Synergies of HTS Magnet Programs – how do we effectively make useful HTS magnets routine?

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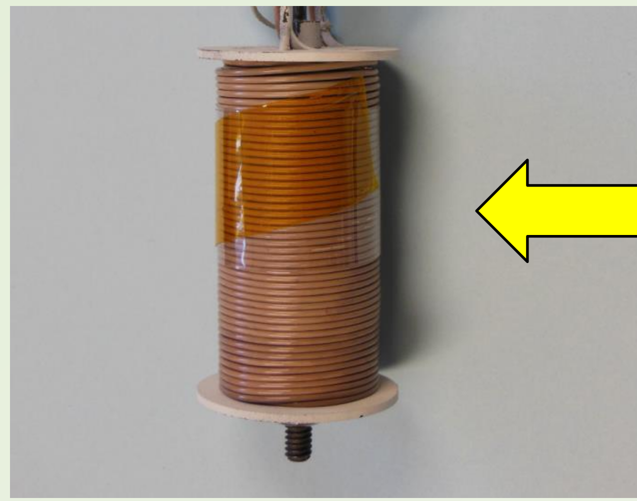
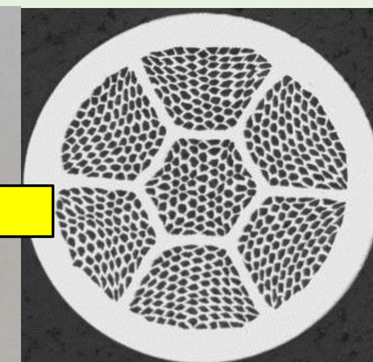
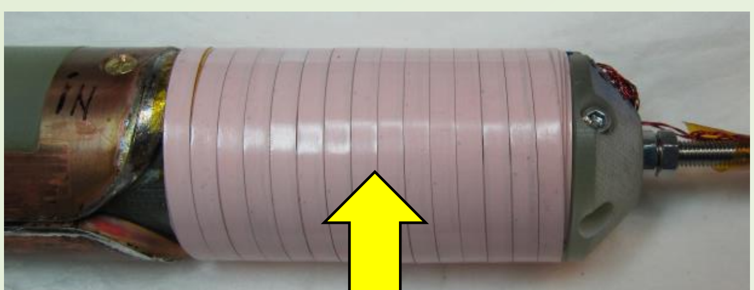




34T (in 31T) – Bi-2212



35T (in 31T) – REBCO coated conductor

Key people at the MagLab

- 32 T team
  - Huub Weijers, Denis Markiewicz, Andy Gavrilin, Hong-Yu Bai, Patrick Noyes, Dima Abraimov, and many others
- Platypus team
  - Ulf Trociewitz, David Hilton, George Miller, Ernesto Bosque, Daniel Davis, Peng Chen and many in the broader 2212 effort
- 2212 team
  - Eric Hellstrom, Jianyi Jiang, Fumitake Kametani, Peter Lee, Maxime Matras, and Ulf Trociewitz, Natanette Craig (now IBM), supported by Bill Starch and Lamar English
- REBCO team
  - Dmytro Abraimov, Jan Jaroszynski, Xinbo Hu, Anatoly Polyanskii, Lidia Rossi, Michael Santos and Huub Weijers
- Management
  - Greg Boebinger, Eric Palm and Mark Bird with strong NMR support from Lucio Frydman, Tim Cross, Joanna Long and Bill Brey

Partnerships and collaborations

- **Bismuth Superconducting Strand and Cable Collaboration (BSCCO)** – (leaders Larbalestier, Hellstrom, Cooley (FNAL), Godeke (LBNL), Ghosh (BNL) – direct DOE support to NHMFL (2013-2015, with FNAL and LBNL lab support through GARD funds)
  - Industrial collaborations with Oxford Superconducting Technology (OST), Nexans and CERN
  - Conductor Development Program (Dan Dietderich and Ken Marken leads)
- **BSCCO MOU with CERN for contributions to EUCARD2, (WP10)** to develop 5-10 kA HTS cable for 5 T HTS insert dipole magnet –US side coordinator is David Larbalestier, leveraging BSCCO effort with support from the Conductor Development Program of DOE-HEP for industrial production, leader Dan Dietderich (LBNL).
- **NMR collaboration with RIKEN** – 2212 coil to be built for Professor Hideaki Maeda's 500 MHz system
- **Coated Conductor Round Table** – meeting of REBCO coated conductor project labs (NHMFL, MIT-NMR, MIT-PFC, BNL, CAPS-FSU, SuperPower, Advanced Conductor Technologies) coordinated by Trudy Lehner (SP), David Larbalestier (NHMFL) and Yuki Iwasa (MIT)
  - The partnership with SuperPower on REBCO coated conductor starting in 2007 is what enabled us to propose 32 T so early
  - R&D partnership with group of Selvamanickam at TcSUH through former PhD Aixia Xu
- **32 T outsert coil design and manufacture** – Oxford Instruments team led by Ziad Melhem

Collaborator talks

Wednesday 21 May 2014

14:35	[7] HTS development and industrialization at Superpower (25'+5')	HAZELTON, Drew

Thursday 22 May 2014

09:30	[25] Review of Ic variation, Rc, RRR and other parameters (25'+5')	ABRAIMOV, Dmytro

Friday 23 May 2014

V. Bi-2212 - I (08:30-11:10)

- Conveners: Ballarino, Amalia

time	[id] title	presenter
08:30	[30] Powder Optimization (15'+5')	RIKEL, Mark
08:50	[31] OST - Present and future practical performance (25'+5')	PARRELL, Jeff
09:20	[32] Optimization parameters space (best performance and compromise) (25'+5')	HELLSTROM, Eric
09:50	Coffee break	
10:10	[33] Wire critical surface and cable properties (25'+5')	GODEKE, Arno
10:40	[34] Fermi program of optimizing Bi-2212 conductor (25'+5')	COOLEY, Lance

