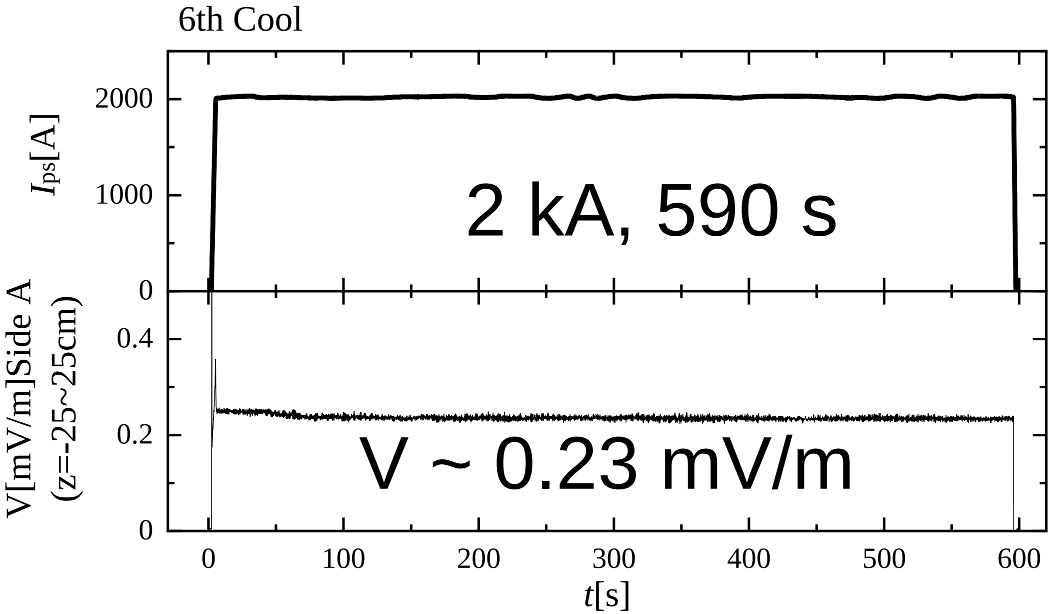
Y. Narushima, S. Matsunaga



REBCO 6-tapes + BSCCO 2-tapes
Tolerable degradation after cooling cycles



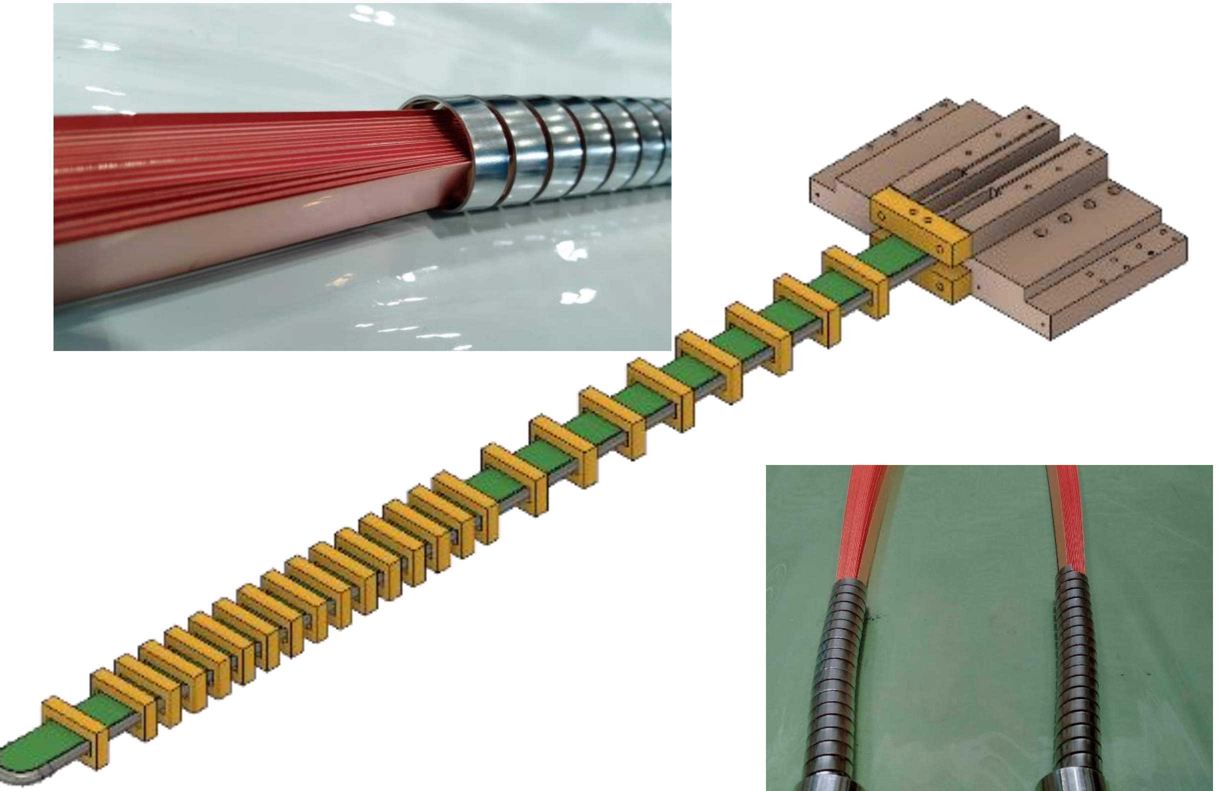
REBCO 22-tapes + BSCCO 2-tapes
Quench-free excitation at 2 kA for 590 s



