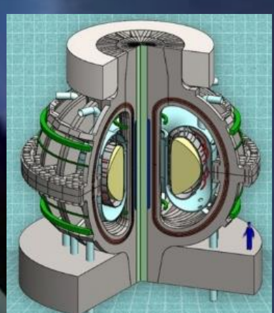
核融合マグネットへの適用をめざした大電流高温超伝導導体の開発

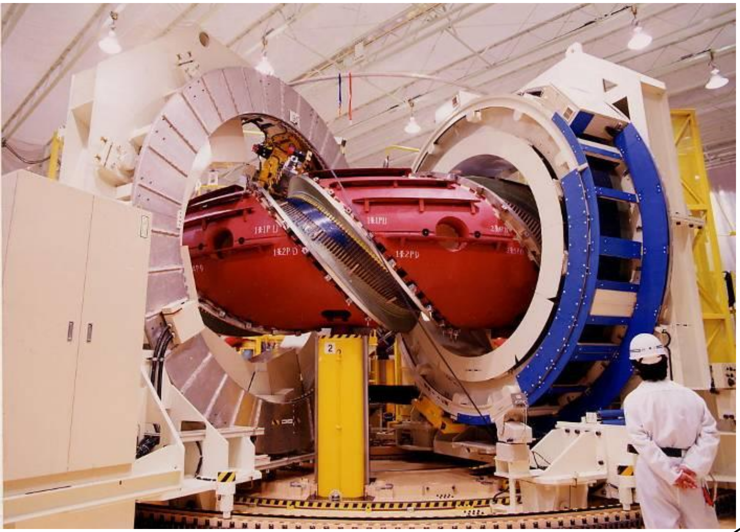
核融合科学研究所

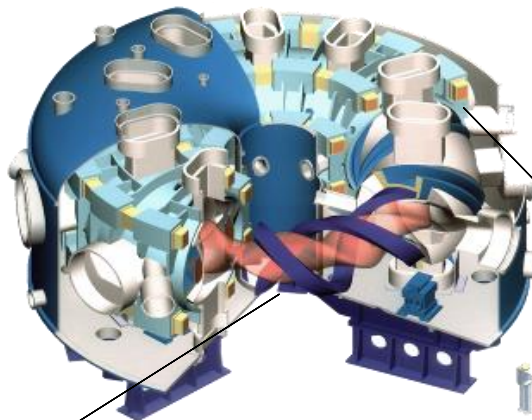
柳 長門

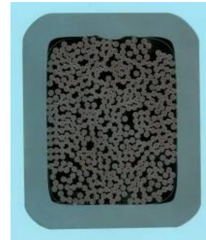


第16回 QUEST 研究会
2019年10月4日
九州大学 応用力学研究所

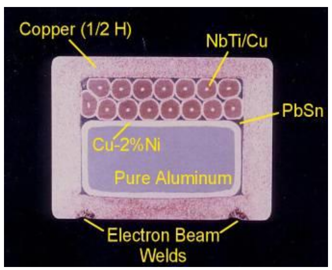
From LHD *to* FFHR







Poloidal Coils
NbTi-CICC (world first)



Helical Coils
NbTi
pool-boiling

Construction : 1990-1998
Operation : 1998-

What kind of superconductor should be used?

SC Material Selection

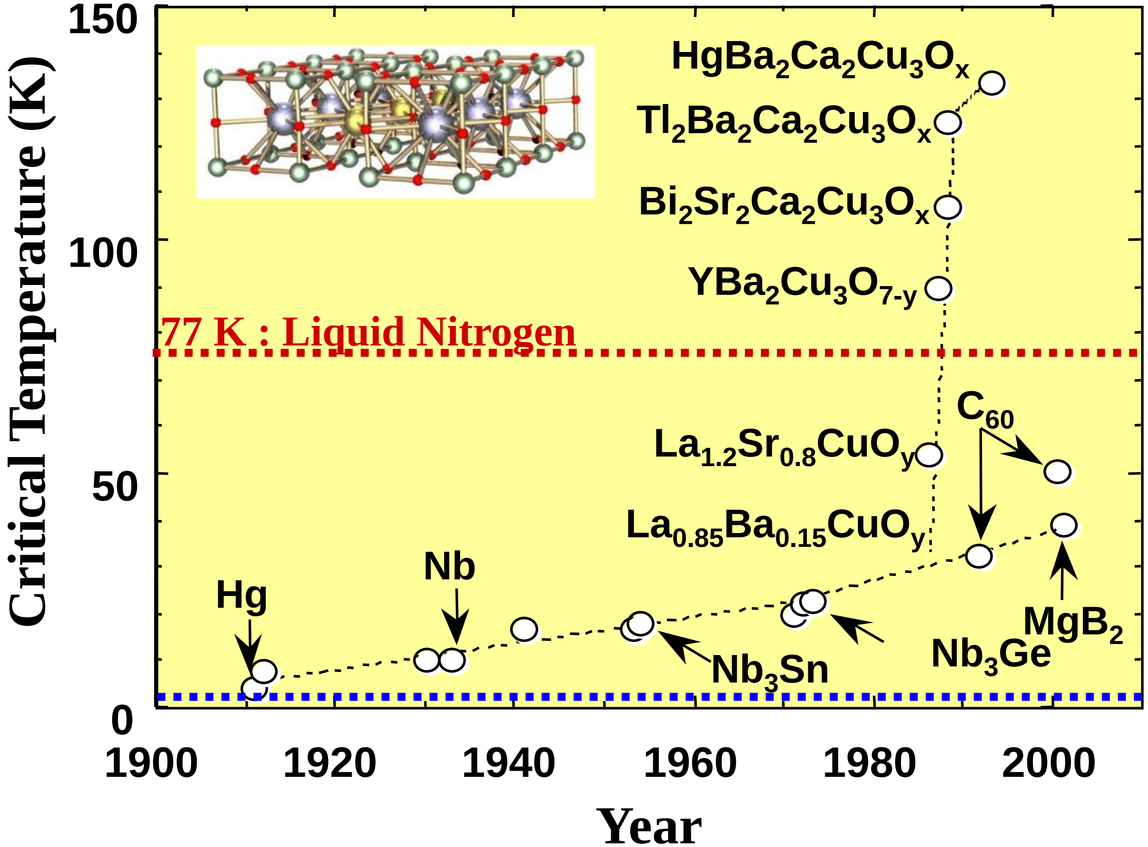
1. **LTS ➔ Nb_3Al, Nb_3Sn**
2. **HTS ➔ YBCO**

Conductor Selection

1. **Force-cooled LTS-CIC conductor**
2. **Indirectly-cooled LTS conductor**
3. **Helium gas cooled HTS conductor**

A. Sagara et al., Fusion Engineering and Design 89 (2014) 2114

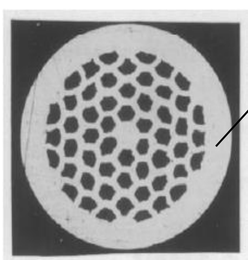
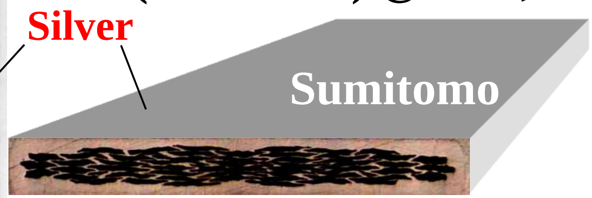
High-Temperature Superconductors (HTS)



- Discovery of superconductivity of copper-oxide materials in 1986
- Tremendous progress of wire (tape) production technology
- Applicable to semi-conductor production, power cable, motor, transformer, MRI, medical accelerator, MAGLEV, SMES
- *What about for fusion magnets?*

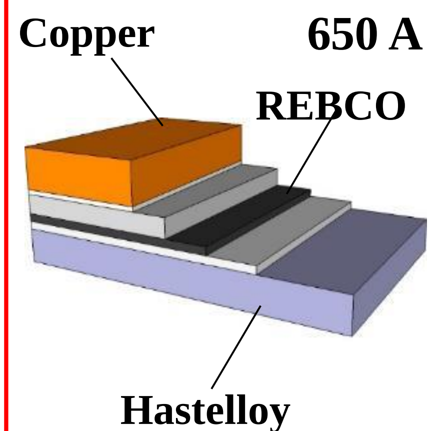
Bismuth-based 1st generation HTS（Bi-2212, Bi-2223)

200 A (4.2 mm-w) @77 K, s.f.

Rare Earth-based 2nd generation HTS（YBCO, GdBCO)

650 A (10 mm-w) @77 K, s.f.

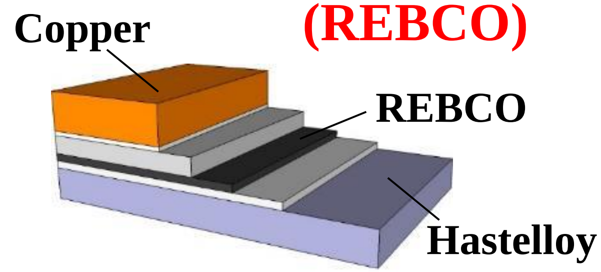


High-Temperature Superconductor (HTS)

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

- High field
- High temp.
- High heat

Rare-Earth Barium Copper Oxide (REBCO)



Stability Margin

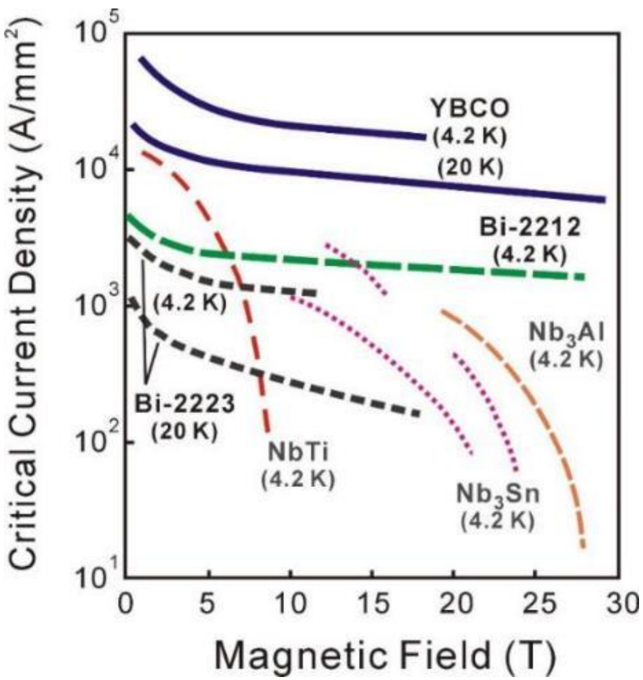
$$\Delta Q < C_p \rho \Delta T$$

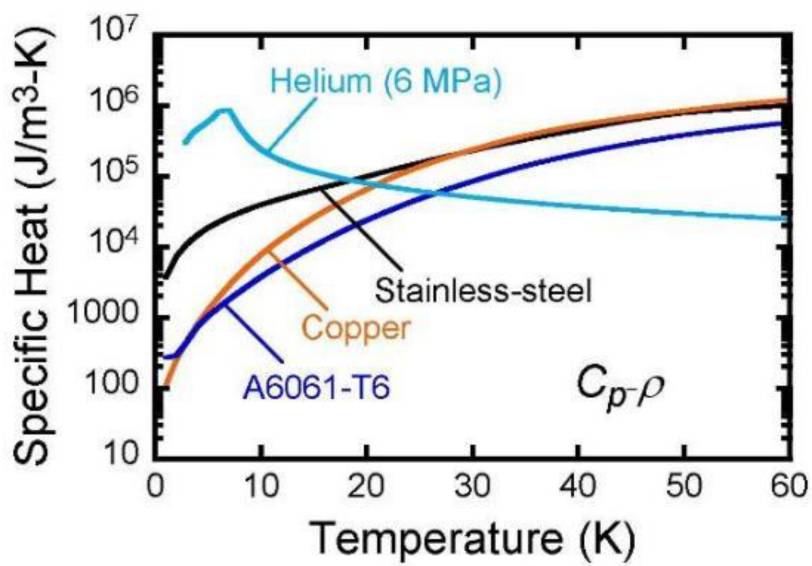
$$C_p \rho \Delta T \approx 2\times10^5\ (\mathrm{J/m^3K})\times 10\ (\mathrm{K})$$

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

Higher than CIC conductor

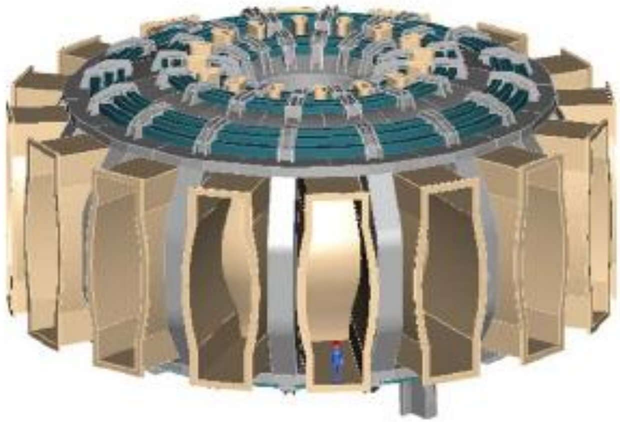
➔ Low quench risk!



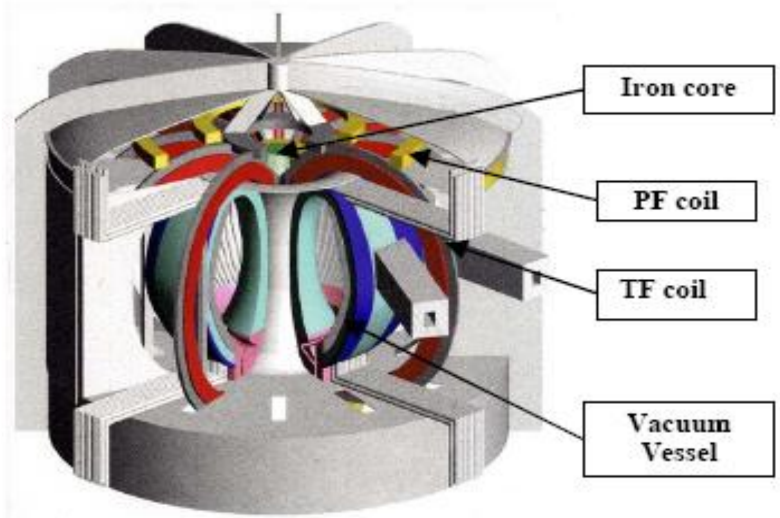


N. Yanagi, S. Ito, et al., Plasma and Fusion Research 9 (2014) 1405013

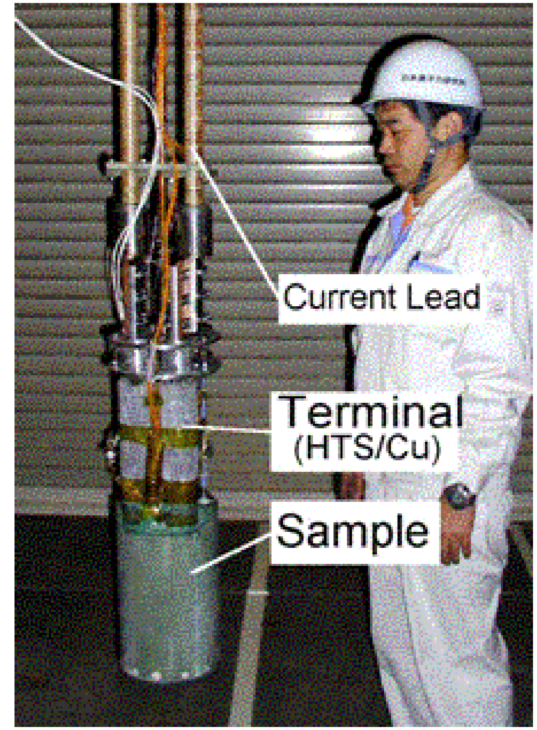
Pioneering Work of
applying HTS to tokamak reactor designs



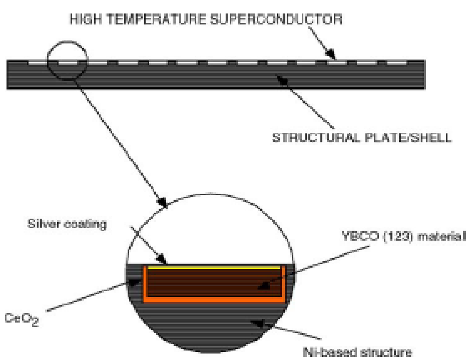
ARIES-AT (USA)



VECTOR (JAEA)

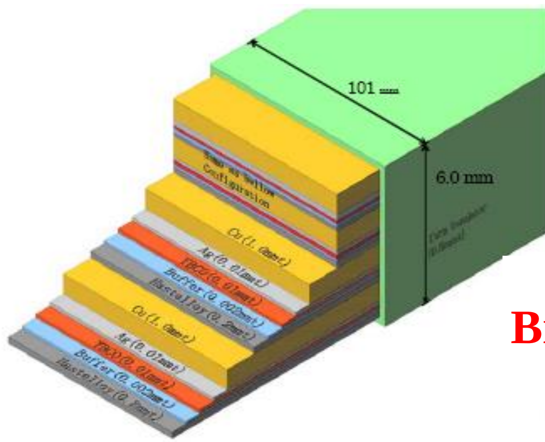


Bi-2212 CIC conductor
10 kA@20 K, 12 T
T. Isono *et al.*
(2003)



YBCO

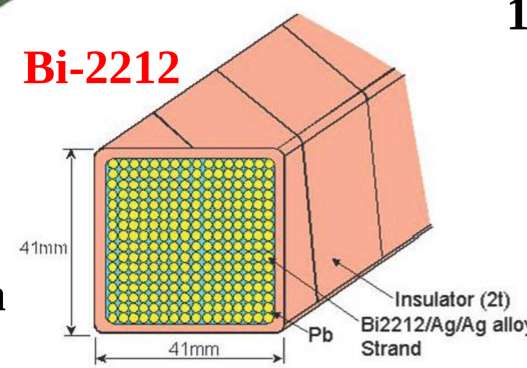
F. Dahlgren *et al.*
(2006)



YBCO

T. Ando, S. Nishio, H. Yoshimura
(2004)

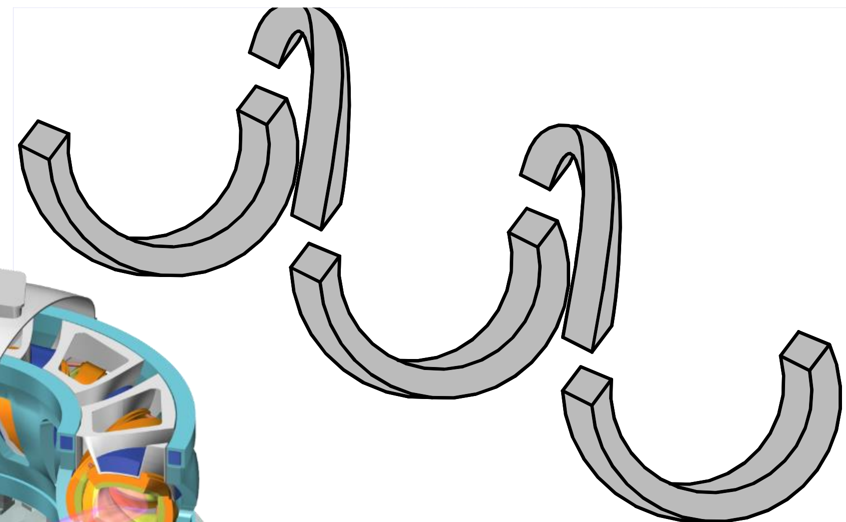
Bi-2212

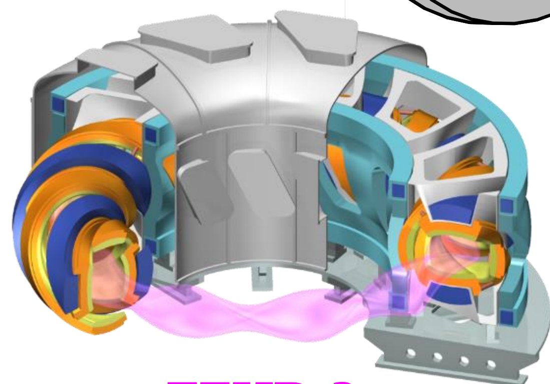


Pioneering Work of
applying HTS to helical reactor designs

H. Hashizume, S. Kitajima, S. Ito, K. Yagi, Y. Usui, Y. Hida, A. Sagara
"Advanced Fusion Reactor Design using Remountable HTc SC Magnet"
J. Plasma Fusion Res. SERIES 5 (2002) 532.

