U.S. MAGNET DEVELOPMENT PROGRAM

Data-Driven Quench Detection Via Current Redistribution Monitoring in Bundled CORC® Cables

May 11, 2022

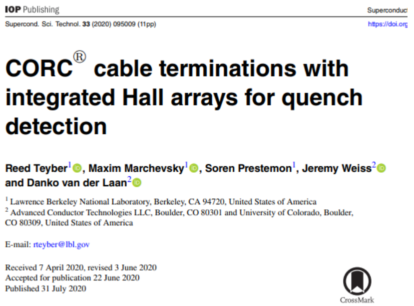
Reed Teyber, Maxim Marchevsky, Lucas Brouwer, Soren Prestemon, Jeremy Weiss, Danko van der Laan

Recap + Motivation

- Phase 2 FES SBIR on Hall Probe based quench detection with ACT
  - Have previously shown redistribution measurements for individual CORC wires and CORC CICC
  - We have a deliverable of “Development of algorithms for producing quench signals” which motivated todays work

- MDP Collaboration meeting 2022
  - Outlined need for extracting cable parameters in context of quality control
    - “REBCO magnet tests are operating blind”
  - Outlined potential model-based quench detection

- Today
  - Outline results of a methodology that can provide quality control, test planning and real-time protection in cables with poor current sharing
    - i.e. 6-around-1, ribbon,…



IOP Publishing Supercond. Sci. Technol. 33 (2020) 095009 (11pp)

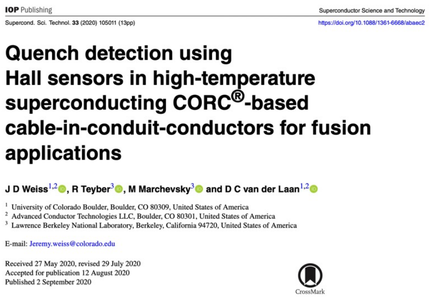
CORC® cable terminations with integrated Hall arrays for quench detection

Reed Teyber[1], Maxim Marchevsky[1], Soren Prestemon[1], Jeremy Weiss[2] and Danko van der Laan[2]

[1] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States of America
[2] Advanced Conductor Technologies LLC, Boulder, CO 80301 and University of Colorado, Boulder, CO 80309, United States of America

E-mail: rteyber@lbl.gov

Received 7 April 2020, revised 3 June 2020
Accepted for publication 22 June 2020
Published 31 July 2020



IOP Publishing Superconductor Science and Technology
Supercond. Sci. Technol. 33 (2020) 105011 (13pp) https://doi.org/10.1088/1361-6668/abaec2

Quench detection using Hall sensors in high-temperature superconducting CORC®-based cable-in-conduit-conductors for fusion applications

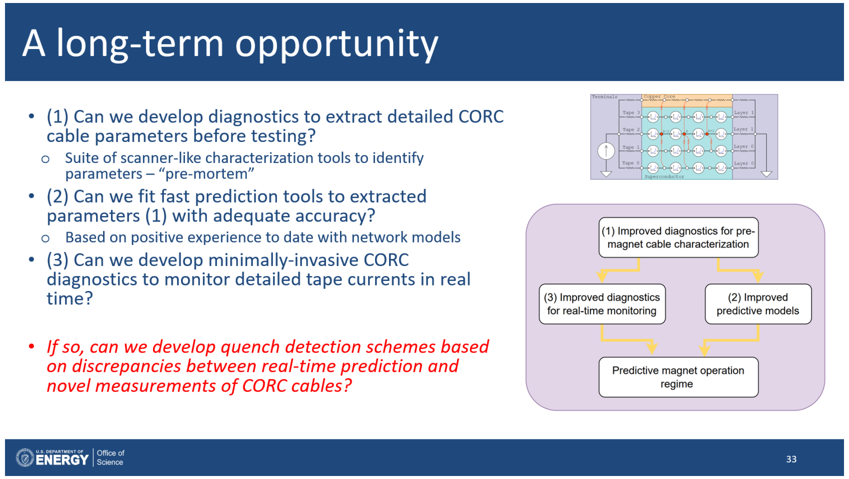
J D Weiss[1,2], R Teyber[3], M Marchevsky[3] and D C van der Laan[1,2]

[1] University of Colorado Boulder, Boulder, CO 80309, United States of America
[2] Advanced Conductor Technologies LLC, Boulder, CO 80301, United States of America
[3] Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States of America

E-mail: Jeremy.weiss@colorado.edu

Received 27 May 2020, revised 29 July 2020
Accepted for publication 12 August 2020
Published 2 September 2020

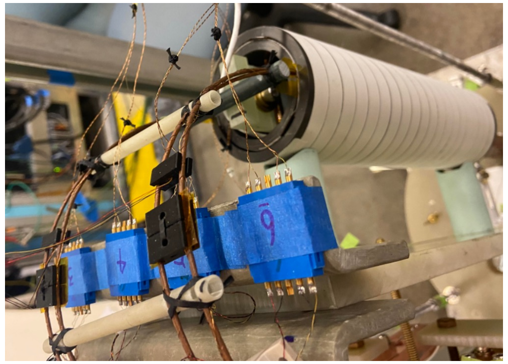
Slide from 2022 MDP Meeting



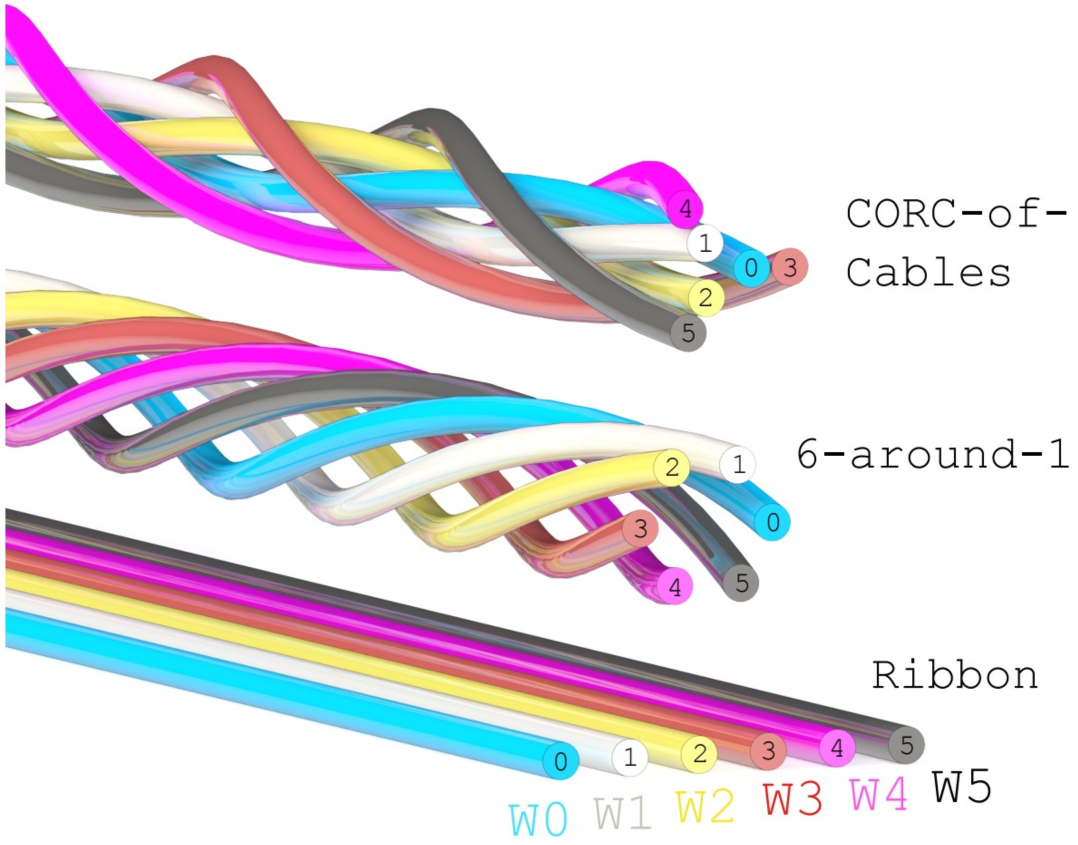
Cables with Poor Current Sharing

- Our research focus (and funding) is CORC CICC cables for fusion
  - However, "Cable-of-cable" concepts apply to HEP magnets

Xiaorong – 2 wire STAR ribbon cable CCT

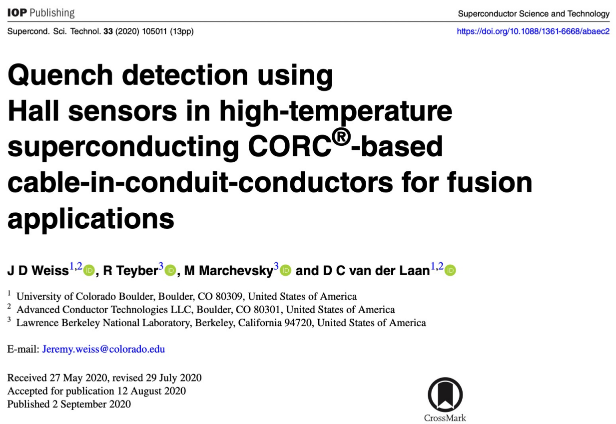


Xiaorong – 6-around-1 STAR for HEP



Previously Published Study

- Jeremy published data using 3-wire CORC ribbon cable – "triplet"
  - Comprehensive 77 K dataset with various I-V curves, ramp rate studies, heater-induced quenches
  - *This is the cable & data todays work*
- Manuscript focused on changing Hall probe signals
  - Fast and promising for slow ramp rates / static cases
    - *But how to interpret the signals to make "smart" decisions?*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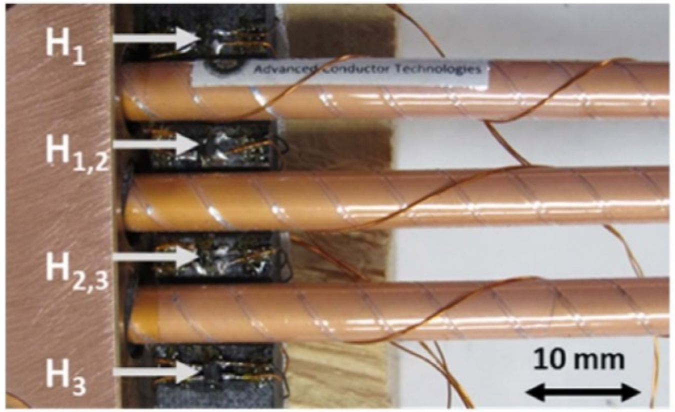
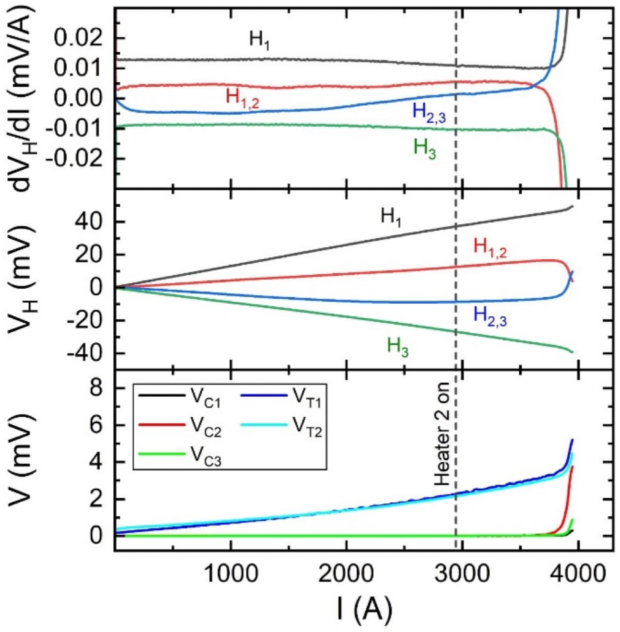


