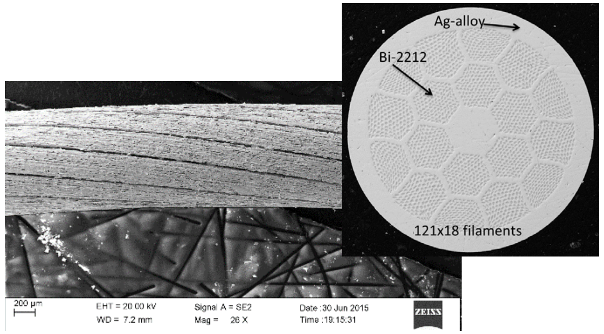
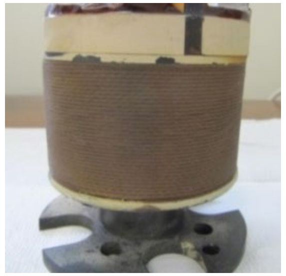
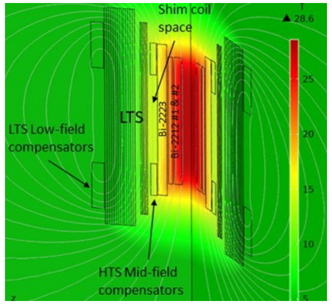
Implementing HTS in STEAM-LEDET from test coils to full-scale systems



HTS Bi-2212





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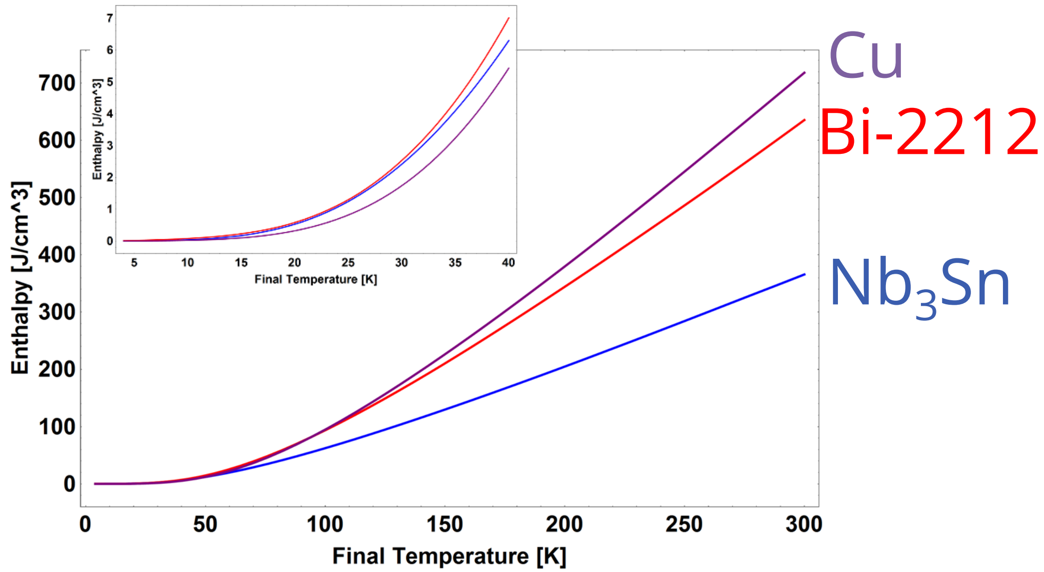
An HTS Experimentalists Perspective: **Start with Test Coils**

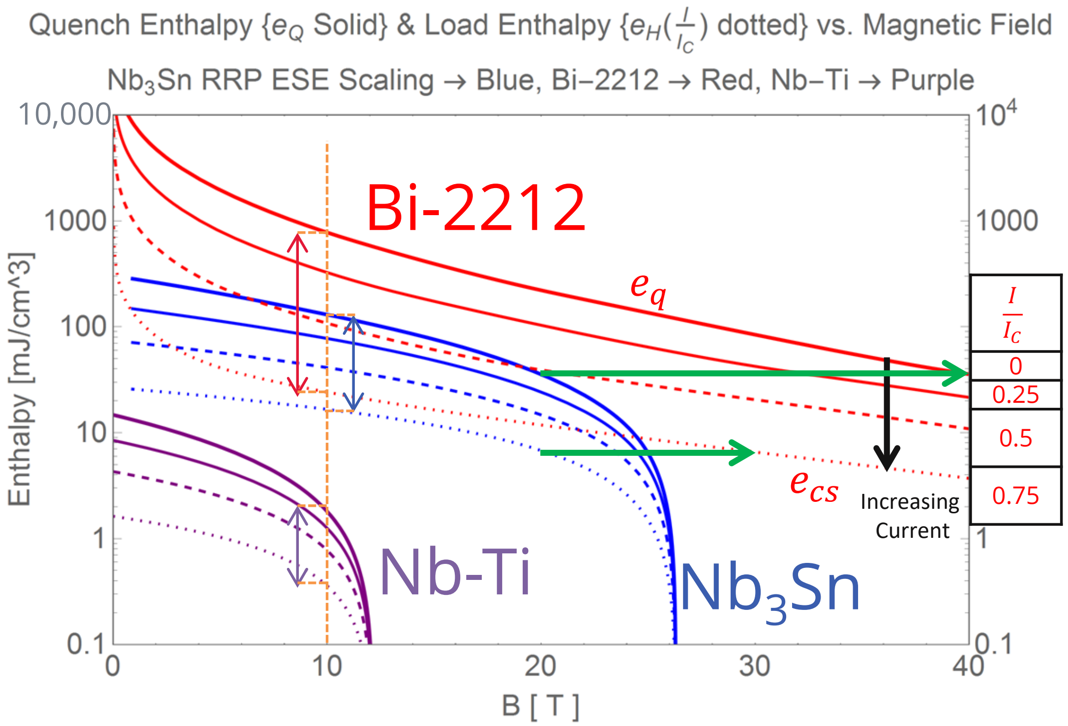
Develop an understanding of HTS Magnet Behavior

- Analytics (margin analysis), idealized cases (forced quenches, low/high I_C, IFCC on/off), replicate a basic test (test solenoid energy extraction, L/R decay)
- Implement materials and physics (Bi-2212 $I_C(B,T)$ scaling, silver alloy mixture models, current sharing, …)
- Add novel behavior and predict results
  - (CLIQ discharge parameter sweeps, solenoid tests at 77 and 4 K)
- Adjust parameters and/or implementation, then try to understand these changes (transverse resistivity, quench propagation, diode losses)
- Initially had to use different code for dipoles(Roxie) versus solenoids(Mathematica) to acquire the magnetic field and inductance profile (now integrated into both Python notebook and executable)

- LEDET and now STEAM have provided a consistent baseline platform for feedback with experiment, while steadily adding more features to replicate realistic behavior.
- I have the perspective of an alpha/beta-tester with a unique application (HTS)
  - Run many simulations with direct feedback of code, models, and experimental results with Emmanuele Ravaioli (LEDET)

Analytics: Bi-2212 is Like a Higher Field Nb_3Sn with More Current Sharing





Specific Heat Capacity → Integrated to get enthalpy

$C_p\left[\frac{J}{g\cdot K}\right] = y_0 + \frac{a}{\left[1+e^{-\frac{T-\tau}{b}}\right]^c}$ {common form of data fit}

Current Sharing Temperature

$T_{cs}[K] = T_C(B) - i\cdot\left[T_C(B) - T_{op}\right]$ {linear dependence is common}

Enthalpy to Current Sharing {T_{CS}}

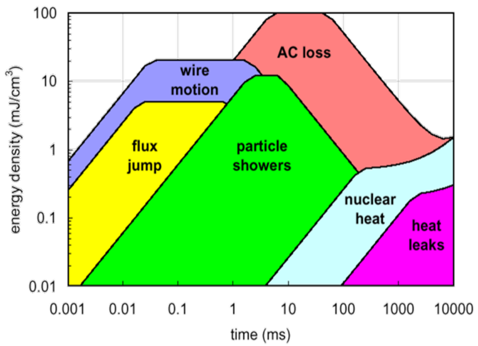
$e_{cs}[J] \equiv h(\mathbf{T_{cs}}(B,i)) - h(T_{op})$

Enthalpy to Quench {T_C}

$e_Q[J] \equiv h(\mathbf{T_C}(B)) - h(T_{op})$

- A deposited heat of e_{CS} will generate dissipation and current sharing until fully normal for e_q deposited
  - Current sharing region ~5x larger for HTS (970 mJ) than LTS (180 mJ) at 10 T
- Bi-2212 e_{CS} at 30 T (or e_q at 40 T) same as Nb_3Sn at 20 T
- An order of magnitude drop in margin from 5 T to 30 T for Bi2212 for quench margin

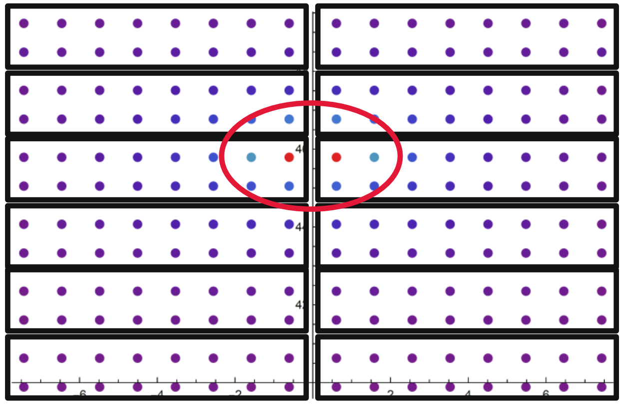
Analytic Feedback: Where the margin is matters.
Quench margin varies with geometry, conductor, and field



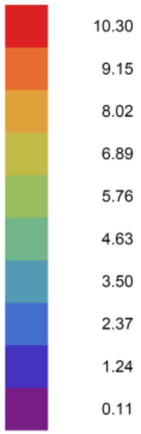
e_{cs} [J/cm^3] energy density margin to current sharing at I/Ic=0.75

Sub-scale Accelerator

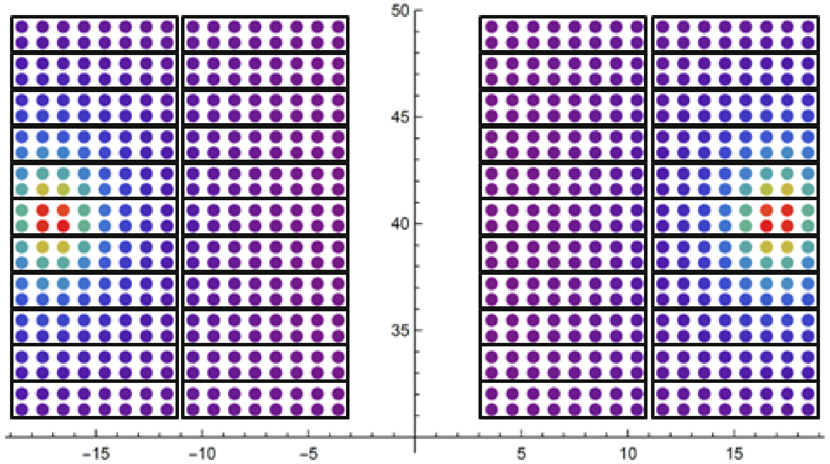
RC-6



e_{CS} [J/cm^3]

