Summary
Magnet Session

Nagato Yanagi

National Institute for Fusion Science

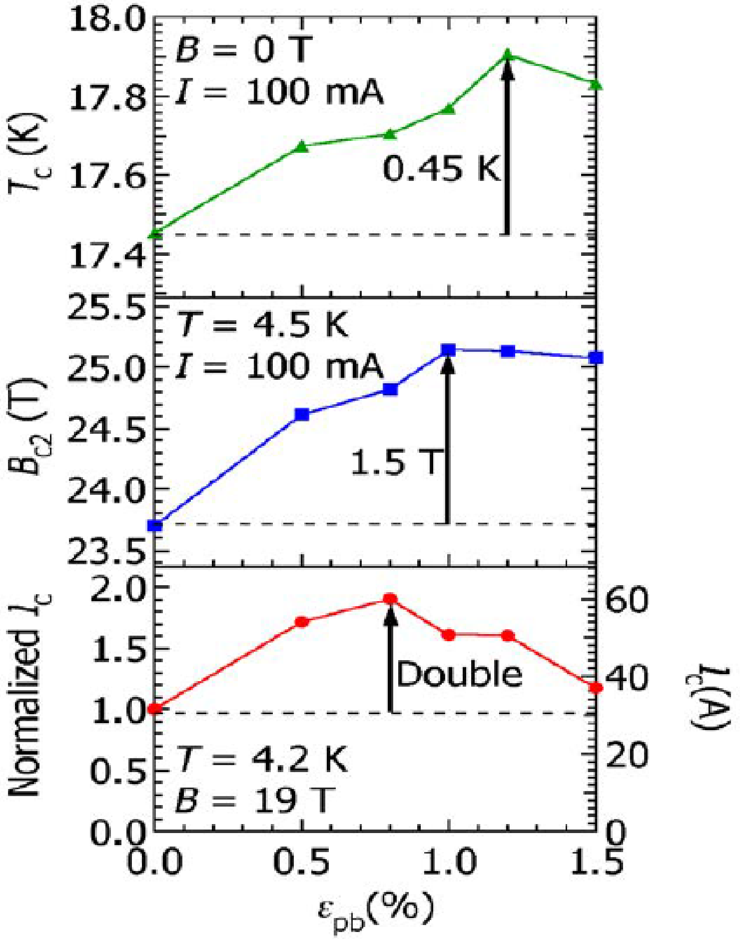
9th DEMO and Fusion Plants Workshop
June 10, 2025, Aomori, Japan

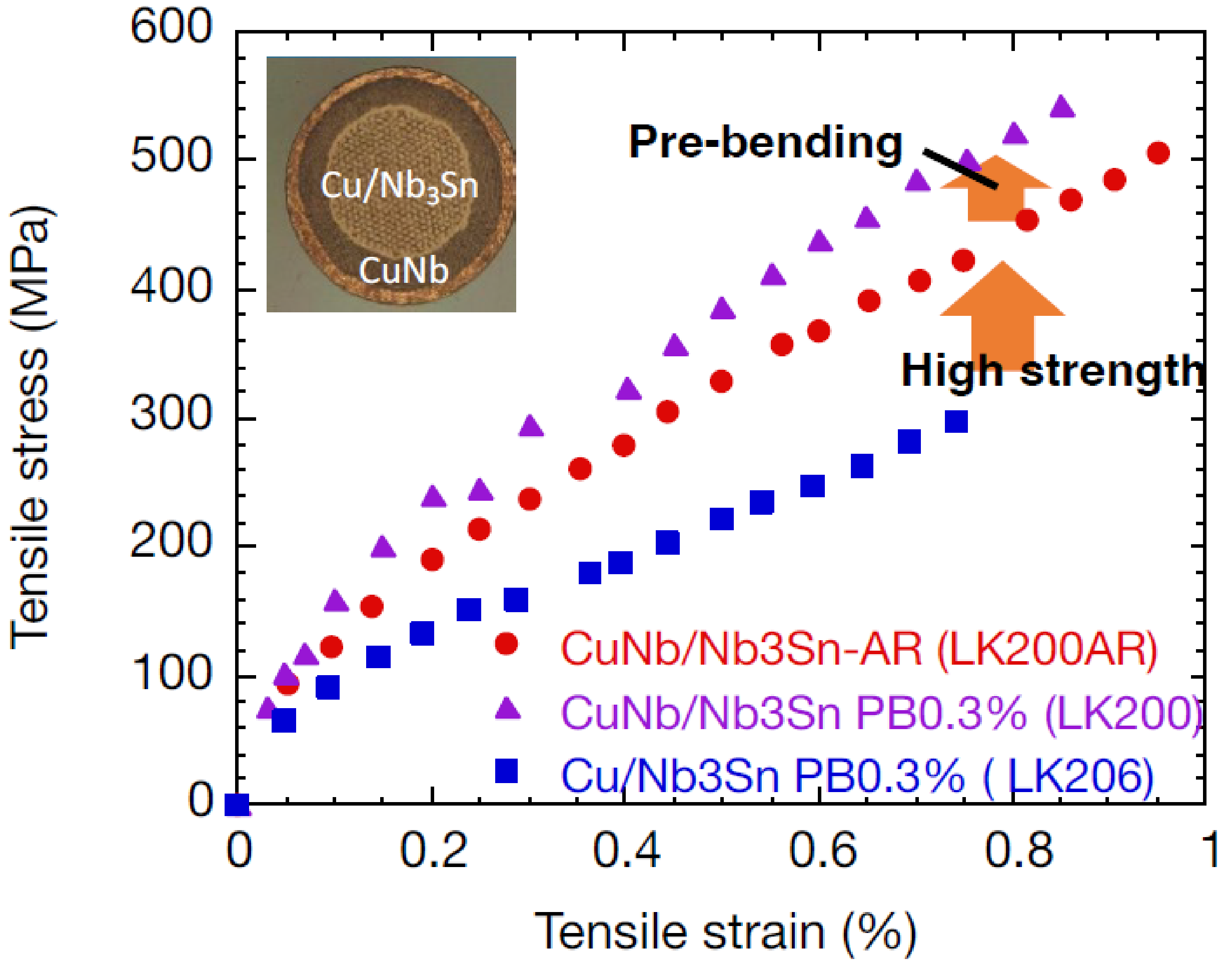
DAY 1: Tuesday, June 10, 2025 - MAGNETS				
Time	Length	Subject	Speaker suggestion	General comments
09:30 - 09:35	5 min	Introduction	Nagato Yanagi (NIFS)	
09:35 – 10:15	40 min	Topic 1 *Development of LTS and HTS wires*	Satoshi Awaji (Tohoku Univ.)	
10:15 - 10:55	40 min	Topic 2 *Magnet development for national project 1 (STEP)*	Ezzat Nasr (UKAEA)	
10:55 - 11:10	15 min	***Coffee Break***		
11:10 - 11:50	40 min	Topic 3 *Magnet development for national project 2 (JA-DEMO)*	Hiroyasu Uto (QST)	
11:50 - 12:30	40 min	Topic 4 *Challenges on REBCO Conductor and Magnet*	Seungyong Hahn (SNU)	
12:30 - 13:50	80 min	***Lunch Break***		
13:50 – 14:30	40 min	Topic 5 *Test facility 1 (CFTER/CRAFT/BEST)*	Xiaohui Guan (ASIPP)	
14:30 – 15:10	40 min	Topic 6 *Test facility 2 (Rep. of Korea)*	Keeman Kim (KENTECH)	
15:10 – 15:25	15 min	***Coffee Break***		
15:25 – 16:05	40 min	Topic 7 *Irradiation*	Arata Nishimura (NIFS)	
16:05 – 16:25	20 min	Discussion	Seungyong Hahn (SNU)	

Issues for large-current conductors / magnets for fusion

• SC Wires / Tapes (LTS, HTS, others, hybrids)	○
• Cabling (twisting / stacking)	?
• Insulation / No insulation / Partial insulation	○
• Cryogenic stability / Cooling	?
• Mechanical stability (EM forces)	○
• Neutron irradiation	○
• Coil winding (3D)	○
• Joint (remountable)	○
• Quench protection	○
• Testing	○
• …	

Improvement of superconducting and mechanical properties by repeated bending treatment (**pre-bending** treatment)