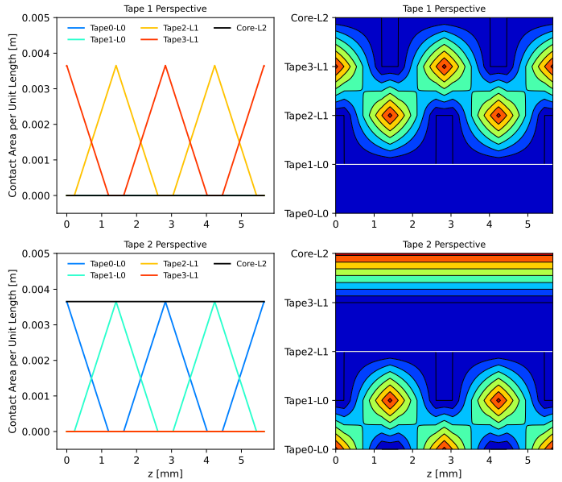


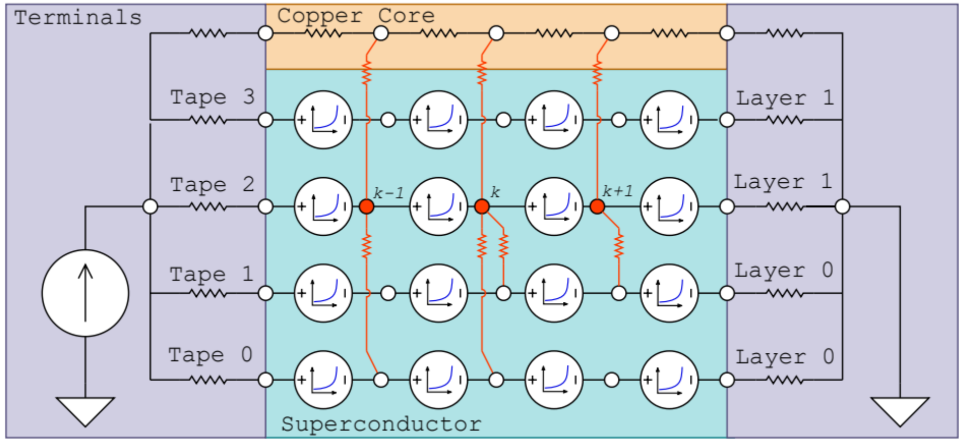
Sub-Methods

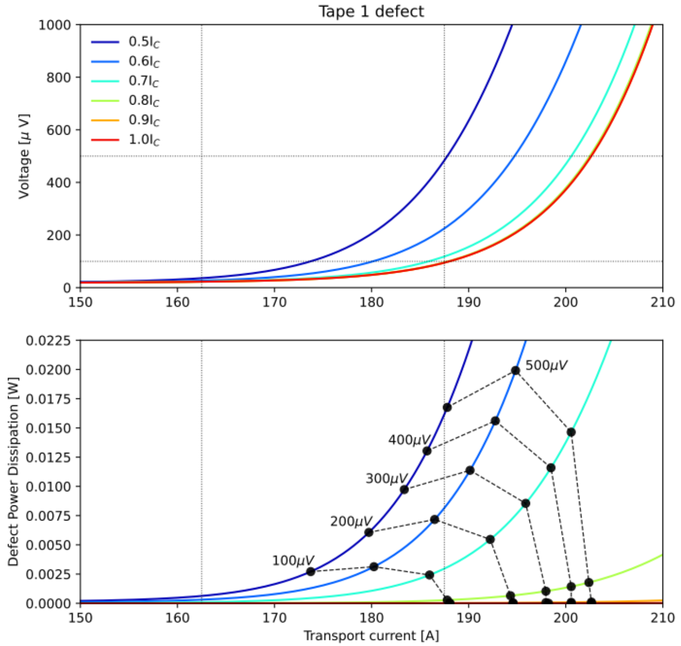
- Need to introduce two topics before getting into research method
- Predict dynamic current distributions
  - *Dynamic SPICE model to simulate current distributions*
- Measure current distributions
  - *Inverse Biot-Savart*

CORC Network Model - Methods

- Developed a static CORC network model with focus on simulating current distributions around defects
  - 10/19/2021 MDP modeling group
  - 2022 MDP collaboration
  - 04/24/2022 MDP REBCO group
  - Recently submitted manuscript, under review
- Here, thousands of differential superconductors for cable







CICC Network Model - Methods

- Develop model for CORC CICC
  - Remove current sharing
    - Allows lumping each wire as single I-V transition
  - Add dynamic capabilities
    - Neumann Integral
    - Evaluates inductance matrix for any input of discrete lines

$$L_{ij} = \frac{\mu_0}{4\pi} \int \int \frac{d\vec{\mathbf{x_i}} \cdot d\vec{\mathbf{x_j}}}{|\vec{\mathbf{x_i}} - \vec{\mathbf{x_j}}|}$$

Correction Term for L_{ii} $\mu_0 l_{wire}/8\pi$

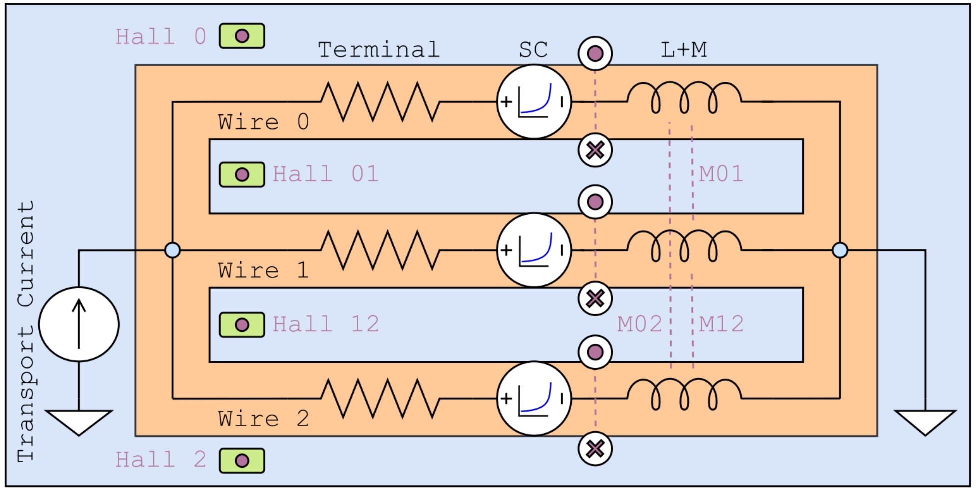
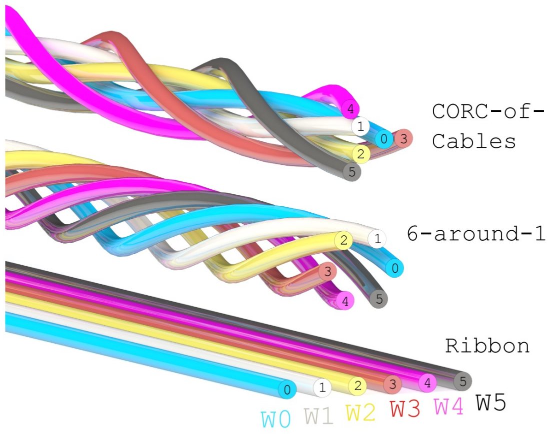


Table 3: Inductance Matrix [micro-Henry] of 6-Around-1 cable.

	W0	W1	W2	W3	W4	W5
W0	8.37	5.85	5.28	5.13	5.28	5.85
W1		8.37	5.85	5.28	5.13	5.28
W2			8.37	5.85	5.28	5.13
W3				8.37	5.85	5.28
W4					8.37	5.85
W5						8.37

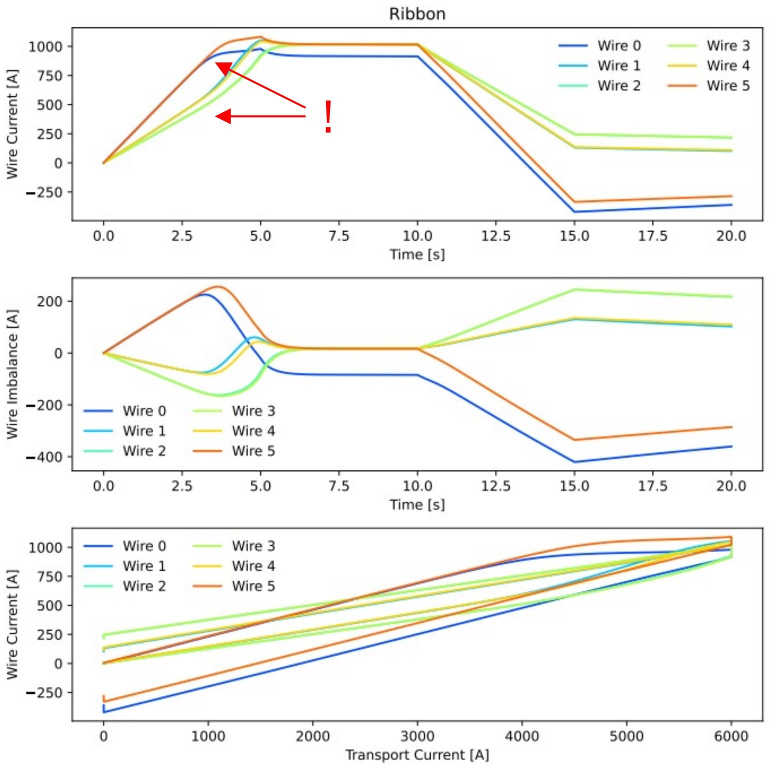
Table 2: Inductance Matrix [micro-Henry] of ribbon cable.

