Quench Detection for CORC® Fusion Magnets via Real-Time Current Recreation

IDSM II 2023

Reed Teyber, Maxim Marchevsky - LBNL

Jeremy Weiss, Danko van der Laan - ACT

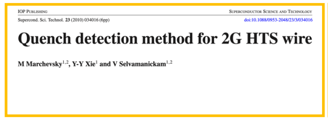
BERKELEY LAB
Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

BCMT
BERKELEY CENTER FOR MAGNET TECHNOLOGY

The Approach

- Can we protect fusion cables by monitoring current distributions?
  - Build capability to predict current distributions
  - Identify current distributions in real time
  - Look for signatures of current redistribution
- *Supplement* voltage and temperature measurements
- Many flavors - inter-cable (~fusion), inter-tape (~HEP), …



IOP Publishing — Superconductor Science and Technology

Supercond. Sci. Technol. **23** (2010) 034016 (6pp) doi:10.1088/0953-2048/23/3/034016

Quench detection method for 2G HTS wire

M Marchevsky[1,2], Y-Y Xie[1] and V Selvamanickam[1,2]

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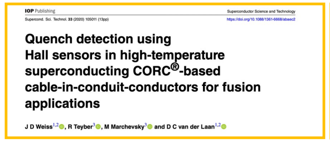
Supercond. Sci. Technol. **33** (2020) 095009 (11pp) https://doi.org/10.1088/1361-6668/ab9ef3

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]



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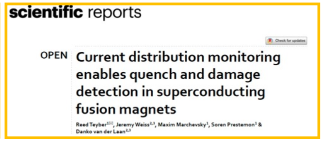
Supercond. Sci. Technol. **33** (2020) 105011 (13pp) https://doi.org/10.1088/1361-6668/abaec2

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]



scientific reports

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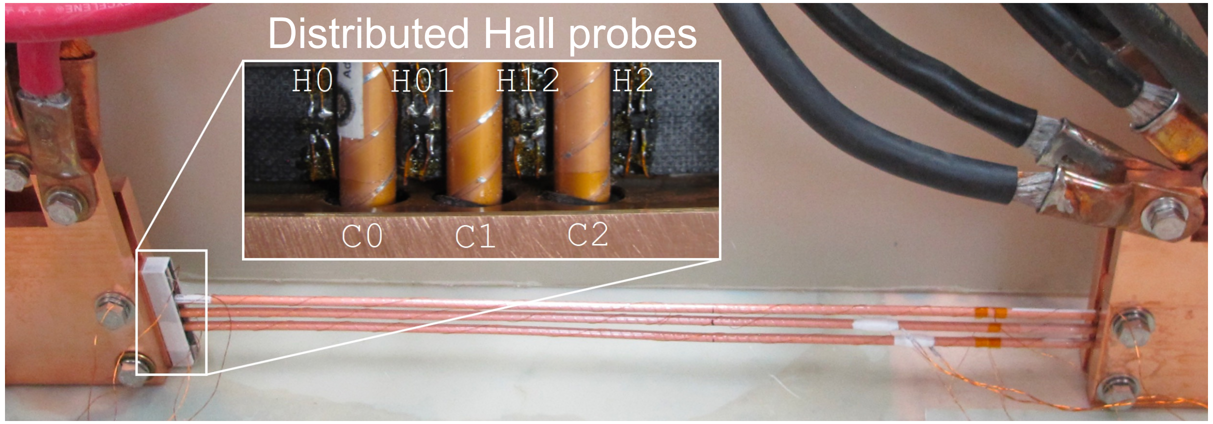
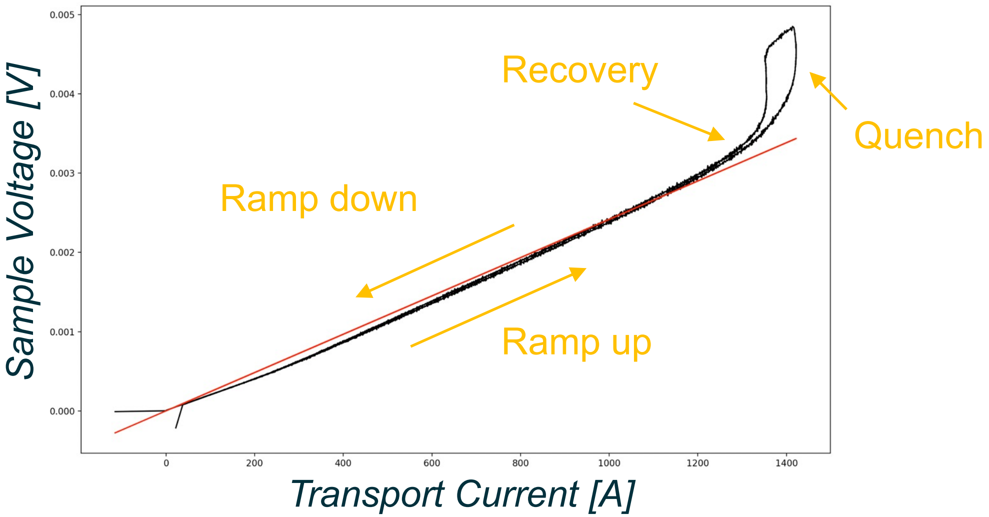
OPEN **Current distribution monitoring enables quench and damage detection in superconducting fusion magnets**

Reed Teyber[1], Jeremy Weiss[2,3], Maxim Marchevsky[1], Soren Prestemon[1] & Danko van der Laan[2,3]

CORC® Ribbon Cable





Inverse Biot-Savart

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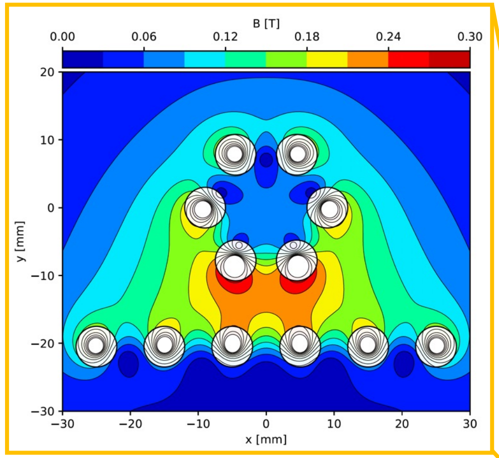
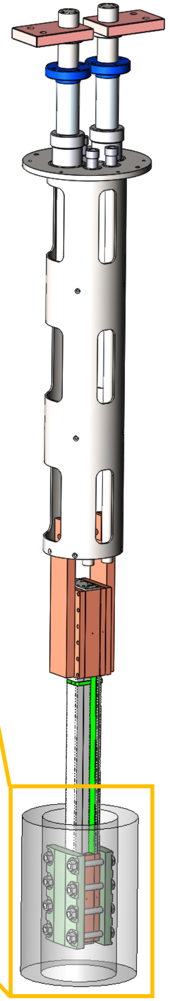
- Recreate current distributions from Hall probes
- Field at each Hall sensor is sum of line current Biot-Savart
  - Invert or solve as constrained optimization problem
  - Not a new method – but key to our approach

