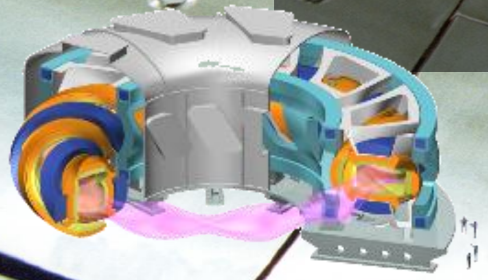
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.
Invited presentation HF-4 was given at the virtual CCA 2021, October 11-15, 2021.

Progress of HTS STARS Conductor Development for the Next-Generation Helical Fusion Experimental Device

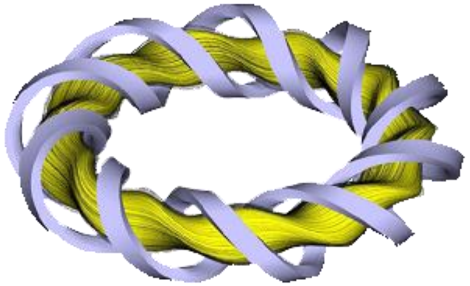
N. Yanagi[1], Y. Terazaki[1], Y. Narushima[1], N. Hirano[1], Y. Onodera[1], S. Hamaguchi[1], H. Chikaraishi[1], S. Takada[1], H. Tamura[1], K. Takahata[1], D. Garfias[2], S. Ito[3], H. Hashizume[3]

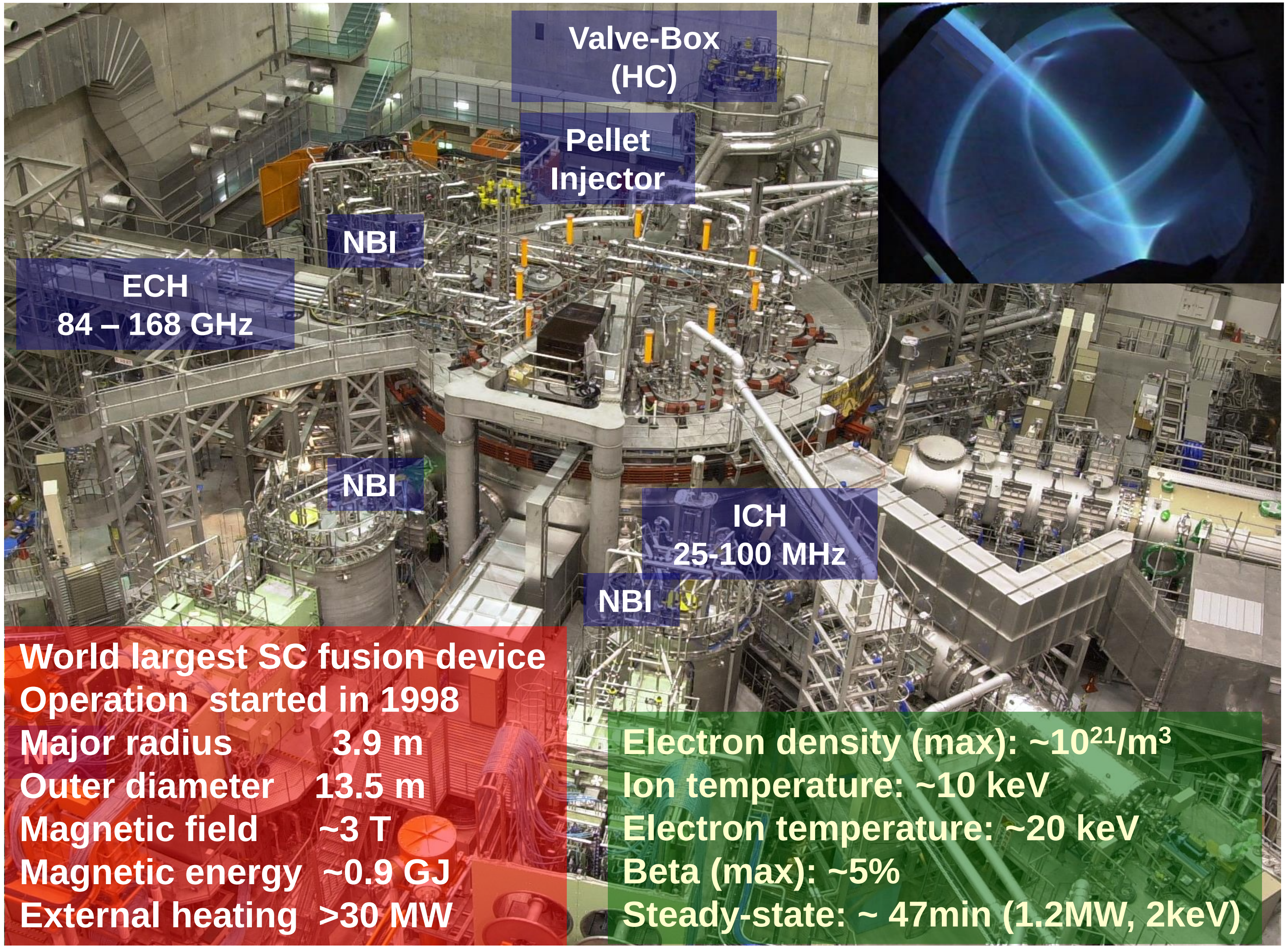
[1] National Institute for Fusion Science
[2] The Graduate University for Advanced Studies, SOKENDAI
[3] Tohoku University



The Virtual CCA 2021
HF-4

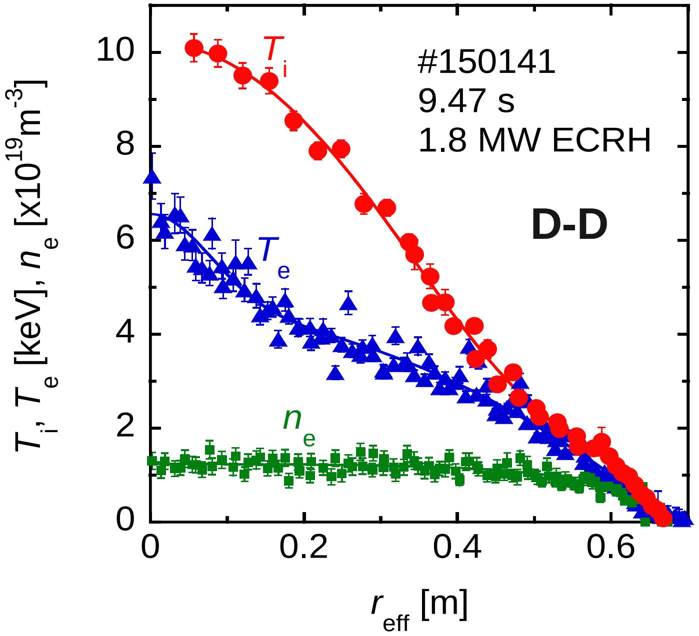
The Large Helical Device (LHD)





World largest SC fusion device
Operation started in 1998
Major radius 3.9 m
Outer diameter 13.5 m
Magnetic field ~3 T
Magnetic energy ~0.9 GJ
External heating >30 MW

Electron density (max): ~$10^{21}/m^3$
Ion temperature: ~10 keV
Electron temperature: ~20 keV
Beta (max): ~5%
Steady-state: ~ 47min (1.2MW, 2keV)



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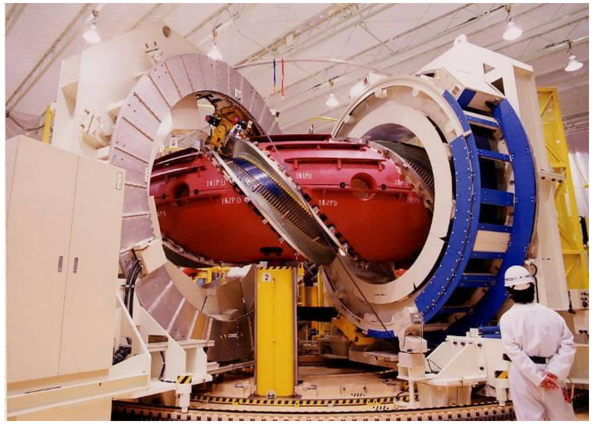
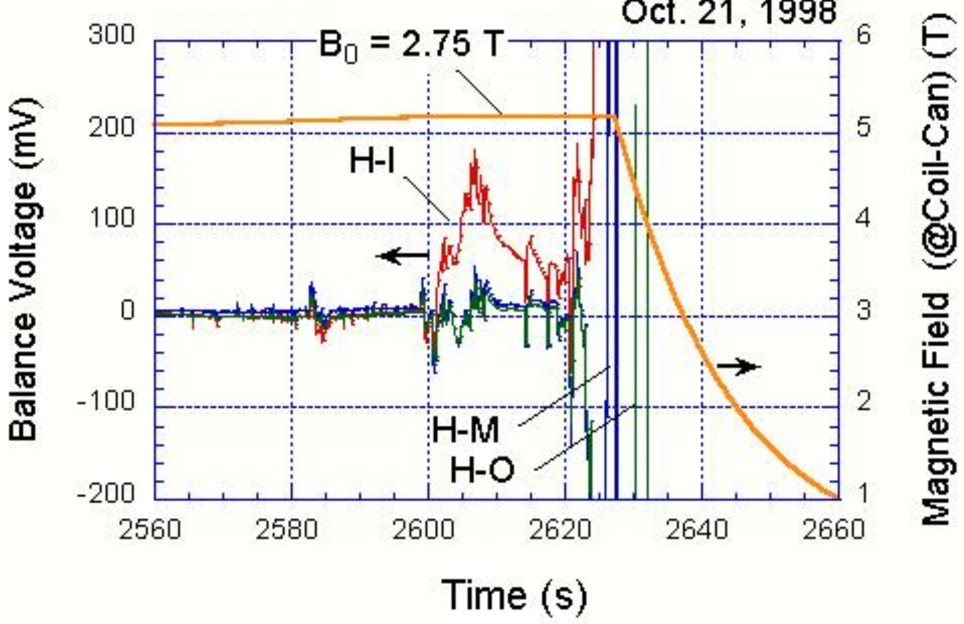


