Superconducting Magnet Design and R&D with HTS Option for the Helical DEMO Reactor

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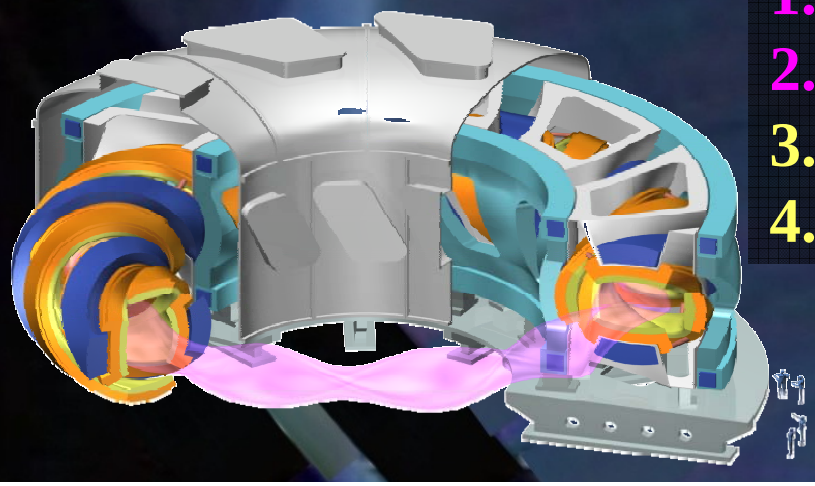

Alternative Ideas:

1. Helical
2. HTS (High-Temperature Superconductor)
3. Simple stacking of HTS tapes
4. Segment-fabricated windings

US-Japan Workshop on Fusion Power Plants and Related Advanced Technologies

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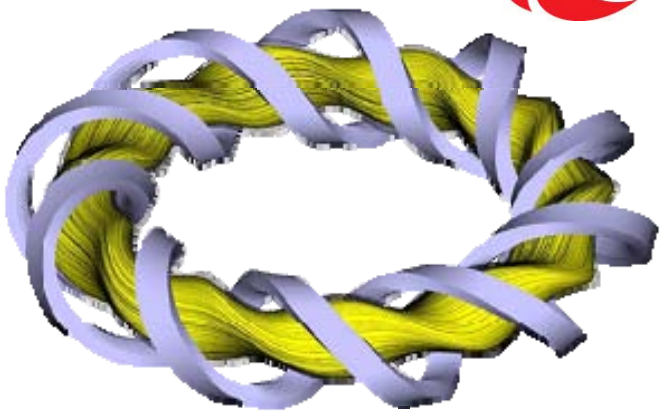
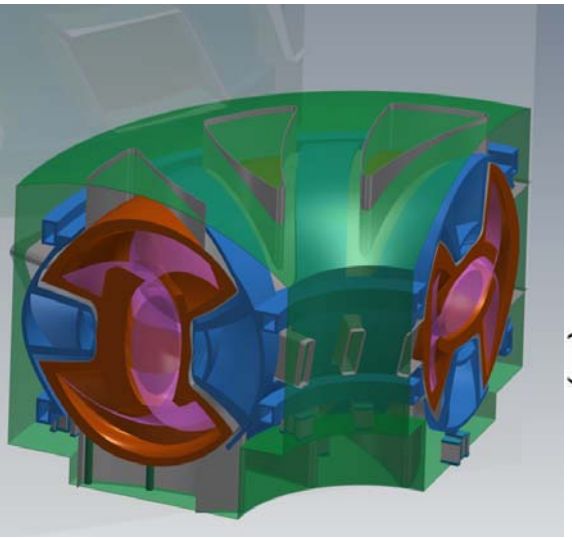
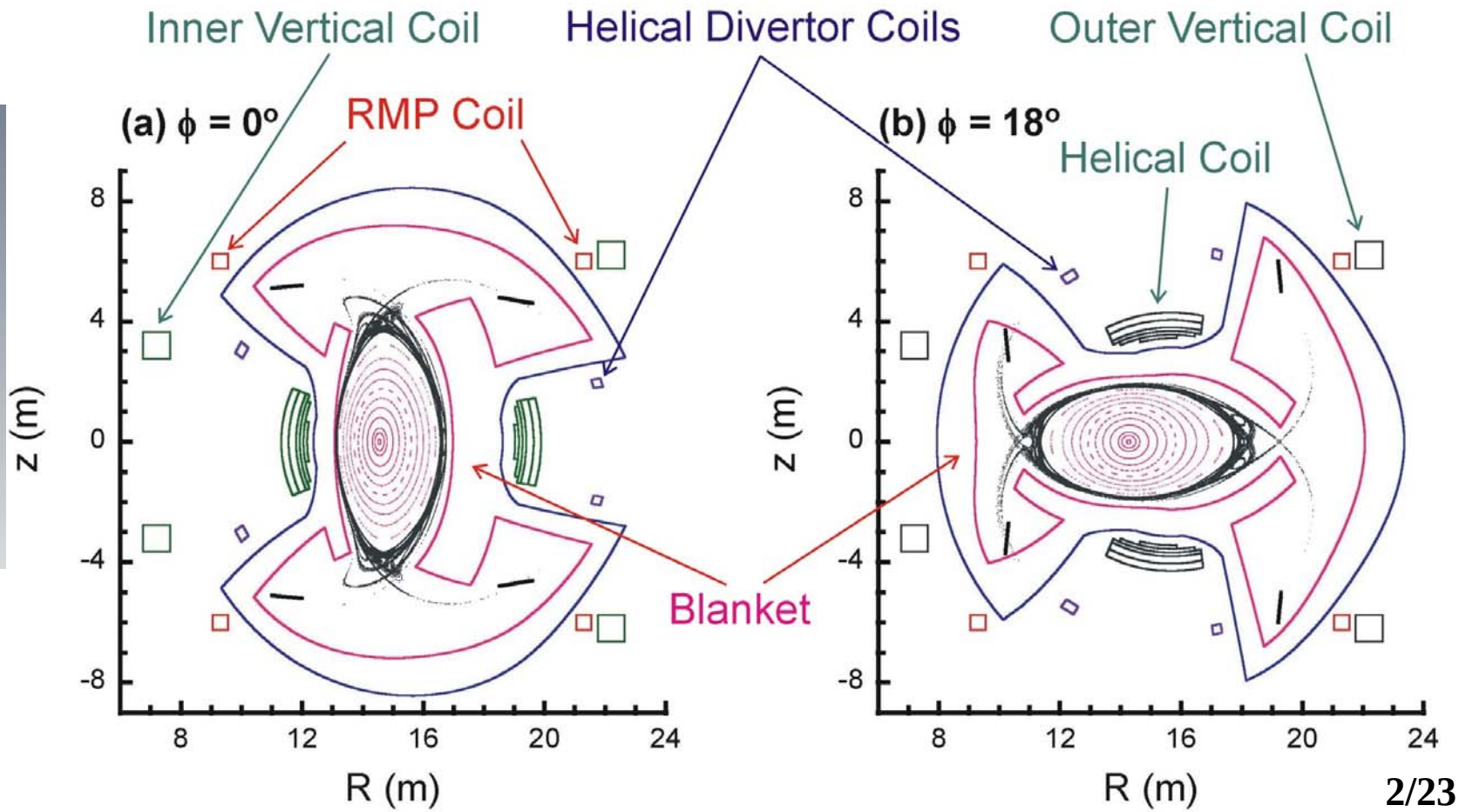
Heliotron Magnetic Configuration

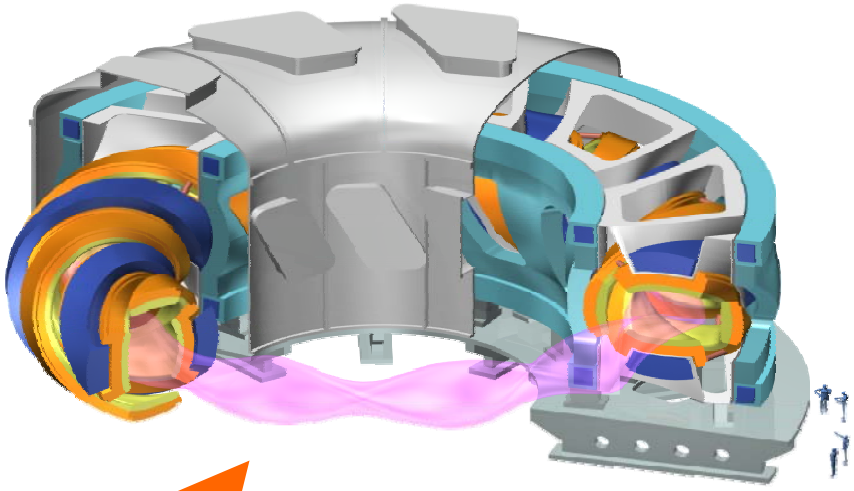
- **Steady-state ➔ no need for current drive and no disruption**
- **Large machine size ➔ low neutron wall load (~1.5 MW/m^2)**
- **Built-in helical divertors**
  - **Heat flux <10 MW/m^2 (on toroidal average)**
  - **Protected from direct neutron irradiation**



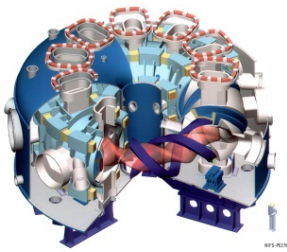




The LHD-Type Helical DEMO Reactor FFHR-d1



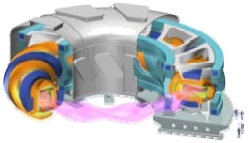
FFHR (R = 15.6 m)



LHD (R = 3.9 m)

Major / minor radius of helical coils	15.6 / 3.9 m
Helical pitch parameter, γ	1.25
Toroidal magnetic field	5.1 T
Stored magnetic energy	160 GJ
Major / minor radius of plasma	14.4 / 2.54 m
Plasma volume	1880 m^3
Fusion power	3 GW
Neutron wall load	1.5 MW/m^2
Average beta	5 %

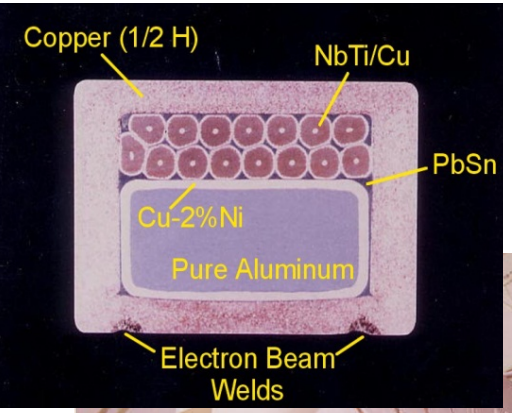
What kind of superconductor should we use?



LHD Superconducting Magnet System

Helical Coils

18 mm



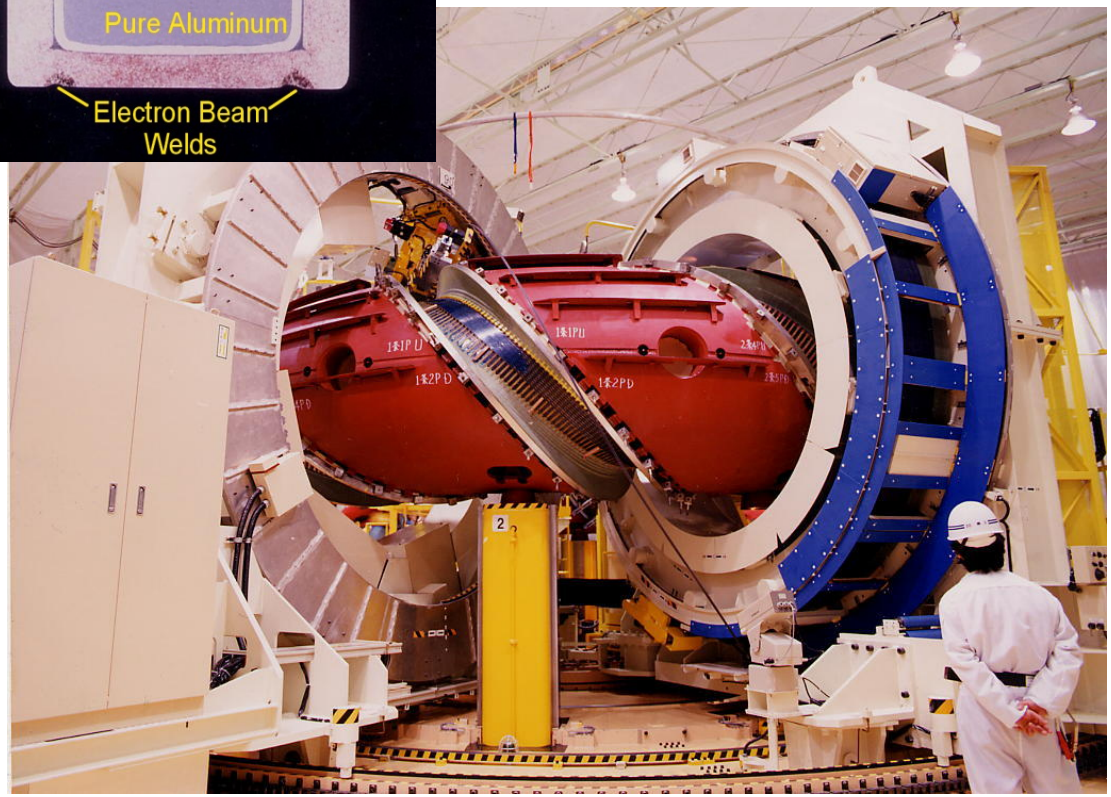
Conductor current : 13 kA

Magnetic field : 6.9 T

NbTi/Cu Rutherford, Al-stabilized

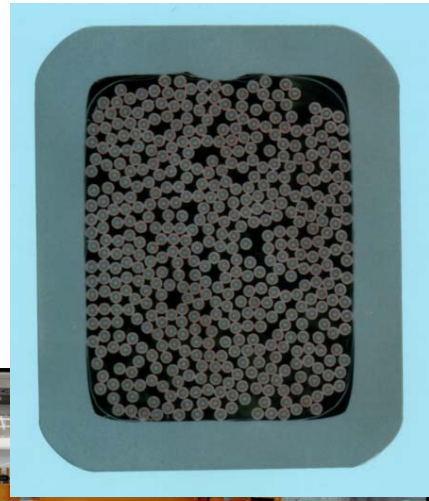
Pool-cooled by liquid helium

Temp. 4.4 K ➔ 3.8 K (subcooled)



