The NHMFL Bi-2212 Coil and Conductor Development Program - Presentation to EUCARD 2013

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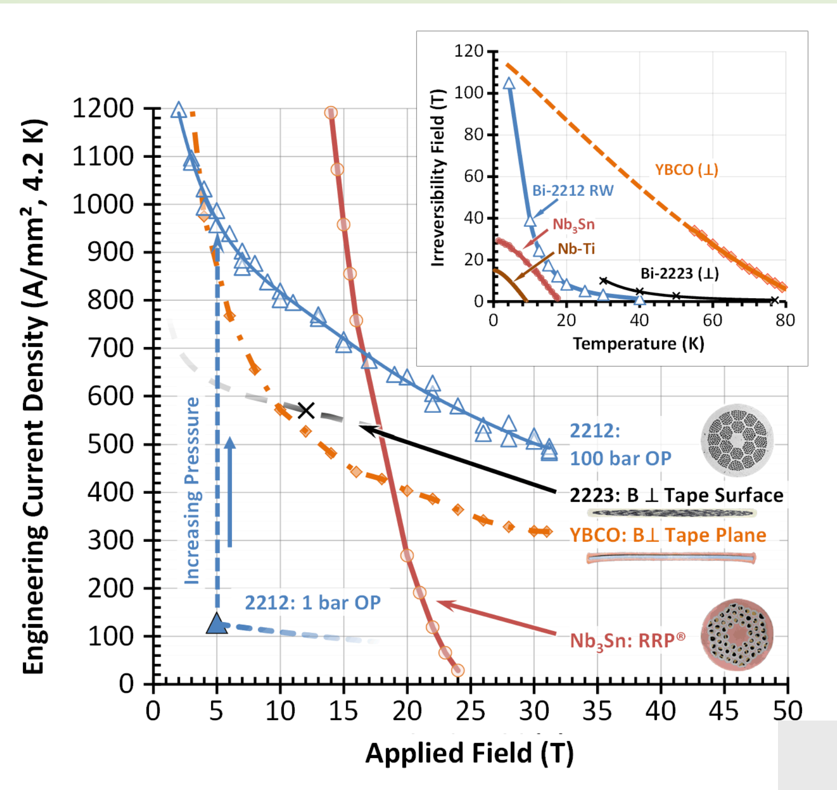

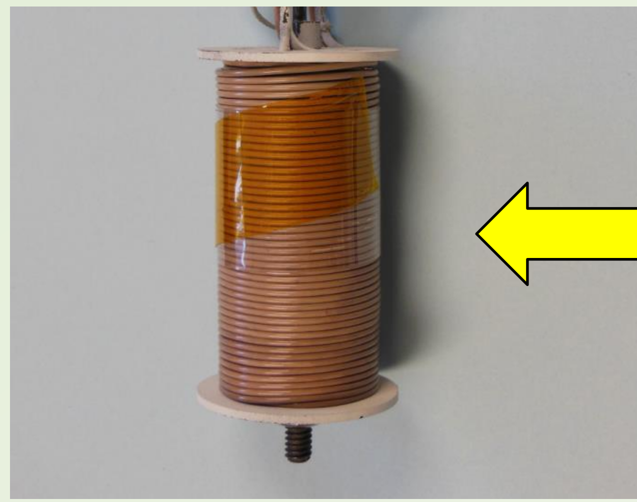

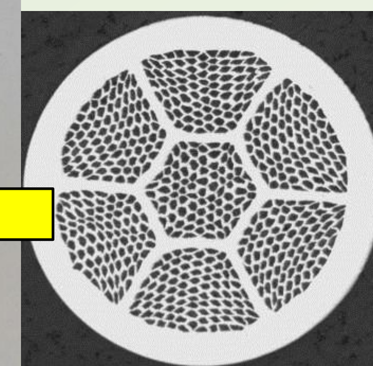

34T (in 31T)

More contributions from Christian Scheuerlein at CERN are expected!

Postdocs: Natanette Craig and Matthieu Dalban-Canassy
PhD students: Peng Chen, Maxime Matras, and Daniel Davis

Driving themes

- Coil performance is central to the NHMFL and the DOE investment
  - DOE supports conductor technology
  - NHMFL through core NSF grant supports coil development
- No superconducting magnet is ever better than its conductor
  - Onnes result of 1913
- 2212 conductors now exceed coil prototype thresholds – now needs pushing to maturity
  - Longer, stronger, cheaper with good understanding of attainable performance envelope
- We are convinced that the very complex present HT can be simplified with OP
  - Each step needs to be rethought using sufficient OP to 1.) prevent sheath expansion and 2.) to make full density 2212 without bubbles

Conditions for developing high J_E

Use OP system (1 bar O_2, balance inert gas) to:

1. Prevent swelling of the conductor driven by internal gas pressure
2. Apply over pressure to fully densify 2212 (all PIT conductors rely on less than full density to allow co-deformation of powder and metal matrix)
3. Control internal gas pressure sources

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Supercond. Sci. Technol. **26** (2013) 055018 (10pp) doi:10.1088/0953-2048/26/5/055018

Evidence for length-dependent wire expansion, filament dedensification and consequent degradation of critical current density in Ag-alloy sheathed Bi-2212 wires

A Malagoli[1,2], P J Lee[1], A K Ghosh[3], C Scheuerlein[4], M Di Michiel[5], J Jiang[1], U P Trociewitz[1], E E Hellstrom[1] and D C Larbalestier[1]

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Supercond. Sci. Technol. **24** (2011) 075016 (9pp) doi:10.1088/0953-2048/24/7/075016

Evidence for long range movement of Bi-2212 within the filament bundle on melting and its significant effect on J_c

A Malagoli[1], F Kametani, J Jiang, U P Trociewitz, E E Hellstrom and D C Larbalestier

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Role of internal gases and creep of Ag in controlling the critical current density of Ag-sheathed $Bi_2Sr_2CaCu_2O_x$ wires

T. Shen,[1,a)] A. Ghosh,[2] L. Cooley,[1] and J. Jiang[3]
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[2]Superconducting Magnet Division, Brookhaven National Lab, Brookhaven, New York 11973, USA
[3]Applied Superconductivity Center, National High Magnetic Field Laboratory, Florida State University, Tallahassee, Florida 32310, USA

A short test sample equivalent to a long sample was needed – sealed end sample

- All prior high J_E wires were short wires allowing internal gas to escape and thus limiting dedensification, wire expansion, but NOT preventing bubble formation
- Only external pressure can densify the 2212 and compress bubbles to small volumes
- Sealed end samples contain all internal gases
  - Residual air in the only 60-65% dense powder
  - Condensed phases such as H_2O or C going to CO_2 that gasify on heating (H_2O) or on 2212 melting (CO_2)

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Supercond. Sci. Technol. 24 (2011) 075009 (7pp) — doi:10.1088/0953-2048/24/7/075009

Bubble formation within filaments of melt-processed Bi2212 wires and its strongly negative effect on the critical current density

F Kametani[1], T Shen[1,2], J Jiang[1], C Scheuerlein[3], A Malagoli[1], M Di Michiel[4], Y Huang[5], H Miao[5], J A Parrell[5], E E Hellstrom[1] and D C Larbalestier[1]

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Supercond. Sci. Technol. 24 (2011) 082001 (5pp) — doi:10.1088/0953-2048/24/8/082001

RAPID COMMUNICATION

Doubled critical current density in Bi-2212 round wires by reduction of the residual bubble density

J Jiang, W L Starch, M Hannion, F Kametani, U P Trociewitz, E E Hellstrom and D C Larbalestier

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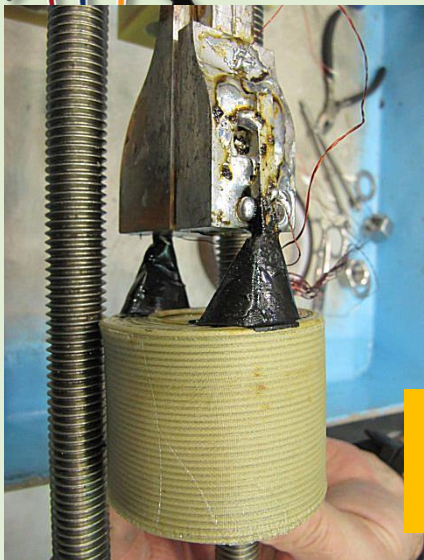
Supercond. Sci. Technol. 24 (2011) 115004 (10pp) — doi:10.1088/0953-2048/24/11/115004

Void and phase evolution during the processing of Bi-2212 superconducting wires monitored by combined fast synchrotron micro-tomography and x-ray diffraction

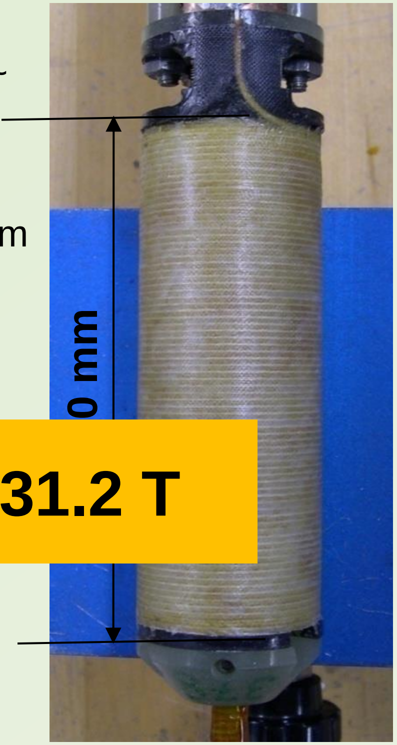
C Scheuerlein[1], M Di Michiel[2], M Scheel[2], J Jiang[3], F Kametani[3], A Malagoli[3,4], E E Hellstrom[3] and D C Larbalestier[3]

