IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2015.
Invited presentation M3OrC-01 given at CEC-ICMC 2015, Tucson, USA, June 28 – July 2, 2015.

Advances in Overpressure Processing Bi-2212 Insert Coils in a New, Large Overpressure Furnace

Eric Hellstrom, M. Boebinger, E. Bosque, P. Chen, A. Constantinescu, D. Davis, L. English, A. Francis, V. Griffin, S. Hahn, D. Hilton, J. Jiang, F. Kametani, Y. Kim, Jun Lu, D. Larbalestier, M. Matras, Y. Oz, W. Starch, U. Trociewitz

Applied Superconductivity Center
National High Magnetic Field Laboratory
Florida State University

Bismuth Strand and Cable Collaboration BSCCo

Funding: DOE-HEP, NSF-DMR, State of Florida

Overview

- **What is overpressure (OP) processing and why do we need it?**
- **Research-scale OP studies**
- **Large-scale OP studies**

- 1989 – first Bi-2212 round wire
- Why the renewed interest in Bi-2212?

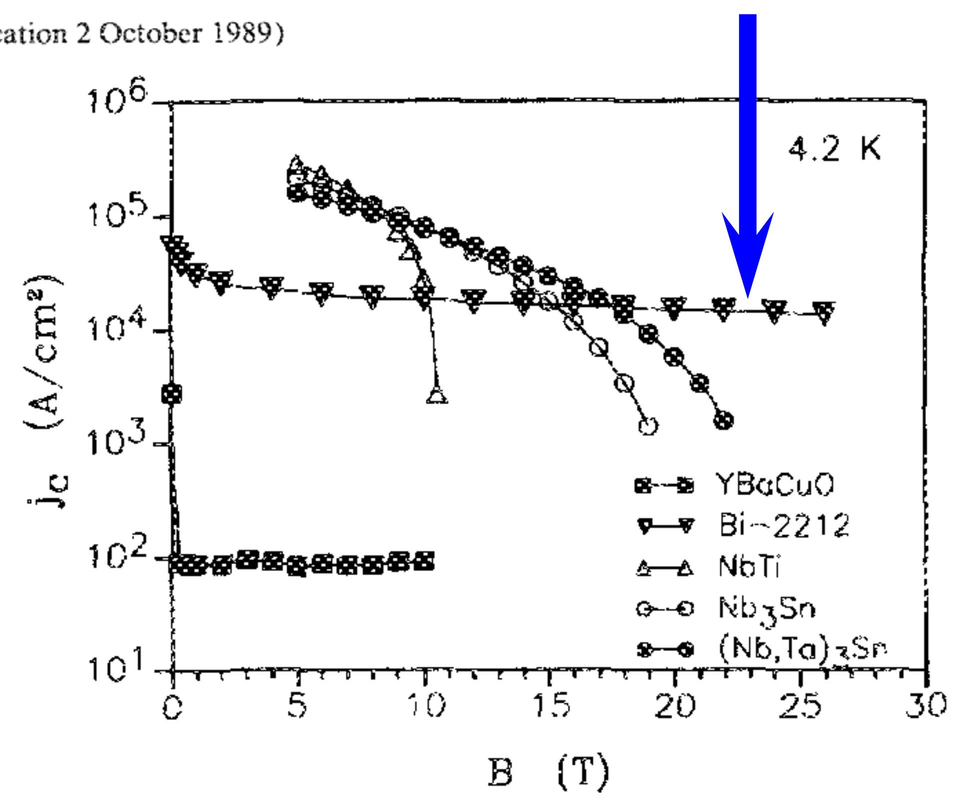
High-field critical current densities in $Bi_2Sr_2Ca_1Cu_2O_{8+x}$/Ag wires

K. Heine, J. Tenbrink, and M. Thöner
Vacuumschmelze GmbH, Grüner Weg 37, D-6450 Hanau 1, Germany

(Received 29 August 1989; accepted for publication 2 October 1989)

APL 55 (1989) 2441

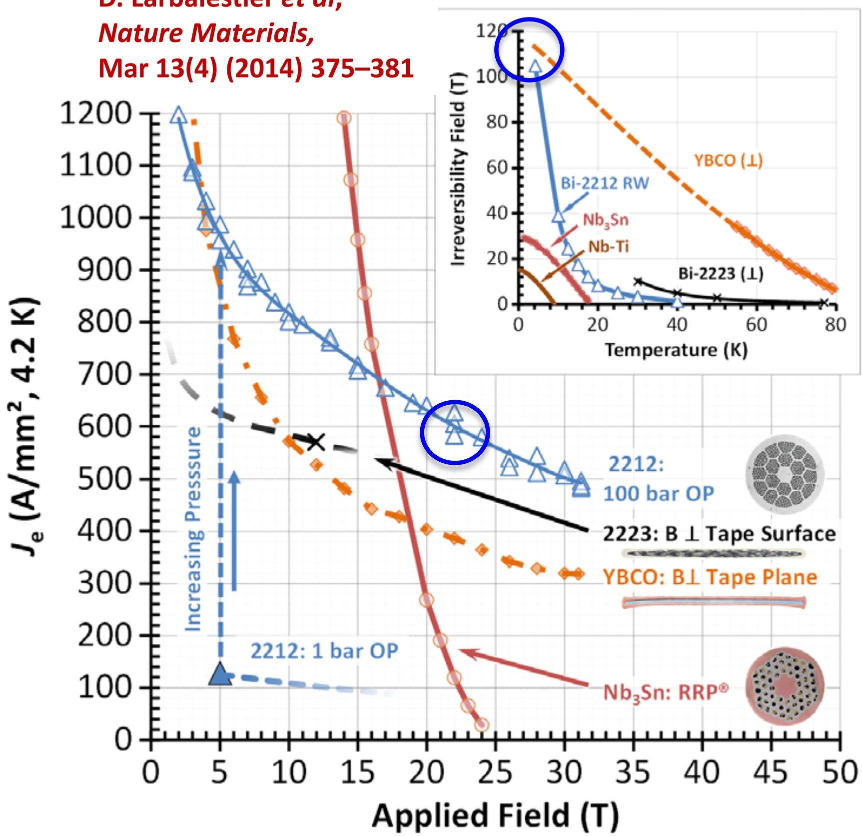
Drawbacks of 2212
- **2212 can only be used up to 10 – 15 K**
- **Much higher J_c in 2212 flat tape**
- **2223 and REBCO are better HTS flat tapes and can be used at 77 K**

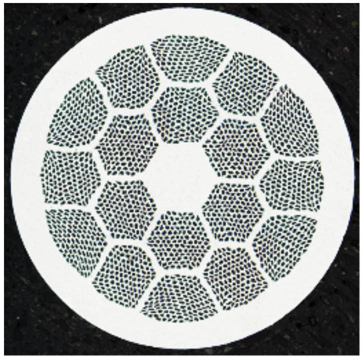


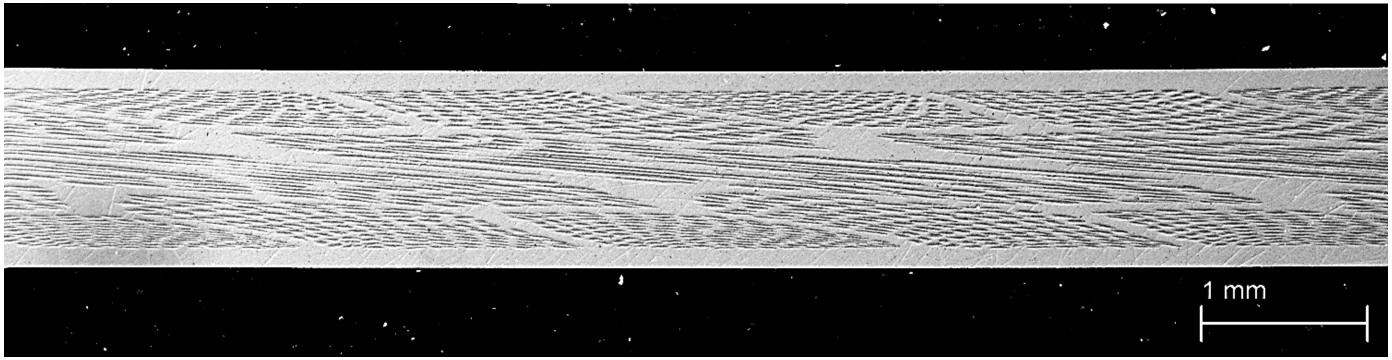
Why Bi-2212 now?