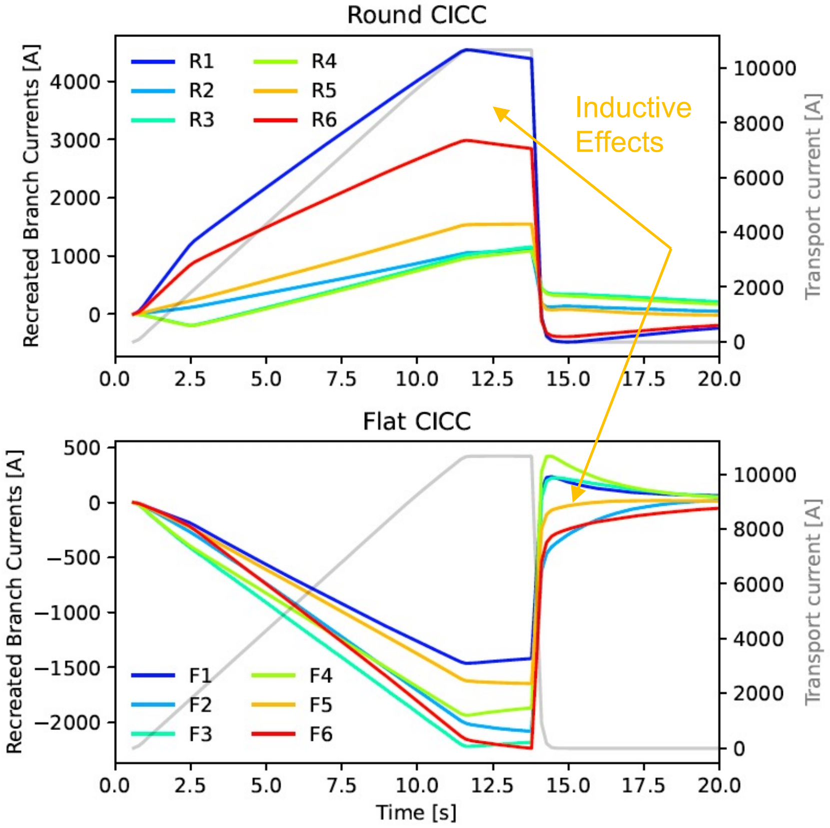
$$\text{Hall Sensors}\updownarrow\underbrace{\overset{\xleftrightarrow{\text{Conductors}}}{\begin{bmatrix} A^*_{00} & A^*_{i0} & A^*_{n_i0} \\ A^*_{0k} & A^*_{ik} & A^*_{n_ik} \\ A^*_{0n_k} & A^*_{in_k} & A^*_{n_in_k} \end{bmatrix}}}_{\text{Geometry}} \underbrace{\begin{bmatrix} I_{0,z} \\ I_{i,z} \\ I_{n_i,z} \end{bmatrix}}_{\text{Currents}} = \underbrace{\begin{bmatrix} B_0 \\ B_k \\ B_{n_k} \end{bmatrix}}_{\text{Fields}}$$





Data + Figures Courtesy Jeremy Weiss
LBNL not involved in experiments

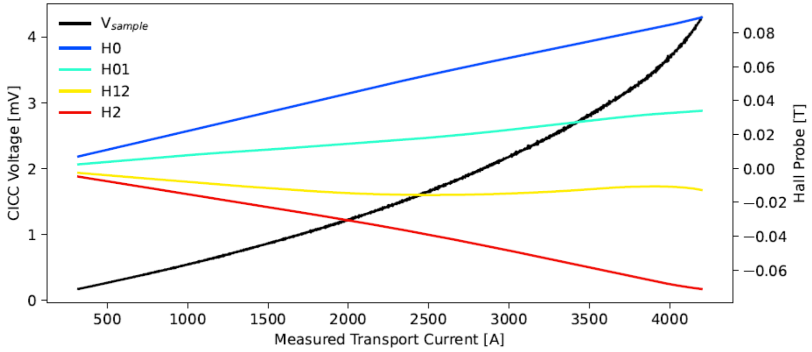
UK Atomic Energy Authority



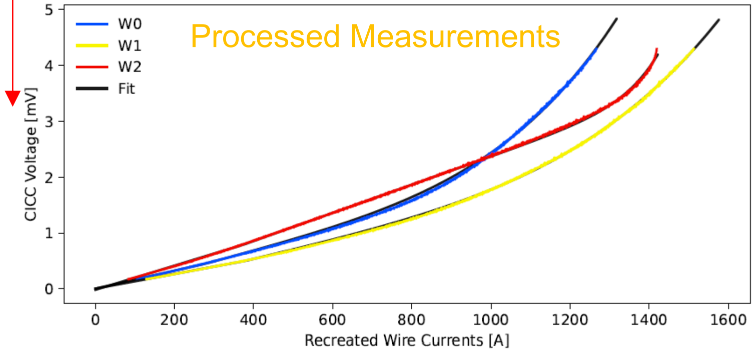
Parameter Extraction

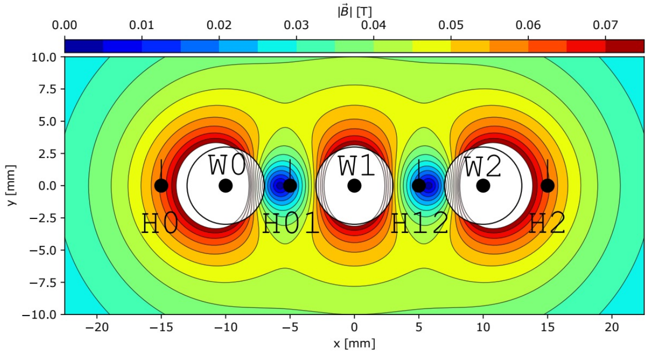
- Single I-V curve with Hall probe measurements
  - Extract all termination resistances, critical currents
  - *Can now run network model with actual parameters of magnet!*

Raw CICC Measurements with Hall probe array



Inverse Biot-Savart

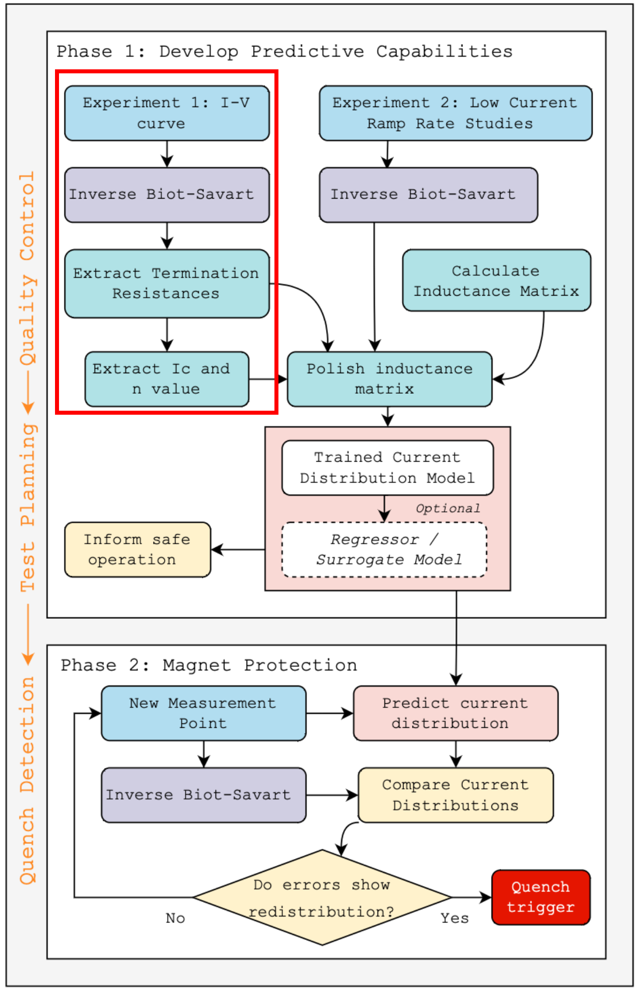




Non-invasively extracted termination resistances and critical currents!