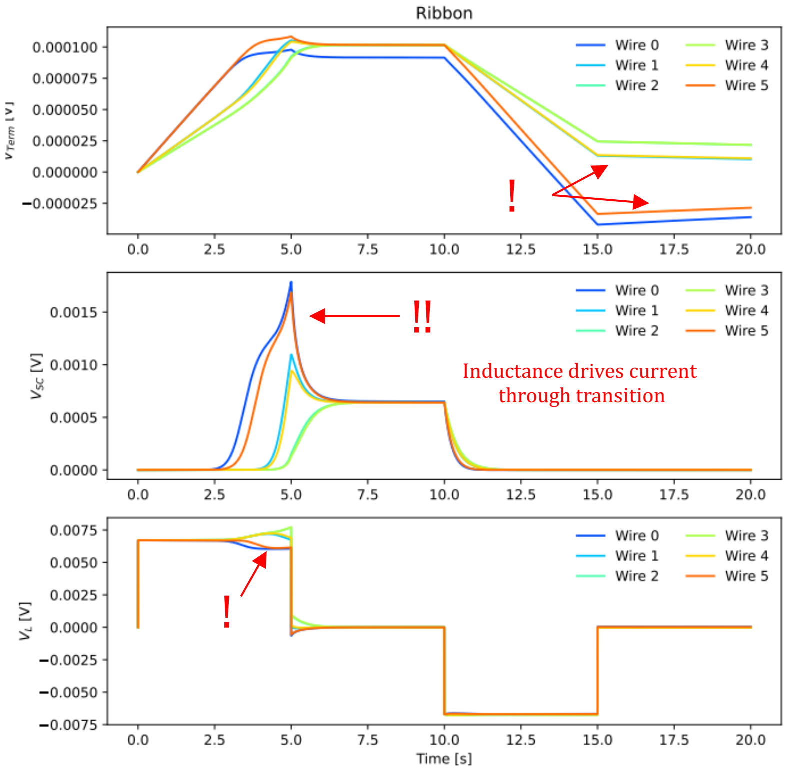
	W0	W1	W2	W3	W4	W5
W0	8.34	5.79	5.1	4.69	4.41	4.19
W1		8.34	5.79	5.1	4.69	4.41
W2			8.34	5.79	5.1	4.69
W3				8.34	5.79	5.1
W4					8.34	5.79
W5						8.34



CICC Network Model - Results

- Example dynamic simulation with a non-transposed cable
  - 5 m long, 6 wire ribbon cable, wire 0 $I_C = 900\ A$, remaining 1 kA
  - Synthetic properties here





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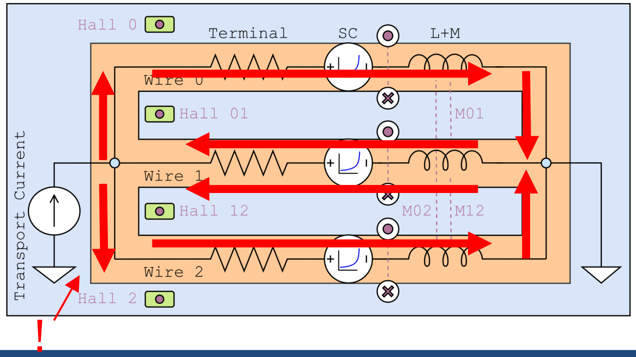
W3				8.34	5.79	5.1
W4					8.34	5.79
W5						8.34

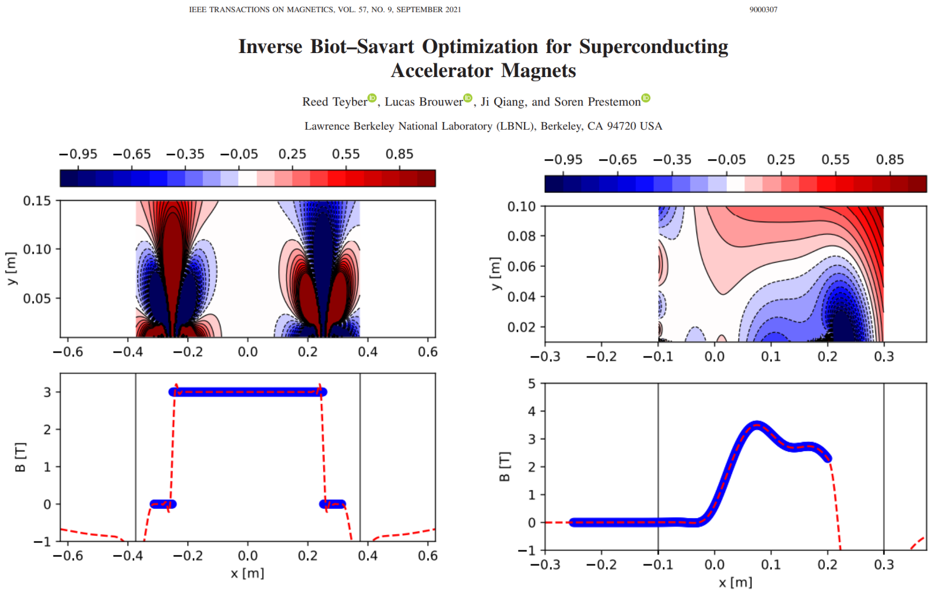


Sub-Methods

- Need to introduce two topics before getting into research method
- Predict current distributions
  - *Dynamic SPICE model to simulate current distributions*
- Measure current distributions
  - *Inverse Biot-Savart*

Inverse Biot-Savart - Background

- Cables with no current sharing can be globally described with few variables
  - *Need to recreate wire currents from terminal Hall probe arrays!*
- We previously had worked on methods to design magnet cross sections for arbitrary desired field distributions
  - Biot-Savart inversion was solved as constrained optimization problem
    - Dense, ill-conditioned matrices
- ITER used Hall probes to recreate current distributions in short sample tests
  - Used Singular Value Decomposition
  - High current sharing did not allow methodology introduced shortly



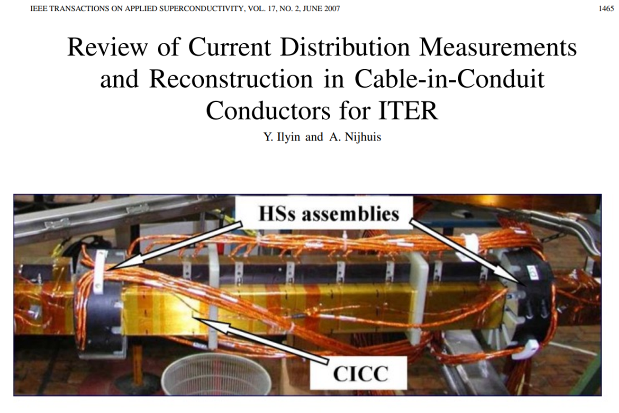
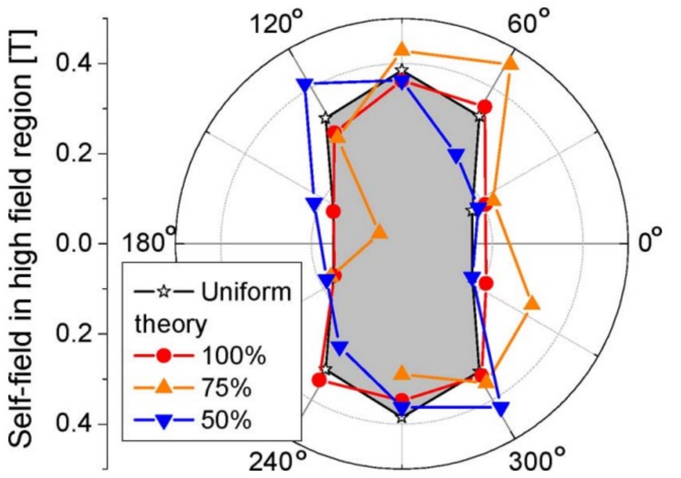
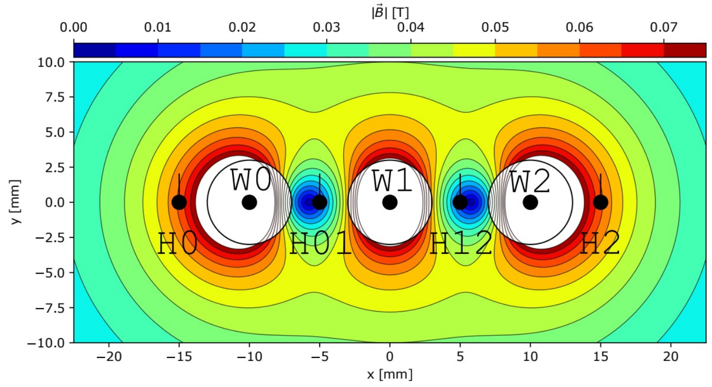


Fig. 3. HS assemblies installed on the NbTi CICC (Bus-Bar III) at FZK, Karlsruhe.