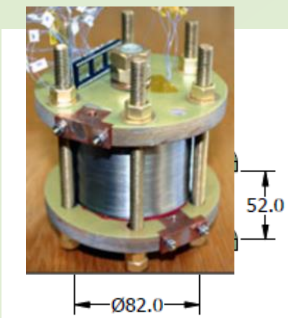
Key issues

- We all want to get HTS into magnets
  - Could be 2223, REBCO or 2212 (here I consider only REBCO and 2212)
  - Collaborations with active, capable and committed partners are vital
- No coil is better than its conductor
  - How good are REBCO and 2212 conductors?
- Coil projects drive our work
  - 32 T all superconducting user magnet is our first key effort – uses SuperPower REBCO
  - Platypus and RIKEN NMR prototype are our second – both will use OST twisted round wire Bi-2212
- Progress has been slow – few real, user HTS magnets so far
  - But now MagSci, NMR uses and CERN/FCC are driving technology expectations
- What can we deliver in the next 2-3 years?
  - 32 T
  - NMR quality coils (MagLab, RIKEN)
  - Accelerator test coils (LBNL, FNAL, CERN)
  - General purpose, routine use coils under consideration
- Successes needed to make MagSci challenge take up plausible

32 T Technology Development now reaches 7 yrs.

- YBCO tape characterization & QA
- Insulation technology
- Coil winding technology
- Joint technology
- Quench analysis & protection
- Extensive testing of components

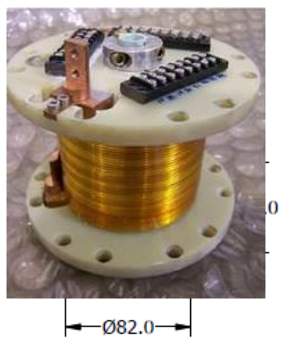
2007



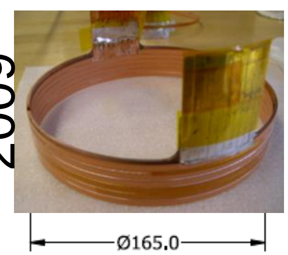
2008

High-B coils
31 T + ΔB

2008



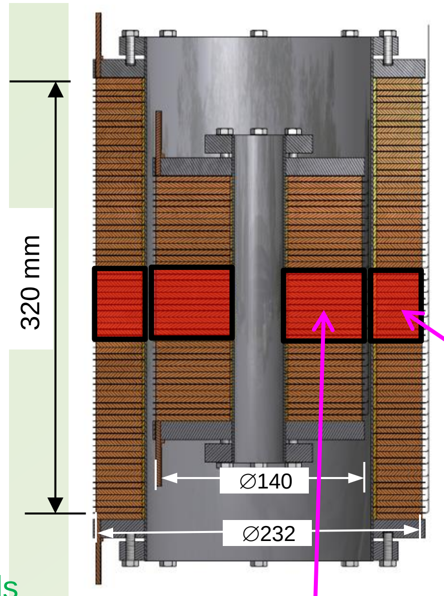
2009

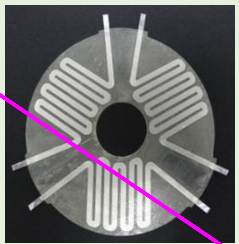


Demonstration inserts
20 T+ ΔB

High Hoop-stress coils
>760 MPa

Proposed Coils ≥ 20x mass increase

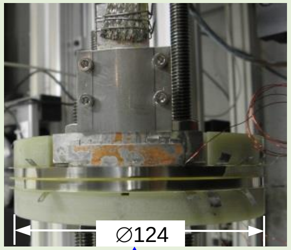




Quench heater

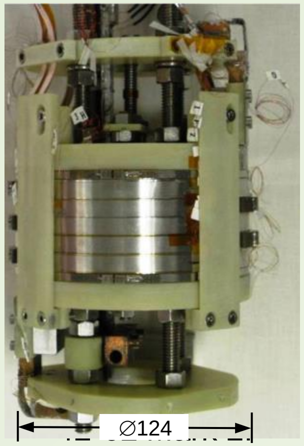
Heater-only quench protection

2011



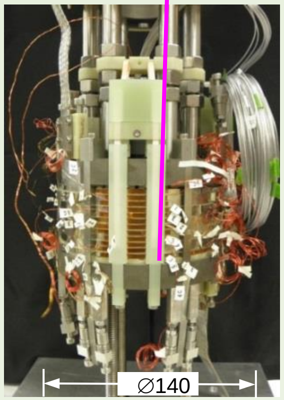
First Quench Heaters
42-62 Mark 1:
1st test coil

