Bi-2212 / Nb_3Sn hybrid dipole for ~20 T LHC Energy Upgrade

Kyle Damborsky, Feng Lu, Al McInturff,
Peter McIntyre, Akhdiyor Sattarov , Elizabeth Sooby
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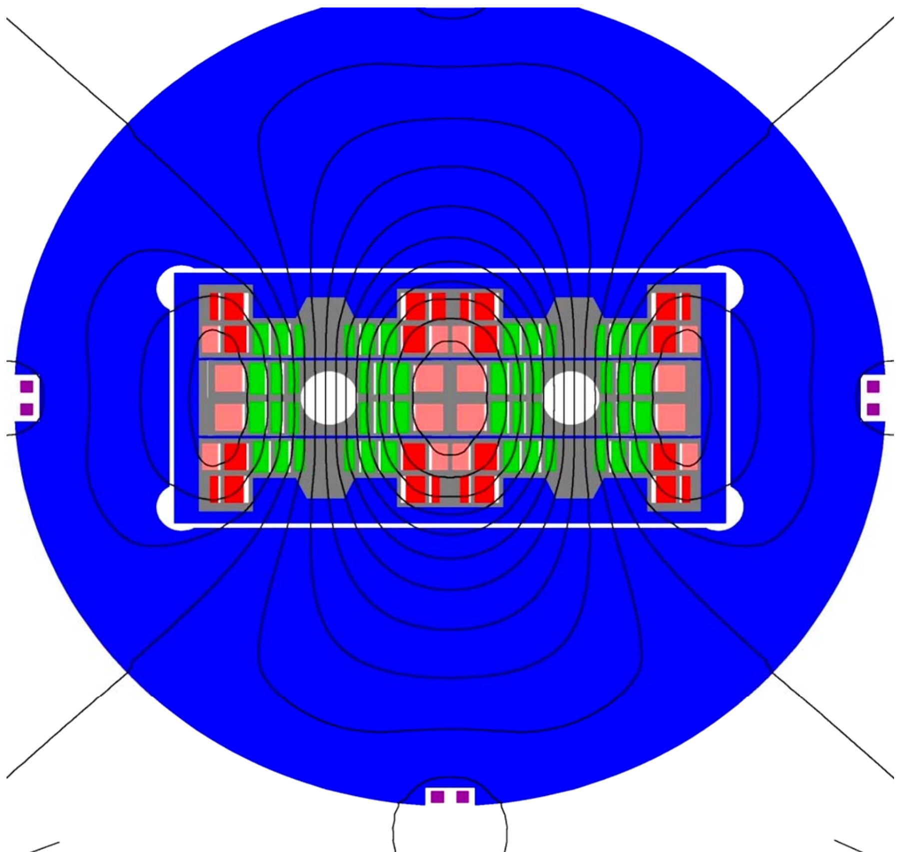
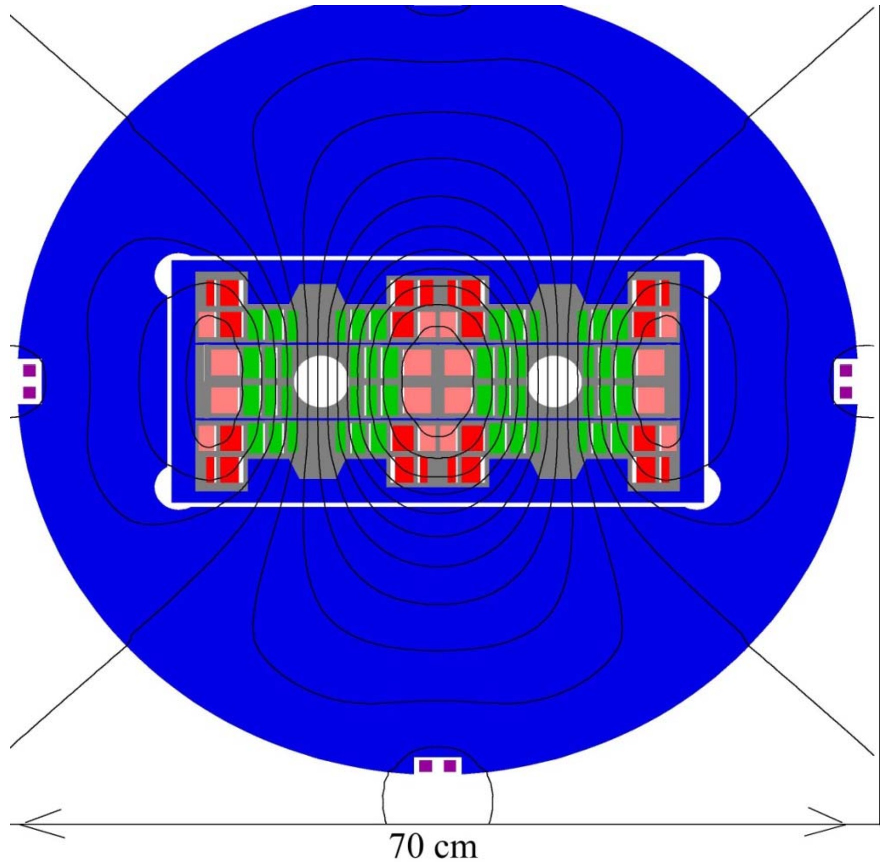


In 1996 I presented a conceptual design for a 24 T dipole for an LHC Tripler

Dual dipole (ala LHC)

Bore field	24 Tesla
Max stress in superconductor	130 MPa
Superconductor x-section:	
Nb_3Sn	26 cm^2
Bi-2212	47 cm^2
Cable current	25 kA
Beam tube dia.	50 mm
Beam separation	194 mm



Several problems:

- The design used Bi-2212 Rutherford cable – how to control Lorentz stress in inner winding?
- How to separately react Bi-2212 in oxygen, Nb_3Sn in argon?
- The design assumed j_e =800 A/mm^2 in Bi-2212 strands. We are still < 400 today!