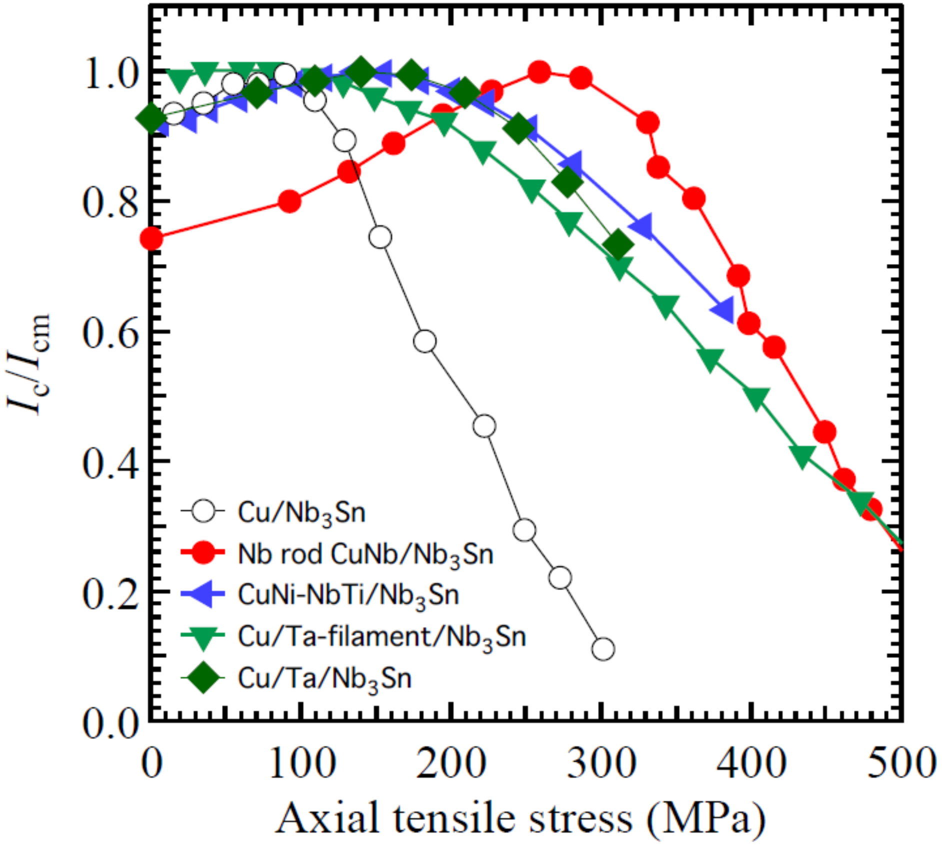


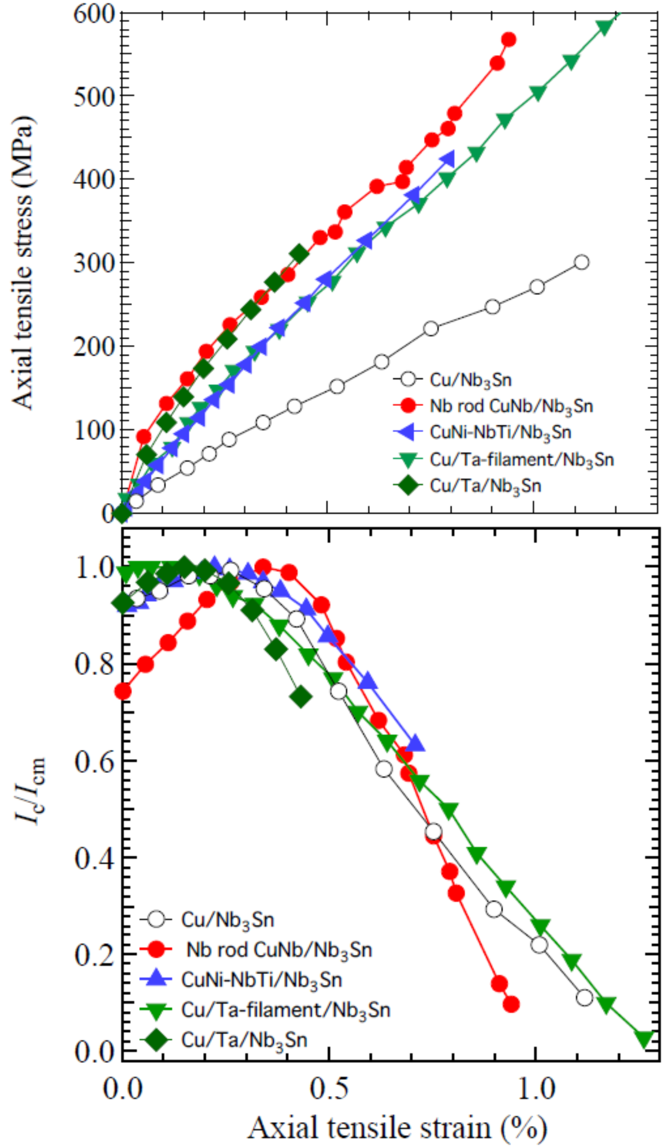


- Pre-bending (repeated bending) improves all superconducting parameters because of a change of residual strain state.
- It also makes steeper of stress-strain curves due to work hardening.

Satoshi Awaji (Tohoku Univ.)

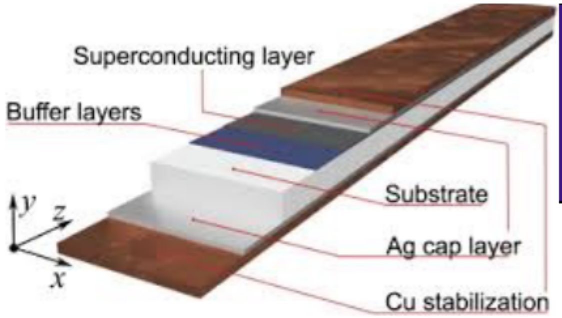
High strength Nb_3Sn





- From application view point,
  Stress is important.
- From material view point,
  Strain controls property.
- Steep SS curve reduces strain

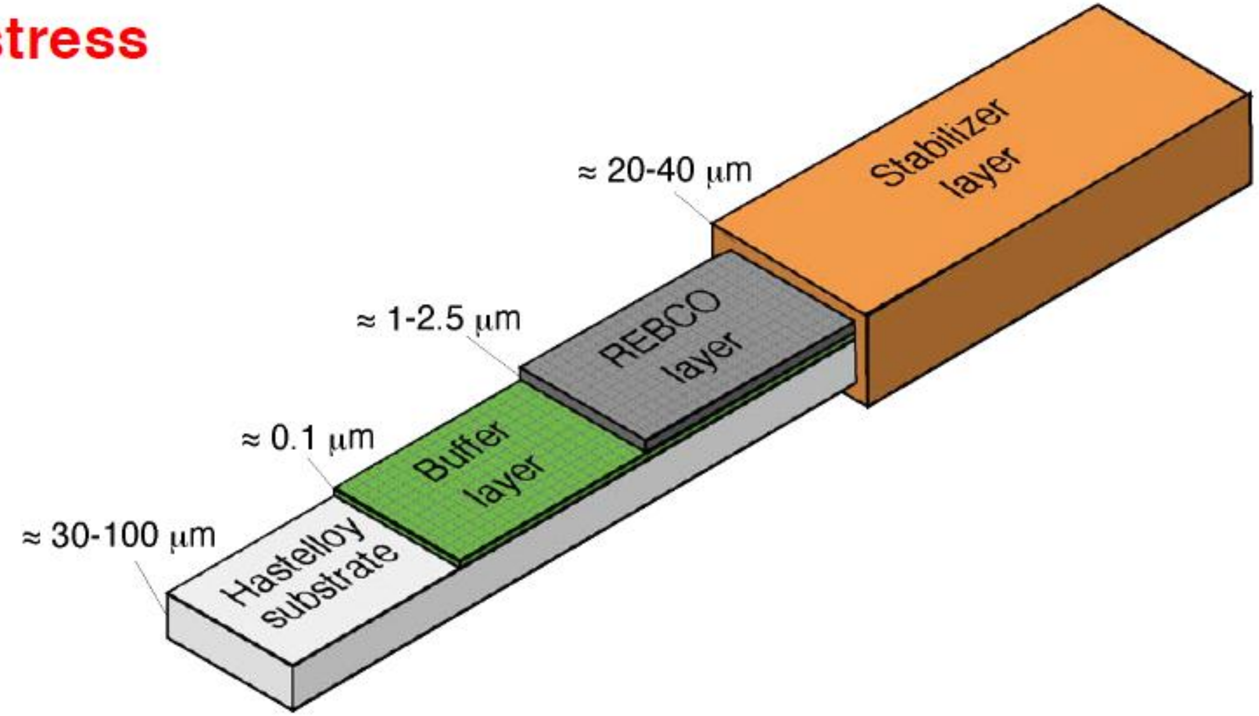
Commercial REBCO tapes



	RE	Method	t_SC (um)	APC	Template	Sub	t_sub (um)	Stabilizer	t_stab (um)
Fujikura	Gd	PLD	≈2	-	IBAD-MgO	Hastelloy	75	Cu plated	10-40 x 2
	Eu		≈2.5	Hf			50		
Furukawa-SP	Y,Gd	CVD	≈1.5	Zr	IBAD-MgO	Hastelloy	(30), 50	Cu plated	20,40 x 2
SuNAM	Gd	RCE	1.3-1.8	-	IBAD-MgO	Hastelloy /SS	60	Cu plated	5-10 x 2
FFJ	Y	PLD	2.3-2.5	Y_2O_3	IBAD-MgO	Hastelloy	40, 60	Cu plated	1-50 x 2
	RE		2.3-2.7	Hf					
SST	RE	PLD	≈2.4	Hf, Zr	IBAD-MgO	Hastelloy	30,50	Cu plated	5-10 x 2
Bruker	Y	PLD	1.5-1.7		ABAD-YSZ	SS	100	Cu plated	40 x 2
AMSC	Y,Dy	MOD	0.8-1.2	Dy_2O_3	RABiTS	NiW	≈100	Cu, Brass, SS laminated	50 x 2
THEVA	Gd	PVD (EB)	≈2.5	-	ISD-MgO	Hastelloy	50, 100	Cu PVD / laminated	30, 40, 100 (lamination) <20 x 2 (PVC)
SEI	Gd	MOD		Zr, Hf	Textured-Cu	SS	100	Cu plated	20 x 2