2012



2nd test coil

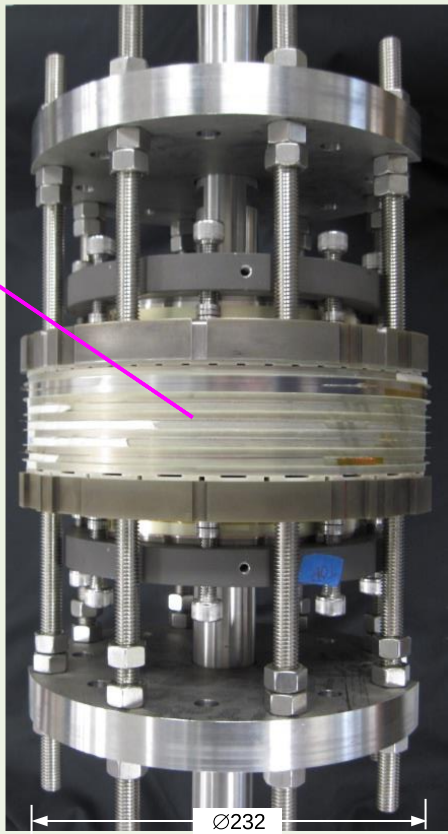
2013



20 - 70: 1st Full-feature Prototype

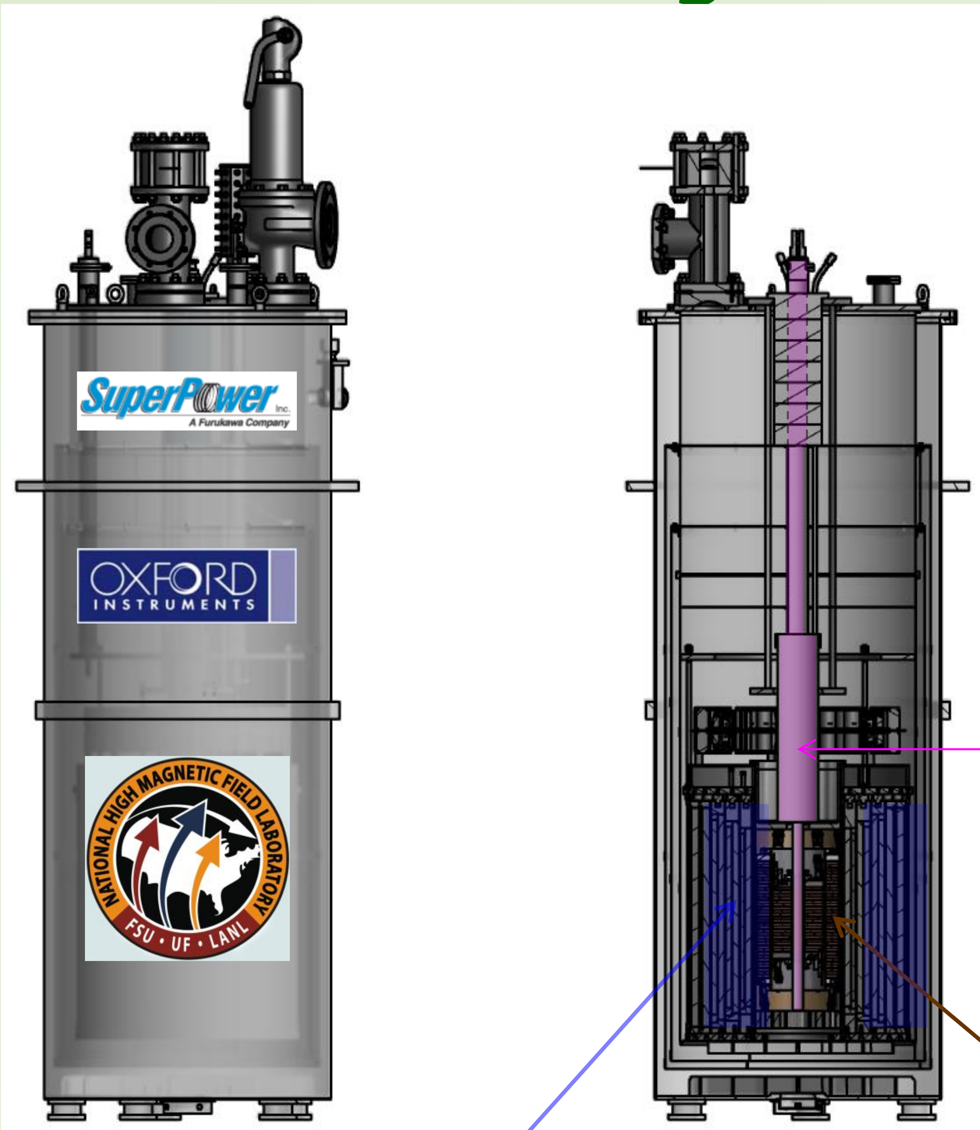
W.D. Markiewicz, H.W. Weijers, et al
Slide by Weijers.

2014



82 - 116:
2nd Full-featured Prototype

The 32 T magnet: a *user* magnet



Cold Bore	32 mm
Uniformity 1 cm DSV	$5 \cdot 10^{-4}$
Total inductance	254 H
Stored energy	8.6 MJ
Ramp to 32 T	1 hour
Cycles	50,000

Dilution refrigerator

2.5 m

32 T will spend most of its life *ramping up and down at 4.2 K*

Two REBCO coils

0.9 m

15 T / 250 mm bore LTS magnet

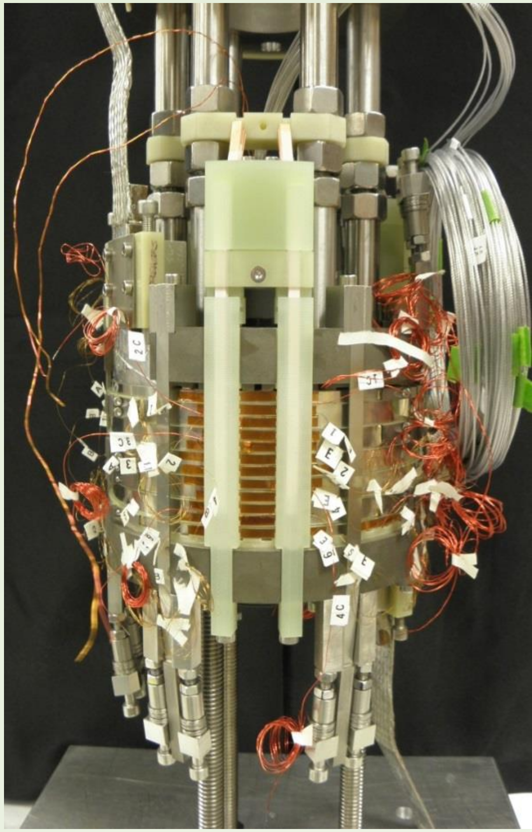
17 T REBCO coils

Full-featured prototype coil

Weijers and Markiewicz

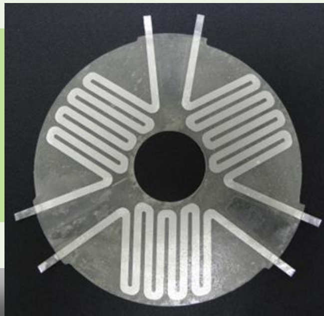
6 modules versus 20 in Coil 1 of 32 T
Much extra instrumentation

- Test results
  - Confirms concept viability: *go ahead as planned*
  - Identified detail areas that need rework
  - "Helium gas bubble" (He diamagnetism) not a problem
    - Measures taken are effective
  - Active quench protection with heaters:
    - Quench initiation study √
    - Quench protection test √
  - Drives activities for second prototype, to be tested in 45T Hybrid outsert (11 T) together with first prototype. Test completion expected in August 2014.
  - Lead to initial design of 32 T quench protection
    - Final design requires combined HTS-LTS analysis