- **Round wire has versatile application potentials for high-field NMR magnets and accelerator magnets *etc*.**
- **Multifilamentary and does not have macroscopic electromagnetic anisotropy.**
- **Twisted wire with significant reduction of hysteretic losses.**
- **A high irreversibility field - above 100 T at 4.2 K.**
- **Overpressure (OP) processing makes J_E of Bi-2212 very competitive.**

D. Larbalestier *et al*, *Nature Materials*, Mar 13(4) (2014) 375–381







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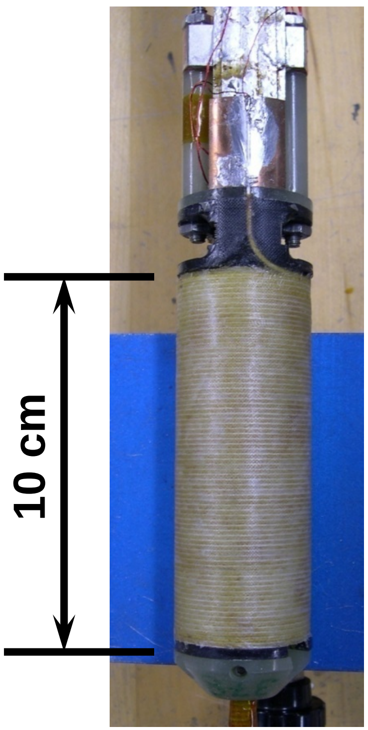
Round wire is preferred conductor geometry to build magnets

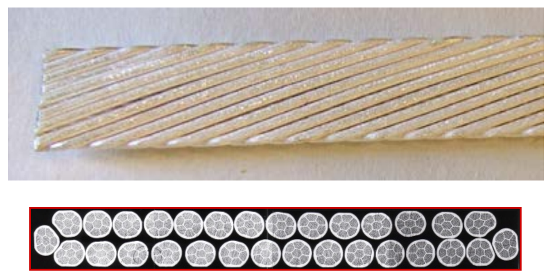
1.1 T in 31 T - first HTS wire-wound coil to go beyond 30 T



Myers, Trociewitz

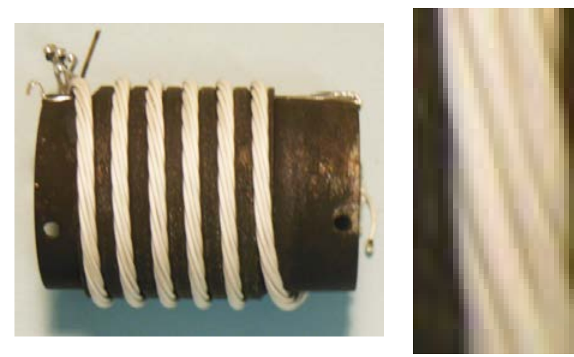
Cables for very-high-current applications

Rutherford



Godeke

6-on-1



Shen

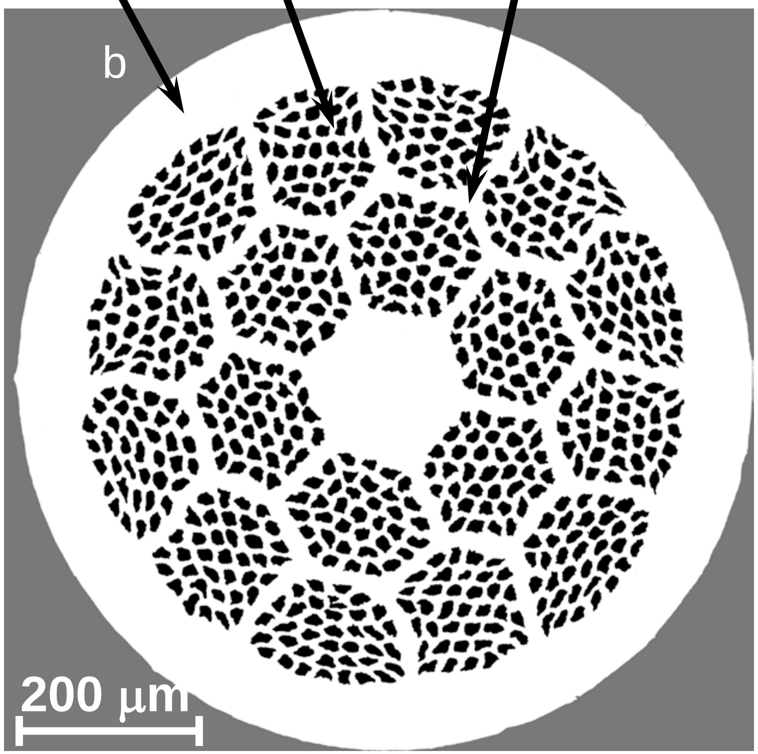
2212 powder in 2212 wire is ~60% dense - bubbles form in 2212 RW during heat treatment

Before

Ag(Mg) Sheath

2212 powder (black)

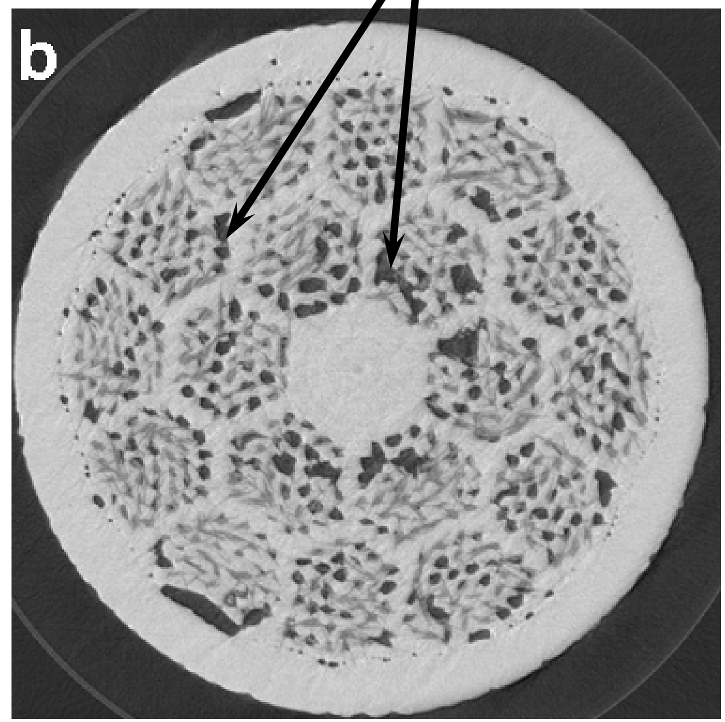
Pure Ag between filaments (white)



OST

After

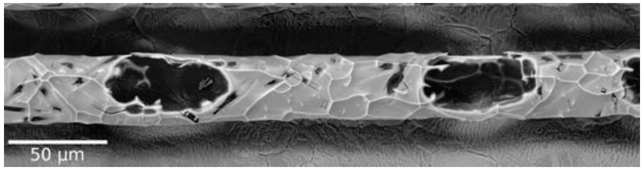
Bubbles



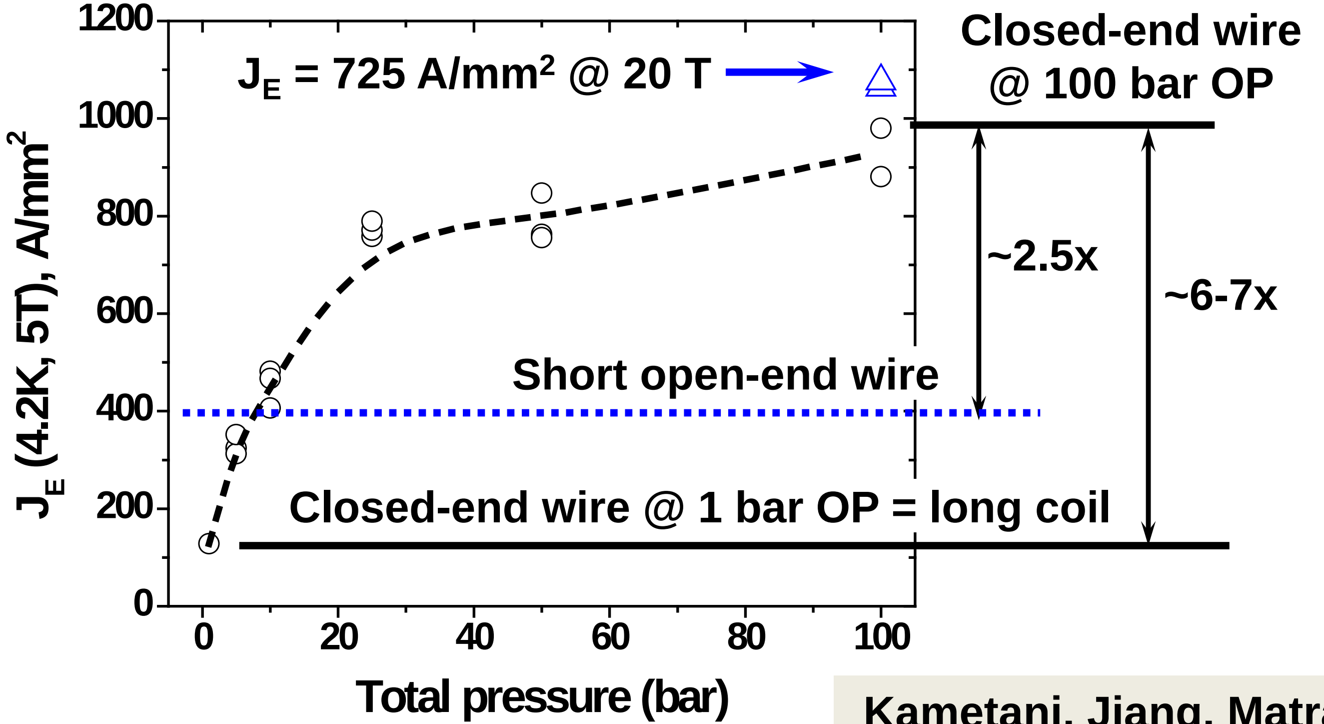
X-ray tomography
Scheuerlein, Di Michiel, Scheel

