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

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Bismuth Strand and Cable Collaboration BSCCo

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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

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APL 55 (1989) 2441

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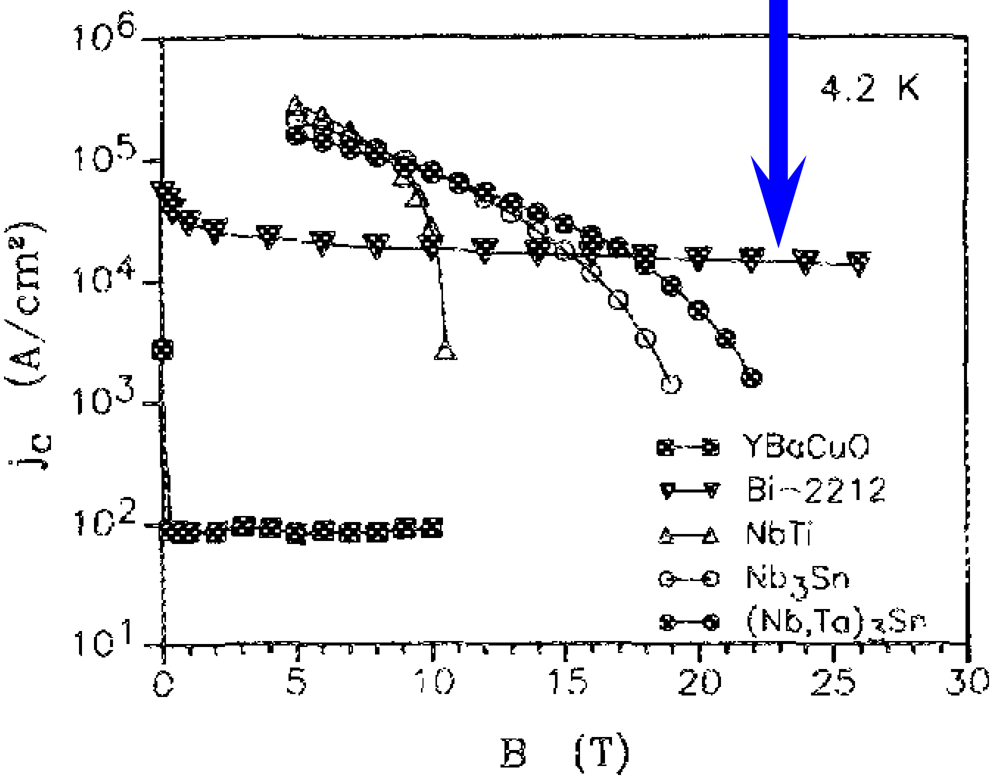
Drawbacks of 2212

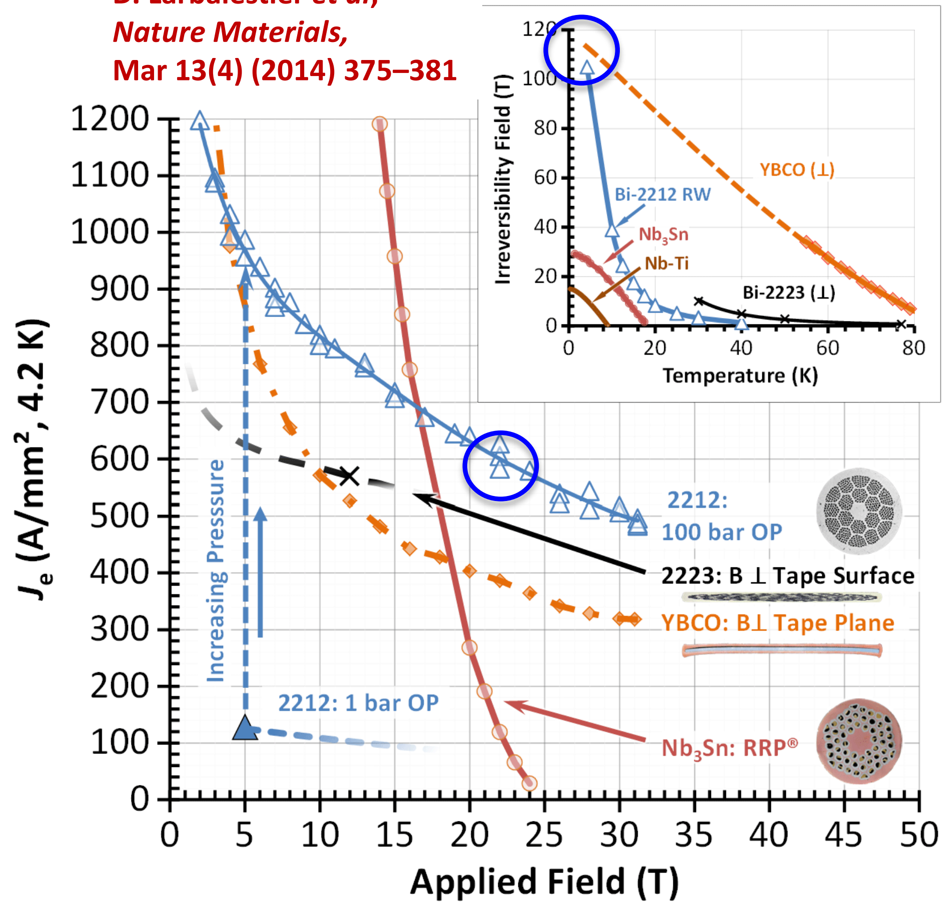
- **2212 can only be used up to 10 – 15 K**
- **Much higher J_c in 2212 flat tape**
- **2223 and REBCO are better HTS flat tapes and can be used at 77 K**

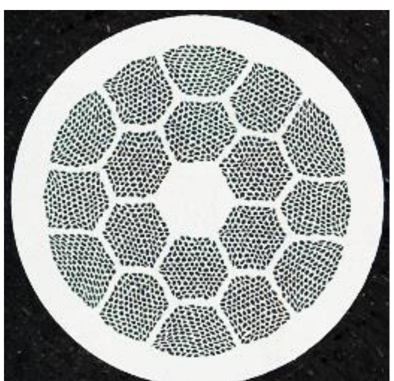


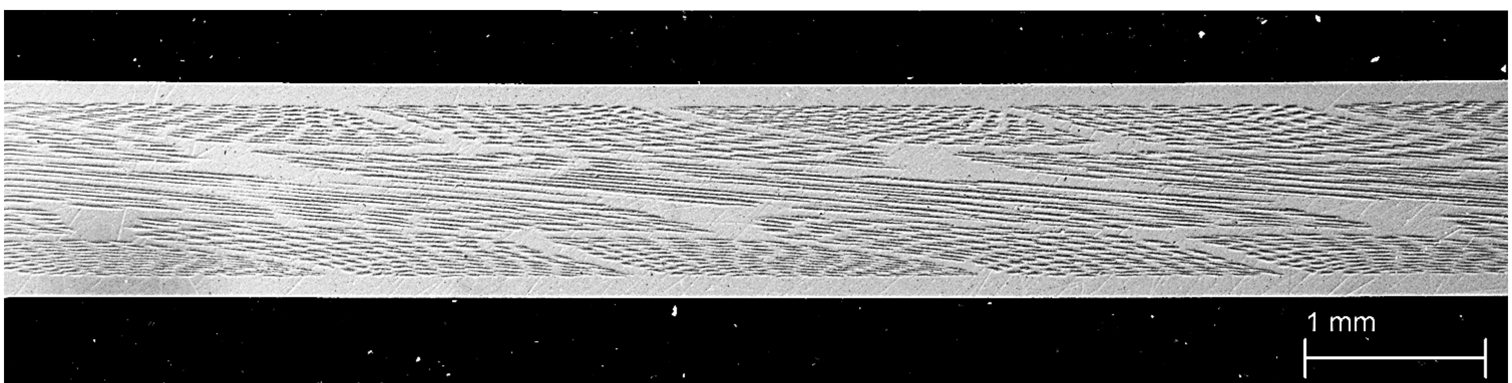
Why Bi-2212 now?

