Round-wire Bi-2212: a high-field magnet material

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Bismuth Strand and Cable Collaboration BSCCo

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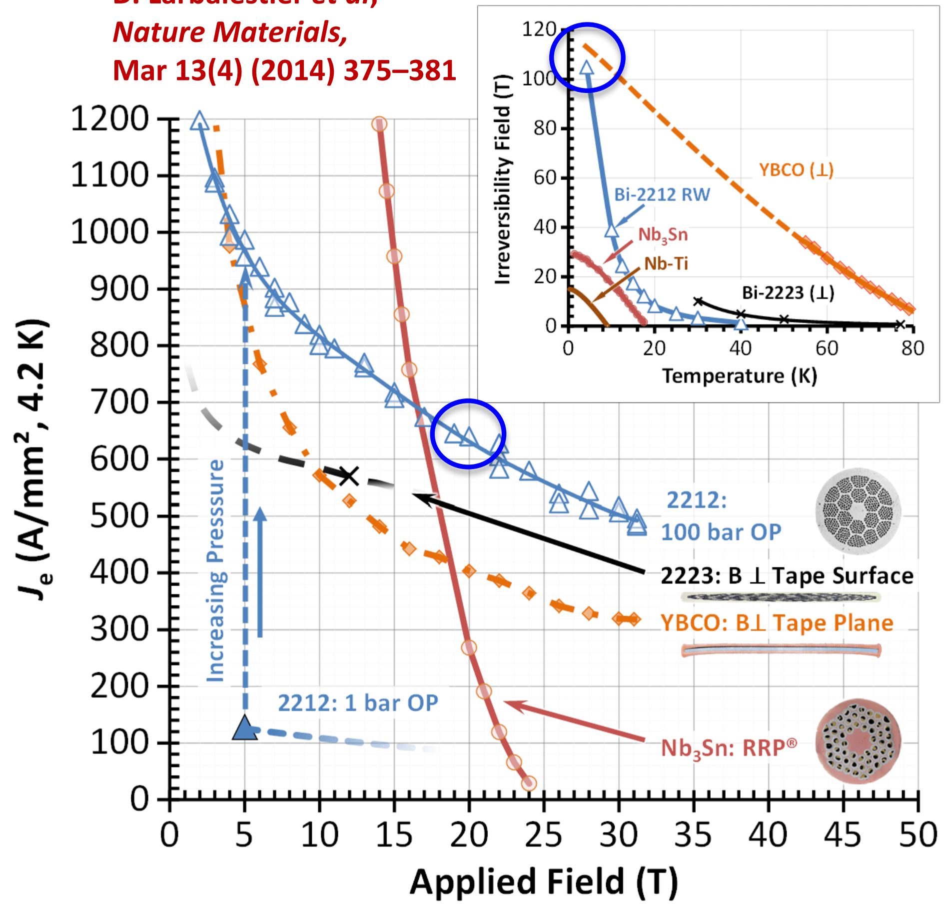
Overview

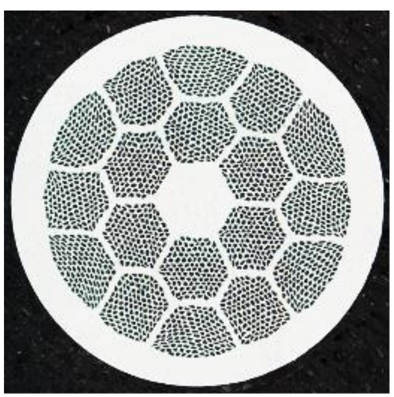
- **What is special about Bi-2212 ($Bi_2Sr_2Ca_1Cu_2O_8$) round wires (RW)?**
- **Normal heat treatment produces bubbles that limit current**
- **Use overpressure (OP) processing to remove bubbles → makes Bi-2212 a viable magnet material**
- **Coils in progress**

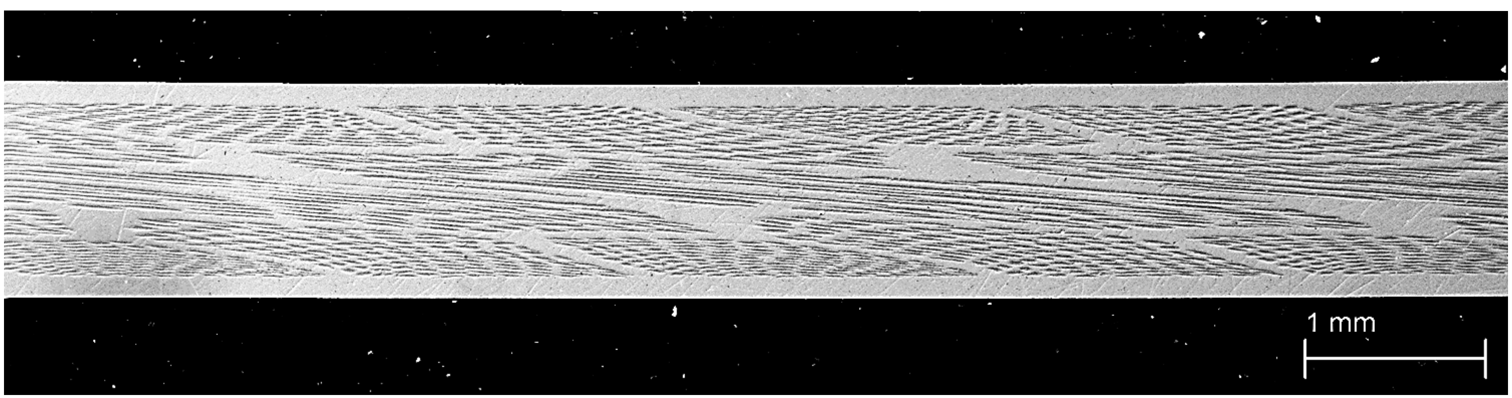
Why Bi-2212?

- **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

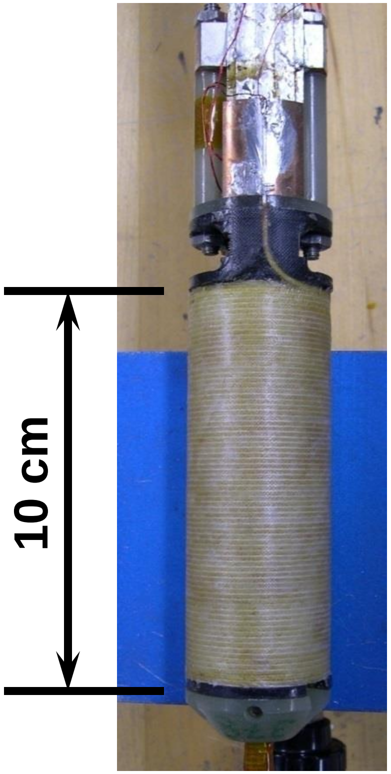






Round wire is preferred conductor geometry to build magnets

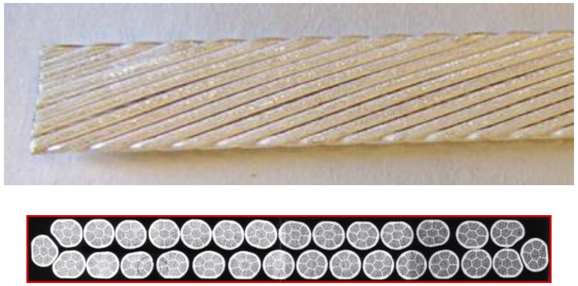
1.1T in 31T - first HTS wire-wound coil to go beyond 30 T



Myers, Trociewitz

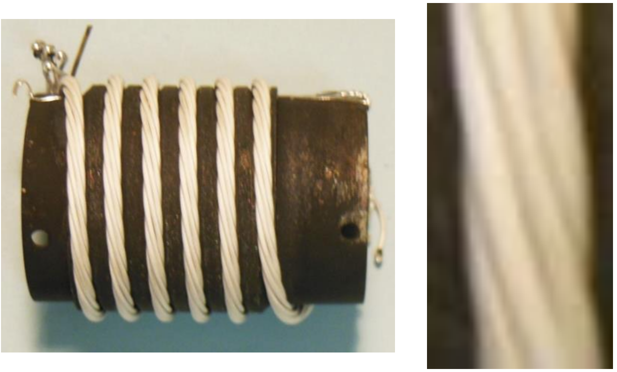
Cables for very high current applications