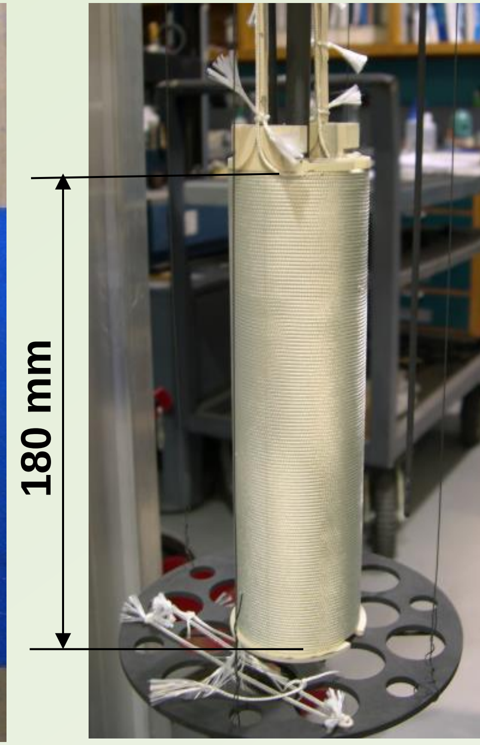
Earlier Bi-2212 RW Coils at NHMFL



High Field Test coil:

- 10 layers/750 turns, L ~ 3 mH
- ID = 15 mm, OD = 38 mm, height = 100 mm
- conductor length ~66 m
- ΔB = 1.1 T at 31 T
- **first HTS wire-wound coil to go beyond 30 T (32.1 T in 31 T**





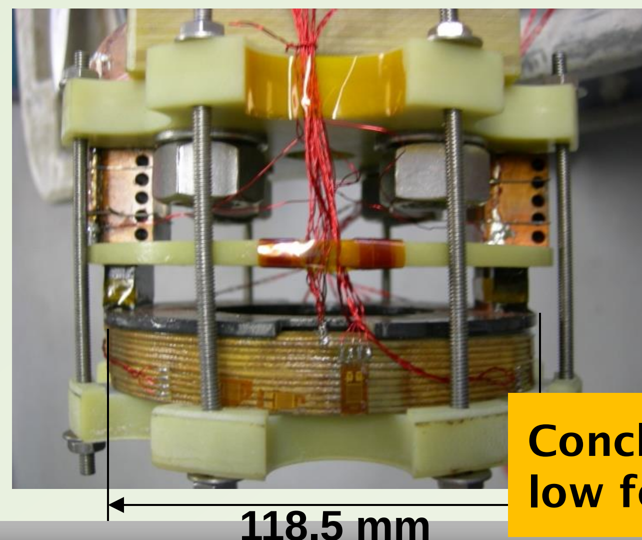
J_w = 80 A/mm^2 at 31.2 T

Bore-tube-free Test Coils:

Minimize chemical interactions with conductor

Large OD σ_{hoop} test coil:

- ID = 92.5 mm
- OD = 118.5 mm
- 10 layers, 10 turns
- Bore tube less
- epoxy impregnated
- ΔB ~ 0.2 T at 20 T
- **210 MPa without degradation**



High Field Test coil “7 T inner shell”:

- 10 layers/135 turns, L = 14.9 mH
- ID = 32.4 mm, OD = 57.4 mm
- height = 180 mm
- conductor length ~220 m

Conclusion: coil J_c and J_w too low for practicality

Q: Are OP tests on 15 cm closed end samples predictive of coil length samples?

- We made many 2212 coils 2007-2011
  - See Weijers et al. IEEE TAS “High field magnets with HTS Conductors”, 20, 576 (2010).
  - Winding current density did not advance over more than 10 years - < 100 A/mm^2 at 20 T
- We insisted to test our short closed sample performance against long length closed end coil length
  - 10 bar OP coil with 34 m of wire (Trociewitz)

