High, Low, Jack and the Game

Ways to tackle the impossible to make 100 TeV hadron collisions

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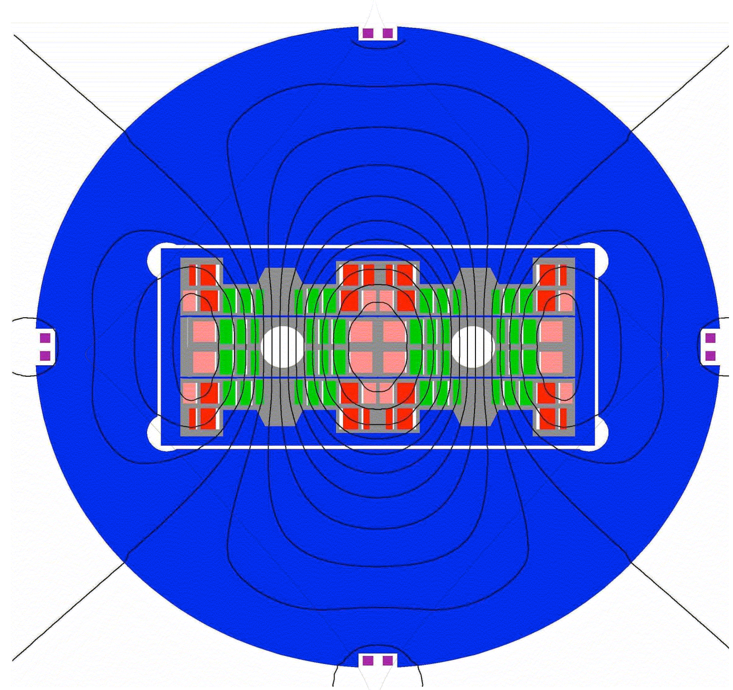
High Field, Low Circumference

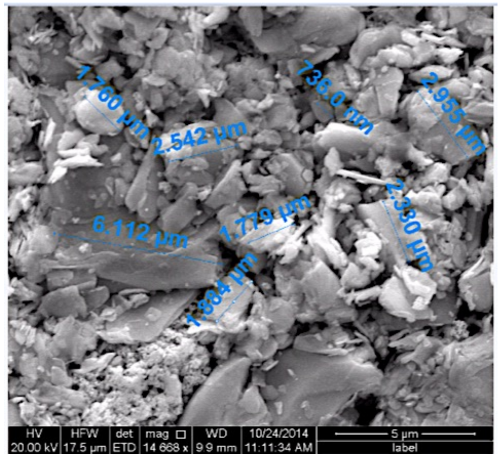
= 16 T, 90 km circumference

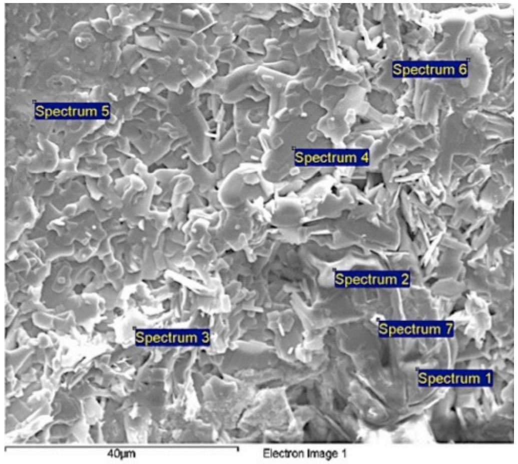


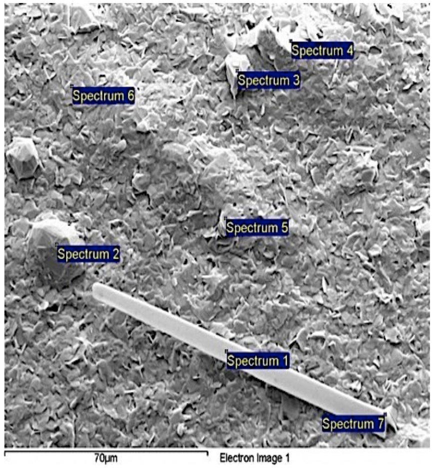
- CERN is blessed with Alps and Jura,
  cursed with <90 km maximum collider circumference.
- Need ~16 T dipoles for the double ring = Nb_3Sn and Bi-2212.
- Very expensive superconductor (wire would be >$15 B today)
- Conductors are fragile, require stress management in windings.

Texas can help two ways…

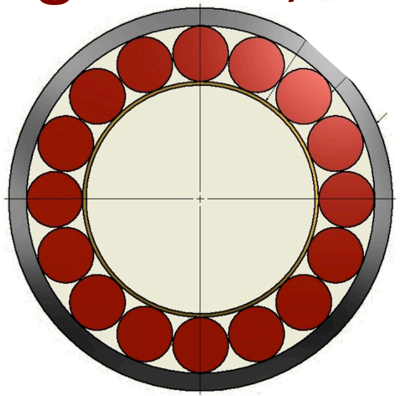
- Enhanced Textured-Powder processing of Bi-2212/Ag to enhance j_c, improve mechanical properties.