Inverse Biot-Savart - Methods

- 4 Hall probe measurements to recreate 3 wire currents
- Field at each Hall sensor is sum of wire Biot-Savart
  - Repeat for each Hall sensor - linear system Ax=b
    - A is "unitary Biot-Savart", x are currents, b are Hall probe measurements
  - Matrix is 100% dense and ill-conditioned
- Matrix system here is rectangular – solve normal equations
  - *Many possibilities for solution, depend on cable in question*
  - $A^T A x = A^T b$



$$B = \frac{\mu_0 I}{2\pi R}$$

Simple Biot-Savart evaluated along hall sensor axis, unit current

$$A^*_{k,i} = \frac{\mu_0}{2\pi |\vec{r}_{ik}|^2} < -r_{ik,y}, r_{ik,x} > \cdot < n_{k,x}, n_{k,y} >$$

$$B_{k,i} = A^*_{k,i} I_{i,z}$$

Single Hall sensor is sum of field from all currents

$$B_k = \sum_i^{n_i} A^*_{k,i} I_{i,z}$$

Each CORC Wire

Each Hall Sensor

$$\begin{bmatrix} A^*_{00} & A^*_{i0} & A^*_{n_i 0} \\ A^*_{0k} & A^*_{ik} & A^*_{n_i k} \\ A^*_{0 n_k} & A^*_{i n_k} & A^*_{n_i n_k} \end{bmatrix} \begin{bmatrix} I_{0,z} \\ I_{i,z} \\ I_{n_i,z} \end{bmatrix} = \begin{bmatrix} B_0 \\ B_k \\ B_{n_k} \end{bmatrix}$$

Currents

Field Measurements

Repeating for each Hall sensor yields matrix

Inverse Biot-Savart - Methods

- Each entry in matrix is a sensor-current line shown
  - Solving for current in triplet takes ~ 10 ms without optimization, potential for real-time
  - Focus today is on triplet, but we have applied techniques successfully on 12 wire samples

Each CORC Wire

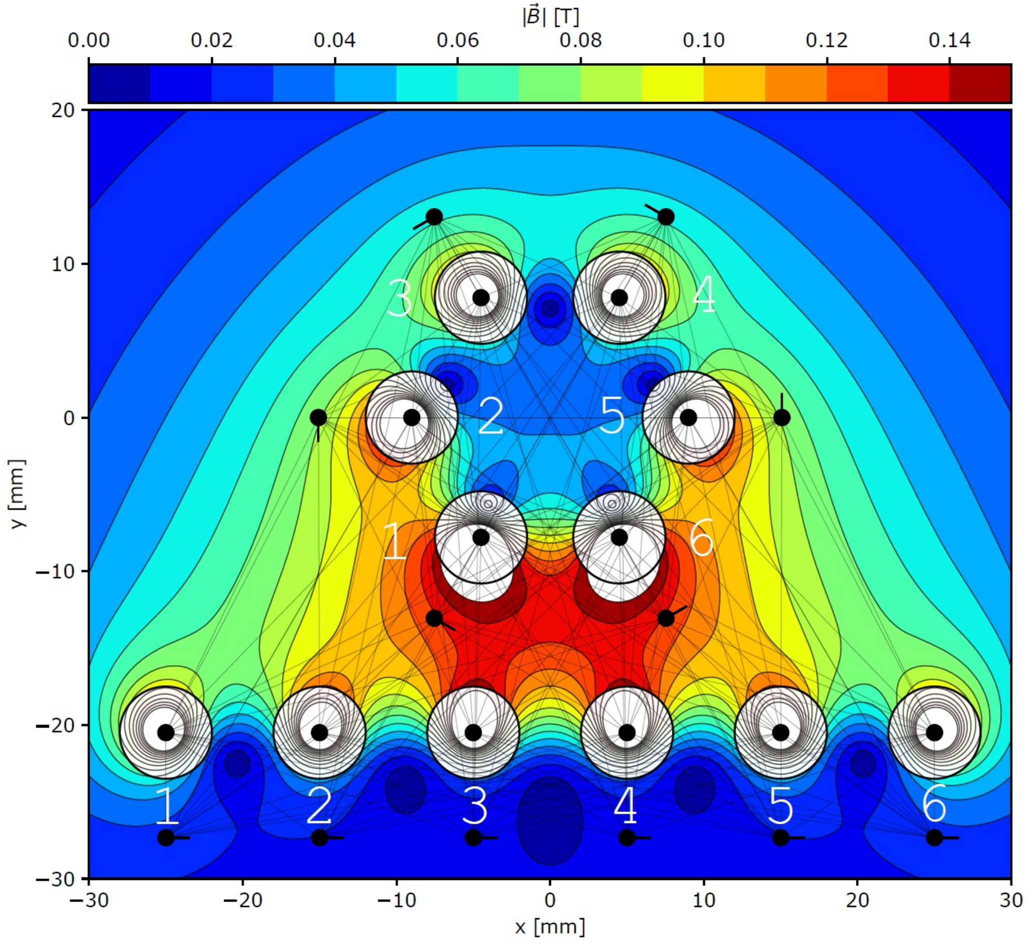
Each Hall Sensor

$$\begin{bmatrix} A^*_{00} & A^*_{i0} & A^*_{n_i0} \\ A^*_{0k} & A^*_{ik} & A^*_{n_ik} \\ A^*_{0n_k} & A^*_{in_k} & A^*_{n_in_k} \end{bmatrix} \begin{bmatrix} I_{0,z} \\ I_{i,z} \\ I_{n_i,z} \end{bmatrix} = \begin{bmatrix} B_0 \\ B_k \\ B_{n_k} \end{bmatrix}$$

Repeating for each Hall sensor yields matrix

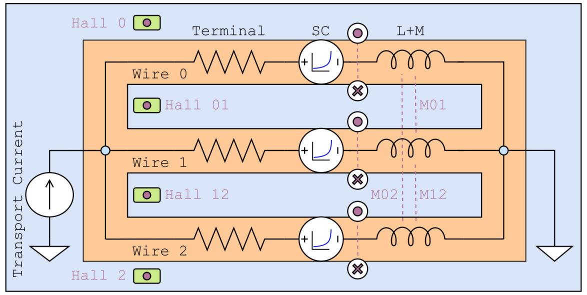
Currents

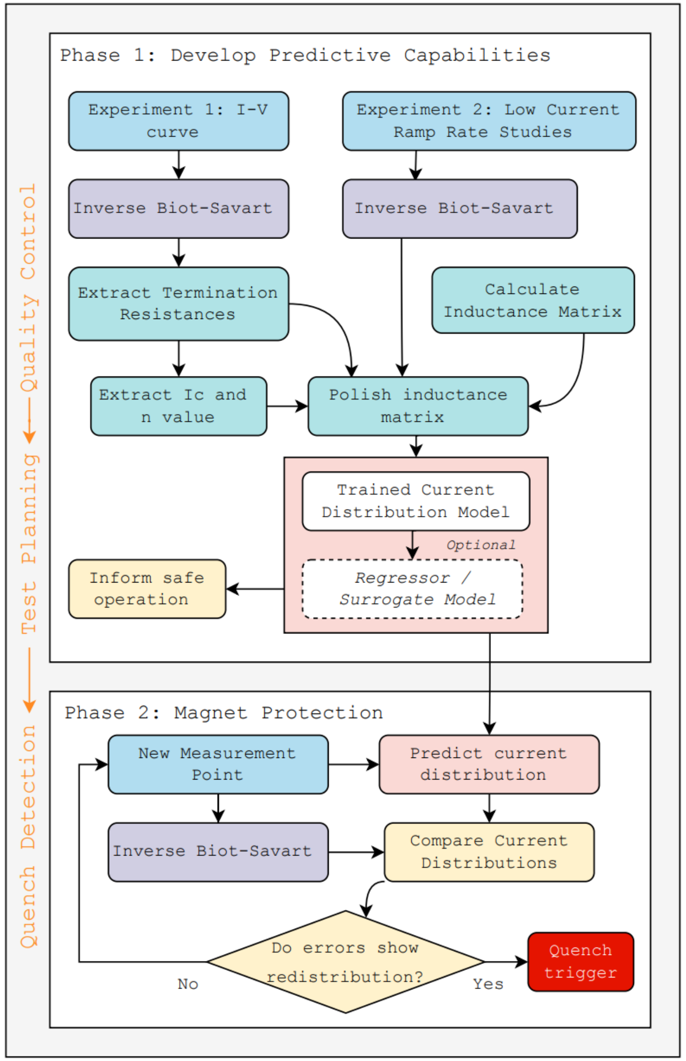
Field Measurements



The Methodology

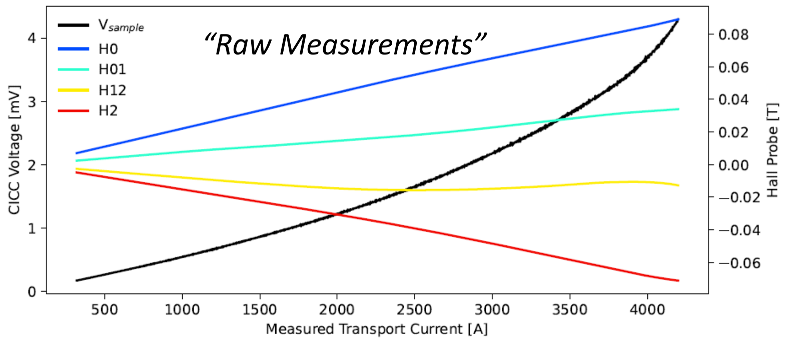
- Methods shown to:
  - Simulate current distributions
  - Recreate experimental current distributions
- ***How do we utilize this to advance magnet diagnostics?***
  - *fit model to recreated currents, use fit model to inform*



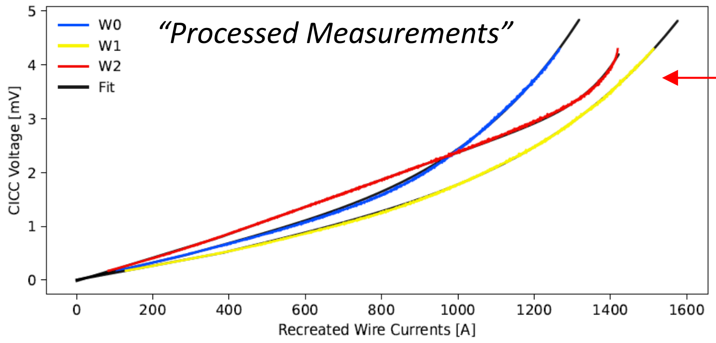


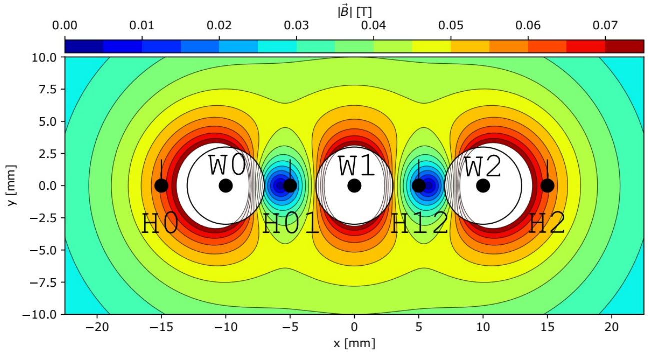
The Methodology – Parameter Extraction

- Single I-V curve with Hall probe measurements
  - Current through each wire is calculated
  - Extract all termination resistances, critical currents!
- Note – QA/QC purpose satisfied with 77 K measurement, model fitting purpose should be performed at magnet operating temp



