High Temperature Superconducting Magnets for Fusion

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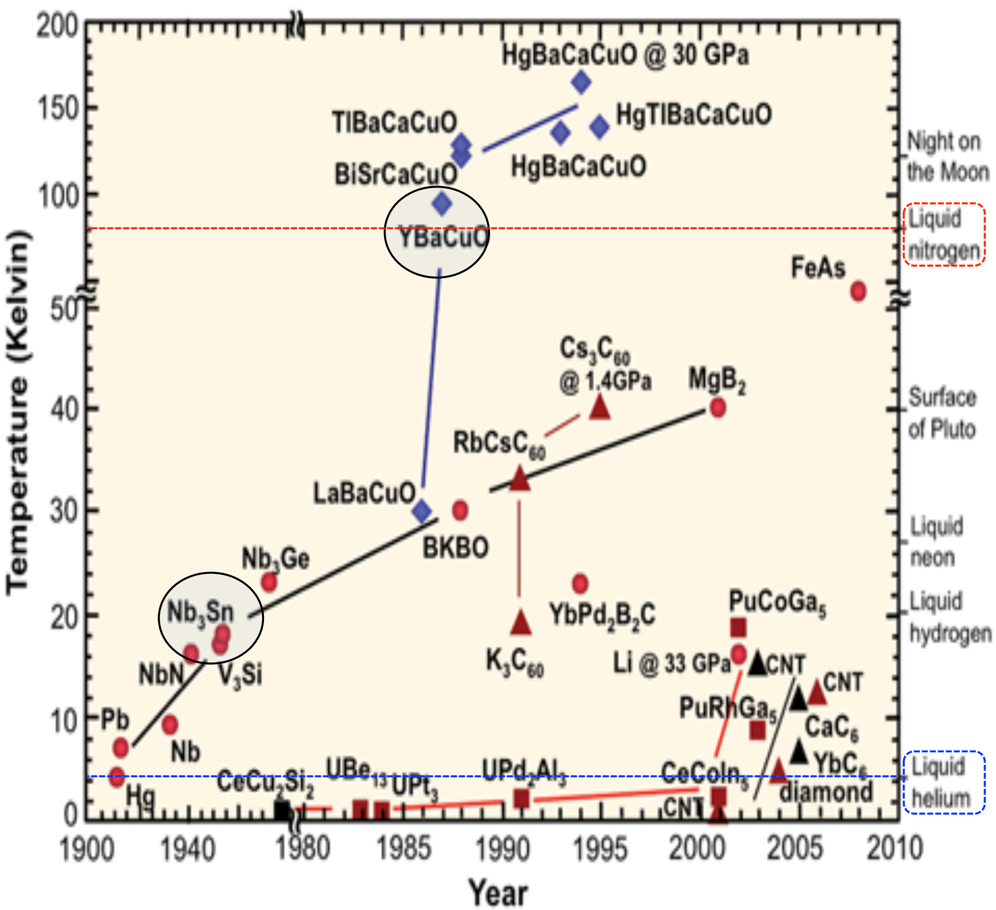
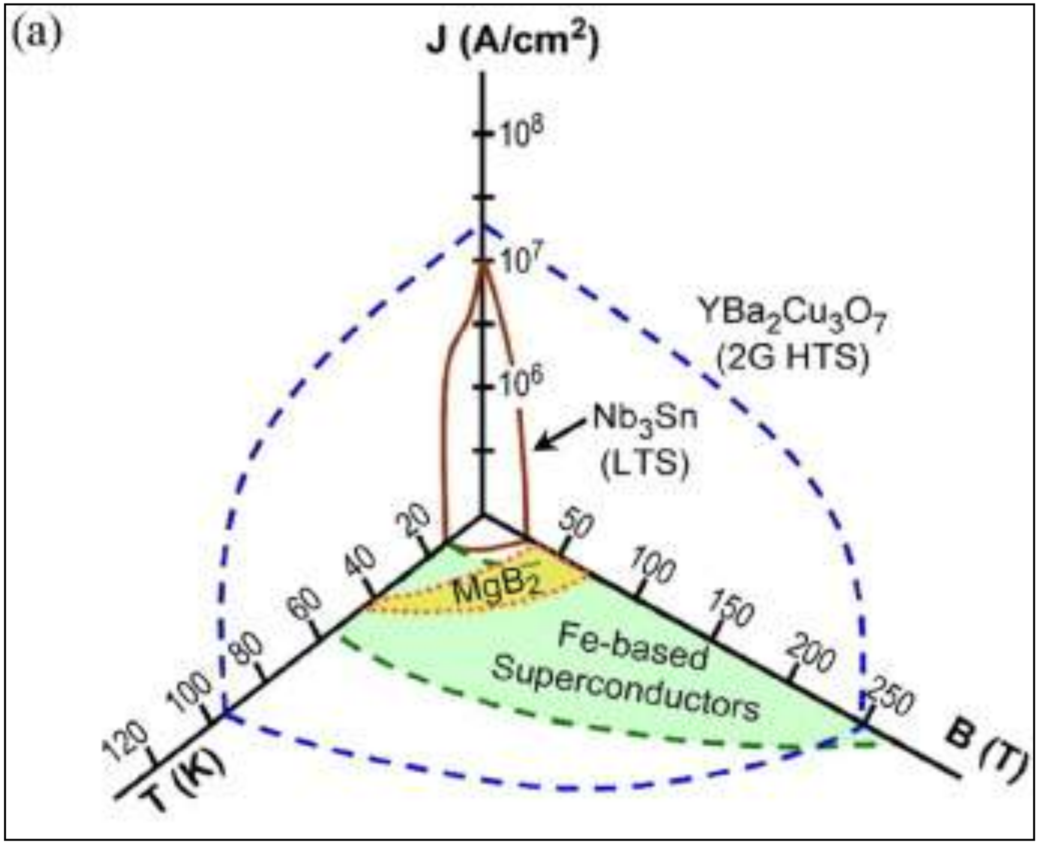
Status of Practical Superconductor Technology-1

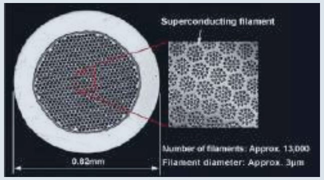
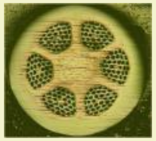
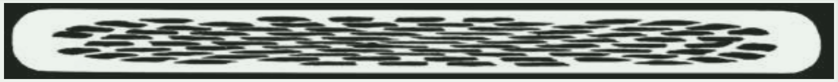
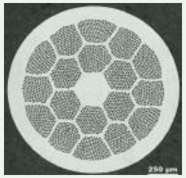
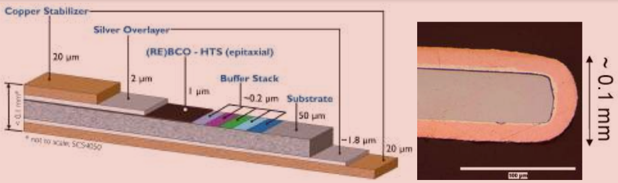


Superconductor Critical Surface (J, B, T)*



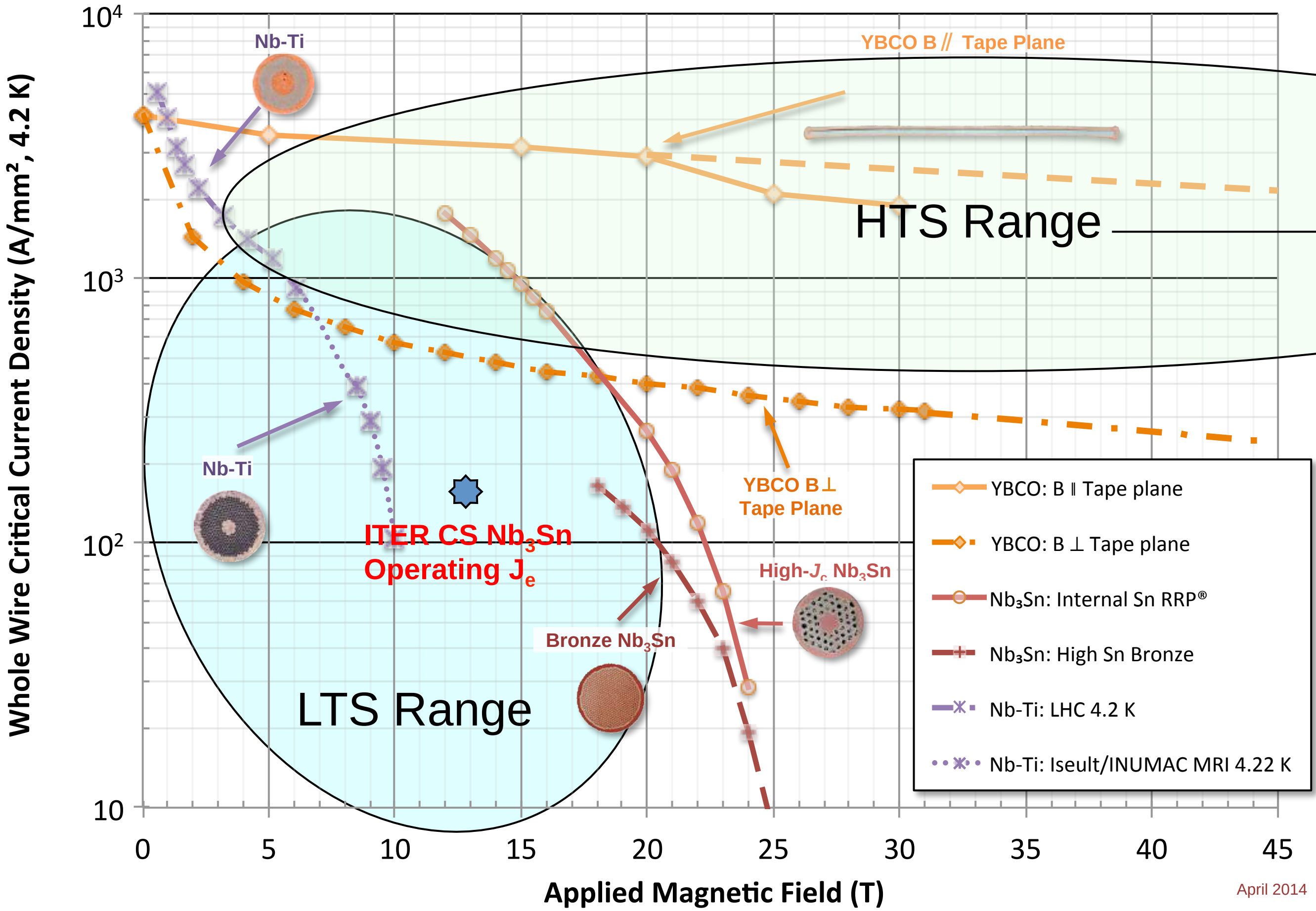
* And sometimes train (ε)

Status of Practical Superconductor Technology-2

	Material	T_c [K]	$\mu_0 H_{c2}$ [tesla]	
LTS	NbTi	9.8	10.5 (4.2 K)	
	Nb_3Sn	18.2	15.3 (4.2 K)	
MTS	MgB_2	39	>15	
HTS	$Bi_2Sr_2Ca_2Cu_3O_{10-x}$ (Bi-2223)	110	108	
	$Bi_2Sr_2CaCu_2O_{8-x}$ (Bi-2212)	110	108	
	$REBa_2Cu_3O_{7-x}$ (REBCO)	93	150	

YBCO *High Temperature* Superconductor is an excellent *High Field* Superconductor

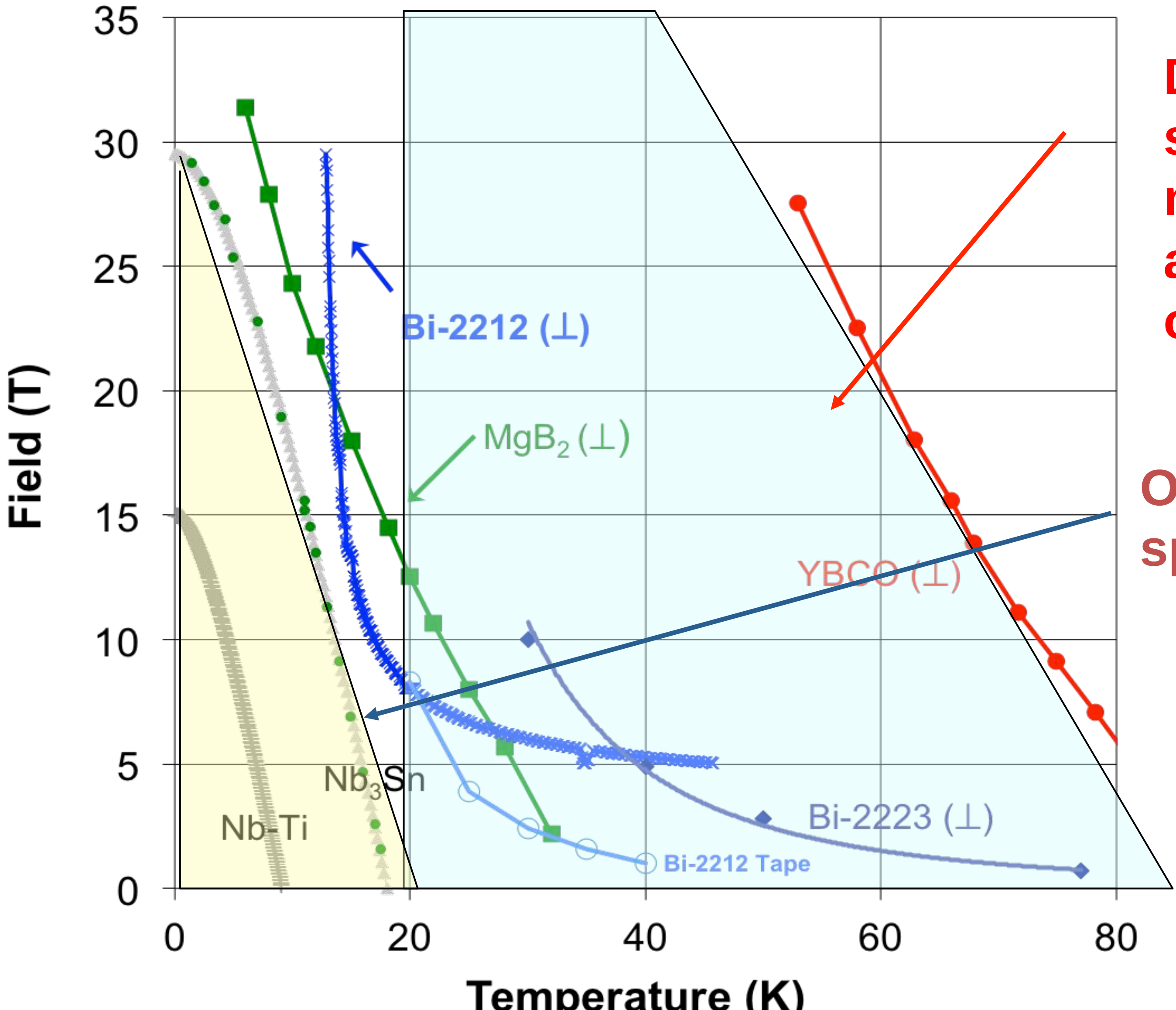
- HTS performance is already good enough for use in fusion magnets and continues to advance rapidly.
- HTS provides high magnet stability and operating margins at T>20K.
- Reduces probability for spontaneous quench.
- Higher T operation increases refrigeration efficiency and nuclear heating handling.



