Fermilab

Operated by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

High Temperature Superconducting Magnets: Pushing Limits

Tengming Shen, Technical Division, Fermilab

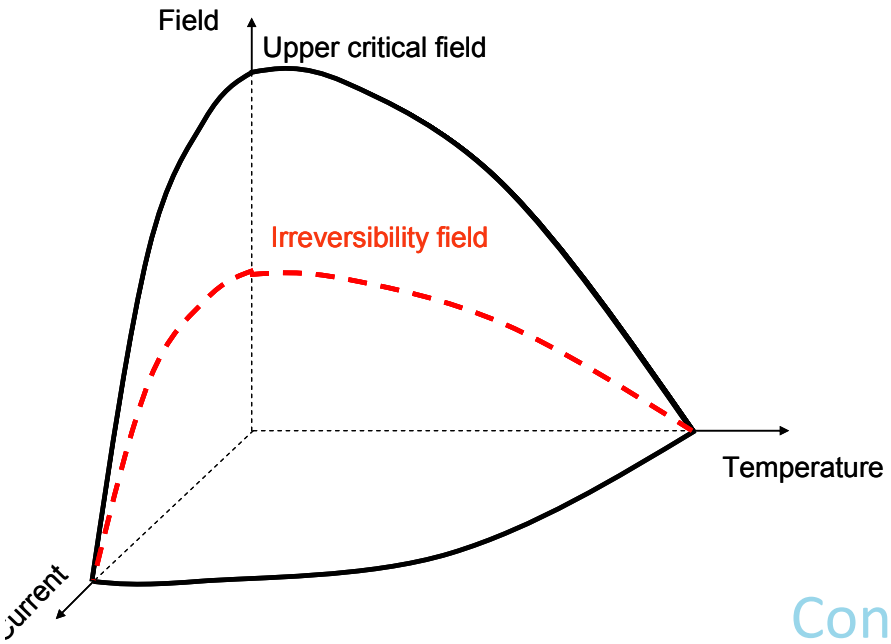
Fermilab Accelerator Physics and Technology Seminar

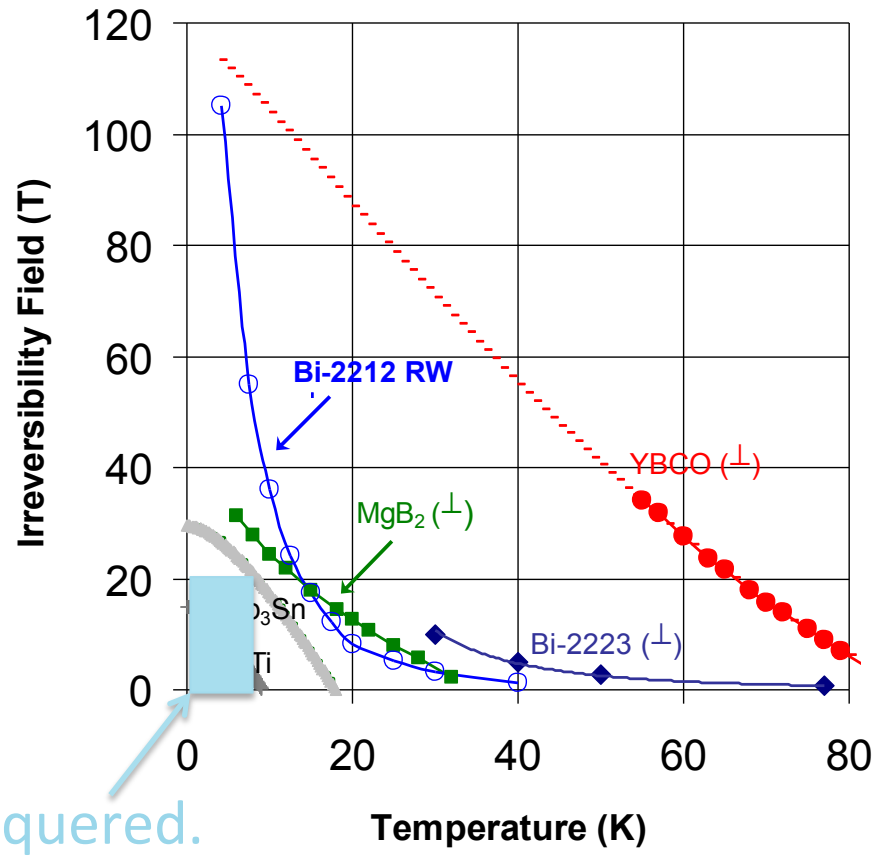
22 May 2014

HTS opens an application space that is not available with present LTS technology

Opportunities: 22-100T@4.2K magnets and 1-5T@20-77K magnets for rotating electric machines and cryogen-free MRI

100 years of superconductivity: Expanding boundaries.





(Courtesy of J. Jiang, FSU)

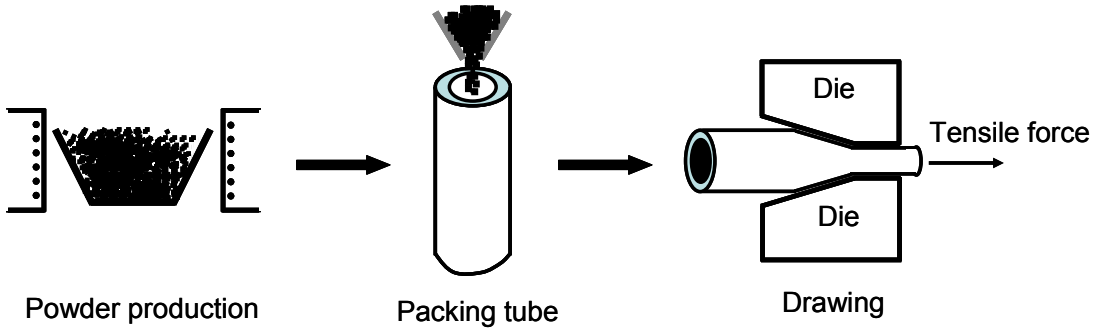
What will be the role of HTS for high-field magnets?

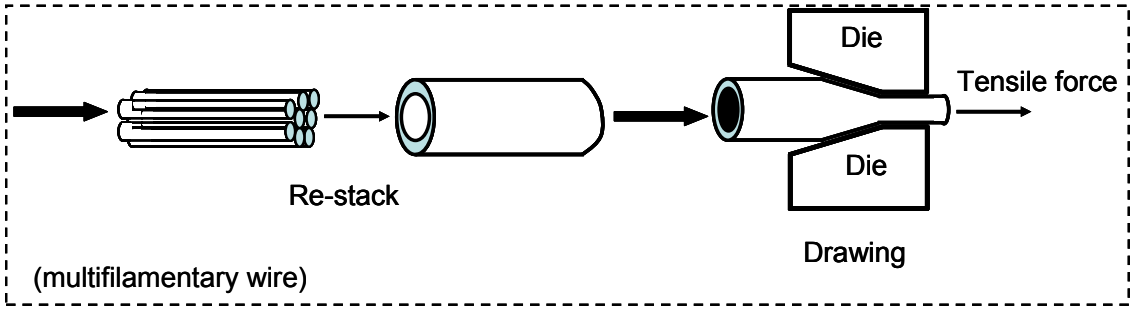
- Muon collider demands solenoids of 30+ T
- Future circular colliders need dipoles of 16+ T
- 10-year magnet challenges supported by U.S. NSF:
  - 30T Nuclear Magnetic Resonance (NMR) (All Superconducting)
  - 60T Hybrid (Resistive + Superconducting)
- Bi-2212 round wire responds to all these needs.

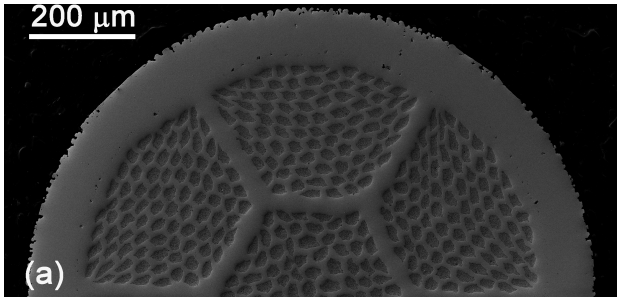
Outlines – A viable HTS, 2212 included, magnet technology requires technology advancements at many forefronts

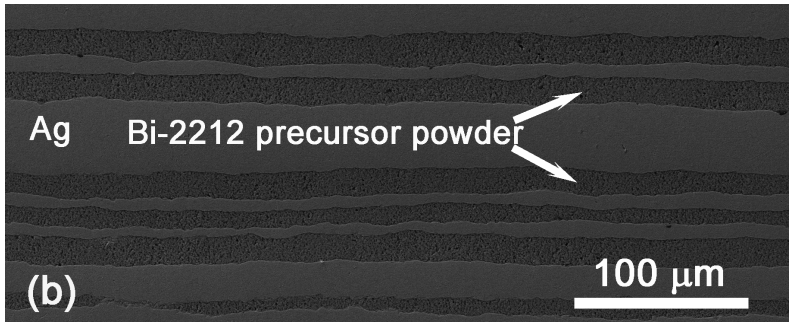
- High J_c in a long-length HTS wire made by an industrial scaling process is hard to get. For 2212,
  - Decode wire fabrication and heat treatment of long-length wire
  - Overpressure processing technology delivers a J_c of several 10^3 A/mm^2 at 20-30 T in long-length Bi-2212
- Magnets are hard to fabricate, may be crashed by high stresses, and are difficult to protect from quenches.
  - Can we detect a quench in HTS magnets?
  - How to protect HTS magnets from catastrophic damages induced by unprotected quenches?

Commercial 2212 round wire is fabricated by a powder-in-tube route





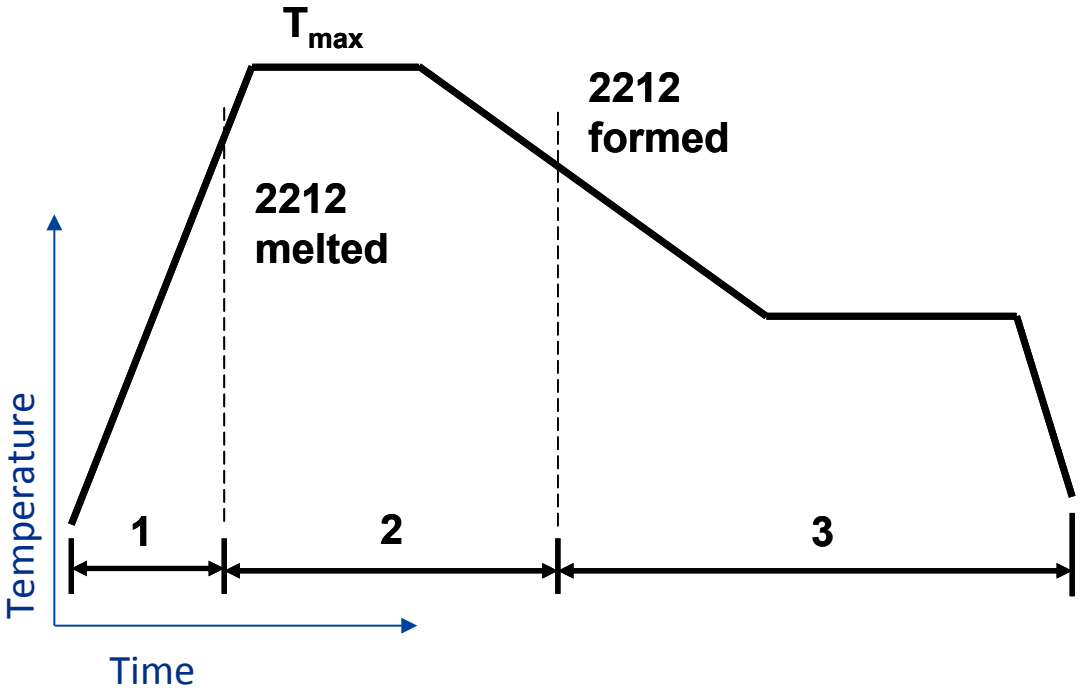




OST
Supercon
Showa Electric

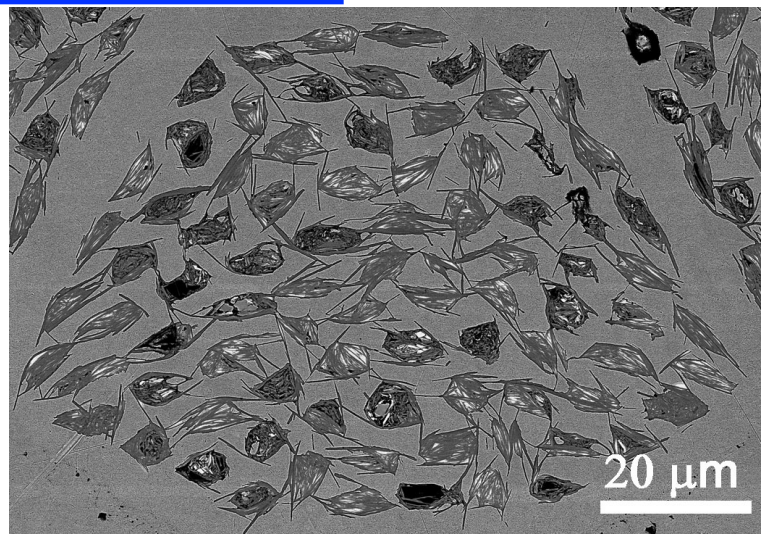
PIT 2212 is transformed to a high J_c conductor using an empirically developed melt processing

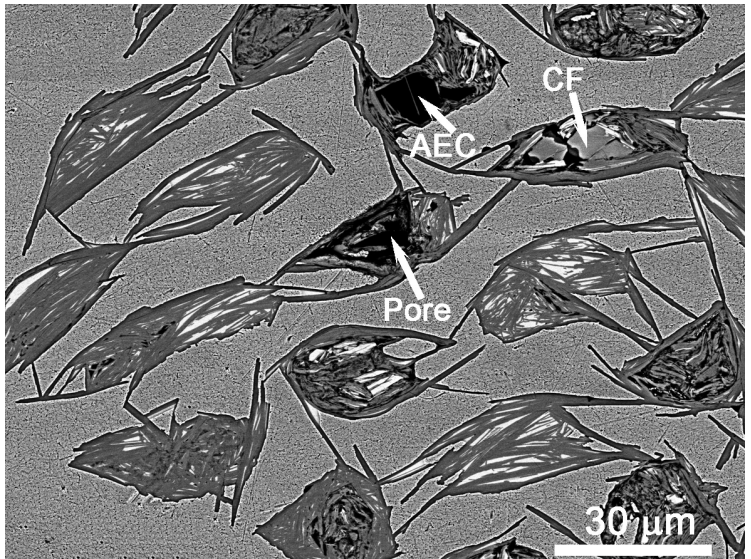
Microstructures of fully reacted wires are complicated.