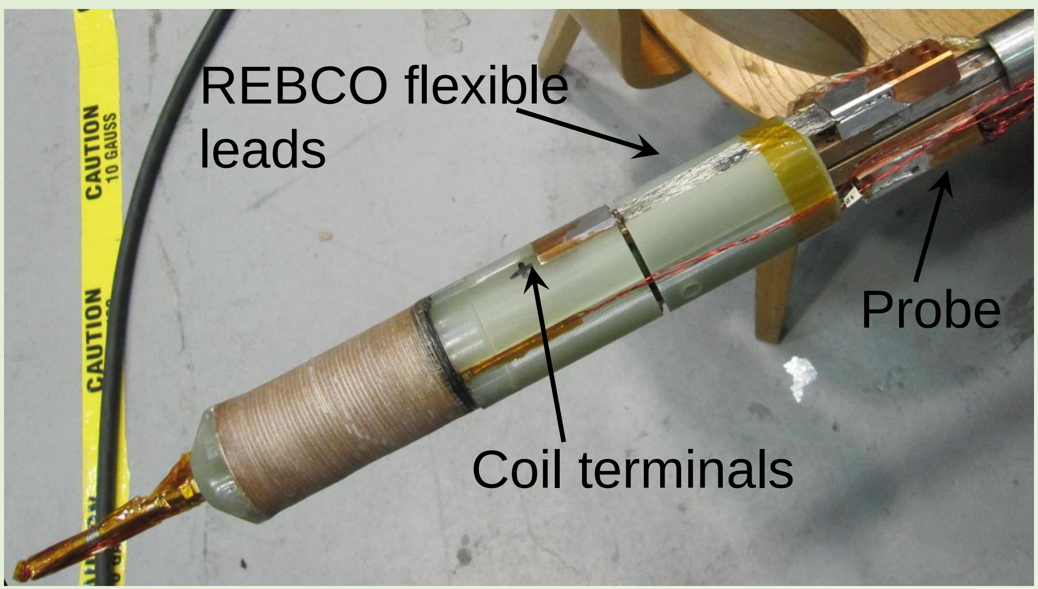
OP Bi2212 Coil with nGimat TiO_2 insulation

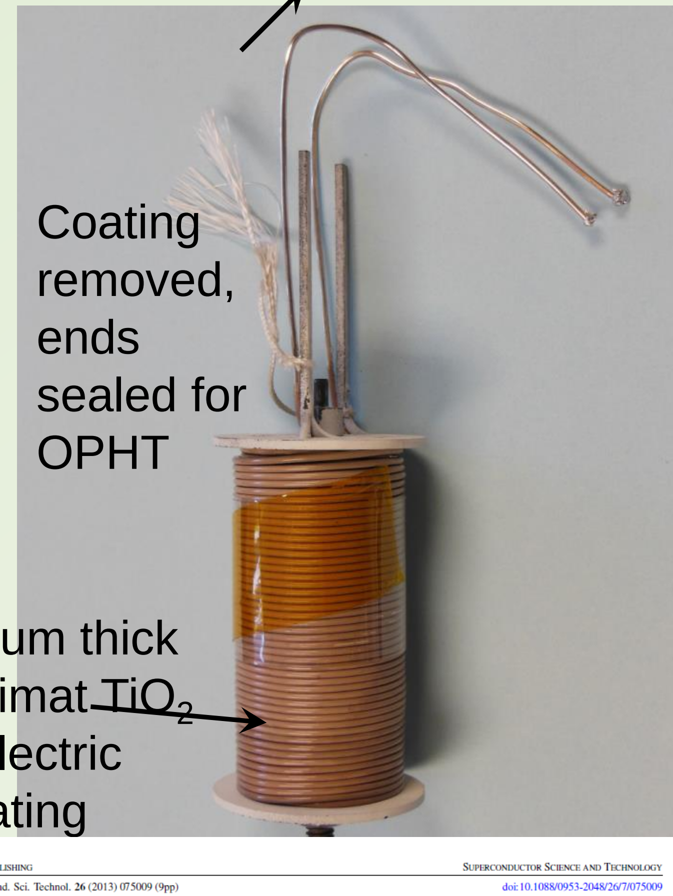
Because we were limited
1. to 10 bar by furnace diameter
2. By short furnace length which put coil terminals in low T zone….
Nevertheless

Coil specs.:

Wire dia. (mm):	1.40
nGimat Insulation (mm):	0.015
Turn-turn non-tightness (mm):	0.085
layer-layer tightness (mm):	-0.065
Inner Radius (a1) (mm):	7.25
Outer Radius (a2) (mm):	18.17
Height (2b) (mm):	71.21
Radial Layers (-):	8
Turnss/Layer (-):	47
Total turns (-):	376
Conductor Length (m):	30.03

Configuration for 31 T test:





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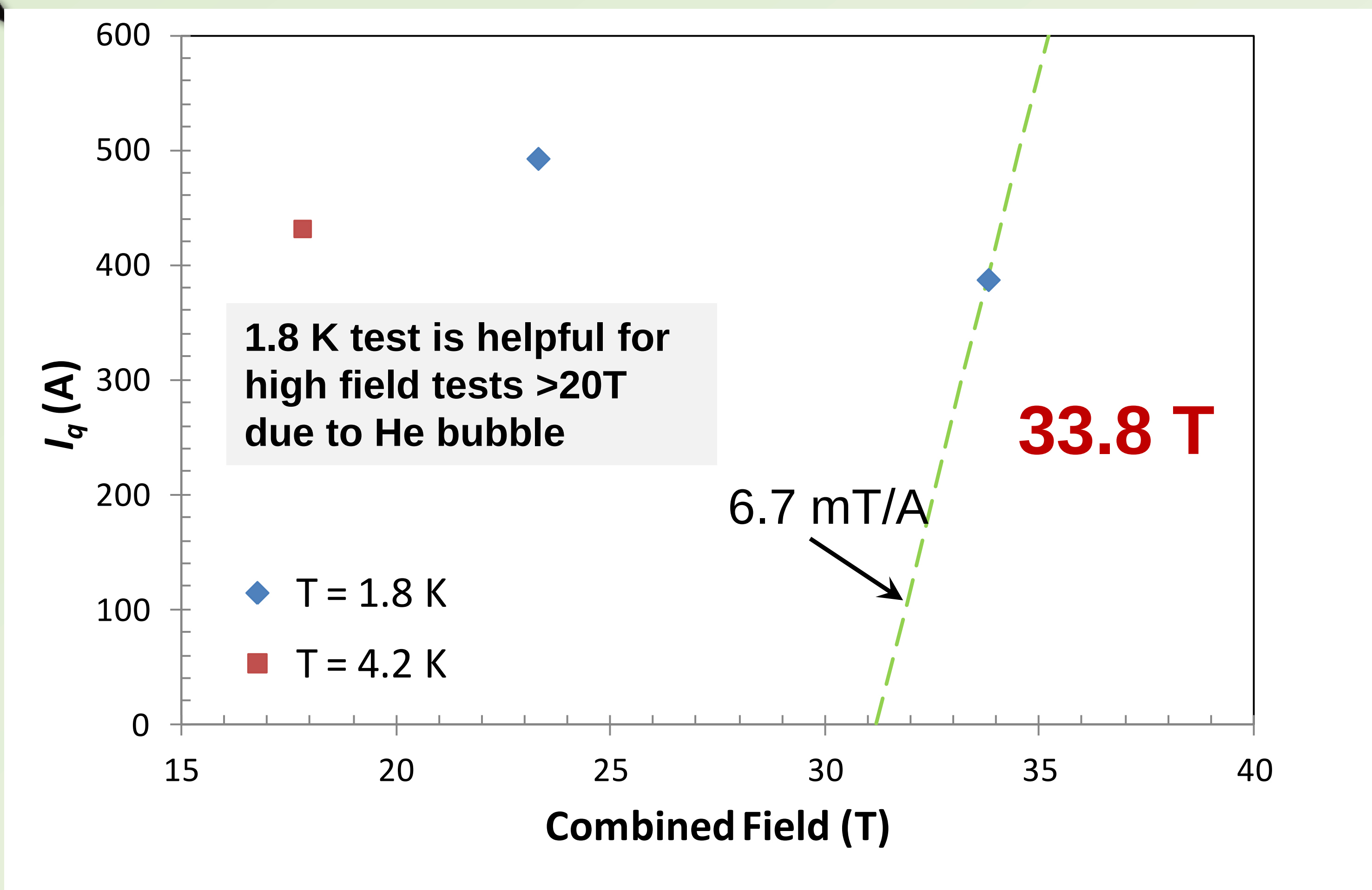
Performance of titanium oxide–polymer insulation in superconducting coils made of Bi-2212/Ag-alloy round wire

Peng Chen[1,2], Ulf P Trociewitz[1], Matthieu Dalban-Canassy[1], Jianyi Jiang[1], Eric E Hellstrom[1,2] and David C Larbalestier[1,2]

- Coil as built (as designed): 47 (50) turns, 8 (8) layers, 36.35 (37.38) mm OD
- 2 innovations: OP process AND thin insulation to drive J_w >> 100 A/mm^2

Field Generation and Coil Load Line



- **2.6 T Field increment achieved in 31.2 T background field (I_q = 388 A, J_w = 187 A/mm²)**
- **Slight degradation on inner terminal after a total of about 20 in-field 4.2 K runs at ramp rates varying from 2.5 – 50 A/s**