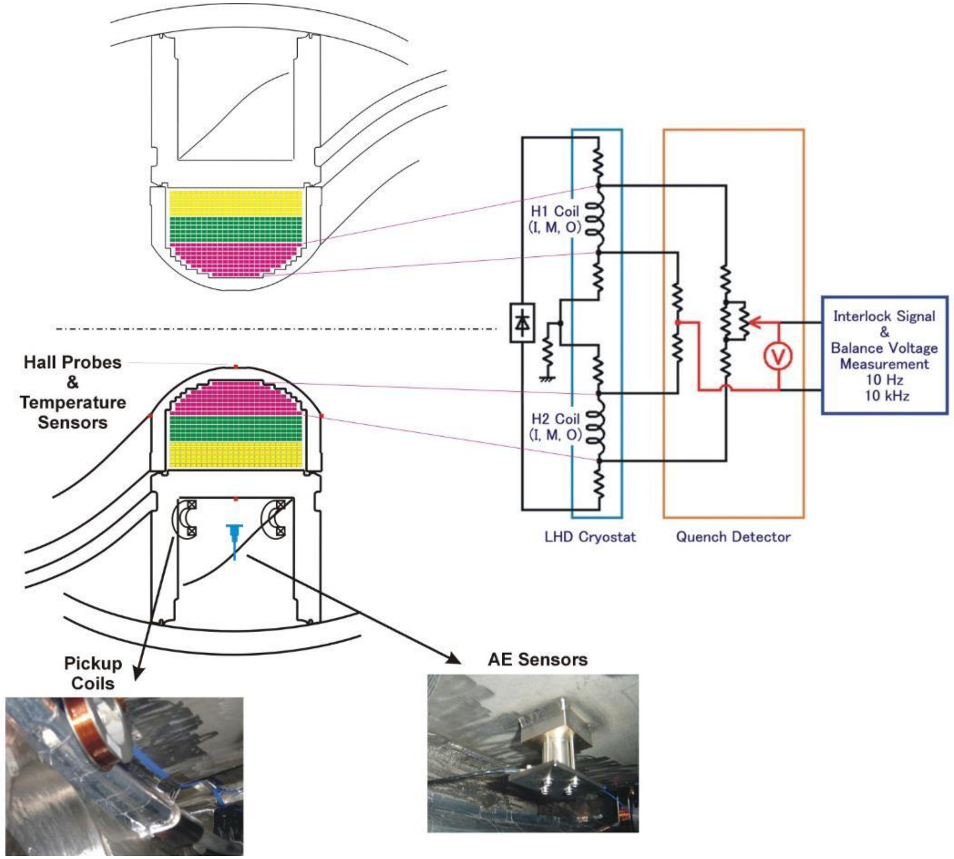
Quench Event in LHD

October 21, 1998

Quench Detection
(200 mV, 3 seconds)



N. Yanagi, S. Imagawa, et al.,
IEEE TAS 10 (2000) 610



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

Magnet

- Joint-winding by HTS conductor is possible in addition to continuous helical winding (LHD method)

Blanket

- Molten-salt and/or liquid metal blankets
- RAFM and/or Vanadium alloy
- Easy maintenance through large ports

  Cartridge-type with external handling

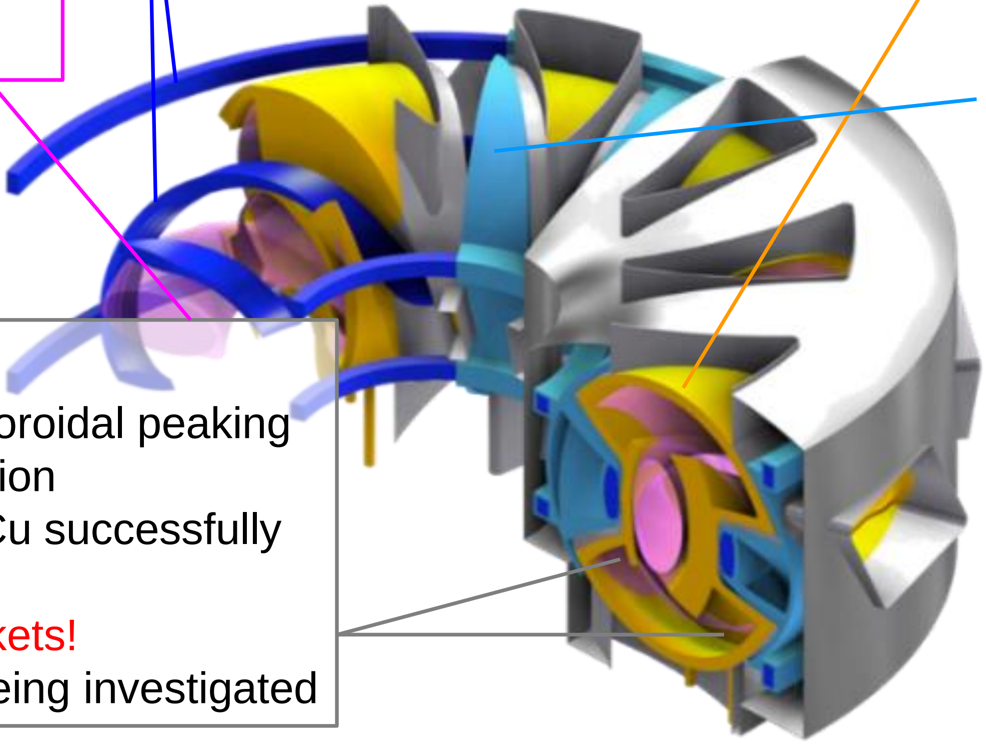
  Helically-shaped with remote handling

Plasma

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

EM Support Structure

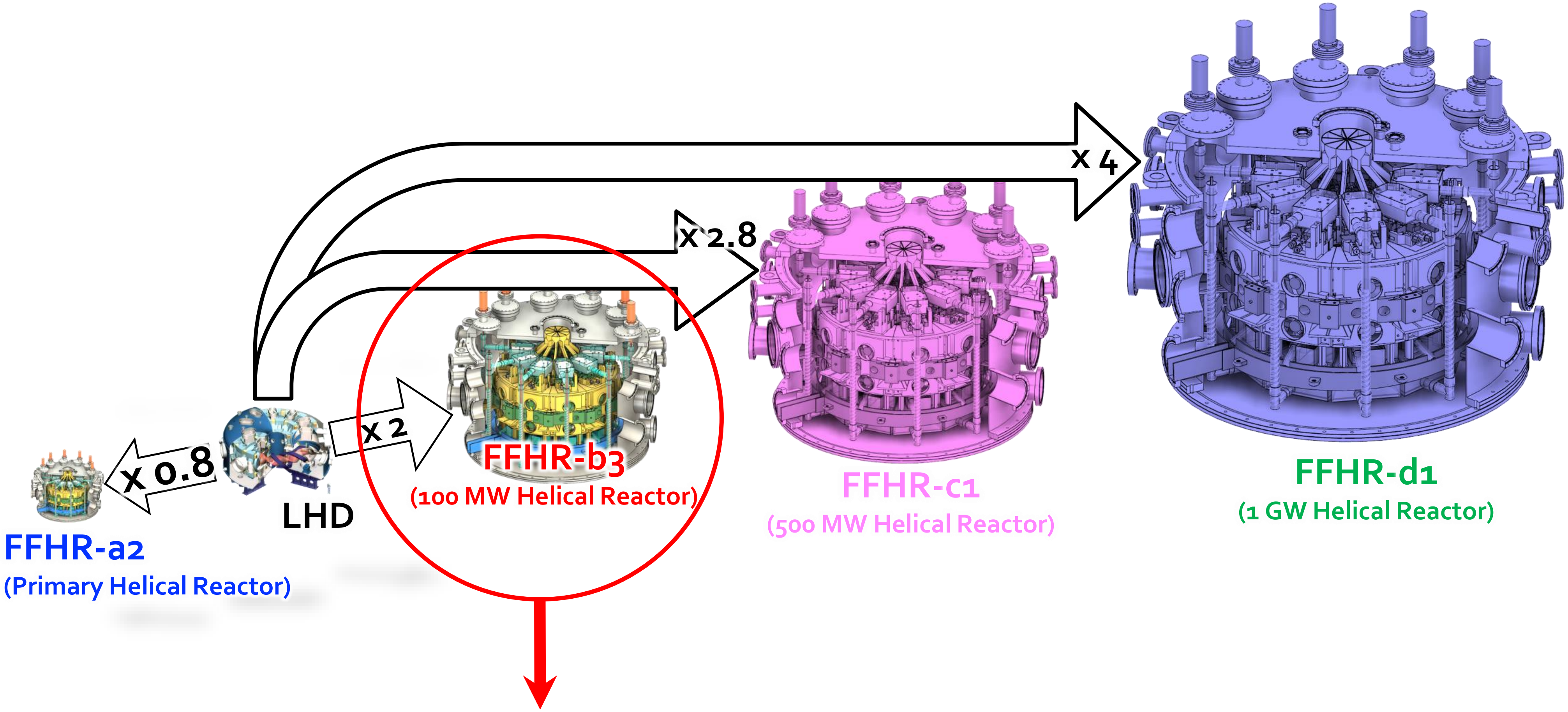
- Topology optimization reduces mass >25%



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!
- Pebble divertor concept is also being investigated

New Strategy for Early Realization of Helical Reactor



Slight improvement of plasma confinement / Innovation for reactor engineering

➔ Early realization of a helical reactor with

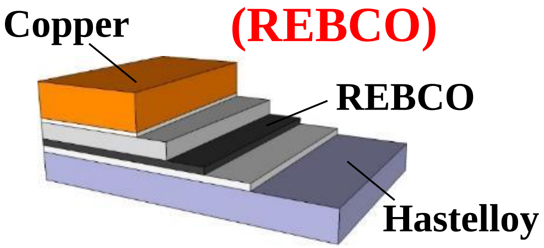
- **Double size of LHD (*R* = 7.8 m)**
- **100 MW net electricity production**

High-Temperature Superconducting Magnet Option

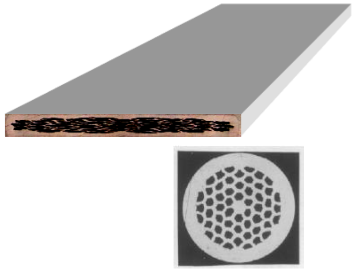
(0) Saving helium resources

(1) High critical current to high field
(2) High cryogenic stability
(3) Low cryogenic power
(4) High mechanical rigidity
(5) Industrial production of tapes

Rare-Earth Barium Copper Oxide (REBCO)



