Bi-2212 Coil Technology

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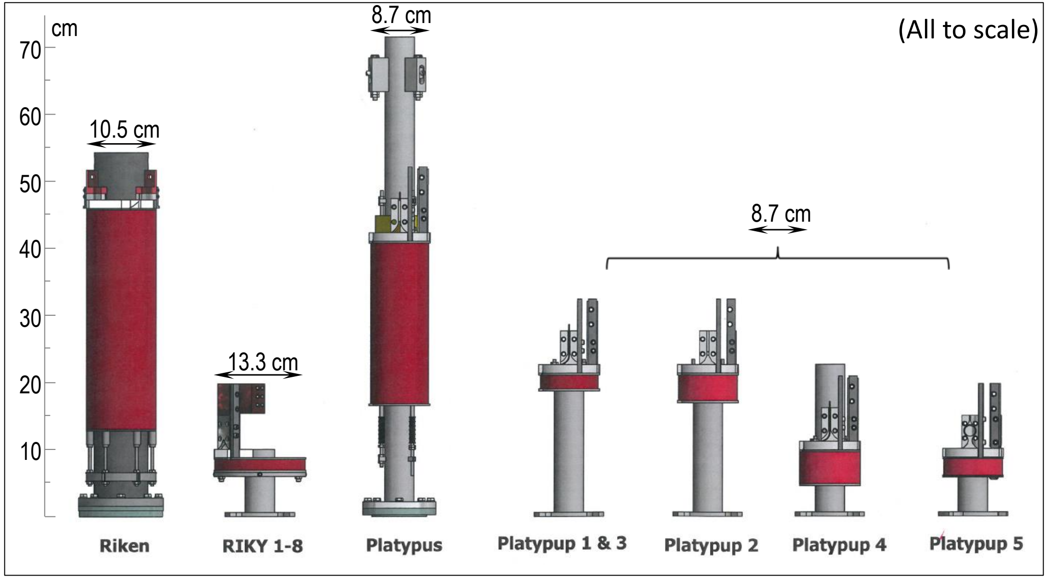
Summary of high-field magnet technology related R&D results for 2212

- Test of key elements of a 2212 coil technology
  - Very high J_e with new powders (>1 kA/mm^2 at 30 T)
  - Long length round wire conductor (~1 mile) that looks like LTS conductor
  - Conductor insulation
  - Successful internal reinforcement of coils
  - Good handling of OPHT (50 bar, ~50 cm homogeneous zone after many modifications)
  - Demonstrated persistent 2212-2212 joints
  - Started looking into more advanced quench protection

2212 Test Coils



- We build Coils of various sizes from small bobbins to fully instrumented larger coils for in-field testing applying analysis lead design
- Serve as confidence builders for larger high-field coils like Platypus and beyond (testing new concepts, models, manufacturing procedures)

About 1 km of conductor each!

Coil Tests: Rikys and Pups

- **Goals: Understand and control performance limits of our 2212 coils**
- **Model coils with conductor resolution**
- **Compare with experiments**

Riky-1:

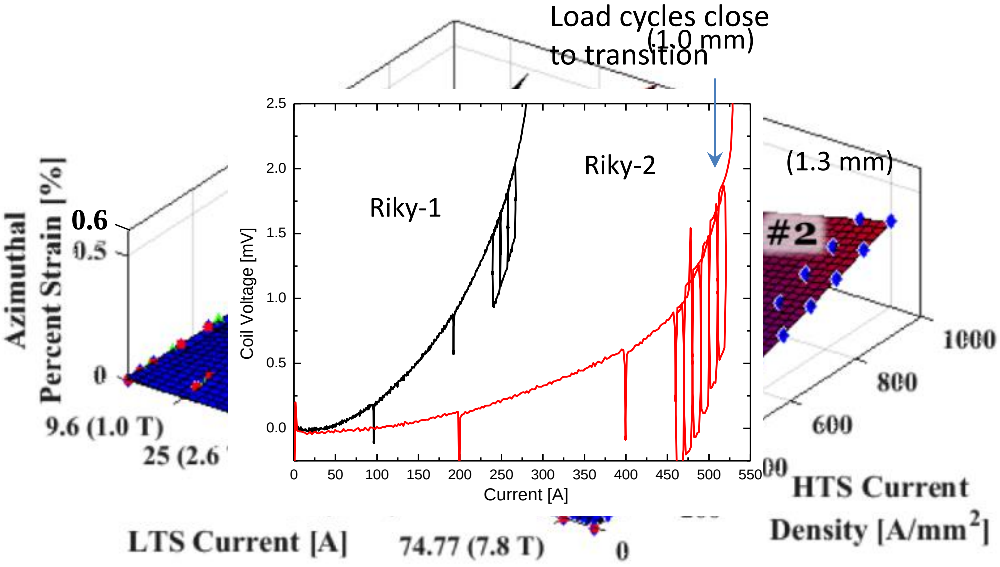
- Epoxy impregnated but otherwise non-reinforced coil

Riky-2:

- Epoxy impregnated, fully reinforced coil
- Could not be strained to degradation in 8 T background

Riky-3:

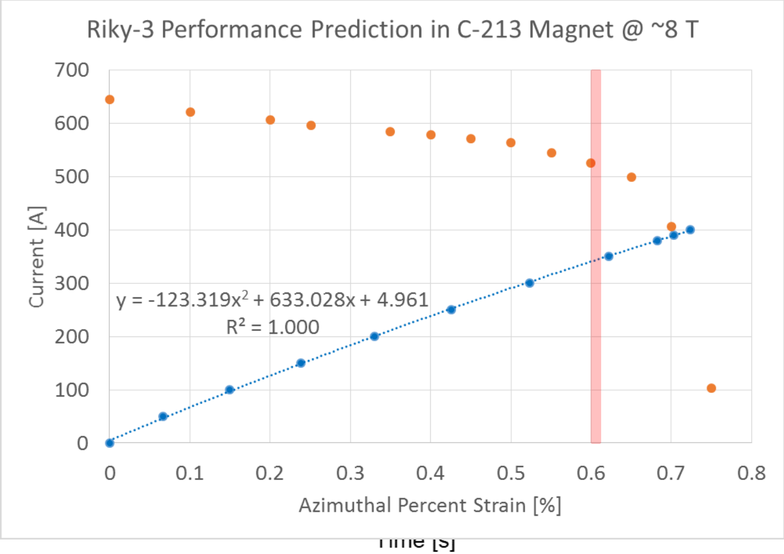
- Epoxy impregnated, partially and targeted reinforced coil