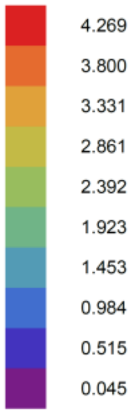


RC-7 & RC-8

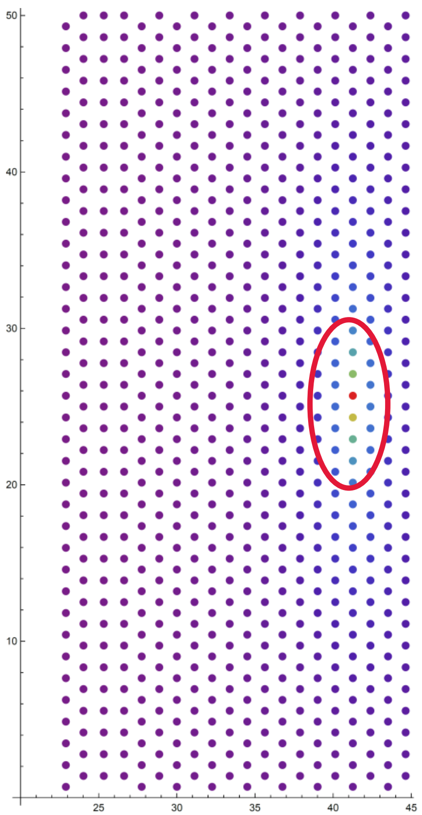


w/ Iron Saturation

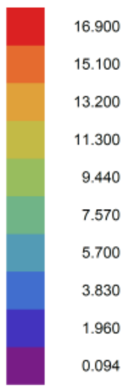
e_{CS} [J/cm^3]



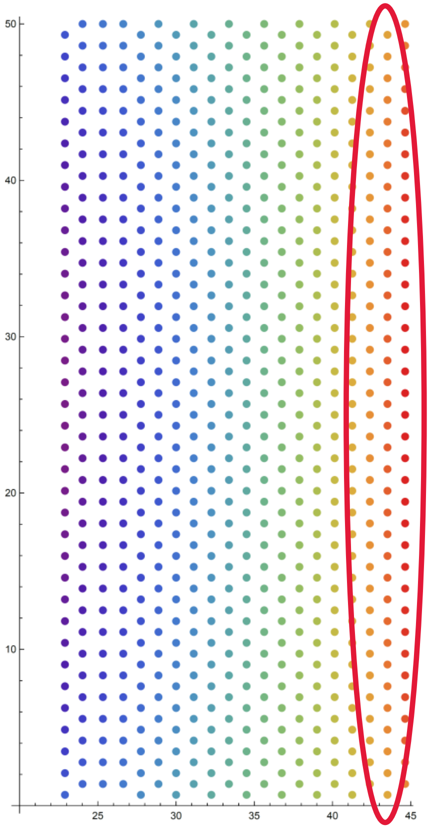
High Field Solenoid (Pup-4)



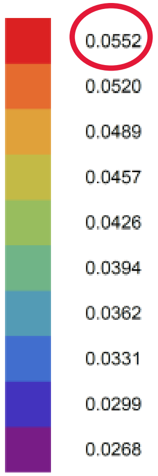
e_{CS} [J/cm^3]



Self Field



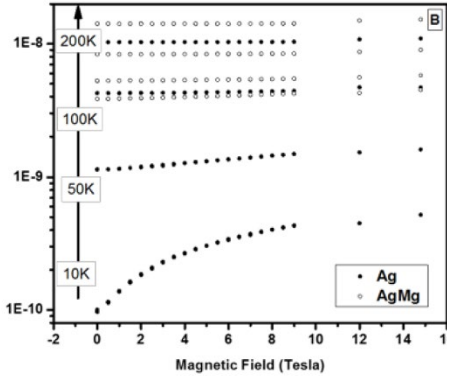
e_{CS} [J/cm^3]

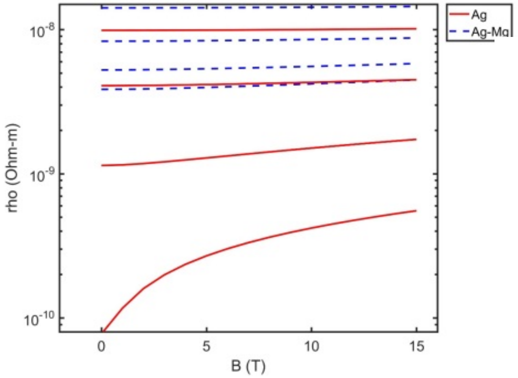


w/ 7.829 T Background

Modelling: Developed non-linear implementations of HTS behaviors

Low index power law current sharing with Ag alloy matrix:



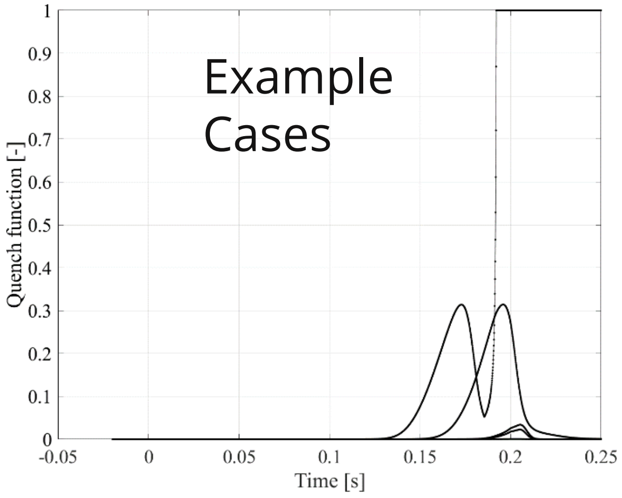


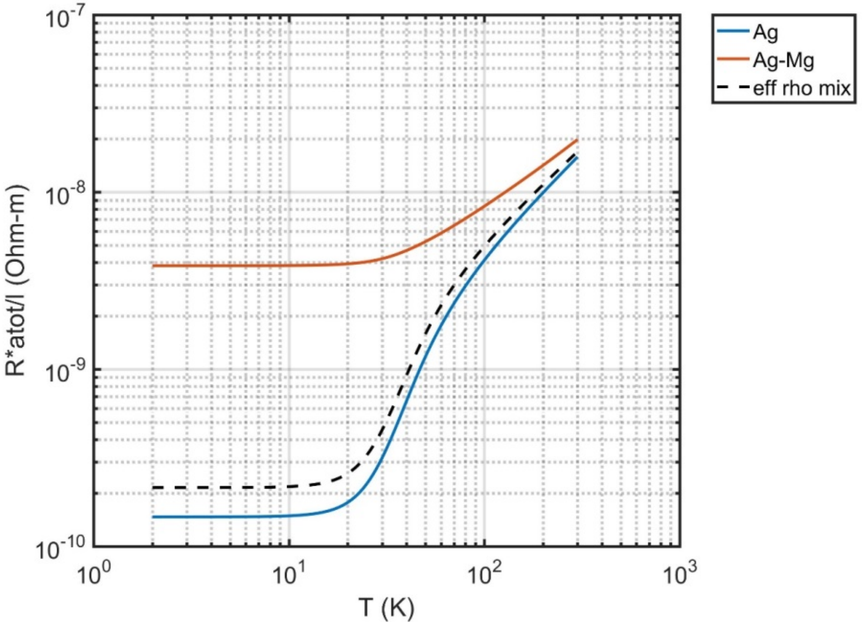
$$\vec{E}(J) = E_C \left(\frac{|\vec{J}|}{J_C}\right)^n \frac{\vec{J}}{|\vec{J}|}$$

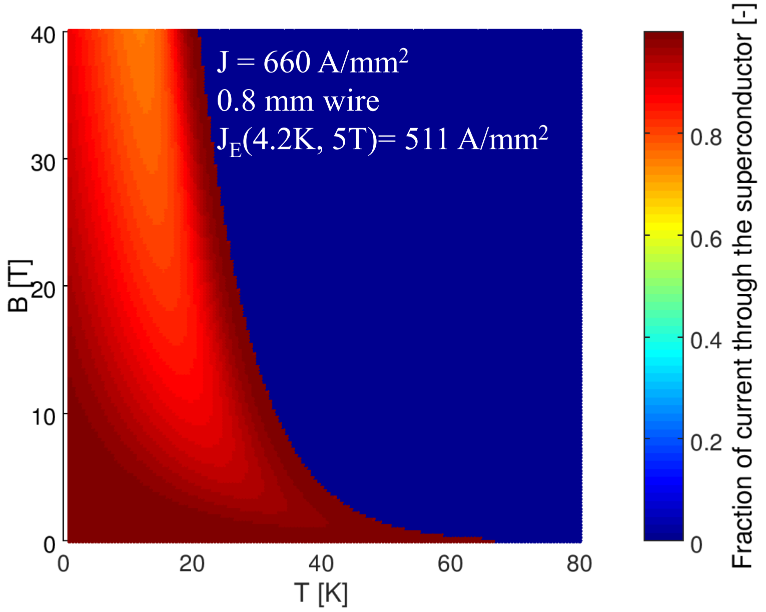
$$V = I_m \cdot \frac{\rho_m}{A_m} \cdot l = I_{sc} \cdot E_C \left(\frac{I}{I_C}\right)^n \cdot l$$

$$I_{tot} = f_{sc} \cdot I_{tot} + E_C \cdot \frac{A_m}{\rho_m} \left(f_{sc} \frac{I_{tot}}{I_C}\right)^n$$

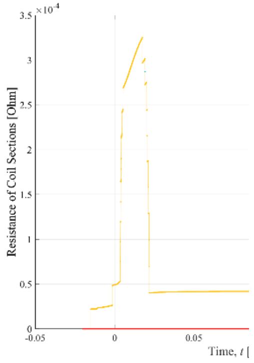
For the moment, non-linear solver choice is important for simulation stability (shorter time steps necessary)



