Quench Analysis of Stacks of No-Insulation REBCO Coils Demonstrating Electromagnetic Quench Propagation and Self-Protecting Behavior

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Points of Discussion

- **Introduction**
  - No-Insulation (NI) Quench Analysis
- **Method of Quench Modeling**
  - Circuit Analysis
  - Thermal Analysis
  - Mechanical Stress Analysis
- **Case Study of Real Magnets**
  - Experiment
  - Simulation
- **Conclusion**

❑ No-Insulation Quench Analysis

NI Quench Modeling

Challenges:

- Anisotropic current path.
- Temperature rise and LHe consumption.
- Temperature dependent parameters.
- Unbalanced forces, stresses & strains.

Significance:

- Understanding of post quench situation ($I(t)$, $T(t)$, $\sigma(t)$, $\varepsilon(t)^{*}$) is important.
- Need to make sure T and $\underline{\varepsilon}$ are below certain limits.

* $I(t)$: Operation current　　$T(t)$: Temperature
$\sigma(t)$: Stress　　$\varepsilon(t)$: Strain

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Multi-Physics Quench Simulation

Circuit Analysis

To find $I(t)$ and $V(t)$ using Inductance / Resistance [L/R] model.

Thermal Analysis

To find $T(t)$ rise due to resistive joule heating, I^2R.

Field Analysis

To find magnetic field, $B(t)$.

Stress Analysis

To find $\sigma_r(t)$, $\sigma_h(t)$ and $\sigma_z(t)$ due to Lorentz's forces.

Coupled, as resistivity (ρ), heat capacity (C_p) and critical current (I_c) are temperature dependent.

Coupled, as $B(t)$ is $I(t)$ dependent.

Coupled, as I_c is ε_h dependent.

❑ Circuit Analysis

▪ Lumped Circuit Model:

Each coil is modeled as:

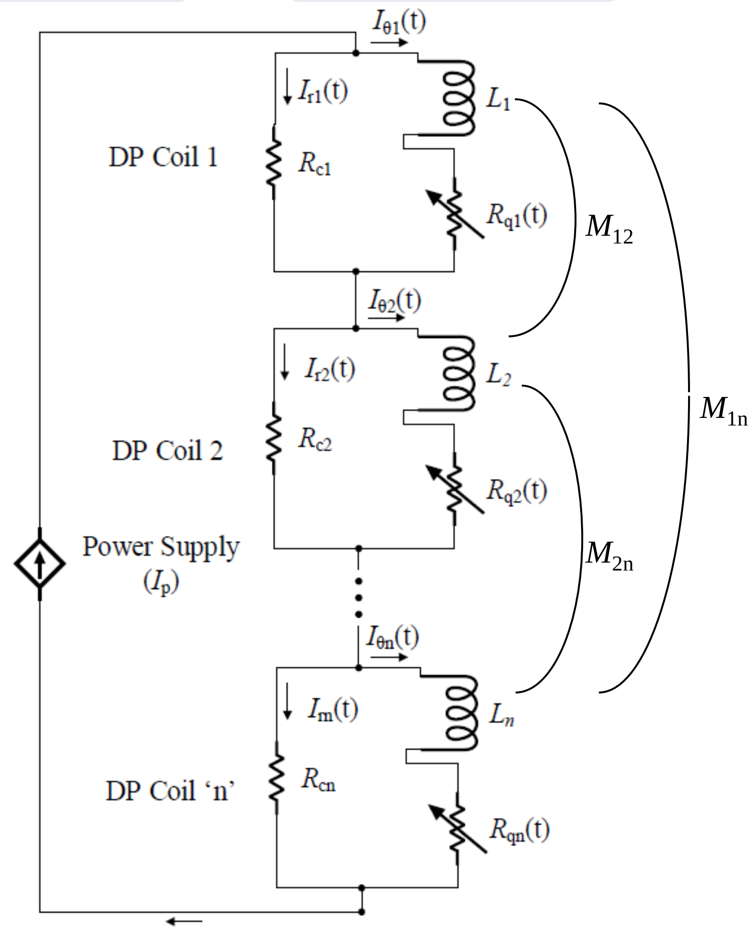
- Inductor, *L-M*;
- Characteristic contact resistance, R_c;
- Quench resistance, $R_q(t)$;

$$R_q(t) = \frac{V_c}{I(t)} \left(\frac{I_{superconductor}}{I_c(B(t), \theta(t))} \right)^n$$

▪ Field, Angle & Temperature Dependency of Critical Current, I_c

Modeled using expressions:

- David K. Hilton *et al.*, "Practical Fit Functions …," *Supercond. Sci. Technol.*, vol. 28, no. 7, June 2015.
- Carmine Senatore *et al.*, "Field and Temperature…," *Supercond. Sci. Technol.*, vol. 29, no. 1, Dec 2015.