- **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

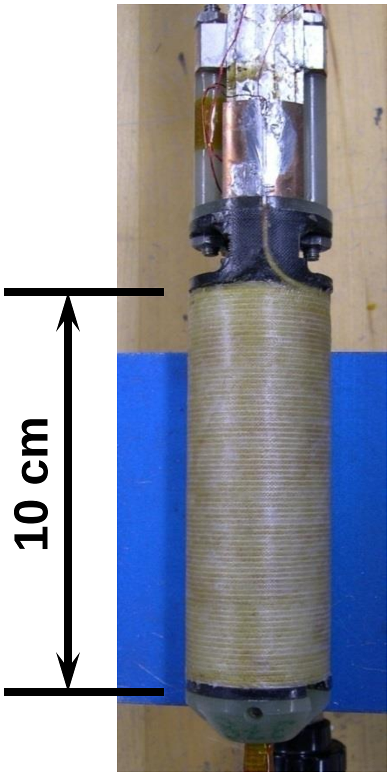






Round wire is preferred conductor geometry to build magnets

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



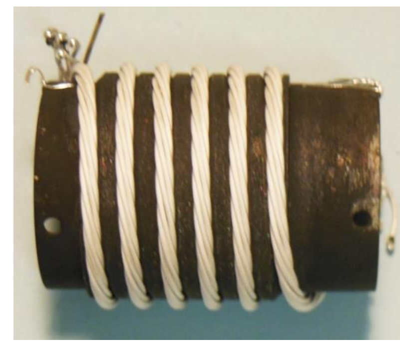
Myers, Trociewitz

Cables for very-high-current applications

Rutherford

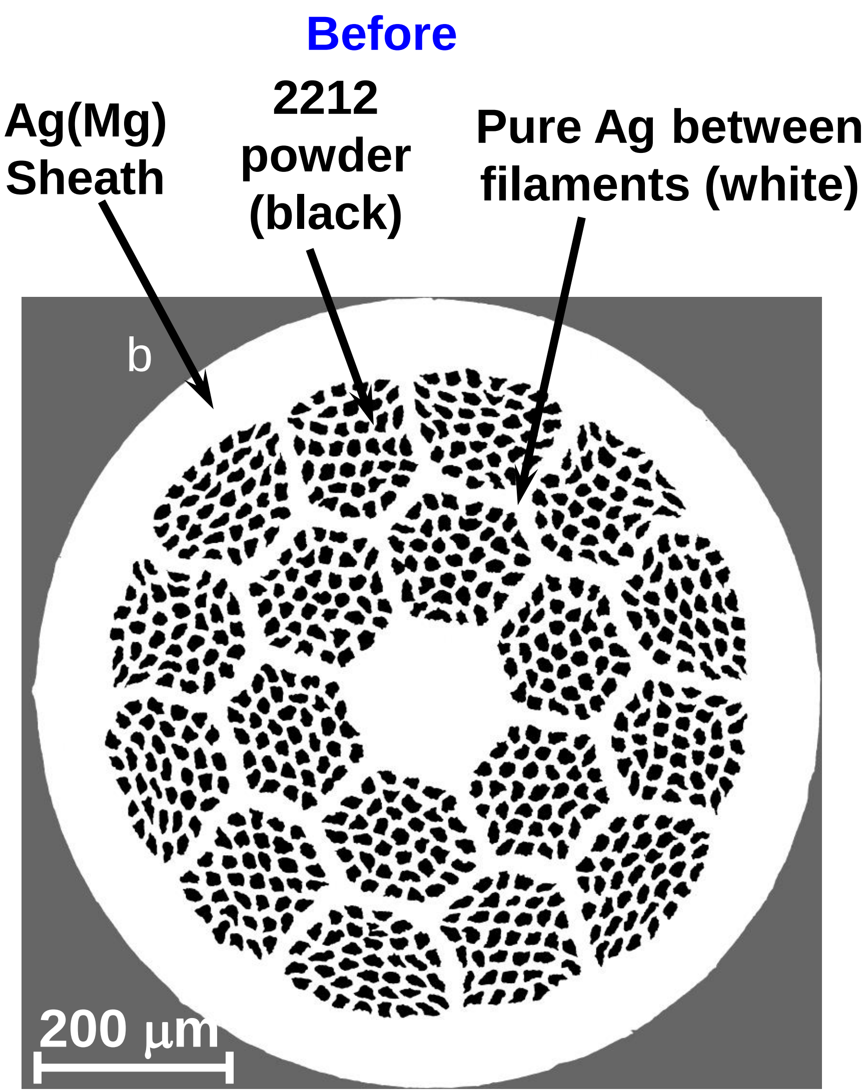
Godeke

6-on-1



Shen

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



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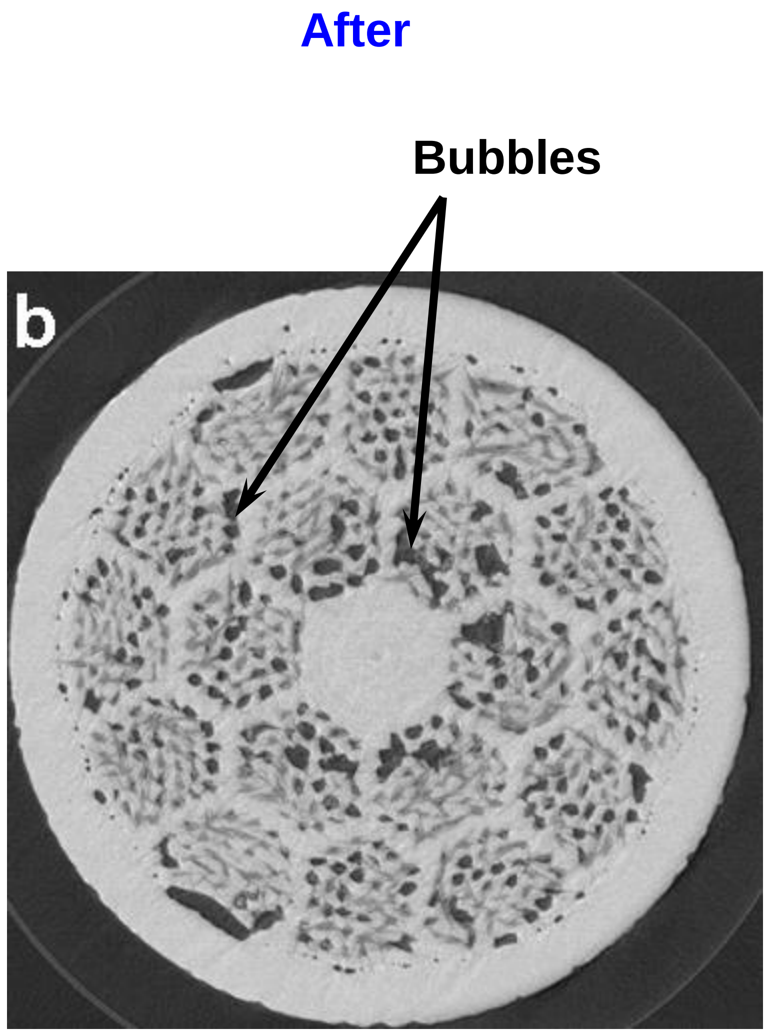
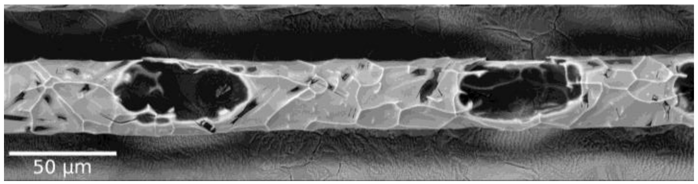