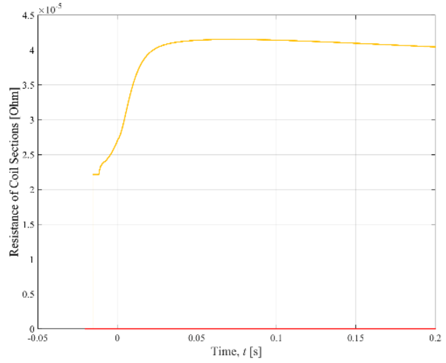




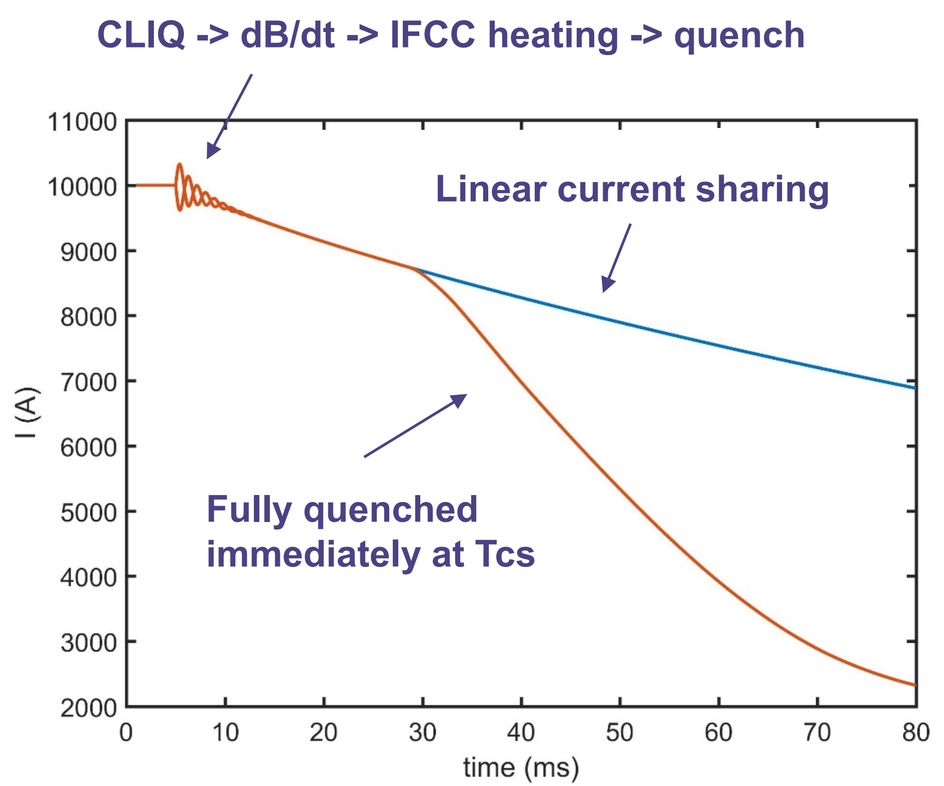
W/out

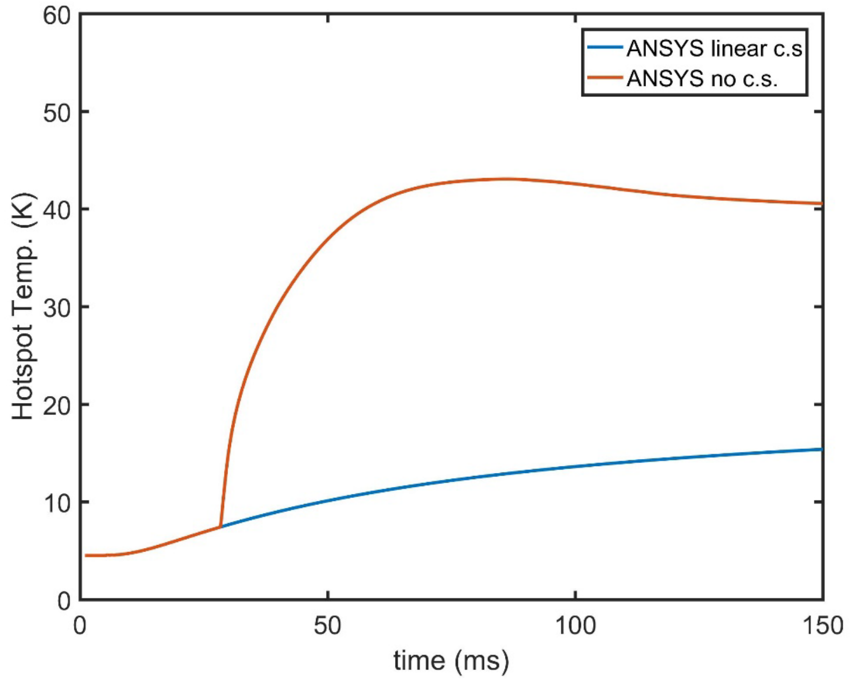


With



Implementation: A Simple Current Sharing Model Dramatically Changes the CLIQ Results for a Common Coil with Coupling Losses Included

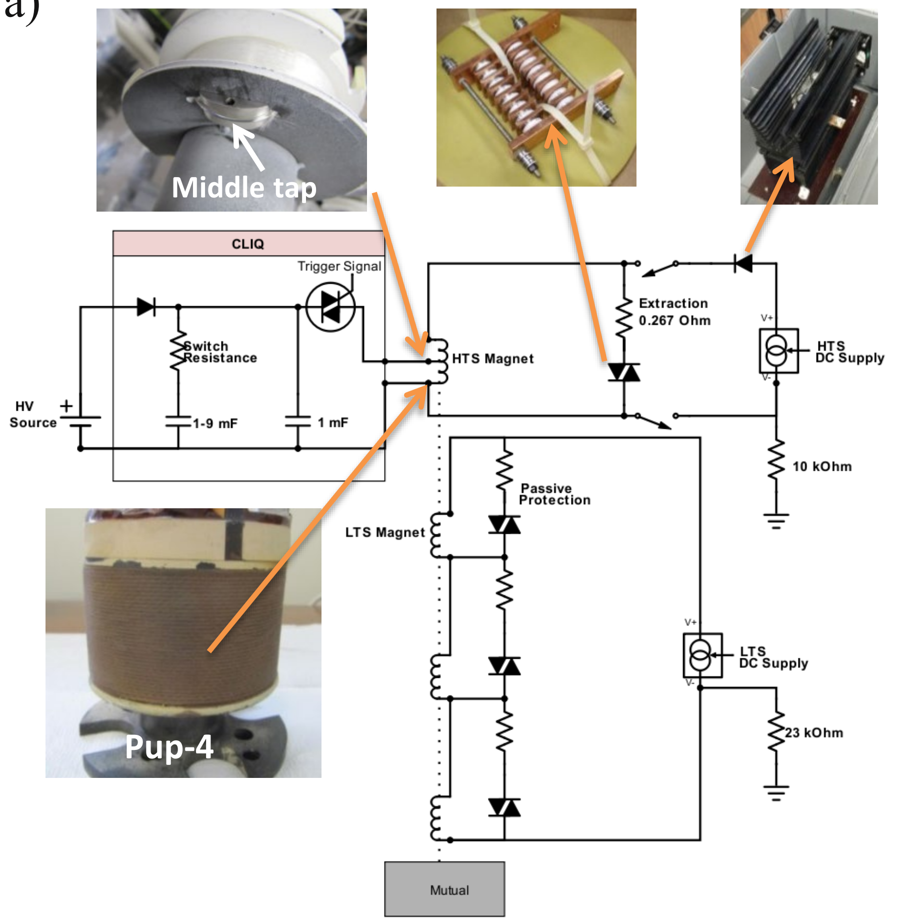




ANSYS simulations by Lucas Brouwer (LBL)

Magnets: Test of “PUP4” Bi2212 Solenoid in Background Field at MAGLAB Allows for First Comparison of LEDET/ANSYS Modeling with CLIQ Data

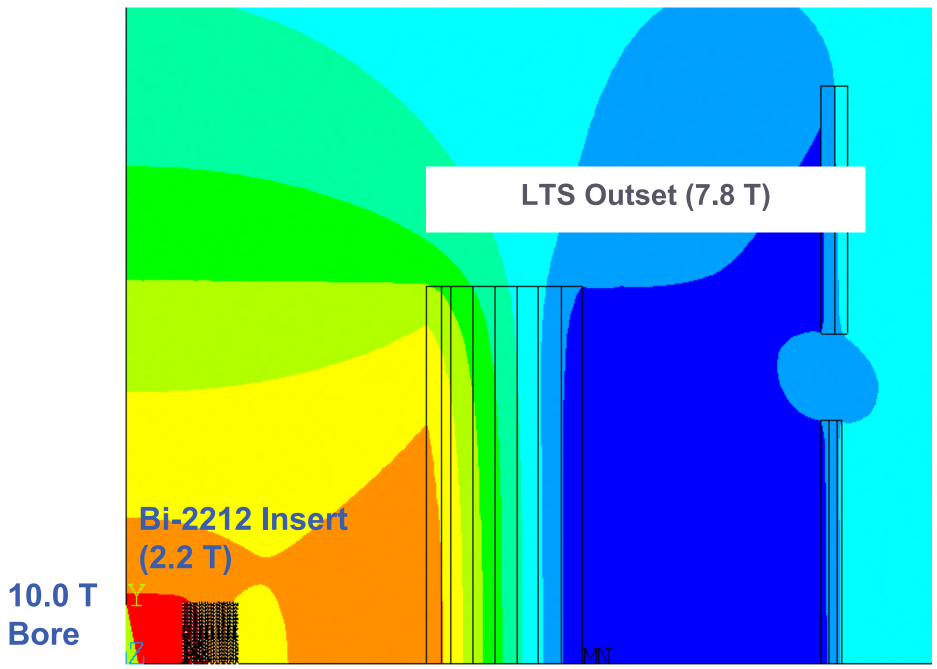
a)



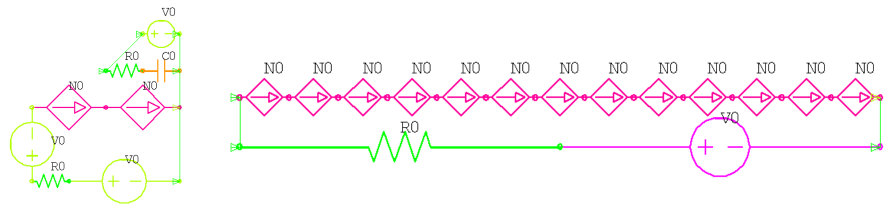
Capacitor bank (CLIQ) is discharged across two sections of the Pup-4 solenoid to induce current oscillation (increases IFCC losses)

b)

