US Magnet Development Program

HTS Accelerator Magnet Development

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Lawrence Berkeley National Laboratory

ADMX workshop at Fermilab

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2212 work supported by U.S. DOE OHEP through an Early Career Award and through the U.S. Magnet Development Program, and performed in collaboration with Bruker OST, nGimat LLC, NHMFL/FSU.

REBCO work supported by U.S. DOE OHEP and FES through the U.S. Magnet Development Program, and by US DOE SBIR-STTR grants in collaboration with Advanced Conductor Technologies LLC

US MDP HTS team/collaborators seek to develop practical HTS *accelerator* magnets

U.S. MAGNET
DEVELOPMENT
PROGRAM

Fermilab + LBNL + NHMFL

- **5 T standalone HTS dipole -> 20 T dipole**
- **Comprehensive tech development from wire to magnet tech.**
- **Approaches: (1) Design and build unique magnets. (2) Integrated collaboration with universities and industry.**

LBNL-Supercon

L. Brouwer, S. Caspi, D. S. Davis, D. Dietderich, L. Garcia Fajardo, S. Gourlay, H. Higley, A. Lin, M. Machevsky, S. Prestemon[+], E. Ravaioli*, J. Swanson, J. Taylor, M. Turqueti, K. Zhang**,**

**** visiting PhD students**

*** Now with CERN**

[+] MDP director

NHMFL

E. S. Bosque, D. S. Davis, C. L. English, Jianyi Jiang, Y. Kim, G. E. Miller, J. Lu, F. Kametani, U. P. Trociewitz, E. E. Hellstrom, and D. C. Larbalestier (ASC/NHMFL/FSU)

Our external collaborators

Yibing Huang and Hanping Miao (B-OST)

Marvis White, Riley Nesbit, Aixia Xu and Andrew Hunt (nGimat)

Suvankar Sengupta and Rao Revur (MetaMateria)

Jeremy Weiss, Danko van der Laan (ACT)

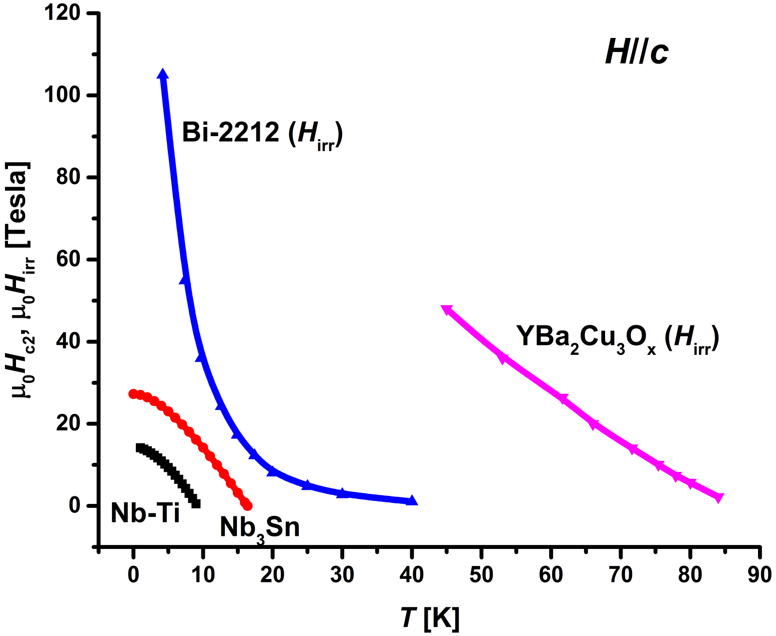
Federica.Pierro, Luisa Chiesa (Tufts)

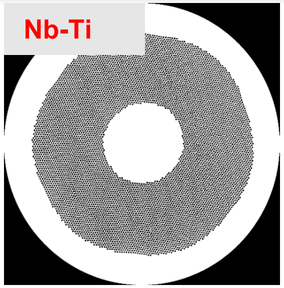
Federico Scurti, Justin Schwartz (PSU)

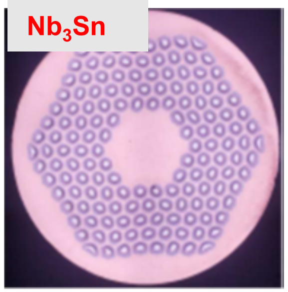
Joe Mineverni (MIT)

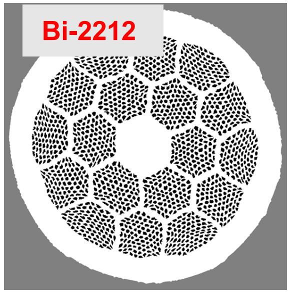
S. Ishmael (Lupine)

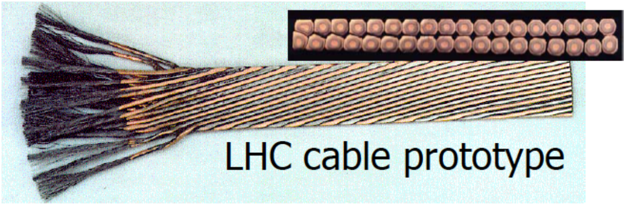
The ceiling for HTS magnets is high – 100 T upper critical fields at 4.2 K. The key question is how to use them to construct accelerator magnets.

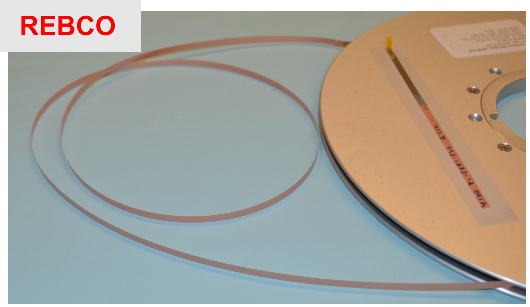












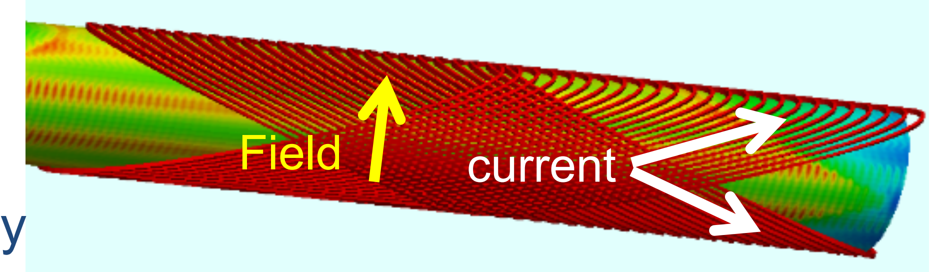
Tape conductor: How to use it in a cable form?

Bi-2212 – how to manage stress for it, and perform reliable heat treatments?

REBCO and Bi-2212 – how to detect and protect magnets against a quench?

For REBCO, our main vehicle is CCT + CORC® wires

- CCT design
  - Low conductor stresses
  - Excellent geometric field quality



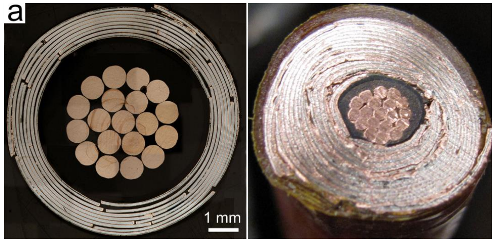
[D. Meyer and R. Flasck, Nuclear Instruments and Methods, vol. 80, no. 2, pp. 339–341, 1970; AV Gavrilin *et al.*, IEEE TAS, 13(2), 2002; S. Caspi *et al.*, IEEE TAS, 4001804, 2014]

CORC® wires (< 3.7 mm diameter)

- Isotropic for magnetics and mechanics
- Flexible (~ 50 mm minimum bending diameter)

[J. D. Weiss *et al.*, SuST, 014002, 2017 and references therein]