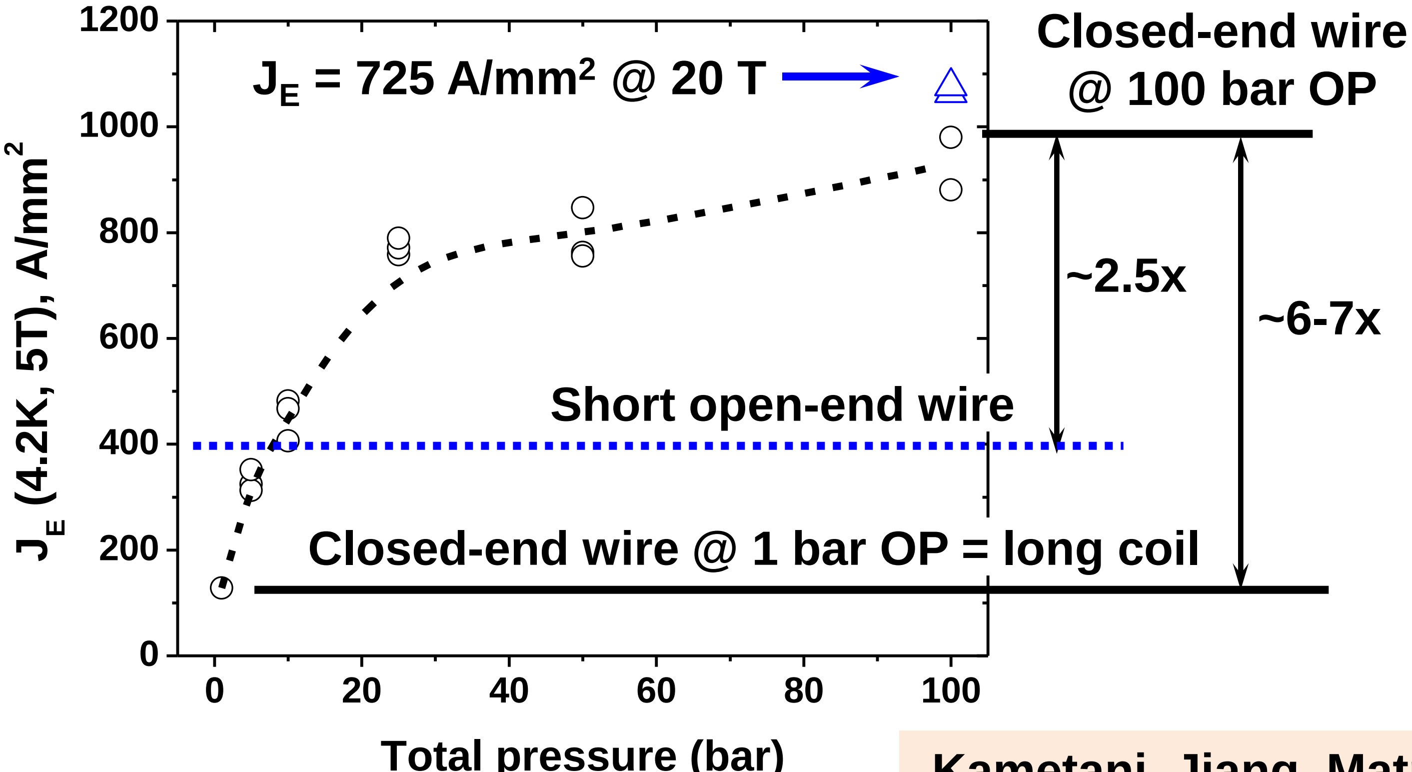
X-ray tomography
Scheuerlein, Di Michiel, Scheel

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

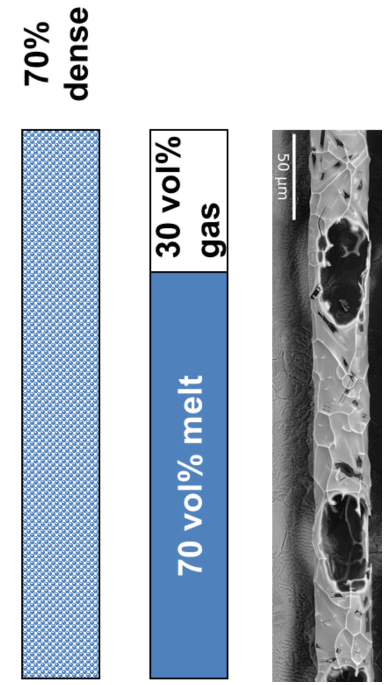
Overpressure processing is a form of Hot Isostatic Pressing (HIP)

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

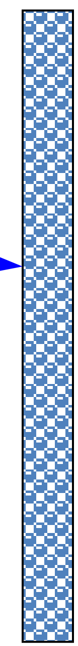


- Compresses wire so volume of Bi-2212 matches filament cavity
  - Removes bubbles
- Prevents gas from expanding
  - CO_2, H_2O
  - Eliminates dedensification and creep-induced leakage

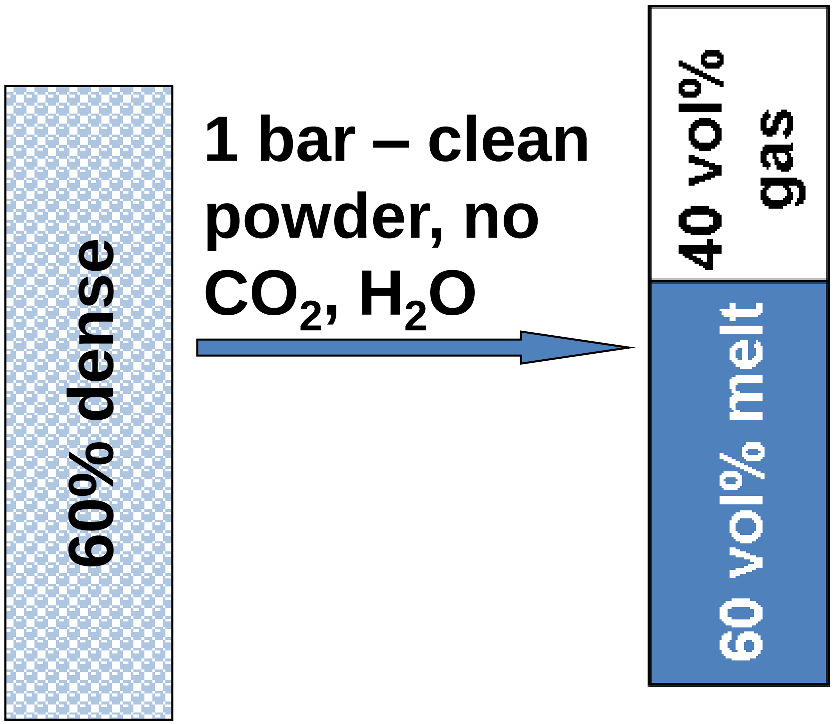
What can happen to 2212 filaments during melt processing?

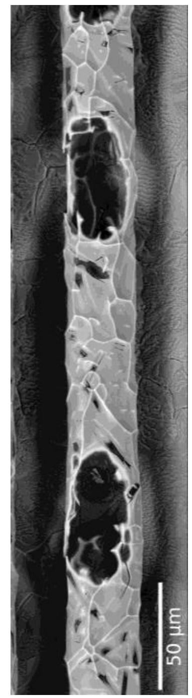
- **Maximum packing density of 2212 powder in filaments is 60-70%**
- **Focus on the 30-40 vol% of the filament that is gas-filled void space**

60% dense 2212 powder in as-drawn wire

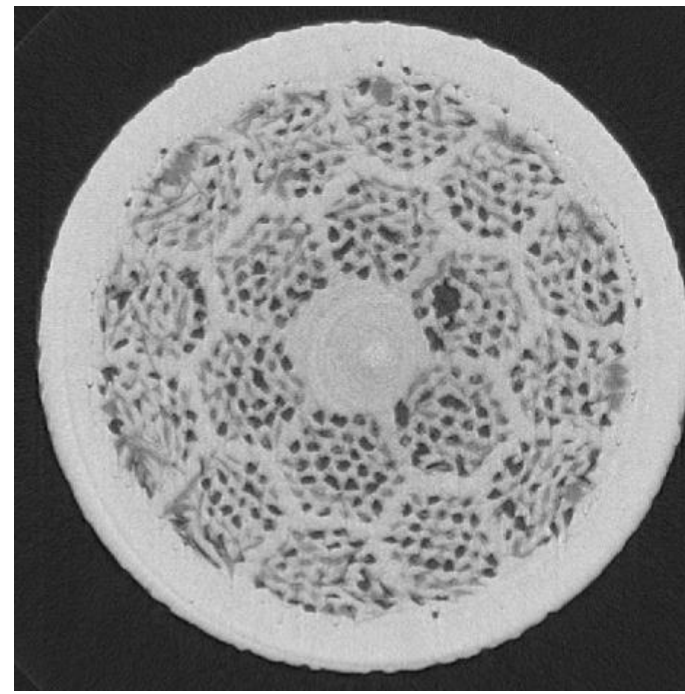


Best case with 1 bar processing: 30-40 vol% gas bubbles in filament





Kametani



Scheuerlein

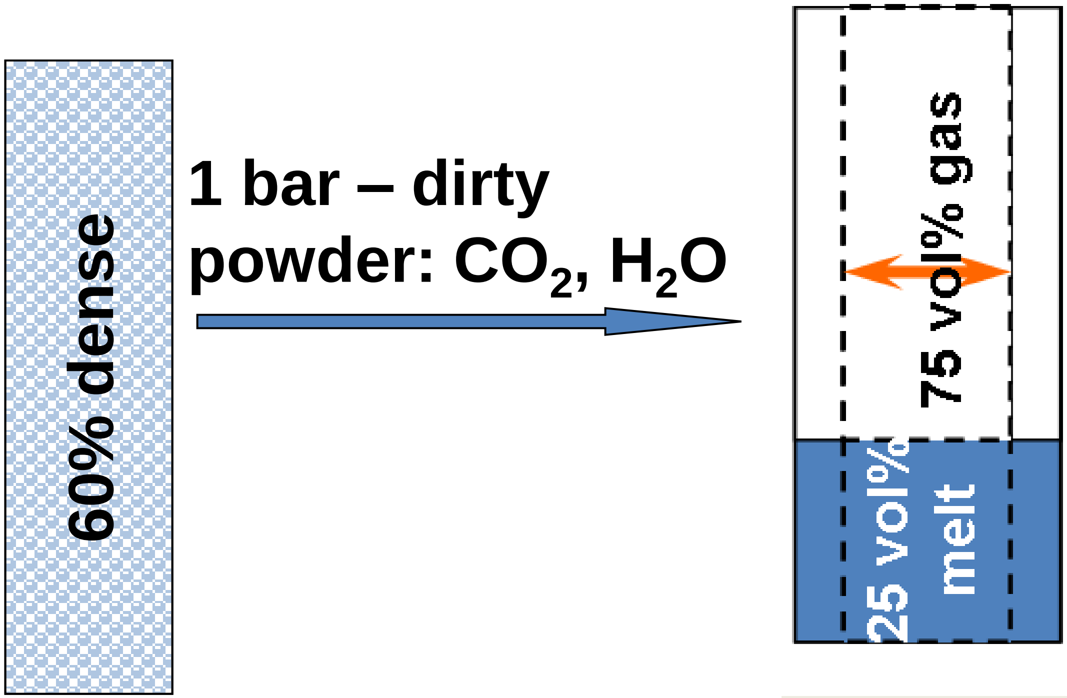
Real-time, *in situ* x-ray microtomography shows how bubbles form and grow during heat treatment