Rutherford



Godeke

6-on-1



Shen

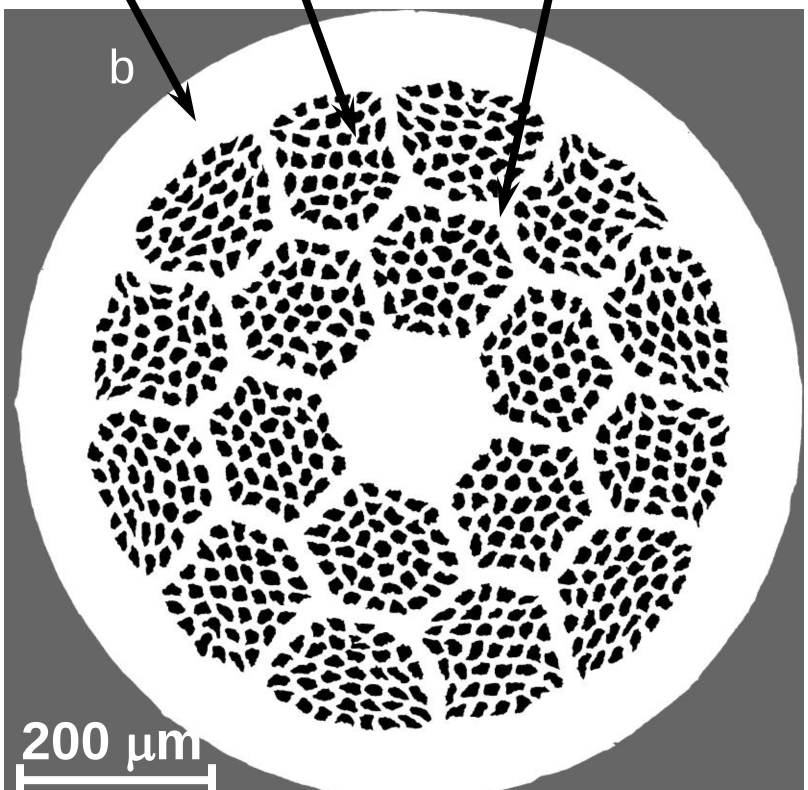
2212 powder in 2212 wire is ~60% dense - bubbles form in 2212 RW during heat treatment

Before

Ag(Mg) Sheath

2212 powder (black)

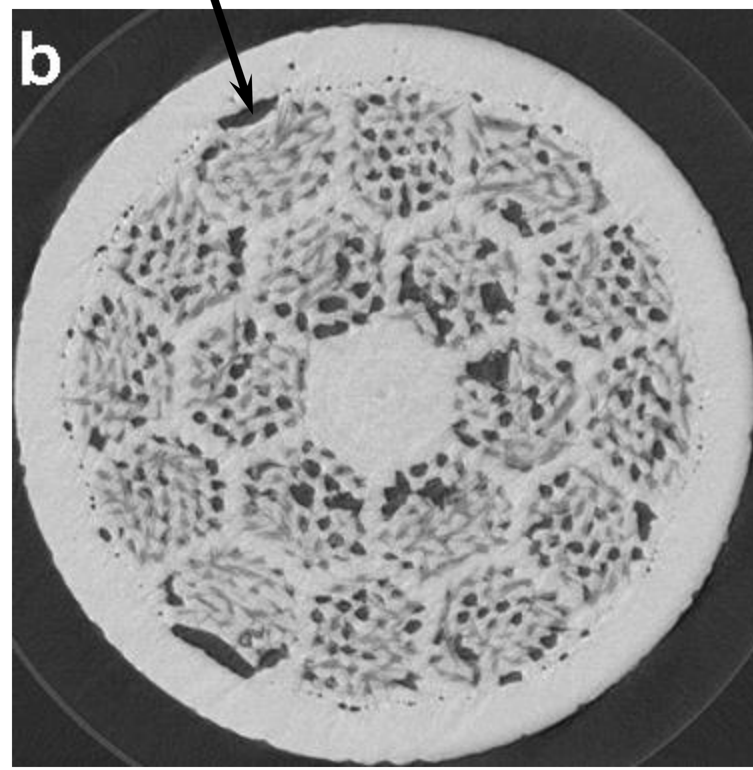
Pure Ag between filaments (white)



OST

After

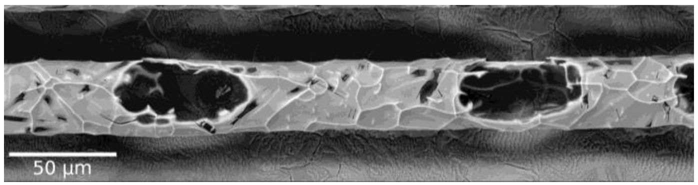
Bubbles



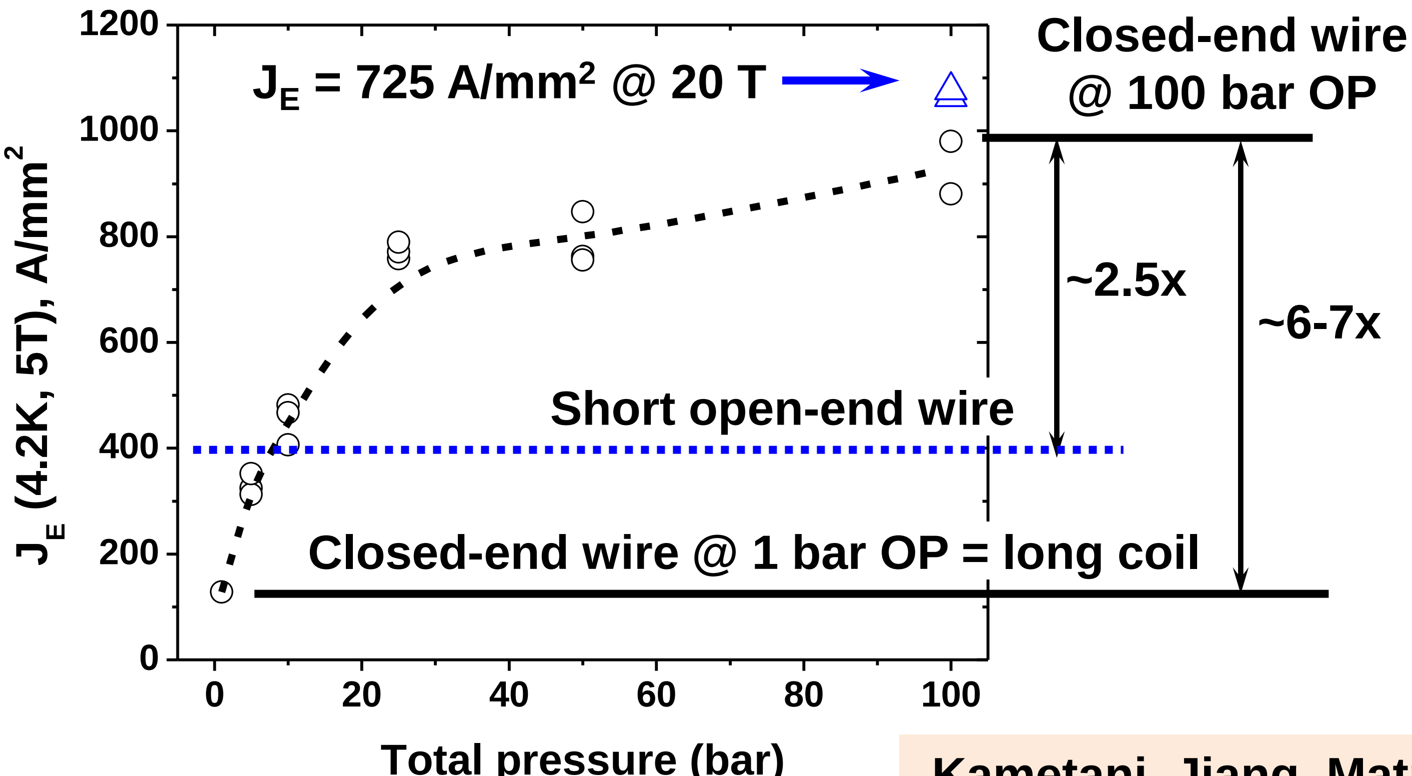
X-ray tomography
Scheuerlein, Di Michiel, Scheel

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

Gas-filled bubbles due to powder being only 60-70% dense



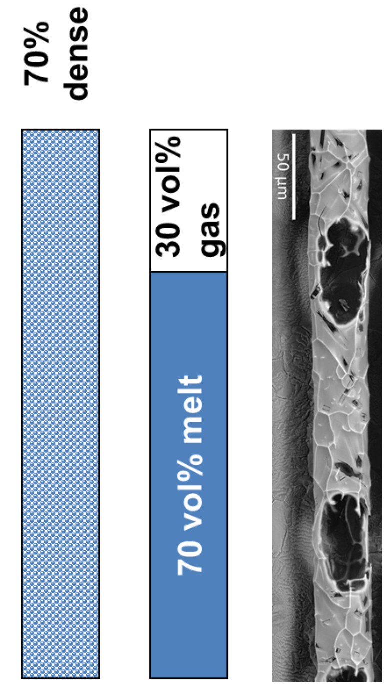
OP processing squeezes wire with gas pressure to remove bubbles



