Status and plans of U.S. HTS accelerator magnet development

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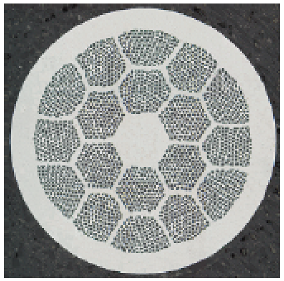
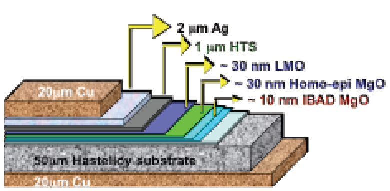
Our Program is aligned with the HEPAP subpanel recommendations

- P5: Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders. Continue to **play a leadership role** in superconducting magnet technology focused on the **dual goals of increasing performance and decreasing costs**

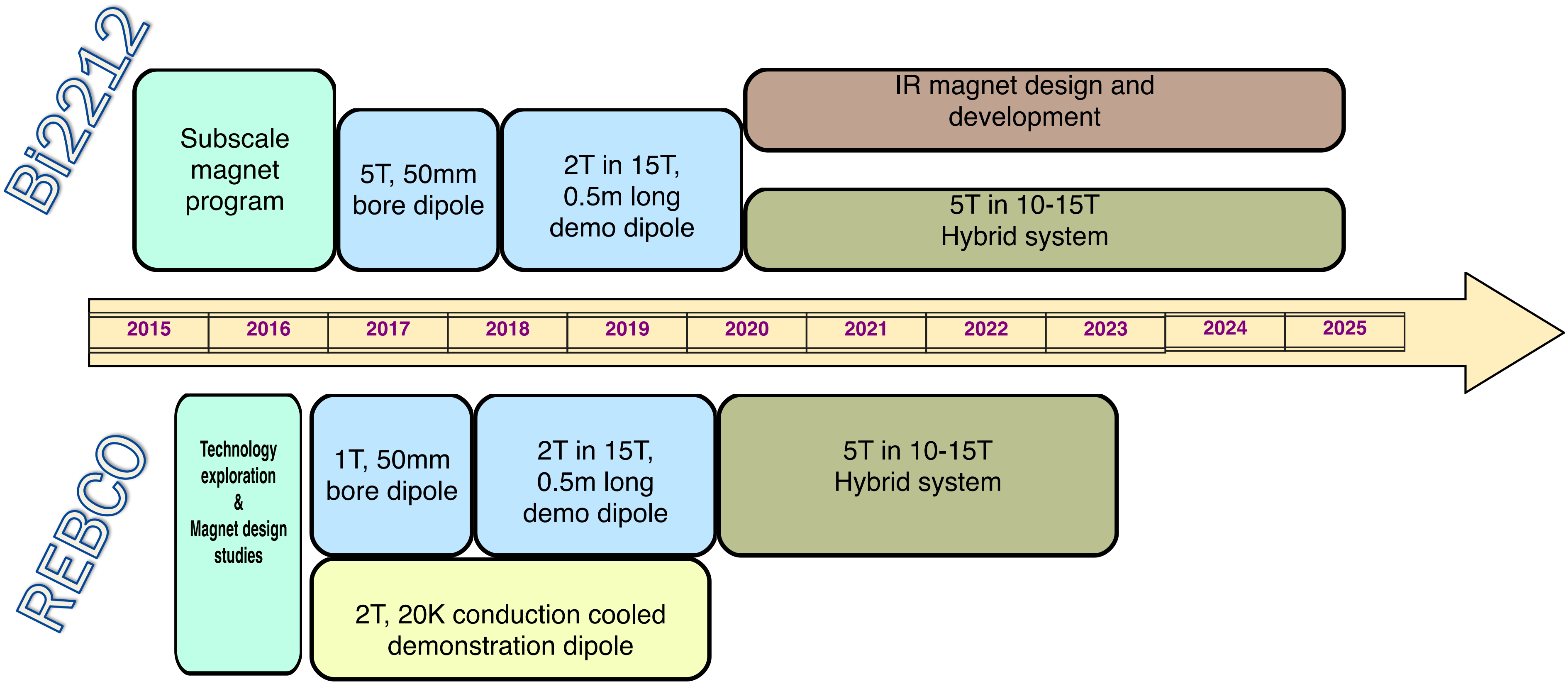
- HEPAP subpanel: Establish and execute a high-temperature superconducting (HTS) material and magnet development plan with appropriate milestones to demonstrate the feasibility of cost-effective accelerator magnets using HTS.

We focus our program on science-based technology development with the goal of developing HTS inserts for high-field accelerator magnets

The primary commercially-available HTS materials have different advantages and disadvantages that merit investigation

Conductor	Pros	Cons
2212 	• Round, multifilamentary, twisted wire with isotropic J_c insensitive to field orientation. • Rutherford cable readily made. • D_{eff} at ~100 um but with low J_c at low field and therefore relevantly small persistent current effect • High J_c, high *RRR*	• Expensive - $155/kA-m at 4.2 K and 20 T. • Small market beyond HEP (>1.3 GHZ NMR) • Strain sensitive. • Weak mechanical properties; poor capability for Rutherford cables to handle transverse stress • Challenging heat treatment - high J_c achieved with high pressure treatments at 890C; narrow processing windows
REBCO 	• High J_c • Strong ability to handle axial stress • Broad applications beyond HEP • Multiple vendors and conductor design. • Potentially cheap in 10-20 years.	• Expensive - $234/kA-m at 4.2 K and 20 T. • Mono-core tape with strong J_c anisotropy – high magnetization effects. • Easy delamination. • Long-length nonuniformity – km conductor cut into 100-300 m pieces.