Removing bubbles with overpressure (OP) processing more than doubles J_E

Direct observation of gas-filled bubbles due to powder being only 60-70% dense



OP processing squeezes wire with gas pressure to remove bubbles



Kametani, Jiang, Matras, Craig

Overpressure processing is a form of Hot Isostatic Pressing (HIP)

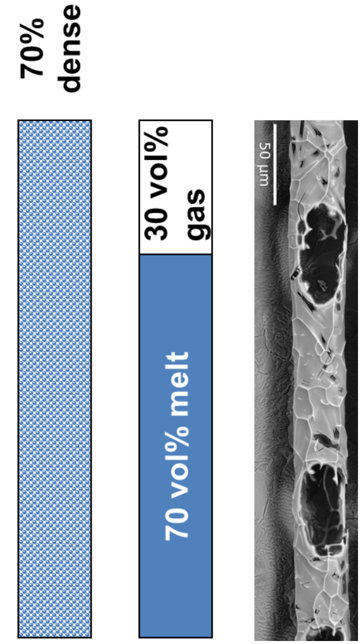
OP processing – gas pressure squeezes wire to remove bubbles

- Flow-through mixture of Ar and O_2
- Total OP pressure ≤ 100 bar
- Wire or tape must be hermetically sealed
  - Ag sheath provides the seal

- Ar – presses on Ag sheath – removes bubbles
- O_2 – diffuses through Ag - sets thermodynamic condition needed to form Bi-2212
- Use an Ar/O_2 gas mixture that sets pO_2 = 1 bar in the OP system

OP processing improves J_c by two mechanisms

- Compresses wire so volume of Bi-2212 matches filament cavity
  - Removes bubbles
- Prevents gas from expanding
  - CO_2, H_2O
  - Eliminates dedensification and creep-induced leakage



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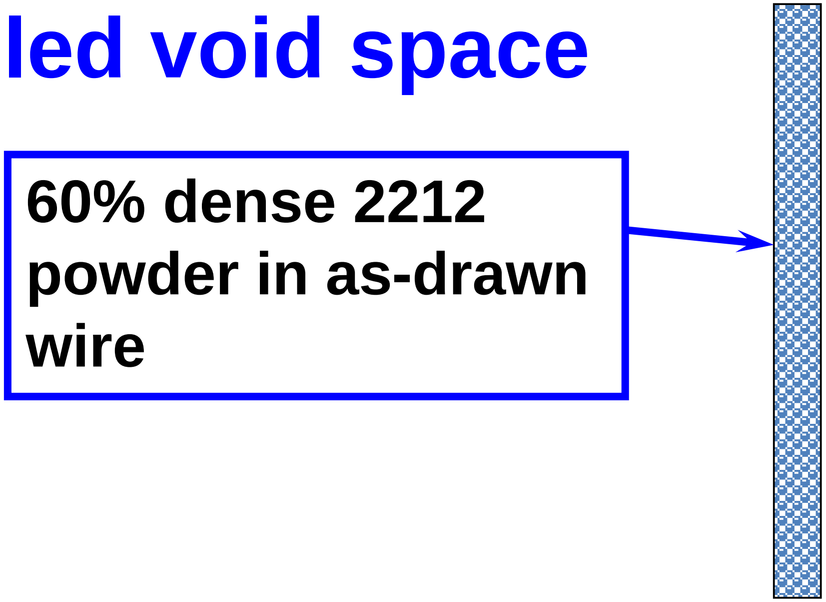
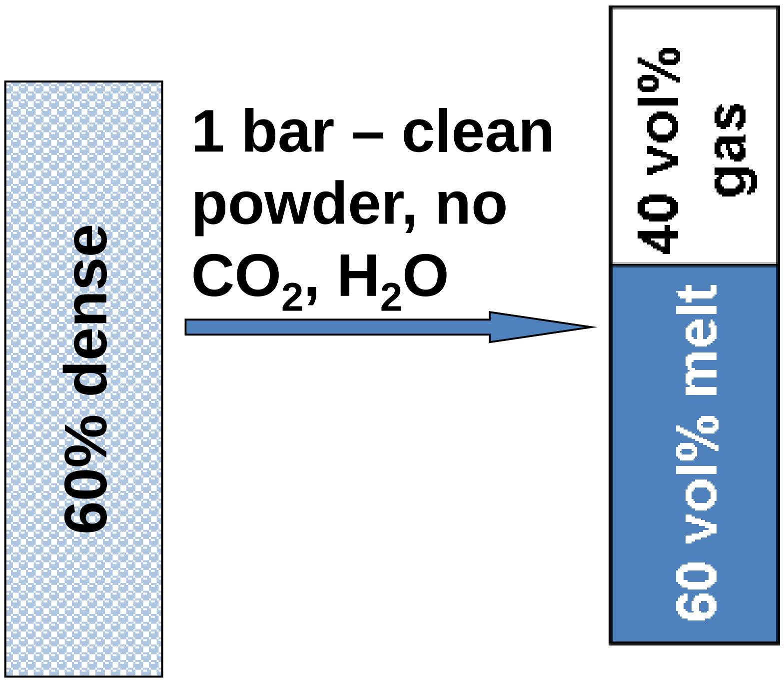
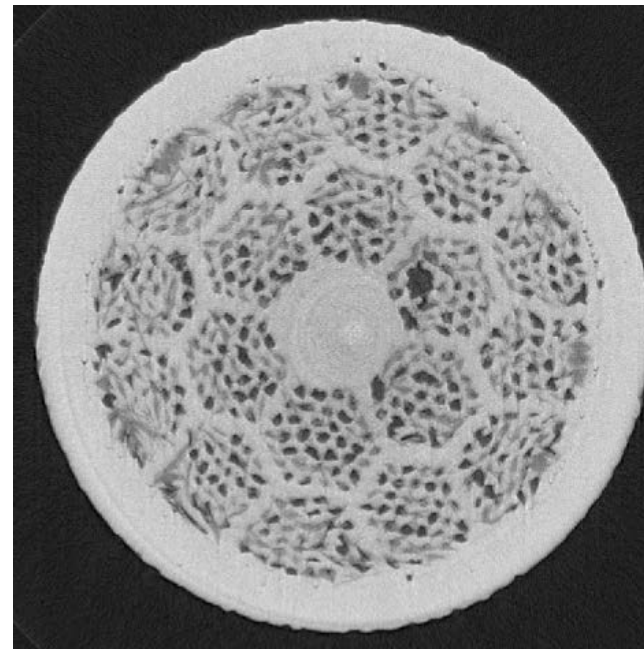
What can happen to 2212 filaments during melt processing?

