Recent progress in developing high performance Bi-2212 wires and coils

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Work of individual students and postdocs indicated on individual slides

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U.S. MAGNET DEVELOPMENT PROGRAM

APPLIED SUPERCONDUCTIVITY CENTER
NATIONAL HIGH MAGNETIC FIELD LABORATORY
FLORIDA STATE UNIVERSITY

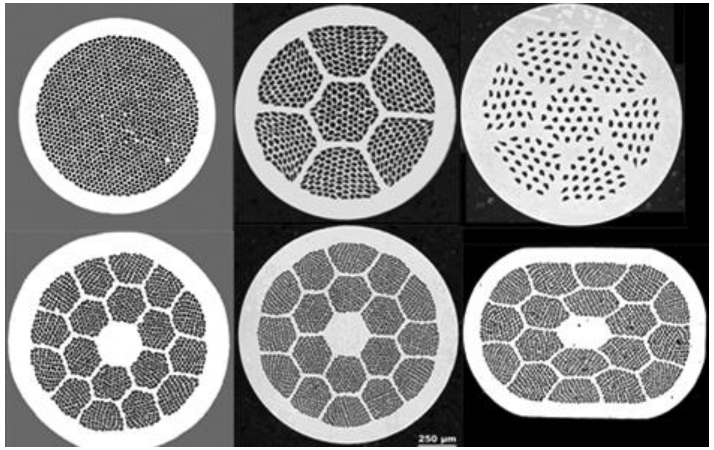
Key points reflecting 10 years of collaborative 2212 work:

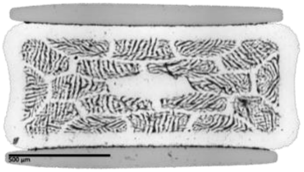
- 2212 is not just a promising conductor but now also a very promising magnet technology
- 2212 conductors have J_E values well above the FCC specification
  - The stability margin of 2212 greatly exceeds that of Nb_3Sn
  - 2212 magnets are not training and their quench onset is safely visible
- Although 50 bar overpressure heat treatment requires a special furnace it is neither complex nor too expensive
- Being round, macroscopically isotropic and twisted 2212 conductors have low hysteretic losses and good magnetic field quality
- The “black magic” behind 2212 processing is now well understood

Significant magnets demonstrating the particular advantages of 2212 are emerging

The conductors have versatile architectures

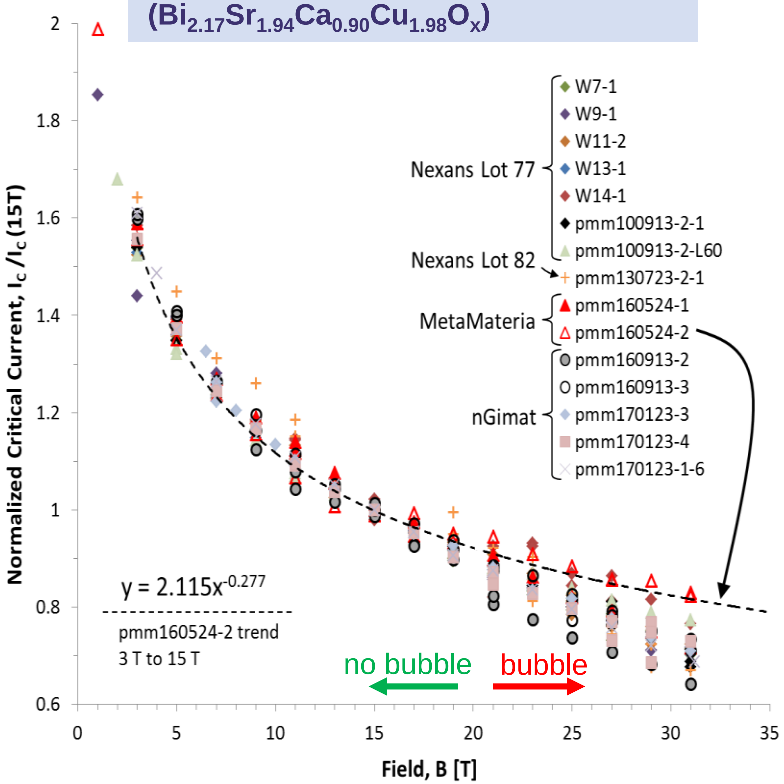
- Many multifilament architectures possible
- Rutherford cable, 6 around 1, single stack or double stack.
- One similar J_c(H) characteristic scaled only by a connectivity factor: $J_C \propto B^{-\alpha}$
- Low hysteretic loss
- J_c is now very high with optimized HT and nGimat powder





Top right by Supercon, all others by B-OST, strengthened by Alex Otto SMS

521 composition wires: ($Bi_{2.17}Sr_{1.94}Ca_{0.90}Cu_{1.98}O_x$)