Advanced Conductor Technologies LLC



CORC-Conductor on Round Core

- Compliments to efforts in EU and Japan

X. Wang, H. Higley

Advanced Conductor Technologies LLC
www.advancedconductor.com

BERKELEY LAB

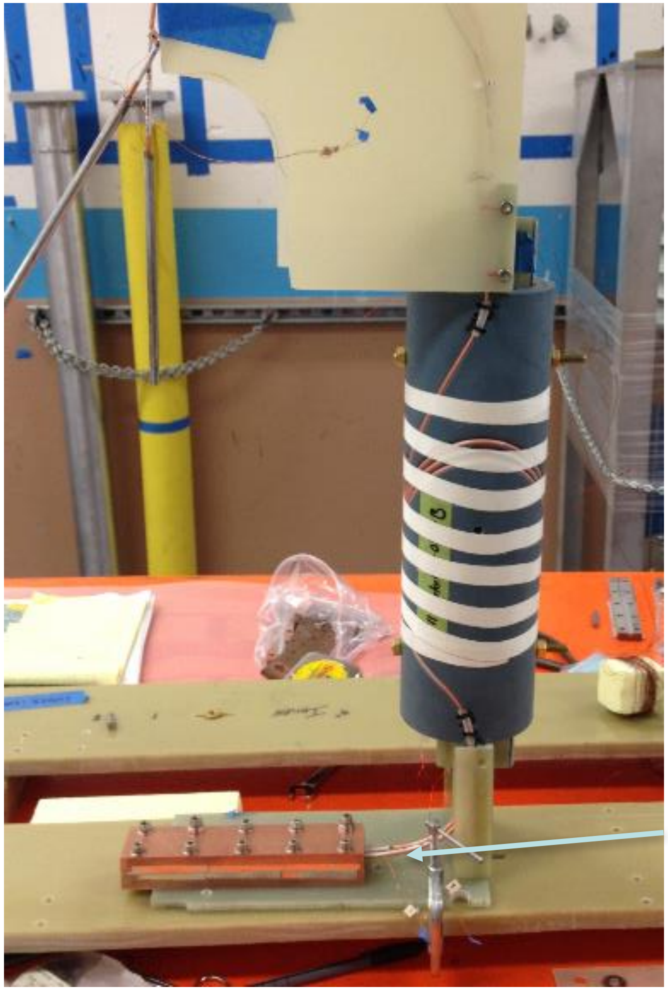
We developed methods to wind CORC into CCT coils

Hugh Higley (left) and Andy Lin (right) winding a 40-turn mockup coil

X. Wang, H. Higley

We developed methods to make convenient joints between CORC wires with acceptable performance

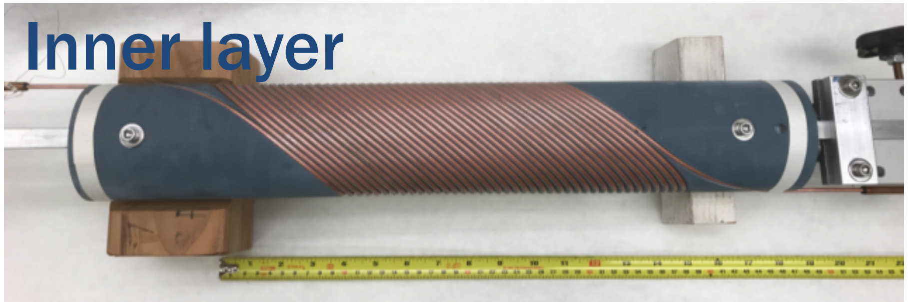
Indium foil pressure contact



Praying-hand joint

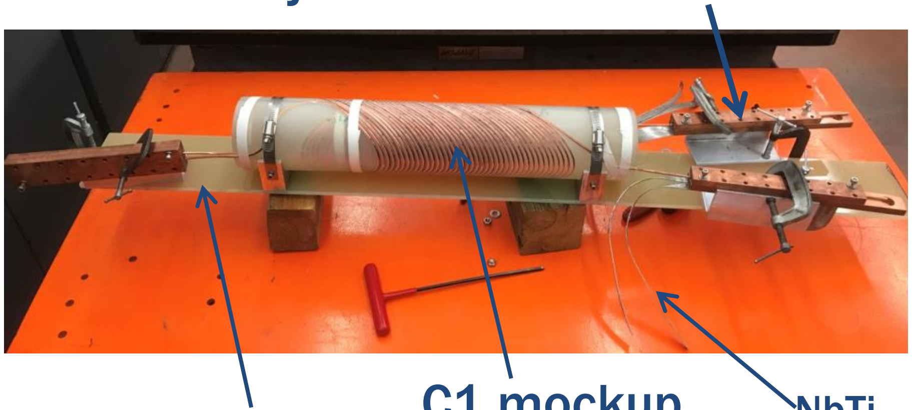
X. Wang, H. Higley

Successfully wound two 40-turn coils for magnet C1, each coil used ~ 15 m long CORC® wires, and developed magnet assembly procedures



Inner layer

Outer layer



Return-end joint

Lead-end joint

C1 mockup

NbTi cable leads

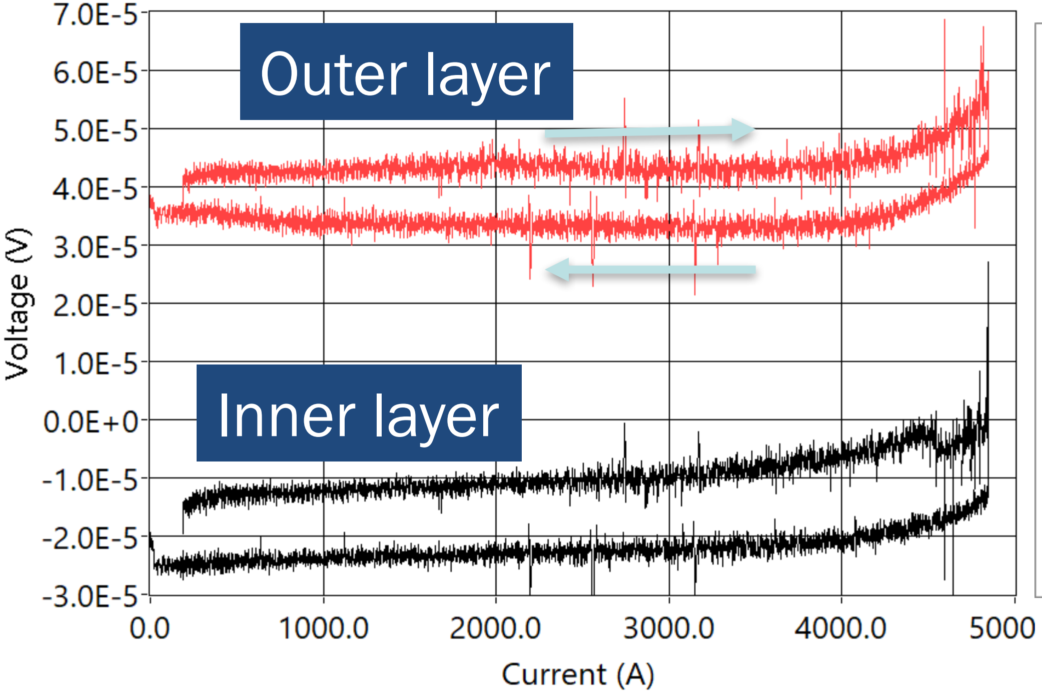
Strongback to anchor the coils and joints

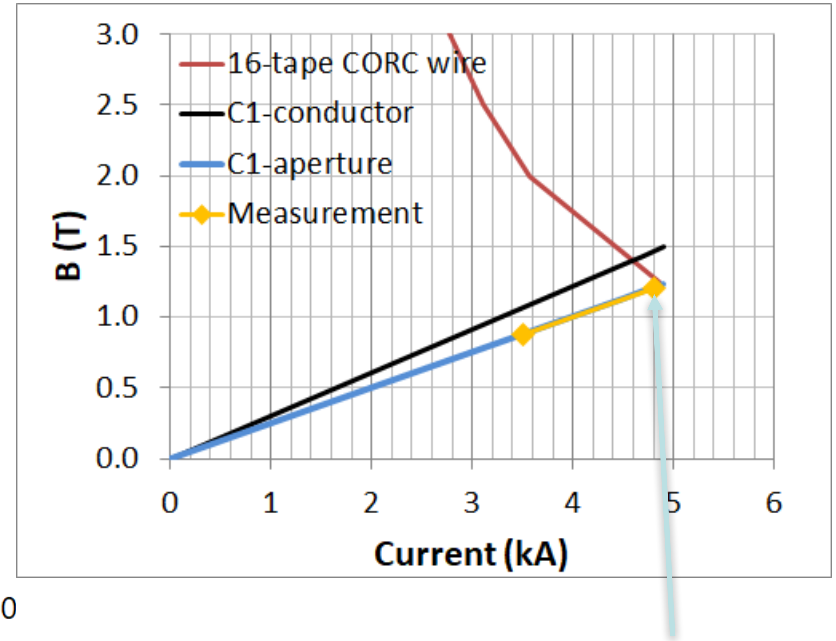
- Co-wound instrumentation wires to reduce inductive noise in voltage-based quench detection

X. Wang

C1 started transition around 3.5 kA in the inner layer, 76% expected short-sample limit