- **Maximum packing density of 2212 powder in filaments is 60-70%**
- **Focus on the 30-40 vol% of the filament that is gas-filled void space**



Best case with 1 bar processing: 30-40 vol% gas bubbles in filament





Kametani

Scheuerlein

Real-time, *in situ* x-ray microtomography shows how bubbles form and grow during heat treatment

- **Video shows filaments in 2212 wire during heating and cooling in 1 bar air**

Scheuerlein

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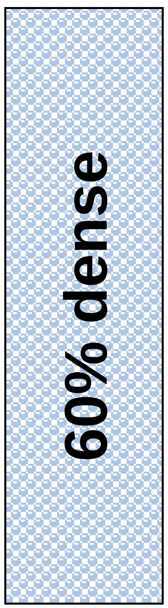
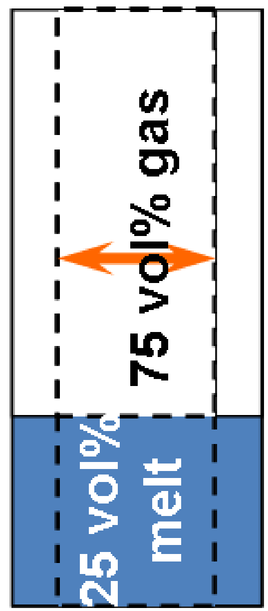
Worst case with 1 bar processing: dedensification and leakage

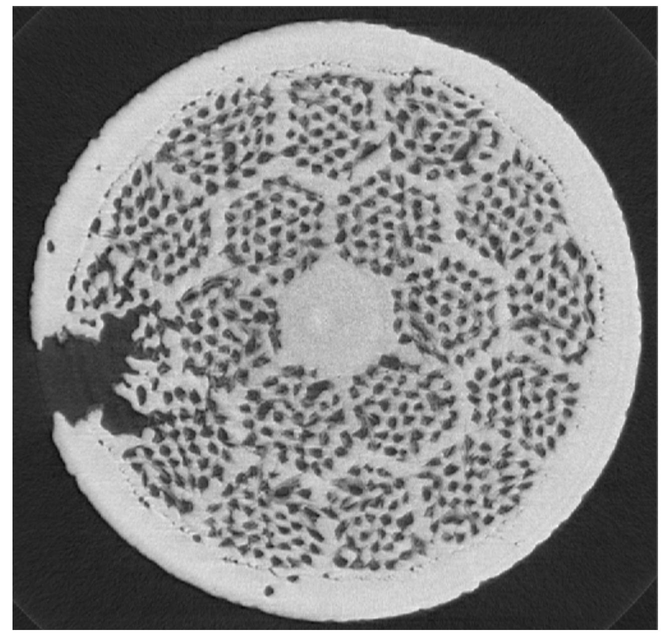


1 bar – dirty powder: CO_2, H_2O

Internal gas pressure expands filament hole



- Malagoli
- Shen

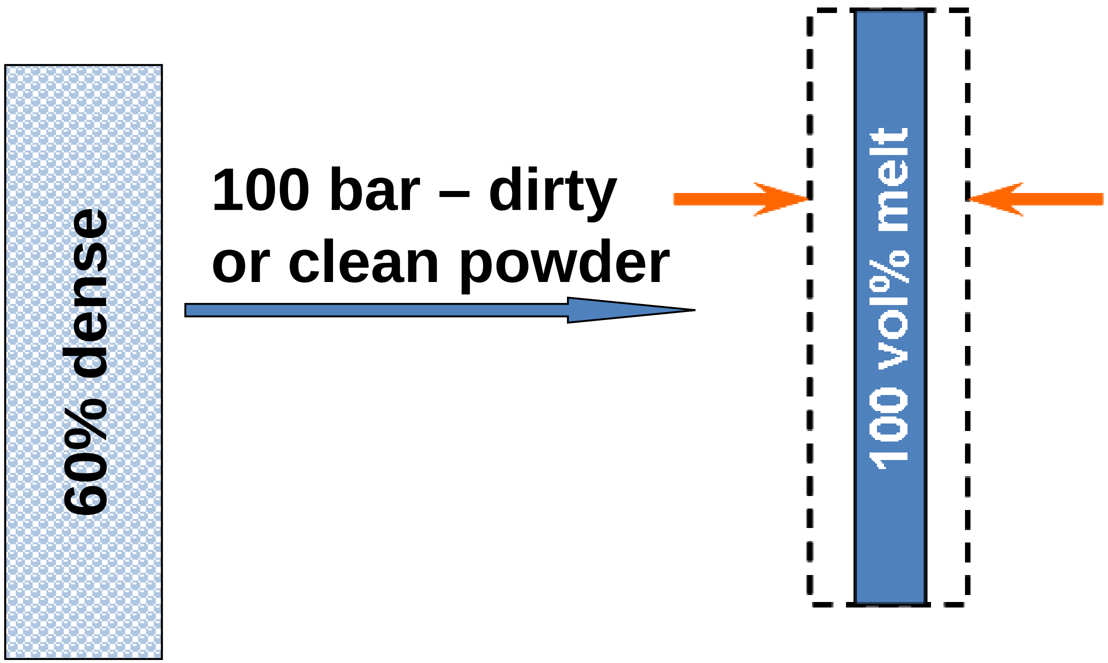


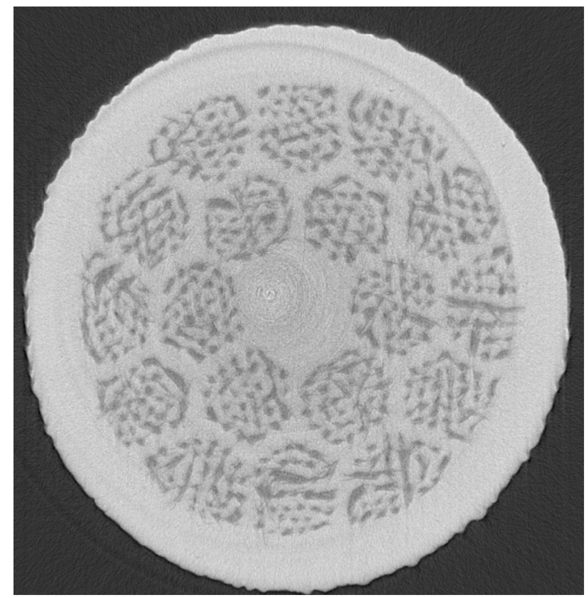
Scheuerlein

Best processing: apply overpressure to squeeze Ag so filament hole matches 2212 volume ⇒ 100% dense

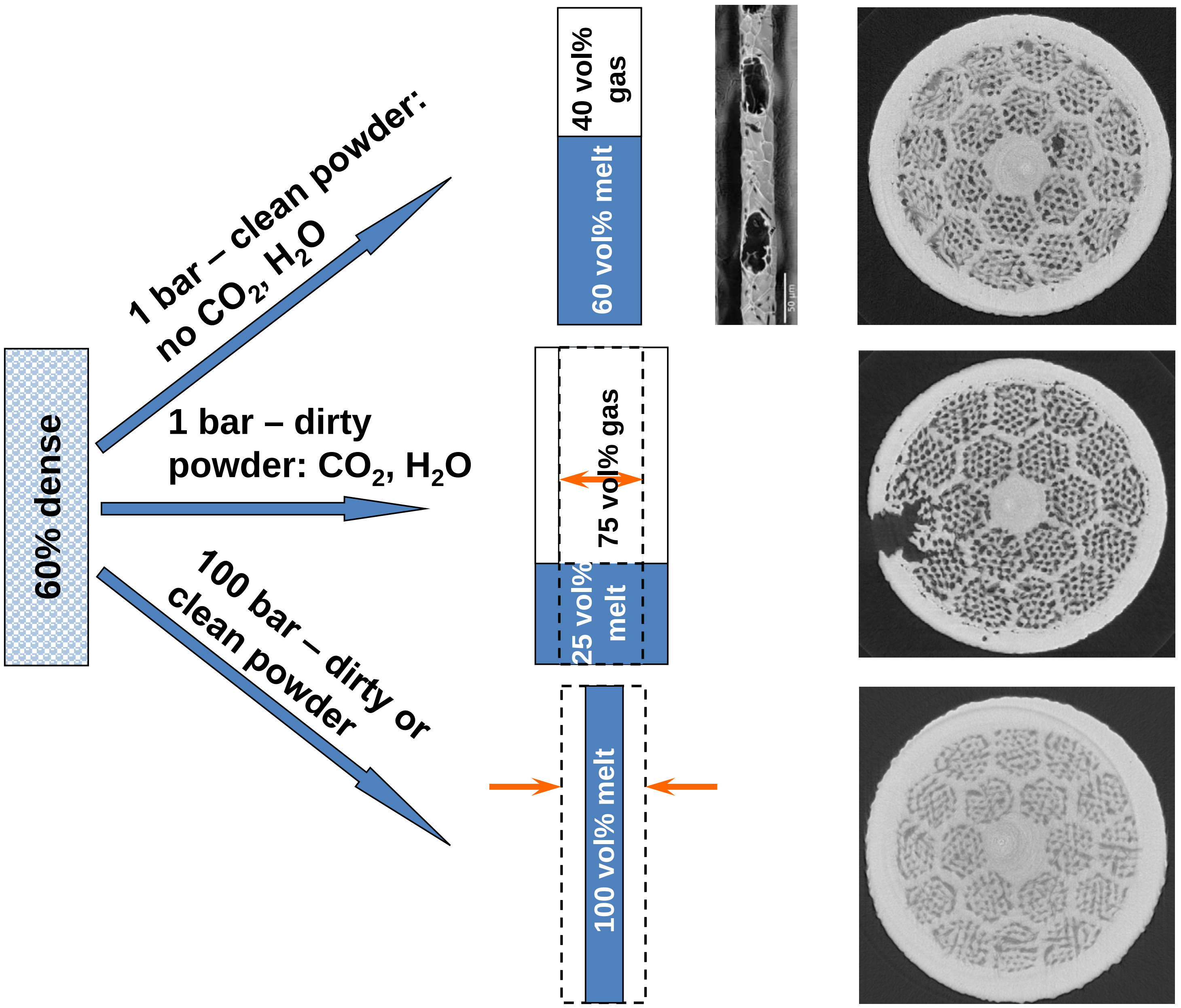
External overpressure decreases filament hole