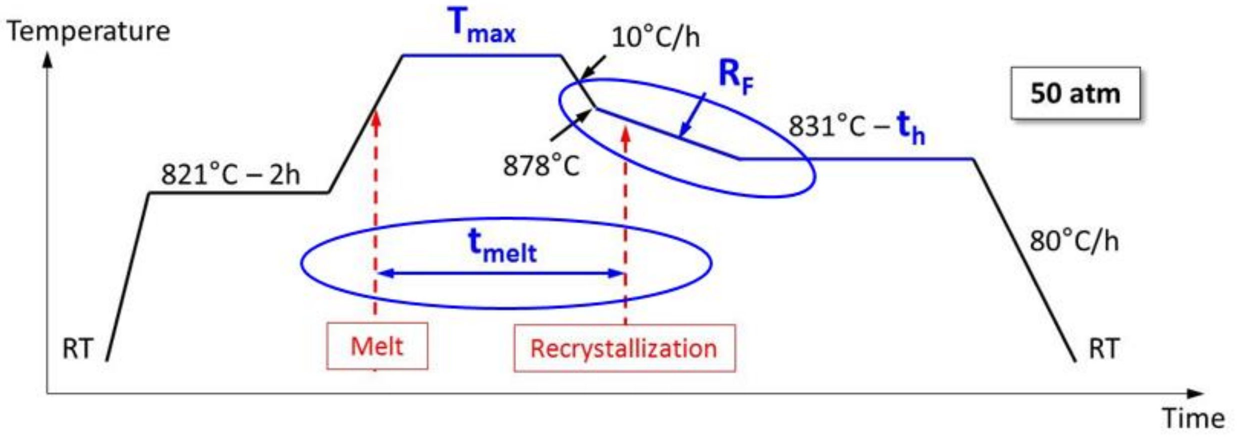


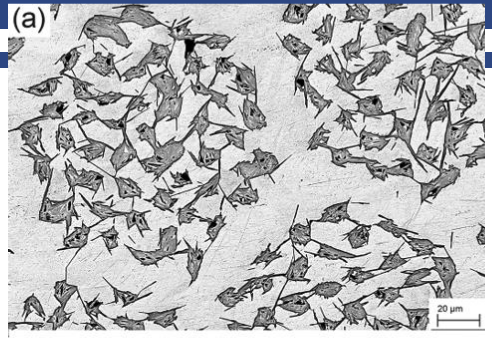
M. Brown et al. IEEE TAS 2019, PhD FSU 2018, J. Jiang et al. IEEE TAS 2019.

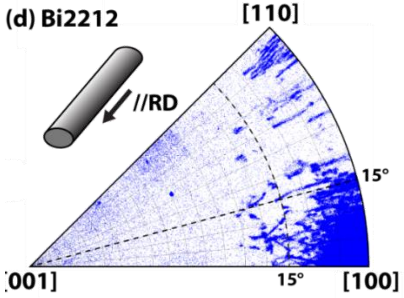
One simple power law fit for J_c(B), where α = 0.28: $J_C \propto B^{-\alpha}$

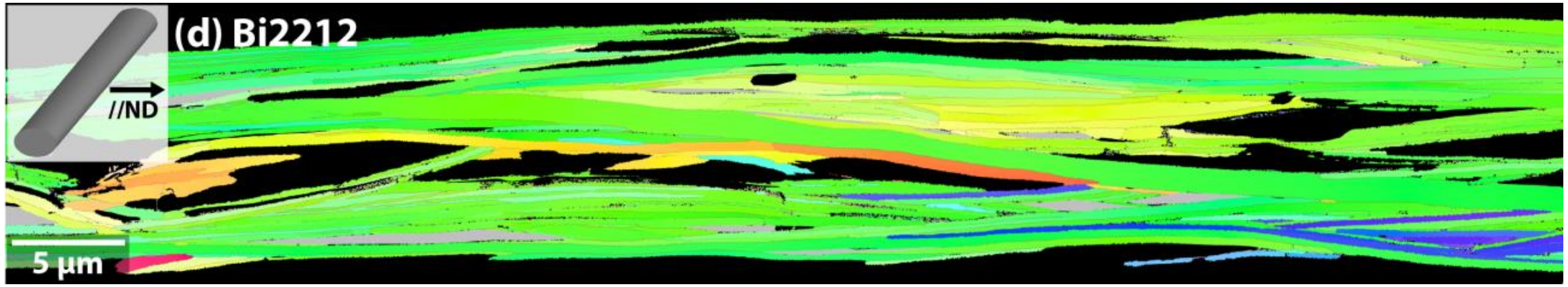
Heat treatment drives strong biaxial texture and high J_c

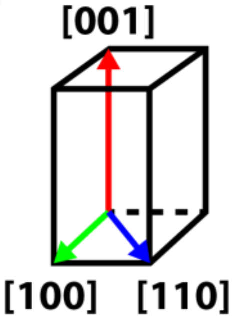
- Complexity of the HT is now well understood, especially that the critical time in melt and cooling rate transition to slow R_F at ~878 °C are most important

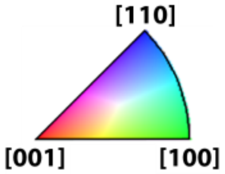








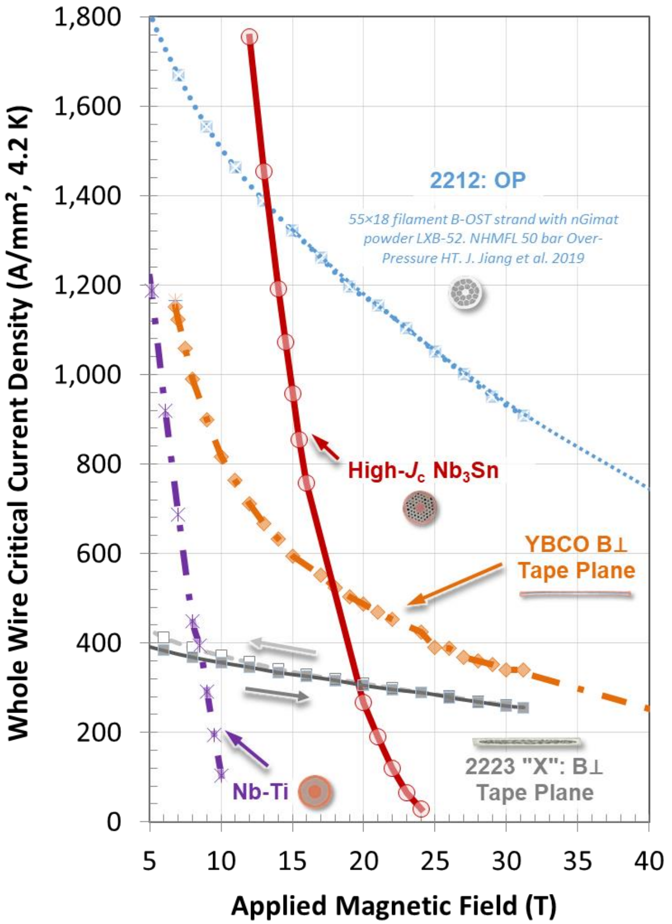


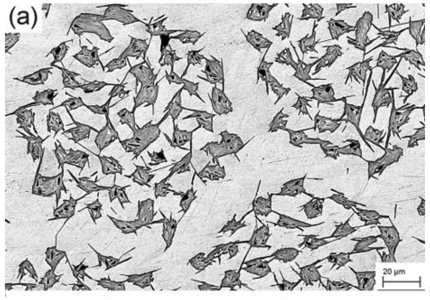


- Optimum HT generates ~15° biaxial texture and well separated filaments with low AC loss