FEM-ANSYS model with insert, outsert, and their equivalent circuits

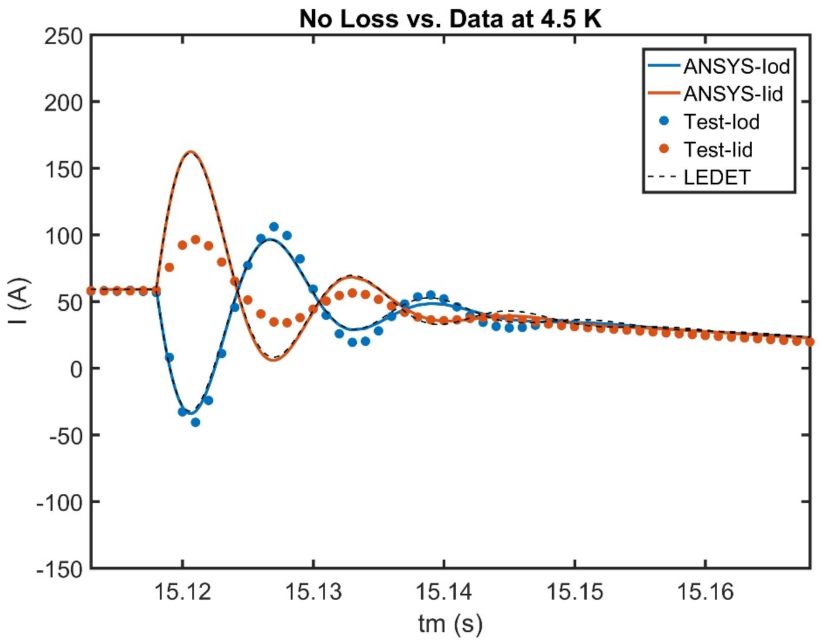


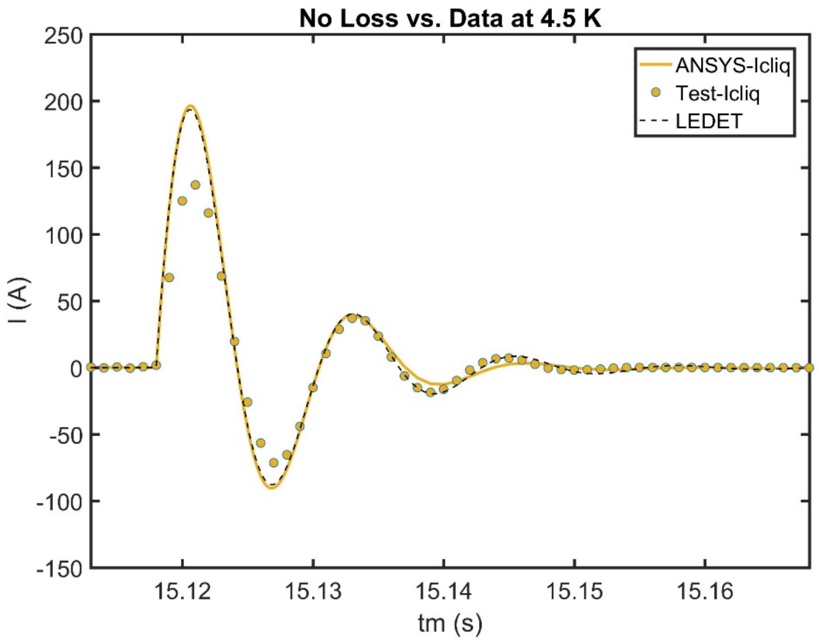
c)



Validation: Comparison of ANSYS to Data From the PUP4 Tests at 4.5 K

CLIQ at 4.5 K with 7.8 T background field: C = 4.75, V = 100 V



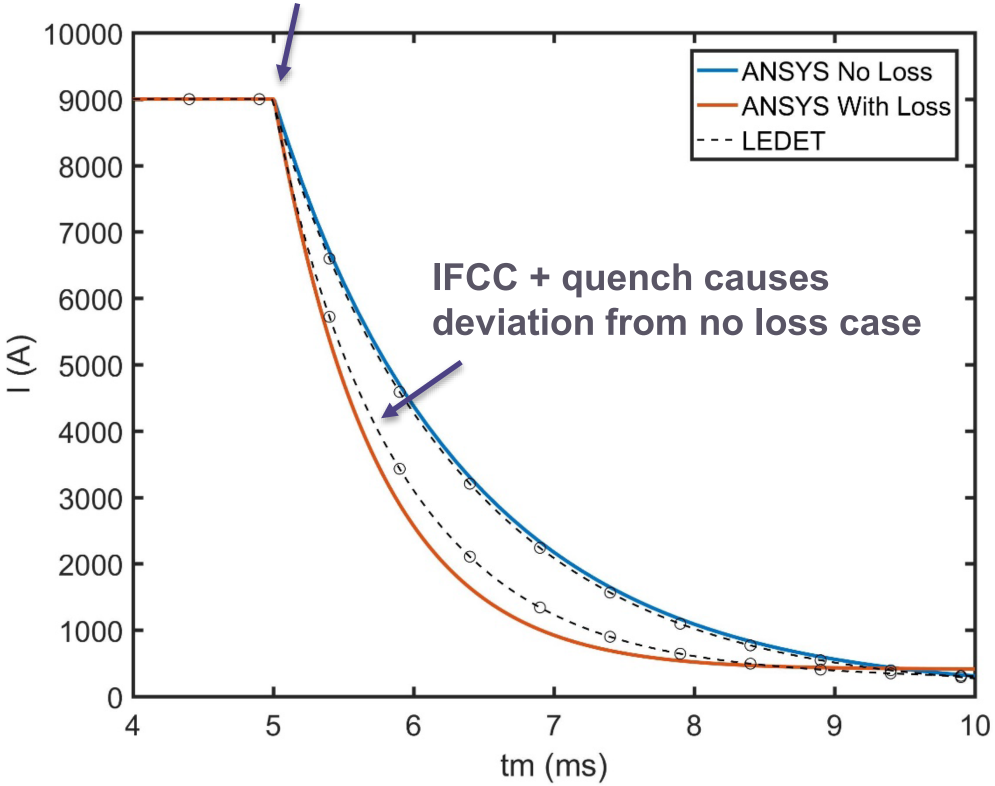


ANSYS/LEDET show agreement, match to data is promising

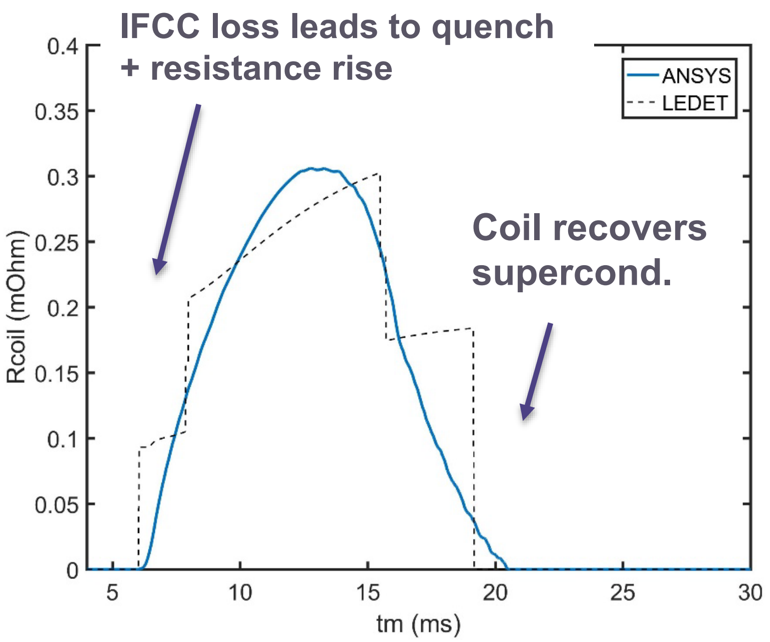
ANSYS simulations by Lucas Brouwer (LBL)

Validation: Simulations Predict Current, Resistance, and Temperature Rise for Bi2212 Racetrack Coils During Extraction

At 5.0 ms a 20 mOhm dump resistor is placed in series with the magnet (extraction at 90% of SS)