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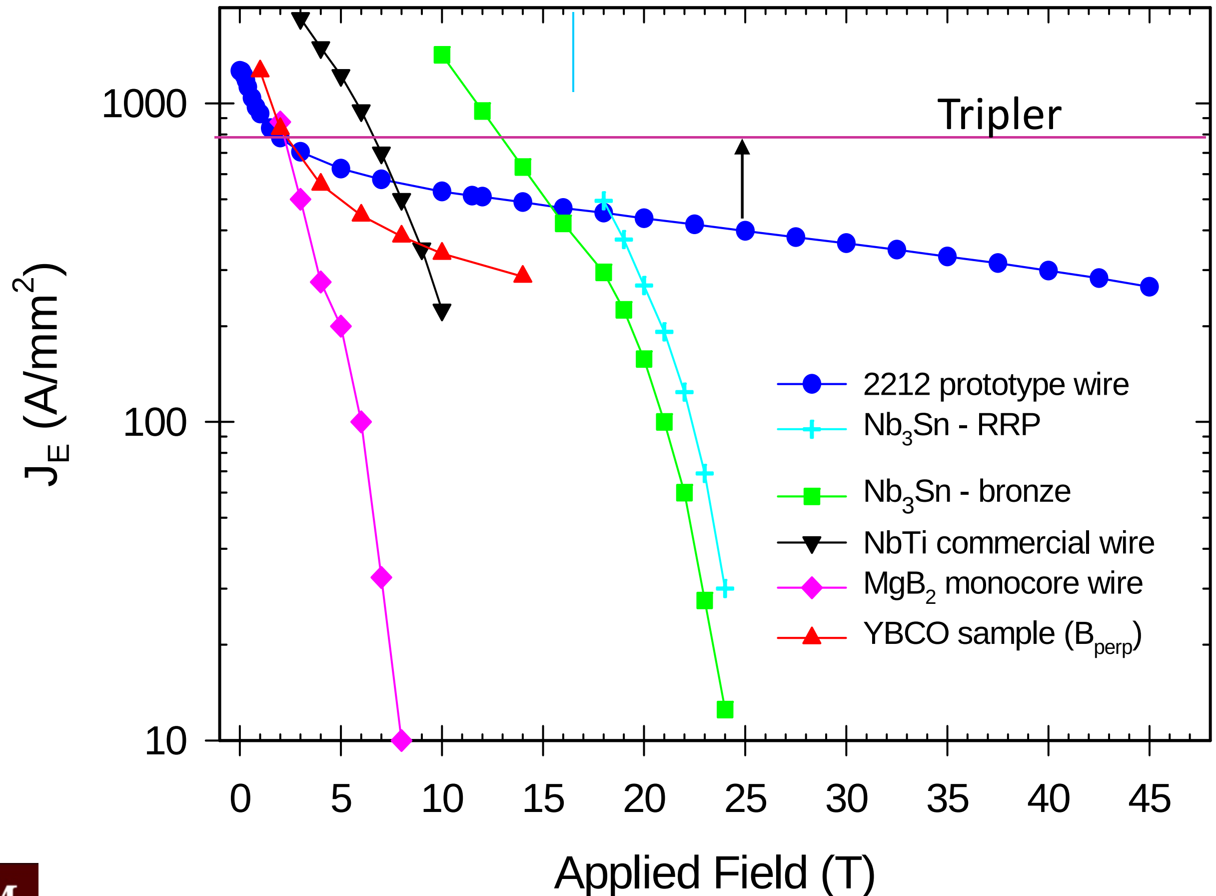
j_E in Bi-2212 strand tripled in 2001-2006, *but*…

We need 800 A/mm^2 but have <400.

Not much improvement in j_e since 2006.

And performance is still ~ 1/L!



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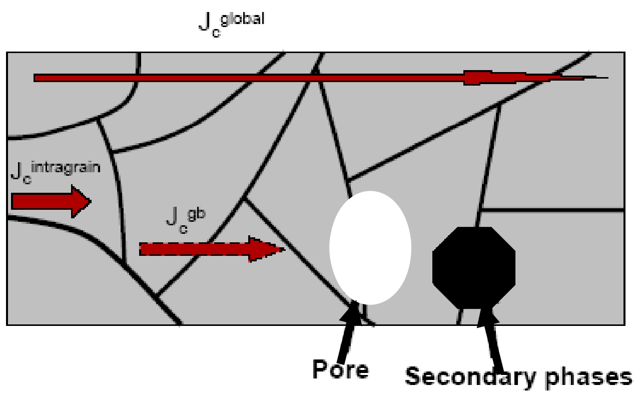
See if we can devise a way to cure the ills of OPIT.

Current transport in OPIT Bi-2212/Ag strand is limited by **high-angle brain boundaries, porosity, parasitic phases**

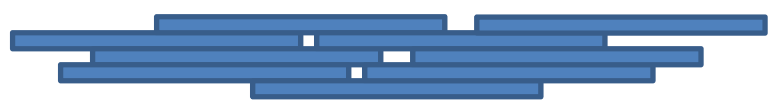
Bi2212 J_c limitation



Unfortunately, $J_c^{global} < J_c^{gb} < J_c^{intragrain}$

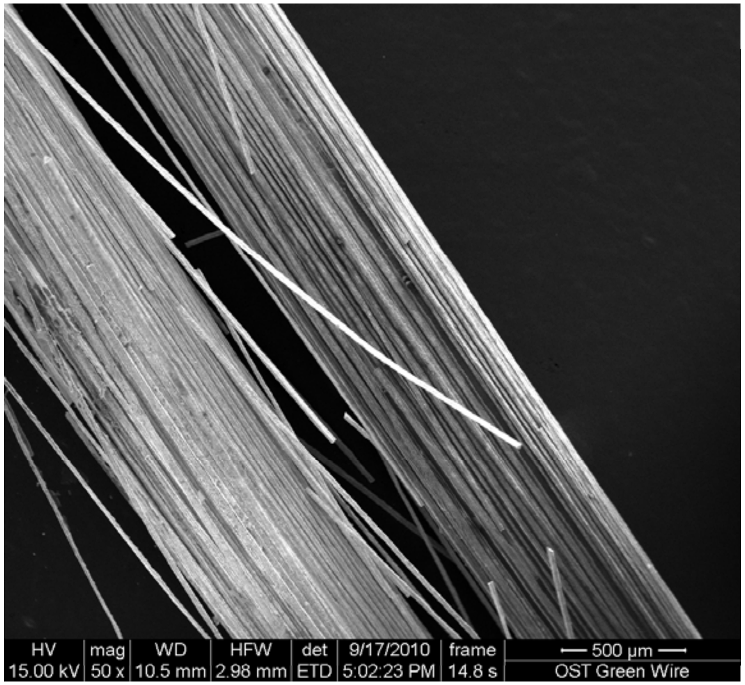
- **High Angle Grain Boundary (HAGB)**
- **Defects**
  - **- Pores**
  - **- Impurities**
  - **- Cracks**

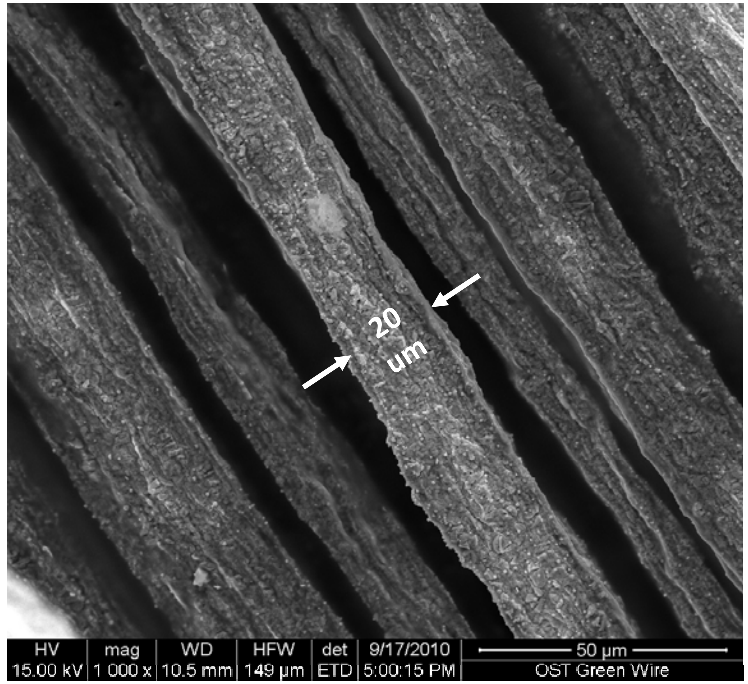
We might go far to eliminate all of these problems if we could fully texture the powder in the subelements:



But how to do it?