F. Kametani *et al*. Sci. Rep. 5, 8285 (2015), Maxime Matras PhD FSU 2016

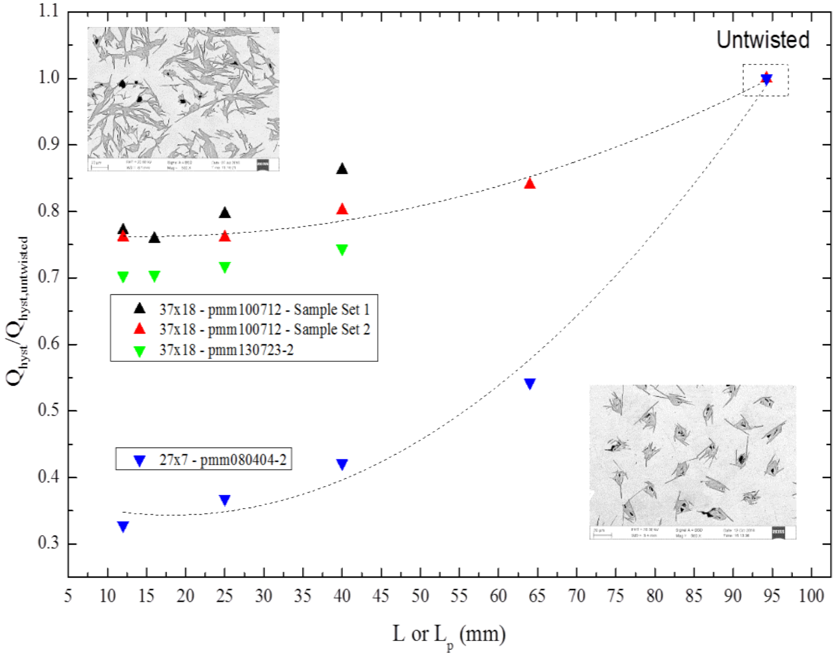
Best conductor properties well exceed FCC specifications





T_{max} = 885.5 °C and J_E(4.2 K,5 T) = 1900 A/mm²

T_{max} = 894 °C and J_E(4.2 K,5 T) = 936 A/mm²



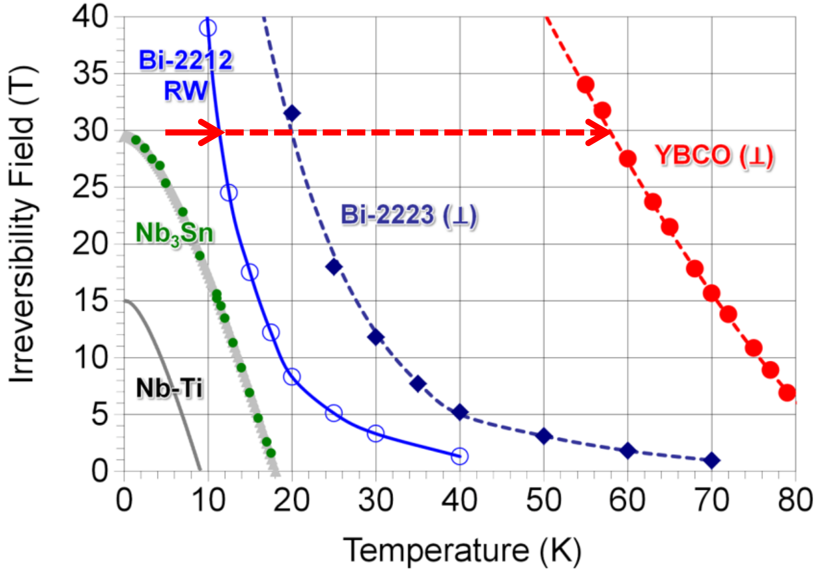
Yavuz Oz PhD work in progress

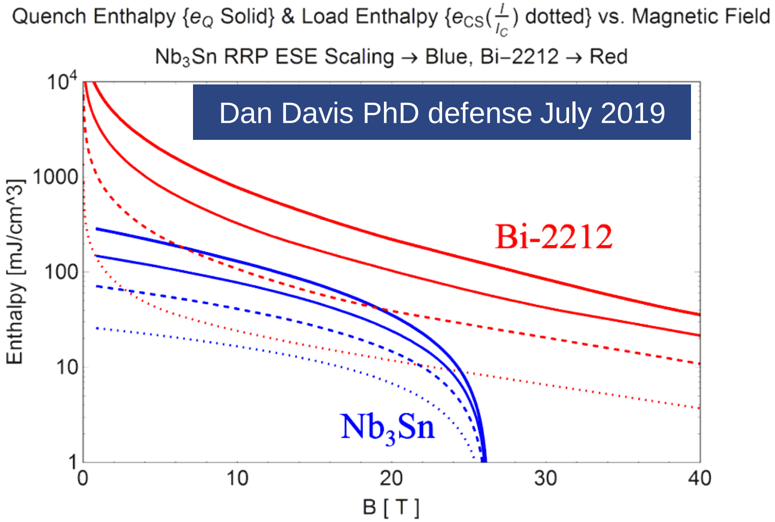
Twisting reduces AC losses to ITER levels, best transport Jc and AC losses when interconnect density is low

Best conductor properties depend sensitively on cooling rate: these 20% fill factor conductors have J_E (16 T) = 1300 A/mm² and J_c = 6500 A/mm² with RRR (Ag) > 100 and no need for diffusion barrier

What are our magnet goals?