Brief History of BSCCO Coils up to now

Conductor	*HT style*	*Coil style*	*B applied (T)*	*delta B (T)*	*Jwinding (A/mm^2)*	*Year*	*Institution*	*Comment, ID/OD*
2212 round wire	W & R	Layer W.	9	0.13	48	1994	Vacuumschmelze	*early test coil*
2223 tape	R & W	DP* stack	22.5	1.5	48	1995	Sumitomo/MIT	*1st decent insert*
2212 tape	R & W	DP stack	21	1.8	128	1996	Hitachi/NIMS	17 / 45 mm
2212 tape	W & R	DP stack	21.4	2	112	2000	Hitachi/NIMS	17 / 48 mm
2212 tape	R & W	DP & Layer W.	20	5.1	69	2003	NHMFL 5T	45 / 165 mm
2223 tape	R & W	DP stack	11.5	5.4	91	2004	KIT (HOMER)	60 / 180 mm
2212 round wire	W & R	Layer W.	31.2	1.1	[illegible]	[illegible]	[illegible]rogram	15 / 38 mm
2212 round wire	W & R	Layer W.	20	3.3	238	2012	NHMFL, 2212-program	15 / 38 mm
same coil	same coil	same coil	31.2	2.[illegible]	[illegible]	[illegible]	[illegible]gram	same coil

80 A/mm^2 at 31.2 T

187 A/mm^2 at 31.2 T

* DP = double pancake type coil

- **Winding current density more than doubled since 2008 coils**
- **OP coil duplicates short sample properties**

Ulf Trociewitz, Matthieu Dalban-Canassy and Peng Chen (see MT23 invited paper by Trociewitz)

OP furnaces are needed to allow short samples to be translated into coils – NHMFL capabilities

Diameter	Length	Max pressure	Comments
25 mm	15 cm	100-200 bar	Today's workhorse
48 mm	15 cm	25 bar	Commissioning now
45 mm	25 cm	75-120 bar	On order, June delivery
170 mm	50 cm	100 bar	On order, July delivery

- Capabilities are available to all in BSCCo and many samples have been shared with LBNL and FNAL
- FNAL is designing a 100 bar capability for straight Rutherford Cables suitable for reacting 2212 cable designed for test in FRESCA at CERN

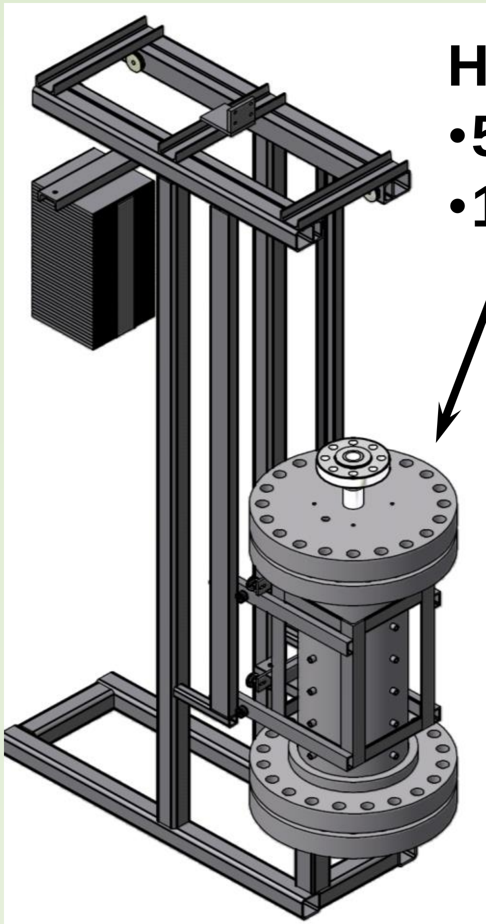
New OP furnaces increase capacity for moderate sized coils and scientific studies