LBNL ongoing activities and plans



Explore other HEP Stewardship applications: Medical, BES, etc

Overview of 2212 wire industry and U.S. collaboration

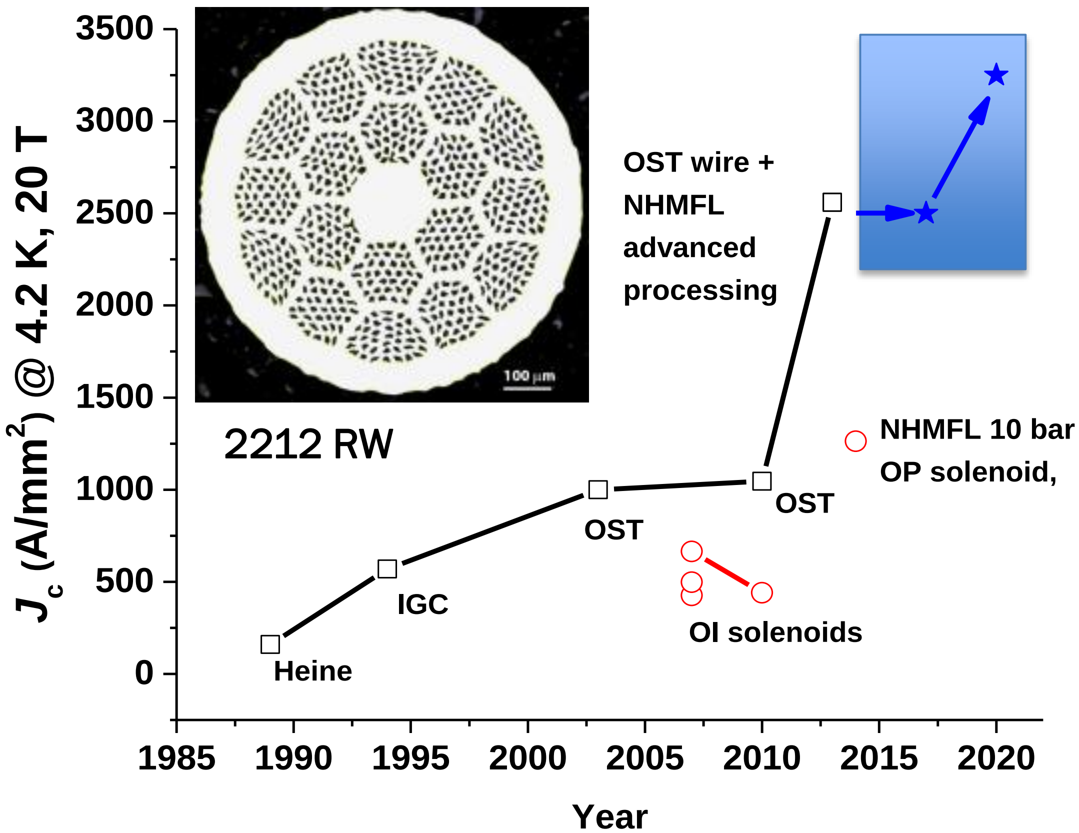
- Wire manufacturers – OST, Supercon, Supermagnetics.
  - 2.5 km billet length, and 10 kg billet mass

- Powder manufacturers – Nexans out in 2015, and two U.S. suppliers emerging (Metamaterials and nGimat)

- Two insulation options – mullite braided sleeve for Rutherford cable and TiO_2-polymer coating for solenoid.

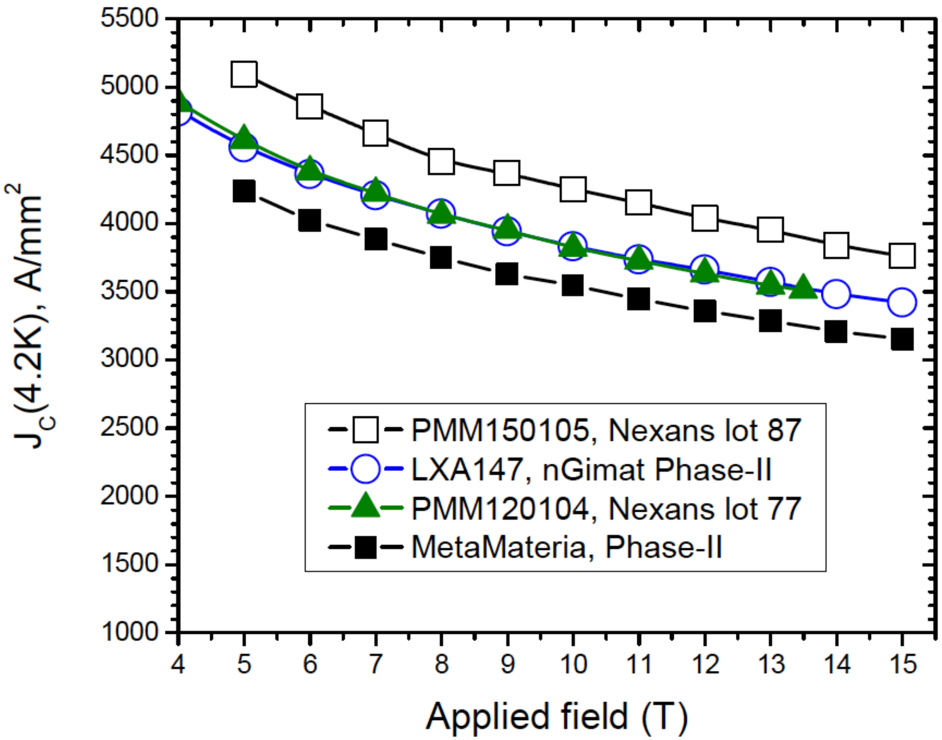
- U.S. Bi2212 collaboration:
  - Florida State University: Developing high J_c wires through overpressure processing and other advanced heat treatment; NMR application demonstration.
  - OST – improving wire performance and reducing wire costs.
  - SBIR/STTR industries: Powder, insulation, et al.
  - LBNL/MDP – Developing Rutherford cable and demonstrating dipole/quadruple technologies

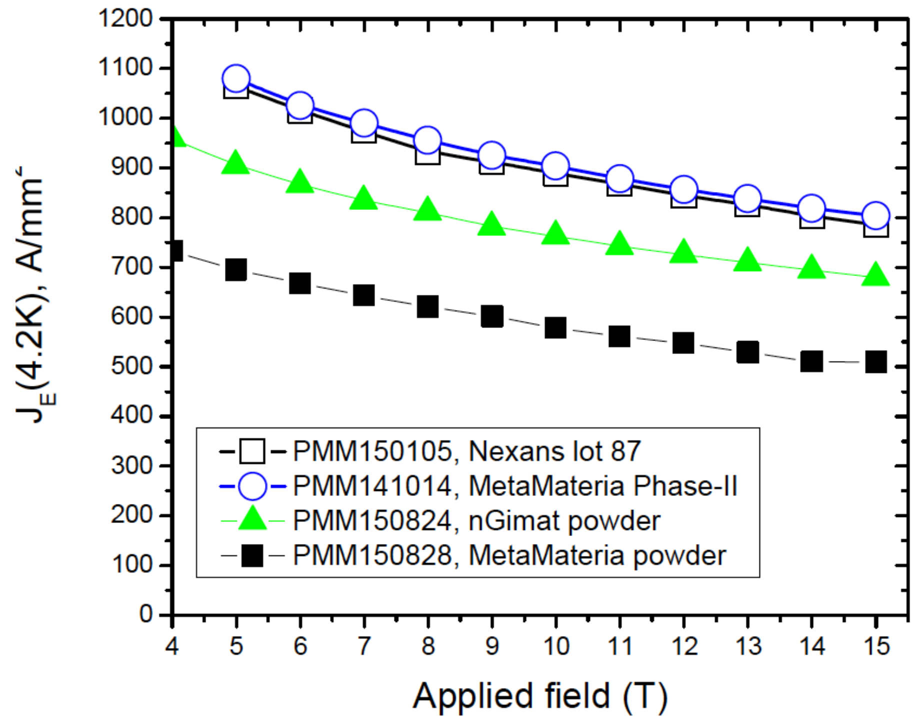
Bi-2212 has demonstrated significant transport current advances recently, making it a viable candidate