Equivalent *L-R* Circuit Model of No-Insulation Magnet with 'n' Number of Coils.

REF: K.R. Bhattarai *et al.*, "Quench Analysis of a Multiwidth…," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, p. 4603505, June 2017.

❑ Circuit Analysis

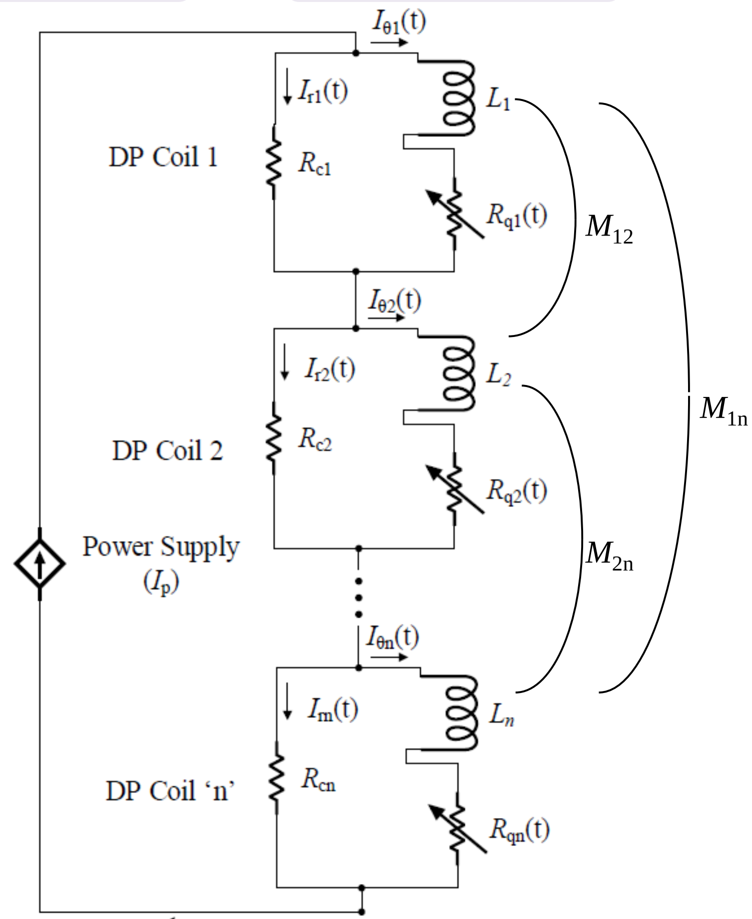
- Governing ODEs from Kirchhoff's Law solved to obtain $I(t)$ and $V(t)$.

$$L_{11}\frac{dI_{op1}(t)}{dt} + M_{12}\frac{dI_{op2}(t)}{dt} + \ldots + M_{1n}\frac{dI_{opn}(t)}{dt} + I_{op1}(t)Rq_1(t) = [I_p(t) - I_{op1}(t)]Rc_1$$

$$\vdots$$

$$M_{n1}\frac{dI_{op1}(t)}{dt} + M_{n2}\frac{dI_{op2}(t)}{dt} + \ldots + L_{nn}\frac{dI_{opn}(t)}{dt} + I_{opn}(t)Rq_n(t) = [I_p(t) - I_{opn}(t)]Rc_n$$

- Advantage of Lumped Model: Fast and seems reliable.
- Disadvantage of Lumped Model: Not possible to obtain coil spatial information.



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❑ Thermal Analysis

$$\rho C p \frac{dT}{dt} = \dot{q} + k\nabla^2 T + h(T - T_\infty)\frac{P}{A}$$

- Heat Stored: $\rho C p \frac{dT}{dt}$
- Heat Added (Joule Heating): $\dot{q}$
- Conduction: $k\nabla^2 T$ = 0, (Lumped Capacitance Model Assumed)
- Dissipation: $h(T - T_\infty)\frac{P}{A}$ = 0, (Adiabatic Assumption)

Simplified equation:

$$mC_p(t)\frac{dT(t)}{dt} = I(t)^2 R(t)$$

- Solved to obtain *T*(t)
- *T*(t) is used to recalculate parameters such as $R(t)$, $I_c(t)$ and $C_p(t)$.

