Test and Analysis of Stacked-Tape-Wound Laboratory-Scale NI HTS TF Single Pancake Coil

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MT27 (hybrid), Fukuoka, Japan

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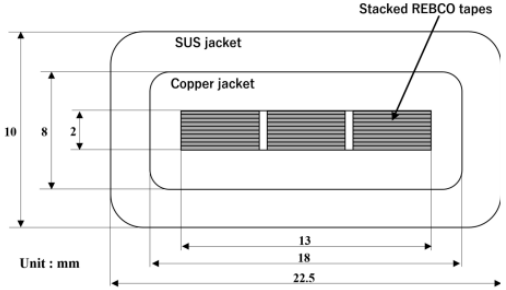
Background: Active Use of the HTS for Fusion

- Various research and developments are being conducted from HTS cables and conductors to stacked tape wound magnets

NIFS
National Institute for Fusion Science

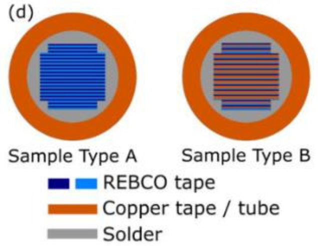
STARS conductor



T. Obana and N. Yanagi, Cryogenics **115** (2021) 103278

KIT
Karlsruher Institut für Technologie

CroCo conductor

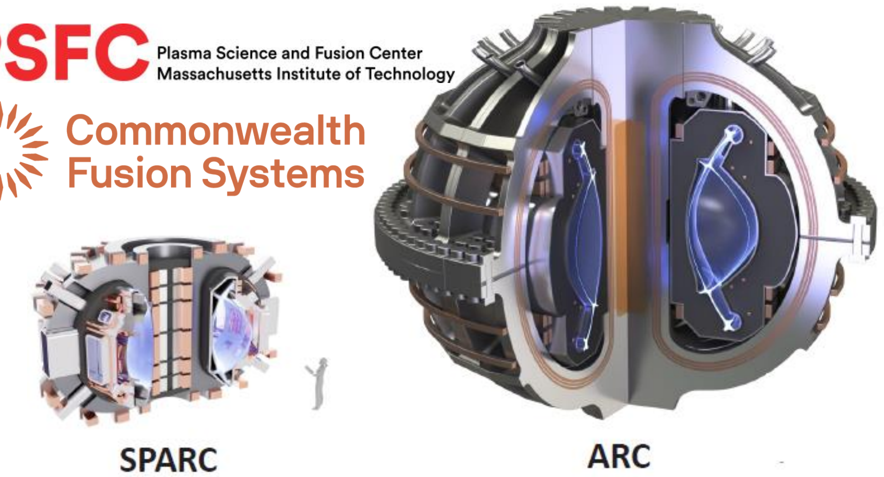


M. J. Wolf, *et al.*, *Fusion Eng. Des.* **172** (2021): 112739.

Advanced Conductor Technologies LLC
www.advancedconductor.com

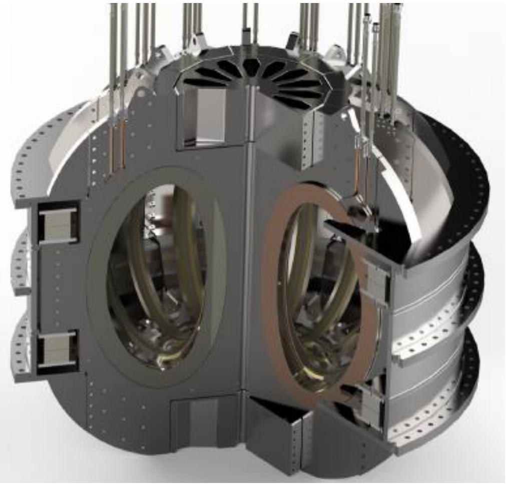
PSFC Plasma Science and Fusion Center
Massachusetts Institute of Technology

Commonwealth Fusion Systems

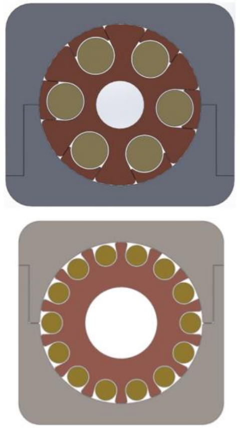


Z. Hartwig, Oral presentation at Applied Superconductivity Conference, Wk1LOr2B-01, 2020; https://cfs.energy/technology

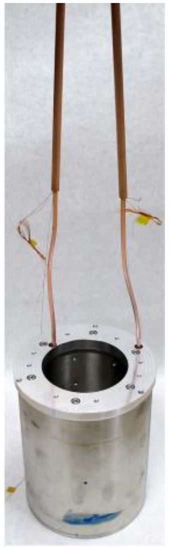
tokamak energy
a faster way to fusion



Z. Melhem, *et al.*, *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, June 2015.
A. Down, Oral Presentation at Applied Superconductivity Conference, Wk1LOr2B-05, 2020.



CORC® cable insert solenoid →



D. C Van Der Laan, *et al.*, *Supercond. Sci. Technol.* 33 (2020) 05LT03 (10pp)

https://cfs.energy/technology/#hts-magnets-enabling-technology
https://www.cnbc.com/2021/09/08/fusion-gets-closer-with-successful-test-of-new-kind-of-magnet.html

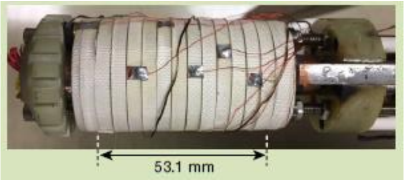
Previous Works: No-insulation and Co-winding Methods in Solenoid Shape

■ Development of No-insulation (NI) HTS Coil

The first NI HTS coil

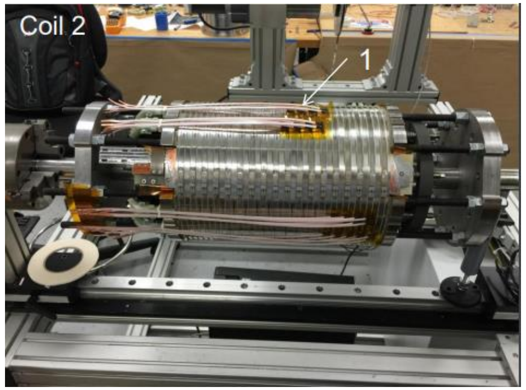
S. Hahn, *et al.*, *IEEE Trans. Appl. Supercond.* 21.3 (2010): 1592-1595.

The highest magnetic field (45.5 T) achieved by NI HTS coil, LBC III



S. Hahn, *et al.*, *Nature* **570**, 7762 (2019): 496-499.

NHMFL 32 T

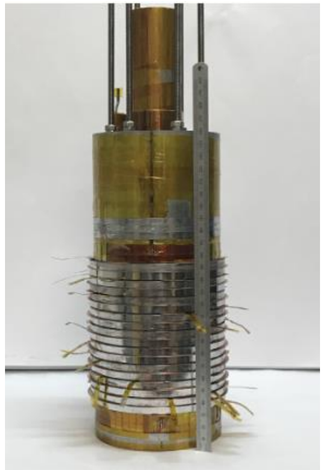


H. W. Weijers, *et al.*, " The NHMFL 32 T superconducting magnet," *EUCAS 2017.*

CAS 32 T

J. Liu, *et al.*, *Supercond. Sci. Technol.* 33.3 (2020): 03LT01.

Grenoble 32 T

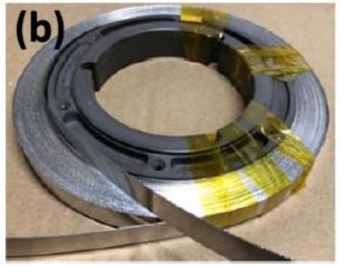


P. Fazilleau, *et al.*, *Cryogenics* 106 (2020): 103053.

■ Features of Co-winding Coil

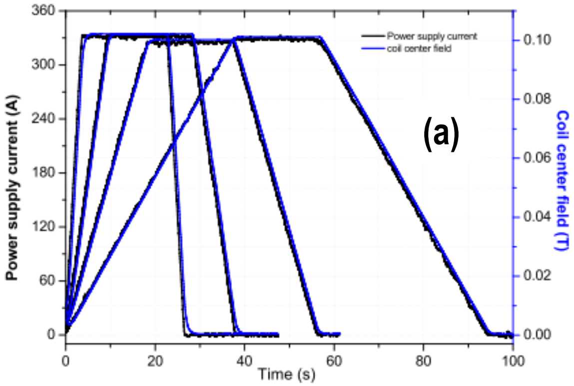
- ☐ Reduced charging delay compared to NI HTS coil
- ☐ Reduced coil voltage and charging loss
- ☐ Increased engineering current density