This unexplored range is where innovation in magnet technology can potentially have a great impact on future fusion devices.

http://magnet.fsu.edu/~lee/plot/plot.htm

HTS Makes Much Higher Magnetic Fields Accessible at Higher Temperatures

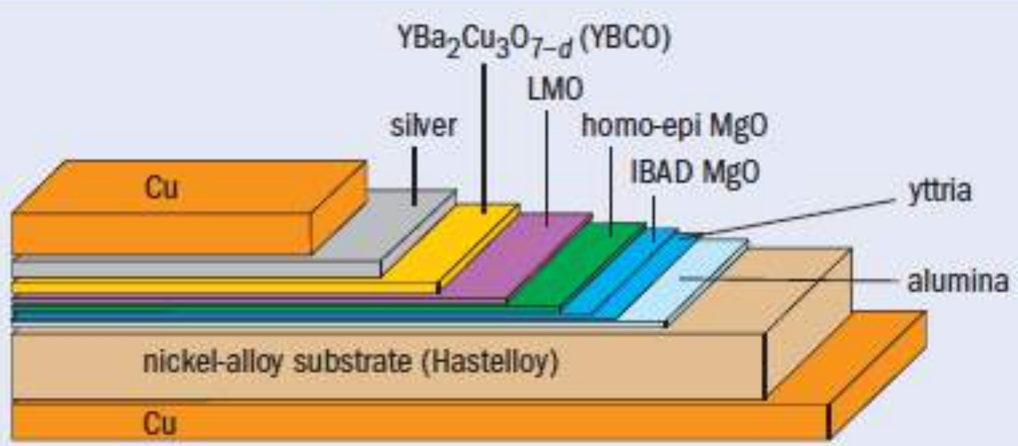


Developing superconducting magnets to take advantage of this new operating space

Old operating space

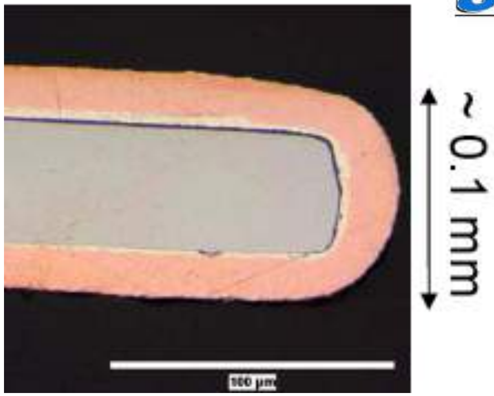
YBCO Tape (2nd Generation-HTS)

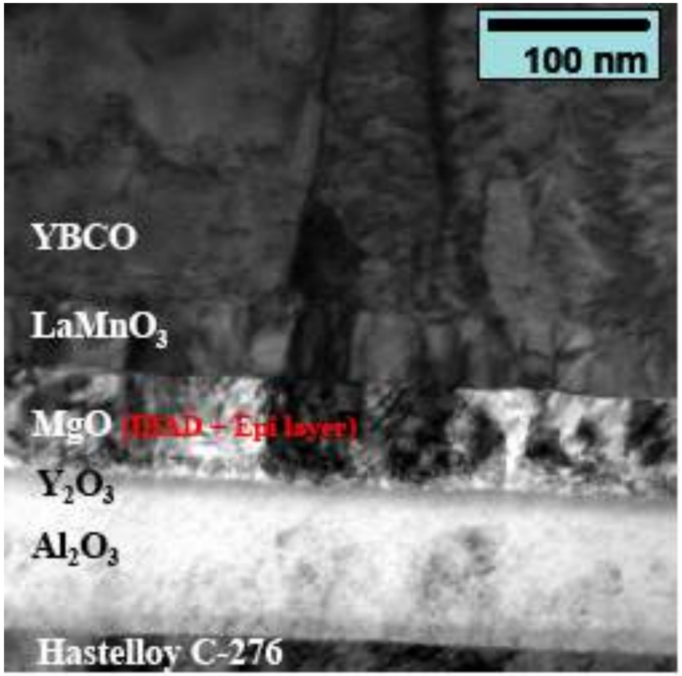
3 Wired for superconductivity



The make up of a second-generation superconducting wire, showing the multiple layers required to achieve good conductivity in the YBCO. Layers of copper (Cu) protect against transient resistive voltages, while layers of lanthanum manganate (LMO) and two types of MgO form substrates for growing single-crystal YBCO films.

SuperPower Inc.
A Subsidiary of Intermagnetics General Corporation





REBCO is Commercially Produced in at Least 6 Countries

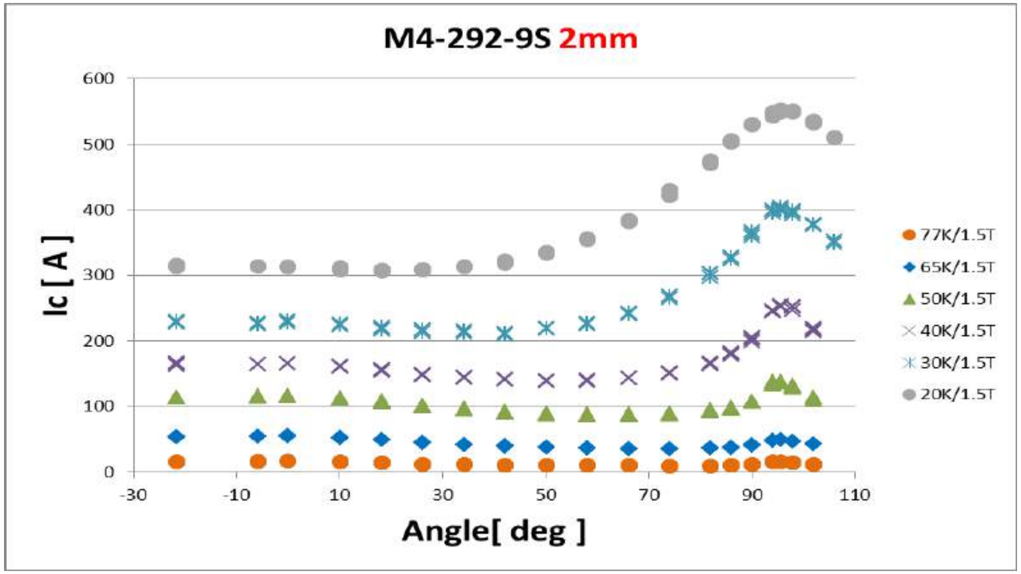
Company	Country
AMSC	USA
SuperPower*	USA
STI	USA
Fujikura	Japan
Sunam	Korea
SuperOx**	Russia
BEST	Germany

- SuperPower is owned by Furukawa of Japan

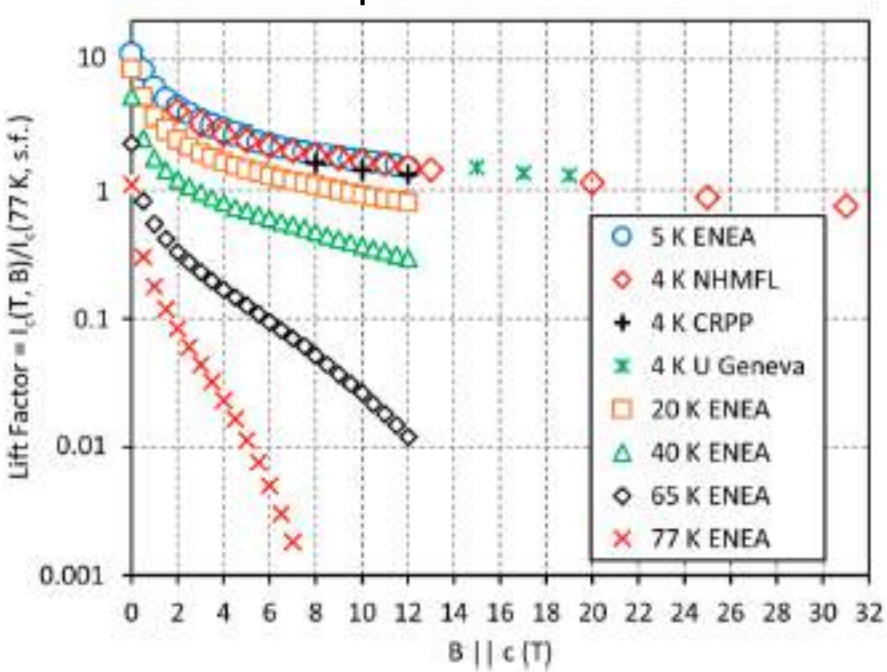
** Part of SuperOx production process is performed in Japan

I_c(B,T) Typical Data

SuperPower Data



SuperOx Data

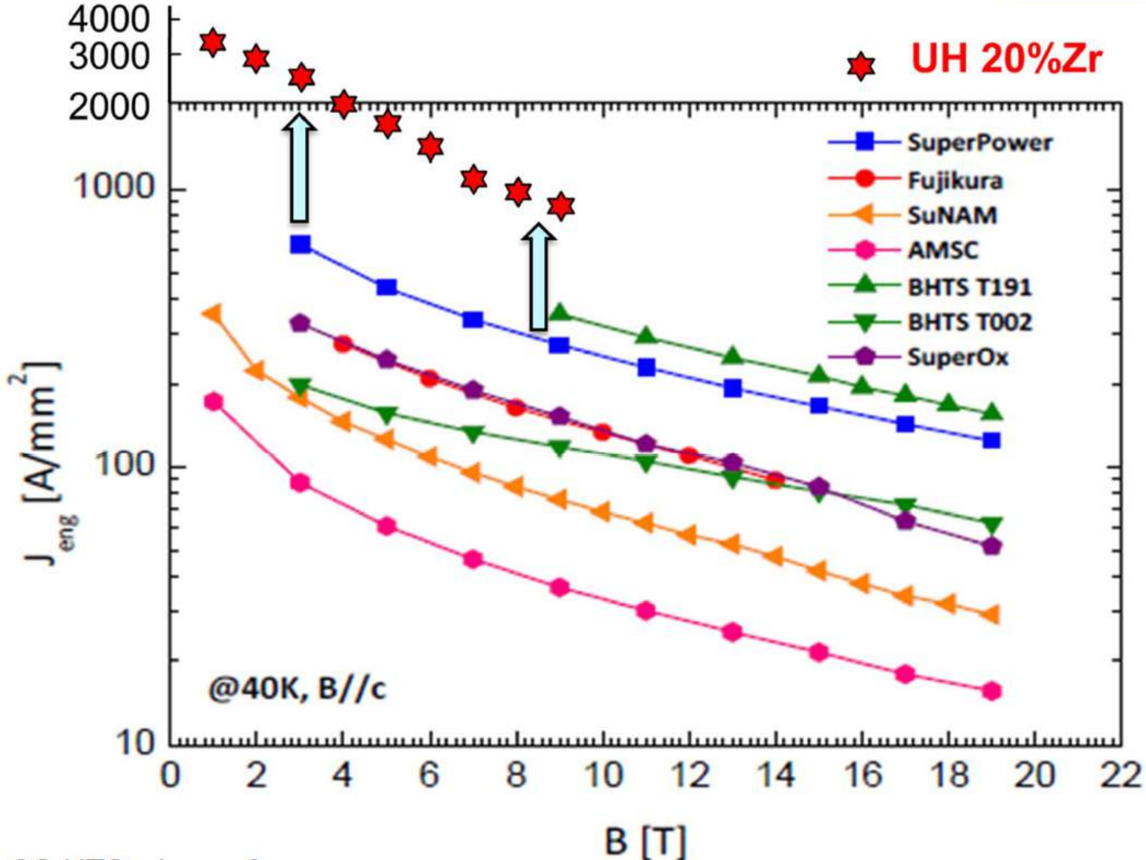


Engineering Current Density Improved Several Fold by Addition of Artificial Nano-Pinning Centers

UNIVERSITY of HOUSTON

TcSUH

J_e of 20% Zr-added tapes 3X – 4X higher than SuperPower's production AP wire at 40 K



Data of industry 2G HTS wire performance
Presented by C. Senatore at the 1st Workshop on Accelerator Magnets in HTS, 21-23 May 2014, Hamburg, Germany

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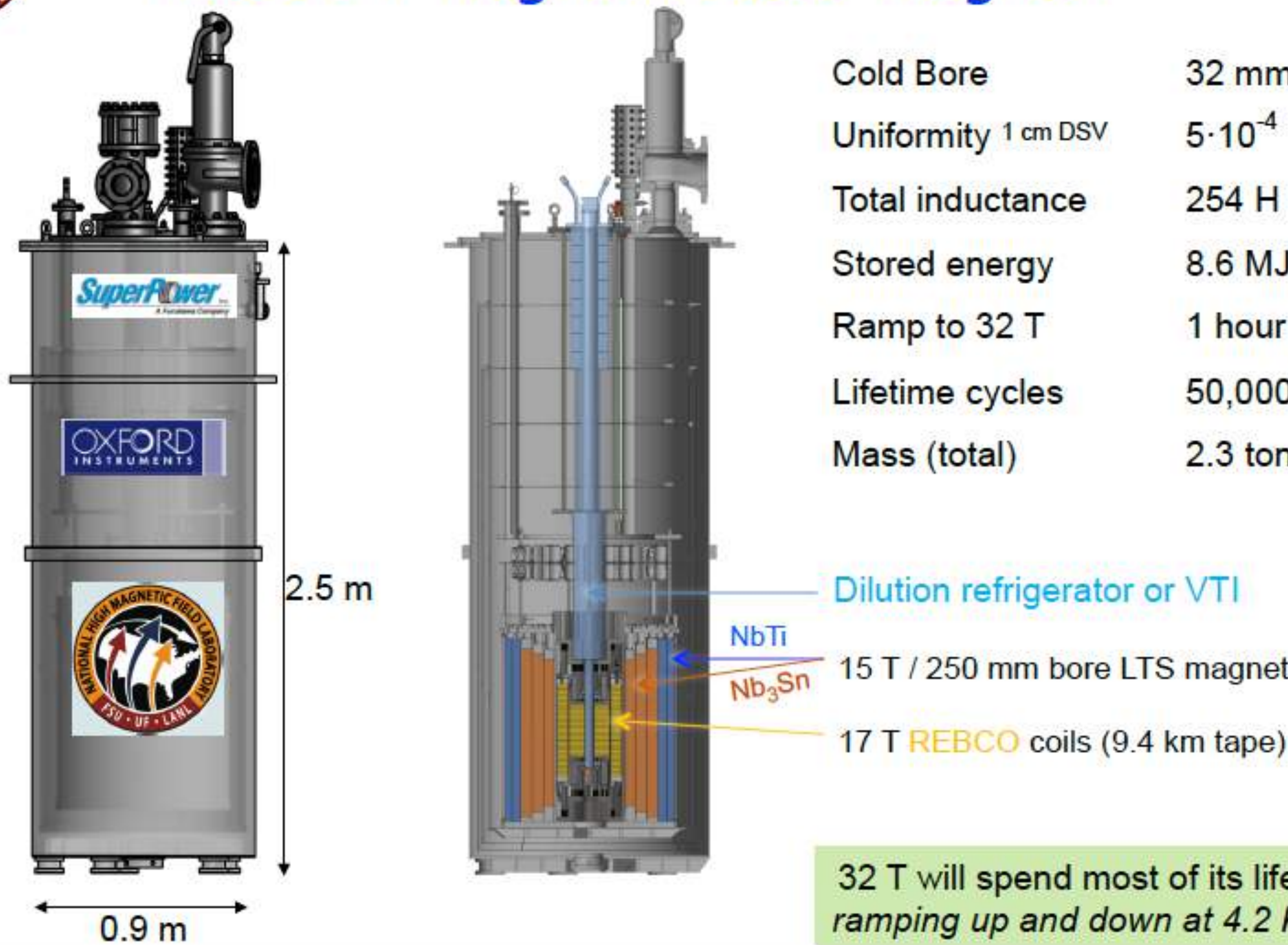
Very High Field Magnet Technology Will Be Demonstrated at 32 T