Bismuth-based HTS



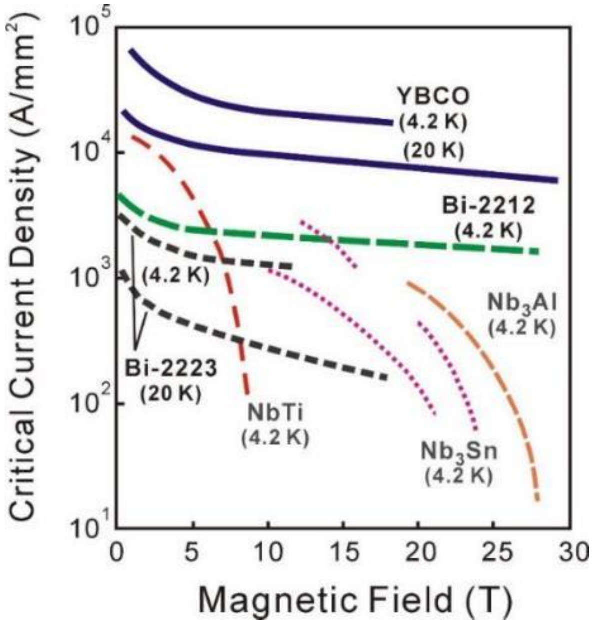
Stability Margin

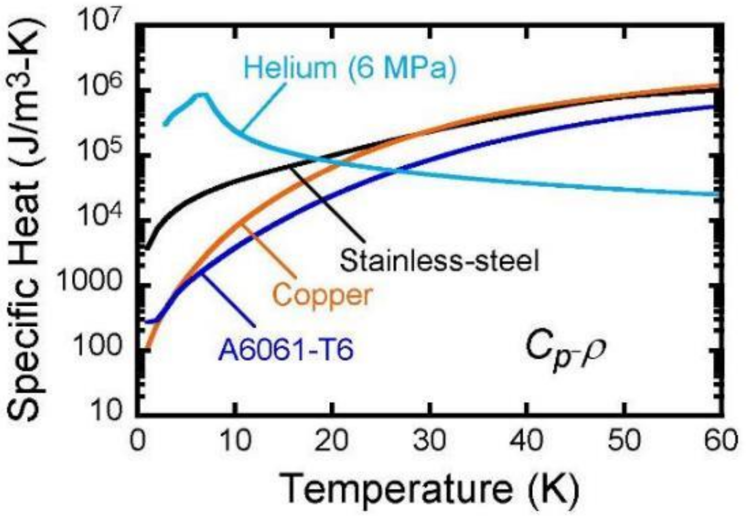
$$\Delta Q < C_p \rho \Delta T$$

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

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

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





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

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.
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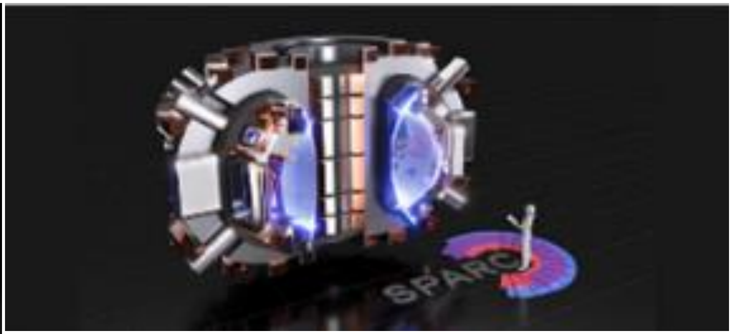
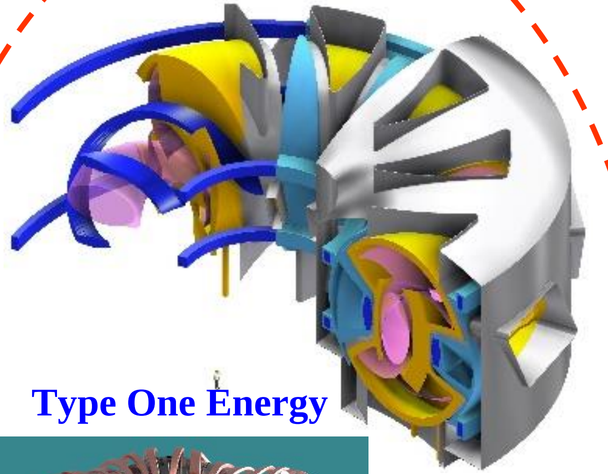
Fusion reactor designs with HTS magnet in the World

ARC & SPARC (MIT/CFS)

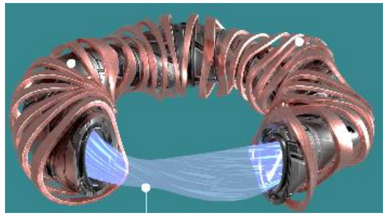


B_t = 9-12 T
B_{max} = 21-23 T

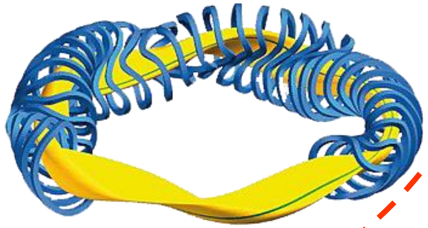
FFHR-d1 (NIFS)



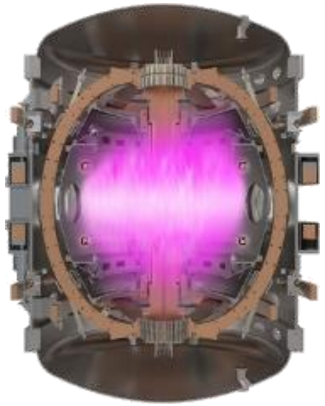
Type One Energy



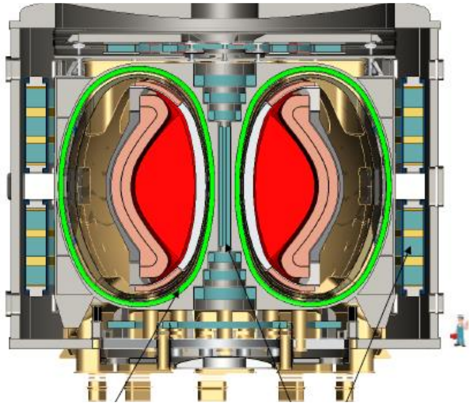
Renaissance Fusion



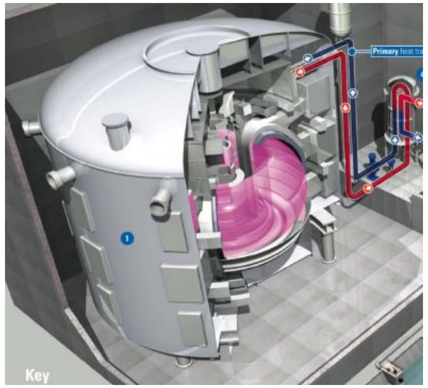
Tokamak Energy



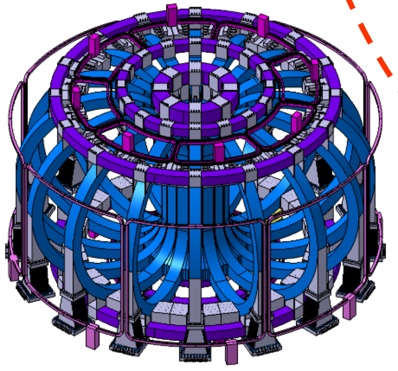
FNSF-ST (PPPL)



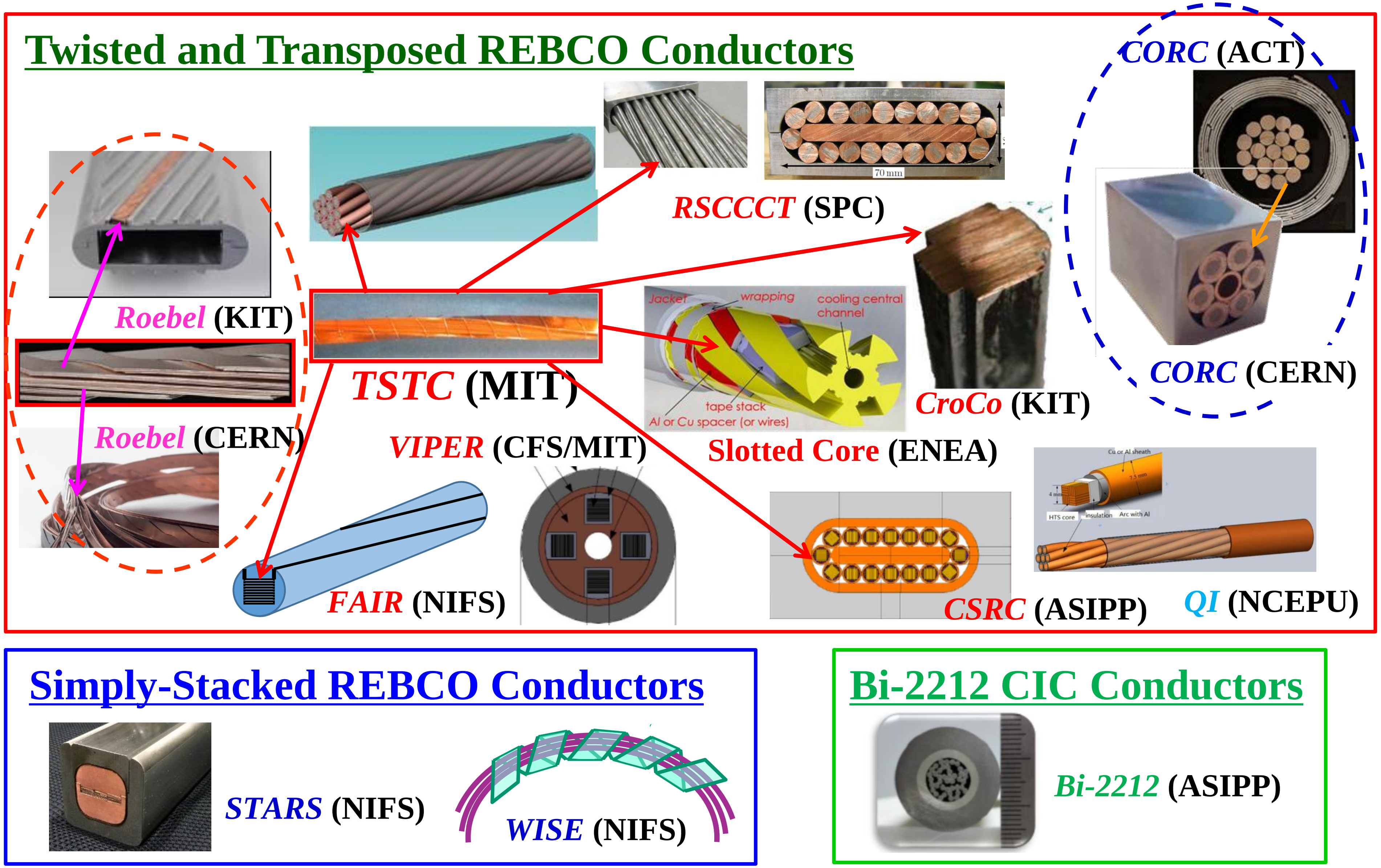
EU DEMO HTS option (EUROfusion)