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



Phase 1: Develop Predictive Capabilities

Experiment 1: I-V curve

Inverse Biot-Savart

Extract Termination Resistances

Extract Ic and n value

Experiment 2: Low Current Ramp Rate Studies

Inverse Biot-Savart

Calculate Inductance Matrix

Polish inductance matrix

Trained Current Distribution Model

Regressor / Surrogate Model

Inform safe operation

Phase 2: Magnet Protection

New Measurement Point

Predict current distribution

Inverse Biot-Savart

Compare Current Distributions

Do errors show redistribution?

Quench trigger

Reed Teyber *et al.*, IDSM II 2023

Quench Detection

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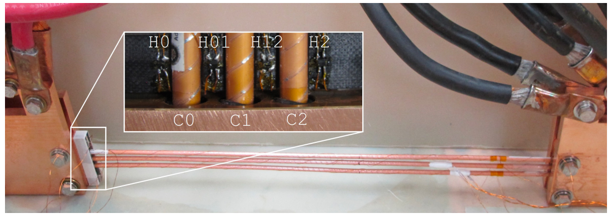
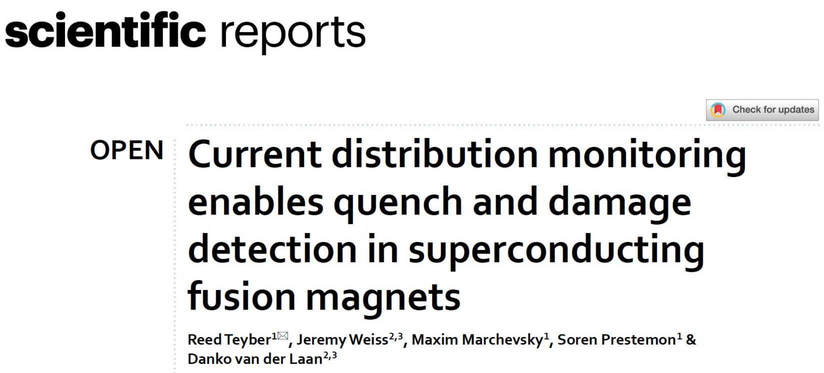
- Compare dynamic simulation with extracted parameters to recreated current distributions
- Dynamic (and challenging) case – 2,000 A/s
  - Algorithm searches for signatures of current redistribution in error rate
- Heater applied to middle wire (yellow)
  - *None of this information is currently available!*





scientific reports

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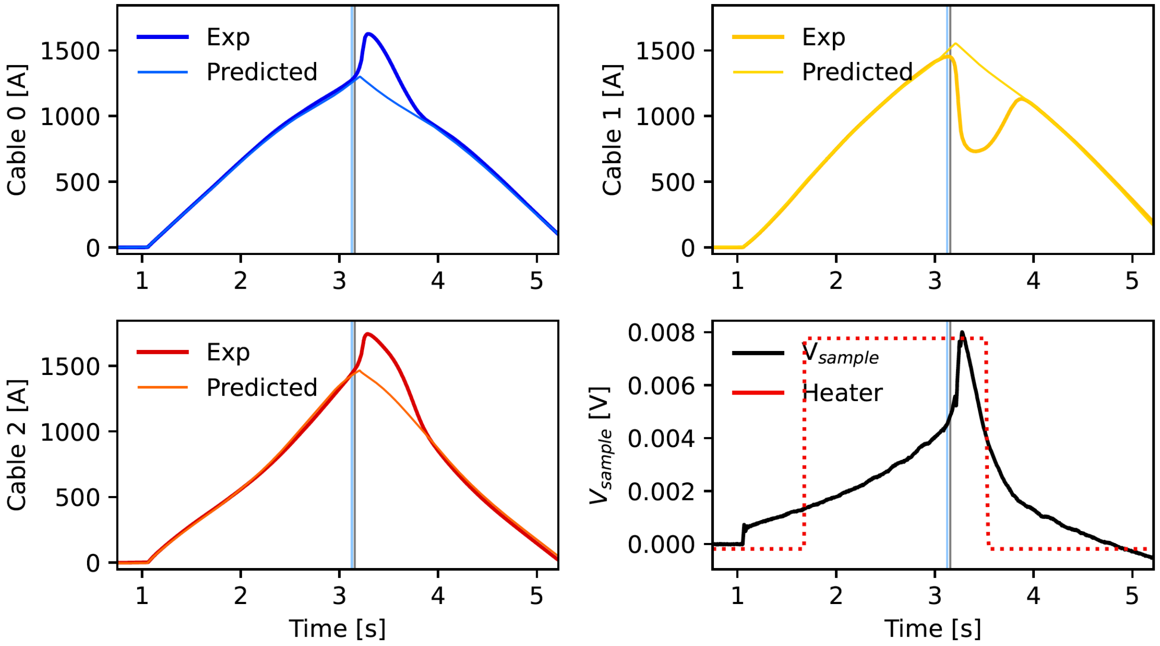
OPEN **Current distribution monitoring enables quench and damage detection in superconducting fusion magnets**

Reed Teyber[1]✉, Jeremy Weiss[2,3], Maxim Marchevsky[1], Soren Prestemon[1] & Danko van der Laan[2,3]