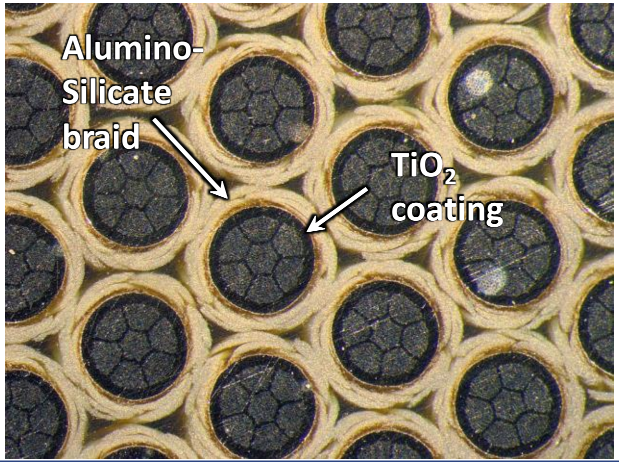
- At the MagLab, we wish to see 2212 magnets in the 25-35 T range
  - Near term goals are high 20 T range inside 160 mm bore,14 T magnet
- At LBNL, we wish to get a reliable racetrack and CCT (canted cosine theta) technology in place in goal of ~20 T dipole magnets



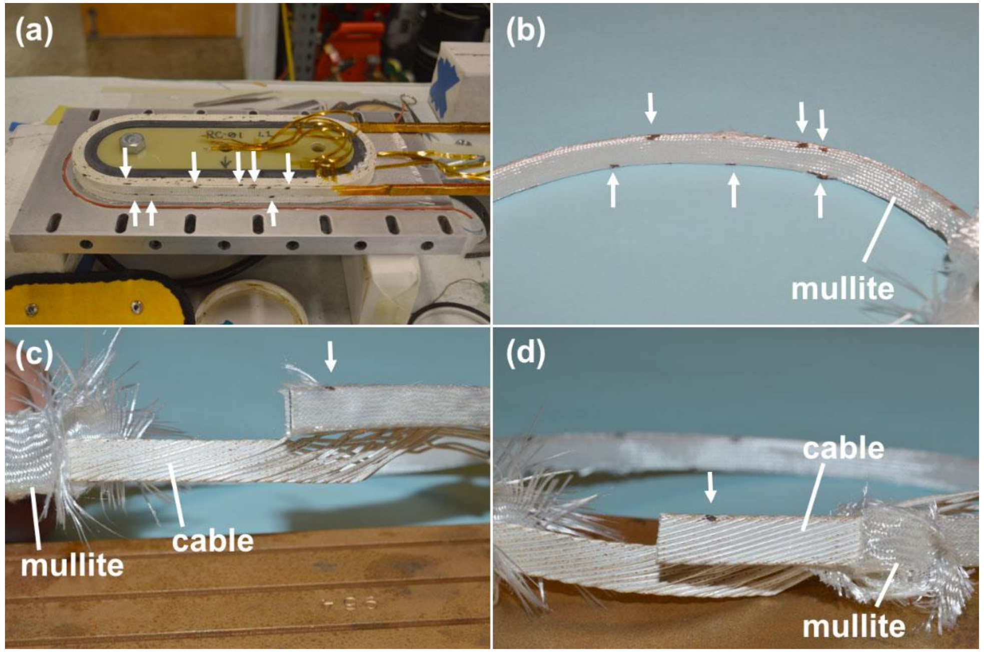


Key points:
1. Required quench energies are significantly MORE than in Nb_3Sn, thus magnets more disturbance stable
2. Energies are much smaller than for REBCO, making active quench protection much easier

Coil technology requires insulation, compatible support materials and stability through reaction

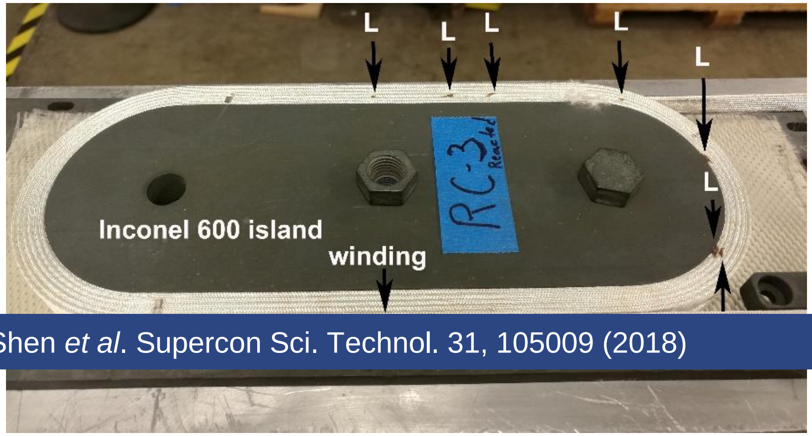


FSU insulation scheme is Mullite braid around TiO_2 coating: prevents Ag shorts and reaction between Ag and Mullite



