Development and Optimization of Bi-2212 Superconductors at Fermilab

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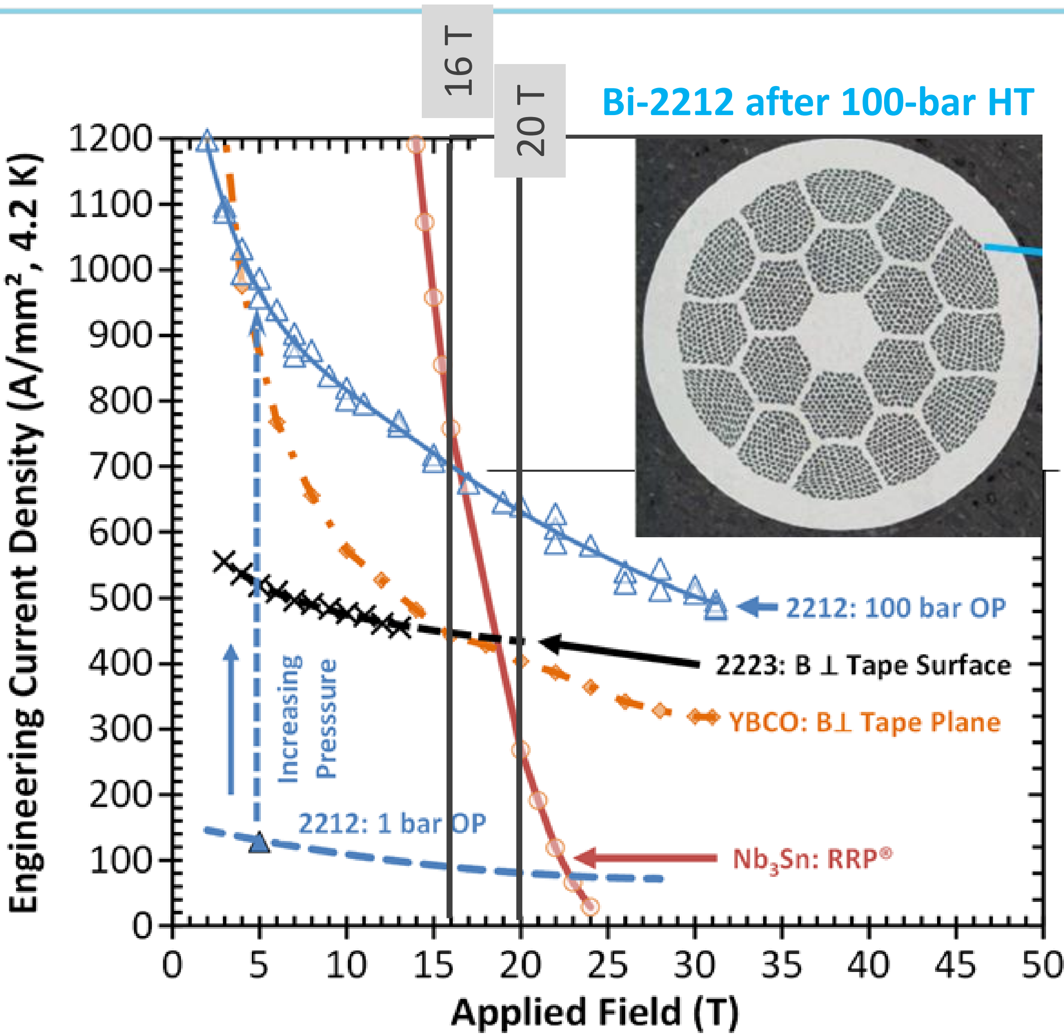
WAMHTS

DESY Hamburg, Germany, 23 May 2014

Take-away points

- Future accelerator needs: 30+ T special magnets, 16 T dipoles
  - Now *pulling* conductor R&D for Nb_3Sn, Bi-2212, and YBCO
    - YBCO is not in this talk – it's not a round wire
- High-current Nb_3Sn: present and future magnet *conductor*
  - *THREE* parameters are now being addressed simultaneously
  - Parameter choice reflects conductor *industrialization*
- Beyond 16 T: Round-wire Bi-2212 emerges with *overpressure process*
  - Multi-Lab collaboration: conductors pass basic checks for magnets
  - J_E is now high enough to merit development!
  - Racing toward OP cables and small coils – paths to real magnets?
  - 100% dense – time to start/resume R&D on flux pinning, grain size control, pinning mechanism, Hirr, etc etc

Nb_3Sn is the choice for 16 T, and the platform upon which HTS may go far beyond

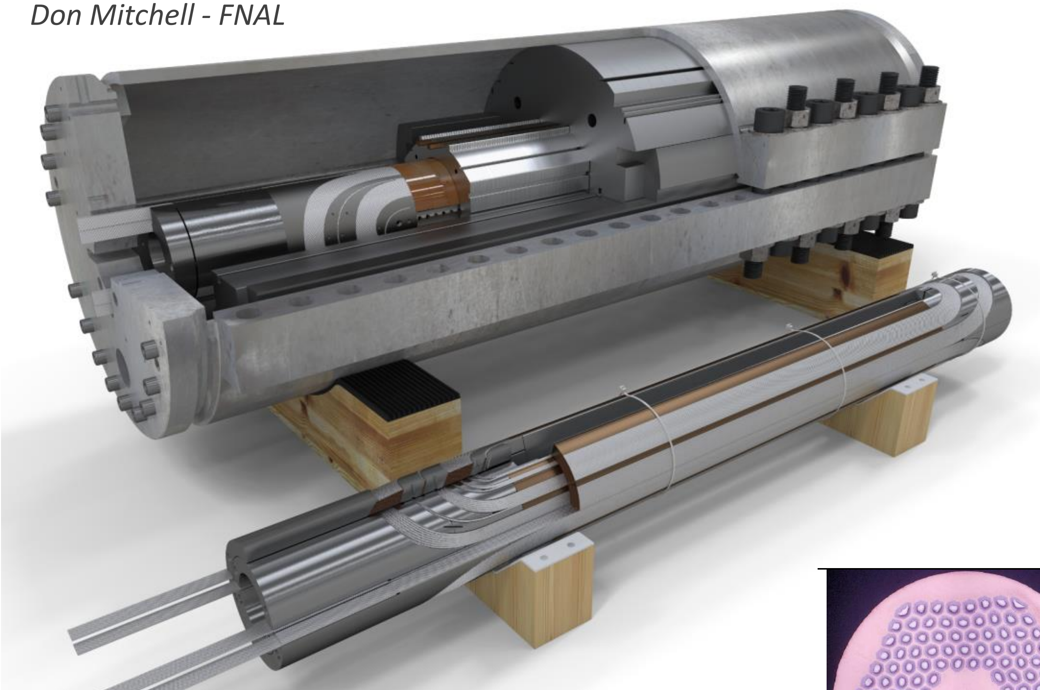


- Accelerator magnets need ~2x higher current density than solenoids
- 500 A/mm² across the strand is a "Go / No-Go" criteria for magnet development
  - 1000 A/mm² is what should be achieved in the superconductor

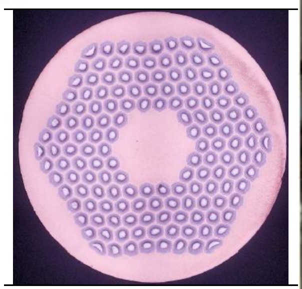
Adapted from Larbalestier et al., MagSci report.
See also Nature Materials, 13 (4), 375-381 (*2014*)