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

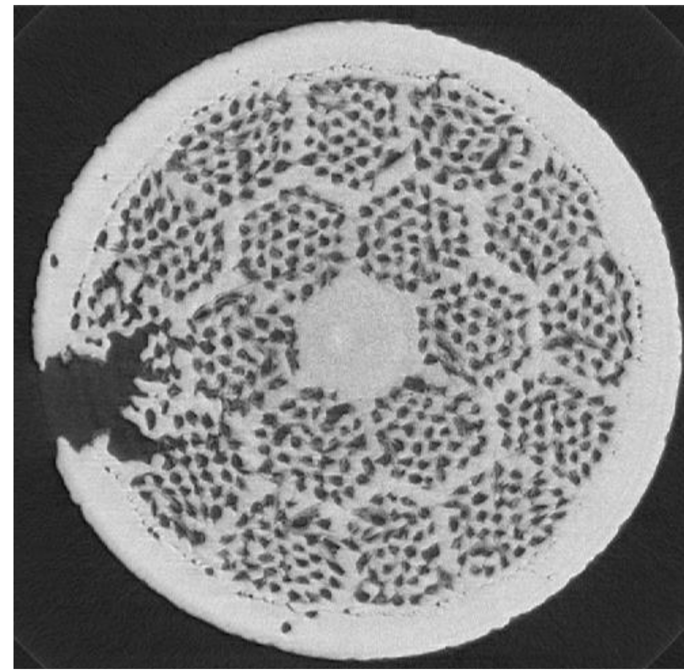
Scheuerlein

Worst case with 1 bar processing: dedensification and leakage

Internal gas pressure expands filament hole



- Malagoli
- Shen

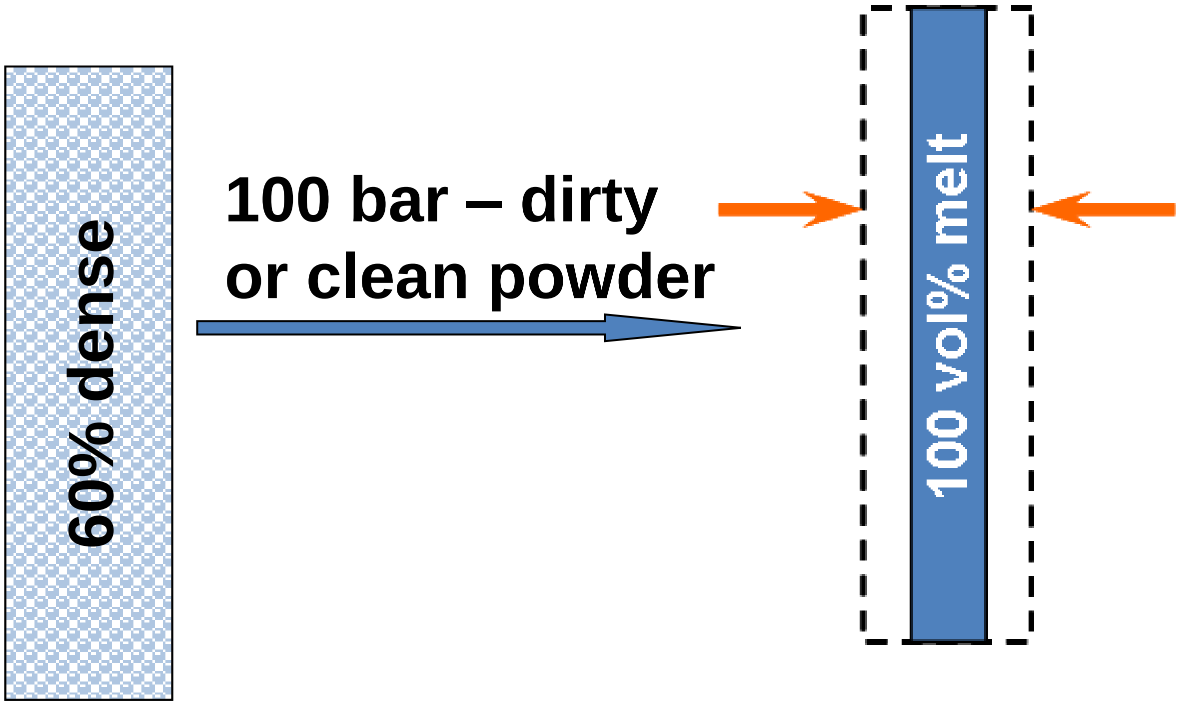


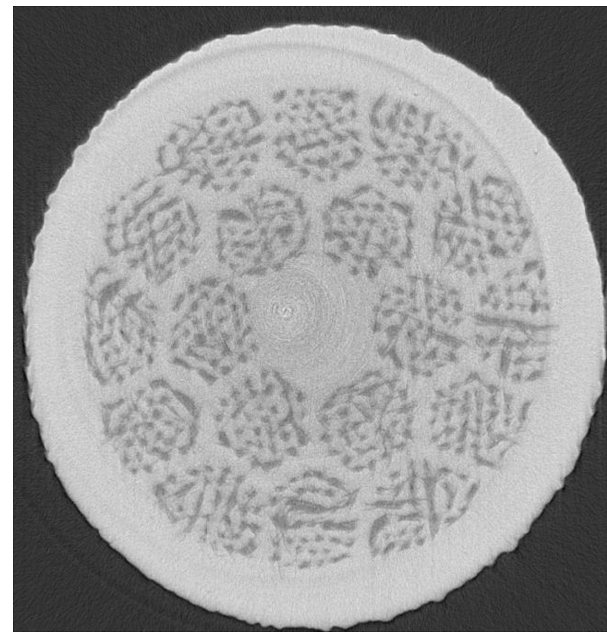
Scheuerlein

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

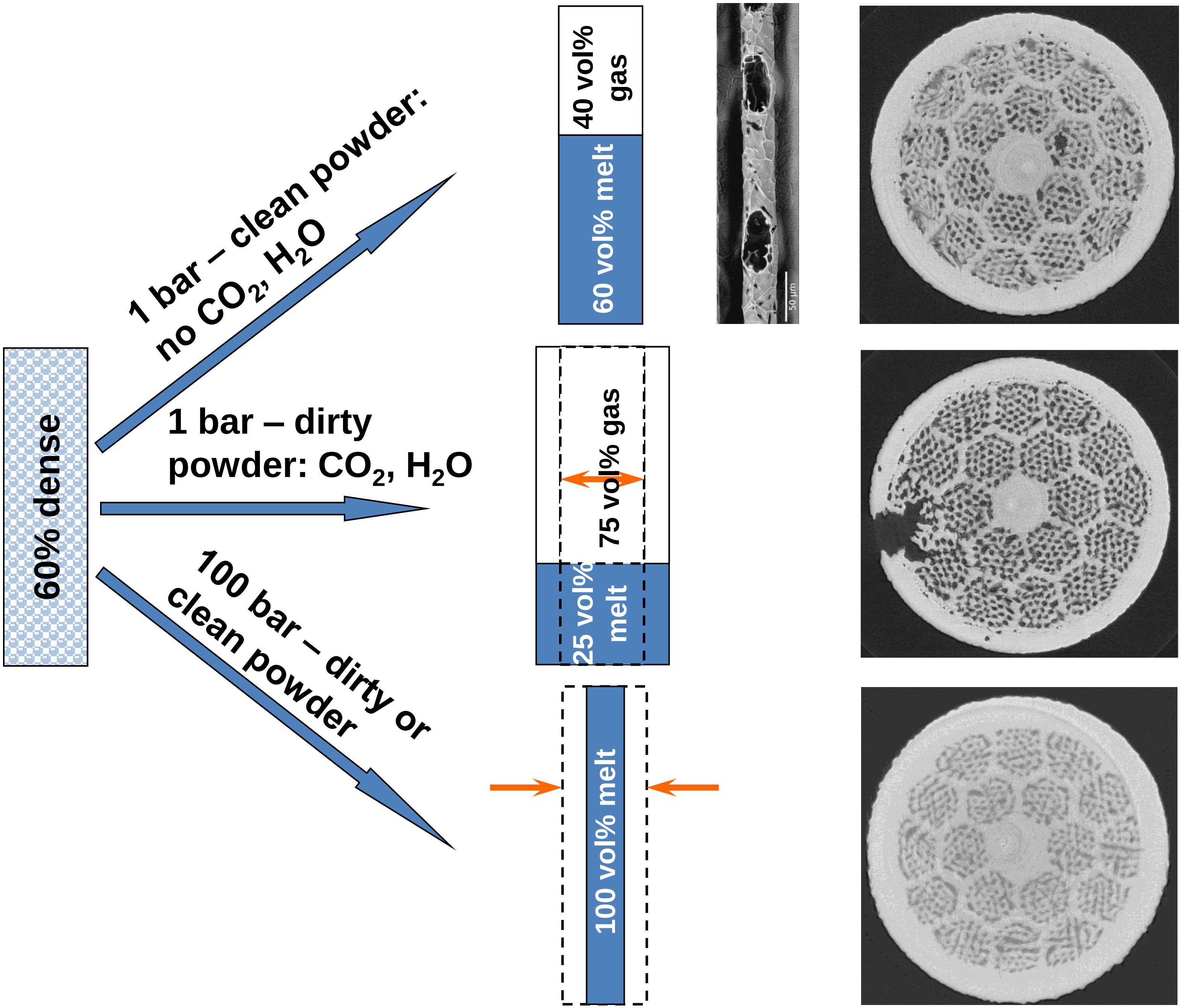
External overpressure decreases filament hole

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