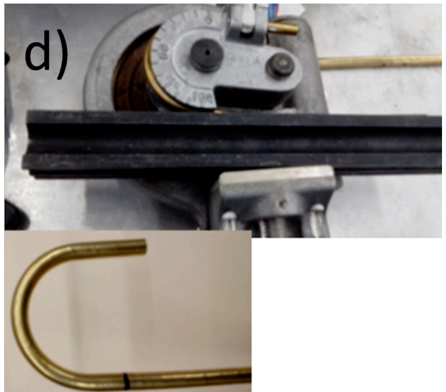






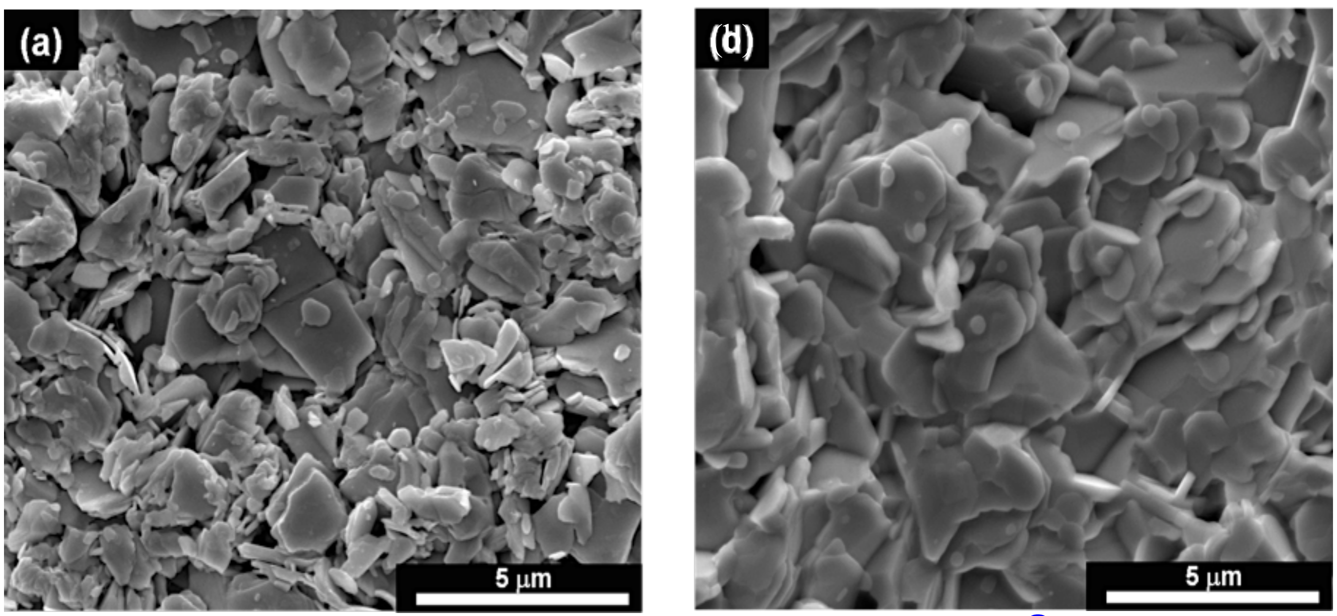
- Stuctured cable-in-conduit provides intrinsic stress management, compatibility for heat treatments.





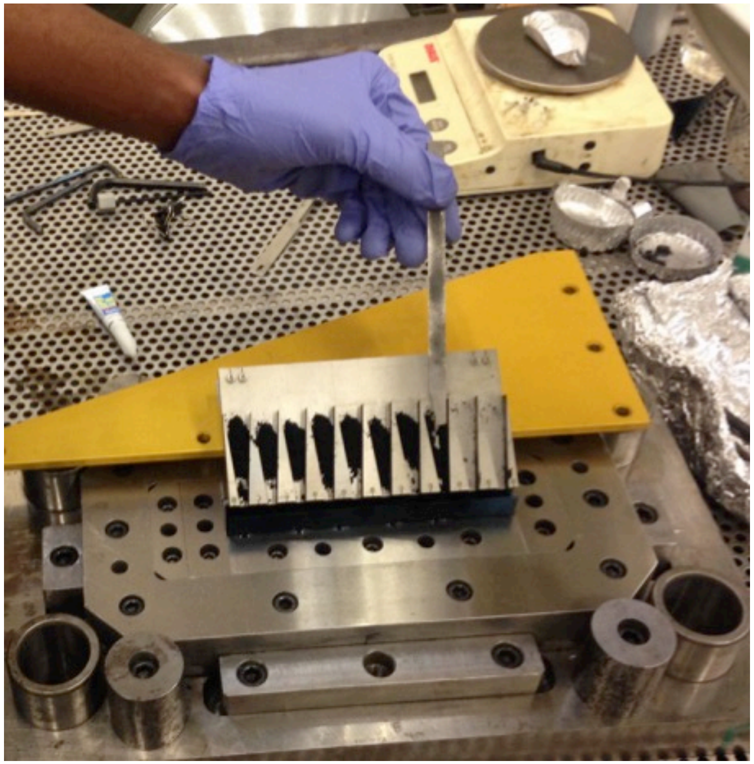
We began several years ago to seek a way to achieve connectivity without melting

- Textured-Powder© processing:
  - Achieve >80% texture of a-b plane orientation using unixaxial compression of Bi-2212 fine powder
  - Press the cores to form tablets, square bar subelements
  - Heat treat <T_{melt} to grain growth by solid-phase diffusion