CFETR (ASIPP) for CS coils

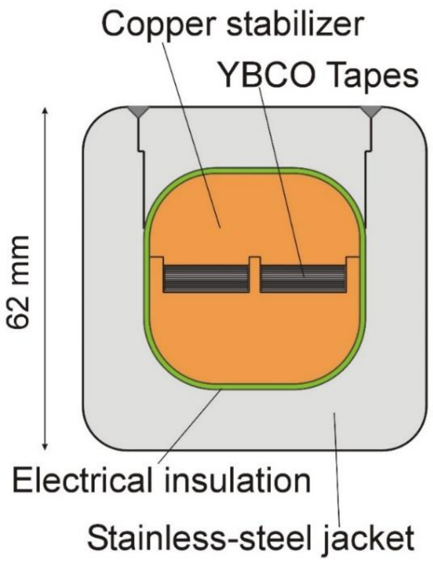


Large-current HTS conductors developed for fusion magnets

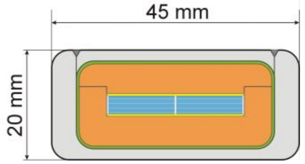


100 kA-class HTS Conductor for FFHR-d1 Helical Fusion Reactor
"STARS" (*Stacked Tapes Assembled in Rigid Structure*)

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



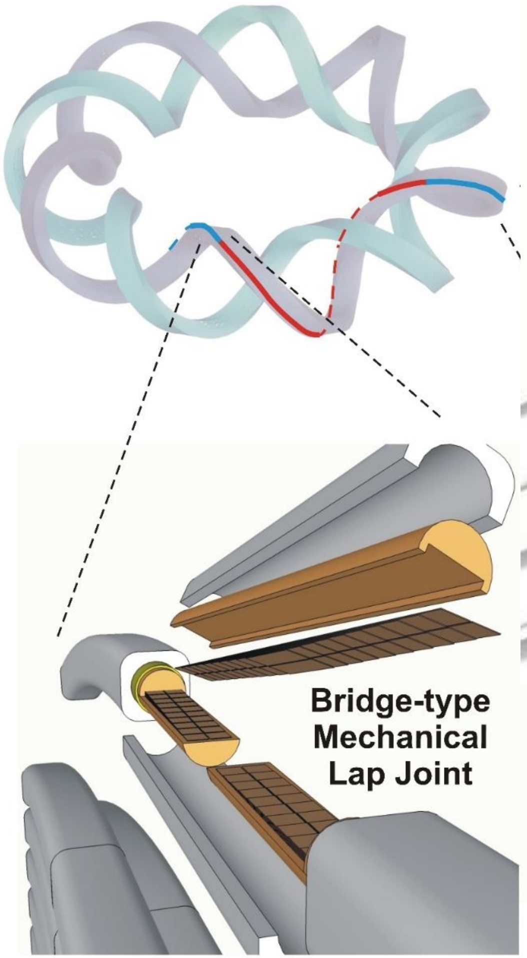
STARS
for FFHR-b3
66 kA, 80 A/mm^2

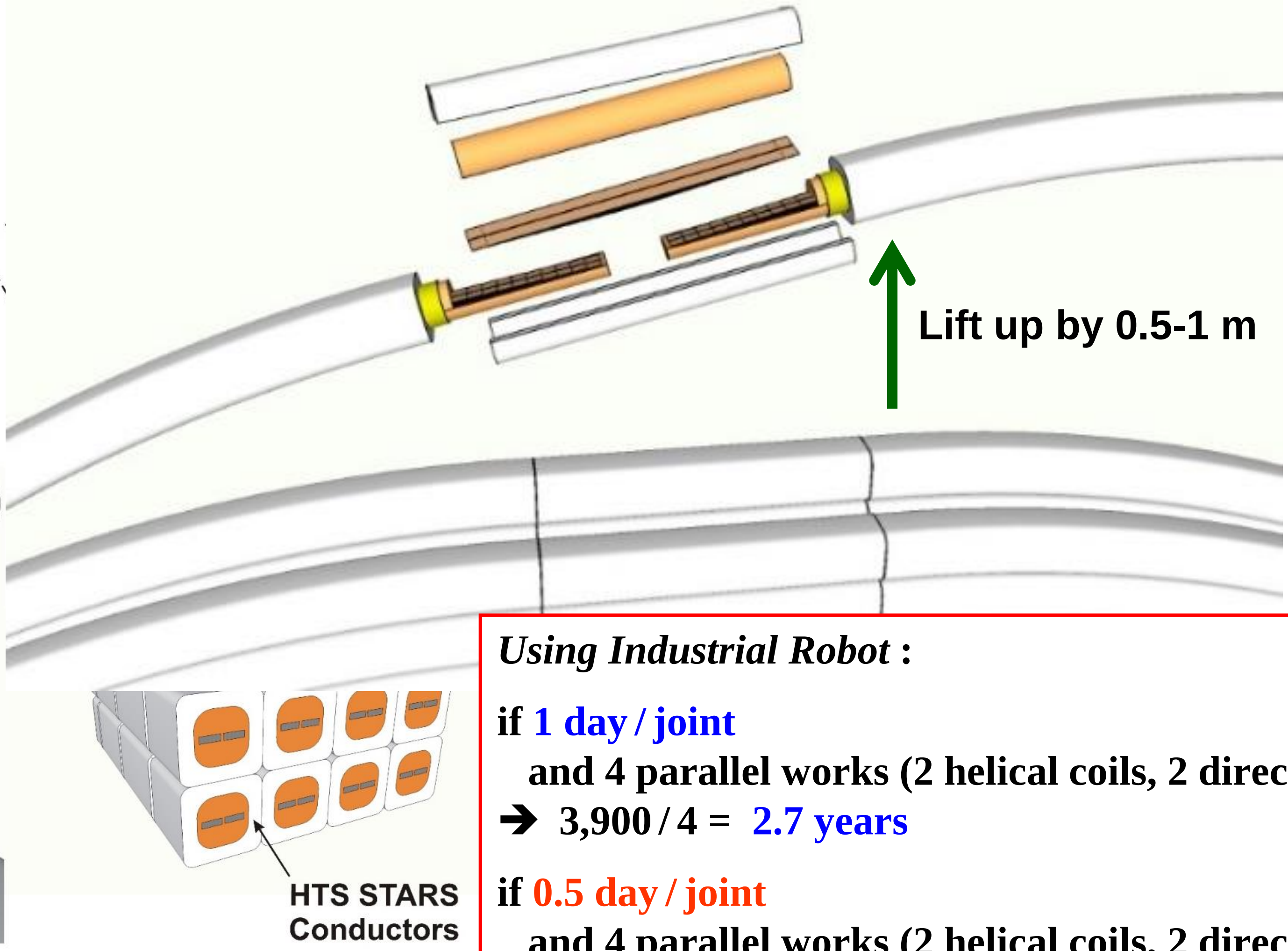
Simply-stacked HTS conductor for DC helical coils

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

“Joint-Winding” of Helical Coils

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

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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)

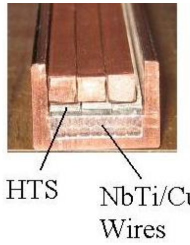
2007-2008 — **15-kA-class HTS STARS conductor sample**
YBCO / GdBCO tapes + Cu (soldered)

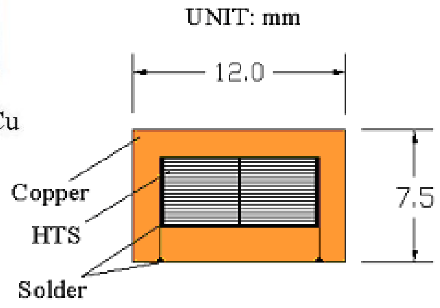
2012-2013 — **30-kA-class HTS STARS conductor sample**
GdBCO tapes + Cu + SS (bolted)

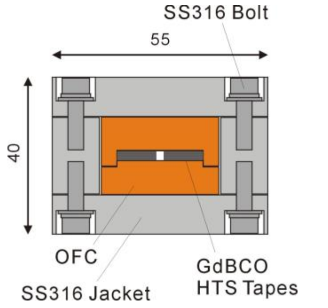
2013-2014 — **100-kA-class HTS STARS conductor sample**
GdBCO tapes + Cu + SS (bolted)

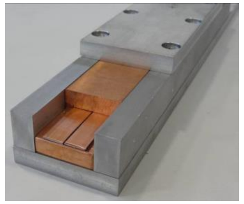
2019-2020 — **20-kA-class HTS STARS conductor sample**
EuBCO + Cu + SS (welded)

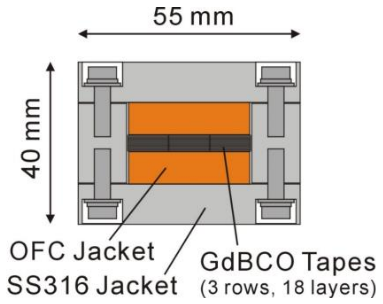
2020-2021 — **20-kA-class HTS STARS conductor sample**
GdBCO + Cu + Kapton + SS (welded)

