Real-time Field Mapping of Screening Current induced Fields in an HTS Pancake Coil using a Hall Sensor Array

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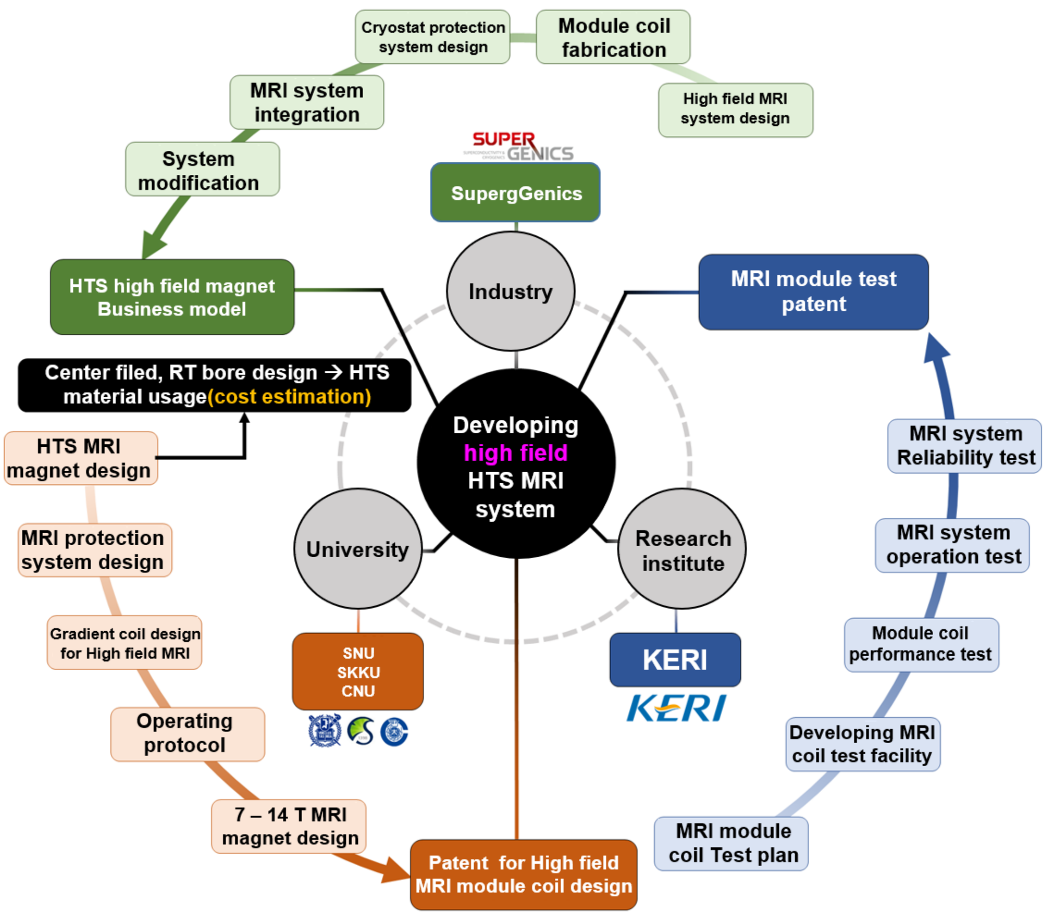
Part I. Motivation

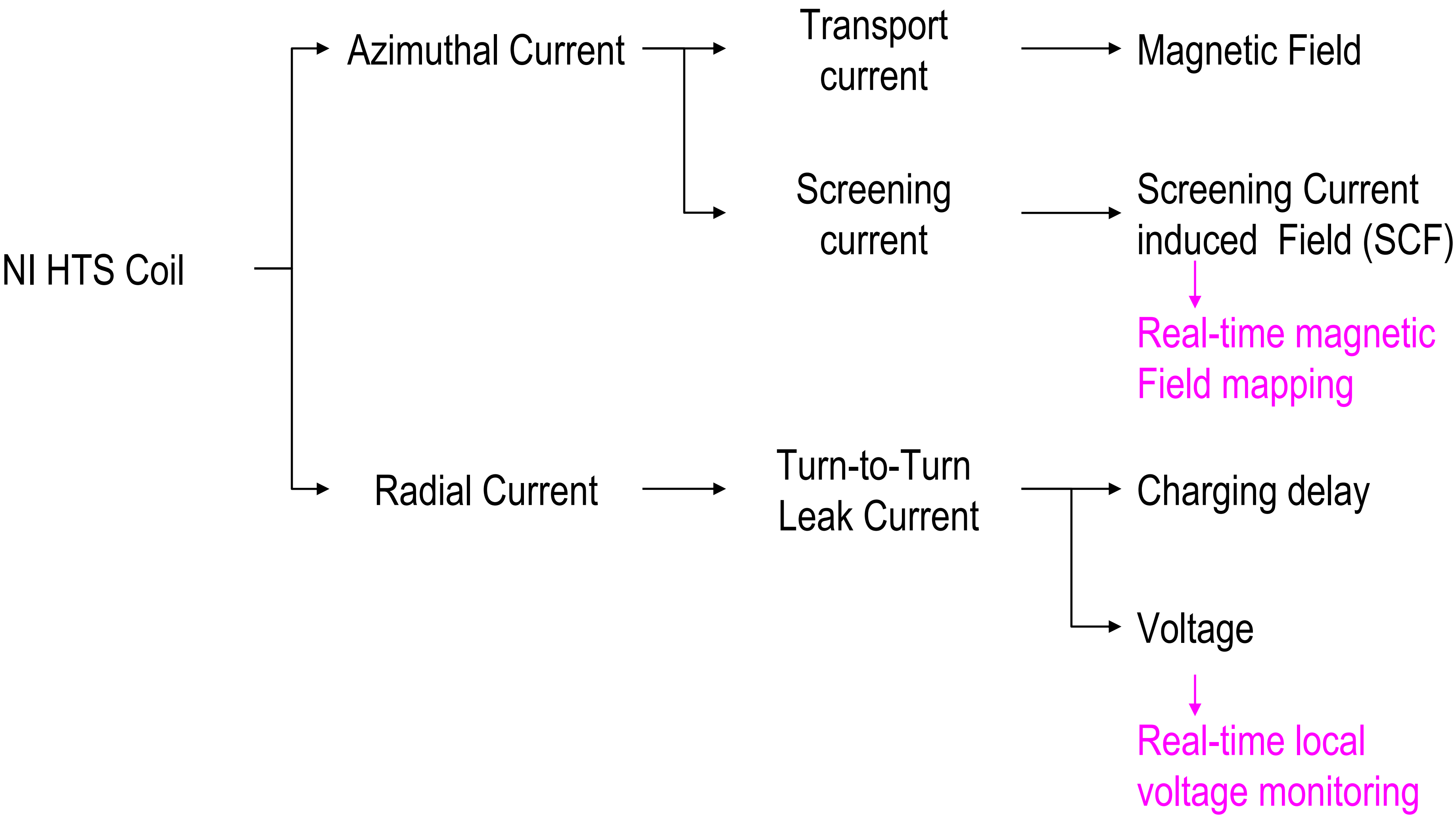
National Project of Next-Generation High Field MRI: a High Temperature Superconductor (HTS) Magnet Development