OST 2212 filaments – Longitudinal SEM of etched subelements





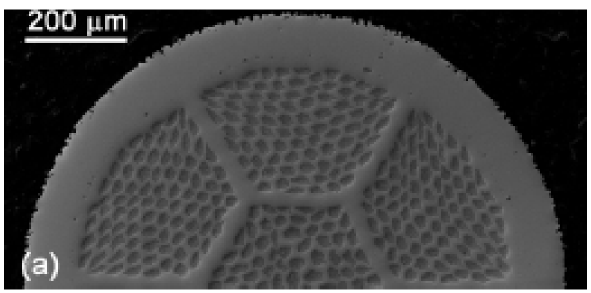
D_{wire} ≈ 1.04 mm

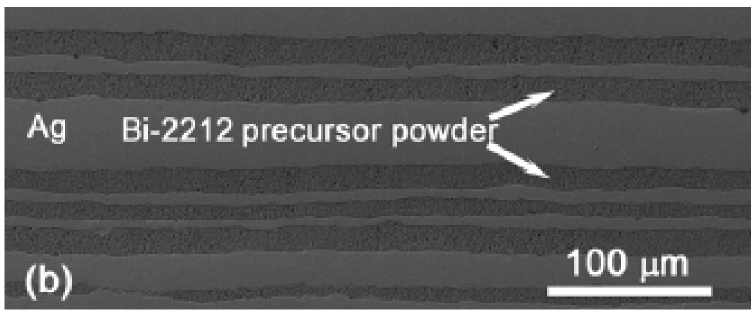
$D_{filament}$ ≈ 20 μm

Uniform

Well separated

No sausaging





OST 85 x 7 filaments

T. Shen thesis

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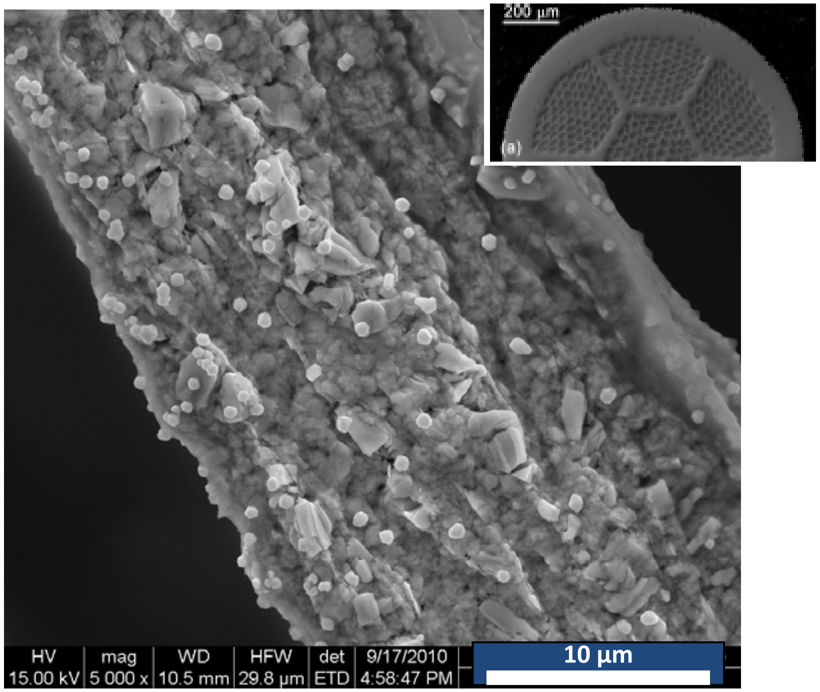
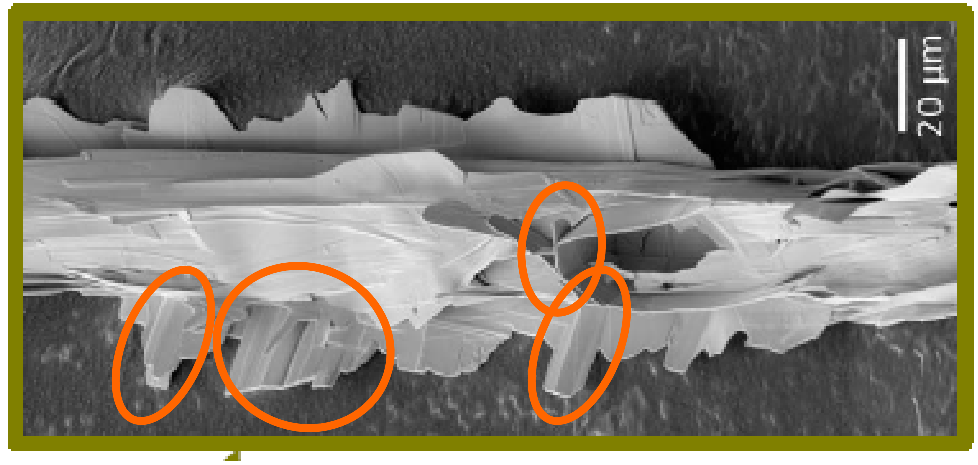
Commercial high J_c Bi-2212/Ag wires show many HAGB

Green State



Fully Processed



Imaged by F. Kametani

Wires from Oxford Superconducting Technology

- **Lots of misaligned grains – HAGBs**
- **J_c(4.2 K) much lower than fundamental limit**
- **Clear sign of much great performance**
  - **One path is to improve grain alignment (texture)**

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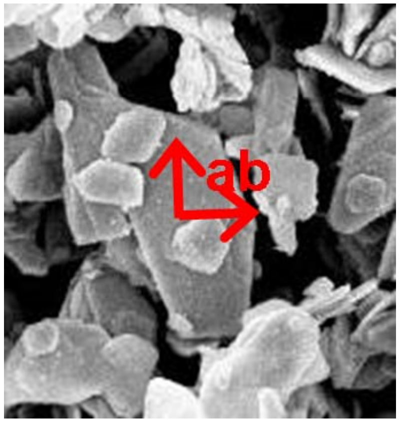
Texture is evaluated using SEM and XRD



- **Microstructure by Scanning Electron Microscopy (SEM)**
  - ✓ **2212 is micaceous, growing preferentially in the ab plane**
  - ✓ **C-axis is normal to large, flat 2212 surfaces**

- **Orientation by X-ray Diffraction (XRD)**
  - ✓ **(00L) family of peaks correspond to c-axis orientation**
  - ✓ **Texture parameter to semi-quantify texture**

$$\tau = I_{(0010)Scaled}/(I_{(0010)Scaled} + I_{(115)})$$

where $I_{(0010)Scaled} = I_{(0010)} - \varepsilon * I_{(115)}$

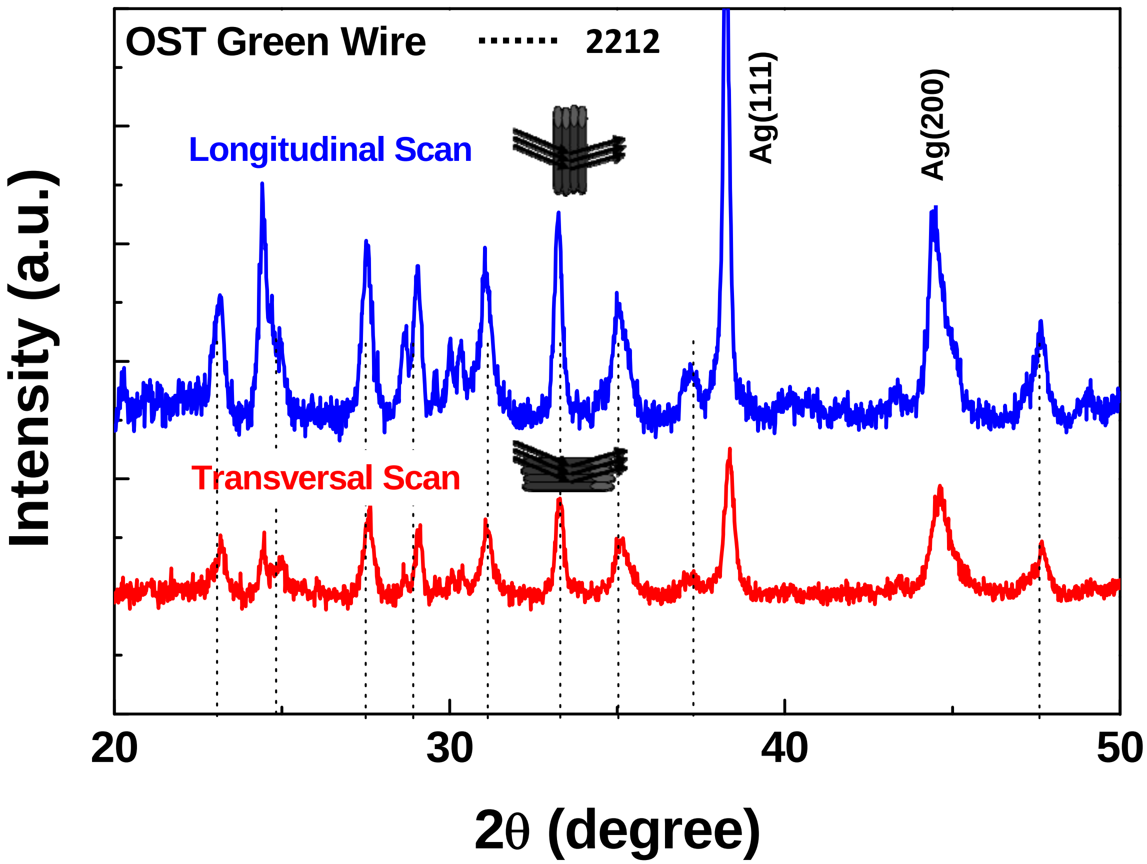
$\varepsilon = I_{(0010)}/I_{(115)} = 0.25$ (*from PDF-2 data*)