Thermal Analysis: $R(t)$, $C_p(t)$ → simplified equation

Circuit Analysis: $R(t)$, $I_c(t)$

Mechanical Stress Analysis

- Radial stress [$\sigma_r(t)$] and hoop stress [$\sigma_\theta(t)$].

Force balance governing equation at magnet mid-plane:

$$r\frac{\partial \sigma_r}{\partial r} + \sigma_r - \sigma_\theta + rJ_\theta B_z(r) = 0$$

REF: Bobrov, E.S. and Williams, J.E.C (1980) in *Mechanics of Superconducting Structures*, vol. 41, Proceedings of the Winter Annual Meeting Chicago, IL., November 16-21, 1980 (ed F.C. Moon), ASME, New York, pp.13-41.

- Stress in self supporting condition; $\sigma_\theta = B_z(r) \cdot J \cdot r$
- Solved to obtain $\sigma_r(t)$, $\sigma_\theta(t)$.
- Using generalized Hook's law, strain can be calculated.

$$\varepsilon_r = \frac{\sigma_r}{E_r} - \nu_{hr}\frac{\sigma_h}{E_h} - \nu_{zr}\frac{\sigma_z}{E_z}$$

$$\varepsilon_h = \frac{\sigma_h}{E_h} - \nu_{rh}\frac{\sigma_r}{E_r} - \nu_{zh}\frac{\sigma_z}{E_z}$$

$$\varepsilon_z = \frac{\sigma_z}{E_z} - \nu_{rz}\frac{\sigma_r}{E_r} - \nu_{hz}\frac{\sigma_h}{E_h}$$

- 95% I_c retention when ε_h is ~ 0.5%.

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  - Experiment
  - Simulation
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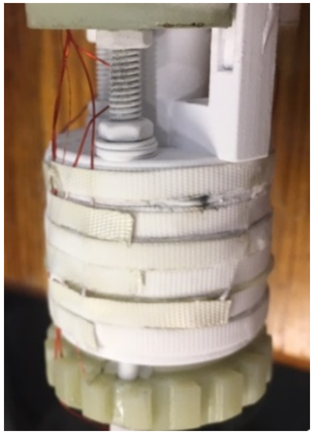
❑ Case Study I: 2 DP NI REBCO insert in 31.1 T background magnet.

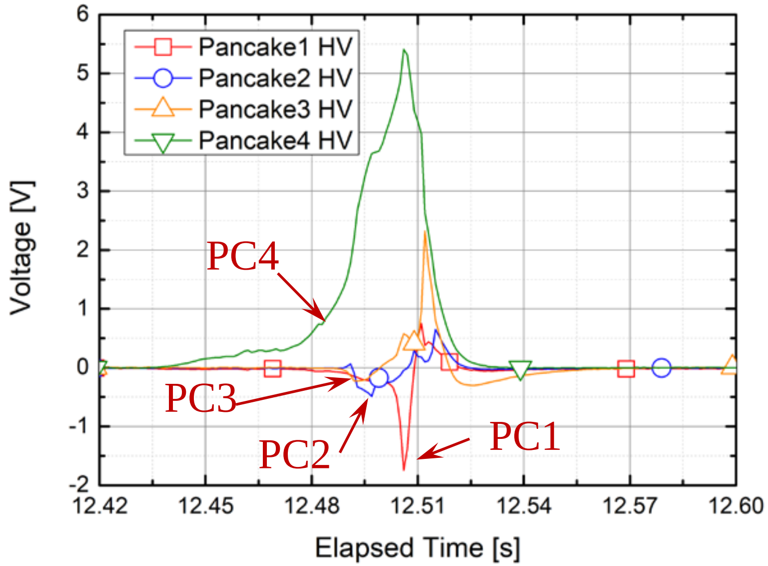
- Some parameters that go into the simulation.

Parameters		Values
Tape width	[mm]	4.03
Tape thickness	[mm]	0.045; 0.01
Stabilizer material		Cu RRR50
Winding inner radius, a_1	[mm]	7
Winding outer radius, a_2	[mm]	17
Overall height	[mm]	16.48
Total number of turns		859
Inductance, L_{HTS}	[mH]	10.25
Measured characteristic resistance, R_c	[mΩ]	2.4
Young's modulus, E_r; E_h; E_z	[GPa]	69; 144; 144
Quench current	[A]	210



- Case Study I: 2 DP NI REBCO insert in 31.1 T background magnet.