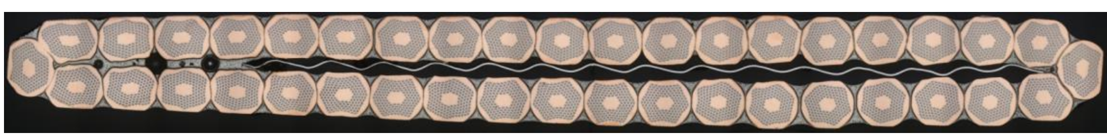
Snapshot
Technology for 11 T Nb_3Sn dipole magnets

Computer-generated cut-away "photograph"
Don Mitchell - FNAL

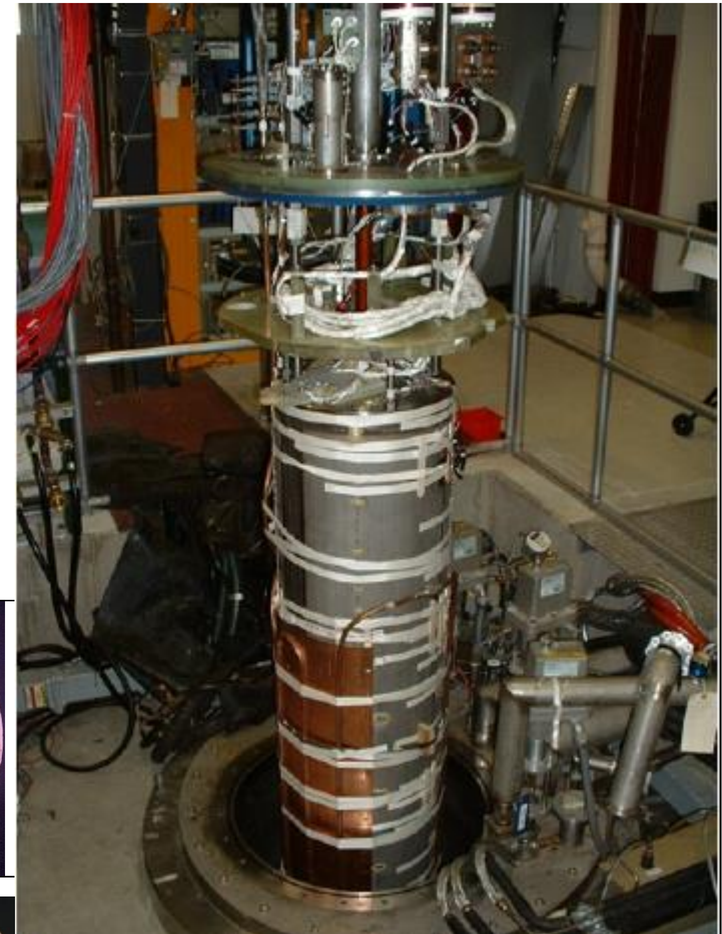


RRP Nb_3Sn wire
150/169 stack
0.7 mm



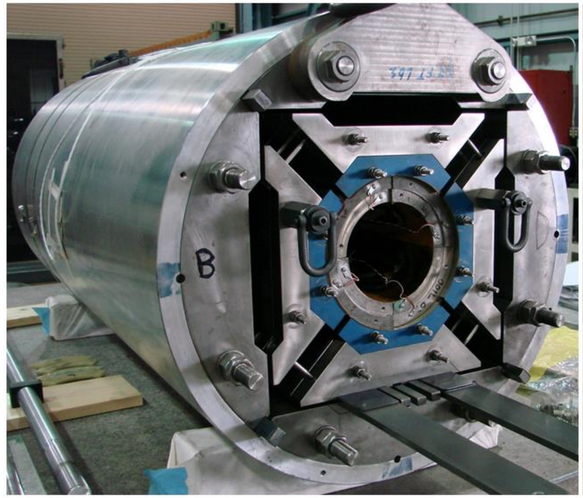


40-strand cable with stainless steel core



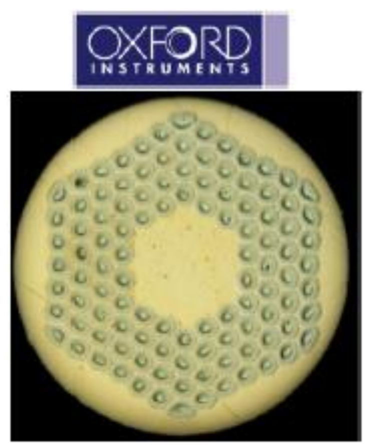
Model coil test in 2013

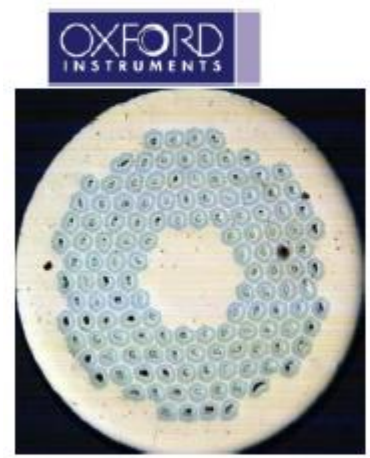
Snapshot
>13 T quadrupole magnets



RRP Nb_3Sn wire
108/127 and
132/169 stack
0.85 mm

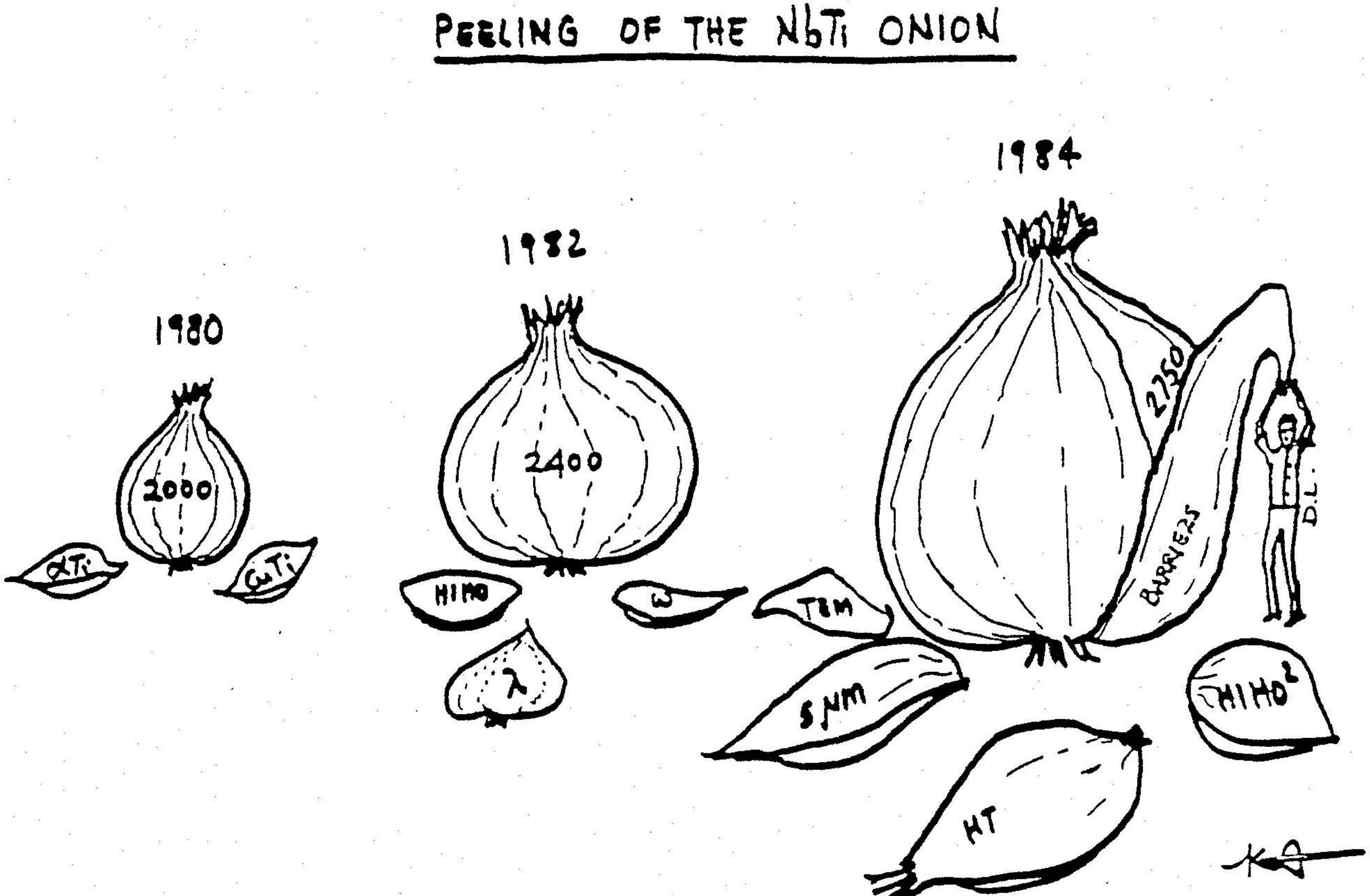
A Ghosh - BNL





Conductor maturity – reaching the heart of the onion

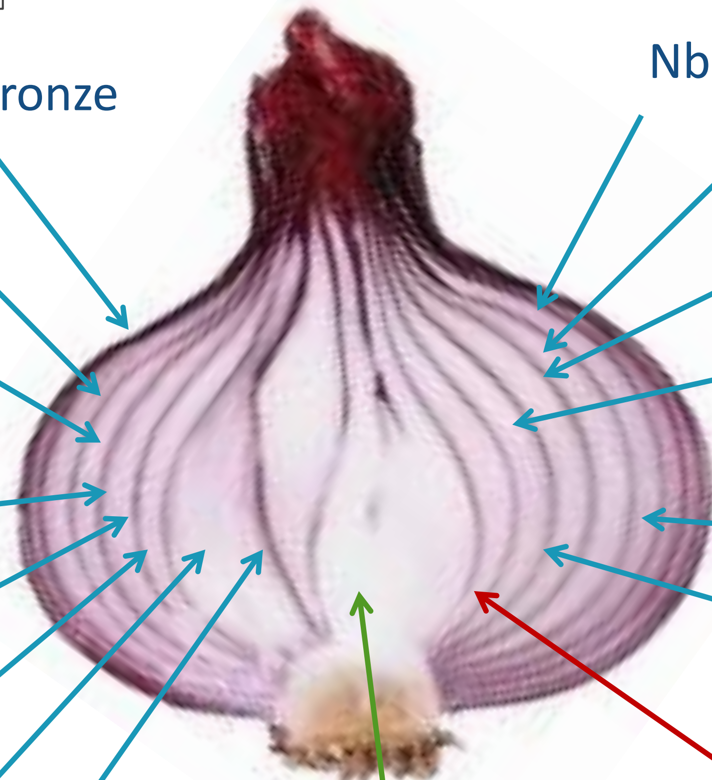
Hem Kanithi, IGC Advanced Superconductors (now Luvata)



Are we nearing the center of the Nb_3Sn onion?

Conductor architecture

In the Sub-element



1998: Bronze

2000: MJR

2002: PIT, v.1

Composition Gradients

54/61

108/127

2005: RRP 132/169

180/217

2008: PIT, v.2

What's next: APC?
Double-stack RRP or PIT?
Quaternary RRP or PIT?