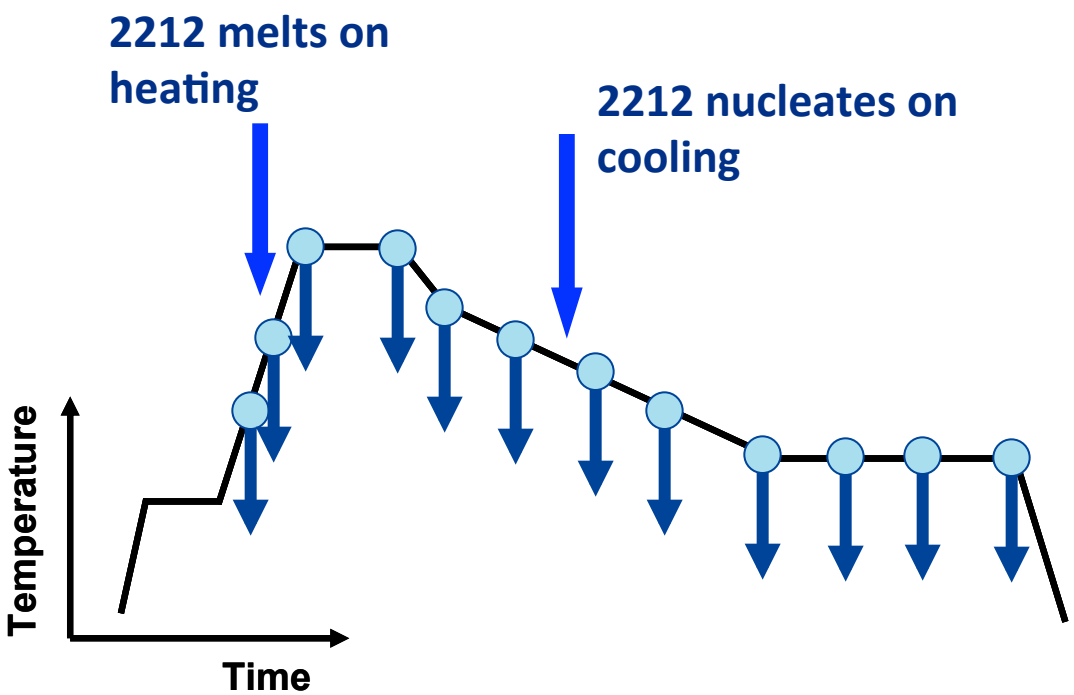
2212 $\xrightarrow{T\uparrow}$ Liquid + solid phases $\xrightarrow{T\downarrow}$ 2212

Hellstrom, HTS materials, 1995

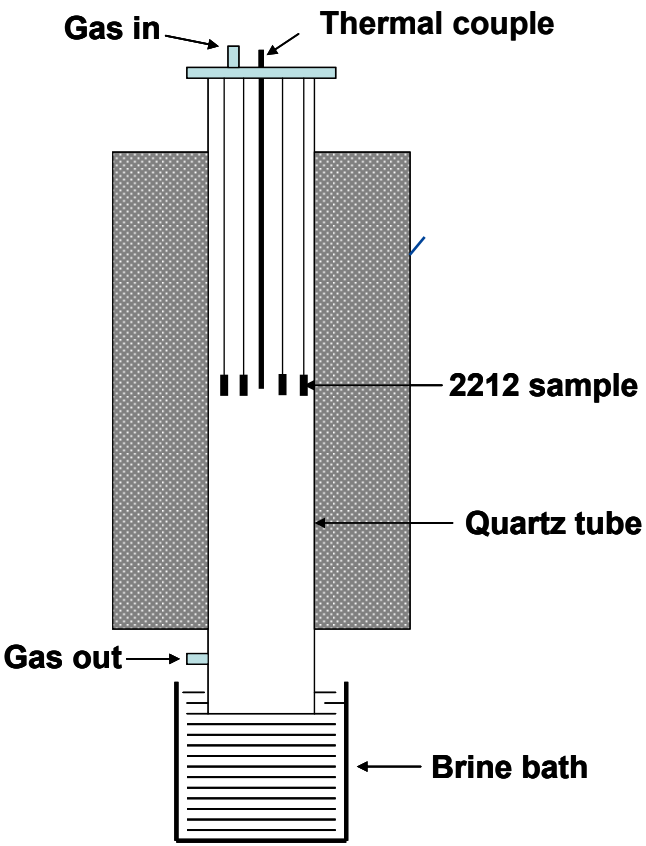




Through-process quench studies to understand how 2212 develops – goal to develop understanding driven process



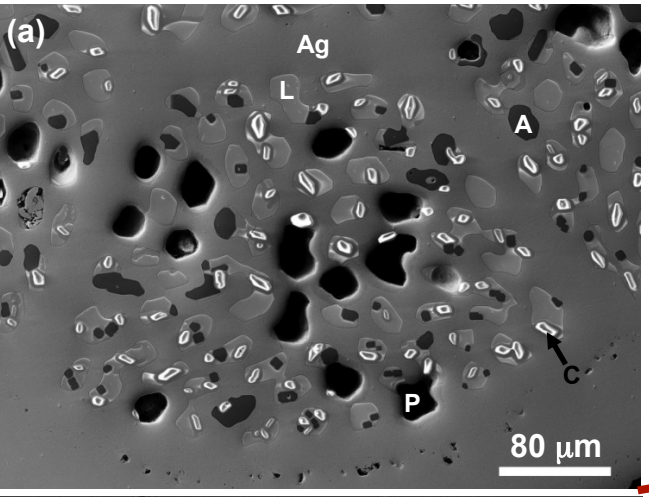
Quench furnace system

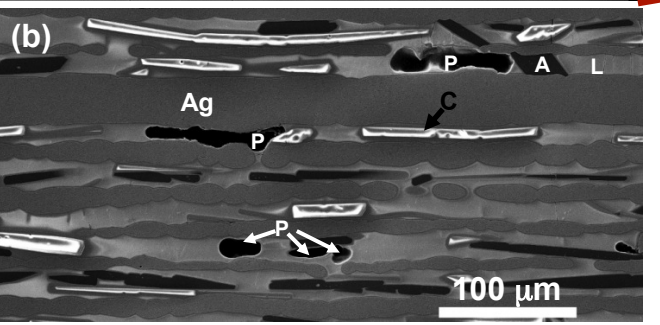


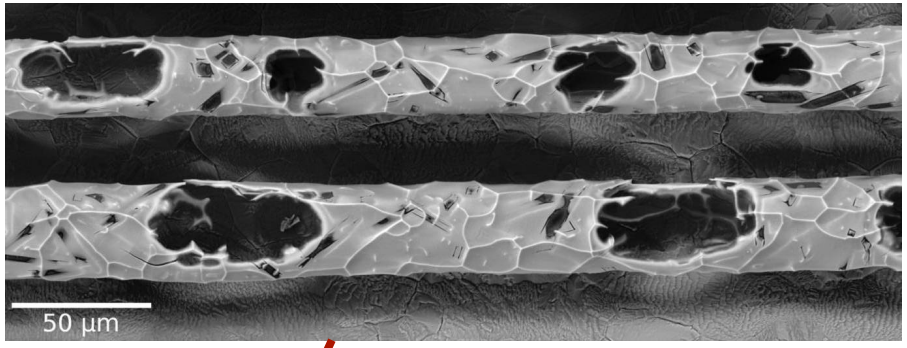
Decode the processing: Porosity agglomerates into gas bubbles that strongly limit J_c

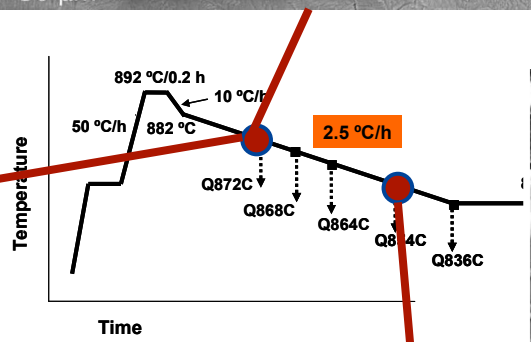
Shen et al. Supercon. Sci. Tech., 23, 025009 (2010)

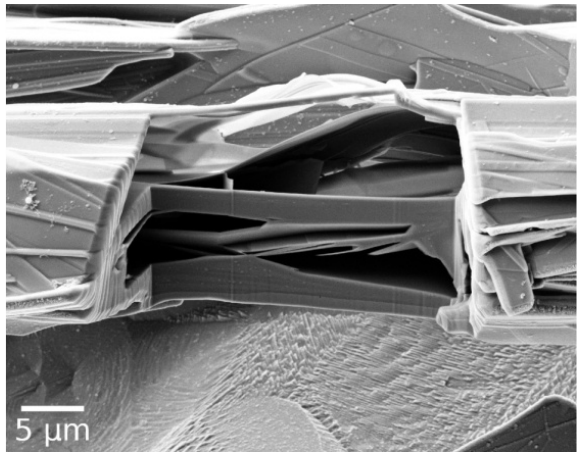
Kametani and Shen et al. Supercon. Sci. Tech., 24, 075009 (2011)

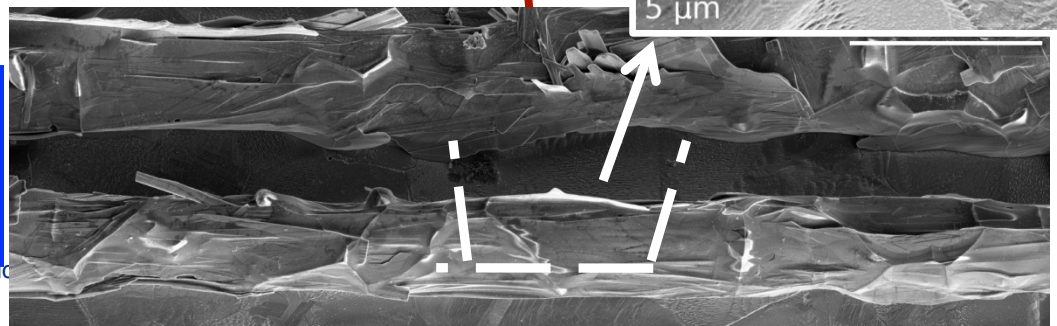












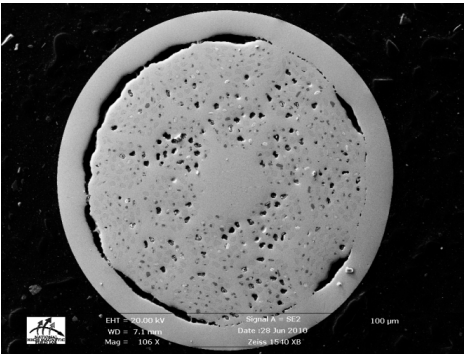
- Gas bubbles are large
  - 10s to 100s of µm along length of wire

Porosity, endemic to all PIT wires, is a major obstacle to getting high J_c in 2212 wires

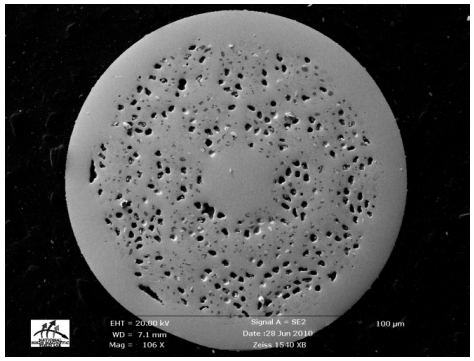
- **Very High Field Superconducting Magnet Collaboration: (PI: D. Larbalestier and A. Tollestrup)**

In 2010, J_c of 10 VHFSMC conductor batches and two OST conductors varies from 1000 A/mm^2 to 2880 A/mm^2 at 4.2 K, 5 T.