Poloidal Coils

27.5 mm



Conductor current : 31.3 kA

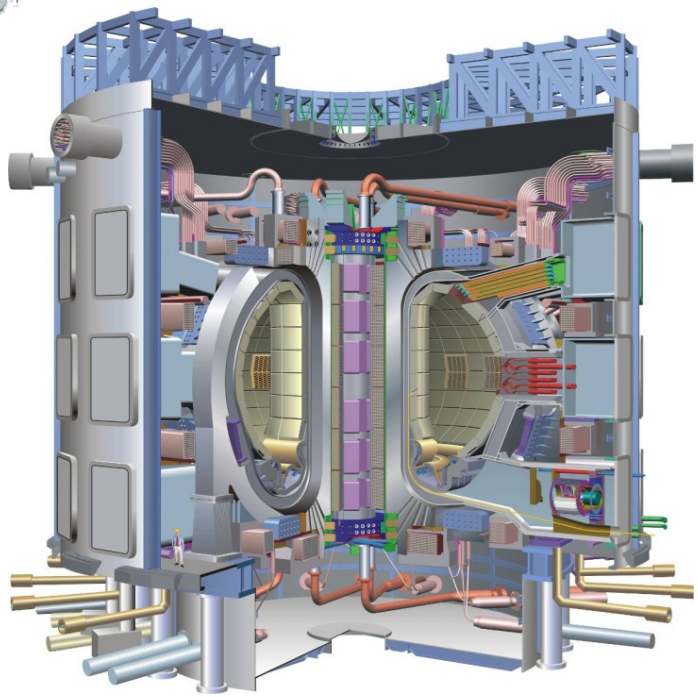
Magnetic field : 5 T

NbTi/Cu Cable-in-Conduit

Force-cooled by supercritical helium

Temp. 4.5 K

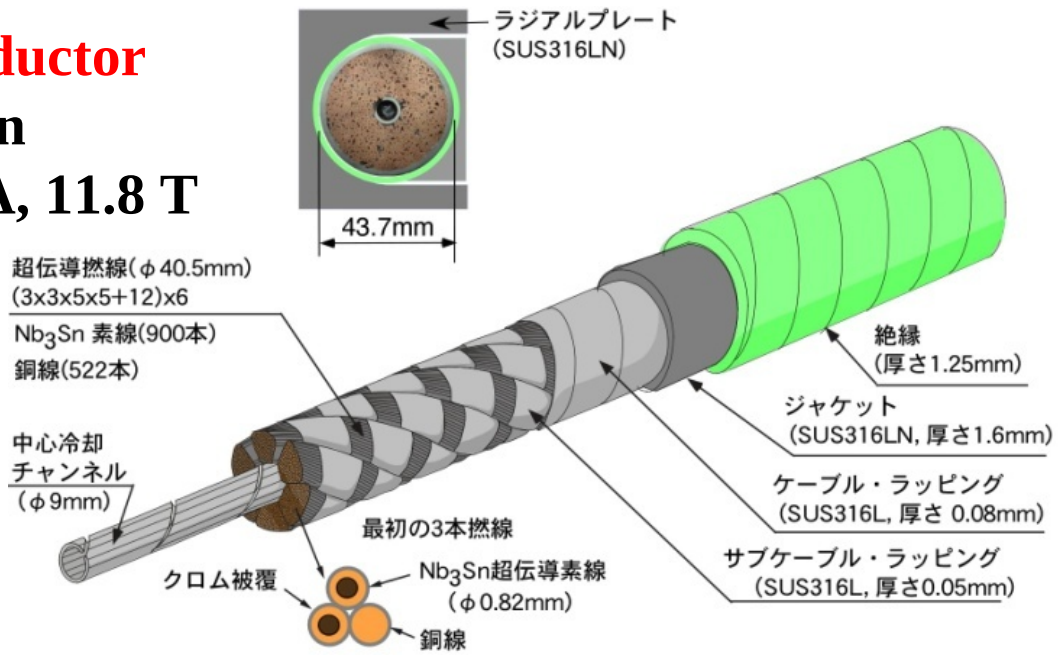
Cable-in-Conduit (CIC) Conductors for ITER



TF Conductor

Nb_3Sn

68 kA, 11.8 T

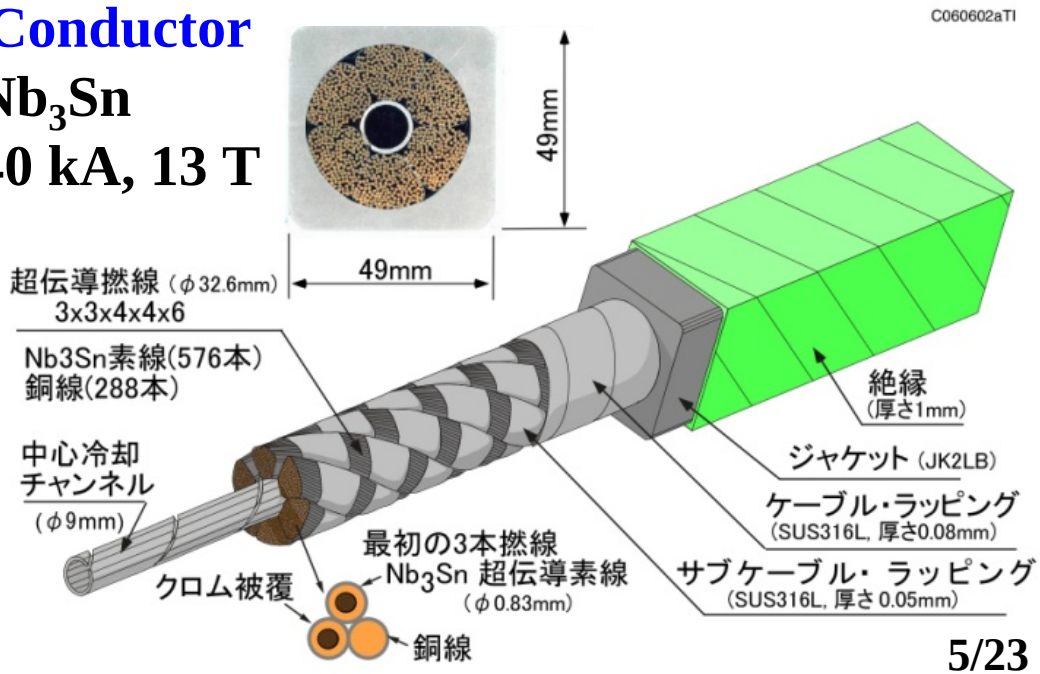


- **Well established and current standard for fusion magnet**
- **High cryogenic stability by internal cooling with supercritical helium**
- **High mechanical and electrical rigidity**
- ***Complicated plumbing (worry of leakage) and limited conductor length***
- ***Degradation by repetitive excitation***

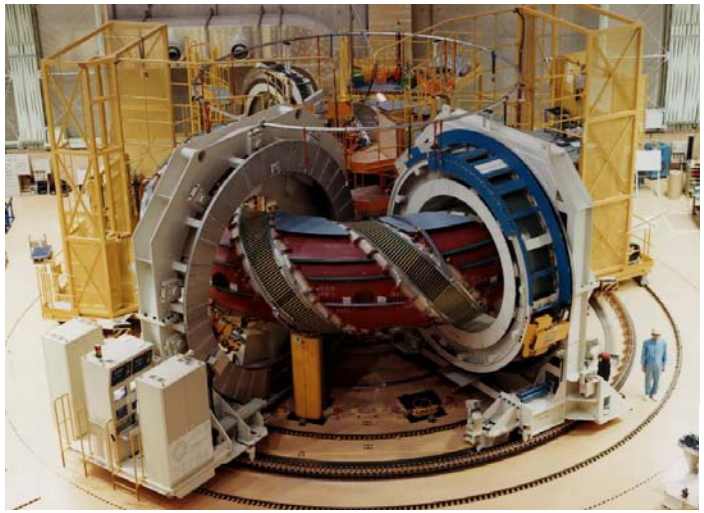
CS Conductor

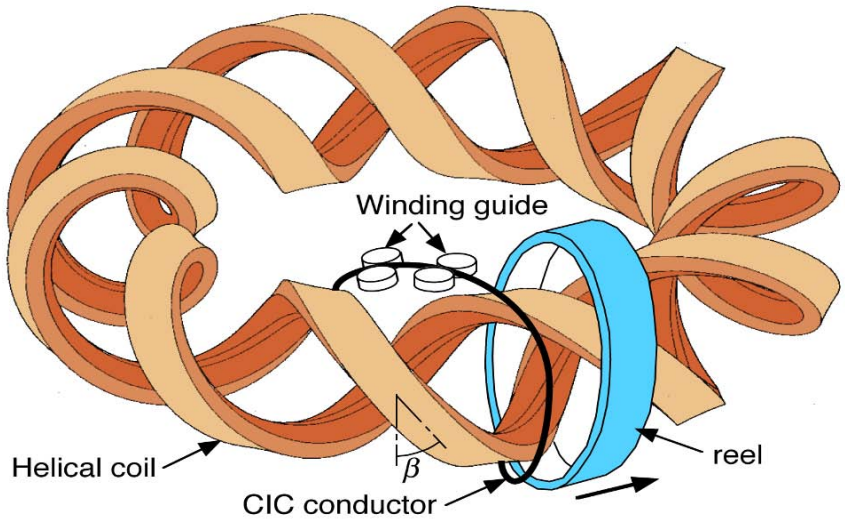
Nb_3Sn

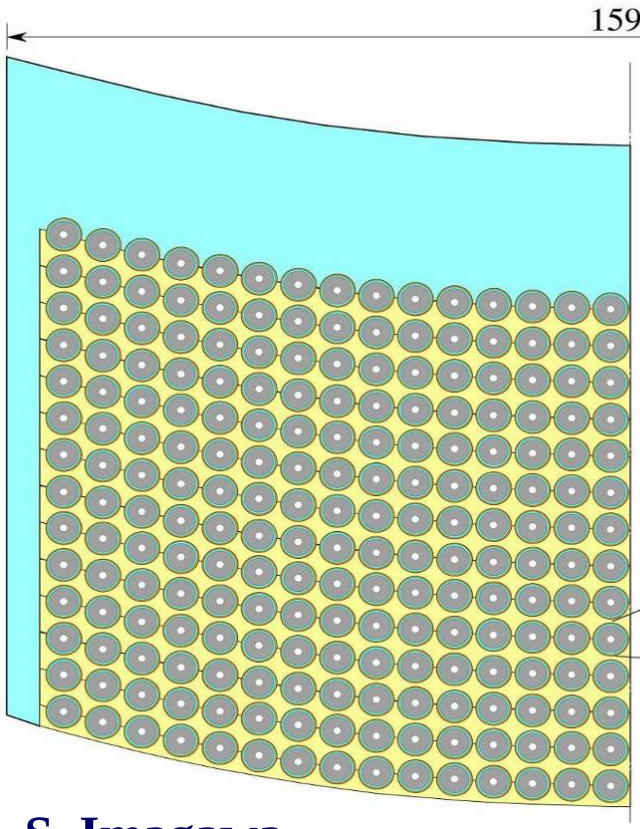
40 kA, 13 T

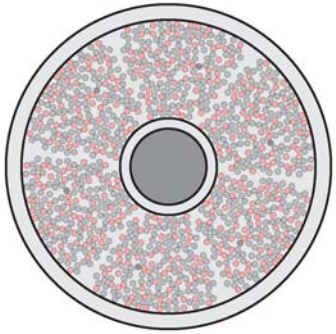


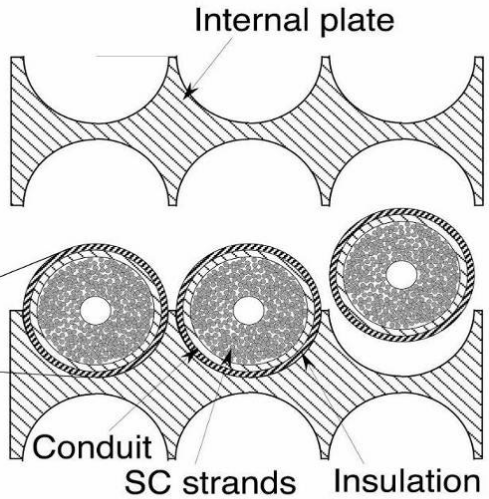
Helical Coil Winding with Nb_3Al CIC Conductor