Nb Barrier reaction

Ta alloying

Ti alloying

Thick barrier

3.6:1 Nb:Sn

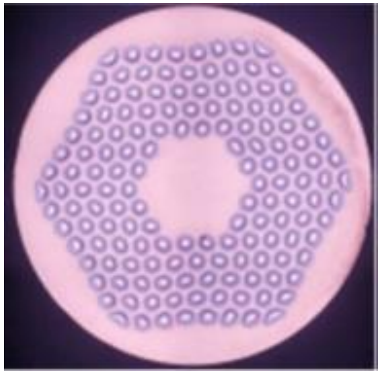
In the magnet

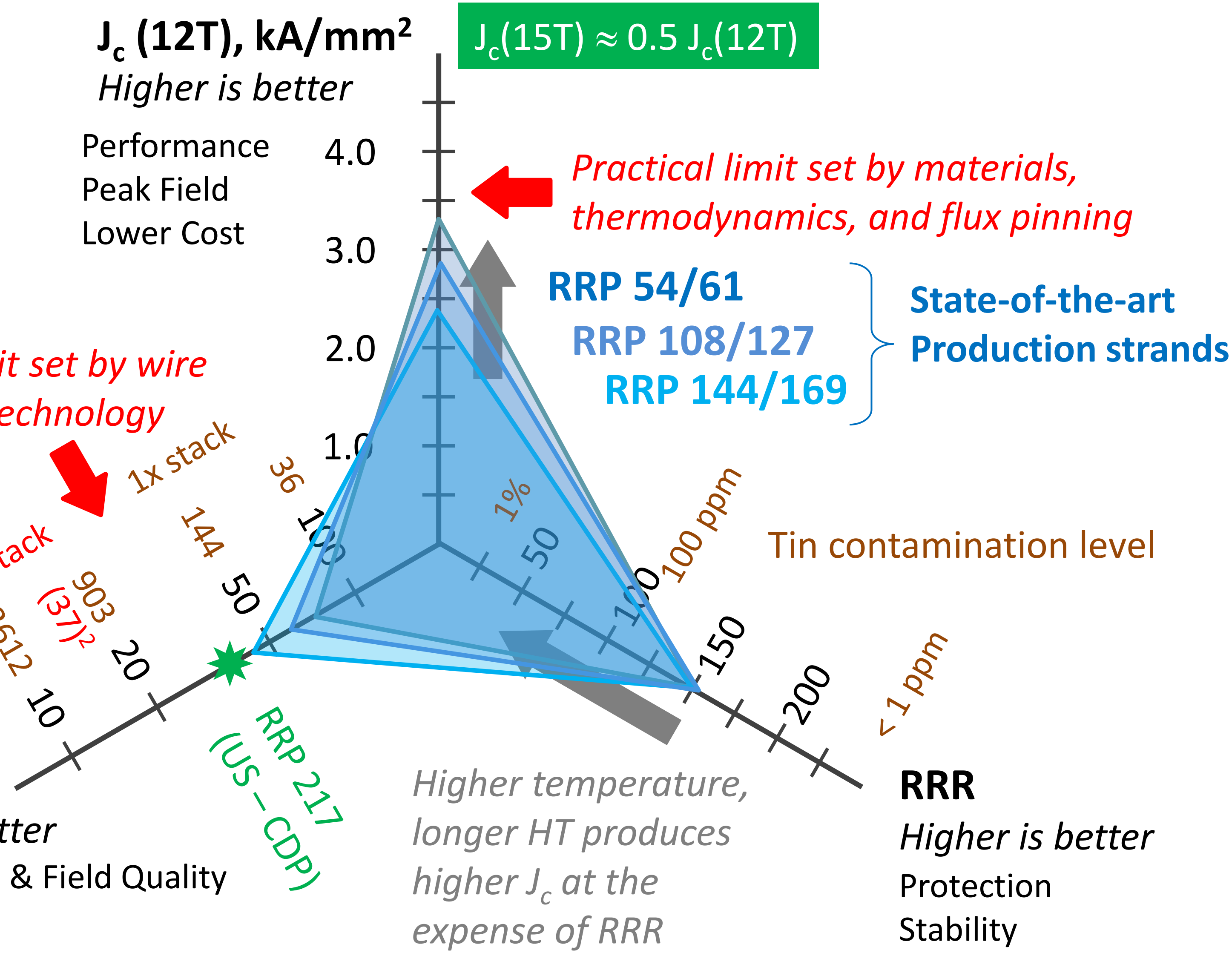
2004: Stability threshold

2007: 2-parameter optimization:
Jc and RRR

2010: 3-parameter optimization:
Jc and RRR and Ds

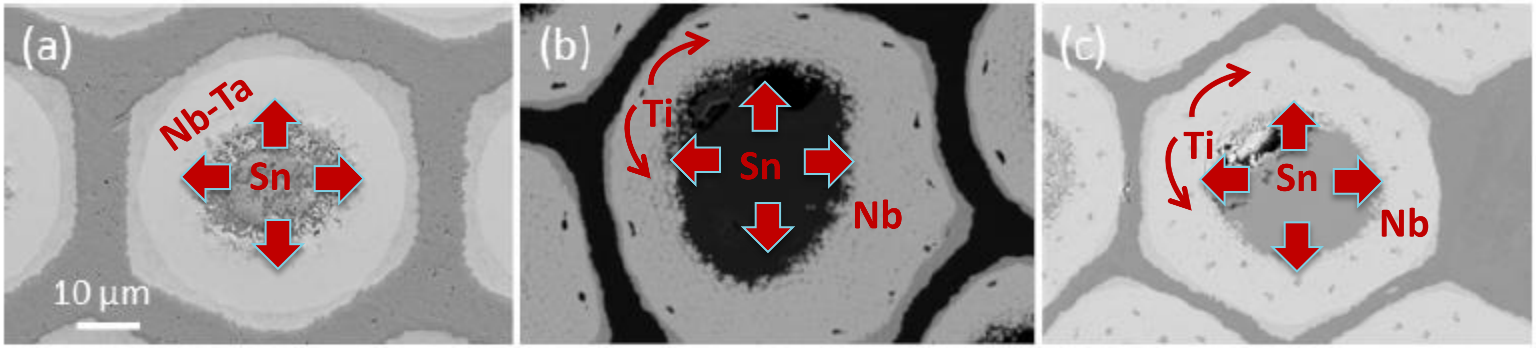
Nb_3Sn conductor development – 3 parameter optimization