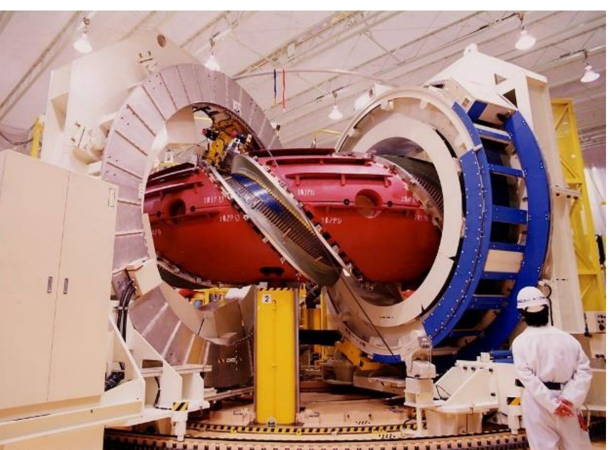
(1) Construction cost reduction of magnet
(2) Repair of magnet module if damaged
(3) Maintenance of blanket modules





FFHR-2

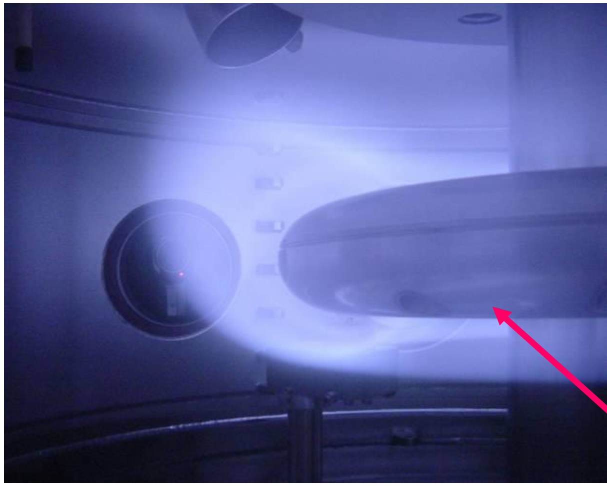
×3~4



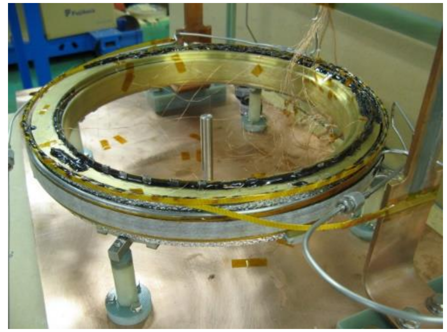
LHD
continuous helical winding
(1995-1996)

Application of HTS to Plasma Research

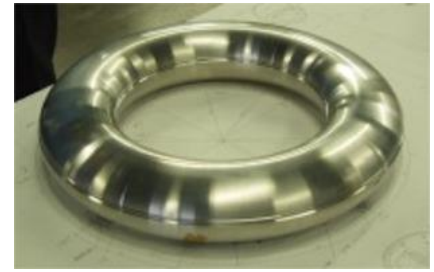
RT Project at Univ. of Tokyo

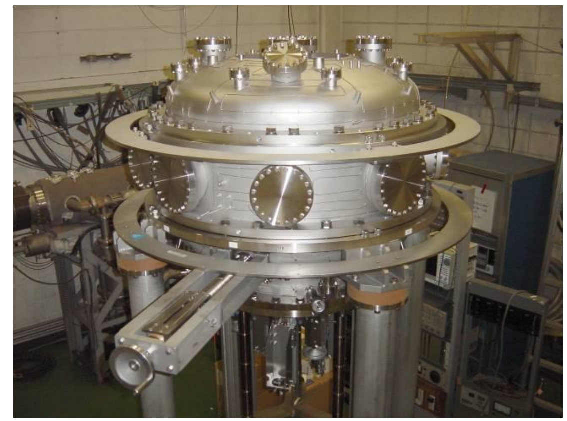


Mini-RT (2003)

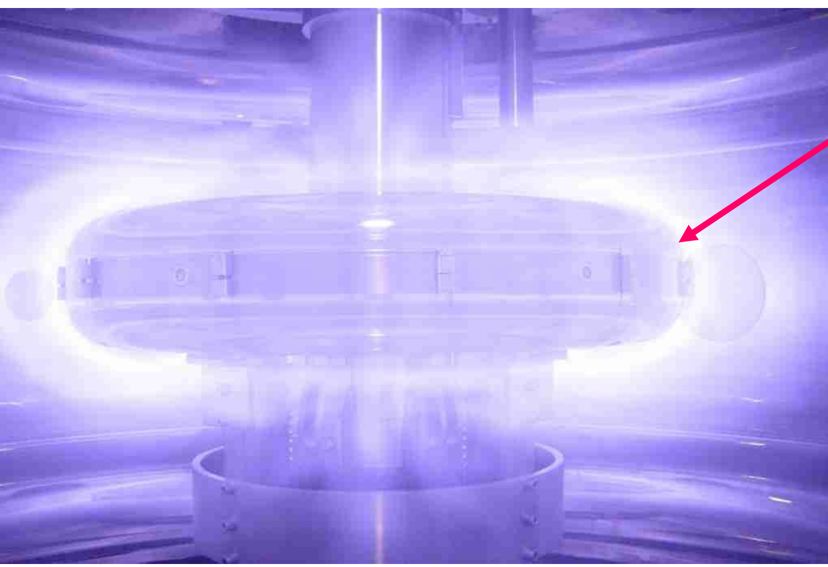


Upgrade to GdBCO (2012)





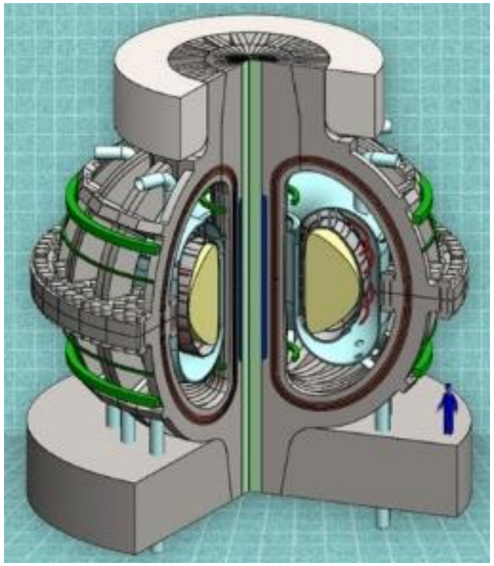
Bi-2223 HTS floating coils



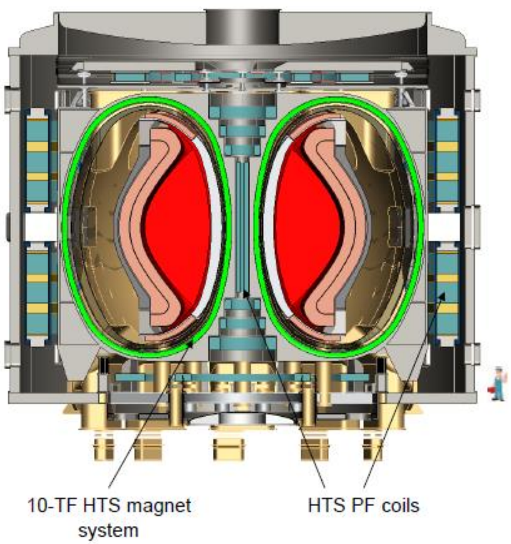
RT-1 (2006)

HTS Magnet Concepts for Fusion in the World (2018)

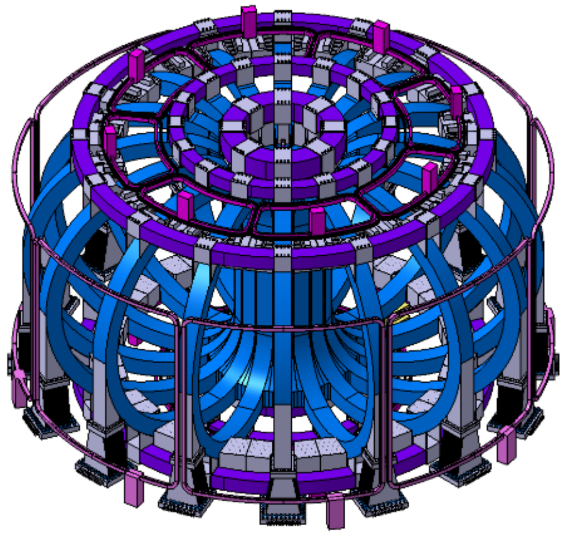
ARC (MIT, US)



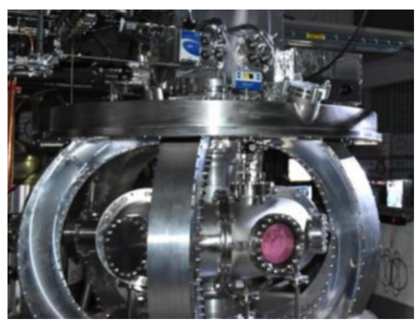
FNSF-ST (PPPL, US)



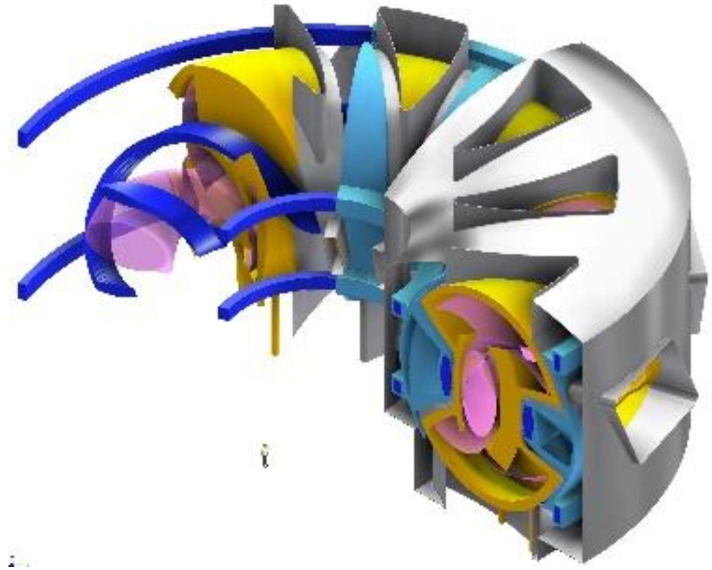
CFETR-Phase II (ASIPP, China)



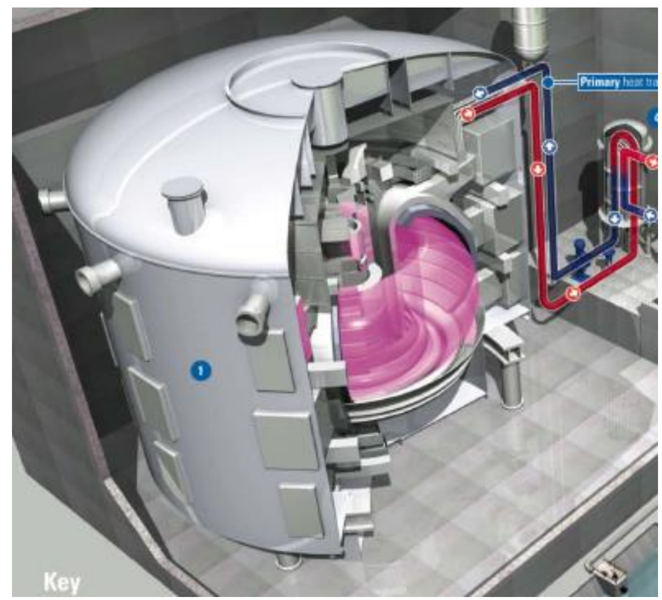
Tokamak Energy (UK)



FFHR-d1 (NIFS, Japan)



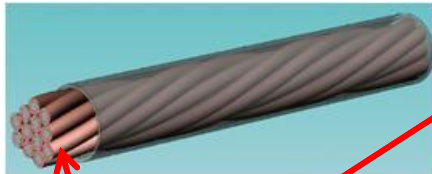
EU DEMO HTS option (EUROfusion)



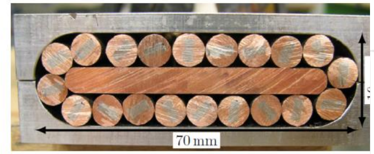
Large-Current HTS Conductors

Twisted and Transposed REBCO Conductors

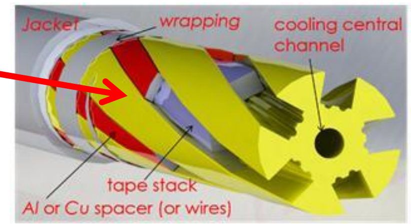
Roebel **(KIT)**



TSTC **(MIT)**

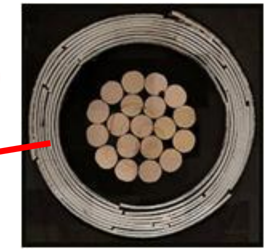


RSCCCT **(SPC)**



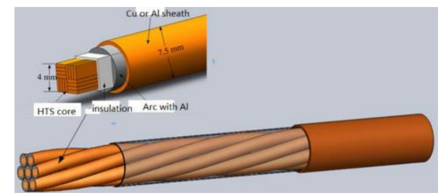
Slotted Core (ENEA)

CroCo **(KIT)**

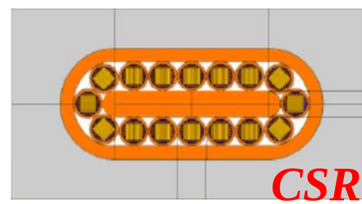


CORC **(ACT)**

Roebel **(CERN)**



QI **(NCEPU)**

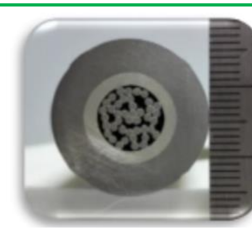


CSRC **(ASIPP)**

Simply-Stacked REBCO Conductors

STARS **(NIFS)**

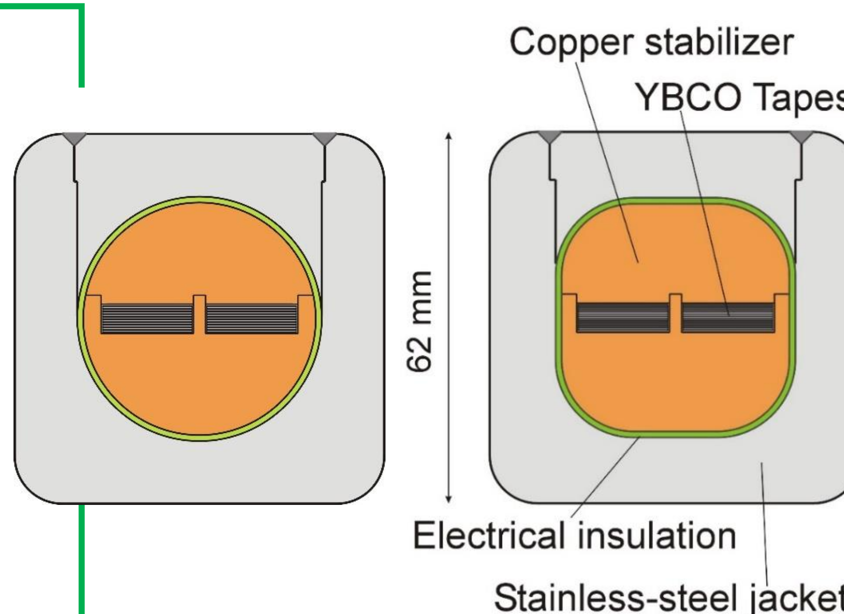
Bi-2212 CIC Conductors



Bi-2212 **(ASIPP)**

100 kA-class HTS Conductor for FFHR-d1
"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 or LNe
Superconductor	REBCO
Critical current	>900 A/cm @77 K, s.f.