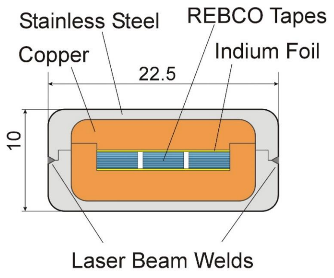


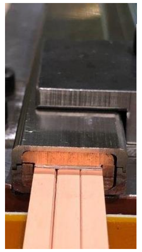


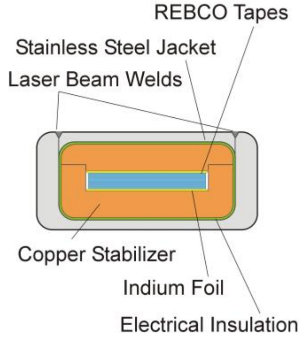




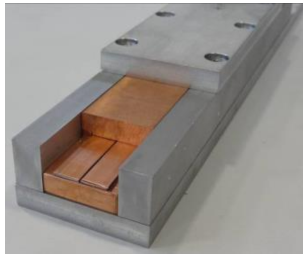


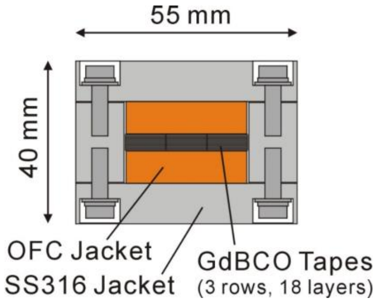




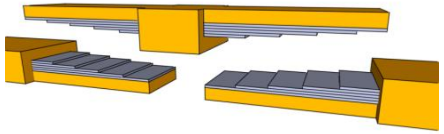


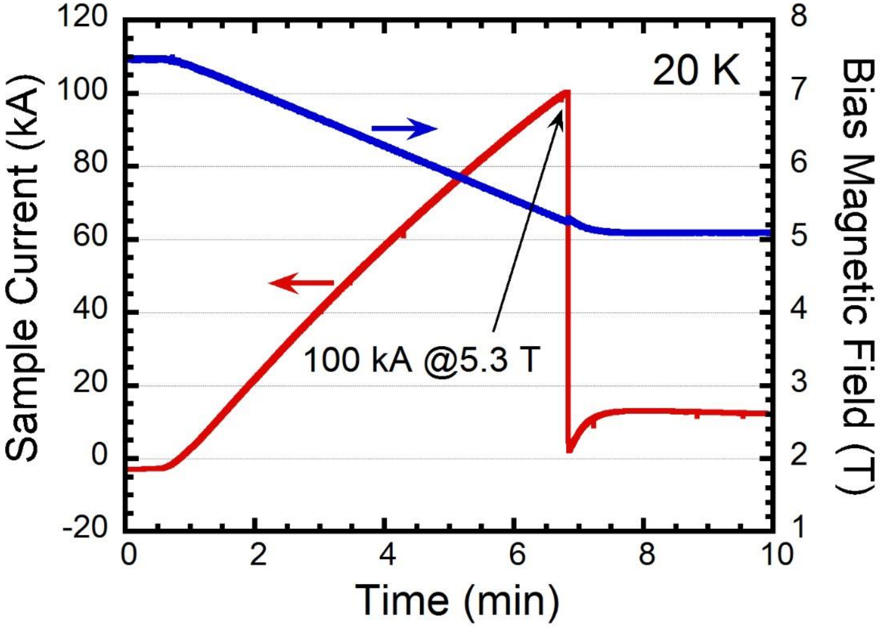
100 kA-Class Prototype STARS Conductor Test

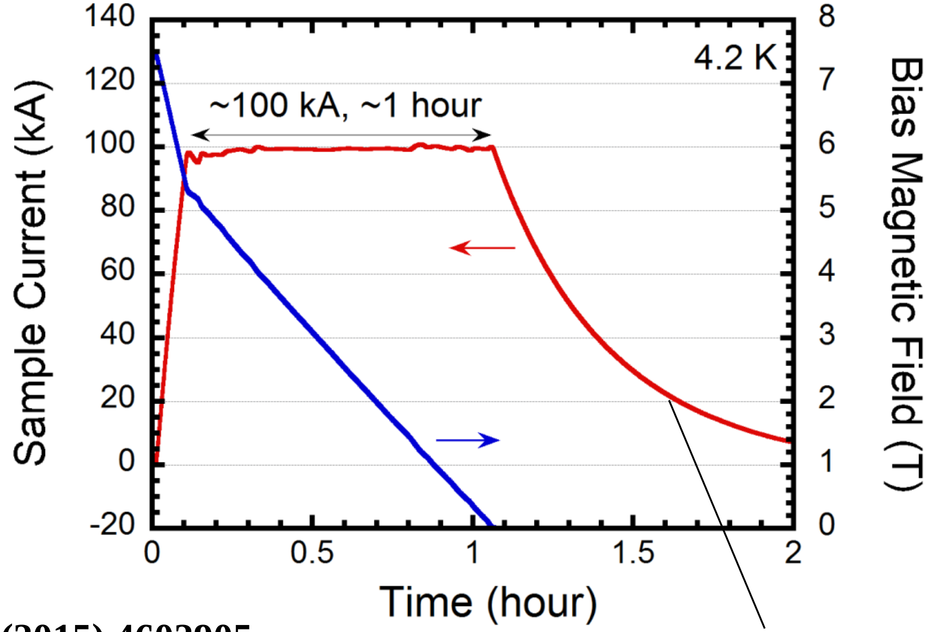


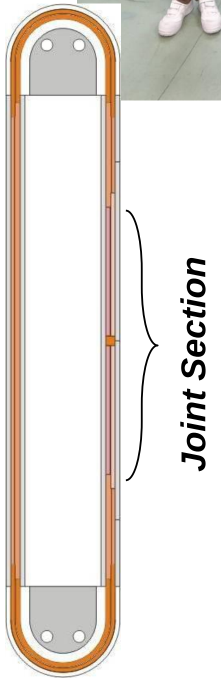


Bridge-type mechanical lap joint
"*Invisible joint*"







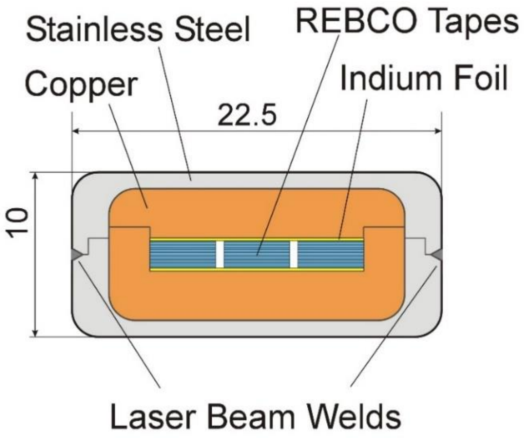


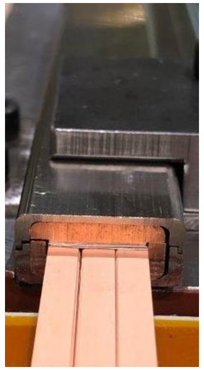
Joint resistance ~1.8 nΩ

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

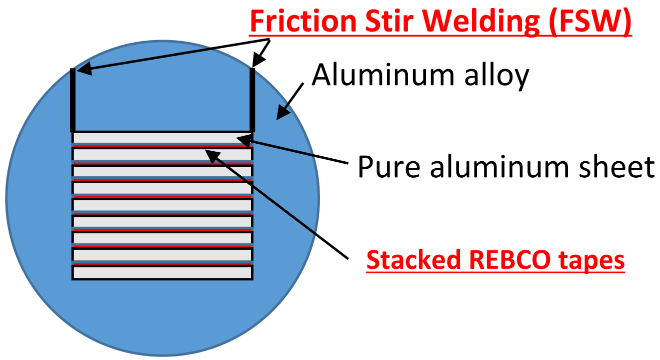
Practical HTS conductor development for the next-generation helical device

STARS
(Stacked-Tapes Assembled in Rigid Structure)

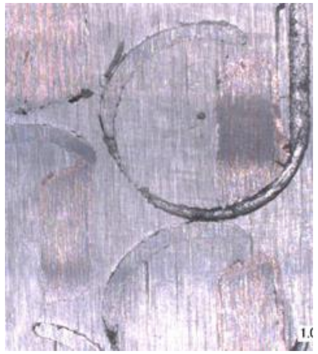




FAIR
(FSW, Al-alloy, Indirect-cooling, REBCO)



WISE
(Wound and Impregnated Stacked Elastic tapes)



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

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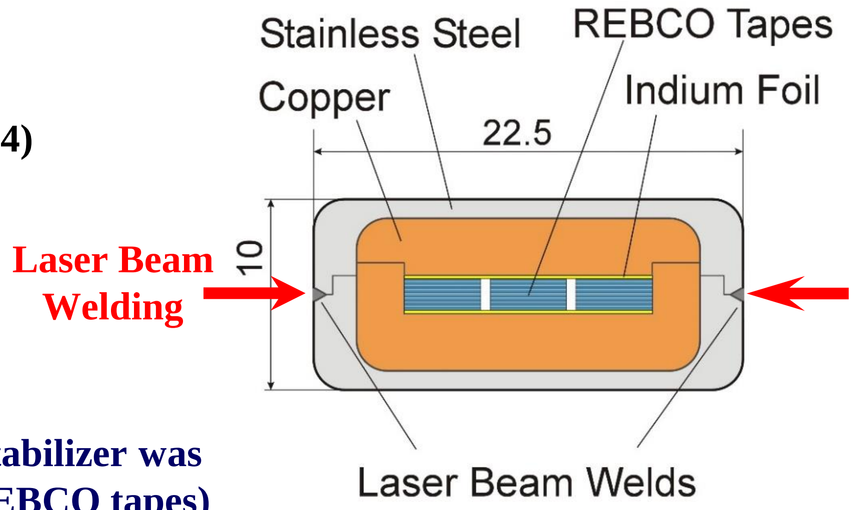
20 kA-class STARS Conductor

- **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**



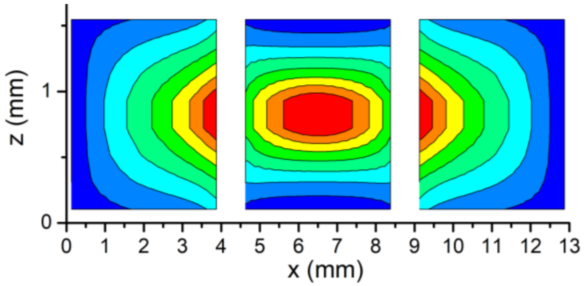
Temperature at the inner wall of Cu stabilizer was 44 °C << 200 °C (allowable limit for REBCO tapes)