Experiment



Simulation

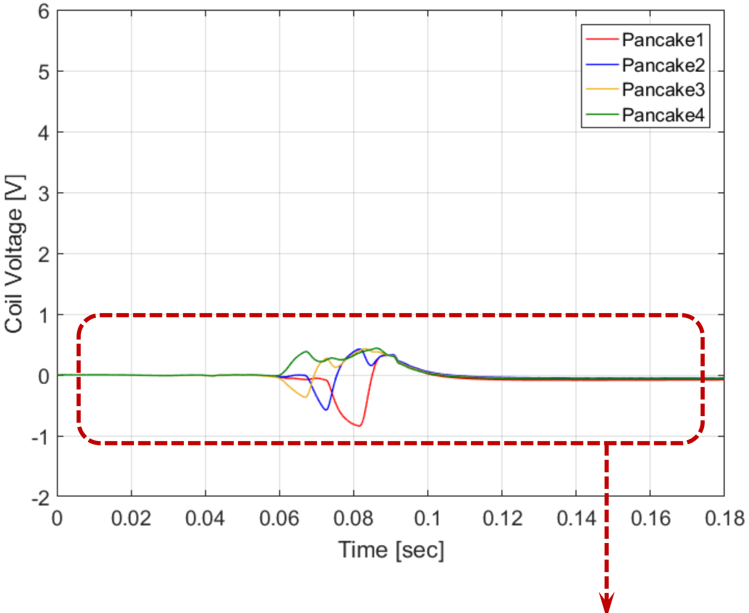
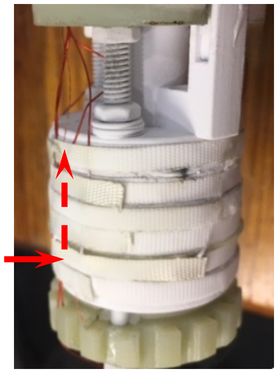


Table 1: Key Magnet Parameters

Parameters	Value
Inner radius [mm]	7
Outer Radius [mm]	17
Height [mm]	16.48
Time Constant [sec]	3.817
Quench Current [A]	210
Stored Energy [J]	240.8

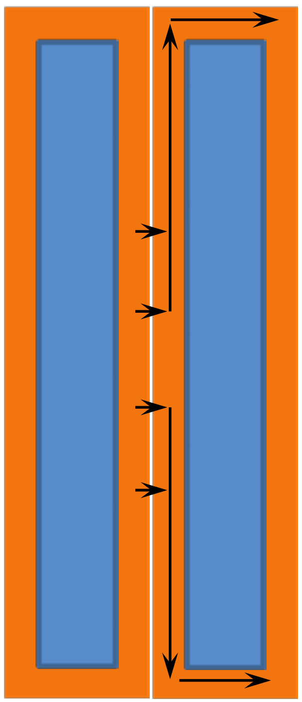


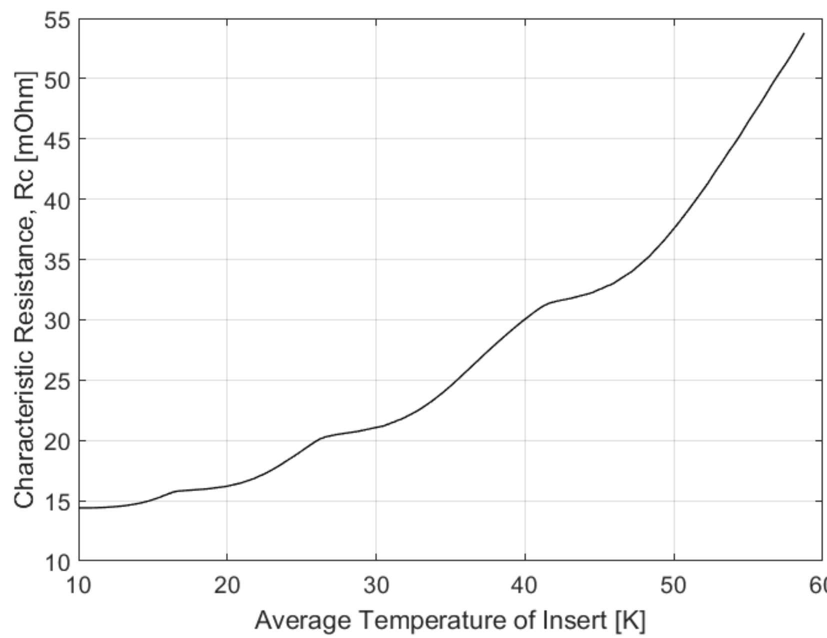
Significant error. Simulation voltage range is only ~15% of the experimental voltage range.

❑ Increase in Characteristic Resistance, R_c due to temperature rise.

