Developing accelerator magnet technology based on Bi-2212 round wire: Breakthroughs, progresses, and crucial next steps

Tengming Shen

Fermi National Accelerator Laboratory

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With inputs from **Pei Li** and **Liyang Ye**

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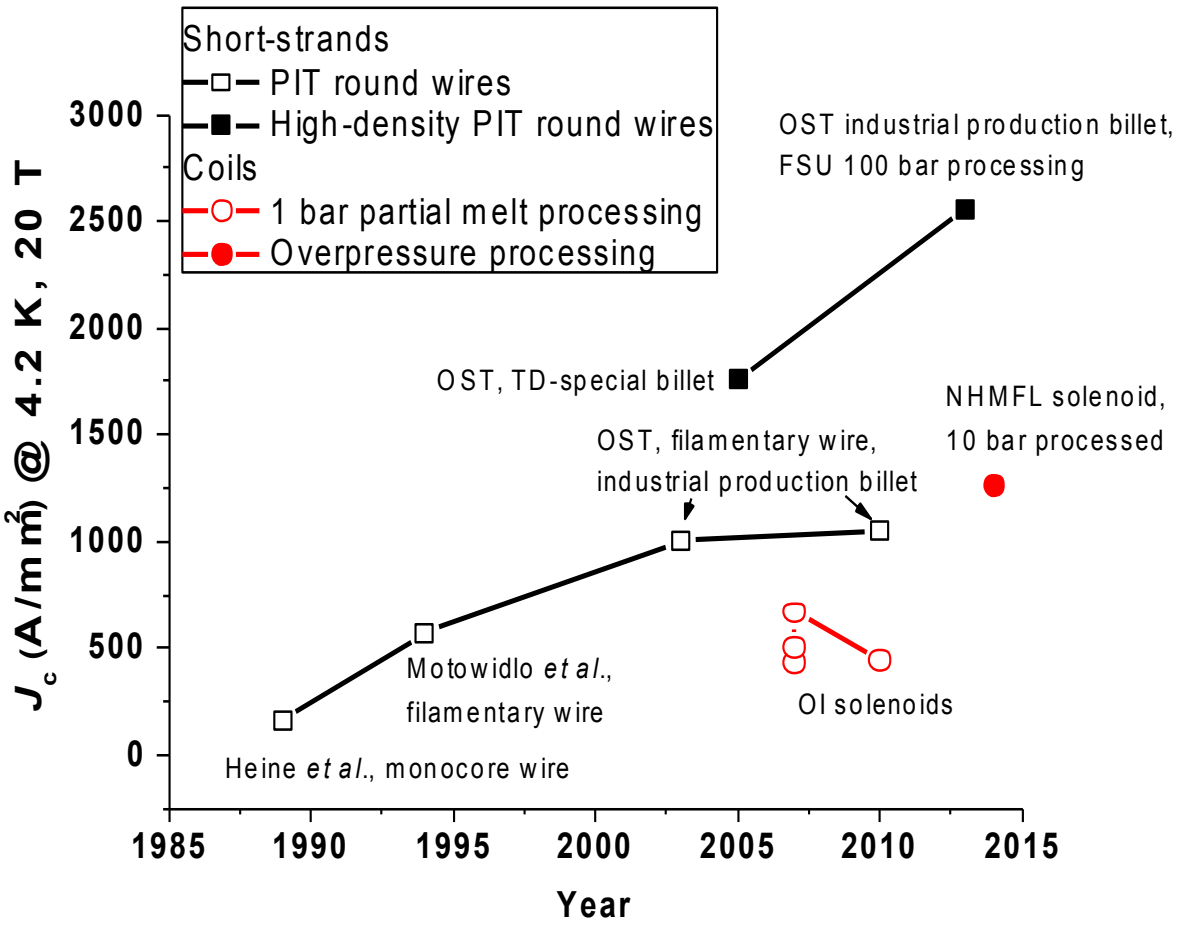
Outline

- Wire development: 2212 as a HEP-grade magnet conductor
  - J_c history, its processing, and industrial development
  - J_c-stress-strain relationships
  - Quench (degradation) behaviors and its dependence on stress
- Building accelerator dipoles using 2212: challenges and a roadmap