Existing 100 bar system

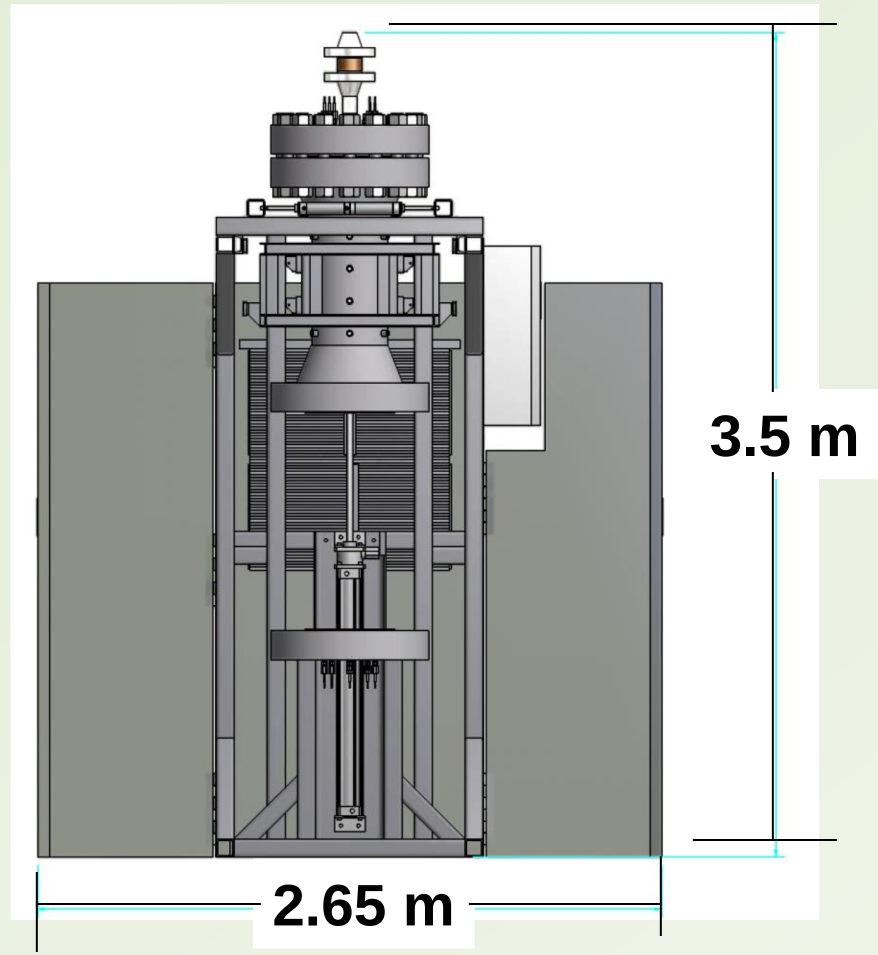
25 bar system – on order

100 bar system – on order

100 bar OP furnace for large coils



Hot zone
- **50 cm high**
- **16 cm diam**

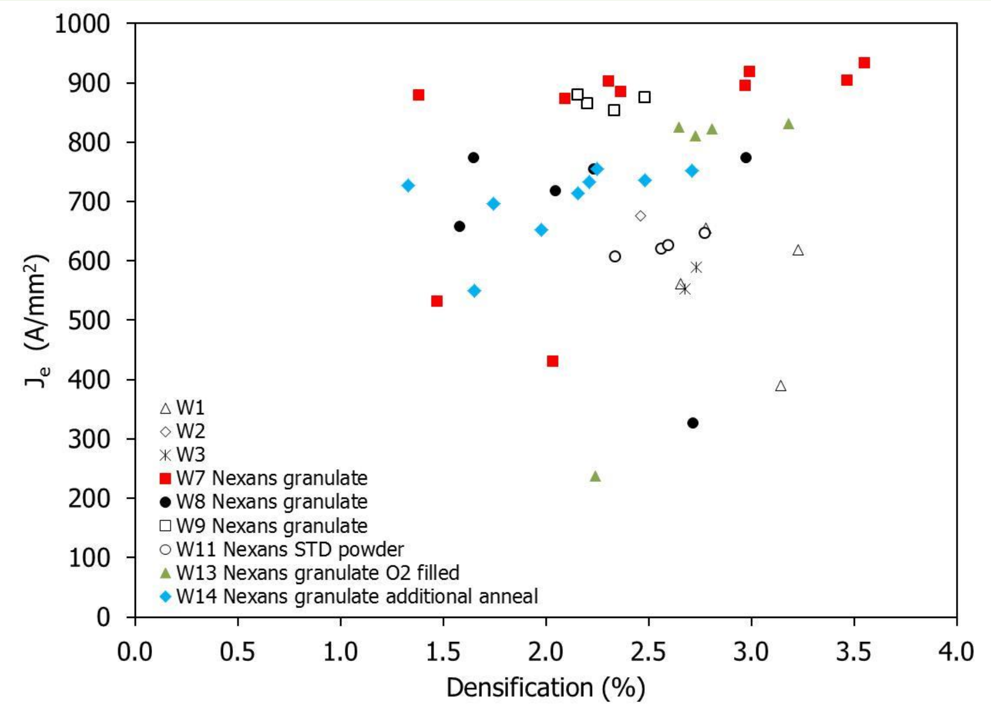


Present conductor driving questions

- 1. Is there any clear evidence that one powder is better than another? Yes – based on 20 billets made in last 3 years
- 2. How uniform along the length does OP leave the samples? So far no serious worries but more tests needed
- 3. Do cleaner billets require less OP pressure? Jiang MT23 talk
- 4. What really is the optimum filament diameter (d_f) for optimum Jc? Early signs are that smaller than present design (<15 μm) may be better
- 5. Can we do a better ODS on both Ag/Mg and Ag/Al than we are doing at present? Probably – in process
- 6. How do we measure powder quality? In process
- 7. How do filaments couple and is there any change as filaments become closer and smaller? In process
- 8. Can we simplify the heat treatment? We believe so