adapted from Bottura MT-23 and Larbalestier P5 presentations





The action in the sub-element determines composition and properties

Scheuerlein *et al.* Supercond. Sci. Technol. **27** (2014) 025013

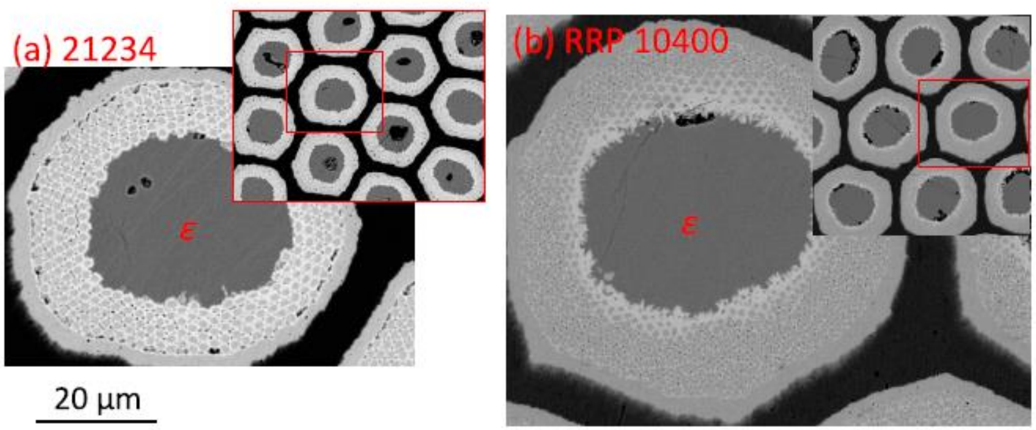


PIT: Nb7.5Ta tube

RRP: Nb + Nb-Ti

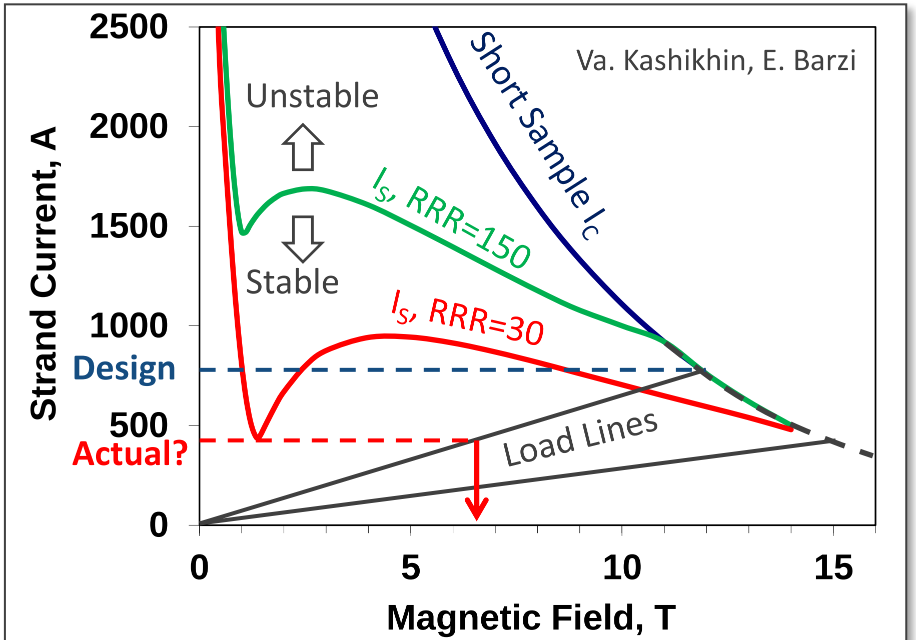
RRP: Nb + Nb-Ti

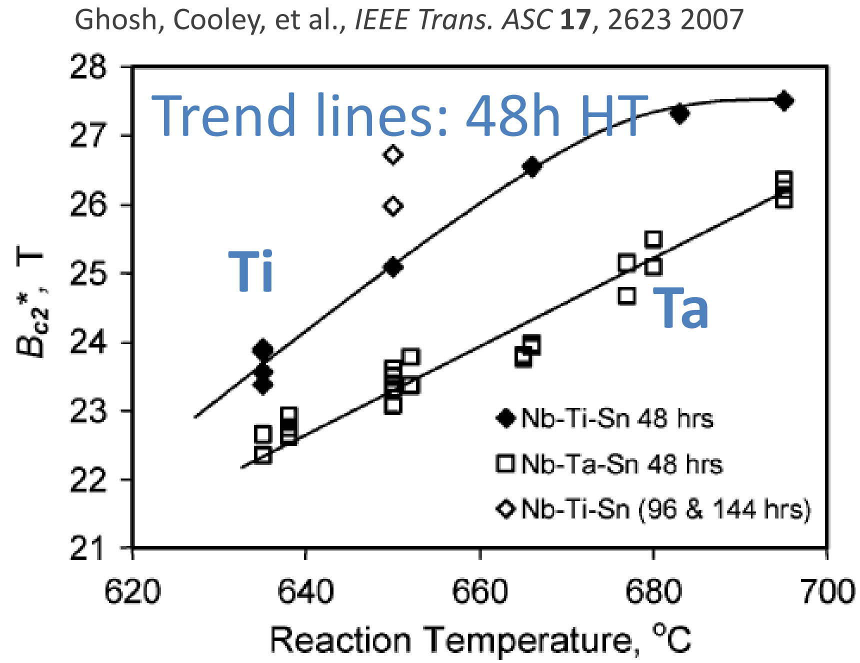
Pong, Oberli, & Bottura Supercond. Sci. Technol. **26** (2013) 105002