Issues of REBCO tapes

- ✓ **Delamination** and the local degradation related to multilayer structure
- ✓ **Screening current induced field and stress**
- ✓ **Piece length**: Typically, 2-300 m
- ✓ **Protection** from the hot-spot



INBOARD BUILD CHALLENGE

Design Driving

REMOUNTABLE JOINTS

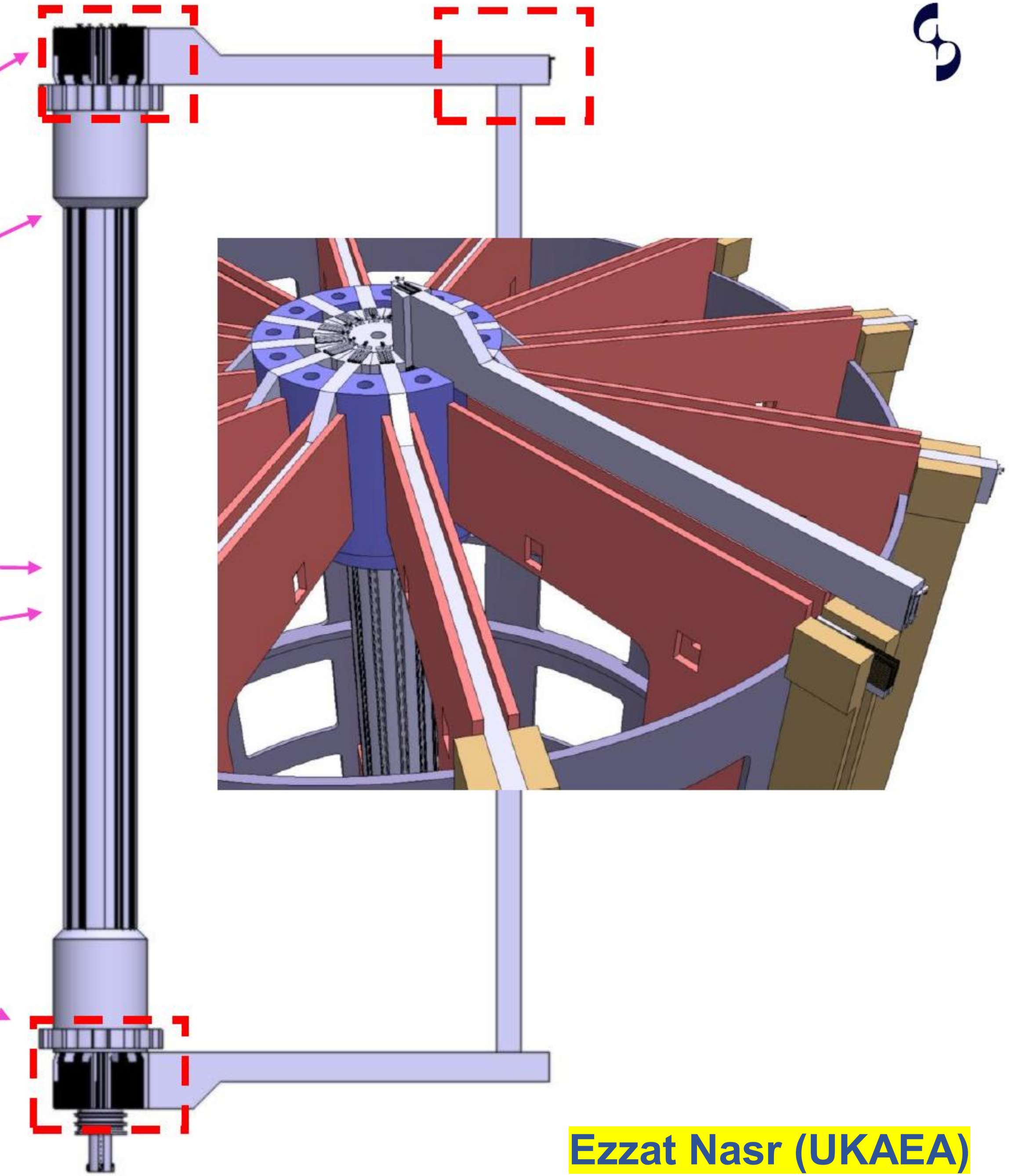
CAPTIVE PF/CS COILS

HIGH NEUTRON FLUX

HIGH FIELD, CURRENT DENSITY

STRUCTURAL CONNECTION

REMOTE OPERATION



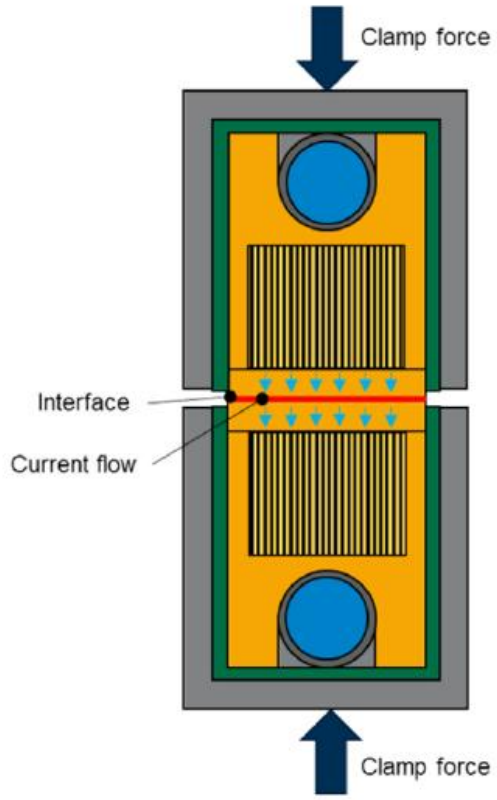
Ezzat Nasr (UKAEA)