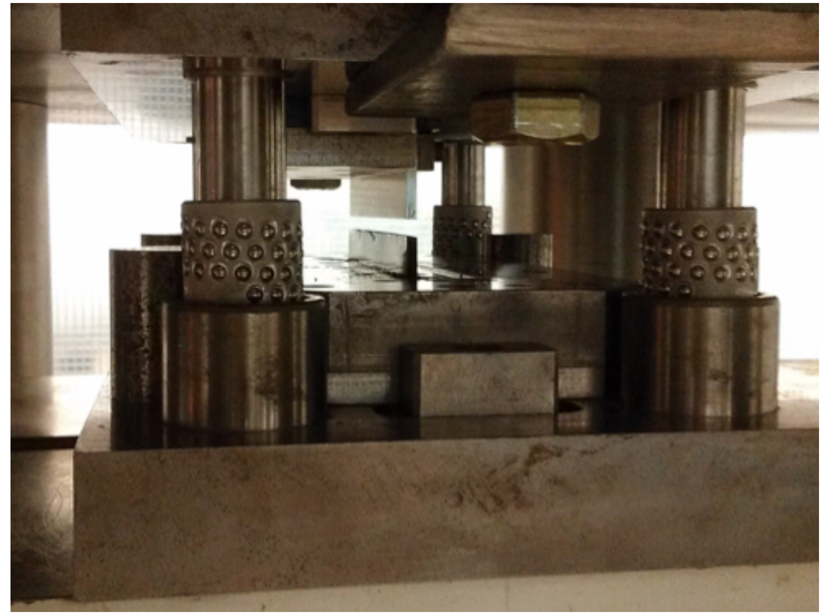


©US patent 8,592,346 (2013)

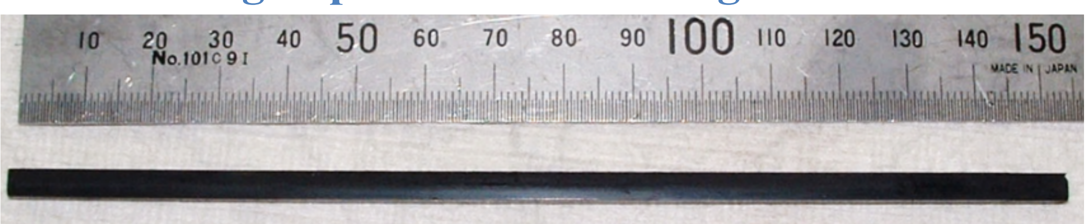
Fabrication of textured-powder monocores



loading of powder into rectangular die



die assembled in hydraulic press ready for compression to 30 ksi



4 mm^2 cross-section Bi-2212 bar

bar assembled in a Ag monocore billet.

The germ of an idea

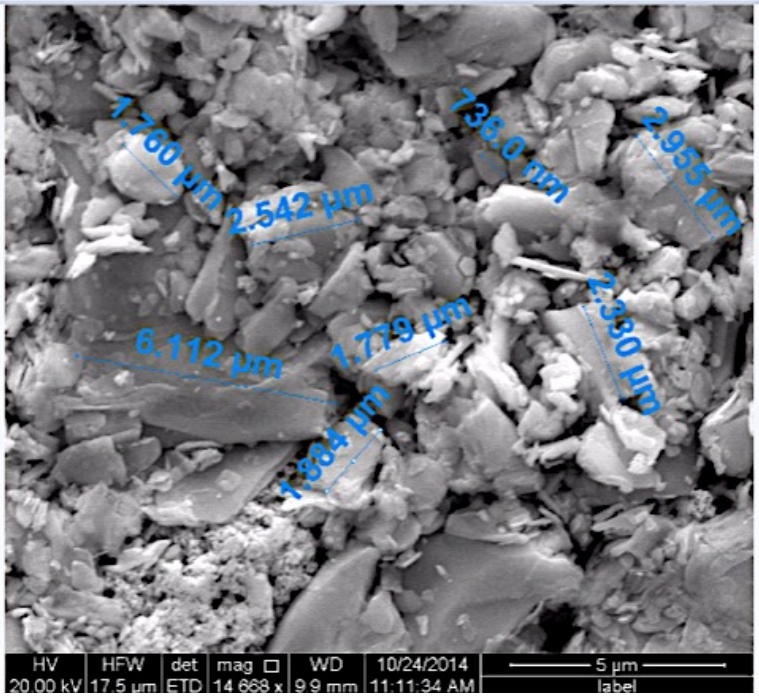
- It has long been known that Ag lowers the melt temperature of Bi-2212 at the interface.
- To some degree Ag guides the texture during re-crystallization.

Hasegawa *et al.*, 'The effect of Ag on the formation of Bi-2212 thick film', Physica **C222**, 111 (1994).