Under construction at NHMFL, Tallahassee, FL

The 32 T magnet: a user magnet

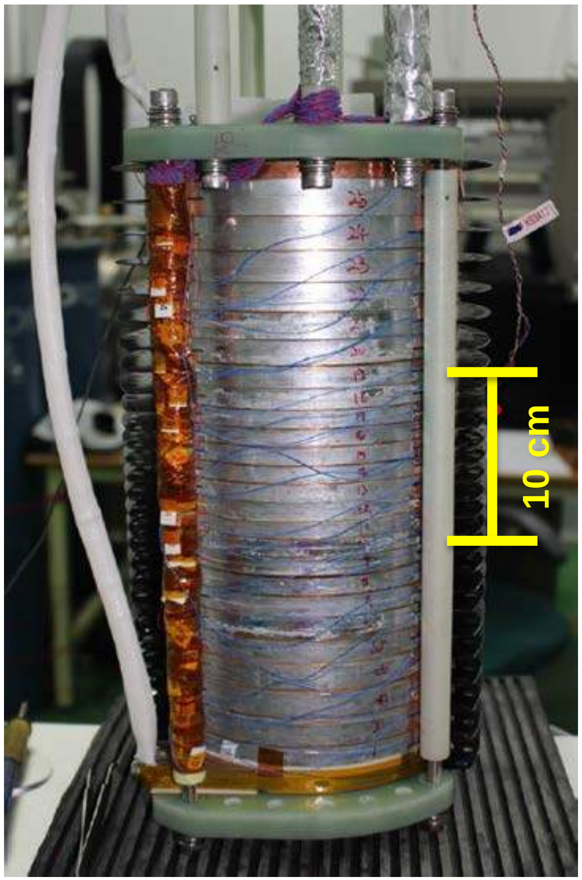


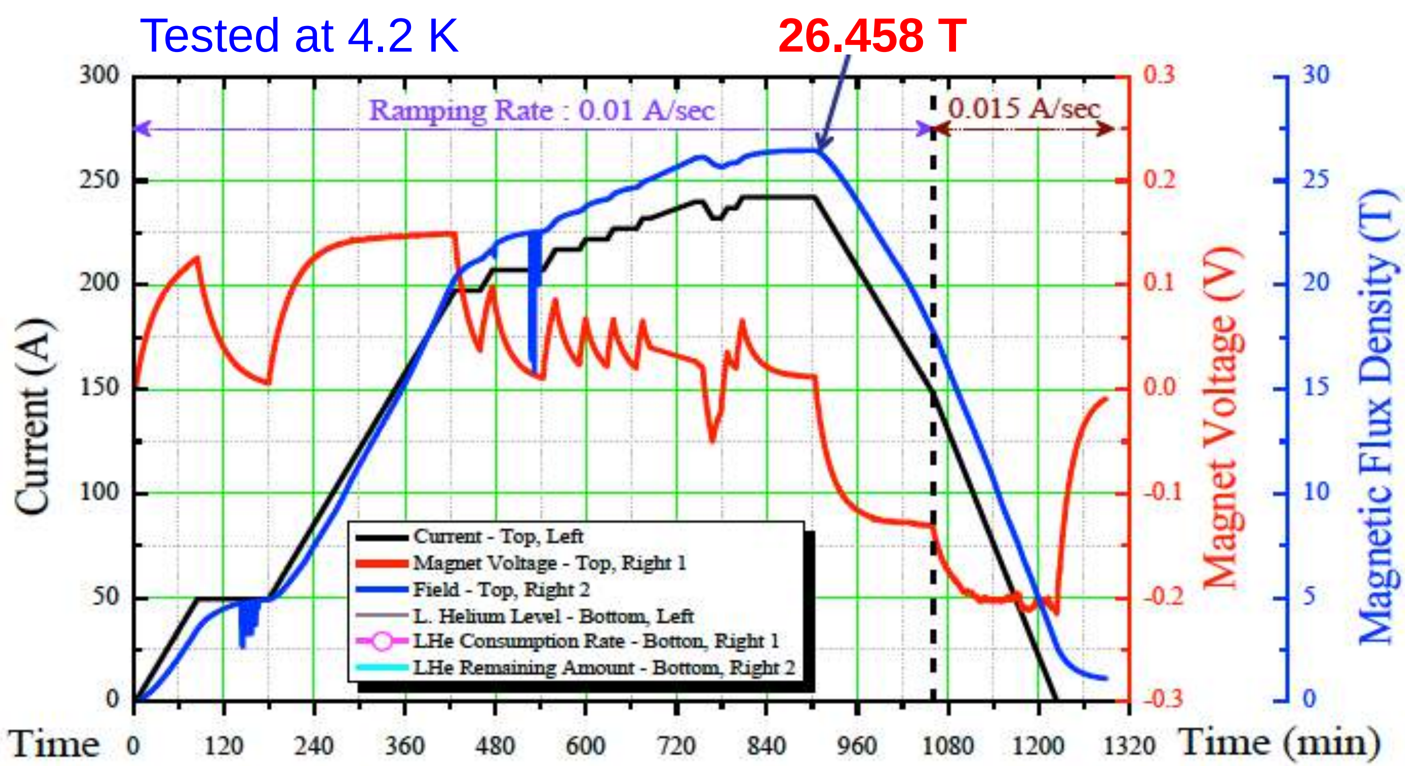
Cold Bore	32 mm
Uniformity 1 cm DSV	$5 \cdot 10^{-4}$
Total inductance	254 H
Stored energy	8.6 MJ
Ramp to 32 T	1 hour
Lifetime cycles	50,000
Mass (total)	2.3 ton

32 T will spend most of its life *ramping up and down at 4.2 K*

26.5 T All HTS (REBCO) Magnet Has Already Been Demonstrated

S. Hahn, J.M. Kim, et al. NHMFL, FSU, SUNAM, MIT

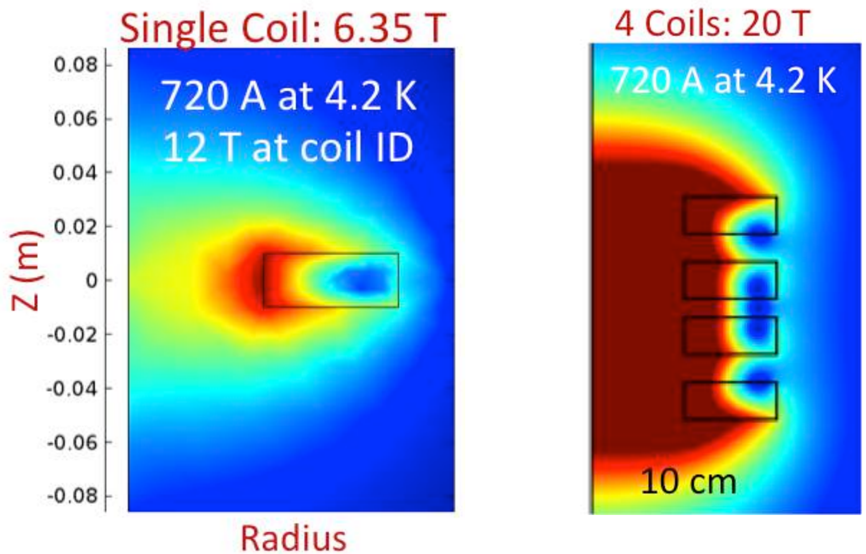


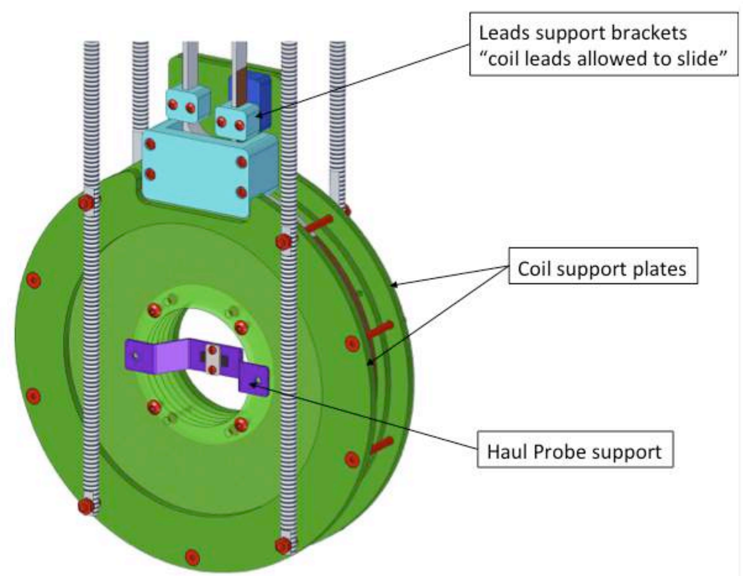


26 Double Pancakes

MIT is Building an HTS Test Solenoid

- 1000 turn double pancake construction
- 10 cm central bore diameter
- 20 cm outer diameter
- 12 mm X 0.106 mm HTS Tape (GdBCO)
- 1.05 T on axis at 77 K at 120 A (Ic = 500 A sf)
- 6.35 T on axis at 4.2 K at 720 A (Ic = 1750 A sf)
- A No-Insulation (NI) design will be tested
- Immunity to quench
- No issues with insulation failure
- High turn-to-turn strength
- Coil has been fabricated and is being tested

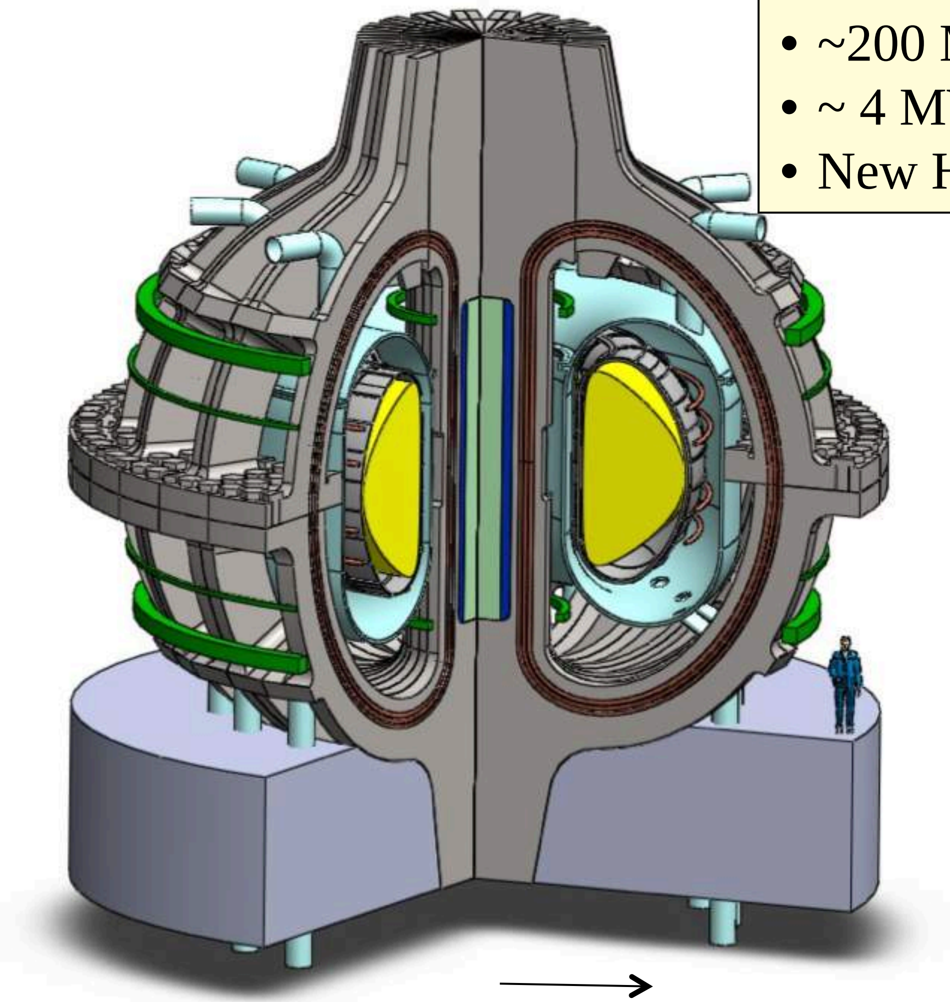




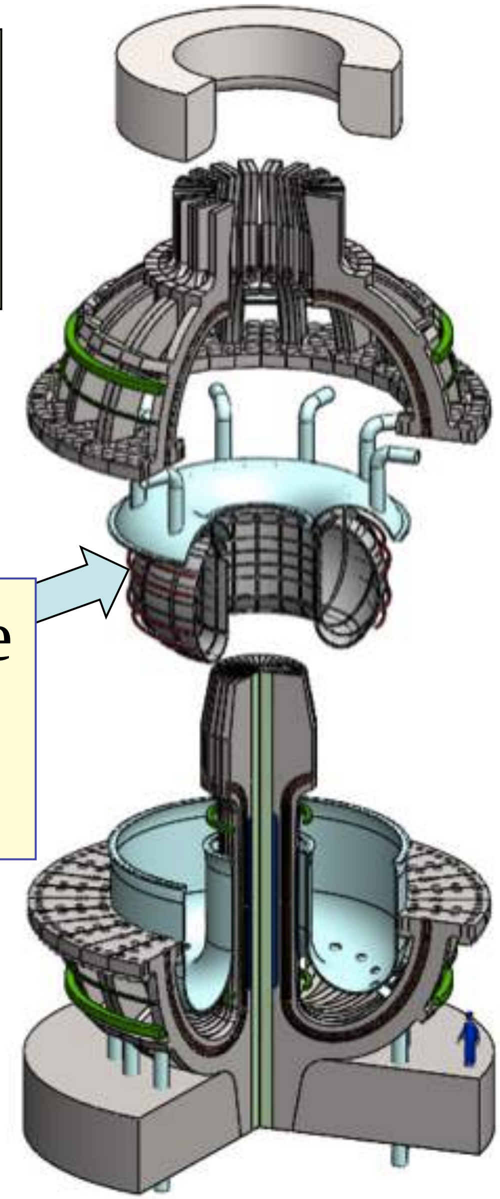
The ARC conceptual design:
Fusion power at small size = Power density