The sub-element is a very complex arrangement of the necessary items: tin, niobium, alloying elements, pathways for diffusion, protection of copper…

Onward to 16 T…
Plan A: push the present conductors to the limit





- More layers, so more tesla/amp
  - Low-field regions never reach instability
- Lower RRR may be ok
  - Reactions can be pushed hotter, longer

- Hotter, longer raises B_{c2}^*
- Ti and Ta respond differently
  - See Tarantini talk
- Start making quaternary $(Nb,Ti,Ta)_3Sn$?

Above 16 T: HTS → Bi-2212 round wire

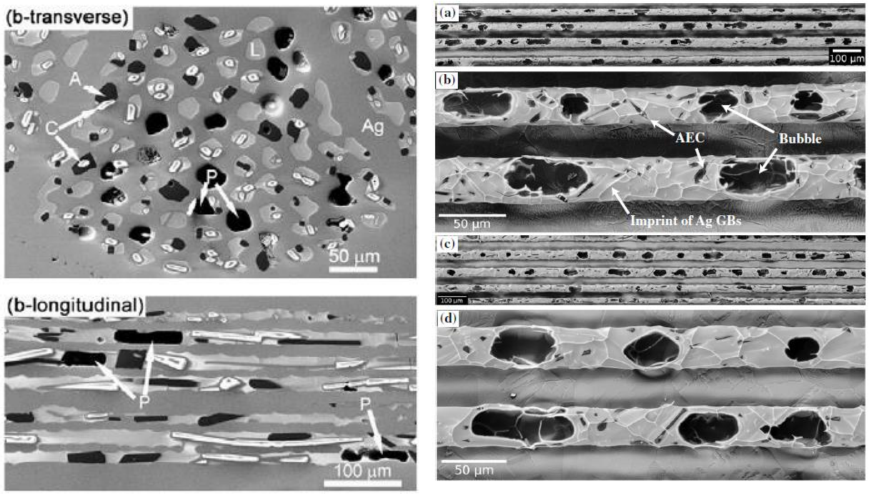
Many conductor development aspects resemble those for Nb-Ti and Nb_3Sn

- Fermilab strategic decision: focus on round-wire Bi-2212
  - Funds not sufficient for YBCO too
- 2009: Very High Field Superconducting Magnet Collaboration (VHFSMC)
  1. Buy wire (7 km purchased)
  2. Demonstrate aspects of magnet technology
     1. Cables made
     2. Small solenoids tested to 32 T in resistive-magnet background
     3. Cable-wound racetracks reached 75% of short-sample limit
  3. Demonstrate compatible insulation, structural material

- 2012: Bi-2212 Strand and Cable Collaboration (BSCCo)

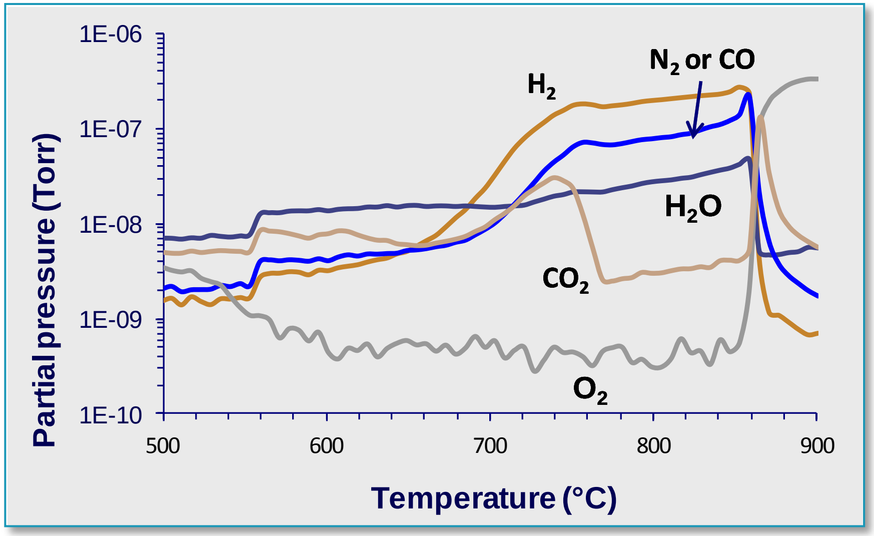
  NHMFL, FNAL, LBNL, BNL
  1. Develop powder sources
  2. Identify and remove limits to Jc using coil-relevant processes

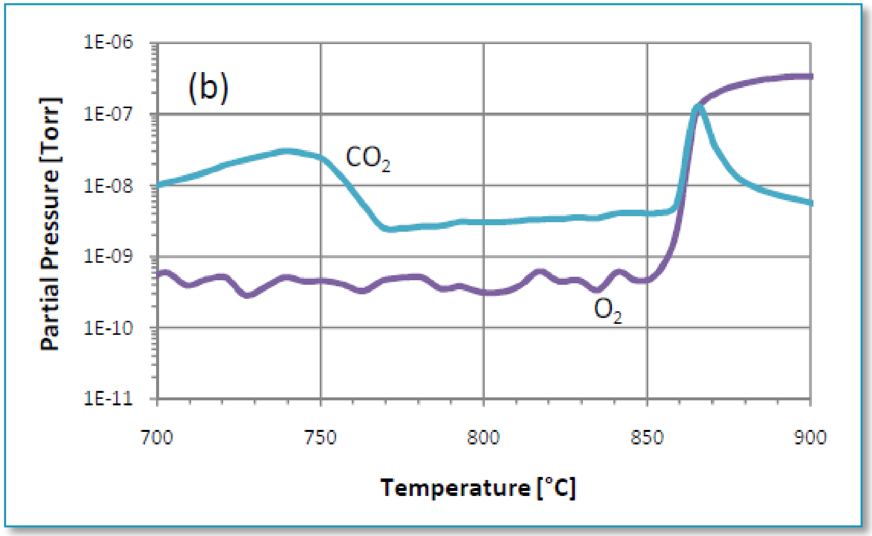
Kametani et al., SuST **24** 075009 (2011)



Over pressure processing – Bi-2212 round wire is a pressure vessel undergoing creep at high temperature