Without TiO_2, "thermodynamic" leaks can occur

Painting with TiO_2 slurry largely avoids leaks

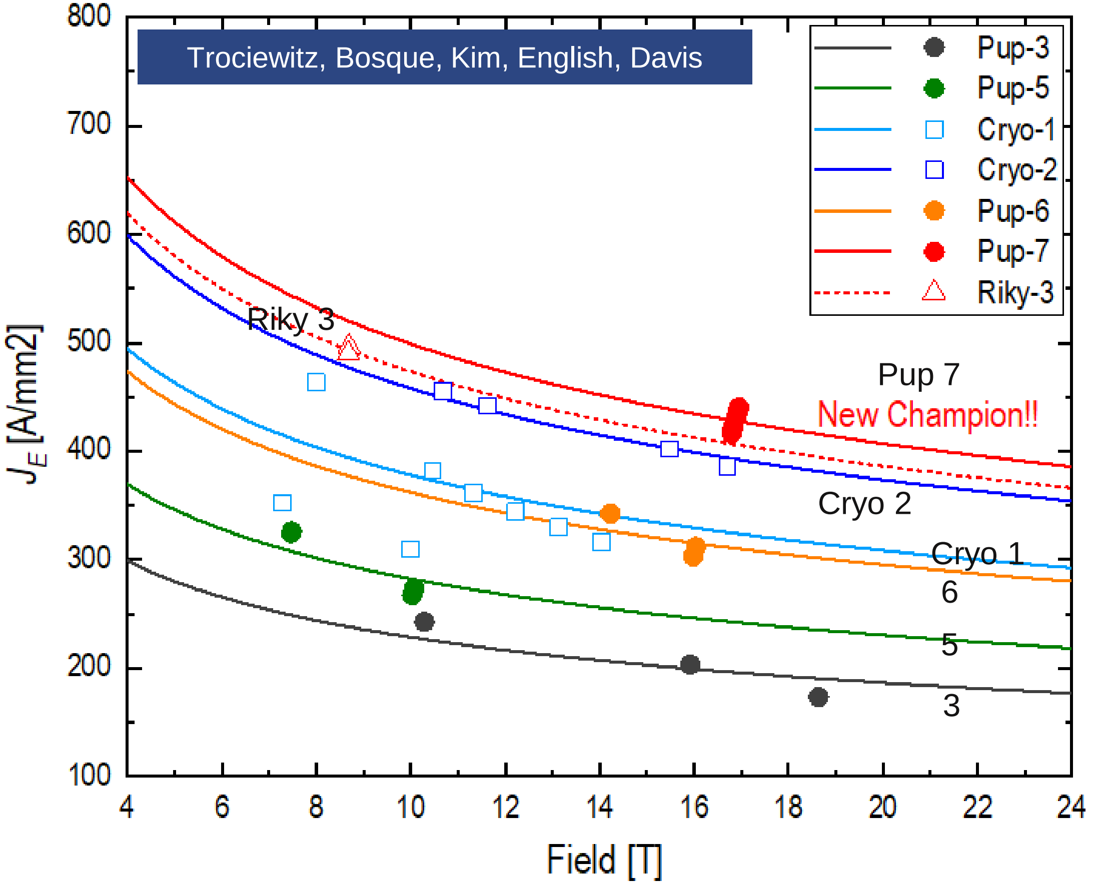


Zhang, Shen *et al*. Supercon Sci. Technol. 31, 105009 (2018)

DOE-HEP is funding a new 50 bar OP furnace 1 m long and 25 cm diameter to allow full scale solenoids and 1 m dipoles (present one is 14 cm dia, 43 cm long

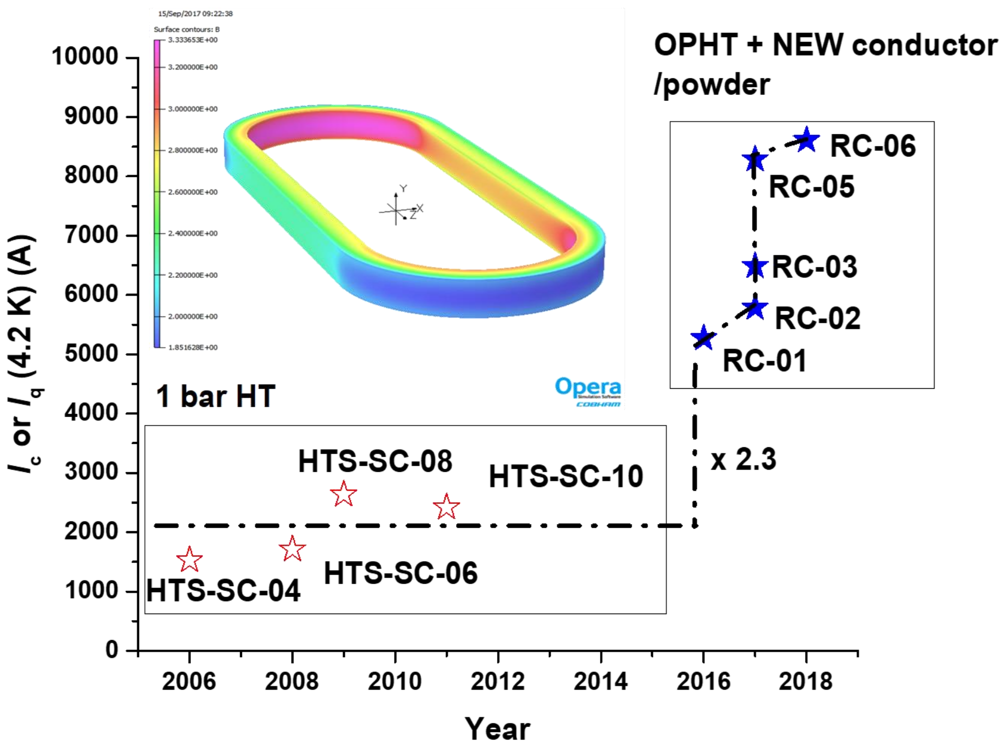
Many test solenoids aimed at incorporating reinforcement into the windings to allow > 30 T use in solenoids