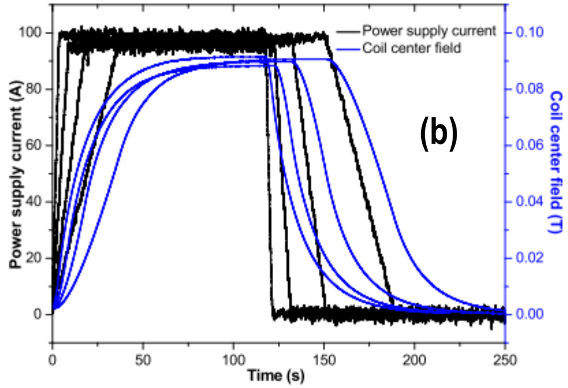
3 HTS tapes co-wound NI coil



Single tape NI coil

J. Geng and M. Zhang. *Supercond. Sci. Technol.* 32.8 (2019): 084002.





Co-winding method introduced by Tokamak Energy

Tokamak Energy, https://youtu.be/43TI39CYhNM?t=33

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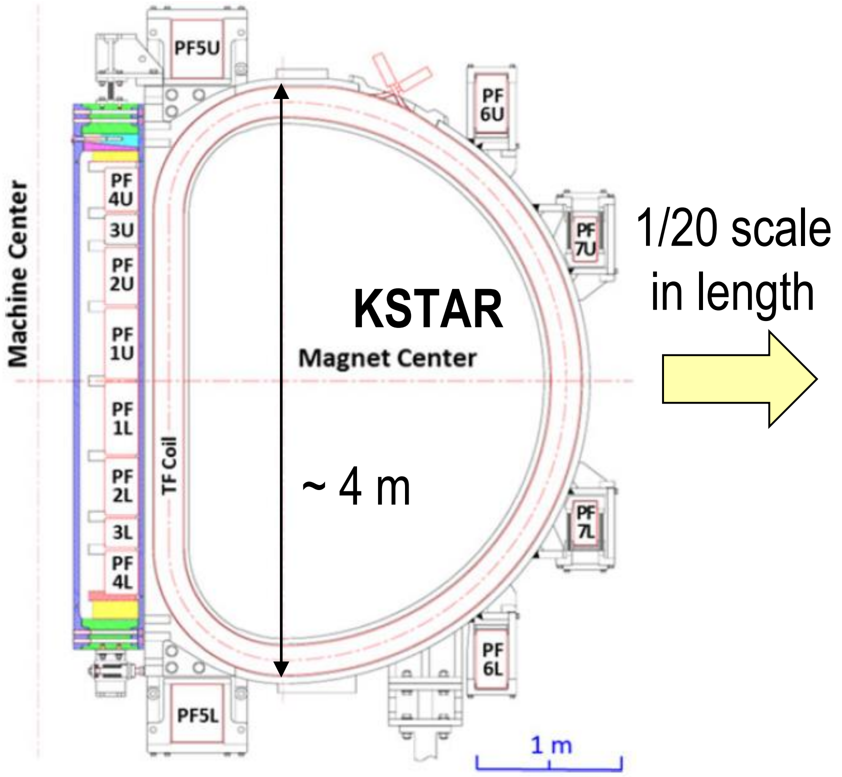
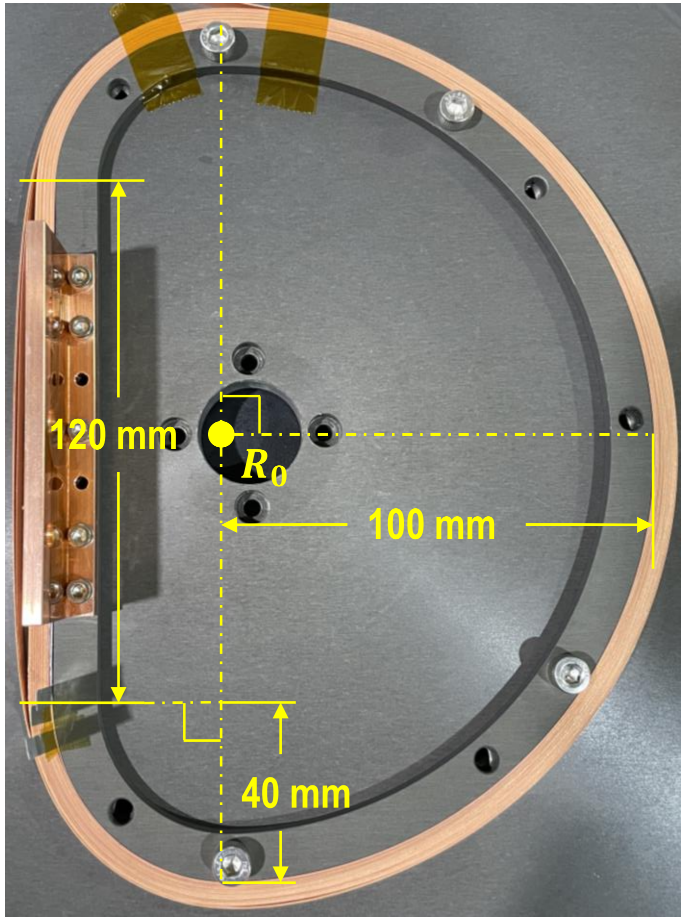
Laboratory-scale NI HTS TF Single Pancake Coil
:The First D-shaped NI HTS Coil in Korea for High-field Fusion

- Design and winding practice, initial investigation on the D-shaped coil characteristics
- The KSTAR was chosen as a reference in size and shape to make 1/20 in length



*Ref: H. J. Ahn *et al.*, *IEEE Trans. Appl. Supercond.*, Vol., 28, No. 3, 2018. (4204105)



Parameters	Unit	Values
Conductor		
Manufacturer		SuNAM
Average width	[mm]	4.1
Average thickness	[mm]	0.14
Critical current at 77 K, self-field	[A]	> 150
Coil		
Length of straight section	[mm]	120
Radius of quarter circular section	[mm]	40
Radius of half circular section	[mm]	100
Bobbin width; height	[mm]	140; 200
Number of HTS tapes per turn, N_{tape}		1; 2; 3
Number of turns, N_{turn}		36; 18; 12
Conductor length	[m]	20.72
Inductance	[μH]	565.3; 141.3; 62.8