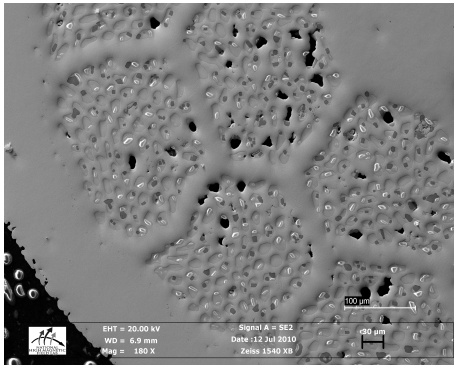
W9, 2400 A/mm^2



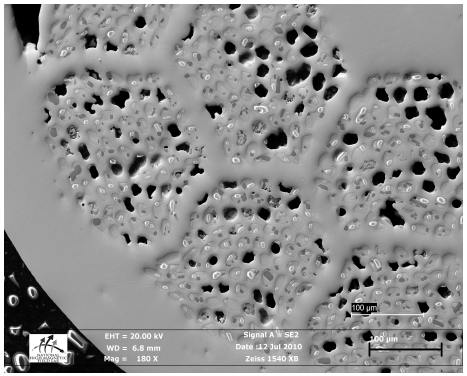
W8,1700 A/mm^2



OST-W1, 2880 A/mm^2



OST-W2, 1650 A/mm^2

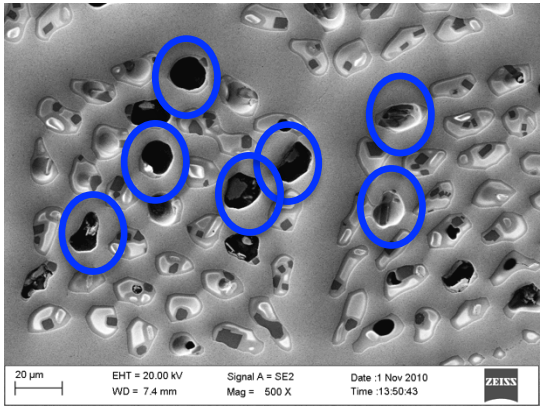


5/22

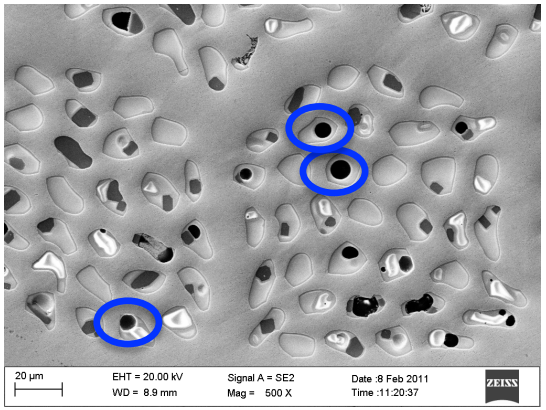
Removing bubbles using cold-densification methods more than doubles J_c/J_e of short samples

Cold isostatic processing of Bi-2212: Jiang et al. Supercon. Sci. Tech., 24, 082001 (2011)
Swaging of Bi-2212 (S. Hong HJC Enterprise, SBIR phase I): Jiang et al. IEEE Trans Appl. Supercond. 23, 6400206 (2013)

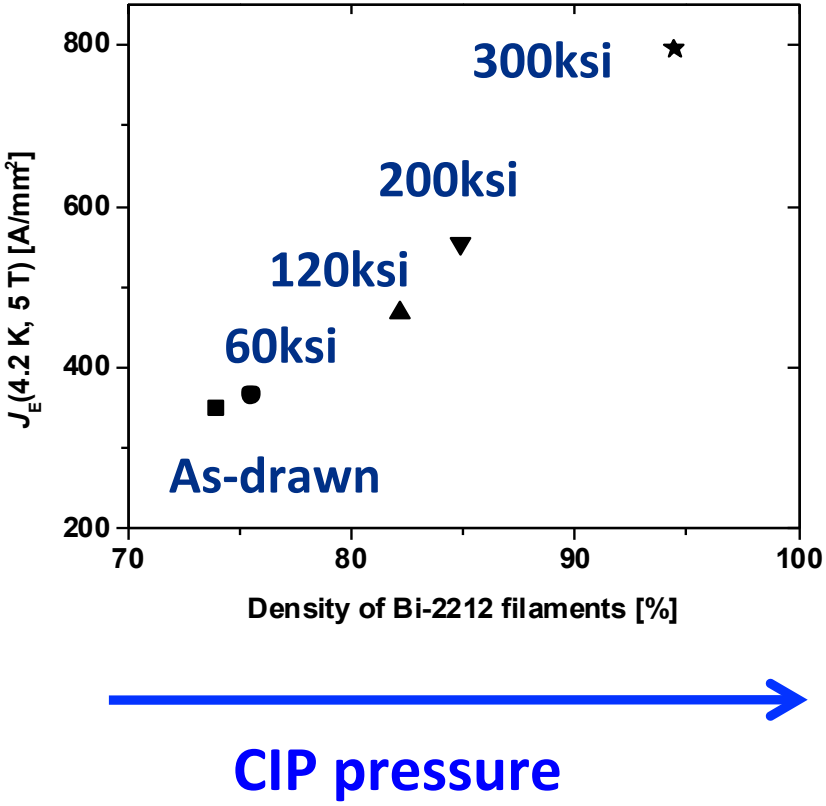
Regular PIT wires, quenched@887C



PIT+300 ksi CIP wires, quenched@887C



Shen et al., J. Appl. Phys., **113**, 213901 (2013)



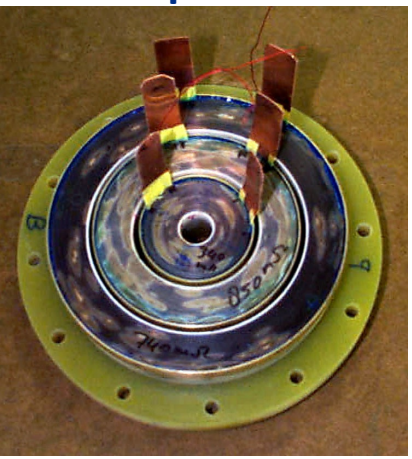
For 20 years, the performance of long length Bi-2212 wires has been much worse than in short pieces.

Short pieces: J_E=500 A/mm^2 at 4.2 K and 20 T
Long pieces: J_E<200 A/mm^2 at 4.2 K and 20 T

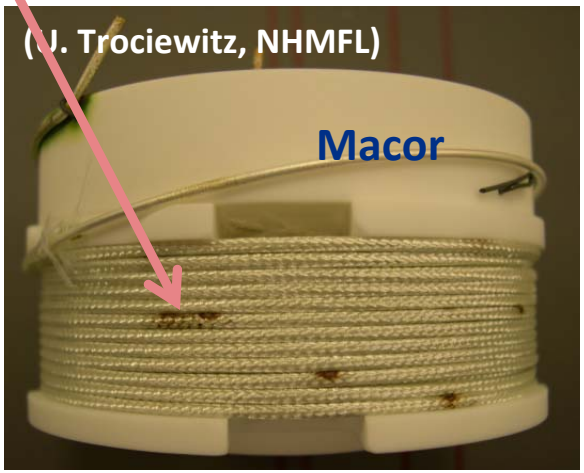
CIP didn't help. (Jiang et al. FSU)

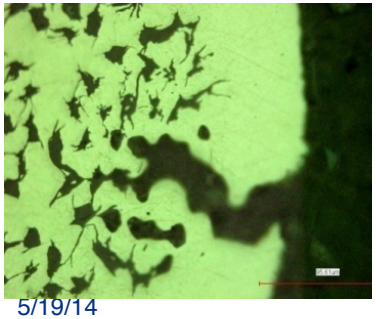
Mysterious leakage appearing in long length wires during the forming reaction.

NHMFL, 1999, 3 T insert from tape



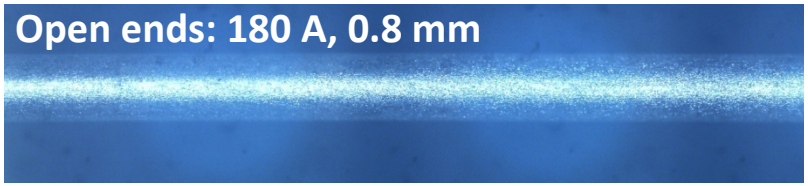
OST, 2006

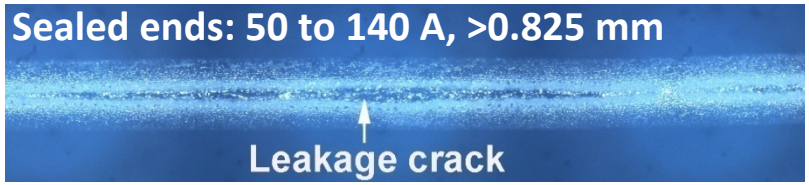


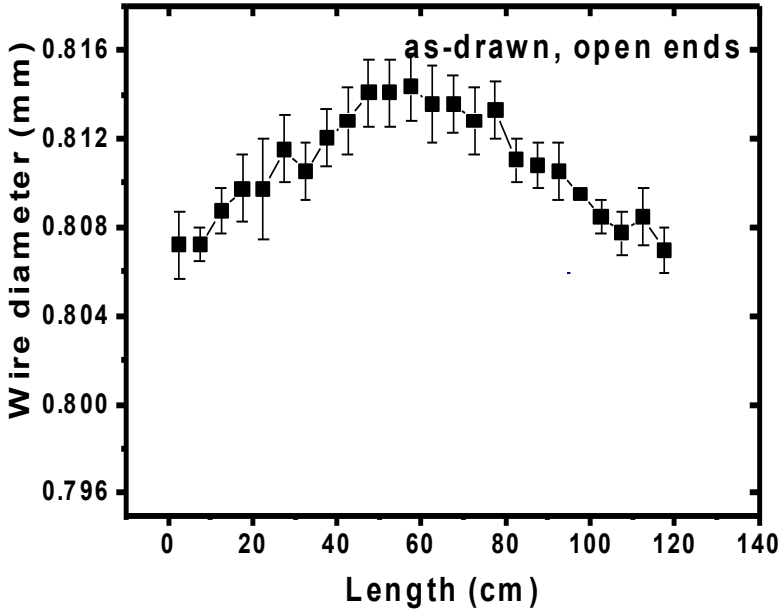


Start-up observations: Wire swells, J_c is degraded in 1-3 m long wires, and low J_c correlates well with large wire swelling

Wire swells, leaks, and carries 3 times less I_c when melt processed with its ends being sealed.







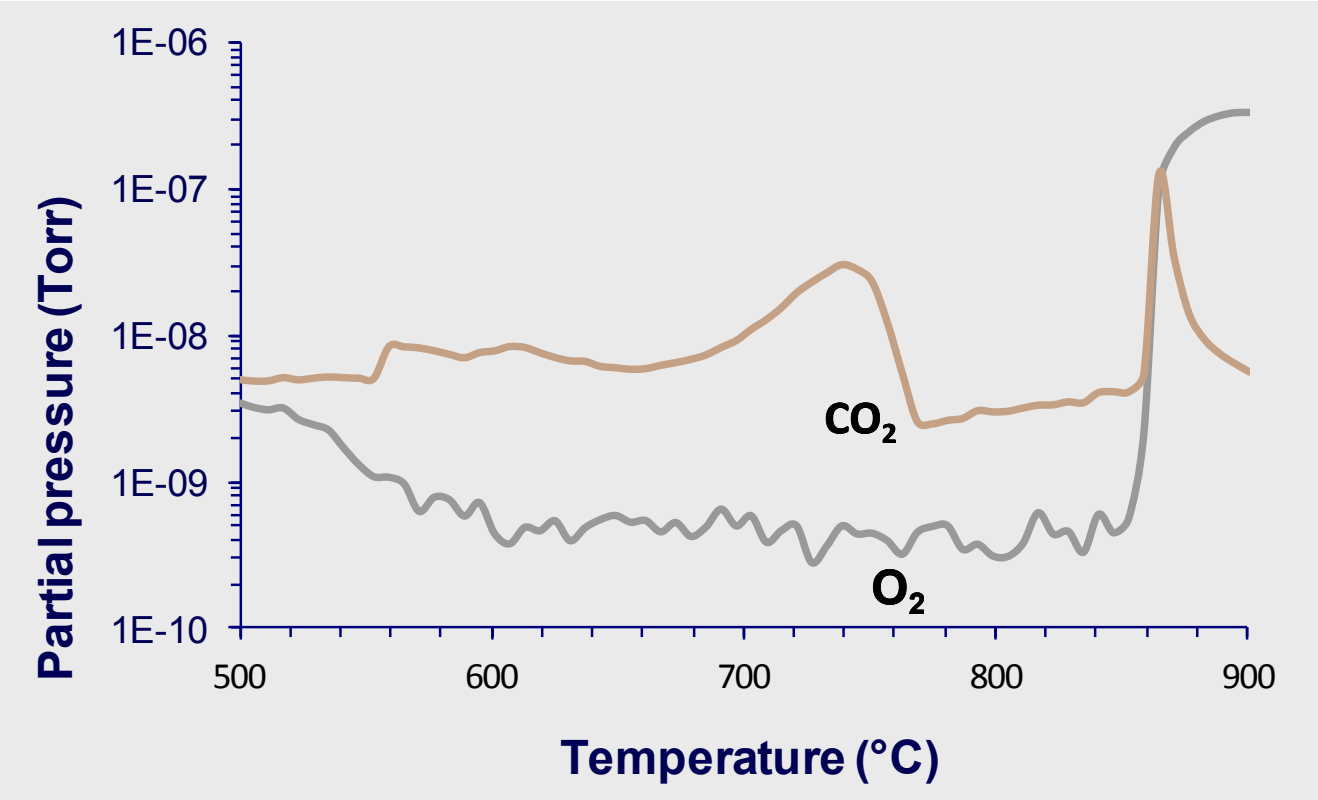
Kuroda et al., *Physica C* **357-360, Part 2**, 1098 (2001)
Malagoli et al., Supercond. Sci. Technol. **26**, 055018 (2013)
Shen et al., J. Appl. Phys., **113**, 213901 (2013)