- **Riky-1** experienced fast ramp to 410 A (8 T background) and degraded
- In subsequent tests reached 275 A repeatedly without further degradation
- Model predicted ~0.6 % strain at 300 A
- **Riky-2** clearly showed improved stress management compared with Riky-1 and did not reach its predicted strain limit
- Reached 528 A and quenched due to introduced heat from external leads
- Both coils could be load-cycled close to transition many times without further degradation

Test Coil Riky-3

- Clearly showed that the FEA modeling works to predict coil performance, 348 A predicted for onset of damage
- The first trip was observed at 350 A!
- Very clearly not an Ic transition but rather a strain induced trip
- In no-reinforced condition the outer layer would have experienced a stress of ~300 MPa: reinforcement is effective
- Showed saturation of I_c retention on subsequent quenches
- Below onset of thermal runaway the coil could be load-cycled many times



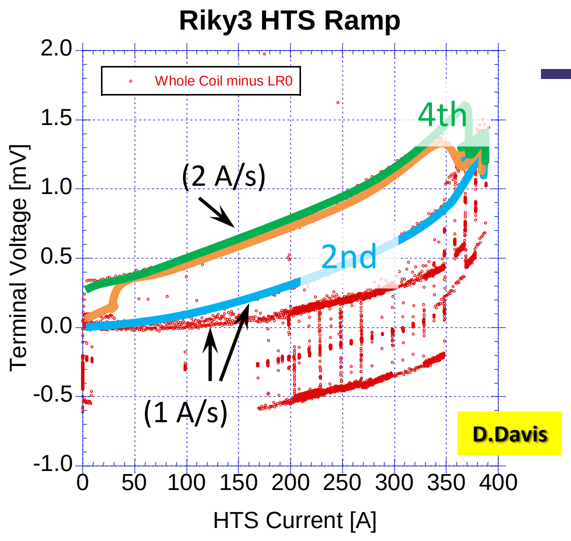
Predicted peak strain expected for given Riky-3 operating currents are shown as blue line plotted against I_c/I_{c0} retention curve based on data by C. Scheuerlein*, CERN

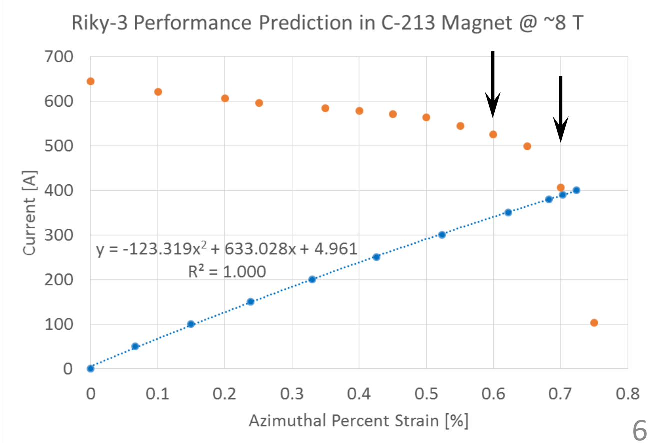
*R. Bjoerstad, C. Scheuerlein, M. Rikel *et al.*, Supercond. Sci. Technol. 28 (2015) 062002

Test Coil Riky-3 contd.

- The first trip was observed at 350 A
- A second quench observed at 391.5 A, which was very clearly an I_c transition (voltage creep)
- Subsequent quenches also transition at about the same I_c with some slight degradation (387.4 A to 385.5 A)
- So how do we get to 391.5 A (at 0.708%) after already tripping at the 'critical strain' of 0.6 % strain???
- 0.6 % strain is associated with the cliff - onset of damage - from the I_c retention curve
- At ~390 A the conductor I_c and coil load line cross

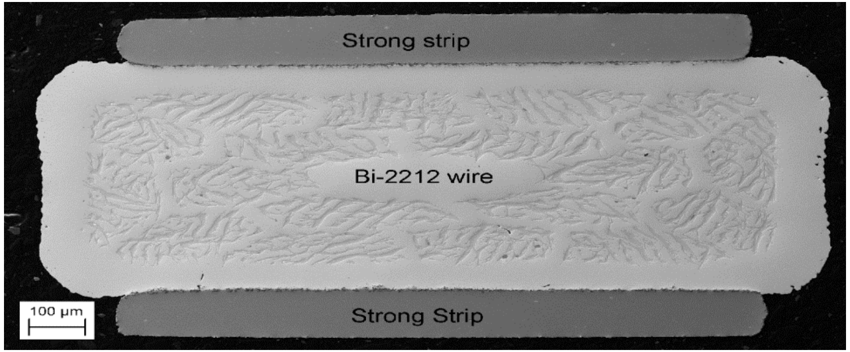
It is interesting to note that the coil does not "fall off the cliff" like a short conductor sample under these conditions





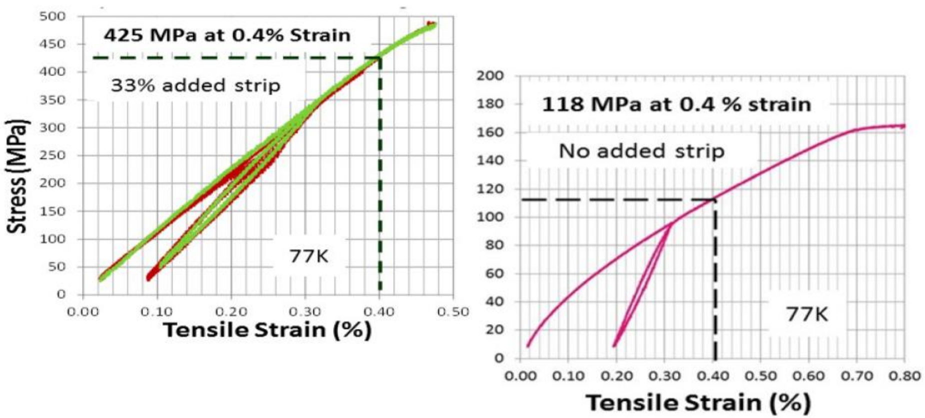
Advances in Bi-2212 Conductor Strengthening

- Low aspect ratio applied to preserve electro-magnetic isotropy of wire



- Shown here is a wire bonded with reinforcement tape made by Solid Materials Solutions (SMS, Alex Otto)