Ref : Google Image ‘Phillips Helium free MRI system’

Key specification of an HTS MRI magnet	
Central field	>6 T
Room-temperature bore	>200 mm
Operating temperature	~ 20 K
Spatial field uniformity	<10 ppm
Temporal field stability	<1 ppm/hr

Challenges: "Unknown" Spatial and Temporal Behaviors of Non-linear Current Distribution in a No-insulation (NI) HTS Coil



Example of Real-time Monitoring: "Fluorescent Thermal Imaging" of an NI HTS Coil during Quench

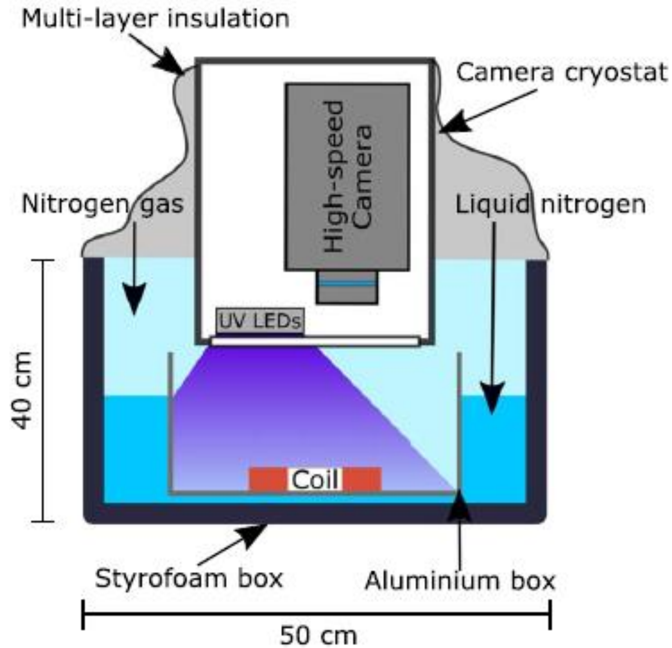


Figure 1. Cross-section view of the experimental setup.

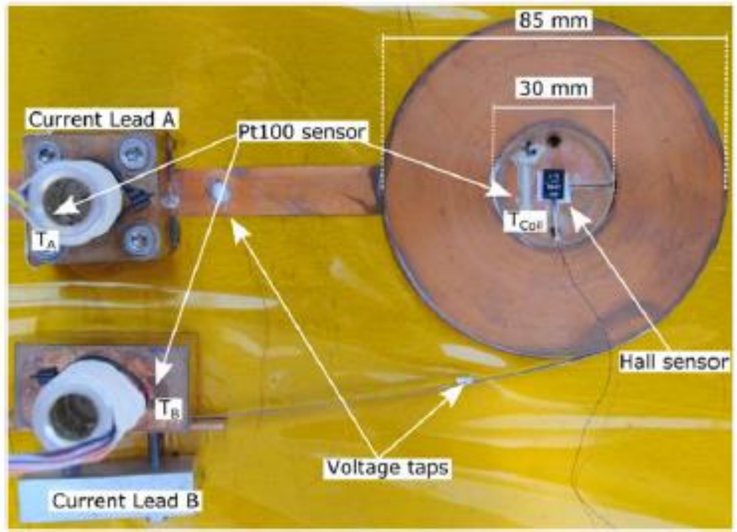
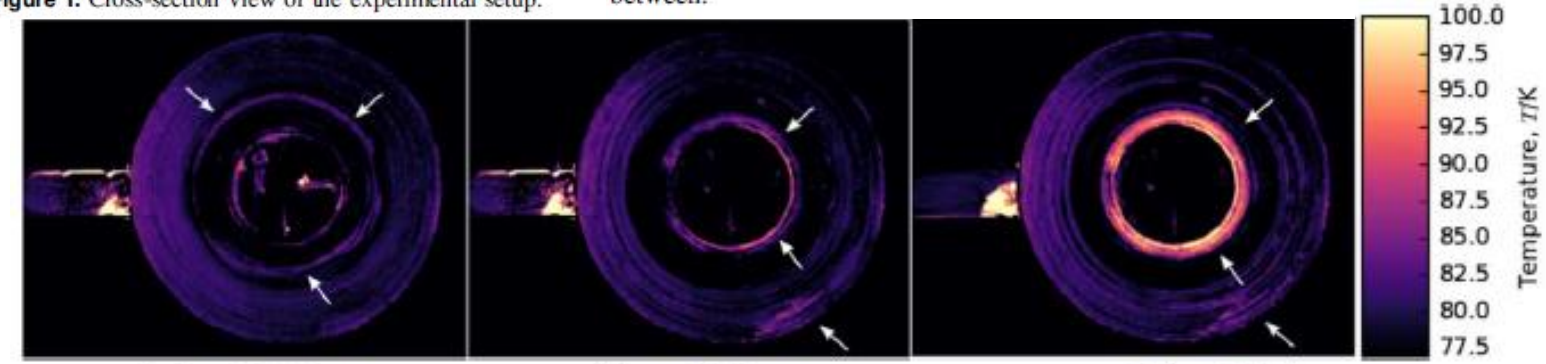


Figure 2. HTS non-insulated coil placed at the bottom of an aluminum box. A Kapton sheet served as electrical insulation in between.