50 µm

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

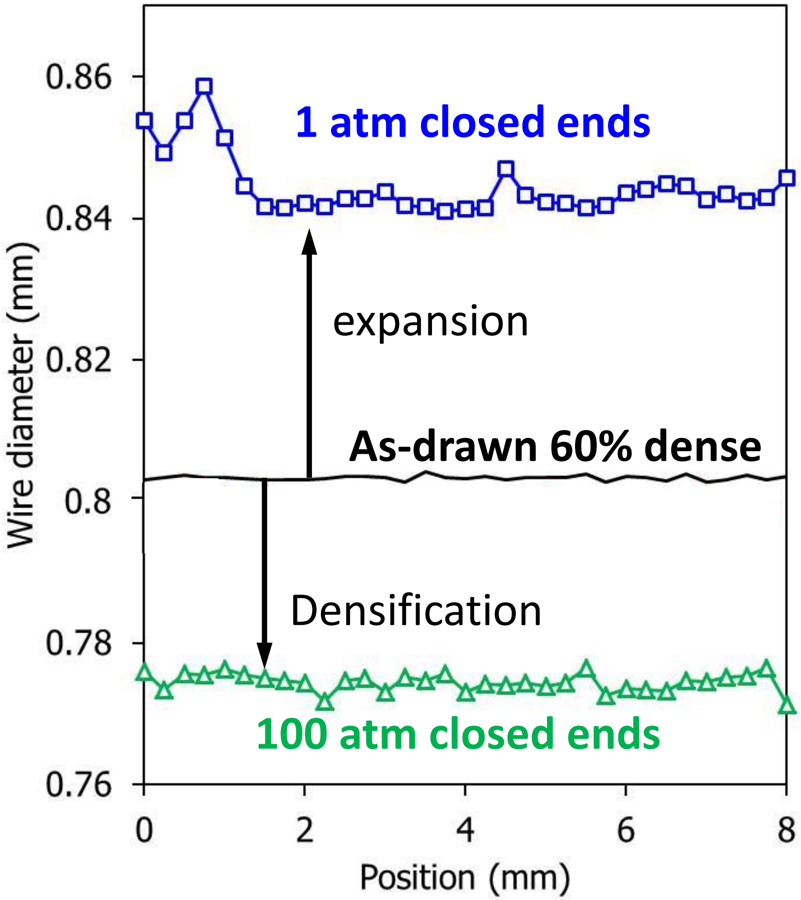
- Small OP system originally designed, built, and used for Bi-2223

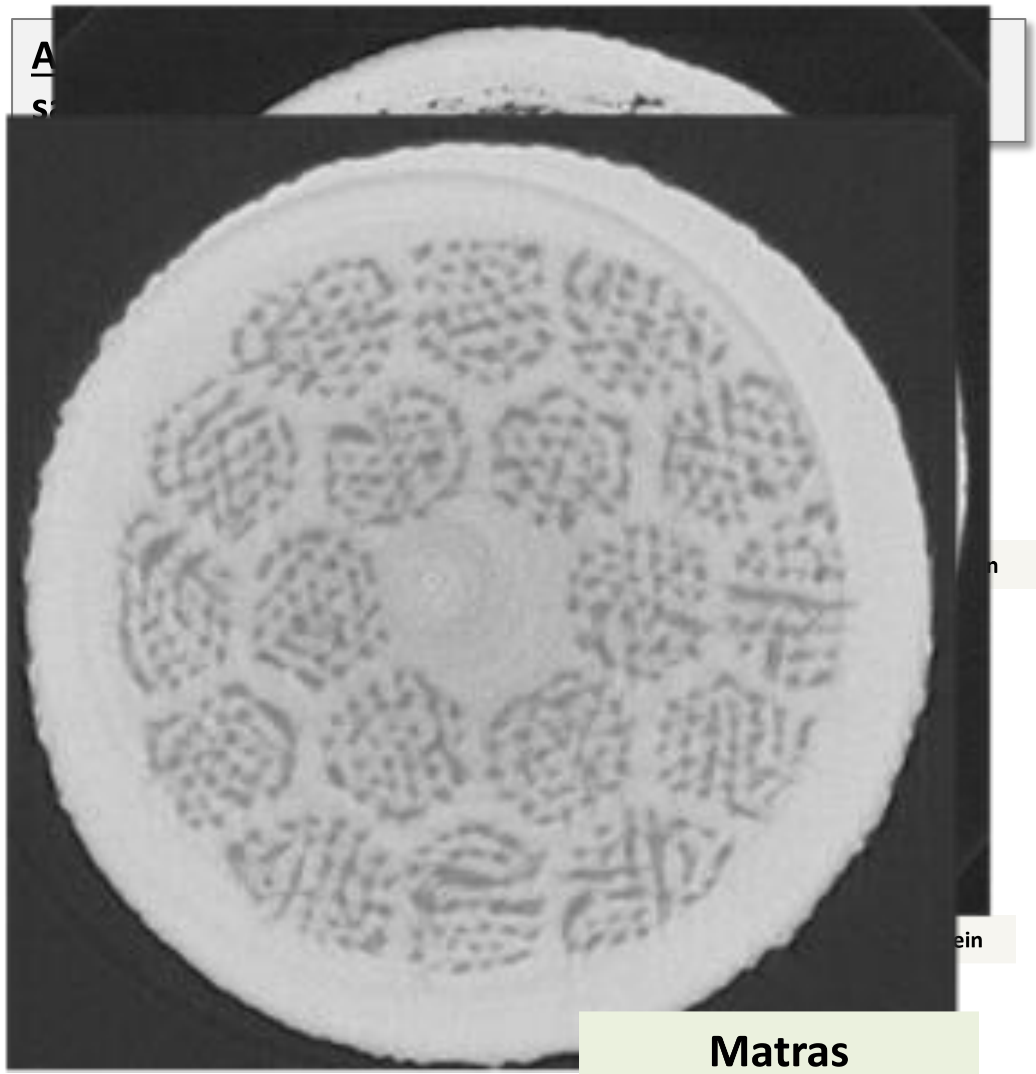
ASC's 2.5-cm bore research OP system

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

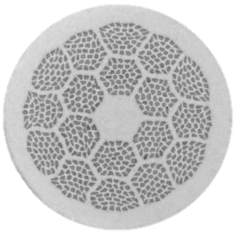




Matras

Dense filaments are the key for high J_E

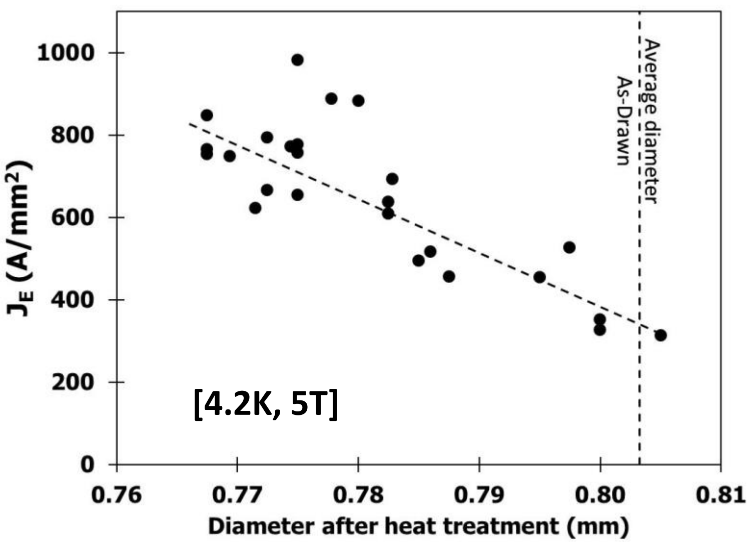
Cross section as-drawn 37x18 (0.8mm diameter)