4.2 K





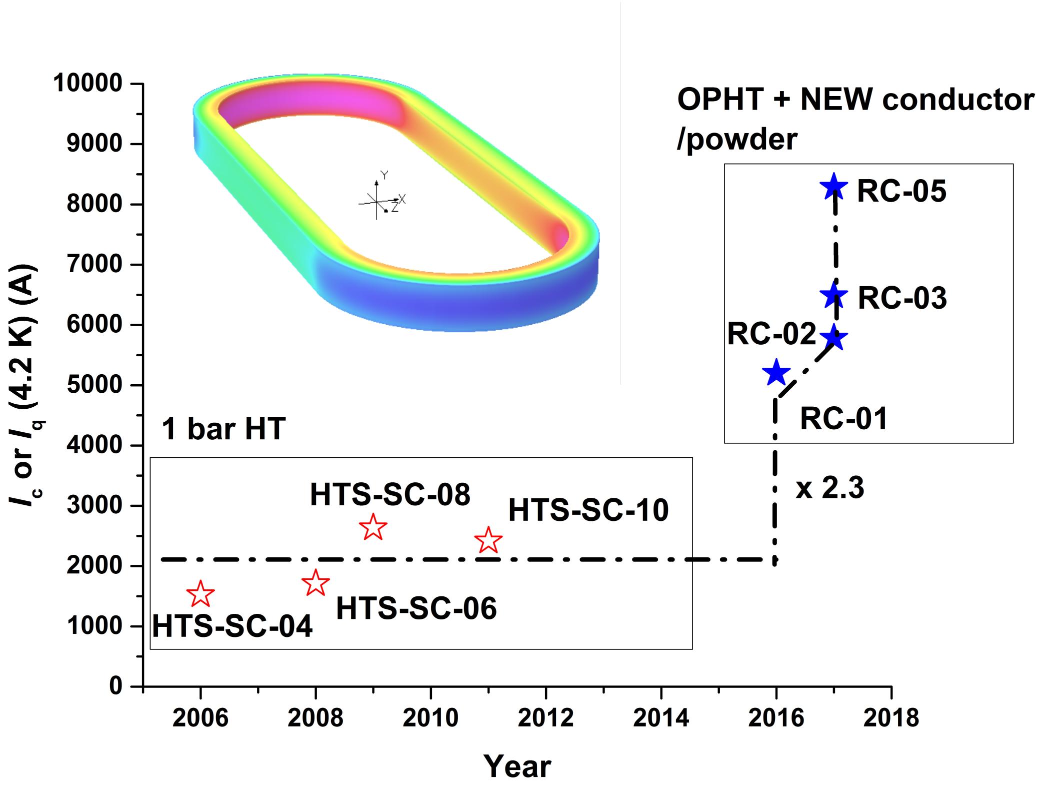
J_e = 640 A/mm^2

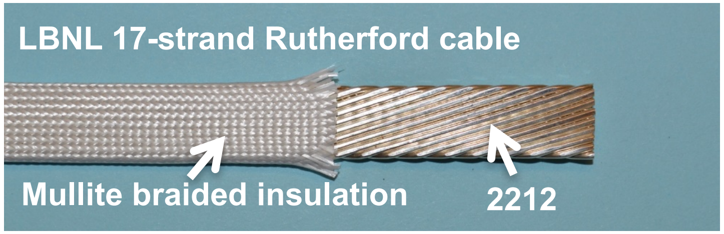
C1 reached 1.2 T at 4.2 K, 104% of the expected performance. Reproducible after thermal cycles

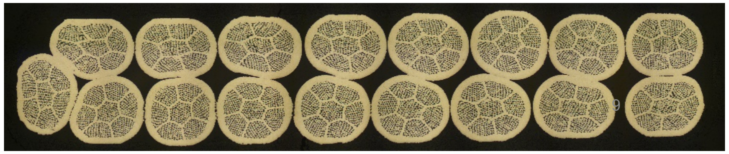
X. Wang

LBNL HTS (2212) subscale magnet program topped with new RC-05 results

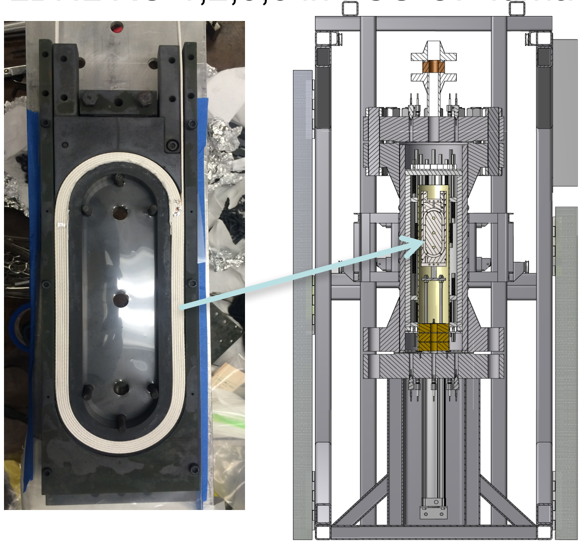
Subscale coils allow fast-turnaround test of cable and magnet-relevant technologies.




LBNL 17-strand Rutherford cable

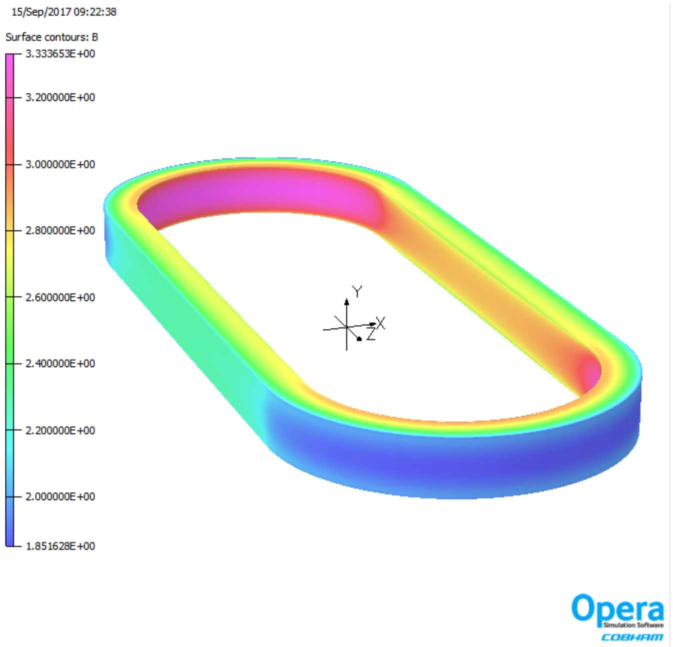


LBNL RC-1,2,3,5 in FSU OP furnace



Parameters of LBNL HTS-SC and RC coils show Bi2212 is now a very relevant high-field conductor

RC5 – peak field – 3.33 T



2-layer x 6-turn racetrack coil based on 17-strand Rutherford cable (1.44 mm x 7.8 mm, strand diameter = 0.8 mm)

140 m conductor, 8 m cable

18 lbs coil thermal mass, 37 cm x 12 cm x 3.1 cm.

50 bar OPHT (@FSU) for RC coils.

RC-01 (5.2 kA, (effective) J_{cable}=463 A/mm^2, (effective) wire J_e=588 A/mm^2.), wax impregnation

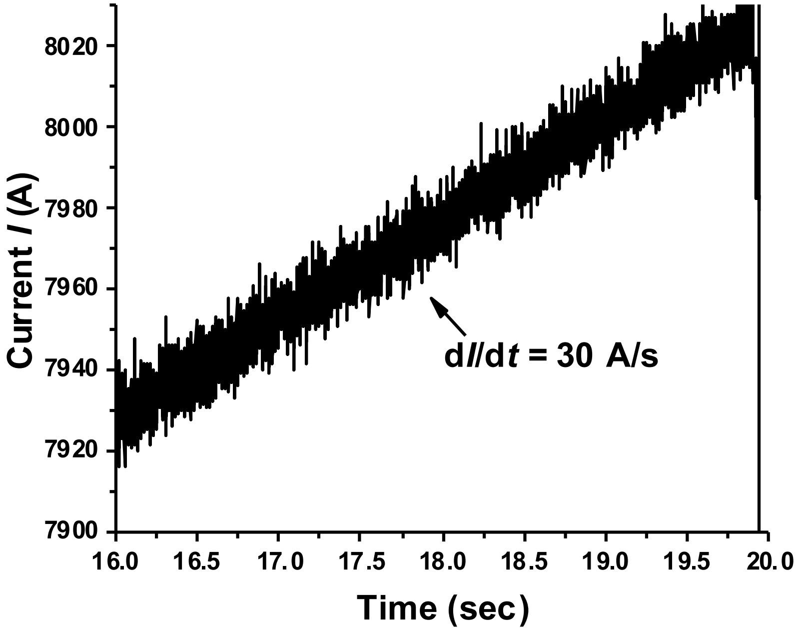
RC-02 (5.8 kA, (effective) J_{cable}=516 A/mm^2, (effective) wire J_e=656 A/mm^2.), wax impregnation