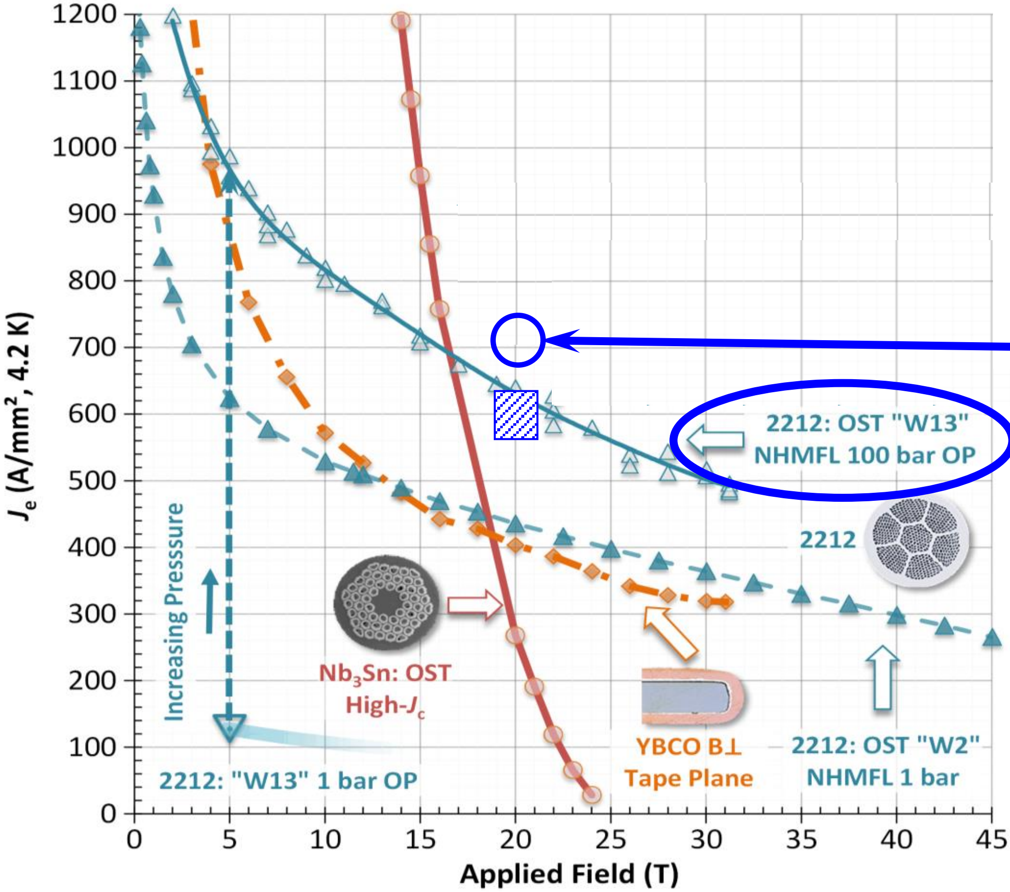
Kametani, Jiang, Matras, Craig

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



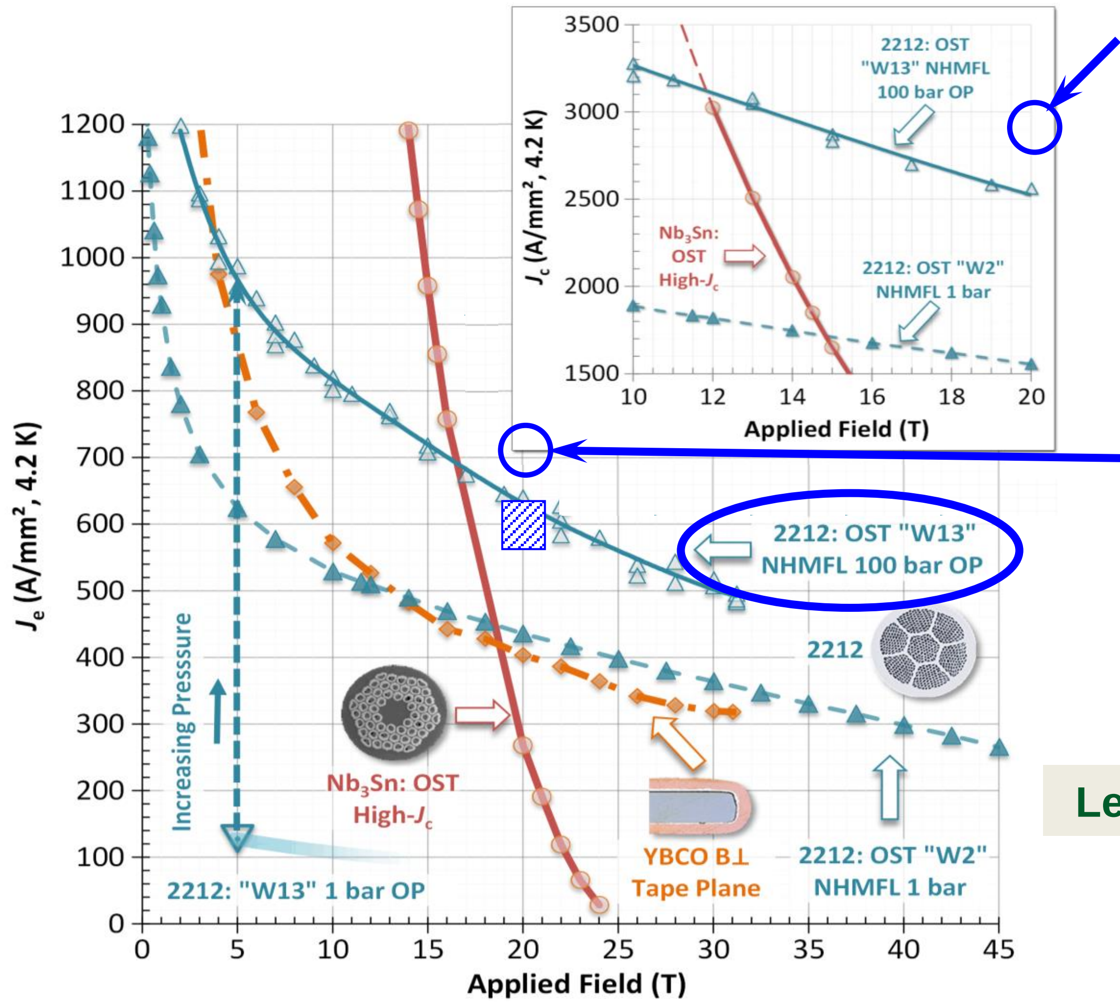
High J_c and J_E in OP wire (4.2 K, 20 T)
J_E = 640 A/mm² J_c = 2500 A/mm²



J_E = 725 A/mm²

Lee and Dalban-Canassy

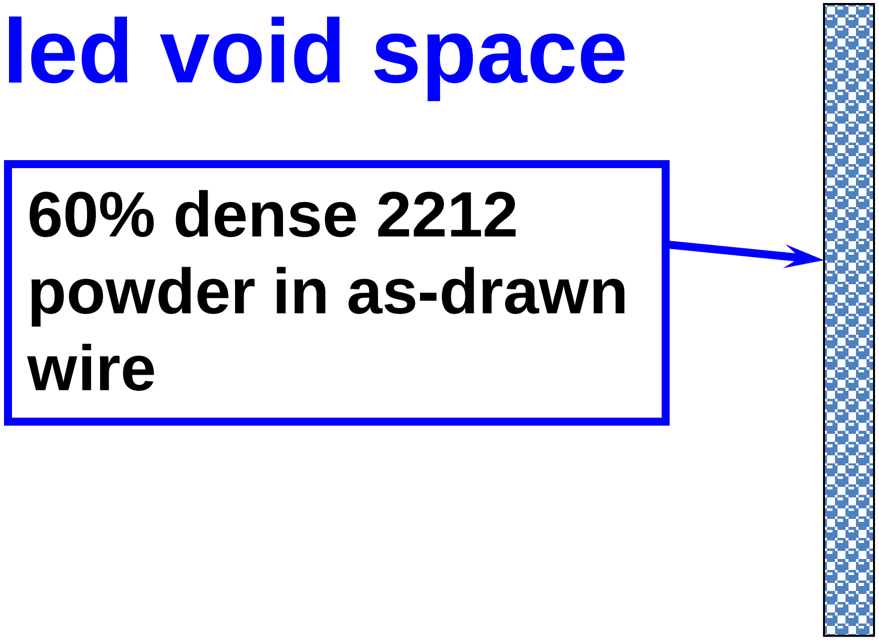
High J_c and J_E in OP wire (4.2 K, 20 T)
J_E = 640 A/mm² J_c = 2500 A/mm²