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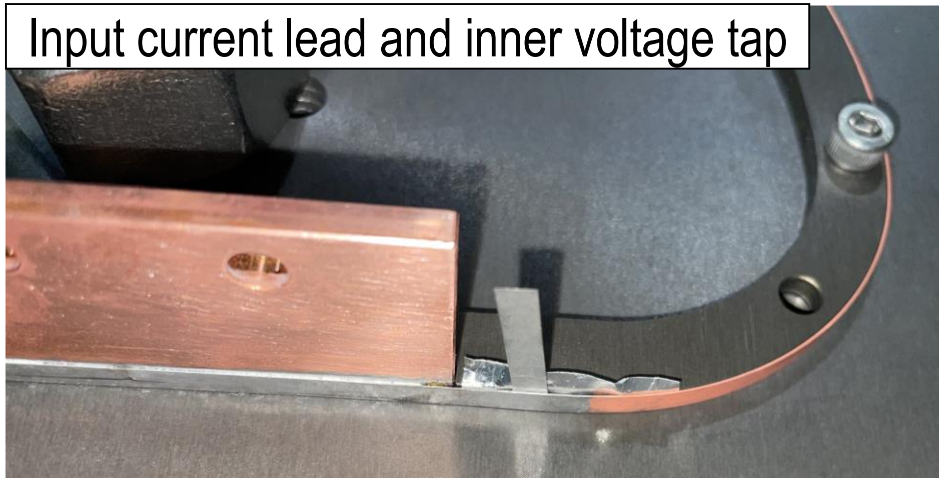
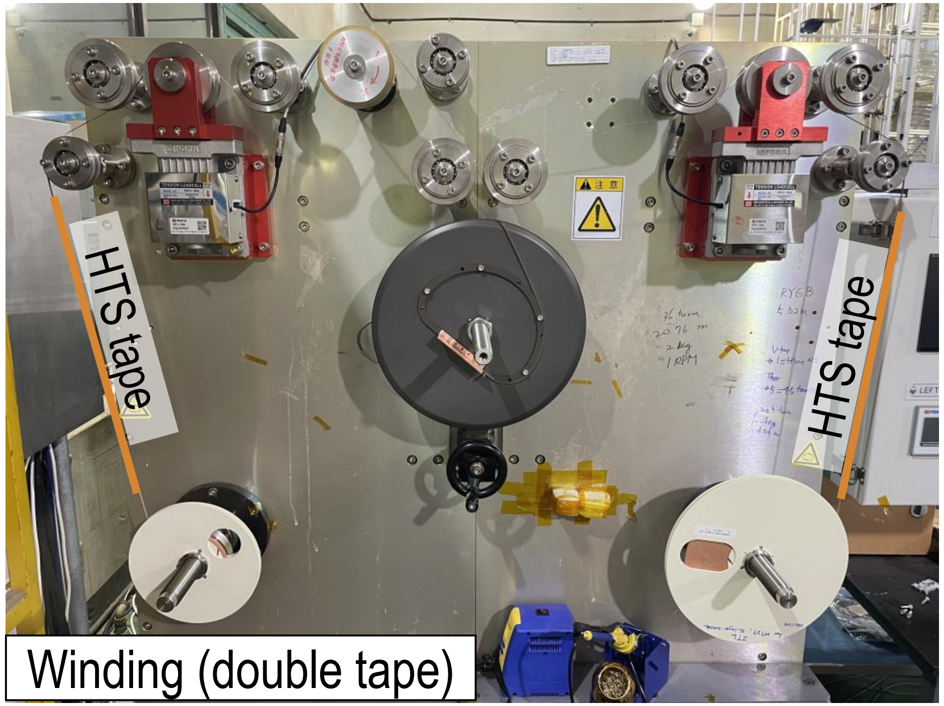
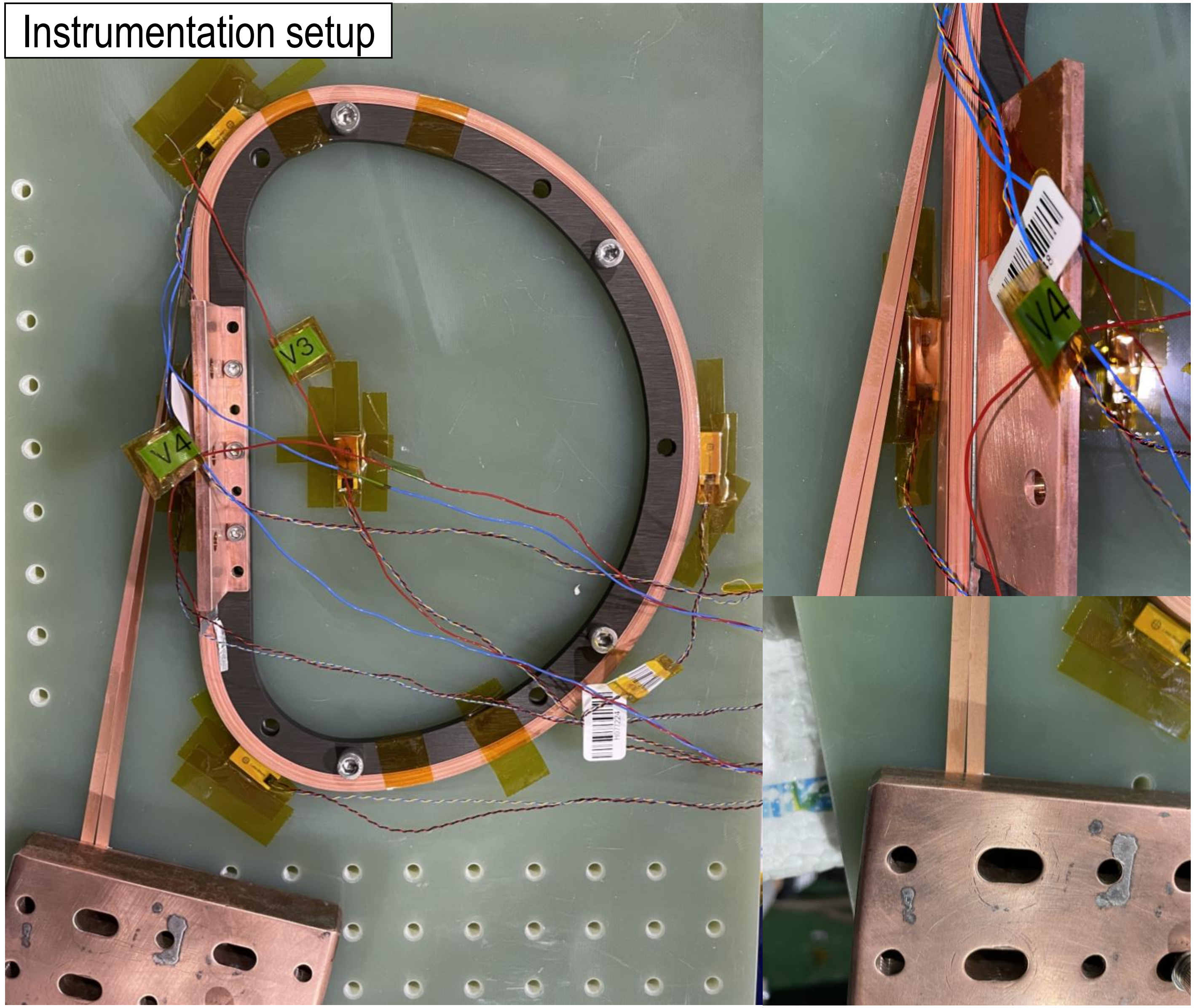
Fabrication of the Co-wound NI HTS TF Module Coil


Input current lead and inner voltage tap



Winding (double tape)