LBNL + ACT



(New) Quench Detection

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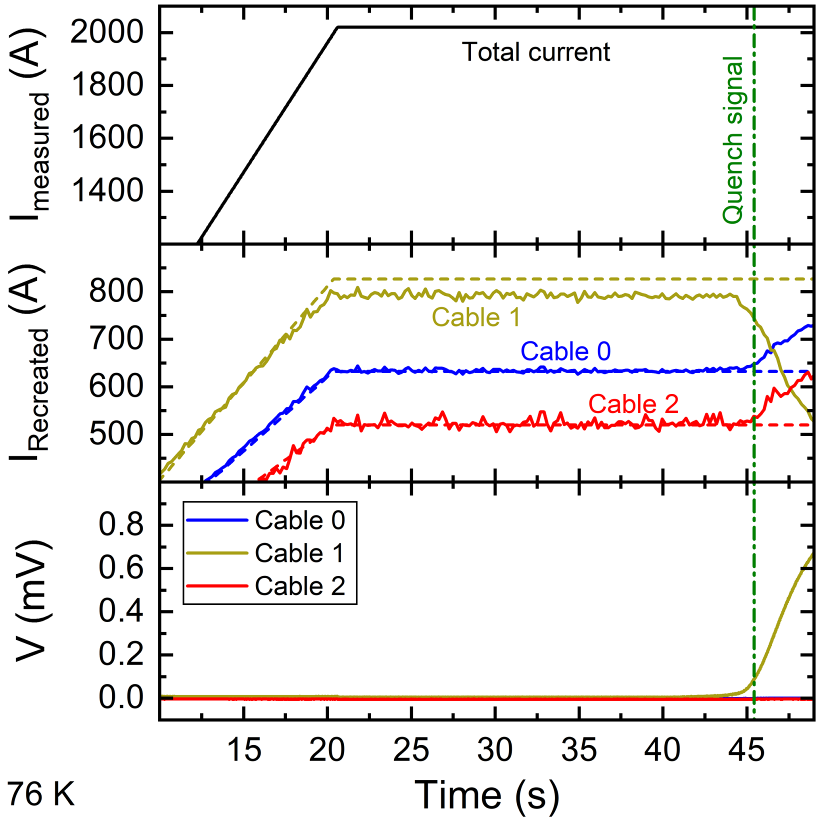
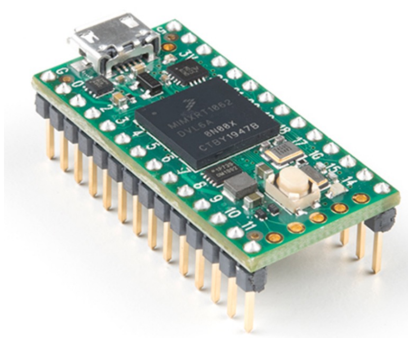
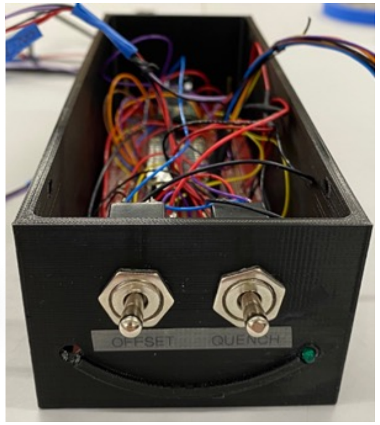
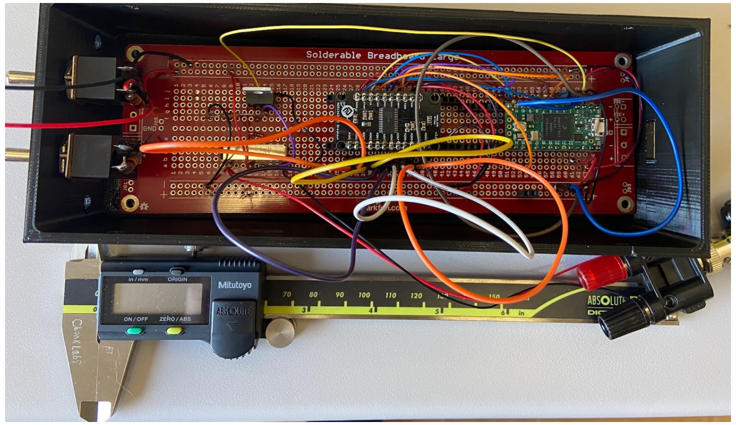
- Quench detection prototype built and tested based on published approach
  - Expected current distribution defined by extracted termination resistances (low-ramp rate only)
  - Inverse Biot-Savart problem implemented on ARM Cortex M7
- Recreated experiments on last slide
  - Quench trigger produced in real-time after firing quench heater









Reed Teyber *et al.*, IDSM II 2023

Next Steps

- Technique is very promising for quench detection and system health monitoring
- Having said this, many caveats for implementation
  - Short/moderate length cables, HTS CICC, limited inter-cable current sharing, …
- Toroidal Field coils with demountable joints
  - Current can redistribute between conductors of each CICC at each demountable joint at each turn
  - More complex current recreation and prediction problems in real time
- Seeking funding to build a scale prototype of this concept with ACT and General Atomics

GENERAL ATOMICS

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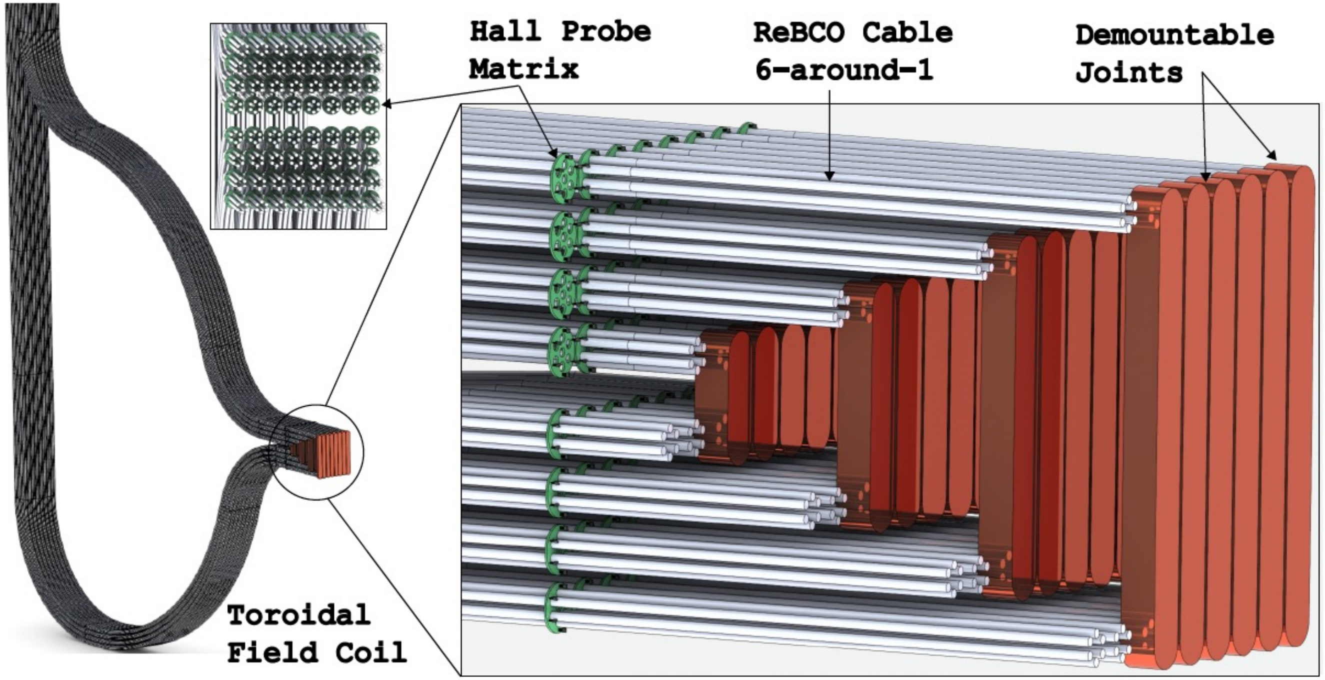
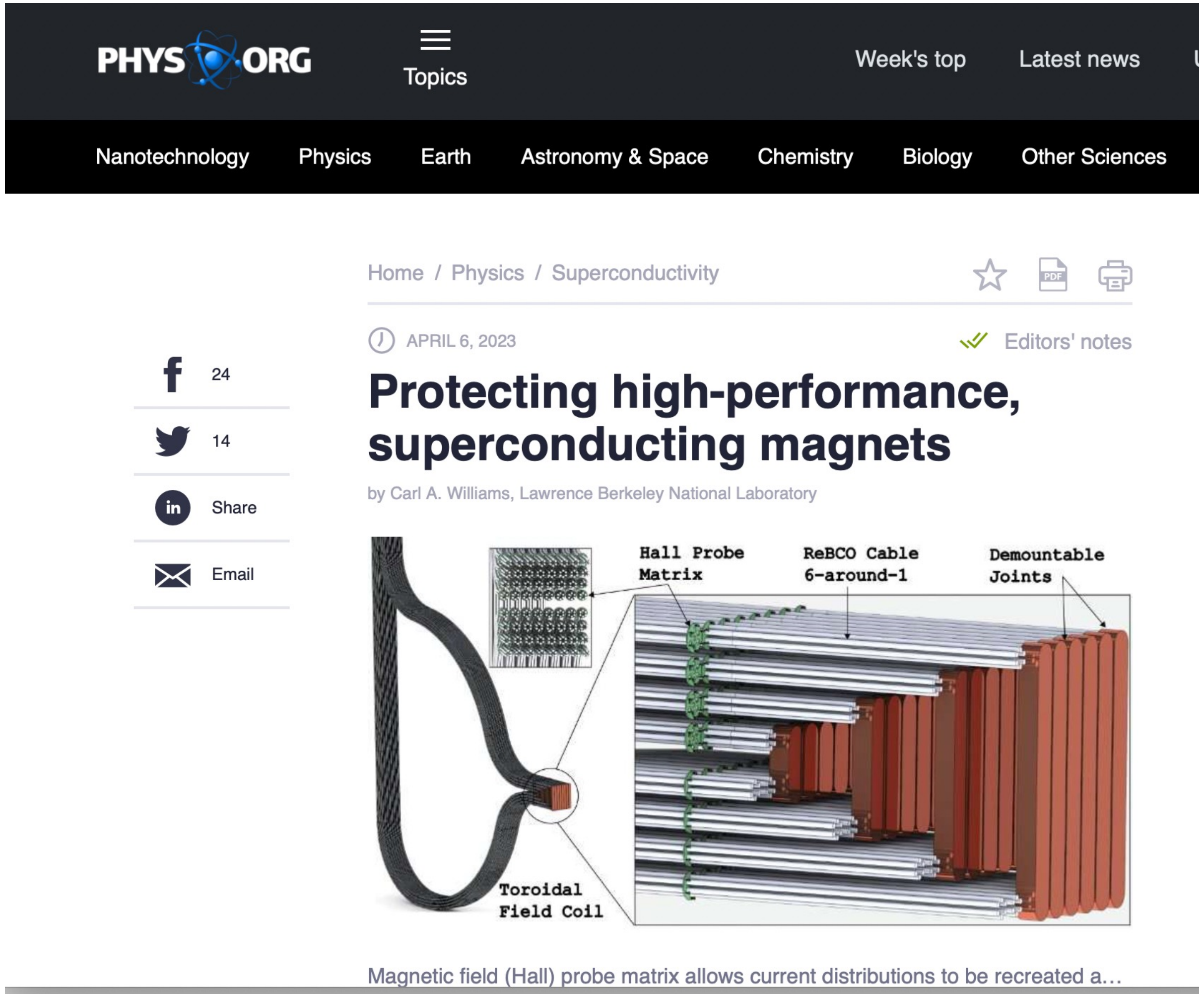