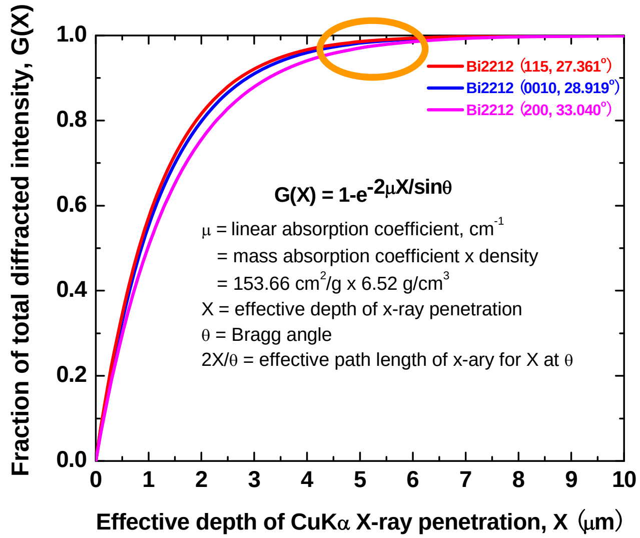
giving:

Random orientation: $\tau \approx 0$

Fully textured: $\tau = 1$

OST 2212 filaments - XRD



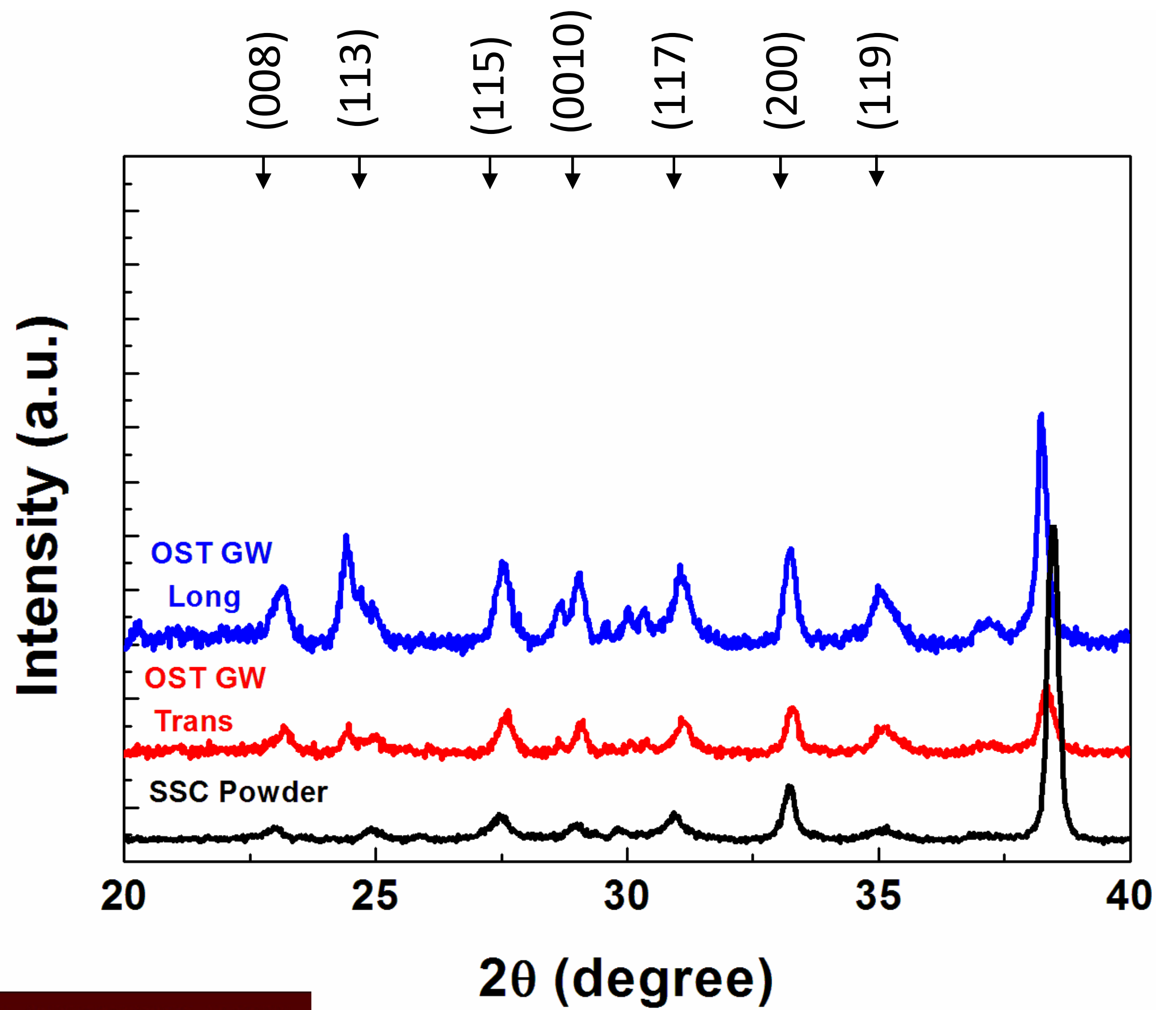


Cu Kα X-ray penetration depth on 2212 is ~ 5-6 μm.

Both longitudinal and transversal scan show strong 2212 peaks.