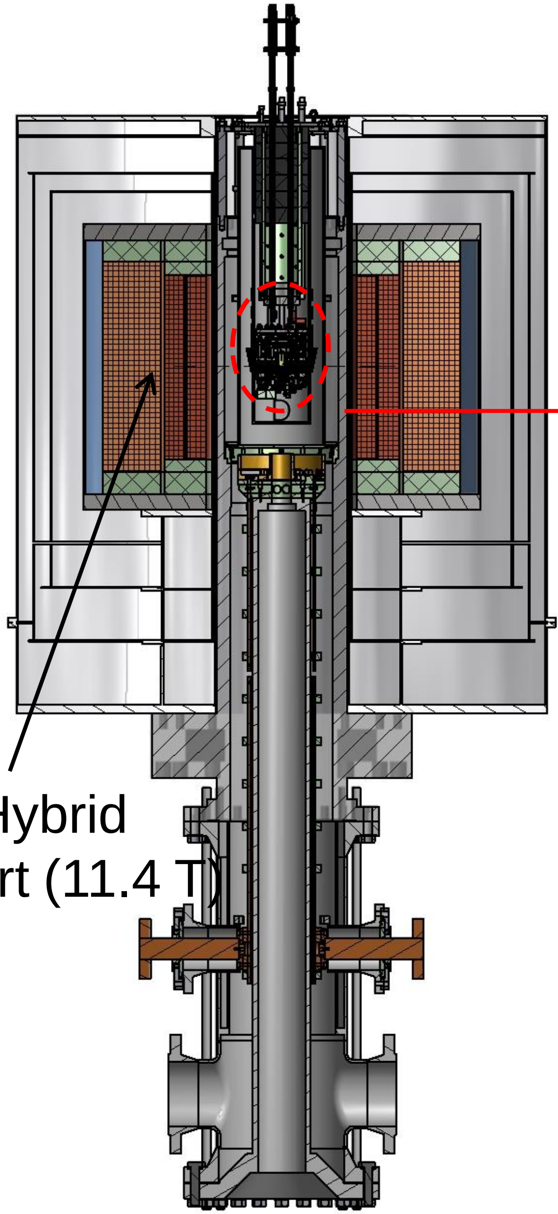
Complete prototype coil
with instrumentation and wiring

Quench heater spacer

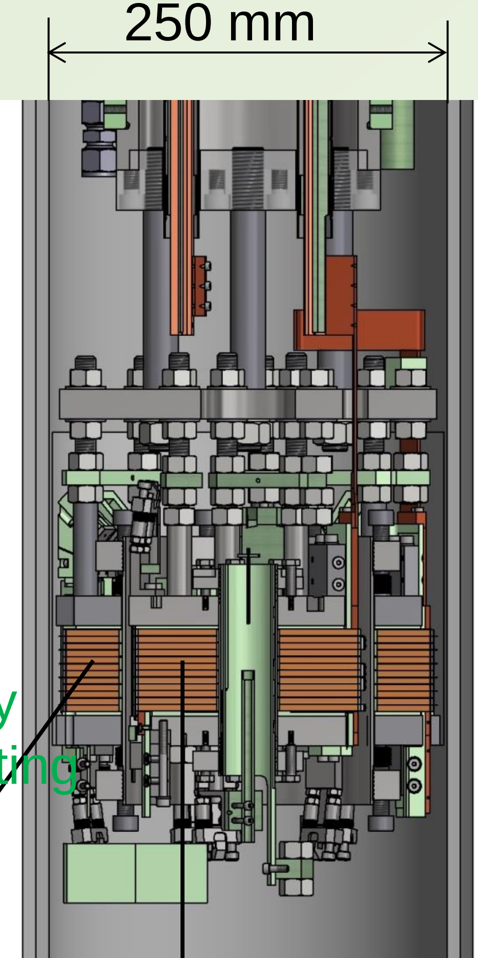


Our Quench Protection approach is unique (and furthest in development)
amongst groups working on REBCO coils (too large for dump resistor)
"No-Insulation" was dominant (at MT-23), but not suitable for 32 T

Test setup for the testing of both prototype coils for the 32 T magnet



Cryostat with REBCO coil inside Resistive Magnet housing



- 1.9 km of REBCO in
- 12 double pancakes
- Realistic stress levels
- Exceed current density
- Extensive Quench testing
- 21 T all-SC at 200 A
- Higher possible

The 32 T winding team

High Magnetic Field Science and Its Application in the United States: Current Status and Future Directions

The recommendations (Halperin (Harvard) Chair)

- Consider **regional 32 T superconducting** magnets at 3-4 locations optimized for easy user access.
- Establish at least **3 US 1.2 GHz NMR** instruments (planned commercial) for broad access and plan for ~1.5 GHz class system development
- Establish high field **(~30 T)** facilities at neutron and photon scattering facilities
- Construct a **20 T MRI instrument** (for R&D)
- A **40 T all-superconducting magnet** should be designed and constructed,
- A **60 T DC hybrid magnet** that will capitalize on the success of the current 45 T hybrid magnet at the NHMFL-Tallahassee should be designed and built.

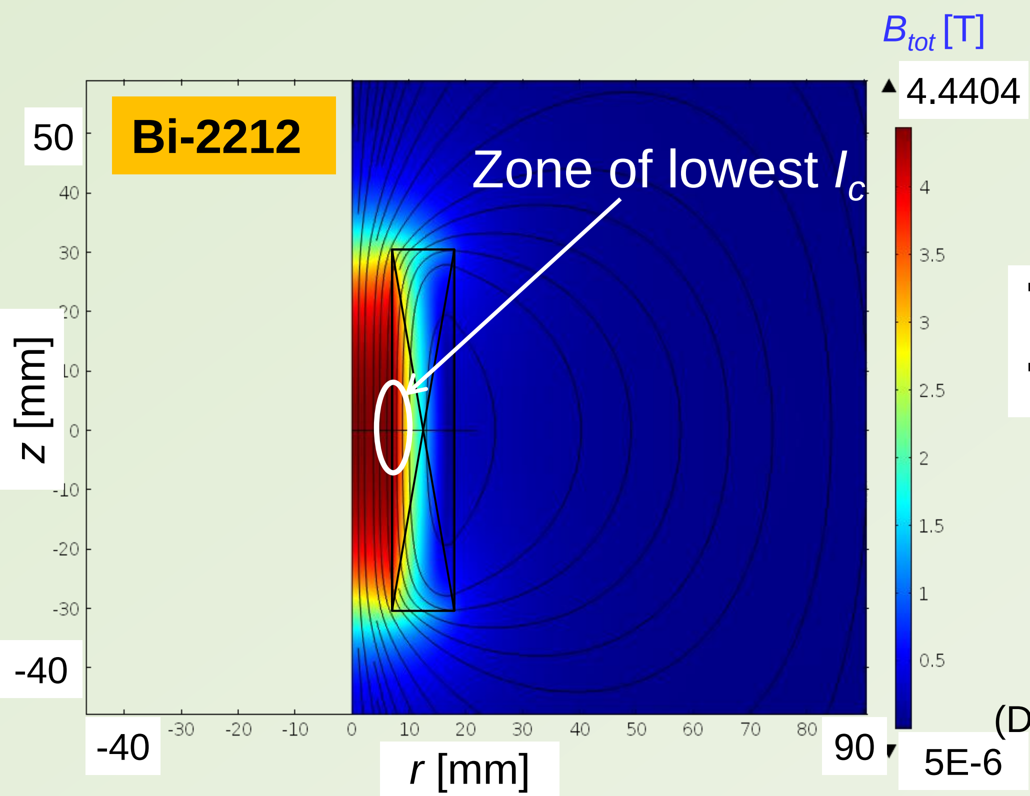
Very strong synergy with High Energy Physics goals (LHC energy upgrade and Muon Accelerator), DOE-BES (APS and SNS) and we hope NIH goals for NMR and MRI