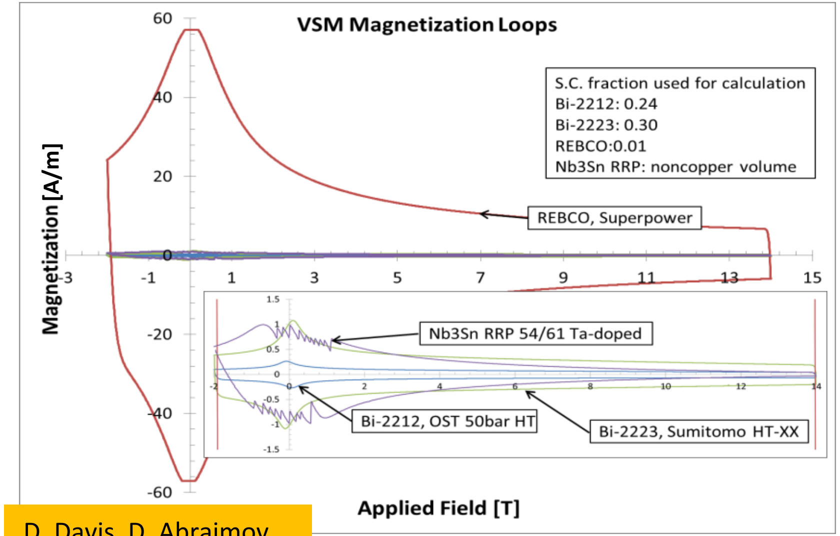
Measurements on OPHT processed wires



425 MPa at 0.4% strain versus **118 MPa for 2212/Ag**
~3.5 fold benefit with 33% strip area (similar to SEI 2223 NX).

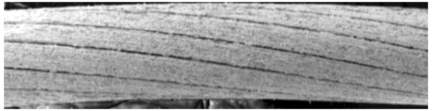
- Work on reinforced conductor and applications in coils is ongoing

Coil Tests: Field Hysteresis of Coils made with Twisted Conductor

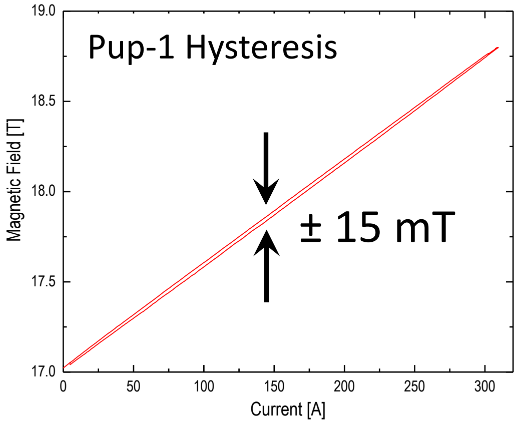


D. Davis, D. Abraimov

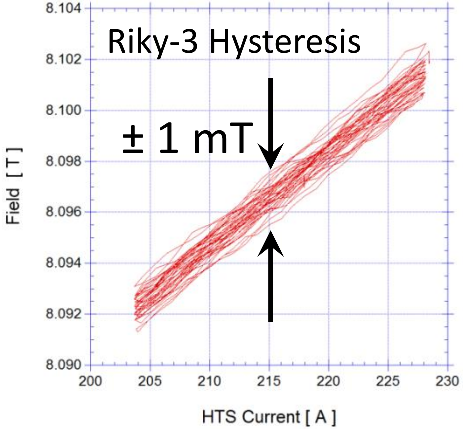
- Much smaller Magnetization for 2212, comparable with Nb_3Sn wire
- Twisting further reduces magnetization of 2212 conductor

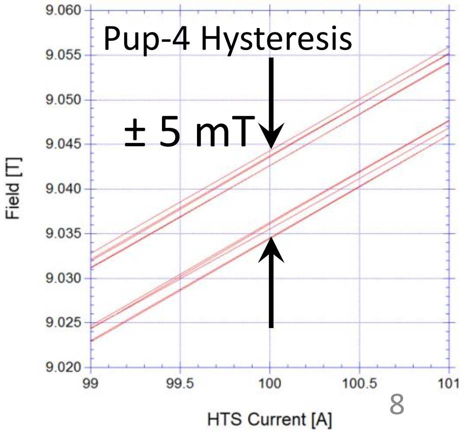


Untwisted 2212:

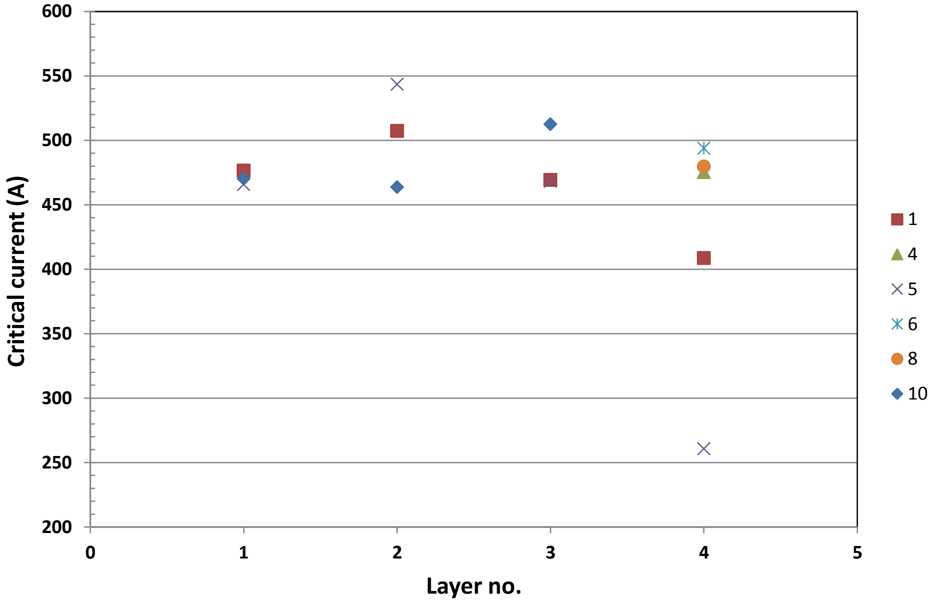


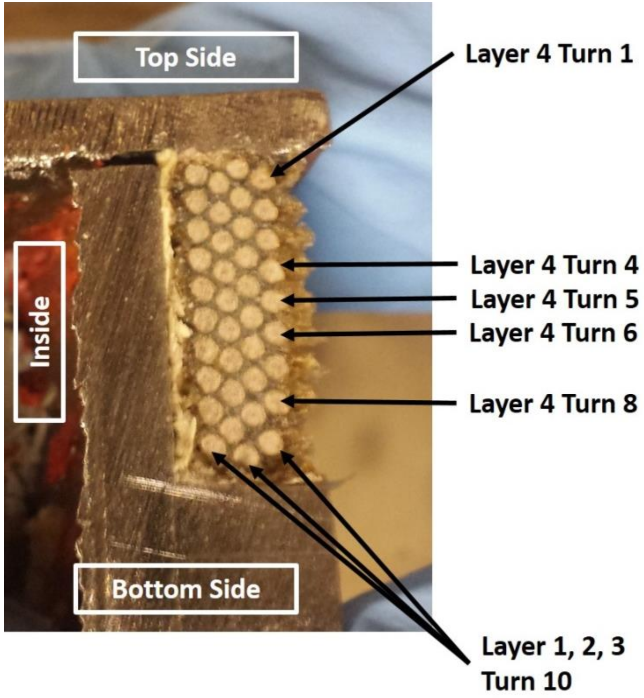
Twisted 2212:





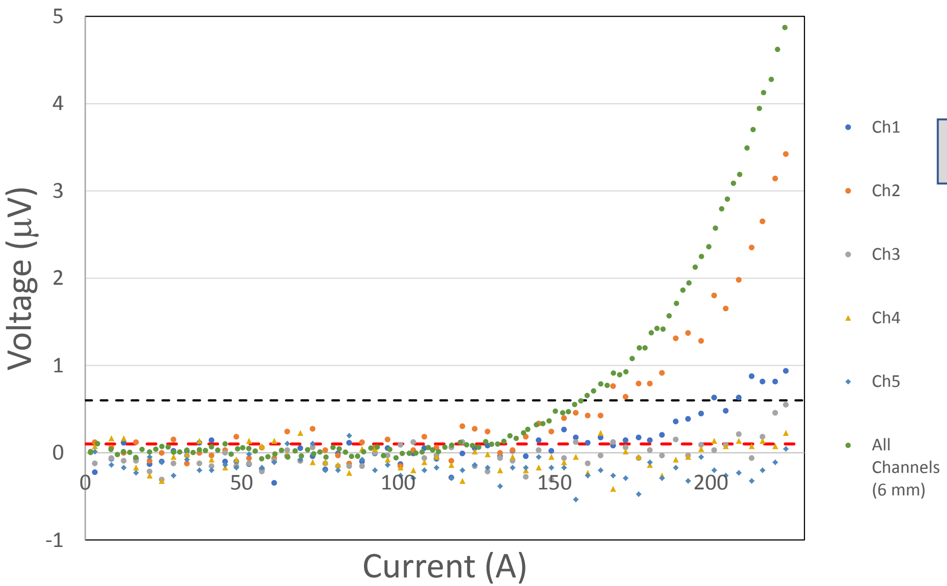
Good Powder QC required

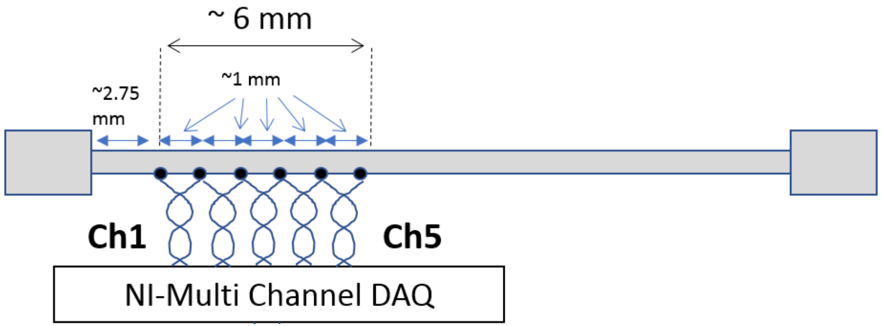




- Riky-5, made with Lot-82 conductor had low I_c
- Coil did not reach any critical strain value
- Systematic coil deconstruction revealed one small low I_c section (layer 4, turn 5)

A Closer Look at Layer 4-Turn 5



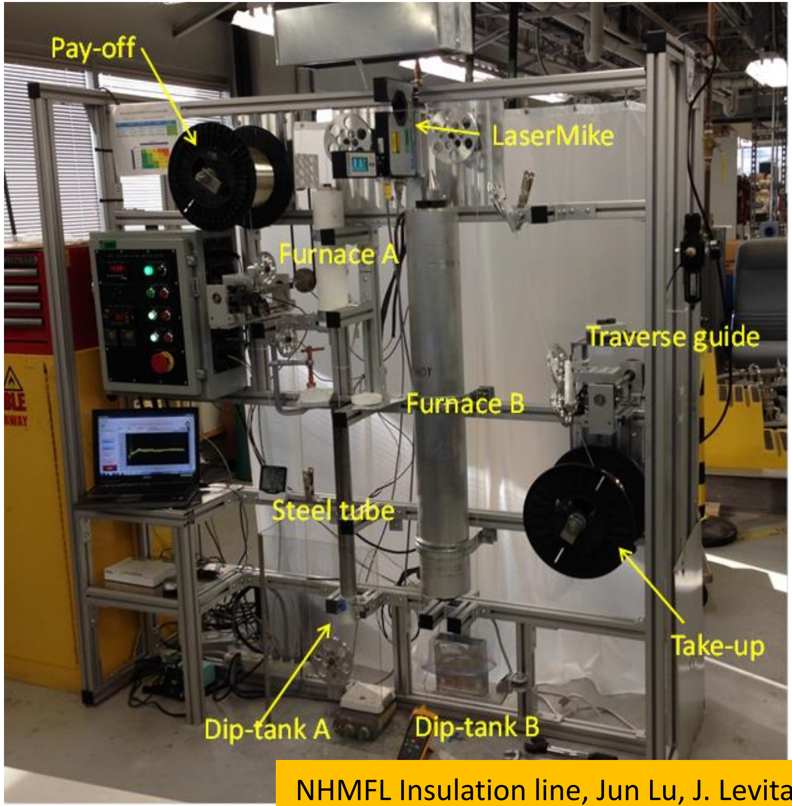


- It appears that particle inclusions (clunkers) do more that just lowering the average transport properties

	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5
I_c (A)	155	**137**	190	193	150
n	5.8	7.2	9.1	6.8	5.8