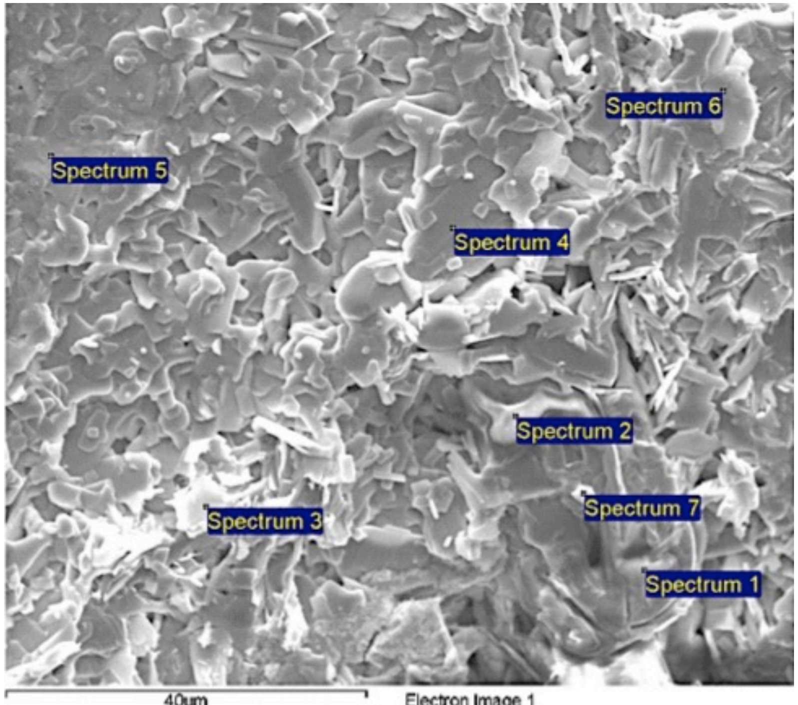
- In melt processed Bi-2212/Ag wire, supercurrent flows primarily close to the Ag interface.
- ***Nate Pogue's idea:*** suppose we bring the Ag interface into contact with all surfaces of all grains of Bi-2212 in a textured powder.
- ***Enhanced Textured-Powder© :*** Homogeneously disperse Ag nanopowder in Bi-2212 fine powder. Then follow the procedures for Textured-Powder processing.

©PTO patent applied for

Homogeneous mixing of nanopowders is tricky – we have succeeded.



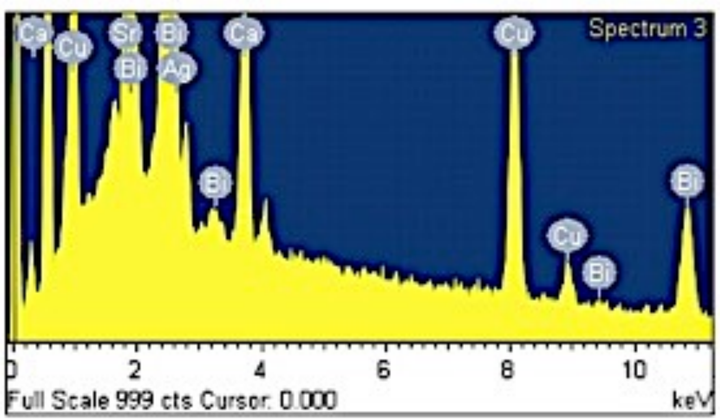
Admixture of Ag nanoparticles and Bi-2212 powder.



Cu-free phases

Spectrum	In stats.	Ca	Cu	Sr	Ag	Sb	Bi	Total
Spectrum 1	Yes	45.20	5.61	207.36	1.73		441.68	701.58
Spectrum 2	Yes	51.88	8.56	242.70	2.08	14.97	506.42	826.61
Spectrum 3	Yes	37.97	116.13	198.96	3.15		540.39	896.61
Spectrum 4	Yes	30.18	113.88	170.72	0.69		451.96	767.43
Spectrum 5	Yes	38.67	140.18	187.65	-0.03		449.54	816.01
Spectrum 6	Yes	32.40	106.43	133.86	1.77		408.42	682.88
Spectrum 7	Yes	32.87	87.82	184.58	12.46		506.36	824.10
Max.		51.88	140.18	242.70	12.46	14.97	540.39	
Min.		30.18	5.61	133.86	-0.03	14.97	408.42	

