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Electromagnetic and **Mechanical Properties** of Edge-impregnated REBCO Coils under High Magnetic Field

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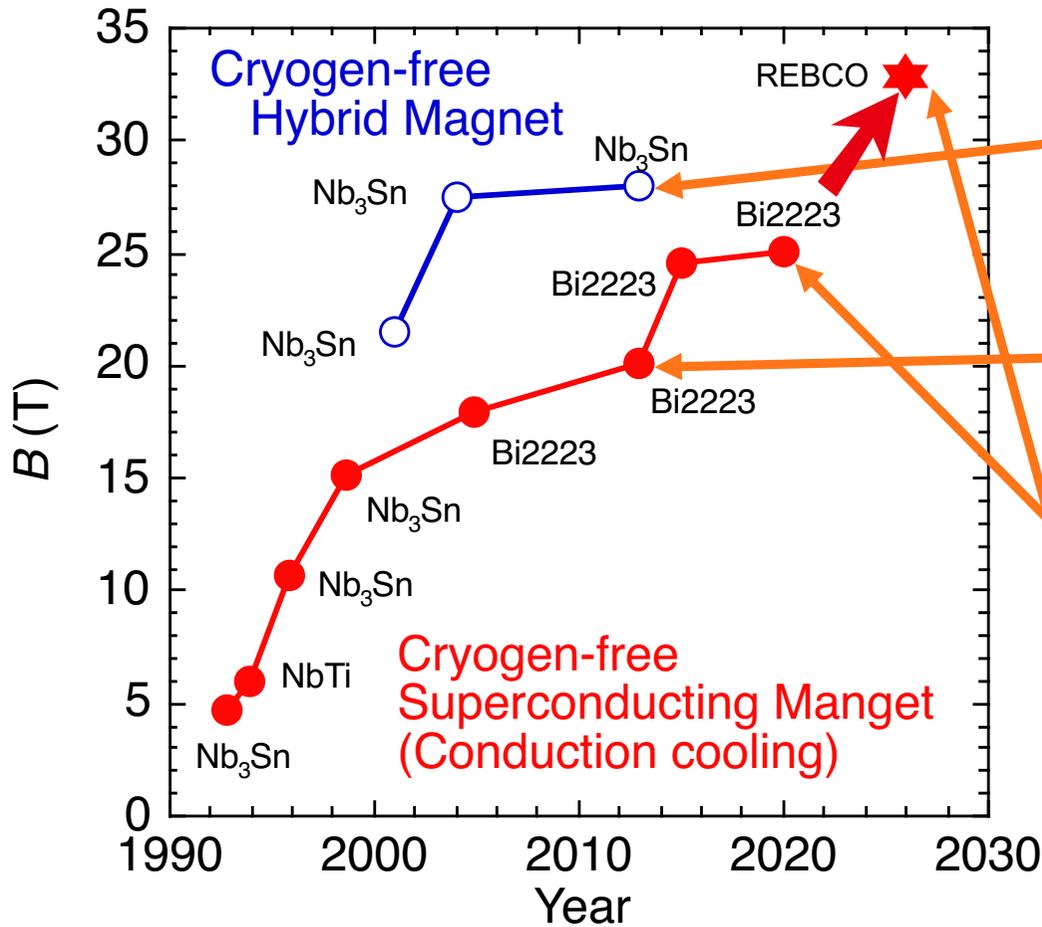
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28T-CHM ($\phi 32RT$)

- $\phi 360-9T$ -CSM
- CuNbTi/Nb₃Sn strand
- $\phi 32-19T$ -WM (8MW)
- Double Bitter



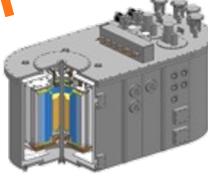
20T-CSM($\phi 52RT$): 1988 days (18 years)

- $\phi 196-15.57T$ -LTS
- CuNbTi/Nb₃Sn, NbTi: 234 MPa
- $\phi 90-4.45T$ -HTS
- Cu-alloy/Ag/Bi2223 (SEI HT-CA): 212 MPa



25T-CSM($\phi 52RT$): >1000 days (9 years)

- $\phi 300-14T$ -LTS
- CuNb/Nb₃Sn Rutherford, NbTi: 251 MPa
- $\phi 96-11T$ -HTS
- Ni-alloy/Ag/Bi2223 (SEI HT-Nx) : 323 MPa



33T-CSM($\phi 32RT$): under construction

- $\phi 320-14T$ -LTS
- CuNb/Nb₃Sn Rutherford, NbTi: 270 MPa
- $\phi 68-19T$ -HTS
- REBCO (Robust coil concept)

Overview of 33T-CSM

HTS insert

- 19 T- $\phi 68$ mm ($\phi 32$ mm RT bore)
- Impregnated two REBCO tape co-wound insulation coil (Robust REBCO Coil)

LTS outsert

- 14 T- $\phi 320$ mm layer wound impregnated coil with Rutherford Cables

Cooling system

- Conduction cooling with He circulation
- 4 x 4K-GM cryocooler for HTS coils (4 x 1.5W@4.2K)
- 1 x GM/JT cryocooler for LTS coils (9W@4.2K)
- Thermally separated LTS and HTS coils