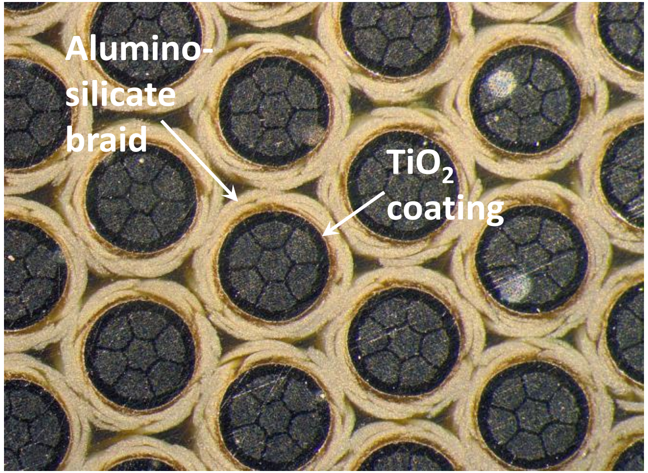
Insulation for Bi-2212 Conductor

- Dip coating process with TiO_2 particles dispersed in a polymer
- Polymer burns off leaving strong ceramic layer



NHMFL Insulation line, Jun Lu, J. Levitan

- >1 km lengths now being coated reliably
- Added alumino-silicate braid to improve stand-off and winding pack integrity



- Tests at LBNL of their coated and braided race-track coils have also shown higher leak resistance along with an improvement of transport properties

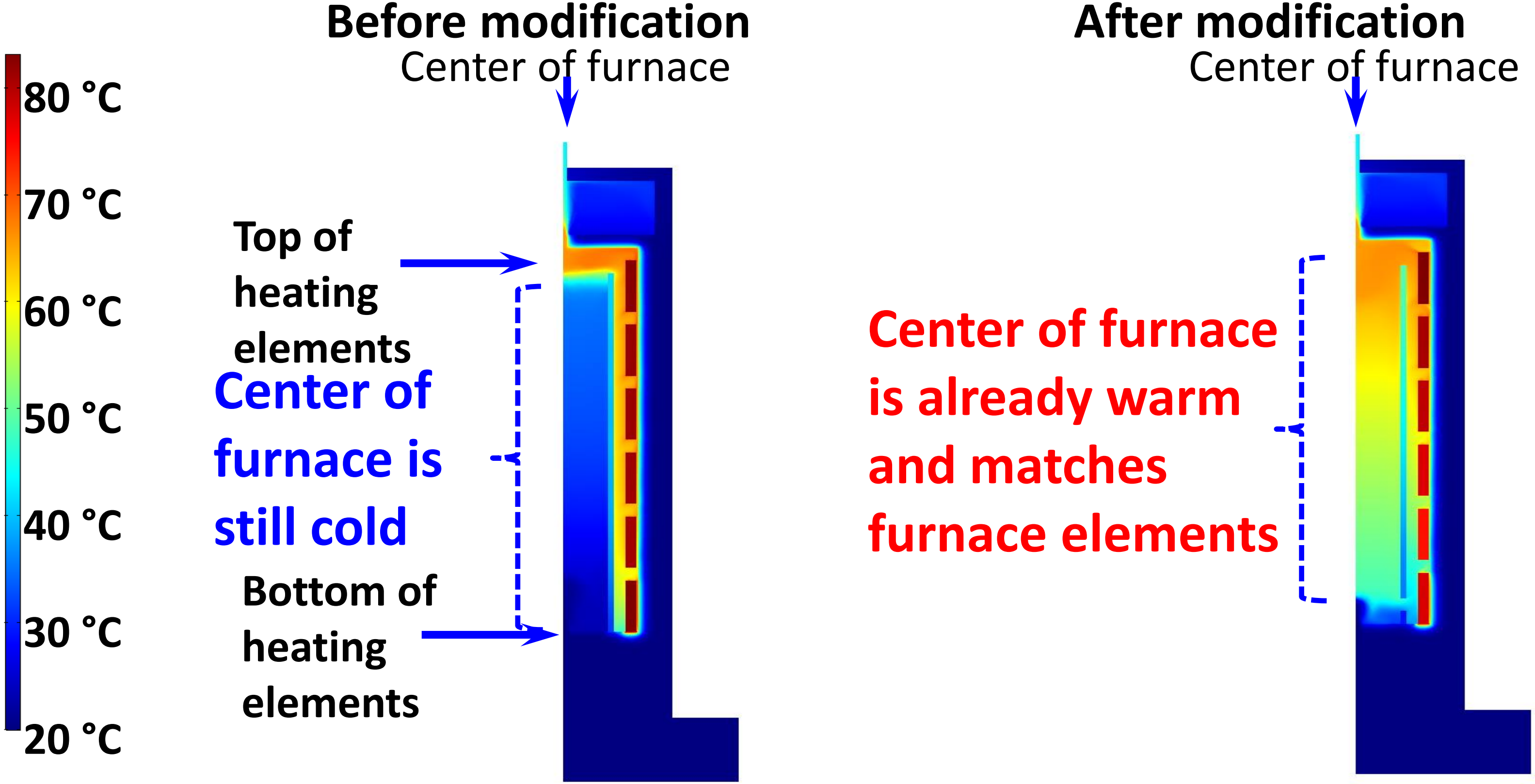
Our High Pressure Furnace is the Work Horse for Bi-2212 Coil Heat Treatment

- First-of-its-kind pressurized 6-zone furnace built by Deltech
- Currently largest OP furnace available for Bi-2212 heat treatment
- Design parameters: 900 °C, 100 atm total pressure, 500 mm hot zone – currently use 50 atm and the hot zone is ~430 mm (130 mm dia.)
- This furnace required extensive in-house engineering to make it a robust, reliable equipment
- Successful heat treatment of many coils

Outer wall dia: 324 mm
Working Hot Zone dia: 130 mm
Working Hot Zone height: 430 mm