Next Steps



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APRIL 6, 2023

Editors' notes

Protecting high-performance, superconducting magnets

by Carl A. Williams, Lawrence Berkeley National Laboratory

Magnetic field (Hall) probe matrix allows current distributions to be recreated a…

Inter-Tape Redistribution

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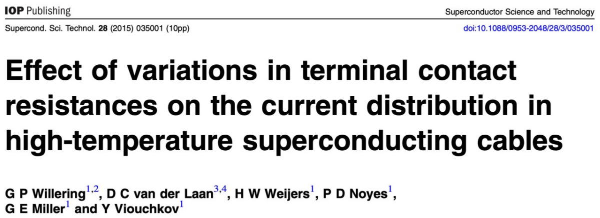
- Early inter-tape current redistribution measurements in short samples was promising
  - But scaling to long length cables can be challenging

See work by Gerard Willering



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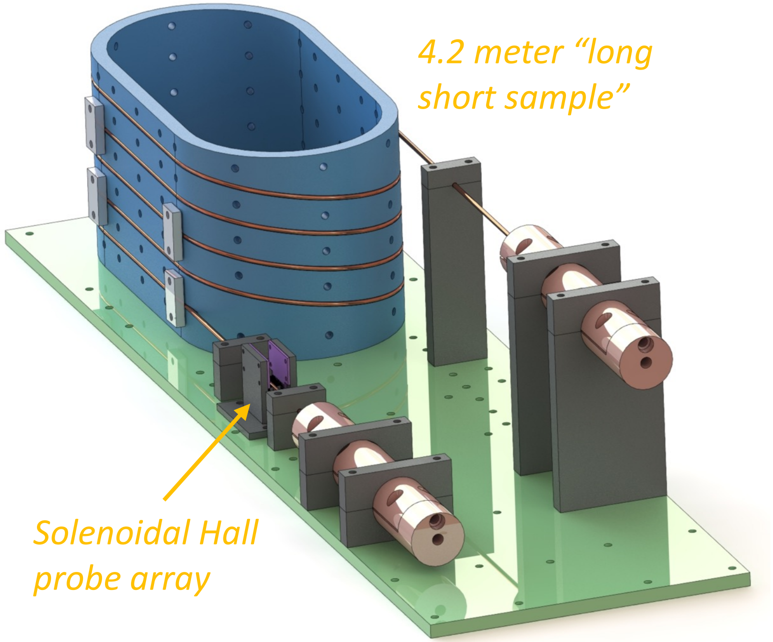
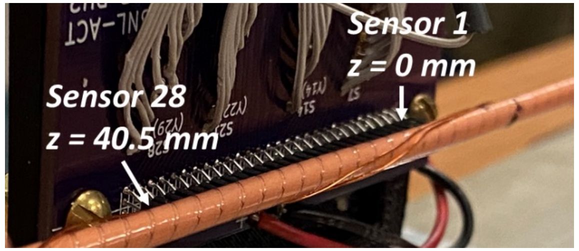
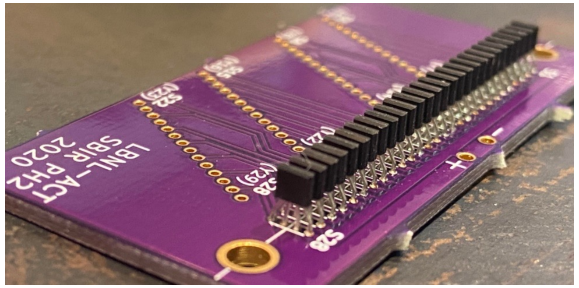
Supercond. Sci. Technol. **28** (2015) 035001 (10pp) — doi:10.1088/0953-2048/28/3/035001

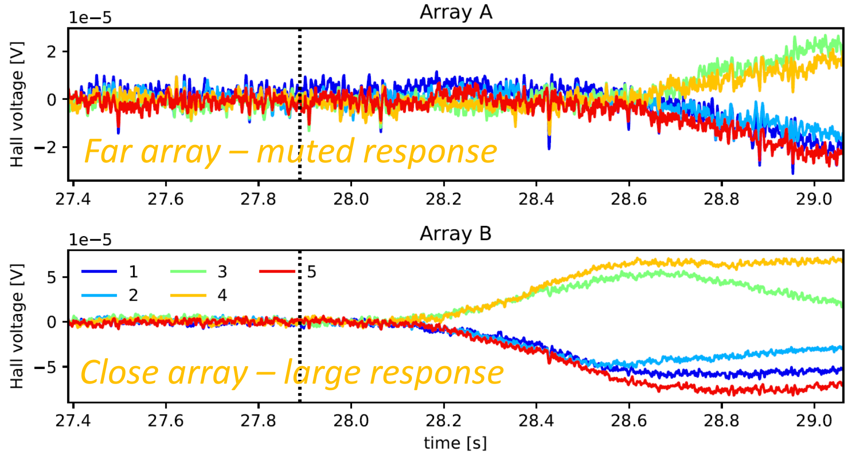
Effect of variations in terminal contact resistances on the current distribution in high-temperature superconducting cables