- Assumption: R_c maybe increasing proportionally, as the copper resistivity rises with temperature.

$$R_c(T) = Rc(4.2)\,\frac{\rho_{cu}(T)}{\rho_{cu}(4.2)}$$



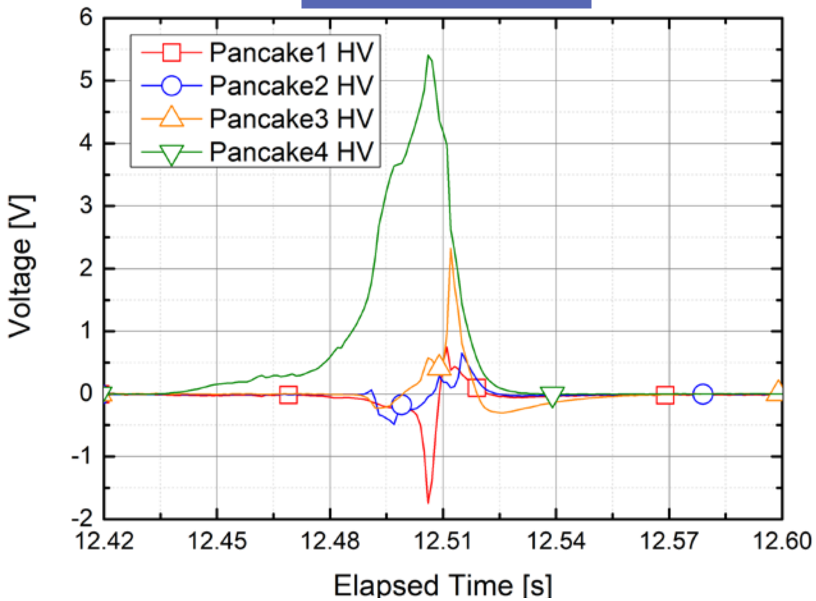


- R_c increase due to temperature rise is also proposed by J. Lu et al.

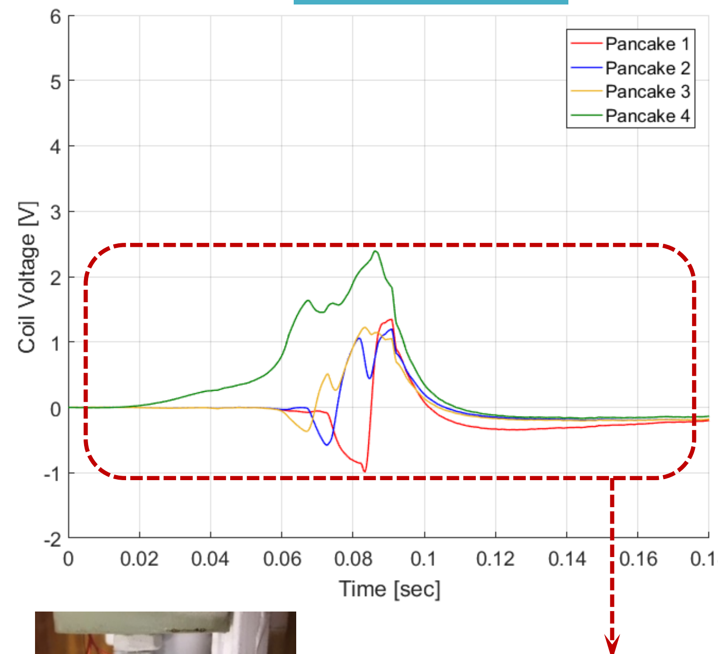
REF: J. Lu *et al.*, "Contact resistance between two REBCO tapes under load and load cycles," *Supercond*. Sci. Techol., vol. 30, p. 045005, 2017.

- Case Study I: 2 DP T NI REBCO insert in 31.1 T background magnet.
  - With variable Characteristic Resistance, R_c