B. Sorbom et al FED 2015

- 500 MW fusion power
- ~200 MW electricity
- ~ 4 MW/m^2 fusion power density
- New HTS magnet at~20 T, 20 K

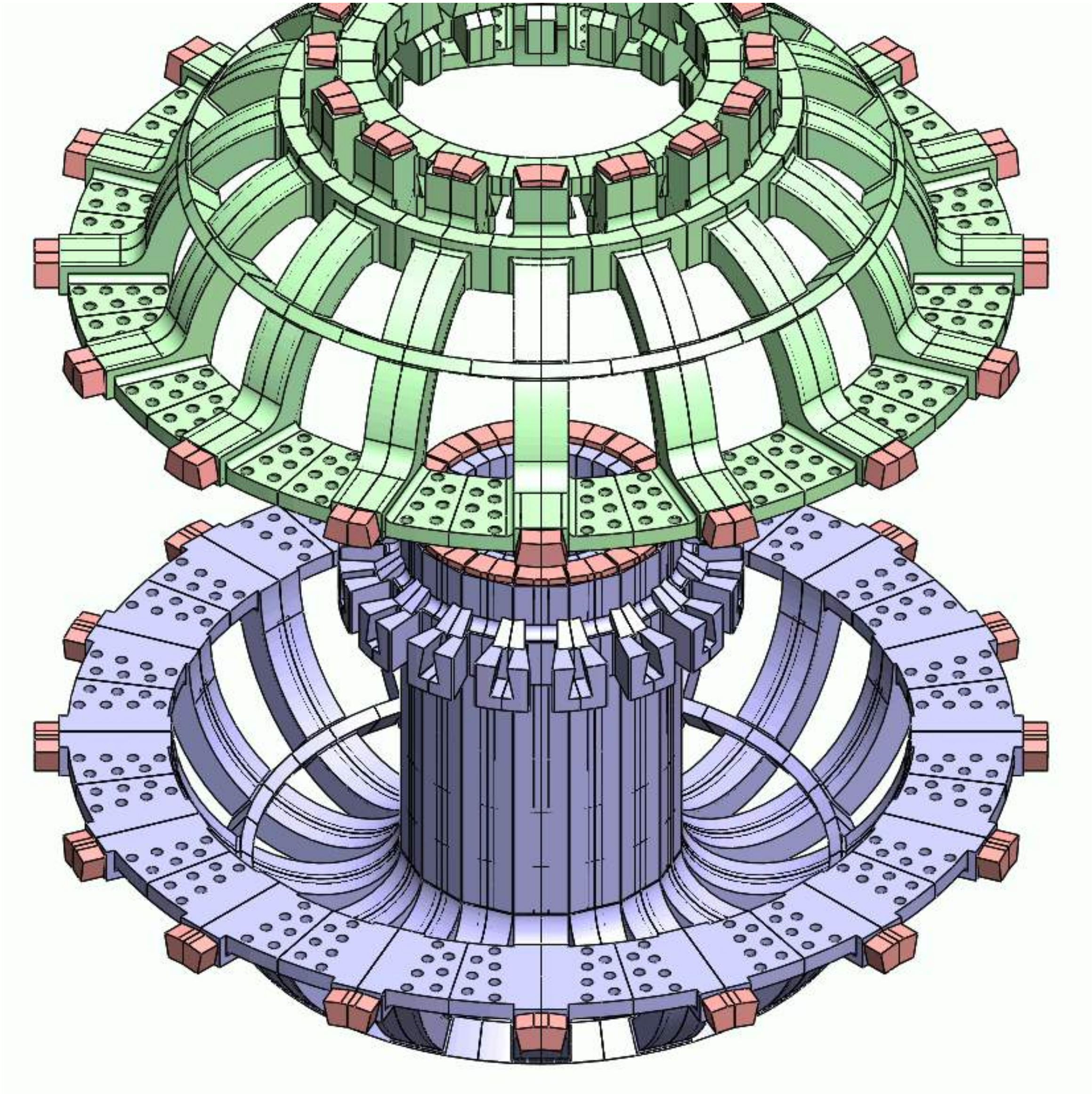


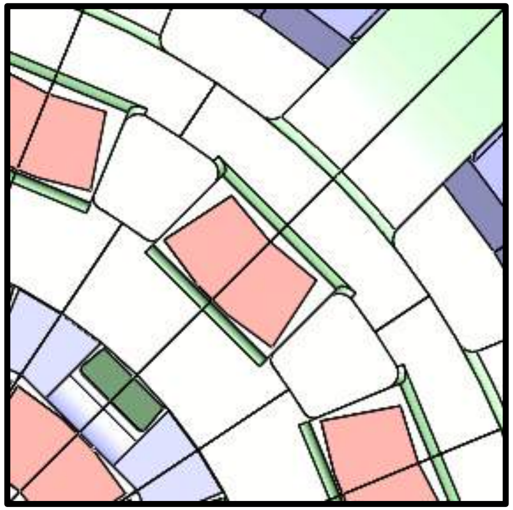
R=3.2 meters



Replaceable “core” module

Coil Assembly Concept

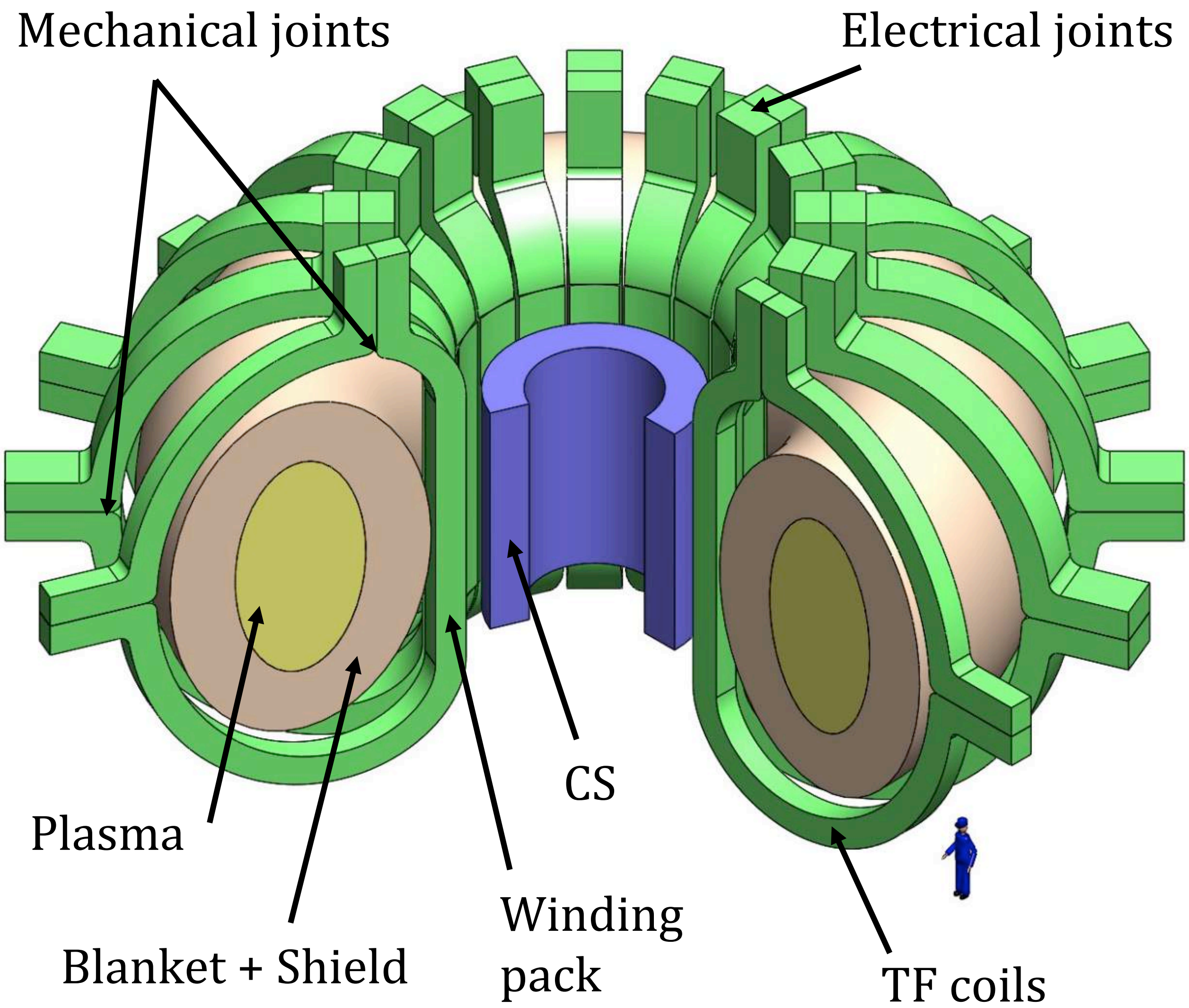




Auxiliary part detail

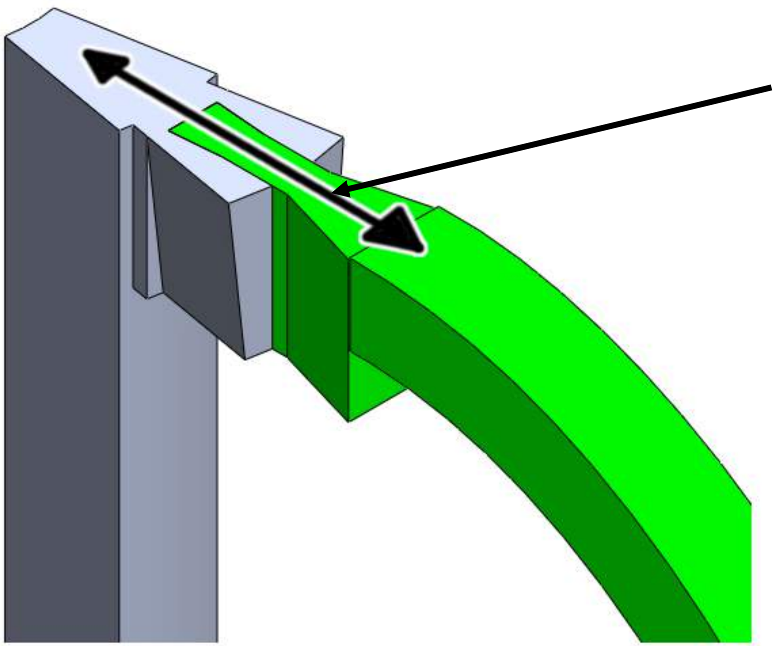
- Machine would operate ~20 K and allow resistive joints

Reactor Design Based on Aries-I



B_{max} = 20 T
B_0 = 11 T
R = 6.75 m
R/r = 4.5
I_{cond} = 100 kA
I_{TF} = 24 MA
240 conductors
P_E = 1000 MW

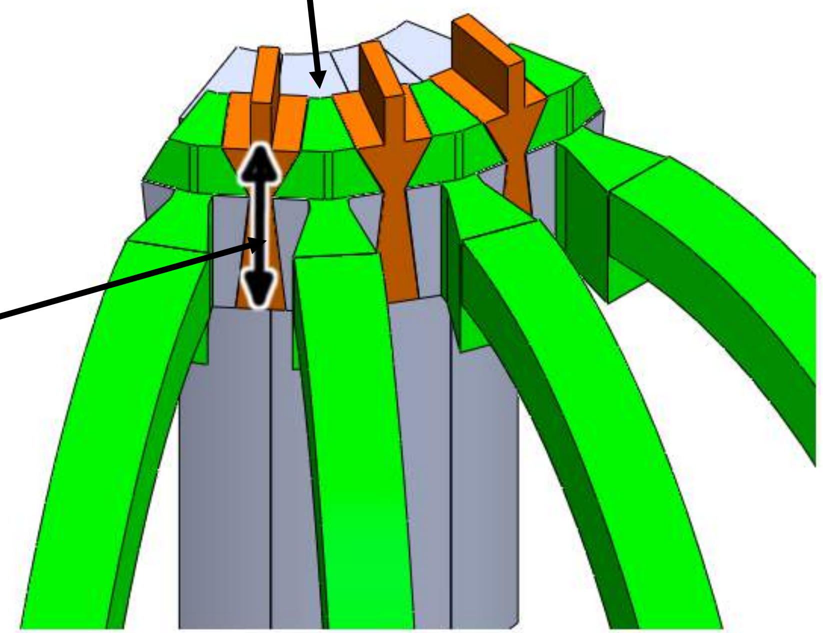
Top Mechanical Support: Triple Dovetail



Top TF leg slides in vertically inside bottom leg. This dovetail supports bursting radial force

Bottom TF leg

Inner TF legs supported by wedging



Auxiliary part slides in radially between TF coils. Double dovetail supports vertical force and also first dovetail socket