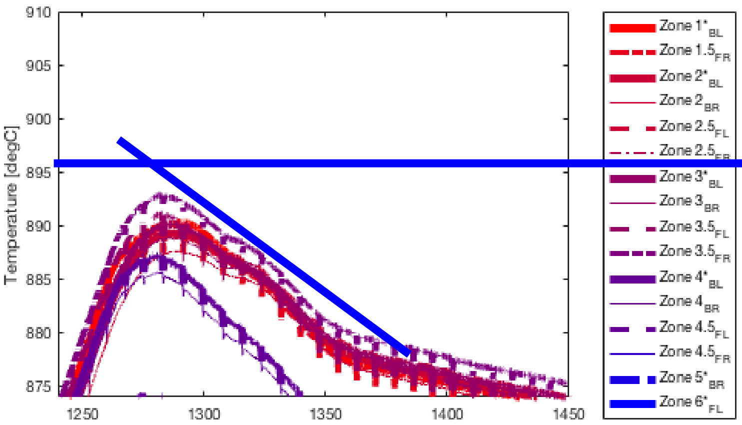
Modified Furnace Based on Extensive Modelling – Significantly Improved Heat Flow and Uniformity

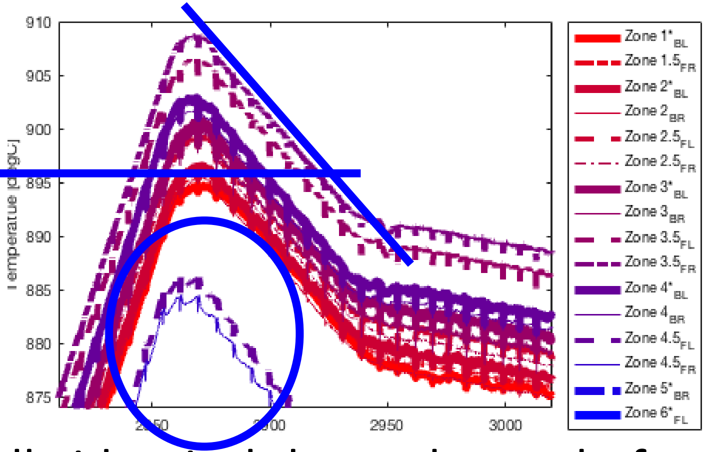
Snapshot of temperature in furnace after heating 10 min



Modifying the Furnace Gives Improved Control of the Furnace and the OP Heat Treatment

Before modification **After modification**



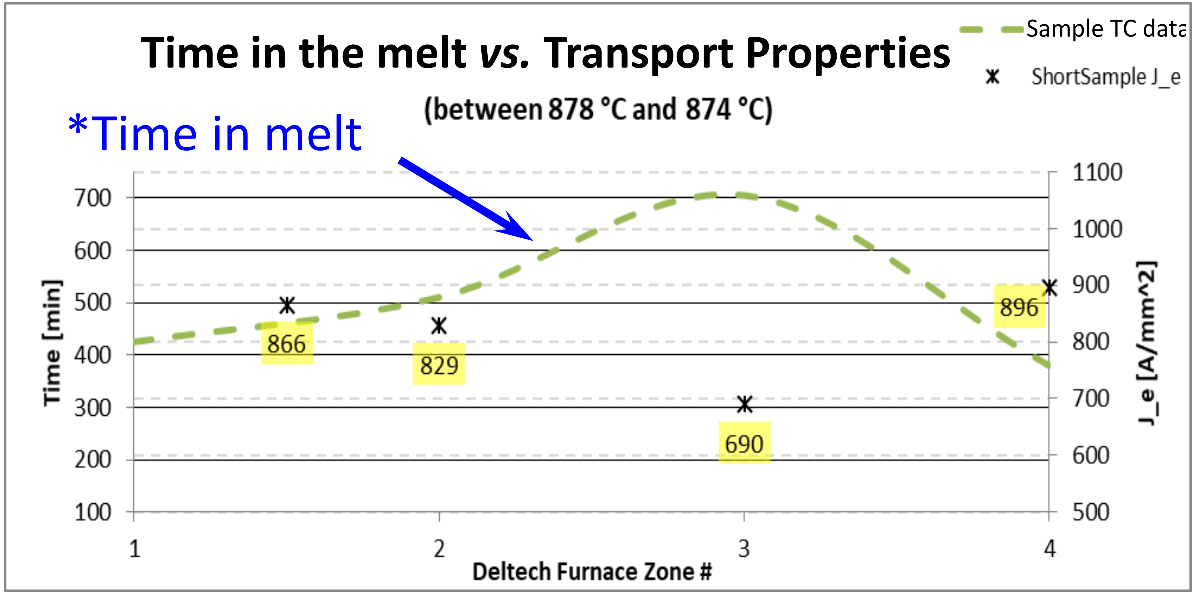


Used same furnace settings and essentially identical thermal mass before and after modifications

Improvements after modifications:

- Increased temperature in uniform hot zone
- Provided more precise control of cooling rates
- Raised temperature of lower zones - lengthened hot zone

Improved Temperature Regulation Gives More Control of Time in the Melt



* Time in the melt curve derived from temporal behavior of 16 sample TC data over 4 zones

Important implications:

- **Bi-2212 time in melt (t_{melt} , time from melting to re-solidification) is a powerful parameter controlling J_c**
- **Longer t_{melt} yields lower J_c**

Coils OPHT'ed in Deltech, for Maglab and Collaborations

Date	Coil	OPHT
2/11/15	Platylong	Success
2/18/15	Platypup-1	Success
2/23/15	Platypup-2	Success
6/01/15	Platypup-3	Success
6/23/15	PreDensified / Compression Coil	Success
8/31/15	Platypus	Insulation (solved 2016)
4/01/16	Riky-1	Success
4/28/16	Riky-2	Success
6/09/16	LBNL RaceTrack-1	Success
7/26/16	LBNL RaceTrack-2	Success
10/25/16	RIKEN	Heat distribution
1/07/17	CERN/Twente Rutherford Cable	Success
1/12/17	OI Coil	Success
1/30/17	Platypup-4	Success
2/13/17	LBNL RaceTrack-3	Success
4/18/17	Riky-3	Success
4/26/17	Riky-4	Success
8/14/17	LBNL RaceTrack-4	Success
8/17/17	LBNL RaceTrack-5	Success
12/05/17	Riky-5 and Platypup-5	Success
01/29/18	LBNL RaceTrack-6	Success

→ Coil debilitating issue diagnosed as electrical shorting through very thin TiO_2 coating