All results in weight%

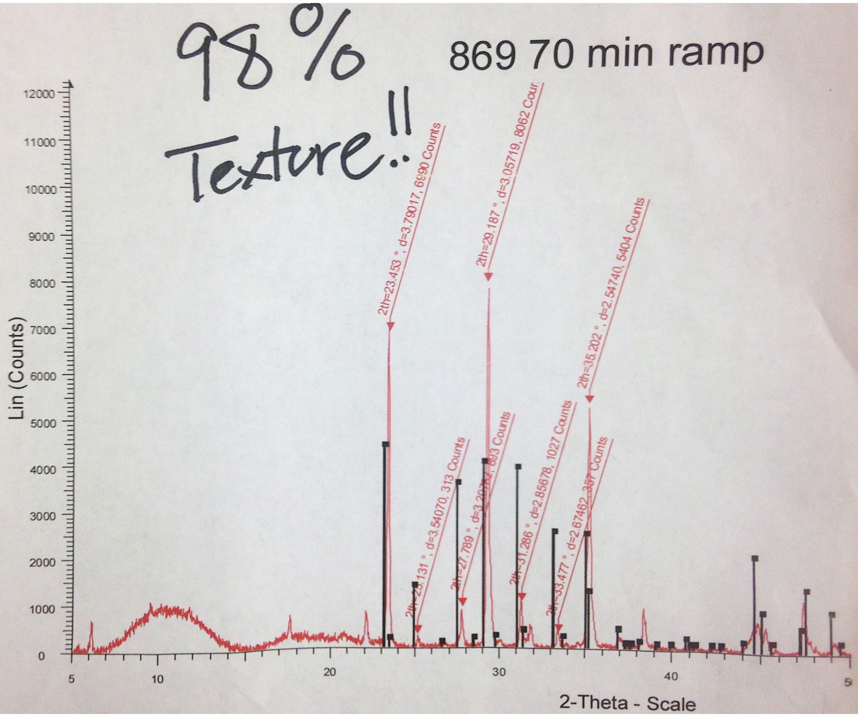


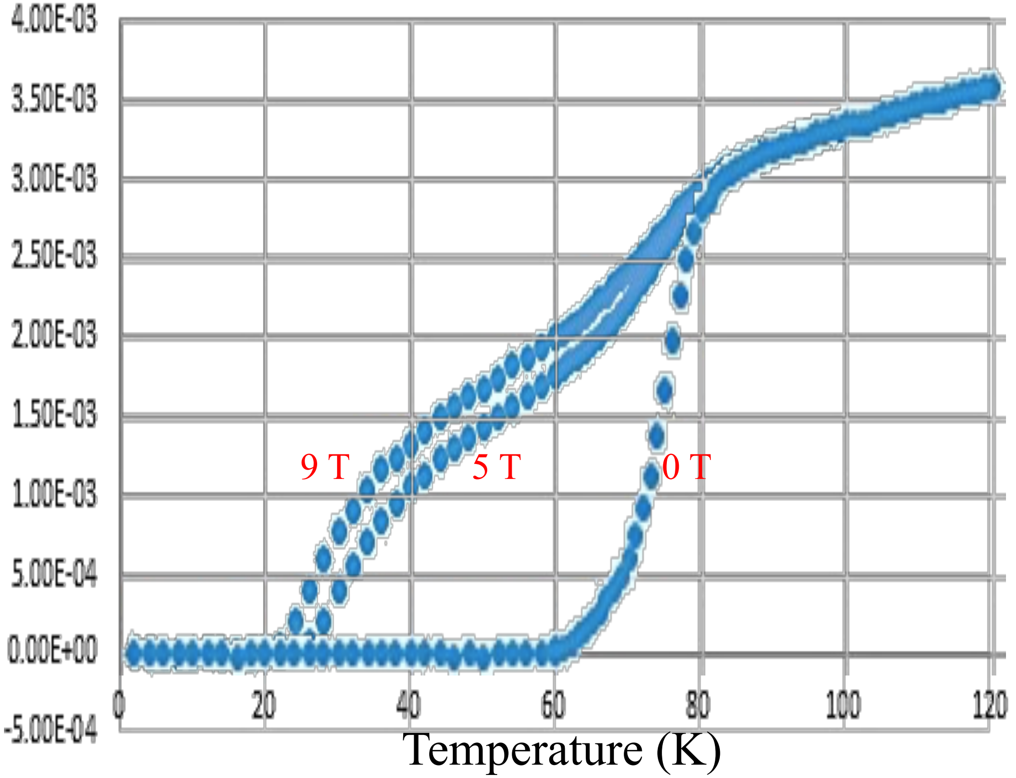
870 C for 2 hours, then fast ramp down-ramp

Some parasitic phase formation

Perfect texture

Current transport in Tablet samples

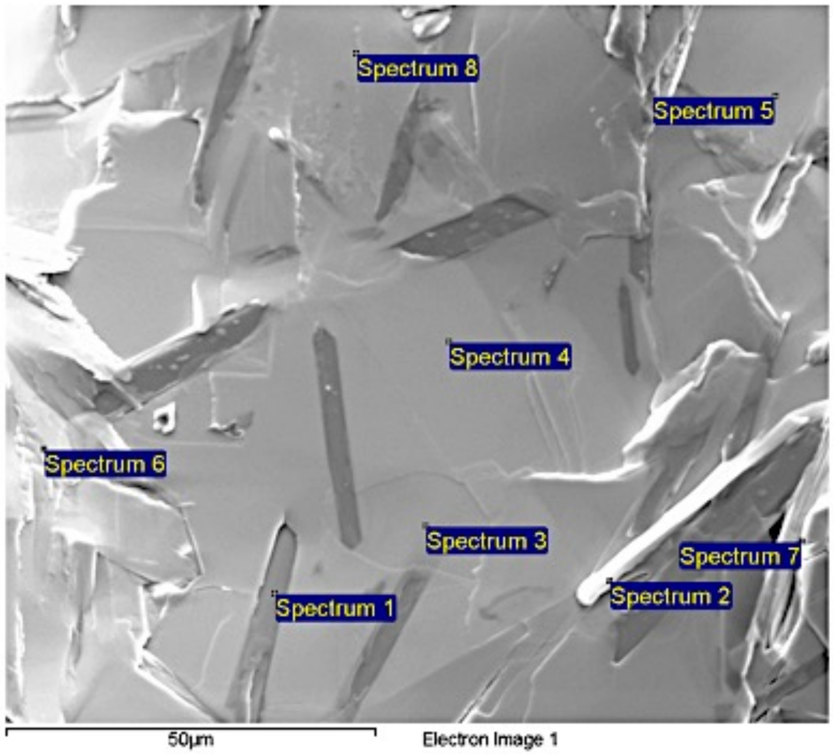




We have achieved macroscopic supercurrent transport over ~cm scale with tablet samples following non-melt heat treatment of nanopowder-enhanced textured-powder Bi-2212.

Now we are working to fabricate multifilament wire…

Is there melting in the TP core?