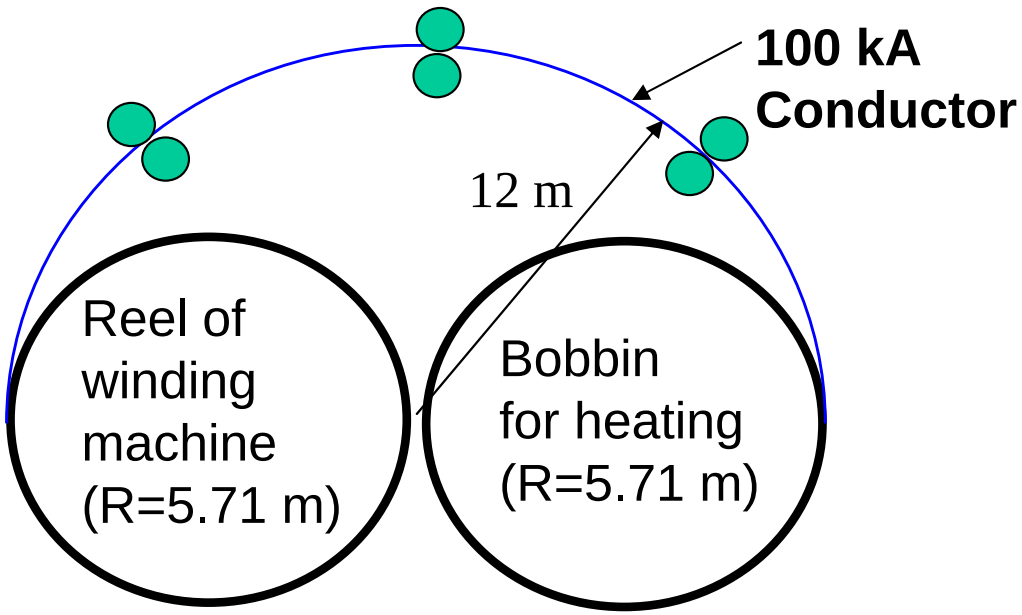
(1) CIC conductors are heat treated in a "reel" and transferred to a "spool" with a same diameter
(2) Conductor is extracted and formed into a helical shape and imbedded into grooves of the internal plate
(3) Conductors are wound in 5 parallel paths (the cooling path <500 m)
(4) Complicated layout for plumbing of supercritical helium and joints
(5) Huge winding machine is required

S. Imagawa

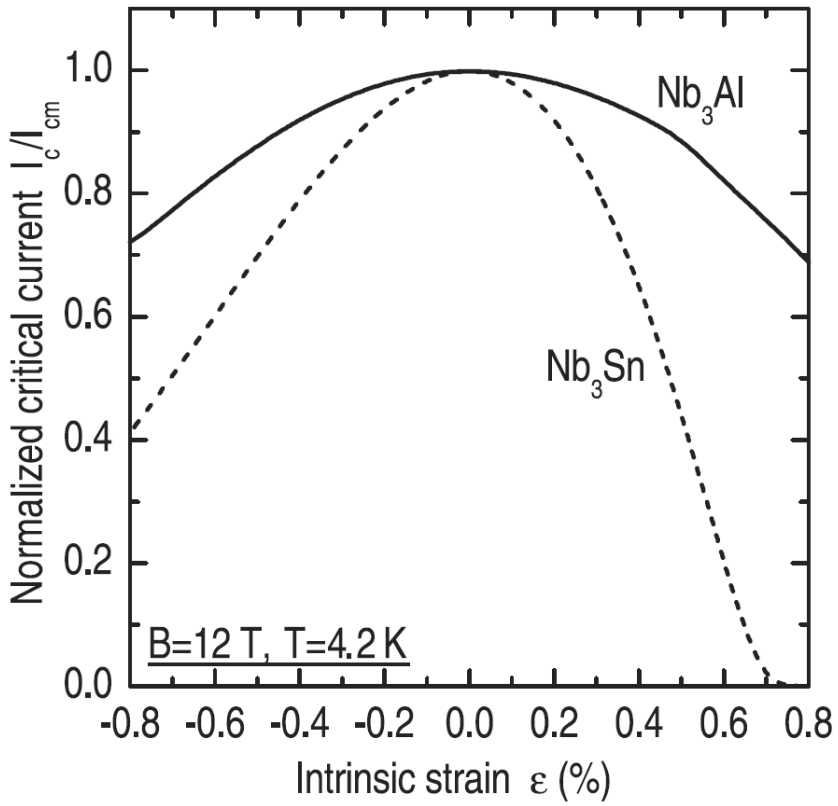
Strain due to helical winding with LTS

Strain due to the difference of thermal contraction between strands and jacket : ~0.7%

Torsional strain during the helical winding : ave. ~0.3%, max. ~0.6%

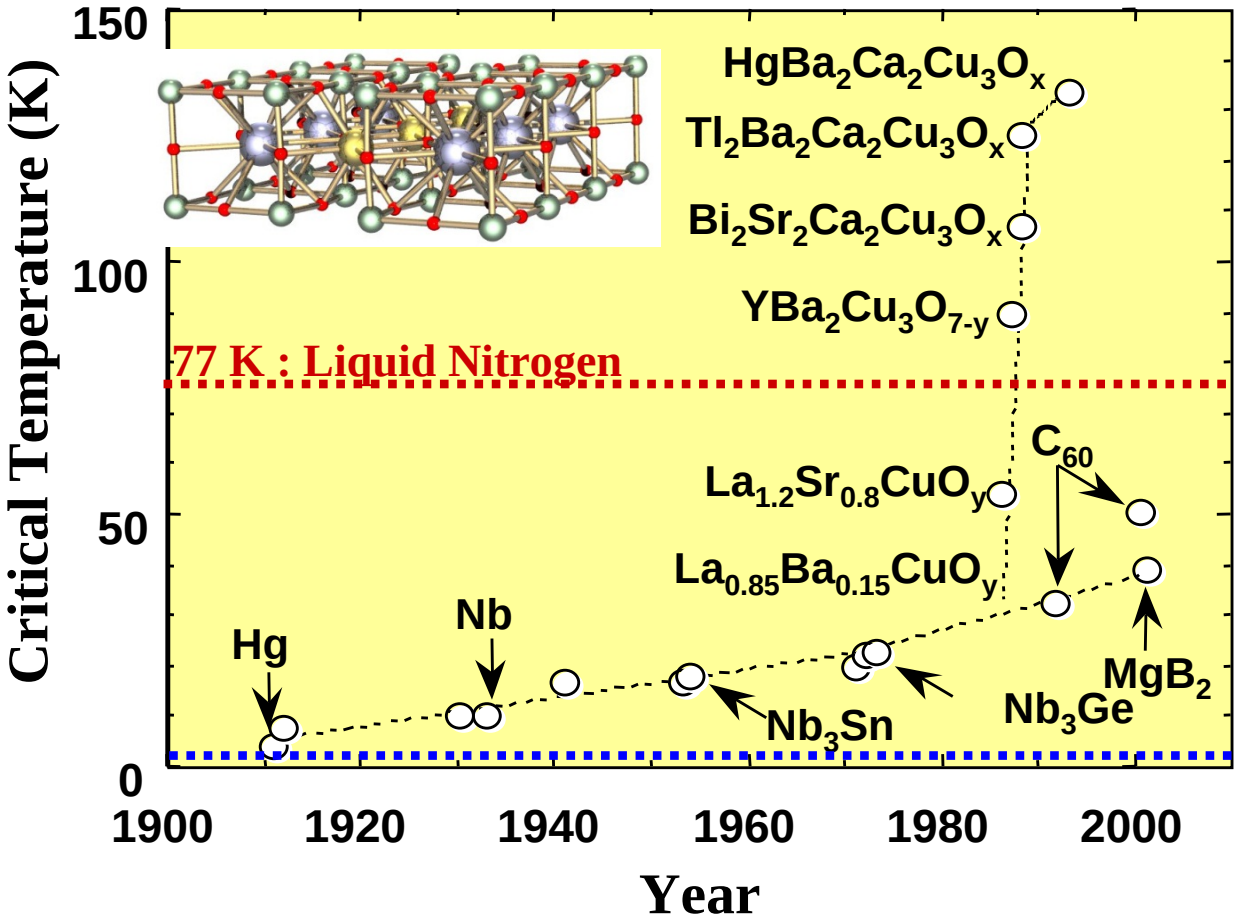


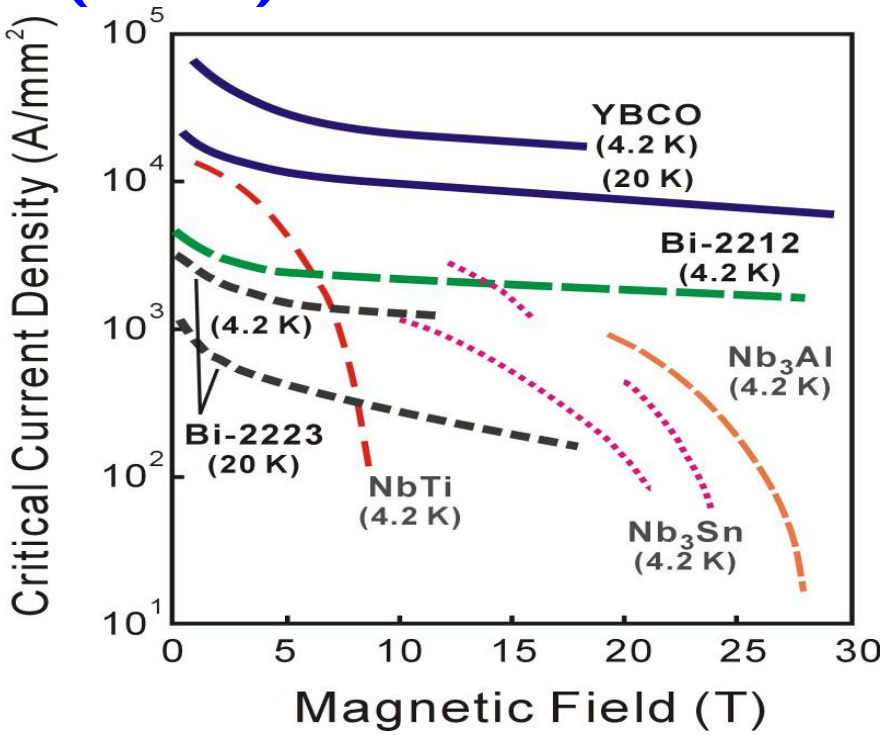
S. Imagawa et al., Nucl. Fusion 49 (2009) 075017



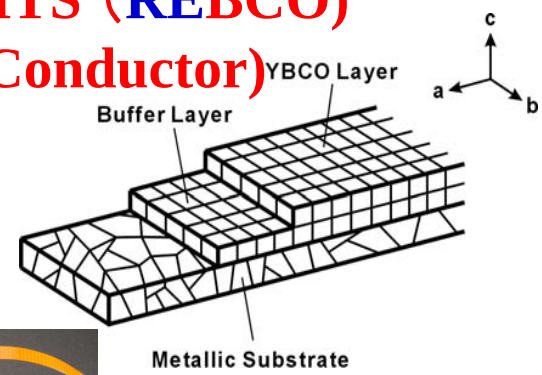
N. Koizumi, T. Takeuchi and K. Okuno, Nuclear Fusion 45 (2005) 431.