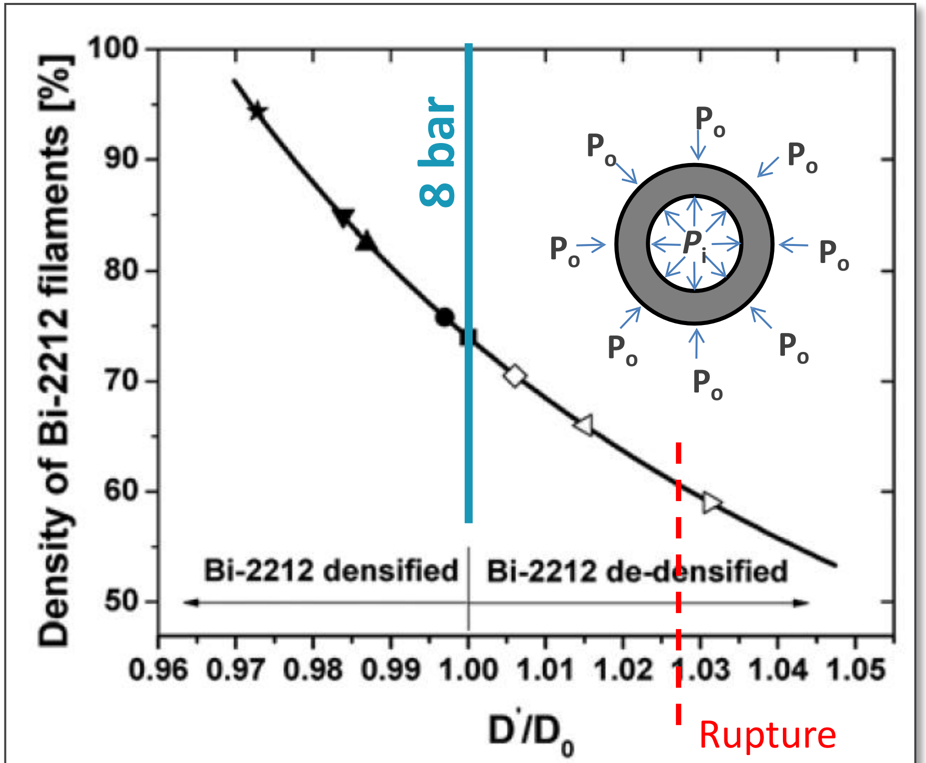
Partial pressures observed during heating of a Bi-2212 strand with open ends

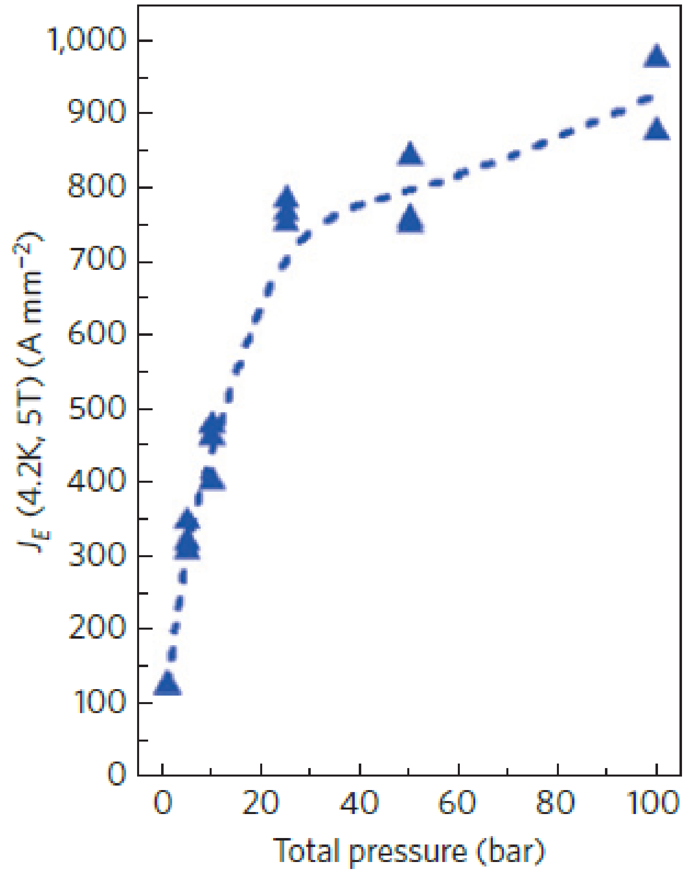




Shen et al., *J. Appl. Phys.*, 113, 213901 (2013)

Over pressure processing – Bi-2212 round wire is a pressure vessel undergoing creep at high temperature





Squeezing on the wire only controls bubbles, it also compacts powder before / during melt texture

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

Larbalestier et al., *Nature Materials* 13, 376 (2014)

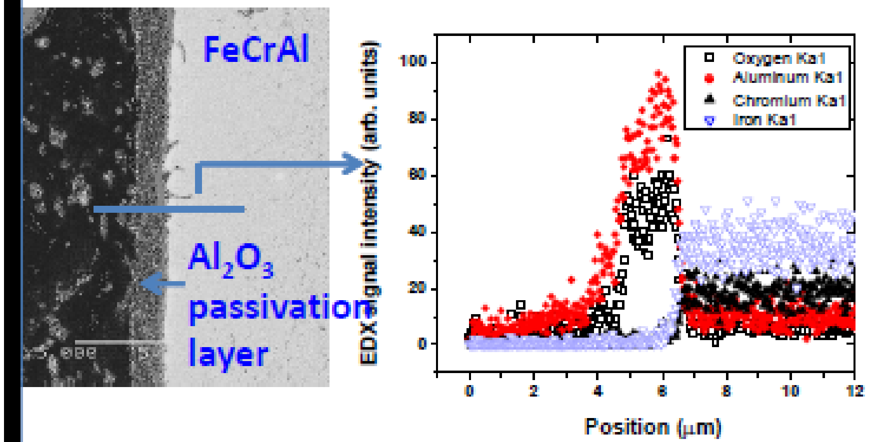
Goals of Fermilab program within BSCCO

- Focus on elements of HFM program: cables and strands
- Commission OP furnace
- Conduct OP process of simple Bi-2212 cable
  - Have 24-strand cable from VHFSMC in hand, plan to make a fixture for flux-transformer test
  - Extend 6+1 cable to 100 bar
- Understand quench behavior
  - Ph.D. thesis of Liyang Ye, from NCSU
- Investigate mechanical properties
- Understand implications / opportunities of powder composition changes and vendor changes
  - Dip-coated tapes with Nexans (Rikel), OI-ST (Huang), FSU (Jiang, Hellstrom)

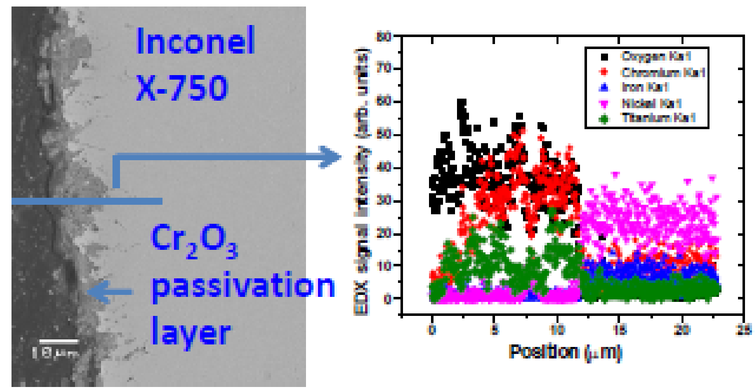
Reinforced and insulated cables are possible

T. Shen and P. Li, to be published

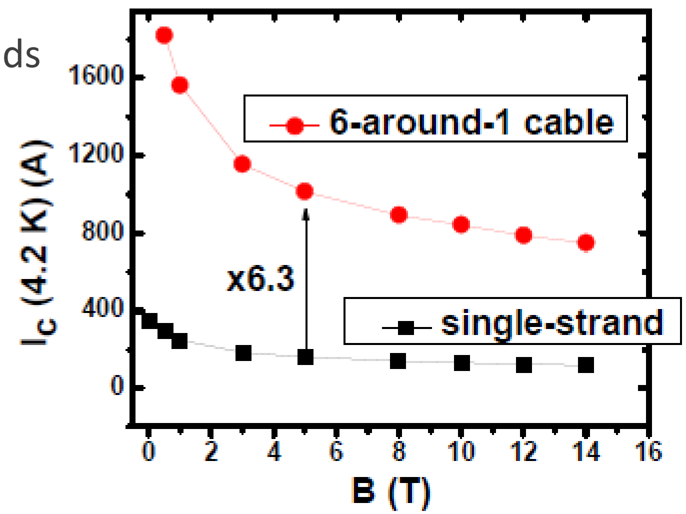
Fe-Cr-Al preserves 2212 J_c.