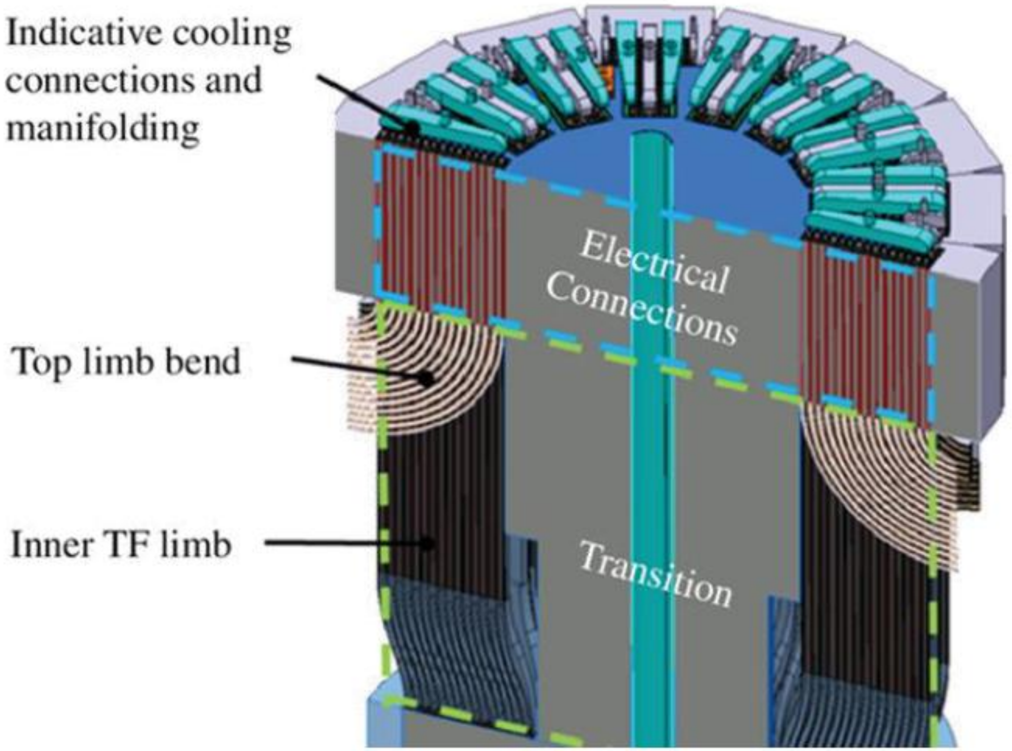
REMOUNTABLE JOINTS

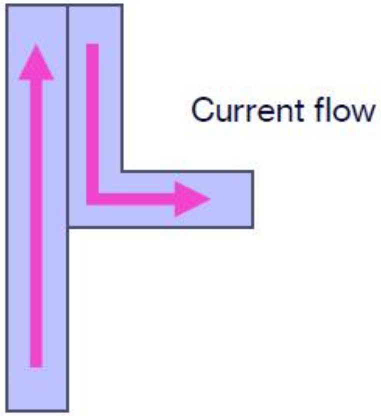
Design Development

Key Architecture Decisions:

- ❑ Praying hands
- ❑ Interleaving pancakes
- ❑ Clamped edge to edge joints







TF conductor design for JA DEMO

DEMO DESIGN
JOINT SPECIAL TEAM

QST

Design target on JA DEMO:

✓Bt=6T at Rp=8.5m
(requirement from system design)
✓T_{cs} > 6 K (Temp. margin: 1.5 K)

- Large TFC leads to increase coil inductance (long current decay time).
  ➔increase conductor current (83kA)

- The EM force of the DEMO magnets is quite higher than the ITER magnets.

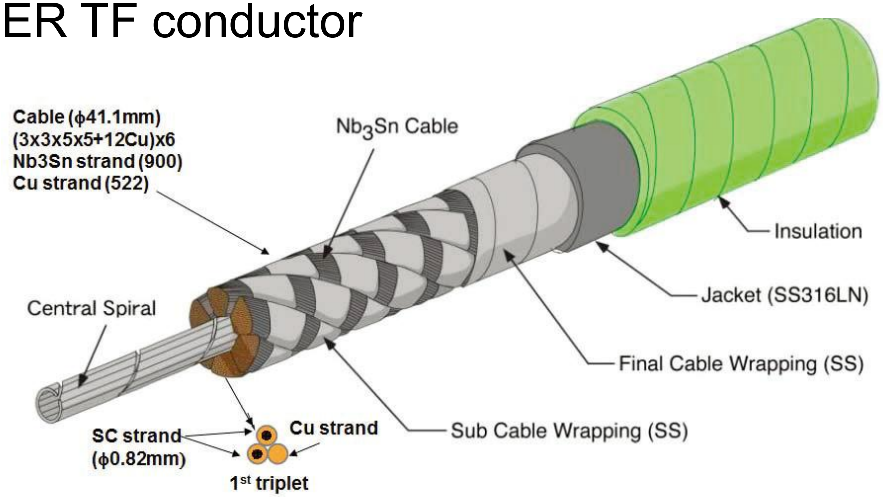
⇔In ITER conductor testing, the performance degradation is thought to be caused by EM forces and strain.

Issue

Hiroyasu Uto (QST)

- Development of high current conductors on high EM forces and strain

ITER TF conductor



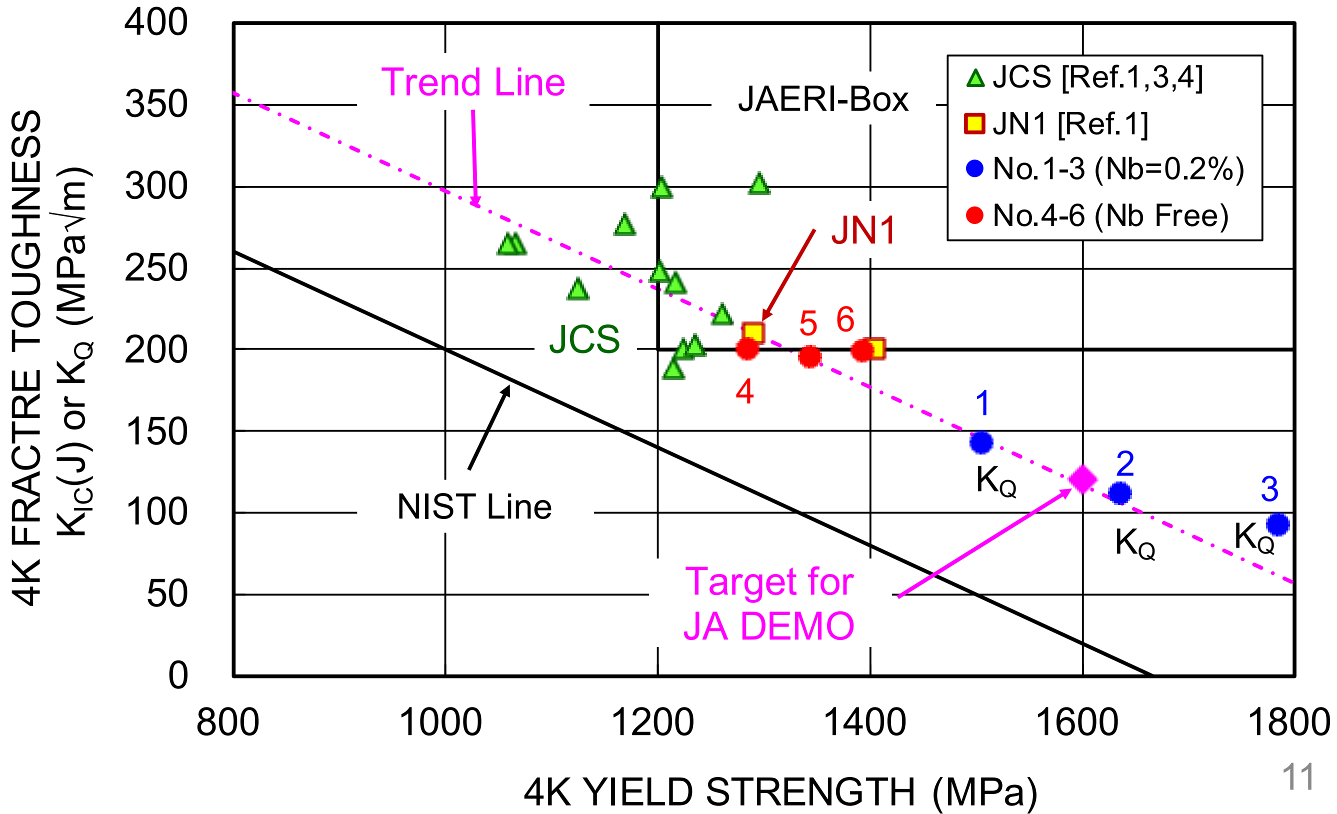
	ITER	JA DEMO
SC strand	Nb_3Sn	Nb_3Sn
Number of TFC	18	16
B_{tmax}	11.8 T	13.9 T
Conductor current	68 kA	83 kA
EM force (B x I)	802 kN/m	1154 kN/m
N. SC strand	900	1512
N. Cu strand	522	906
Cable diameter	39.7	50.4

x 1.5

Current status of Cryo. Steel R&D

- Trial production and evaluation of new materials
  - Results:
    - ✓ YS increases with Nb due to finer grain
    - ✓ Nb exhibits brittle behavior → requiring further investigation
    - ✓ V to strength increase is small → No V

We continue evaluation of other candidate materials having higher N content to determine basic chemical compositions of high-strength materials for DEMO based on these results.