2212 wire J_c history, milestones, and implications

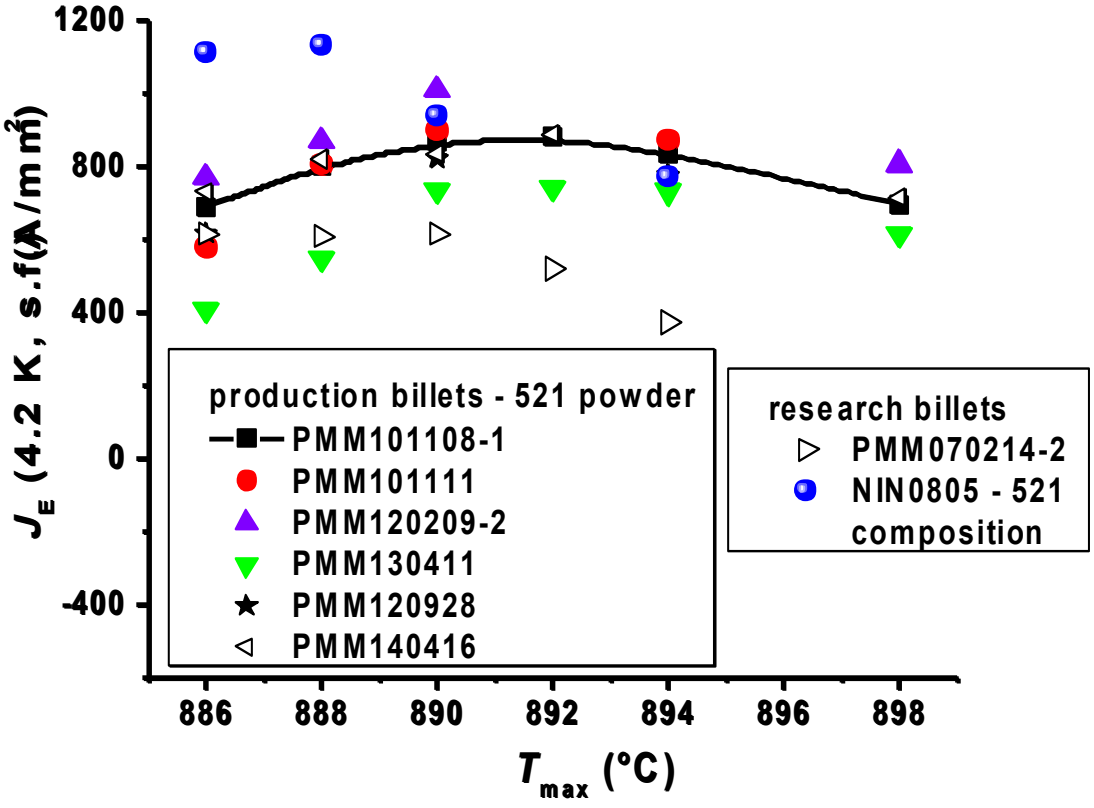


- Getting high J_c in long-length wire is not easy.
- Overpressure processing in 2012
  - 2212 20 T J_c now on par with Nb_3Sn 12 T J_c
- Industry hasn't made significant progress for 10 years
- 2212 now <= Nb_3Sn in 1990
  - Still learn to build solenoids
  - Need to walk the road that Nb_3Sn colleagues have been walking.

Industrial development, wire cost, and Rutherford cables

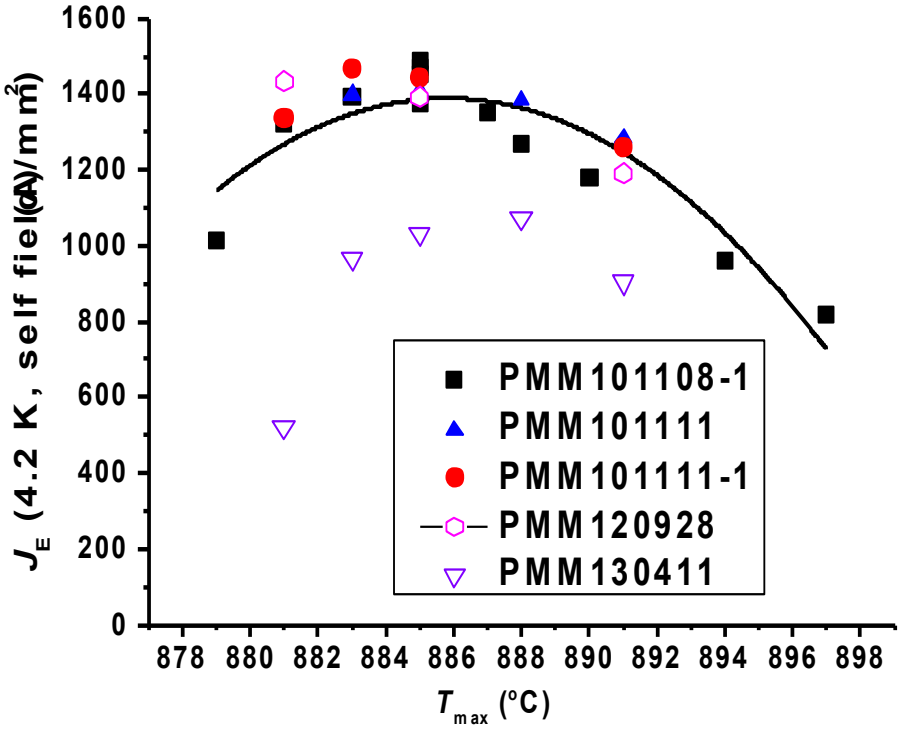
- **Wire manufacturers – OST as the leader.**
  - Need more participants (Supercon, Supermagnetics, Showa, WST/ NIN, Innost…)
- **Billet length – <1 km, going up with the support of the U.S. CDP**
- **Cost - $50-70/m for 0.8 mm wire**
  - $3-6 for silver; cost dominated by labor.
- **Powder sources and cost**
  - Nexans' 521 composition powder – industrial standard since 2003.
  - Nexans dropped 2212 powder production in 2015.
  - Cost on bar with silver
- **Rutherford cables successfully made with suitable insulation**
  - 100 - 150 μm thick mullite sleeve - $20/m.