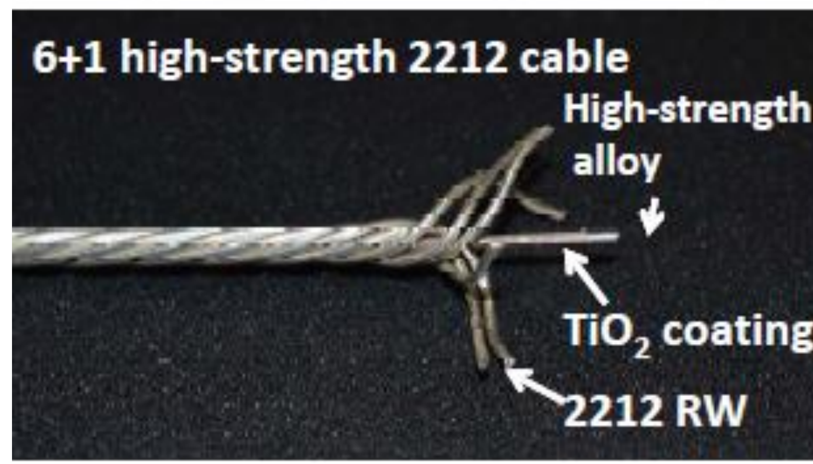


Inconel-X750 degrades 2212 J_c.



Open ends
1 bar

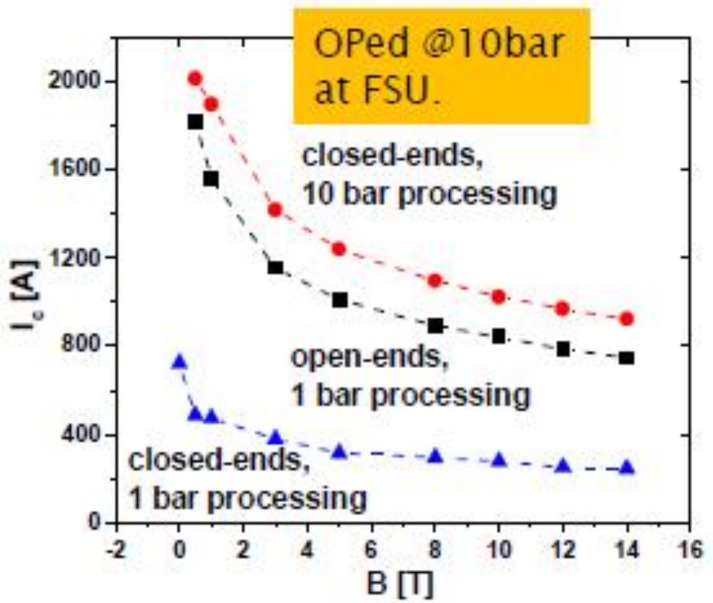


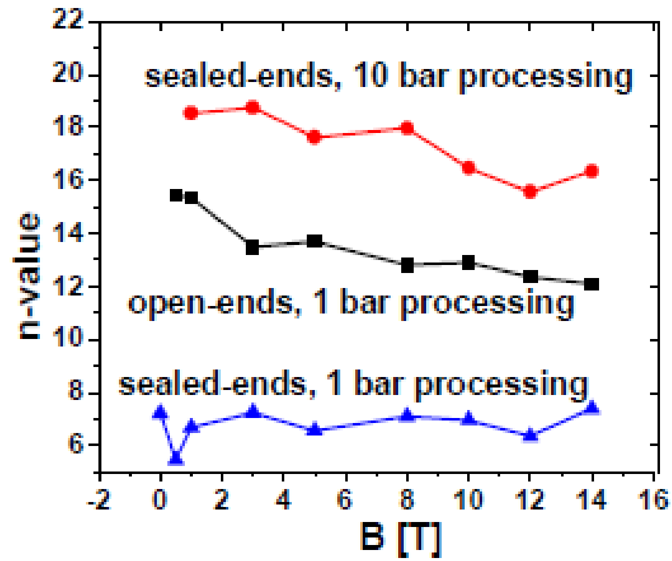


Start of OP activities – using FSU oven

T. Shen (FNAL) and J. Jiang (FSU), to be published

- 6-around-1 cable, 10 bar vs. 1 bar:
  - 120% vs open ends, 4x increase above closed ends
  - Closed ends is expectation for magnet
- 100 bar expected soon

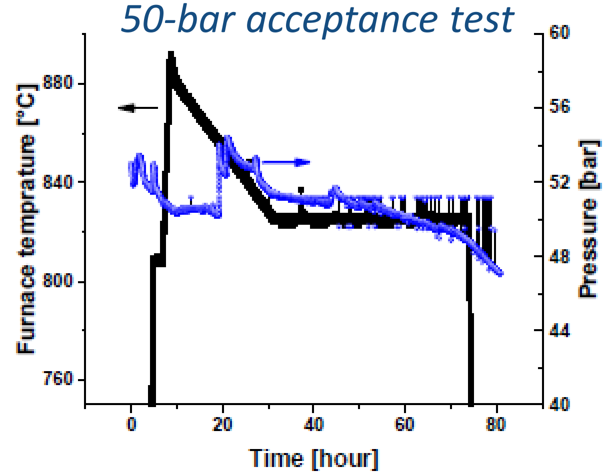




New OP systems – Building, installing, and clearing for ops

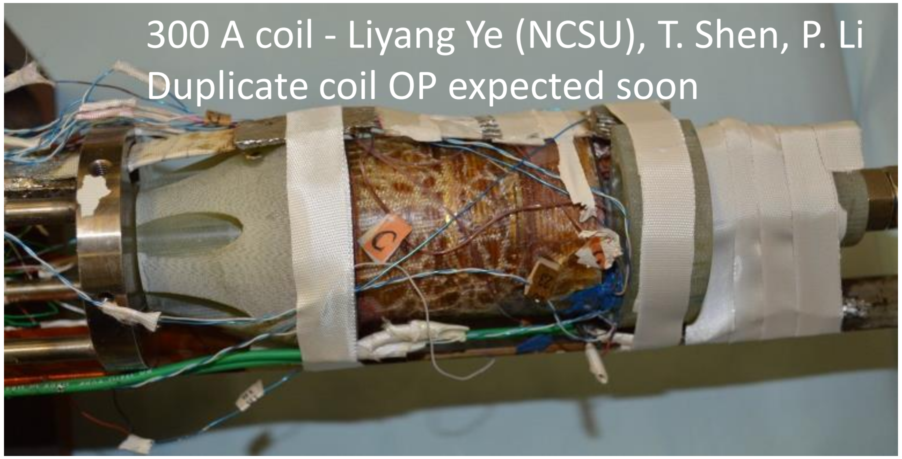
- Operational 30 April
- 1 year elapsed between specification & operation
- Cylindrical hot zone
  - Quartz-lined superalloy
- Reinforced end flanges
- Gas flow: control PO_2 while it is consumed