OP decreases wire diameter





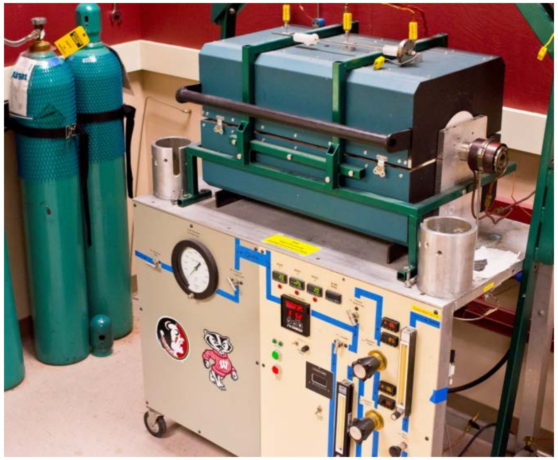
Scheuerlein


60% dense
1 bar – clean powder:
no CO_2, H_2O
1 bar – dirty
powder: CO_2, H_2O
100 bar – dirty or
clean powder
40 vol%
gas
60 vol% melt
75 vol% gas
25 vol%
melt
100 vol% melt

Demonstrated that OP processing works for Bi-2212 with small-bore OP system

- Small OP system originally designed, built, and used for Bi-2223

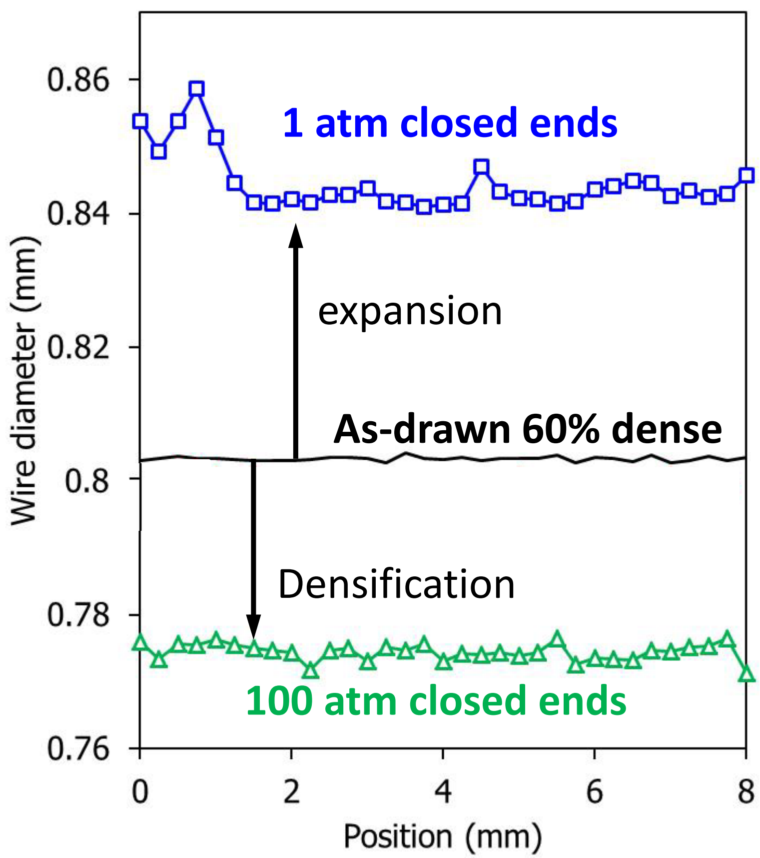
ASC's 2.5-cm bore research OP system



Sumitomo Electric's 4-story-tall OP system for commercial Bi-2223 tape

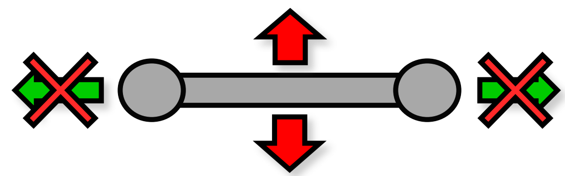
Overpressure (OP) densifies 2212 wires

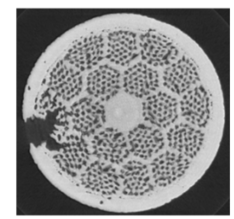
0.8 mm diameter
closed ends 8 cm long samples



Assumption: closed ends short samples behave the same as long coil length

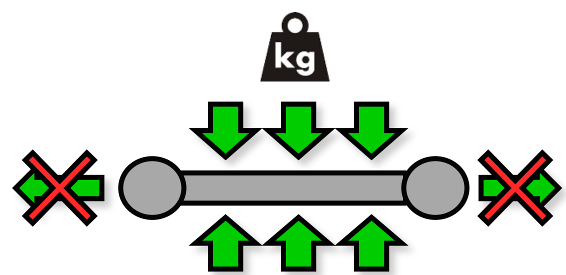
- **Closed ends 1 atm: gas trapped <60% dense**

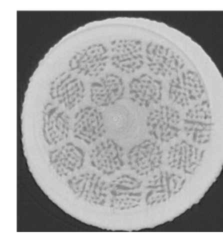




Courtesy Dr C. Scheuerlein

- **Closed ends 100 atm OP:**



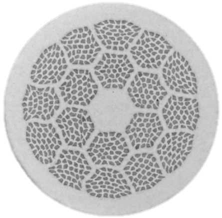


Courtesy Dr C. Scheuerlein

Matras

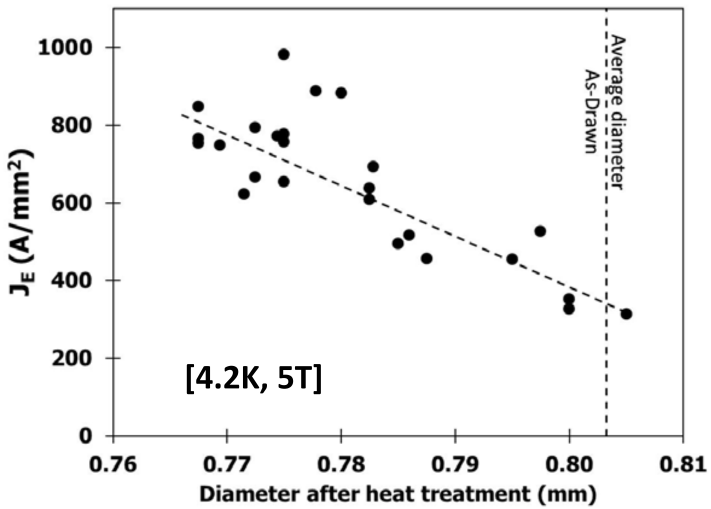
Dense filaments are the key for high J_E

Cross section
as-drawn 37x18
(0.8mm diameter)