Instrumentation setup

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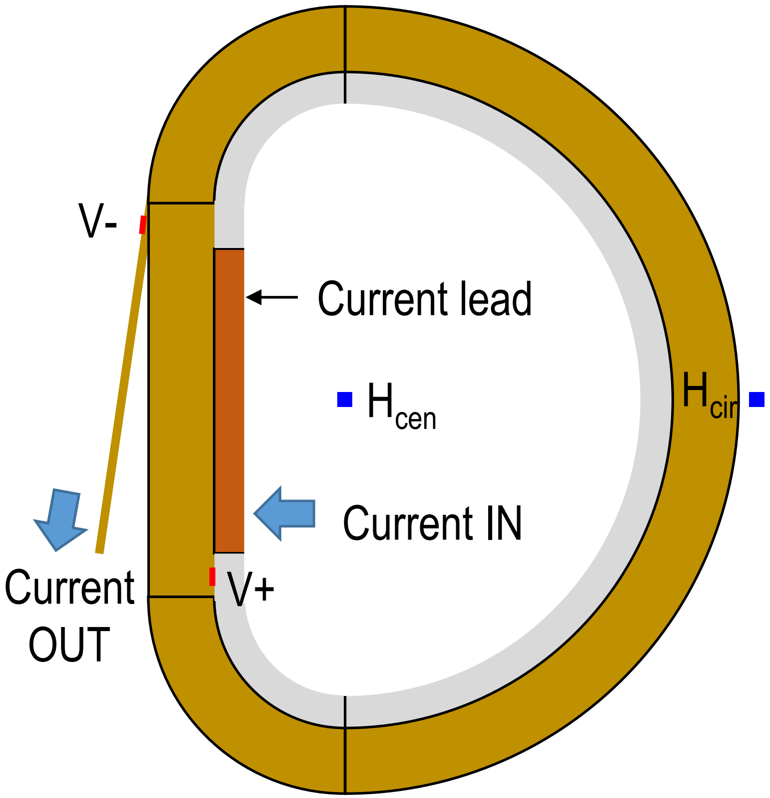
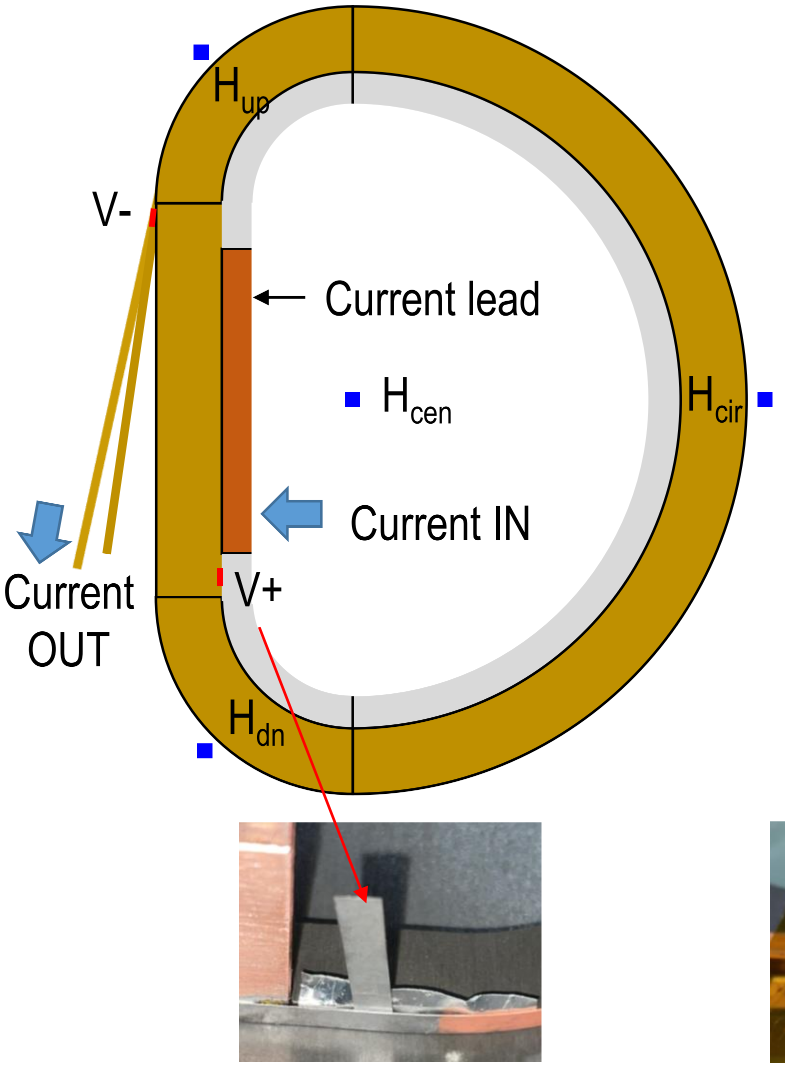
Voltage Taps and Hall Sensors Configuration

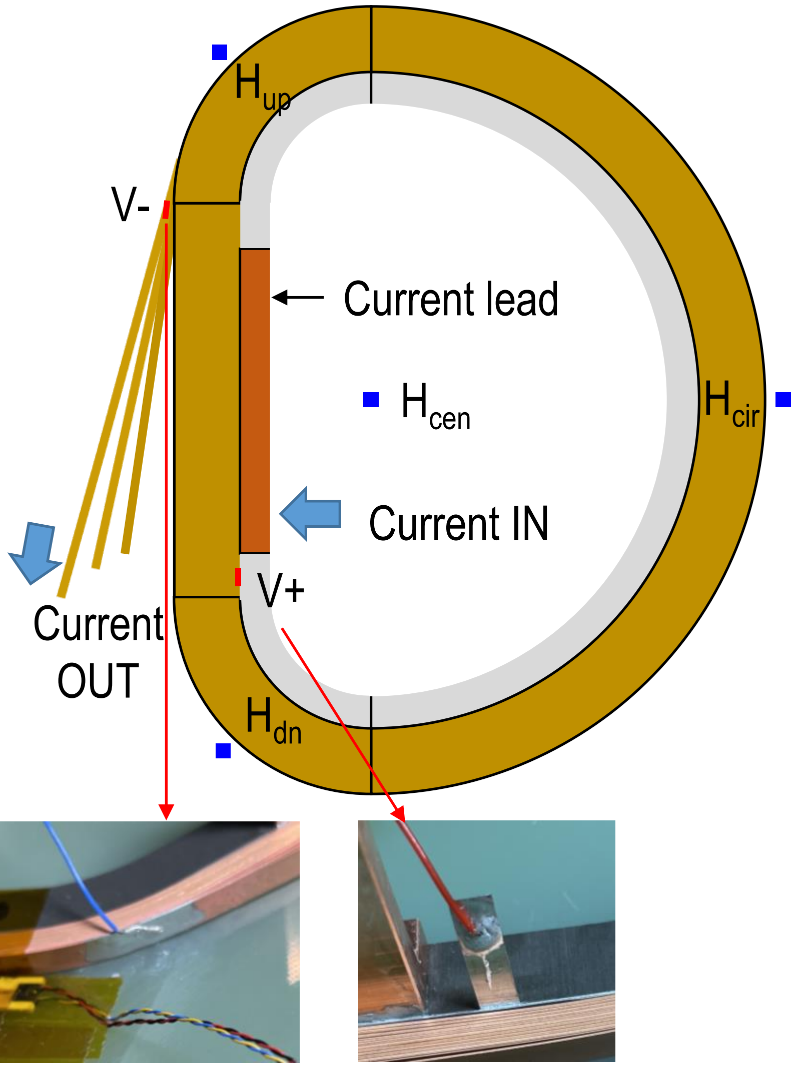
Single Tape Wound NI Coil (NI-1)



Double Tape Co-wound Coil (NI-2)



Triple Tape Co-wound Coil (NI-3)