Experiment



Simulation



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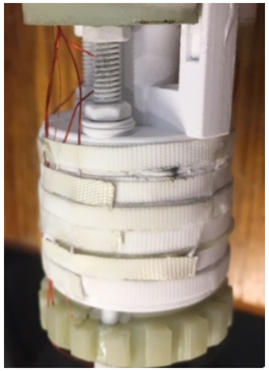
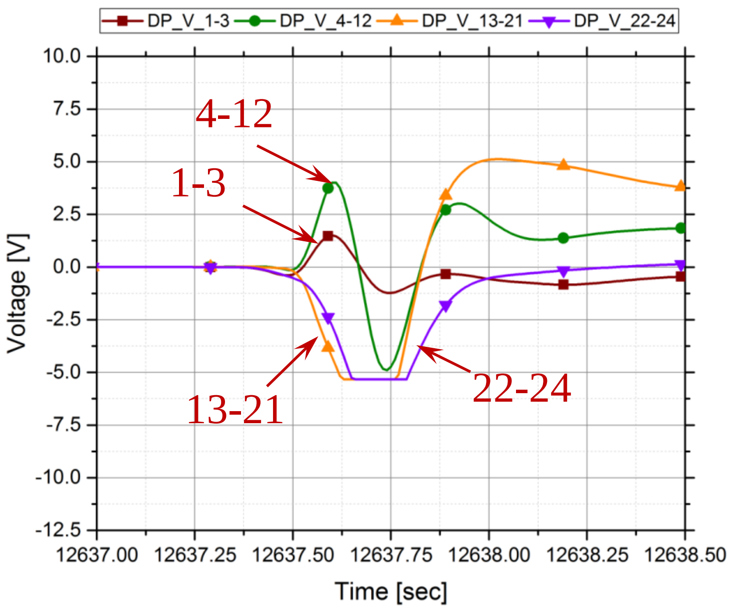


Simulation voltage range is about ~60% of the experimental voltage range

- Case Study II: 12.5 T NI REBCO insert in 6.5 T LTS.
  - With variable Characteristic Resistance, R_c

Experiment



Simulation

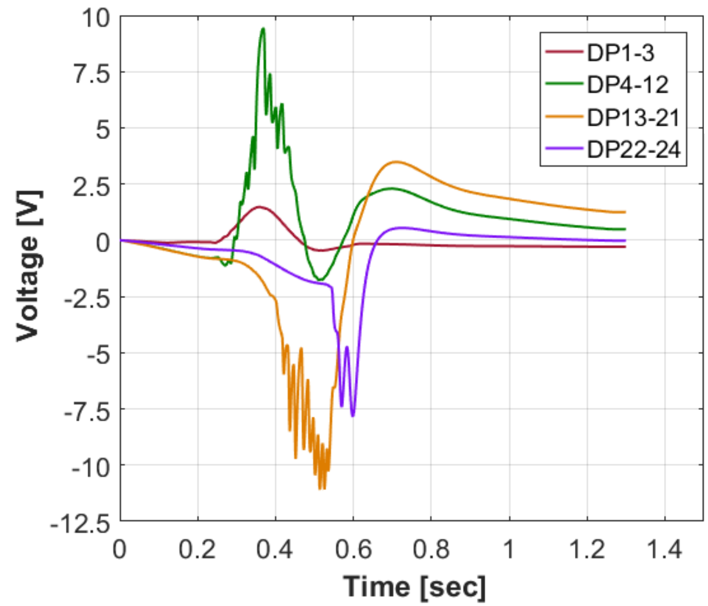
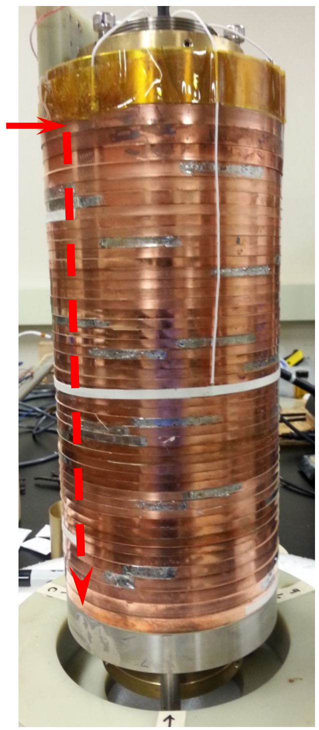