872 C 70 m ramp-up,
30 m dwell, fast ramp-down

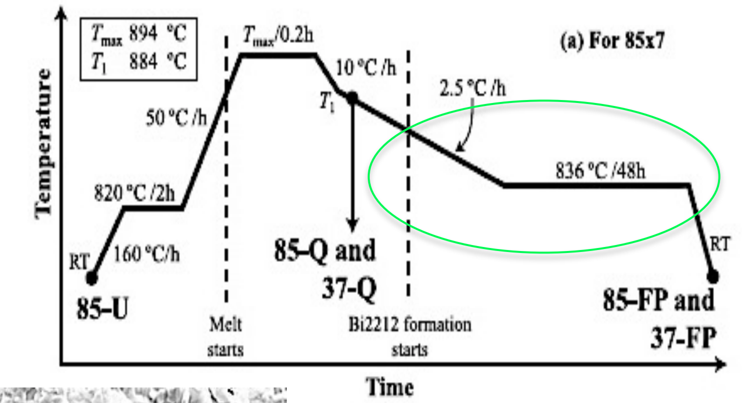
For 860 C-870 C, we see no evidence of melting in any sample

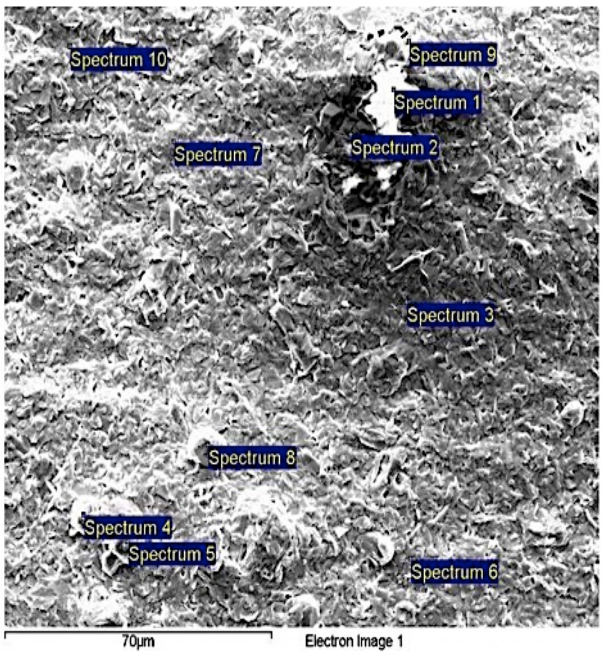
Processing option : All elements analysed

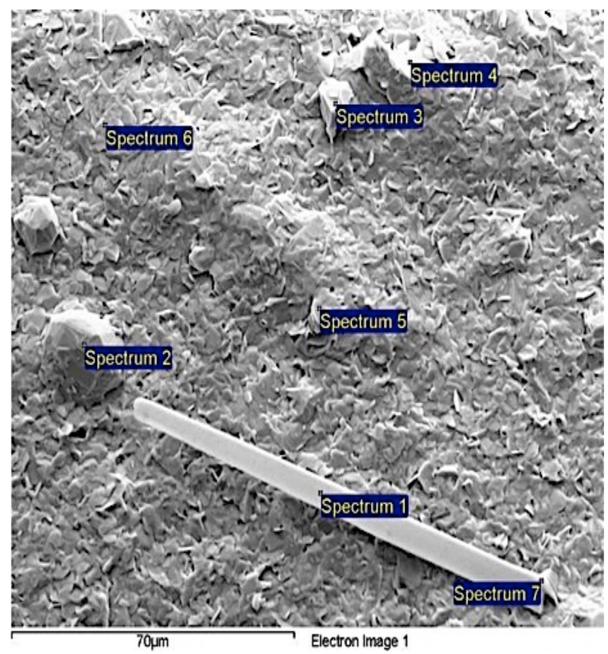
Spectrum	In stats.	C	Al	Ca	Cu	Zn	Sr	Ag	Bi	Total	
Spectrum 1	Yes	-11.45		61.33	384.12	0.42	295.63	-0.91	22.18	751.32	AEC
Spectrum 2	Yes			33.49	110.74		156.46	2.33	498.61	801.62	
Spectrum 3	Yes			16.95	97.99		194.92	1.76	606.89	918.50	
Spectrum 4	Yes			14.74	79.54		198.59	-0.41	652.01	944.47	
Spectrum 5	Yes			16.35	82.22		206.11	-1.11	687.24	990.81	
Spectrum 6	Yes	9.48		18.05	81.70		204.22	2.93	670.97	987.35	
Spectrum 7	Yes		1.99	8.99	73.71		96.46	0.52	335.88	517.55	
Spectrum 8	Yes			12.91	78.32		180.74	2.83	600.32	875.12	
Max.		9.48	1.99	61.33	384.12	0.42	295.63	2.93	687.24		
Min.		-11.45	1.99	8.99	73.71	0.42	96.46	-1.11	22.18		

And then we add the slow down-ramp of Kametani…

Kametani *et al.*, 'Bubble formation within filaments of melt-processed Bi2212 wires and its strongly negative effect on the critical current density', SUST **24**, 075009 (2011).





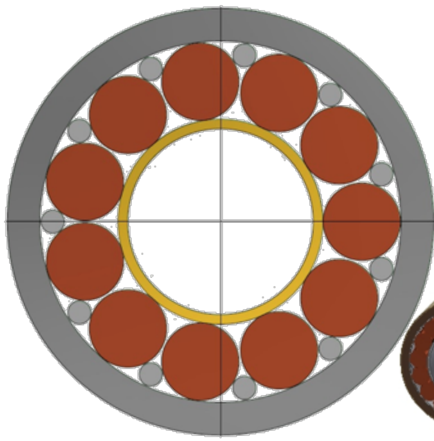
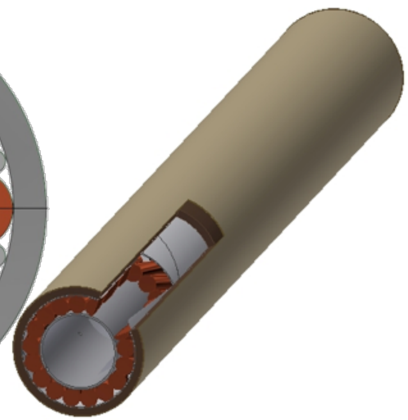
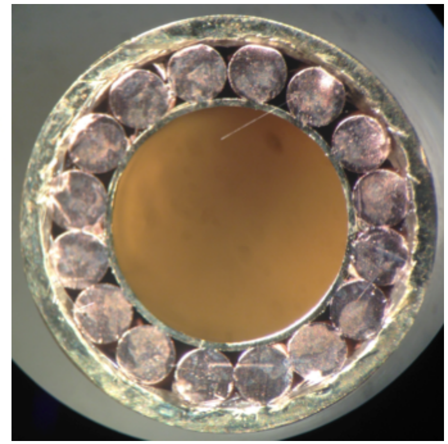