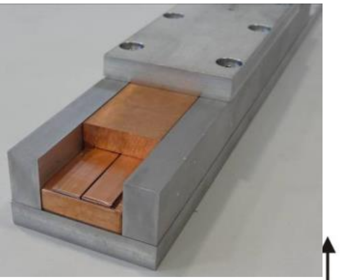
Type-1 *rotatable*

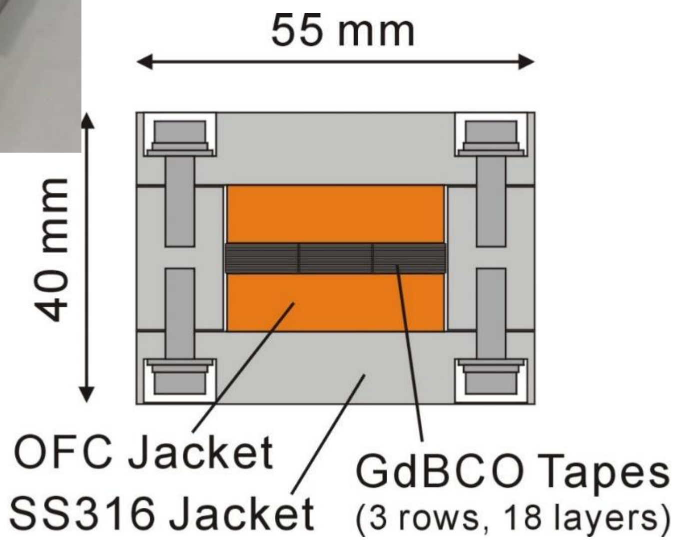
Type-2 *not rotatable*

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 and low resistance joint

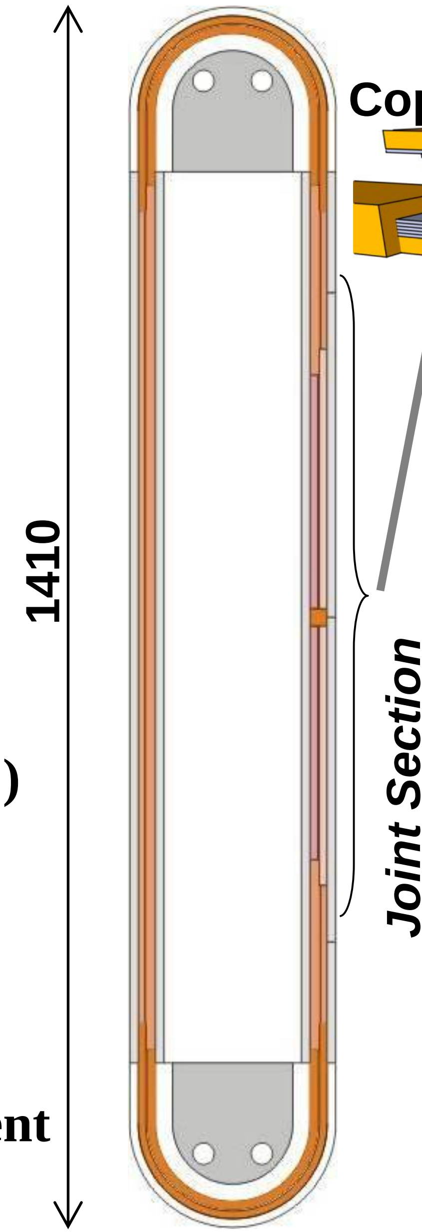
100 kA-Class Prototype Conductor Test

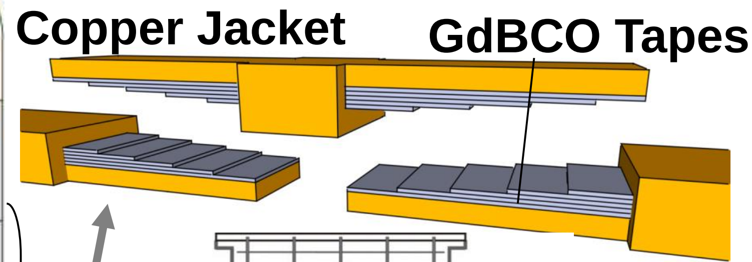


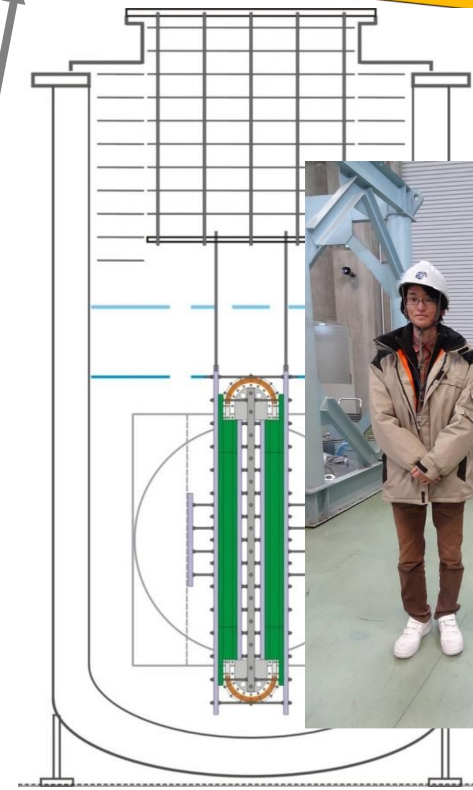


- **GdBCO tapes**

  Fujikura, FYSC-SC10 (IBAD + PLD)
  Width: 10 mm, Thickness: 0.22 mm
  (Copper lamination : 0.1 mm)
  Ic ~ 600 A @77 K, self-field
- **Simple stacking of 54 GdBCO tapes**
- **Stainless-steel jacket for reinforcement**
- **FRP jacket for thermal insulation**

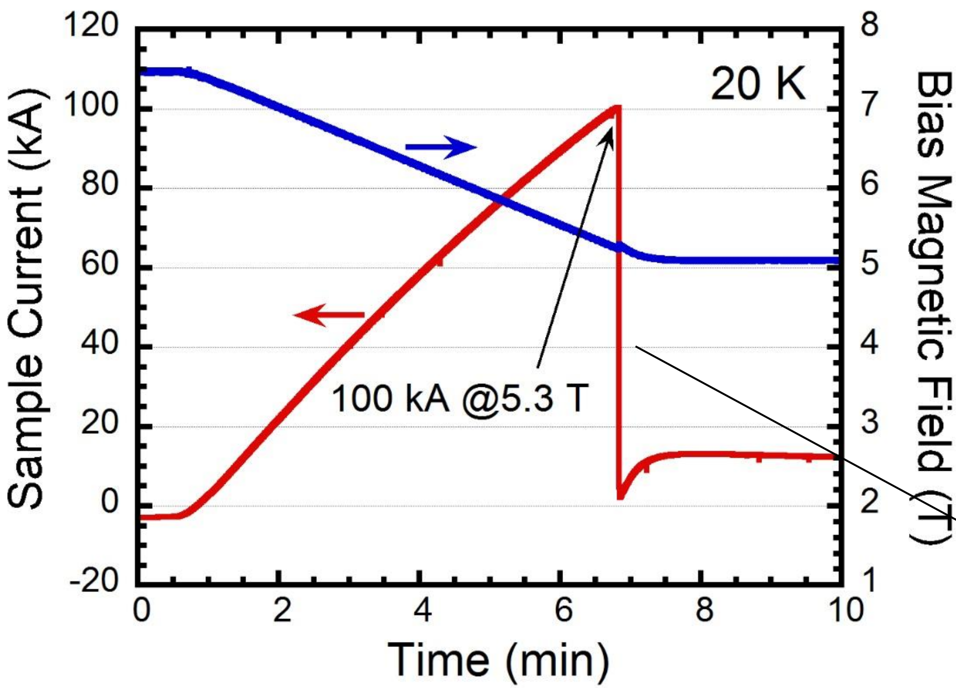


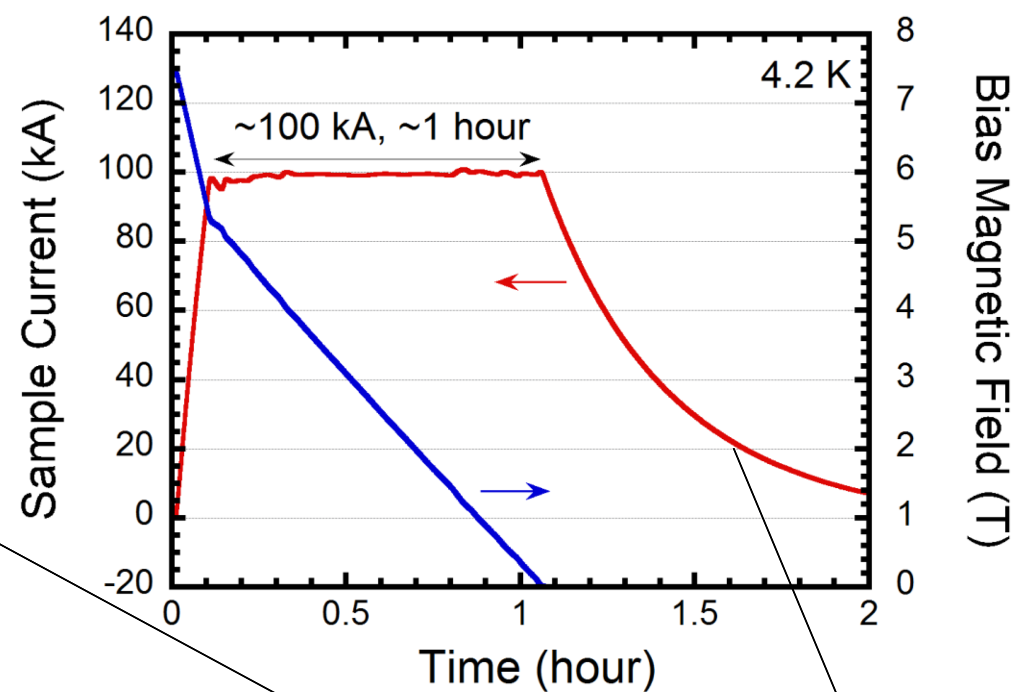




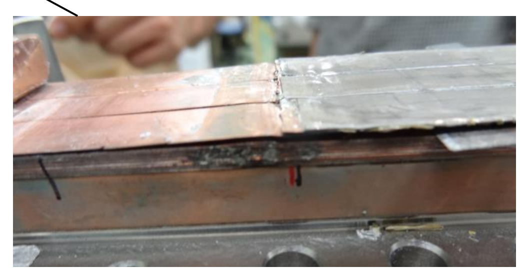
$$I_{sample} = \frac{M}{L_{sample}} I_{coil}$$

100 kA-Class Prototype Conductor Test



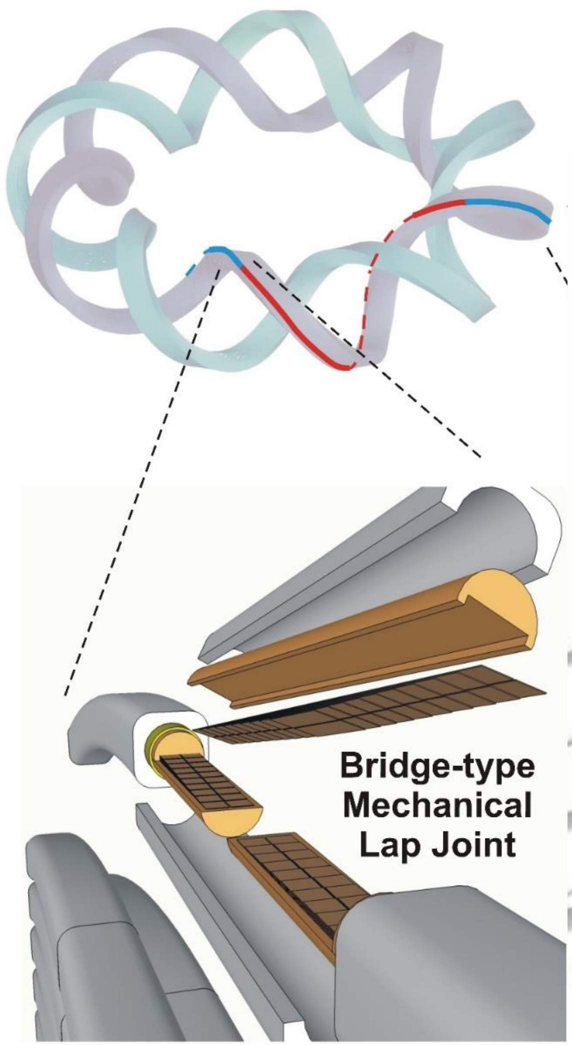


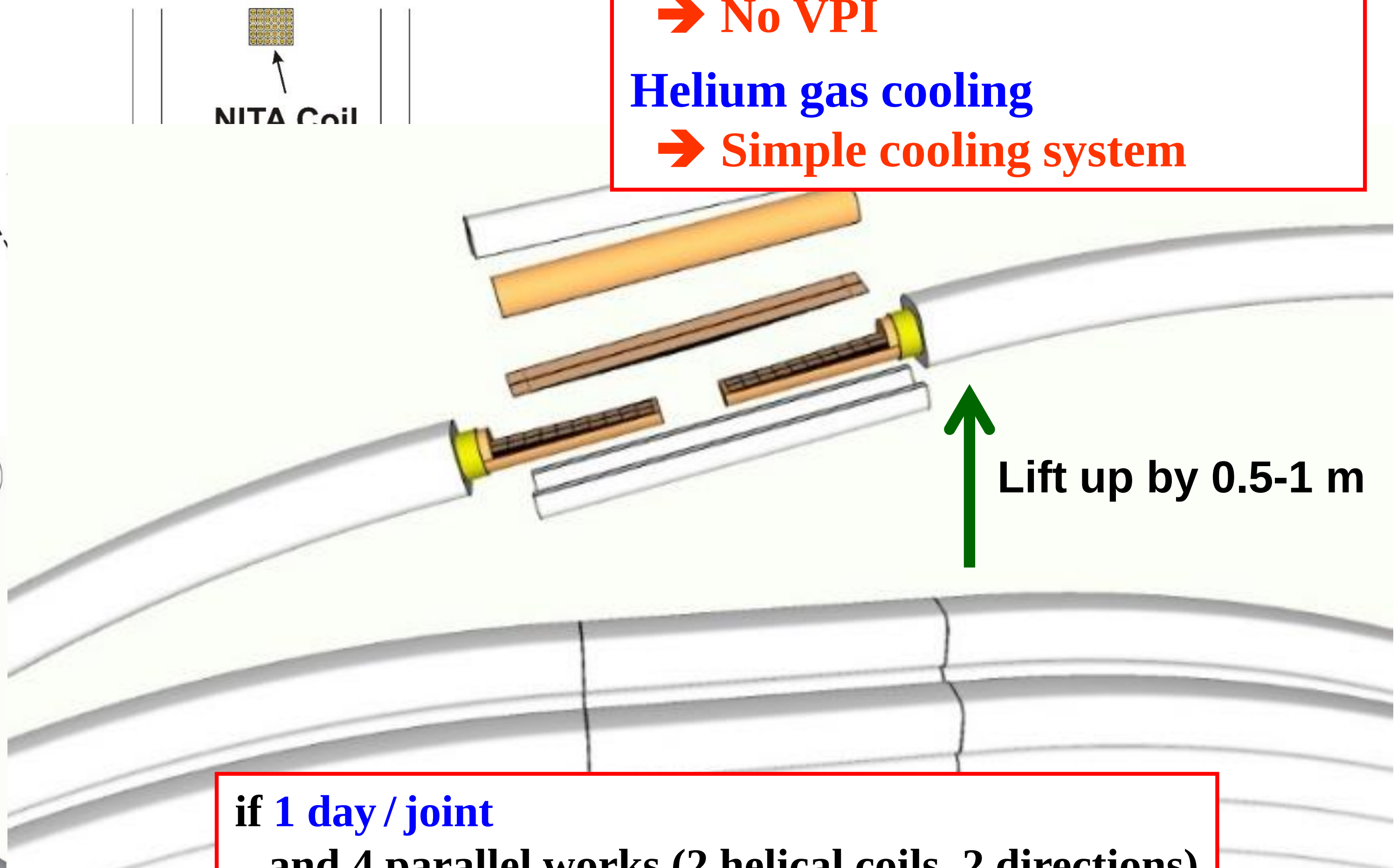
Joint resistance
~1.8 nΩ



- **100 kA achieved @20 K, 5.3 T (quench)**
- **118 kA achieved @4.2 K, 0.45 T (no quench)**
- **100 kA current was successfully sustained for 1 hour @4.2 K**
- **Decay time constant : ~ 1000 s ➔ Joint resistance : ~1.8 nΩ**
- ***Quench occurred due to a failure in the joint manufacturing***

“Joint-Winding” of Helical Coils





Welding of neighboring windings
➔ No VPI

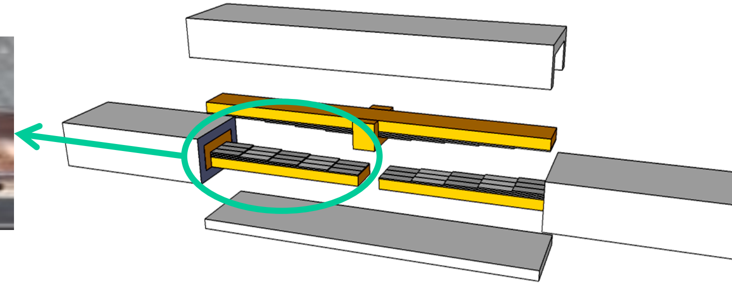
Helium gas cooling
➔ Simple cooling system

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

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

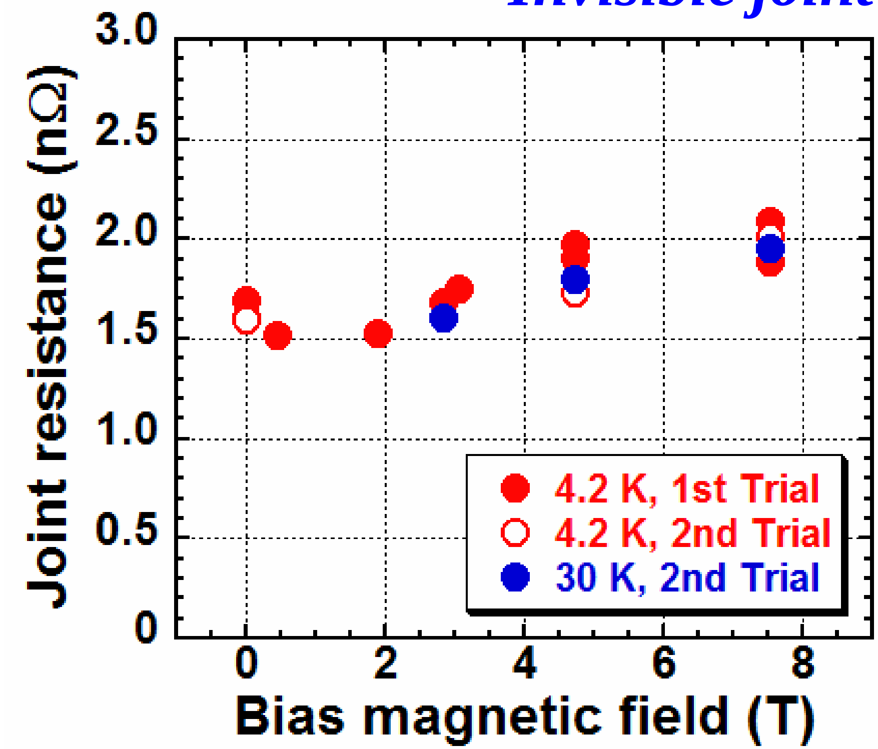
Evaluation of Joint Resistance

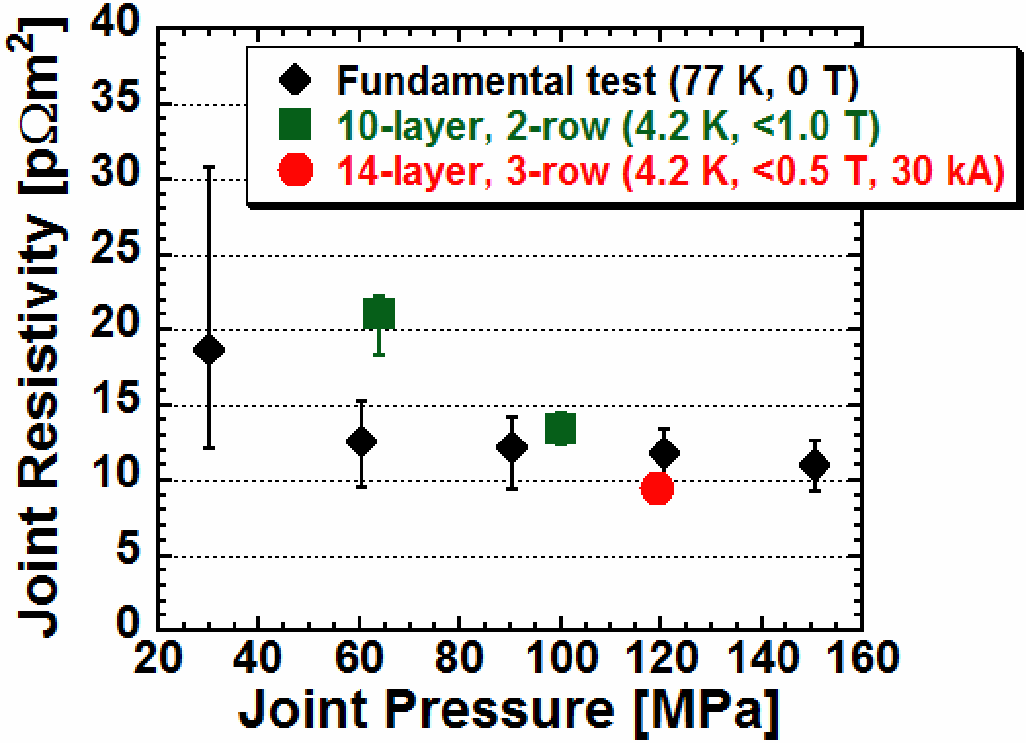


Bridge-type mechanical lap joint

"*Invisible joint*"