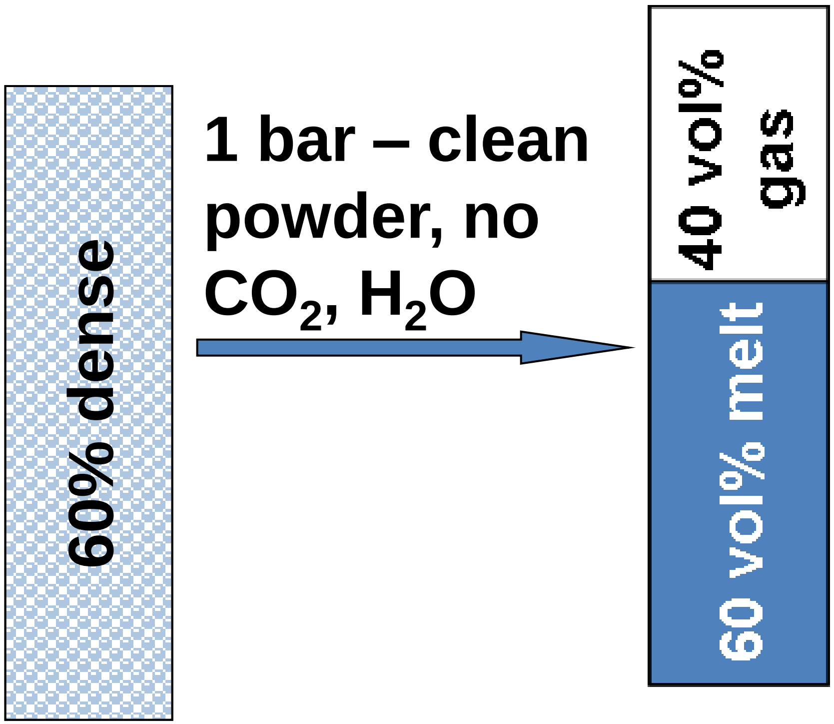
Lee and Dalban-Canassy

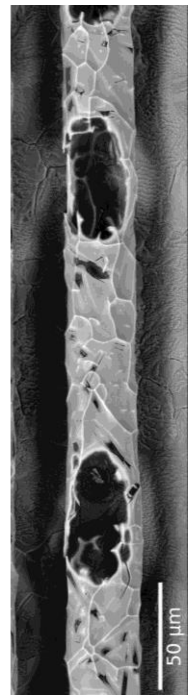
What can happen to 2212 filaments during melt processing?