- **Near term top priorities:**
  - Demonstrate high critical current density in Rutherford cable in a coil environment
  - Explore the mechanical and quench limits of 2212 coil technology.
  - Proof-of-principle fabrication of CCT dipoles

Two U.S. manufacturers now capable of providing 2212 powder with qualities on bar with those of best Nexans' 2212 powders





Powder developed at MetaMateria and nGimat Inc. and wire fabricated at OST. Development supported by US DOE SBIR/STTR programs through DOE-OHEP, U.S. DOE-OHEP CDP.

Slide courtesy of Dr. Jianyi Jiang at NHMFL, FSU.

Long-length I_c uniformity is good:

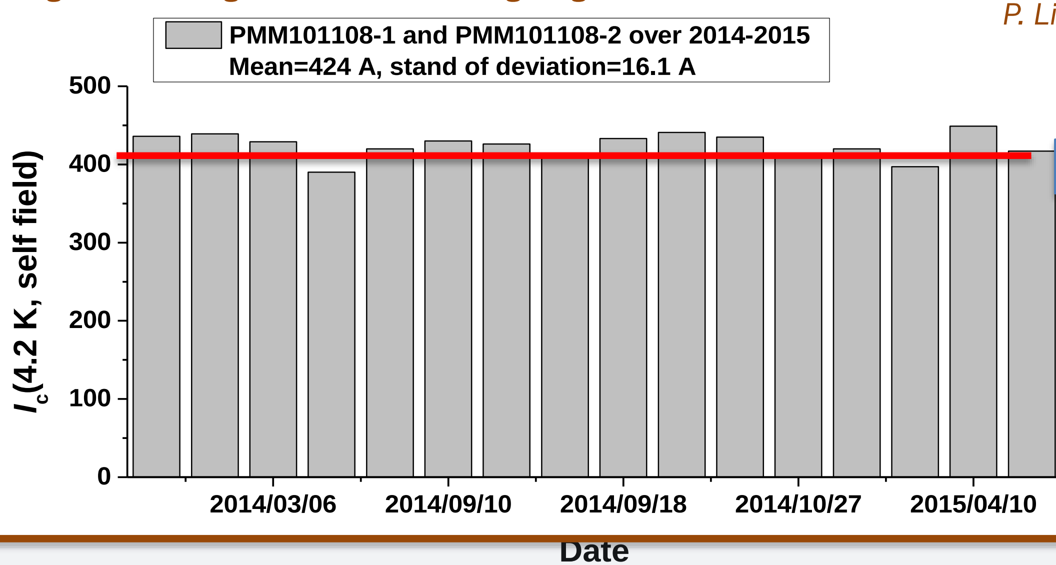
+/-5% J_c variation along 800 m conductor heat treated in a one-year period

Short sample treatments showing no internal gas effects in the long-length wires.