RC-03 (6.5 kA, (effective) J_{cable}=580 A/mm^2, (effective) wire J_e=735 A/mm^2.), NHMFL mix 61 impregnation

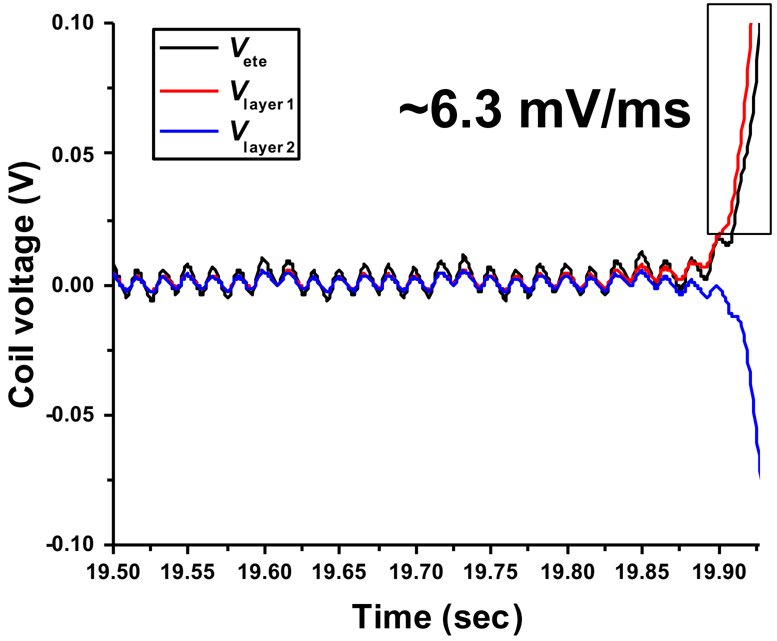
RC-05 (8.3 kA, (effective) J_{cable}=740 A/mm^2, (effective) wire J_e=940 A/mm^2.), CTD101-K impregnation

RC5 reached 8.3 kA and were safely protected. $J_{e,cable}$=740 A/mm^2 and $J_{e,strand}$=940 A/mm^2 (at 3.4 T) are practical current densities for applications

- (Extrapolated to 20 T) $J_{e,cable}$=412 A/mm^2 and $J_{e,strand}$=535 A/mm^2
- Coil was safely protected against quenches.

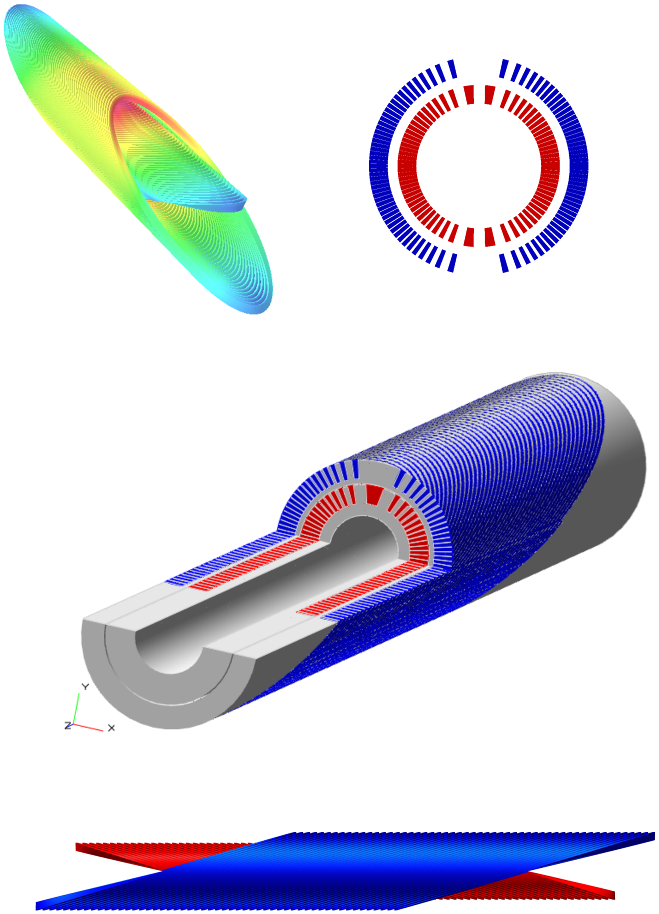


- A thermal run-off.



Redefine what is possible: A route to 20 T dipole - Extending CCT to 2212

L. Garcia Fajardo, L. Brouwer

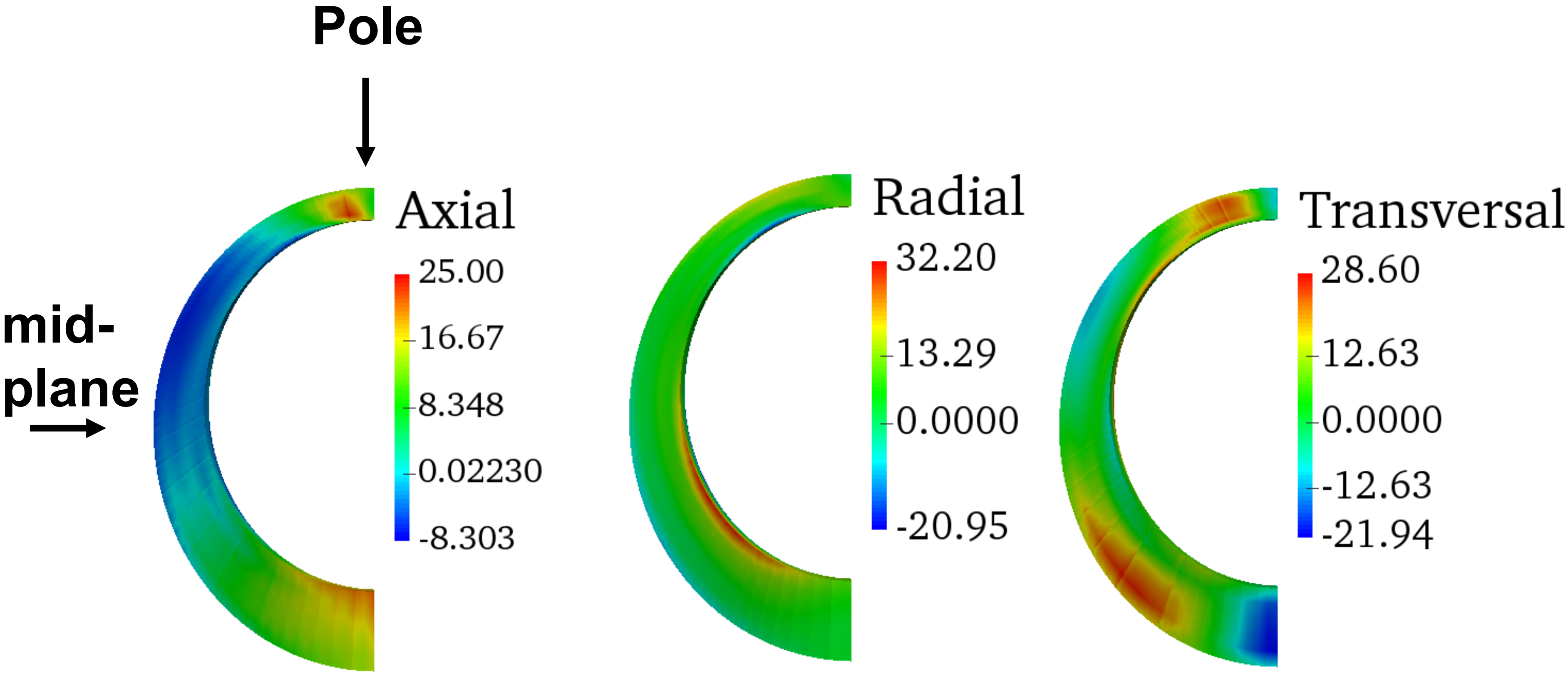


Design 1: 19-strand Rutherford cable, 0.8 mm strand, bore=40 mm, OD=98.4 mm

Background field (T)	PMM170123 strand (90% SSL assumed)	
	I–Design (kA)	**Dipole field in the bore (T)**
0	9.8	**5.4**
15	7.0	**18.9**

CCT technology is effective at managing stresses in Bi-2212 coils within limits, even at 20 T