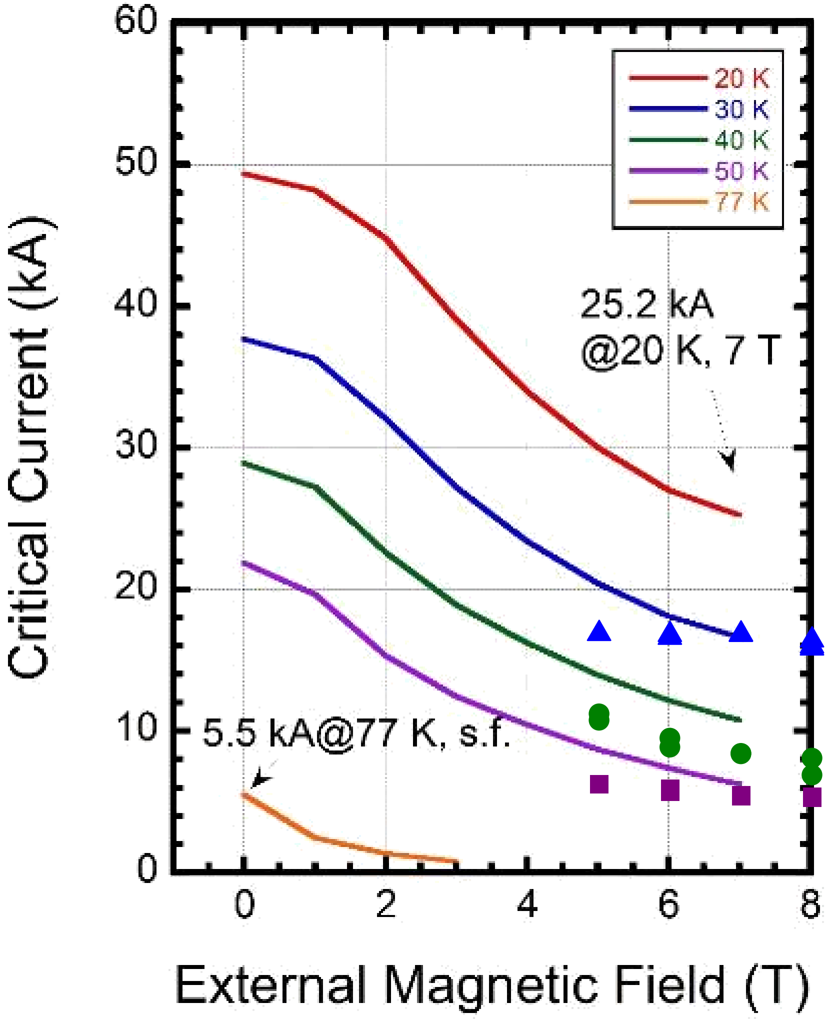
Future Plan

- Better selection of low-melting-temperature metal for mitigating differences of thermal contraction
- Fabrication of a double-pancake coil and test
- Short conductor test in low temperature (4-50 K) and magnetic field (< 9 T)

Overall view of WISE-U



Test of WISE-U

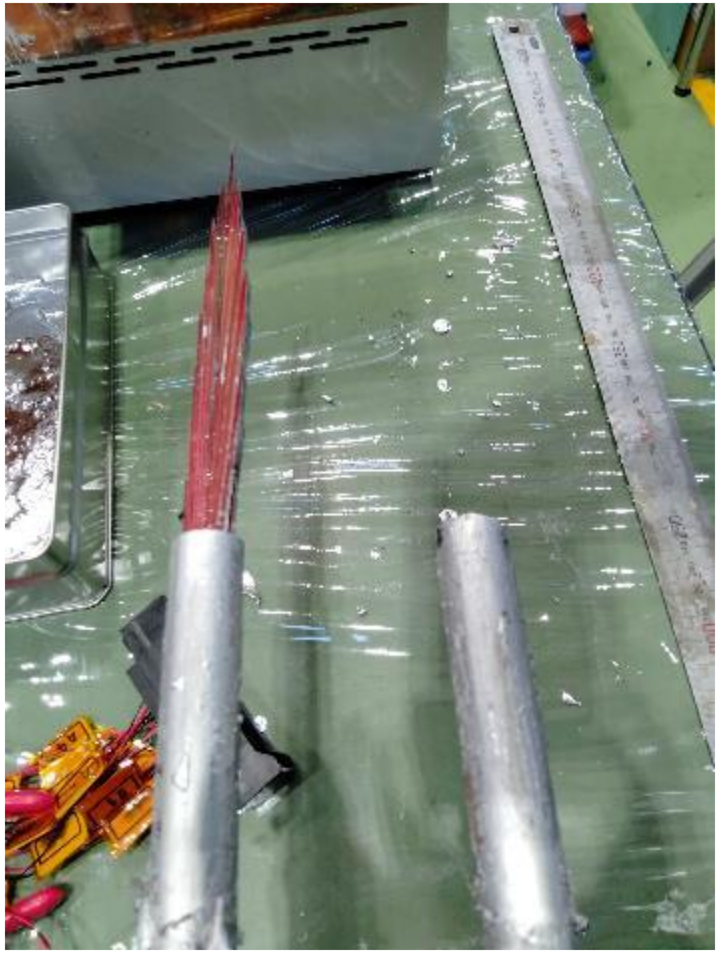


- Maximum current : 16.9 kA @30 K, 7 T achieved
- Experiment data shows lower critical current than calculation (overall trend is consistent)

Damage at the end of the aluminum pipe

Positive side
Alive

Negative side
HTS tapes lost



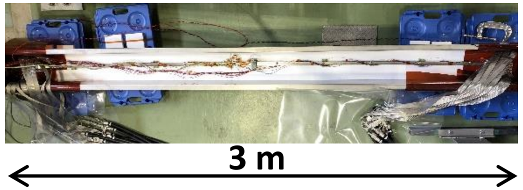
Aluminum pipe at current feeding section
burned out