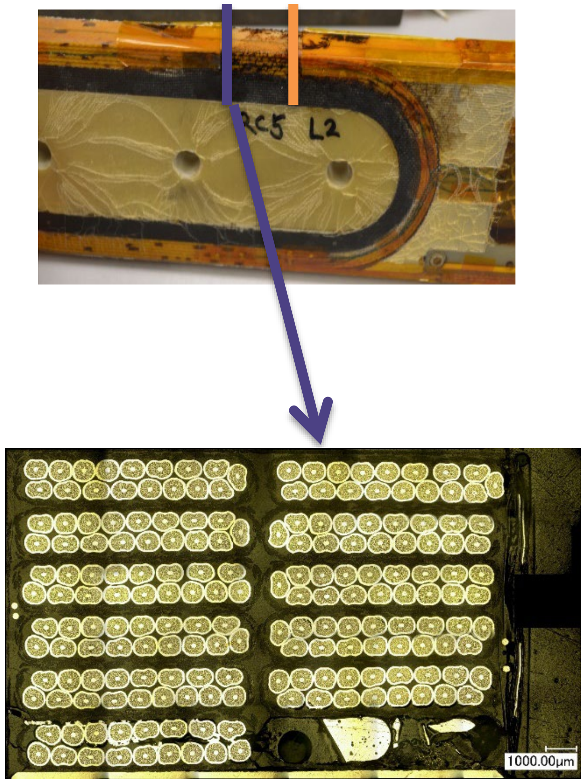
ANSYS Hotspot: 43 K
LEDET Hotspot: 45 K

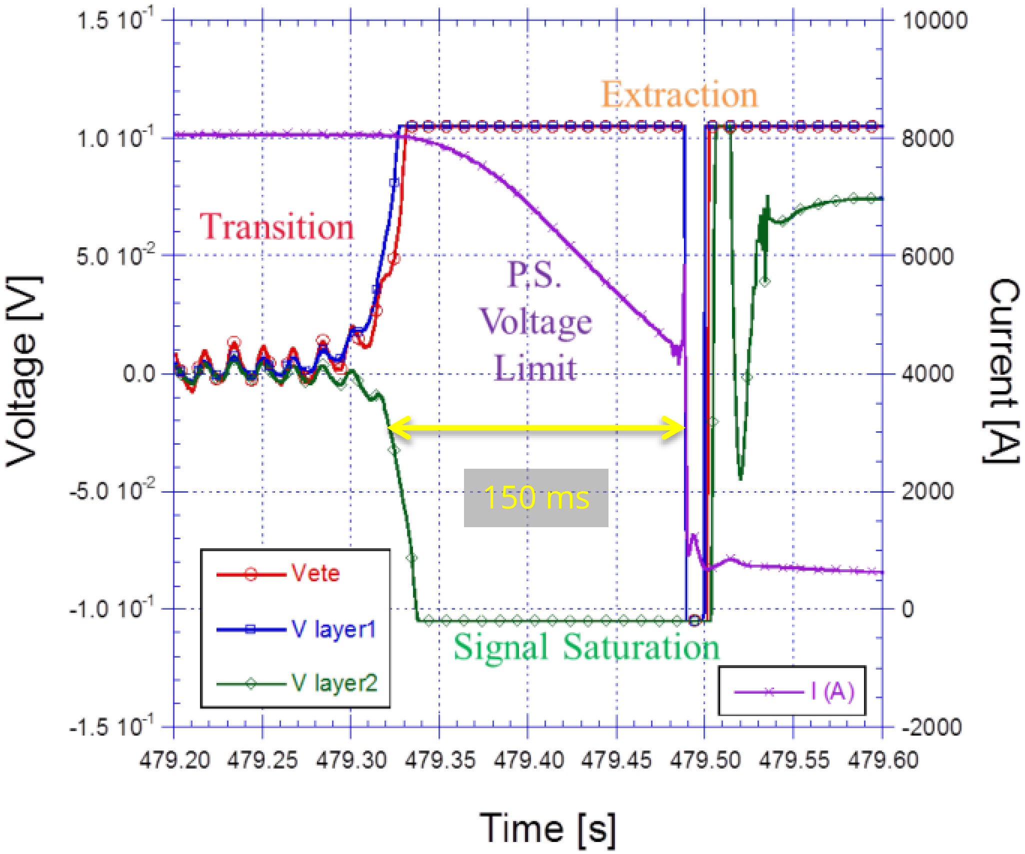


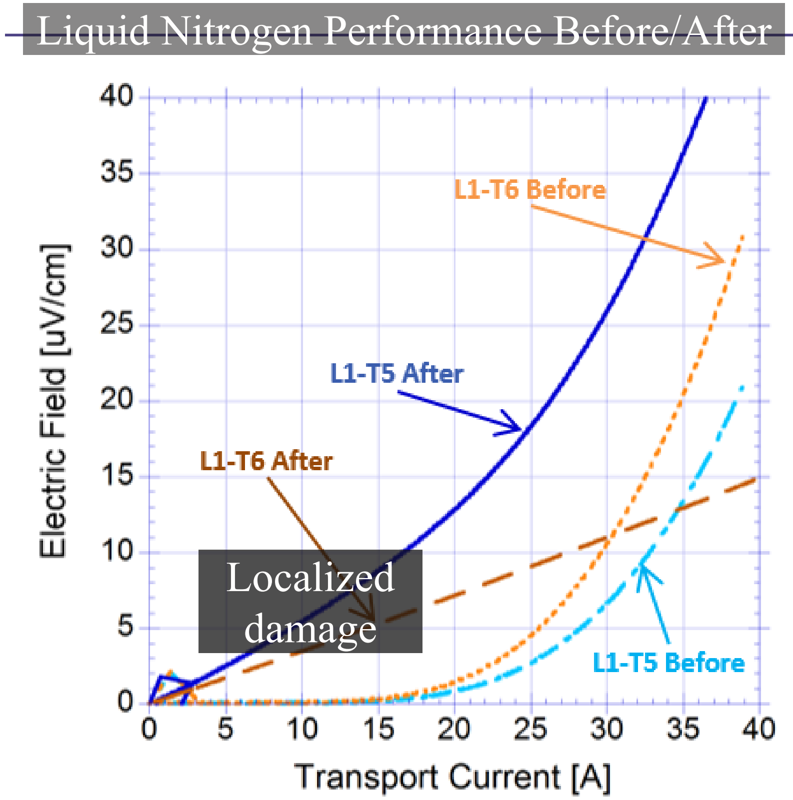
Two very different codes (ANSYS-FE, LEDET-Lumped Elem. 2D) predict similar behavior

ANSYS simulations by Lucas Brouwer (LBL)

RC5: Delayed extraction led to a high MIITs quench







- Detection system did not record a voltage rise.
  - A voltage spike 150ms after transition began tripped the energy extraction
- Simple sum of 1 kHz data $\sum_{479.3\ s}^{483\ s} I * I * 0.001s = 9.01\ kA^2s$

MIITs (Deposited Energy)

$$\int_0^\infty I^2(t)dt = A^2 \int_{T_0}^{T_{\max}} \frac{C(T)}{\rho(T)} \mathrm{dT} = \Gamma(T_{\max})$$

Adiabatic Quenched Turn Prediction

MIITs (Deposited Energy)

$$\int_0^{\infty} I^2(t)dt = A^2 \int_{T_0}^{T_{max}} \frac{C(T)}{\rho(T)} \mathrm{dT} = \Gamma(T_{max})$$

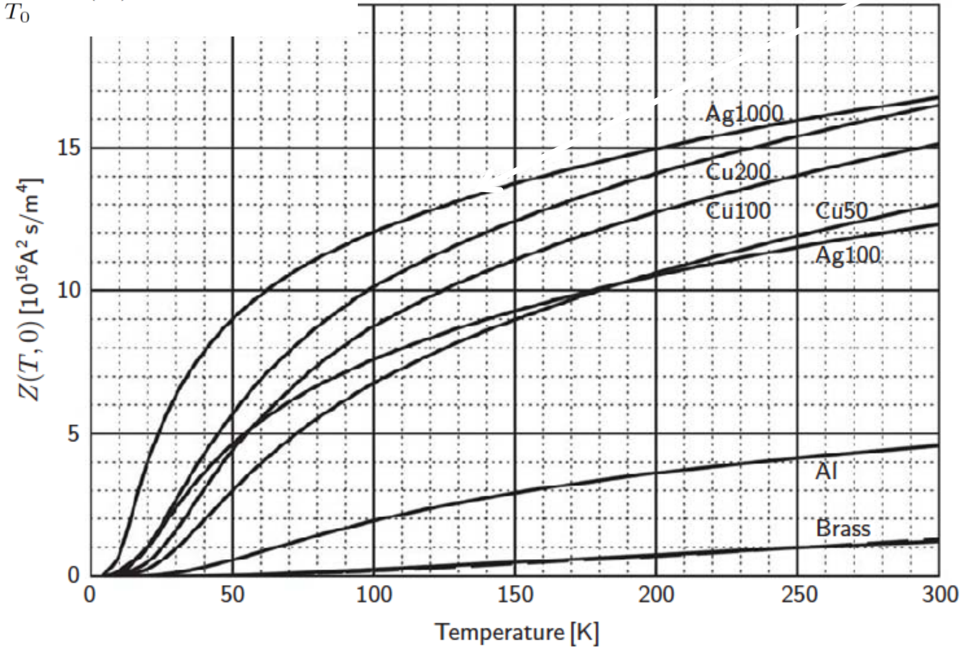
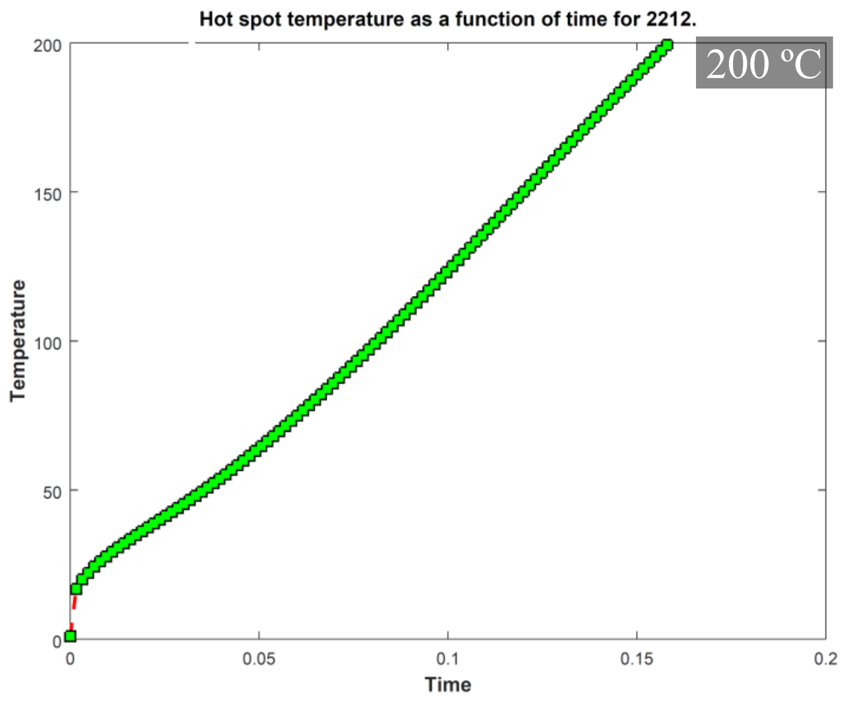


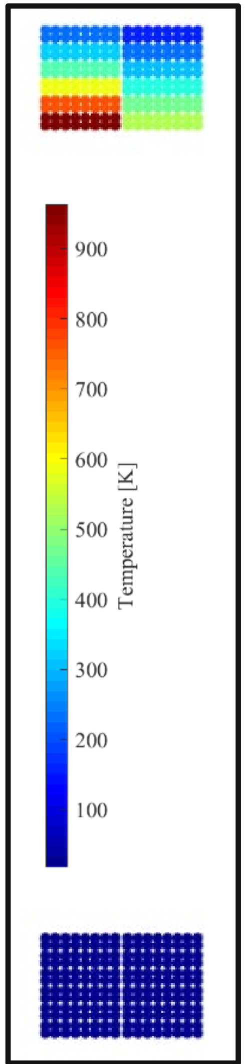
Fig. 8.2 $Z(T,0)$ plots. Ag1000 (RRR:1000); Ag100; Cu200; Cu100; Cu50; Al (Grade 1100); Brass (70Cu-30Zn)—also dashed line (Eq. 8.10*b*, with $\tilde{\rho}_m = 5.5\times10^{-8}\,\Omega\,\mathrm{m}$).



Calculates the Z-function of a typical Ag-sheathed
Bi-2212 round wire with a superconductor area ratio of 21% and a packing density as 100% inside 2212 filaments (50 bar HT OP samples)

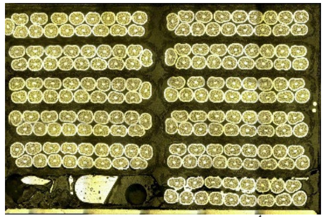
Current drops linearly from 470 A per strand (7990 A cable) to 265 A (4505 A cable)

Implementation: Localized damage can be simulated with quench propagation and current sharing

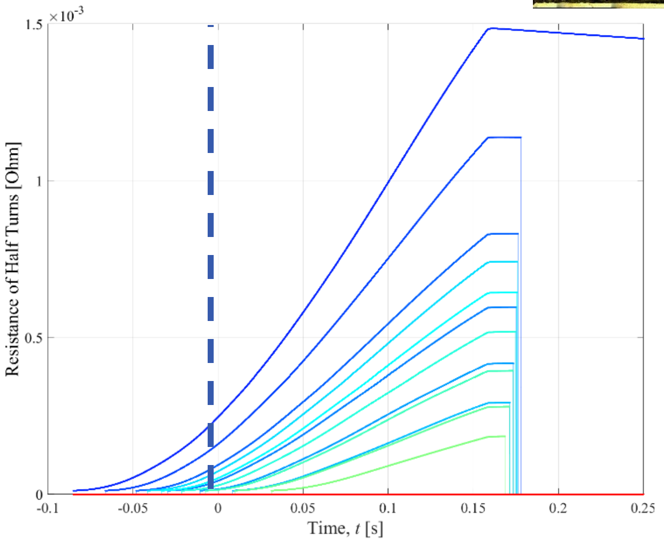


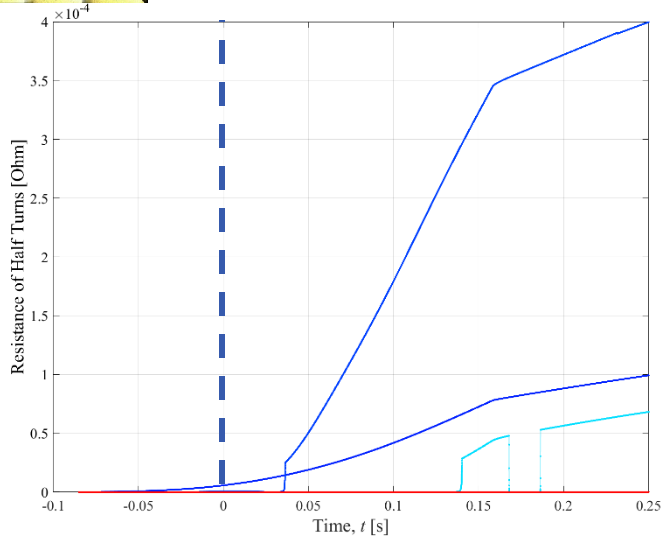
No Current Sharing or Quench Propagation