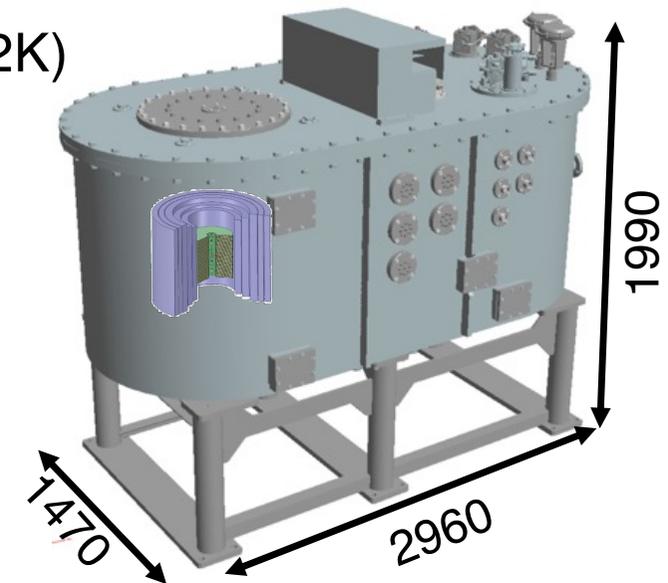
Protection

- Passible protection with a dump resistor

Others

- < 90min ramping
- Magnetic field monitor

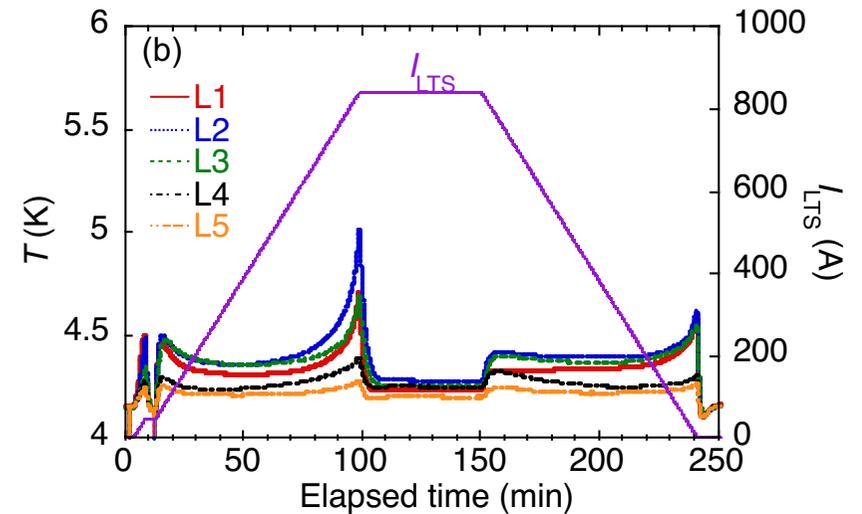
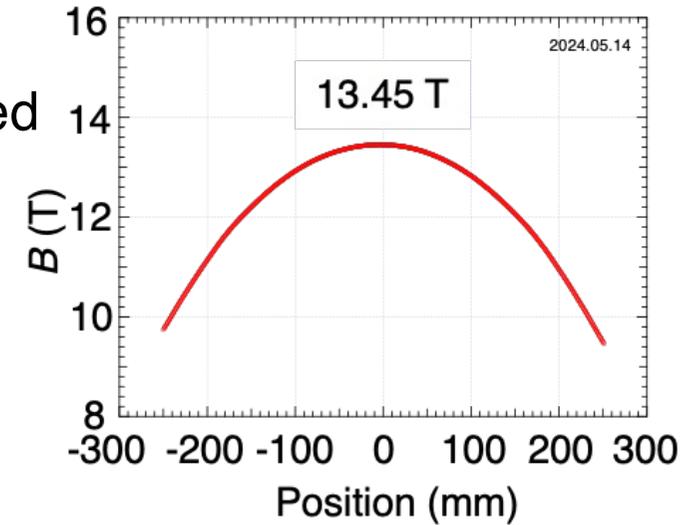
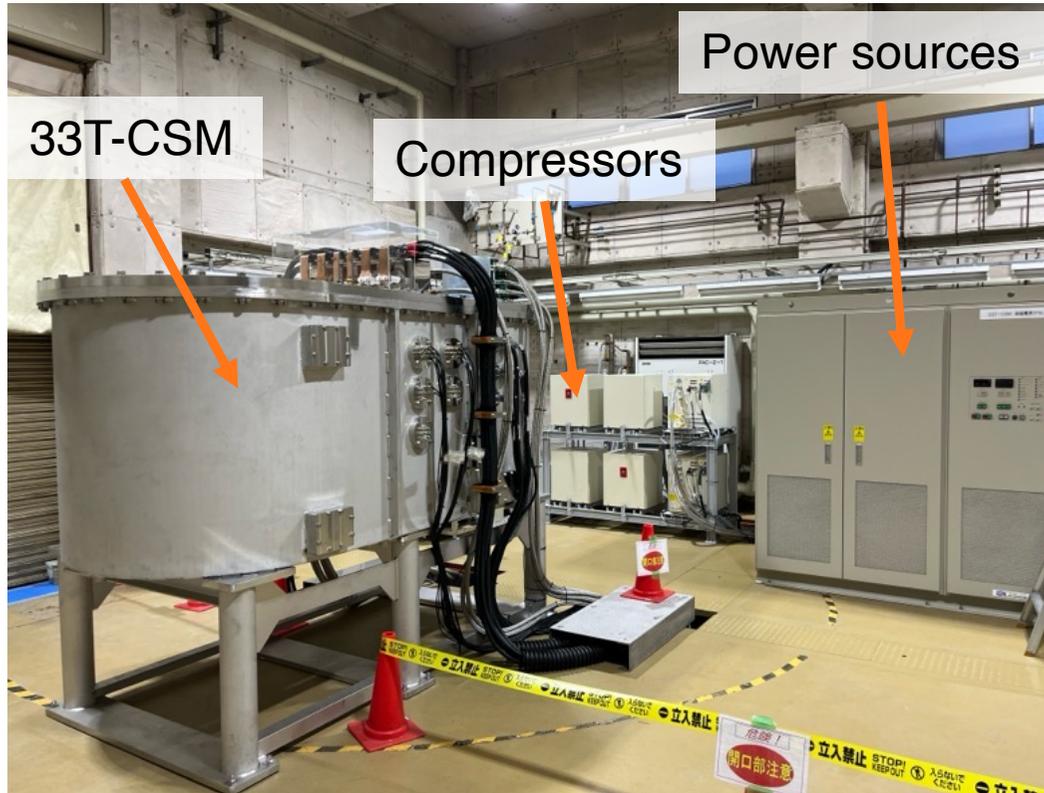
completed



LTS test of 33T-CSM (w/o HTS insert)

2022 March: The project was budgeted.

2024 March: Whole system of 33T-CSM was installed without a 19 T-REBCO insert.



Concept of "Robust" REBCO coil

Two tape bundle winding with a face-to-back configuration
 Current share at **local damaged area**.
 Reduce amount of insulation (Increase J_{space}).