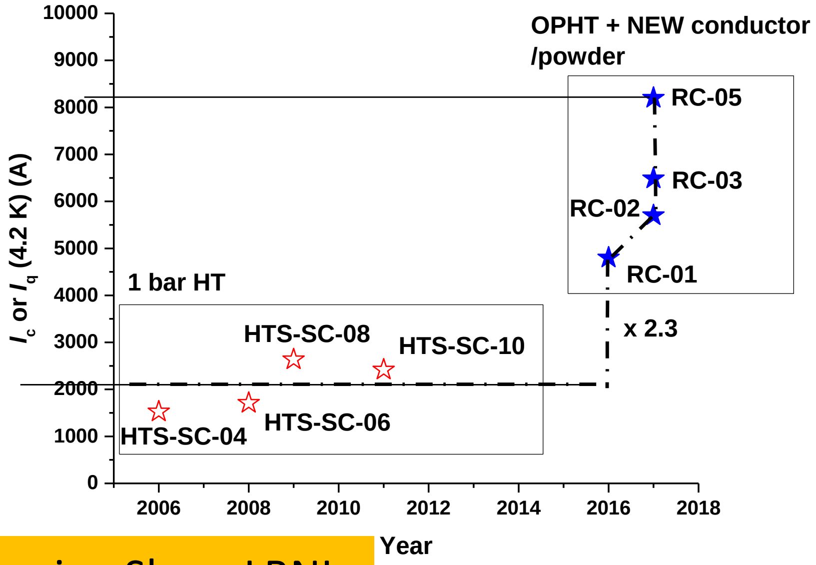
→ Transport issues at coil ends diagnosed as thermal mass and heat sink issue during OPHT

10 coils OPHT'ed in 2017

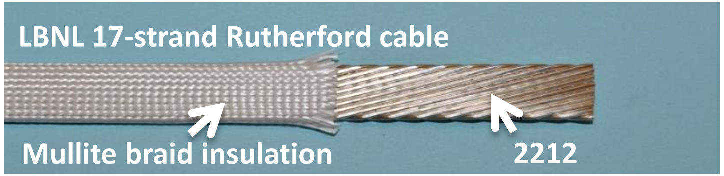
- … coils of various dimensions and shapes plus many, many other OPHT runs on short samples, furnace balancing, and tuning
- Due to many changes and improvements on furnace design and controls, furnace operation has become increasingly comfortable with a high rate of success

Racetrack Coils with Rutherford Cable

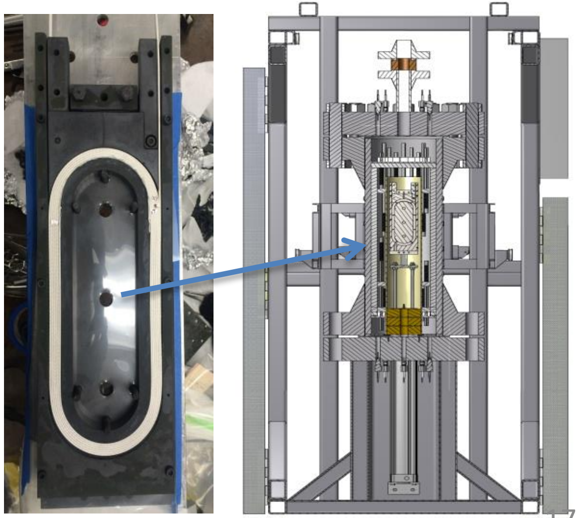
- Recent coils yielded exceptionally high transport properties
- RC-01 through RC-05 all OPHT'ed
- RC-05 and 06 with better powder



Tengming Shen, LBNL



LBNL RC in FSU OP furnace



Coils in Collaboration with B-OST/OI

Not only successes with own racetrack coils and own solenoids but also with solenoids for others:

- 2212 coil made by OI and successfully OPHT'ed at NHMFL

*

Wire dia. (mm)	Coil height (mm)	IR (mm)	OR (mm)	No. layers (-)
1.5	50	14	35.7	14

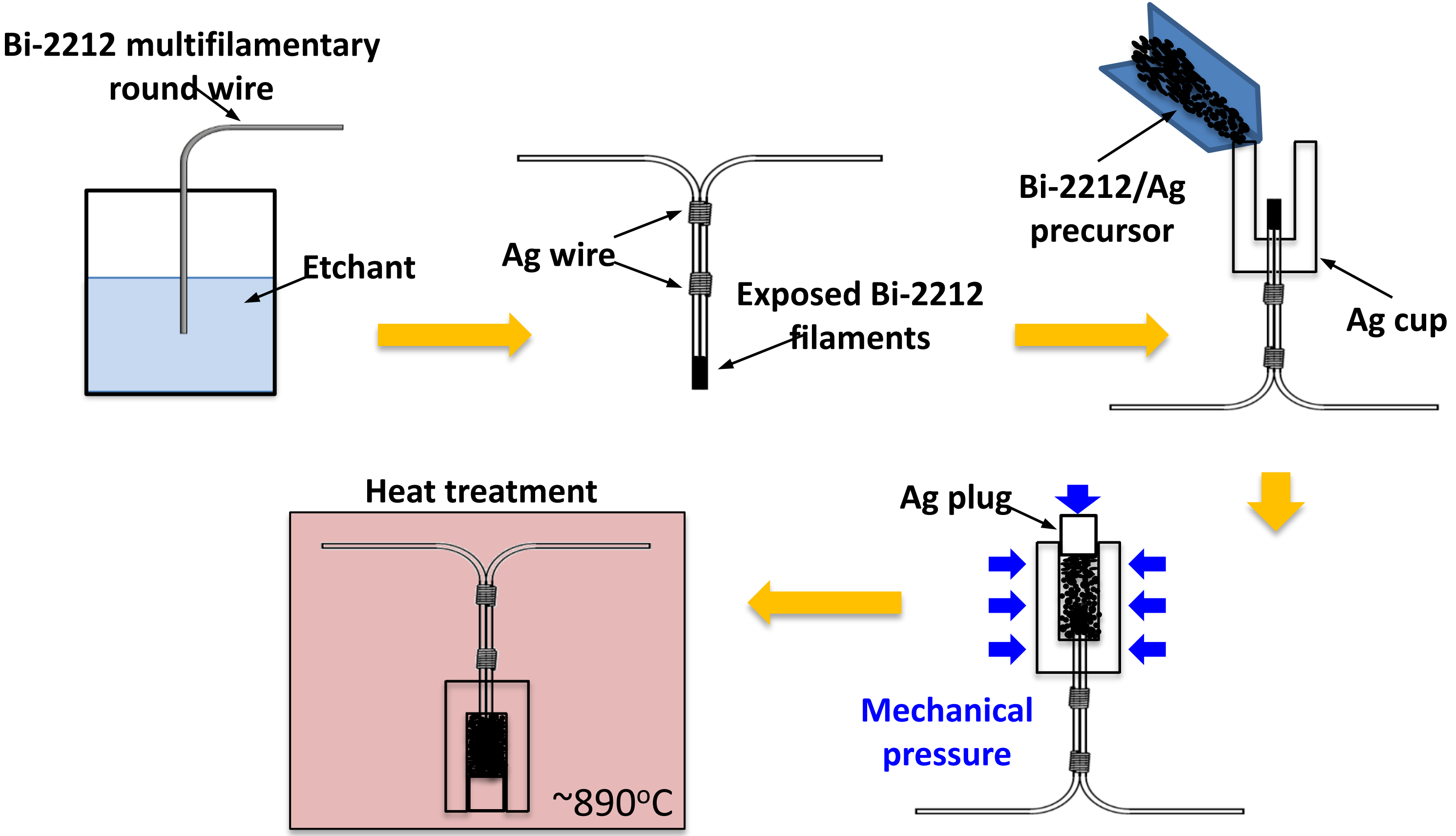
- Coil did not show any leaks after OPHT and was shipped without impregnation and arrived without damage at B-OST
- * At OI, coil generated 2.75 T in 19 T background when current limit of the power supply was reached at 400 A