Table 1: Key Magnet Parameters

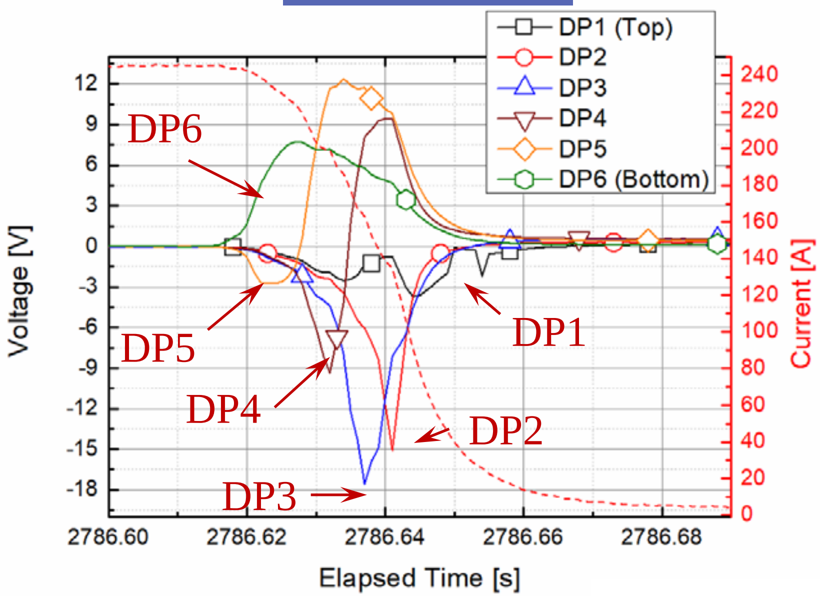
Parameters	Value
Inner radius [mm]	29.9
Outer Radius [mm]	57.5
Height [mm]	232.55
Time Constant [sec]	54
Quench Current [A]	216
Stored Energy [kJ]	62.99



REF: T. Painter *et al.*, "Design, Construction and Operation of a 13 T 52 mm No-Insulation REBCO Insert for a 20 T All-Superconducting User Magnet," *Oral Presentation @ MT Conference 2017*. Thu-Mo-Or31

- Case Study III: 14.36 T NI REBCO insert in 31.1 T background magnet.
  - With variable Characteristic Resistance, R_c

Experiment



Simulation

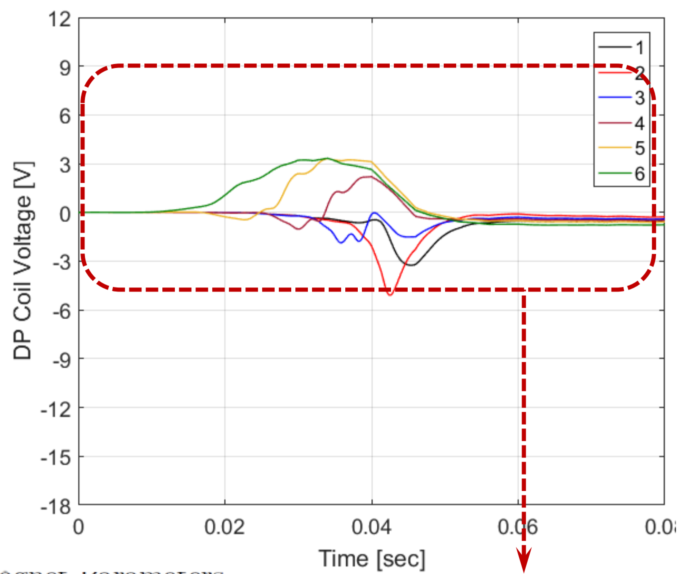
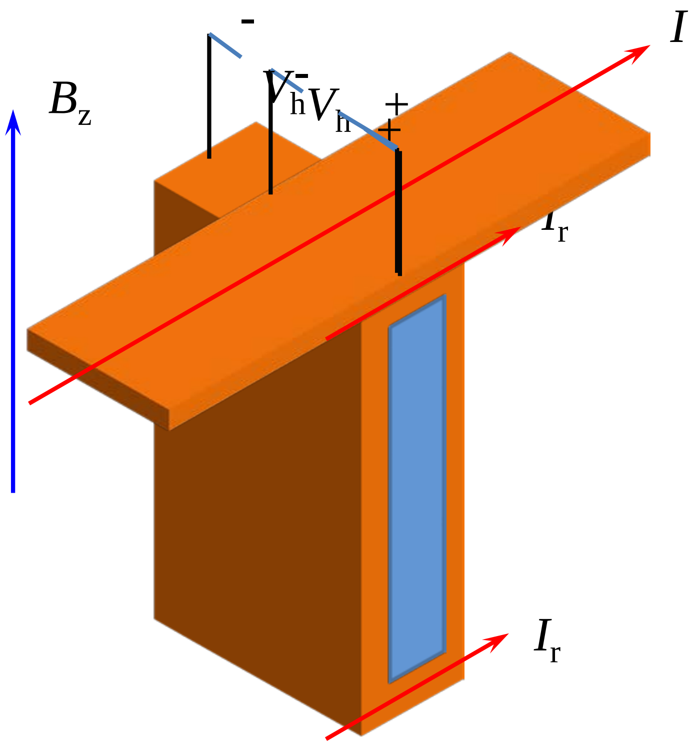