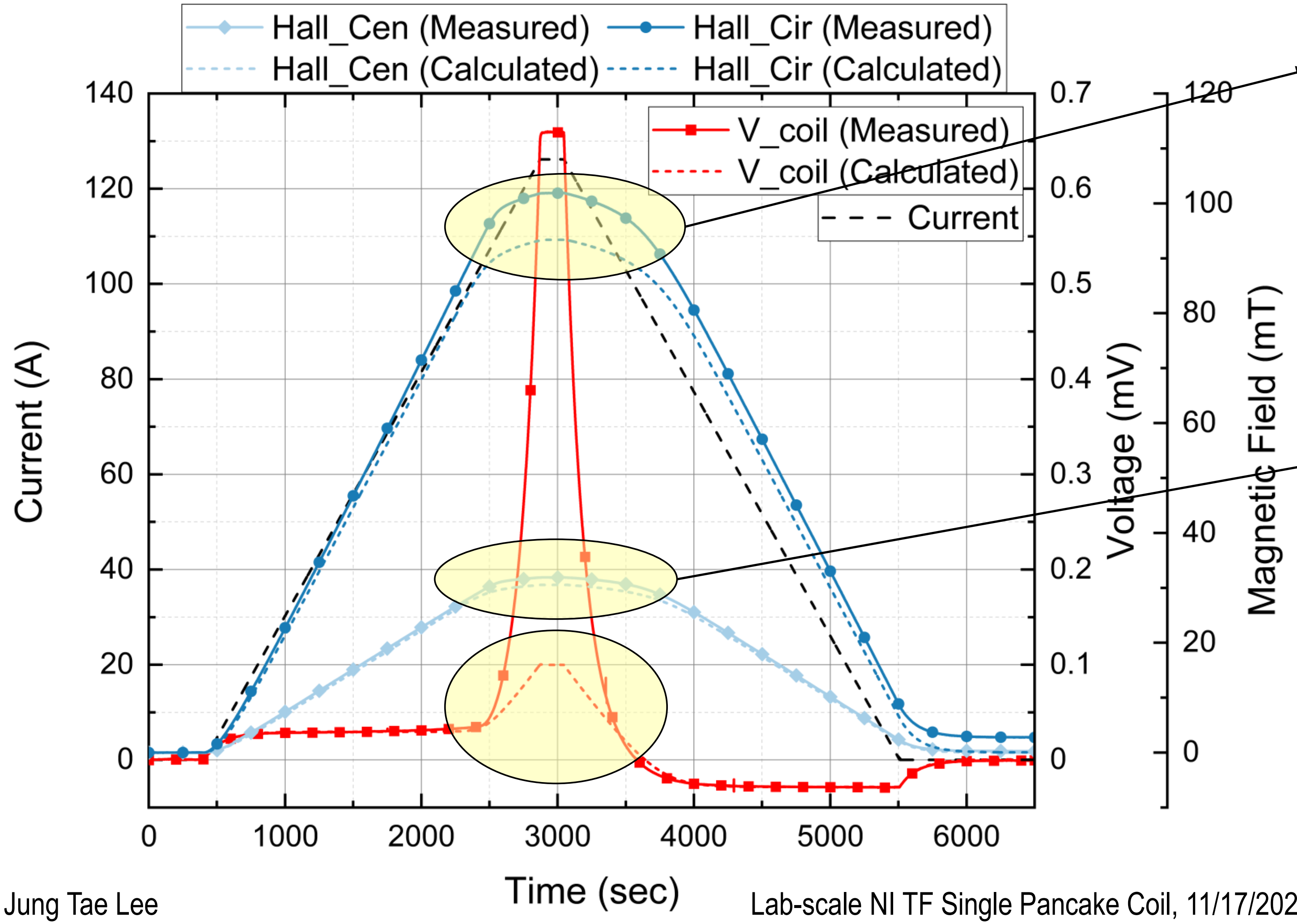


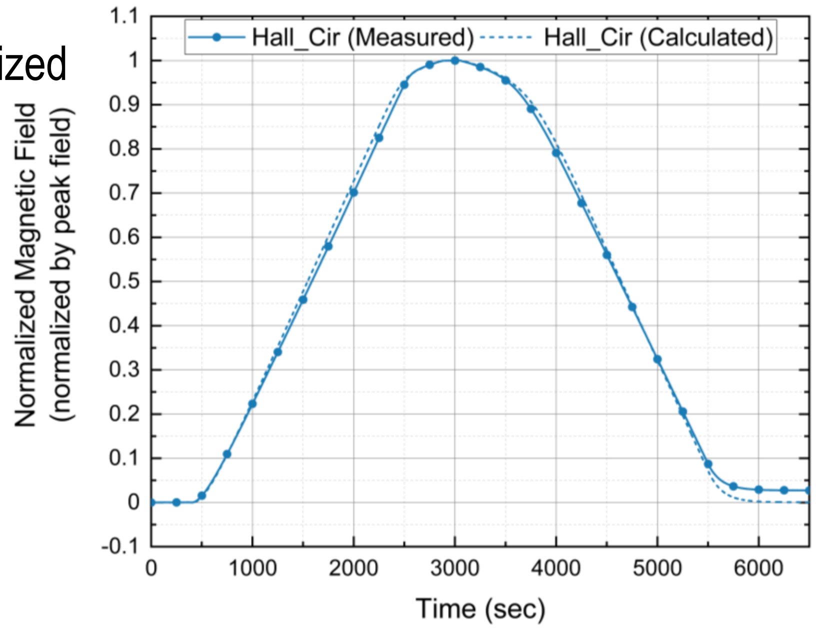
- Voltage taps
- Hall sensors

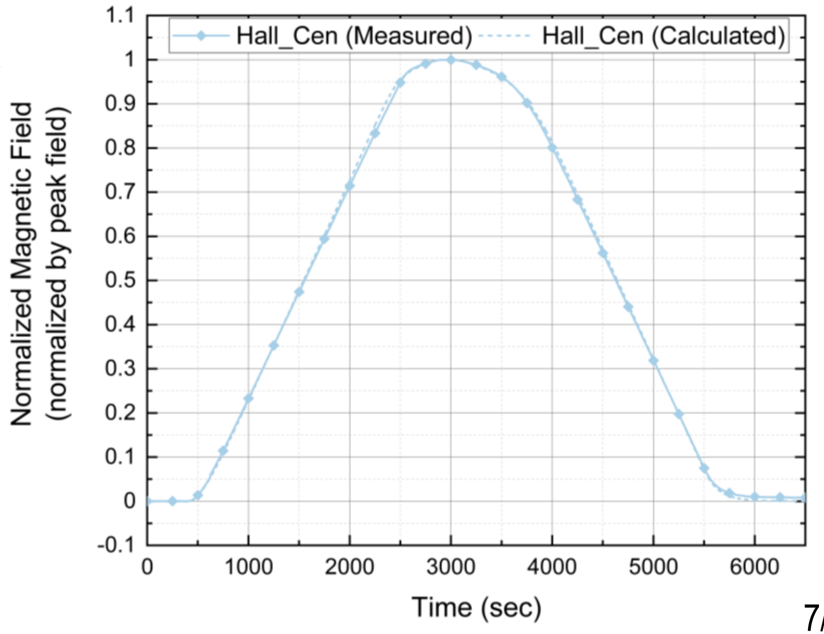
Test Results: Single Tape NI HTS TF Pancake Coil