S. Ito (Tohoku Univ.)



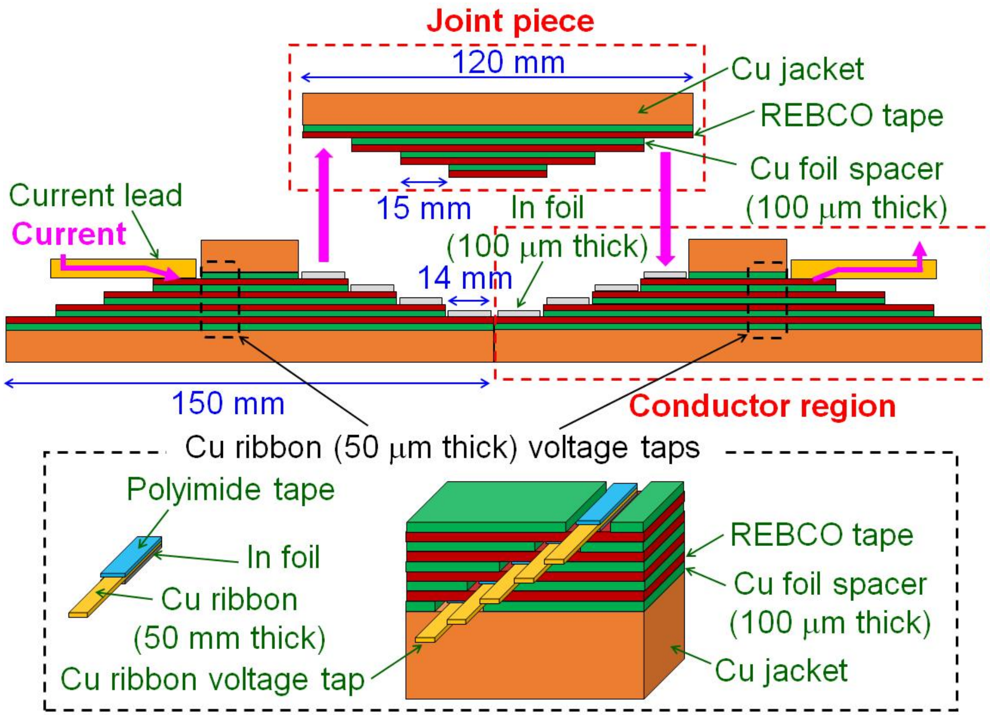


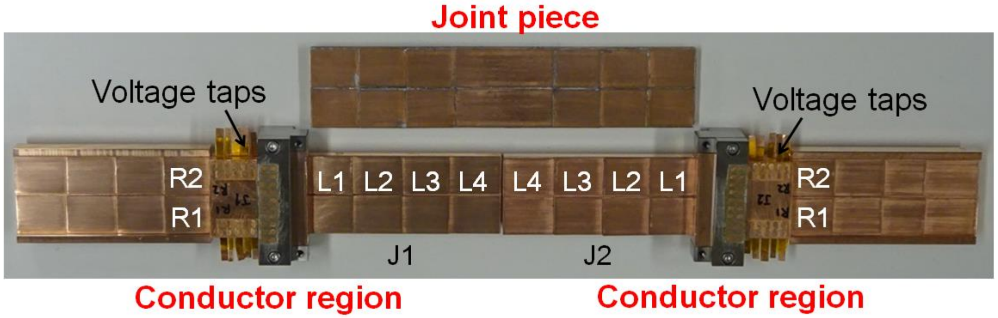
Joint resistance : ~2 nΩ ➔ Joint resistivity : ~10 pΩm²

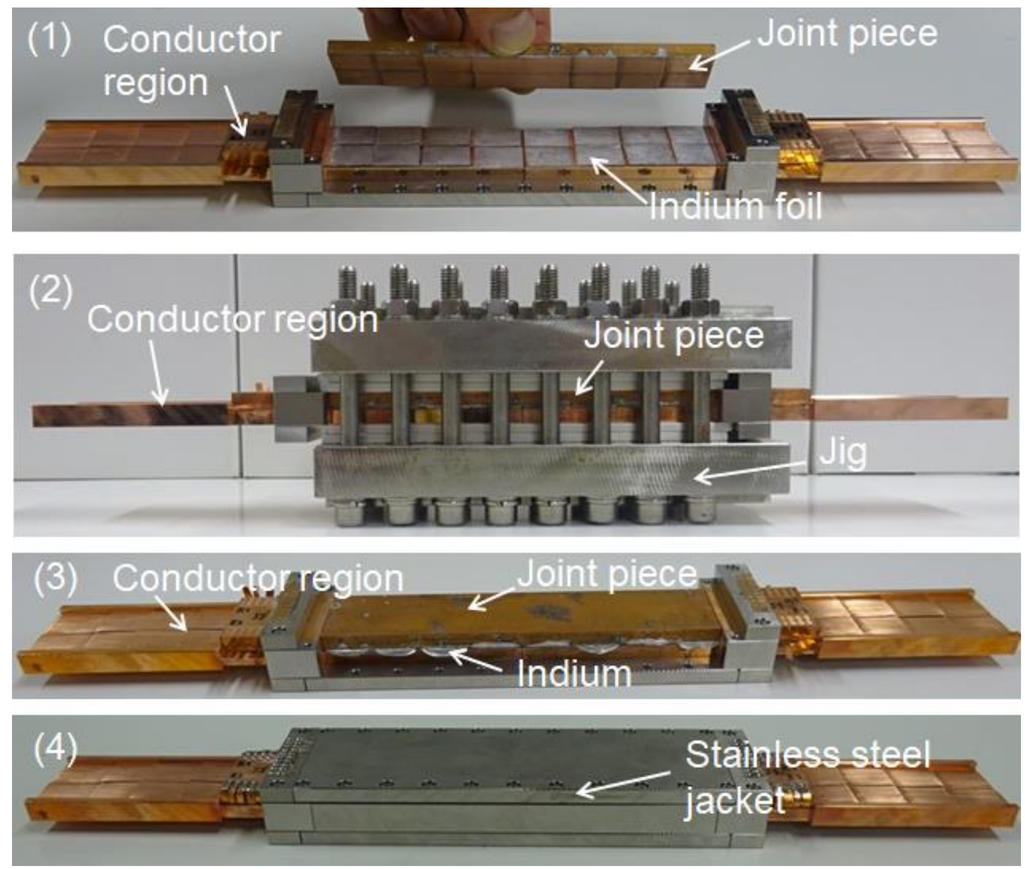
Required electrical power of the cryoplant at R.T. < 5 MW (for 3,900 joints)

一体式ジョイントピースを用いた低抵抗機械的ラップ接続に成功

S. Ito, et al.
presented in SOFT 2018
to be published in FED







LHD 後継計画 & NIFS 次期計画

LHD project 1998-2022

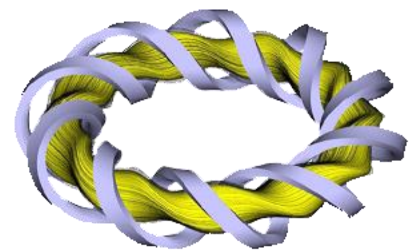
LHD upgrade 2023-2028

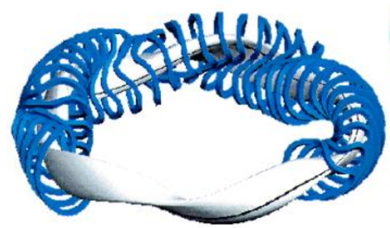
Divertor tiles will be changed from graphite to tungsten
High-power steady-state plasma production (2 MW x 3 hours)

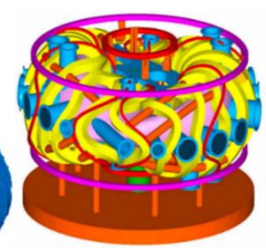
Post-LHD project 2029-2038

Presently, two proposals are being examined in parallel

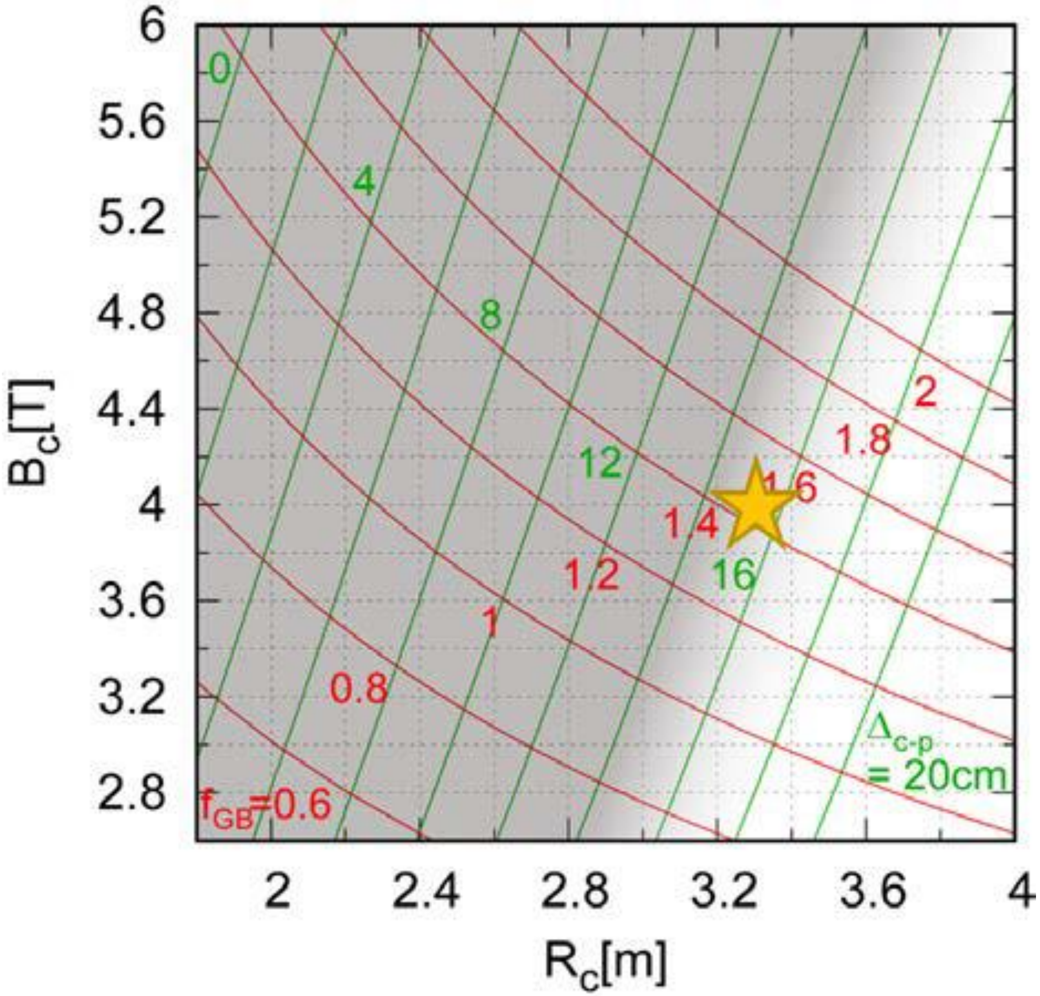
- HTS heliotron by optimizing LHD magnetic configuraion
- Modular stellarator with new magnetic configurtion


LHD


W-7X


CFQS

HTS ヘリカル装置の大きさと磁場強度



T. Goto, K. Takahata

プラズマと第一壁の間の距離を十分とるために、

ヘリカルコイル巻線部の電流密度：80 A/mm^2

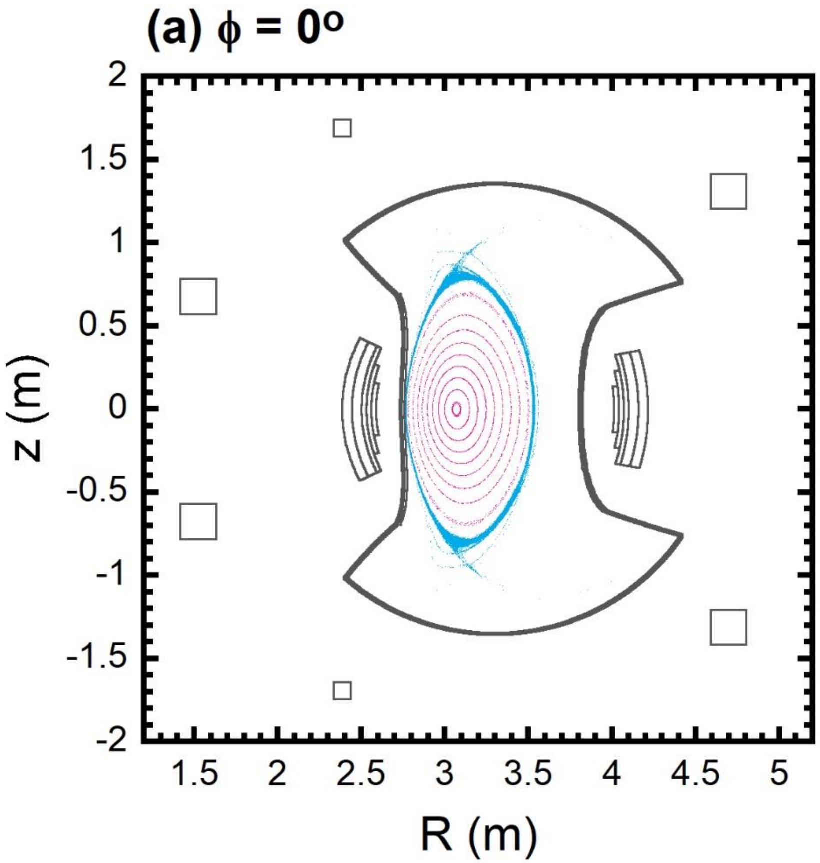
➔ R = 3.3 m, B = 4 T（現在の候補）

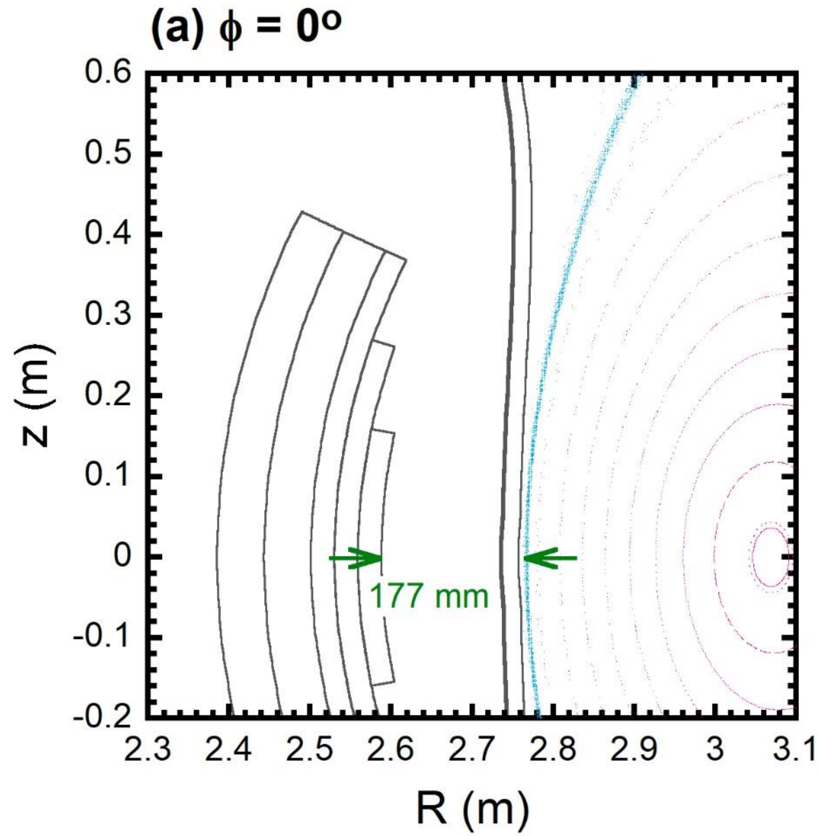
LHD：
R = 3.9 m, B ~2.7 T
40 A/mm^2（設計）
(35 A/mm^2 実績)