Key observation: Gases are released from wires while they were heated, detected by mass spectrometer

Shen et al., J. Appl. Phys., **113**, 213901 (2013)

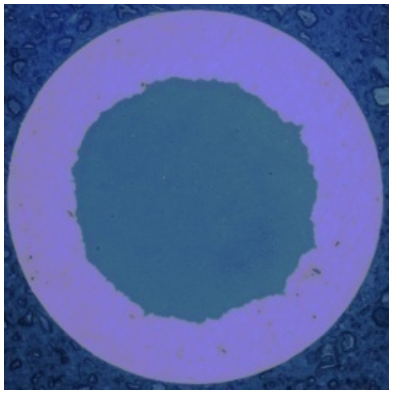
C and H species gasifying at high-temperatures. Significant gas releases when 2212 melts.

Gas species detected by a residual gas analyzer while heating Bi-2212 wires at 180 °C/h in vacuum.

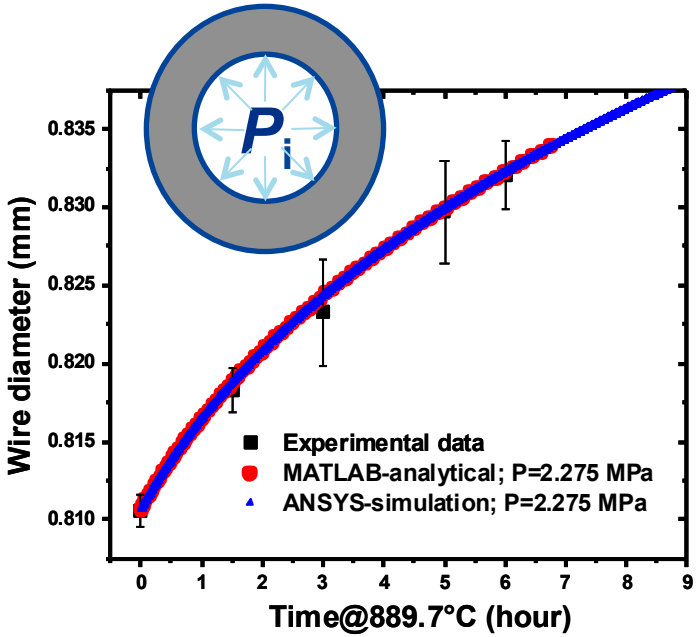


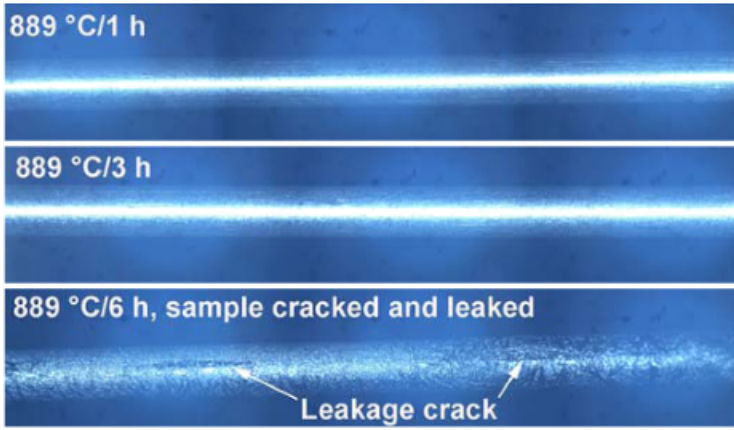
At high temperatures, 2212 wire creeps like cylindrical pressure vessels subjected to internal pressure

Key understanding:
- Silver creeps outward, producing more porosity in 2212 and lowering J_c in long-length wire
- Leakage is a natural consequence of the creep rupture of AgMg at the strain of ~3%.



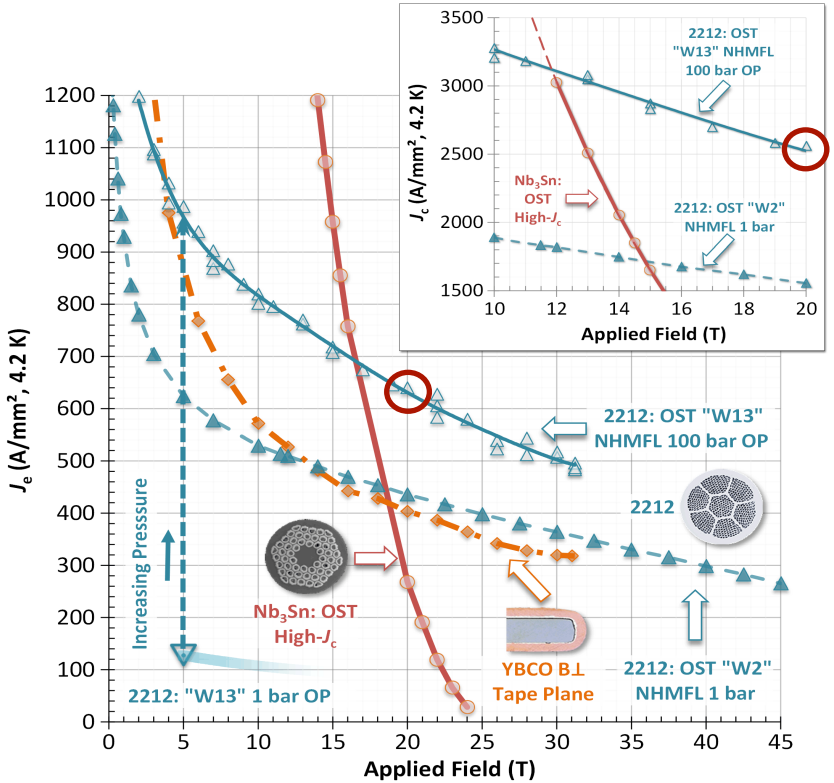
D_i=0.517 mm
D_o=0.803 mm
PF=75%
Courtesy of OST





The problem can be cured by applying external gas pressure during heat treatment

Overpressure processing can take the long length wire J_E to >600 A/mm^2 at 4.2 K and 20 T



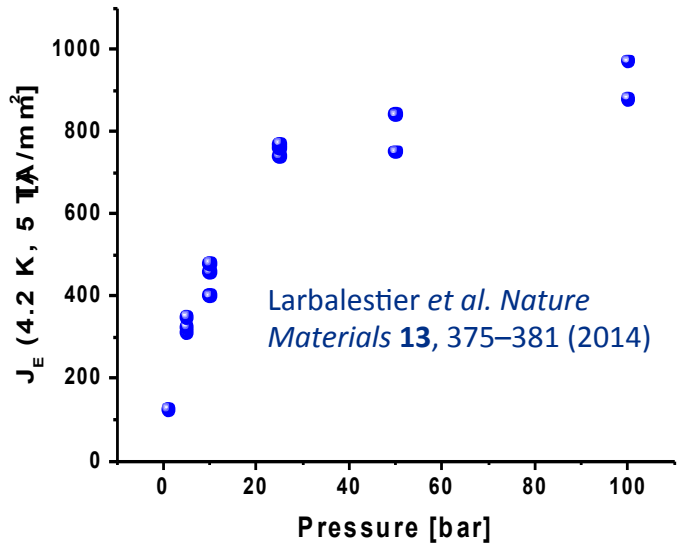
Larbalestier *et al. Nature Materials* **13**, 375–381 (2014)

Some history:

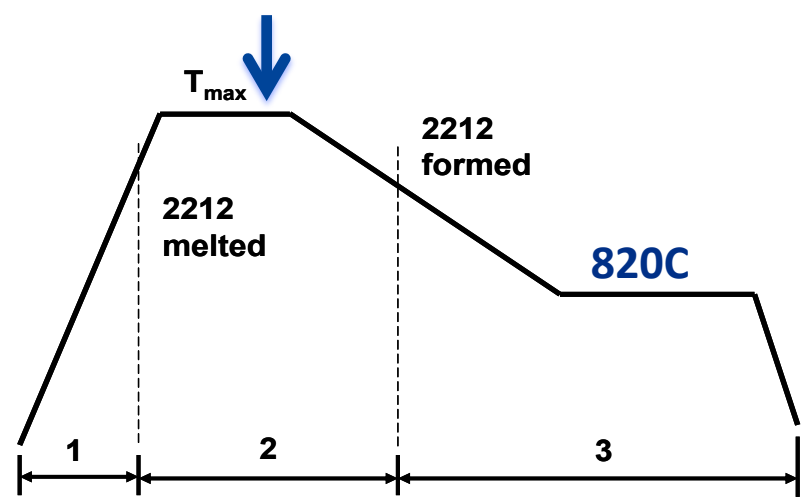
- **Tried for 2212 in 1990s but limited success was found.**
- **Developed into the core technology for 2223 industry in early 2000s.**
- **Picked up by VHFSMC/FSU to initially remove porosity (gas bubbles).**

Critical questions for optimizing and scaling up overpressure processing (OP)

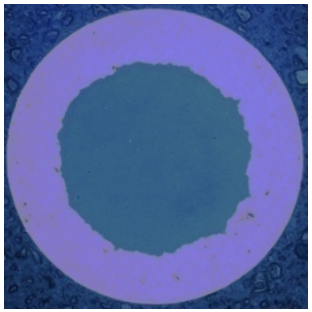
- **Is it possible to OP accelerator magnets?**
  - **5-15 m in length, 50-150 mm bore, 100 bar@900C, temperature control within ±3C**
- **To what pressure should the OP system be built?**
  - **Capital and safety costs go up quickly with pressure.**
- **At what heat treatment stages should overpressure be applied?**



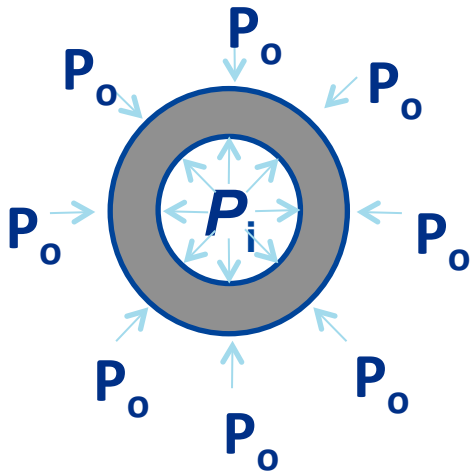
890-900C, ±3C temperature control

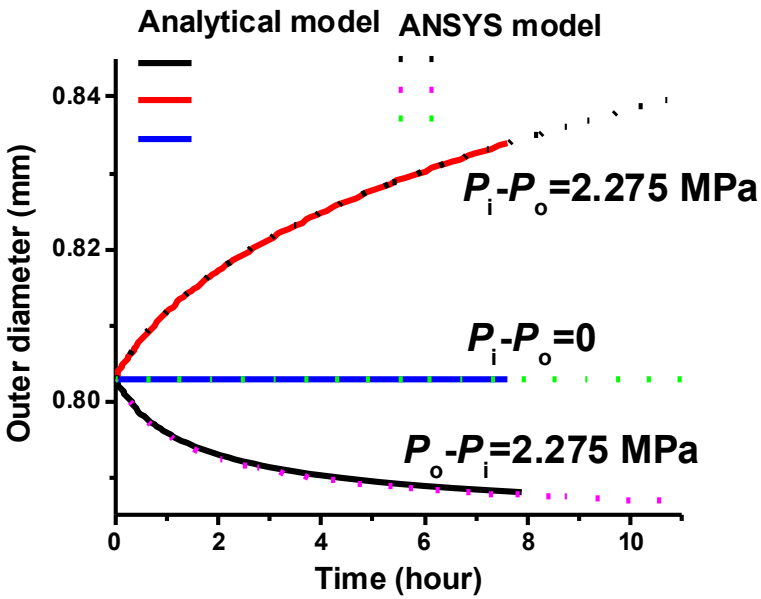


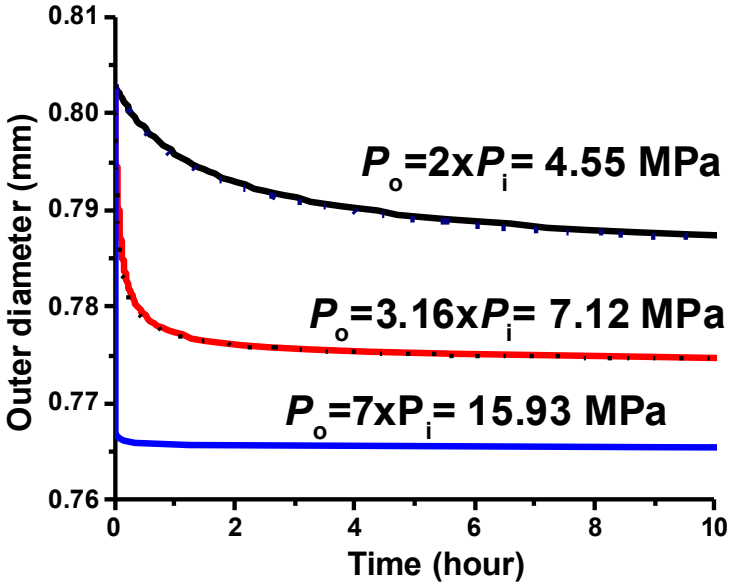
Under external pressure, Ag creeps inward, producing denser Bi-2212 core and raising J_c