a) 875 C with 6 hr at top, no anneal; 9 parasitic phase grains were observed;
b) 867 C with 24 hr at top, 24 hr anneal; no parasitic phase grains are observed.

The anneal appears to reverse all parasitic phases back to Bi-2212.
The core is fully dense, and contains only Bi-2212 and Ag.

Will we be able to enhance j_c beyond what is achieved by overpressure?
Stay tuned – we plan to present first multi-subelement wire tests at ICMC.

Cable-in-conduit for Bi-2212/Ag
Robust 15 kA cable for hybrid dipoles

- Rutherford cable is ill-adapted for use in a hybrid-conductor dipole.
  - Nb_3Sn and Bi-2212 have radically incommensurate heat treatments – 650 C in Ar *vs.* 870 C in O_2.
  - One cannot separately prepare and heat-treat insert and outsert windings. It would be impossible to preload them thereafter for stress management.
- Solution: single-layer cable-in-conduit of Bi-2212.
  - Spiral-wind round-strand Bi-2212/Ag onto thin-wall spring tube;
  - Form/weld sheath tube on outside using continuous tube forming;
  - Draw sheath down onto cable to compress strands against spring tube

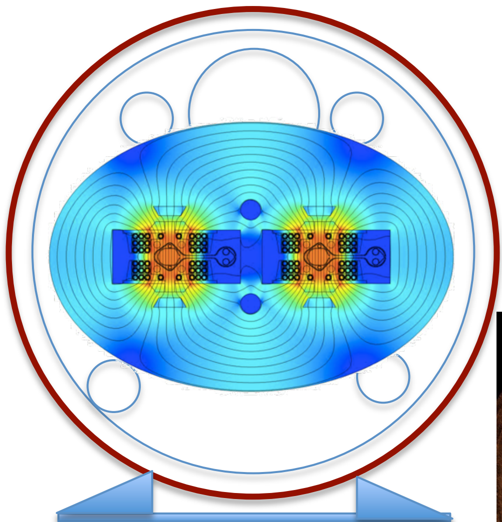
The CIC cable provides an ideal basis for insert windings

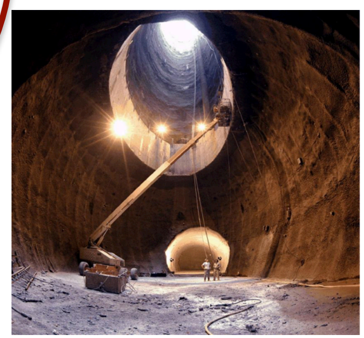
- It bends readily for flared end windings
  - Bend radius 8x cable radius maintains inner registration, no strain to strands
- Spring and sheath tubes made from Al bronze
  - no degradation of Bi-2212, diffusion barrier protects bronze
- CIC cable provides the retort for overpressure processing (if necessary) – no bombs…
- O_2 atmosphere only bathes the CIC interior, no oxidation to structural elements.
- Insert is stable and intact after HT
  - outsert windings can be wound onto insert and heat-treated without effect on insert
- Intrinsic stress management
  - Lorentz stress bridges through sheath tubes, Bi-2212 unharmed

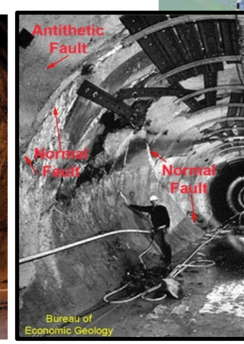
We have developed CIC cable fabrication, use in dipole windings