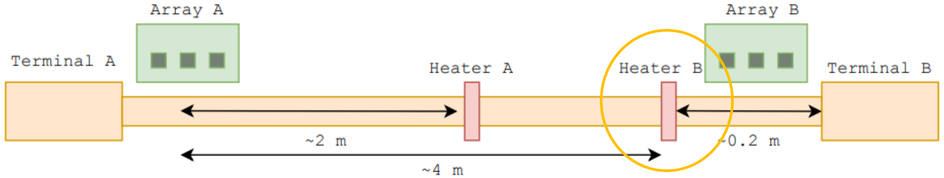
G P Willering[1,2], D C van der Laan[3,4], H W Weijers[1], P D Noyes[1], G E Miller[1] and Y Viouchkov[1]











Conclusion

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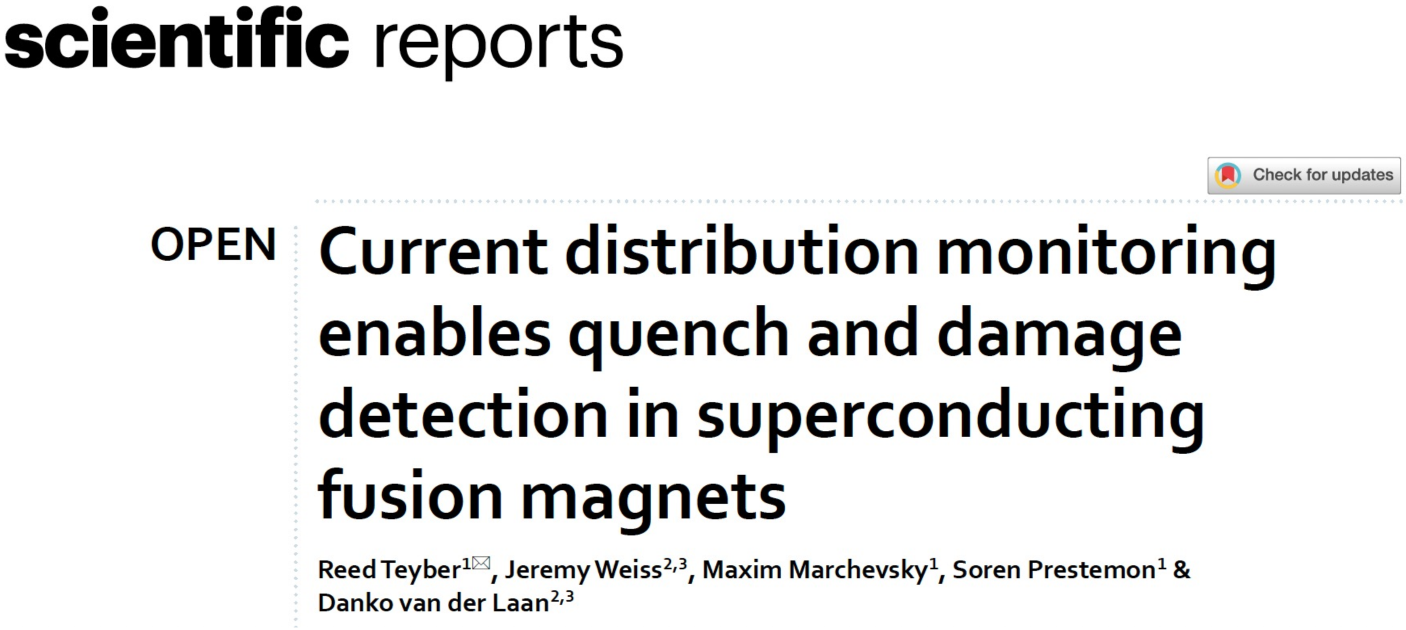
- Many implementation details not covered today
  - If interested – please see following manuscript
- Would like to re-iterate the collaboration with ACT
- Thank you for your attention!



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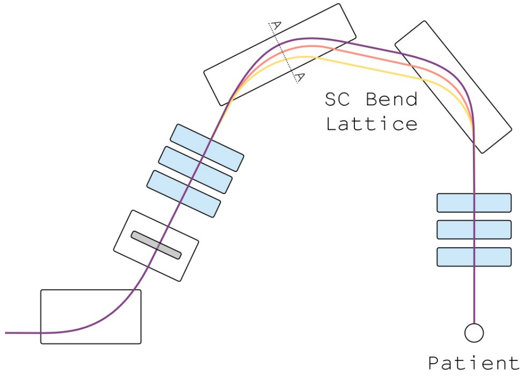
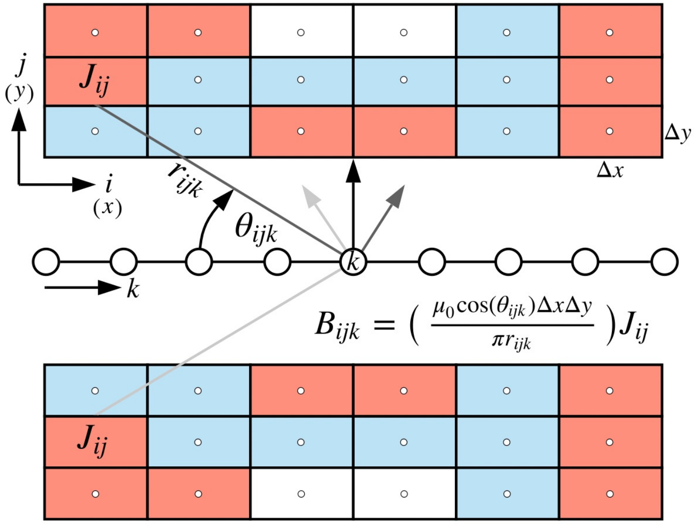
Current distribution monitoring enables quench and damage detection in superconducting fusion magnets

Reed Teyber[1]✉, Jeremy Weiss[2,3], Maxim Marchevsky[1], Soren Prestemon[1] &
Danko van der Laan[2,3]