- **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**

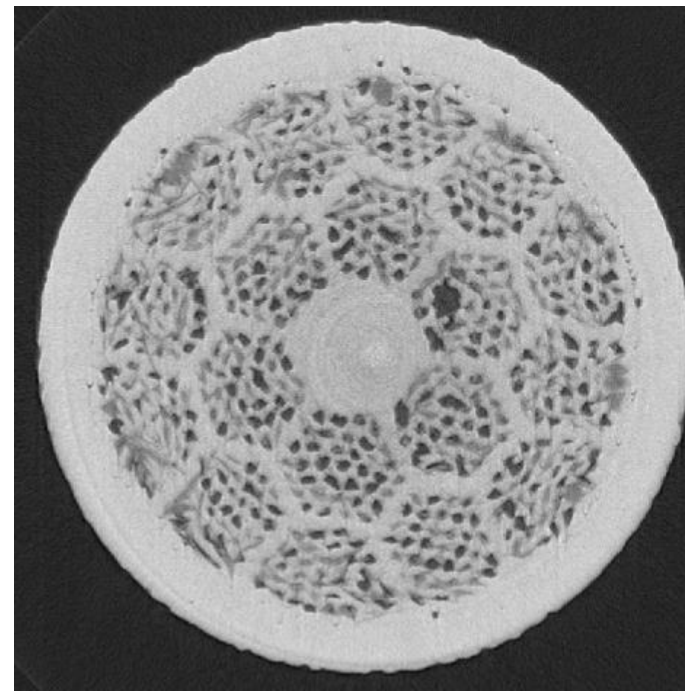


Best case with 1 bar processing: 30-40 vol% gas bubbles in filament





Kametani



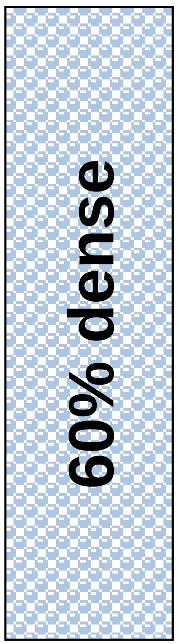
Scheuerlein

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**

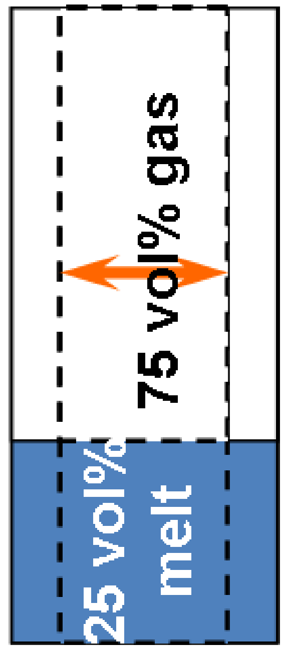
Scheuerlein

Worst case with 1 bar processing: dedensification and leakage

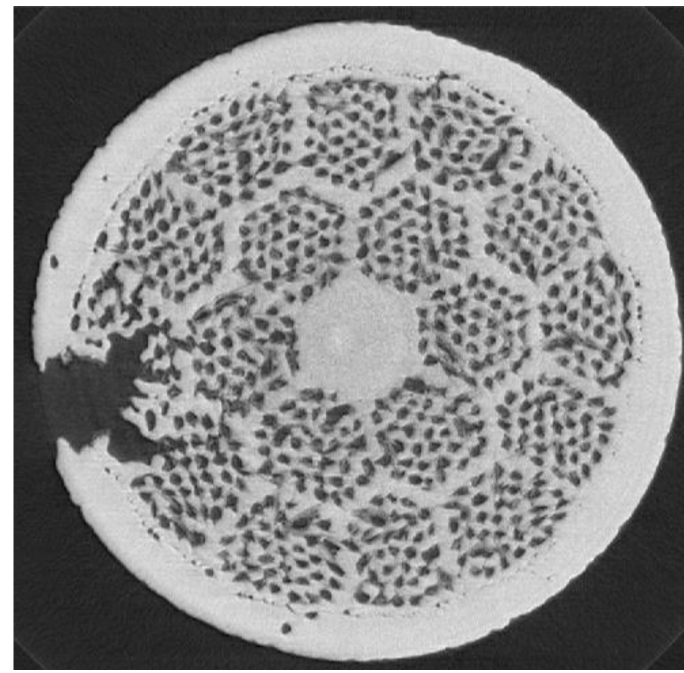


1 bar – dirty powder: CO_2, H_2O

Internal gas pressure expands filament hole



- Malagoli
- Shen

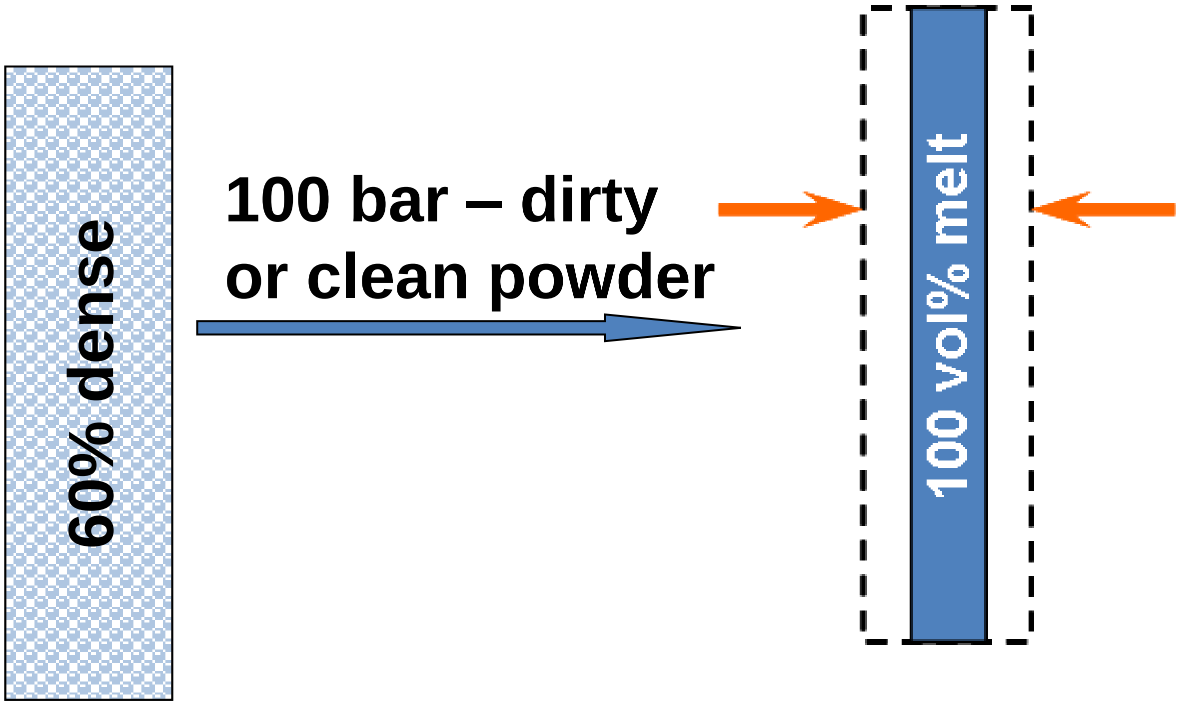


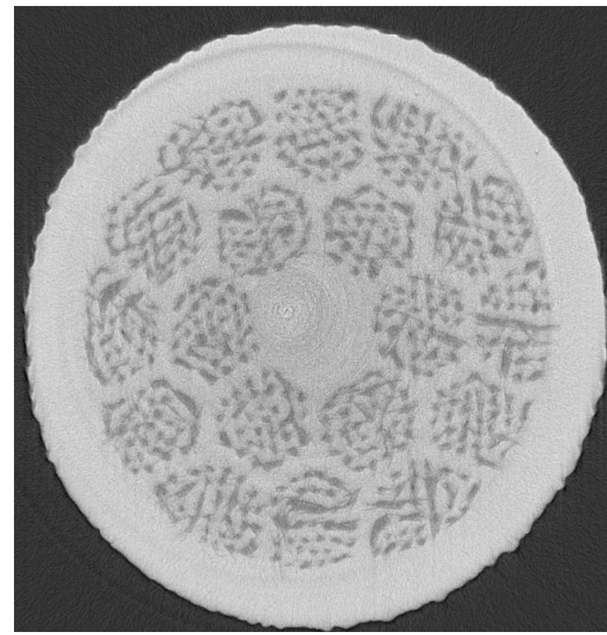
Scheuerlein

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

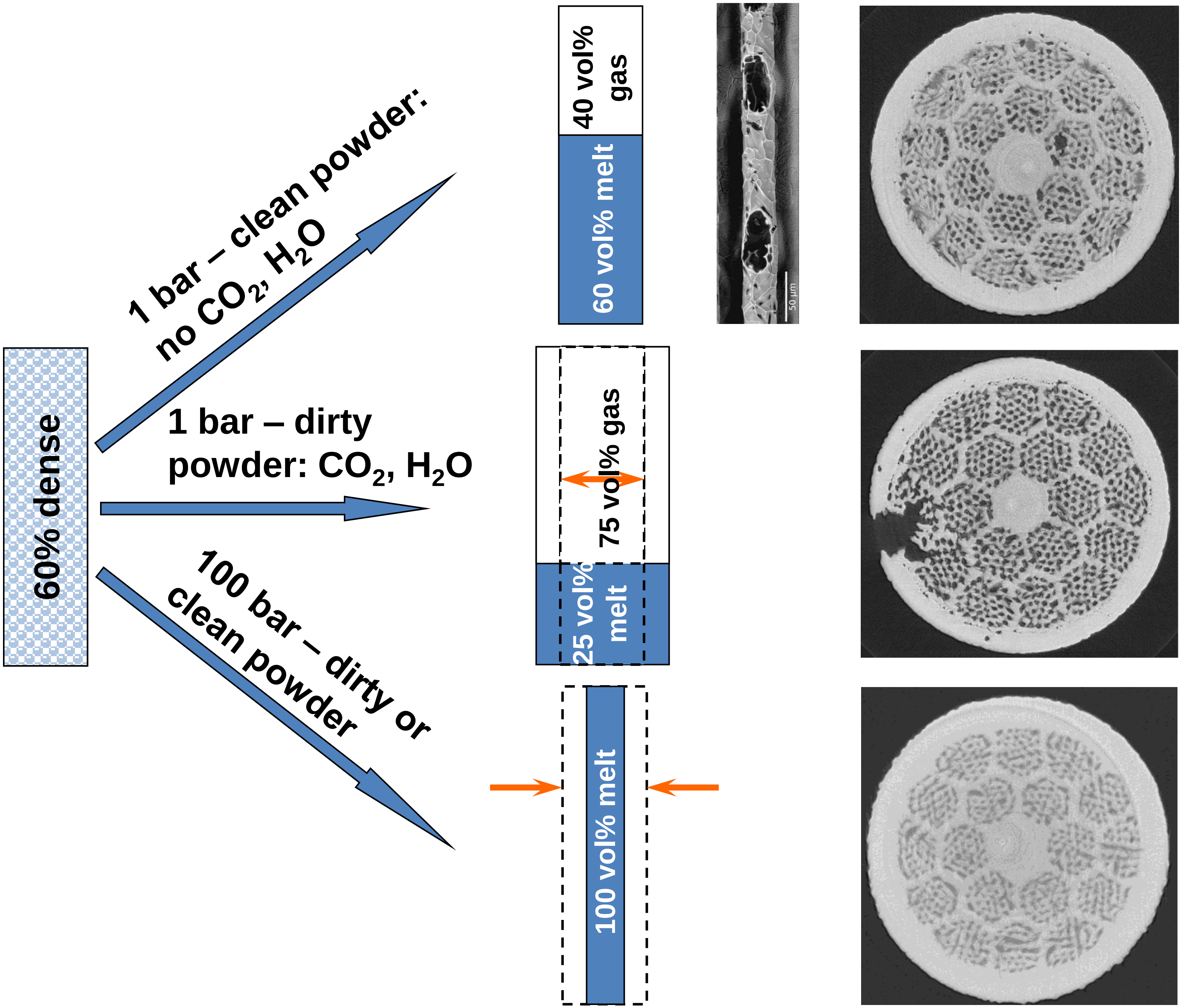
External overpressure decreases filament hole

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
50 µm
75 vol% gas
25 vol% melt
100 vol% melt

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

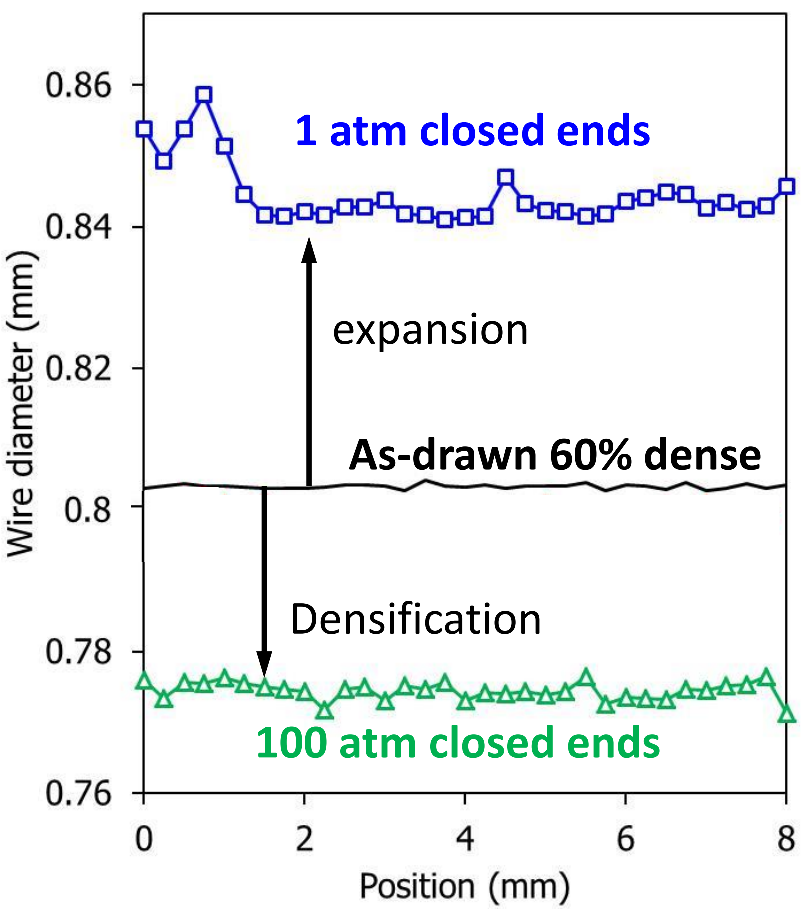
- **Small OP system originally designed, built, and used for Bi-2223**