Low field, high circumference

= 4.5 T field, 270 km circumference

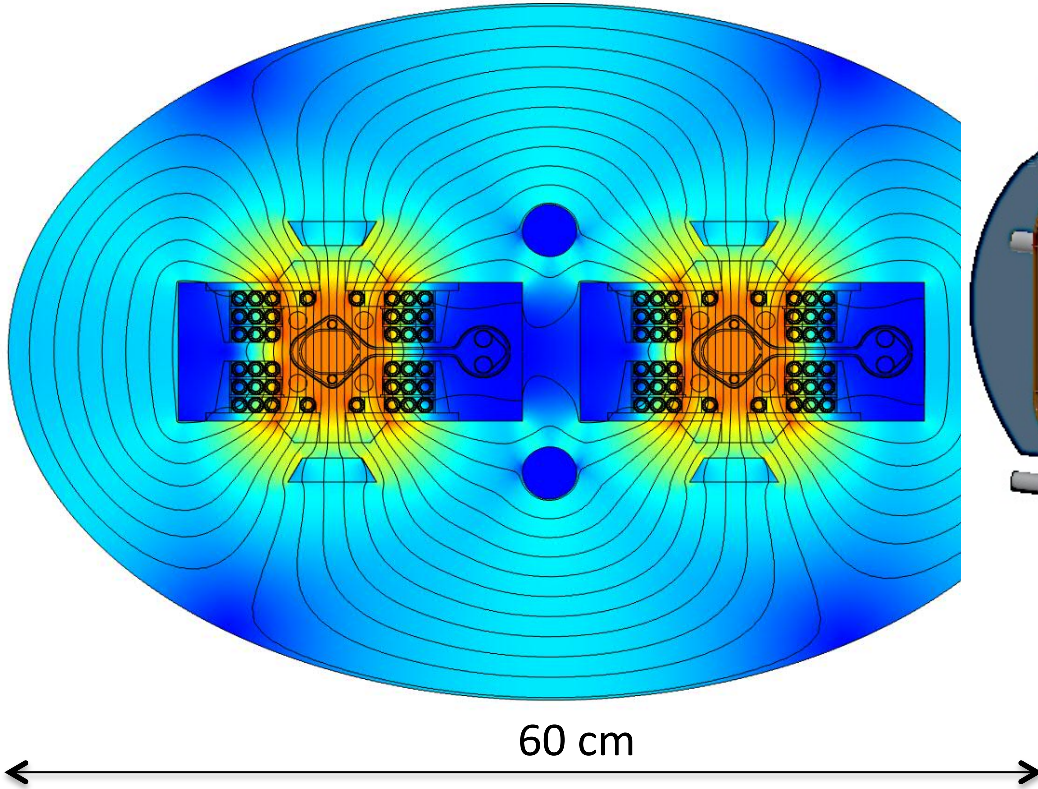


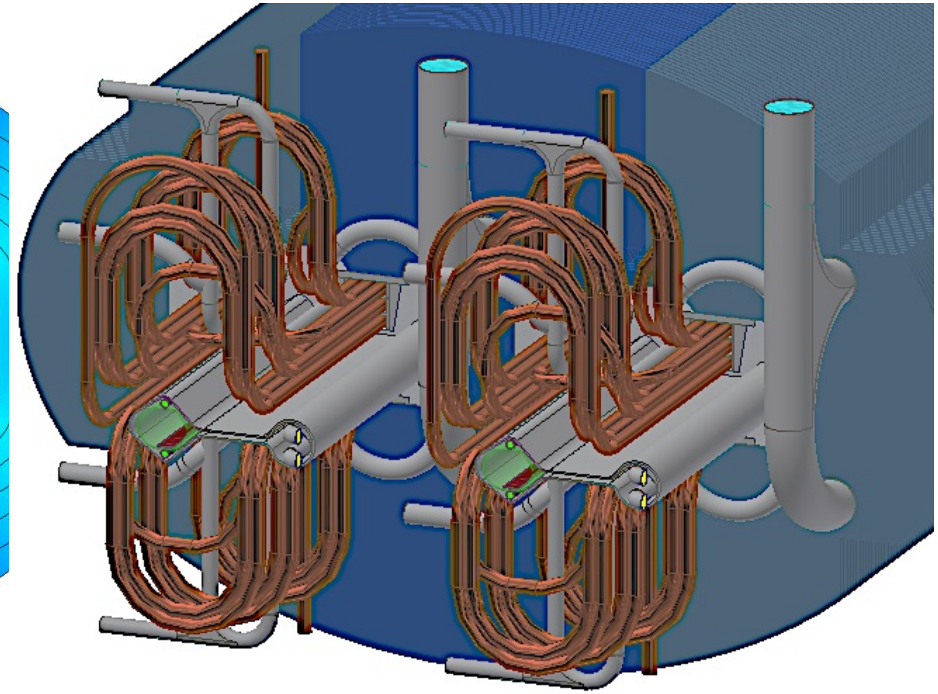




- Texas is blessed with Austin Chalk and Taylor Marl, *nature's ideal tunneling medium*.
- The SSC tunnels are the fastest-rate, lowest-cost tunnels ever built.
- $1,000/ft, $1.7 B today for 270 km, less cost than 90 km @ CERN
- We have designed a 4.5 T NbTi C-dipole that is ideal for the collider.

We have combined the simplicity of the low-field superferric SSC dipole with a cable-in-conduit conductor:





- **4.5 Tesla dipole field**
- C-dipole: synchrotron radiation is absorbed at 150 K in a side chamber (like LEP).
- Refrigeration is 100x more efficient, so heat load not a limit.
- Clearing electrode suppresses electron cloud; 25 ns bunch spacing feasible.
- Superconducting winding has 20 turns total, wound from round cable-in-conduit.

The 4.5 T NbTi dipole is key to manufacturability and cost

- Each dipole winding contains a total of 20 turns of cable.
- Quench protection is provided by driving current pulse in cable sheath – quenches all turns without voltage spike.
- Total cross-section of superconducting strand in one dipole is 8 cm^2 NbTi.
- Compare to 39 cm^2 NbTi for LHC,

  105 cm^2 of Nb_3Sn and 32 cm^2 of NbTi for 16 T dipole.
- Total cost of superconductor for 16 T ~$22.8 billion.
- Total cost of superconductor for 4.5 T ~$2.4 billion.

Jack and the Game…

- The world will not pay an unlimited amount of $ + € + ¥ for future discovery in high energy physics.
- It is incumbent upon us to make Moore's Law work for HEP, so the next collider costs no more than the last collider.
- We must seek lowest-cost technology for magnets, and lowest-cost sites for tunnels.
- Then perhaps we can play…