J_E of commercial/research billets produced in the last decade – 1 bar standard processing



- PMM101108-1, PMM101111, PMM120928
  - 37x18, 0.8 mm, 521 comp.
- PMM120209-2, PMM140416
  - 85x18, 1.2 mm, 521 comp.
- PMM130411
  - 19x36, 0.8 mm, 521 comp.
- PMM070214
  - 37x18, 0.8 mm, not 521
- NIN0805
  - 37x18, 1.0 mm, 521

J_E-T_{max} of these strands – 25 bar overpressure processing

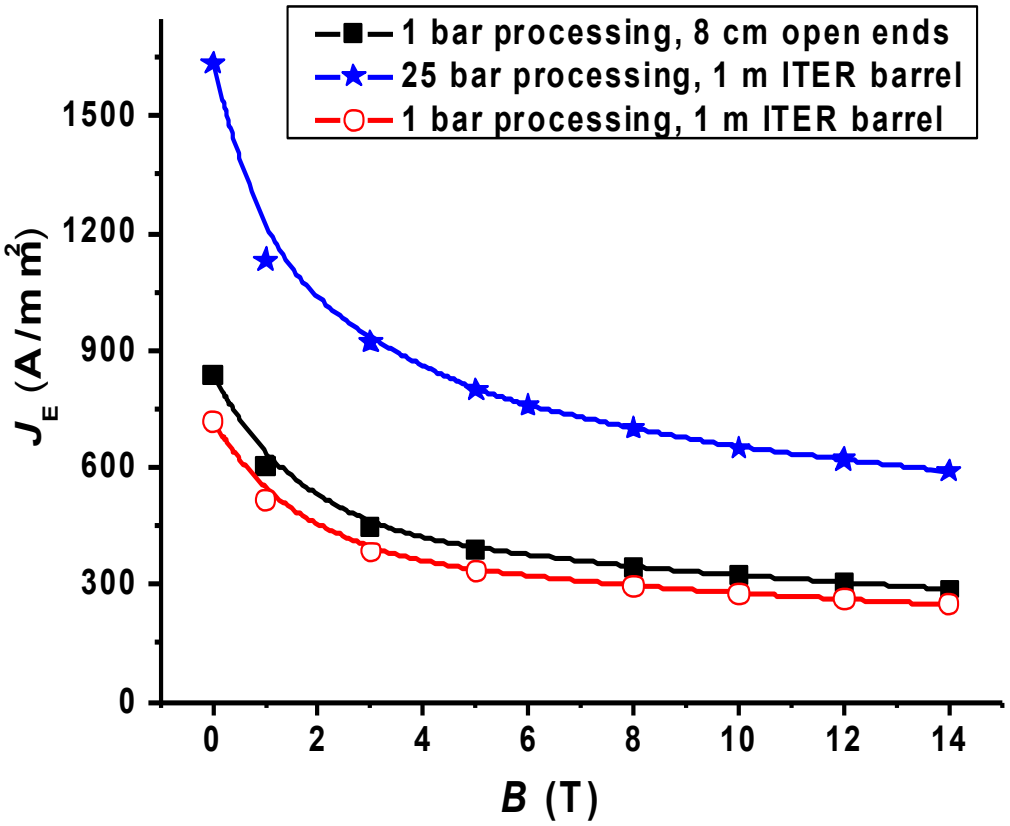


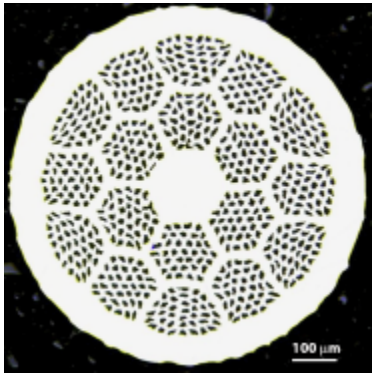
- 25 OP increases I_c by 70%
- Processing window doesn't narrow

Pei Li

Overpressure processing brings high J_E to long-length conductor

- For 1 bar processing, long-length wire has leakage and degraded J_c, due to internal gases