大型コイルにかかわらず、高い電流密度が要求される

➔ クエンチ保護が課題 ➔ 短時定数遮断（耐電圧）、早期検出、クエンチヒータ、無絶縁？

Vacuum Magnetic Surfaces of a LHD-similar configuration with j_{HC} = 80 A/mm^2

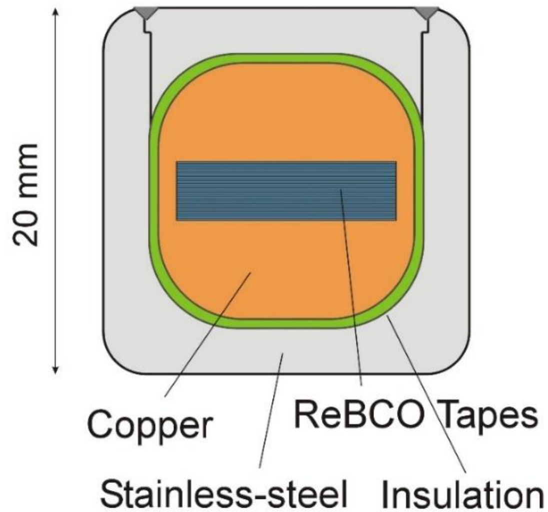




トーラス内周部におけるエルゴディック層境界とヘリカルコイル巻線部最内層との距離: **177 mm > 150 mm**

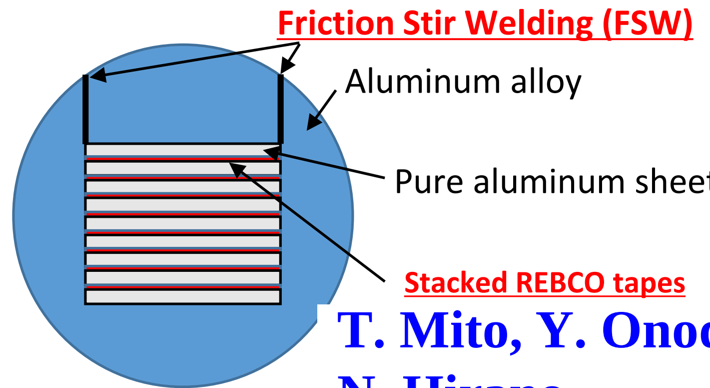
Three Candidate Conductors (HTS 10 kA-class)

STARS
(Stacked-Tapes Assembled in Rigid Structure)



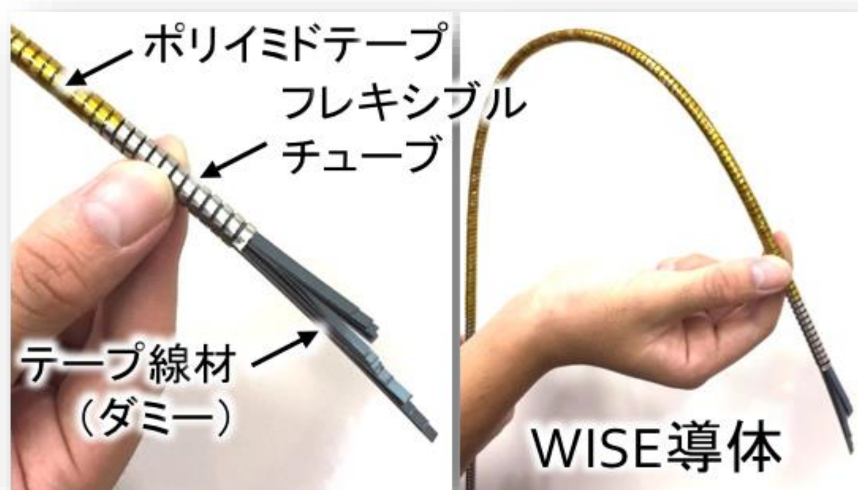
N. Yanagi, Y. Terazaki, S. Matsunaga, S. Ito (Tohoku Univ.)

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



T. Mito, Y. Onodera, N. Hirano

WISE
(Wound and Impregnated Stacked Elastic tapes)

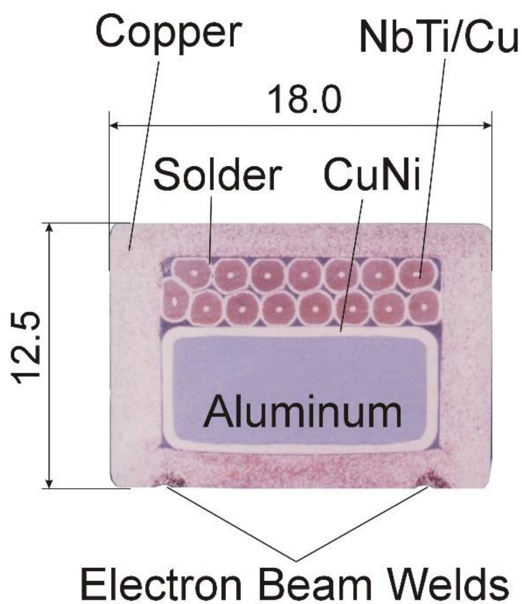


J. Miyazawa, Y. Narushima, S. Matsunaga

Conductor for Helical Coils
LTS vs. HTS

LTS (for LHD)

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

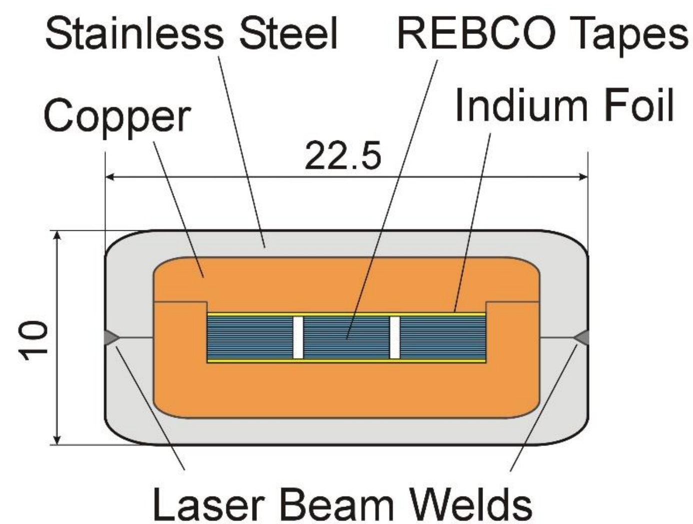


Effective Young's modulus: 100 GPa

HTS (for Post-LHD)

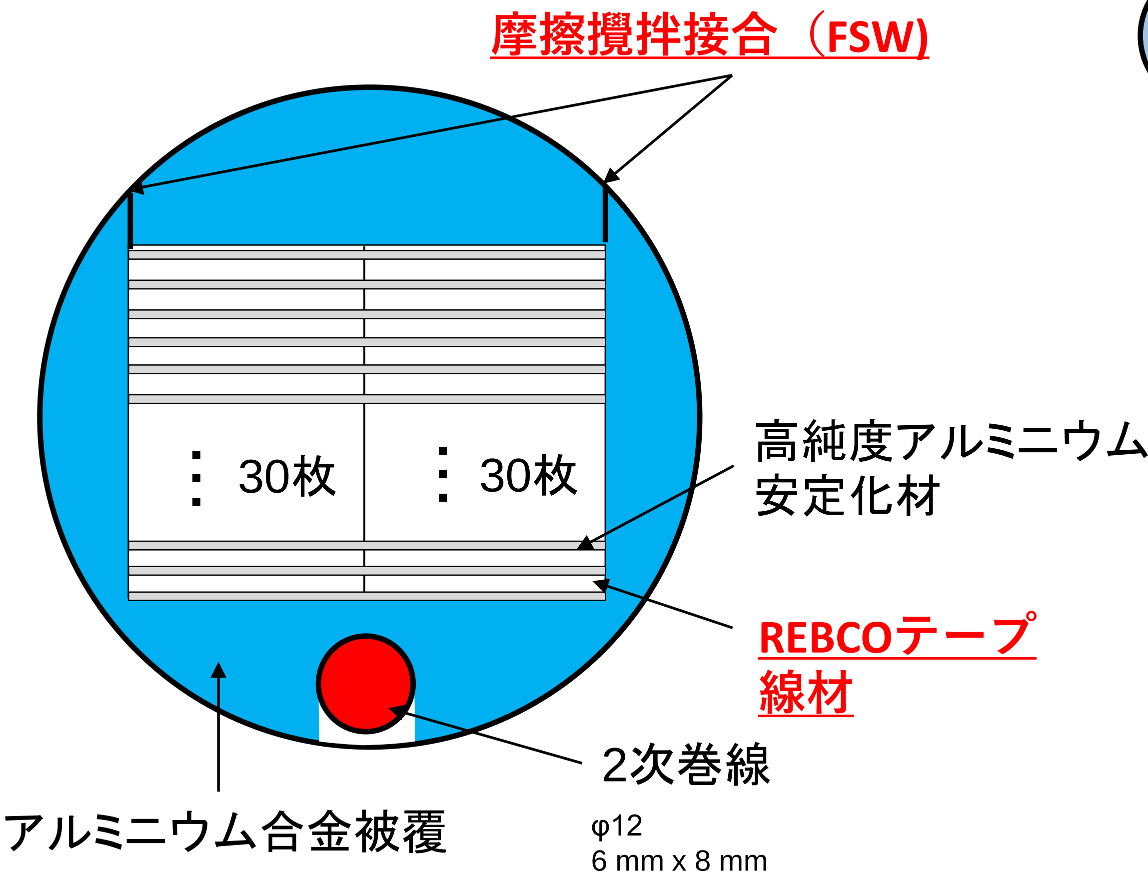
REBCO + Cu + SS
18 kA @ ~10 T, 80 A/mm^2

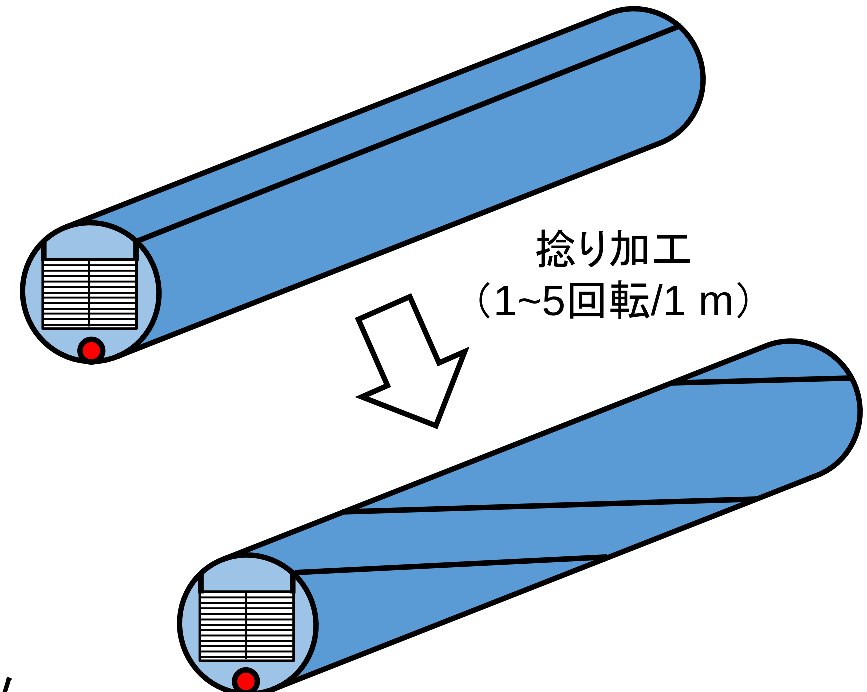
Bi-2223 can also be used

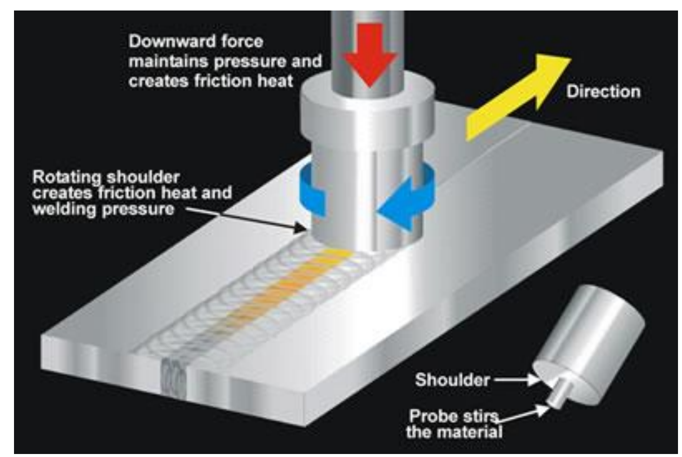


Effective Young's modulus: 150 Gpa
Similar bending (winding) by further flattening

摩擦攪拌接合(FSW)、アルミニウム合金被覆(Aluminum alloy jacket)、間接冷却(Indirect cooling)、REBCO導体の頭文字をとってFAIR導体と命名



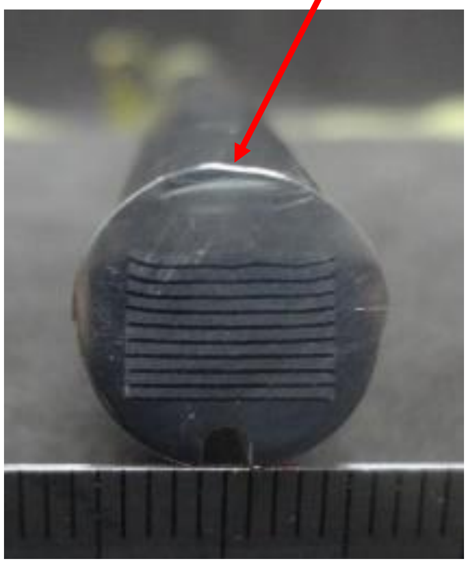




Friction stir welding (FSW)

FIRST TRIAL PRODUCTION OF FAIR CONDUCTOR

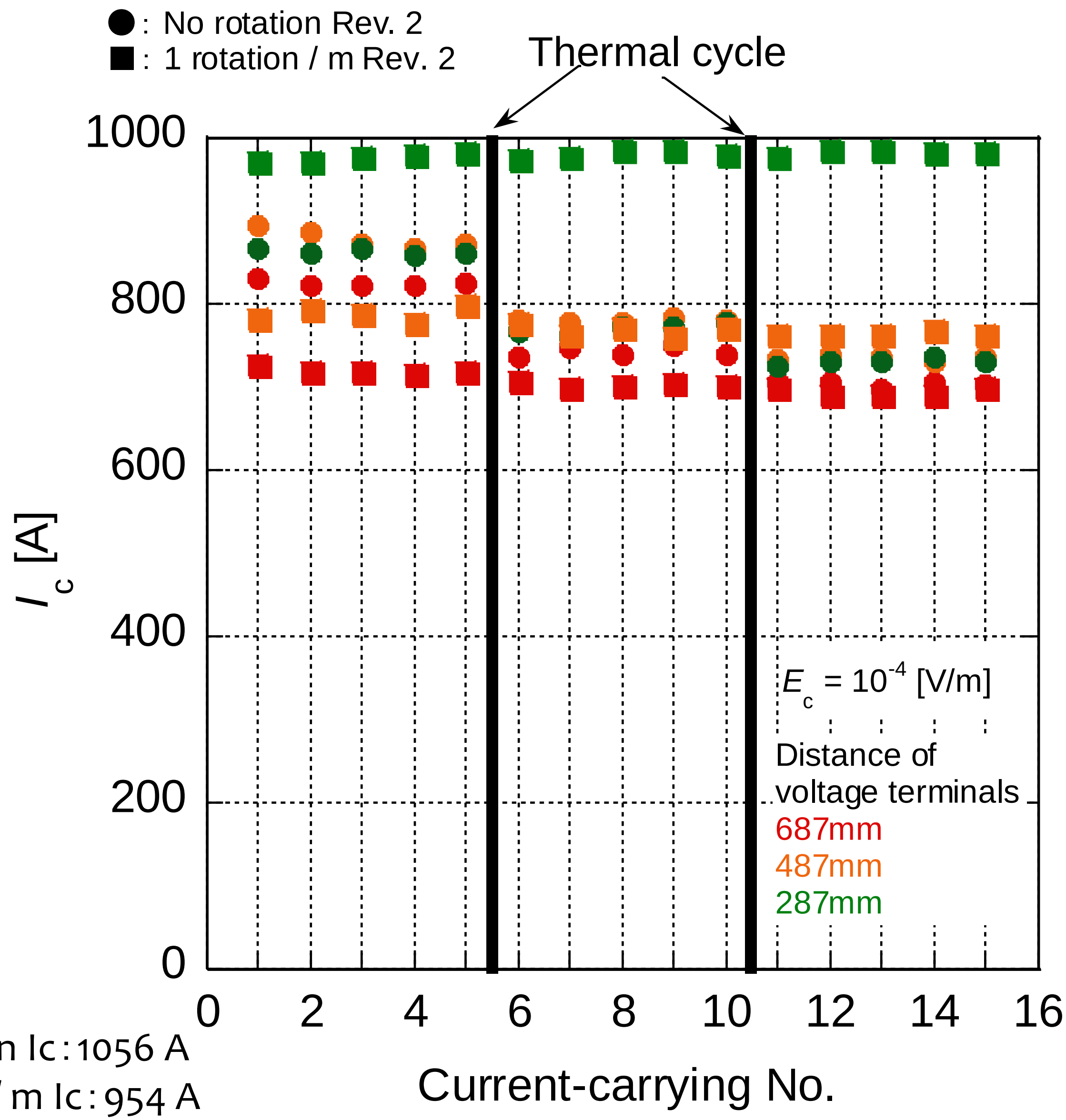
Cross section of FAIR conductor

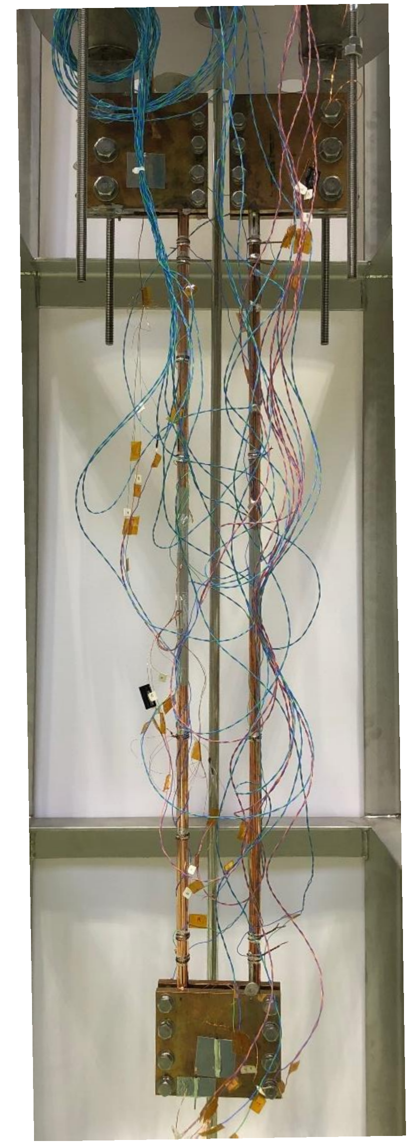


Twist pitch: 2 rotations / m

REBCO tapes : SuperPower Inc. SCS4050-AP

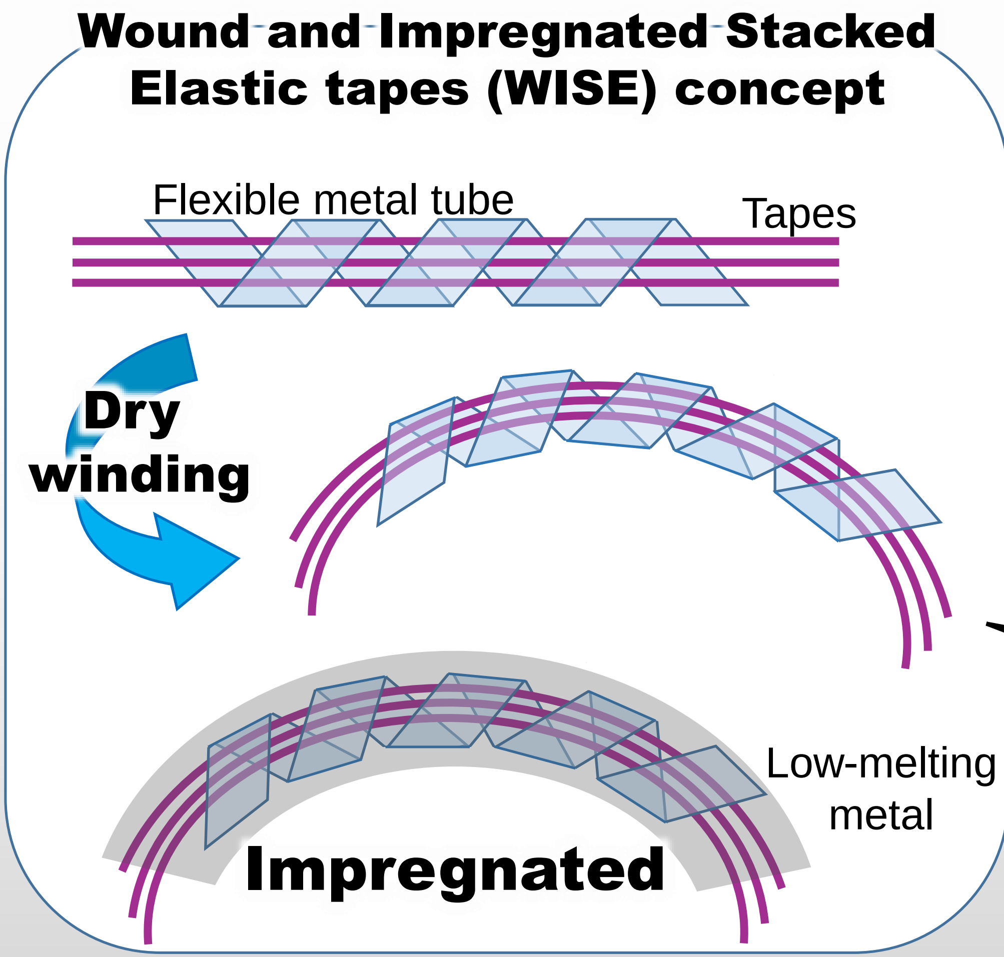
TEST RESULTS OF THE SECOND TRIAL PRODUCTION CONDUCTOR