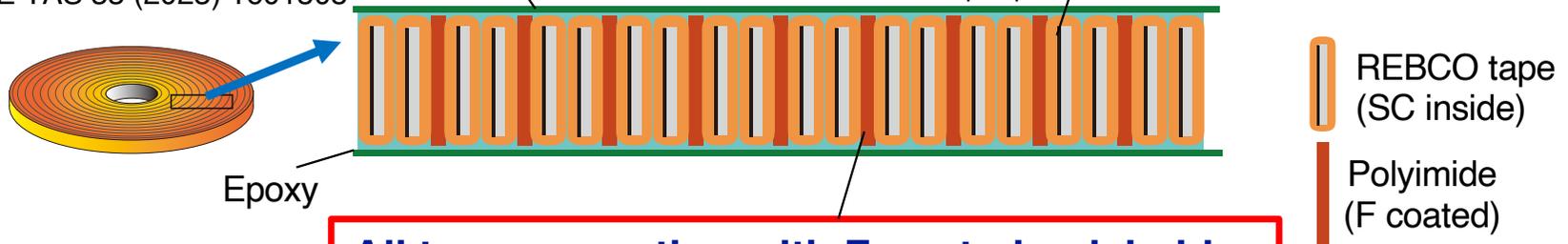
Abe *et al.*, IEEE TAS, 32 (2022) 4603306

Edge impregnation
Thin FRP plate glued on coil & Impregnation
 (Improve coil stiffness, optimize **stress distribution**, reduce screening current induced stress)

40 μm Cu stabilizer
 (Reduce hot-spot temp & **delamination strength**.)

Muto *et al.*, IEEE TAS 28 (2018) 6601004 .

A. Badel *et al.*, IEEE TAS 33 (2023) 1601505



All turn separation with F-coated polyimide
 (Reduce **delamination force** on REBCO tape)

Miyazaki *et al.*, IEEE TAS 24 (2013) 4600905

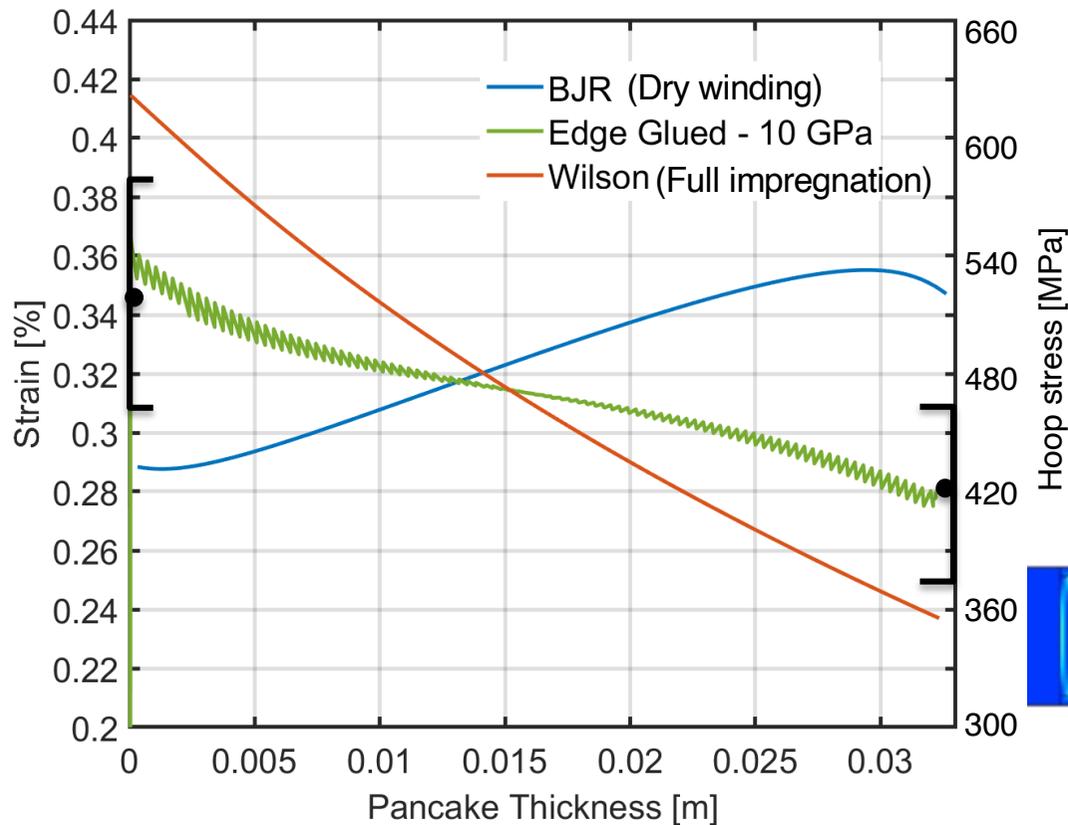
S. Awaji IEEE TAS 31 (2021) 4300105

Stress distribution in the robust coil

Wilson: Full impregnated coil (all turns glued strongly together)