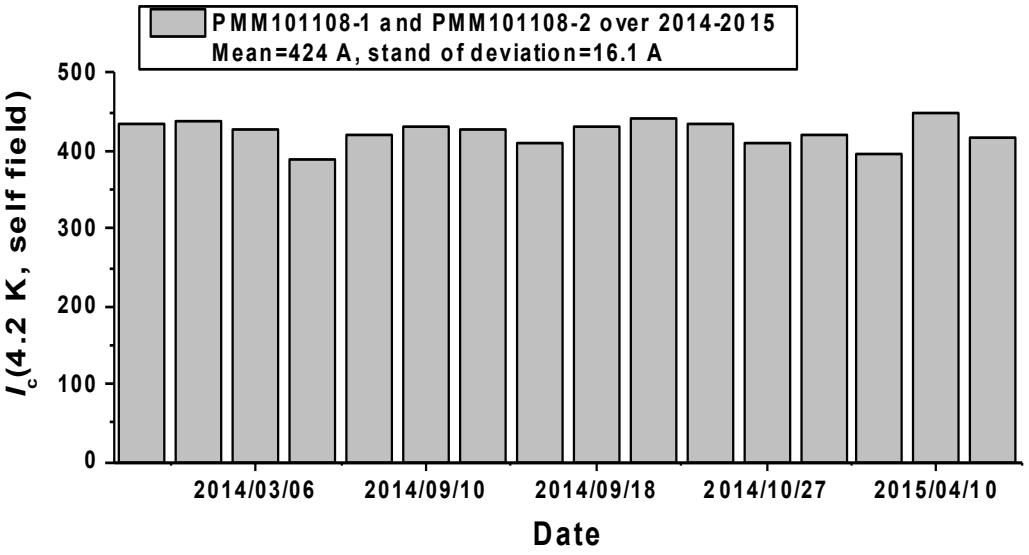




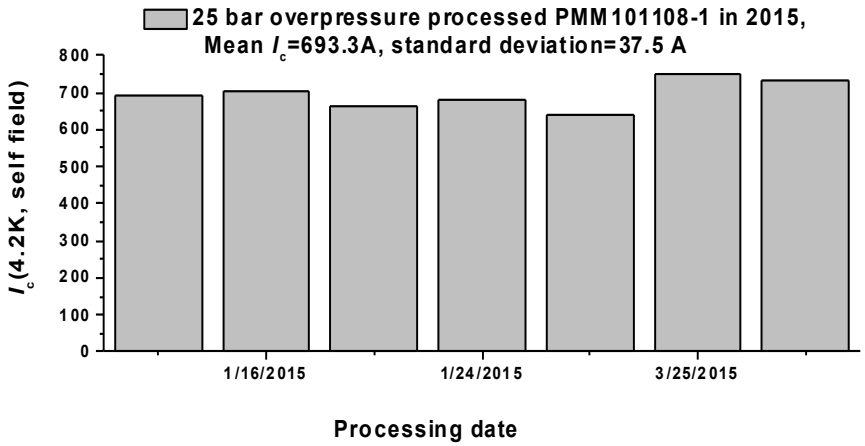
Shen et al, 2013 J. Appl. Phys. **113** 213901
Larbalestier et al. 2014 Nat. Mater. **13** 275

I_c uniformity: +/-5% J_c variation along 800 m conductor heat treated in an one-year period