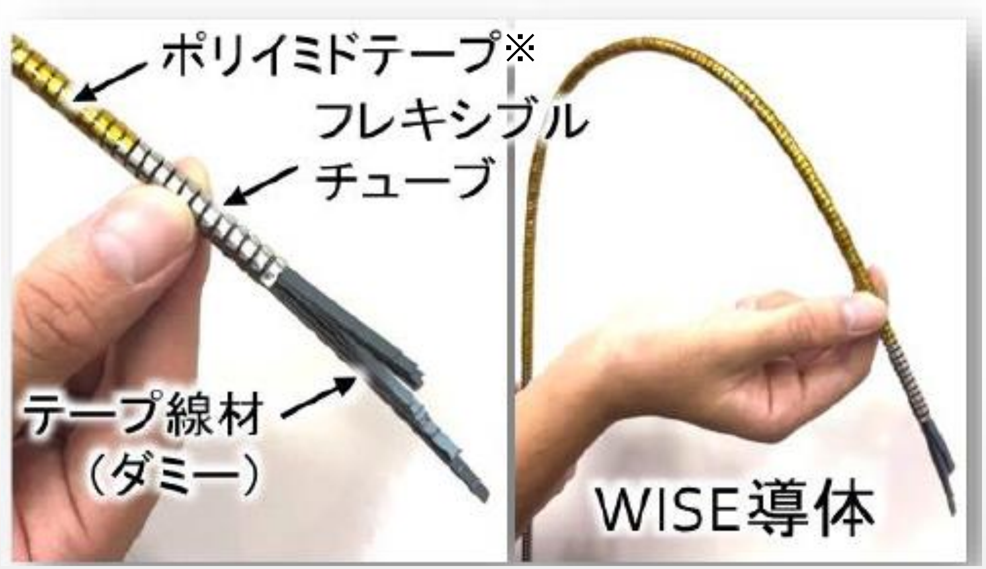




No rotation Ic : 1056 A
1 rotation / m Ic : 954 A

“Wound and Impregnated” on the WISE concept

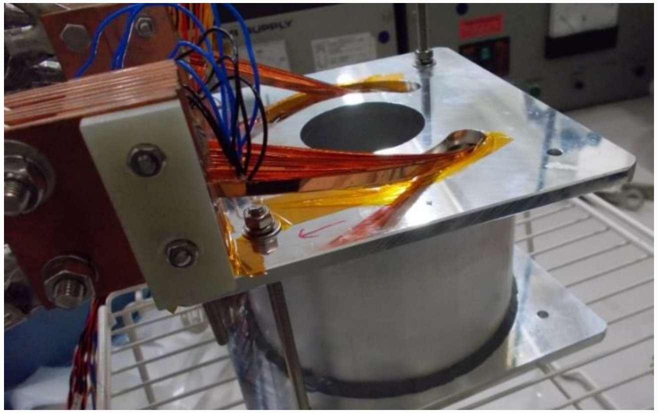


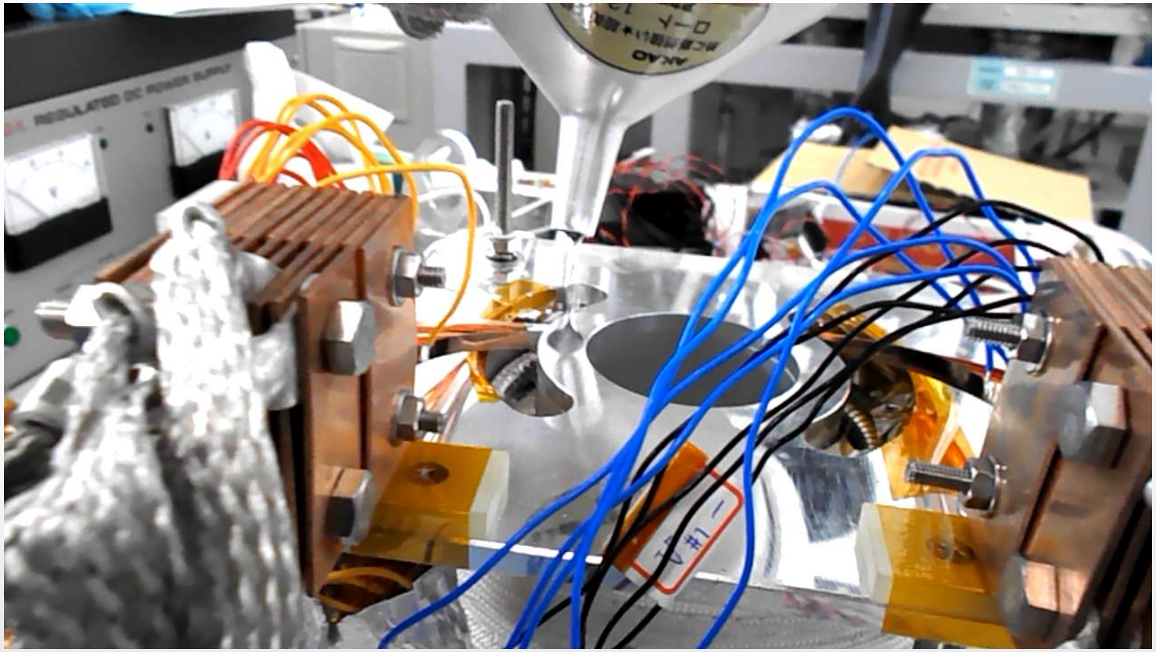


※ポリィミドテープなしも可

Tapes naturally deform
⇒ No hard bending

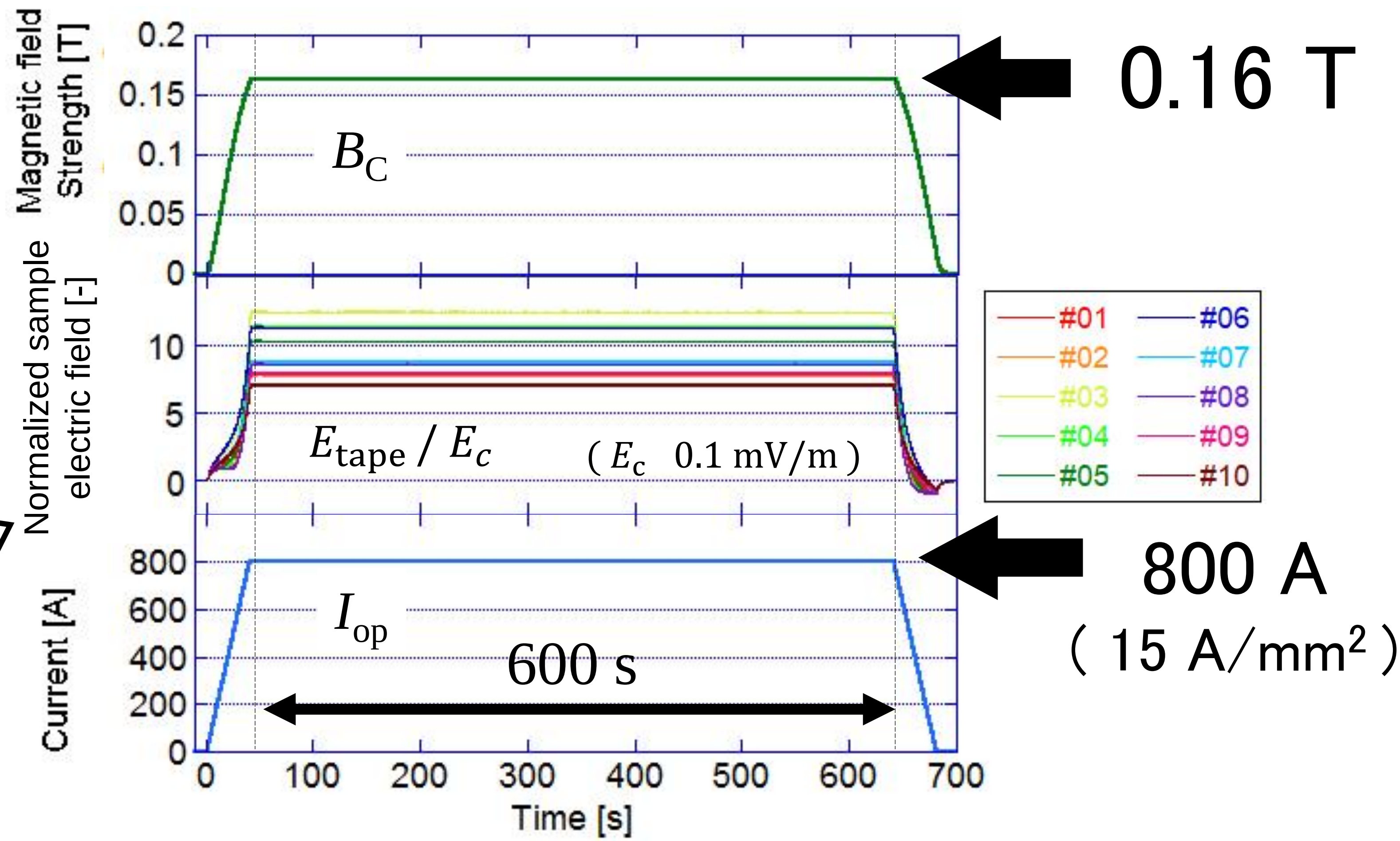
Wound and Impregnated



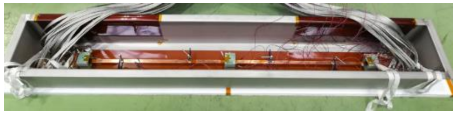


Achieved 0.16 T @ 800 A, 77 K

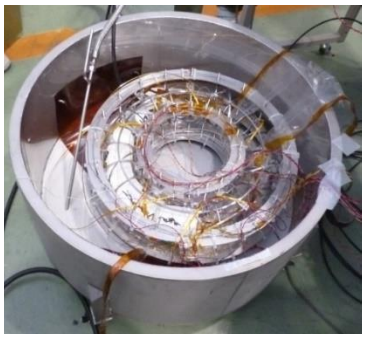
Despite $\frac{E_{\mathrm{tape}}}{E_{\mathrm{c}}}$ ~10, quench did not occur.



Development Plan of HTS-STARS Conductor for the Next-Generation Helical Device

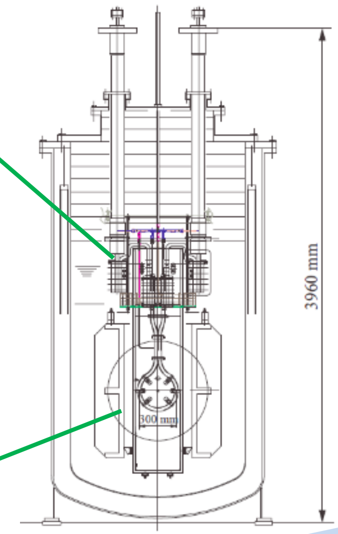


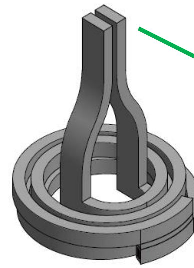
Short sample (~3 m) test
Straight @77 K, 0 T



Short sample (~3 m) test
Bent radius :1-0.2 m
@77 K, 0 T

Short sample (~3 m) test
Coiled (ϕ0.5 m) @20 K, 9 T





Short sample (>3 m) test
Coiled (ϕ0.6 m) @20 K, 13 T

Mechanical lap-joint
(developed by Tohoku Univ.)

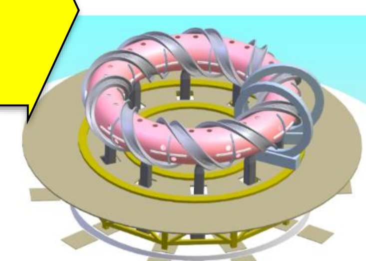
FY2019 | FY2020 | FY2021

Short length (~3 m) → Longer length (> 3 m)

Conductor test
Magnetic field 0 T → 9 T → 13 T

Long conductor (~10 m)

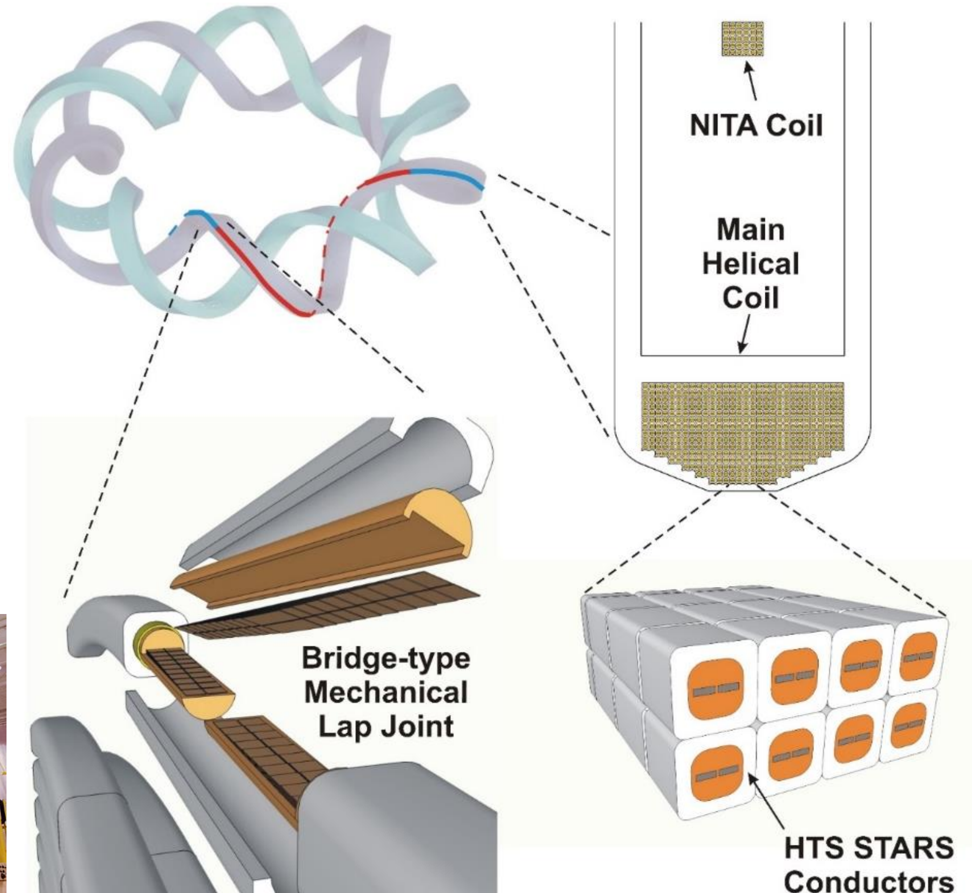
3D helical coil winding technology

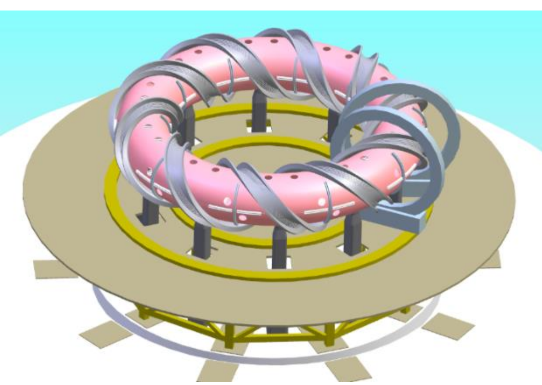


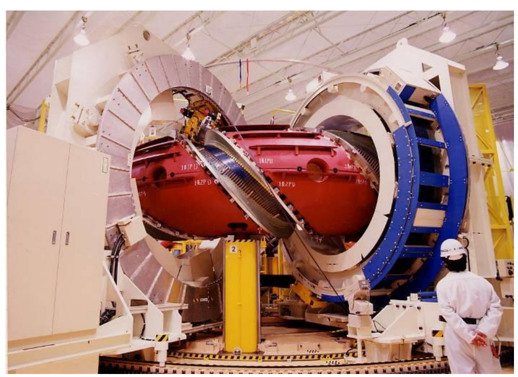
Helical Coil Winding

Continuous vs. Joint

- **Continuous Winding**
  - **Experience by LHD construction**
  - **Long conductor (~ 1 km) necessary**
  - **Optimized twisting angle**
- **Joint-Winding**
  - **Challenging but rewarding**
  - **~ 4000 joints = high risk**
  - **Industrial robot (manufacturing and inspection)**