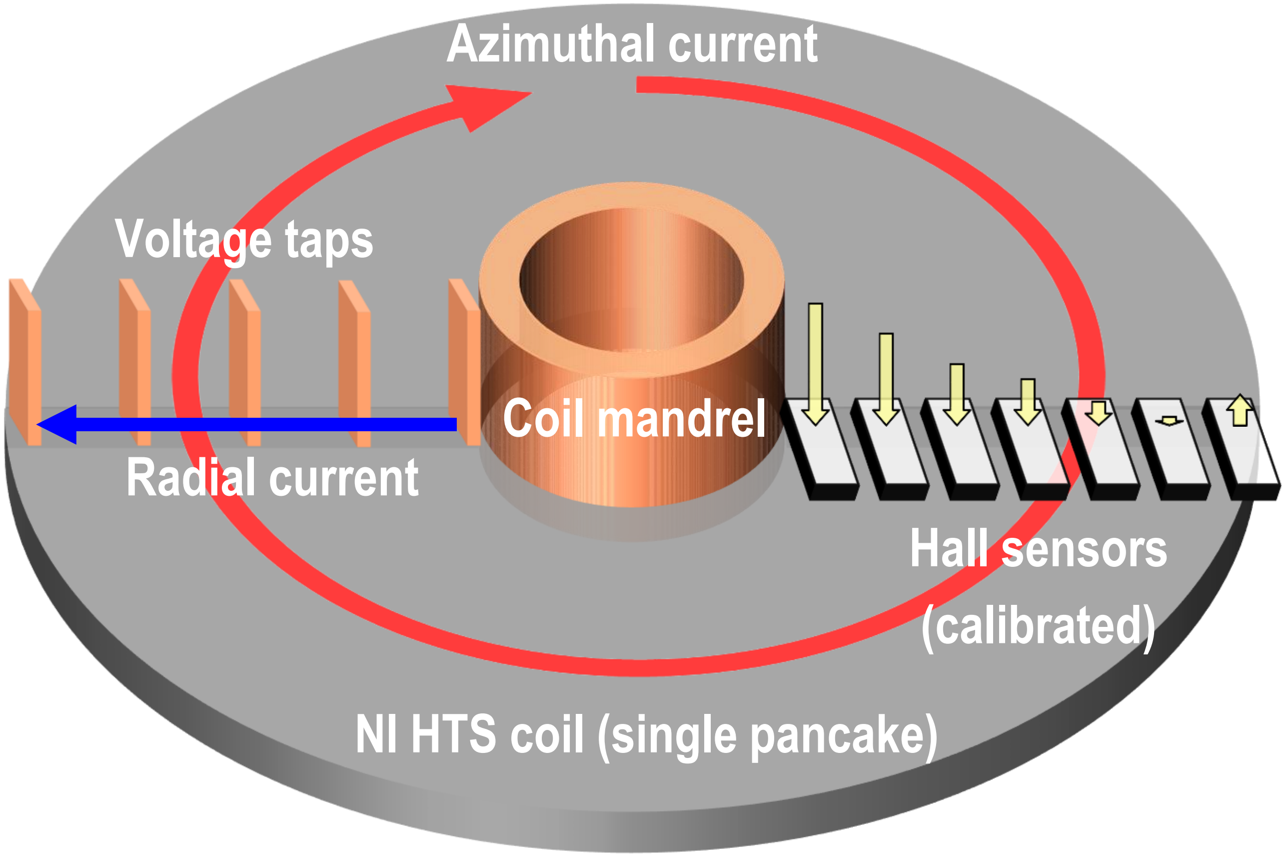
[1] Gyuráki, R., *et al.*, "Fluorescent thermal imaging of a non-insulated pancake coil wound from high temperature superconductor tape," *Supercond. Sci. Technol., vol. 32, 2019, Art. no. 105006.*



(a) t=320.0 s (b) t=340.0 s (c) t=345.0s

Key Idea: "Real-time" Monitoring of Electromagnetic Behaviors using Hall Sensors and Voltage Taps

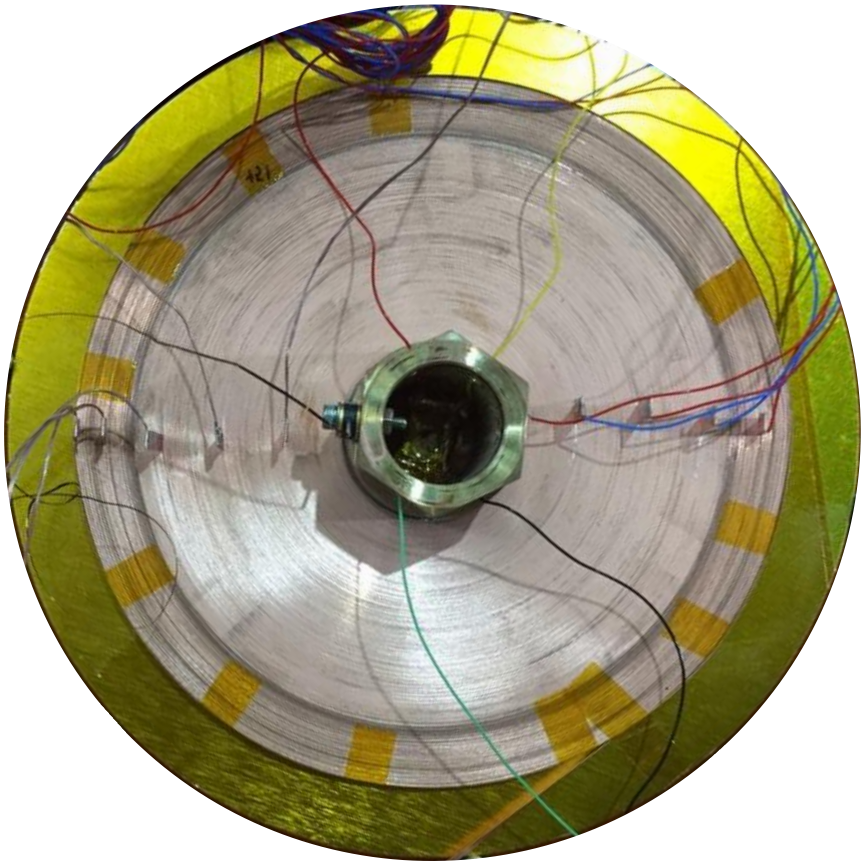
- This idea (using a Hall sensor array) was firstly proposed by the late David Hilton at National High Magnetic Field Laboratory (NHMFL).