Copper Oxide High-Temperature Superconductors (HTS)

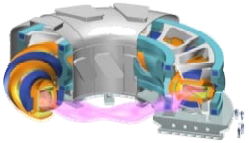




Rare Earth-based 2nd generation HTS（REBCO) (Coated Conductor)



Bismuth-based 1st generation HTS（Bi-2212, Bi-2223)



Characteristics of HTS Conductors

(1) **High critical current density** up to high magnetic field

(2) **High cryogenic stability** by thermal capacity of metals at 20-30 K

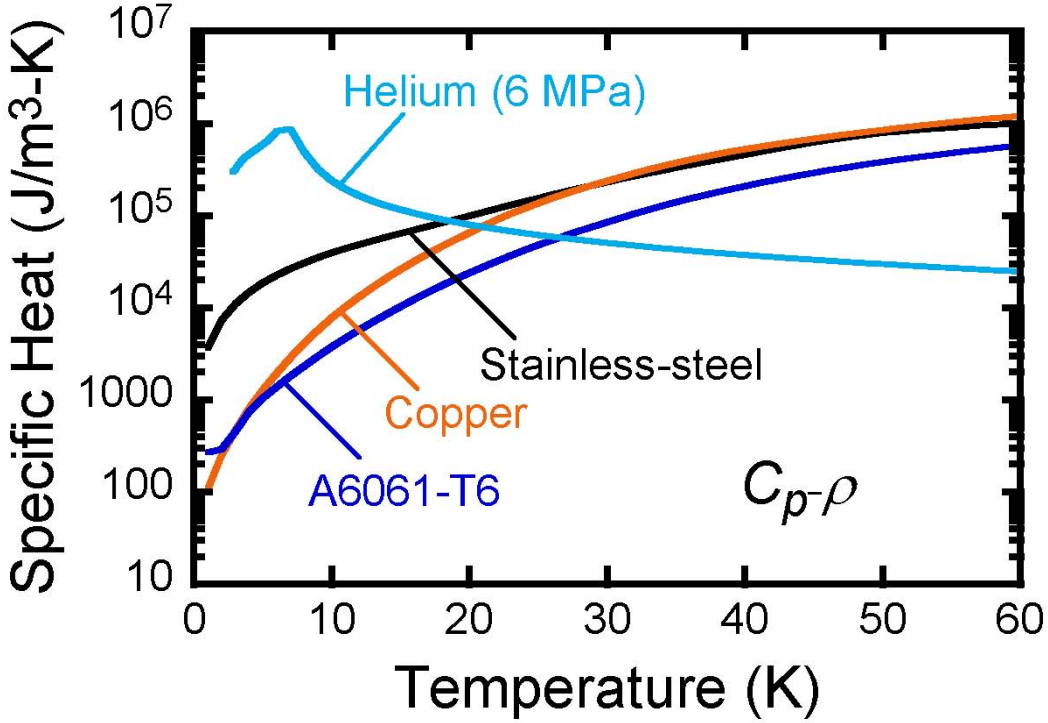
(3) Low cryogenic power

(4) **Mechanically strong** with REBCO tapes
Hastelloy substrate (>1 GPa rigidity) + stainless-steel (or Al-alloy) jacket w/o. void

(5) **Industrial production** of HTS tapes (Bi-2223 and REBCO) for electrical power applications (transformers, power cables, SMES, motors, etc.)

(6) Beneficial for the preservation of helium resources

(7) Robust against neutron irradiation



Stability Margin
(Allowable Disturbance)

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

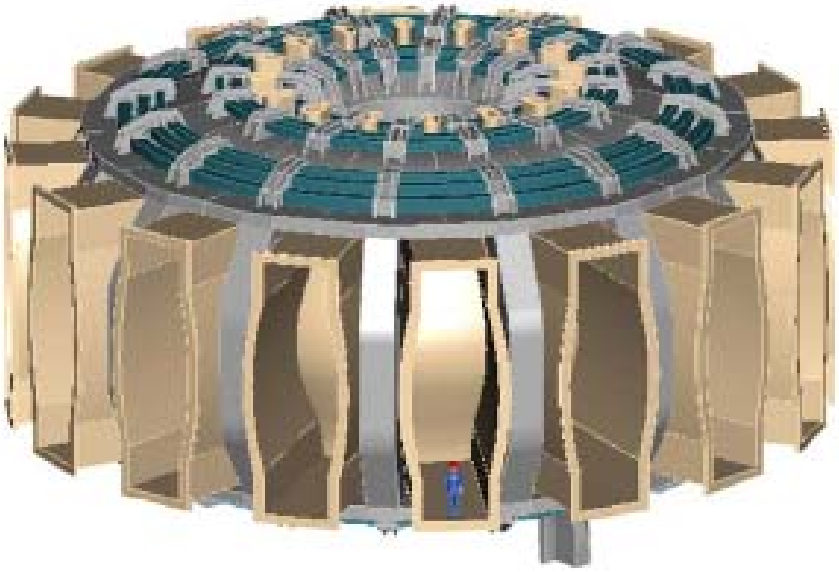
$$C_p \rho \Delta T \approx 2\times10^5 \text{ (J/m}^3\text{K)}\times 10 \text{ (K)}$$

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

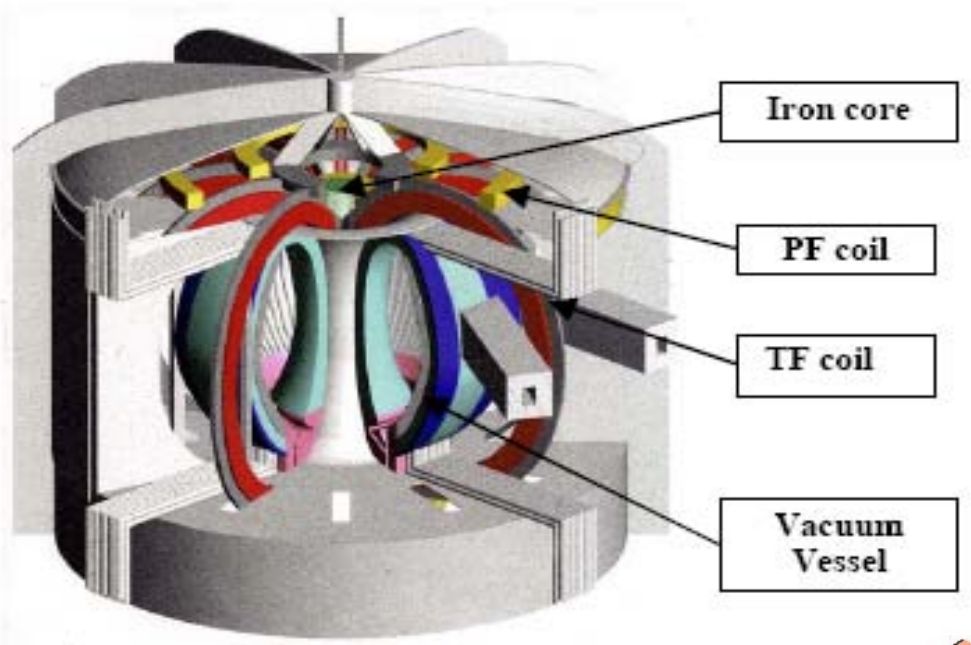
Larger stability margin than CICC

➔ **Lower probability of coil quench!**

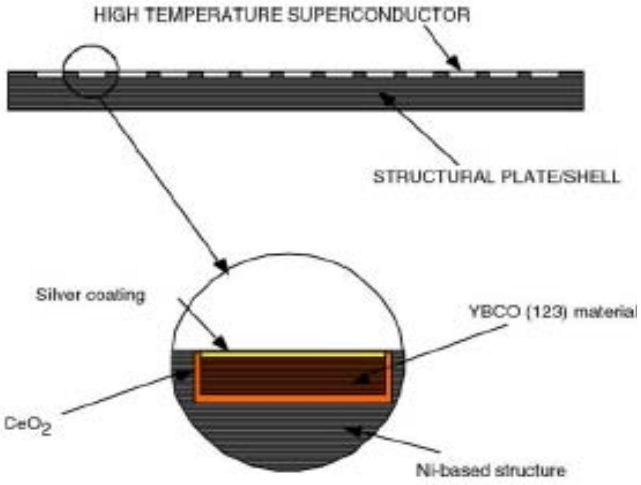
Tokamak Reactor Design by HTS (~2000)



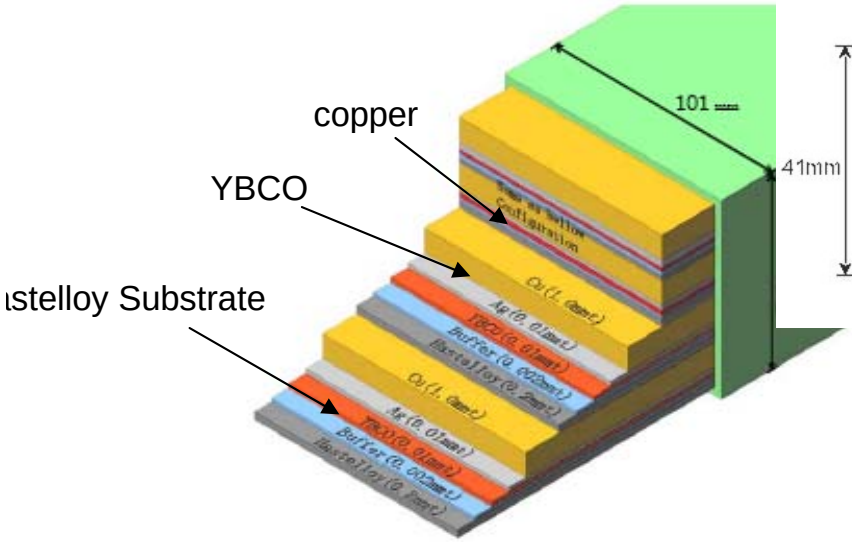
ARIES-AT (USA)



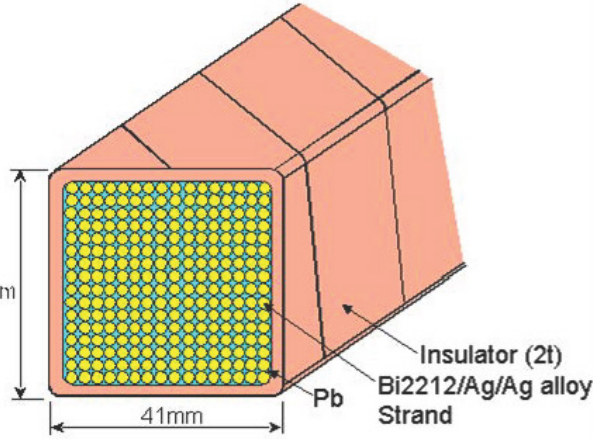
VECTOR (JAEA)



YBCO



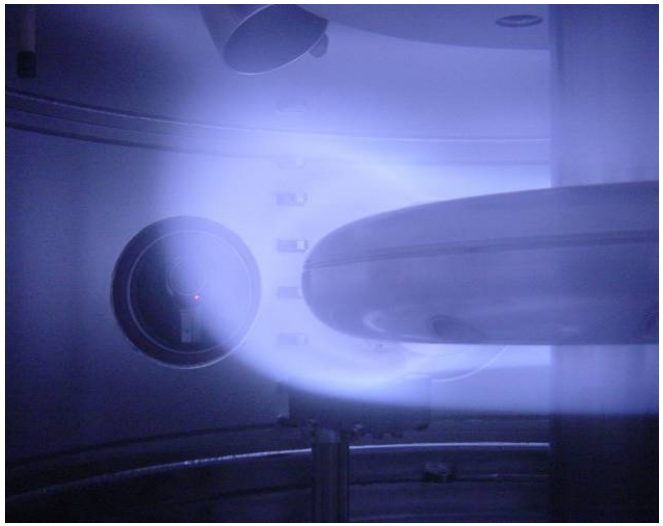
YBCO



Bi-2212

Application of HTS for Fusion

RT Project at Univ. of Tokyo



Mini-RT (2003)

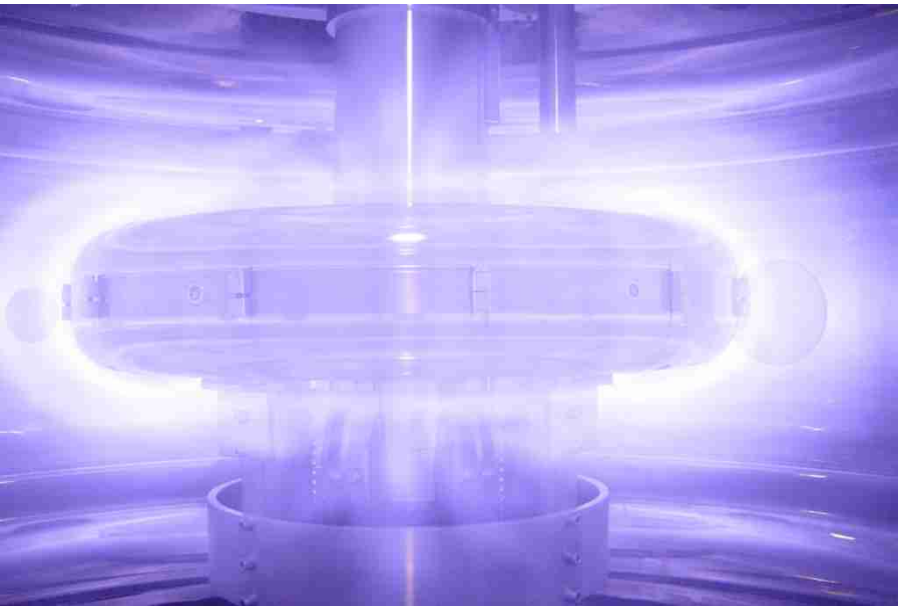
HTS floating coil with Bi-2223

τ ~ 40 hrs

Mini-RT/Y (2012)