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

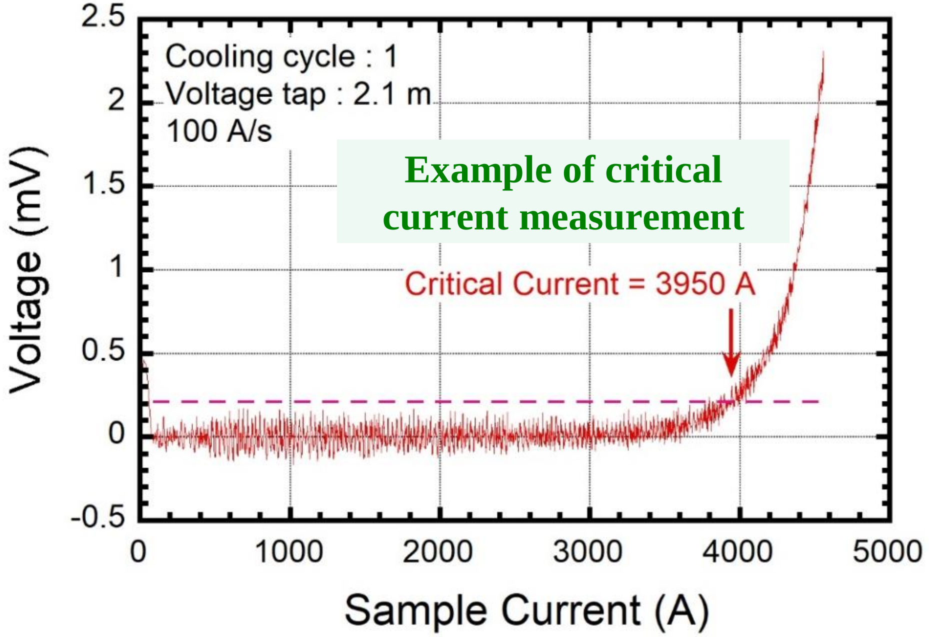
  Verified by numerical simulation with current density and magnetic field distribution, extrapolation to 20 kA at 20 K and 10 T
- Tolerable reduction (~1%) of critical current by cooling cycle
- Further reduction (~2%) with 3000 mm bending radius
- Recovery by releasing (straightening)

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

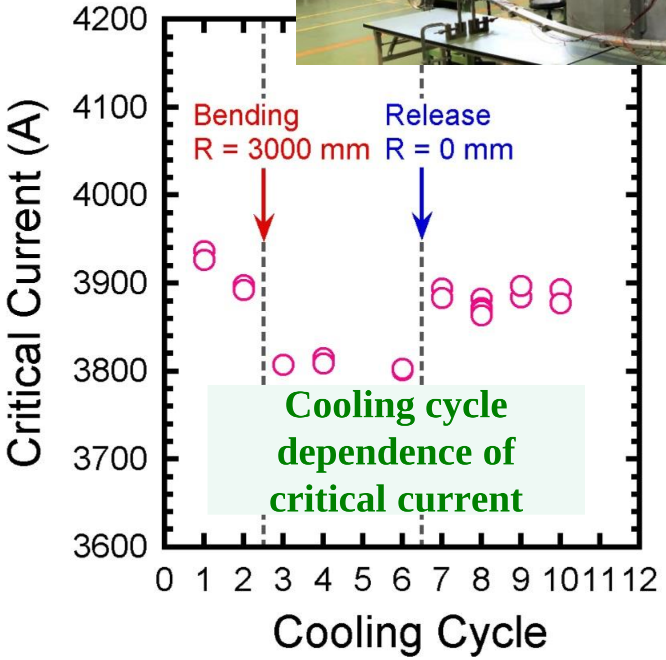


Numerical simulation of J and B distribution

Y. Terazaki



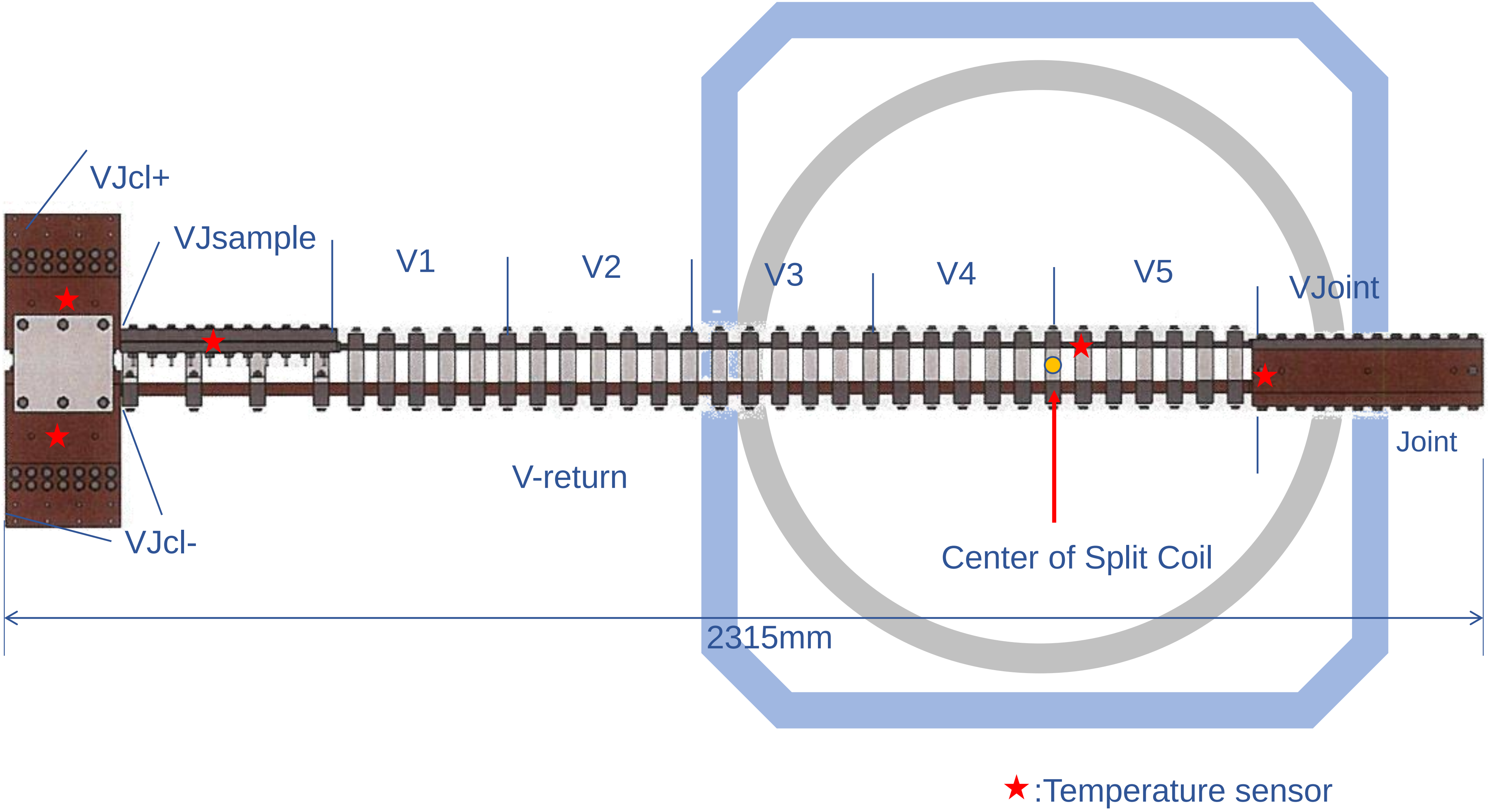
Example of critical current measurement

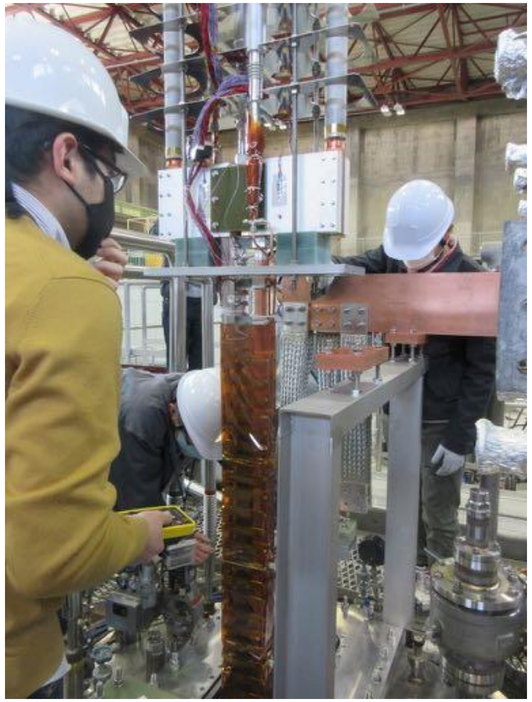


Cooling cycle dependence of critical current

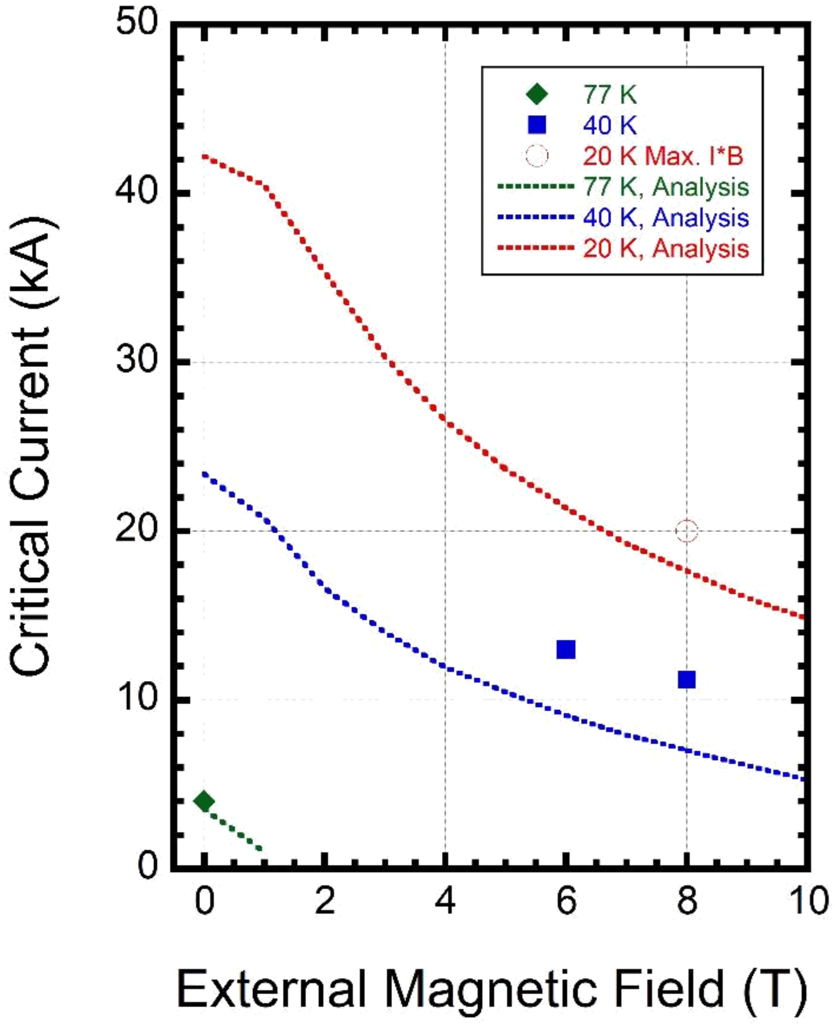
20 kA-class STARS conductor test in large-superconductor testing facility