Part II. Experimental Set-up

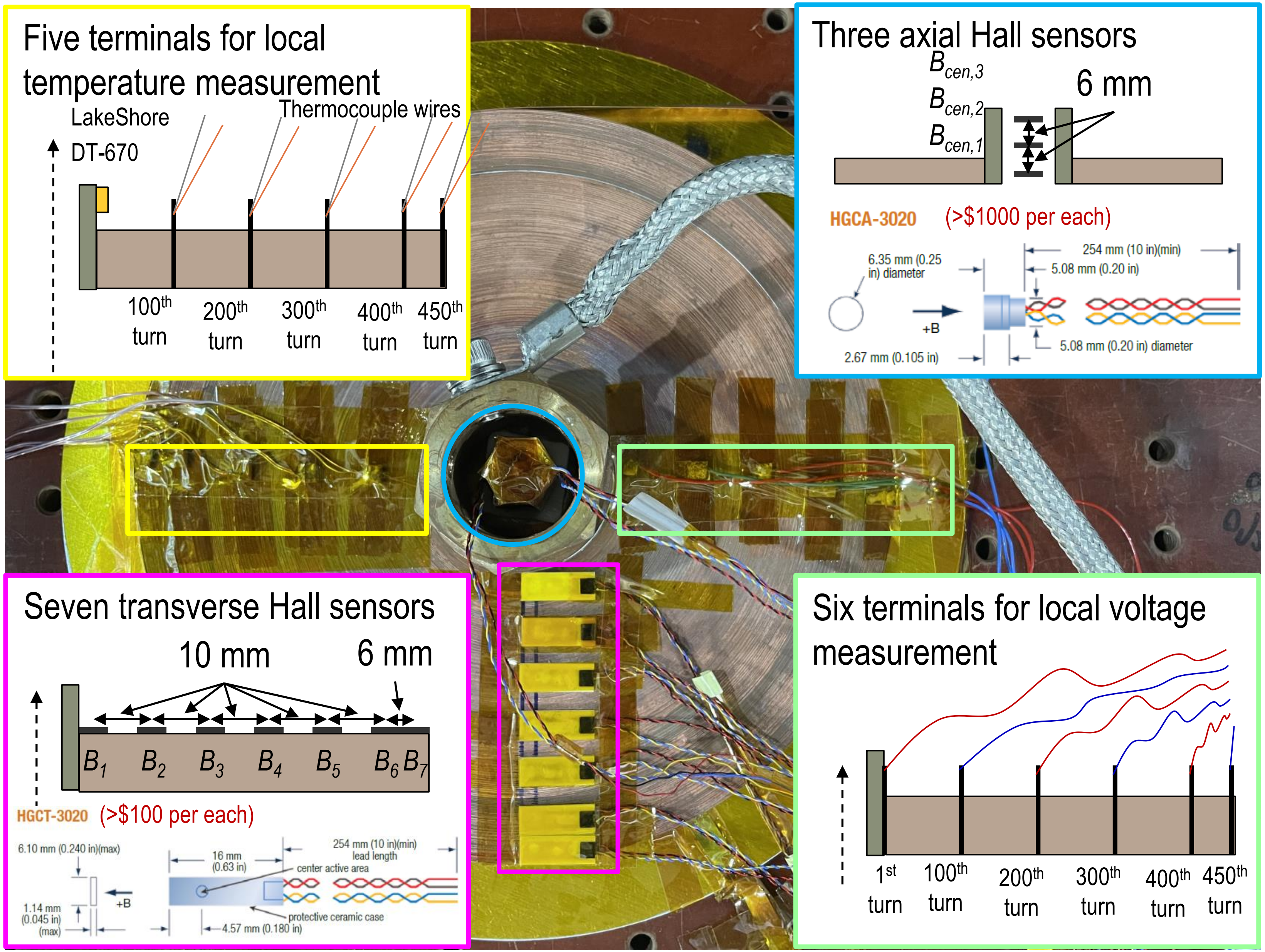
Key Parameters of No-insulation (NI) HTS Coil

- A "thick" solenoid (aspect ratio $\alpha \approx 4$) coil with "small" bore (20 mm)
  - Large NI charging delay
  - Large critical current gradient along the radial direction



Coil parameter	Unit	Value
Tape width/thickness	[mm]	4.1/0.14
Inner/outer radius	[mm]	20/83
Number of turn		450
Conductor length	[m]	146
Inductance	[mH]	19
Contact Resistance	[μΩ]	126
Time constant	[s]	150
Critical electric field	[μV/cm]	1

Instrumentation: Voltage Taps and Calibrated Hall Sensors



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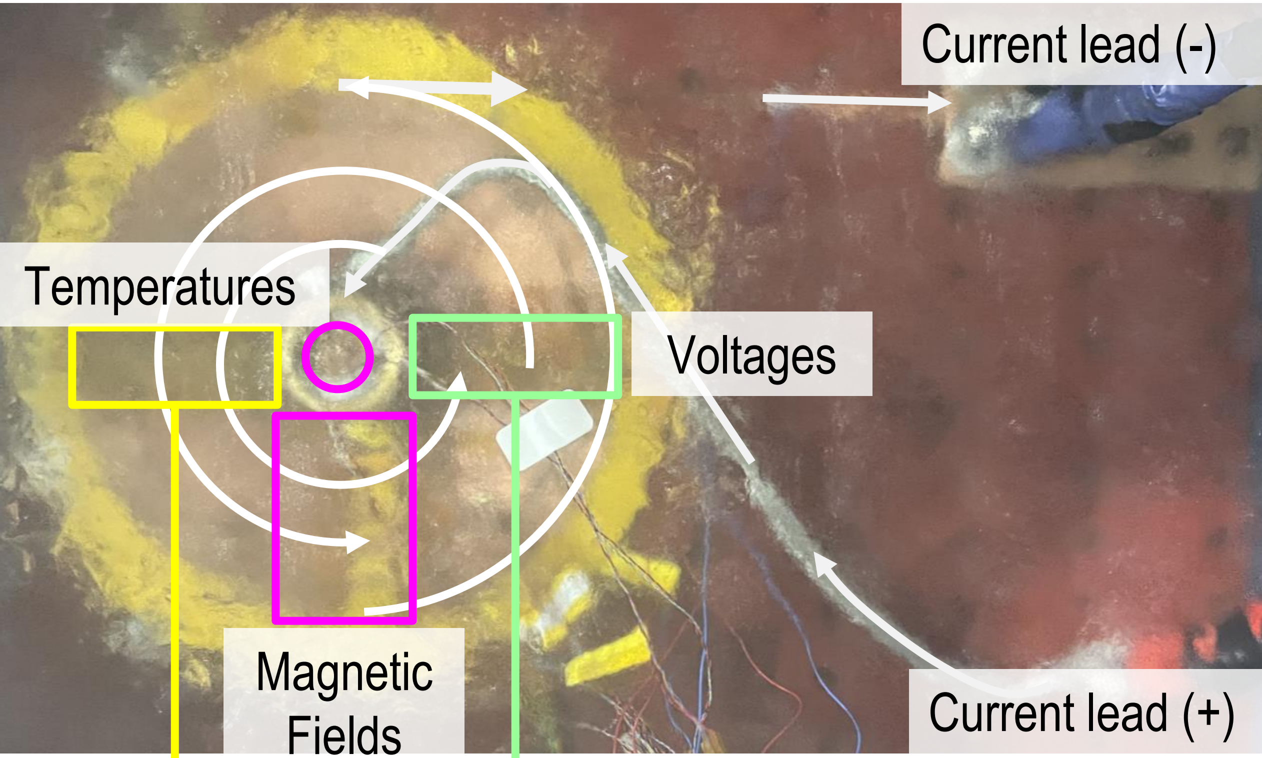
Test Apparatus and Data Acquisition System for LN2 Experiment



Oxford iPS Mercury (1M-3S)

- Operating Current: 100 A
- Ramp-rate: 0.05 A/s
- Current resolution: 0.1 mA
- Current stability: ±2 mA
- Charge resolution: 0.01 A/min