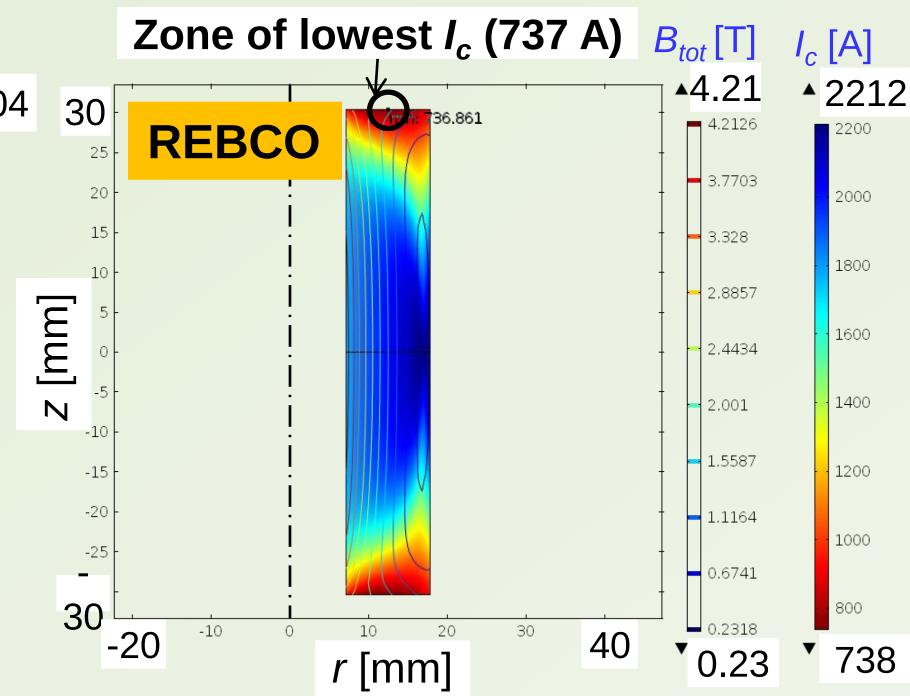
HTS coils for NMR

- Leading programs at RIKEN (J), Bruker (D) and MIT and NHMFL (US)
- Bi-2223 capability established by RIKEN
  - Some issues with REBCO
  - 2212 version under consideration
- Bruker is planning on a 28 T using REBCO
- MIT is planning on a 30 T coil using REBCO
- We first considered REBCO but have now selected 2212

Layer wound NMR prototype coils: How does conductor (an)isotropy play out?

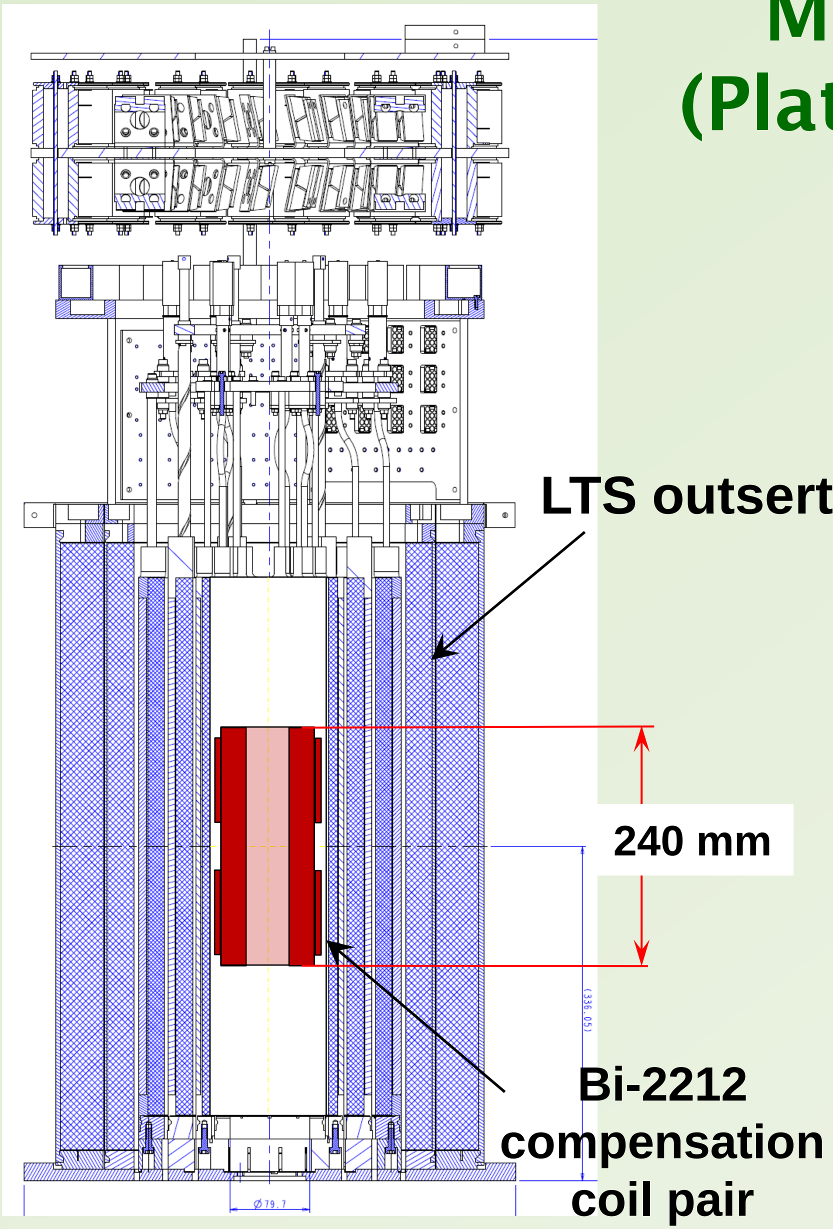
- Bi-2212 is isotropic: high |$\underline{B}$| => low I_c, with no field orientation dependence
- REBCO is anisotropic: both |$\underline{B}$| and its orientation wrt tape plane matter
- **In absence of other defects (hot spots etc.) a Bi-2212 RW coil will likely quench from inside, while REBCO coil will quench from its ends**
- Cooling may become an issue (He-bubble)





(Design by Ulf Trociewitz and $I_c(B,\varphi)$ fit by D.K. Hilton)

A Bi-2212 High Field Homogeneity R&D Magnet (Platypus II)



Why Bi-2212 round wire?