Inverse Biot-Savart

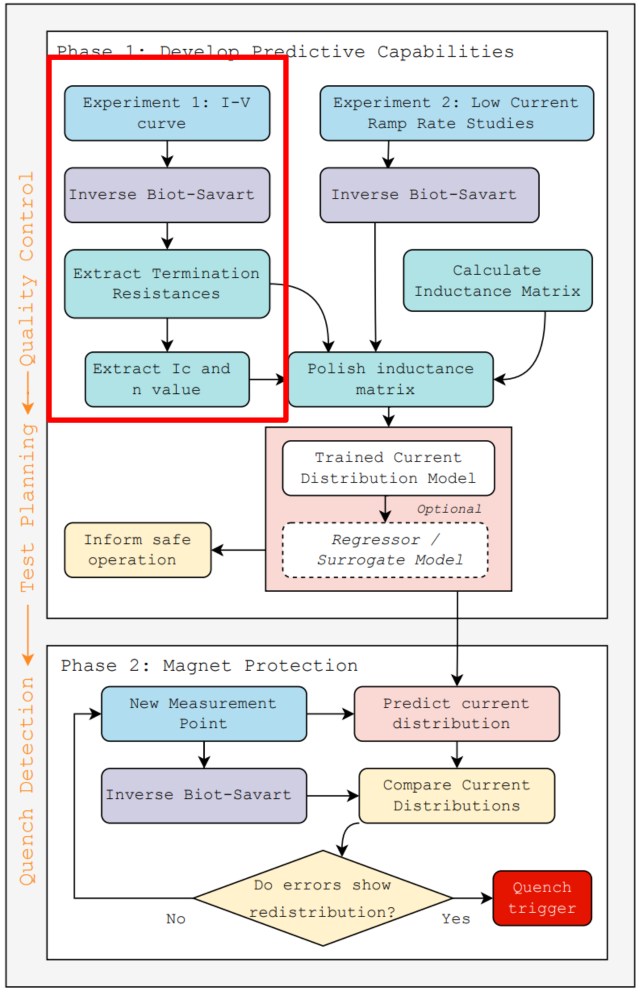




Extracted termination resistances and critical currents

Wire	$I_C[A]$	$n[-]$
Wire 0	963	5.0
Wire 1	1146	4.8
Wire 2	1385	16.4

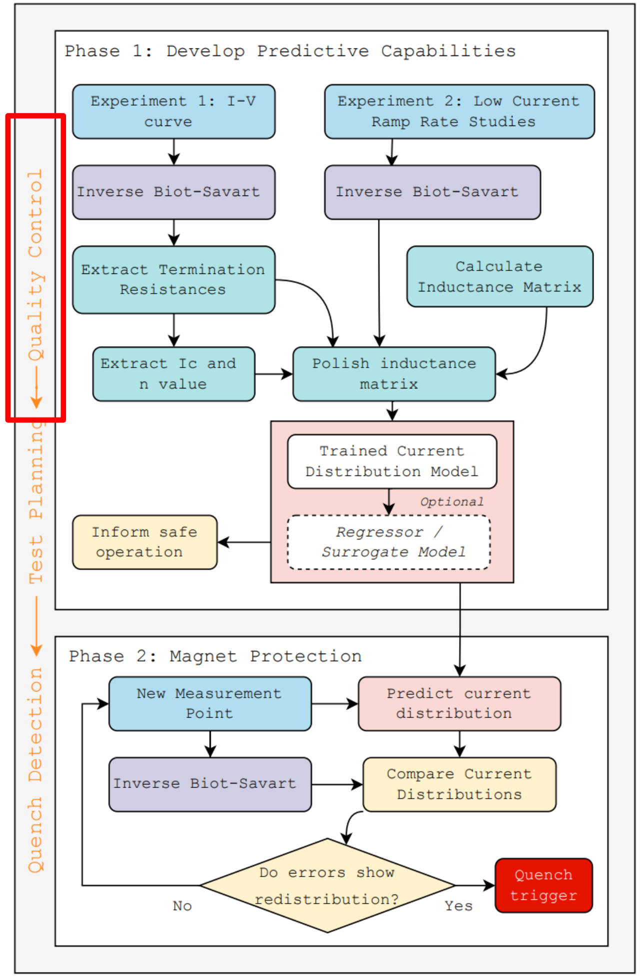
Wire	$I_{thresh}[A]$	$R^{<}_{term}[\mu\Omega]$	$R^{>}_{term}[\mu\Omega]$
Wire 0	320	1.63	1.93
Wire 1	377	1.30	1.64
Wire 2	313	2.07	2.50



Disclaimer – "upstream" voltage includes bus bar resistance (intentionally)

The Methodology – Quality Control

- This could be very useful for quality control
  - Single measurement yields entire distribution of termination resistances, critical currents in "final configuration"
- A low quality joint can be identified and fixed before operating the magnet in a dangerous regime
- A damaged wire from bending can be identified and used to re-define safe operating limits
- This information gives insight into how test can be safely performed
- This can be repeated on a periodic schedule to track changes in performance over time

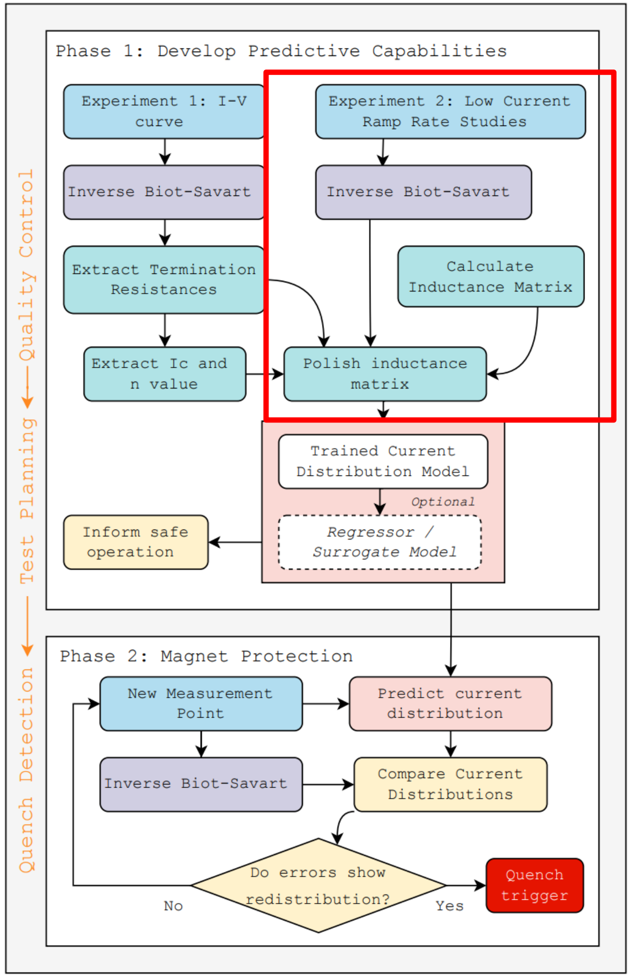


The Methodology – Dynamic Treatment

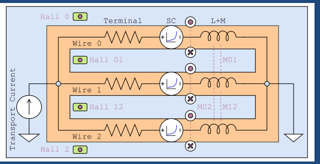
- Need to feed inductance matrix into fit predictive model
  - Difficult to extract all elements of inductance matrix from experiments
  - Line treatment of CORC wires makes analytical calculation "imperfect"
- Proposed methodology:
  - Calculate inductance matrix analytically
  - Run optimization problem to "polish" values to **low-current** ramp rate experiments
    - Optimization variables: allow wire locations and wire lengths to vary by ~ 10 percent
    - Optimization objective: L_2 norm of error between spice model and experiment
  - Was found to make small difference here, but will help with larger inductance magnets
    - Also helps tune the L/R decay when the "R" doesn't fully capture induced current paths through bus bars

	W0	W1	W2
W0	0.53	0.37	0.29
W1		0.52	0.35
W2			0.51

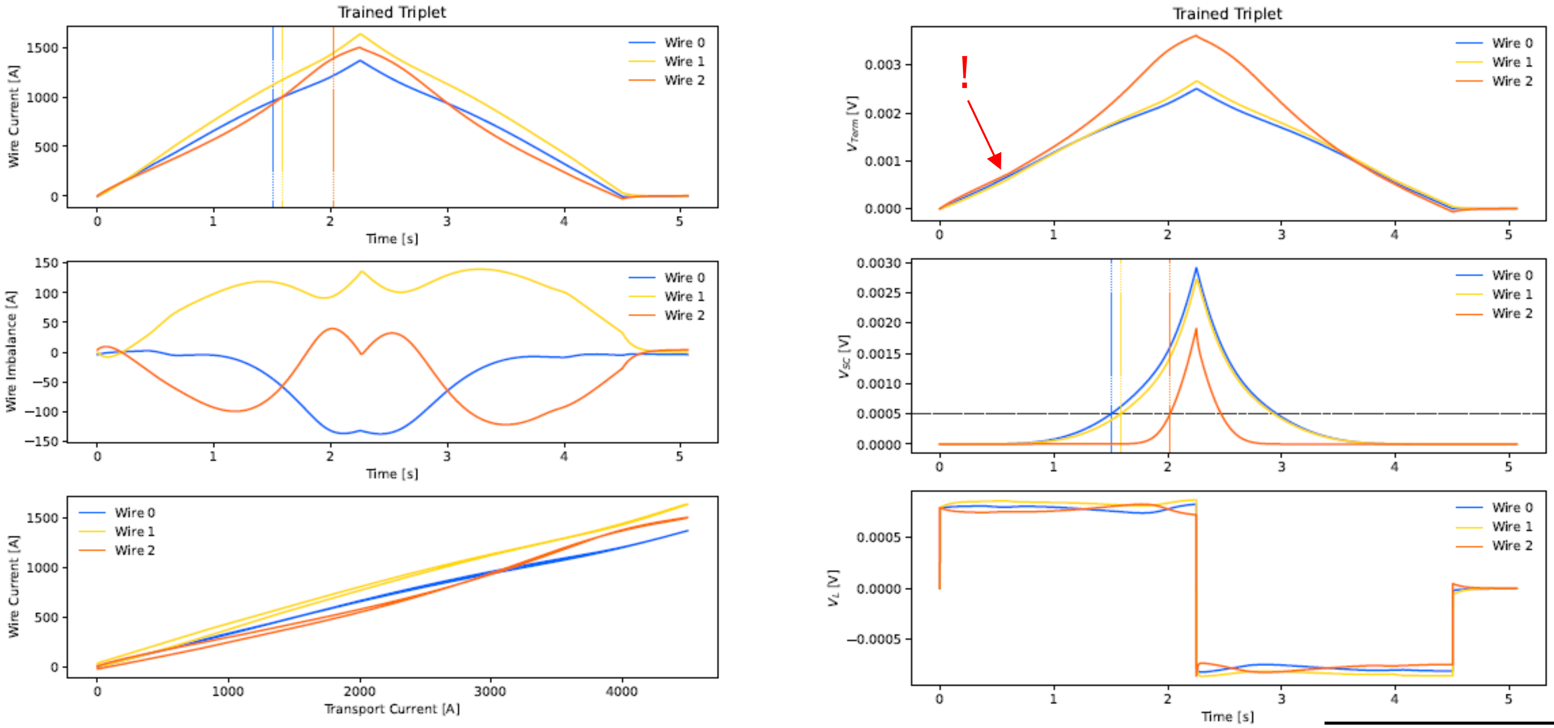
[micro-Henry]