OST 2212 filaments – XRD, cont

- No obvious texture, only slightly better than loose powder
- Detectable 2201



Texture Parameter τ

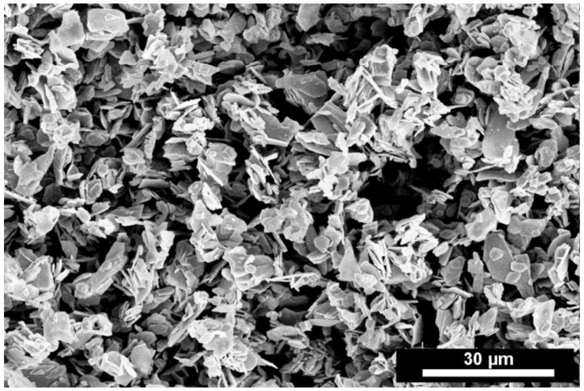
0.37

0.31

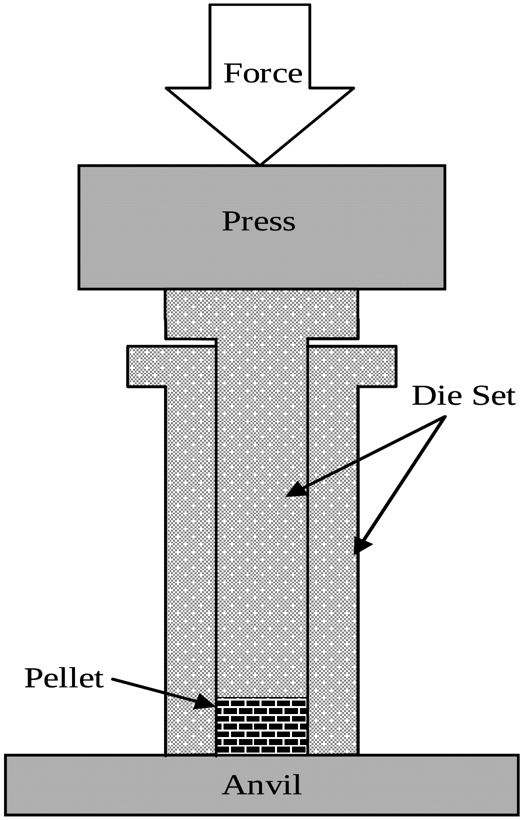
0.27

The simplest way to texture a micaceous powder: press a tablet:

- **Precursor Powder**
  - ✓ **Praxair Bi2212 powder, non-agglomerated**



- **Powder Pellet**
  - ✓ **Uniaxial pressing up to 60 kpsi**
  - ✓ **1 – 1.2 mm thick**
- **Texture analysis**
  - ✓ **Surface and bulk**



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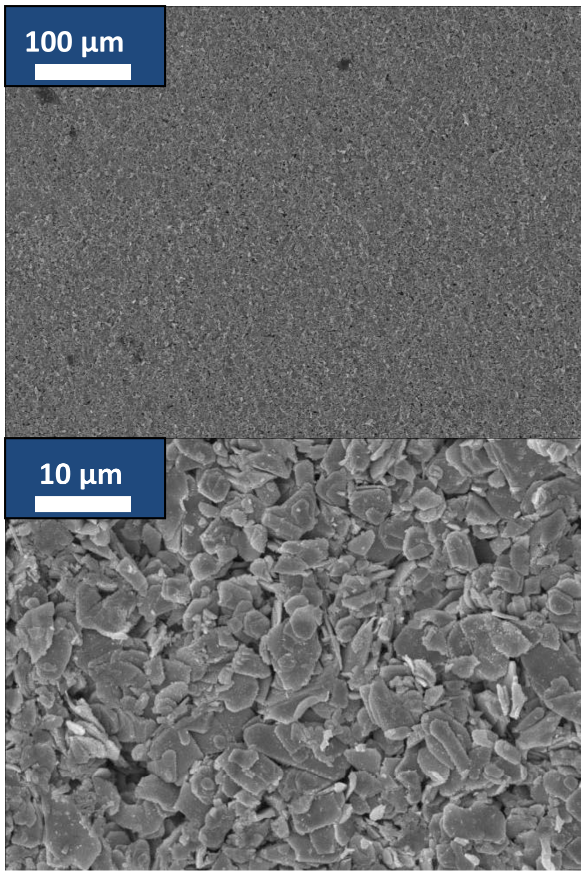
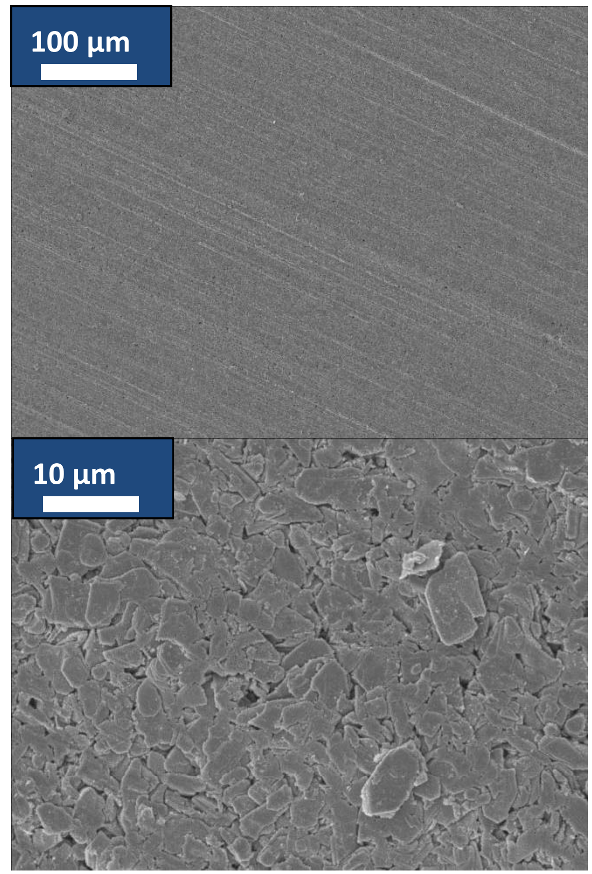
Almost all grains are aligned along c-axis

- ✓ **Uniform powder layer**
- ✓ **Orientated micaceous grains ~ 5-10 µm**
- ✓ **Better connectivity and texture with higher pressure**

20 kpsi



60 kpsi



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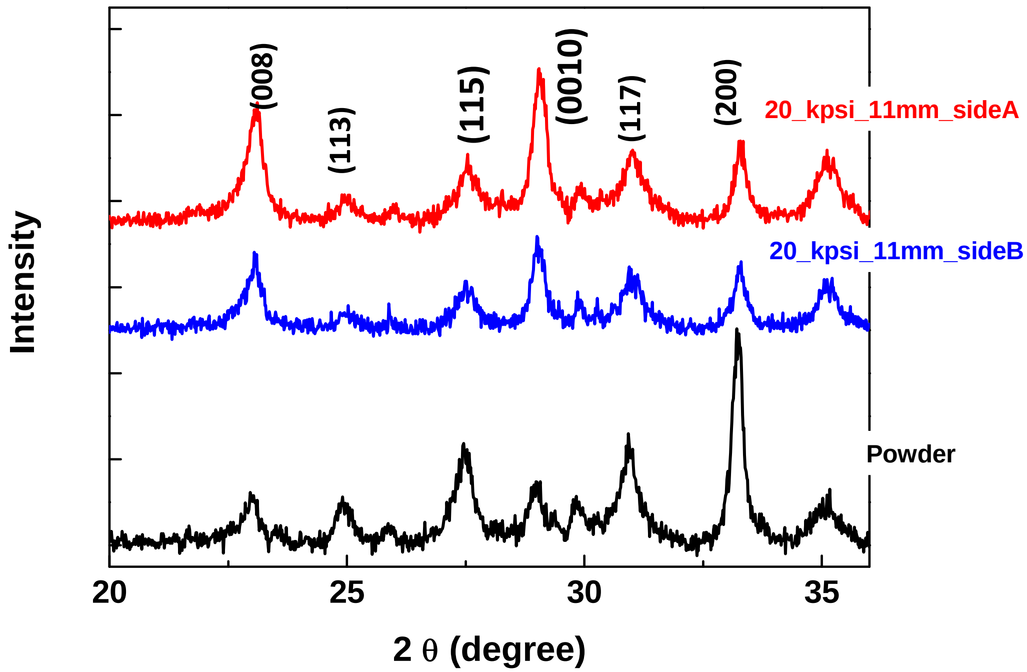
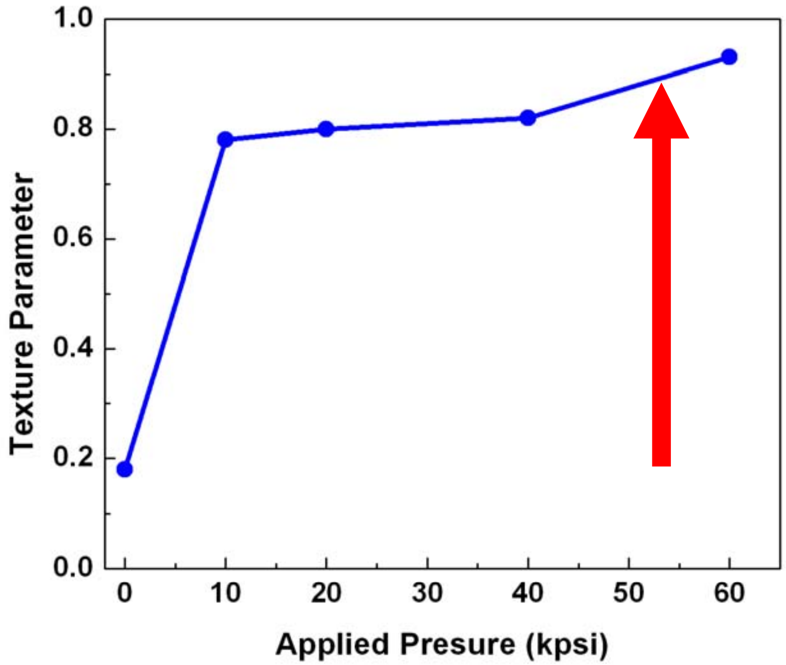
Texture is highly enhanced by pressing