Higher magnetic flux supply by CS option - Concept of Hybrid CS -

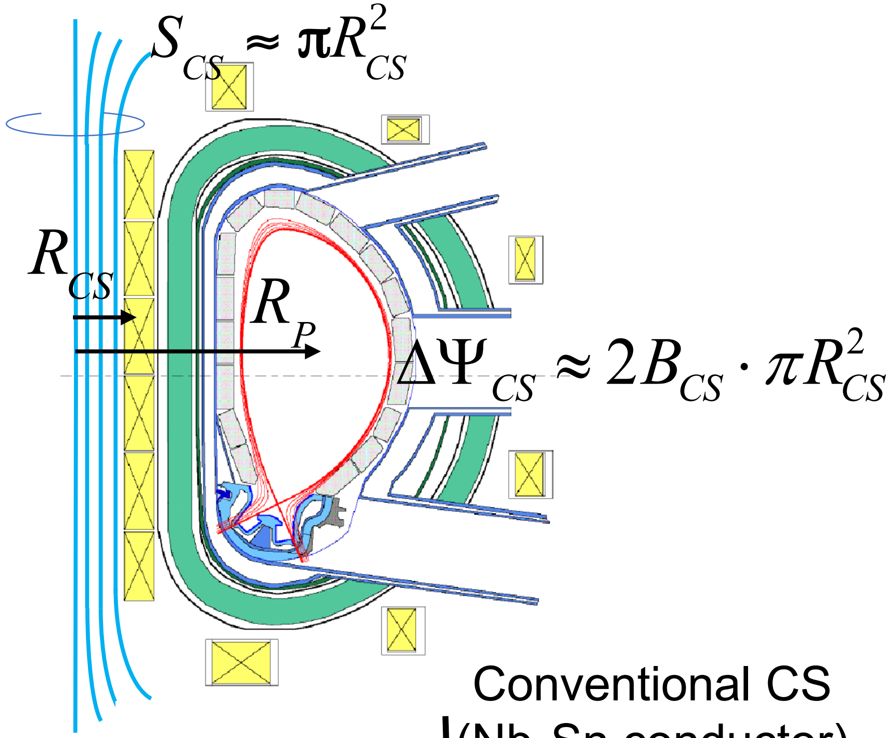
DEMO DESIGN
JOINT SPECIAL TEAM

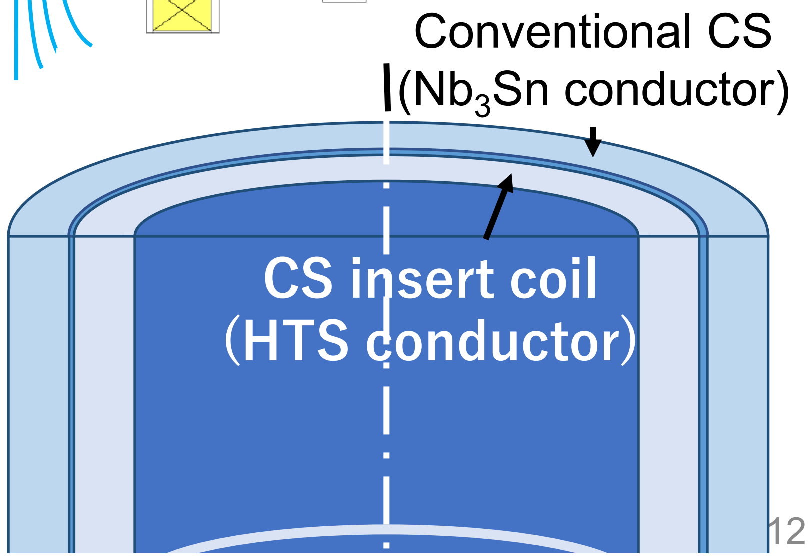
QST

- Center Solenoid (CS) has an important role for plasma current ramp-up (poloidal flux supply) and an effect on reactor size (CS radius, R_{cs}).
- Larger CS flux requires higher B_{cs} or Larger CS radius. (trade-off with conductor and reactor system design)
- To evaluate an effect of “Hybrid CS” on reactor downsizing, conceptual study of Hybrid CS was started.

❖ Hybrid CS concept would provide higher CS flux on same CS outer radius (~+20%).

❖ Design optimization and R&D of HTS conductor on insert coil and detailed evaluation of AC loss will be done.





Where We are with the Latest REBCO Magnet Technology?

*"We don't even understand spatial and temporal distribution of **currents (transport, screening and radial leak) in REBCO** layer yet **define critical current** of a magnet even calculate **mechanical stress**. The **quench analysis** sounds vague for an REBCO magnet.*

*"Even modern REBCO magnets are designed and operated without precise estimation on **electrical and mechanical limits** in confidence."*

Unfortunately, devil's in details

*"To date, REBCO magnets, either NI or insulated, that reach their full field over 30 T **more than twice** are rare, none under **routine** operation."*

Seungyong Hahn (SNU)

Observations on No-insulation Class REBCO Magnets

Mechanism

Single Coil

- Multi-turn to single-turn transition (Current Sharing)
- Other examples of CS: multi-filamentary, CORC

Magnet (Multi-coil)

- Electromagnetic quench propagation (thus fast) among magnetically coupled coils due to flux conservation

Categorization Challenges

- Ambiguity in damage
- Performance change vs. damage
- Quench initiation mechanism
- Hidden damage

Categorization of Quench Behaviors

Self Protected: identical EM behaviors before & after quench

LN2 Test

- MIT 0.45 T 40 mm 18 mH magnet (137 A/mm^2, bare-tape)

LHe Test

- CEA metal Insulated 6 mH magnet (830 A/mm^2, 60 quenches)
- MIT 7 T 78 mm 0.5 H magnet (895 A/mm^2, fast EM NZP confirmed)
- MIT 8.7 T 91 mm 2.4 H magnet (510 A/mm^2, sudden discharge)
- CAS 26.9 T 30 mm 1.5 H magnet (869 A/mm^2, 22 T retested)

Conduction-cooled Test

- SuNAM 4 T 203 mm 7.8 H magnet (255 A/mm^2, 15 K)
- SuperCoil 1.3 T 707 mm 0.5 H magnet (280 A/mm^2, 15 K)

Survived: minor damage in auxiliary pats without coils reassembly

LN2 Test

- SNU 0.12 T 40 mm 0.44 mH (105 A/mm^2, Ebonol insulated, lead damage)

LHe Test

- MIT 3 T 25 mm (1580 A/mm^2, lead damage)
- SuNAM 26 T 35 mm 12.8 H (404 A/mm^2, axial movement)
- NHMFL 13 T insert T 35 mm 2.8 H (439 A/mm^2, SCS observed)
- KBSI 0.6 T 16 mm (1055 A/mm^2, metal cladding, lead damage)

Failed: catastrophic damage, replacement after quench

LHe Test

- CEA 19 T/14 T 35 mm 42/36 mH (1337/2053 A/mm^2), minor buckling)
- LBC 45.5 T 14 mm, 50 mH magnet (1260 A/mm^2, SCS deformation)
- SuNAM 18 T 70 mm 19 H magnet (397 A/mm^2, DP replacement after sudden discharge)

Conduction-cooled Test

- SuperGenics, 7.8 T 61 mm 60 mH racetrack (990 A/mm^2, 40 K, support failure)
- SNU, 5 T WLS 50 mm 5.4 H racetrack (158 A/mm^2, 20 K, Ic degradation after long-term storage)

Discussion on Explanations and Solutions

Conductor

- Weak delamination force
- Dimensional unevenness

⇨ Conductor Improvement

Electrical

- Lead failure → flexible current lead
- "Slow" transition → quench "prediction (early detection)"
- Chemical or mechanical aging → long-term storage protocol

Mechanical

- Lorentz force in overband (axial motion) → controllable overband
- Uneven winding (local stress concentration) → controlled winding
- Compressible winding (buckling & excessive strain)
  → conductor improvement, controlled tension and support

Modeling

- Screening current modeling: boundary condition, current model
- Characteristic inductance with frequency dependenc)
- Buckling modeling: burn-out vs. buckling
- Compressible winding (buckling & excessive strain)
  → conductor improvement, controlled tension and support

Thank you for your attention!

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Cold test facilities for fusion magnet at ASIPP

Huajun Liu et al.

Institute of Plasma Physics Chinese Academy of Sciences, Hefei, China

Xiaohui Guan (ASIPP)

E-mail: liuhj@ipp.ac.cn

ASIPP devotes to the development of nuclear fusion technology. Serials SC magnet test facilities are under construction or have already been completed. These magnet test facilities will be open to the world.

CFETR TF magnet test facility
(~25m*15.5m*10m)

CFETR CSMC test facility
(6.5m (ID) *9m (H))

ITER CC test facility
(7.7m (ID) *11m (H))

EAST magnet test facility
(3.1m(ID)×4.2m(H))

Cold test facilities for fusion magnet at ASIPP

Huajun Liu et al.