- Recent process improvements driven J_w >> 100 A/mm^2
- Ease of application
- Not affected by field angle & shielding currents

What is our concept?

- Existing Oxford LTS magnet as test bed
- Bi-2212 layer-wound central solenoid (TiO_2 insulated, epoxy impregnated) and Bi-2212 layer-wound compensation coils to set magnet homogeneity baseline
- HTS insert powered separately from the LTS using low noise power supply (Danfysik)

Trociewitz and Hilton

Platypus II Coil Specifications

Bi-2212 Central solenoid			
Wire dia. [mm]:	1.3	Operating Current [A]:	400
Insulation [mm]:	0.01	Je (Engineering) [A/mm^2]:	301.4
Inner Radius (a1) [mm]:	22.23	Jw (Winding) [A/mm^2]:	229.6
Outer Radius (a2) [mm]:	45.99	B(0,0) [T]:	6.58 T
Height (2b) [mm]:	236.28	Coil Constant (0,0) [mT/A]:	16.44
Windings/Layer [-]:	179	Homogeneity , solenoid only (10 mm dsv) [ppm]:	192.6
Radial Layers [-]:	18	L [H]:	141
Total Windings [-]:	3222	Total Field Energy [kJ]:	11.3
Conductor Leng [m]:	0.7 km	op stress at a2	233 MPa

Bi-2212 Compensation Coils (each)			
Wire dia. [mm]:	1.3	Operating Current [A]:	400
Insulation [mm]:	0.01	Je (Engineering) [A/mm^2]:	301.4
Inner Radius (a1) [mm]:	50.04	Jw (Winding) [A/mm^2]:	229.6
Outer Radius (a2) [mm]:	54.0	Hoop stress at a22 [MPa]:	270 MPa
Height (2b) [mm]:	60.72		
Windings/Layer [-]:	46		
Radial Layers [-]:	3		
Total Windings [-]:	138		
Conductor Leng [m]:	45 m		

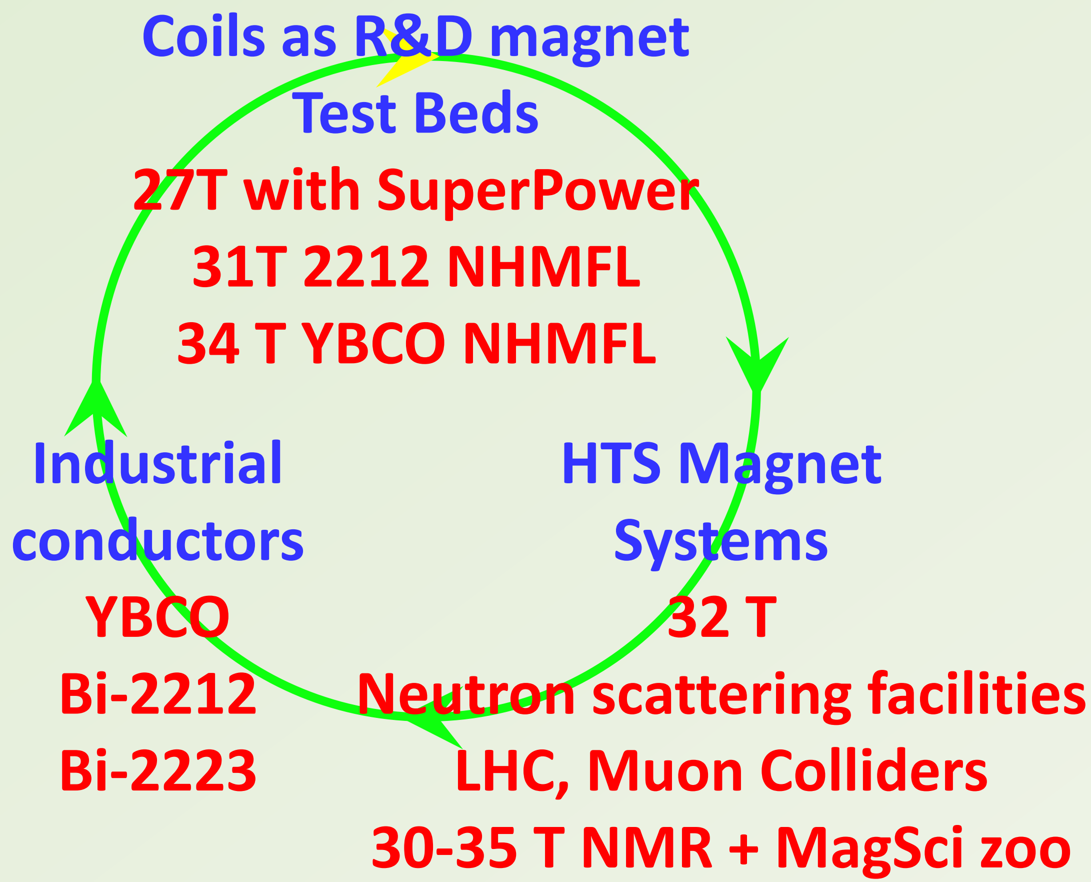
- Insert approaches “long coil” (B_{insert} = 6.58 T *vs.* B_{insert} = 6.85 T for β -> inf.)
- homogeneity increase achieved through introduction of series-connected compensation coil pair

- Likely to require external reinforcement

Trociewitz and Hilton

What do we need for a secure HTS magnet technology?