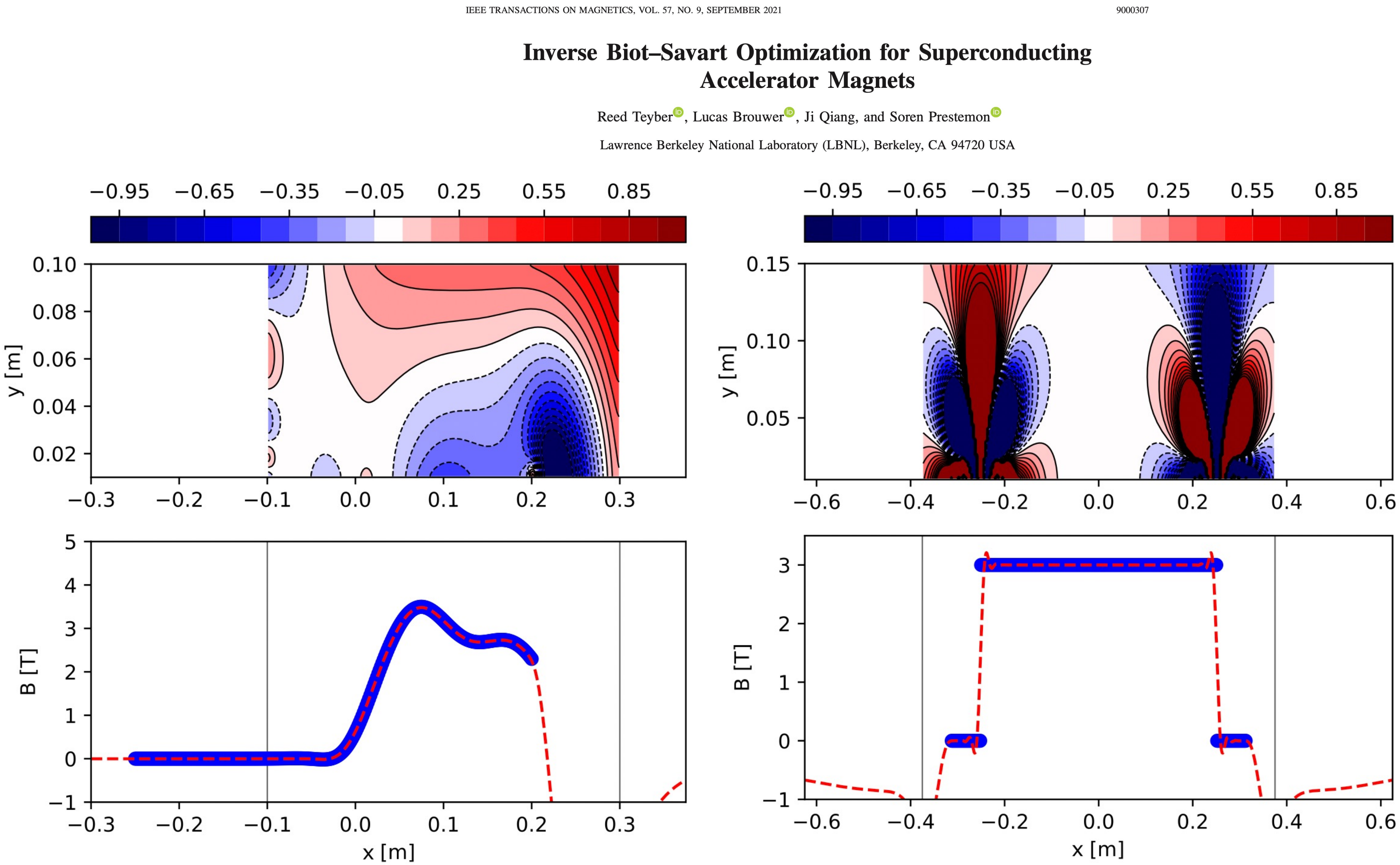
Extra slides

Coil design





$$B_{ijk} = \left(\frac{\mu_0 \cos(\theta_{ijk}) \Delta x \Delta y}{\pi r_{ijk}} \right) J_{ij}$$



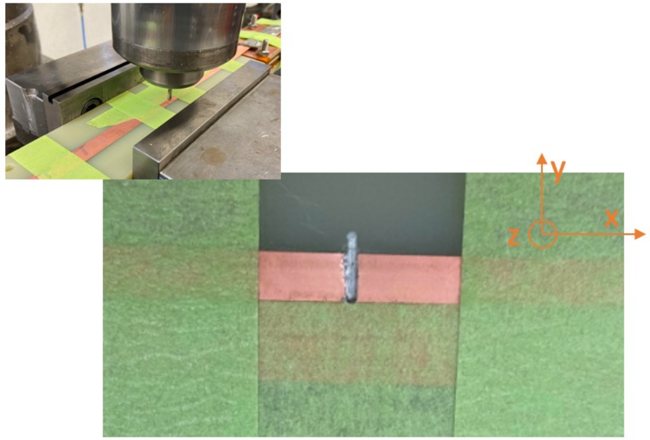
IEEE TRANSACTIONS ON MAGNETICS, VOL. 57, NO. 9, SEPTEMBER 2021 9000307

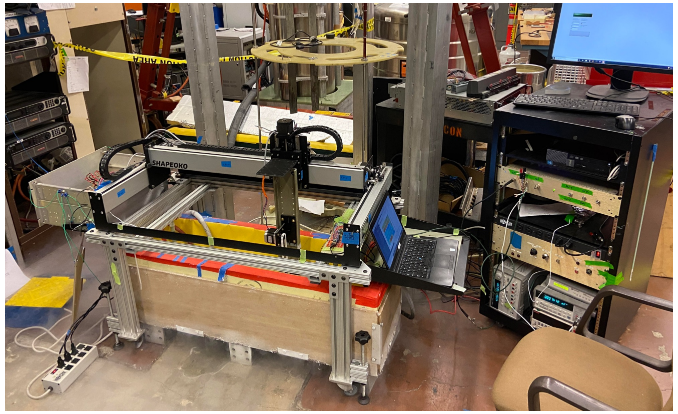
Inverse Biot–Savart Optimization for Superconducting Accelerator Magnets

Reed Teyber, Lucas Brouwer, Ji Qiang, and Soren Prestemon

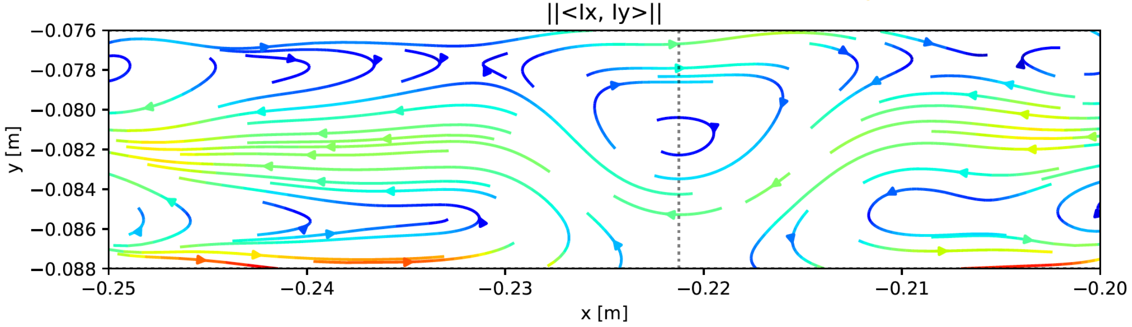
Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA 94720 USA