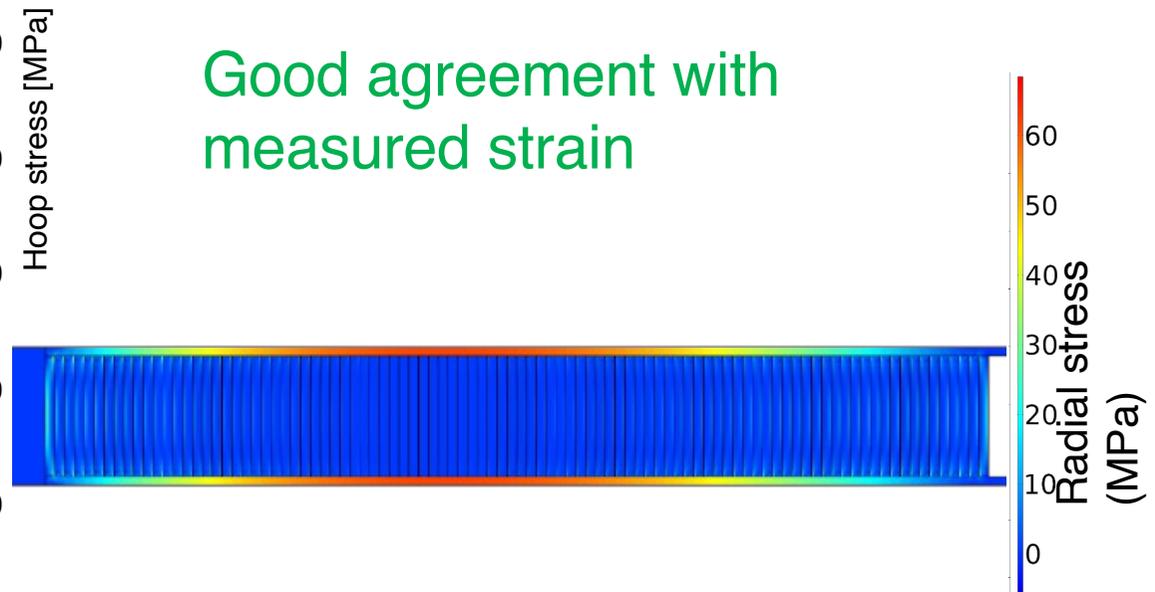
BJR : Dry winding coil (all turns acting independently)

Edge Glued: Edge impregnation coil (all turns partially glued)



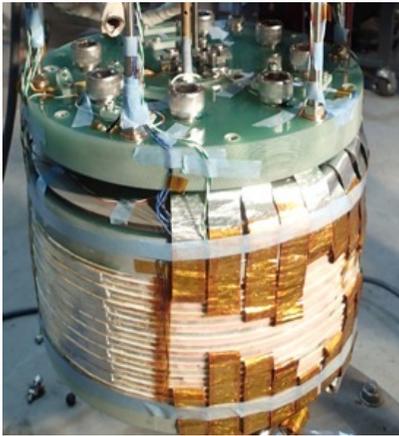
Conductor : 4mm wide, 2 x 150 um Fujikura tape
 Rin : 60 mm x Rout : 93.5 mm, Turn # : 96
 Experiment @ 600 A under 11 T back

Good agreement with measured strain

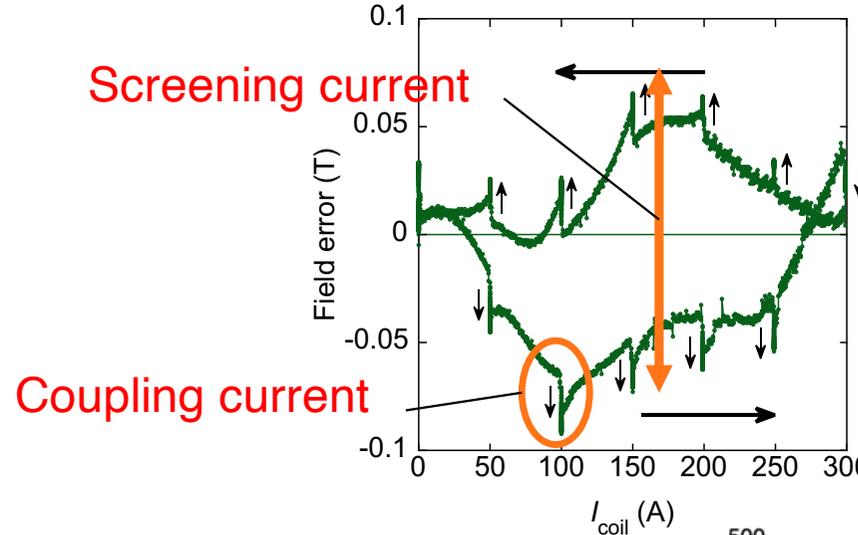


Large-scale prototype REBCO coil (20 stacked)

K. Takahashi et al., IEEE TAS, 33 (2023) 4601405
 A. Badel et al., IEEE TAS, 33, (2023) 4601505



20-stacked Coil	
No. of bundled tapes	2
Inner diameter (mm)	68
Outer diameter (mm)	266
Height of coil (mm)	120
No. of turns / PCs	271-294
I_c of pancake	121-174
n -value of pancake	22-27
No. of pancakes	20

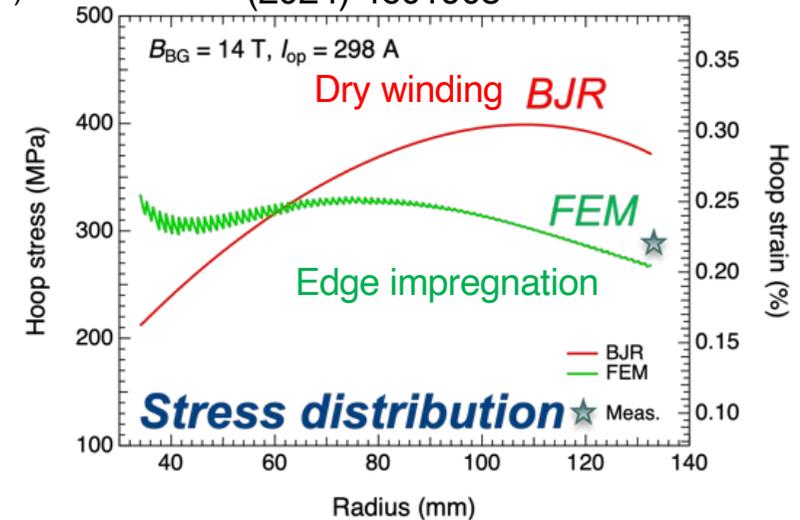


25T was achieved under $B_{BG}=14$ T @NIMS

Screening current induced field B_{SCIF} and coupling induced field B_{CCIF} appear.