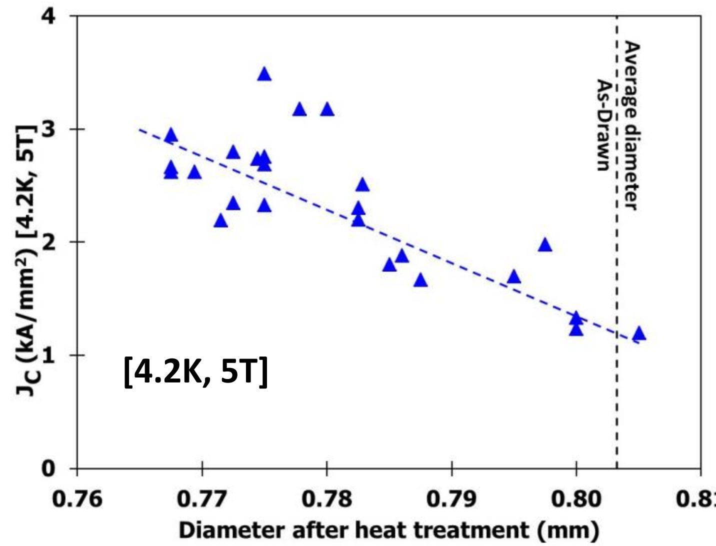


- J_C is calculated using the as-drawn wire filament cross sectional area (60% dense filaments)
- J_C increases (actually it triples) with decreasing wire diameter as full physical connectivity occurs.

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

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





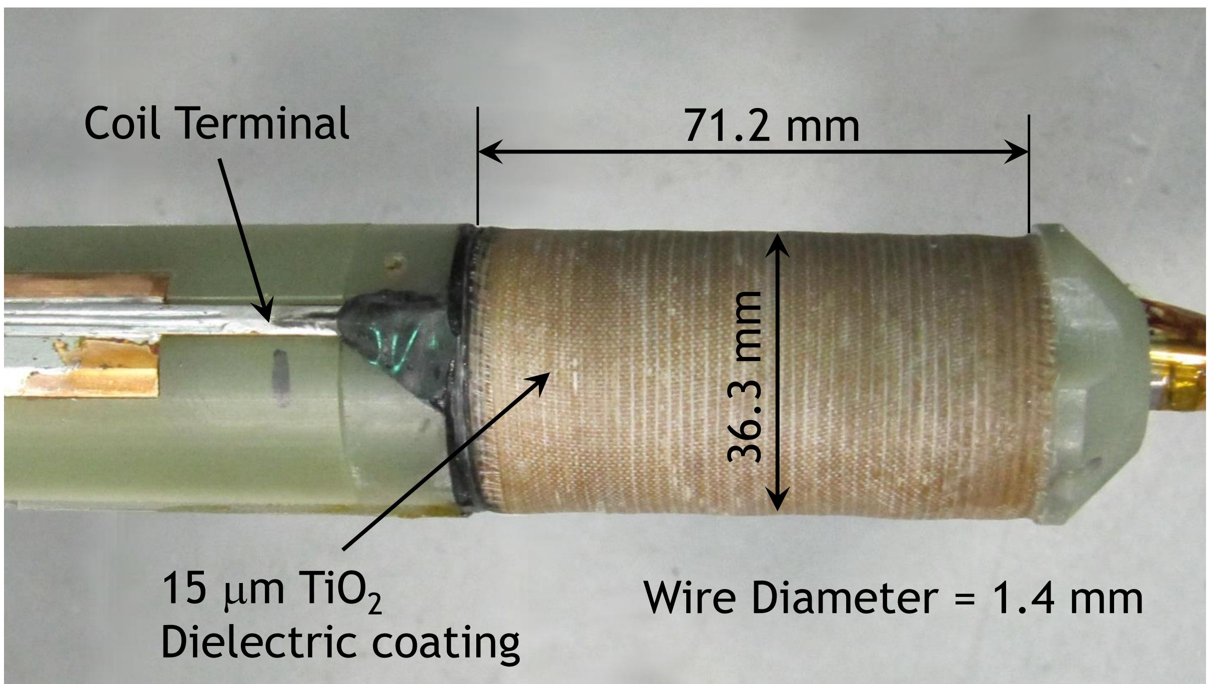
Experiment done on short wires (8 cm long)

Matras

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

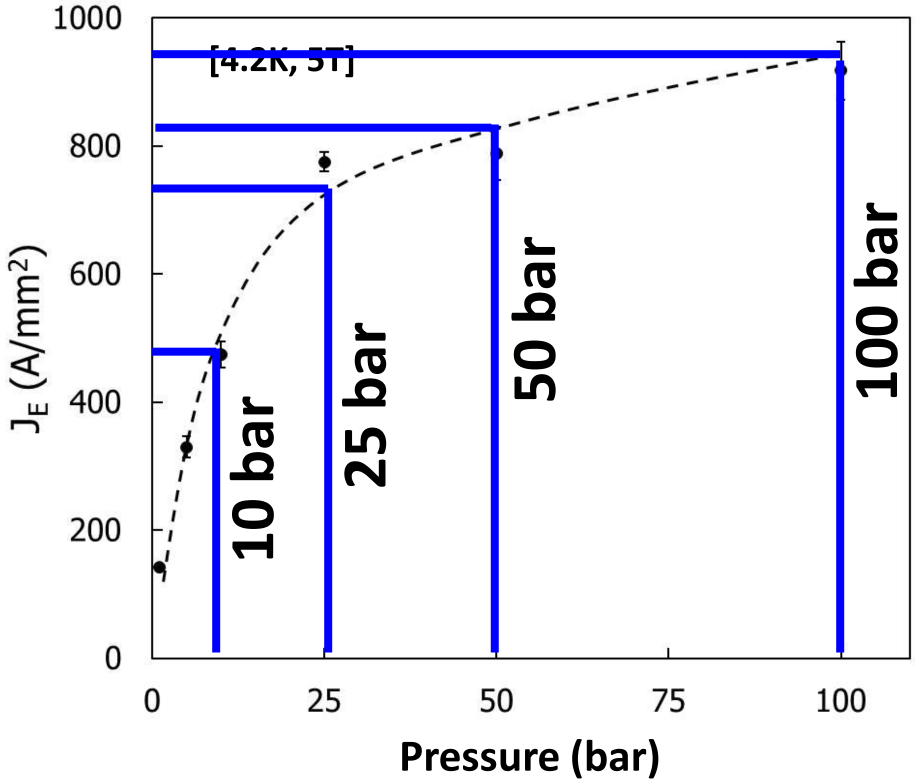
Deltech built a large OP furnace for Bi-2212 coils - custom built, first of its kind

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)



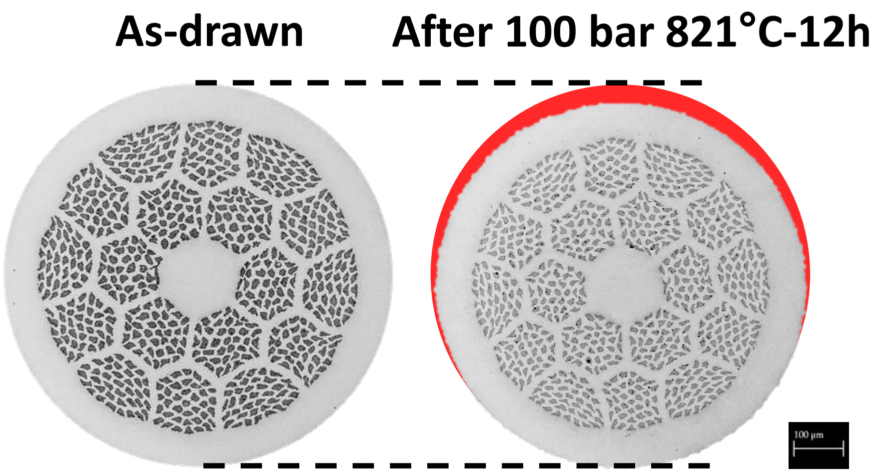
- **35 m long 10 bar coil fell on the curve**