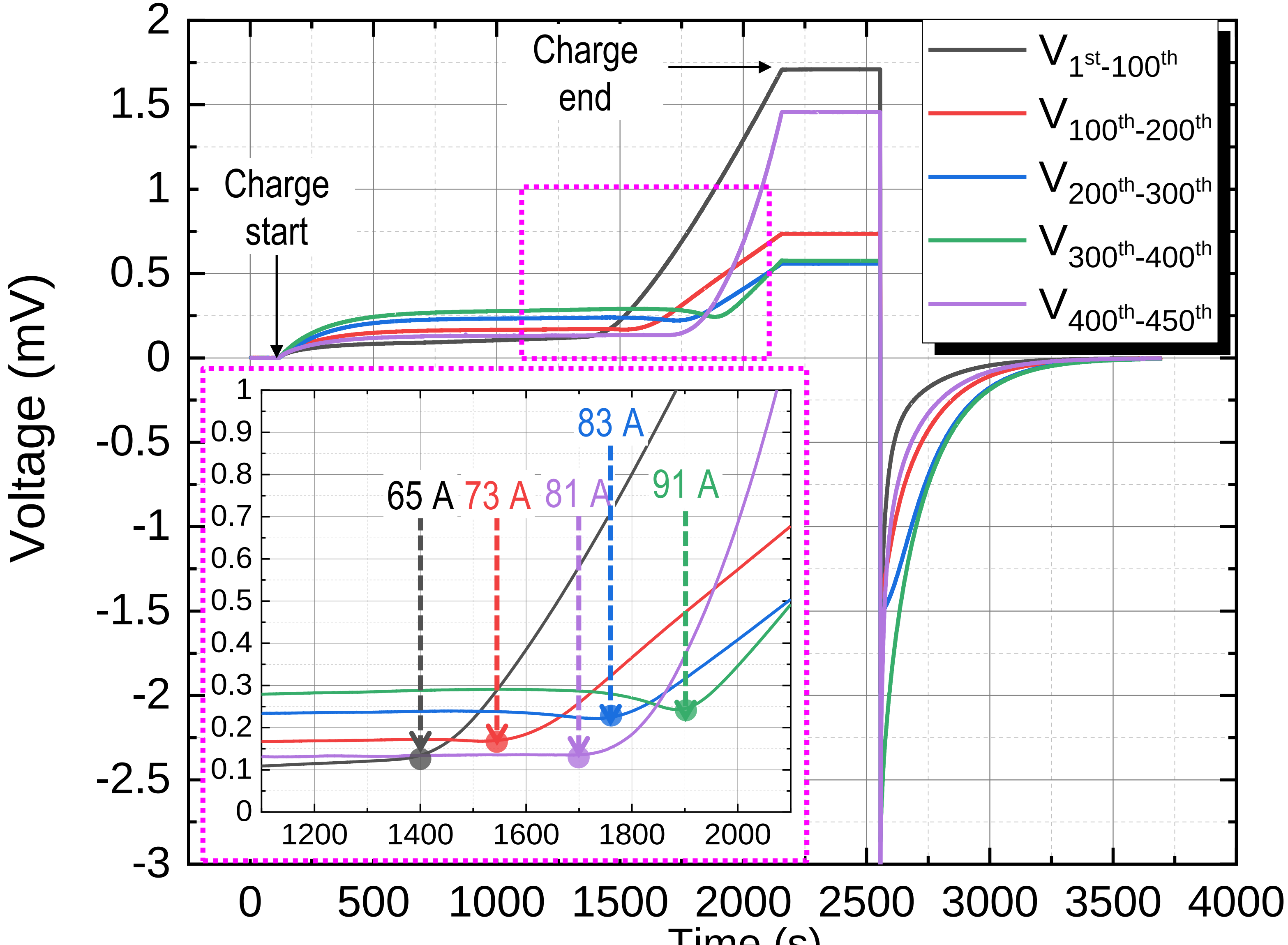
National Instrument SCXI set (1000-1125-1305)

- Sampling rate: 10 Hz
- Voltage range: ±5 mV
- Abs. Accuracy: <1 uV
- Gain error: 5000 ppm

Part III. Result and Discussion

Test Result I: Real-time Monitoring of Local Voltages

- Charging protocol: coil current of 100 A energized with 0.05 A/s



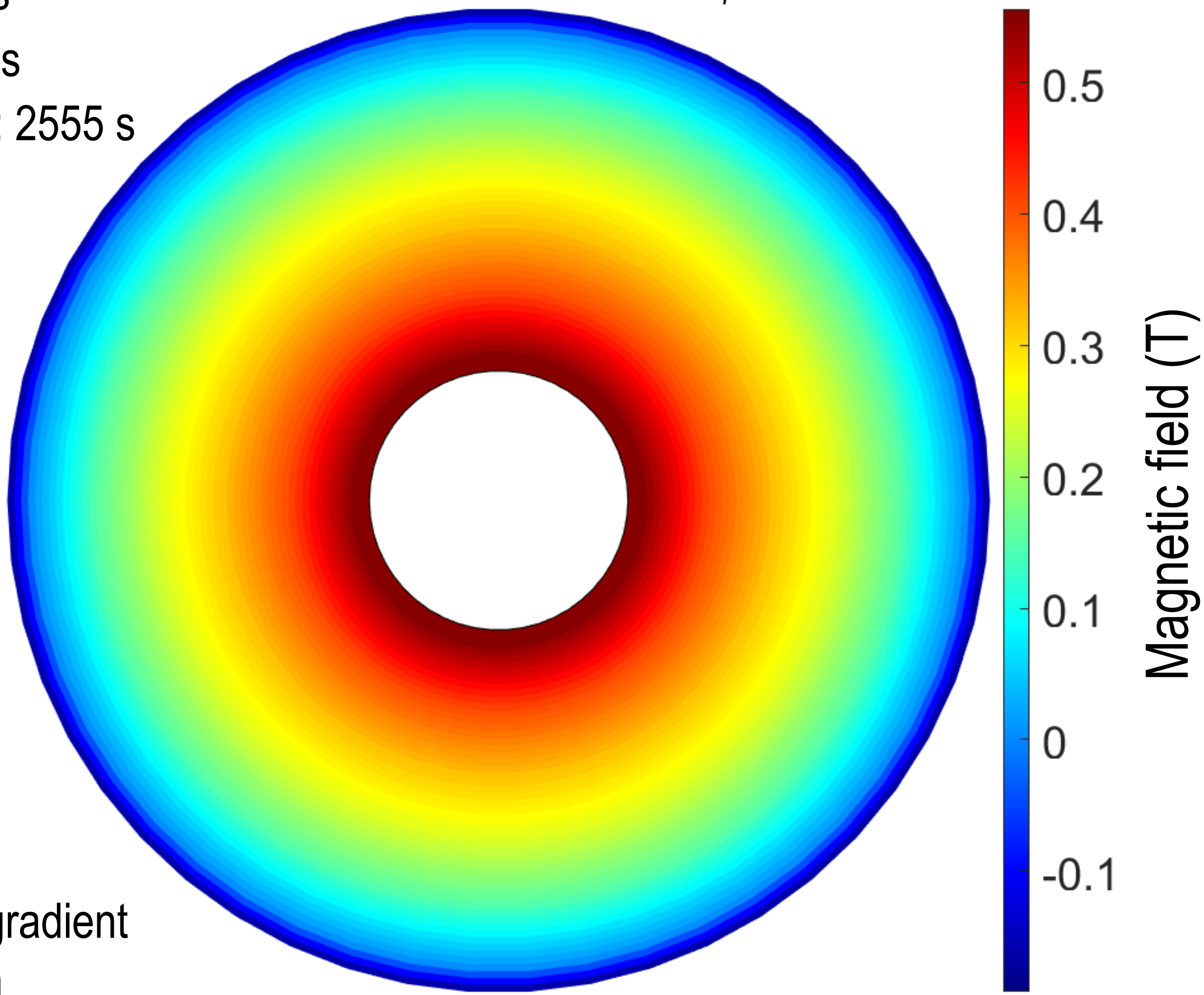
Test Result II: Real-time Monitoring of Axial Fields on the Coil Surface