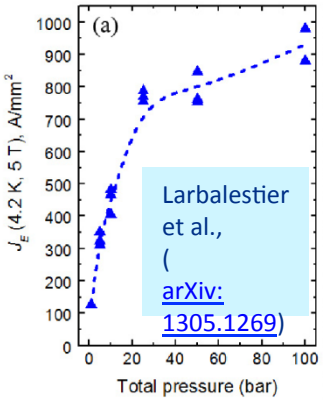
(courtesy of OST)

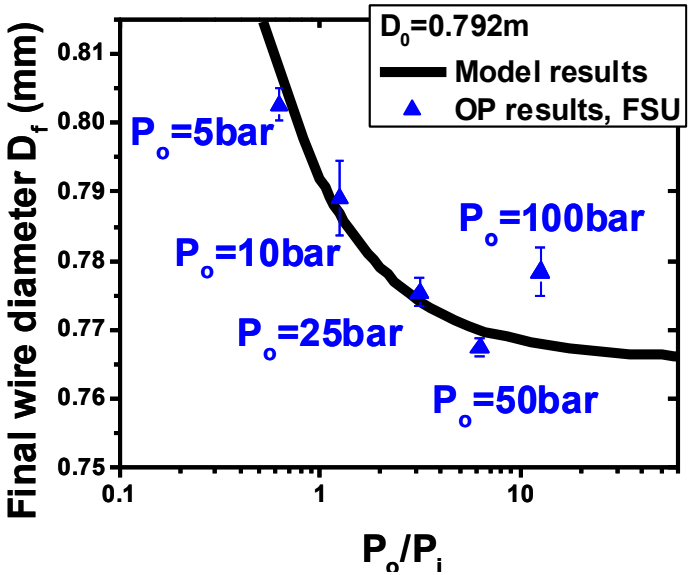


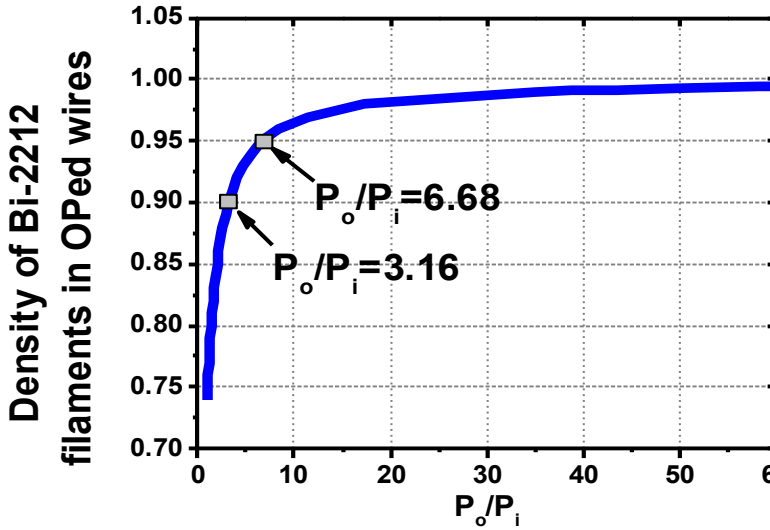




Using the concept of equilibrium pressure, model predicts a simple dependence of the density of filaments in Op Bi-2212 on the P_o/P_i ratio







Note: Experimental results obtained on multifilamentary conductor.

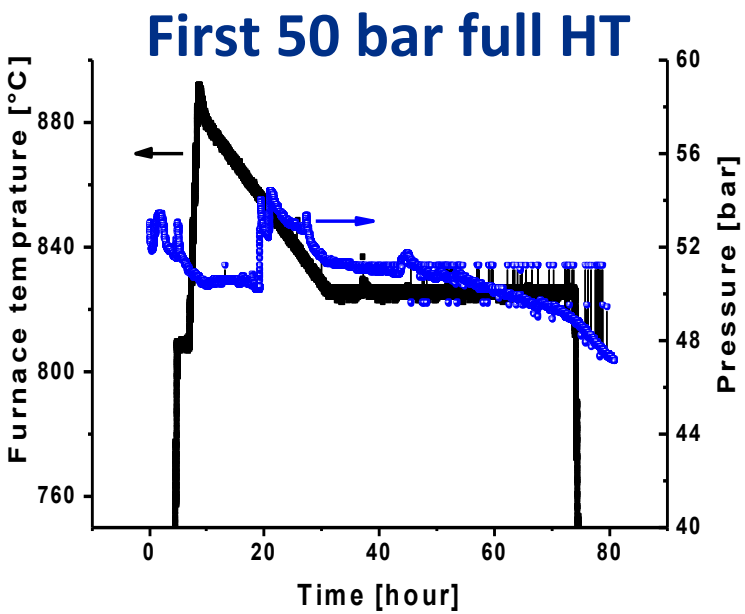
Implications:

- Overpressure requirement decreases with decreasing gas impurities levels in the wire.

Overpressure processing furnace system installed, approved to use, and being commissioned

- 3-zone MTI tube furnace, 50 mm bore
- ±1 °C in 16 cm
- Operated at 100 bar@900 °C
- $76 K (M&S only)

- 05/30/2013: Specification finalized
- 08/20/2013: Auction completed
- 09/02/2013: PO placed
- 01/30/2014: Pressure tested (vendor)
- 02/26/2014: Delivered to TD
- 03/04/2014: ORC review initiated
- 05/01/2014: Operations approved by TD
- 05/20/2014: First 50 bar OP samples produced

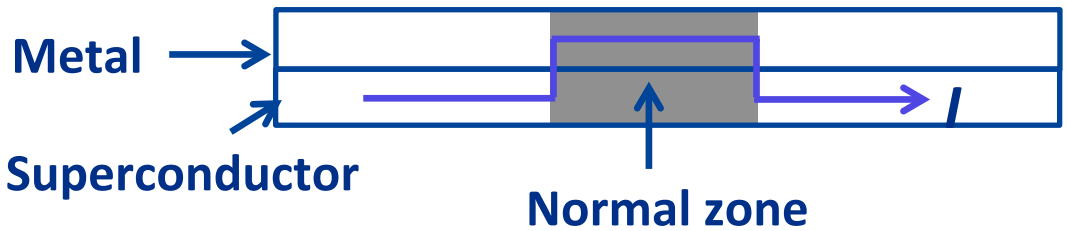


Acknowledgement: Meiyu Chen, TD-MSD (Fred Nobrega especially), Romesh Sood, Tom Peterson, Dan Assell

Section summary

- **High J_c in a long-length wire made by an industrial scaling process is hard to get.**
  - **In 2010, J_c of wires produced by U.S industry varied by a factor of 3.**
  - **Discovered that porosity agglomerates into large gas bubbles and that it strongly limits conductor J_c.**
  - **Removing gas bubbles doubles J_c.**
- **Identified the internal gases as the fundamental cause for low J_c as well as leakage in long-length conductor, demonstrated that silver creep is the fundamental mechanism**
- **Developing overpressure processing technology that delivers a J_c of several 10^3 A/mm^2 at 20-30 T in long-length Bi-2212**
  - **Developed theoretical description of the overpressure processing**
  - **Installed and commissioning a Fermilab overpressure processing furnace system**

Quench detection and protection remain an outstanding problem for HTS magnets

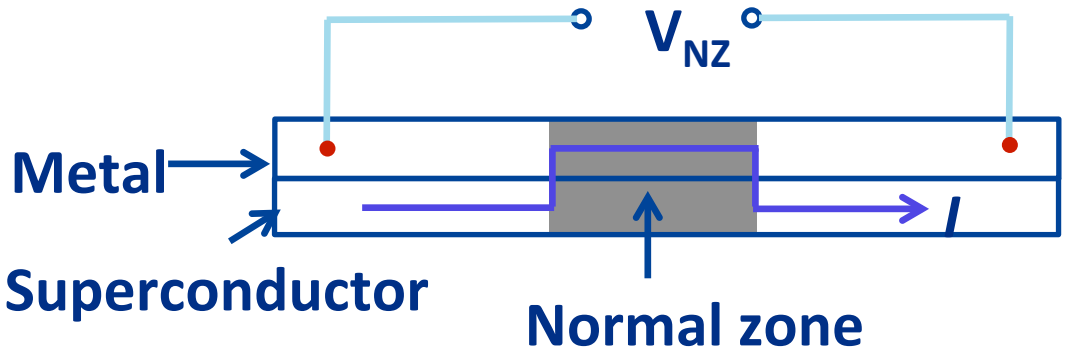


Unprotected quenches can destruct a magnet.
Hot spot temperature rises to a dangerous level in a fraction of a second.

Adiabatic heat balance: $J_m^2 \rho(T) dt = C(T) dT$

For temp rise T_m<200 K, RRR=30, Ag fraction=0.75, the required time constant is:
0.73 sec for J_m=400 A/mm^2
0.18 sec for J_m=800 A/mm^2.

An unsettling question is whether a quench can be detected, how it can be detected, and to what degree temperature, magnetic field, and operating current will affect the quench detection?



Normal zones in HTS propagate very slowly.

Superconductor	V_{NZPV}[mm/s]
NbTi	>1000
Nb_3Sn	>500
Bi-2223	~1-10
YBCO	~1-10
Bi-2212	~1-10

$$V(t) = I(t) \cdot R_{NZ}(t) = I(t) \cdot \int_{-(L_0+V_{NZPV}\cdot t)}^{(L_0+V_{NZPV}\cdot t)} \rho(z)/A_m \cdot dz$$

If the initial normal zone ($2xL_0$) is small

$$V_{NZ}(t)=I(t) \times R_{NZ}(t)$$
$$=I(t) \times V_{NZPV} \times t \times \rho(T_{NZ})/S_m$$
$$= J_m \times \rho(T_{NZ}) \times U_{NZ} \times t$$

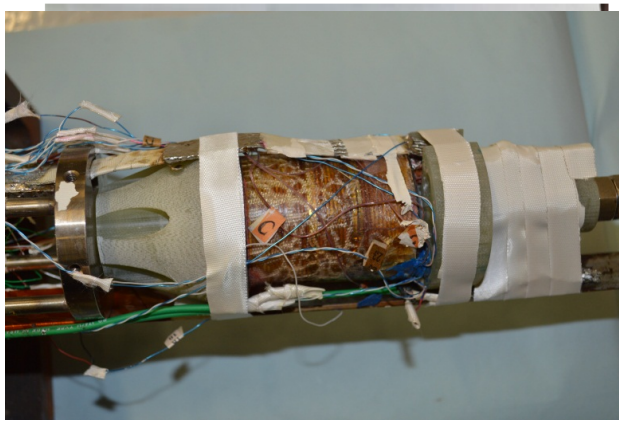
For V_{max} to reach 0.1 V,

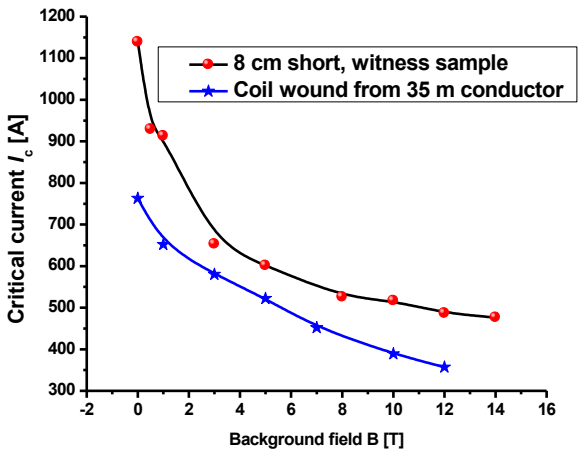
- Nb_3Sn: 10 ms, temp rise <30 K.