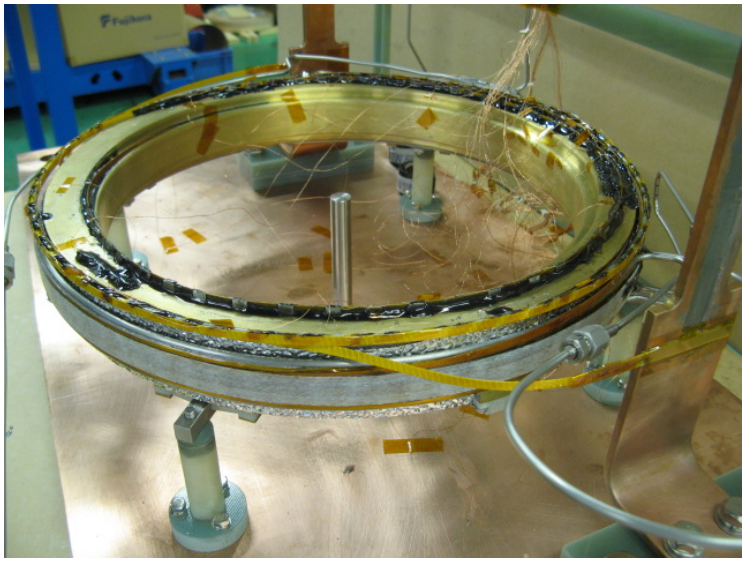
HTS floating coil with GdBCO

τ ~ 230 hrs



RT-1 (2006)

HTS floating coil with Bi-2223



Discussion for Large-Current HTS Conductor (1)

Basics for LTS conductors

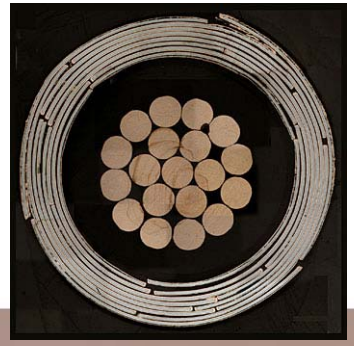
- Multi-filamentary strands ⟷
- Transposition of strands ⟷
- Twisting of strands ⟷

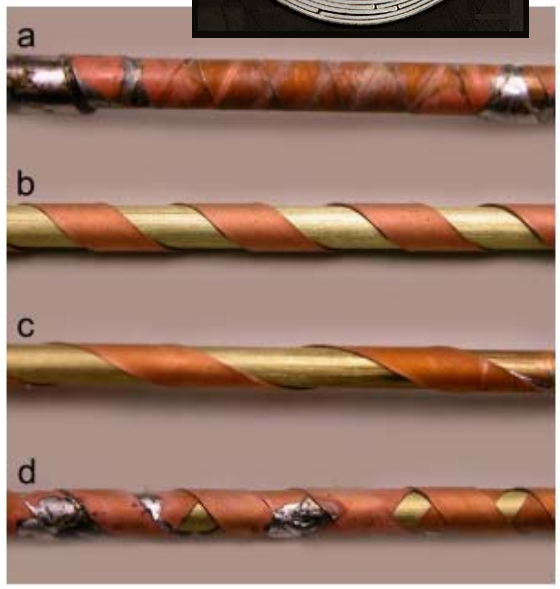
Conductor design with HTS tapes (Present trend in EU and US)

- Subdivision of HTS tape
- Transposition by "Roebel"
- Twisting by "Twist-stack" or "Conductor On Round Core (CORC)"

Roebel

Twist-stack





CORC

Discussion for Large-Current HTS Conductor (2)

- Subdivision
- Roebel
- Twist-stack and CORC

→

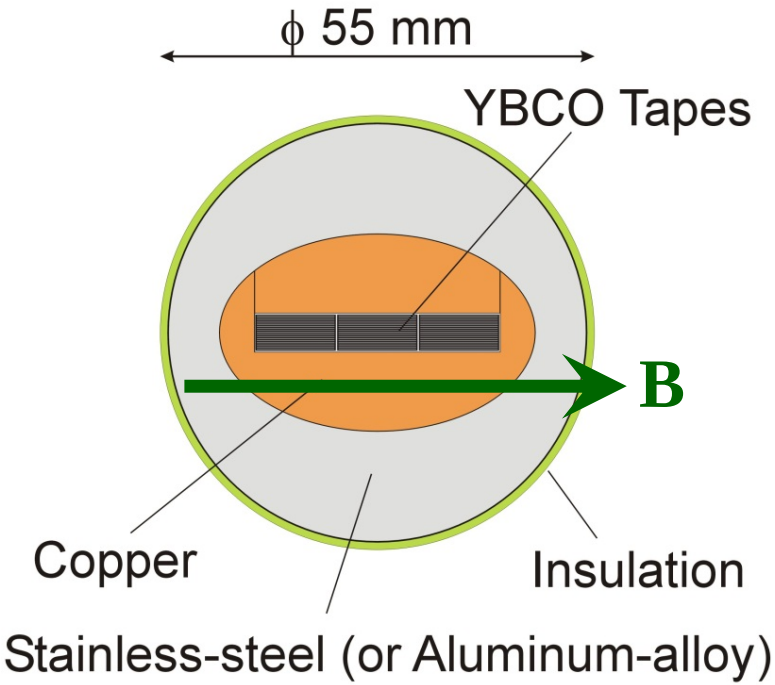
- Complicated production method
- Critical current degradation by anisotropy (B parallel to c-axis)
- Mechanically weak
- High cost

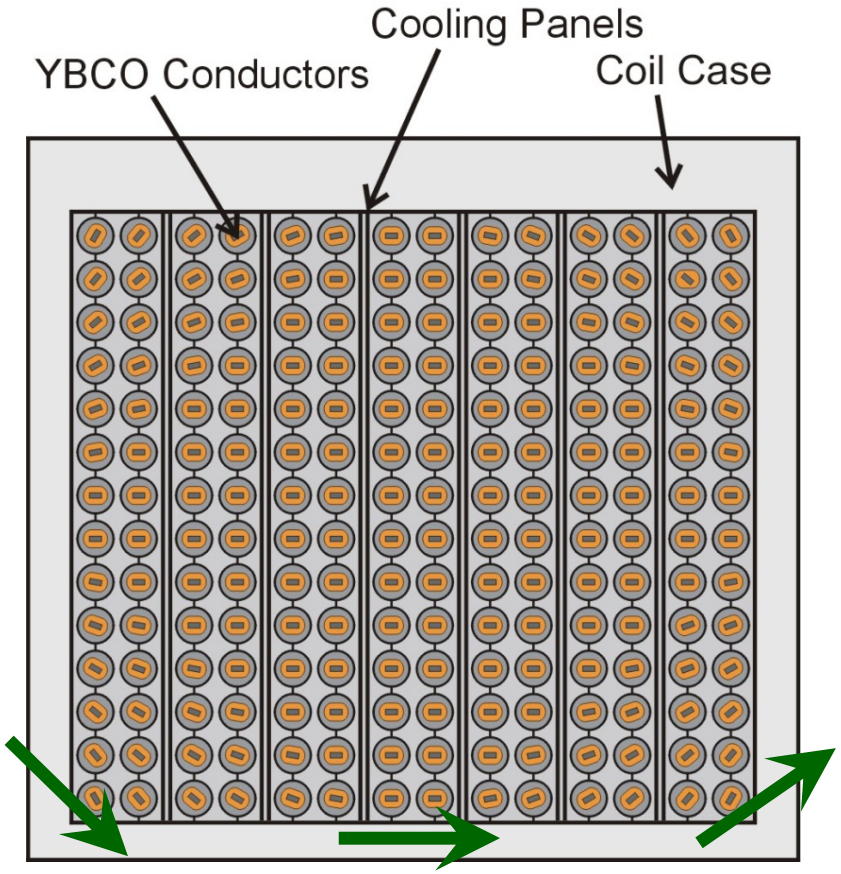
Is simple-stacking of HTS tapes available?

- Non-uniform current distribution among tapes can be allowed due to high cryogenic stability (especially for DC magnets)
- AC losses are accepted (especially for DC magnets)
- Adjustment of tape orientation (*B* parallel to ab-axis) gives high critical current and low AC losses
- Mechanically strong
- Low cost
- Low joint resistance
- Roebel structure could be included at joints on demand by "Roebel-MITO"

10 kA class HTS conductor w. Bi-2223 tapes & Cu jacket NIFS (2005)

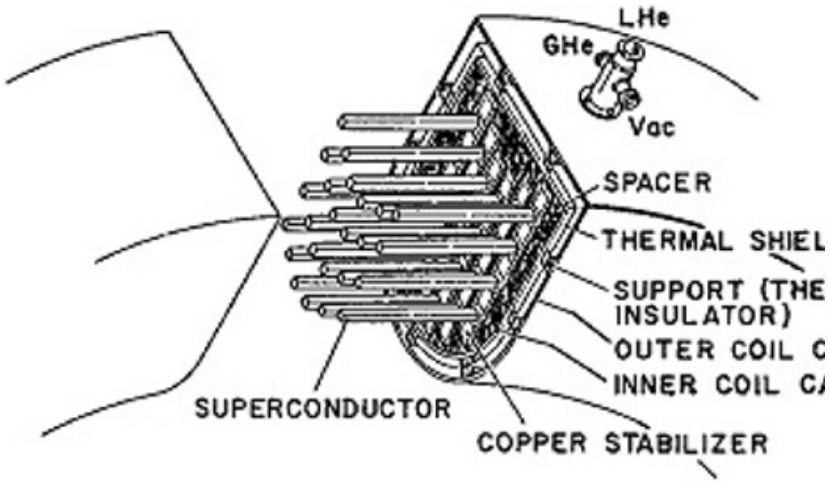
100 kA-Class HTS Conductor Design for FFHR

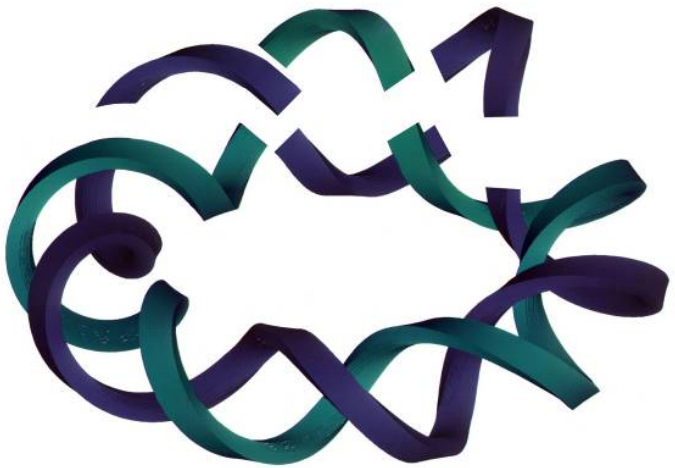


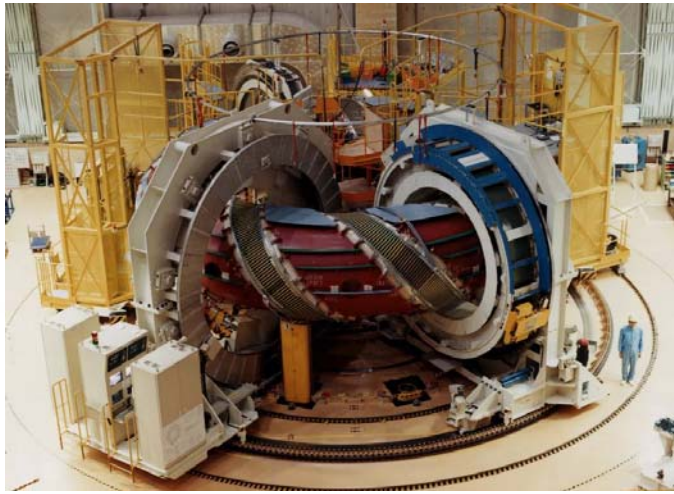


Superconductor	**YBCO**
Conductor size	**ϕ55 mm**
Operation current	**100 kA**
Maximum field	**~13 T**
Operation temperature	**> 20 K**
Current density	**~40 A/mm^2**
Number of HTS tapes	**39**
Cabling method	**Simple-stacking**
Outer jacket	**Stainless-steel or Al-alloy**
Cooling method	**Indirect-cooling**