- Charging/discharging test in LN2 bath
- Simulation by lumped circuit model

Magnetic field normalized by its peak value







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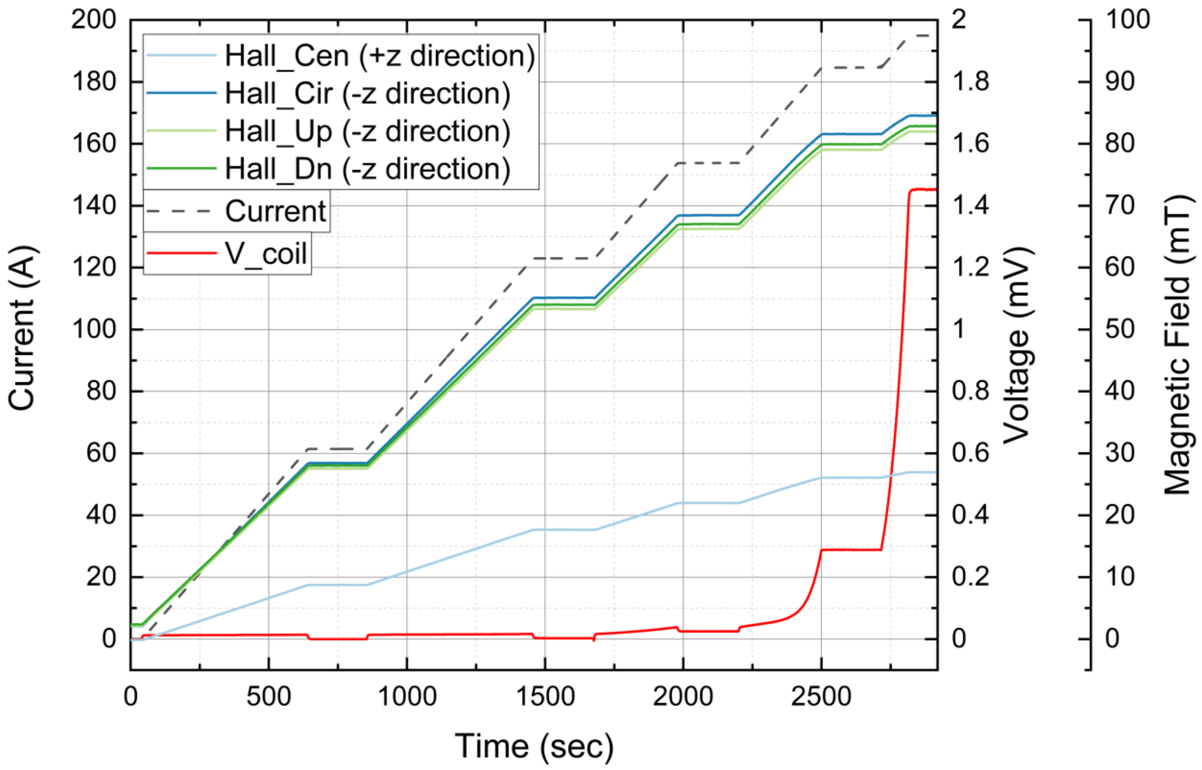
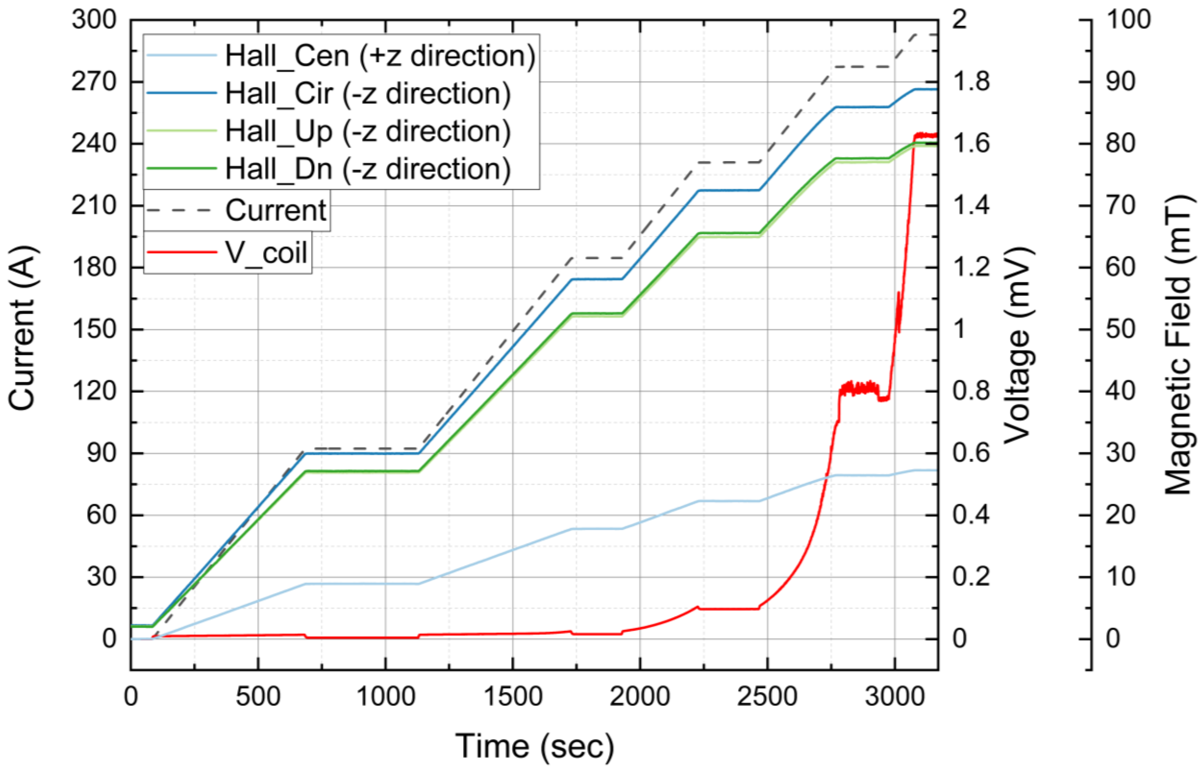
Test Results: Co-wound NI HTS TF Pancake Coils

Double Tape Co-wound Coil (NI-2)



Triple Tape Co-wound Coil (NI-3)



- Step-hold charging test in LN2 bath
- Ramping rate set to match the Ampere-turns for both coils
  → NI-2: 0.1 A/s × 18 Turns = 1.8 A-turns/s
  → NI-3: 0.15 A/s × 12 Turns = 1.8 A-turns/s

Fitted coil parameters	NI-2	NI-3
Critical current, I_c [A]	193.9	280.3
Index number, n	27	12
Contact resistance, Rc [$\mu\Omega$]	59.4	41.2