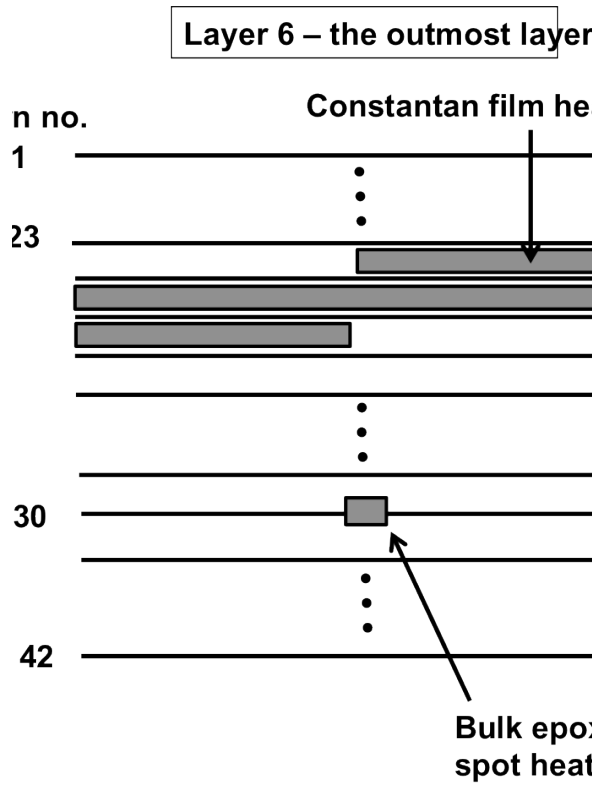
- HTS: >1 s, temp rise>100 K

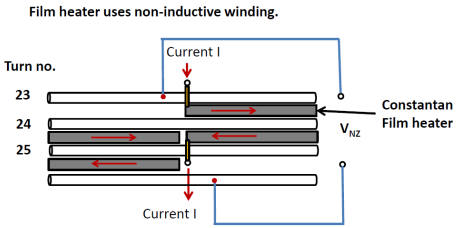
Experimentally study quench behaviors of small-scale coils in strong magnetic fields – previous experiments were mostly on short-samples and pancakes of YBCO at 4.2 K and self field

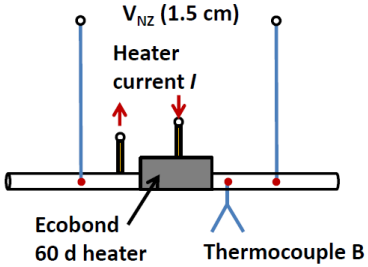
6-layer, 32 m Ag/Bi-2212 wire,
244.5 turns, ID=33.40 mm, OD=48.1 mm;
Length=57.80 mm





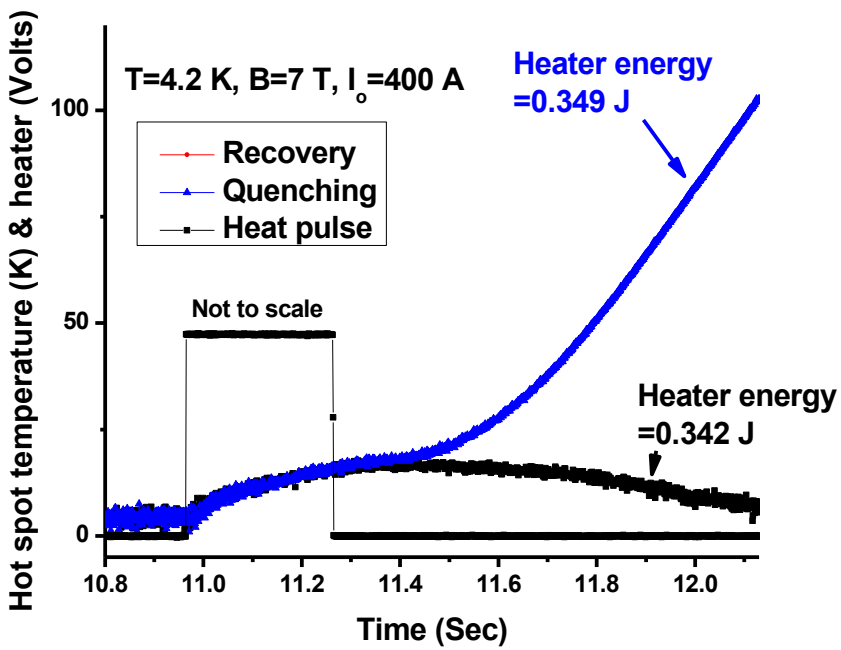


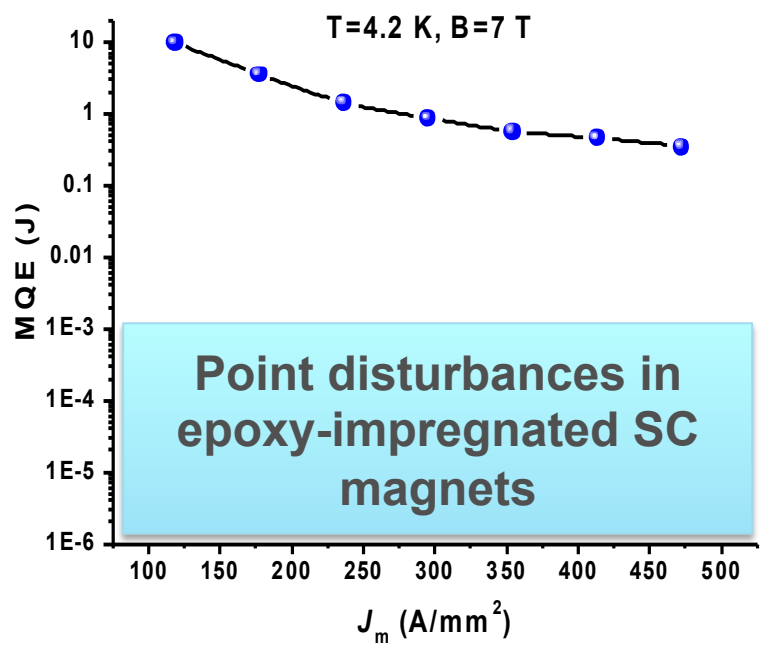




The coil is very stable – its minimum quench energy is greater than 0.1 J at 4.2 K and 7 T

- **MQE of Bi-2212 exceeds 0.1 J**
  - three orders of magnitude of greater than energy disturbances produced by conductor motion and epoxy cracking



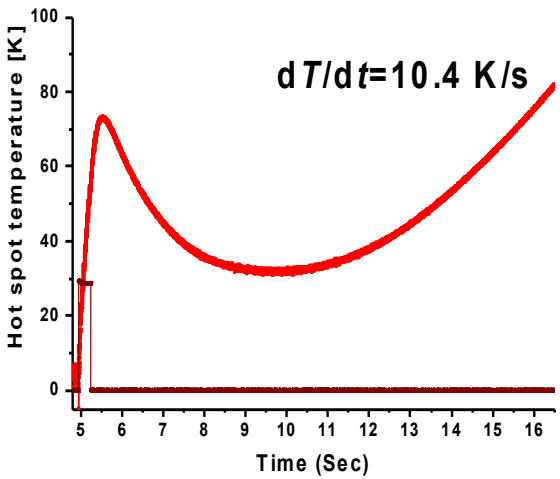


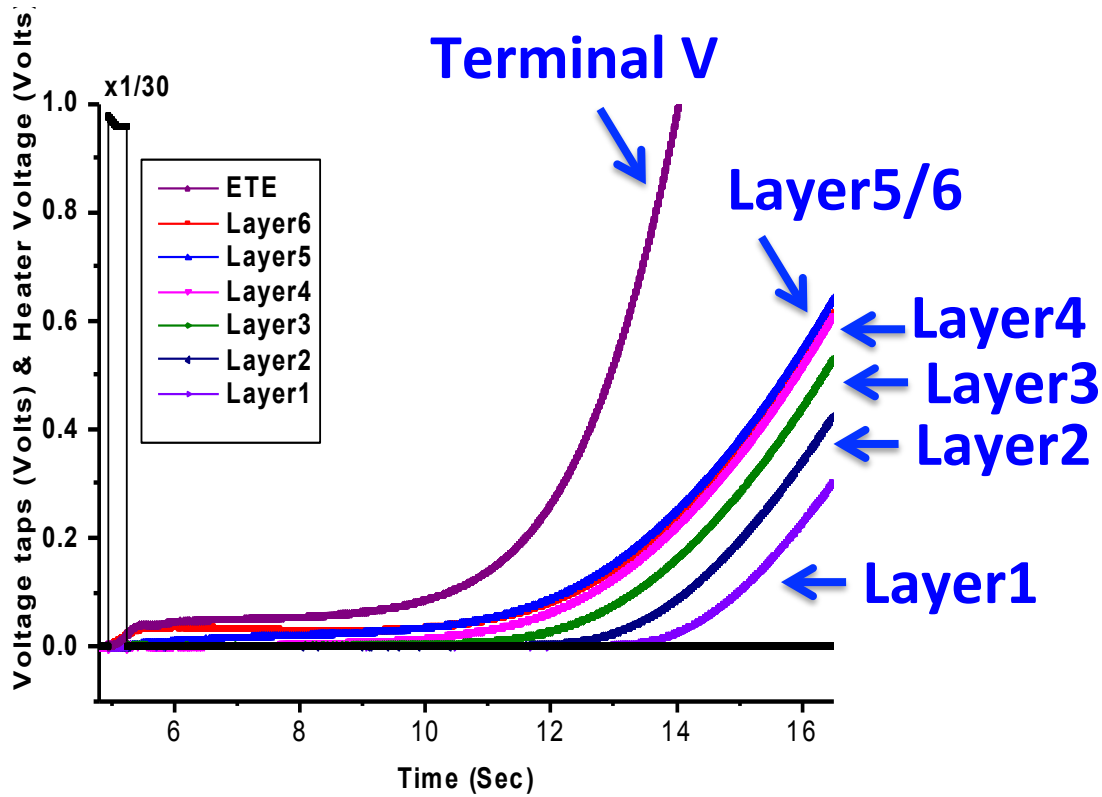
Point disturbances in epoxy-impregnated SC magnets

Temperature rise and quench propagation when J_m=118 A/mm^2 (I_o/I_c=24%)

- Temp goes up at ~10 K/s.
- Normal zones propagate from layer 6 to layer 1. V_{NZPV}(transverse)=1.4 mm/s

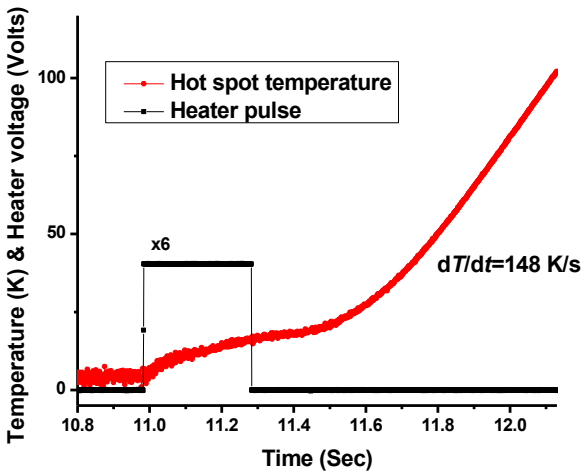
T=4.2 K, B=7 T, J_m=118 A/mm^2

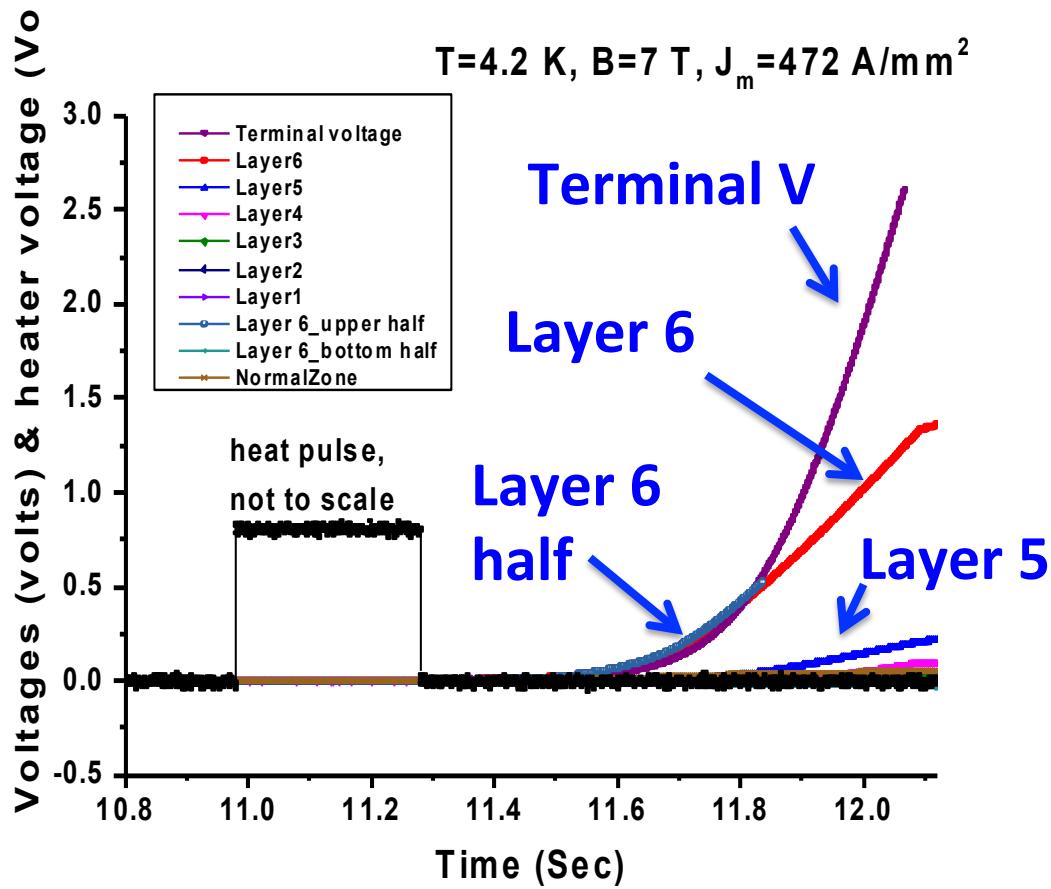




Temperature rise and quench propagation when J_m=472 A/mm^2 (I_o/I_c=95%) – "point-like" quench zones