Charge start: 116 s

Charge end: 2157 s

Sudden discharge: 2555 s

Saturated axial magnetic fields at I_{op} = 100 A



* Assumption: no gradient along winding path

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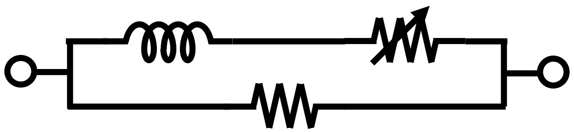
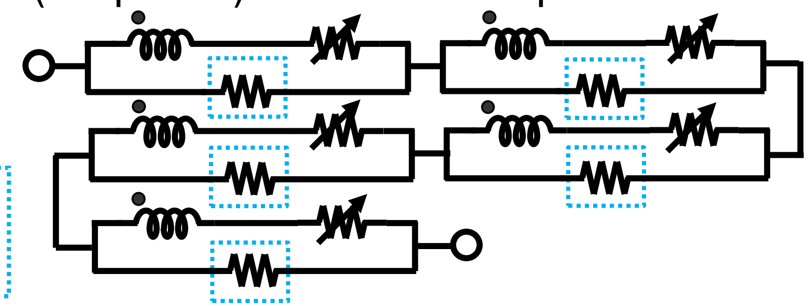
Simulation Method for Replication of Electromagnetic Behaviors induced by an NI HTS Coil

- **Coil current/voltage** calculation: "modified" lumped circuit simulation
  - (Conventional) lumped circuit model

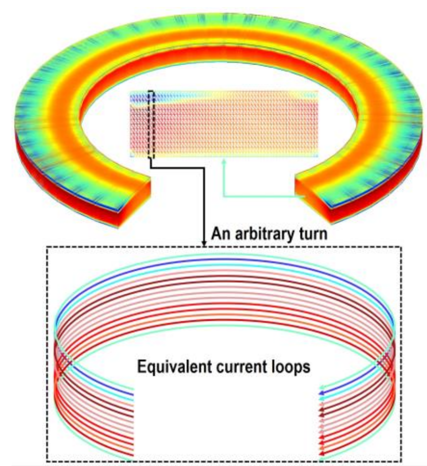


  - (Proposed) "Modified" lumped circuit model



(Note) Characteristic resistances in "modified" lumped circuit are determined from preliminary test results

- Spatially distributed **current density, magnetic field, and harmonic coefficient** calculation: H-formulation simulation, and "segmentation" method
  - H-formulation[2] for current density
    - Governing equation: Maxwell's equation
    - Integral constraints: Domain homogenization technique adopted
    - Measured field-dependent critical current and "index" value employed
  - "Segmentation" method[3] for Harm. Coeff.