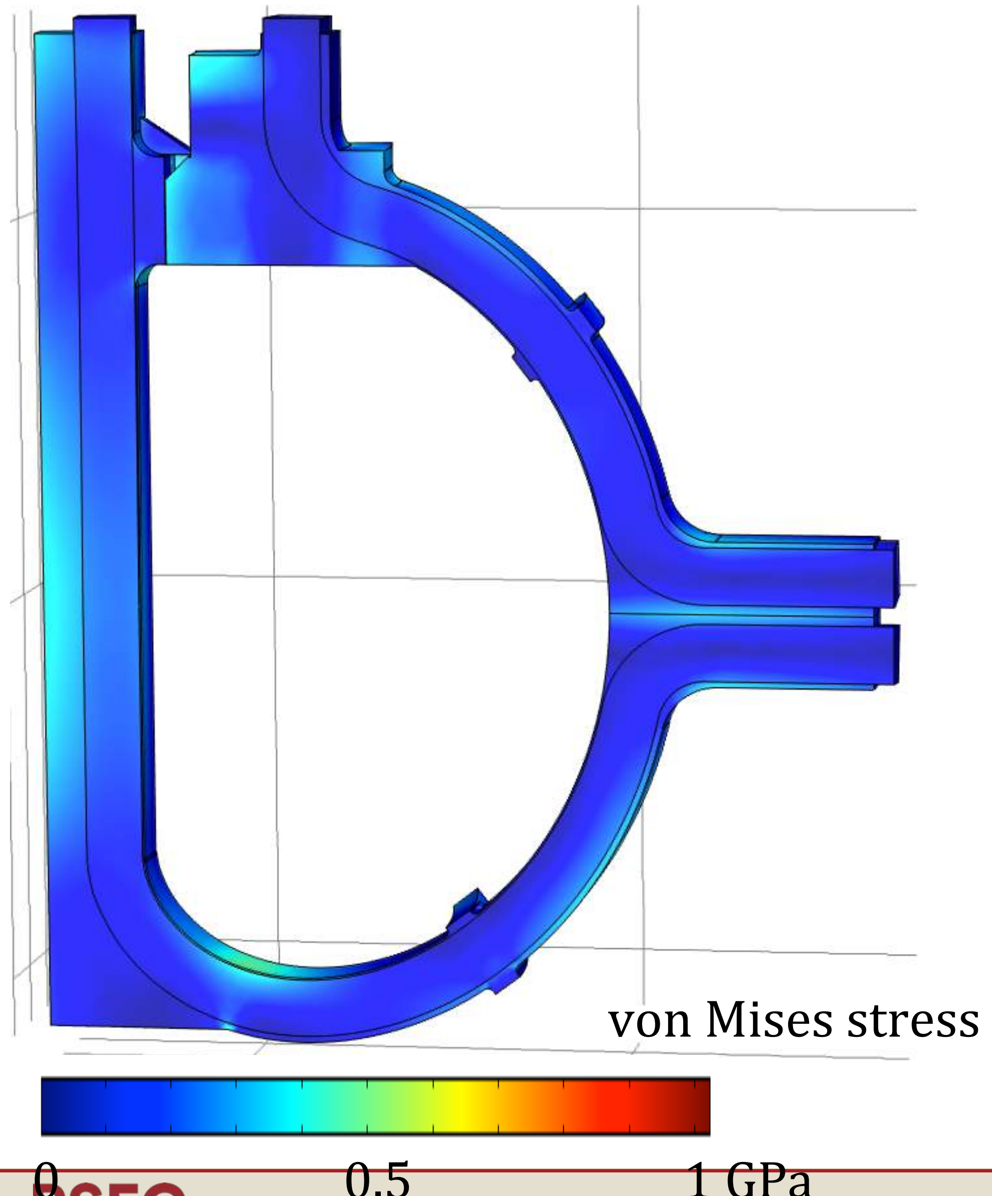
Acceptable Stress Levels in the Structure at 20 T

Structure: 316LN

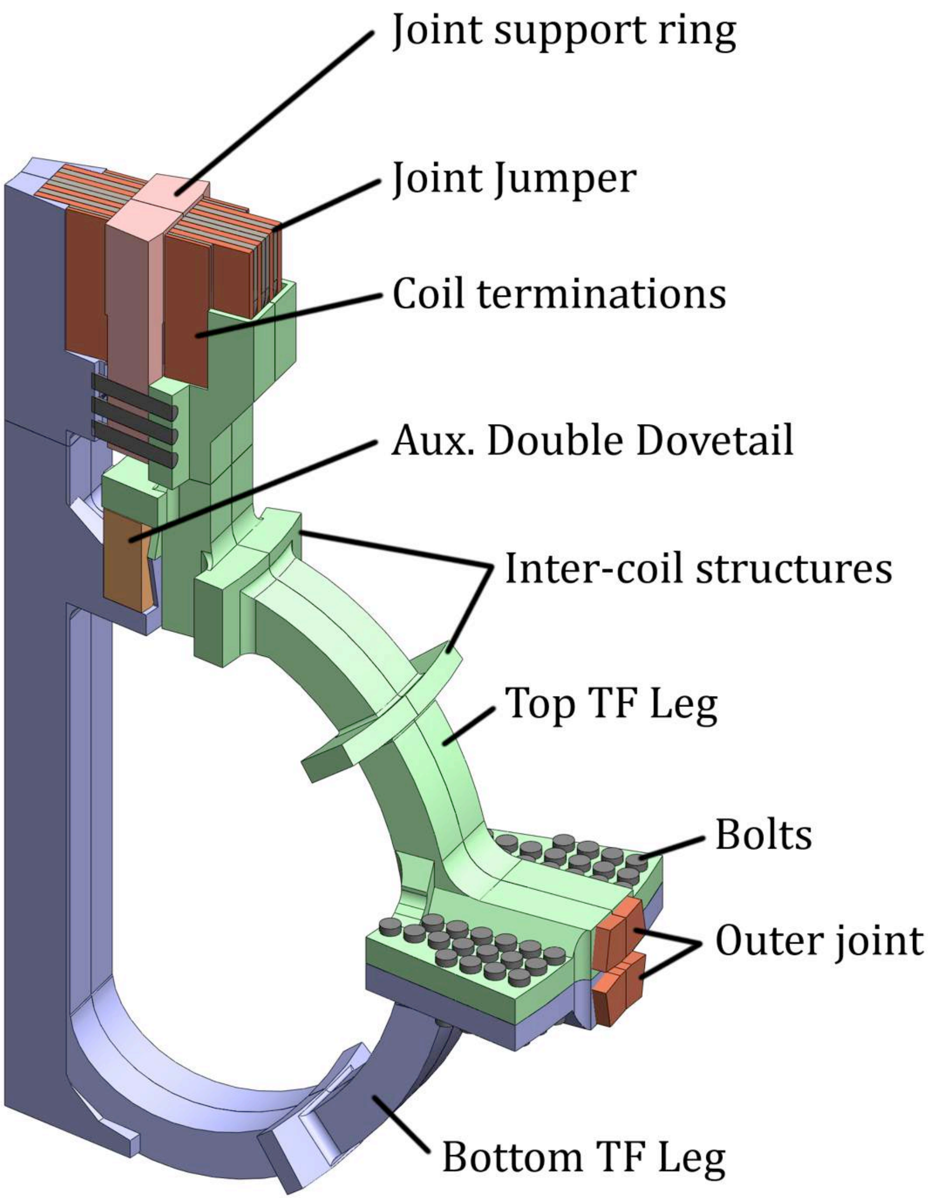
Stress in most of the structure: less than 500 MPa

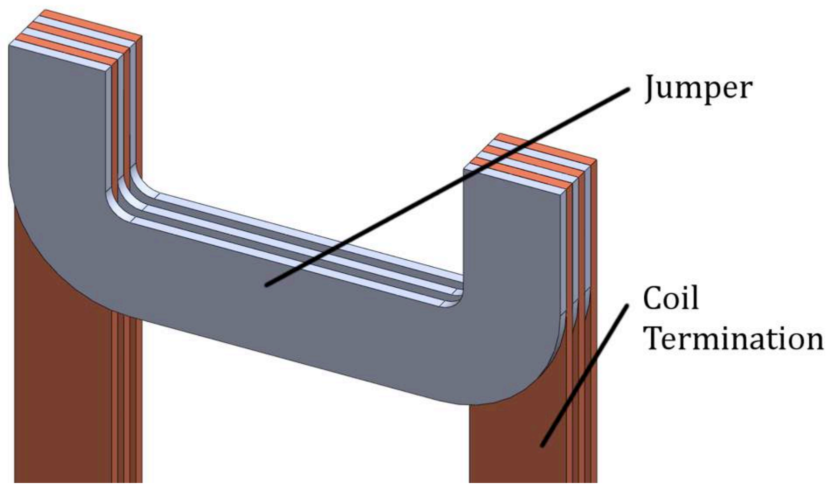
Limit in CICC: 680 MPa

Critical points: inter-coil structures, auxiliary dovetail (less than 700 MPa)

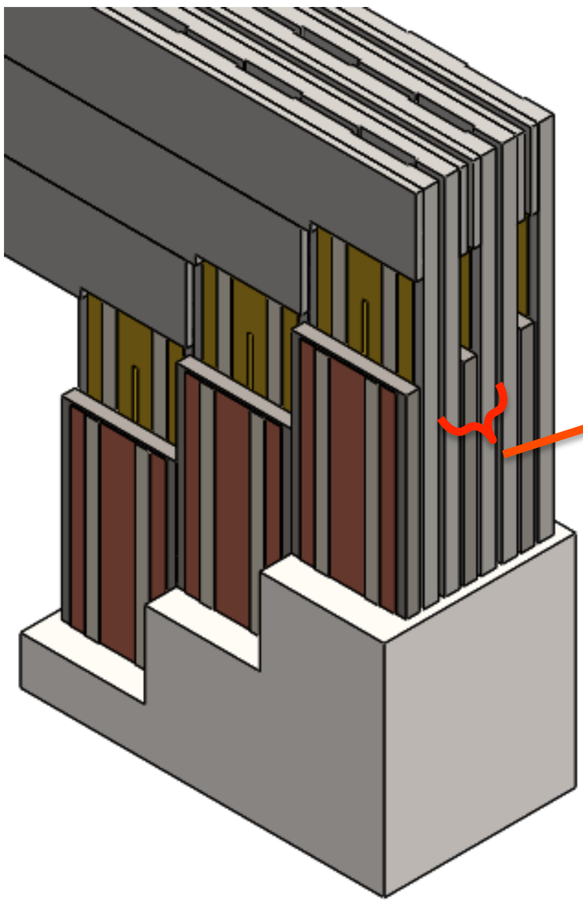


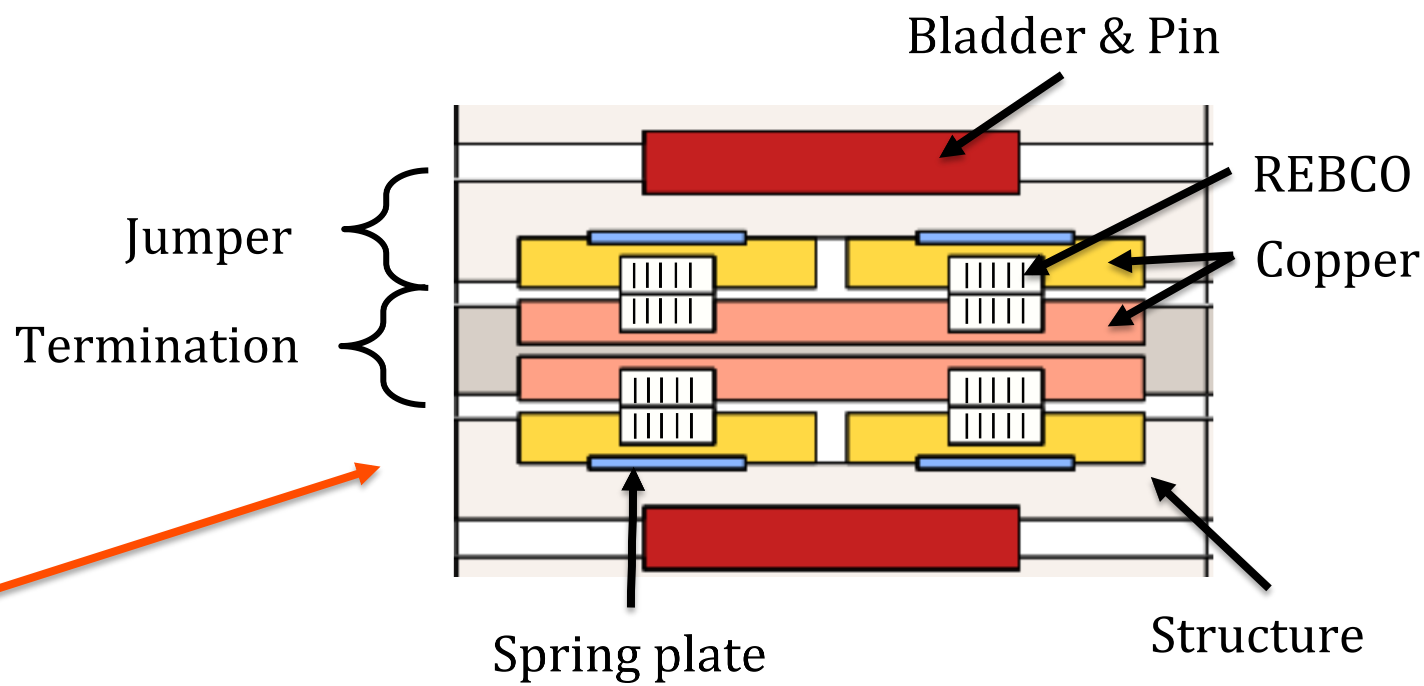
Electrical Joint: Resistive Terminations Linked with "Jumper" Plate





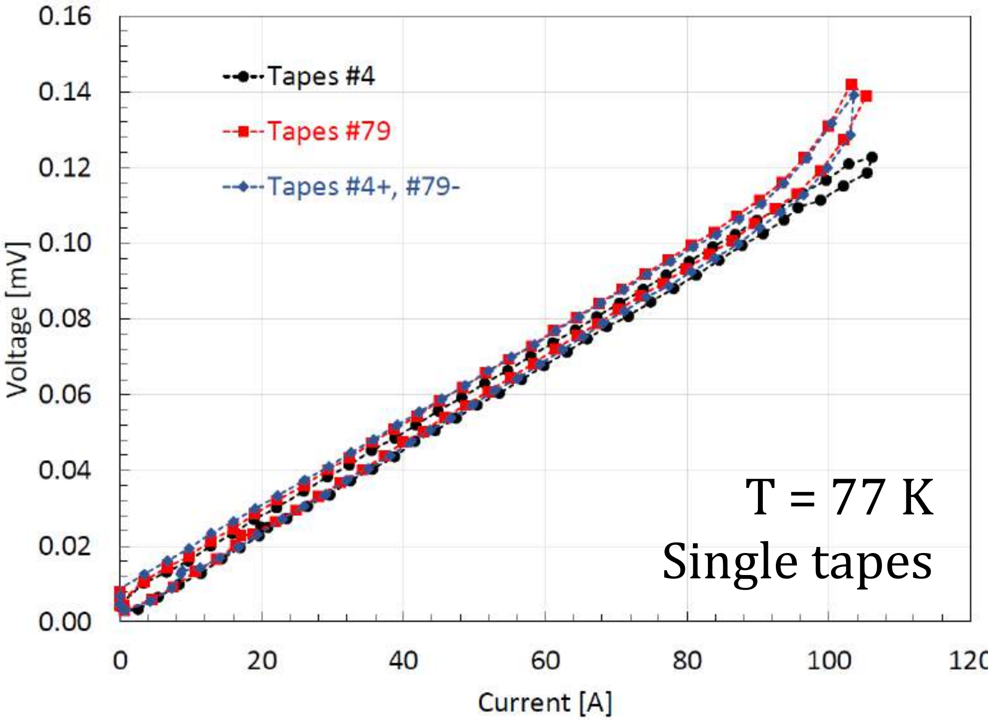
Electrical Joint Design: Section of One Joint