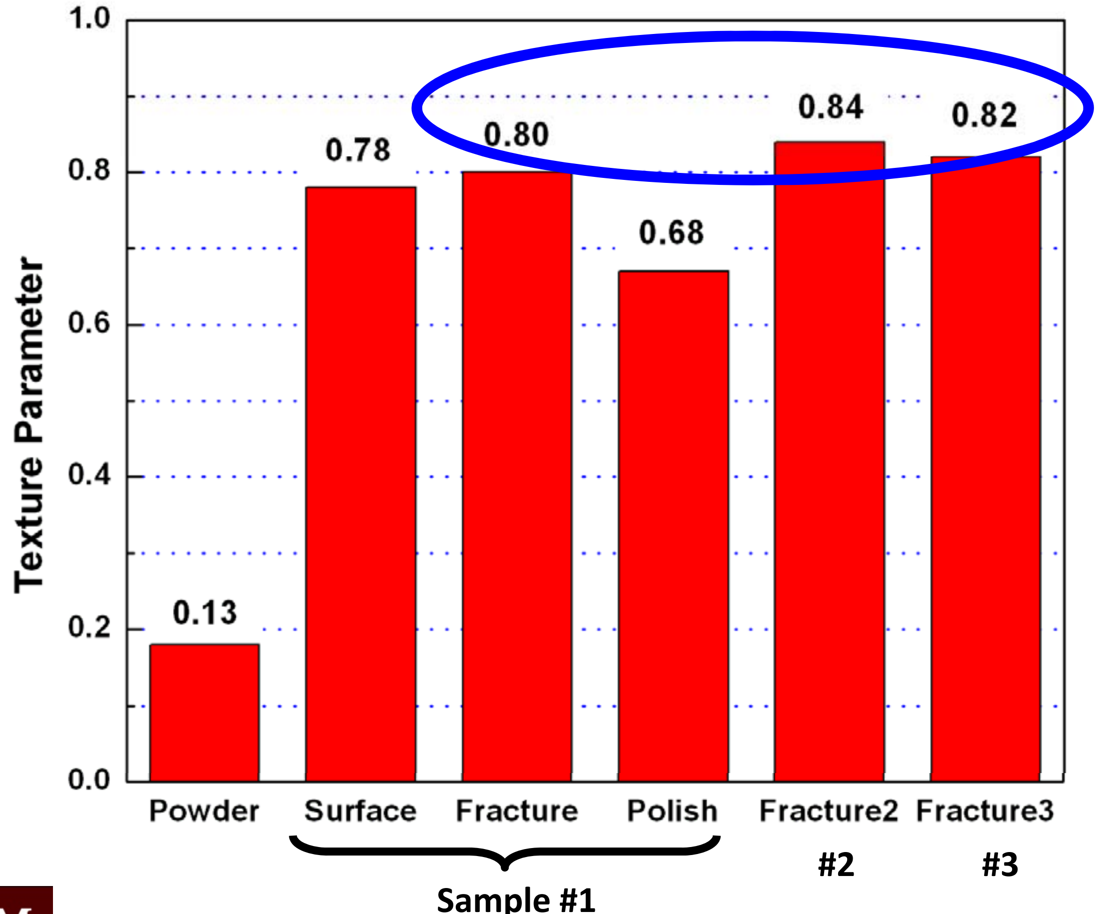
- ✓ Intensity of (00L) peaks dramatically increased
- ✓ Texture parameter 4 times higher
- ✓ Texture parameter increases with increasing pressure





Texture is homogeneous through bulk and reproducible sample-sample

- ✓ Surface and fracture have similar texture parameter
- ✓ Polish may re-texture powder
- ✓ The process and result can reproduce well