- Prototype coils with 20 – 100 m of wire are tested in 160 mm bore 8 T and 14 T magnets to probe safe reinforcement techniques
- Safe operation at almost twice the wire breaking stress is now demonstrated: JBr stresses of 290 MPa at 0.4% 2212 strain without damage



Pup 7 test coil (June 2019) operated at J_c = 2200 A/mm^2 at 16 T with conductor having RRR of Ag > 100 with no needed diffusion barrier

LBL 2212 racetrack program has long lineage: after OP reaction and good, new powders, performance has HUGELY increased



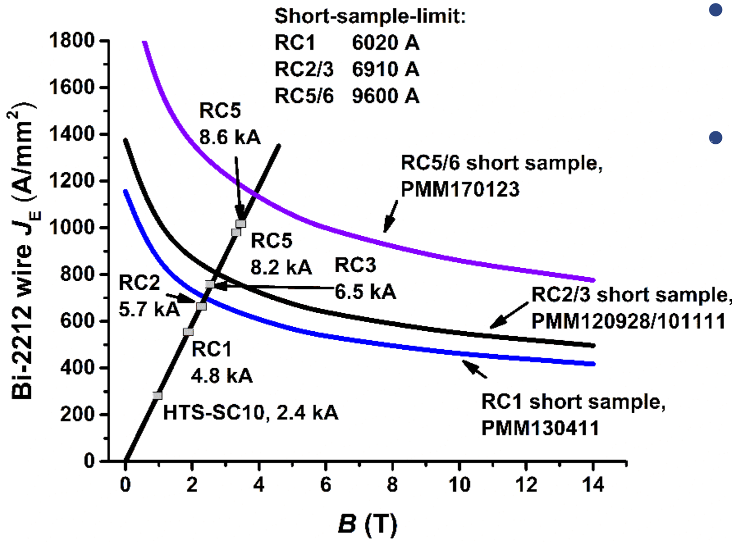
- **2-layer, 6-turn racetrack using 8 m of 17-strand Rutherford cable (1.44 mm x 7.8 mm, strand diameter = 0.8 mm)**
- **8 kg coil thermal mass, 37 cm x 12 cm x 3.1 cm heat treated in 50 bar FSU furnace.**
- **RC-05 (8.2 kA, (effective) J_{cable}=740 A/mm^2, (effective) wire J_e=940 A/mm^2.), CTD101-K impregnation**
- **RC-06 (8.6 kA, (effective) J_{cable}=770 A/mm^2, (effective) wire J_e=970 A/mm^2.), NHMFL mix-61 impregnation**

Shen, Higley, Davis, Zhang, coil fabrication and test
Bosque, English coil heat treatment at FSU

RC5/6 wires fabricated by Bruker OST with a new precursor powder developed by nGimat (now Eng-imat) under support of DOE-SBIR, and donated to LBNL. Conductor characterization by J. Jiang, FSU

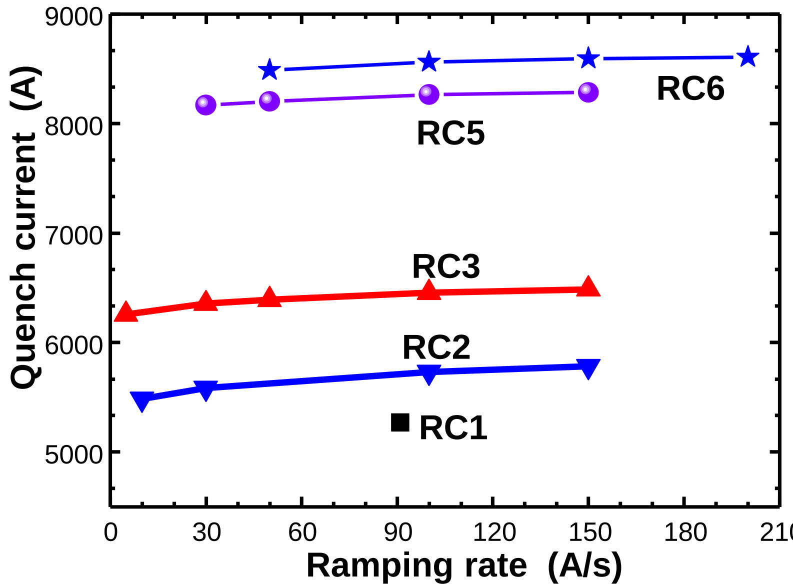
TiO_2 slurry – courtesy of Jun Lu, NHMFL

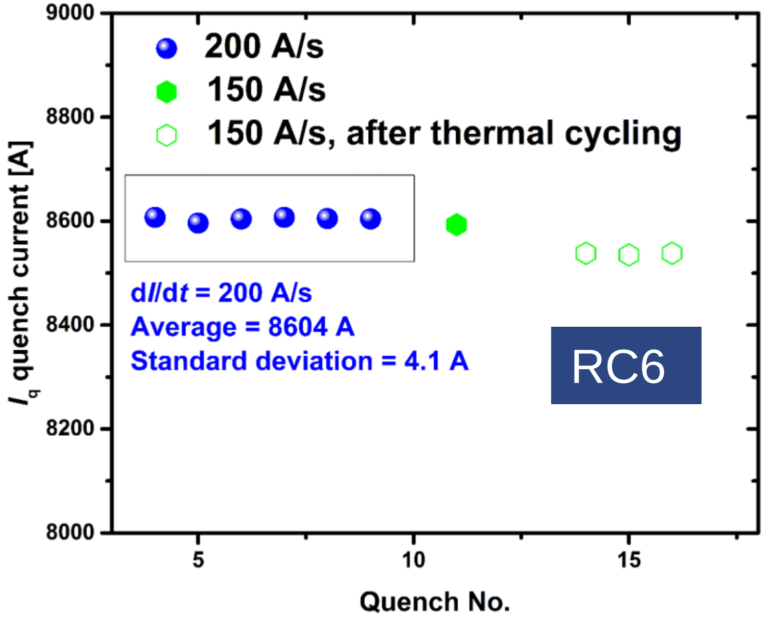
RC6 reached 8.6 kA and was safely protected. $J_{e,cable}$=770 A/mm^2 and $J_{e,strand}$=1020 A/mm^2 (at 3.5 T) are practical current densities for applications