- A real applications pull that can generate continuous conductor orders
- Conductors worth continuous orders



See also Maeda and Yanagisawa IEEE TAS, DOI 10.1109/TASC.2013.2287707 MT23 plenary talk

A quick view of important REBCO and 2212 issues (see also Abraimov, Cooley, Godeke, Hellstrom and Huang talks)

- REBCO – single filament tape, still supplied in short lengths (even if made in long lengths)
  - Complex processes prone to yield problems
- Bi-2212 – multifilament, twisted conductor looks like Nb-Ti, Nb_3Sn and the new power-supply link conductor MgB_2
  - Requires expensive, low modulus Ag, requires force support, requires 20-100 bar overpressure reaction

REBCO conductor specification issues

- Geometrical properties
- Mechanical properties
- Electrical properties
  - Normal state properties
  - Superconducting properties
- Magnetic properties
- Environmental
- Traceability and records
  - Materials and production procedures
- Quality Control, Quality Assurance
  - Measurement techniques, procedures, standards
- Handling Non-conformity

Collaboration with SuperPower has been excellent

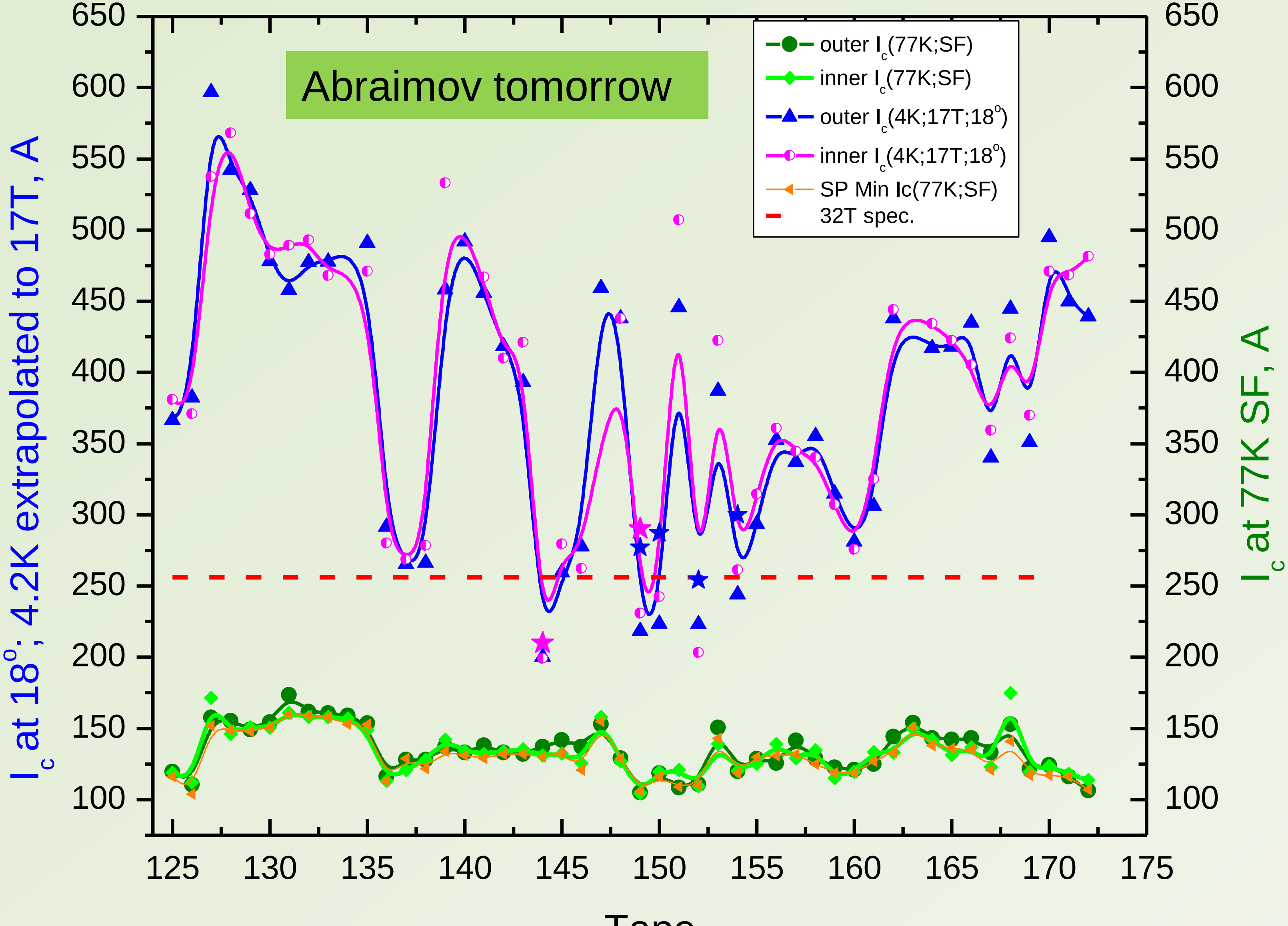
+ tolerances (uniformity)

Two examples follow

Routine for LTS, breaking new ground for HTS conductors

Progress in I_c measurements for recent delivery : SP125 – SP172 (~3720m)

Data arranged by NHMFL numbers – delivery time line



Only SP144,149,150,152,154 did not passed I_c(4K, 17T) test

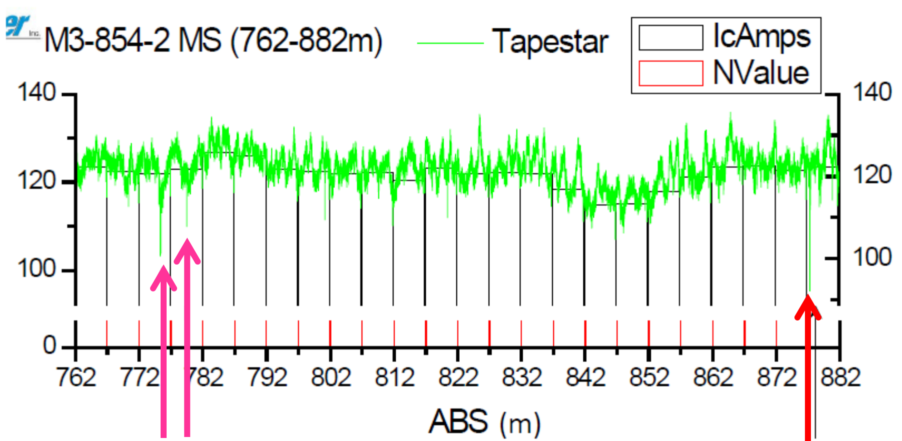
SP144, SP 152 did not passed I_c test at any ab-plane orientations

Very good correspondence between I_c(77K; SF) measured in ASC and min I_c(77K;SF) measured by SP

Stars mark I_c data measured at different ab-plane orientation

Superconducting length (non) uniformity

Data courtesy of SuperPower



Not detected with LANL device ("Yatestar")