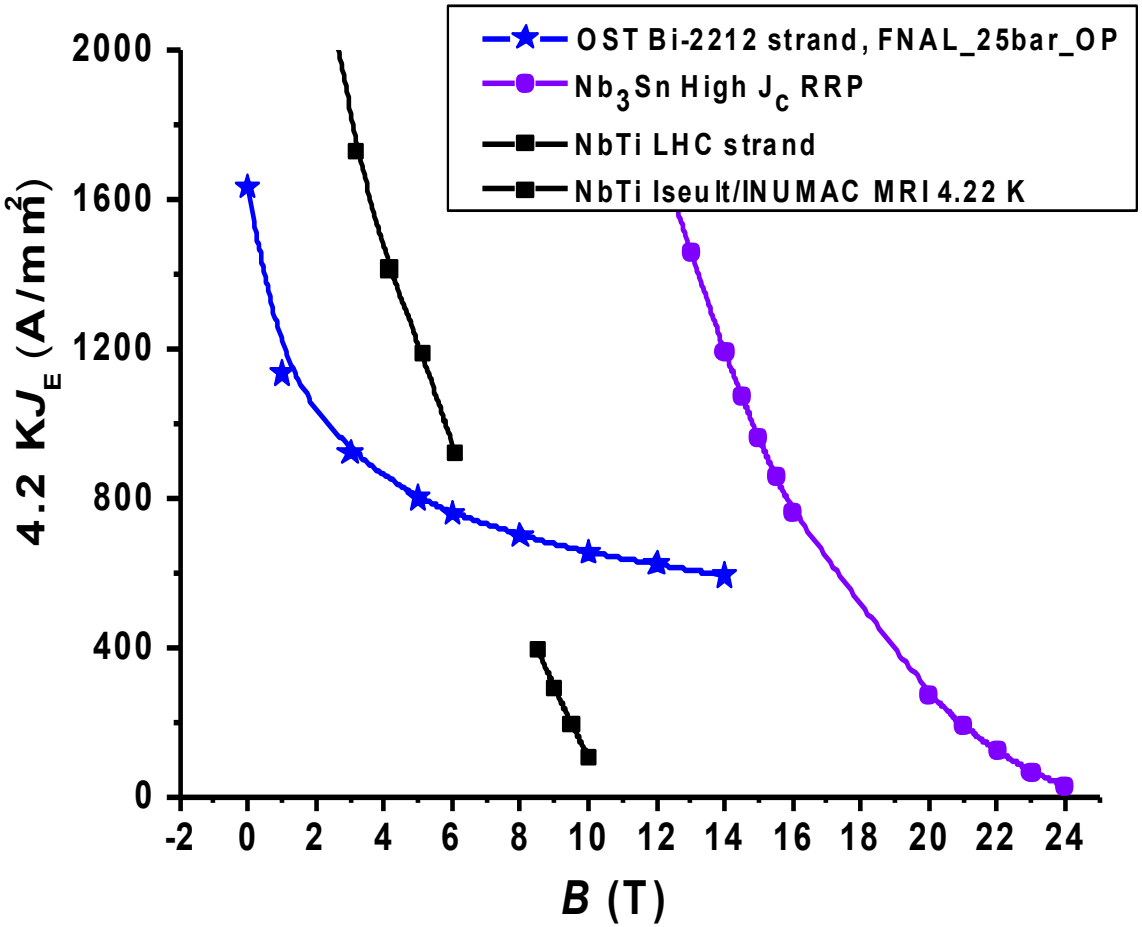
1 bar heat treatment



25 bar OP heat treatment

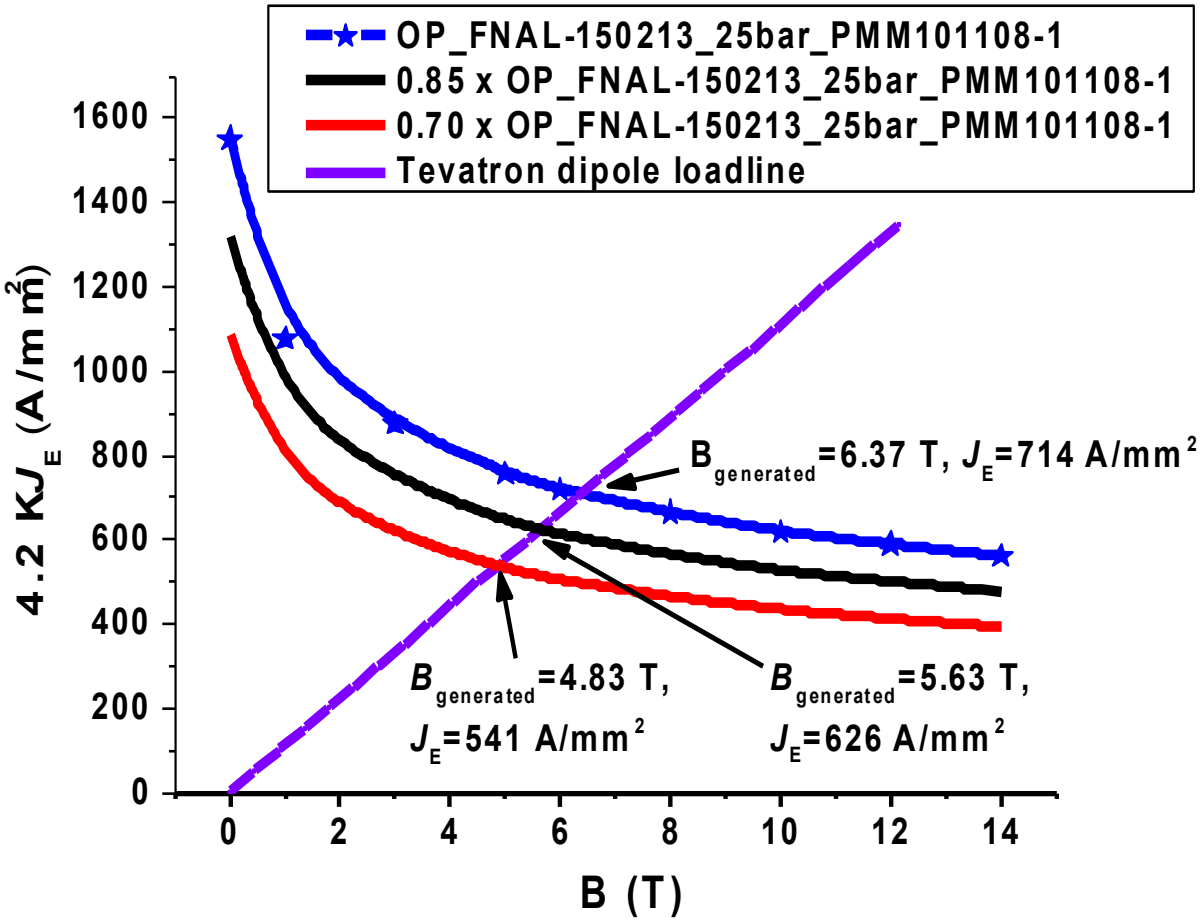


25 bar OP 2212 wire J_e vs Nb-Ti and Nb_3Sn

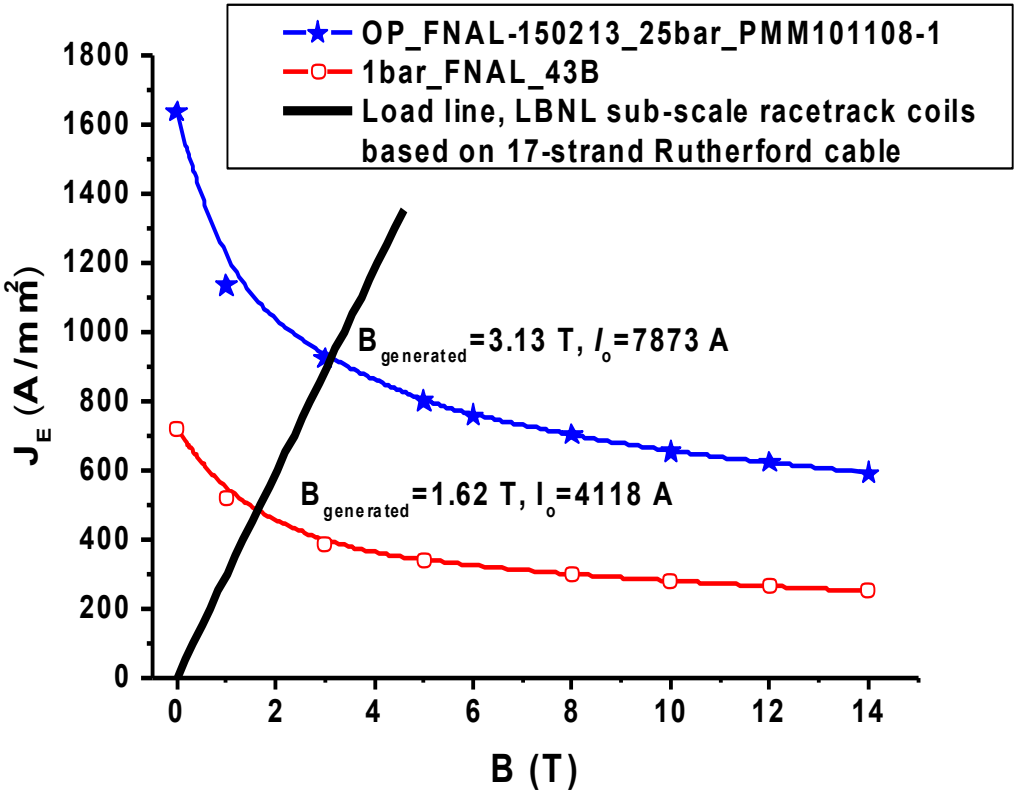


What can be expected - 4-6 T accelerator dipoles based on 2212 can be built

- Would be the world's first HTS accelerator magnet.
- Of course, many challenges are ahead of us.