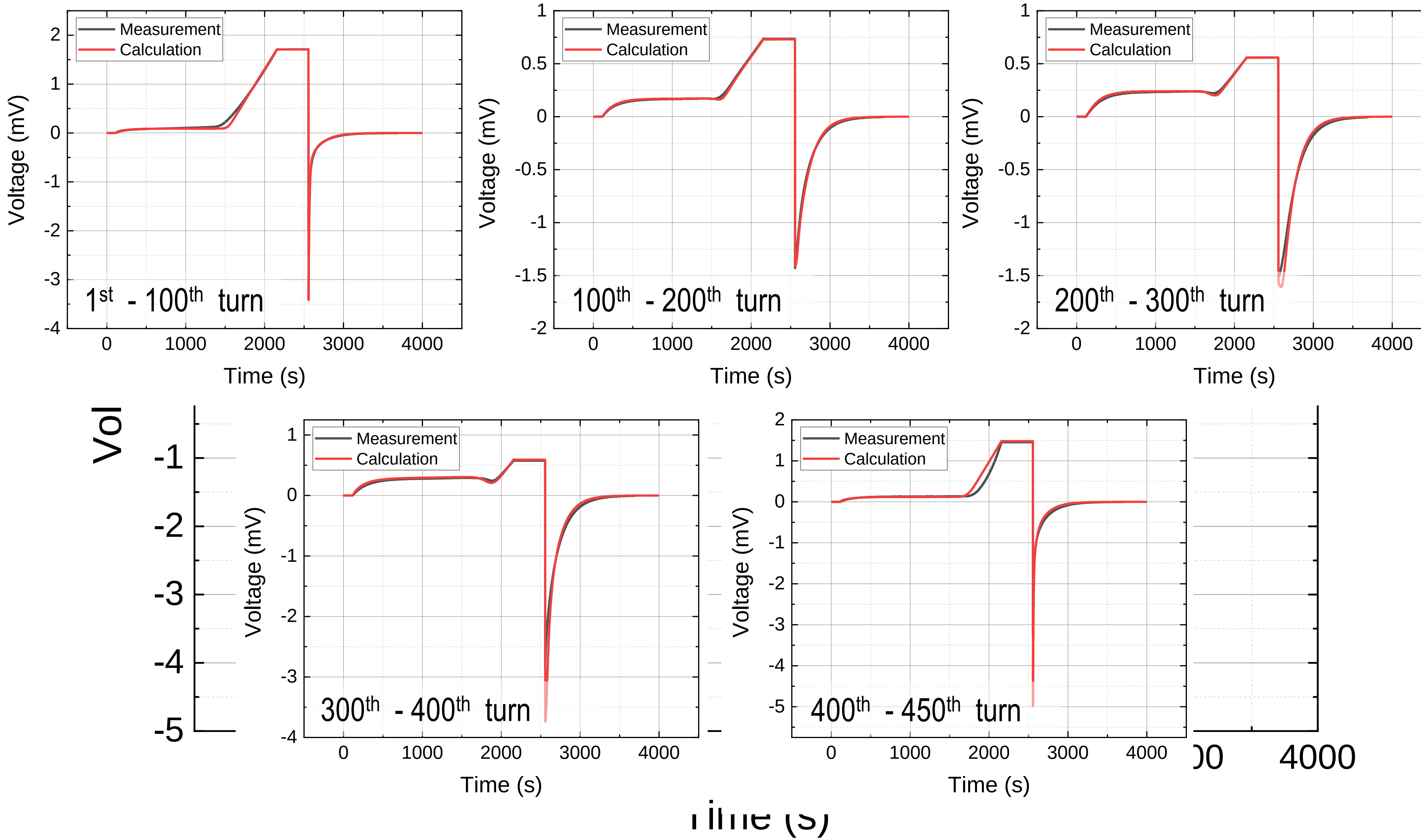


$$B_z^{loops}(z) = \sum_{seg=0}^{2\times p\times q}\sum_{n=0}^{\infty}\left(\frac{Zn_{seg}}{n!}\right) z^n = \sum_{seg=0}^{2\times p\times q}\sum_{n=0}^{\infty}\left[\frac{\mu_0 I_{seg}\sin\alpha_{seg}}{2r_{seg}^{n+1}}P_{n+1}^{1}(\cos\alpha_{seg})\right] z^n, \quad (5)$$

[2] Brambilla, F. Grilli, and L. Martini. "Development of an edge-element model for AC loss computation of high-temperature superconductors.," *Supercond. Sci. Technol.*, vol. 20, 2007, 16-24.

[3] J. Bang, et al. "A Numerical Method to Calculate Spatial Harmonic Coefficients of Magnetic Fields Generated by Screening Currents in an HTS Magnet." *IEEE Trans. Appl. Supercond., vol. 30, 2020, Art. no. 4901405*

Real-time Local Voltage Estimation: Good Agreement in Coil Terminal Voltage ; Also Good Agreement in Local Voltages



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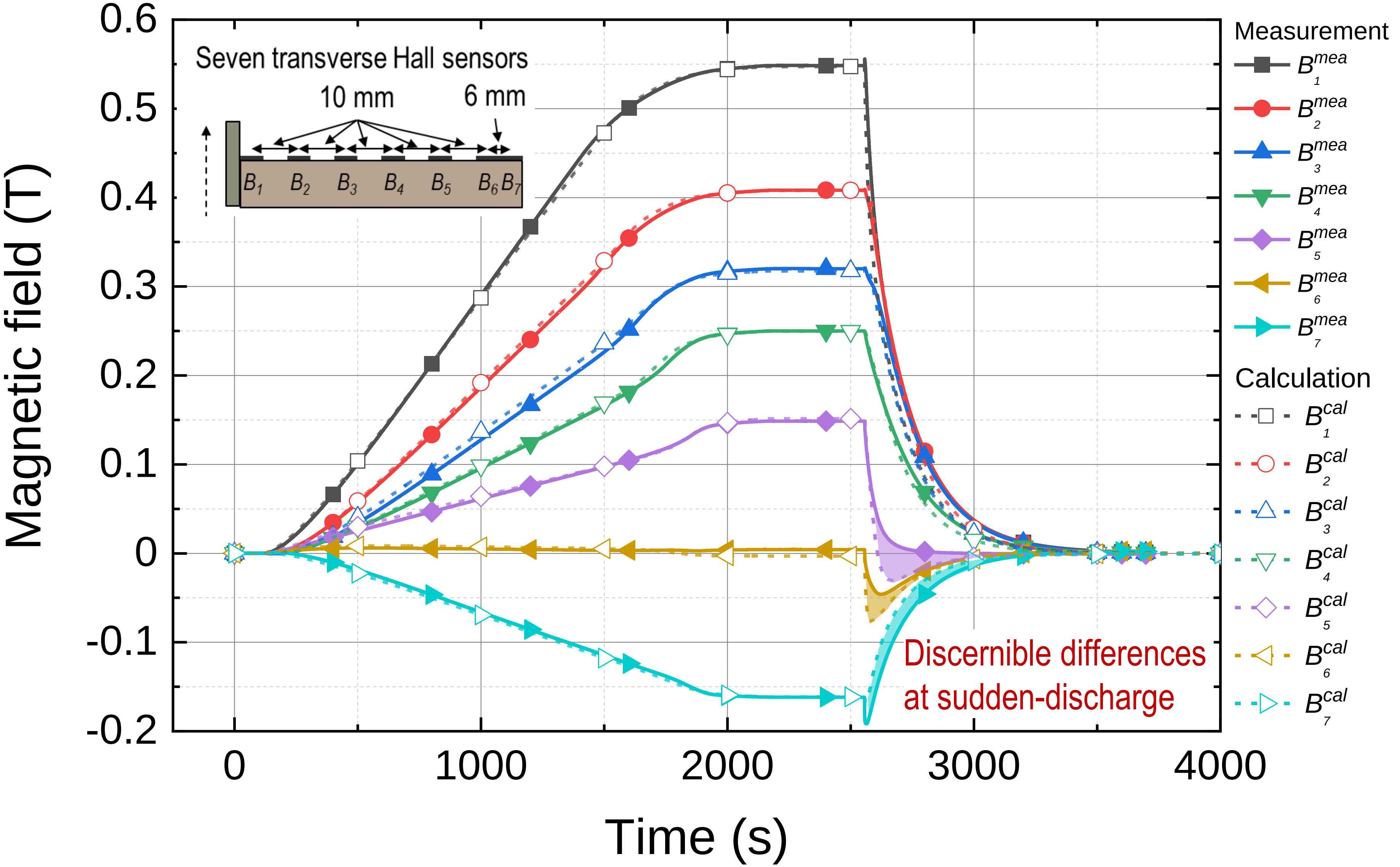
Real-time Spatial Magnetic Field Estimation: Good Agreement during Coil Charge ; Errors during Sudden Discharge