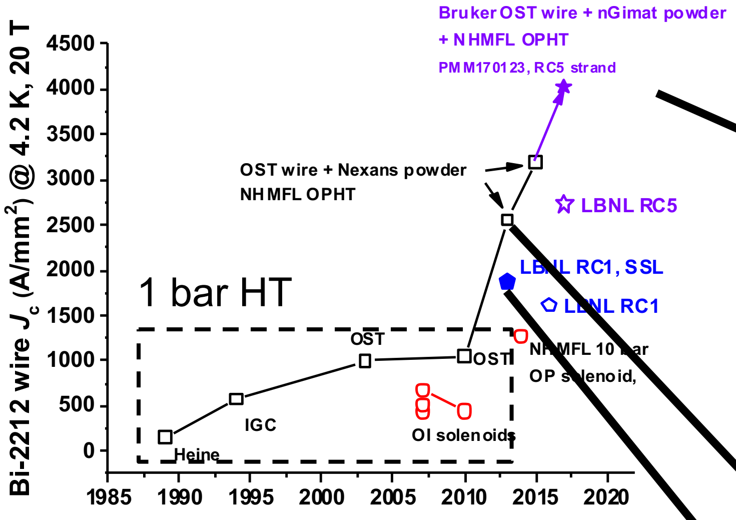
L. Garcia Fajardo, L. Brouwer

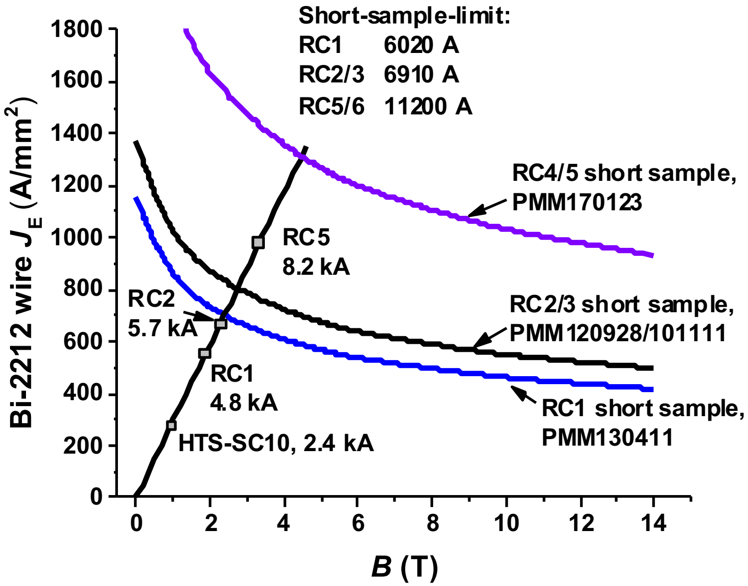


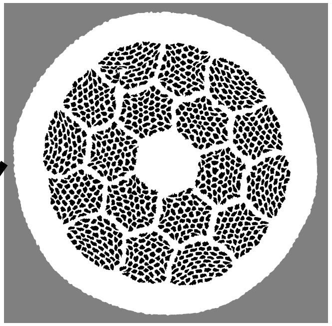
Stress in one-half turn of Bi-2212 cable for design 1 at 18.9 T

RC5 is possible because of advances in powder, wire, cable, and OPHT technologies,

and it also verifies progresses and technological readiness on these fronts.

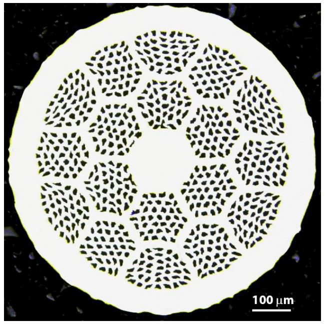




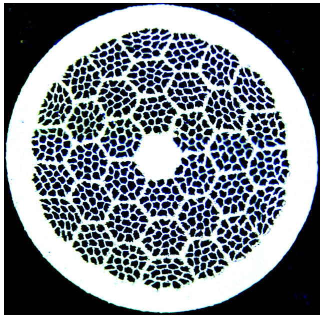


PMM170123, 55x18, nGimat power LXB-52

Conservative short sample J_E used.
See Larbalestier, MT25 talk



PMM101111, 36x18, Nexans powder 77

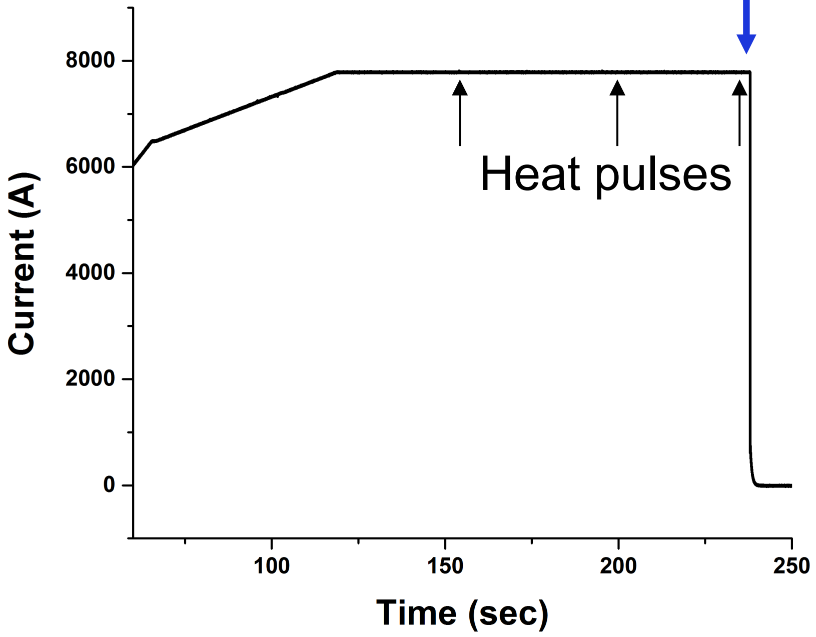


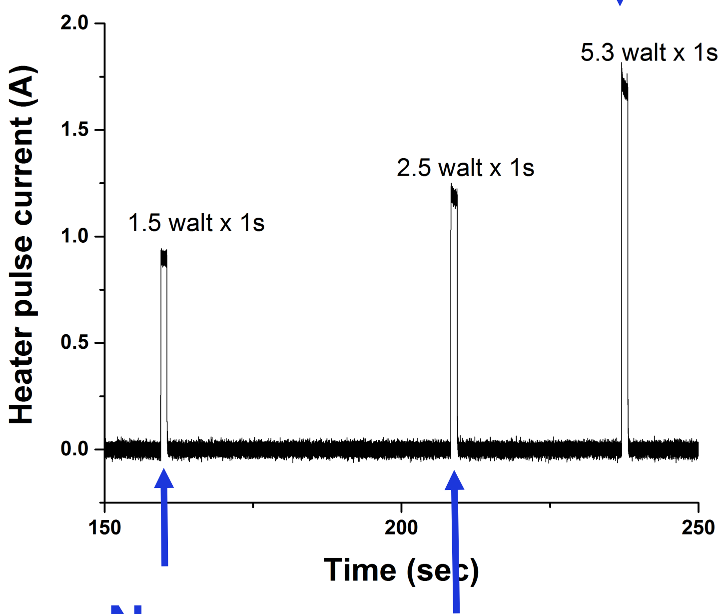
PMM130411, 19x36, Nexans powder 77

RC5 is quite stable against disturbances, even at 7925 A => robust against training

- **No quench against heater pulses at 1.5 W for 1 s, and 2.5 W for 1 s. Finally quenched at 5.3 W for 1 s.**
- **Heat pulse applied at the turn #1 (straight section, B≈2.5 T).**