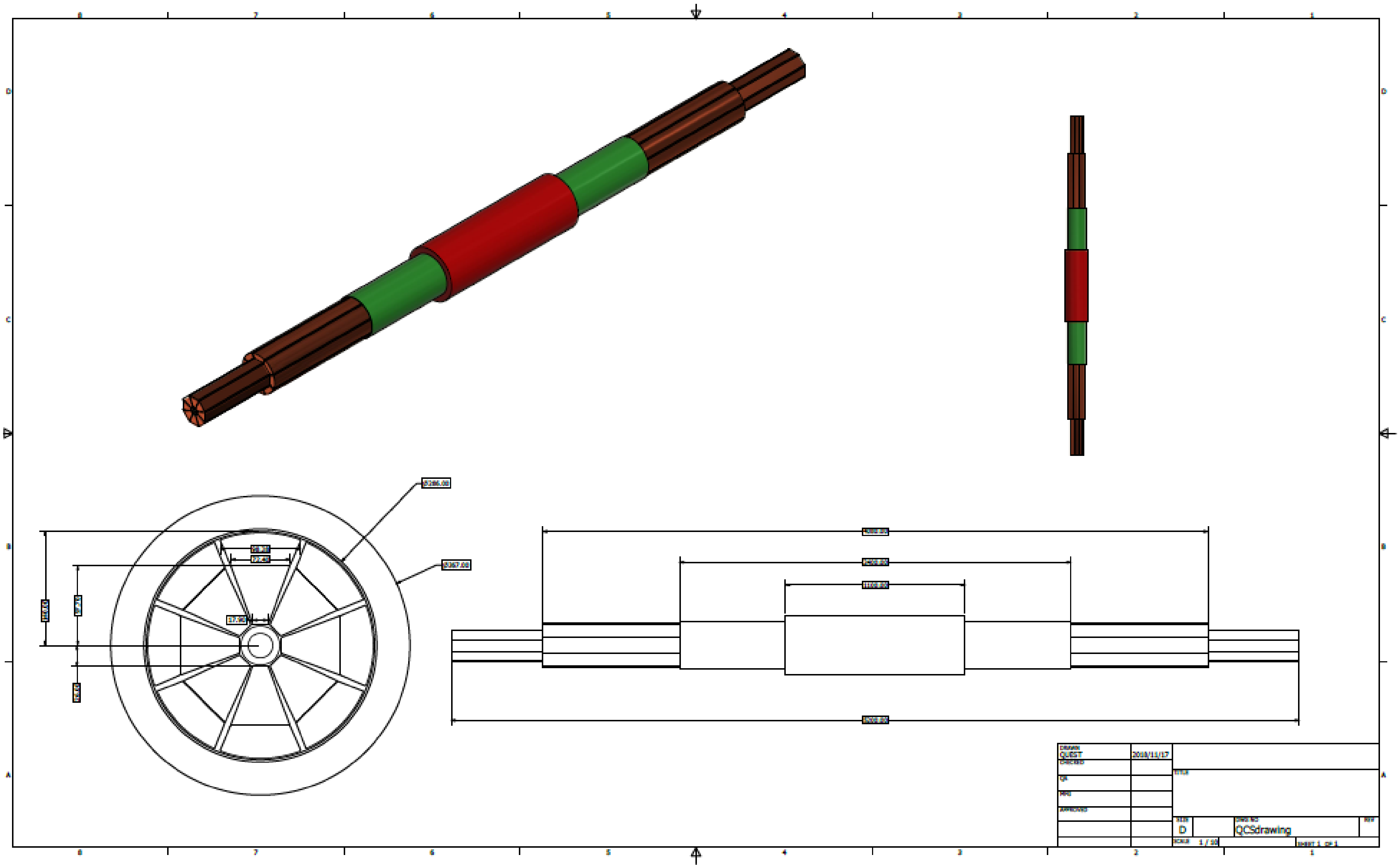






NIFS 次期計画への適用をめざした大電流 HTS 導体の開発

- 高電流密度 HTS 導体
  - 80 A/mm^2 目標
- 3種類の候補導体を並行して開発に着手
  - STARS, FAIR, WISE
- クエンチ保護
  - 短時定数遮断、早期検出
  - ２次巻線によるクエンチバック
  - 無絶縁巻線の可能性（励磁時定数、コイル全体温度上昇等、課題）
- ヘリカルコイル巻線
  - 最適な連続巻線方法の考案
  - ヘリカルコイルの傾き角調整によるエッジワイズ曲げ歪の低減
  - 接続巻線を早期に確立（産業用ロボットによる施工）
- 今後の開発計画
  - 短尺試験、長尺試験 ➔ ３年以内ターゲット
  - コイル試験、ヘリカル巻線 ➔ ５年以内ターゲット

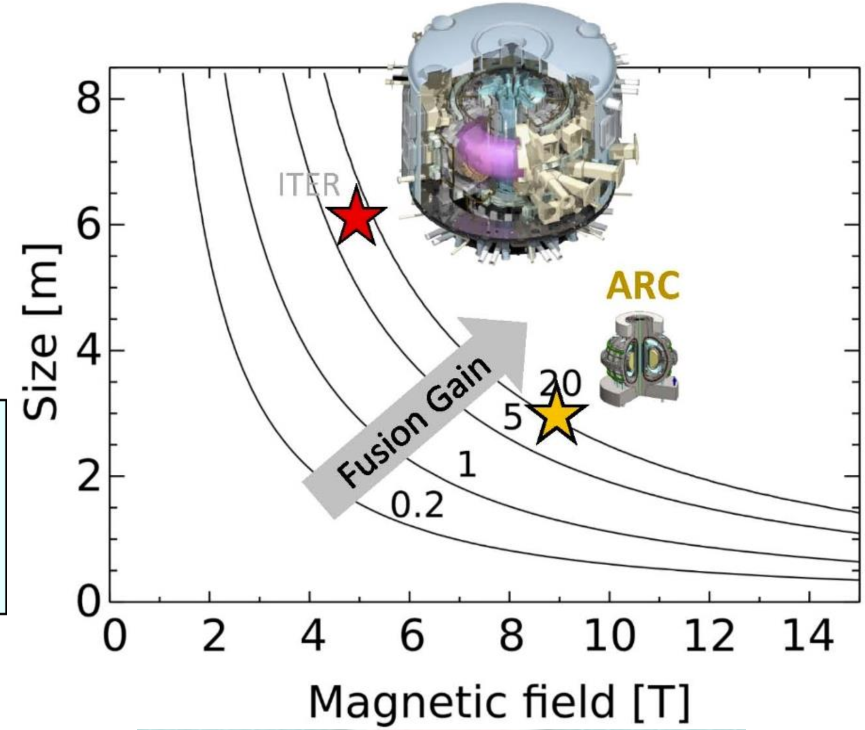

QUEST
D
QCSdrawing

ARC & SPARC @MIT

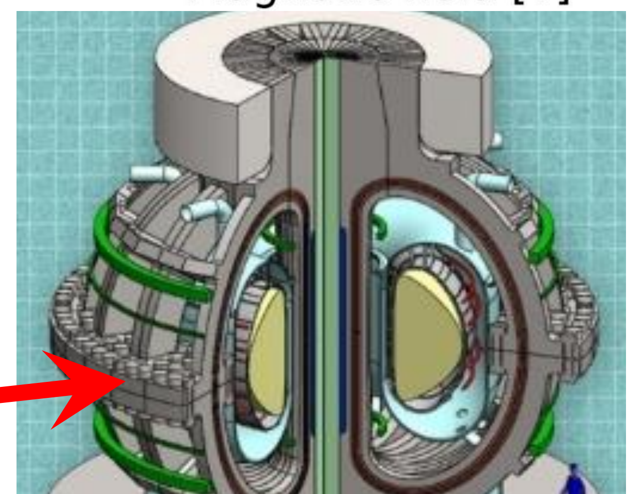
$$\frac{P_f}{V_P} \propto 8\langle p\rangle^2 \propto \beta_T^2 B_0^4$$

$$nT\,\tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$$

$$\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N^{\,2}\epsilon^2}{q_*^2} R B^4$$



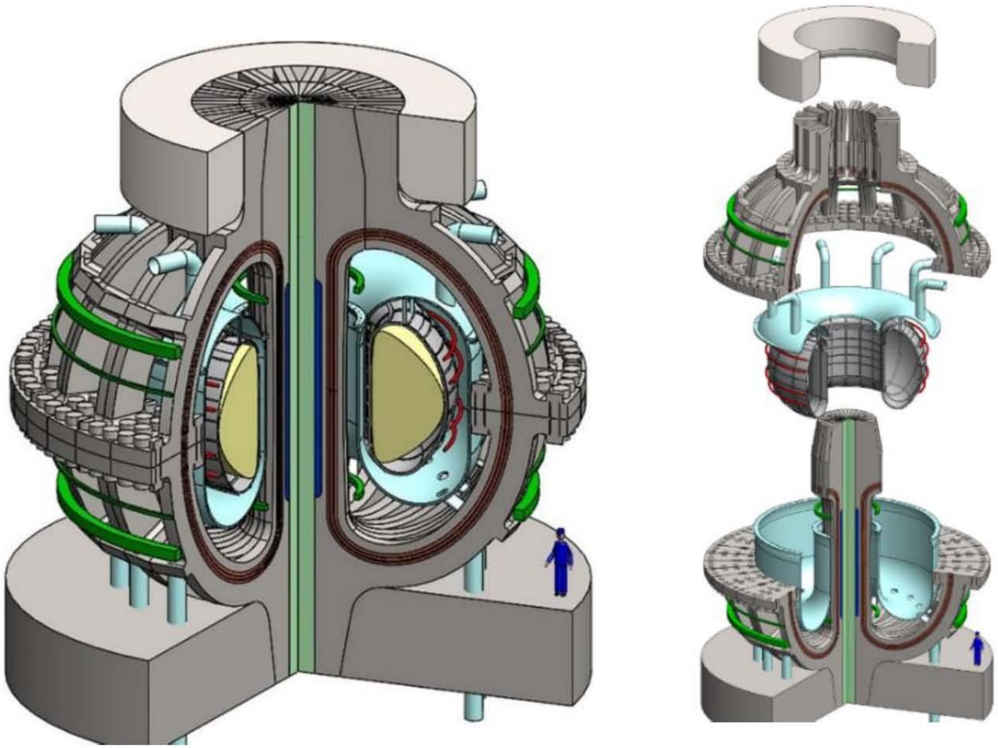
SPARC
R = 1.65 m, B_t ~ 12 T
P_f ~ 50-100 MW



ARC
R = 3.3 m, B_t ~ 9 T, B_{max} ~ 23 T
P_f ~ 500 MW

ARC is a student-led fusion pilot plant concept that leverages high-field REBCO magnets to achieve numerous innovations at 10x smaller scale

PSFC

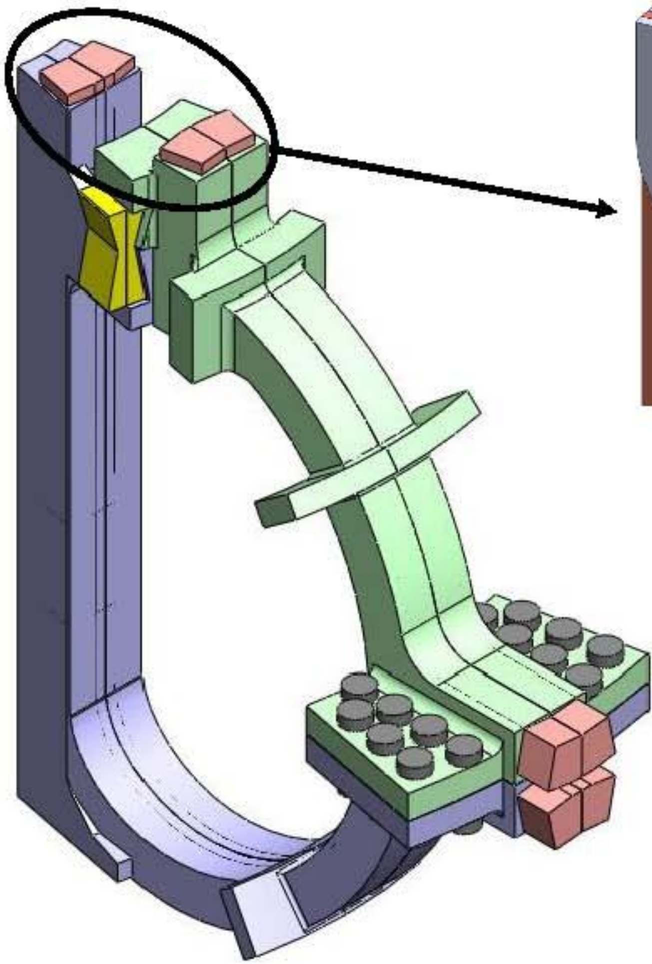


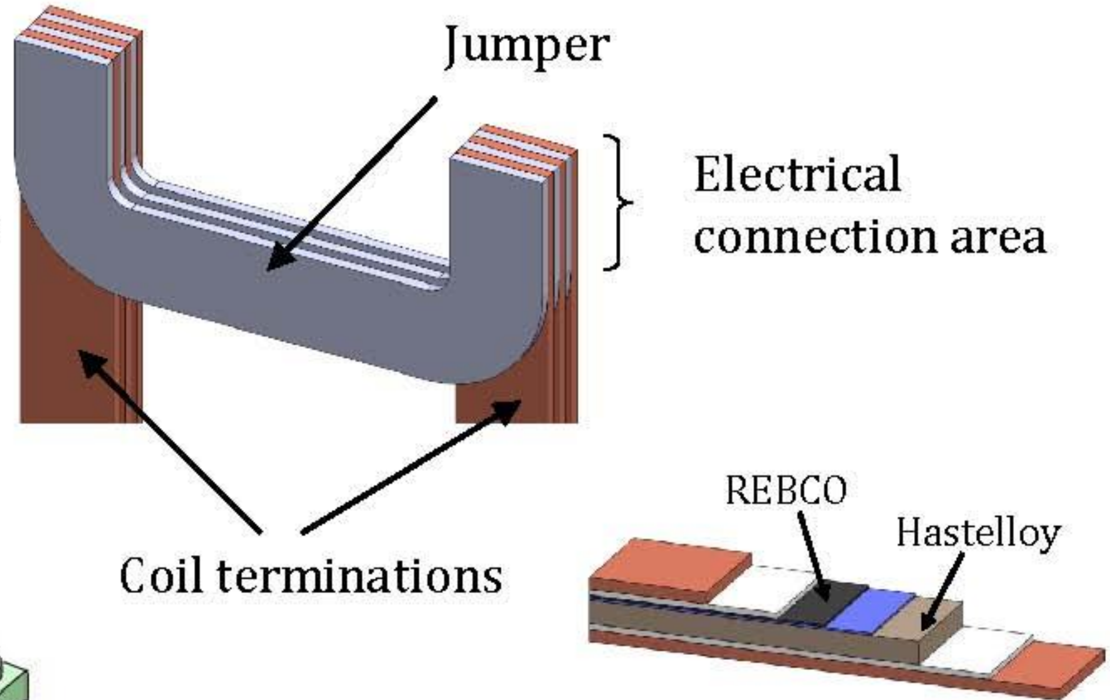
B.N. Sorbom, "ARC: A compact, high-field fusion nuclear science facility and demonstration power plant with demountable magnets," *Fus. Eng. and Design* **100** (2015) 378.

Design Parameters	Value
Fusion Power	500 MW
Total Thermal Power	700 MW
Conversion Efficiency	0.40 – 0.50
Net Electric Power	~200 MW
Plasma Gain, Q	>10
Major Radius, R	3.3 m
Inverse Aspect Ratio, ϵ	0.34
Toroidal Field, B_T	9.2 T
Plasma Current, I_p	8 MA
Bootstrap Fraction	>60 %
Normalized Beta, β_N	2.5
Avg. Plasma Temperature, $< T_e >$	14 keV
Avg. Plasma Density, $< n_e >$	1.75×10^{20} m^{-3}
Tritium Breeding Ratio	1.10
Plant Lifetime	~10 FPY

PSFC

Electrical joint: resistive terminations linked with "jumper" plate

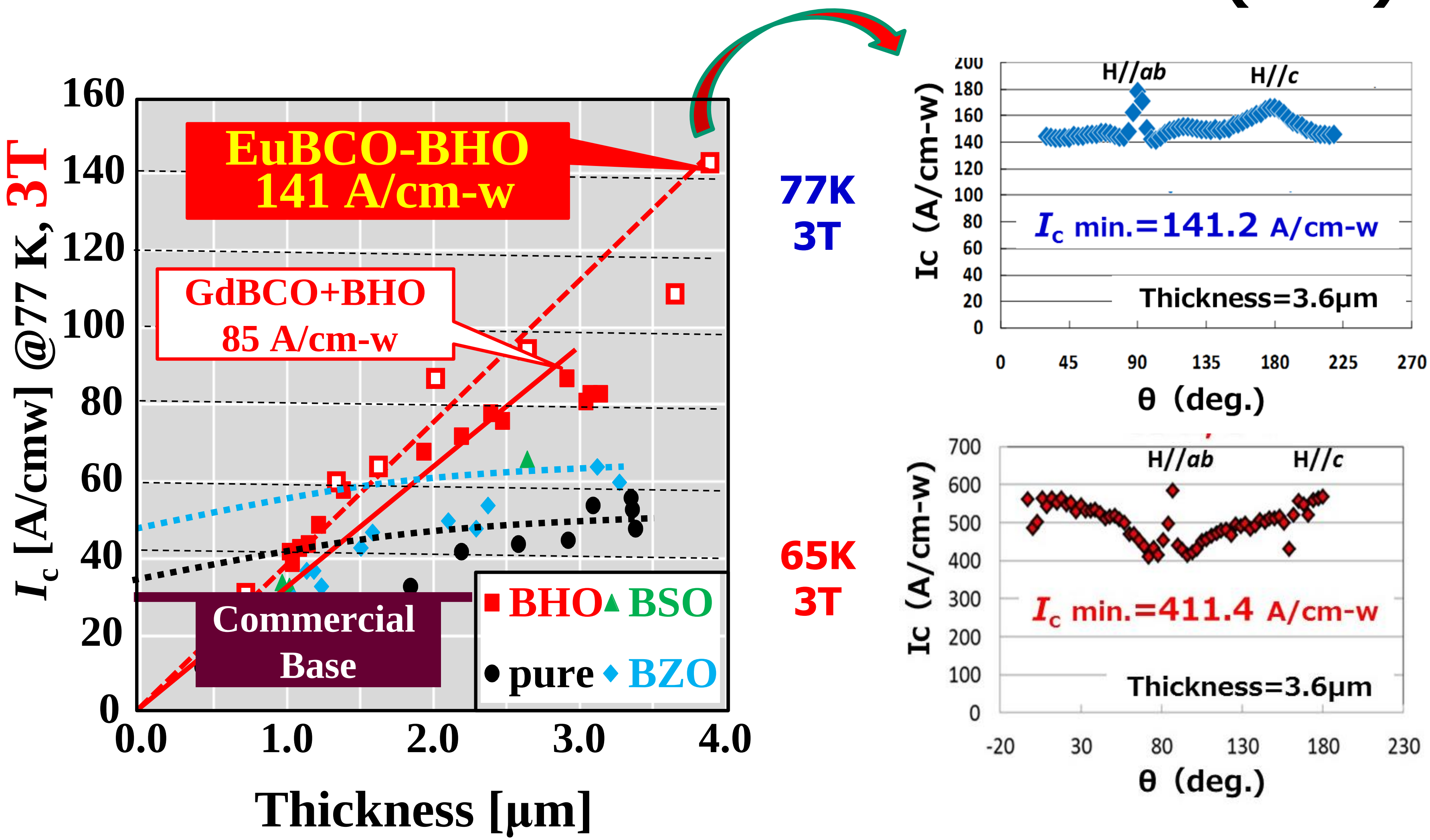




- Orientation of REBCO tape respect joint surface is critical
- Four electrical joint designs considered