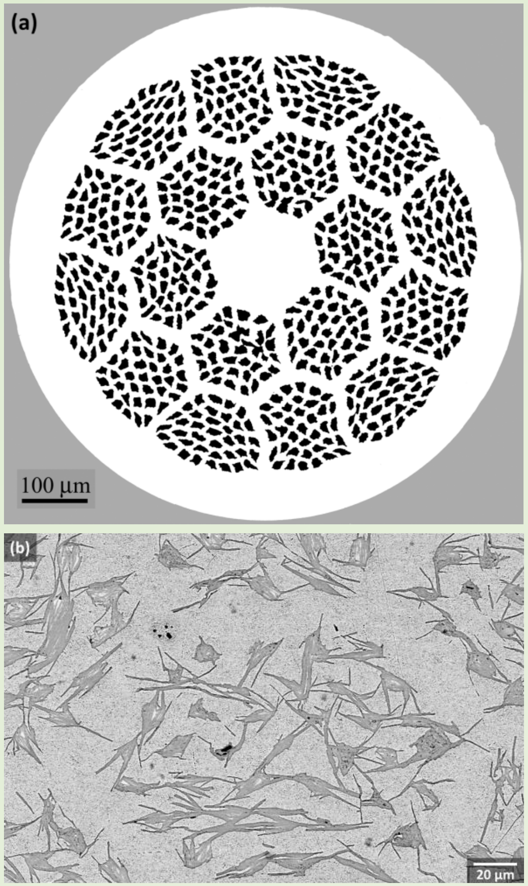
Is one powder better than another?

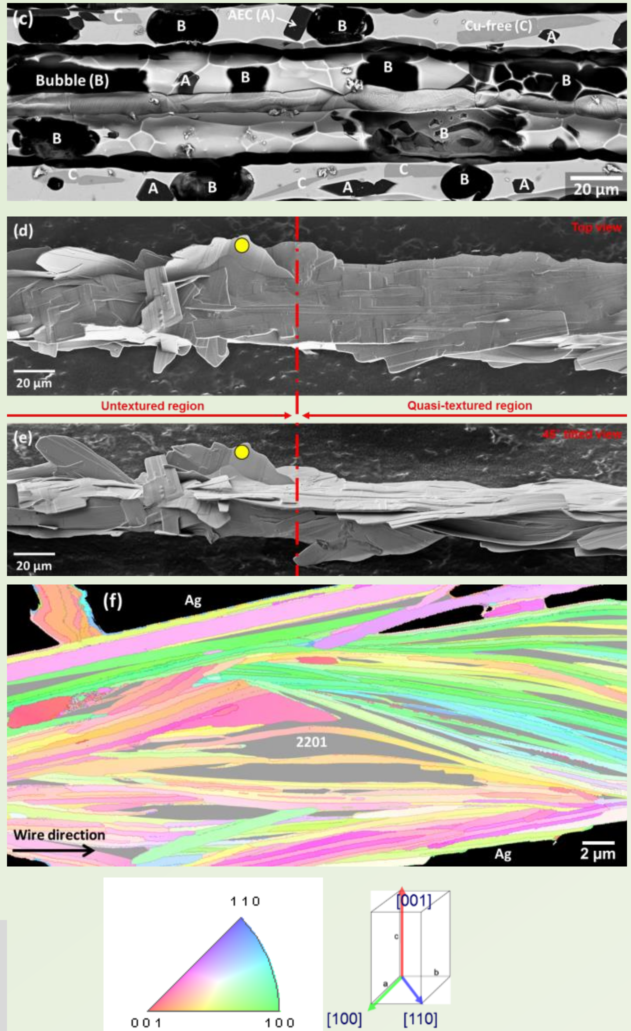
- For now the answer seems to be that (more recent) Nexans granulate develops higher J_E than (older) Nexans standard fine powder
- New powder from Nexans will provide a new test that eliminates powder age as variable
- All evaluations done at 100 bar OP



Je data taken at 5T and densification is $D_{original}/D_{after\ OP} - D_{original}$
Data from Matras, Craig and Jiang – see Jiang MT23

2212 Filaments contain many HAGBs – and (without bubbles) have high Jc





Kametani and Jiang - see DCL arXiv 1305.1269

Transverse section images

Longitudinal section images

Polished sections of filaments in their surrounding Ag

Exposed filaments show their plate-like nature and frequent strong misalignments.

EBSD images show some local texture and significant 2nd phase content within filaments

The filaments cannot be fully connected – yet do have high Jc

Outlook is very positive

- 34 T (in 31T) with 2212 has been safely and reproducibly generated
  - This was a 10 bar coil – we expect more from new 25 and 100 bar coils
- Very strong collaboration between BSCCo labs and Nexans and OST has really allowed rapid progress with great flexibility
  - BSCCo unites Fermilab, LBNL, BNL and NHMFL on 2212
  - CERN is linked to BSCCo through EUCARD2 task 10 20 T magnet aspect of LHC energy upgrade
  - CDP is an essential component of the collaboration