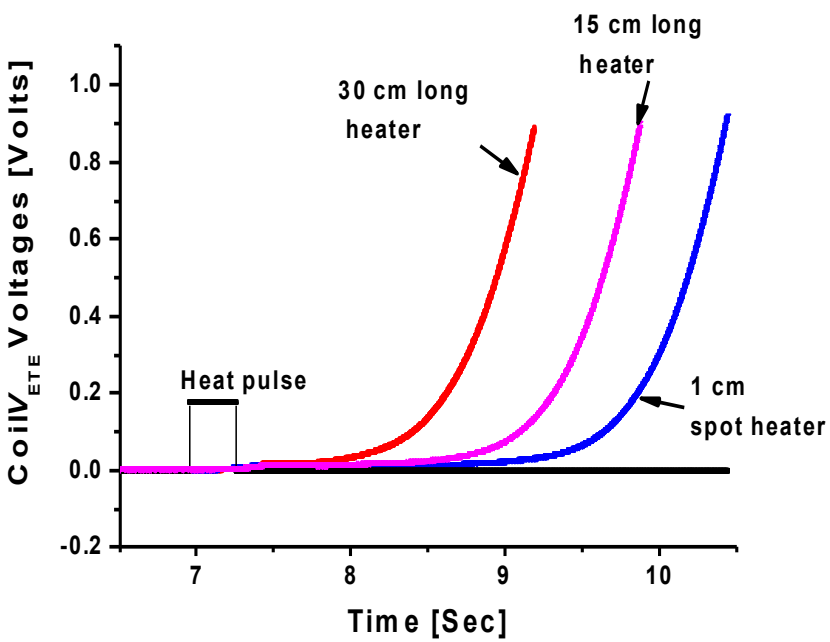
- Temp goes up at ~148 K/s.
- Quench zone is small, confined in layer 6. V_{NZPV}(transverse)=7.4 mm/s

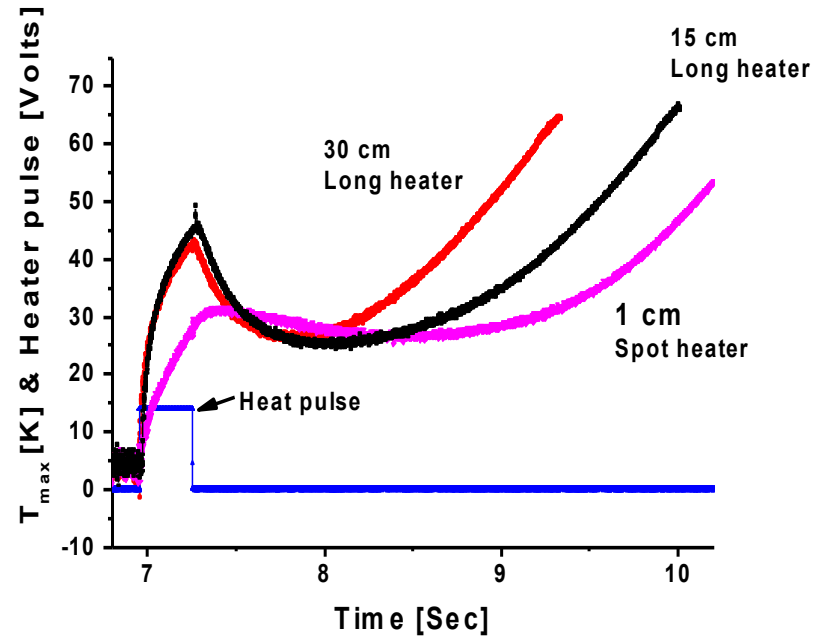


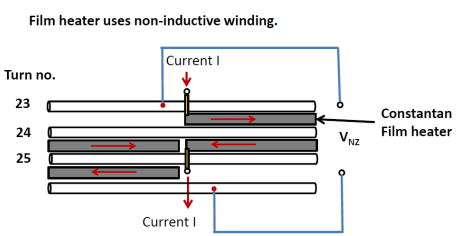


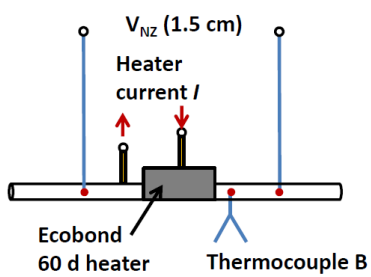
30 cm & 15 cm heaters vs. 1 cm heater: what do they tell us? "Point-like" quench zones develop into a length greater than 30 cm before thermal run-off

- Length of critical normal zone is proportional to MQE.



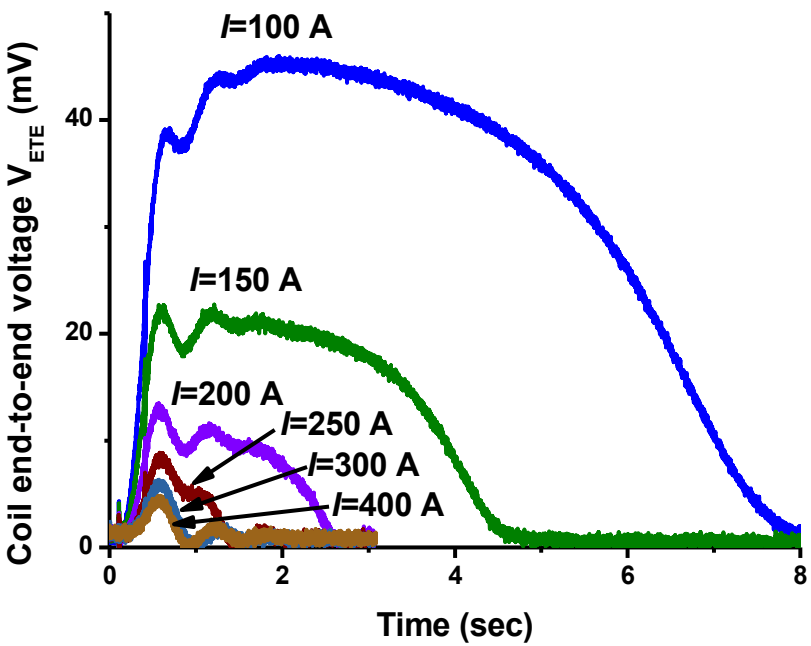


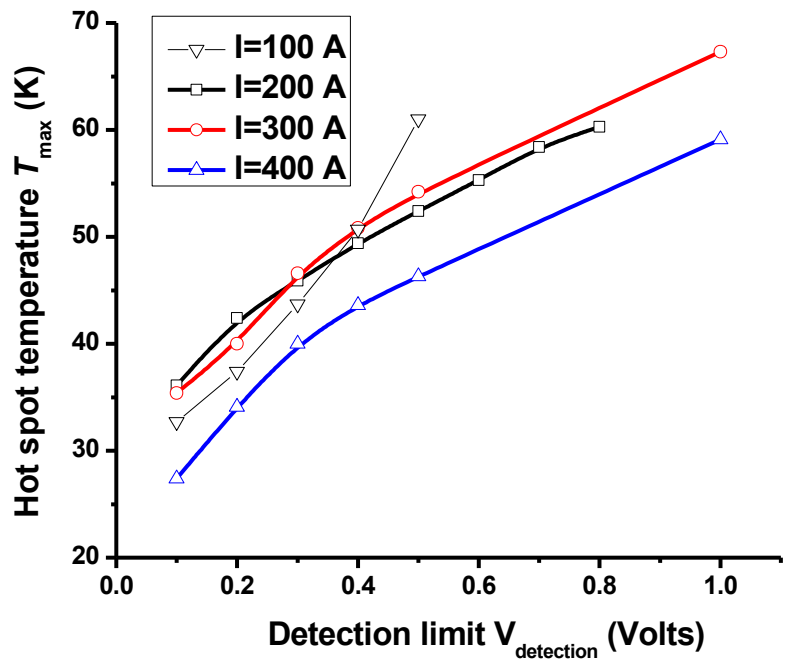




Quench detection voltage: how high should it be and how will it affect the hot spot temperature?

Coil terminal voltage during recovery cases





Section summary

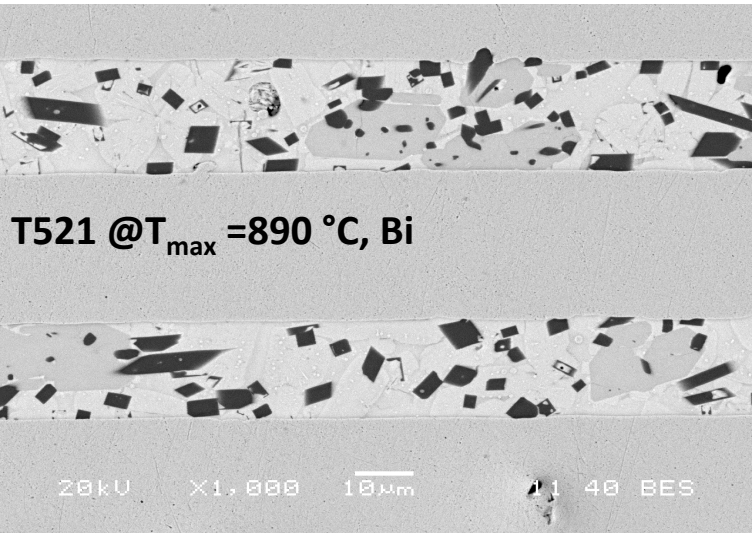
- Experimentally determine quench behaviors of sub-scale coils of Bi-2212 at 4.2 K and strong magnetic fields
  - MQE>0.1 J, V_{NZPV} (transverse to conductor)~1-10 mm/s
- Revealed that "point-like" normal zone develops into a length greater than 30 cm before thermal run-off.
  - Enabling quench detection using resistive voltages.
  - The ability of quench detection depends on critically on MQE, modestly on NZPV. This is in strong contrast of LTS, whose normal zones are in μm-mm in length and depends on normal zone propagation.
- First determined the dependence of hot spot temperature upon quench detection on the detection voltage criterion.

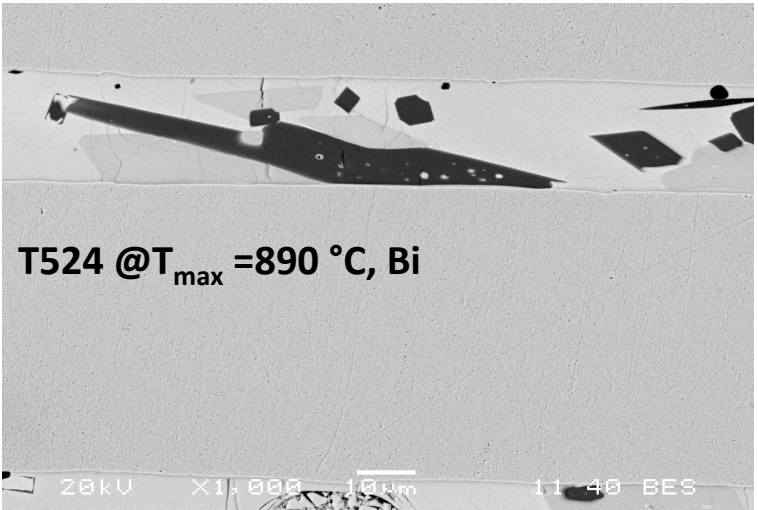
Future plans

- Continue systematic exploration of processing-microstructure-performance relationships and push J_e of 2212 conductors to >1000 A/mm^2 at 20 T through innovative processing and close collaboration with U.S. industry, and study new concepts and tools of fabricating, designing, and operating HTS magnets
  - DOE Early Career Award - $2.5M over 5 years (2012-2017)
- Develop, optimize, and innovate practical HTS magnet systems
  - 22+ T solenoids for MAP
  - 16+ T dipoles for future accelerator and the cable they depend on
  - Technology transfer and commercialization (22+ T solenoids, Muons Inc. DOE-SBIR)

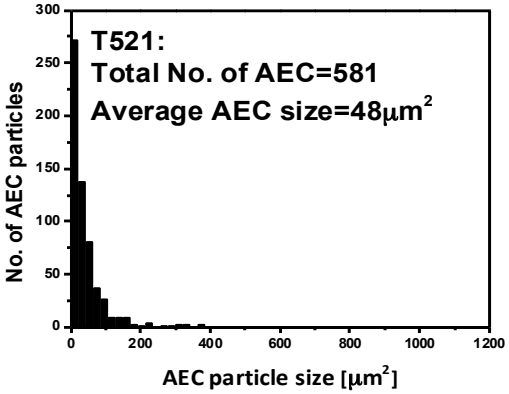
Further increase conductor J_c – the possibility is high

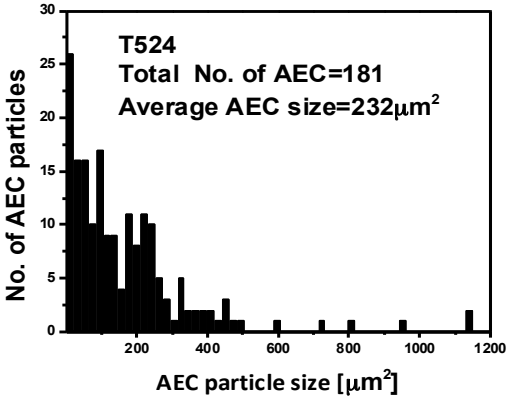
Tuning precursor powder composition led to a 4-times difference in J_c and we are providing some answers why (Pei Li).