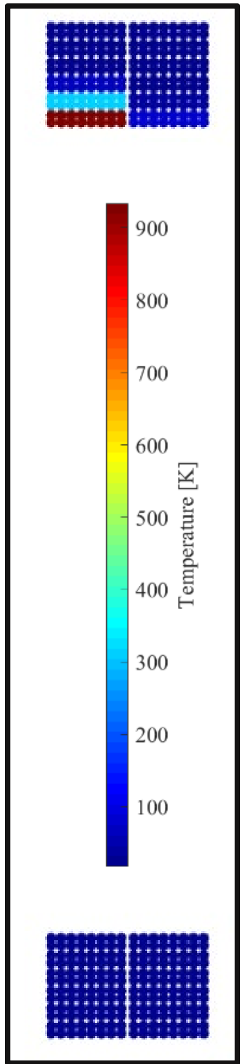
RC5 High MIITs Quench
1 turn quenches at -85ms



With Current Sharing and Quench Propagation





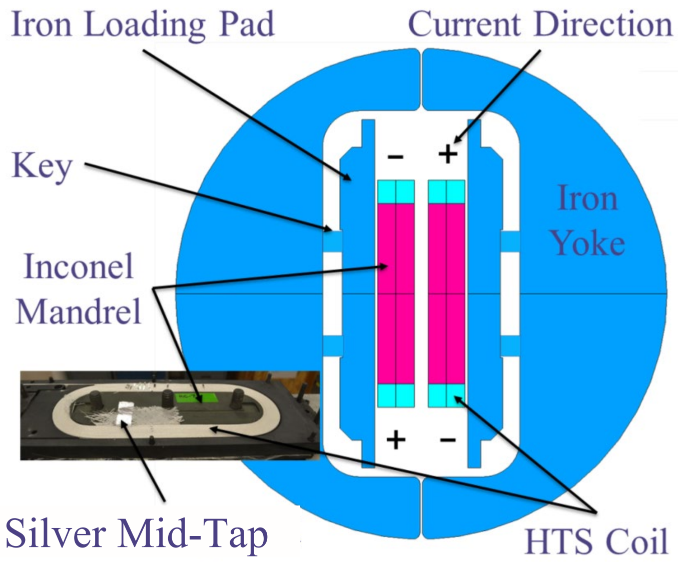


Lower voltage rise before time 0

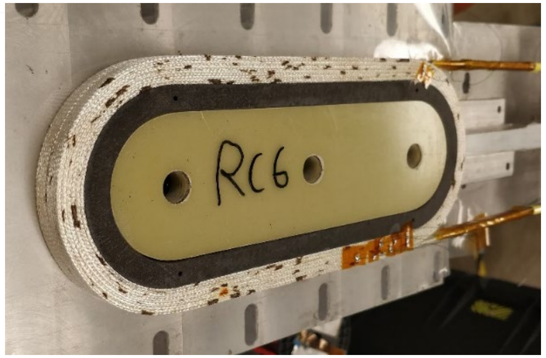
Turns Quench All at Once

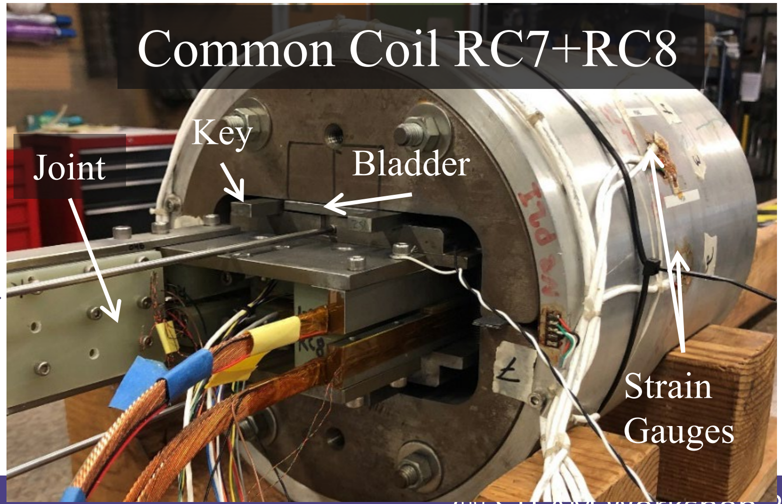
NZPV 3 cm/s
Initial Quench Spot 1 mm

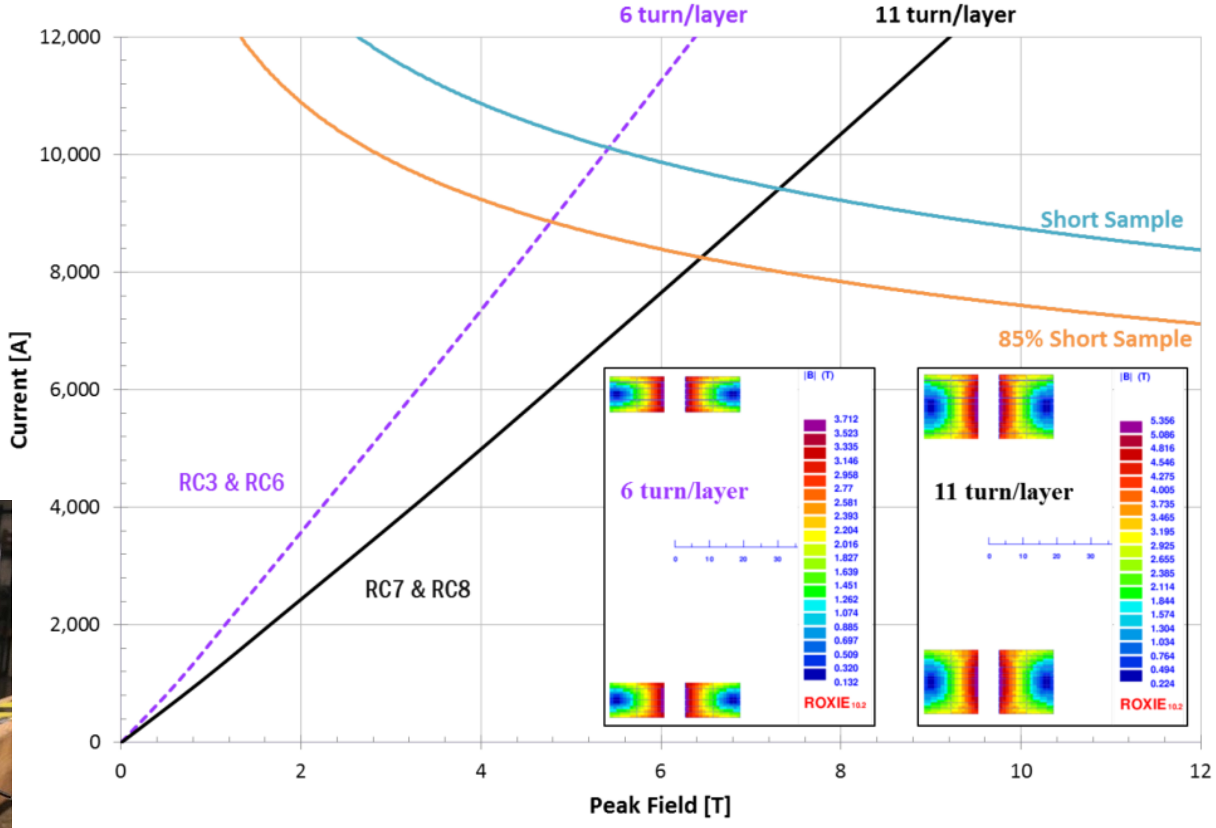
Mid-scale Magnets: RC7+RC8 Common Coil as a Quench Test-bed



Double Pancake Windings





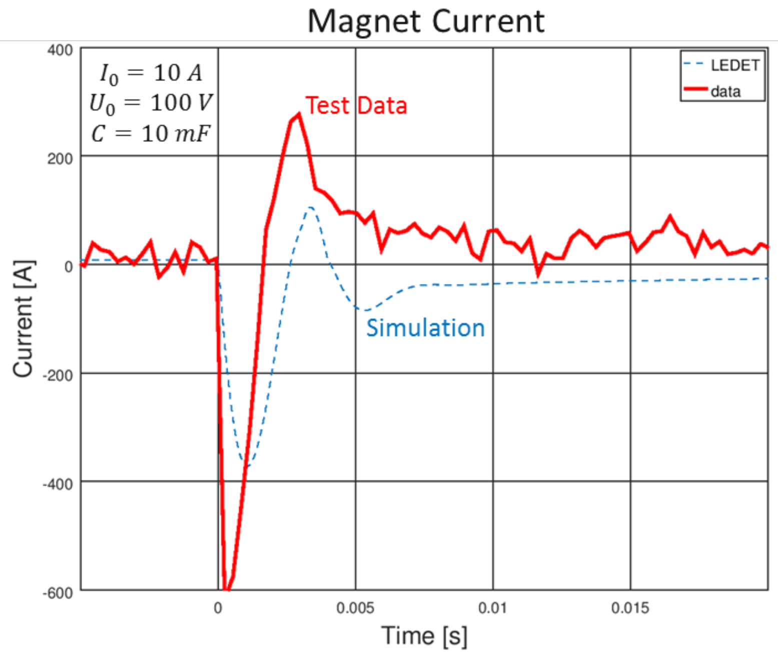


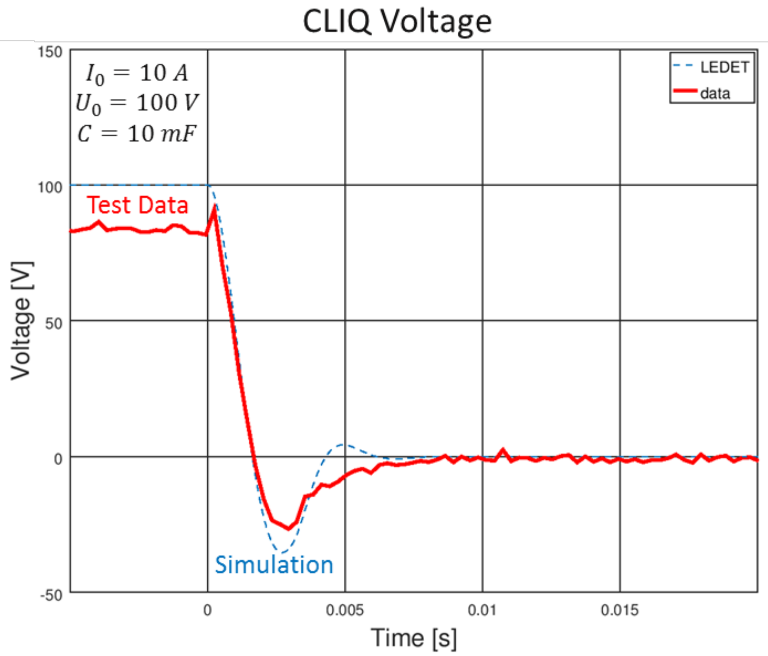
In Collaboration with Tengming Shen (LBL)