Table 1: Key Magnet Parameters

Parameters	Value
Inner radius [mm]	7
Outer Radius [mm]	17
Height [mm]	51
Time Constant [sec]	1.07
Quench Current [A]	245
Stored Energy [kJ]	1.512

Simulation voltage range is about ~30% of the experimental voltage range

❑ Hall effect.



$$V_h = -Rh\,\boldsymbol{J} \times \boldsymbol{B}$$

I: Current [A]

I_r: Leak Current [A]

B_z: Axial Field [T]

V_h: Voltage due to Hall Effect [V]

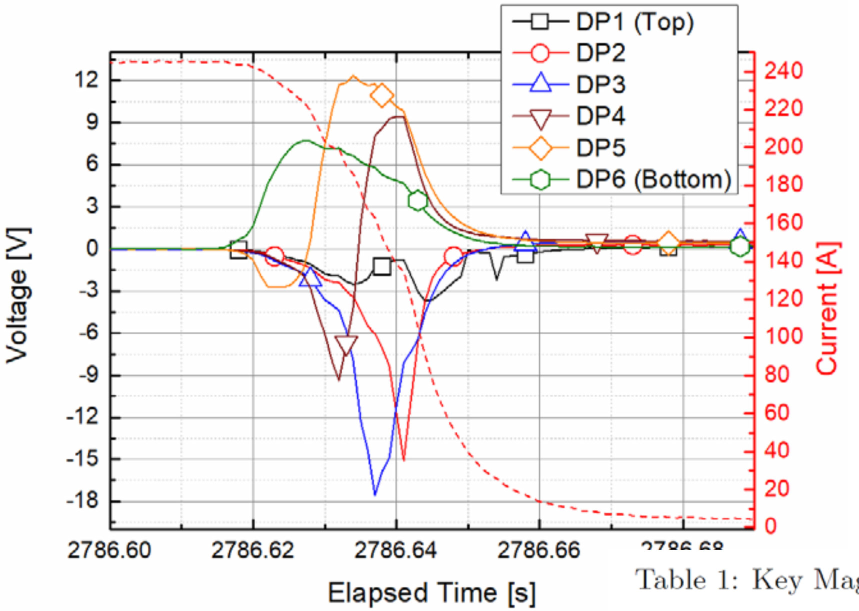
R_h: Hall coefficient

- Proposed by So Noguchi et al.

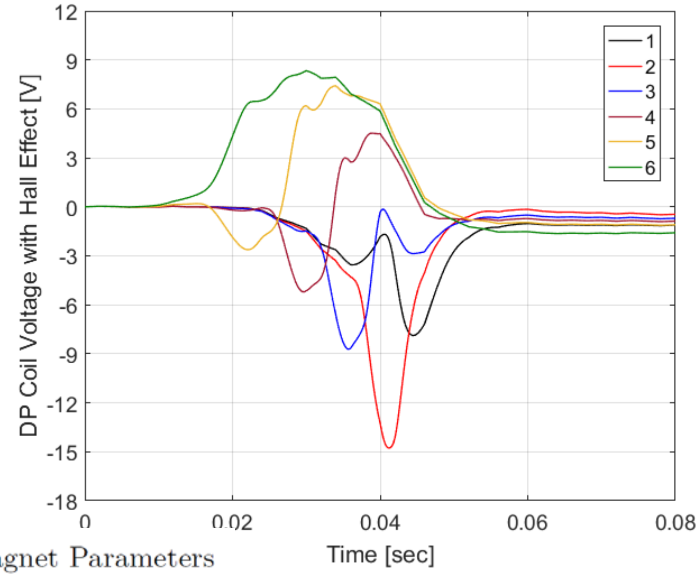
REF: S. Noguchi *et al.*, "Electrical Field Generation by Hall Effect in High Field No-Insulation REBCO Pancake Coils," *Poster Presentation @ MT Conference 2017*. Thu-Af-Po4.11

- Case Study III: 14.36 T NI REBCO insert in 31.1 T background magnet.
  - With variable Characteristic Resistance, R_c
  - With Hall Effect

Experiment



Simulation



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Discussion and Conclusion

- Characteristic Resistance, R_c seems to be increasing during quench. Possible reason is due to the increase in the resistivity of the contact material. This issue needs further research.

- Hall effect could be another the contributor towards large voltage rise during quench. This effect also needs further research and validation.

- These are some of the first no-insulation simulations
  i. of real magnets that have quenched.
  ii. using lumped approach in magnet level.

- Lumped approach: computationally faster than distributed approaches.

- Despite limited accuracy, demonstrates electromagnetic interaction between coils during quench.

Thank you for your attention!