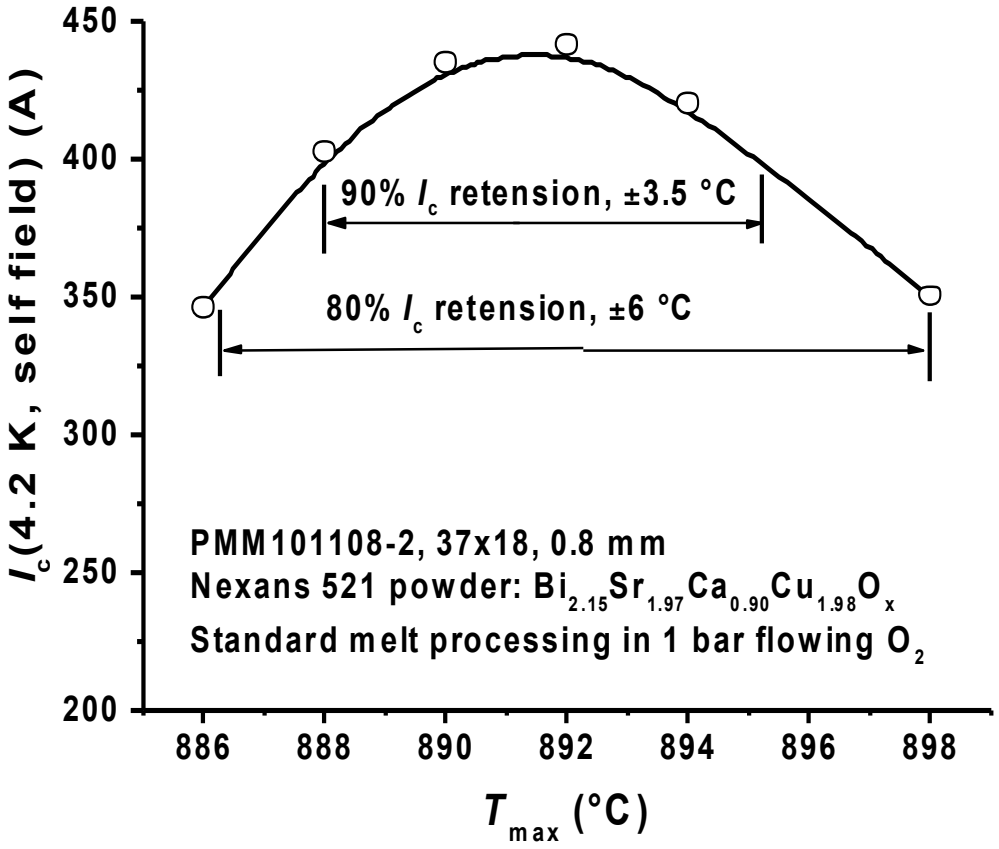


Reality check – Godeke's 2 layers-6-turns/layer racetrack coils

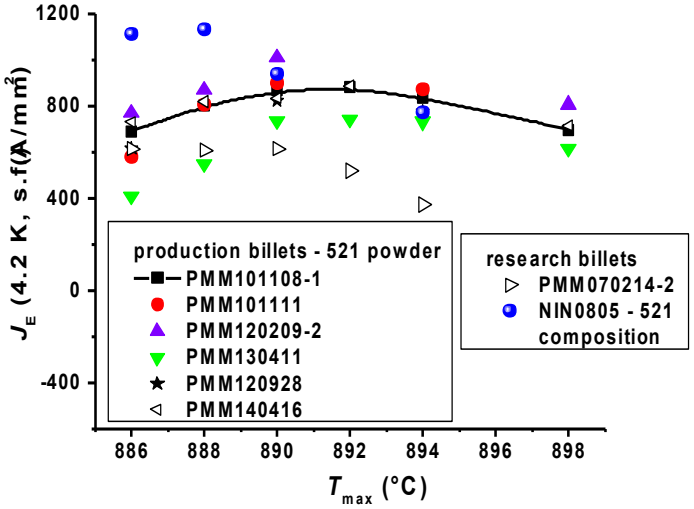


- Godeke – HTS-SC08: 2600 A, 65% of SSL (with internal gas effects considered)