The Methodology – Test Planning



- We now have all the parameters required to simulate the *actual* sample!
  - Trained model below shows when I_C criterion in each wire is reached at fast ramp rate of 2,000 A/s
  - Defines safe operating parameters and limits before operating magnet
  - *Note – none of this information is typically available to magnet operators!*



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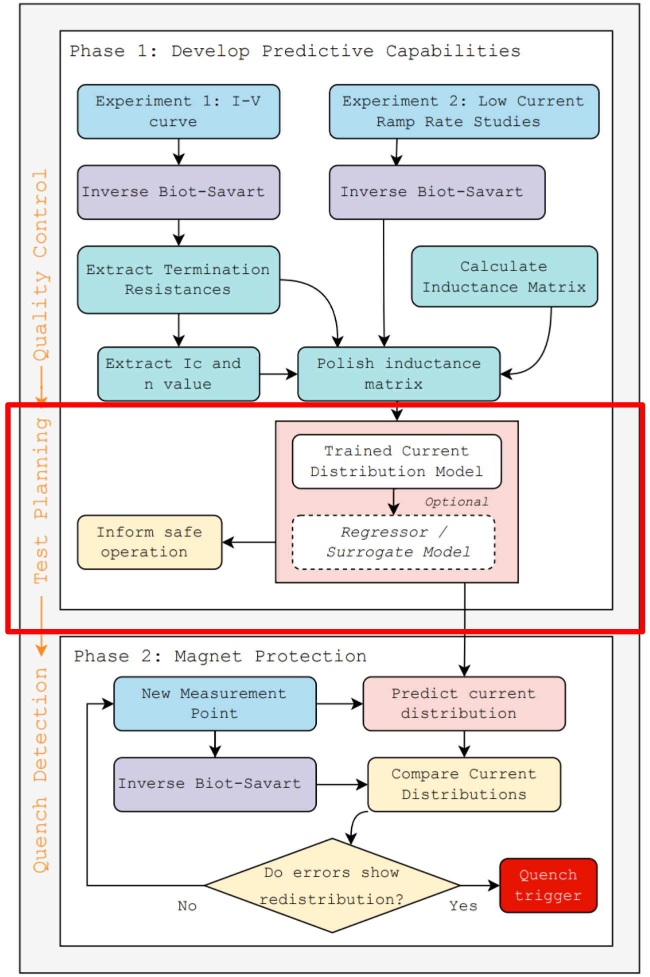
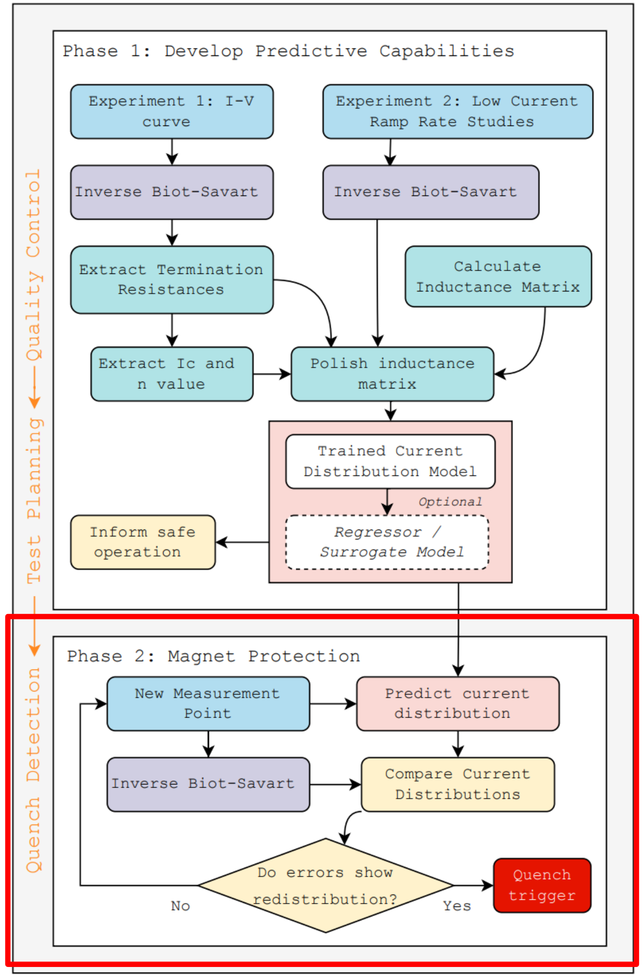


The Methodology – Quench Detection

- **Compare simulated current distributions with inverse Biot-Savart recreated current distributions in real time**
  - Generate quench trigger when they disagree
  - i.e. "current redistribution monitoring"

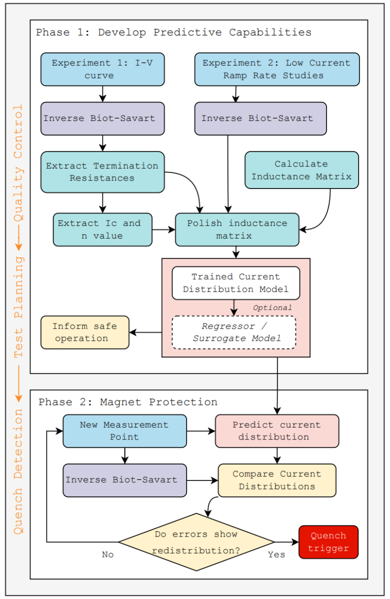
- False positive quenches greatly reduced by:
  - Look for error *rates* – rapid departures between measurements and prediction
  - Look for signatures of redistribution – if threshold is hit in one wire, require increasing current in remaining wires
  - Require violation to occur for several data points in a row

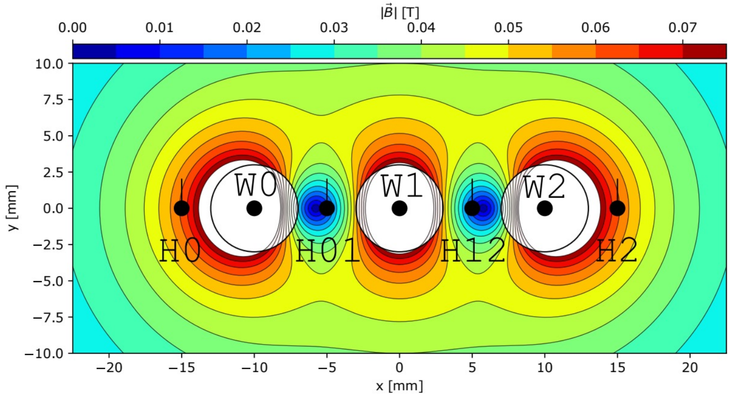
- Work today applies to magnets with pre-defined current waveforms

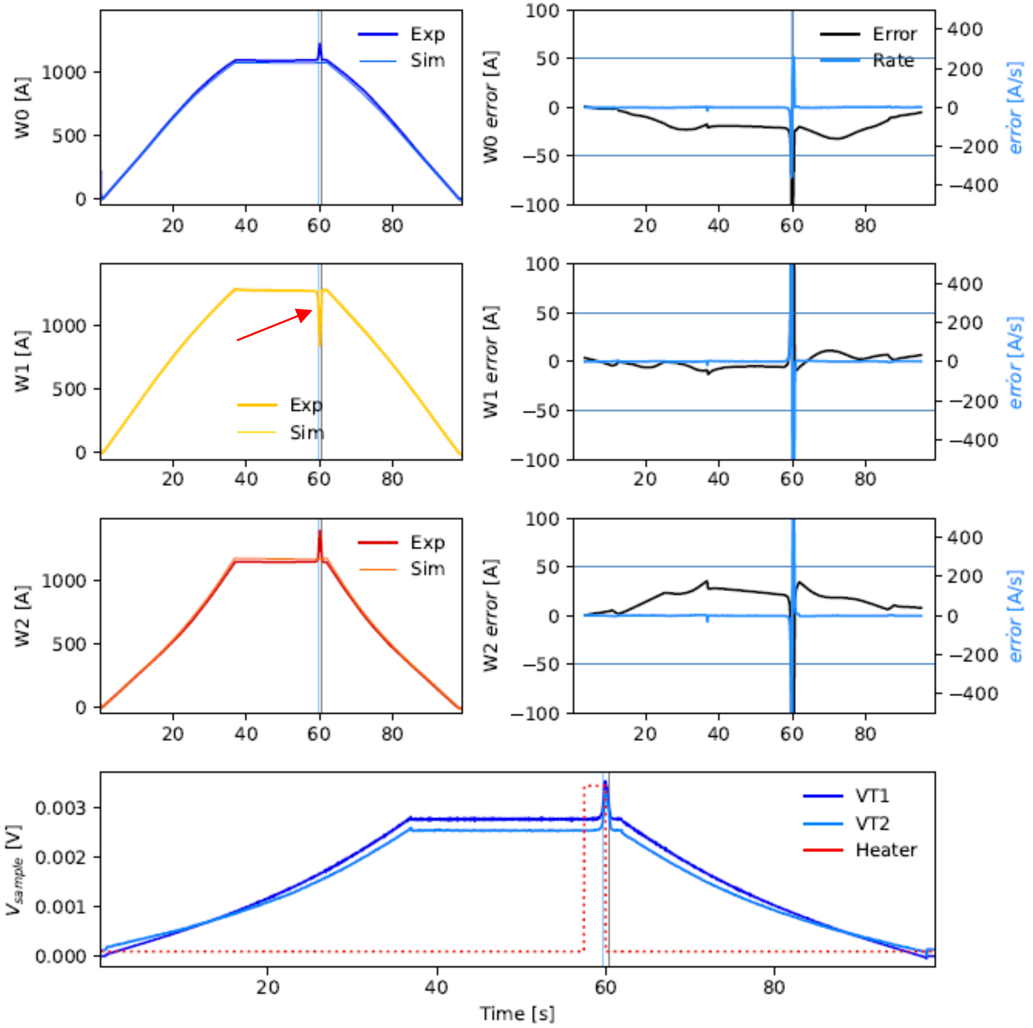


Quench Detection - Results

- Static case
- Heater applied to middle wire
  - Vertical lines = quench trigger, even though sample recovered
  - Blue = error rate, black = absolute error
- *None of this (current) information is typically available to magnet operators today*