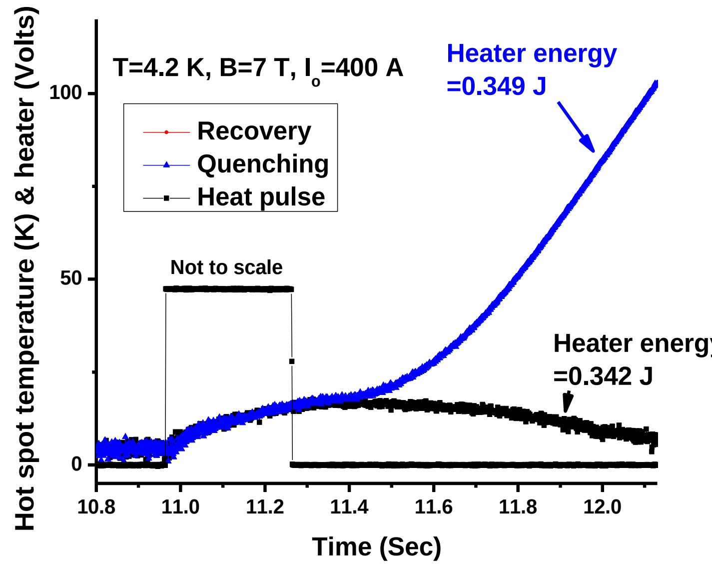
50-bar acceptance test

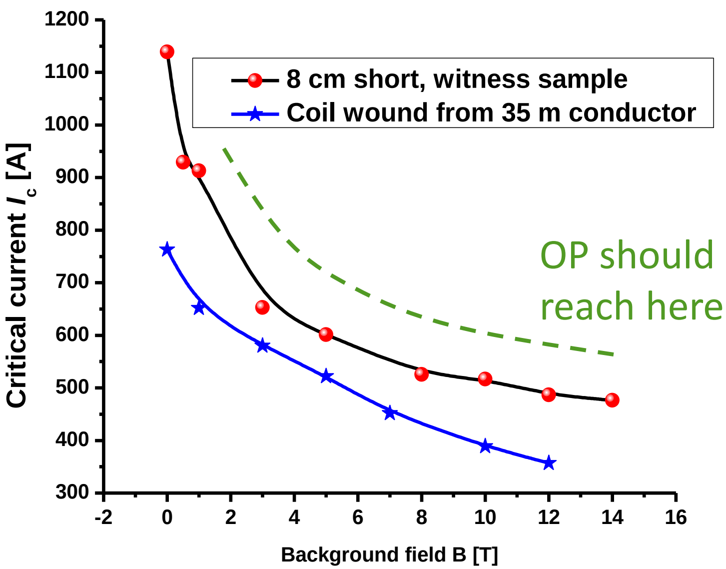


Scalable: A solenoid, or an accelerator magnet coil, might be reacted in a reinforced "pipe" inside an existing magnet reaction oven.

Instrumented small coil



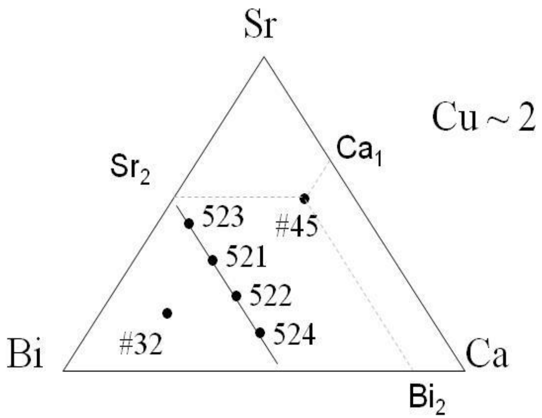




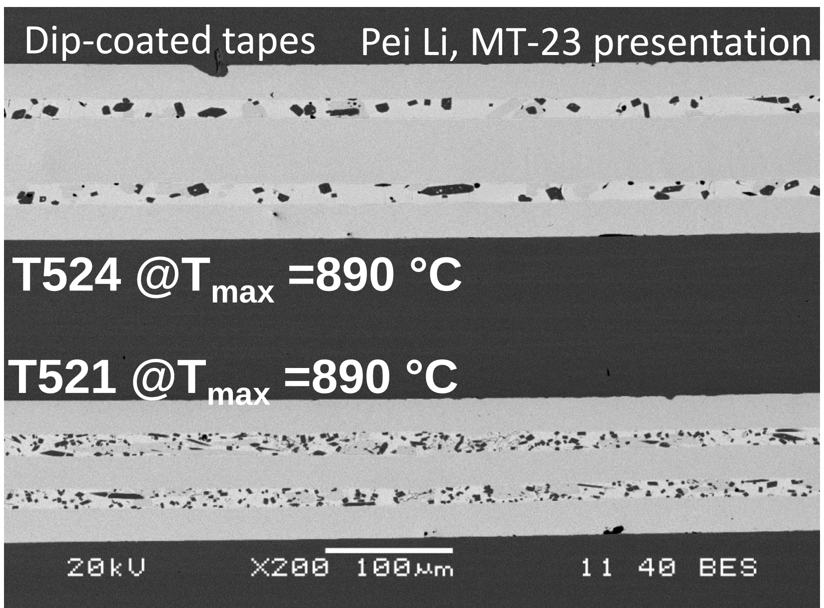
- Coil instrumented with taps and heaters, epoxy impregnated
  - It has now been quenched over 200 times
  - MQE is above typical disturbances for mechanical motion
  - Does usual detection work?
  - Does usual protection work?

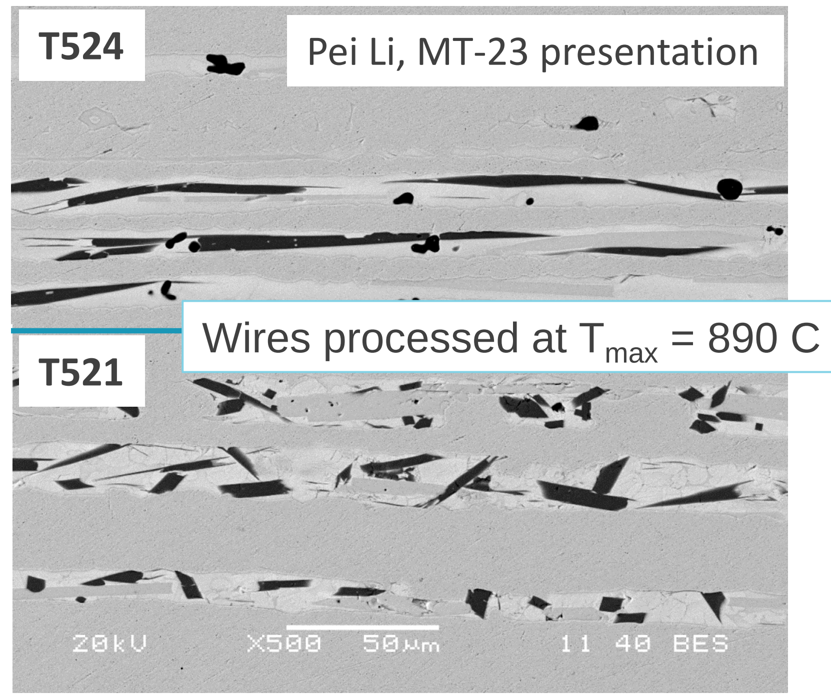
Is the "standard" composition the best?
Are there opportunities to tune grain size and flux pinning?

M O Rikel *et al* 2006 *J. Phys.: Conf. Ser.* **43** 51



- Fully dense wires permit meaningful studies of microstructure control and microstructure - property relationships
- Magnets: Jc, Jc, Jc
  - A process that parallels the Nb_3Sn microstructural studies is beginning now





Fermilab

End

Thank you