Improvement of the current feeding section
is being planned using a copper pipe

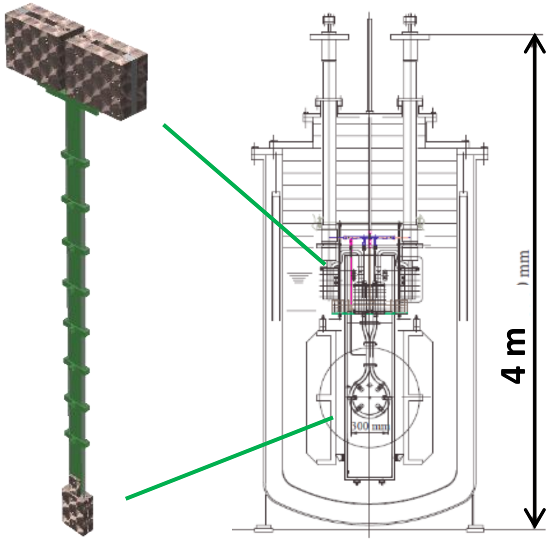
Plan for HTS conductor development

HTS testing facility
77 K (LN_2), 0 T

Short sample
(1-3 m)

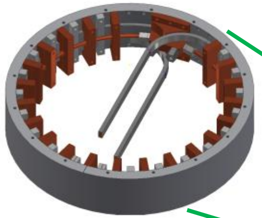


Large Conductor Testing Facility
4-50 K, max. 9 T

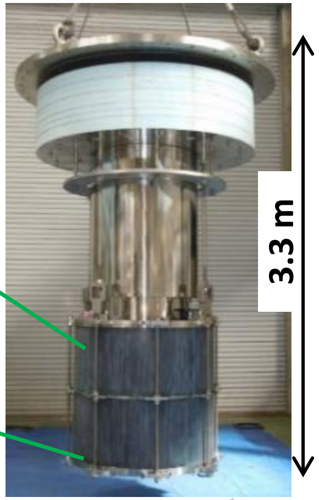


Short sample (2 m)
(Repetitive EM force)

Large-Bore High-Field Conductor Testing Facility
4-50 K, max. 13 T



Coiled sample (6 m)
(Repetitive EM force)



Establishment of basic technology of HTS magnet for helical fusion

Yearly Plan

FY2019	FY2020	FY2021	after FY2022

- Short samples (1-3 m) (FY2019)
- Testing in liquid nitrogen (77 K), no magnetic field (FY2019)
- Short samples (1-3 m) (FY2020)
- Testing in gas helium (4-50 K) and magnetic field (< 9T) (FY2020–FY2021)
- Long samples (3-10 m) (FY2021–FY2022)
- Development of HTS 3D helical coil winding technology

Summary

- **In the conceptual design studies on the helical fusion reactor, FFHR-b3 is newly proposed aiming at 100 MW electricity production with double size the LHD with configuration optimization**
- **Three types of HTS conductors are being developed for the next-generation helical device with high current density 80 A/mm^2**

  STARS conductor

  20 kA conductor is developed with simple stacking of REBCO tapes and laser welding of SS jacket
  Tests in LN_2 show <1% degradation over ten cooling cycles
  Test in 8 T, 20 K with 2-m sample (0.3-m testing region) confirms > 20 kA critical current
  Test in >8 T, 20 K with 6-m sample (uniform) will be carried in Feb. 2022, sample being fabricated

  FAIR conductor

  10 kA conductor is developed with friction stir welding of Al-alloy jacket
  Tests in LN_2 show fabrication improvement with twisting of REBCO tapes
  Test in 8.5 T, 20-60 K shows lower critical current than expected; further improvement planned

  WISE conductor

  10 kA conductor is being developed with low-melting temp. metal impregnation
  Coiled samples tested in LN_2 show improvement with non-insulation concept
  Test in <8.5 T, 30-50 K achieved 16 kA@30 K, 8 T ➔ further test is planned
- **Quench protection is a crucial issue for all conductors; effective methods examined**