← 1 μV/cm criterion

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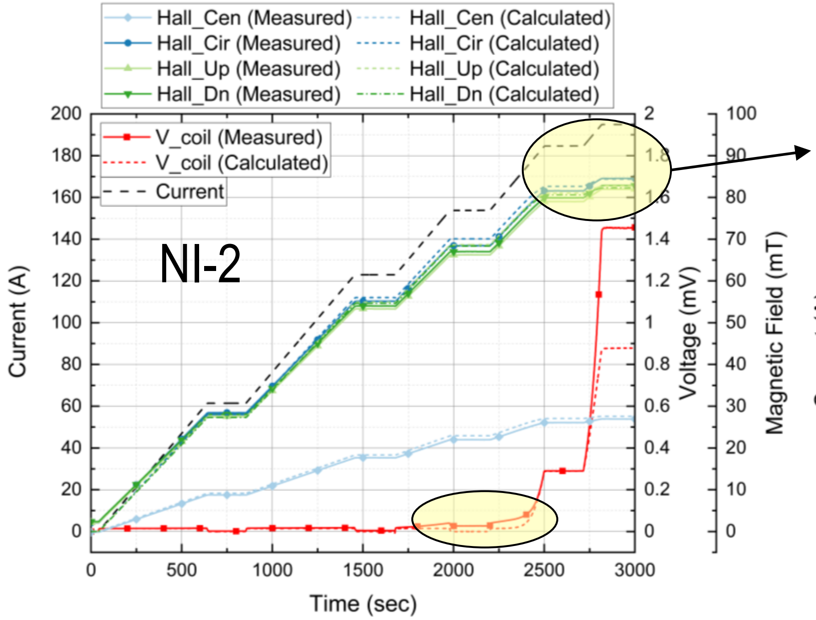
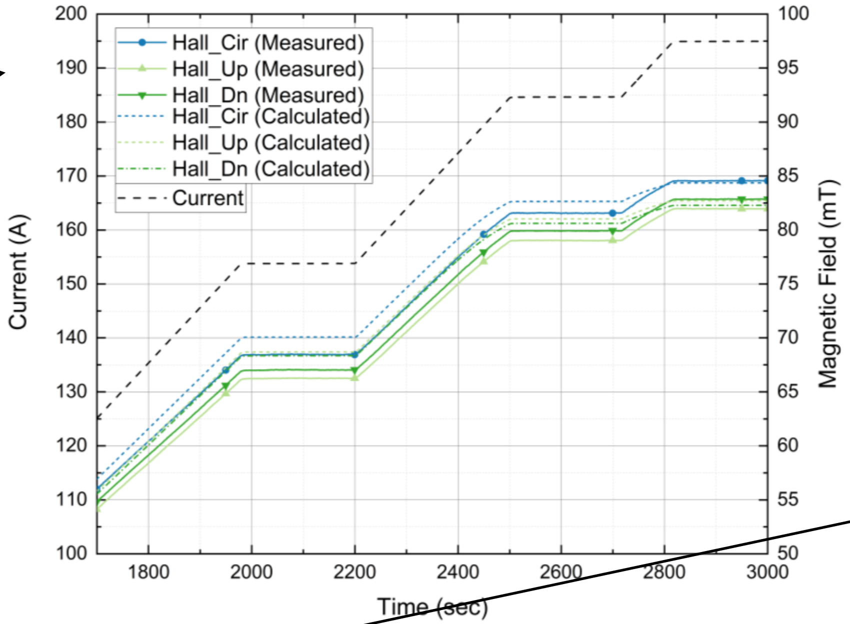
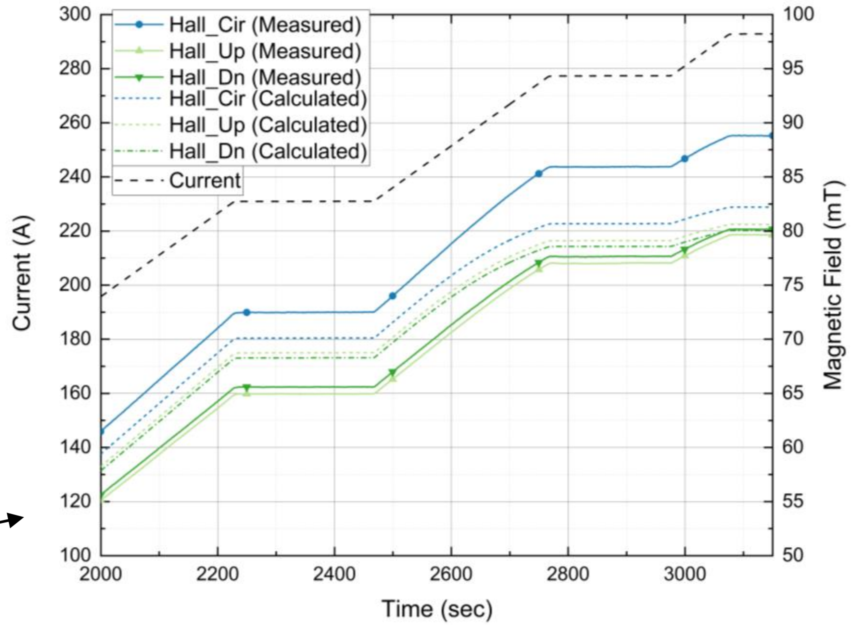
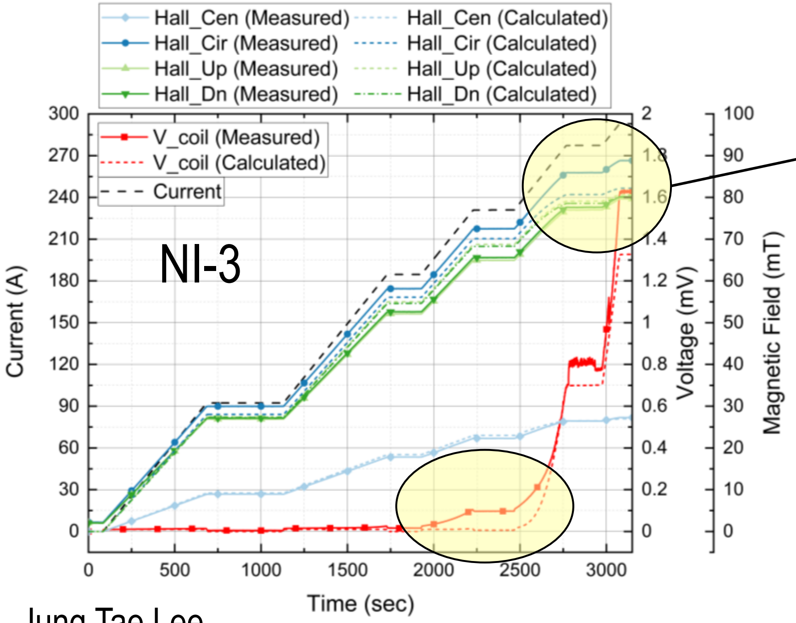
Test Results: Co-wound NI HTS TF Pancake Coils









Coil parameters	NI-2		NI-3	
	Fitting	Simulation	Fitting	Simulation
Critical current, I_c [A]	193.9	178.1	280.3	248.2
Index number, n	27	54	12	34
Contact resistance, Rc [$\mu\Omega$]	59.4	90.0	41.2	60.0

Decrease in I_c, increase in n and R_c

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Time Constant Comparison between the Test Coils

Assuming ideally same winding tension and contact surface conditions between each coil (i.e. same contact resistance),

$$\tau_{NI-1} = \frac{L_{NI-1}}{Rc_{NI-1}},$$

$$\tau_{NI-2} = \frac{L_{NI-2}}{Rc_{NI-2}} \approx \frac{1}{N_{turns}^2}\frac{L_{NI-1}}{Rc_{NI-1}}$$

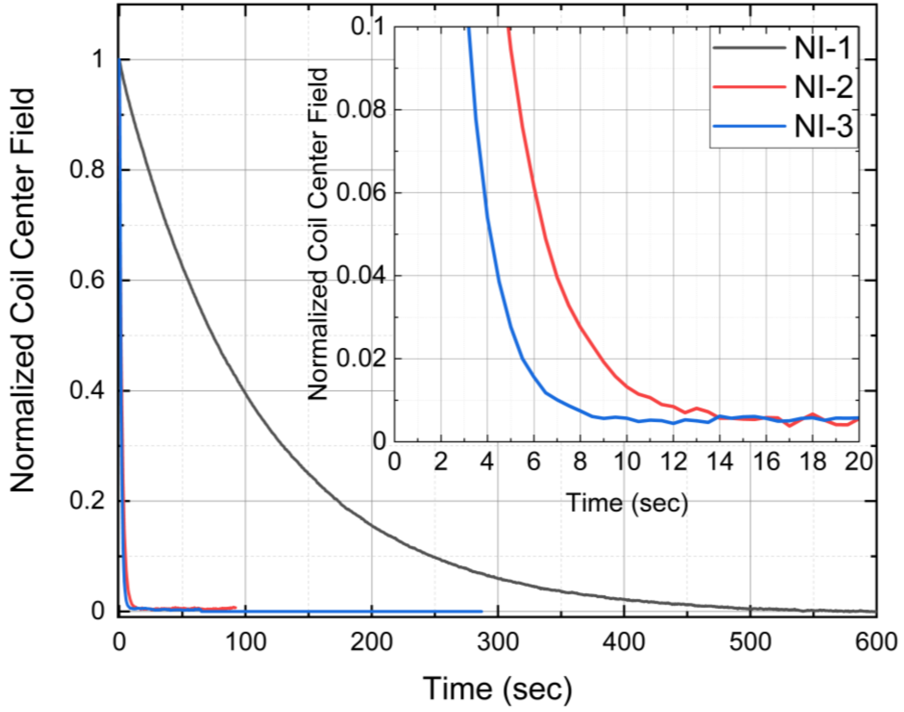
⇨ Time constant is inversely proportional to the square of the number of turns