P. Li (FNAL), T. Shen (FNAL, LBNL)

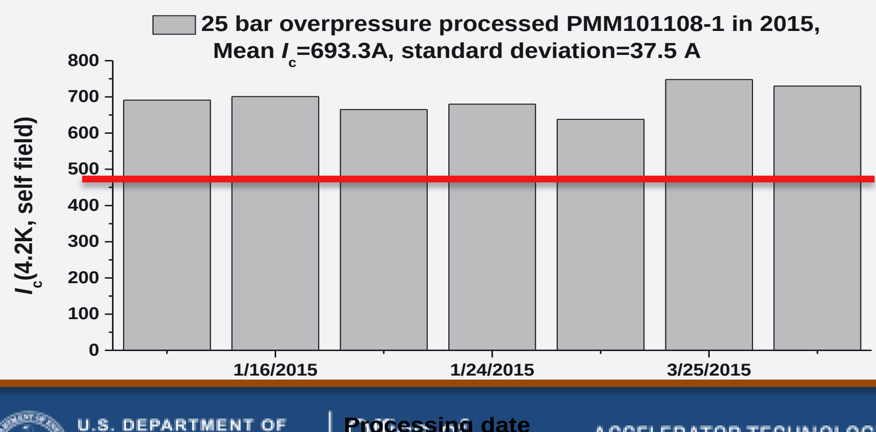
1 bar heat treatment

Average = 424 A

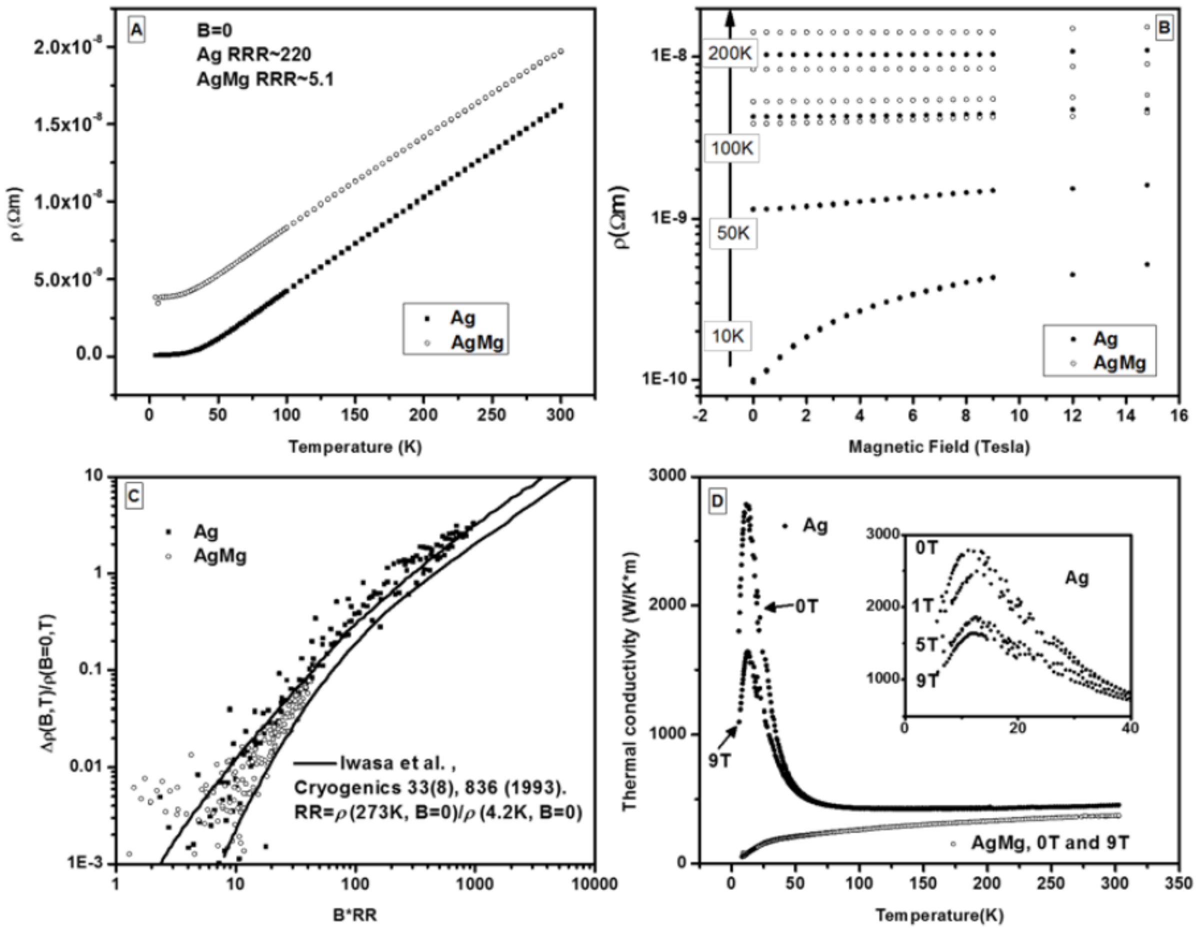


25 bar OP heat treatment

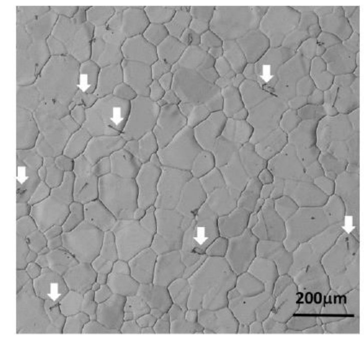
Average = 693 A

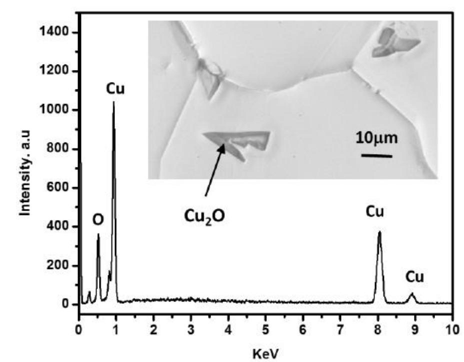


Ag sheath shows high RRR, despite that Cu in Bi-2212 filaments diffuses into Ag matrix during heat treatment



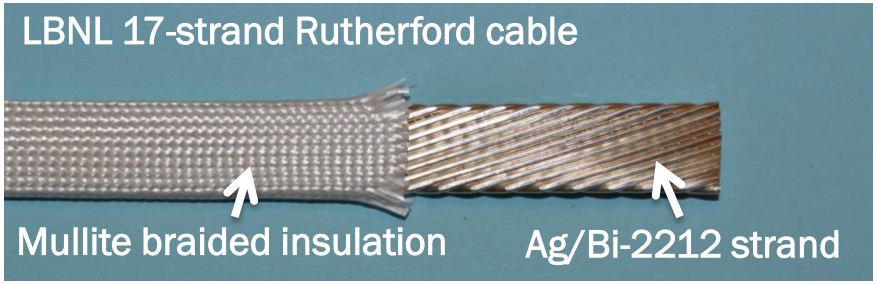
Cu$_2$O on wire surface after reaction





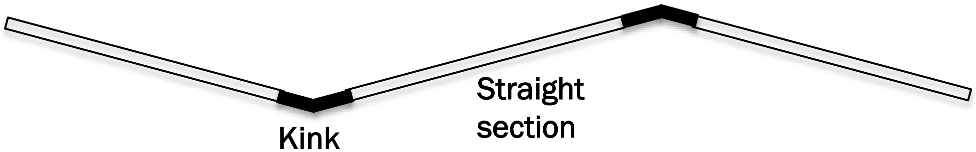
Li, Ye, Jiang, Shen, IOP Conf. Series: Materials Science and Engineering ***102*** *(2015) 012027*

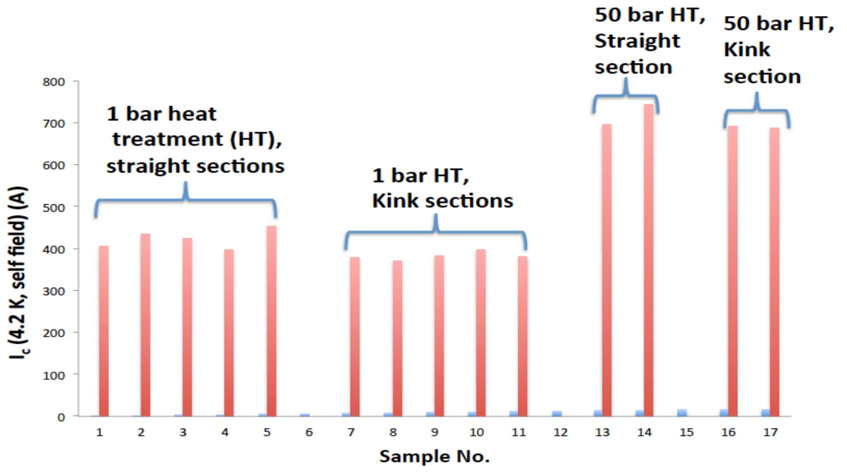
LBNL has made long-length insulated cables successfully and is demonstrating multiple facets of the cable technology



Cable strand no.	Strand diameter	Bare cable dimensions
17	0.8 mm	7.8 mm x 1.44 mm

Insulated cable dimensions	Twist pitch	Packing factor
8.02 mm x 1.66 mm	55 mm	**80%**





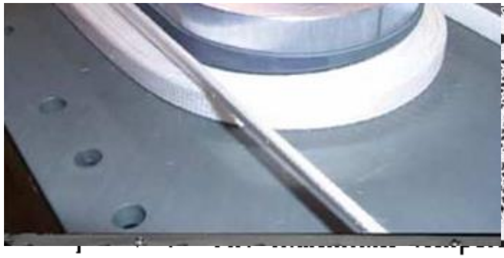
Ongoing developments:

- Understanding failure mechanisms and increasing packing factor from 80% to 90%.
- Cored cable for decreasing coupling current and loss.
- High-field cable I_c test to demonstrate high J_e of 500 A/mm^2 or above at 15-20 T.