20 kPsi, 11 mm dia., ~1 mm thick pellets

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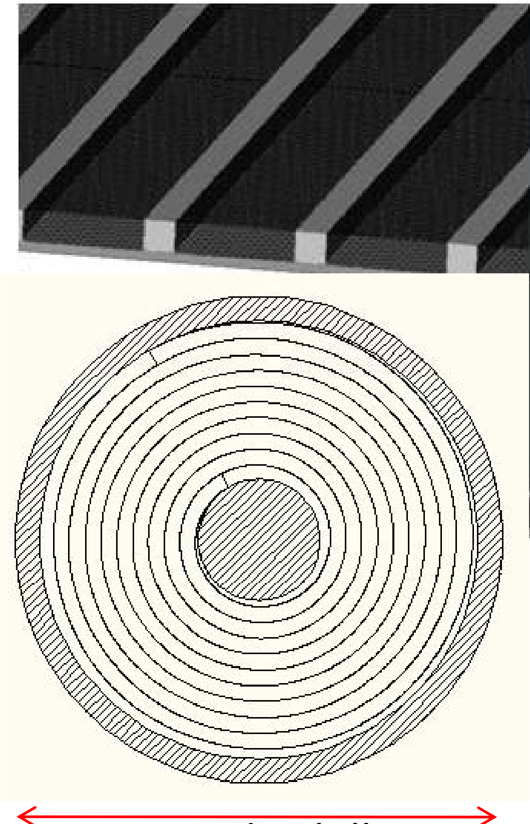
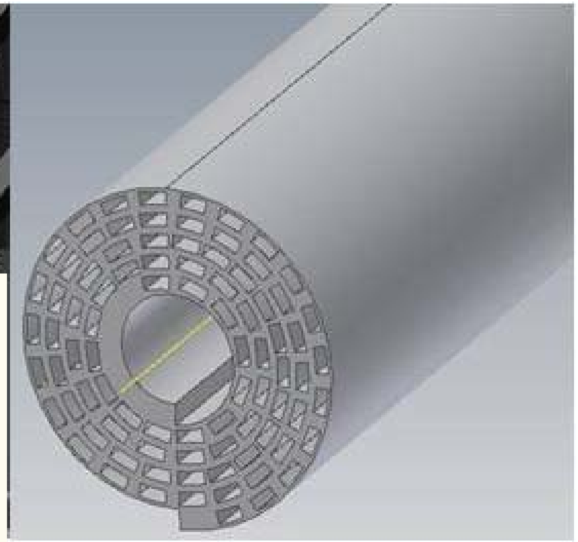
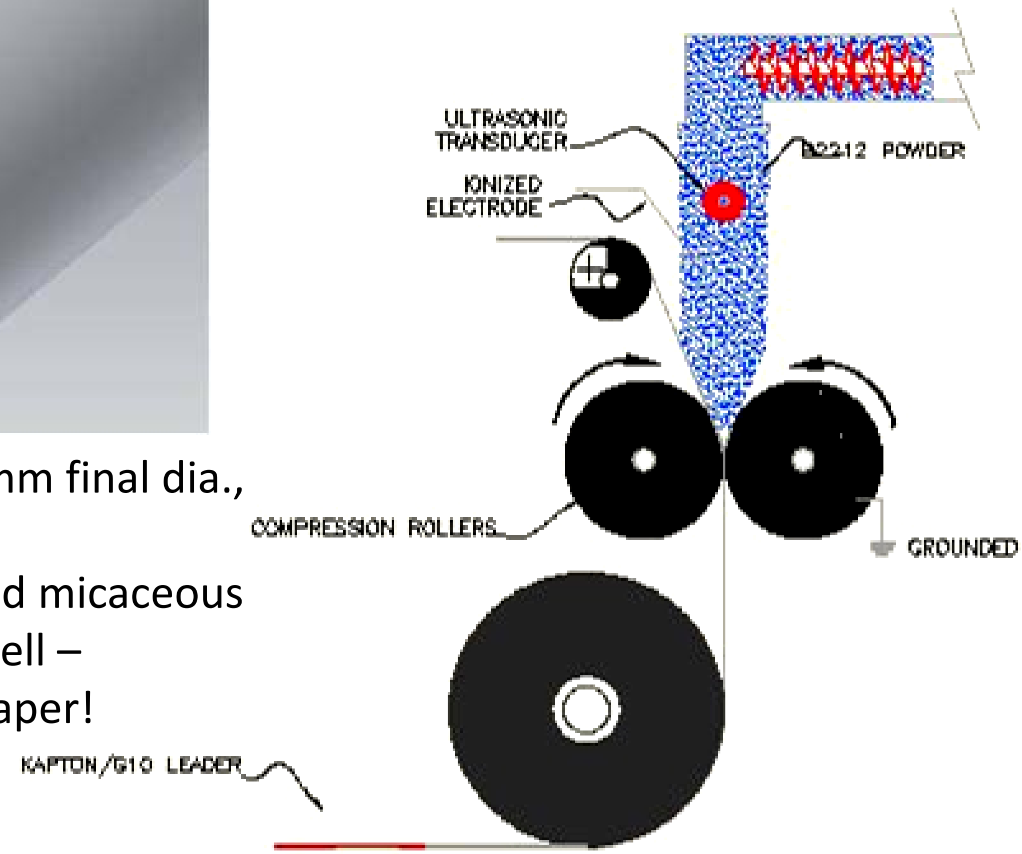
We are developing a process to make continuous ribbons of compressed Bi-2212 fine powder



50 mm dia. billet,
0.5 mm roll pitch



Draw billet to ~1 mm final dia.,
10 μm roll pitch
We expect textured micaceous powder to draw well – remember mica paper!



Goals:

- **jelly-roll conductor with fully textured Bi-2212 cores**
- **Heat treatment using solid-phase diffusion or partial melt**
- **Objective: j_e >800 A/mm^2**

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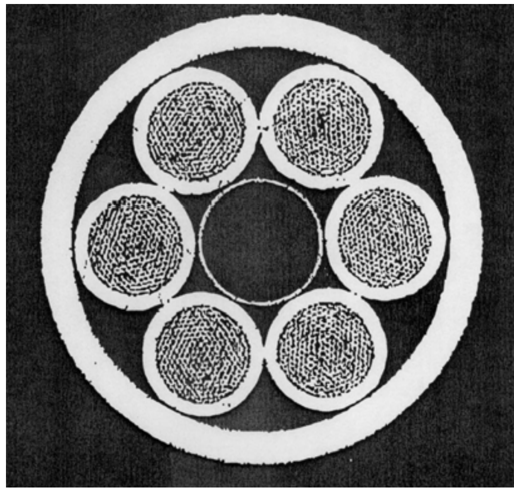
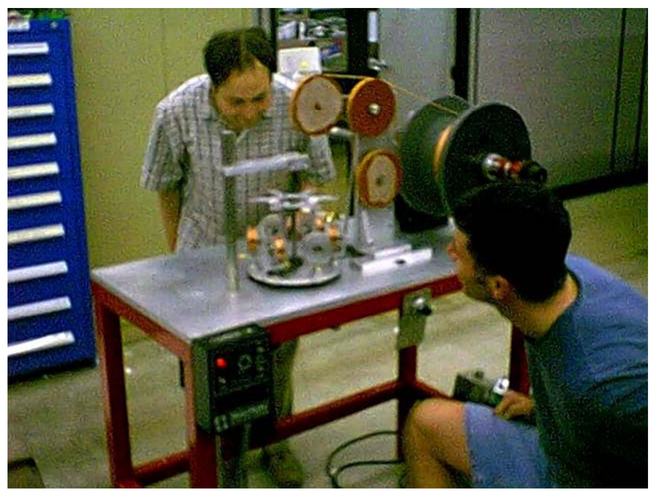
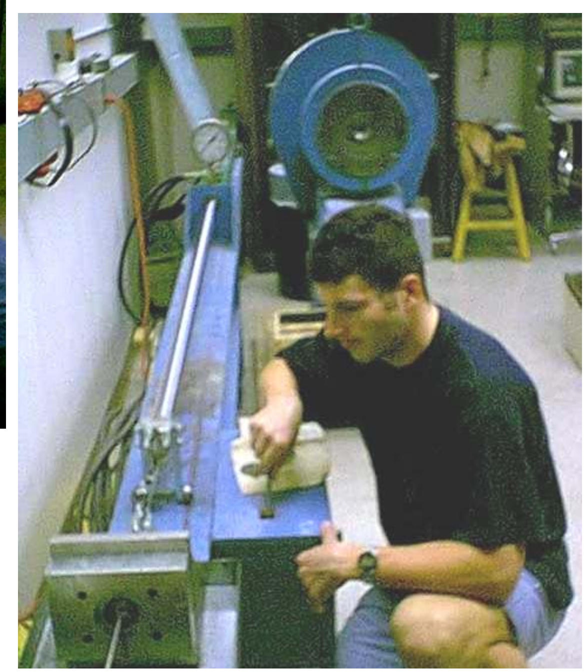
Structured cable of Bi-2212 round strands



Developed 2002
Cable current equals sum of strand I_{ss} :
No degradation from cabling, winding, heat treat in armor sheath

But we need >15 kA cable current for dipole.