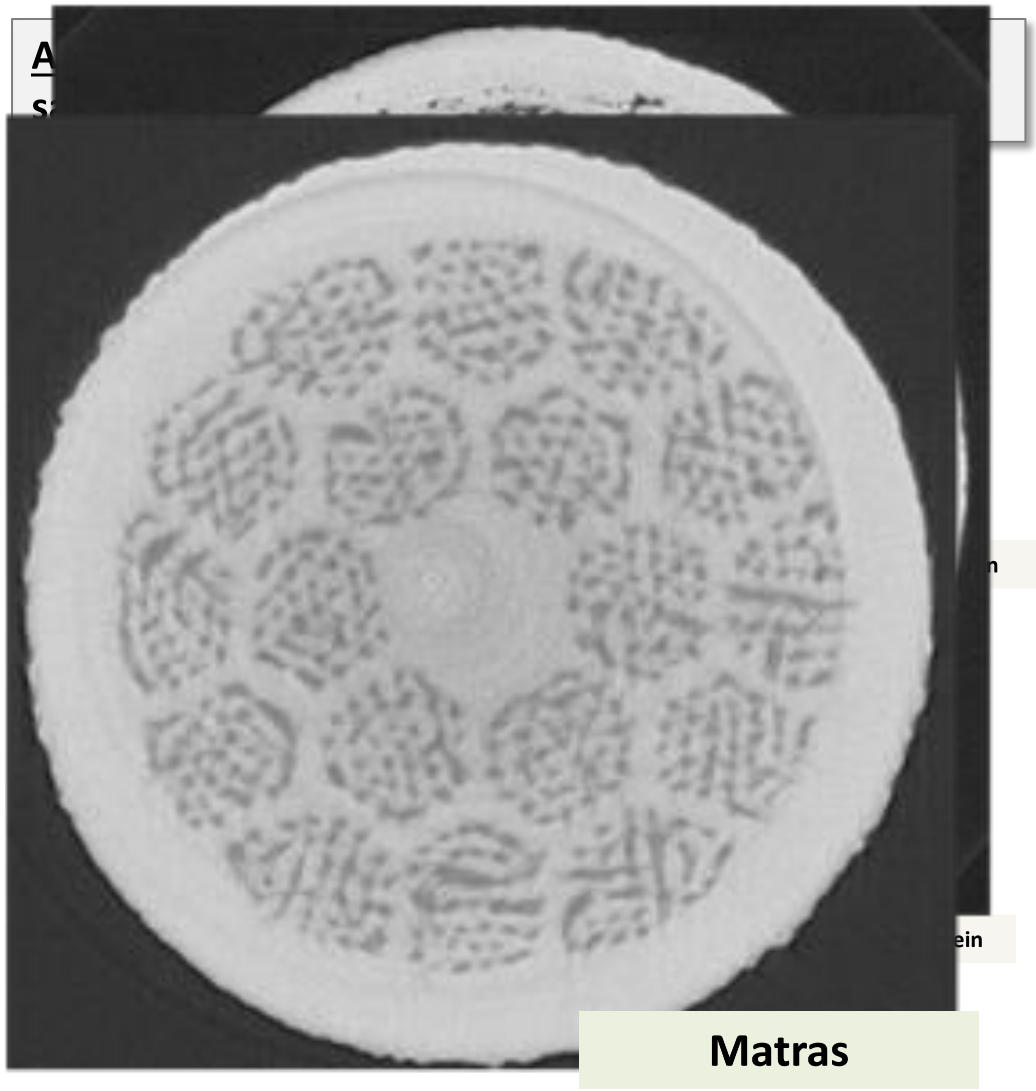
ASC's 2.5-cm bore research OP system

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



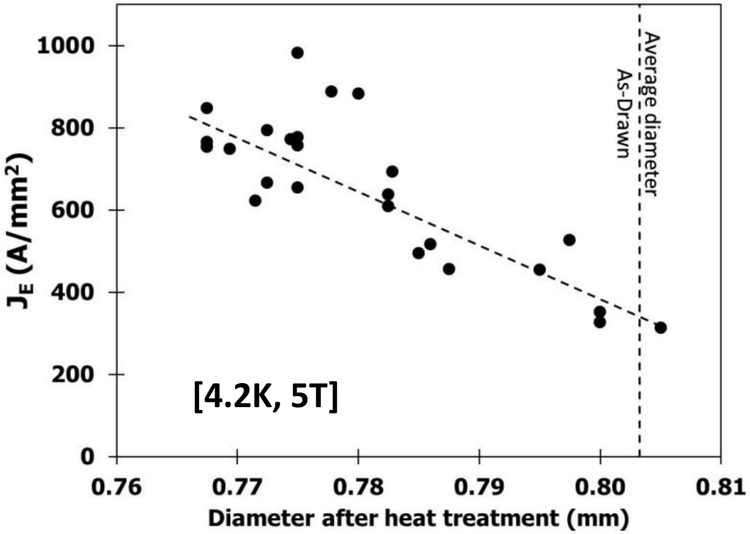


Dense filaments are the key for high J_E

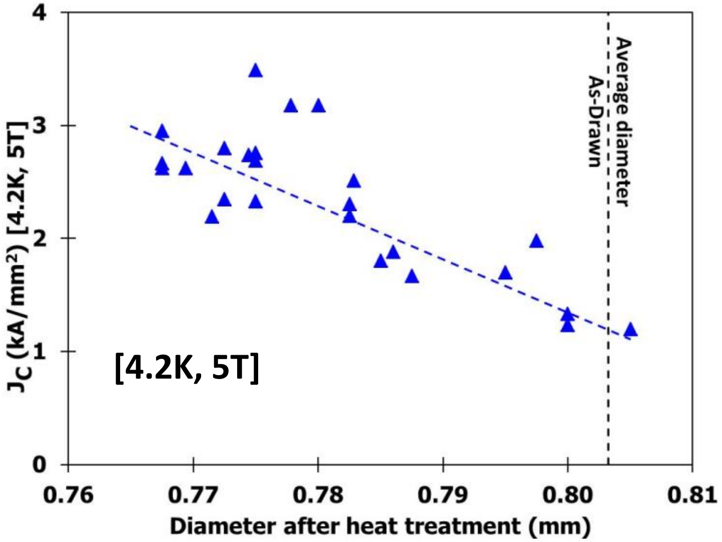
Cross section as-drawn 37x18 (0.8mm diameter)

- **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.**

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



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



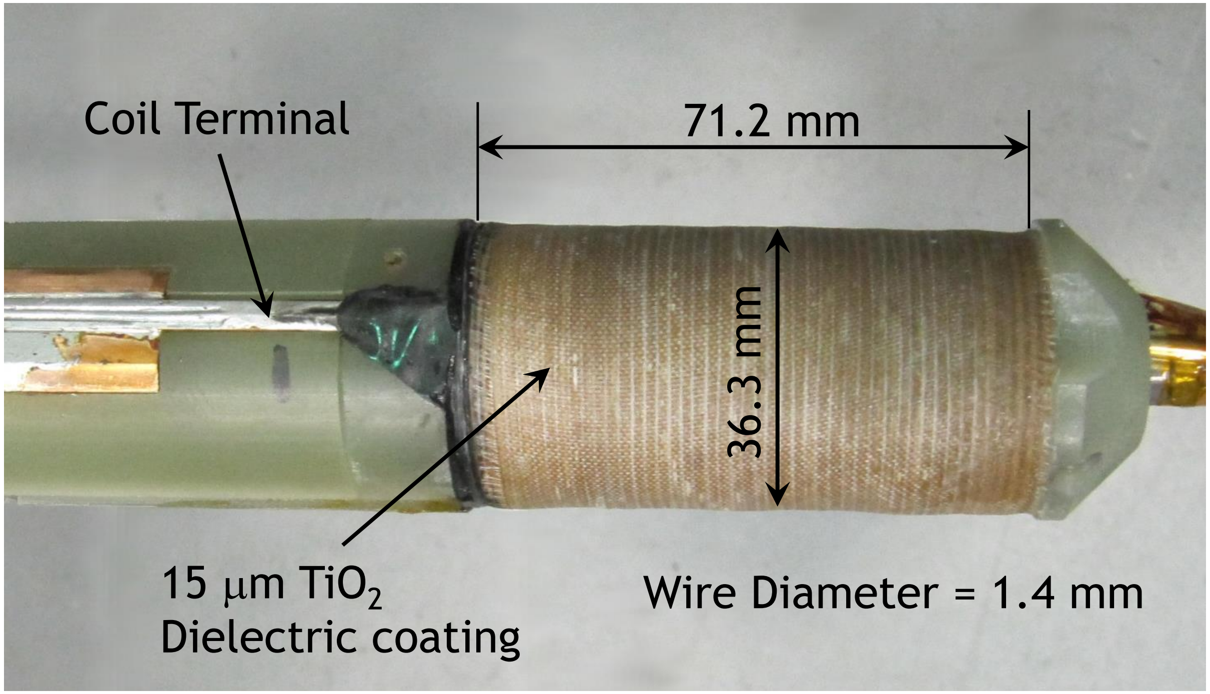
Experiment done on short wires (8 cm long)