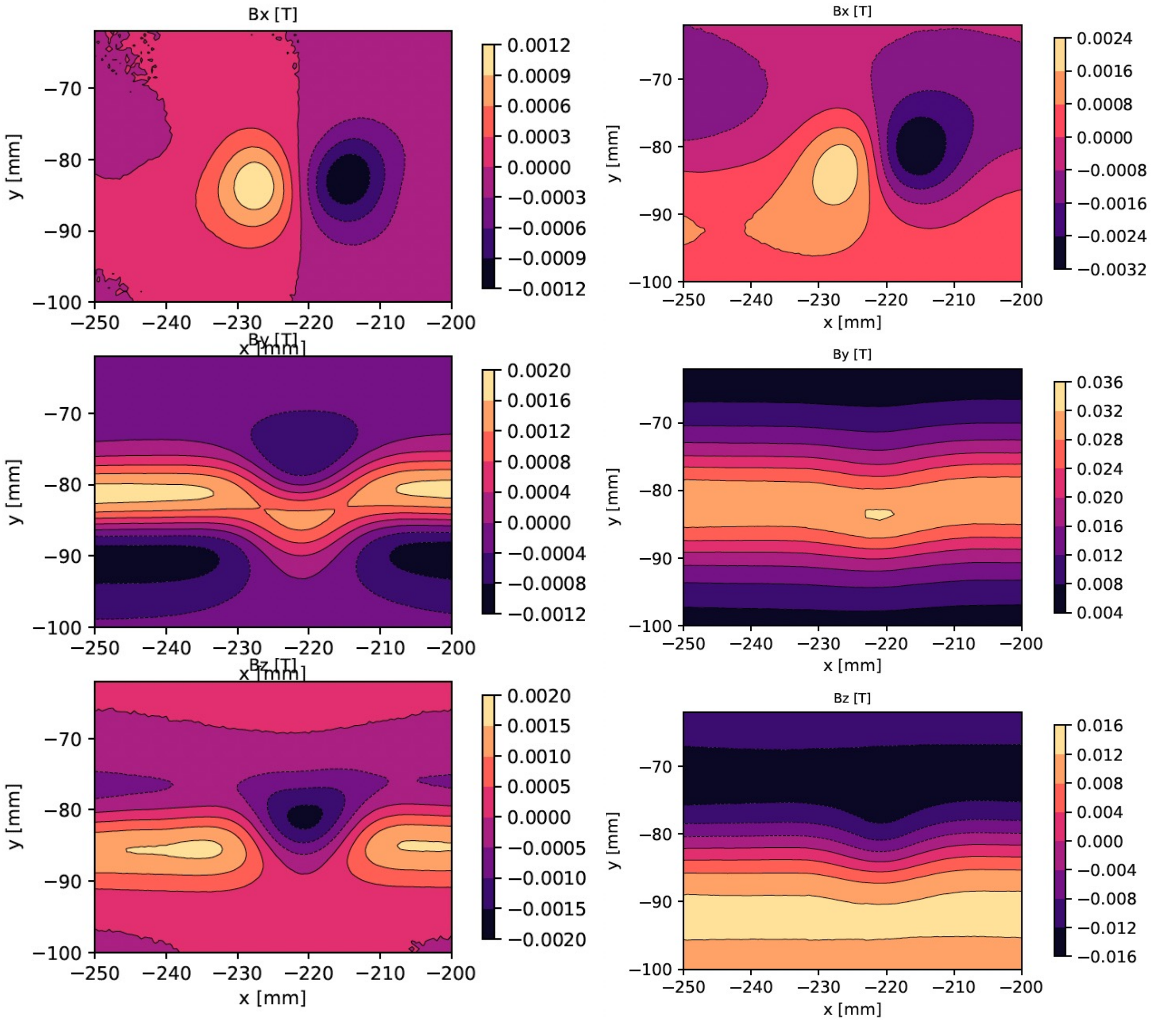
Tape current reconstruction



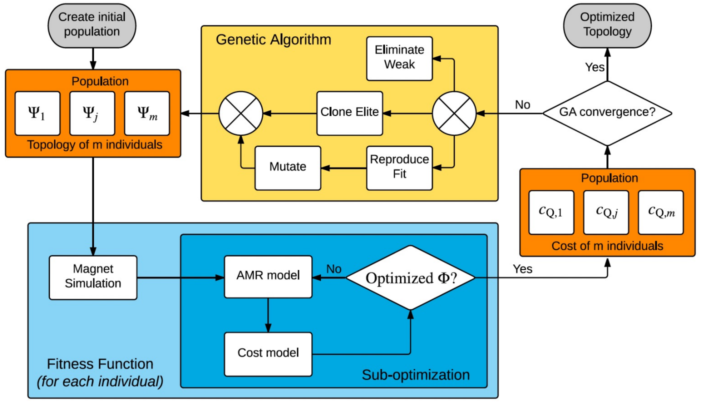


Current recreation calculated on Lawrencium supercluster





Cost-optimal magnet synthesis


Create initial population

Population

Ψ_1 Ψ_j Ψ_m

Topology of m individuals

Genetic Algorithm

Eliminate Weak

Clone Elite

Mutate

Reproduce Fit

No

GA convergence?

Yes

Optimized Topology

Population

$c_{Q,1}$ $c_{Q,j}$ $c_{Q,m}$

Cost of m individuals

Magnet Simulation

AMR model

No

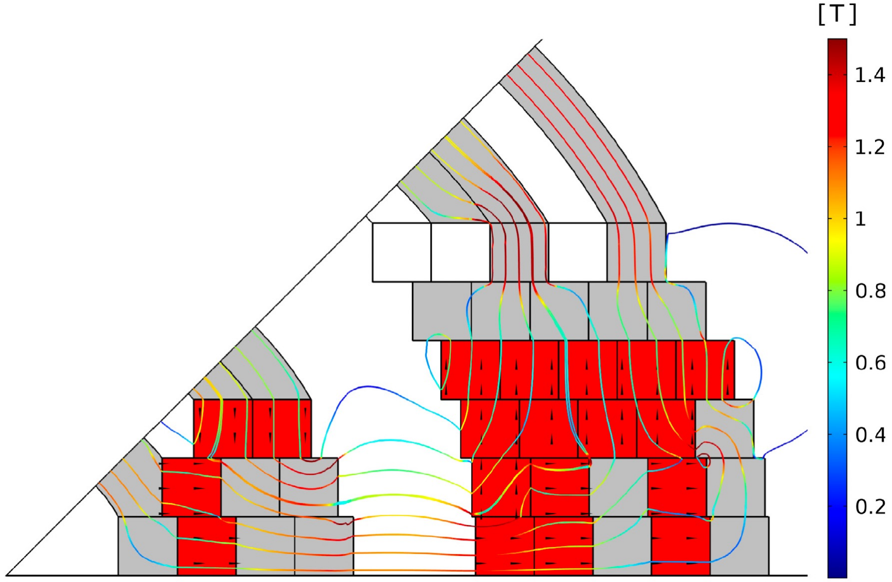
Optimized Φ?

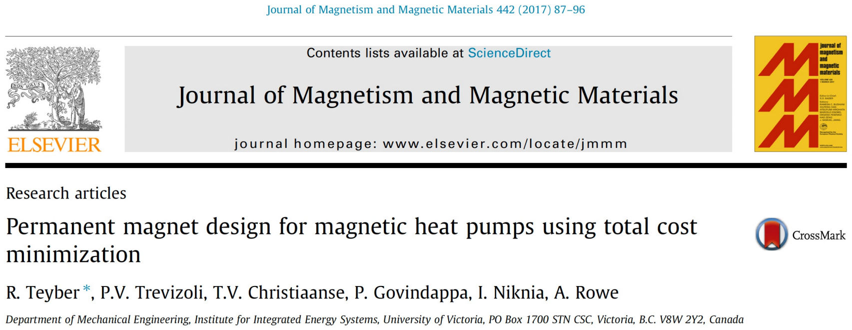
Yes

Cost model

Fitness Function
(for each individual)

Sub-optimization




Journal of Magnetism and Magnetic Materials 442 (2017) 87–96

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Research articles

Permanent magnet design for magnetic heat pumps using total cost minimization

R. Teyber *, P.V. Trevizoli, T.V. Christiaanse, P. Govindappa, I. Niknia, A. Rowe

Department of Mechanical Engineering, Institute for Integrated Energy Systems, University of Victoria, PO Box 1700 STN CSC, Victoria, B.C. V8W 2Y2, Canada