Segmented Fabrication of Helical Coils with HTS







- **Concept of Demountable Helical Coils**

K. Uo, 14th SOFT (1986)

Huge helical coils can be fabricated

Too large joule heating at 4 K with LTS…

- **Renewal of the Concept with HTS**

H. Hashizume, J. Plasma Fusion Res. (2001)

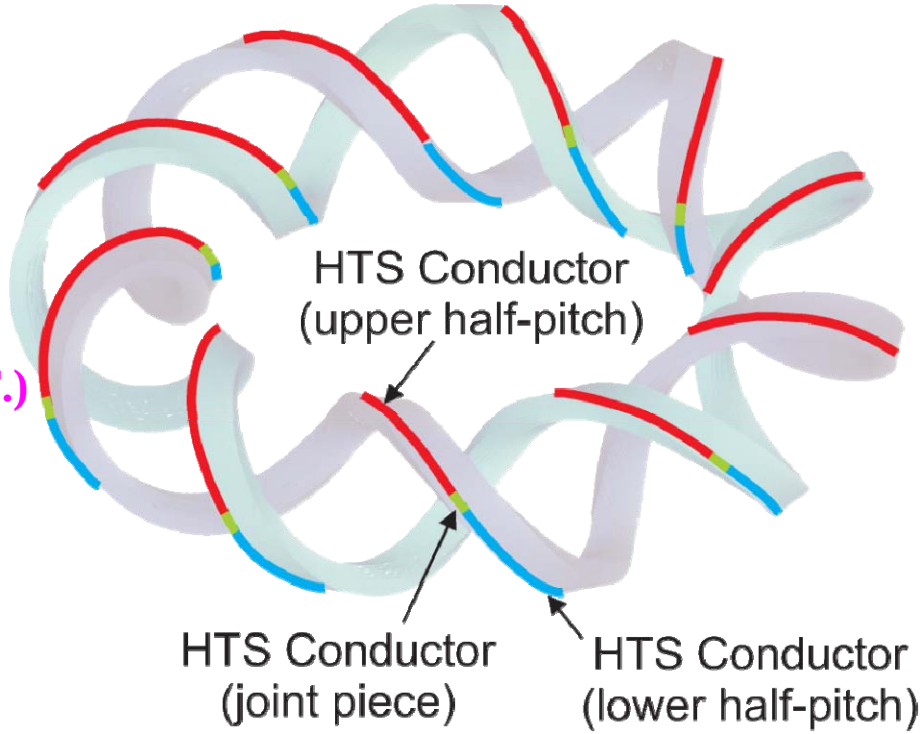
Joule heating accepted for HTS @ >20 K (~3 MW @ R.T.)

Difficulty of connection of whole coil segments…

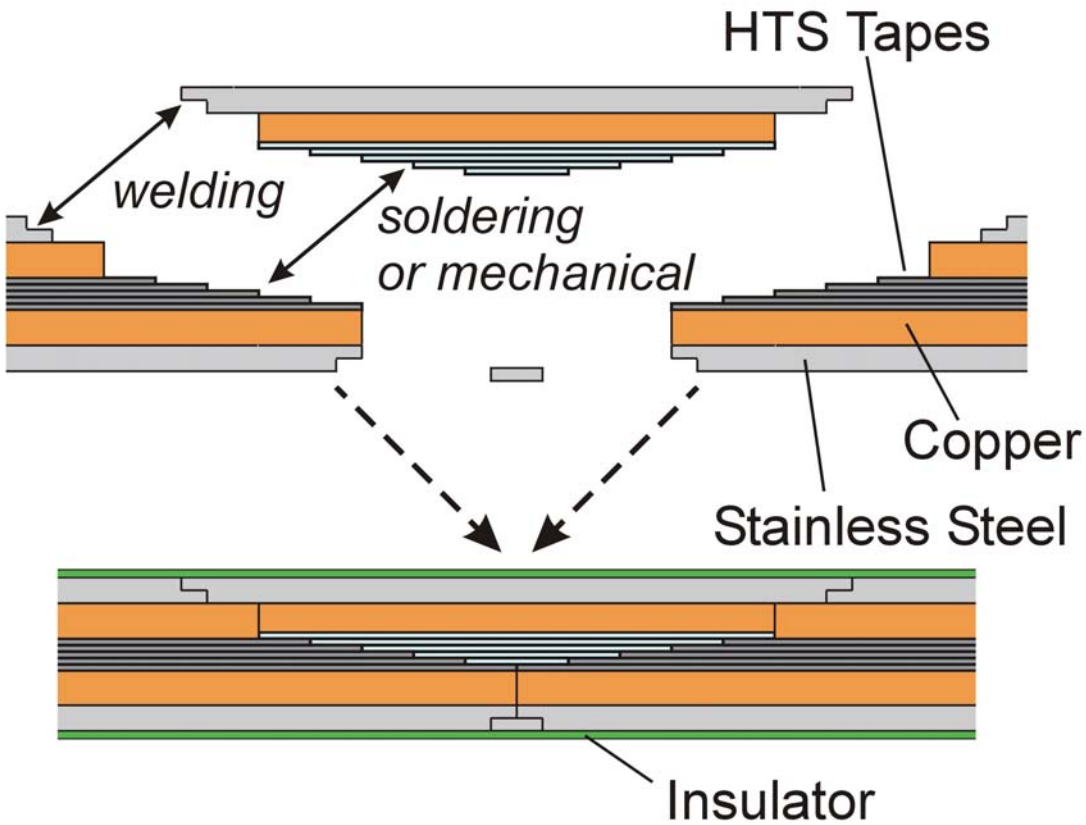
- **Segmented Winding of HTS Conductors**

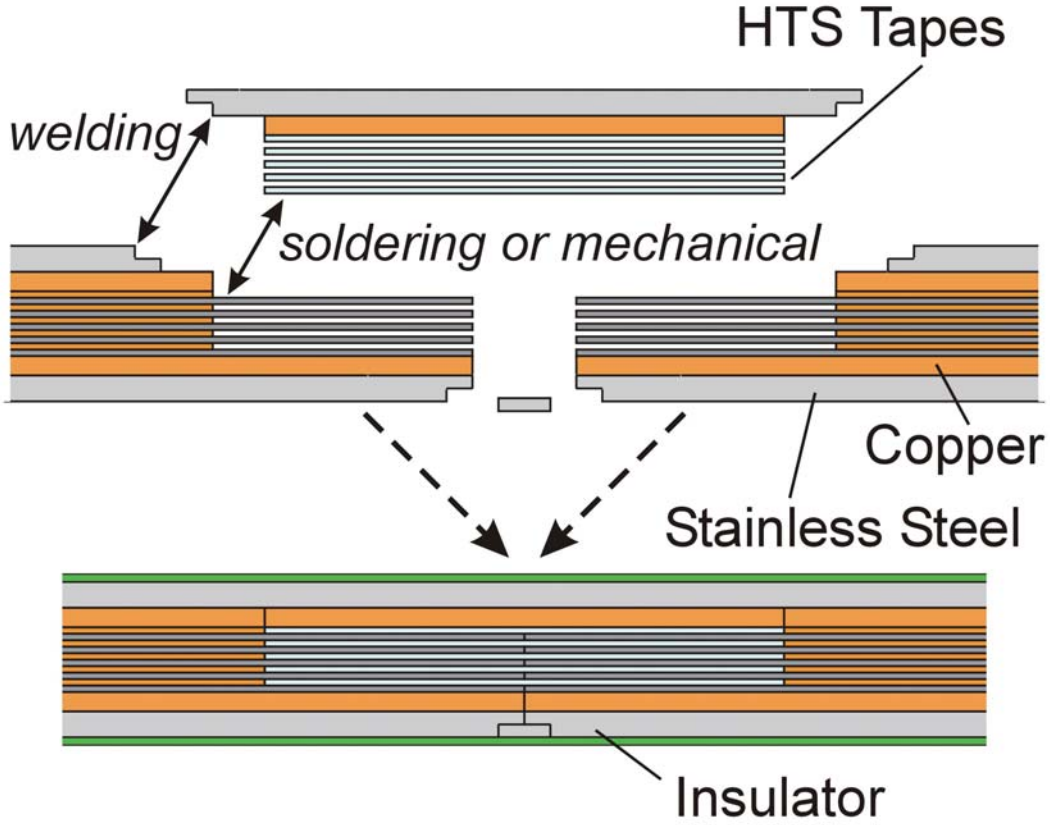
N. Yanagi, Fusion Technology (2011)

Engineering feasibility of connection of segmented HTS conductors with low joint resistance



Segmented Fabrication of Helical Coils with HTS





Bridge-type joint

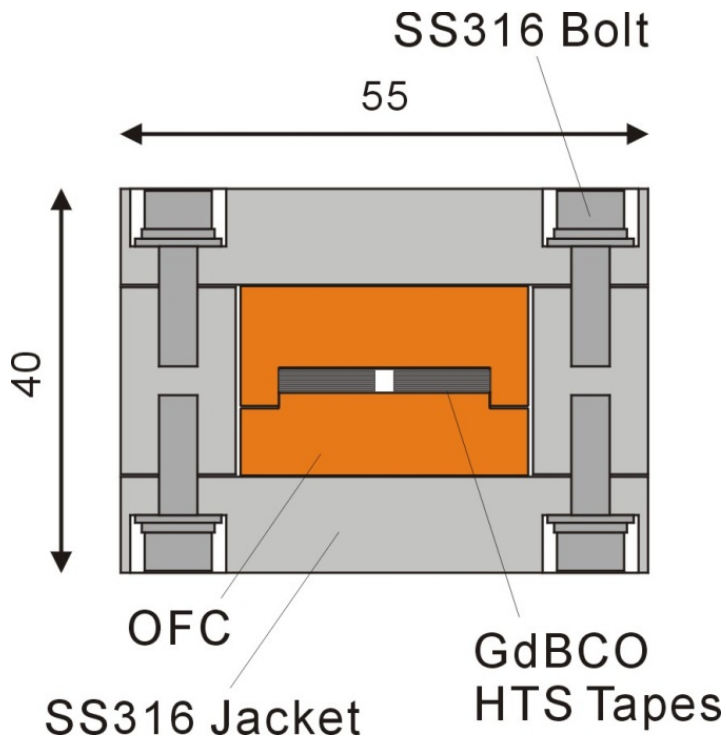
- **Joint resistivity : $1 \times 10^{-11}\ \Omega m^2$**
- **Resistance for one joint : 1 nΩ**
- **Number of joints : 8000**
- **Joule heating with 100 kA : 80 kW**
- **Electrical power : 5 MW**

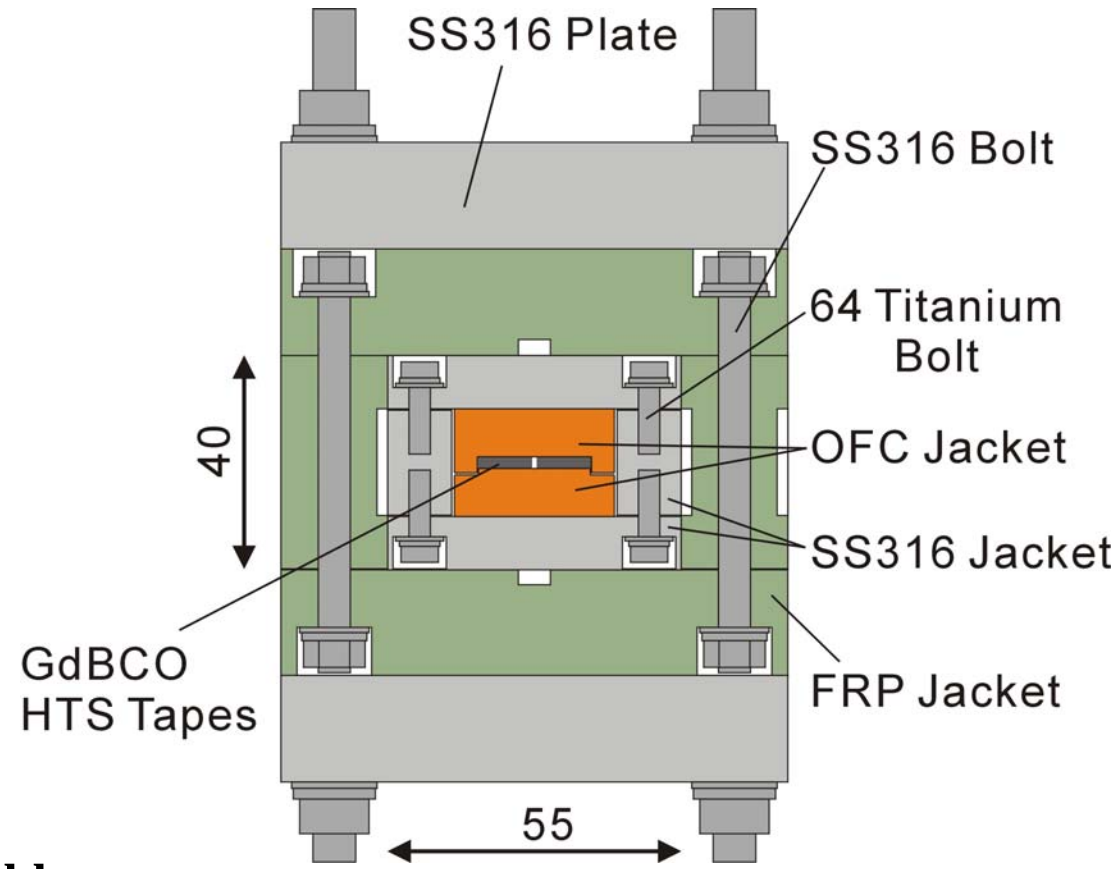
Finger-type joint

- **Joint resistivity : $1 \times 10^{-11}\ \Omega m^2$**
- **Resistance for one joint : 0.1 nΩ**
- **Number of joints : 8000**
- **Joule heating with 100 kA : 8 kW**
- **Electrical power : ~0.5 MW**

30 kA-Class HTS Conductor Test

Collaboration between NIFS and Tohoku Univ.