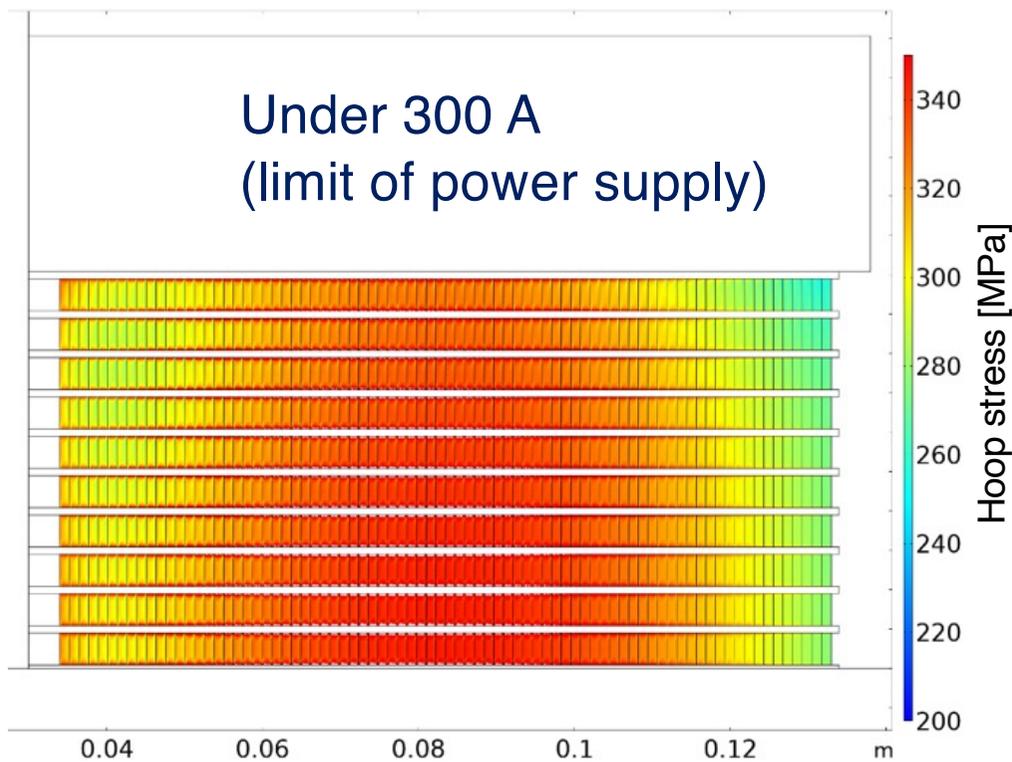
Zampa: 3L0r2E-04
 K. Takahashi et al., IEEE TAS34 (2024) 4601905

Robust coil structure reduces maximum stress and optimizes its distribution in coil.

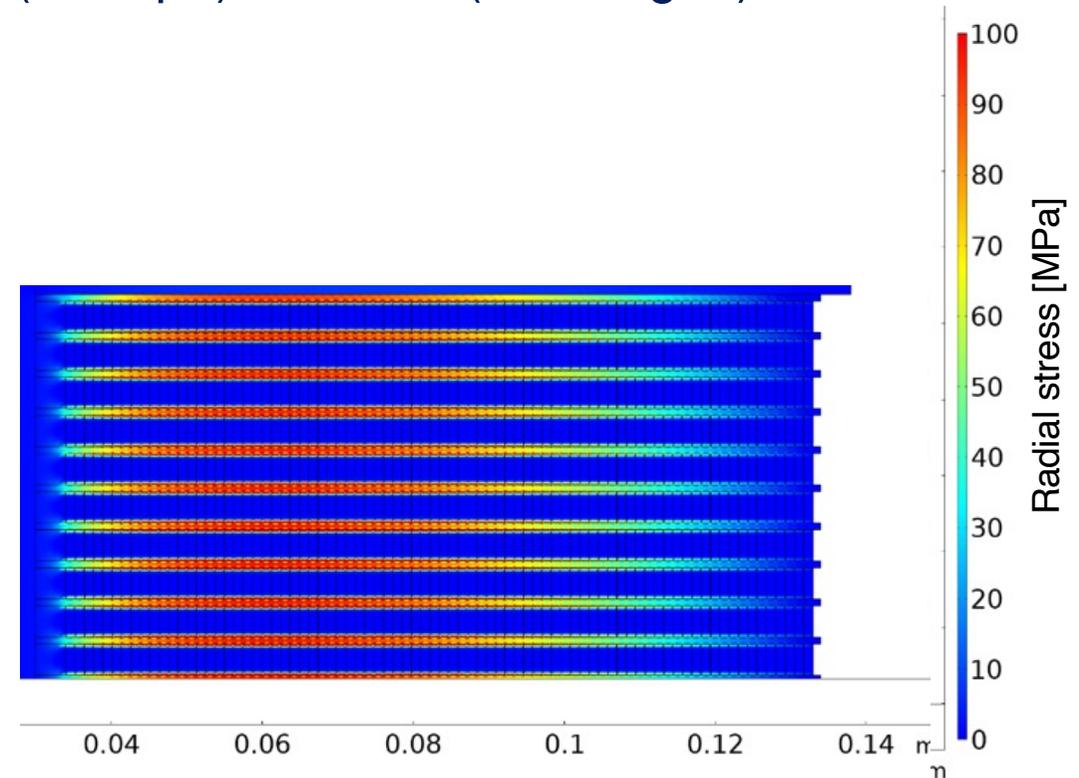


Modelling assumption : Homogenous J
turn to turn separation as soft elastic interface
Elastic regime: Young modulus 130 GPa (for tape), 30 GPa (for flanges)