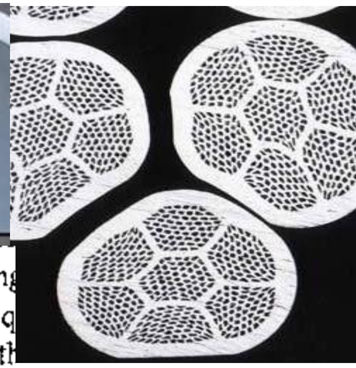
P. Li (FNAL), J. Jiang (FSU), T. Shen (LBNL)

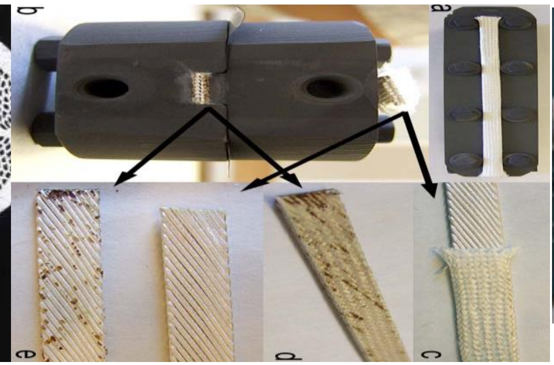
Status – move to racetrack coils – Old 1 bar coils leaked, with relatively low J_c, but establishing critical baselines

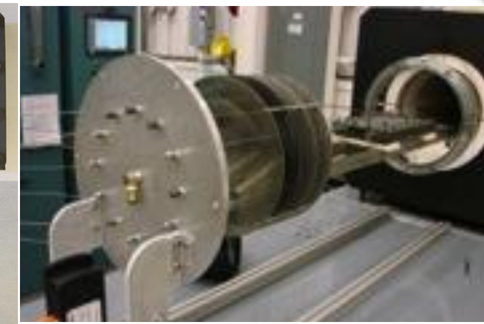
Godeke et al., 2010, SuST, 23 034002; *Godeke et al., 2008, TAS, vol. 18, no. 2.*



elting was 880℃～895℃ and the cooling
ation was 10～1℃/h. Using this techniq
roduce about 4,500 meters of strand with
critical current of 200A±20A (at 4.2K).



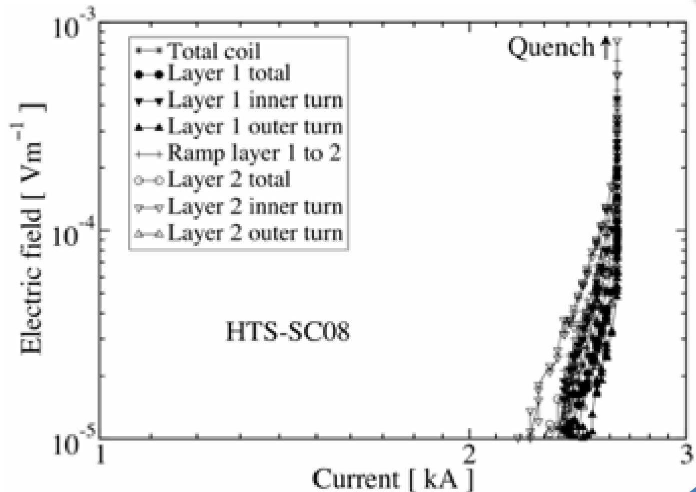




Cable and insulation investigations; infrastructure development

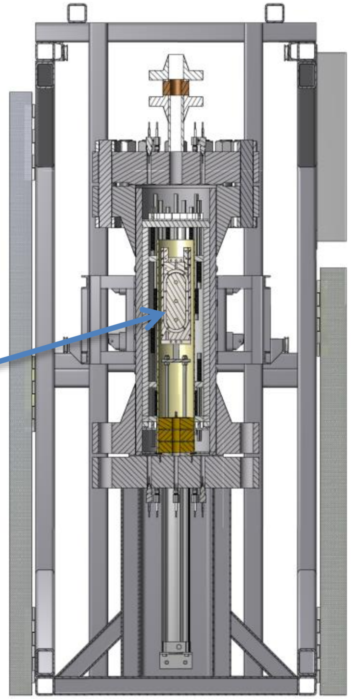
Coil performance

- Coil achieves 85% of *round wire* witness
- Limited by inner turns and ramp
- HTS-SC10: 2417 A (within 10%)

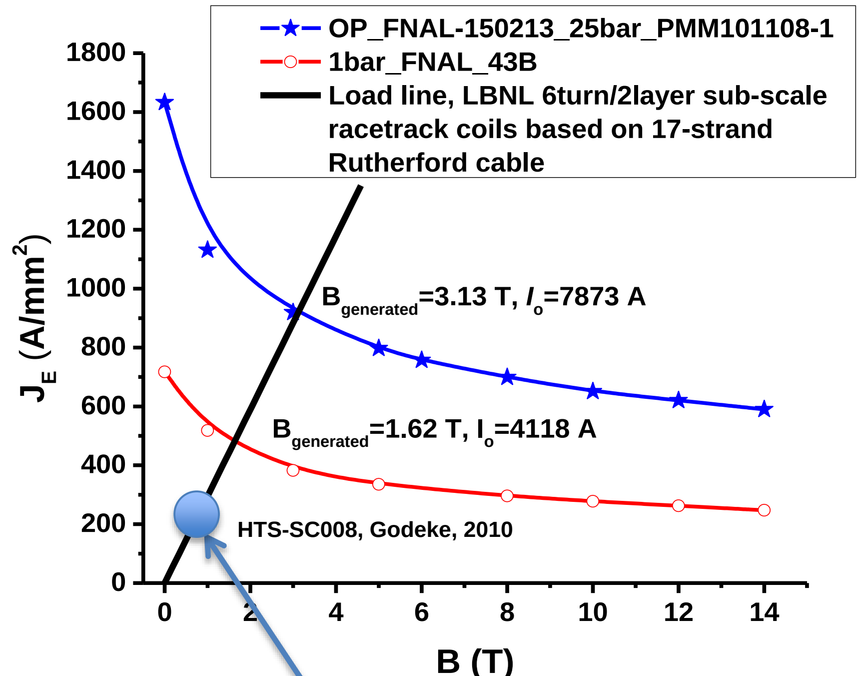


Five racetrack coils are being fabricated using overpressure processing at FSU, and will be tested to their mechanical and quench limits at LBNL