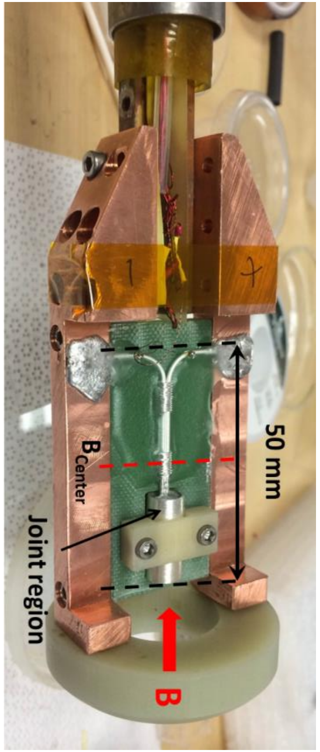
Before OPHT

After OPHT

* S. Ball *et al.*, MT-25, Amsterdam, The Netherlands, 2017

How Can We Make Bi-2212 Superconducting Joints?



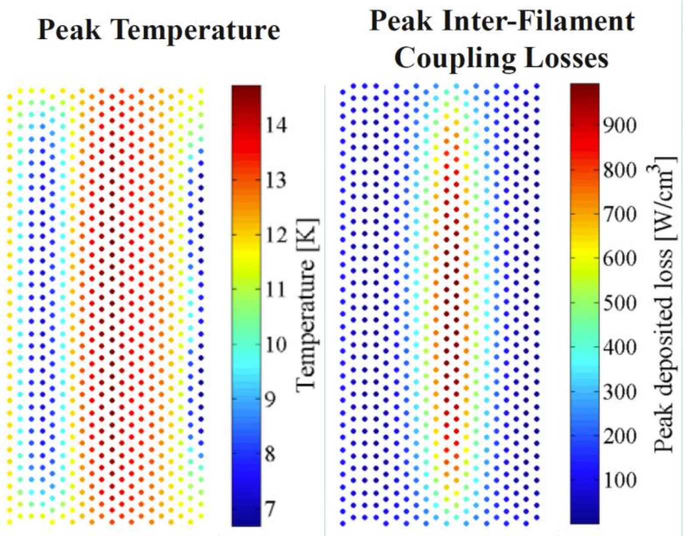


Experimental Joint test configuration

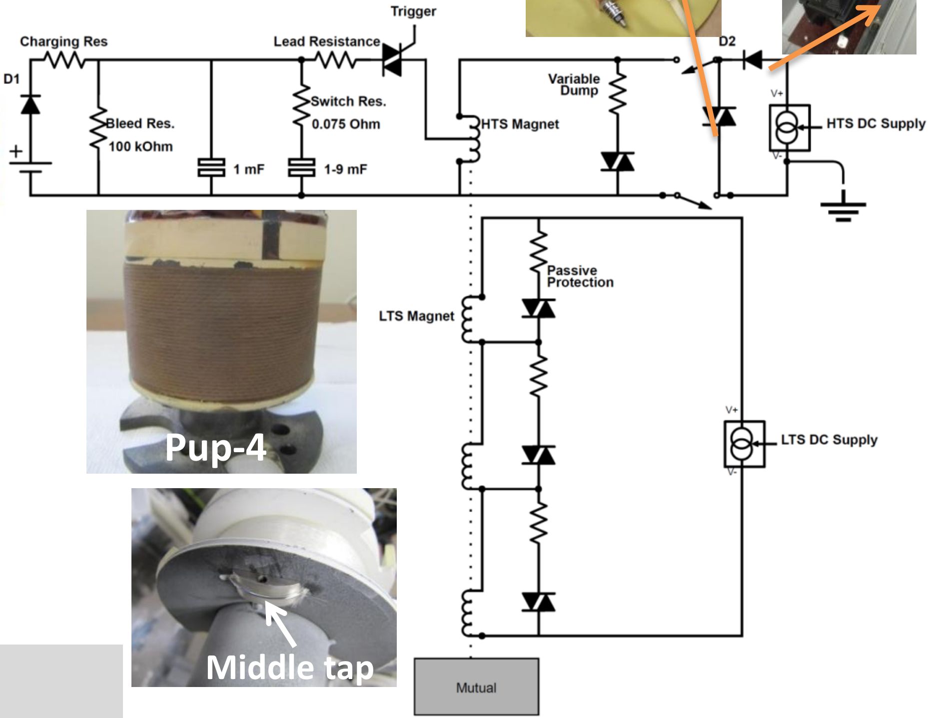
U. P. Trociewitz, P. Chen *et al.*, US patent No. 9,966,167

Quench Protection in 2212 Coils

- CLIQ system put together in 2017 based on E. Ravaioli's design
- Successful initial tests on Pup-4 inside our 8 T magnet system (in *s.f.* and field)



Daniel Davis



More tests needed to fully understand and implement CLIQ into HTS quench protection system

Next Solenoid Plans

- Finish installation of the Cryogenic magnet
- Few more Riky and Pup coils in the meantime
  - Riky-4bis, coil with SRW conductor (wound)
  - Riky-6, Pup-6, reinforced coils, repetition of Riky-5 and Pup-5
- Thick test coils in Cryogenic magnet: 200 m/each (high stress coils)