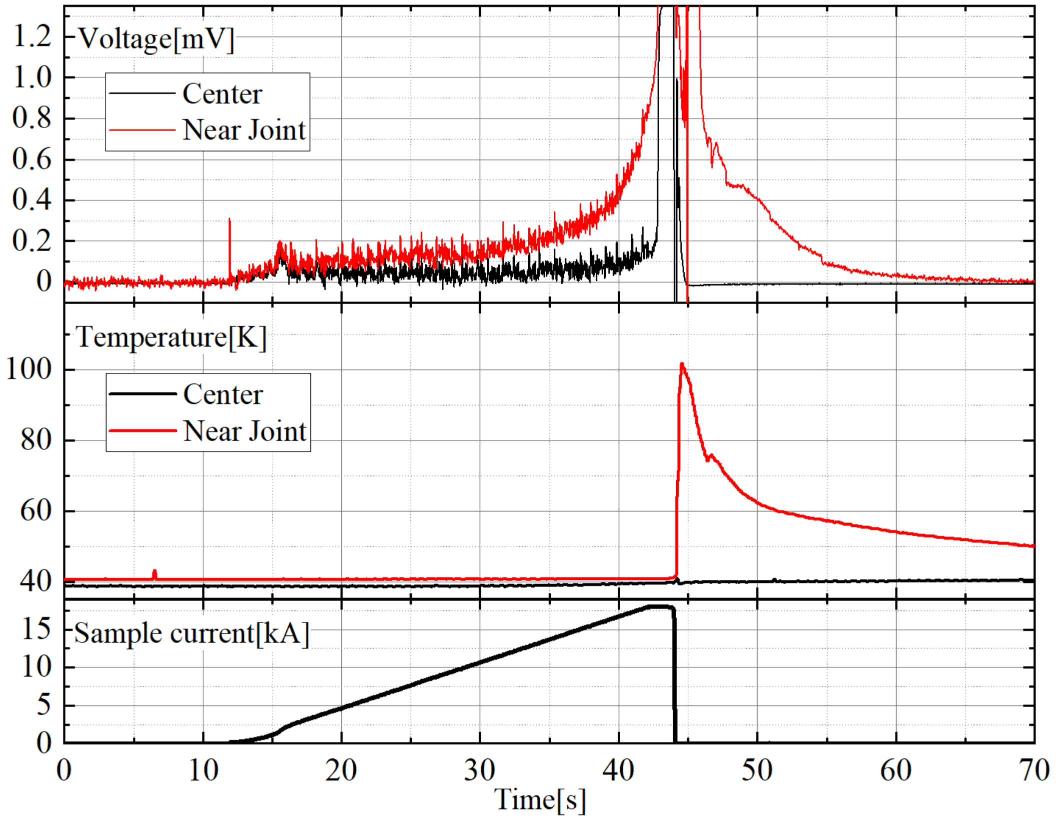
< 9 T, 20-50 K, <20 kA (for the present setup)





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





Mistake in quench detection
➔ sample melted locally

Test in 8 T, 20 K confirms > 20 kA critical current

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

HTS conductor development for next generation helical device

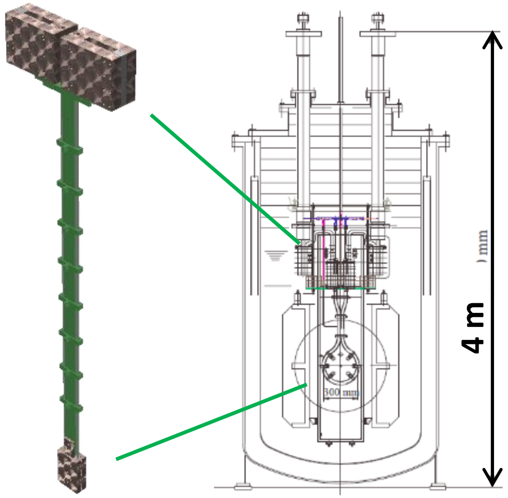
HTS testing facility
77 K (LN_2), 0 T

1 m

Short sample (1-3 m)

3 m

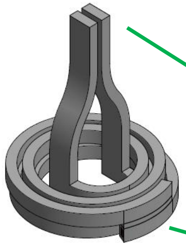
Large Conductor Testing Facility
4-50 K, max. 9 T



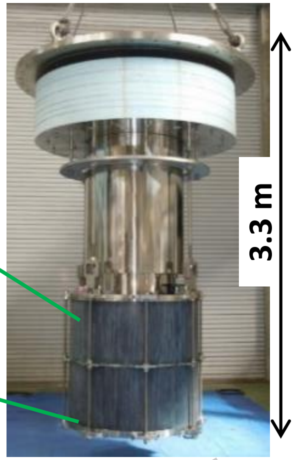
4 m

Short sample (2 m)
(Repetitive EM force)

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



Coiled sample (3-10 m)
(Repetitive EM force)



3.3 m

Establishment of basic technology of HTS magnet for helical fusion

Yearly Plan

FY2019 | FY2020 | FY2021 | after FY2022

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

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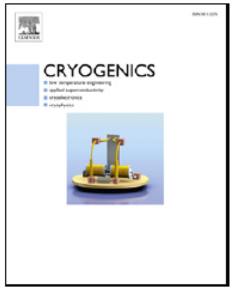

Research paper

Non-twisted stacks of coated conductors for magnets: Analysis of inductance and AC losses

Check for updates

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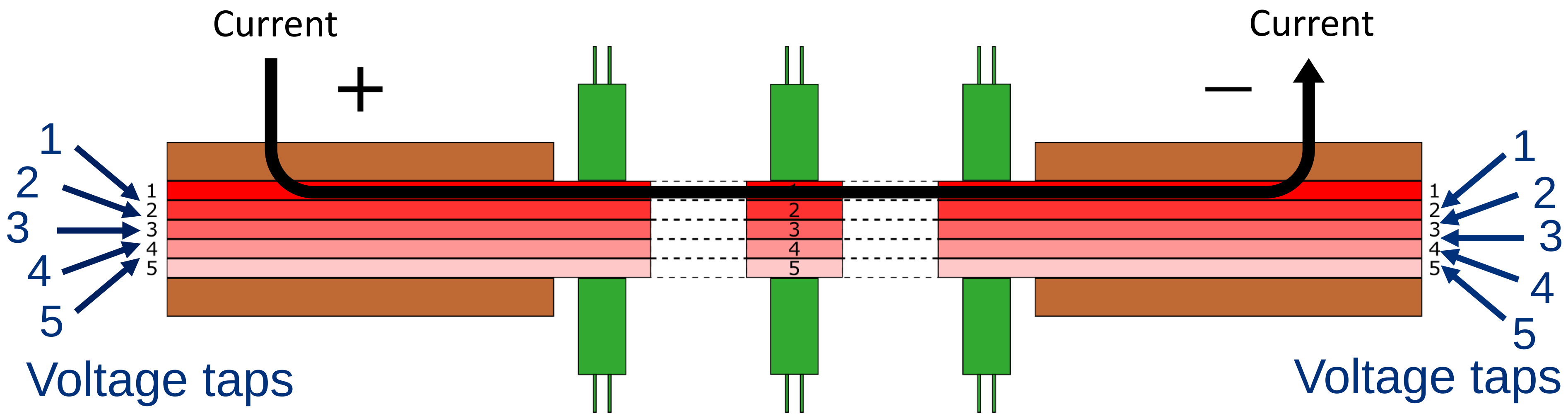
A B S T R A C T

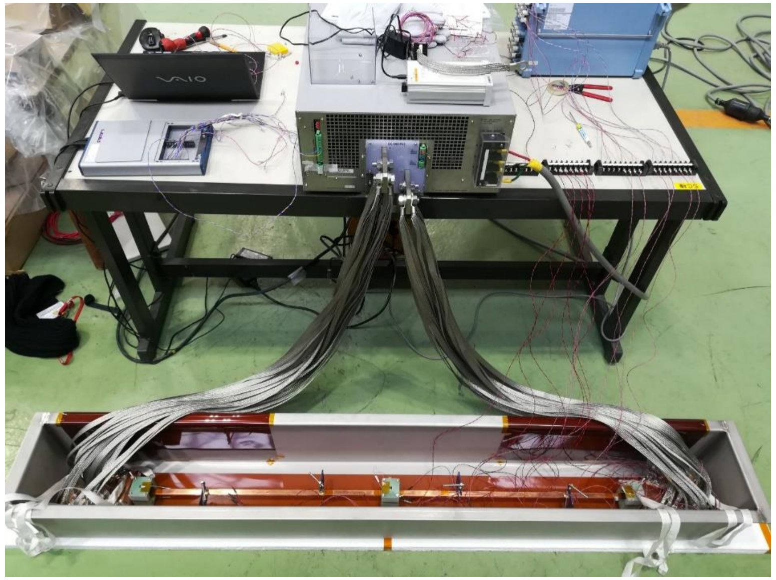
Almost all present High Temperature Superconducting (HTS) cable designs for magnets are based on twisted or transposed concepts that were developed for Low Temperature Superconducting (LTS) cables. However, requirements for LTS materials (like filament twisting) are in general not valid for HTS materials, which are extremely stable; for example, non-twisted multifilamentary Bi-2223 tapes have been successfully used in several magnets. Is twisting necessary for HTS cables? We investigated inductance mismatches and AC losses by numerical and analytical methods in twisted and non-twisted stacks of coated conductors; various experiments reported in the literature support the analysis. Large (hysteretic) losses are common in all magnets built with tapes and are far larger than in magnets built with LTS multifilamentary conductors, because of the aspect ratio and large width of the tape. In small magnets, losses and residual magnetisation could be reduced by replacing a wide tape with a non-twisted stack of narrow tapes. In large cables, we have found that twisting a stack of tapes reduces losses only marginally. Therefore, non-twisted stack cables could be designed to have losses comparable to those of twisted ones. Some examples of non-twisted large cables for fusion applications are discussed: non-twisted stack designs can be simpler, more robust and cost effective than twisted ones, but would require additional R&D.