LBNL racetrack coils in FSU furnace



Courtesy of G. Miller, FSU



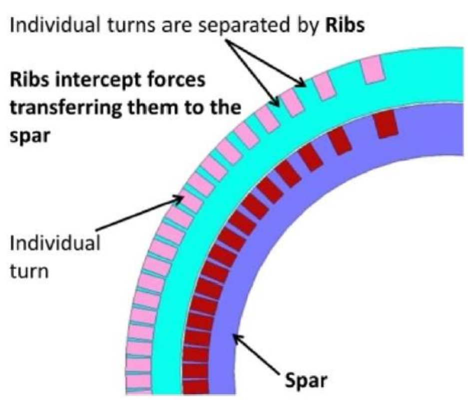
HTS-SC08, *Godeke, SuST, 2010*

Activities summary and goals:

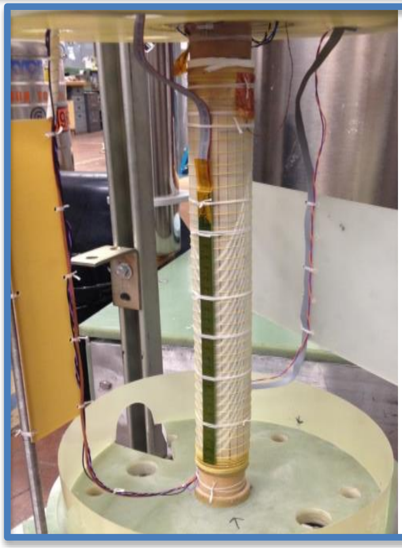
- Five racetrack coils fabricated and overpressure processed at FSU.
- Show high J_e in Rutherford cable in a coil environment (standalone test)
- Explore stress and quench limit of Bi-2212 tech (tested in dipole configuration in a yoke/shell structure and stressed by the bladder-and-key technique.)
- Implement new quench detection and protection methods.

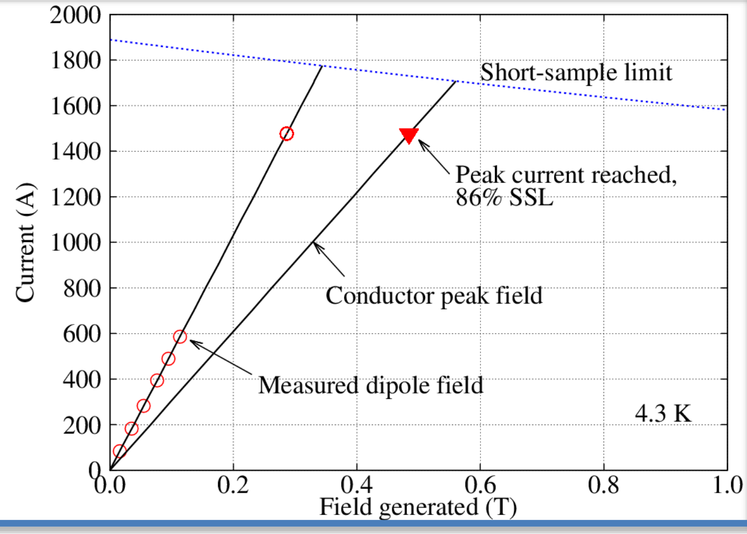
Proceeding with 2212 CCT coils – natural path for high field HTS insert technology

CCT design for stress management



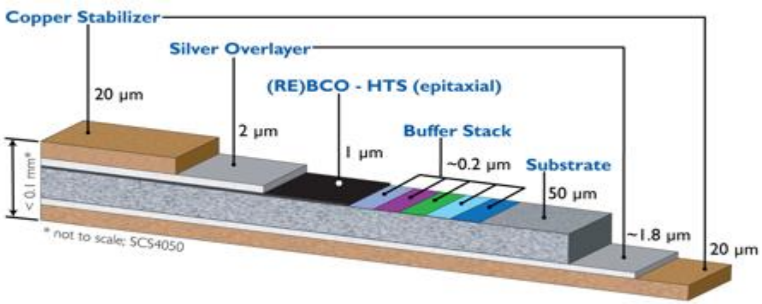
(courtesy of S. Caspi)





- CCT concept well suited for strain-sensitive superconductors – no force build-up
- First test of 1 Atm processing successful
- Ready for first 50 Atm OP magnet

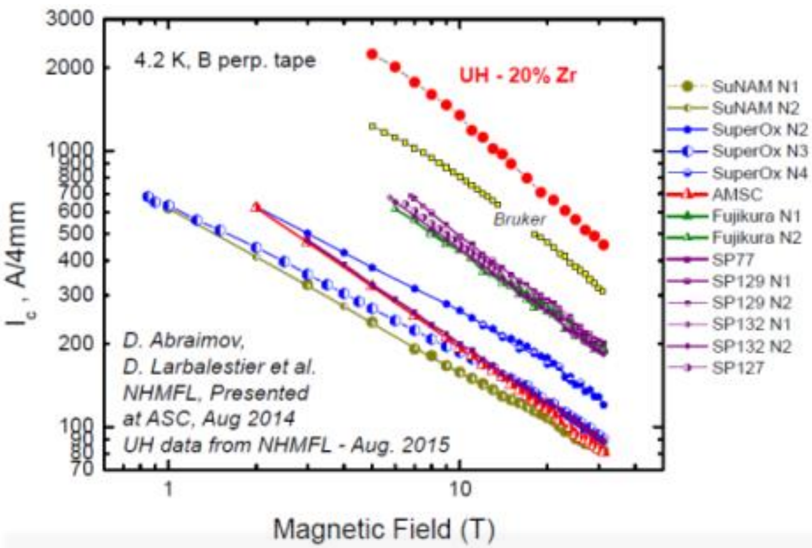
REBCO program – leverage conductor breakthrough