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

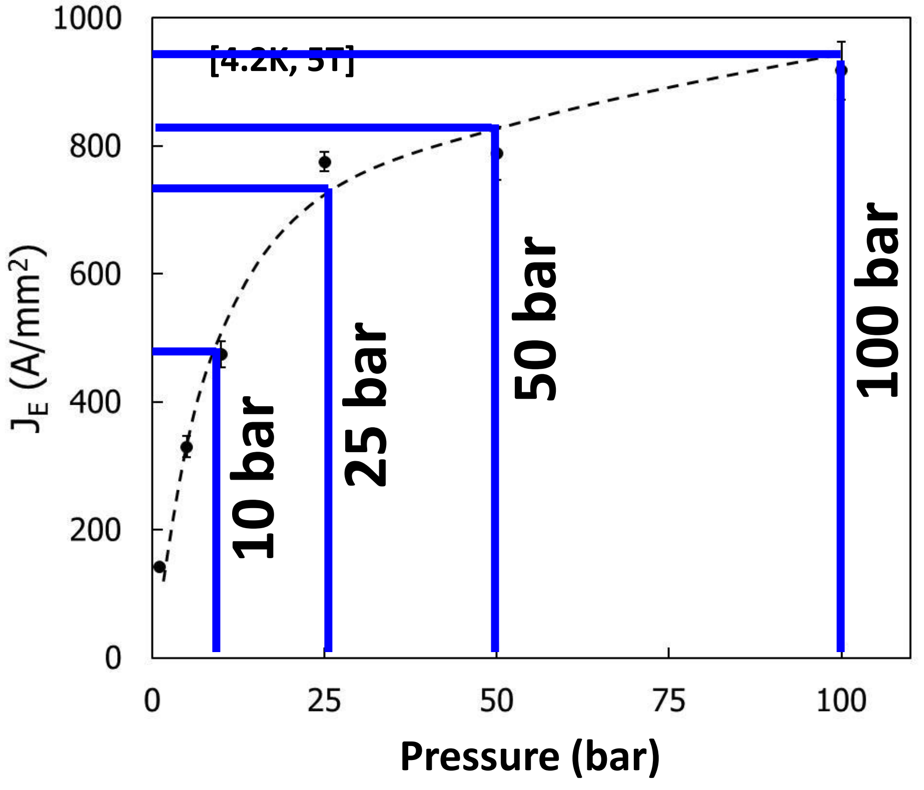
Deltech built a large OP furnace for Bi-2212 coils - custom built, first of its kind

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**

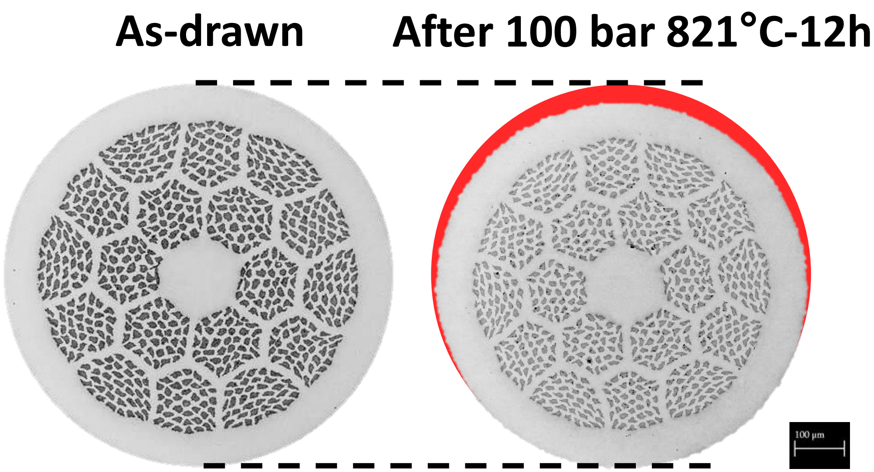
Matras

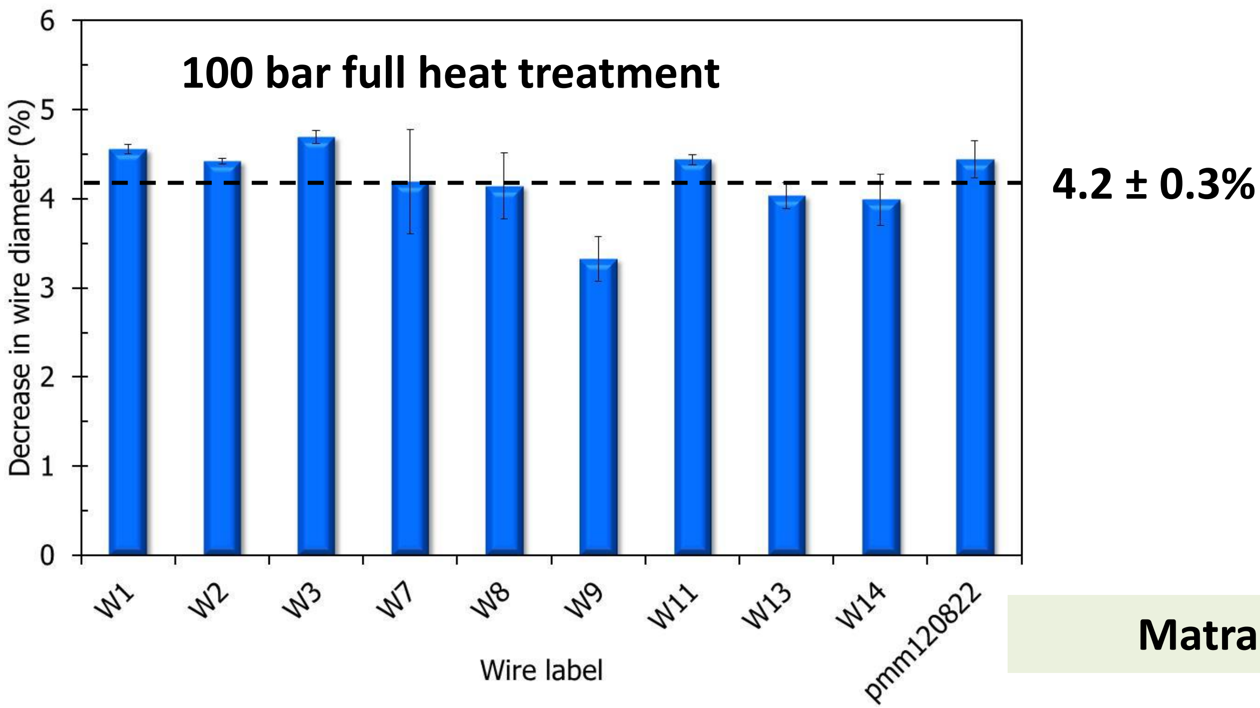
4.2 % decrease in wire diameter at 100 atm

100 bar OP significantly decreases the wire diameter.

Issue:

For magnet construction, this change in diameter poses an interesting challenge.