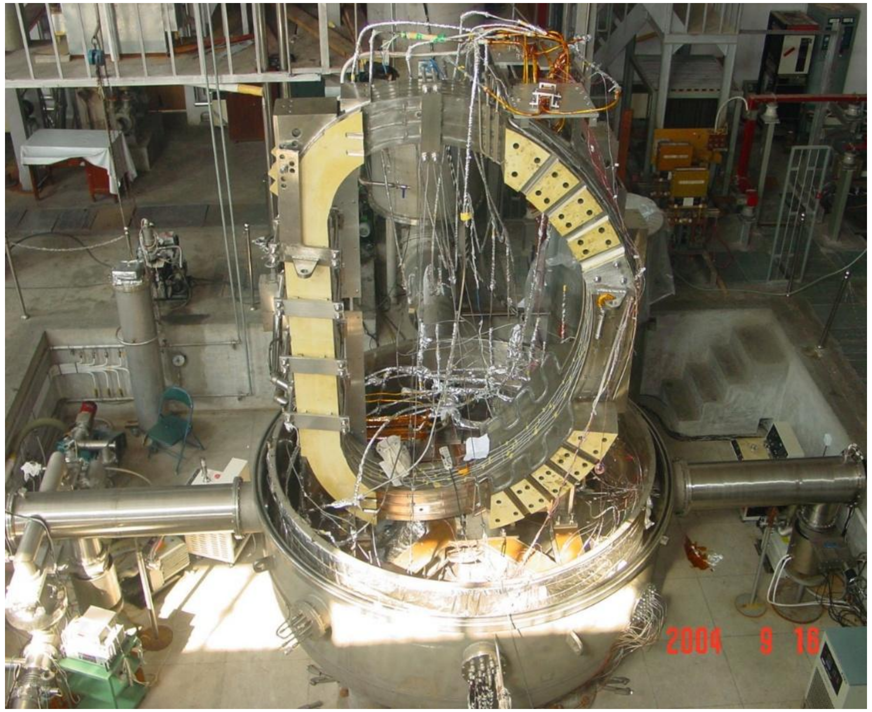
Institute of Plasma Physics Chinese Academy of Sciences, Hefei, China *E-mail: liuhj@ipp.ac.cn*

A large number of experiments for CFETR CSMC, EAST magnets, ITER current leads and etc. have been completed by the facilities.

- ✓ CFETR CSMC test in 2024
- ✓ ITER BCC and SCC FAT
- ✓ All EAST magnet performance tests (**29 times**) were completed during 2002 to 2005.

Test for CFETR CSMC

Test for ITER CC



Test for EAST magnet

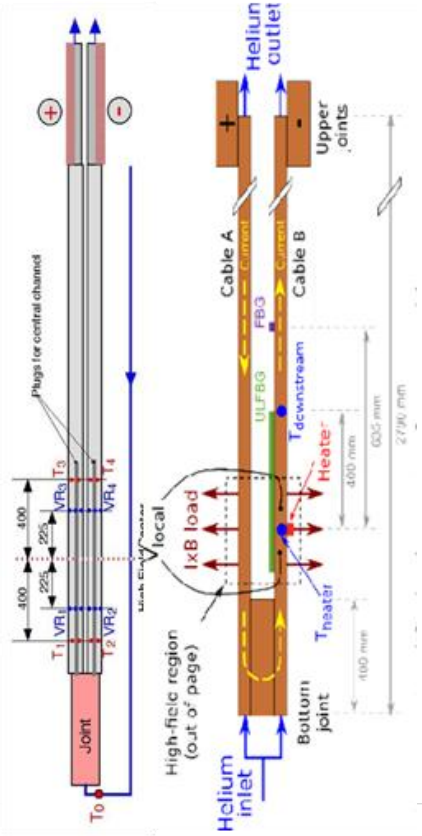
Operation fundamental for SC conductor testing

Keeman Kim (KENTECH)

➢ SC conductor test condition

- Field on Conductor ~16 T (Conductor Self field ~ 0.6T)
- Conductor current & temperature control : Max. 100 kA , 4.5 ~9 K
- Current sharing temperature measurement under Thermal cycle electromagnetic load environments