Improvement of in-field I_c

Effective Combination of REBCO & BMO(APC)

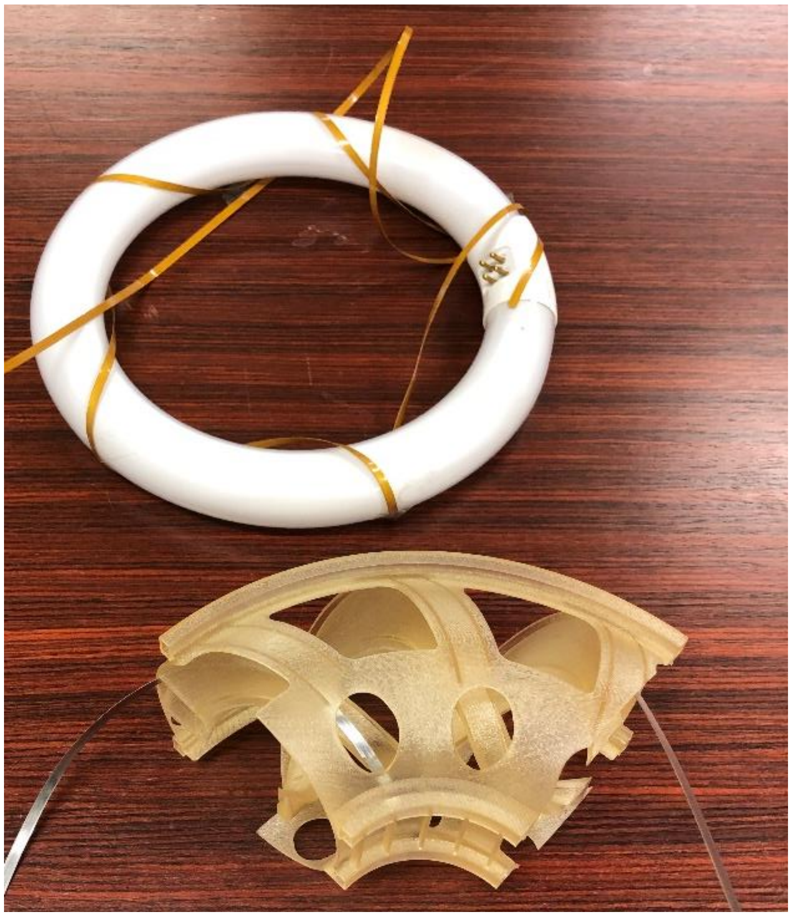


Courtesy of T. Izumi (AIST)

Extra Slides

HTS 導体を用いたヘリカル巻線に関する考察

- エッジワイズ曲げ ➔ フラットワイズ曲げ＋捻りで代用
- ヘリカル巻線方向に対して捻りを調整
  エッジワイズひずみを最小限に抑える
- フラットな導体断面 ➔ フラットワイズに曲げやすい



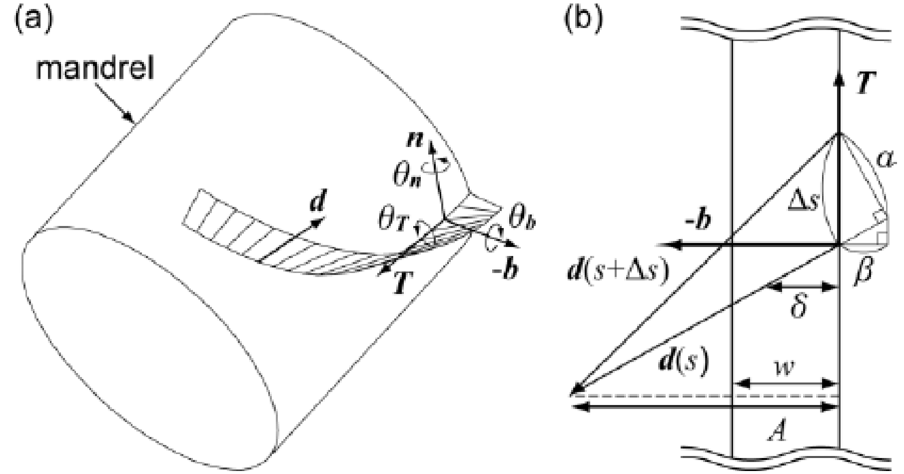
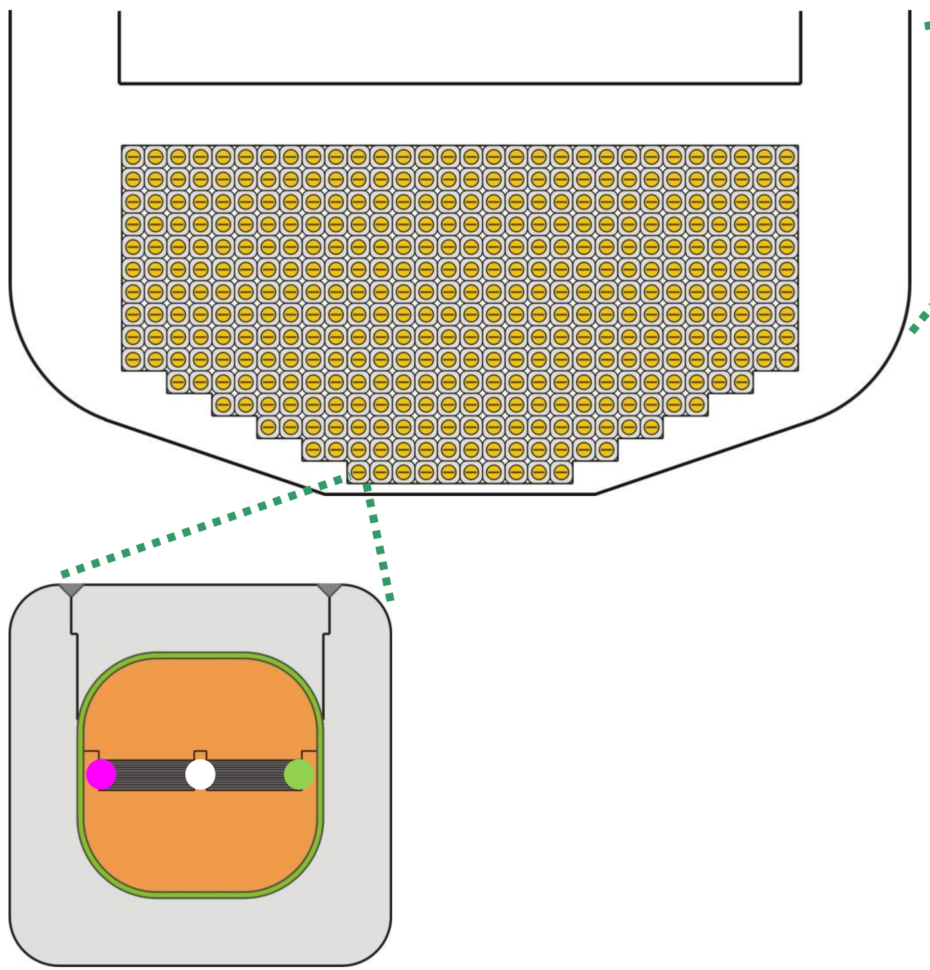
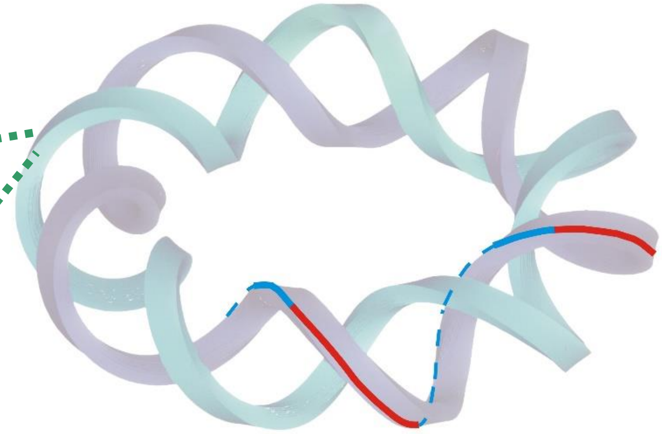


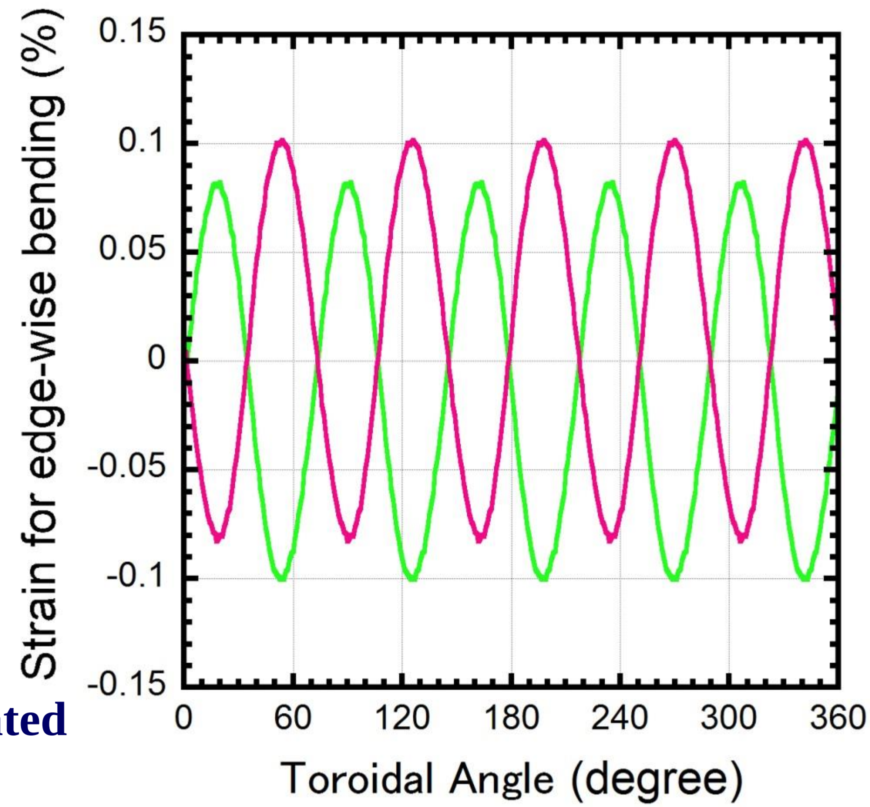
Fig. 2. (a) Conceptual view of three-dimensional winding. (b) Conceptual view of developed surface of tape.

K. Takahashi, N. Amemiya, et al., IEEE TAS 22 (2012)

Edgewise strain on the HTS tape in the FFHR-d1 helical coils

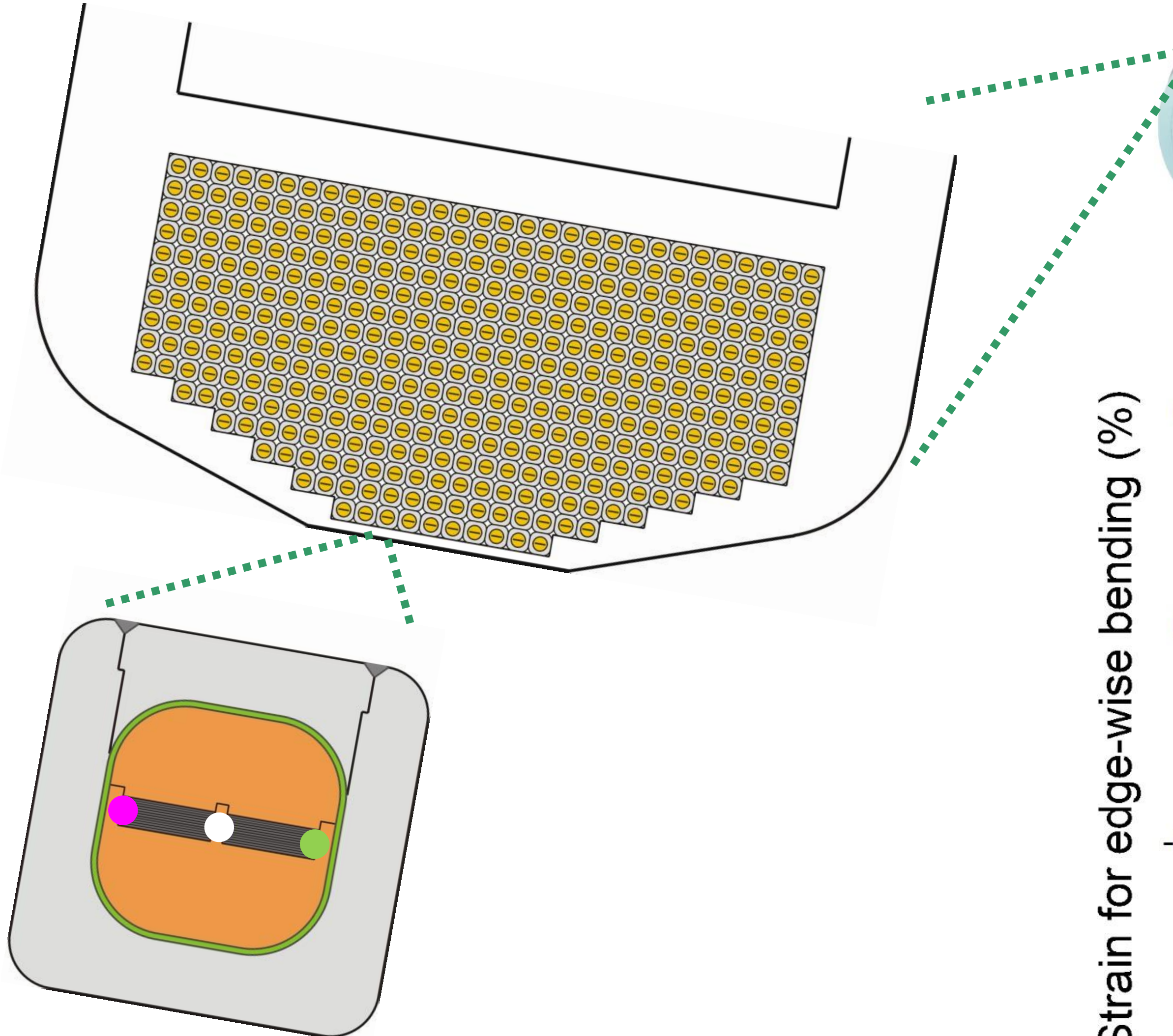


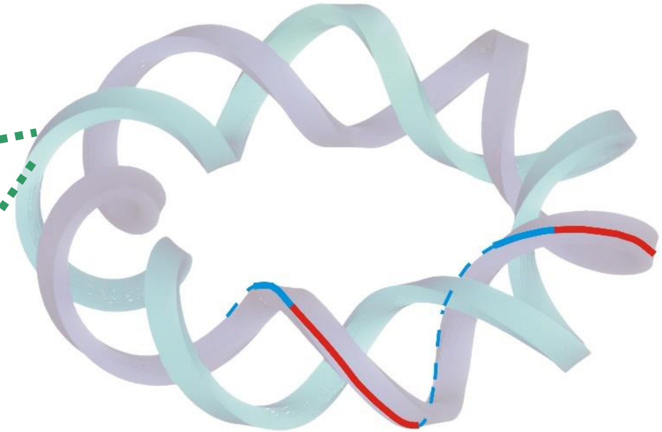


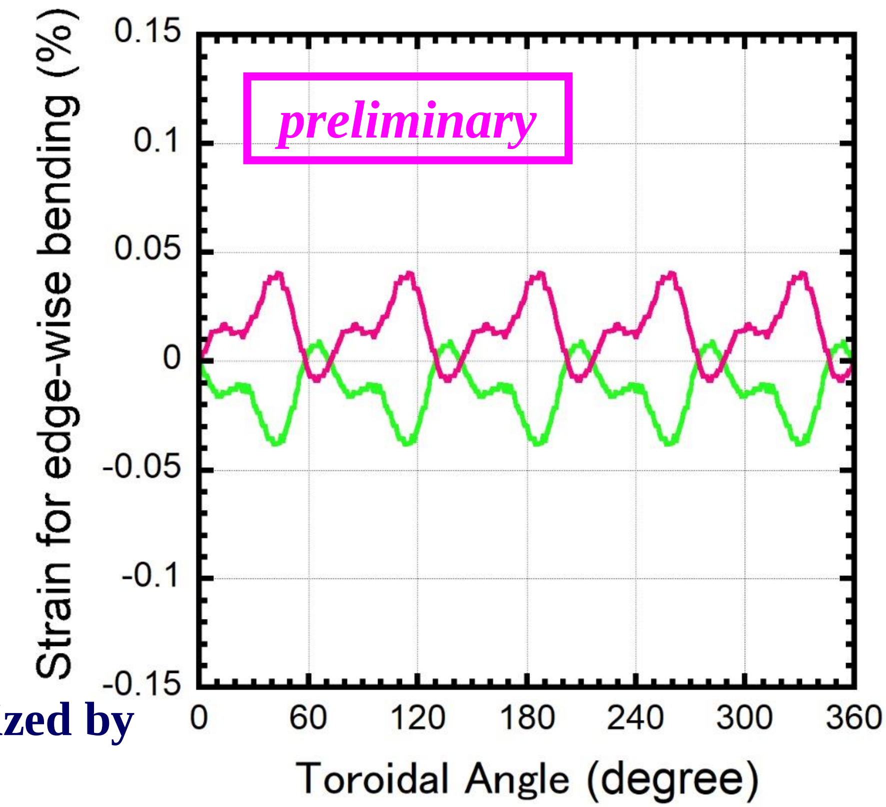


- Difference of path length inside a conductor is calculated for evaluating edgewise strain

Edgewise strain on the HTS tape in the FFHR-d1 helical coils







- **Difference of path length (edge strain) can be minimized by tilting the whole winding package**