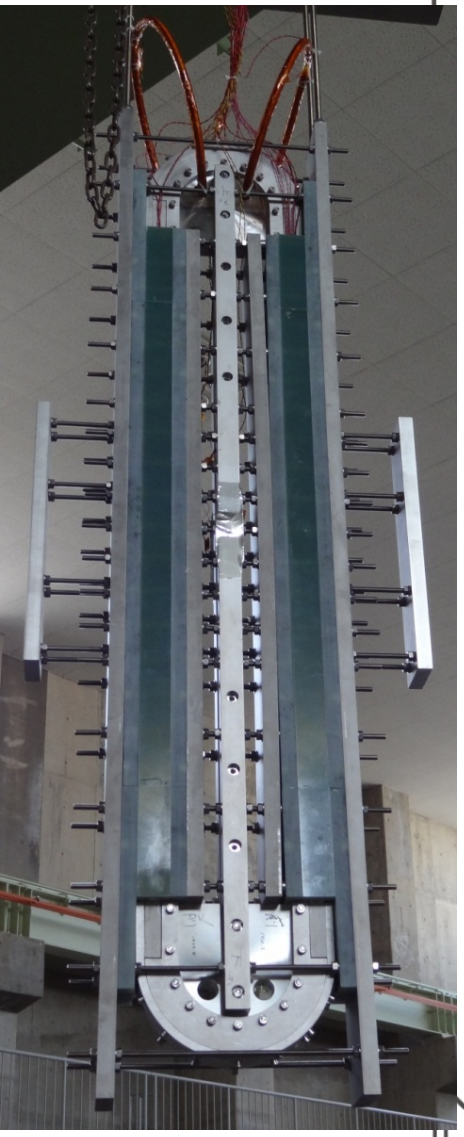


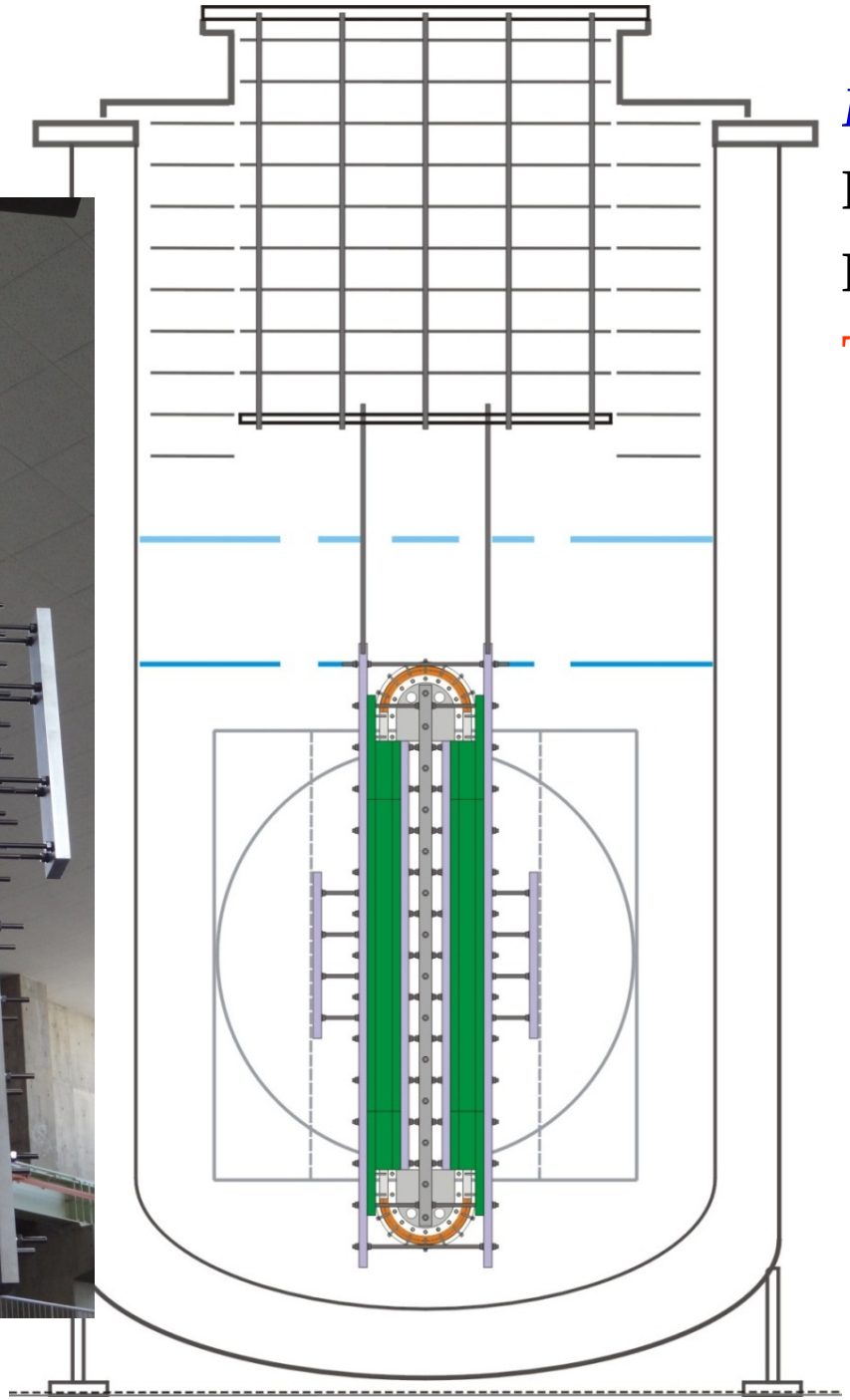
- **GdBCO tapes**

  Fujikura, FYSC-SC10
  Width: 10 mm, Thickness: 0.22 mm
  Critical current : ~650 A @77 K, self-field

  IBAD + PLD
- **Simple stacking of 20 GdBCO tapes in a copper jacket**
- **Stainless-steel jacket for mechanical support**
- **FRP jacket for thermal insulation**

HTS Conductor Sample (Short-Circuit Type)





Excitation by the change of bias field

Large current (> 100 kA)

Low heat load without current leads

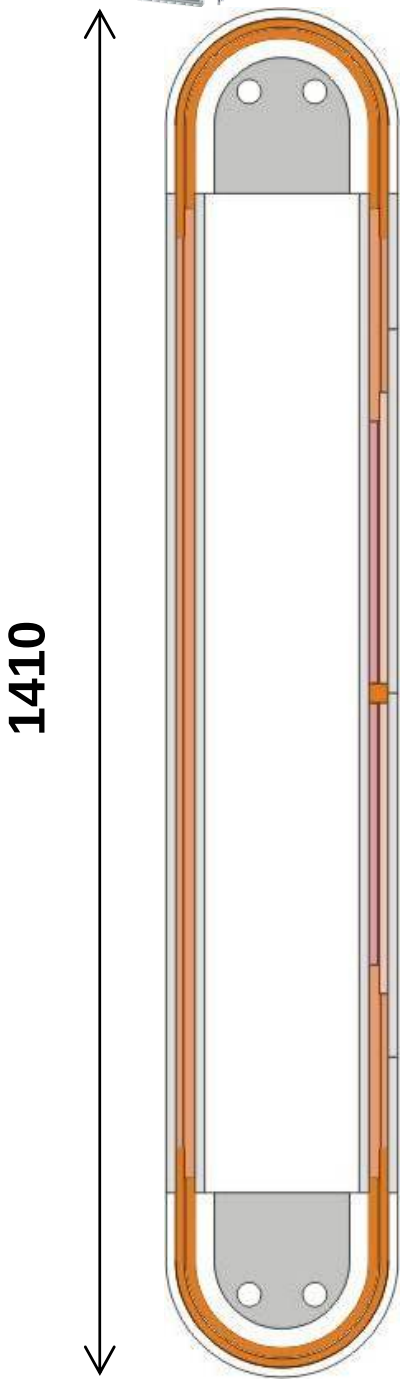
Transient excitation by joint resistance

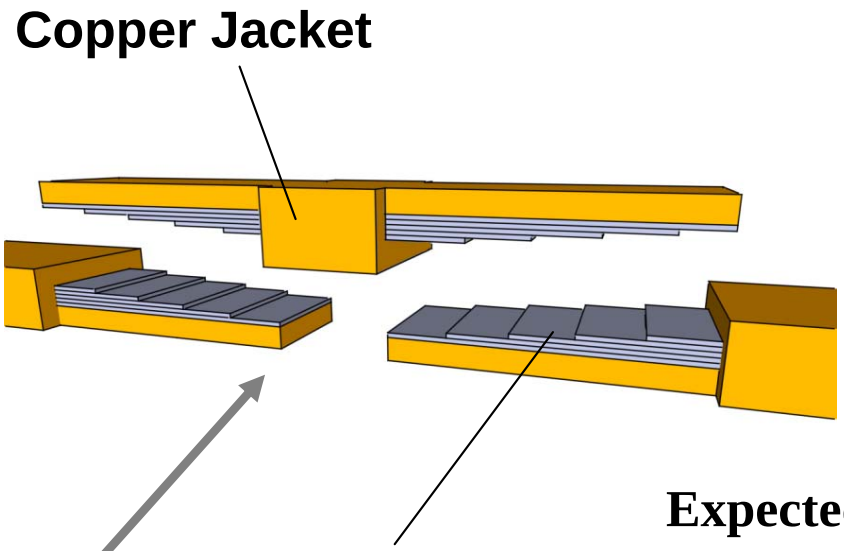
Self-inductance of the sample coil : 2.21 μH
Mutual inductance with split coils : 411 μH

$$\phi = L_S I_S = M I_C$$

$$I_S = \frac{M}{L_S} I_C$$

Conductor Joint



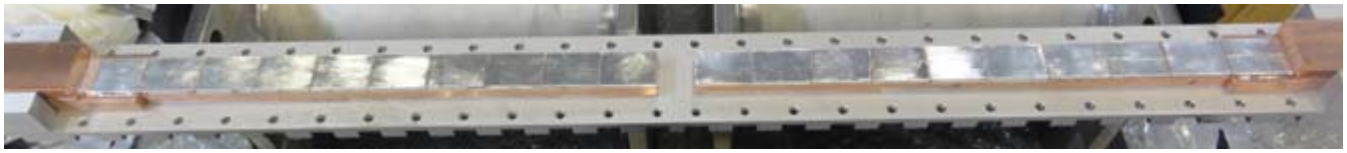


- Mechanical "bridge-type" joint developed by S. Ito at Tohoku Univ.
- Indium foils between HTS
- Titanium bolts for tight connection (6 Nm for 30 MPa)

Expected joint resistivity : 110 nΩ/cm²
Contact area
~ 2.8 cm × 1 cm × 10 layers × 2 rows = 56 cm²
Joint resistance for two joint parts ~ 4 nΩ