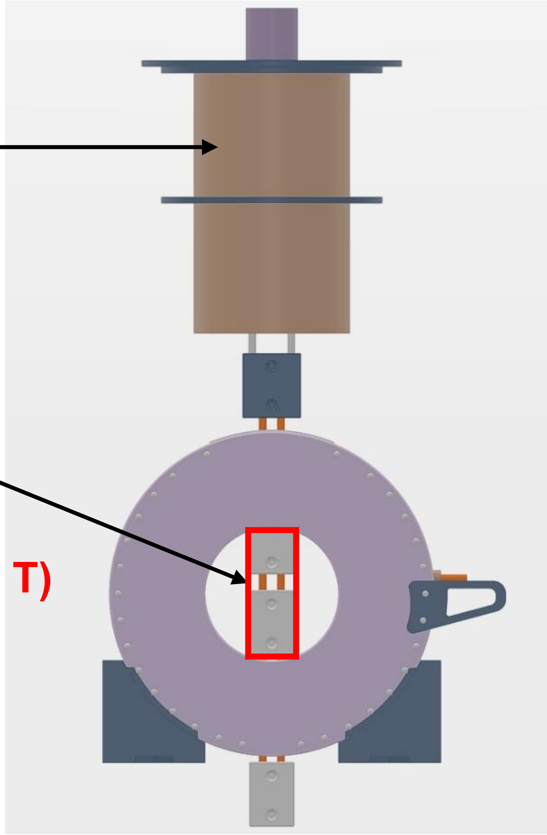
SC conductor sample preparation

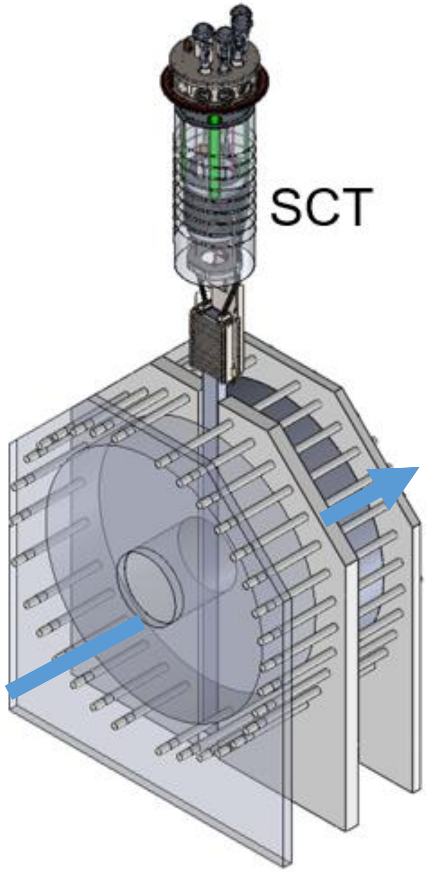


SC transformer

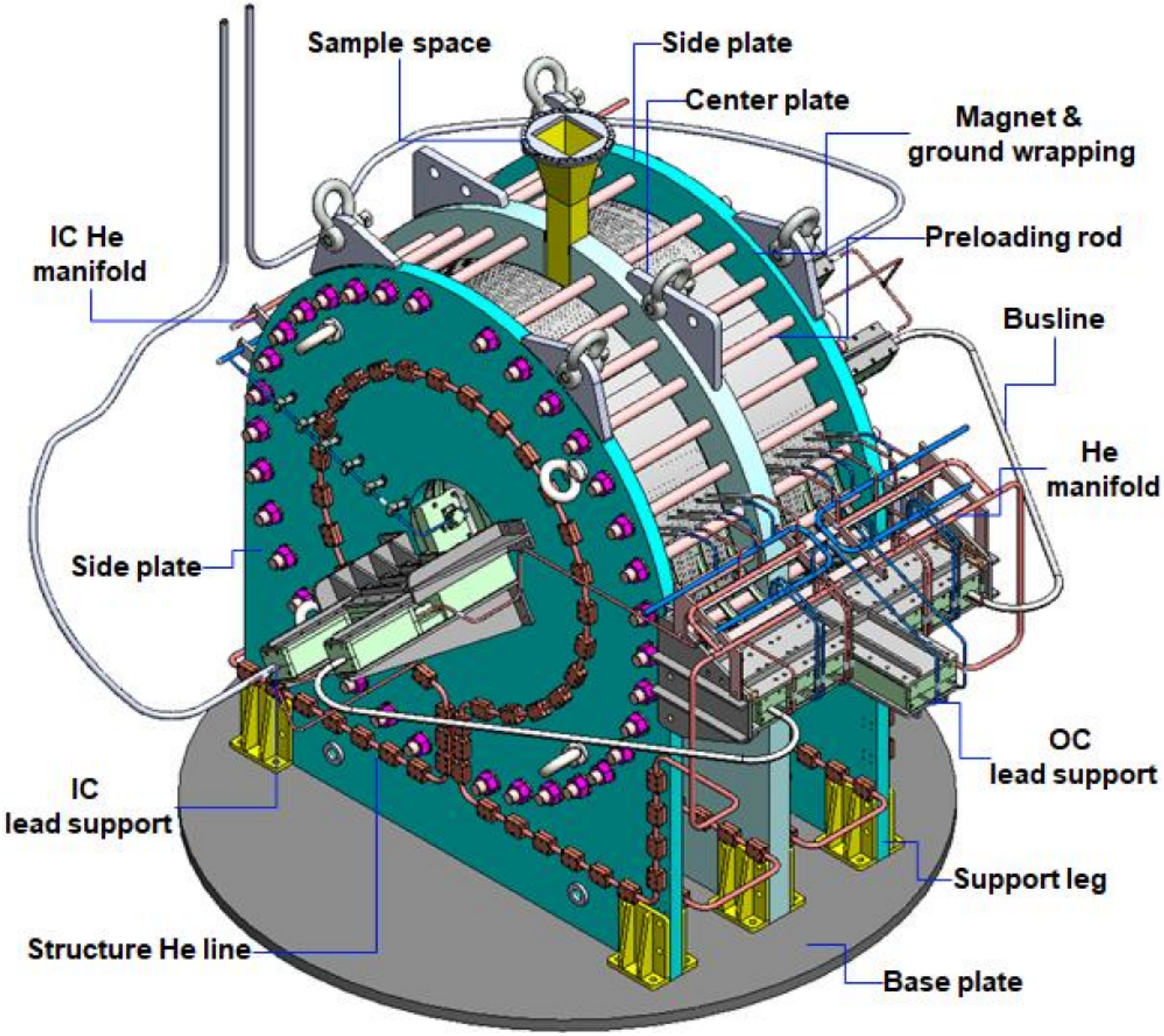
Conductor Sample Space

B-field (up to 15.43 T)



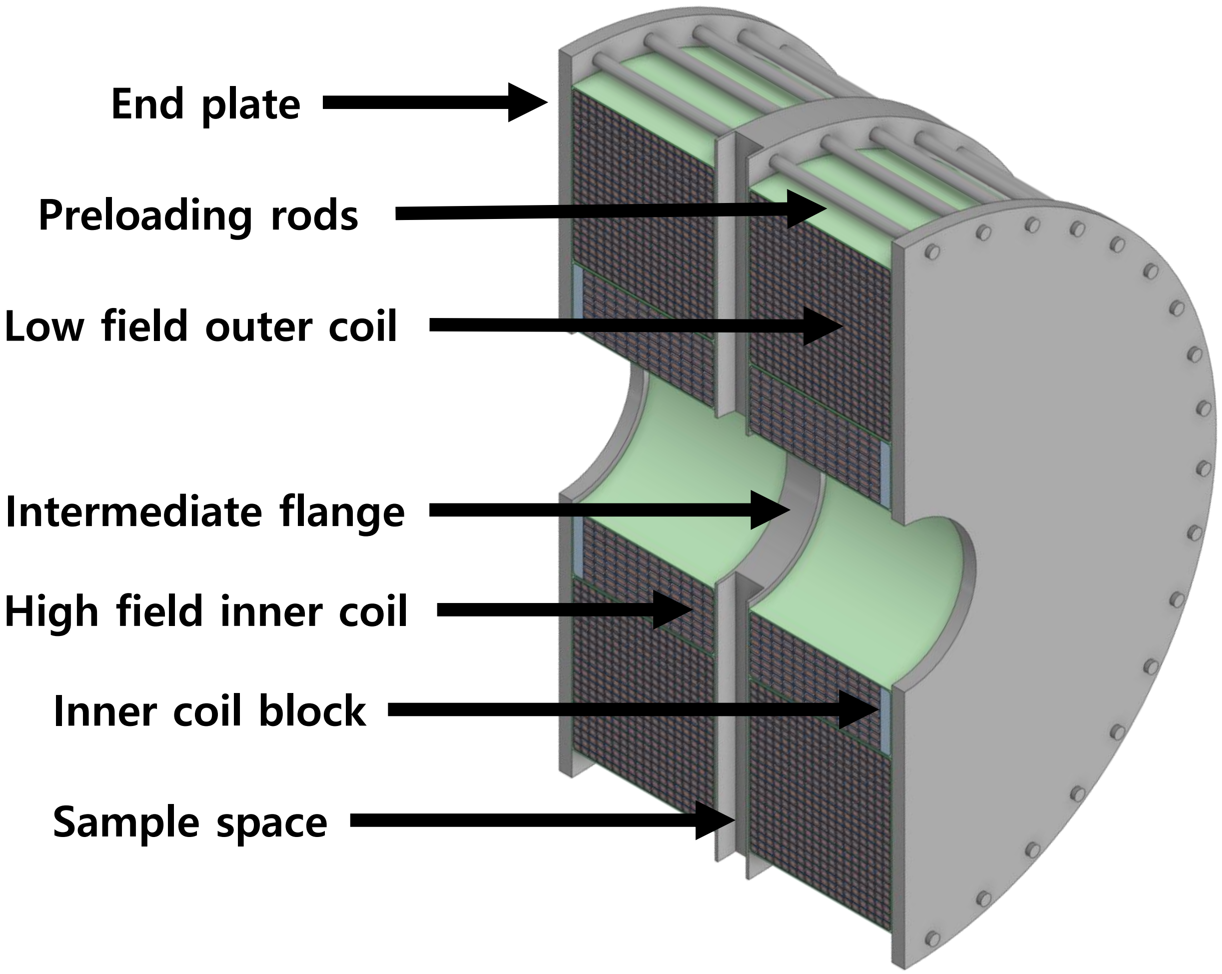


Overview of SUCCEX magnet mystem



Magnet Specification

- **Split pair solenoids**
  - Bore radius : 300 mm
  - Outer radius : 1110.2 mm
  - Height : 1237.2 mm (including gap)
  - Axial gap : 130 mm
  - Operation current : 24.8 kA
  - Field at center : 15.43 T
- **Graded Winding packs**
  - IC : max. 16.2 T, High Jc strand
    8 turns x 12 layers
  - OC : max. 12.36 T, ITER grade strand
    22 turns x 18 layers
- **Sample Space**
  - 110 mm Thick x 140 mm Width
  - Background field : ~15.43 T
  - Field uniformity ~ 1 %



> Neutron irradiation was carried out at JRR-3, and the max. thermal and fast neutrons were 8.29×10^{22} n/m^2 and 1.46×10^{21} n/m^2.

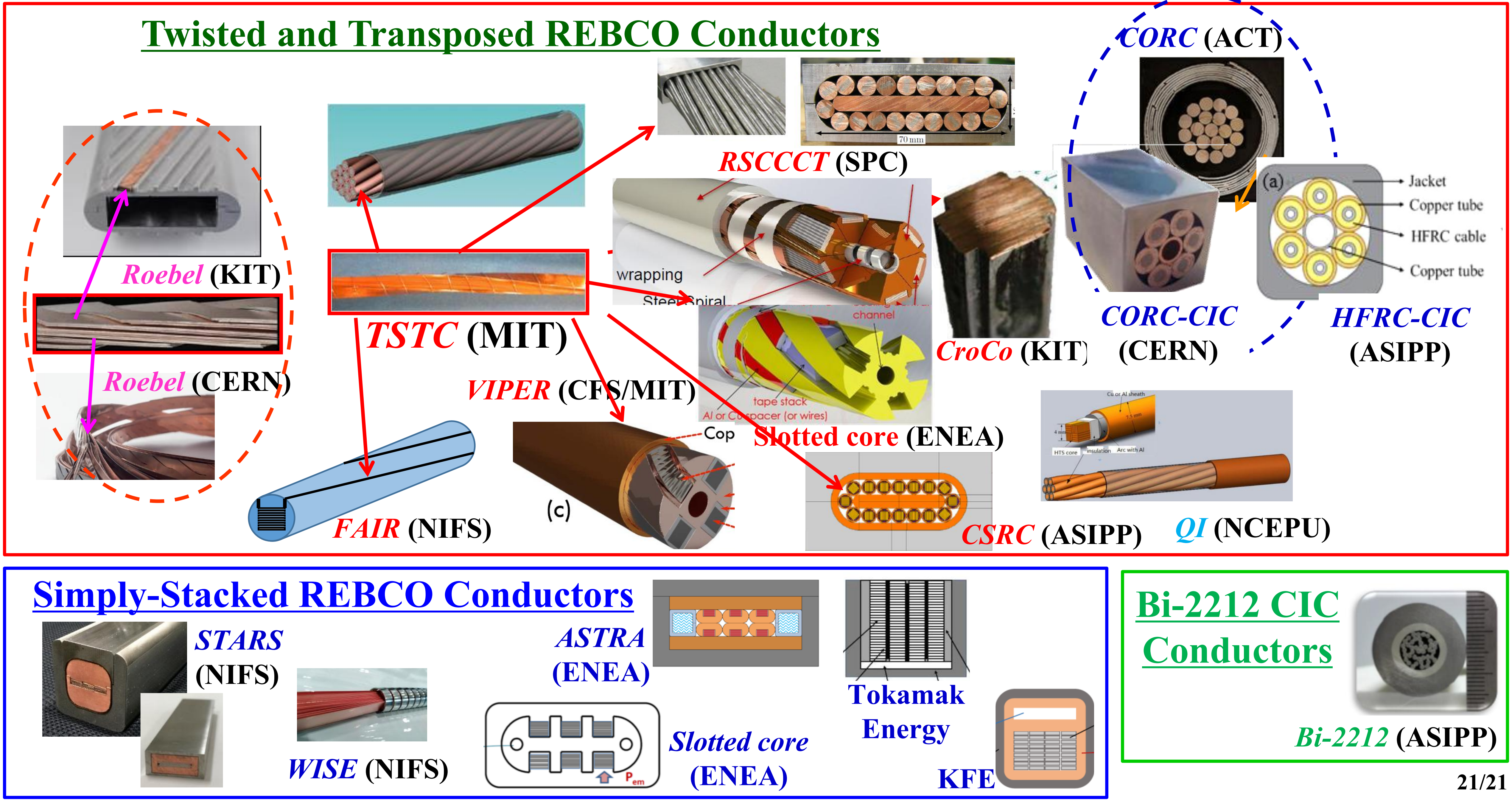
> Isotopes of Gd and Eu were detected after irradiation by a Ge detector, {n,γ} reaction by thermal neutrons causes nuclear transmutation and very large cross sections of {n,γ} reaction of ^{155}Gd, ^{157}Gd and ^{151}Eu is the reason for the nuclear transmutation. Thermal neutron shielding by Cd foil is effective against degradation of SC properties of GdBCO and EuBCO tapes. YBCO tape is not degraded by the thermal neutron at all.