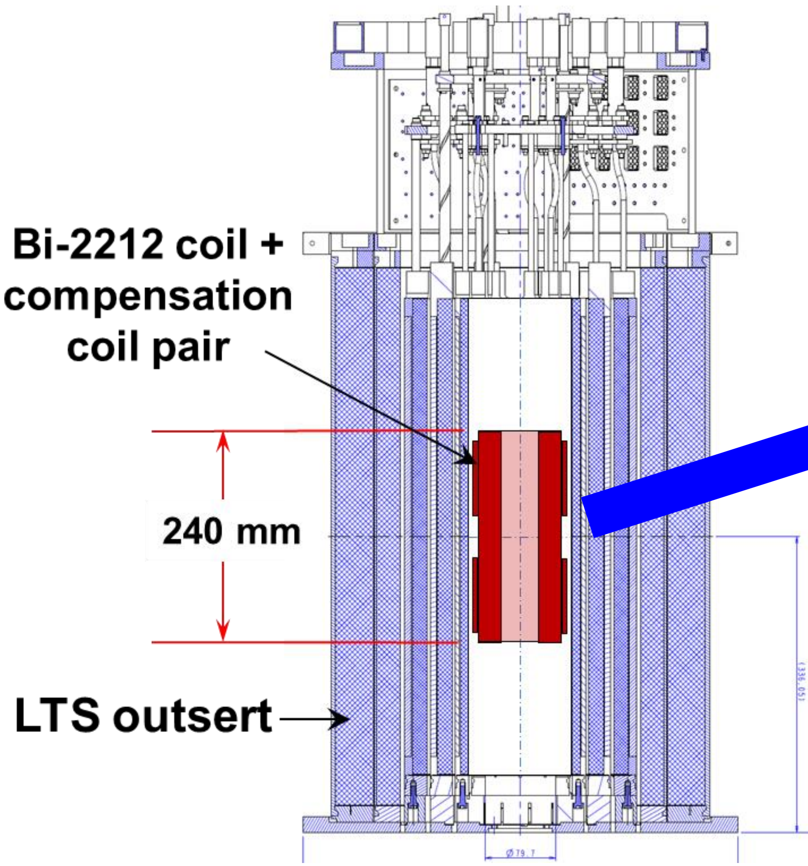




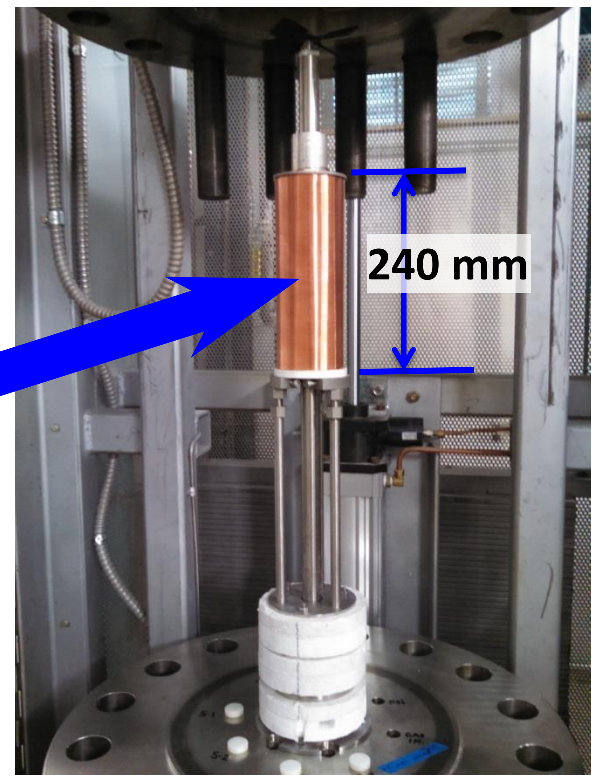
Matras

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

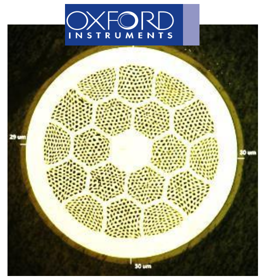
"Platypus": A Bi-2212 NMR Demo-Magnet

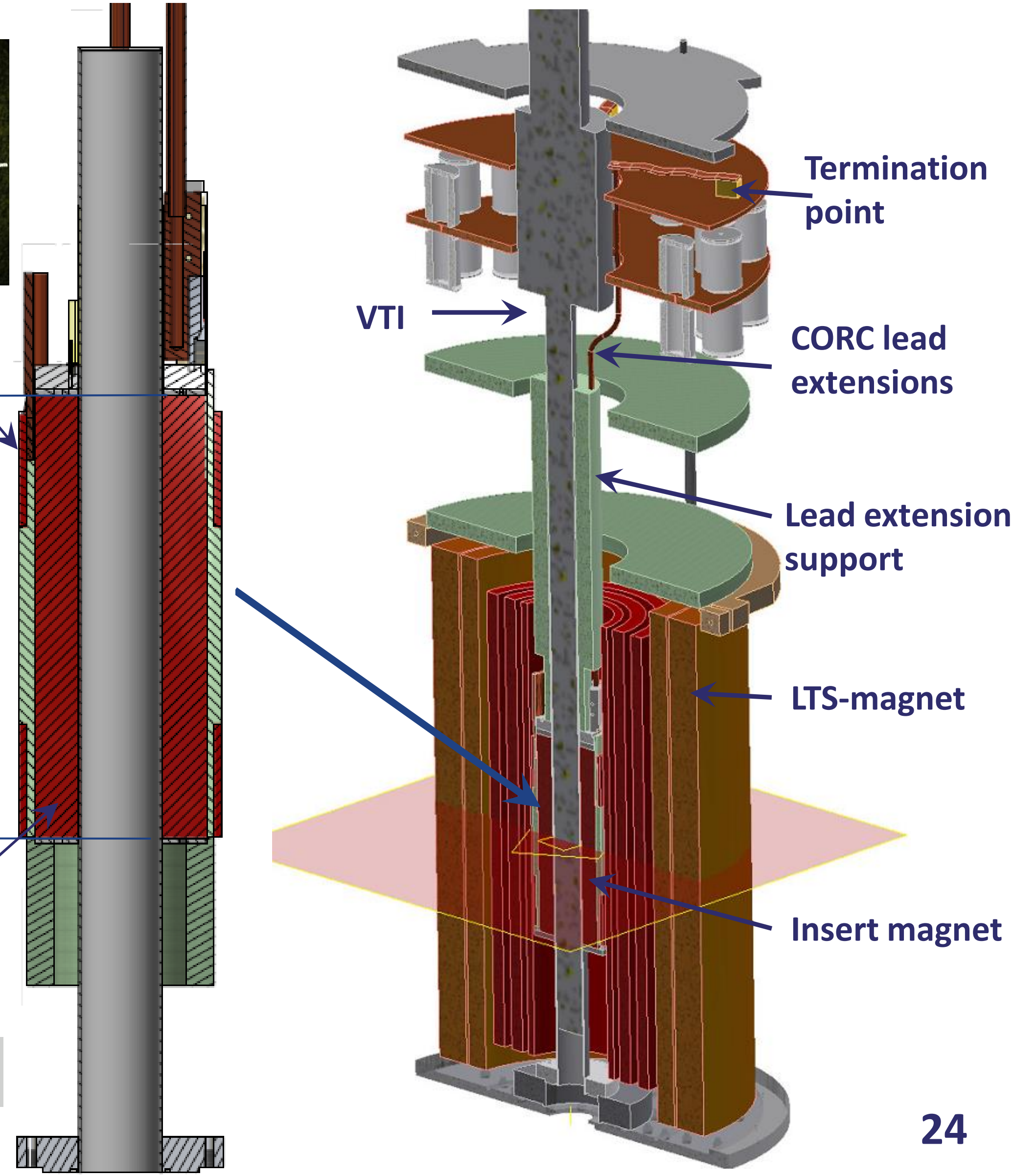
Goals:

- 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





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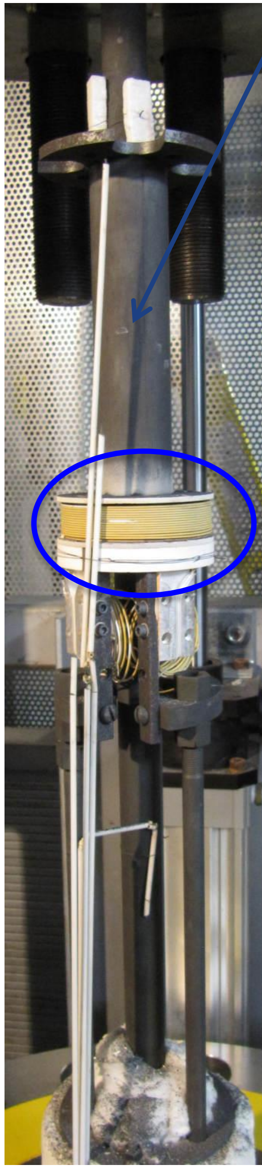
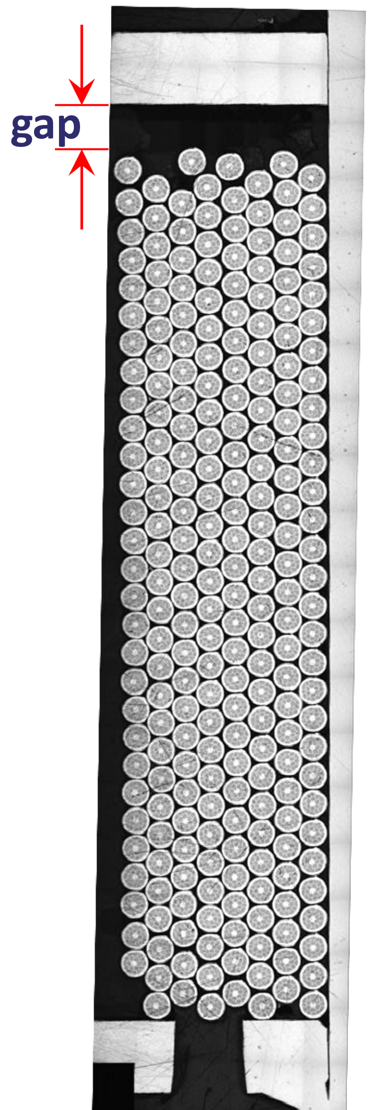
Platypus test coils 2015 ("Platypups")

"Platylong"

"Platypup"



Coil support



- Test coils demonstrated:
  - Thermally homogeneous processing of long, thick coils
  - Reasonable correlation of coil and FEA models
  - Viable terminal design
  - 4% wire densification being dealt with
- Some coils have been tested at 17 T background in the LBRM (cell-4)
- Some coils have been dissected for further analysis of the winding pack and transport characterization of extracted coil segments
- Two new Platypup tests in June 2015

Platypus team

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**

Our 100 bar 900°C furnace with 14 cm dia. X 50 cm long hot zone

Summary

- **OP processing makes Bi-2212 RW 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**