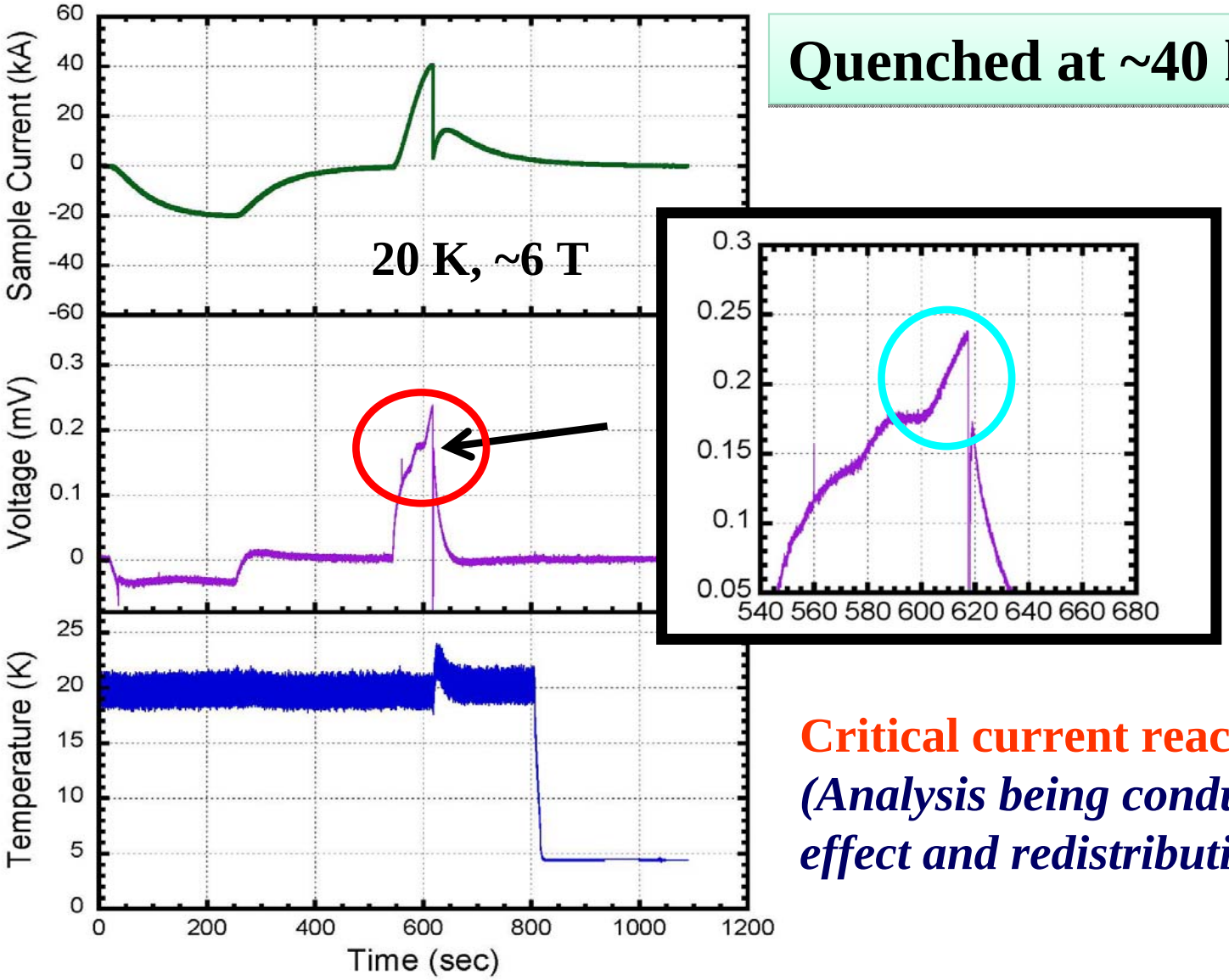
Expected decay time constant of current

$$\frac{L_S}{R} = \frac{2.2\times10^{-6}}{4\times10^{-9}} = 550\ (\mathrm{s})$$



Excitation Test Result #1

(Measurement of Critical Current @20 K)



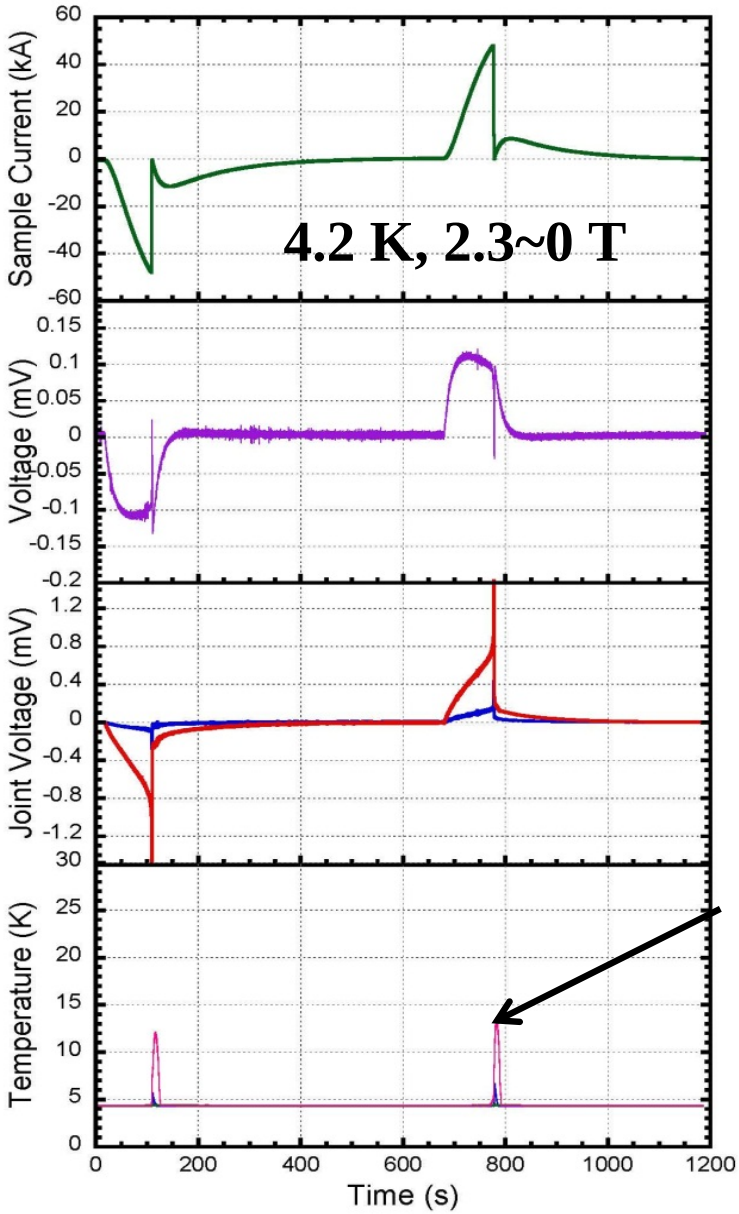
Quenched at ~40 kA @20 K and 6 T

Critical current reached…

(Analysis being conducted including self-field effect and redistribution of current)

Excitation Test Result #2

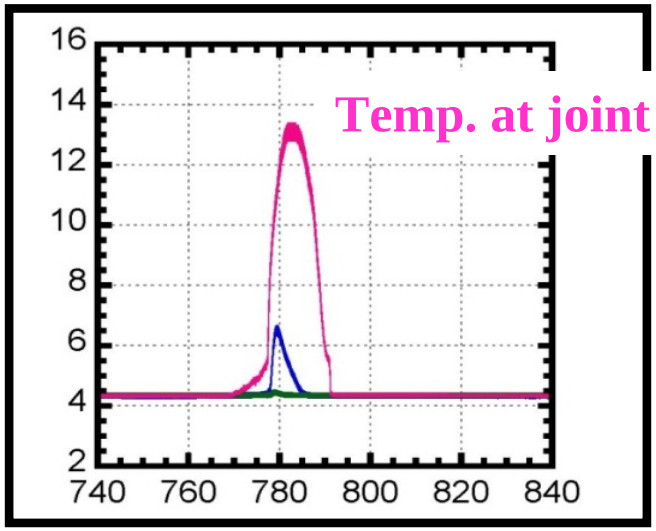
(Trial of Large Current Excitation @4 K)



Quench occurred at the joint part…

Improvement of joint and 2nd test (March 2013)

➔ 100 kA @ 4 K, 2 T …

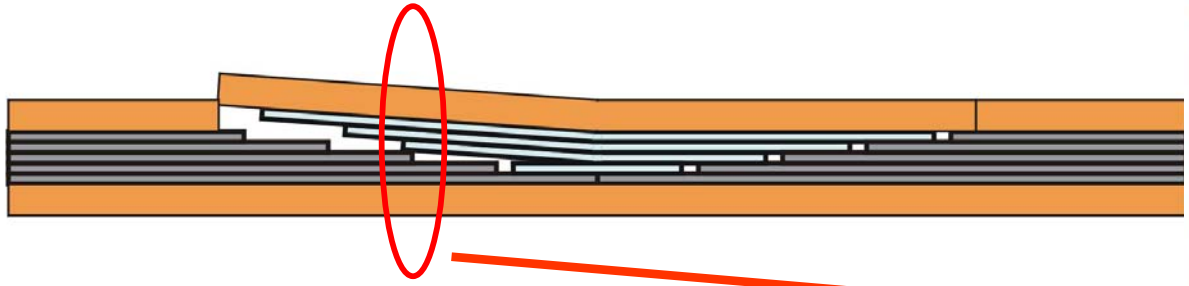


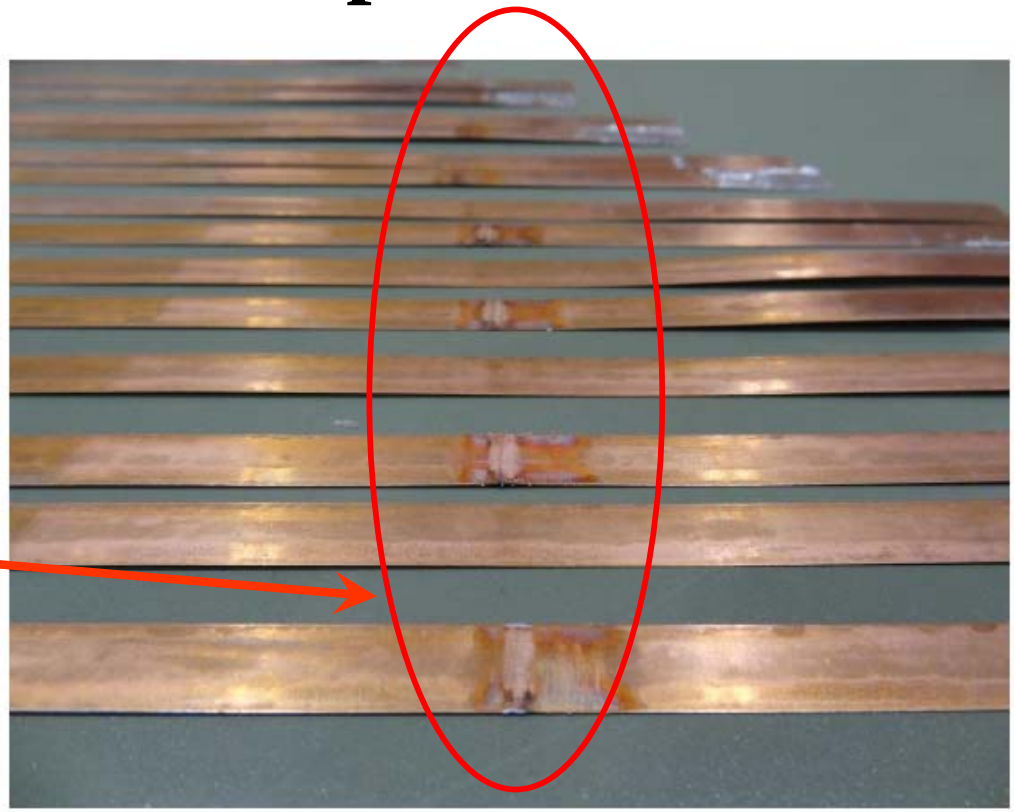
Joule Heating

Joint #1 : ~ 5 W

Joint #2 : ~ 40 W

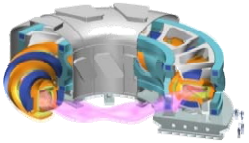
Problem with the Joint and Improvement





Improvement of joint

- Joint length : 620 mm ➔ 860 mm
- Step length : 30 mm ➔ 40 mm (to avoid overlapping)
- SS jacket : 10 mm thick, flat ➔ 20 mm thick, 凸 shape
- Bolts : Ti-alloy, ϕ4 mm, 25 mm pitch ➔ SS, ϕ6 mm, 15 mm pitch
- Cu jacket : one piece, side walls disconnected ➔ two pieces, side walls connected
- Work : done by NIFS ➔ by Tohoku Univ.



Summary

- Helical DEMO reactor is being designed
- HTS option seems feasible owing to the rapid progress of YBCO production technology
- Simple stacking of YBCO tapes : mechanically strong, low cost, low joint resistance, suitable for DC magnets
- Segmented conductors with joints can be a promising method to construct huge & continuous helical coils
- 40 kA @20 K, 6 T has been successfully attained by GdBCO HTS conductor (collaboration of NIFS & Tohoku Univ.)
- 100 kA @4 K, 2 T will be tried in March 2013
- 100 kA @20 K, 6 T will be tested in January 2014
  100 kA @20 K, 13 T is being planned to be tested in 3 years
  100 kA @20 K, 13 T R&D coil is being planned to be tested in 5 years