I_c-T_{max} – the challenge of precise heat treatment control

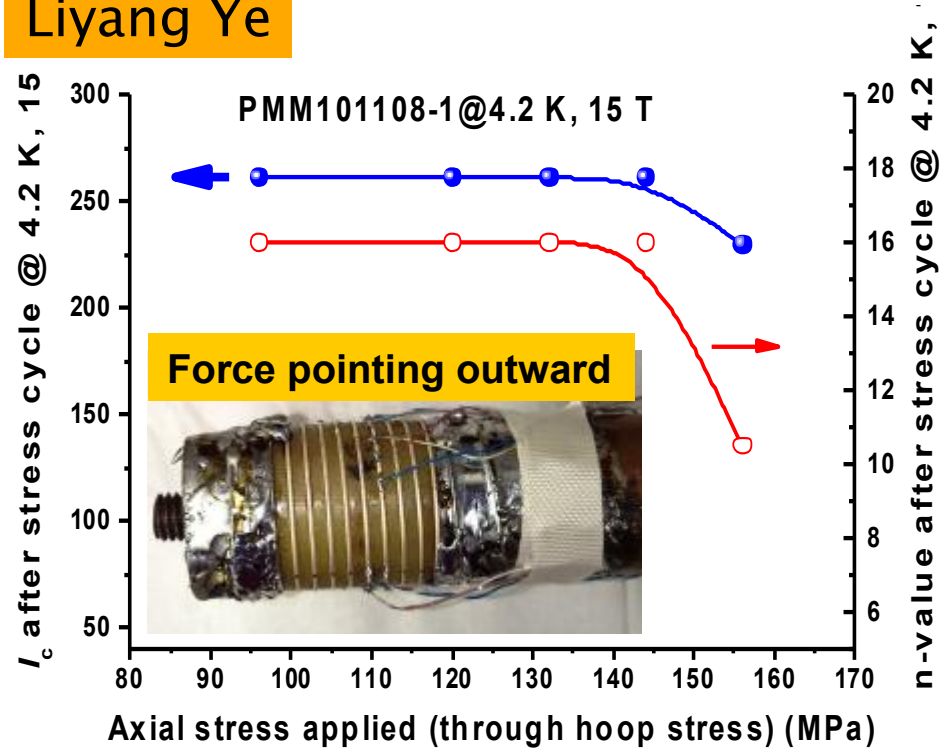


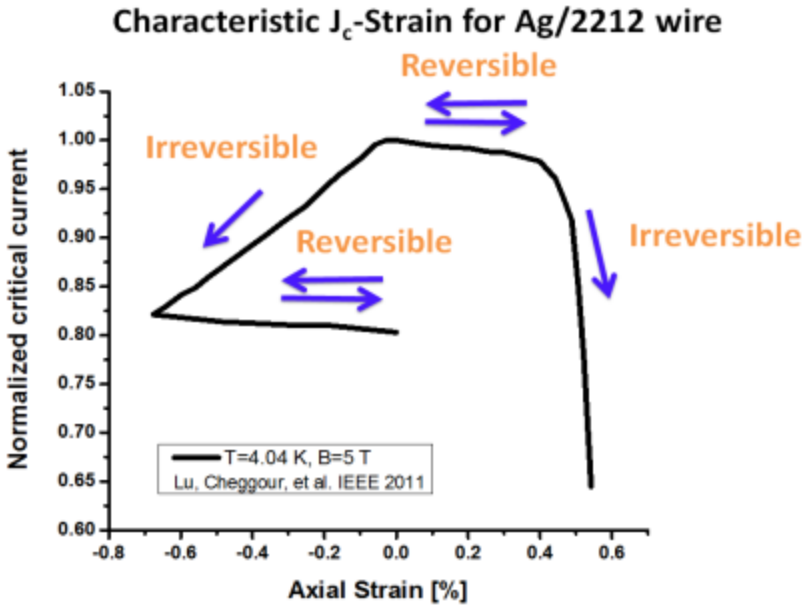
- I_c-T_{max} depends on powder, perhaps also wire design and fabrication



I_c-stress-strain of Bi-2212 wires: axial direction

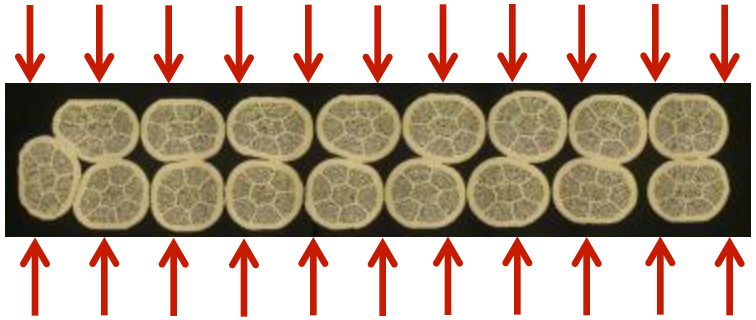
Liyang Ye





- I_c-axial-strain of 2212 wires - similar to that of MgB_2 and Bi-2223, and different from Nb-Ti and Nb_3Sn.

Are we doomed by the transverse pressure?