A. Badel et al., IEEE TAS, 33, (2023) 4601505



Estimated hoop stress up to 346 MPa

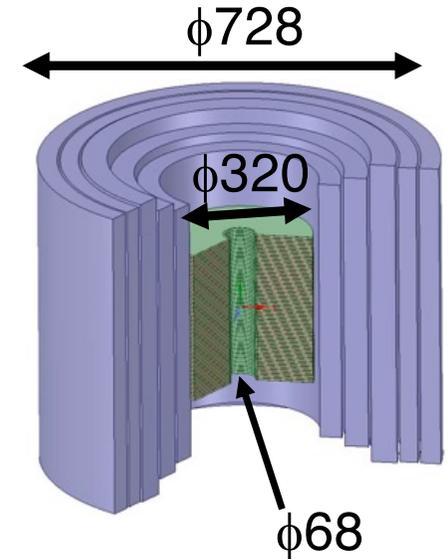


Estimated radial stress up to 100 MPa in flanges

Design of 33T-CSM

S. Awaji IEEE TAS 35 (2025) 4300406.

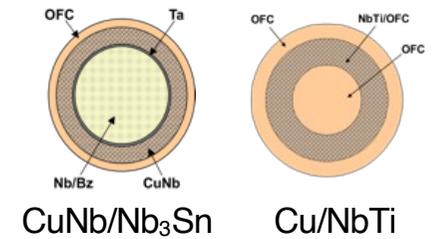
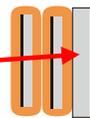
		HTS	NS1	NS2	NS3	NT1	NT2
Strand		REBCO	CuNb/Nb ₃ Sn			Cu/NbTi	
lop	A	361	879				
Rin	mm	34	162.3	210.3	264.2	321.7	356.1
Rout	mm	147.2	205.5	259.4	317.1	362.1	410
Height	mm	324.5	537.6	571.2	632.5	632	632
No of PCs	-	64					
No of layer	-		24	26	28	20	22
Bmax	T	33.27	13.97	10.48	8.06	6.16	5.32
B0	T	19.1	3.22	3.26	2.99	1.91	2.63
Strand size	mm	4.1 x 0.15	φ0.8				
No of strands		2	16	16	18	16	19
Ic @4.2K	A		> 2192 ^{*1}	> 2064 ^{*1}	> 2322 ^{*1}	> 6300 ^{*2}	> 8550 ^{*2}
Reinforcement		1 x 0.1 mm	-	-	-	-	-
Insulation thick	mm	0.06	0.075				
Jcon	A/mm ²	220.1	109.3	109.3	97.2	92.0	124.9
Jcoil	A/mm ²	154.8	71.8	69.2	61.5	55.0	72.7
Tcs	K	-	6.92	9.7	11.9	6.4	6.68
Axial stress	MPa	-51	-51	-50	-48	-38	-43
Hoop stress	MPa	-	275	251	165	82	-28



High stress

^{*1} 12 T, ^{*2} 5 T

reinforcement



Strain analysis in the pancake coil (mid pancake)

Case 0 (no reinforcement)

Current 278 A, center field 33 T

-> Maximum hoop strain 0.35 %

Case 1 (0.1 mm Hastelloy co-wind))

Current 358 A, center field 33 T

-> Maximum hoop strain 0.29 %

Case 2 (0.1 mm x 2 Hastelloy co-wind))

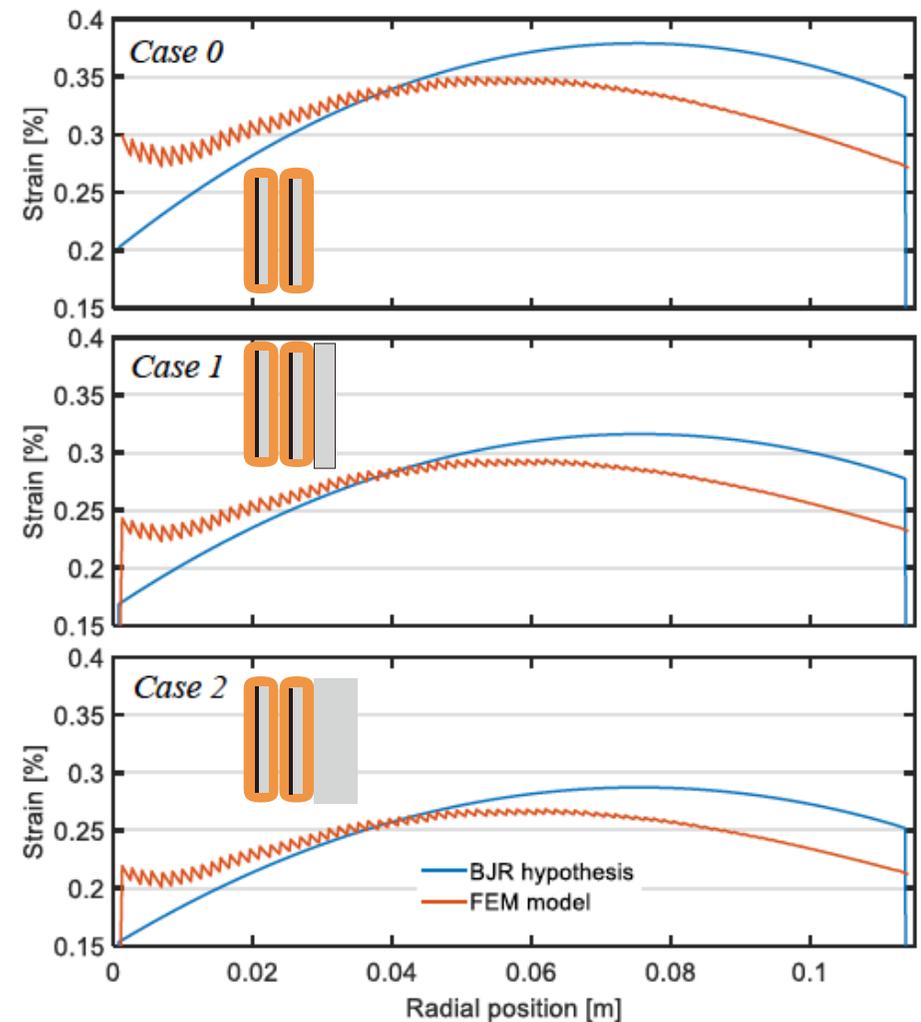
Current 438 A, center field 33 T

-> Maximum hoop strain 0.265 %

Young Modulus assumption :

Tape => 130 Gpa,

Reinforcement => 208 GPa



Concept of Robust REBCO coil

Two tape bundle winding with a face-to-back configuration

Current share at local damaged area.
Reduce amount of insulation (Increase J_{space}).