NI-1: Single Tape Wound NI Coil

NI-2: Double Tape Co-wound Coil

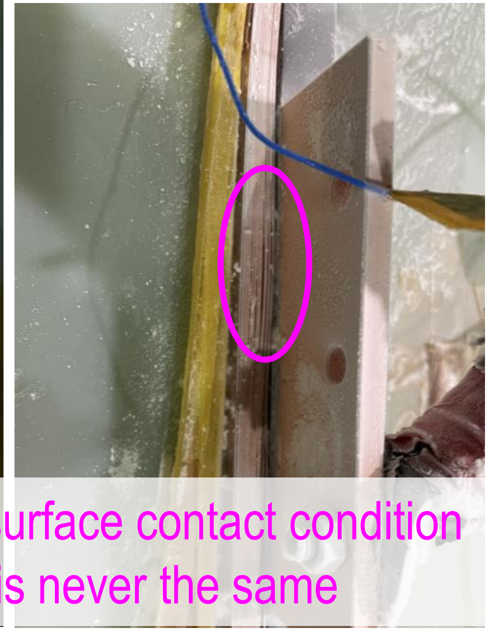
NI-3: Triple Tape Co-wound Coil

N_{turns}: number of co-wound turns



Before test

After test

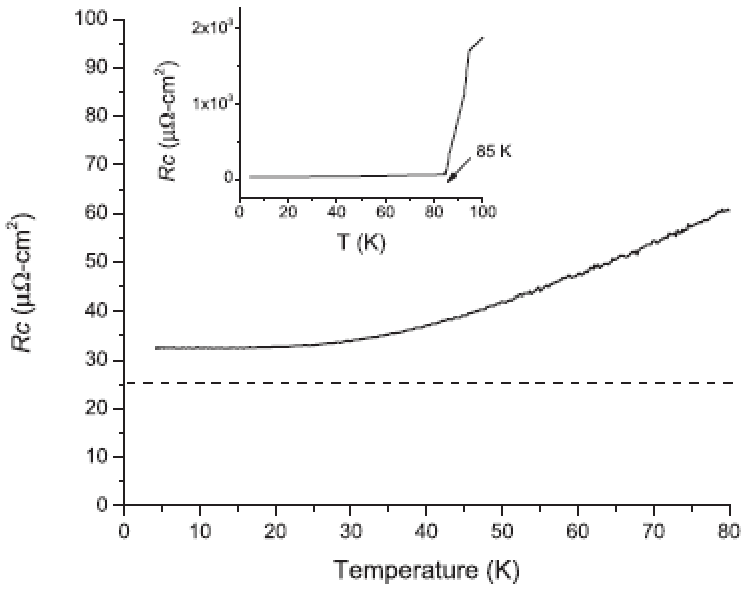


BUT, surface contact condition is never the same

	NI-1	NI-2	NI-3
Inductance, L [μH]	565	141	62.8
Time constant, τ [s]	109	2.38 (1/46)	1.53 (1/71)
Contact resistance, Rc [$\mu\Omega$]	5.17	59.4	41.2

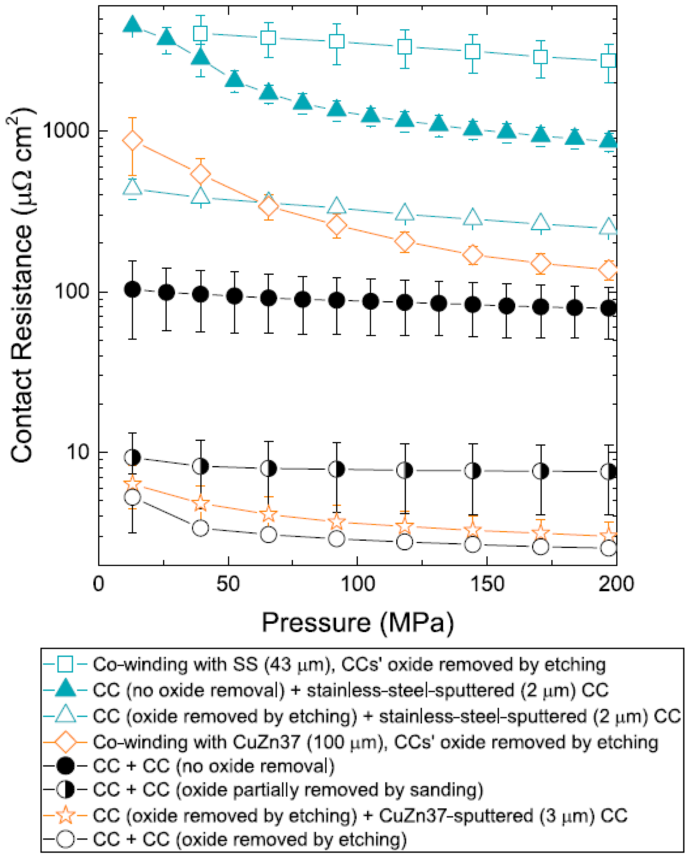
Discussions on Contact Resistance

- Reports on contact resistance under various load and load cycles
  → implication for TF coil would be "to take extra care on the straight section of the coil" as well as other parts of the coil where contact resistance my differ

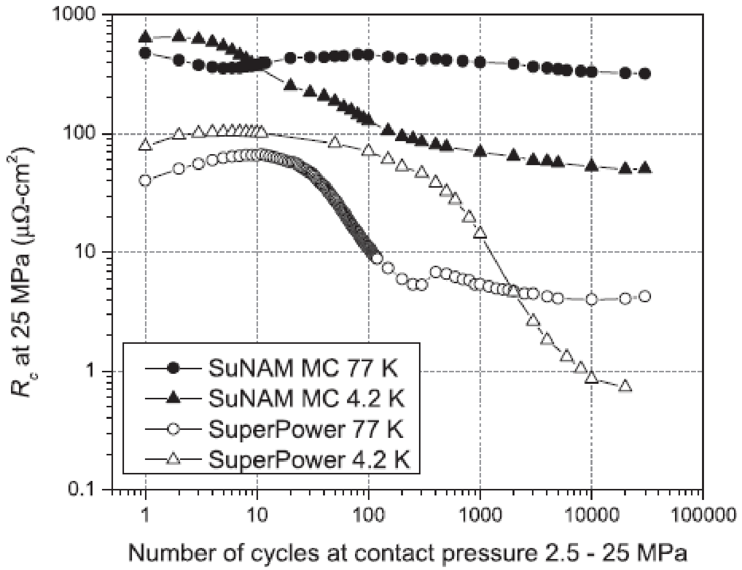


J. Lu, et al., *Supercond. Sci. Technol.* **30**:035020, 2017.

→ Rc decreases dramatically to ~ 50 % of the initial value from 80 K to 20 K and becomes subtle afterwards



M. Bonura, *et al.*, *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, August 2019



J. Lu, et al., *Supercond. Sci. Technol.* **31** (2018) 085006 (8pp)

→ Rc changes even under the same load when the coil experiences load cycles

→ Wide range of Rc with different surface conditions and different load levels

Conclusion: Focus need to be taken on the relation between the unique "D" shape properties and coil performance in further research.

- Double and Triple tape co-wound coils were tested showing some noticeable points to discuss
  - Relatively gradual transition to the index region compared to single tape coil (sharp transition)
    → small index number in coil level
  - Different magnitude of the magnetic field in the same location for double and triple tape co-wound coil
    → possibly due to different current distribution between co-wound tapes? Or by the difference in the contact resistance due to asymmetric shape of the coil?
  - Largely reduced time constant from single tape coil for both co-wound coils → possibly due to the failure in tension control in the straight section leading to high contact resistance

- **Two main takeaways**
  - The straight section of the TF single pancake coil holds large variability which needs to be controlled to analyze the coil more systematically
  - Current distribution between co-wound tapes needs to be investigated relating the effects of the "D" shape contribution to difference in contact resistance in different sections of the coil

Thank you for your attention

Q&A

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2018R1A2B3009249) and also by R&D program of “code No. CN2101” through the Korea institute of Fusion Energy(KFE) funded by the Government funds

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