> The following models were discussed. (1) Gd recoil model, (2) Oxygen deficiency model and (3) Electron capture-release model.

> Natural abundance ratio of ^{155}Gd and ^{157}Gd is 14.80% and 15.65%. About 30% of Gd has a possibility to be transmuted to Eu or Tb after {n,γ} reaction by thermal neutron. So, about 30 % of Gd atom are recoiled or kick off oxygen atoms near Gd atom or cause electron capture/release, and the perovskite structure will be collapsed and disturb SC current running. But a new model that shows the property loss across the 4mm tape width must be studied.

Arata Nishimura (NIFS)

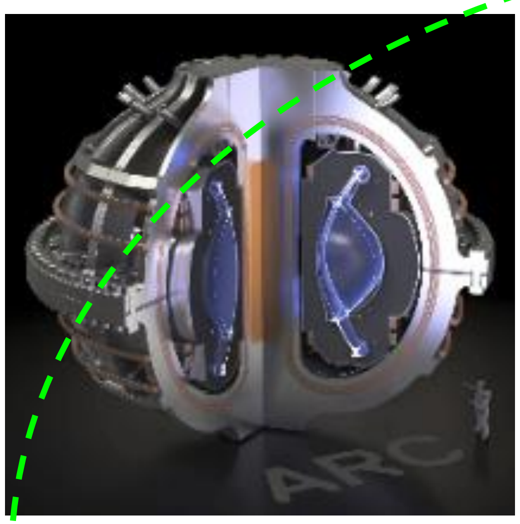
Large-current HTS conductors developed for fusion magnets

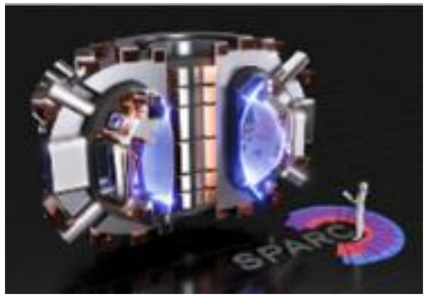


Extra Slides

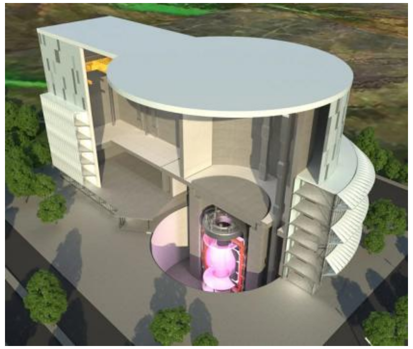
Fusion reactor designs with HTS magnet in the World

ARC & SPARC (MIT/CFS)

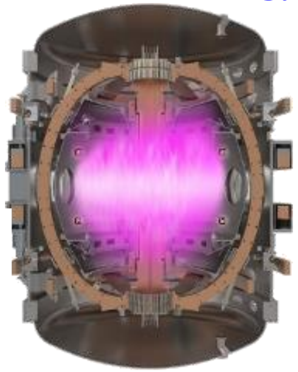




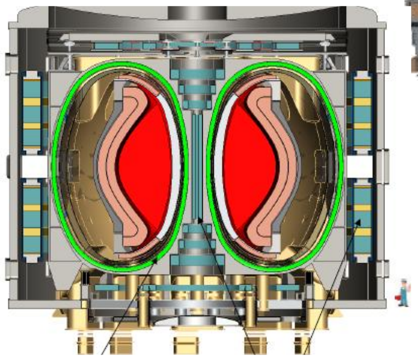
STEP (UKAEA)



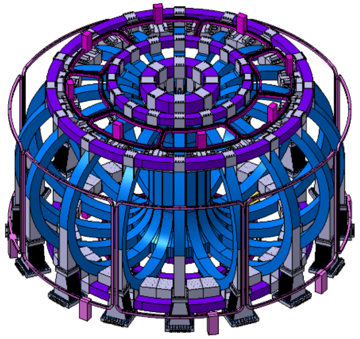
Tokamak Energy



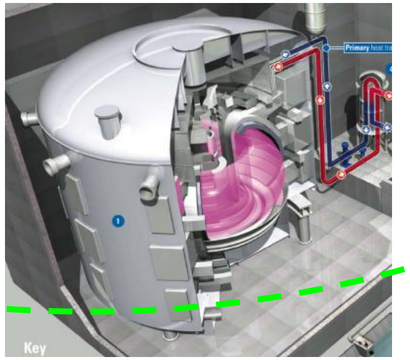
FNSF-ST (PPPL)



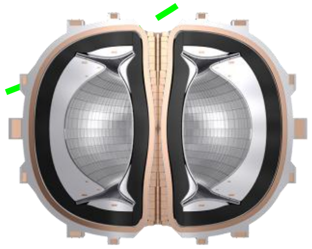
CFETR for CS coils (ASIPP)



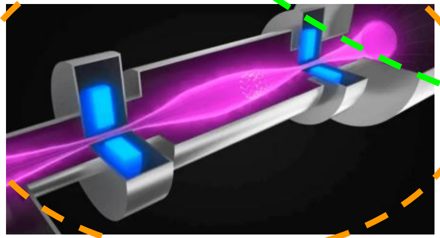
EU DEMO HTS option (EUROfusion)



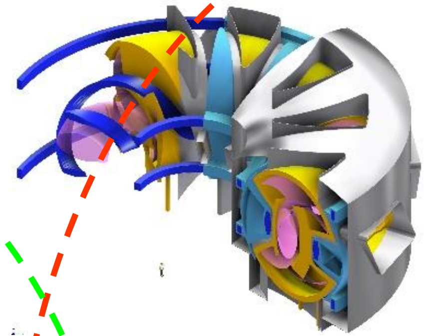
Energy Singularity STARTORUS



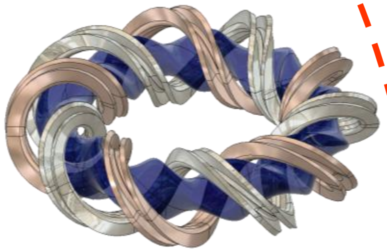
Realta Fusion



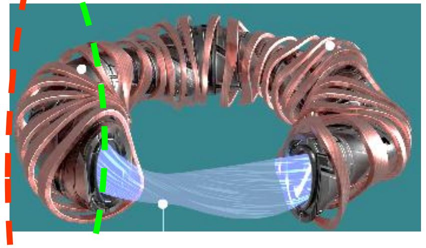
FFHR-d1 (NIFS)



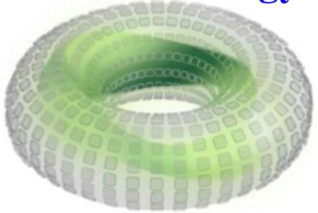
Helical Fusion



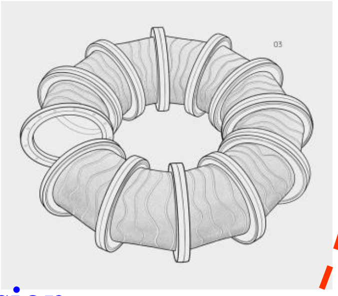
Type One Energy



THEA Energy



Renaissance Fusion



Proxima Fusion