W. Abe *et al.*, IEEE TAS, 32 (2022) 4603306

Edge impregnation
Thin FRP plate glued on coil & Impregnation

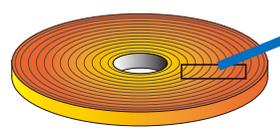
(Improve coil stiffness, optimize stress distribution, reduce screening current induced stress)

40 mm Cu stabilizer

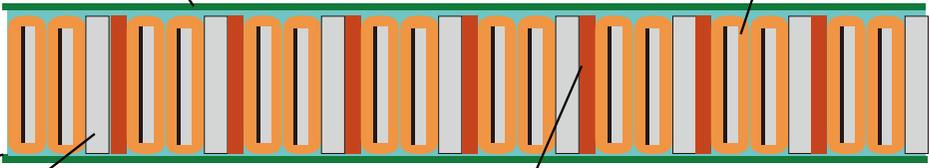
(Reduce hot-spot temp & delamination strength.)

S. Muto *et al.*, IEEE TAS 28 (2018) 6601004 .

A. Badel *et al.*, IEEE TAS 33 (2023) 1601505



Epoxy



-  REBCO tape (SC inside)
-  Polyimide (F coated)
-  Hastelloy (reinforcement)

All turn separation with F-coated polyimide

(Reduce delamination force on REBCO tape)

H. Miyazaki *et al.*, IEEE TAS 24 (2013) 4600905

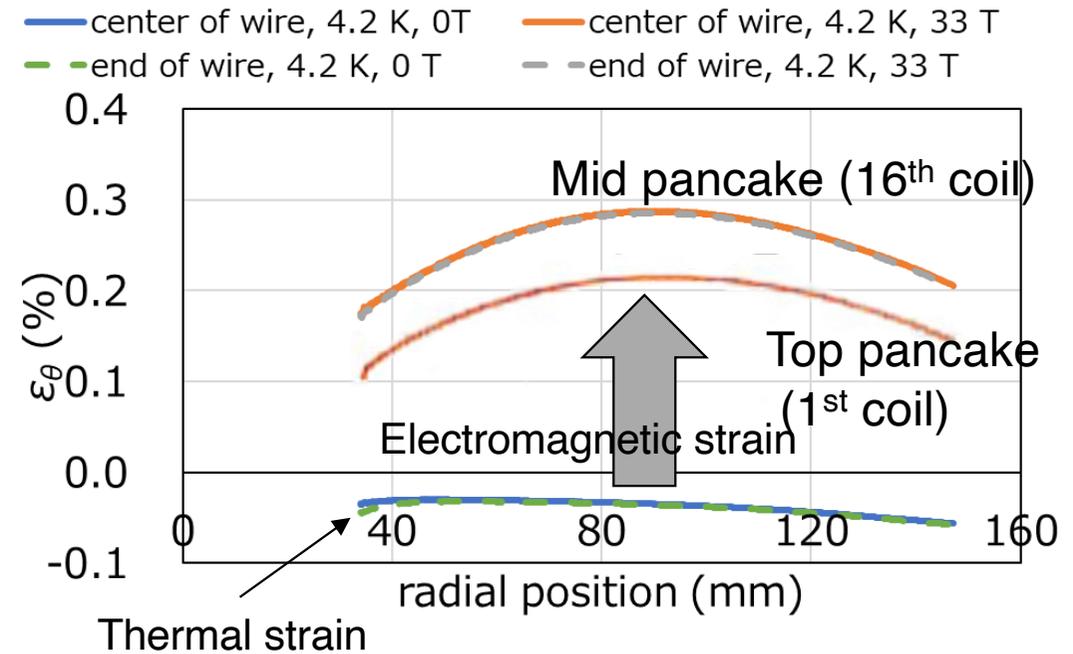
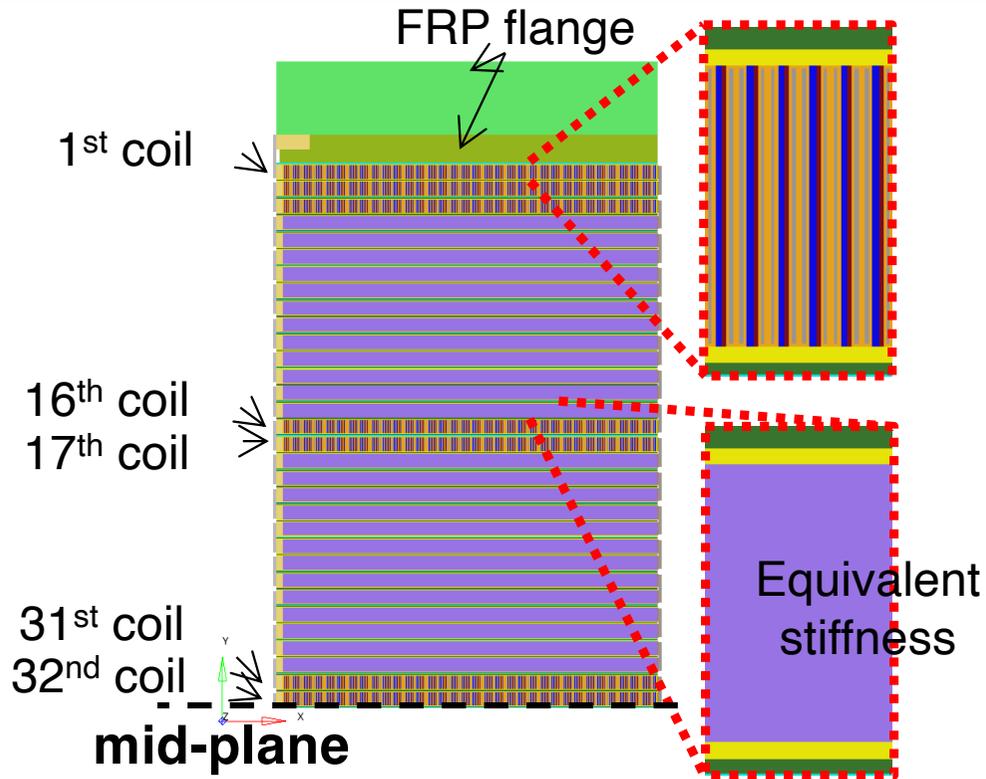
Reinforcement with Hastelloy co-winding