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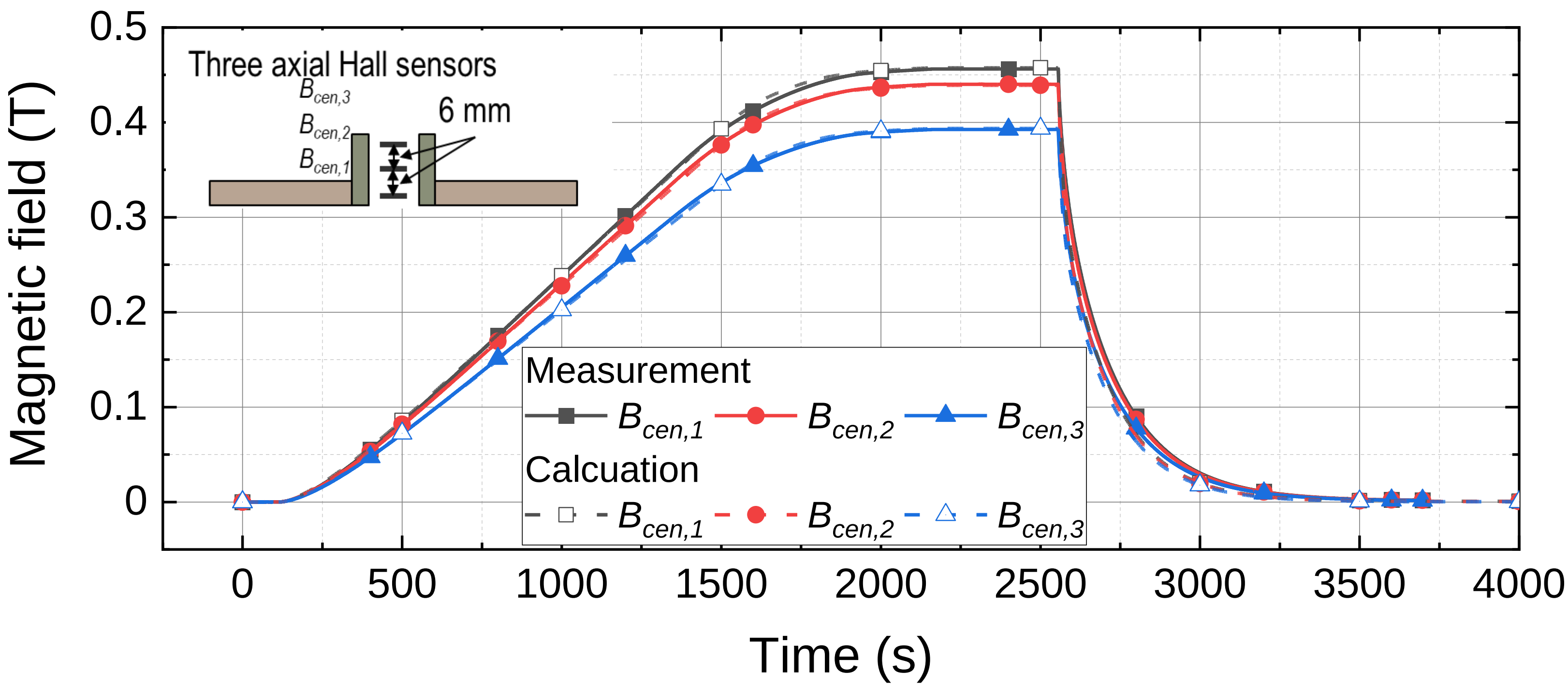
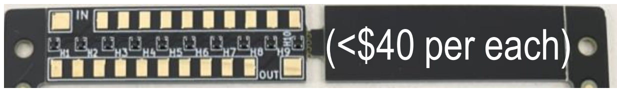
Real-time Field Gradient Estimation: Good Agreement in Field Magnitude; Errors in Harmonic Coefficient



	Unit	Comparison results of zonal harmonic coefficients									
		Calculation ("modified lumped circuit + H-formulation)					Measurement				
		I_{op}=20 A	40 A	60 A	80 A	100 A	20 A	40 A	60 A	80 A	100 A
Z0	[T]	0.0933	0.2176	0.3445	0.4403	0.4575	0.0909	0.2174	0.3465	0.4350	0.4561
Z2	[T/m^2]	-127.0	-281.0	-440.7	-534.8	-544.1	-89.12	-213.1	-339.8	-426.8	-447.3
Z4	[T/m^4]	2.121E5	4.604E5	7.297E5	8.635E5	8.730E5	6.430E3	1.543E4	2.636E4	3.343E4	3.408E4

Future Plan: Implementation of a Hall Sensor “Grid” for HTS Coil Evaluation and Diagnosis in a Practical Way

- **Done**
  - ☐ Sensor board design and fabrication
  - ☐ Cryogenic epoxy impregnation
  - ☐ Confirmation of Operation at 77 K
  - ☐ Installation on the coil surface



GaAs Hall Element

HG-0711

HG-0711は、超小型SON形状GaAsホール素子です。
標準はテーピングリール供給です。(10,000pcs.／Reel)

Shipped in packet-tape reel(10,000pcs per reel)

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●最大定格 Absolute Maximum Ratings

項目 Item	記号 Symbol	条件 Conditions	定格 Limit	単位 Unit
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最大許容損失 Max.Input Power	Pd		150	mW

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Two-component room-temperature-curing epoxy ahesive for bonding CF series strain gauges for use in temperature from cryogenic (- 269 °C) up to 50 °C. Mix the necessary quantity of drugs A and B at the weight ratio of 2 to 1.

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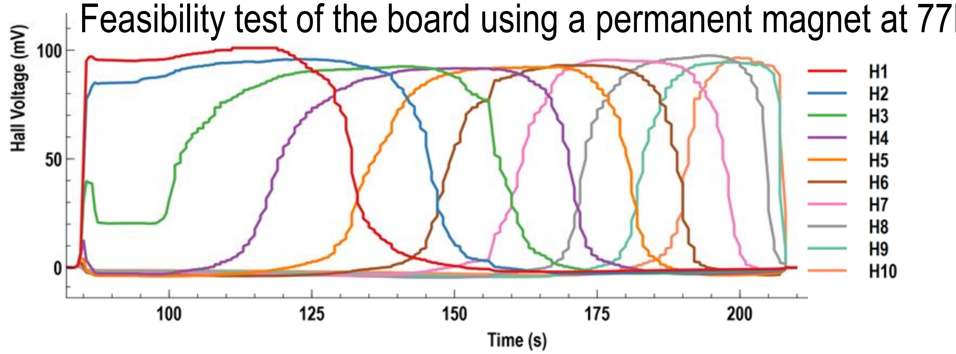
- **To do**
  - ☐ Calibration of Individual sensors
  - ☐ HTS coil evaluation and diagnosis

Feasibility test of the board using a permanent magnet at 77K



Conclusion

- Spatial and temporal electromagnetic behaviors induced by a no-insulation (NI) high temperature superconductor (HTS) coil were investigated.
- Implementation of a real-time monitoring system was performed.
  - Multiple Hall sensors and voltage taps
- Design, construction, and operation results were provided.
  - “Thick” solenoid NI HTS coil with “small” bore was designed, and constructed.
  - A Hall sensor array was mounted on the coil surface, while multiple voltage taps were inserted during coil winding.
- Comparison results between simulation and measurement show good agreement in terms of spatial and temporal electromagnetic behaviors.
  - Modified lumped circuit, H-formulation, and “segmentation method were used.
- “Real-time” monitoring results suggest:
  - Using Hall sensors would be effective in estimating real-time field gradients.
  - It might be possible that a Hall sensor “grid” mounted on a coil surface is used to evaluate and diagnose HTS coil.

Thank you for your attention

Q&A

This work was supported by the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, the Ministry of Food and Drug Safety) (Project Number: 1711138068, KMDF_PR_20200901_0063).

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