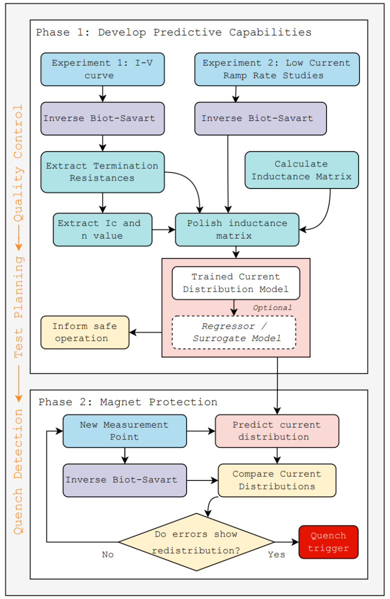


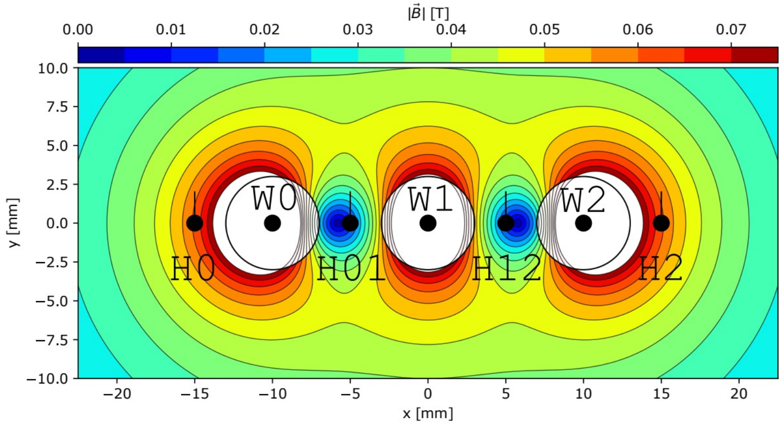


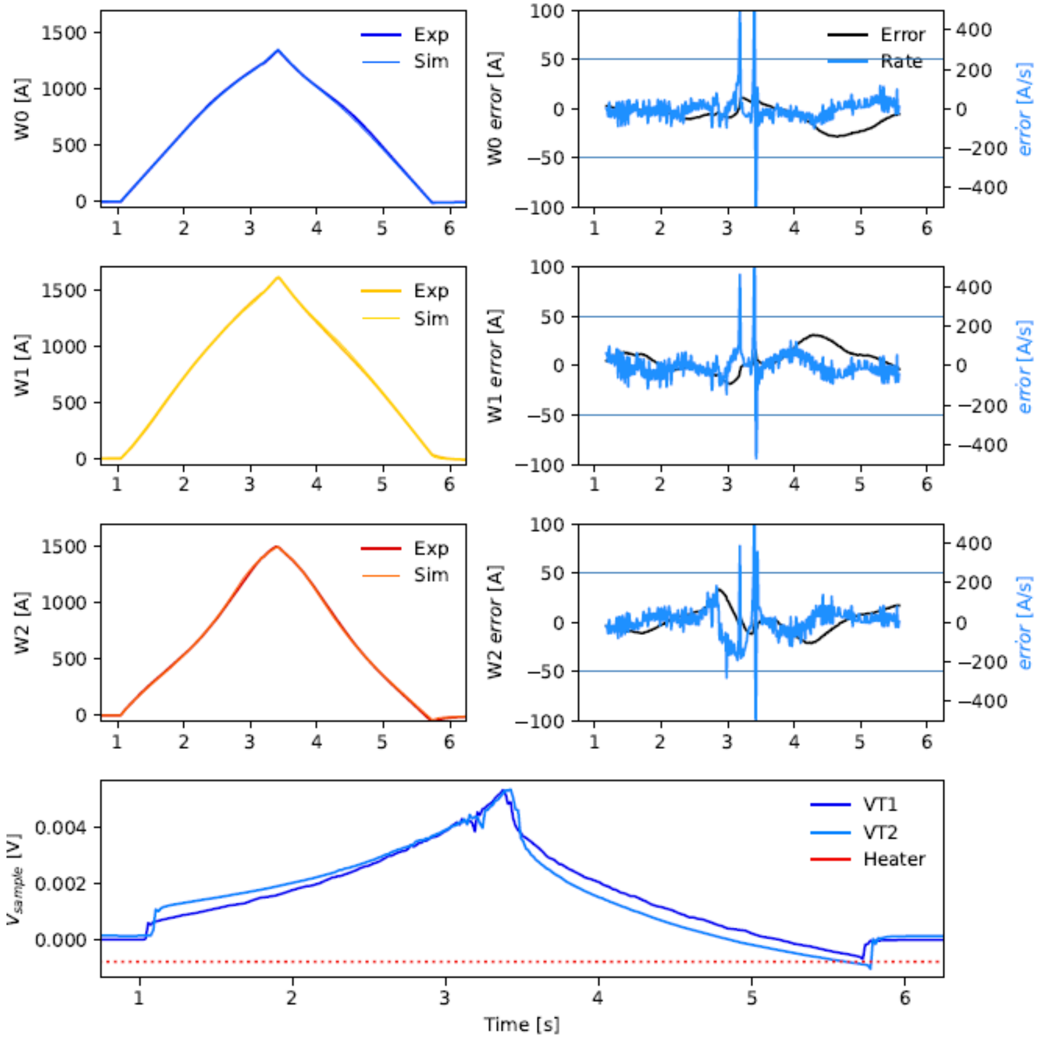


Quench Detection - Results

- Dynamic case – 2,000 A/s
- No heater, no quench – correct prediction of no quench
  - *Note quality of current distribution prediction!*
- Thresholds will be specific to magnet

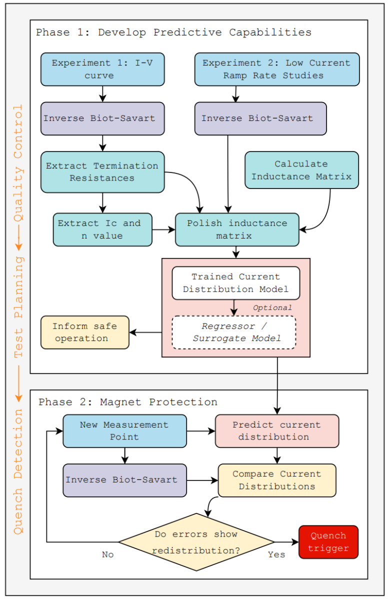


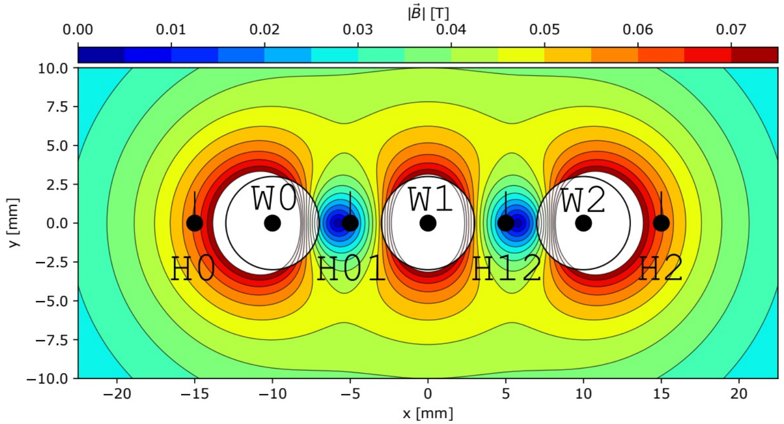


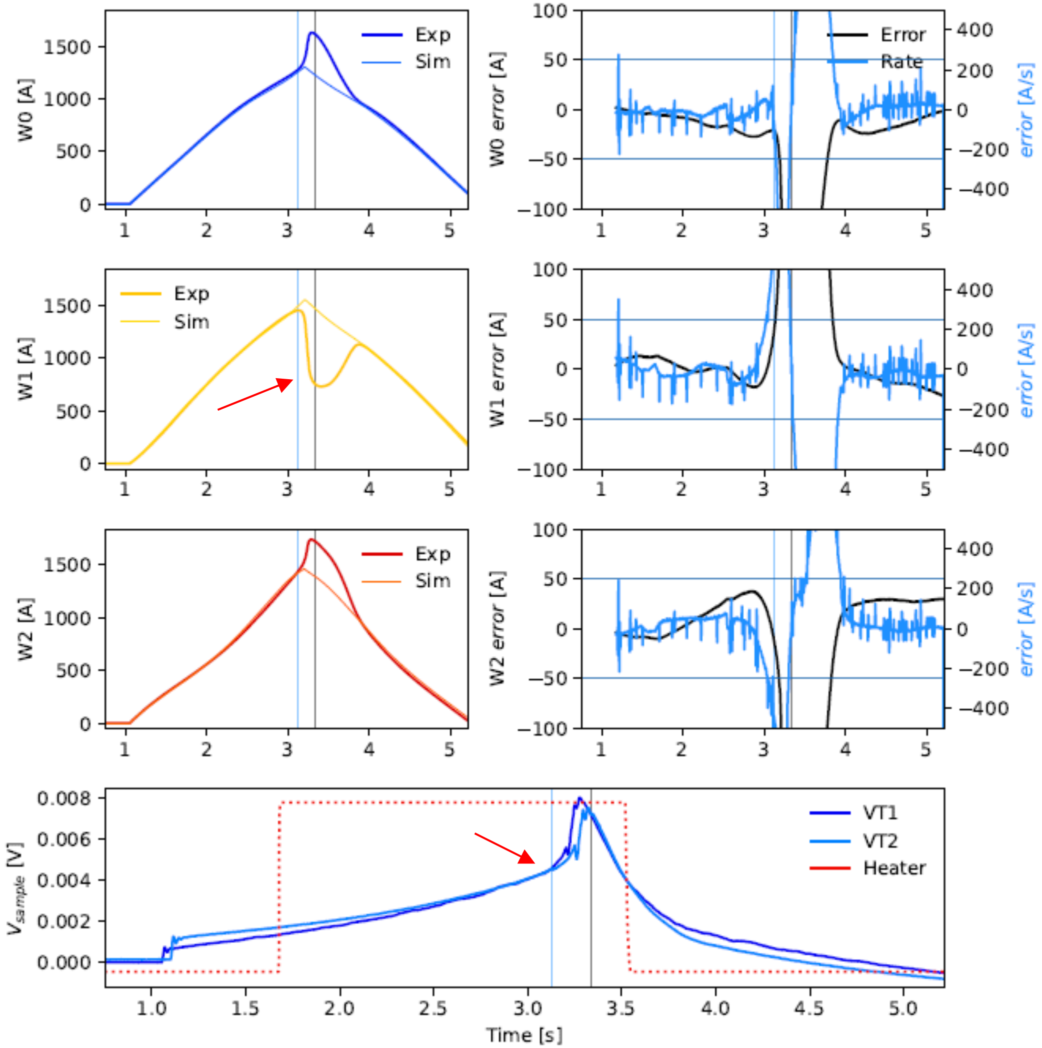


Quench Detection - Results

- Dynamic case – 2,000 A/s
- Heater applied to middle wire
  - Early quench signal produced!
    - 2,000 A/s is tricky case for quench protection