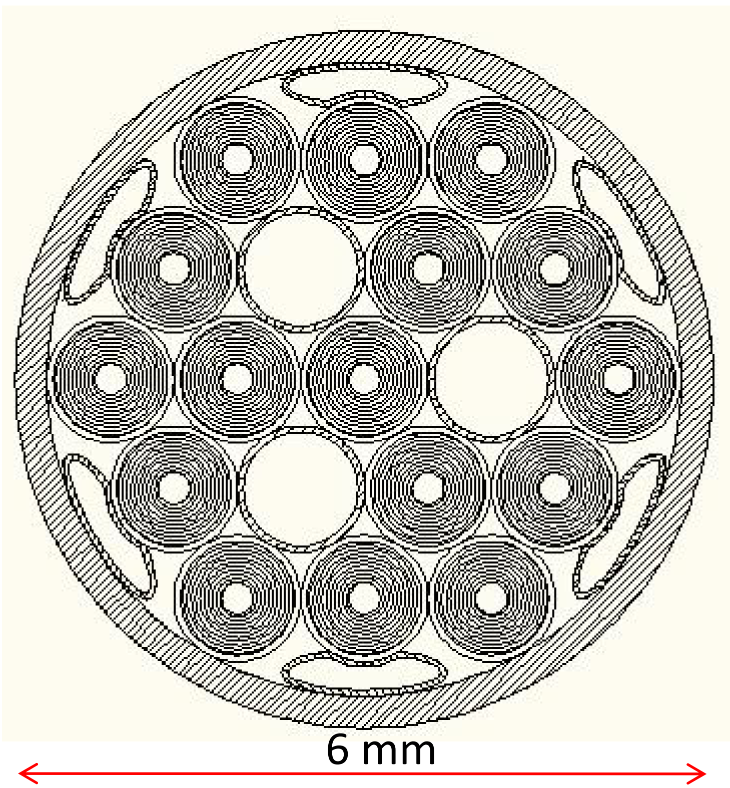


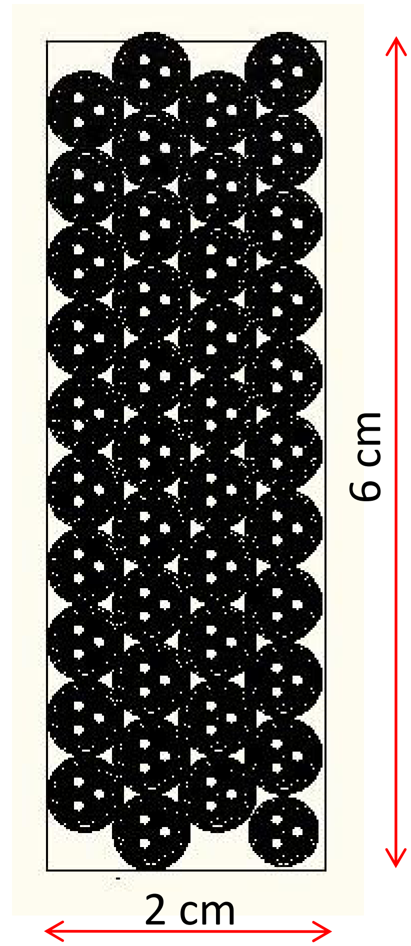


- **Manage stress within cable,**
- **Provide a conduit for oxygen flow during heat treatment**
- **Provide a conduit for cryogen to refrigerate throughout the coil**

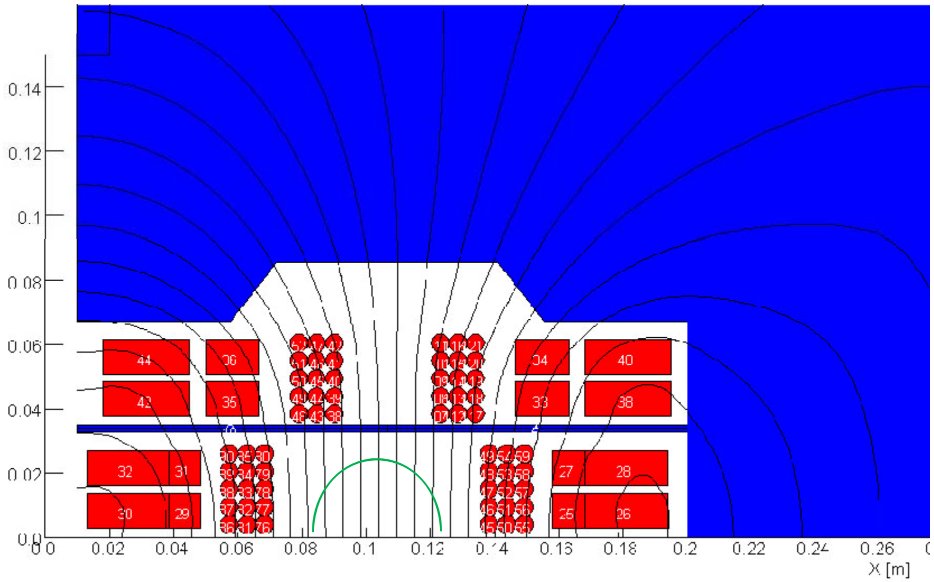
16-strand structured cable

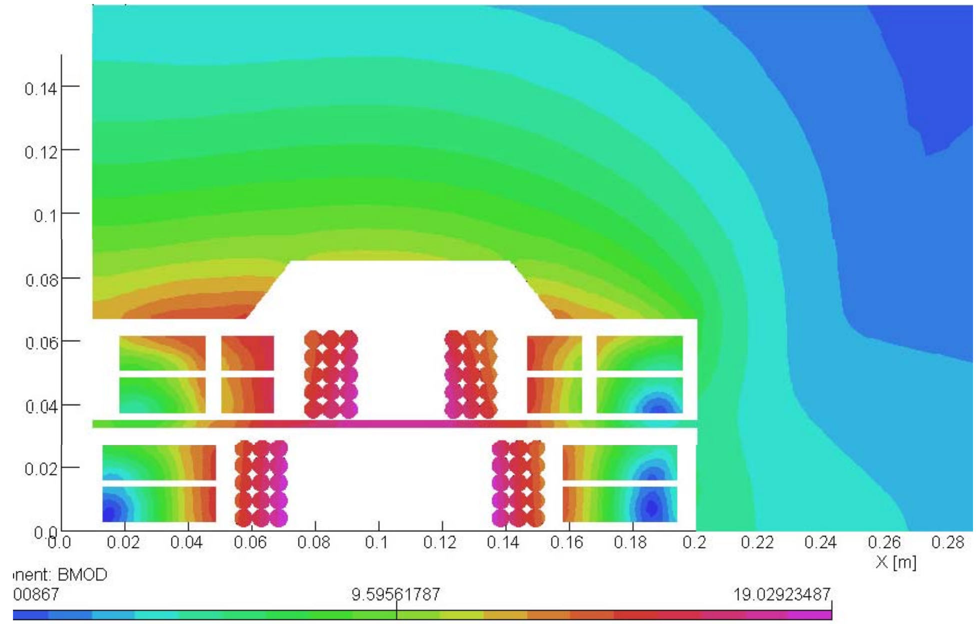
Add another layer of strands in cable.
The 3 spring tubes provide stress management along every touch axis in the cable.
Makes 18 kA cable, winds to a reasonable winding in hybrid coil.





So what could this give us for a dipole?





Bore field (90% short sample)		18 T	
Bore tube		60 (h) x 50 (v) mm	
Coil current		10 kA	
Stored energy		2.64 MJ/bore	
Max stress in Nb_3Sn		<150 MPa	
	Inner Nb_3Sn	Outer Nb_3Sn	Bi-2212/Ag
strand dia.	0.87	0.65	1.0 mm
# strands in cable	22	30	16
# turns in windings: top layer	8x2	21x2	3x5
bottom layer	8x2	22x2	3x5

Conclusions

- We have gone back to basics to try to develop a textured-powder JR strand for Bi-2212
  - Eliminate HAGBs
  - Reduce porosity
  - We hope to achieve optimum connectivity without full melt, thereby knocking out parasitic phases
- We have evolved our Bi-2212 structured cable to add another layer and push up cable current
  - Maintain stress management using a triplet of spring tubes
  - Manifold O2 flow during heat treats
  - Manifold cryogen flow during operation
- We have simplified the winding structure while keeping within bounds for stress in both Bi-2212 and Nb_3Sn windings

Please critique this strategy as we prepare to do serious work!