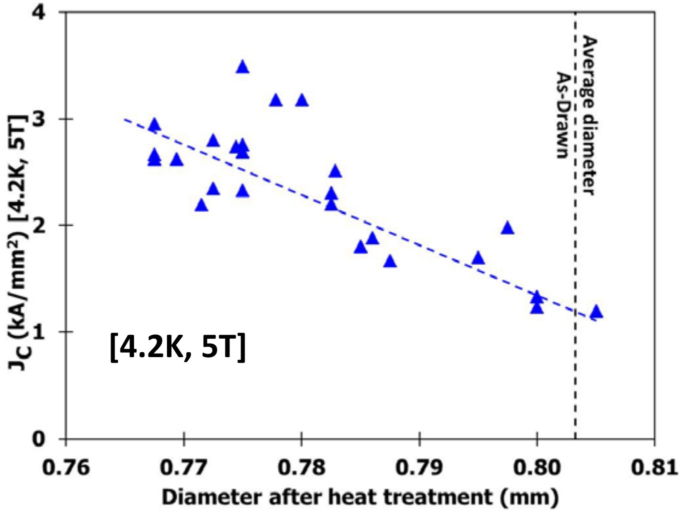


- J_C is calculated using the as-drawn wire filament cross sectional area (60% dense filaments)
- J_C increases (actually it triples) with decreasing wire diameter as full physical connectivity occurs.

$$J_E = \frac{I_C}{area\ OP\ wire}$$



$$J_C = \frac{I_C}{area\ filament\ as-drawn\ wire}$$



Experiment done on short wires (8 cm long)

Matras

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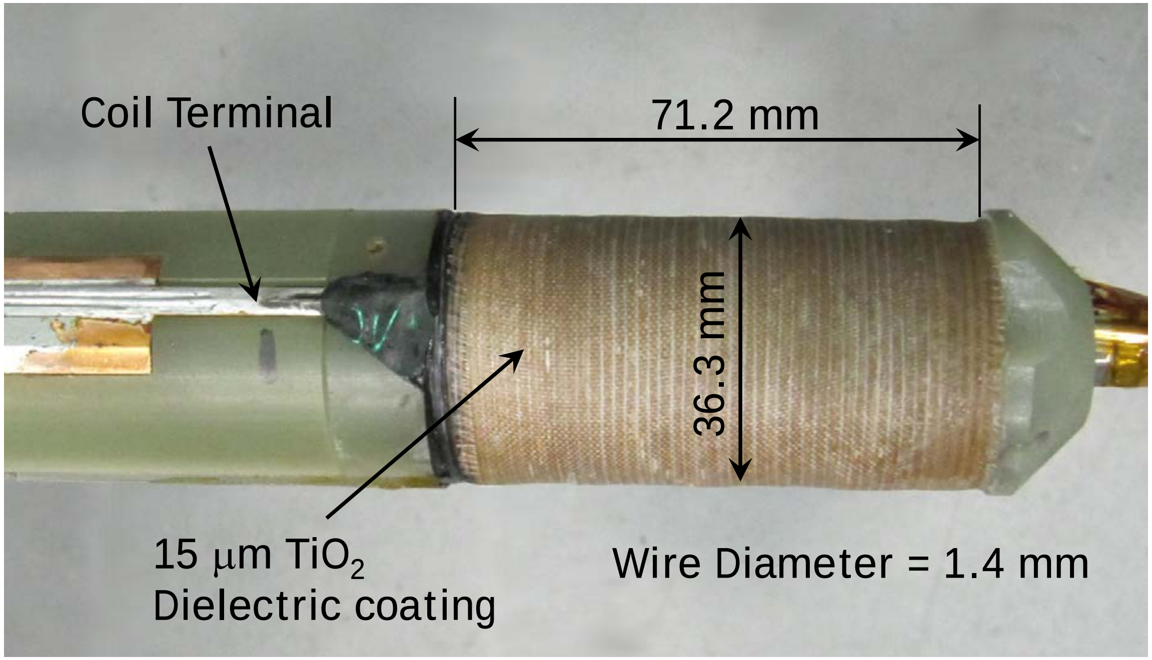
OPed 2212 coil at 10 bar - generated 2.6 T in 31.2 T background = 33.8 T

10 bar OP processing

- Pressure was only high enough to prevent wire from expanding
- Did not compress Ag sheath and remove bubbles
- Insulation - ~15 μm thick TiO_2

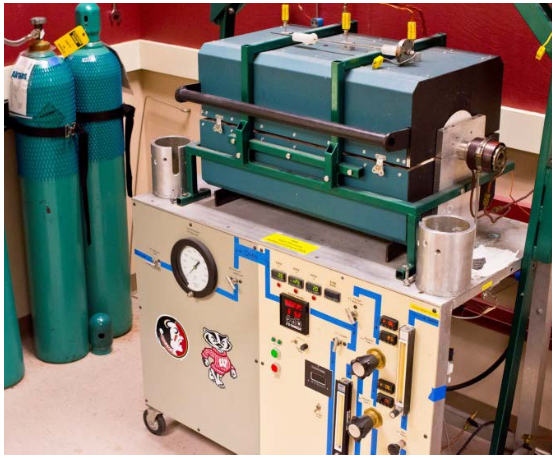


Wire dia. (mm):	1.40
nGimat Insulation (mm):	0.015
Turn-turn non-tightness (mm):	0.085
layer-layer tightness (mm):	-0.065
Inner Radius (a1) (mm):	7.25
Outer Radius (a2) (mm):	18.17
Height (2b) (mm):	71.21
Radial Layers (-):	8
Turnss/Layer (-):	47
Total turns (-):	376
Conductor Length (m):	30.03

Trociewitz

Deltech built a large OP furnace for Bi-2212 coils - custom built, first of its kind

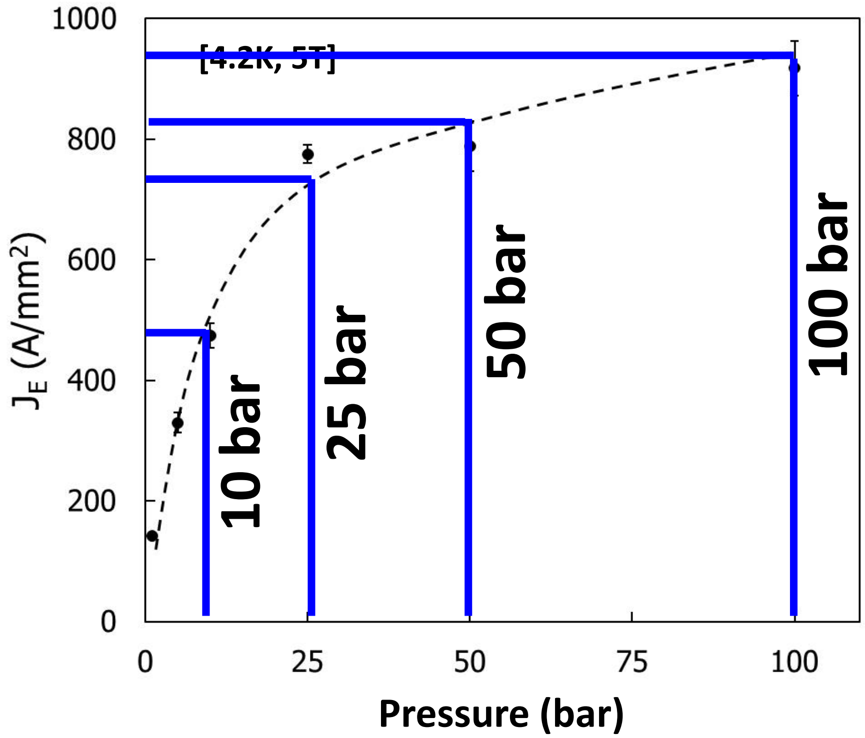
ASC's 2.5-cm bore research OP system



Deltech 100 bar OP furnace

50 bar processing is adequate for NMR demonstration coil

Experiment done on short wires (8 cm long) (37x18)



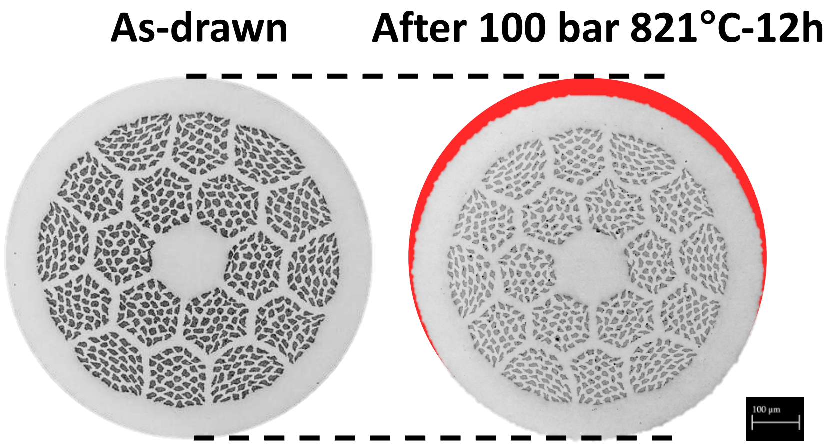
- **35 m long 10 bar coil fell on the curve**