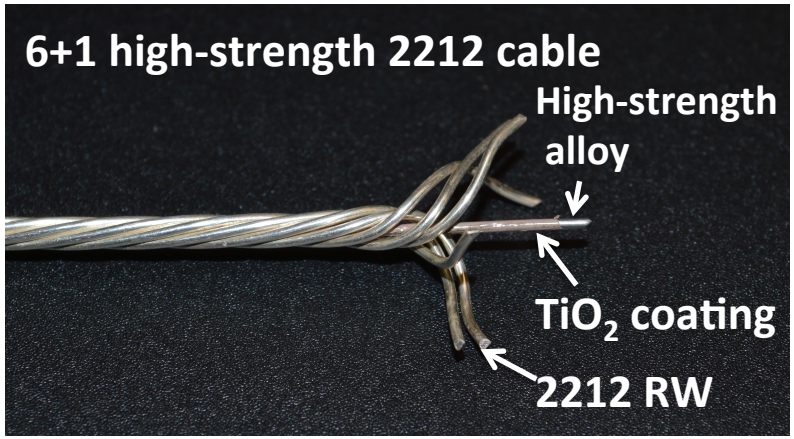


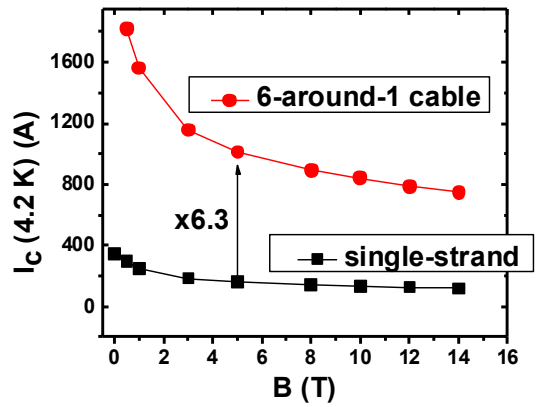
Collaboration with Nexans and OST.



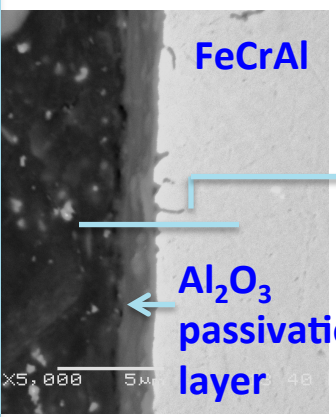


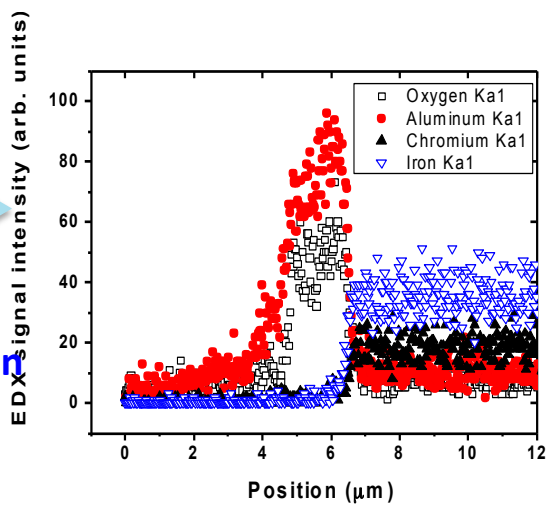
First experience with high-strength cables whose J_c didn't degrade and understanding why



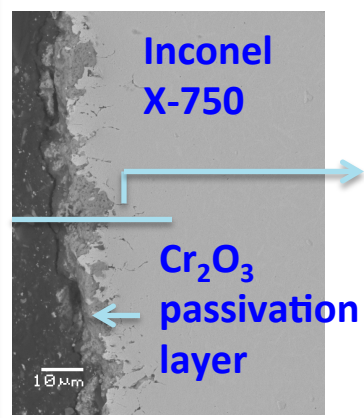


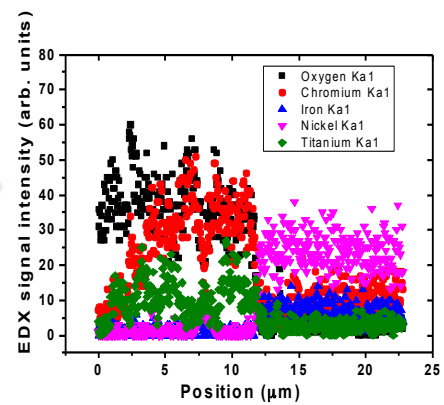
Fe-Cr-Al preserves 2212 J_c.





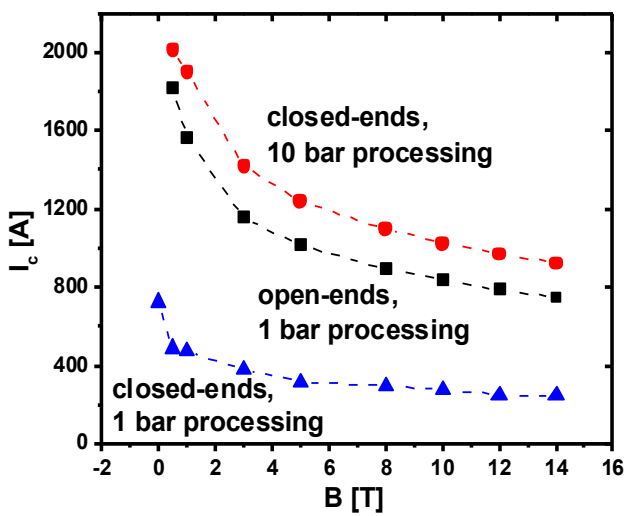
Inconel-X750 degrades 2212 J_c.

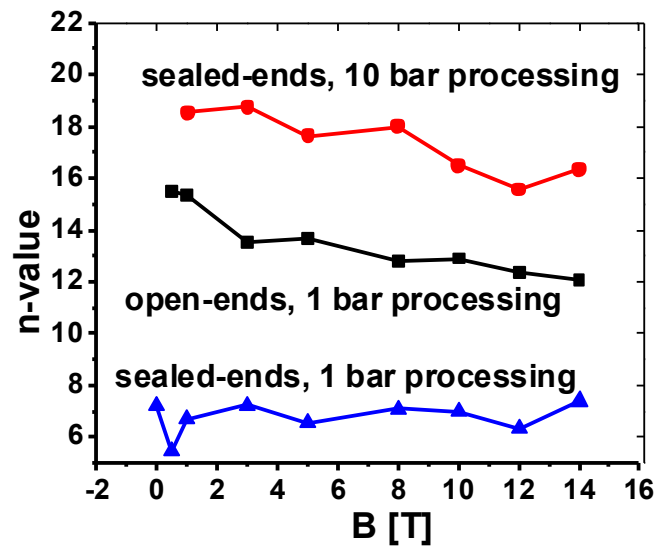




Pushing J_e of cables to 600 A/mm^2 at 4.2 K and 20 T

10 bar OP done at FSU. 100 bar processing at Fermilab coming soon.

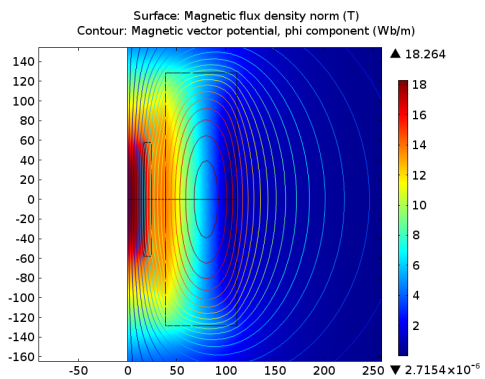


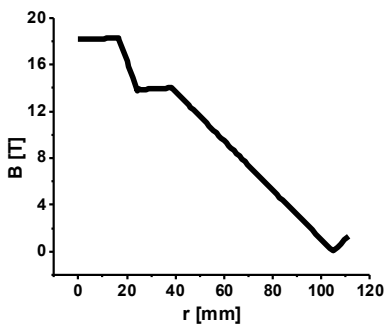


Developing overpressure processing technology for building high-performance coils

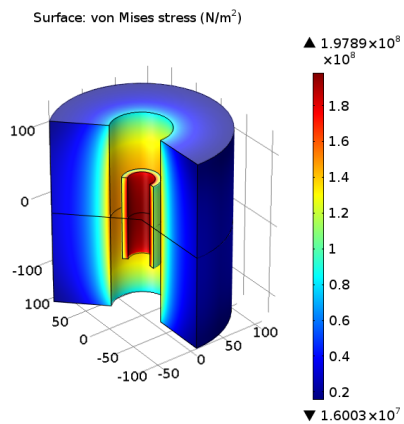
Integrated finite element modeling and thermo-mechanical measurements to access the mechanical limits

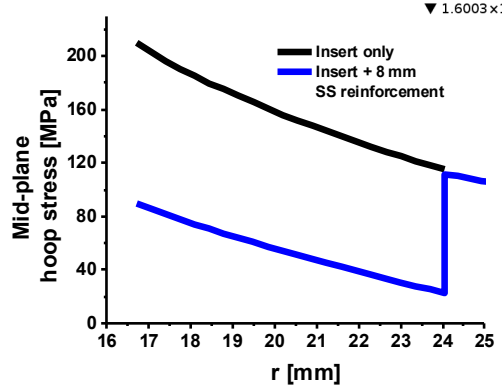
14T LTS outsert + 4 T HTS insert



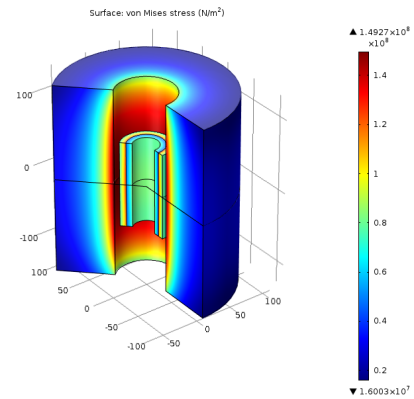


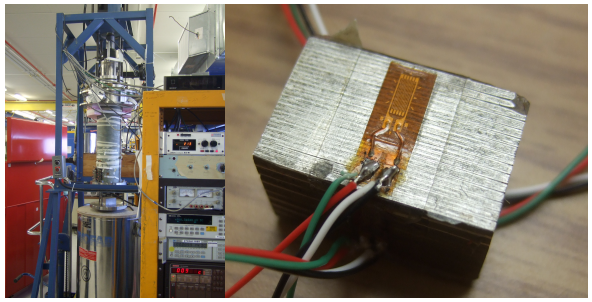
Insert only





Insert + 8 mm SS reinforcement





Conclusions

- LTS conductors approach their limits. Bringing HTS to applications will be revolutionary.
  - 30 T NMR (all SC)
  - 60 T hybrid (R+SC)
  - 30+ T muon cooling magnets and 16+ T dipoles
- Increased J_E of long-length Bi-2212 wire to >600 A/mm^2 at 4.2 K, 20 T
  - Developing overpressure processing technology
- Experimentally determined quench behaviors of HTS coils in strong magnetic fields.
  - With clear implications for quench detection and protection
- Bi-2212 is becoming a magnet grade conductor
  - Immediately open up applications in NMR and muon colliders at 22-30 T (solenoids)
  - Feasible for 16+ dipoles

Acknowledgement

- **Funding support:**
  - **U.S. DOE HEP through early career program, U.S. MAP, and GARD program**
- **Fermilab colleagues**
  - **A. Tollestrup, L. Cooley, M. Palmer, J. Tompkins, P. Li, M. Chen, T. Wokas, D. Turrioni, E. Barzi, A. Rusy, J. Krambis, M. Bossert, T. Van Raes, B. Wands, machine shop and welding shop**
  - **Graduate students and SIST undergraduates: L. Ye, Y. Wang, A. Matta, A.R. Gonzalez, A. Merille**
- **Collaborators:**

D. Larbalestier, E. Hellstrom
J. Jiang, U. Trociewitz
F. Kametani

A. Ghosh

A. Godeke

Y. Huang, H. Miao,
S. Hong

M. Rikel

J. Schwartz

36