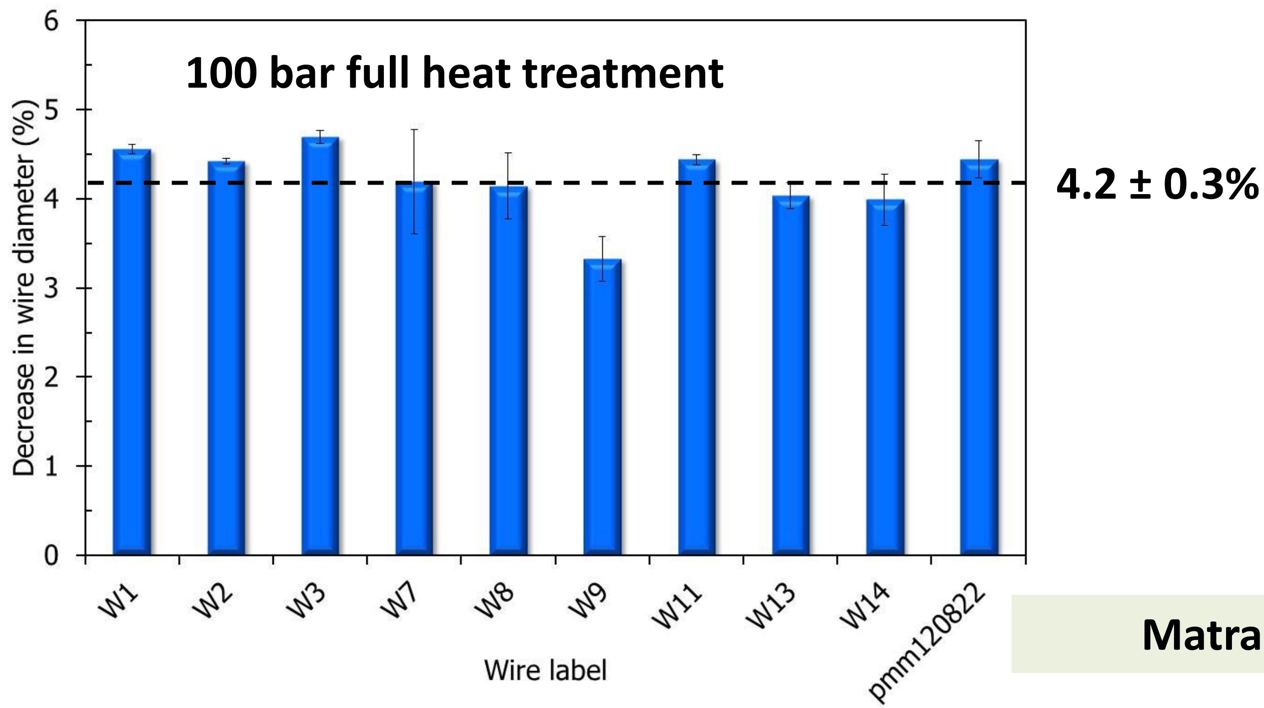
Matras

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.

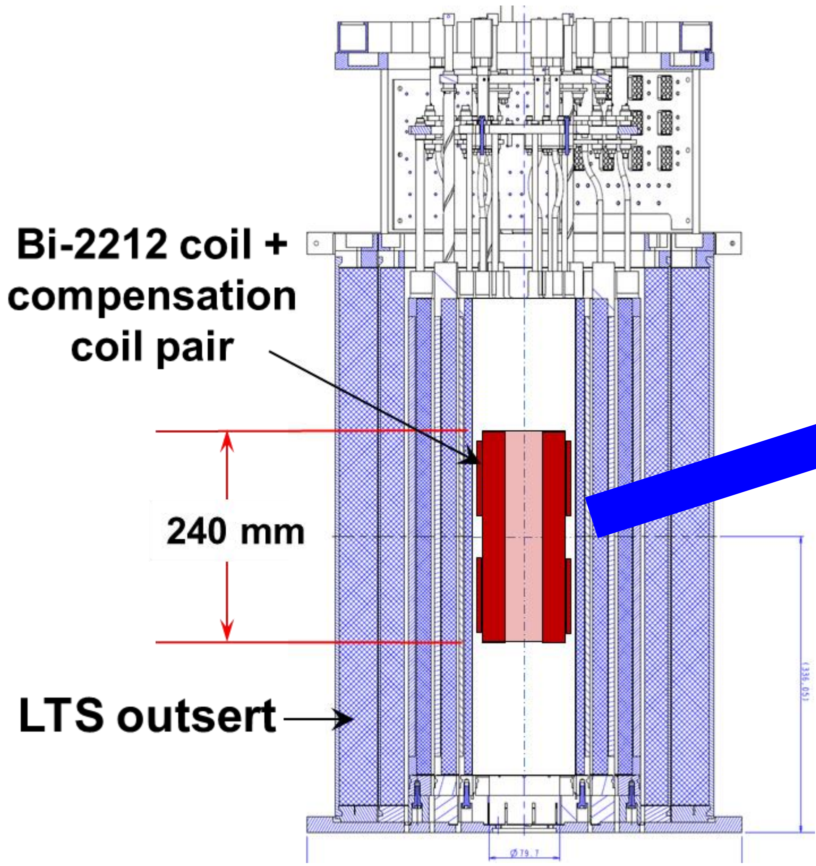




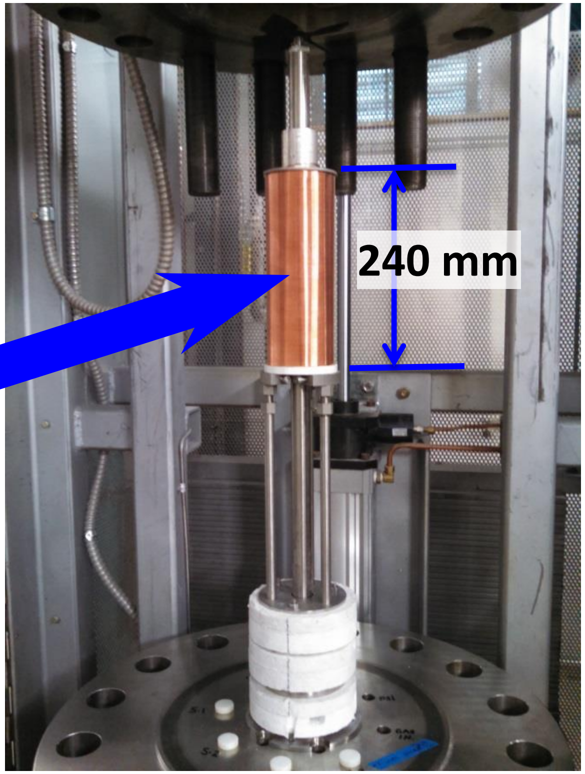
Matras

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

“Platypus”: A Bi-2212 NMR Demo-Magnet

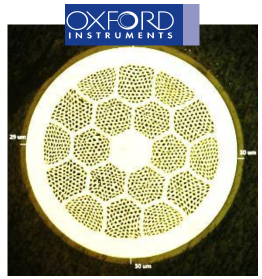
Goals:

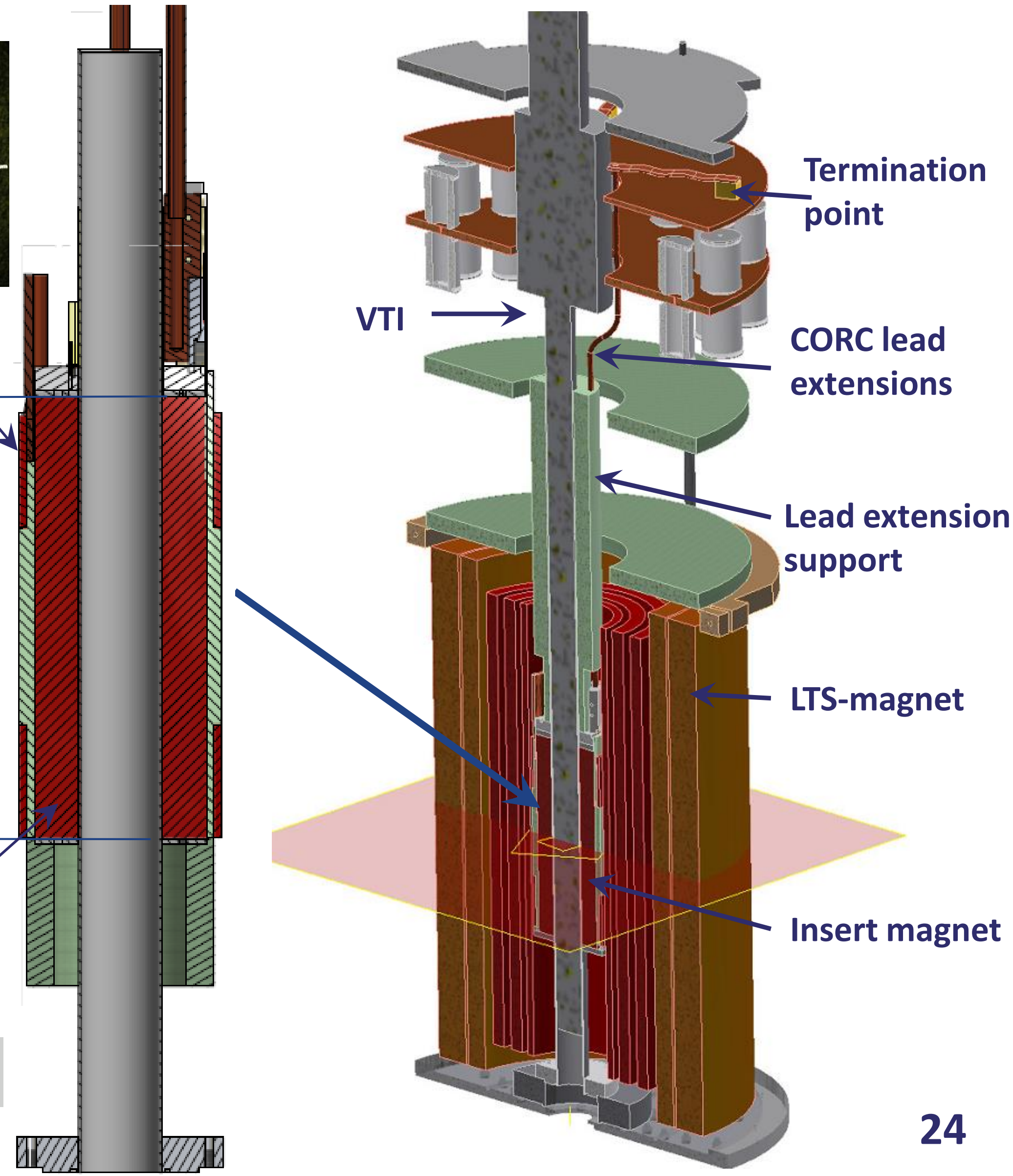
- **MagSci Goal: 30 T NMR magnet using HTS**
- **NMR demo magnet of ~ 1 GHz (24 T) with ppm field homogeneity and stability**
- **Hybrid LTS/HTS coil with all conductors twisted, round and multifilament (16 T Nb-Ti/Nb_3Sn + 8 T Bi-2212)**

Status:

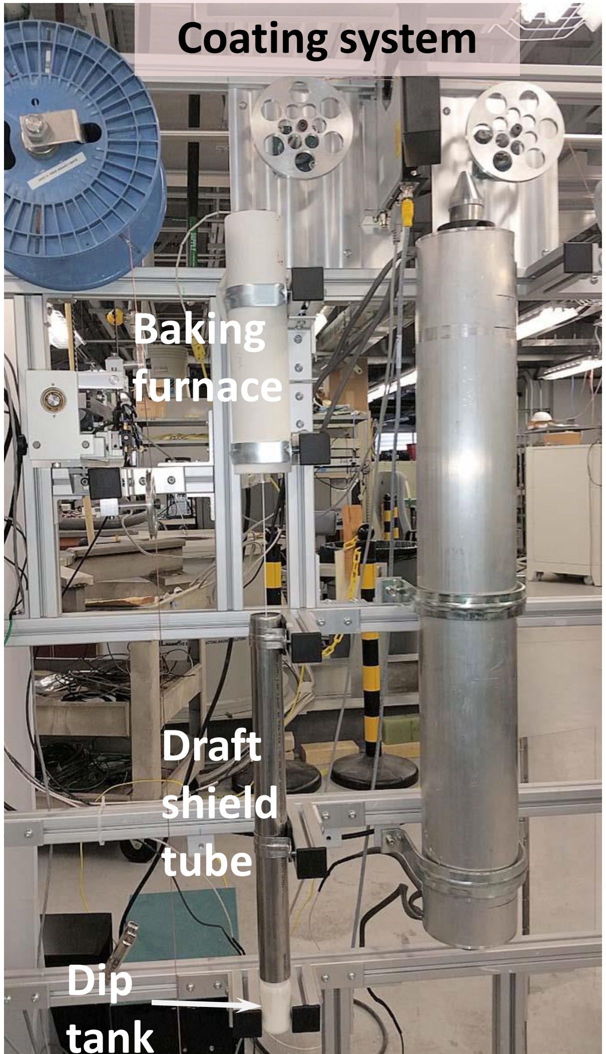
- **Novel 2212 HTS technology has been led by NHMFL**
- **All sub-systems demonstrated**
- **Platypus test planned for summer 2015**
- **Strong DOE-HEP and CERN support for conductor development with industrial partner OST**

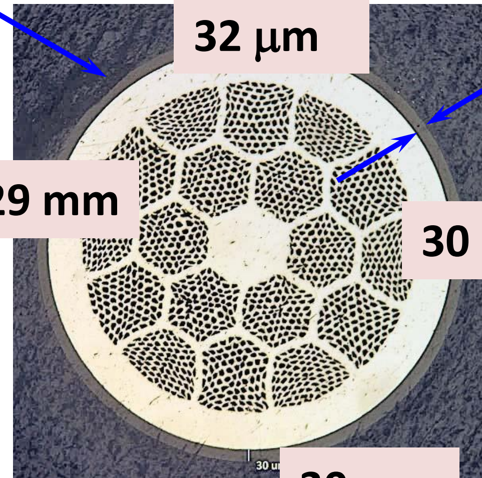
Bismuth Strand and Cable Collaboration BSCCo





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





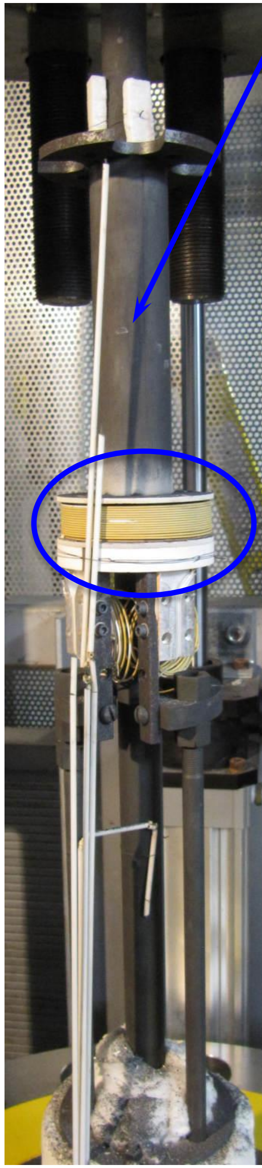
- TiO_2 particles suspended in organic binder
- ~ 30 μm thick adherent coating
- Burn out before OP heat treatment

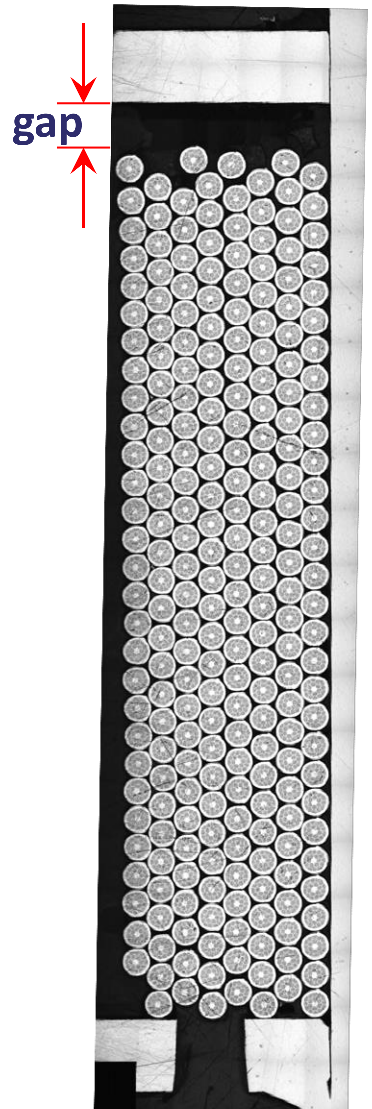
Platypus test coils 2015 (“Platypups”)

“Platylong”

“Platypup”

Coil support





- 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

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