A. Badel *et al.*, IEEE TAS 34 (2024) 4301205

T. Uto: IEEE TAS 35 (2025) 4601405

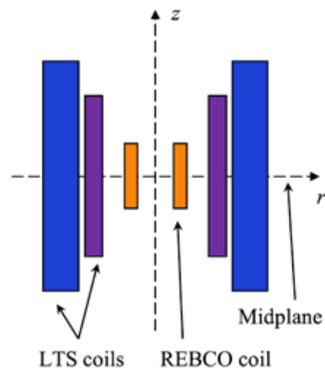
S. Awaji IEEE TAS 35 (2025) 4300406.

2D FEM analysis in the pancake coil



- Maximum hoop strains are about 0.29% for the mid pancake and 0.21% for the top pancake.
- Screening current induced stress/strain should be considered. It is about 10% and negligible in the mid coil.

Screening current induced stress - effect of impregnation -



impregnation
w/o SCIS

REBCO insert for 32T-SM
($B_{LTS}=15T, B_{HTS}=10.7T$)

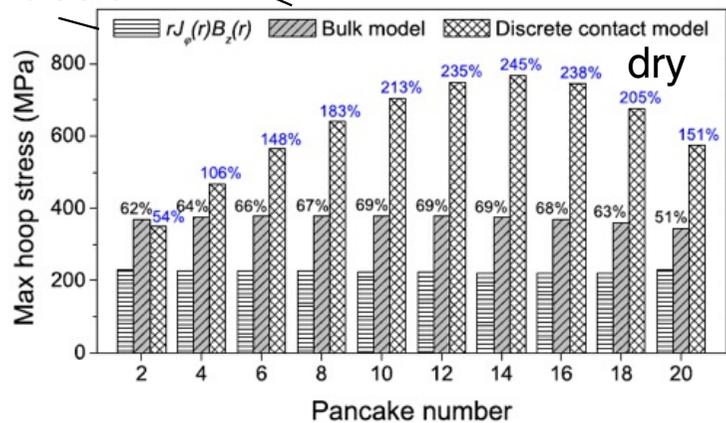
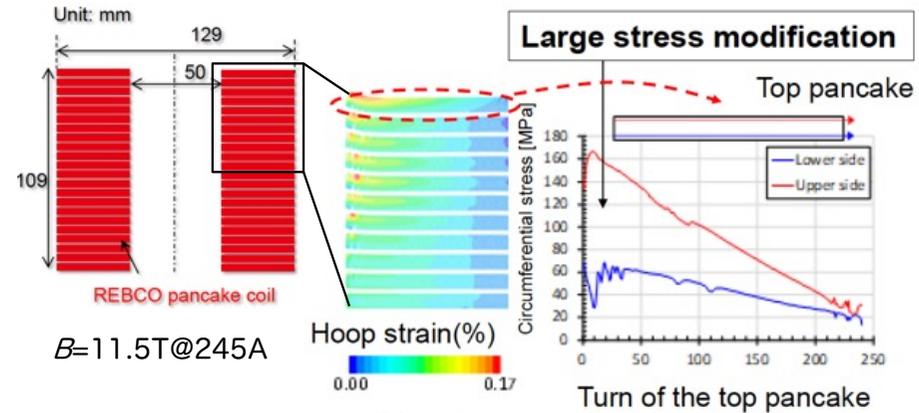
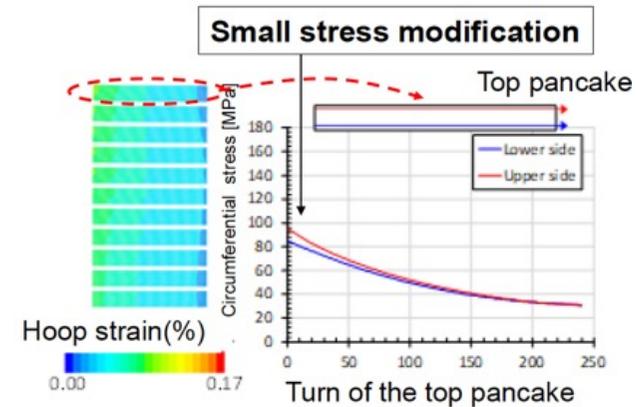
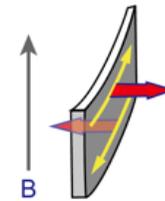


Figure 15. Maximum local hoop stresses in pancakes based on the classic formula (without SC), bulk model (with SC) and discrete contact model (with SC), respectively.

Xia et al, SuST, 32 (2019) 095005



(a) Dry wound coil



(b) Epoxy impregnated coil

Hiroshi Ueda et al SuST. 35 (2022) 054001

Impregnation → reduce the screening current induced stress.

Summary

- 33T-CSM system without a 19T-REBCO insert has been tested successfully.
- Robust REBCO concept is good for the high stress and high field magnet based on REBCO CCs.
 - Stress distribution of the edge impregnated coil is intermediate between the dry winding coil and full impregnated coil.
- $\phi 68\text{mm}$ - 19 T REBCO insert was designed based on the robust REBCO concept.
 - The robust REBCO coil structure (two tape co-winding and edge impregnation) with additional co-winding Hastelloy tape ($\approx 0.1\text{ mm}$) is adopted.
 - The maximum hoop strain of about 0.3 % without screening current induced stress/strain is estimated in the design, which is about 66% of the irreversible strain limit.
 - Edge-impregnation can also reduce the SCIS, although the detail analysis is under way (to be presented in EUCAS2025 by S. Nojima)
 - The 19T-REBCO insert is under construction and will be tested in 2027.