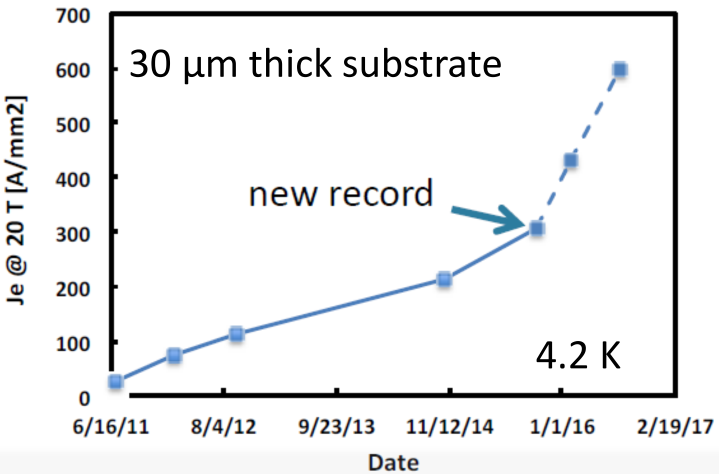


Courtesy of V. Selvamanickam, University of Houston

CORC® wire

Courtesy of D. van der Laan, Advanced Conductor Technologies



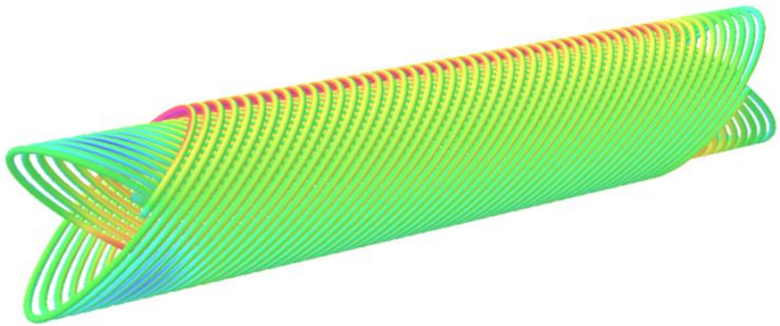


Recent conductor advances allow serious REBCO accelerator magnet development to start.

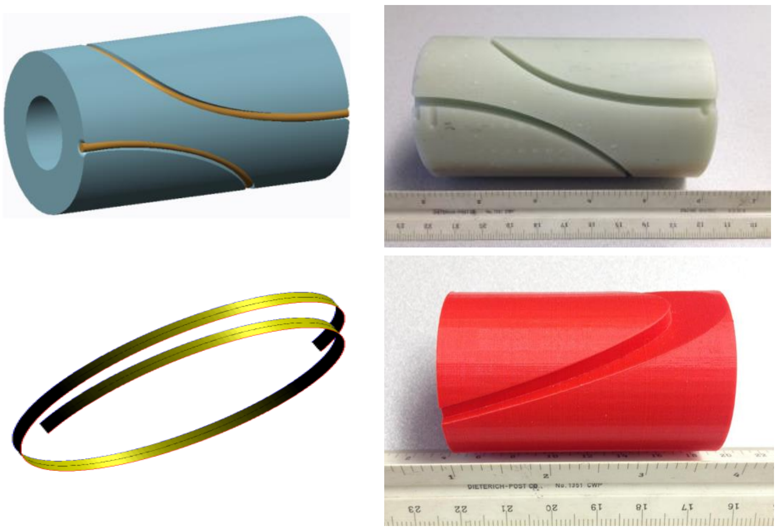
Current focus: establish subscale magnet technology

- Develop fabrication technologies for subscale magnets (winding, impregnation, joints)
- Test magnets to provide feedback to conductor and magnet technology (fabrication, quench detection and protection, field quality)

Investigating CCT configuration with CORC® wire and stacked tapes



Winding-test fixtures for CORC® wire and tape stack



Subscale racetrack coils with single tapes

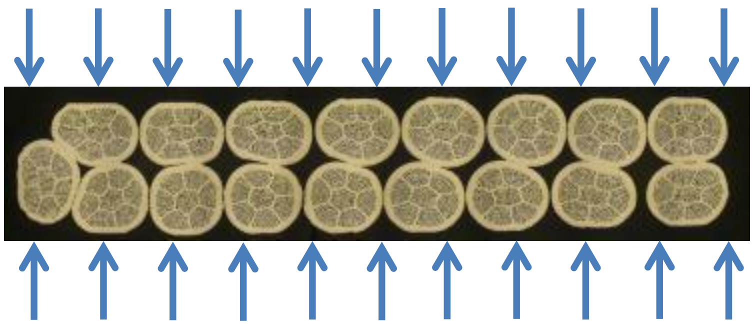
Wang et al, SuST, accepted

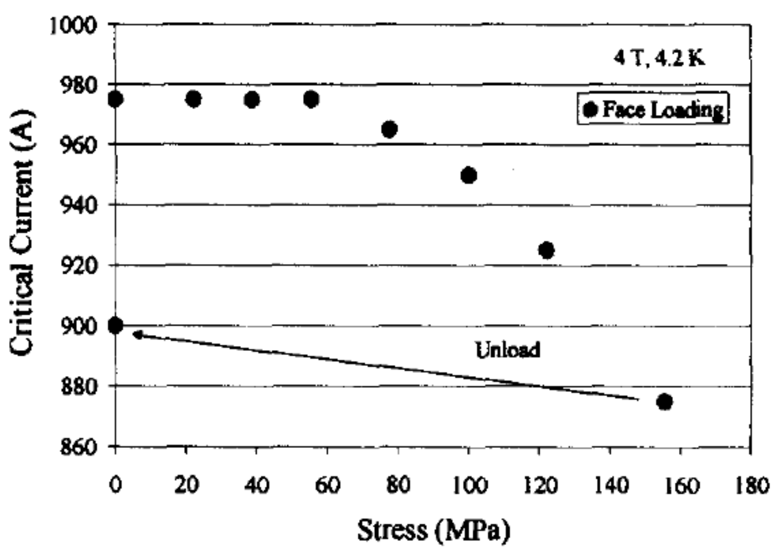
Summary

- P5 and HEPAP-accelerator subpanel support U.S. HTS accelerator magnet development.
- Substantial US Bi2212 conductor development
    - Record J_c by overpressure processing.
    - Good RRR.
    - Good Rutherford cables made.
    - U.S. manufacturers now capable of providing high quality powder.
- LBNL 2212 magnets
    - Racetrack coils made and to be pushed to their electrical, mechanical, and quench limits
    - CCT magnets prototyping in progress.
- LBNL REBCO magnets leveraging major U.S. conductor development with novel magnet designs.