- **(Extrapolated to 20 T) $J_{e,cable}$=433 A/mm^2 and $J_{e,strand}$=554 A/mm^2**
- **Coil was safely protected against quench**

Almost no ramp rate dependence





No training

Great improvement with OPHT and better powder

Shen et al. arXiv:1808..02864.
Zhang, Shen *et al*. Supercon Sci. Technol. 31, 105009 (2018)

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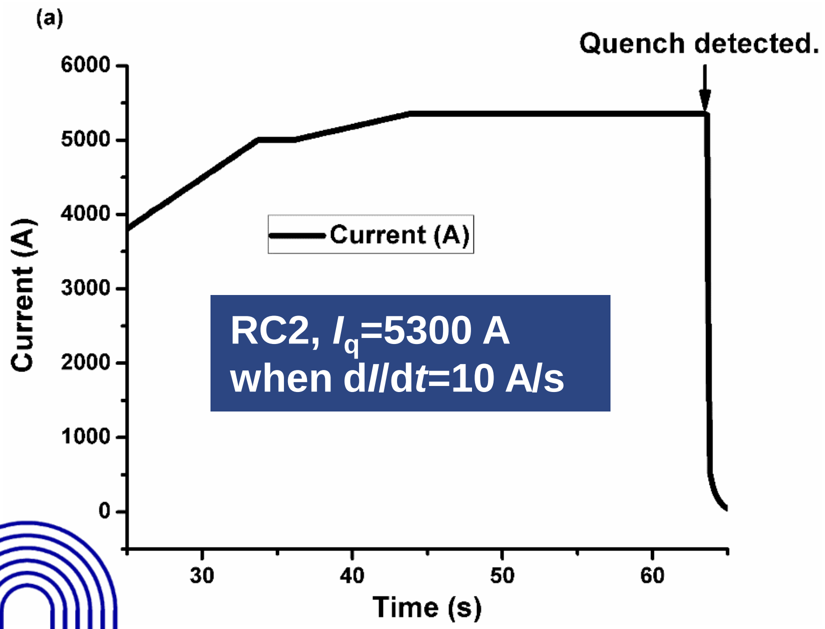
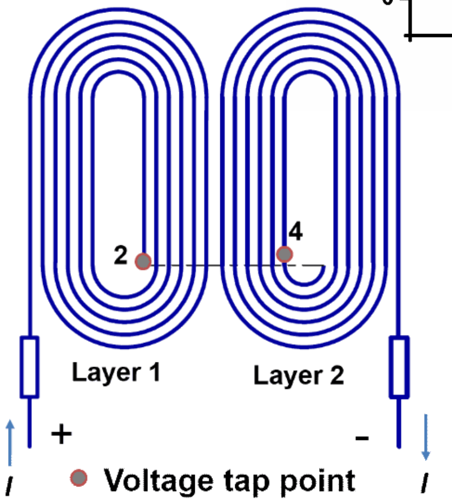
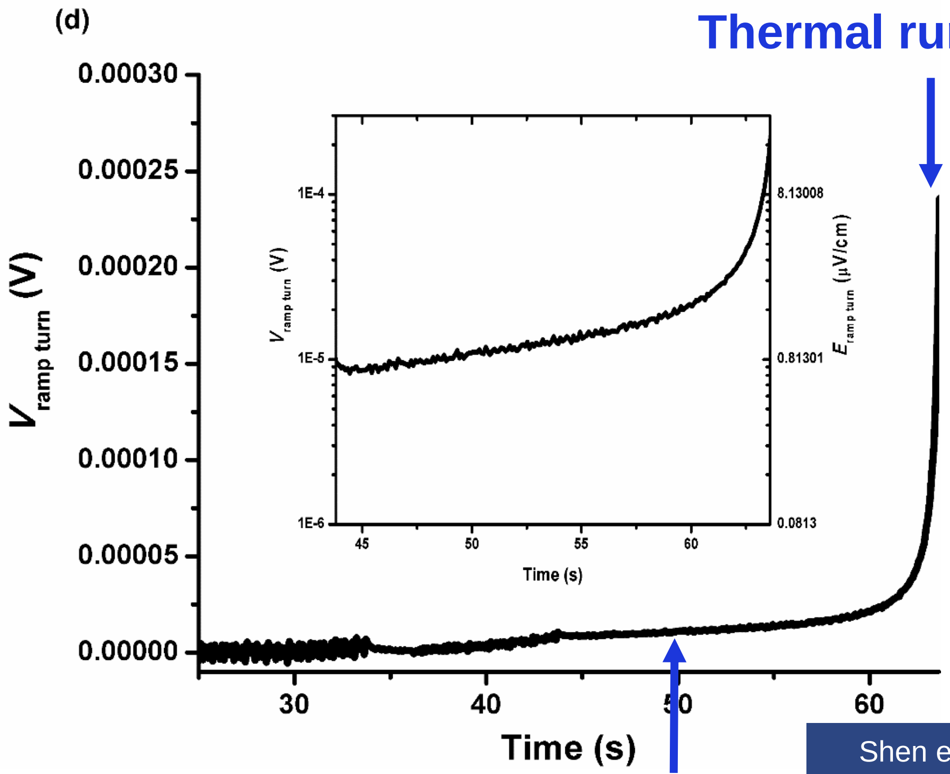
High stability – ability to absorb tens of mW for tens of seconds – not surprising!



RC2, I_q=5300 A
when dI/dt=10 A/s





Thermal run-away

10-20 µV, ~80 mW for a total heat input of ~1.3 J.