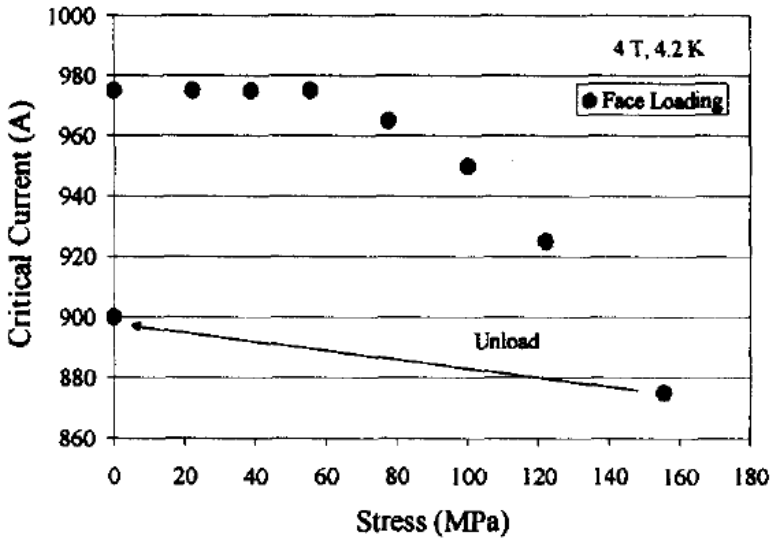


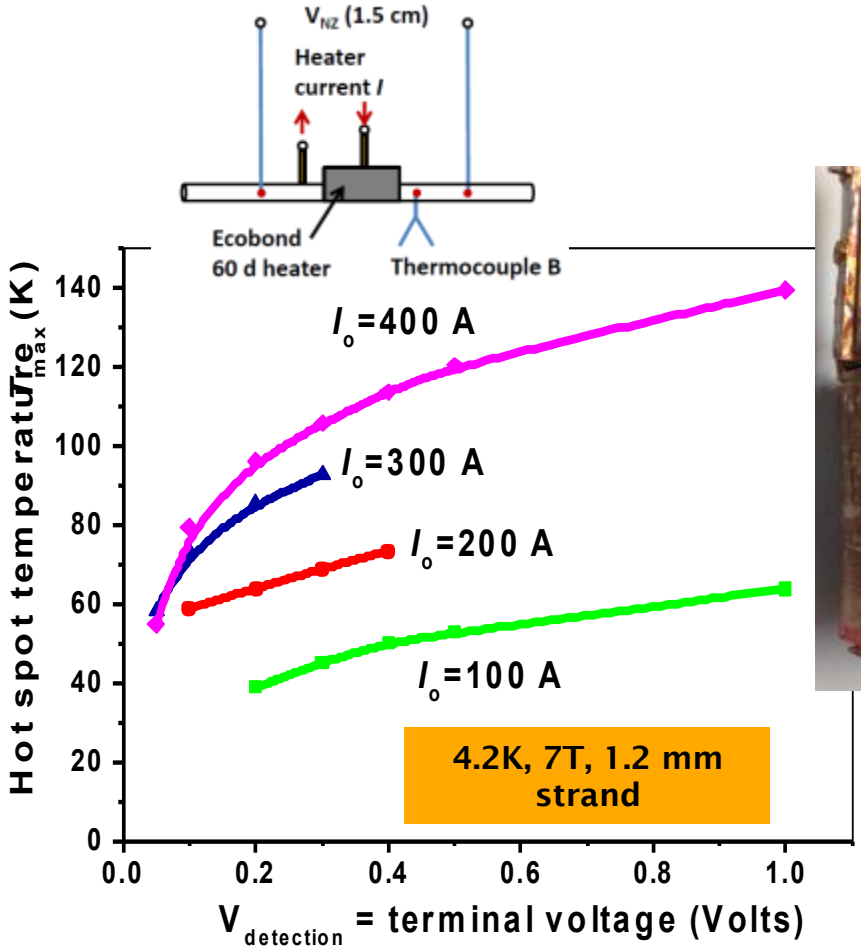
Figure 2. Variation of critical current (4 T, 4.2 K) with stress for a cable that was face loaded.

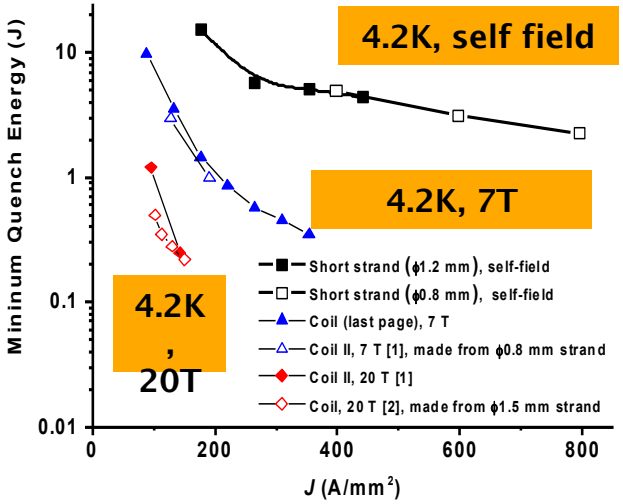
- 100 MPa reduced J_c by 3%.
- 160 MPa reduces J_c by 8% irreversibly.

Dietderich et al., Physica C, **341-348**, 2599 (2000)

Quench – a potential elephant in the room - A quench may not be detected soon enough, though well-built 2212/YBCO magnets may never quench at 4.2 K except in extraordinary situations

Shen, Ye, Yurrioni, Li, 2015 Supercon. Sci. Technol. **28** 075014





20 T dipole with 5 T 2212/REBCO insert – many challenges ahead but now it is the time to invest/ investigate

- Very challenging
  - Six layer graded cosine-theta coil or 8/10 layer canted cosine-theta coil
  - Hybrid dipoles/quadrupoles have not been built.
  - Stress at 20 T is enormous.
  - Magnet is big – the stored energy is high
- But it is time to build and push the technology frontier.

Go back to the 4-6 T dipole - our vision

- FY15-16: Demonstrating 5-10 kA class Rutherford cables with J_e(20 T) of >500 A/mm^2 using small-scale racetrack coils
- FY16: Exploring mechanical and quench protection limits of coils by testing racetrack coils under common coil or dipole configurations
  - With preloads using the Bladder and Key structures.
- FY16-17: Build the world's first CCT or cosine-theta accelerator dipoles generating 4-5 T.

Concluding remarks

- 2212 is no doubt complicated but also promising
  - It is now poising for practical applications
- Things to demonstrate/examine:
  - High 20 T J_e of >500 A/mm^2 in 5-15 kA Rutherford cable
  - Degree to which Rutherford cables can handle transverse pressure
  - Further conductor development to bring 20 T J_e in strands to 800-1000 A/mm^2.
  - Application of overpressure processing to >1 meter long coils
  - Capability of running magnets without quenching, or dealing with the devil of quench protection
- We will build 4-6 T accelerator dipoles in two years using 10 km conductors
  - Work with industry to reduce conductor cost by a factor of 2-3.