Stress and strain tolerance of Bi-2212 Rutherford cables

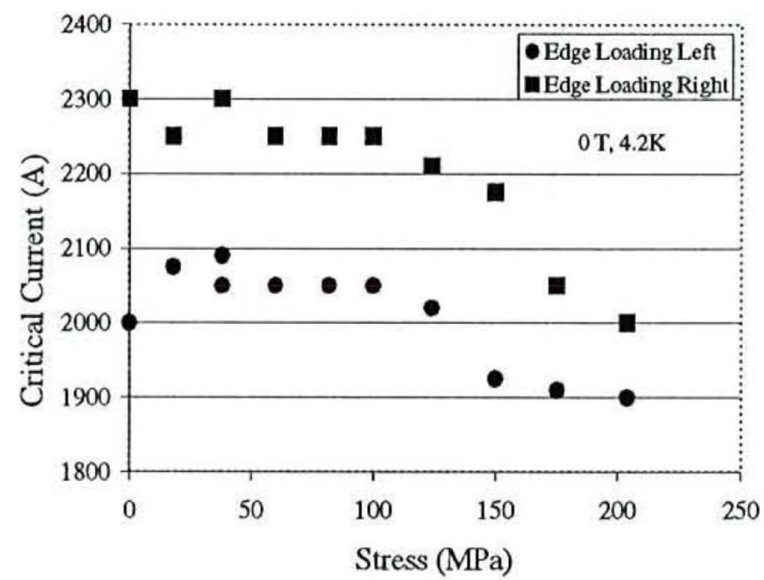
- **Critical stress – 120 Mpa (5% I_c reduction)**





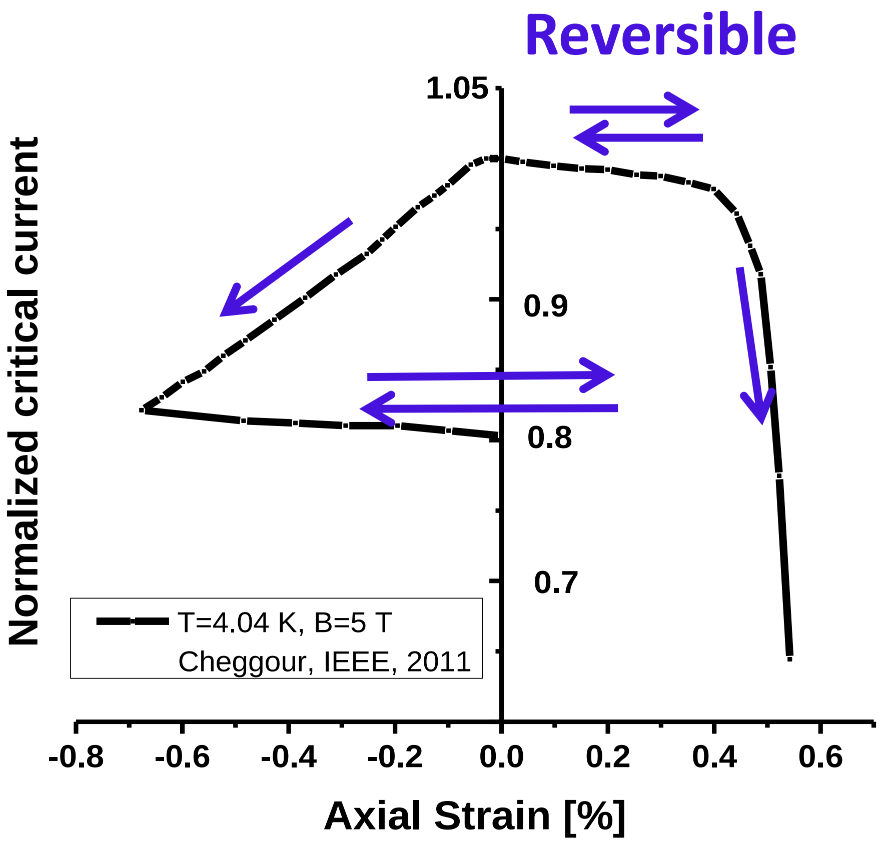
- **Critical stress – 160 Mpa (5% I_c reduction)**

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



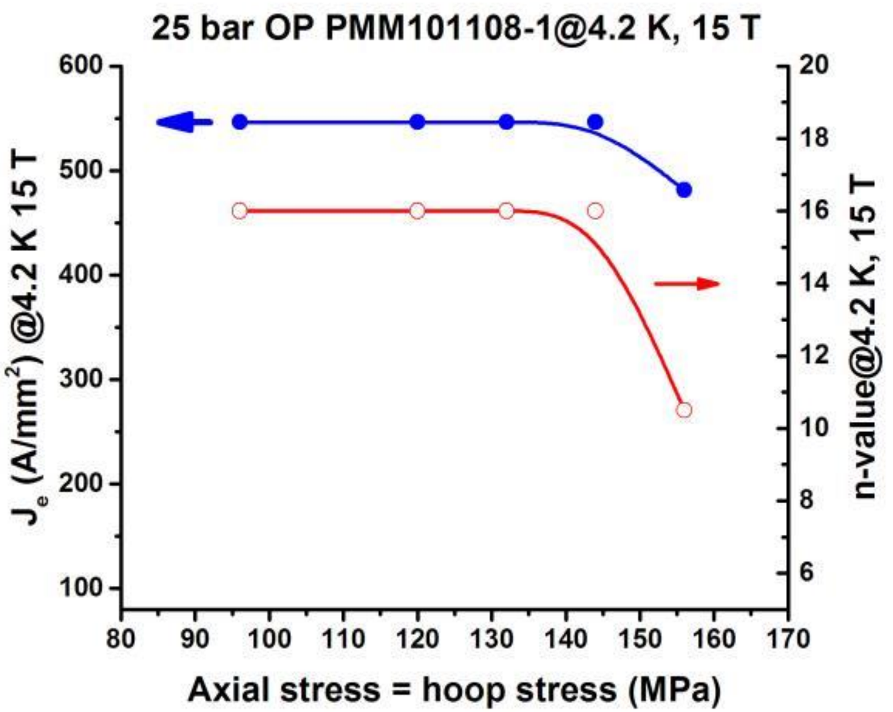
Axial stress and strain dependence of Bi-2212 strands

- Critical tensile strain - 0.4-0.6%.



Established by ten Haken and ten Kate in tapes and early wires, and by Cheggour and Godeke in modern Bi-2212 wires and overpressure processed high current density wires.

- Critical tensile stress – 160 Mpa.



Tested driven by hoop stress using a ITER barrel configuration. Data, obtained by Ye and Shen, to appear in an incoming manuscript.