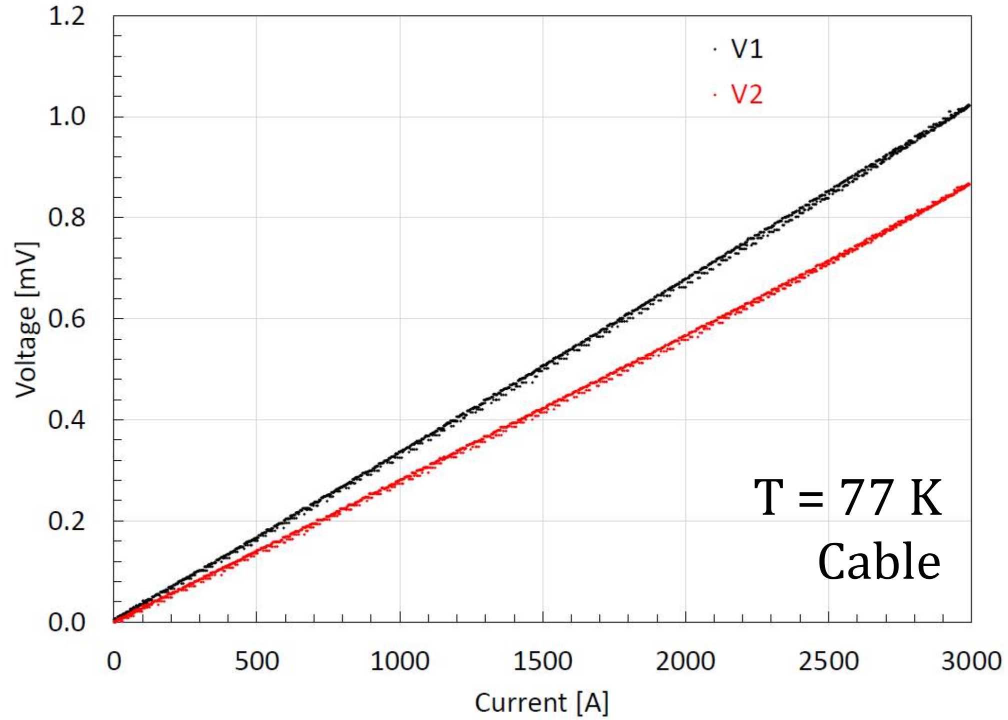


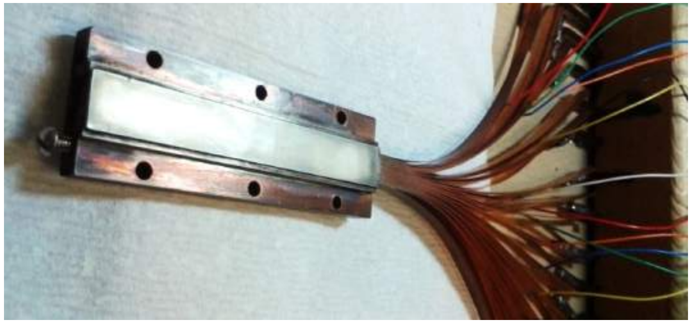


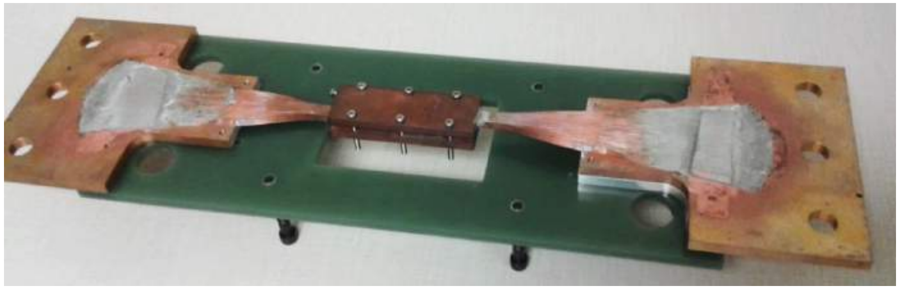
- Edge joint between REBCO stacks
- REBCO stacks covered by 1mm thick protective copper layer
- Bladder & pin hold structure, spring plates press each individual joint

Voltage vs. Current Results for Single Tapes & Cable Experiment





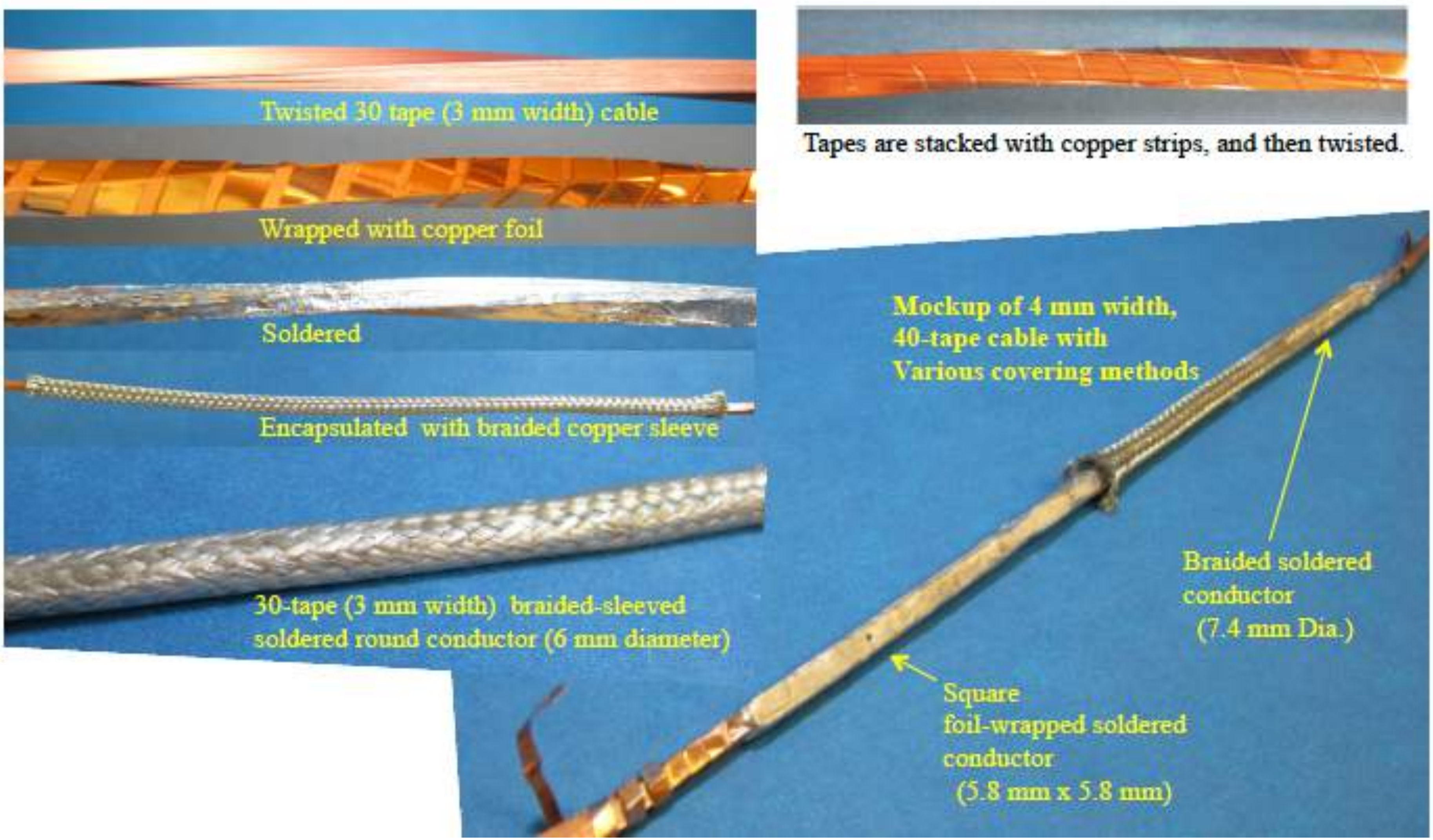




Cable: current capacity larger than 3 kA

Twisted Stack Tape Conductor (TSTC) Developed at MIT

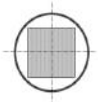
TSTC basic conductors to fabricate multi-stage twisted cable.

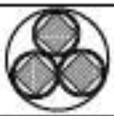
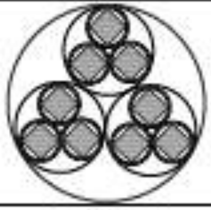
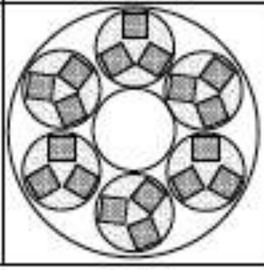


Large TSTC Conductor Current Capacity

Estimated currents and current densities of various conductors

Basic cable : 40-tapes, 4 mm width, 0.1 mm YBCO. Tape critical current : 170 A at 20 T and 4.2 K

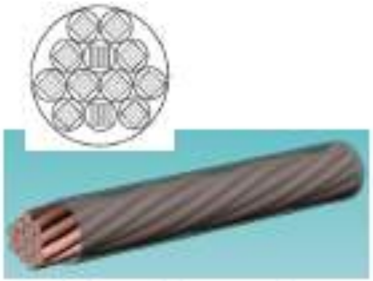


Conductors	I_c at 20 T, 4.2 K (kA) [Je (A/mm^2)]	Conductor Dimension (mm)	Conductor Cross-Section	Stabilizer Volume ratio Tape/Total
Braided soldered	6.8 [158]	Dia. 7.4		37%
Triplet	20 [101]	Dia. 16		24%
3x3 cable	61 [99]	Dia. 35		
Square soldered	6.8 [202]	5.8 x 5.8		48%
3-channel basic cable	20 [81]	Dia. 18		19%
3x6 cable	122 [45]	Dia. 58		

7.4 mm Dia. Braided soldered conductor

Square (5.8 mmx 5.8 mm) soldered conductor

3 x 6 CICC (70 mm x 70 mm)

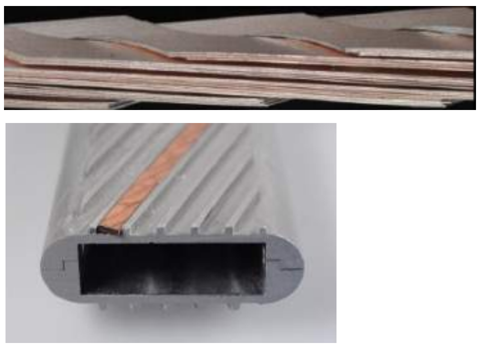


12 sub-cable conductor

Other Countries Are Also Developing HTS Conductors for Fusion

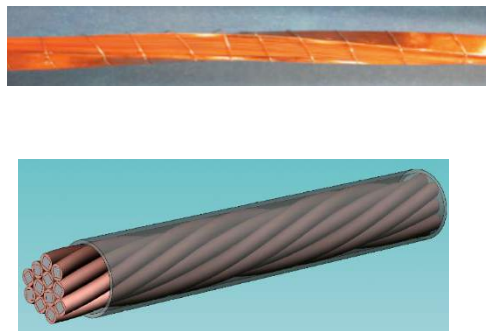
Germany

Roebel (KIT)



USA

TSTC (MIT)



Italy

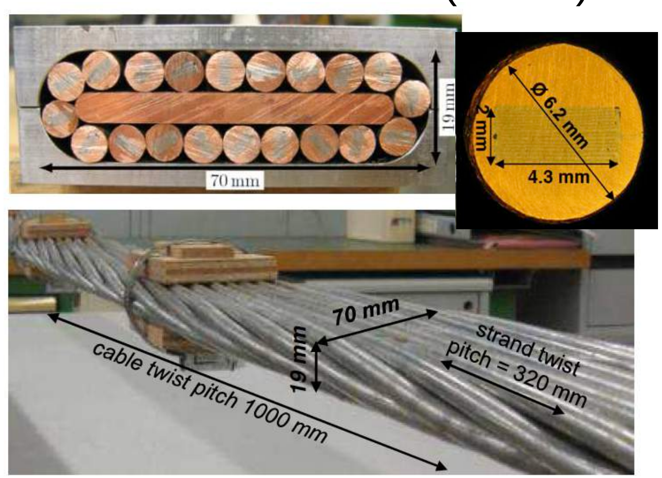
SCHCC (ENEA)

USA

CORC (ACT)

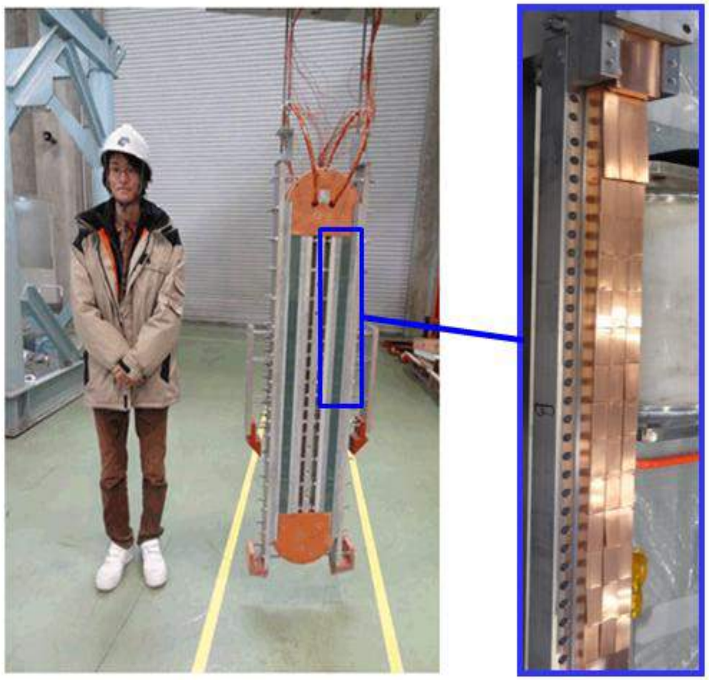
CERN (CICC)

Switzerland *RSCCCT* (CRPP)



Japan *STARS* (NIFS)

Other Countries Are Also Developing HTS Conductors for Fusion



Japan
NIFS-FFHR-d1

Conductor and Joint Tested:
- **100 kA @ 20 K**
- **1.8 nΩ @ 100 kA**

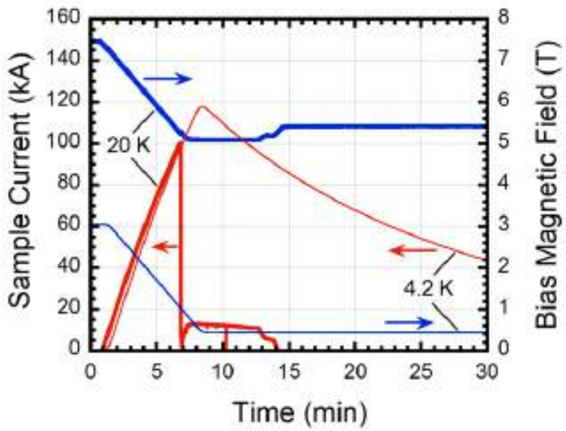
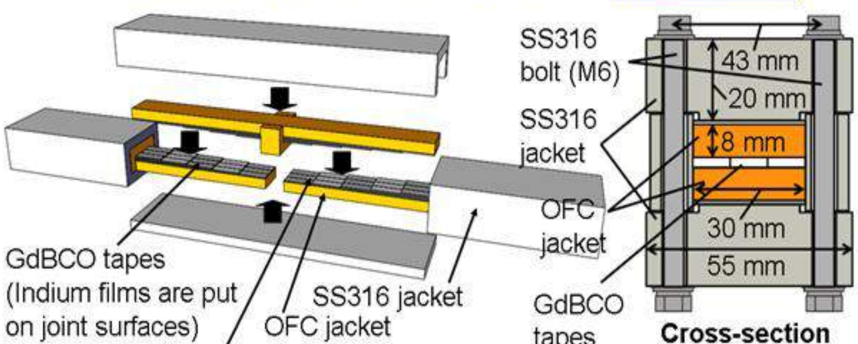
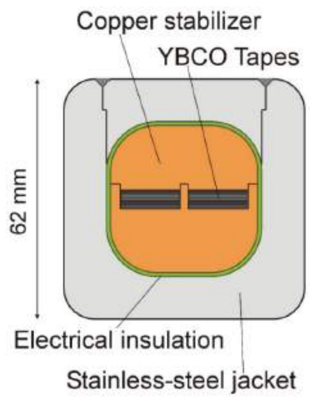


Figure 6. Waveforms for the measured sample conductor current and bias magnetic field at temperatures of 20 K (thick curves) and 4.2 K (thin curves).