Shen et al. arXiv:1808..02864.
Zhang, Shen *et al*. Supercon Sci. Technol. 31, 105009 (2018)

$V_{ramp\ turn}$ = V_{24}, length ~ 14 cm

KEY RESULT: stable dissipation is observed well before thermal runaway, allowing safe quench PROTECTION. Quench is not at a point but occurs consistently in high field regions

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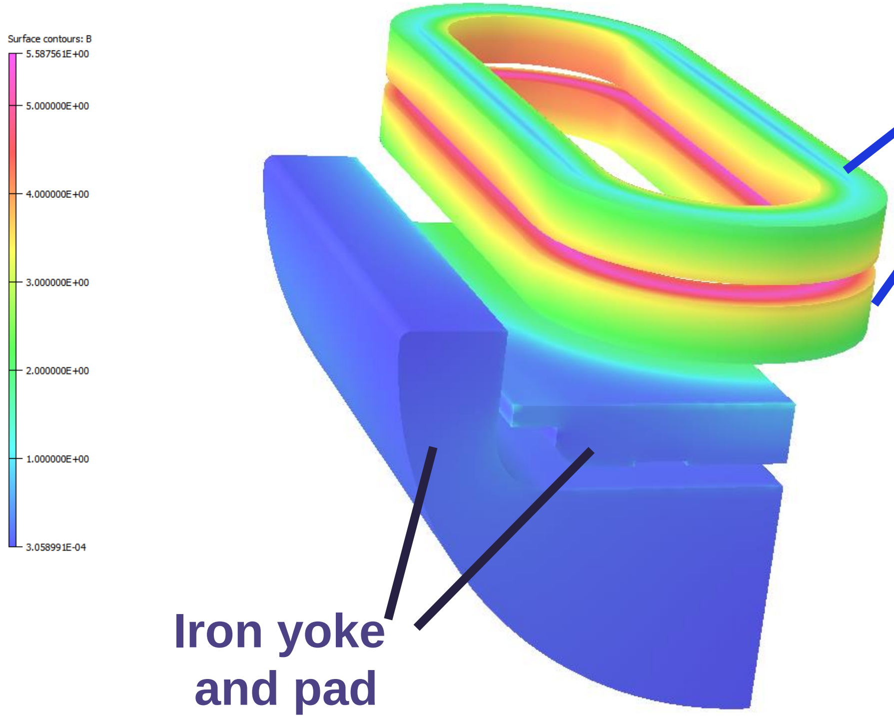
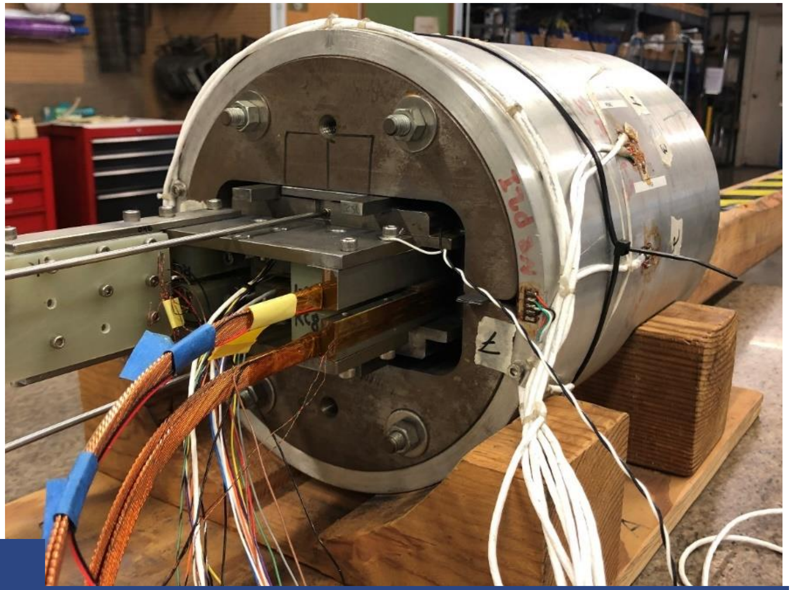
RC7 and RC8 are about to be tested as a pair with CLIQ for quench protection

RC7 + RC8 in LBNL subscale magnet structure (common coil configuration)

Expected – 5.6 T, 6.8 kA.



RC 7 - Twisted wires + more turns



Test expected July 2019

Shen, Davis, Swanson, Higley, Bogdanof, Turqueti coil fabrication and test
Davis, Fajardo, modeling and Bosque and English coil heat treatment at FSU

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Summary

- Bi-2212 is now a magnet technology in development
- 2212 conductor fabrication is by far the easiest of any HTS conductor and its present high price is artificial. Powder quality is now high and becoming well understood: large-scale pricing should be close to RRP Nb_3Sn, not present day boutique pricing
- The isotropic properties and truly multifilament architecture approximate Nb-Ti and Nb_3Sn low loss conductors suitable for magnets with high field quality
- The grave concerns about HTS magnet quench protection that especially exist with REBCO are very much reduced
  - Both in Rutherford cable dipoles and single-strand insulated solenoids, stable transition to the dissipative state can be used to trigger quench protection
- 50 bar overpressure heat treatment is not trivial but is not “black magic.” Compatibility with insulation and conductor strengthening has been demonstrated

Comments by Tengming

- Just want to reinforce a point on your last slide.
-
- Bi-2212 makes possible quench-predictable superconducting magnets:
- Quench locations are known and, unlike Nb-Ti/Nb_3Sn/REBCO, not localized.
- Reliably predicting quenches without thermal runways results in easy quench protection.
- Price will be a key debating point - price of silver per meter (around 4 g/m for 0.8 mm wire, silver at $0.5/g, $2/m). A scaled-up, matured industrial products with strong market competition should be two times raw material costs. In terms of price Bi-2212 can be at least competitive with RRP Nb_3Sn wires.