Does "simple-stacking" really work?



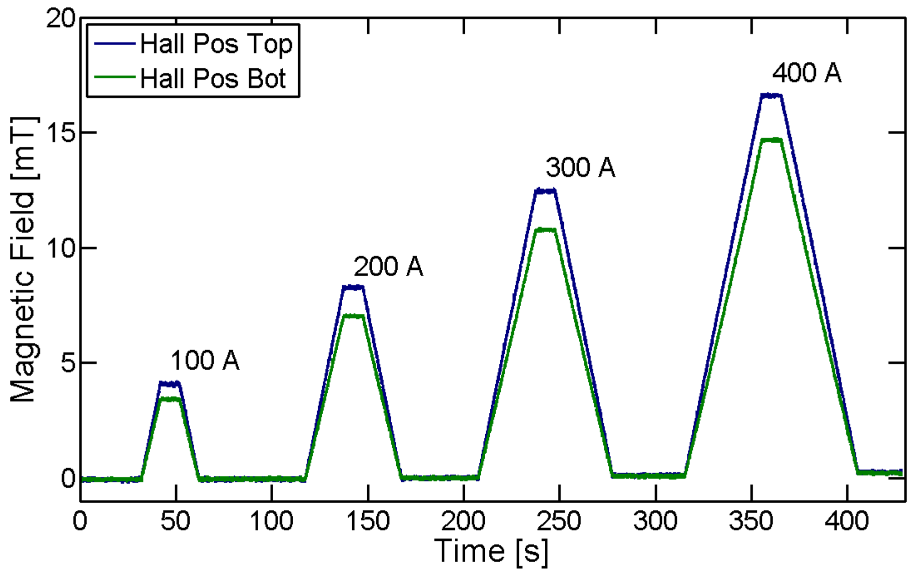
Compulsory formation of non-uniform current distribution in stacked HTS tapes

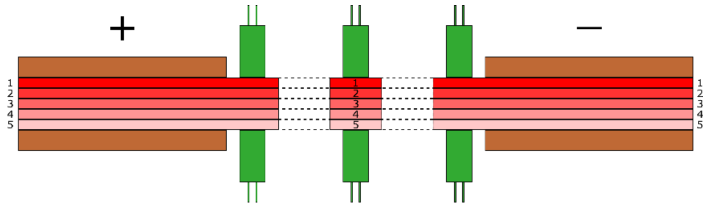
REBCO tapes: SuperOx ST-4-100 (Ic ~ 130 A @77K)

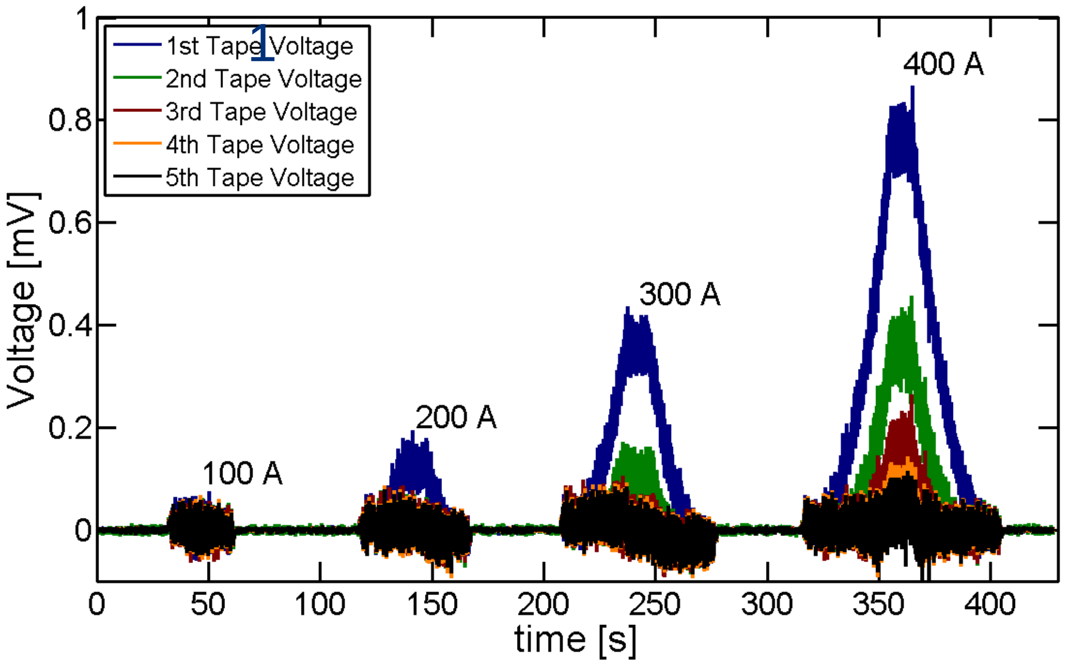


T. Meulenbroeks, S. Matsunaga, et al., Journal of Physics Conference Series (2019)

Examination of non-uniform current distribution in STARS configuration



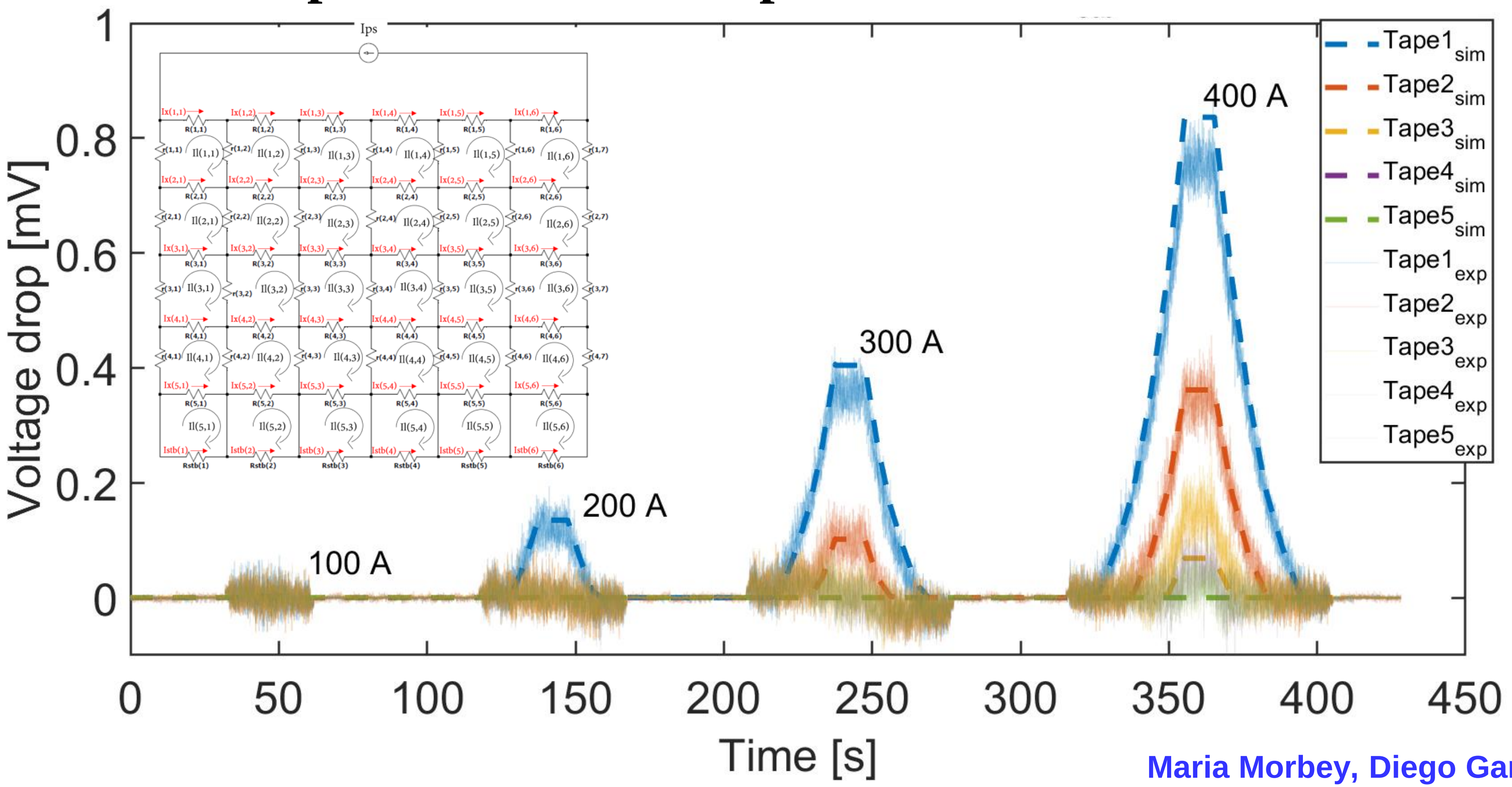




Formation of non-uniform current distribution confirmed by Hall sensors and voltage singals

Nontheless, stable operation up to critical current of the whole conductor!

Comparison between experiment and simulation



Maria Morbey, Diego Garfias

- **Fairly good agreement between experiment and simulation**
- **Joint resistance may be ×100 higher than the originally estimated value due to low contact pressure**
- **The numerical simulation will be expanded to long-length coiled structure by including the inductance of tapes, temperature change, magnetic field change**

Summary

- **The helical fusion reactor FFHR-b3 is newly proposed as the latest version of the FFHR series, aiming at 100 MW electricity production with double size the LHD and configuration optimization**
- **Three types of HTS conductors are being developed for the next-generation helical device (before FFHR-b3) 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 confirms > 20 kA critical current
  Test in 13 T, 20 K will be carried out in the next step; sample being prepared

  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, 20-50 K shows Ic = 7.9 kA@8T - 11.1 kA@5 T for 40 K

- **Quench protection is a crucial issue for all conductors; effective methods examined**