Quench



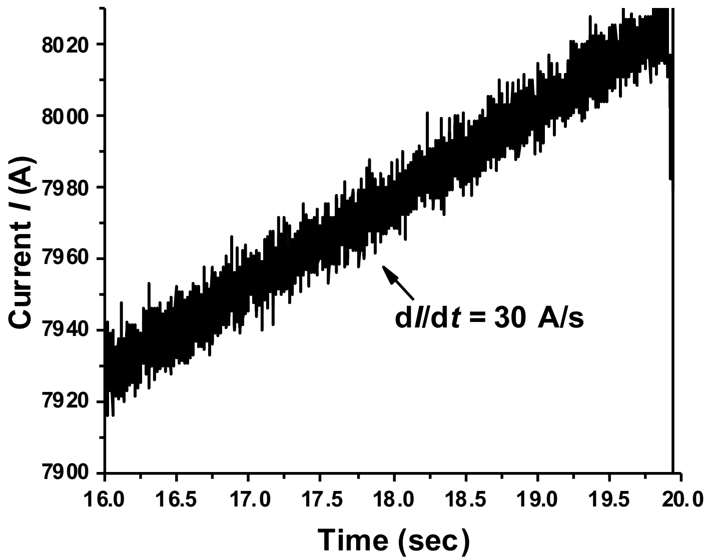


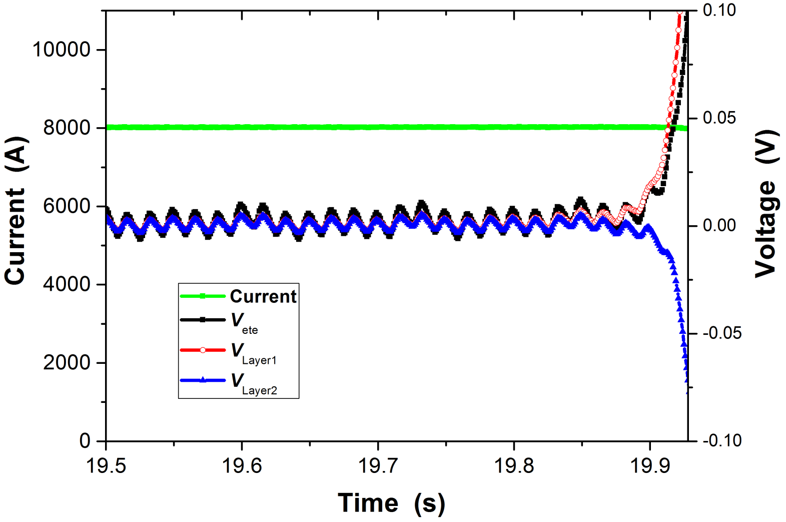
No Quench

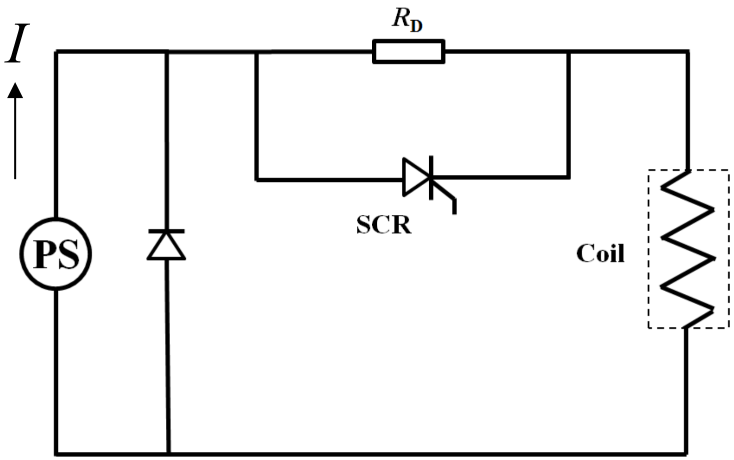
No Quench

Quench detection and protection at wire J_o of 910 A/mm^2

– Example: A linearly increased current run, coil voltage seems no different from those of LTS magnets





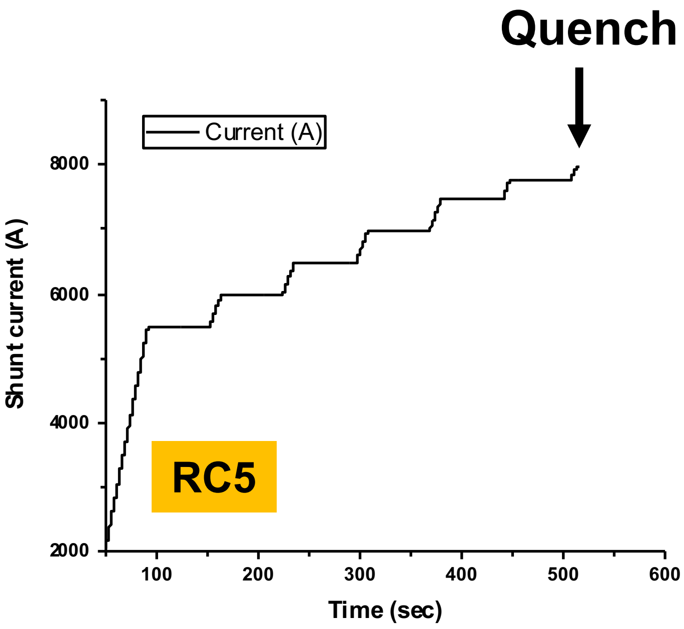


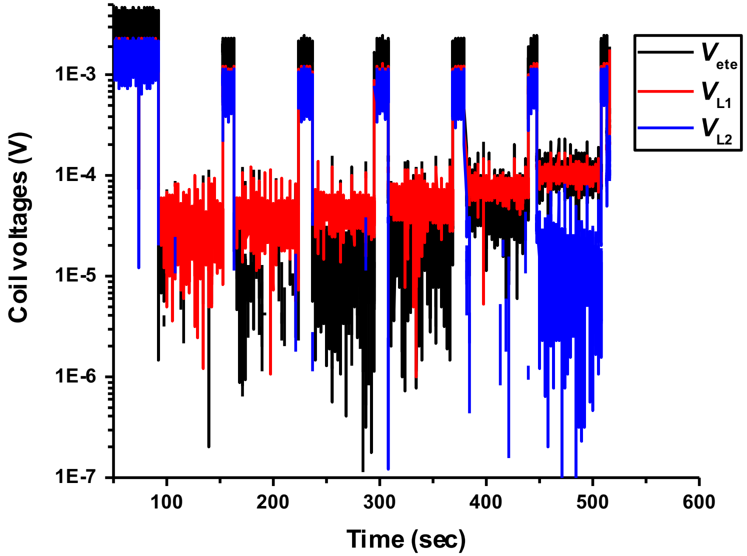
t=19.782 s, *Voltage taking off.*

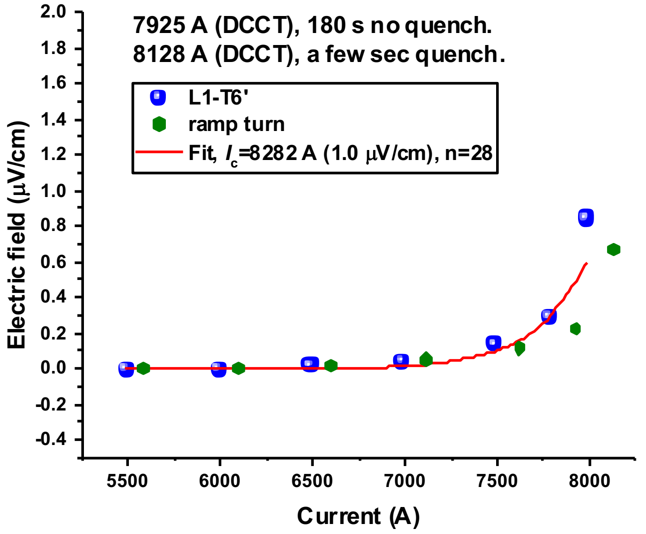
t=19.895 s, V_{ete} = 0.011 V

RC5 – E-J characteristics defined with a stair-case run.
Many resistive, easy to detect signals revealed before the quench

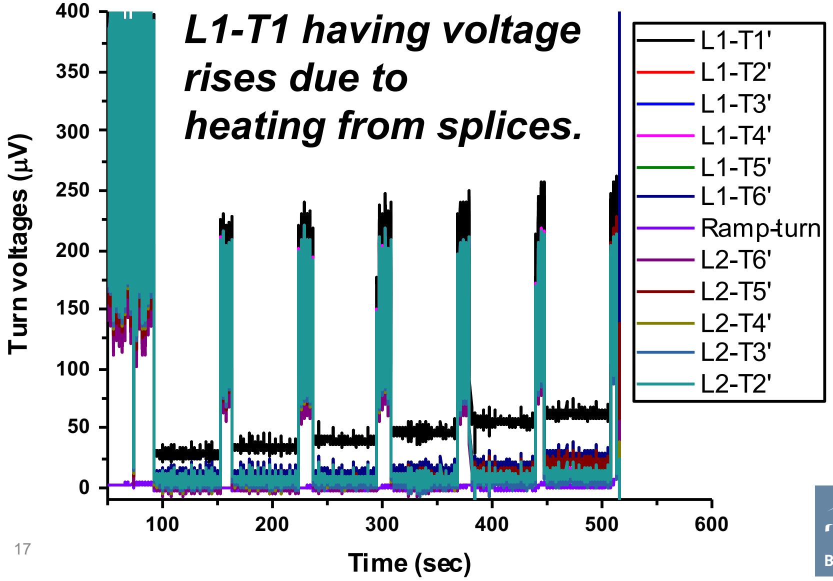
(global superconducting transition driven by continuous joule heating)