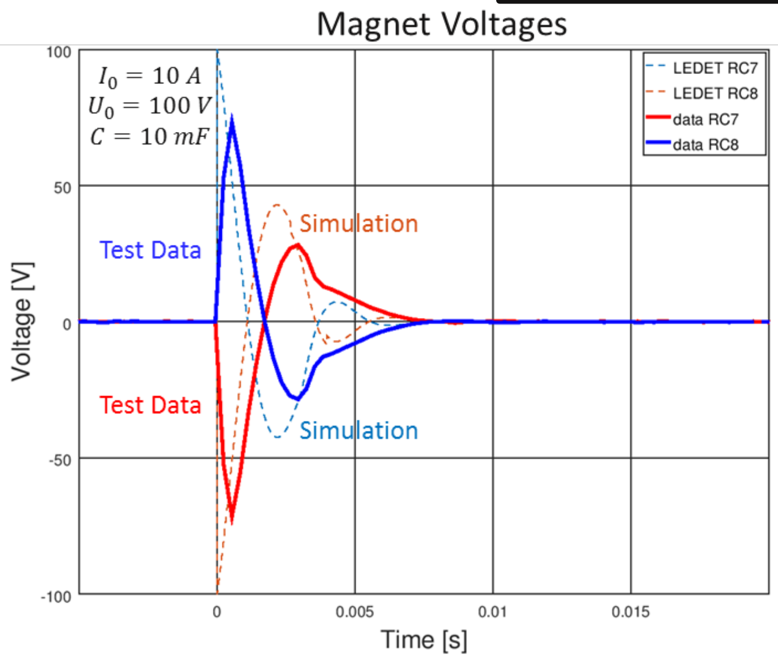
LBL-CLIQ Demonstration on RC7n8 Common Coil Dipole at 77 K

CLIQ: Charged C → RLC Oscillation → dB/dt → Heat (Current Sharing) → Quench

$E_0 = \frac{1}{2} C U_0^2$ | $I_{CLIQ} = -U_0 \sqrt{\frac{C}{L_{eff}}} \sin(\omega t)$ | $\frac{dB}{dt} \propto \frac{dI_{CLIQ}}{dt} \left[1 - e^{\left(-\frac{t}{\tau}\right)}\right]$ | $\frac{P_{IFCL}}{vol} \propto \left[\frac{dB}{dt}\right]^2$ | $T > T_{CS}(T_C, I)$, $\rho_{wire} \rightarrow \rho_{Ag}$



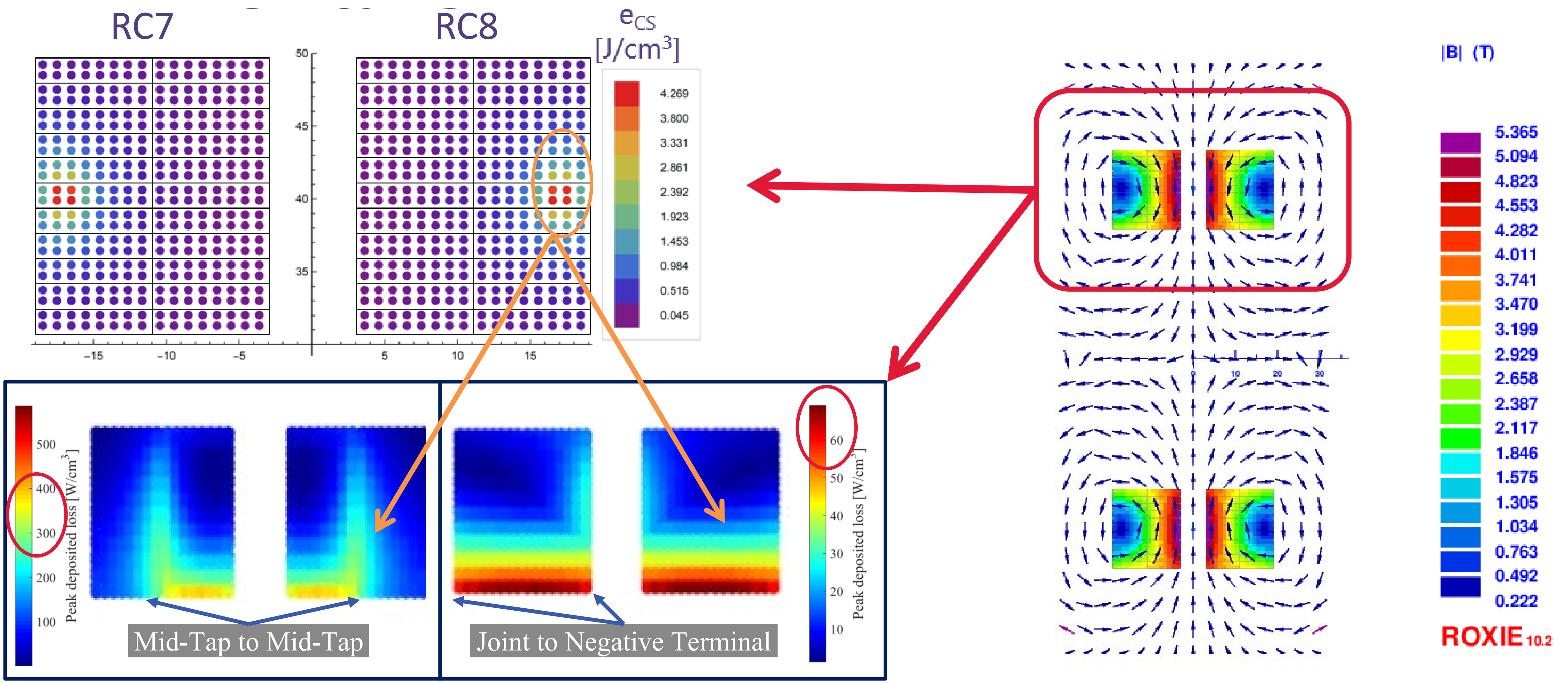




- First CLIQ testing of a Bi-2212 dipole.
- LEDET simulation matches reasonably with measurement.
  - Rapid decay due to dynamic inductance replicated

Further Testing Disrupted by COVID

Analytics: Controlling CLIQ Heat Deposition with Mid-Taps

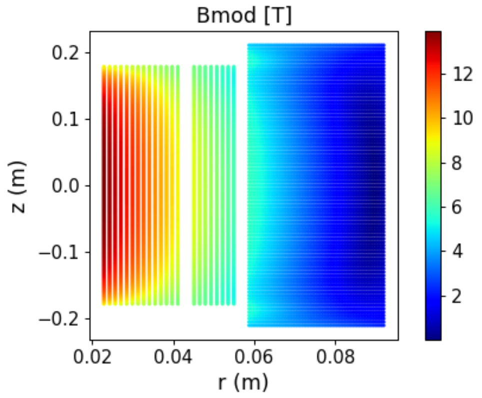


Large Scale

- Validate parameters with reduced height models
  - Get a model to run with basic settings
  - Reduce physics to simple cases
  - Add back in behaviors
  - Electrical order and voltage checks
- Debug scale up settings
  - time-steps, thermal connections, memory limits
  - Implement the most realistic case possible, with circuit details
    - Power supply configurations (diode, crow-bar, voltage limits)
    - Prepare for STEAM integration (P-Spice for a start)

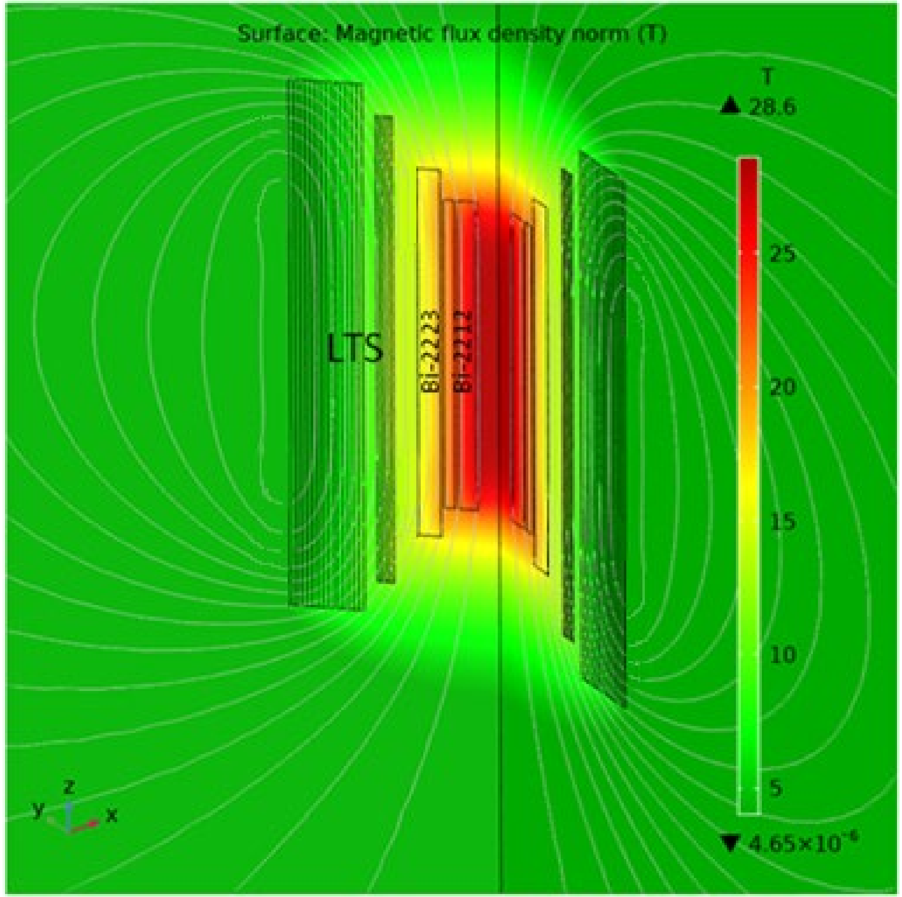
Full-Scale Systems: Ultra-High-Field NMR System Design