Actual layout is 3-row and 14-layer (42 GdBCO tapes having 10 mm wide)
Length of one joint: 30 mm/1-layer x 14-layer = 420 mm



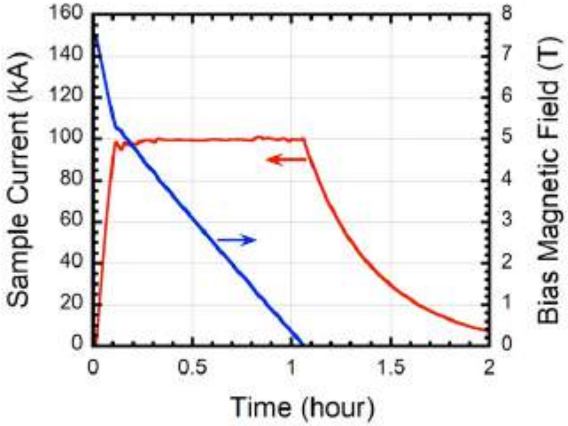
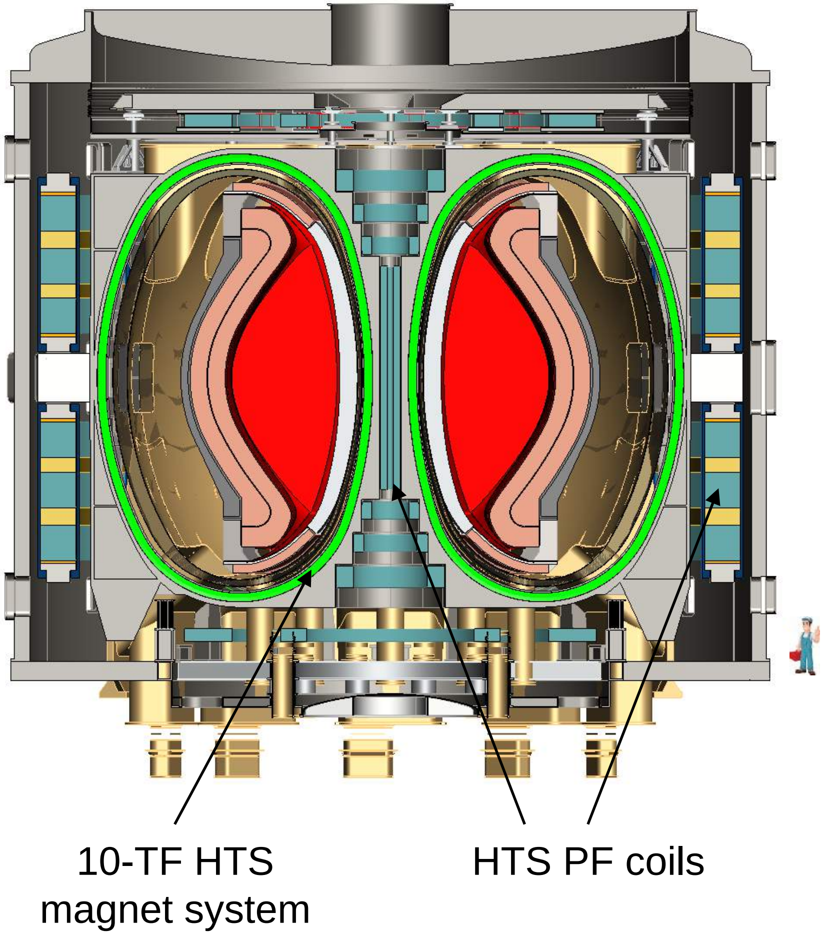


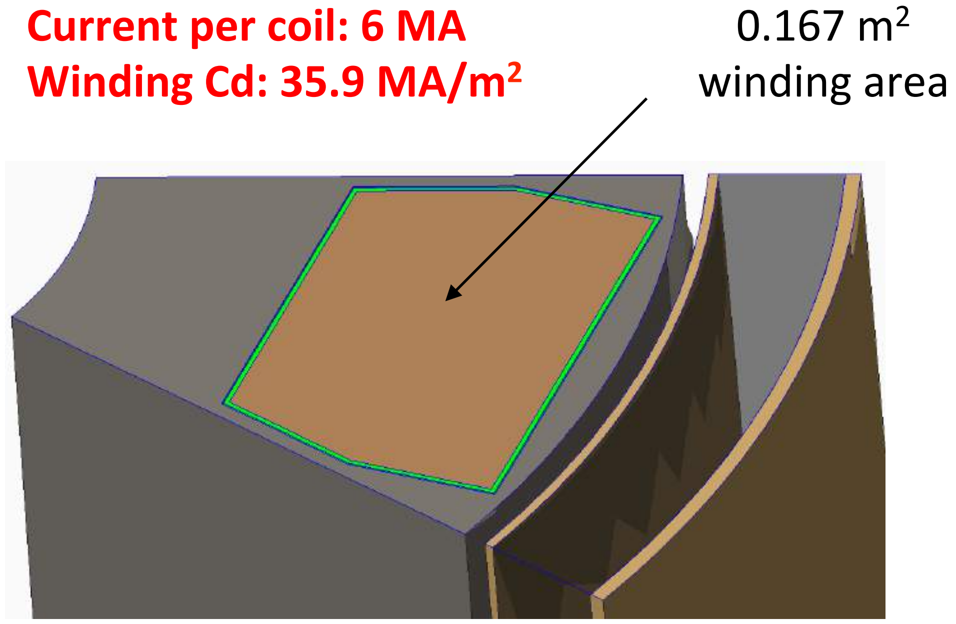
Figure 7. Stable sample conductor current of 100 kA sustained for 1 h at 4.2 K.

3.0-m HTS ST-FNSF design

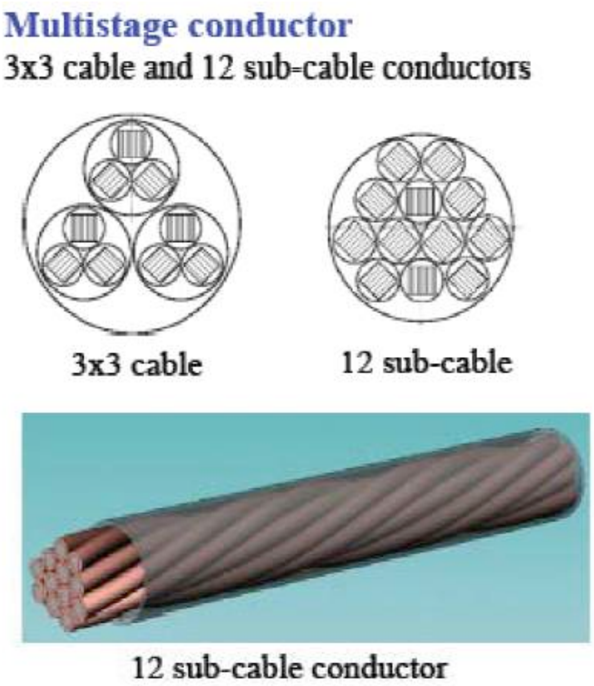
The ST-FNSF design is only feasible with *HTS TF and PF windings*. LTS TF winding Cd is too low. Same condition for most of the PF coils.

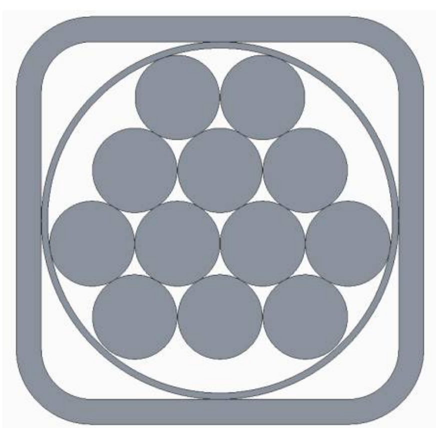


Current per coil: 6 MA
Winding Cd: 35.9 MA/m^2

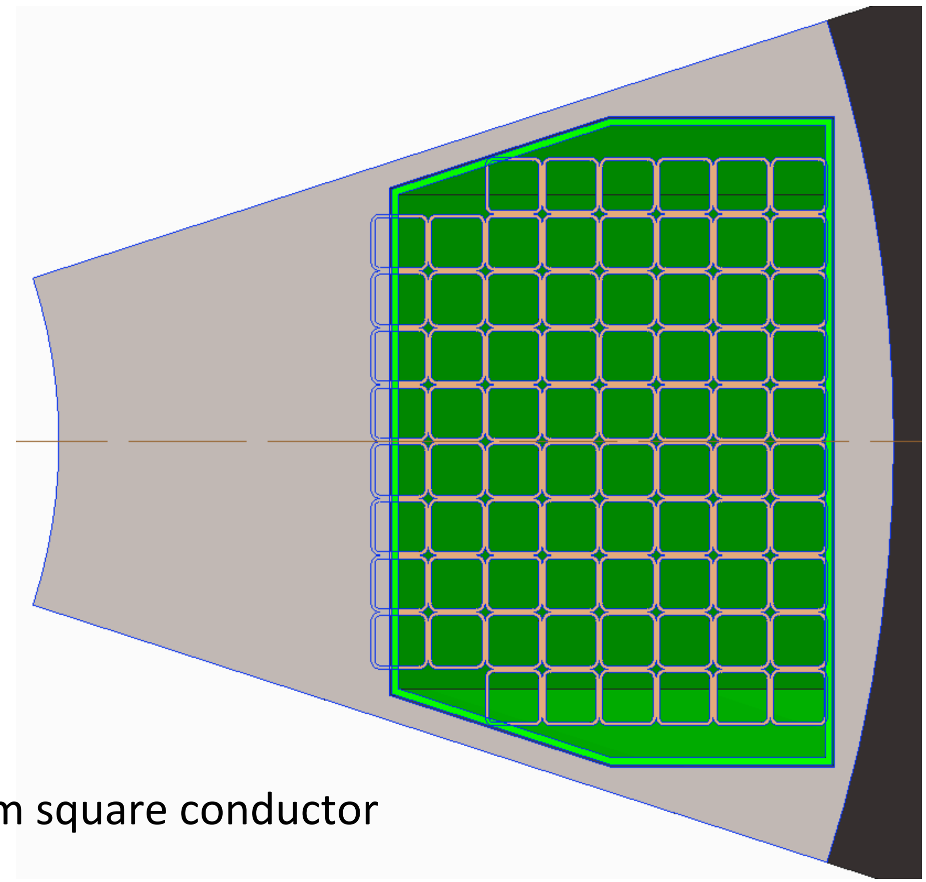


MIT Large TSTC Conductor Highlighting the 12 sub-cable Arrangement





This cable arrangement should work even adding turn-to-turn insulation.

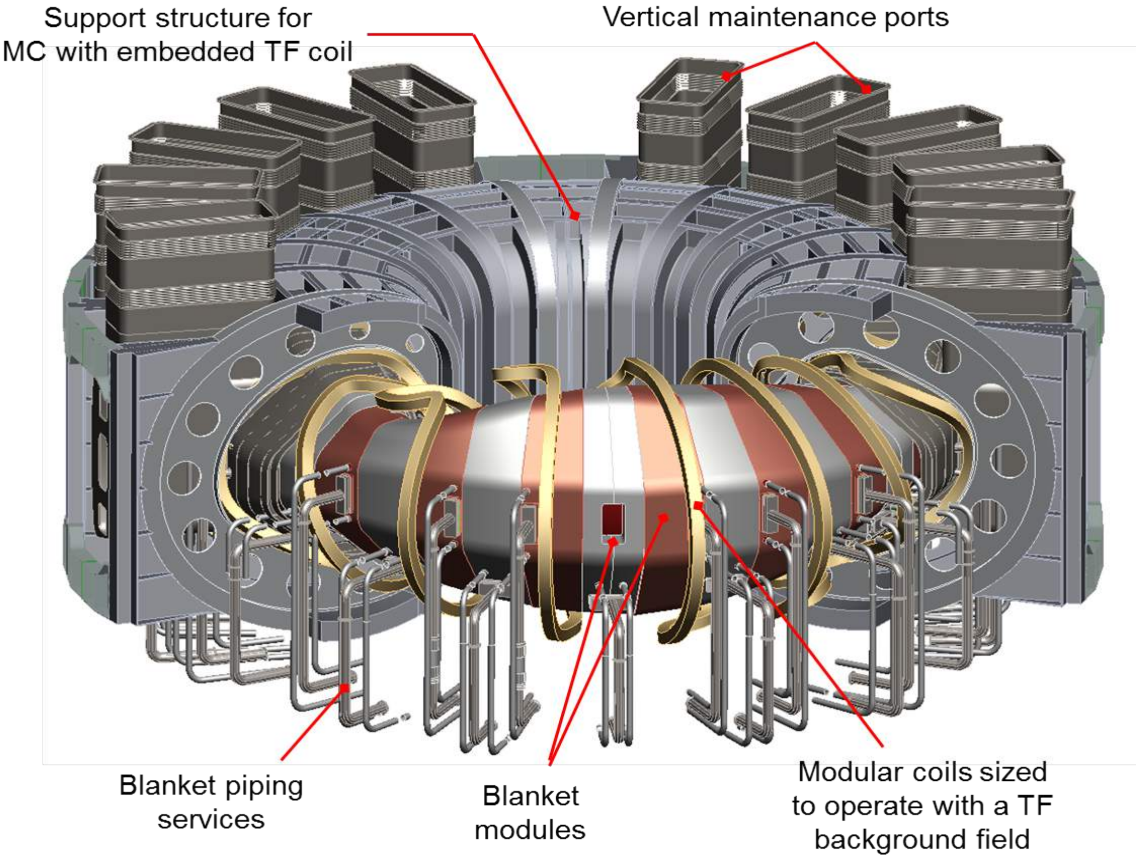


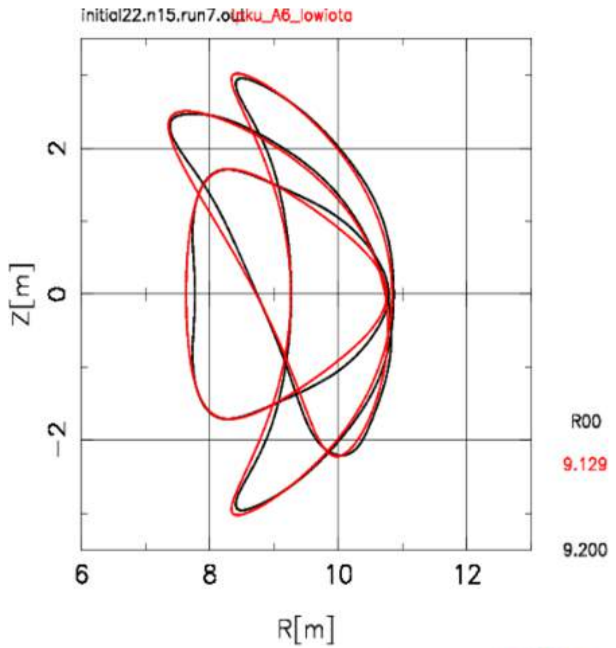
32.6 mm square conductor
81.6 kA
74 turns