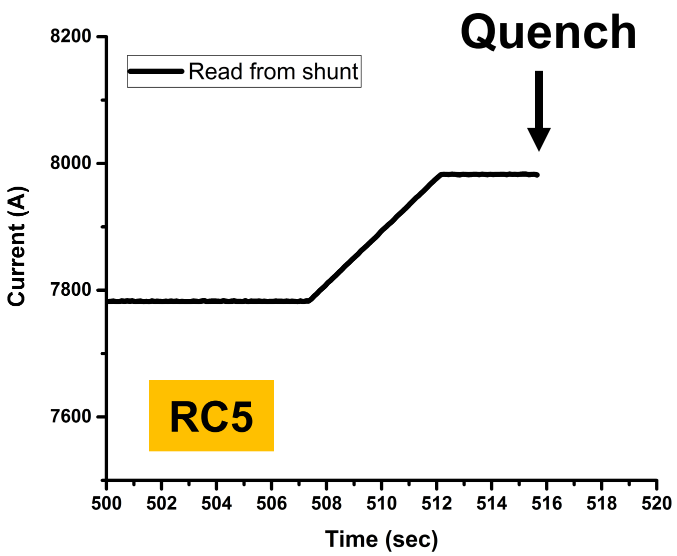


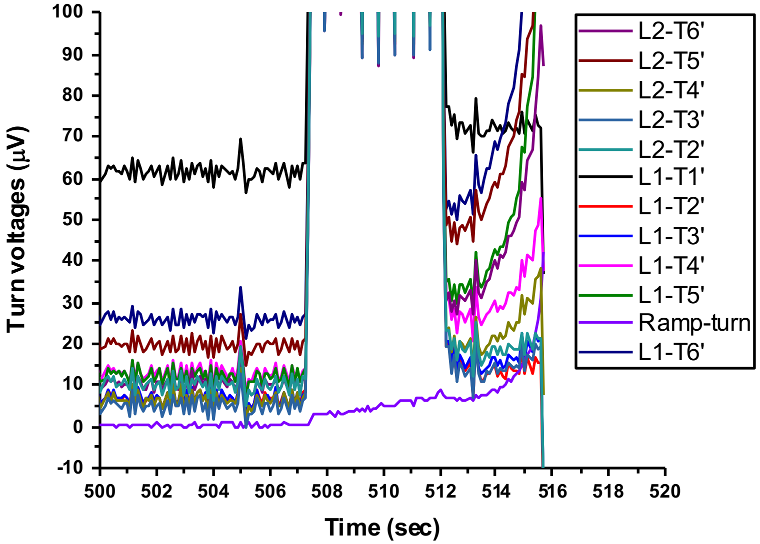
7925 A (DCCT), 180 s no quench.
8128 A (DCCT), a few sec quench.

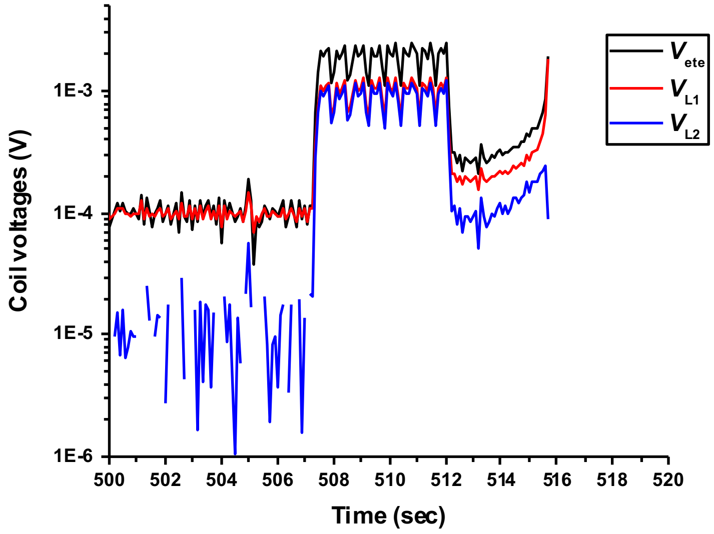


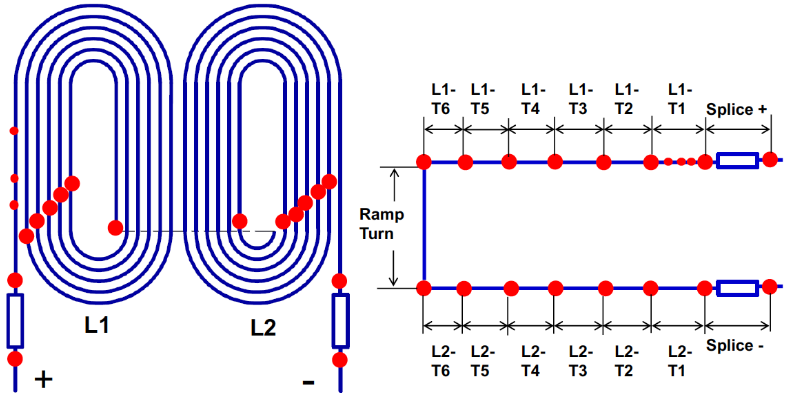
L1-T1 having voltage rises due to heating from splices.

The global superconducting transition - Multiple turns turning normal makes possible easy quench detection.