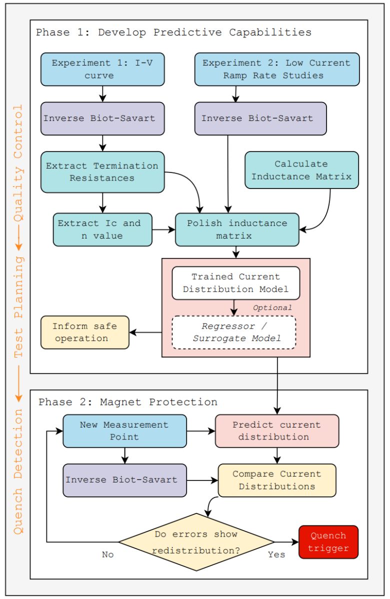


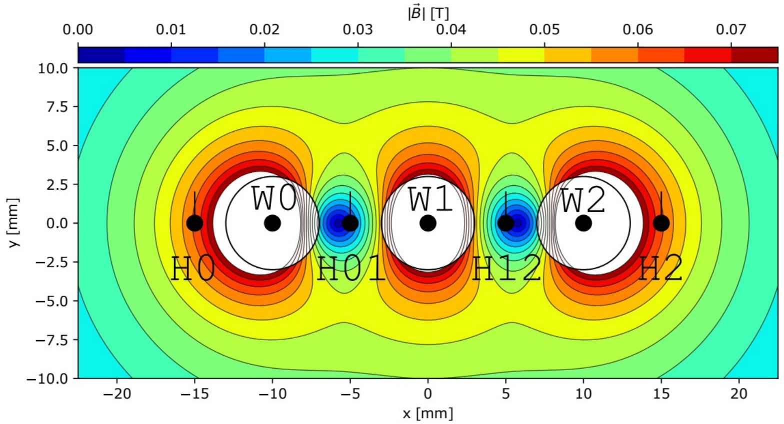


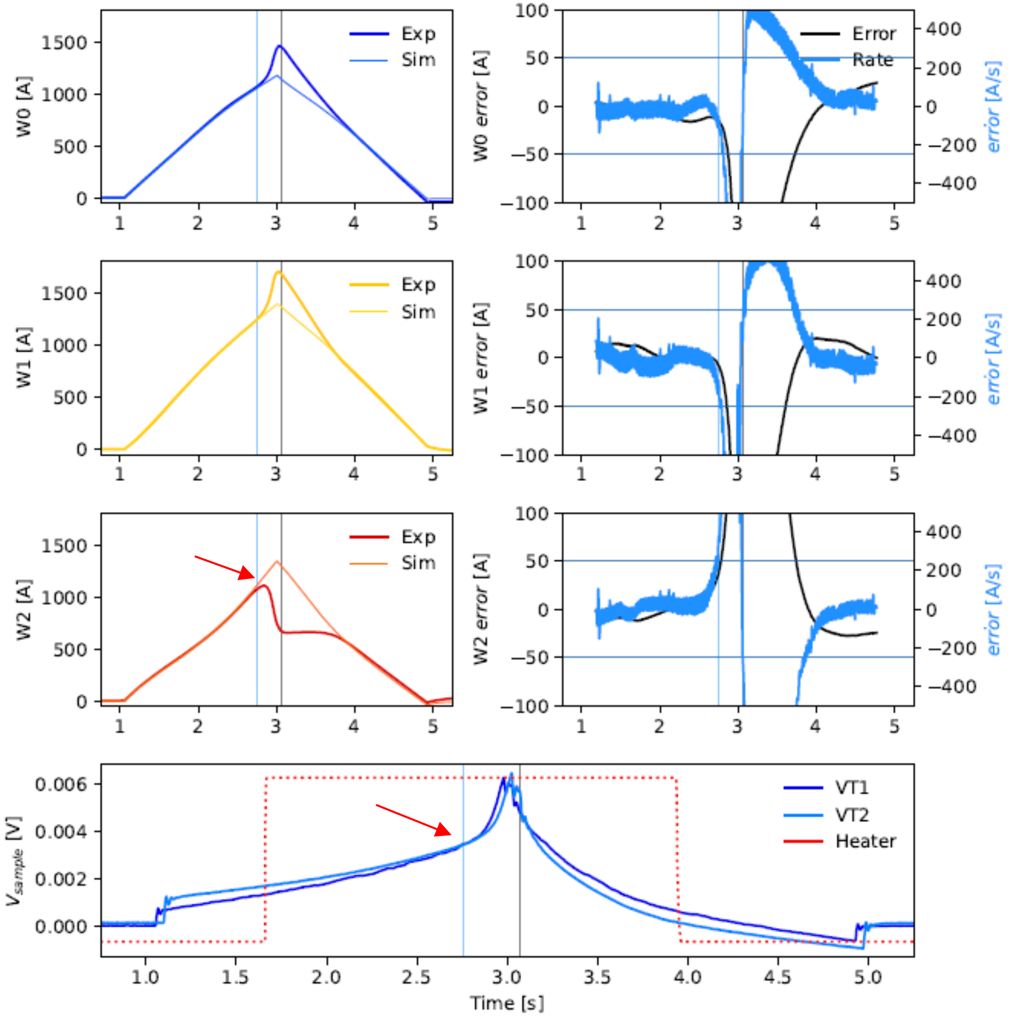


Quench Detection - Results

- Dynamic case – 2,000 A/s
- Heater applied to right wire
  - Early quench signal produced!

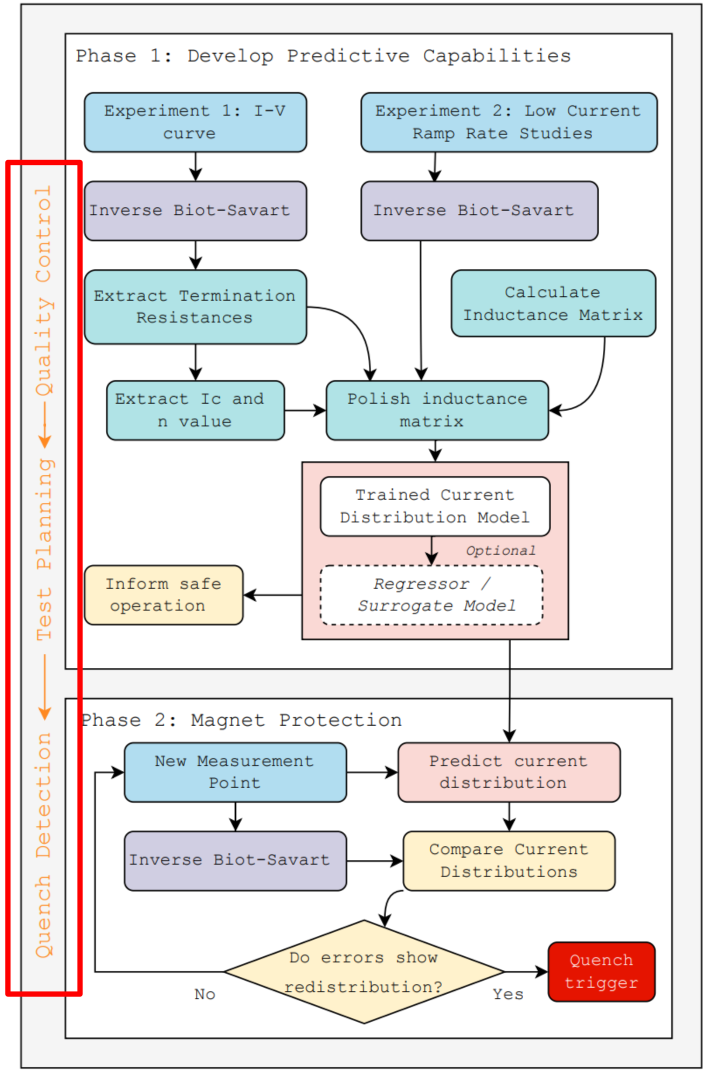






Discussion

- Cons & comments:
  - Requires pre-defined current waveforms at this time
    - *I think this only rules out relatively niche cases, and can likely be addressed – this is textbook case of machine learning*
  - In limit of very high inductance and very high ramp rates, current does not redistribute – technique won't work
    - *Methodology can still provide valuable information in regards to quality control and test planning stages*
  - Only applies to "cable-of-cable" geometries with poor current sharing
    - *The main limitation of this work, cannot be universally adopted*
    - *Possible to modify cables to adopt structure found in "CORC CICC" – ongoing work*
    - *Possible to apply to "baseline cables" with low/moderate current sharing with new experimental methods & elaborate parameter extraction steps – ongoing work*
  - Is all the calculation fast enough?
    - *The results so far suggest that on the order of 10 ms is quite feasible and there are many ways to improve this.*
    - *This will supplement temperature (fiber, acoustic) and voltage measurements, not replace them*
- **Methodology outlined today gives cable-of-cable magnet operators the tools to make informed decisions with their magnets, from fabrication to planning to real time protection**



Conclusion

- Questions?