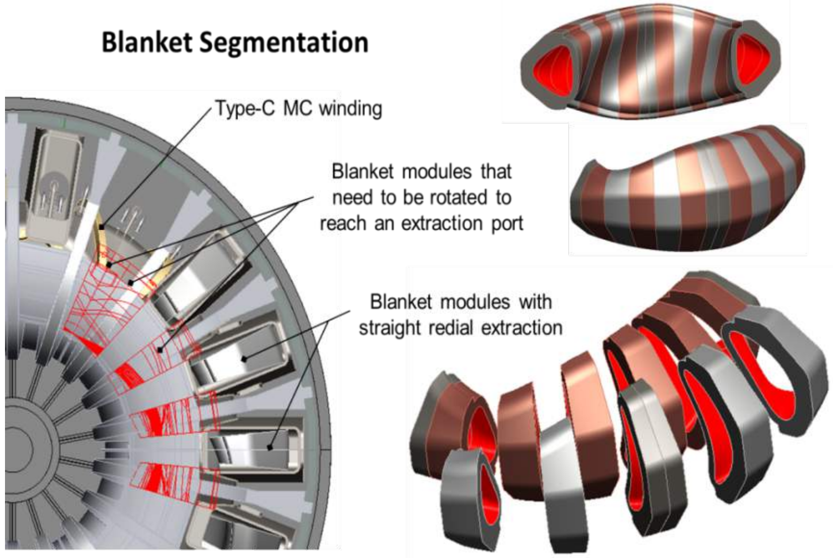
12-sub-cable conductor picture taken from Ziad Melhem presentation

A new stellarator design with straight back legs offers tokamak style vertical maintenance

PPPL
PRINCETON PLASMA PHYSICS LABORATORY





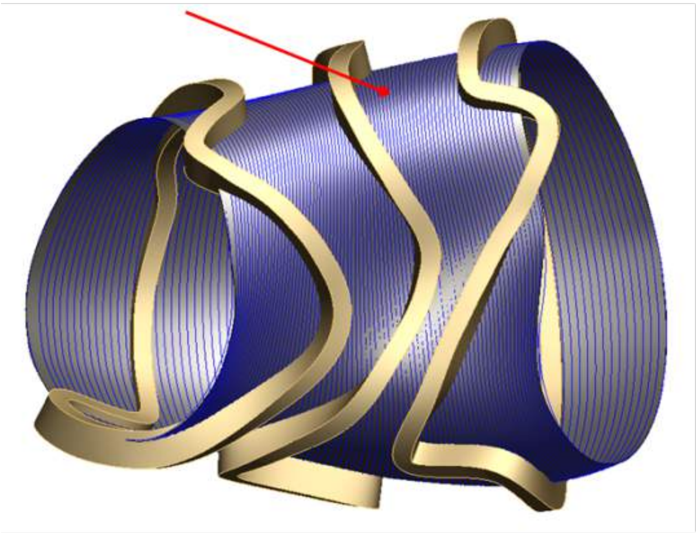


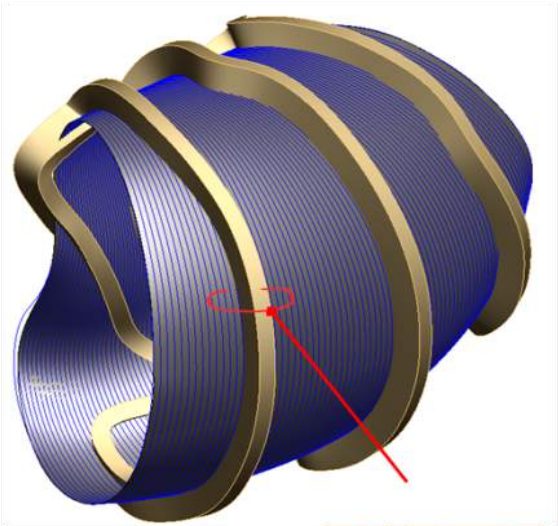
The design was developed using LTS winding. Higher Cd HTS windings offer increased space for gaps, structural support, inboard shielding or reducing distance to plasma.

What are the winding limitations of HTS – if any?

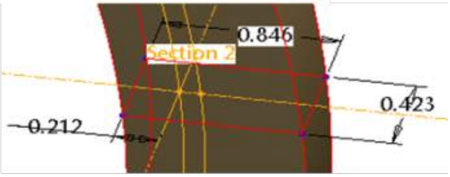
The Type A and B modular coils legs are straight but the inboard section is not. Both Nb_3Sn and HTS windings were defined with and without a TF background field.

MC's developed using an engineering supplied winding surface





MC windings developed assuming 50 MA/m^2 overall CD with no background TF field.



Winding CD defined by specified coil size		
Winding geom. (m)		overall CD
Depth	Width	(MA/m^2)
0.423	0.847	**50.0**
0.423	0.847	44.0
0.423	0.847	42.6

Winding CD defined by specified coil size		
Winding geom. (m)		overall CD
Depth	Width	(MA/m^2)
0.847	0.847	**24.9**
0.847	0.847	22.0
0.847	0.847	21.3

SUMMARY

- Present commercial production of HTS superconductor in the form of REBCO tape is sufficiently advanced to start using it for building small, high field coils now.
- Using even today's performance, advanced fusion reactors can be designed now using this material.
- The performance improvement curve is very steep, easing the reactor designers job for future production.
- REBCO changes the whole reactor design paradigm. We should take advantage of its high field and high temperature performance to design a high field fusion reactor.
- HTS can be used for all magnetic confinement configurations and should be considered for stellarators and helical machines, as well as other, small scale plasma physics experiments.

PSFC

Plasma Science & Fusion Center

Plasma Science and Fusion Center
Massachusetts Insitute of Technology

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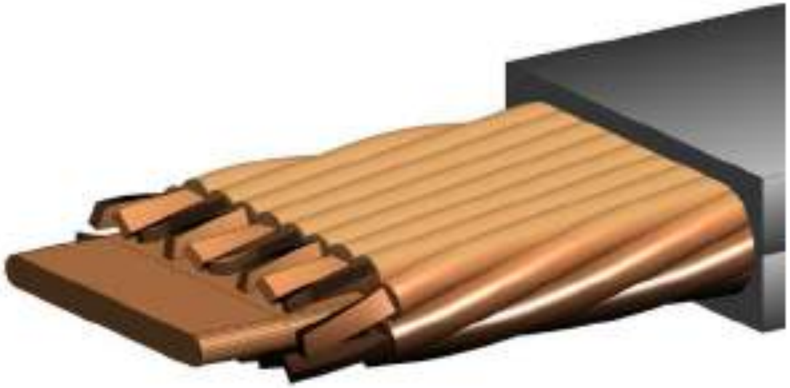
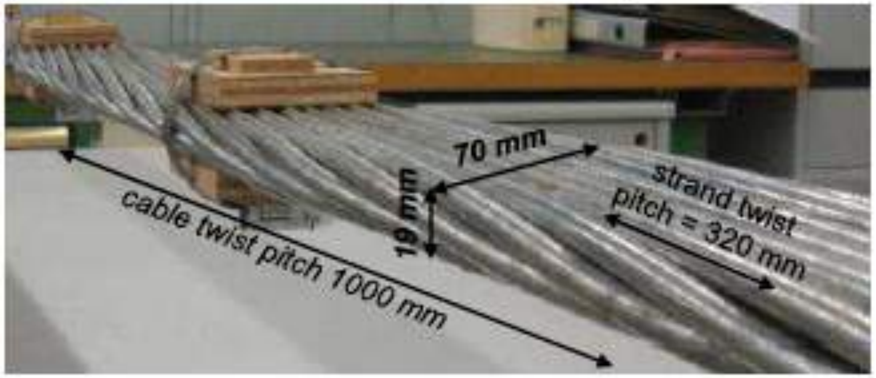
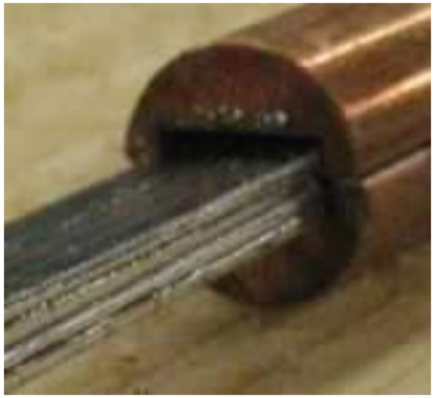
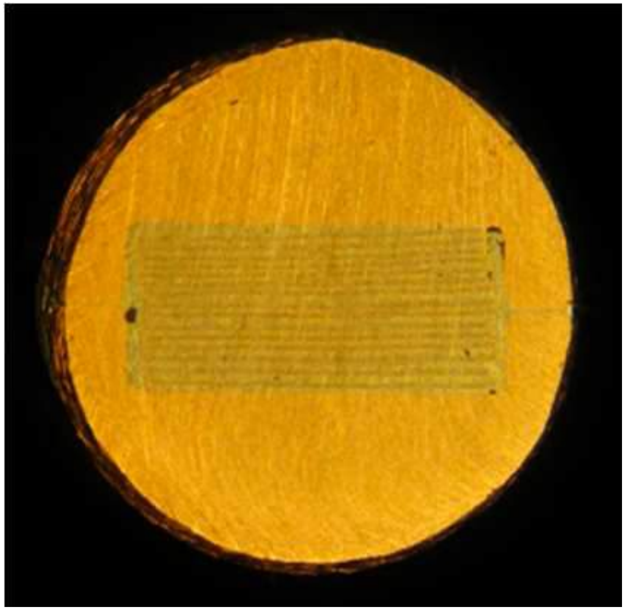
Other Countries Are Also Developing HTS Conductors for Fusion

Swiss Plasma Center-EPFL









Other Countries Are Also Developing HTS Conductors for Fusion

Karlsruhe Institute of Technology

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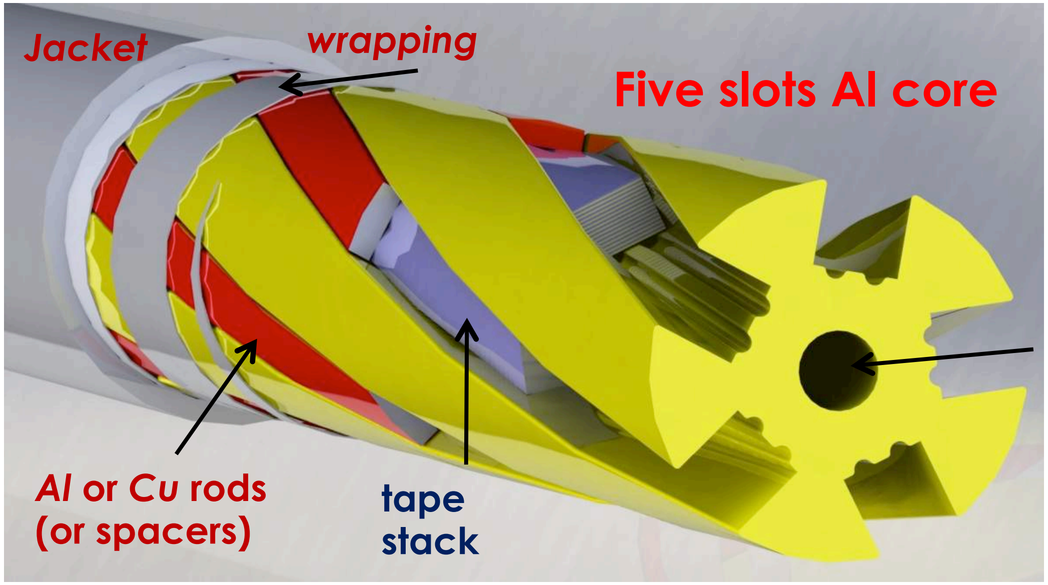
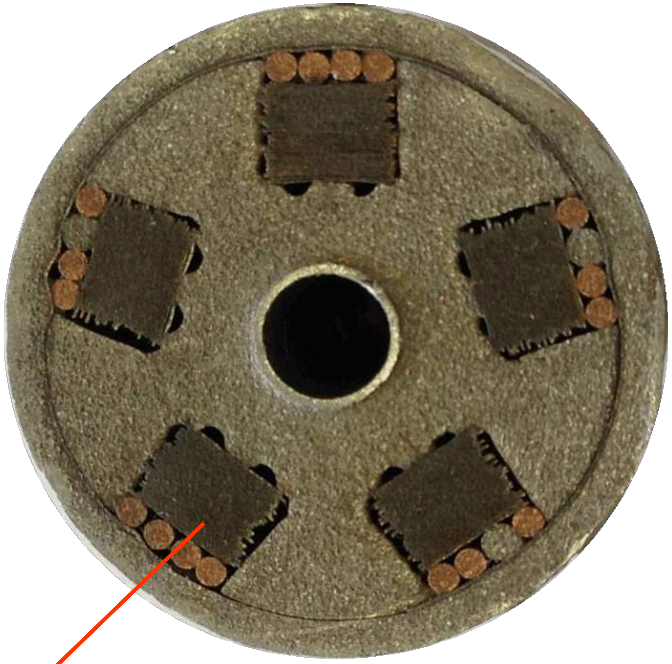
ENEA - TRATOS design for **20 kA – class cable**





Expected $J_e \approx 70$ A/mm^2

20 Tapes (150 μm thickness)