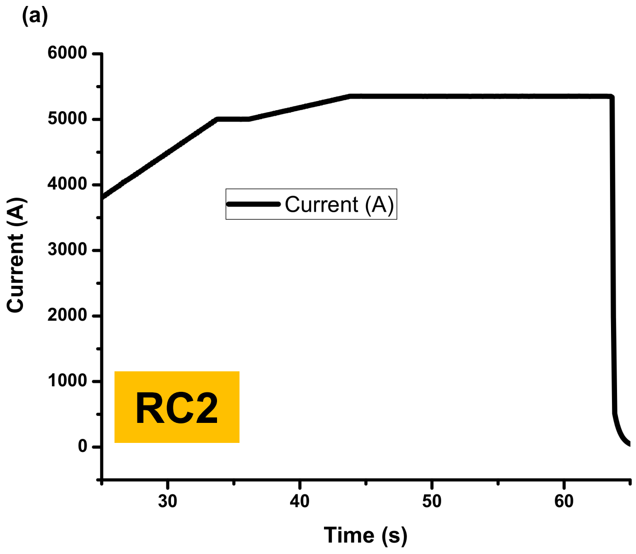


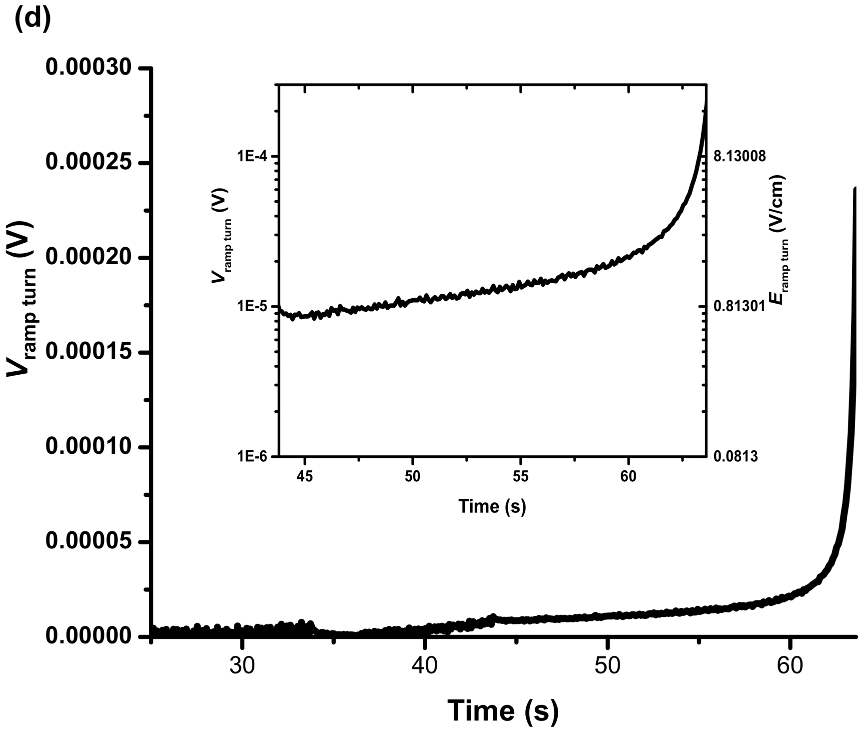






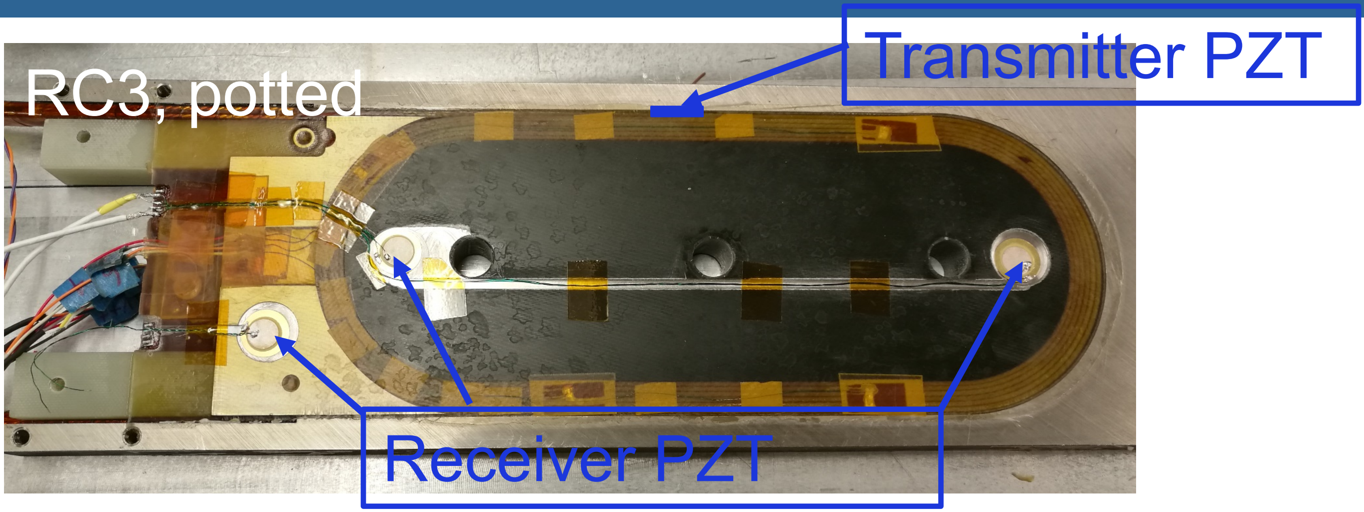
Another operation case that illustrates high-stability and possibility of ~10 μV quench detection.

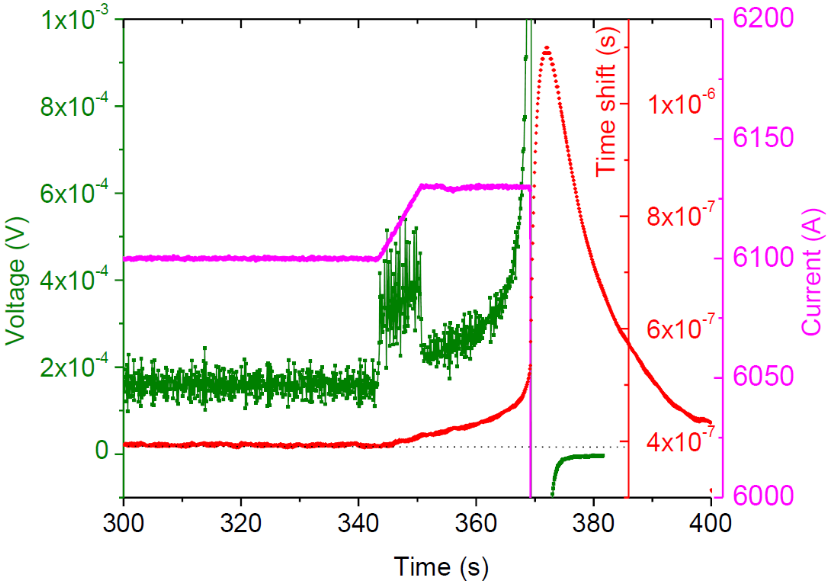




Ball park analysis – 1.125 J into the ramp turn within ~15 s, with the conductor temperature around 14 K.

Noninvasive, fast acoustic sensing technique shown to be promising for quench detection on RC3



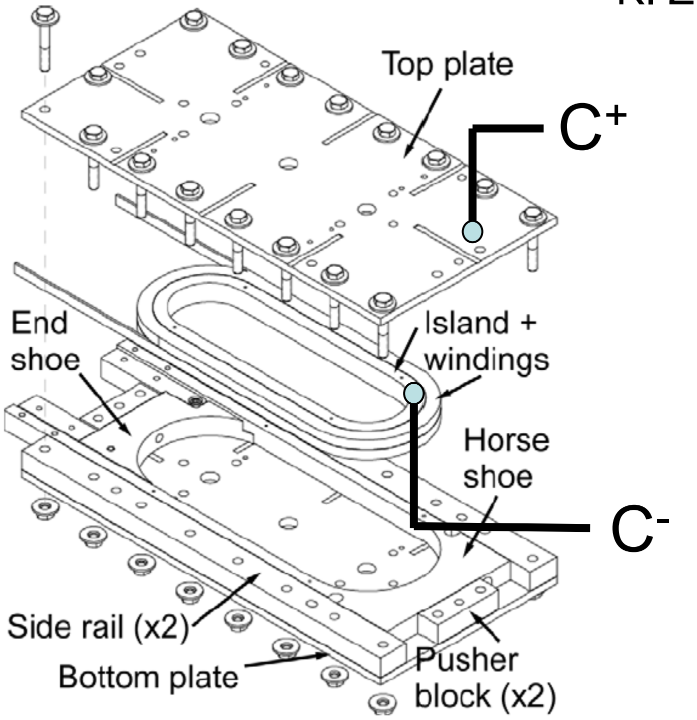


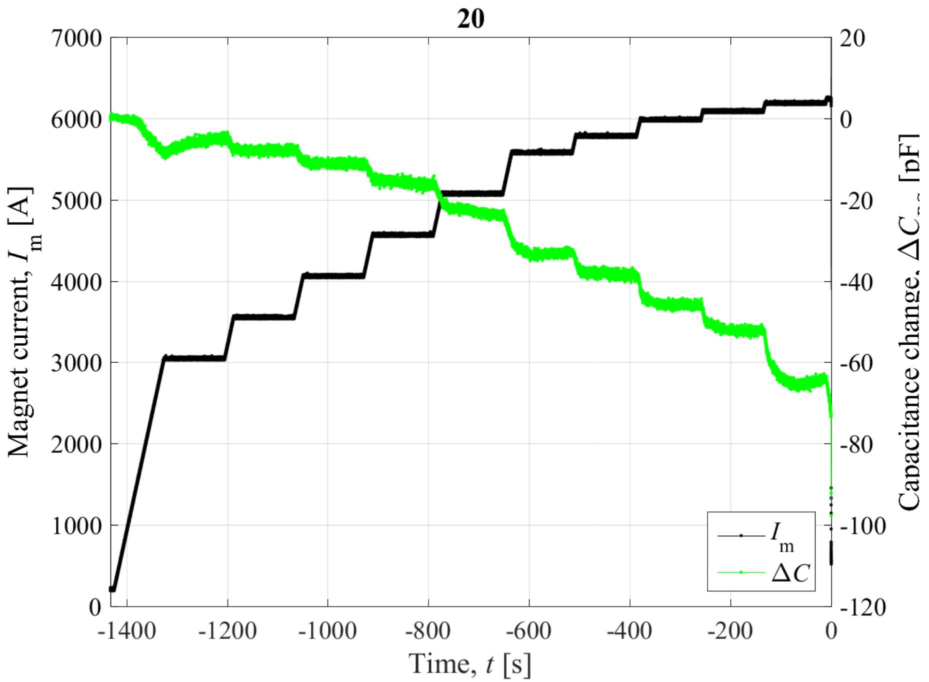
With M. Marchevsky, LBNL

Marchevsky and Gourlay,
Appl. Phys. Lett. **110**, 012601 (2017);

Rugged capacitance probing technique promising for monitoring magnet operation and quench detection tested on RC coils

With **E. Ravaioli (LBNL)**, M. Marchevsky (LBNL), and K. Zhang (IHEP visiting at LBNL)





- ***Capable of detecting joule heating as small as 10 mW.***

Summary

2212 wire J_e – 940 A/mm^2, cable J_e - 740 A/mm^2, cable I_q -8300 A, stable at 7800 A, now achieved in LBNL RC5 subscale magnet.

- 2212 conductors are ready for magnets
- Significant wire J_c increase in 2017.

REBCO – CORC wires made into novel CCT magnets and successfully tested.

Contributors – RC5 is a product of successful collaboration between U.S national lab, university, and industries.

- **K. Zhang**, **H. Higley**, A. Lin, L. Garcia Fajardo, J. Taylor, M. Turqueti, T. Shen

- **E. Bosque**, J. Jiang, U.P. Trociewitz, E.E. Hellstrom, D.C. Larbalestier

The LBNL RC5 was made from the wire PMM-170123, fabricated by Bruker OST with new Bi-2212 powder developed by nGimat LLC (DOE SBIR support) and donated to LBNL.

- H. Miao, Y. Huang

- **M. White**, R. Nesbit, A. Xu, A. Hunt