- HTS coils in series
- Single strand winding
- Aiming for < 1 ppm spatial stability.
- Expect very good temporal stability



Python Notebook Input Generation

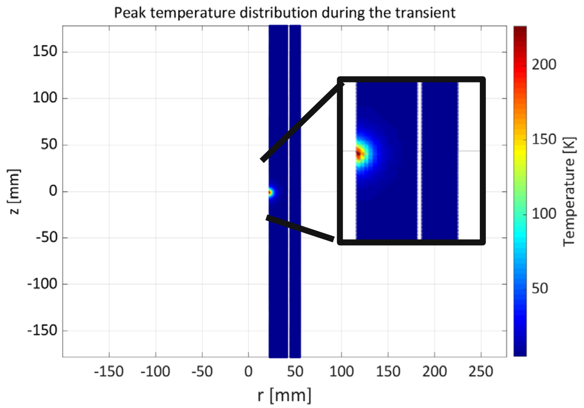
Bi-2212 and Bi-2223 Insert Coil Design for 28.2 T / 40 mm Bore UHF NMR Magnet System		
Bi-2212 Coil #1	a1; a2; z1; z2 [mm]	22.2; 40.5; -178.6; 178.6
	Turns	3920
	Field [T]	5.17
	wire length [km]	0.77
Bi-2212 Coil #2	a1; a2; z1; z2 [mm]	44.45; 55.3; -178.6; 178.6
	Turns	2240
	Field [T]	2.89
	wire length [km]	0.71
Bi-2223 Coil	a1; a2; z1; z2 [mm]	58.5; 81.4; -212.5; 212.5
	Turns	5767
	Field [T]	6.16
	wire length [km]	2.6
HTS Section Current [A]		380.5
Store Energy [MJ]		< 3 (~0.5 MJ in HTS)

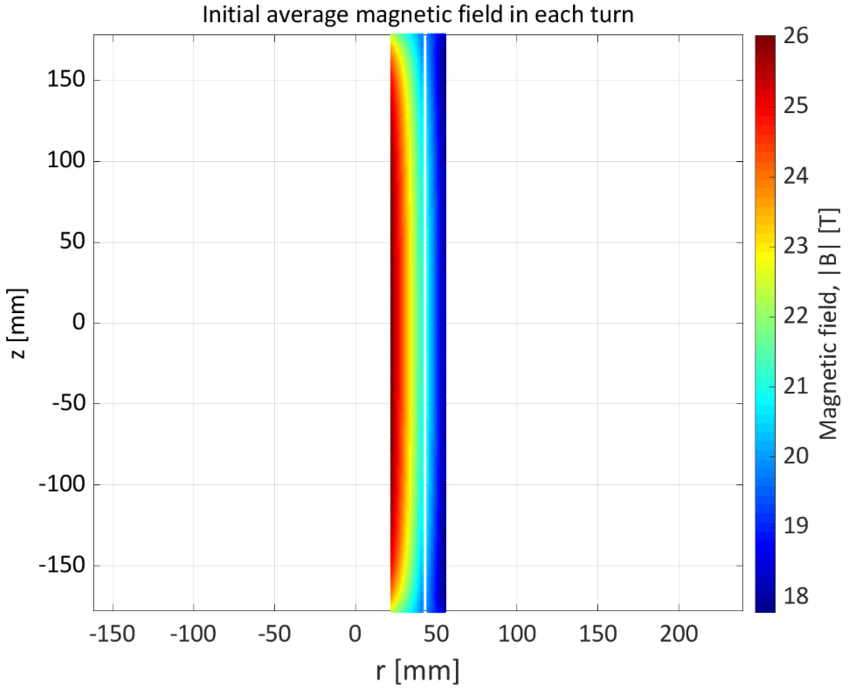


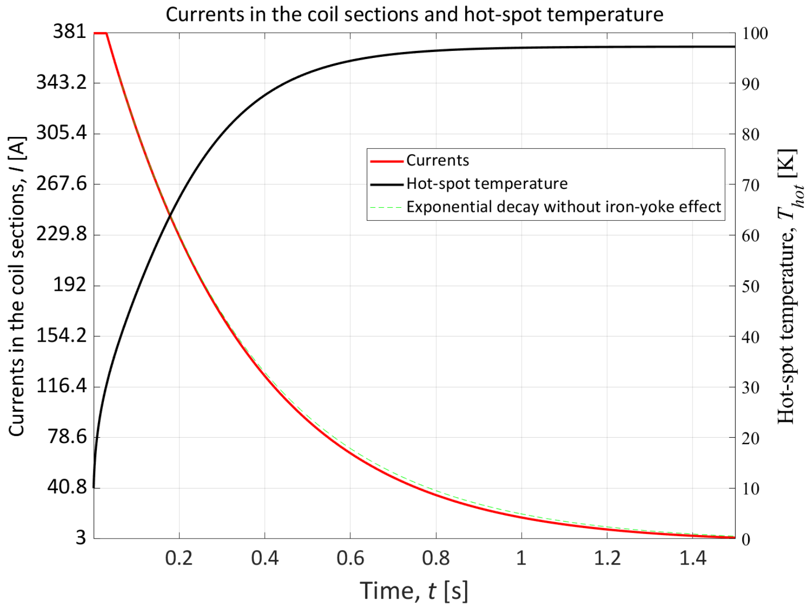
NATIONAL MAGLAB ASC

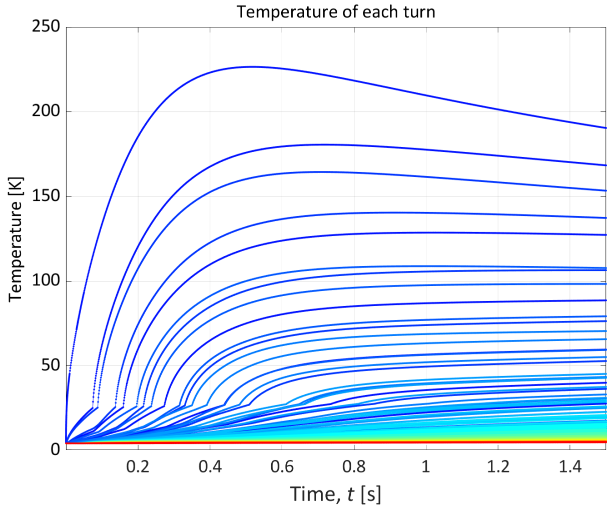
LEDET, Basic EE of Bi-2212 Section

- 18.6 T constant background By
- 30 ms detection + validation time
- < 500 V, EE resistor (1.25 Ohm)



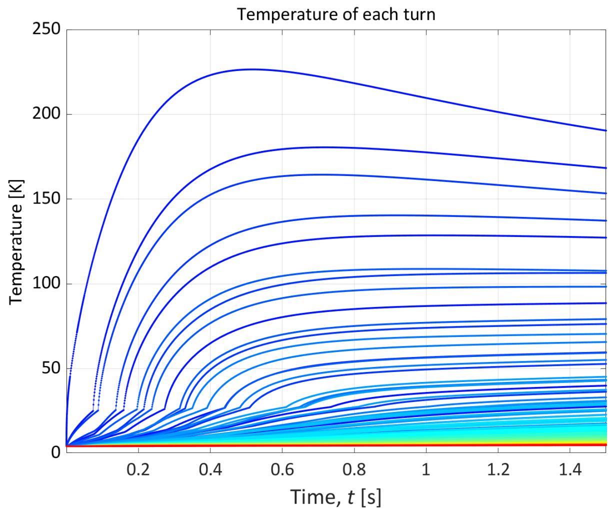


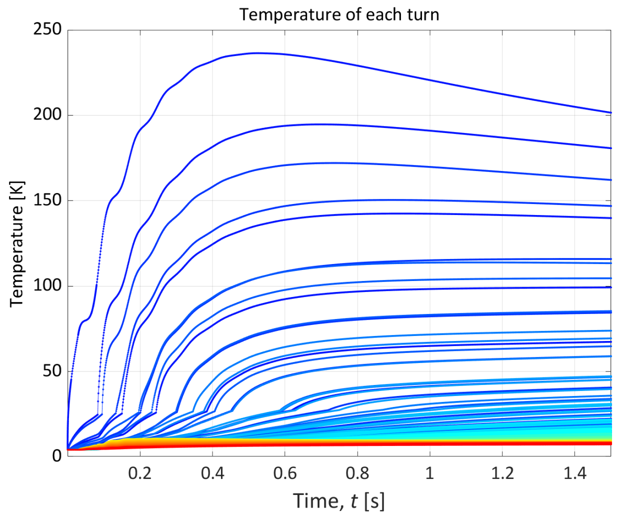


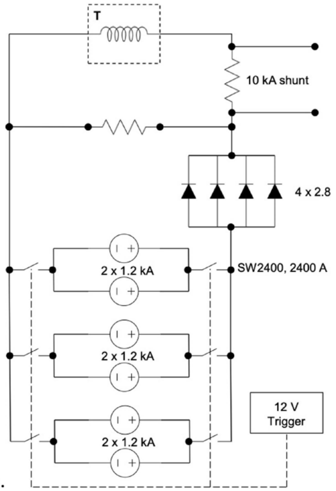


Quick to Eliminate Cases

- No significant benefit from single 10 mF, 500 V CLIQ unit at Coil joint
- Ran cases with/without IFCC, heat exchange, and crowbar extraction to look for expected behaviors
  - tracked down an implementation problem with long twist pitch to simulate untwisted wire
  - Reduced the crowbar resistance and diode voltage to match our system with a passive dump resistor and PS contactors







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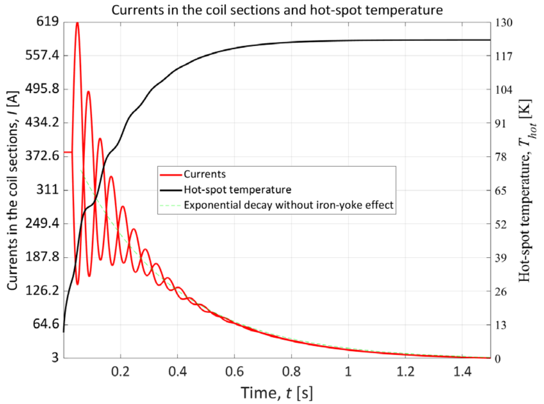

Next Steps: There’s plenty more HTS fun to be had!

For this full-scale UHF-NMR model:

- Build a LEDET for Bi-2223 section sperate and with 2212 sections
- Build a SPICE model for the HTS +LTS circuit
- Run a STEAM simulation to include the inductive coupling to the LTS
- Program a varistor element into SPICE to replicate a Metrosil SiC energy extraction unit
- Run subdivision cases with both resistors and varistors