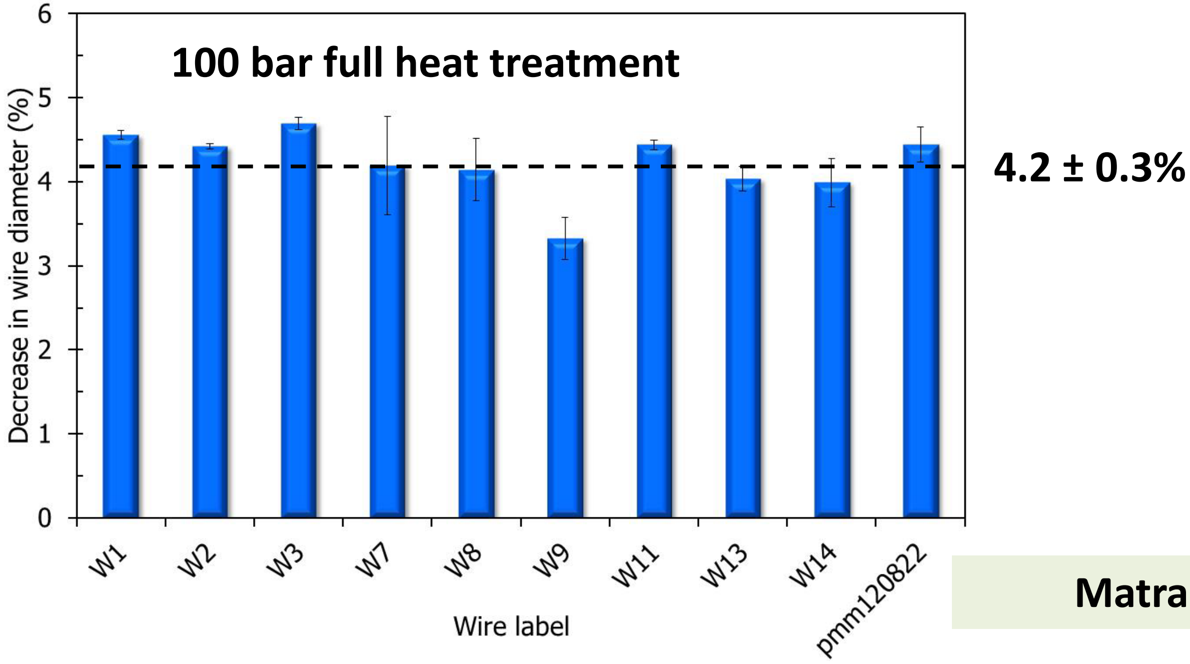
Matras

4.2 % decrease in wire diameter at 100 atm

100 bar OP significantly decreases the wire diameter.

<u>Issue:</u>
For magnet construction, this change in diameter poses an interesting challenge.





Matras

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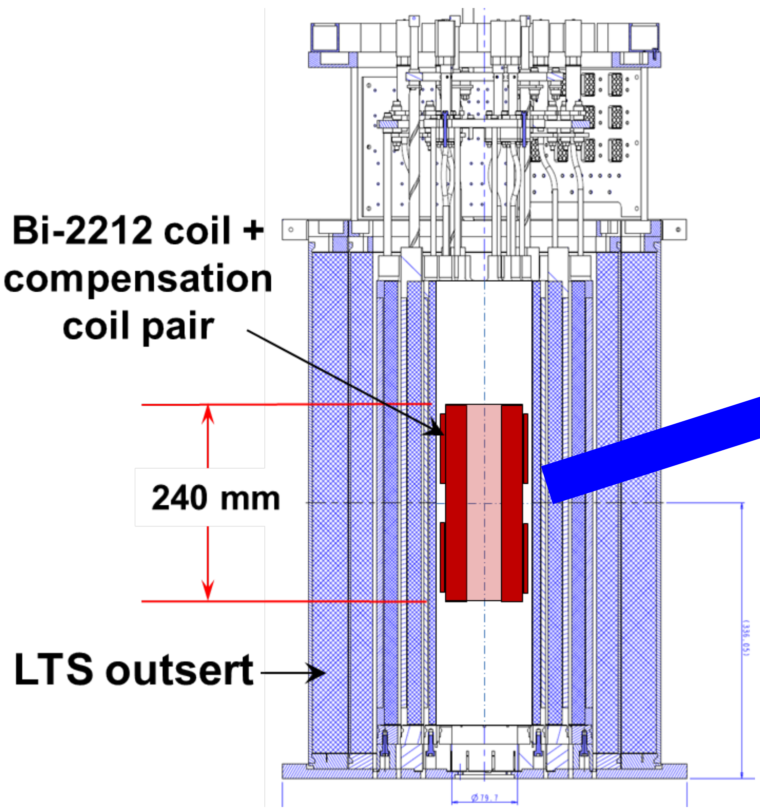
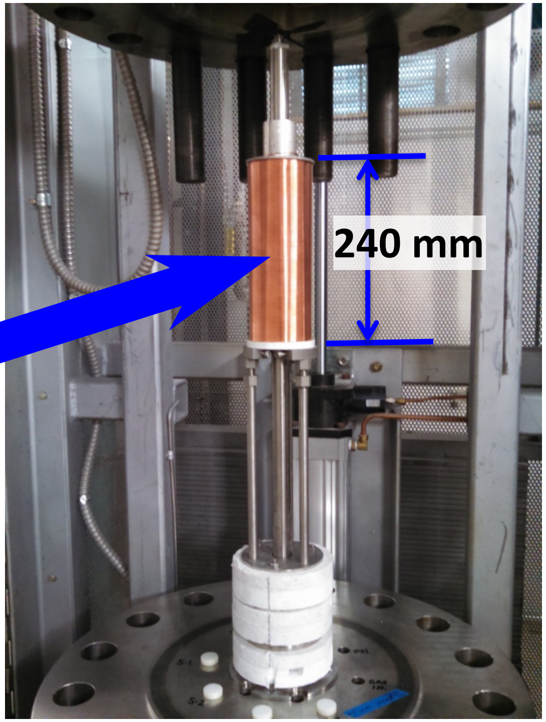
OP furnace and coil being developed together for high-field NMR project

High field coil + shim coils for 1 GHz (24 T) NMR demonstration magnet



Mockup of coil for NMR demonstration project



- 6.6 T
- 240 mm high
- 92 mm OD
- 44 mm ID
- 0.7 km wire
- 179 turns
- 18 layers

Platypus team

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"Platypus": A Bi-2212 NMR Demo-Magnet

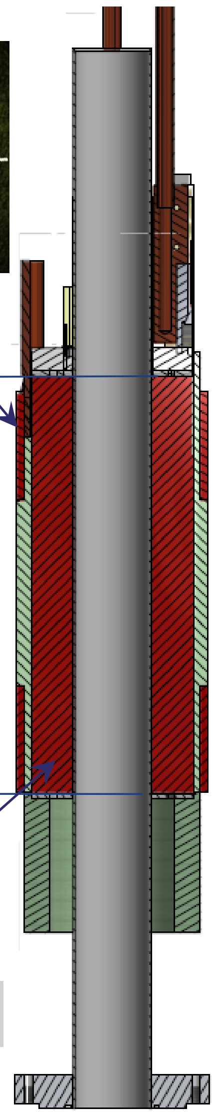
Goals:

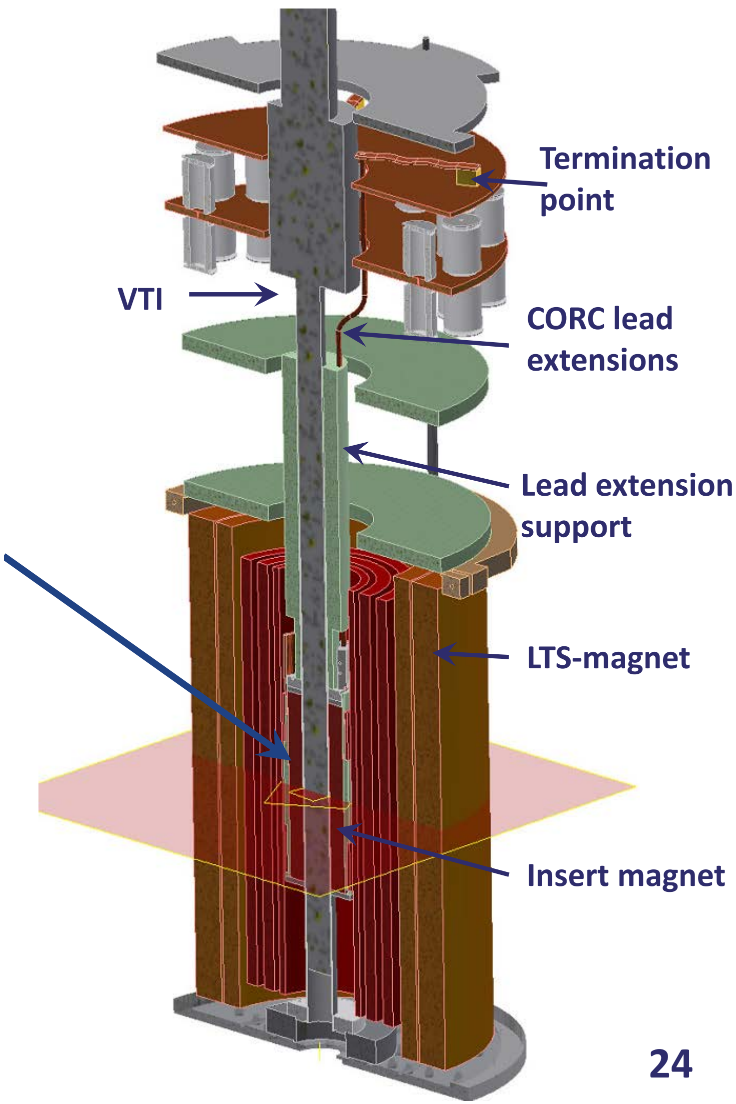
- **MagSci Goal: 30 T NMR magnet using HTS**
- **NMR demo magnet of ~ 1 GHz (24 T) with ppm field homogeneity and stability**
- **Hybrid LTS/HTS coil with all conductors twisted, round and multifilament (16 T Nb-Ti/Nb_3Sn + 8 T Bi-2212)**

Status:

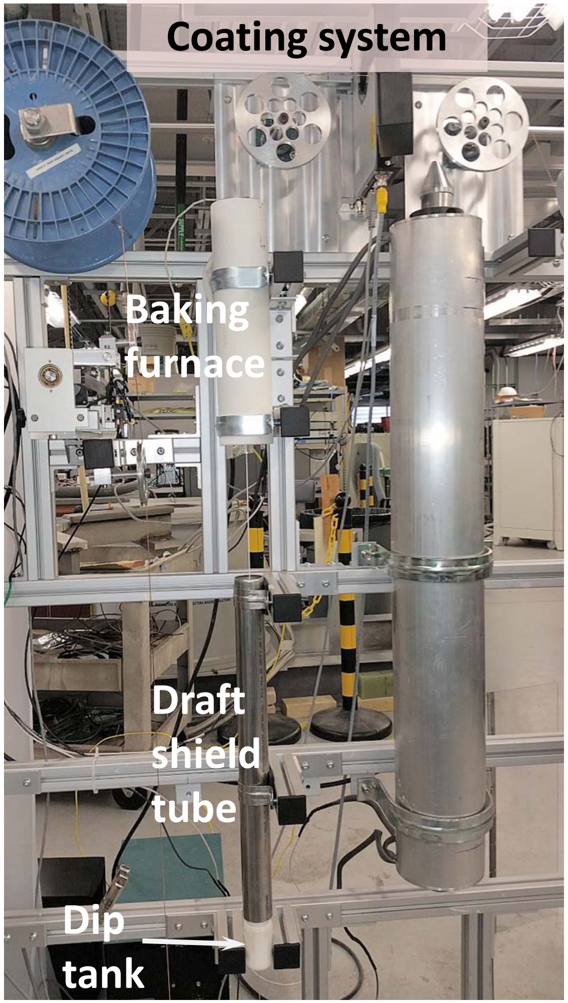
- **Novel 2212 HTS technology has been led by NHMFL**
- **All sub-systems demonstrated**
- **Platypus test planned for summer 2015**
- **Strong DOE-HEP and CERN support for conductor development with industrial partner OST**

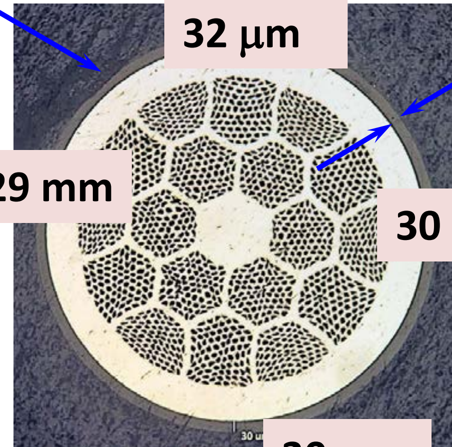
Bismuth Strand and Cable Collaboration BSCCo





Long-length insulation developed in-house – now SBIR partner with nGimat





- TiO_2 particles suspended in organic binder
- ~ 30 μm thick adherent coating
- Burn out before OP heat treatment

In-house coated test-coil

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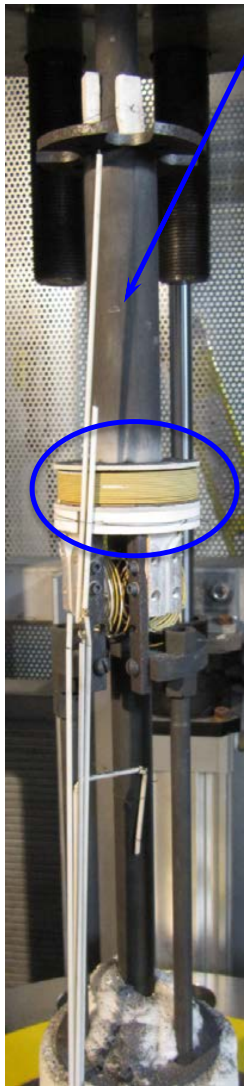
Platypus test coils 2015 (“Platypups”)

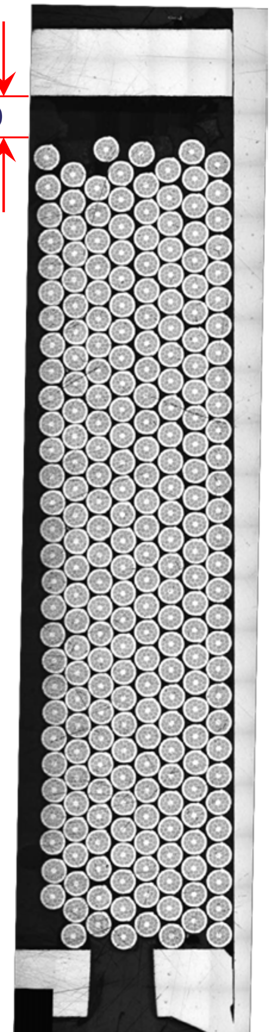
“Platylong”

“Platypup”



Coil support

gap



- Test coils demonstrated:
  - Thermally homogeneous processing of long, thick coils
  - Reasonable correlation of coil and finite element analysis models
  - Viable terminal design
  - 4% wire densification being dealt with
  - Successful epoxy impregnation
- Some coils have been tested in 17 T background at the NHMFL
- Some coils have been dissected for further analysis of the winding pack and transport characterization of extracted coil segments
- Two additional Platypup test coils done in June 2015

Platypus team

Platypus test coils

Platypus test coils

- **Platylong** – full length, 3 layer
  - Evaluate sag from 4% wire shrinkage, furnace uniformity
- **Platypup 1** – 1/10 length, full thickness
  - Impregnation, leads, insulation, 17 T test
- **Platypup 2** – 2/10 length, full thickness (smaller diameter wire)
  - Impregnation, overbanding, confirm FEA modelling, 17 T test
- **Platypup 3** – 1/10 length, full thickness
  - Impregnation, variations in coil winding, 17 T test

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The pluses and minuses of 2212

Pluses

- Round, multifilament and twisted
  - Small magnetization and small field errors
  - Highest J_E of any present HTS
  - Isotropic electromagnetic properties
- Flexible architecture
  - Not one-size-fits-all, like REBCO and Bi-2223

Minuses

- Must be wound in unreacted form and taken through complex HT by magnet builder under 20-100 bar pressure (1 bar O_2) at up to 890 °C
- Must be insulated prior to heat treatment – done!
- 4% densification under pressure needs compensation – being addressed!
- Wire is mechanically weak

100 bar, 900 °C Deltech furnace with 14 cm diam. X 50 cm long hot zone

Summary

- **OP processing makes Bi-2212 round wire a viable conductor for high-field magnets – single strand or cables**
- **Round wire geometry – or wire with small aspect ratio – is preferred geometry to build magnets**
- **Bi-2212 being used in 1 GHz (24 T all SC) demonstration NMR magnet**
- **Subscale coils are being tested on path to full-scale NMR demonstration coils**