Used in section of coil where quenches originate

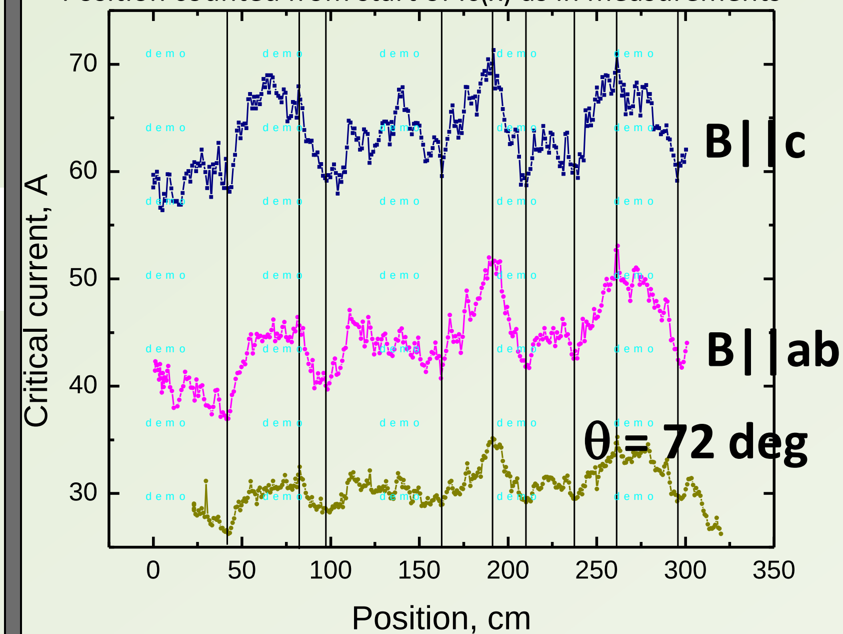
- ***Tapestar:***
- **Magnetization-I_c corresponds well to transport I_c over 5 meters at 77 K**
- **High through-put**
- **Spikes may or may not correlate to physical realities**

We have many elements of what is needed to accurately measure long lengths in transport at 77K and to correlate magnetization at 77 and 4 K

"Yatestar"

- Transport I_c per 2 cm
- T = 75 K (LN_2) B = 0.5 T, …..variable angle
- Low throughput

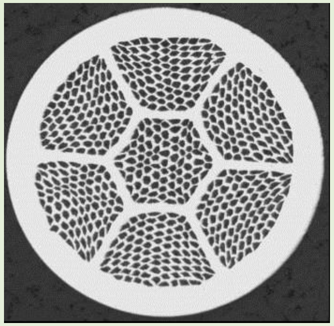
Position counted from start of Ic(x) as in measurements



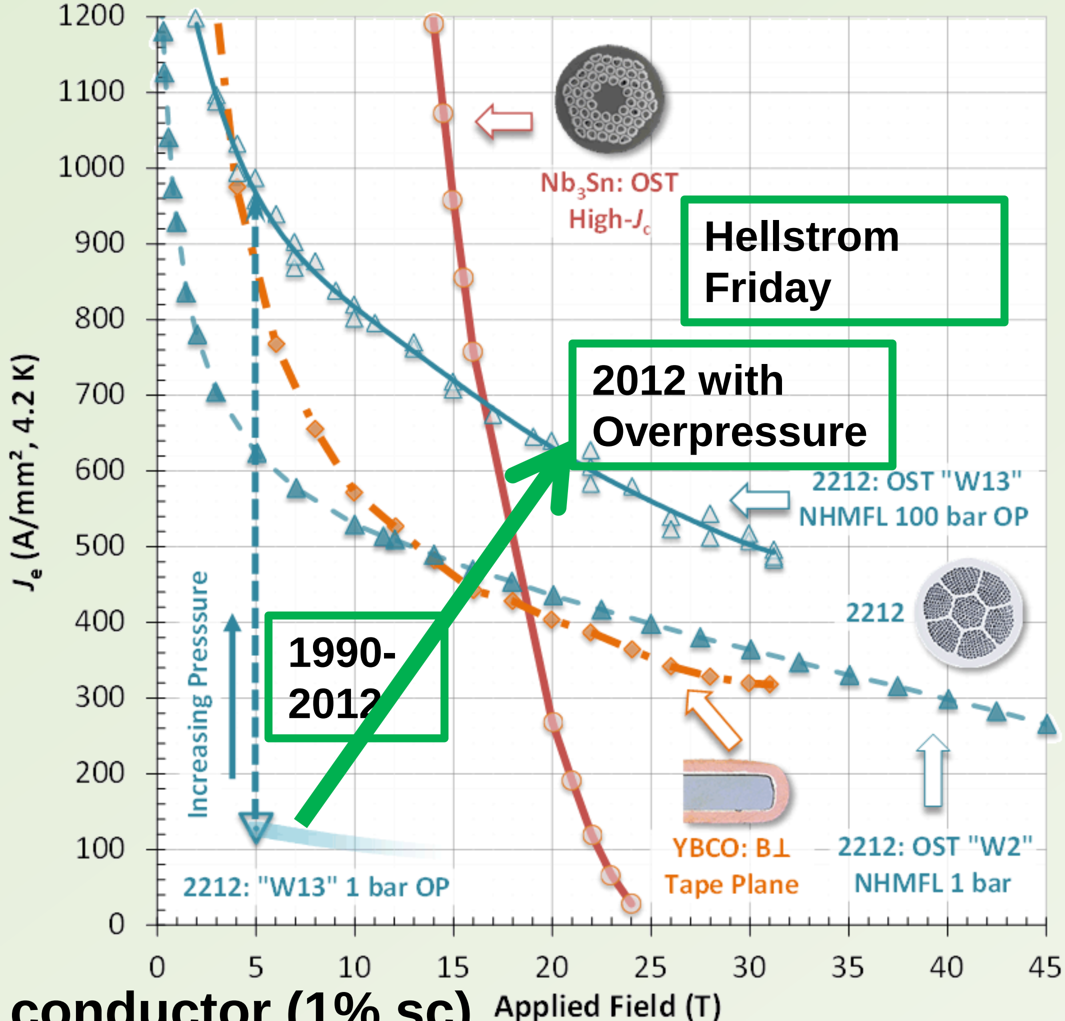
Prototype built at LANL by Yates Coulter and engineered for 200m lengths at NHMFL by Jan Jaroszynski and John Sinclair, now with Hall probes operating at both 77 and 4 K (Alex Stangl)

Prior to 2012, all HTS conductors (Bi-2223, REBCO) were tapes delivered in reacted form

- Bi-2212 upended this paradigm, delivering a high current density (the highest of all actually) in round-wire, multifilament, twisted form
- The first HTS conductor to look like an LTS conductor
- Conductor must be wound, then reacted
  - Big advantage – very flexible architecture



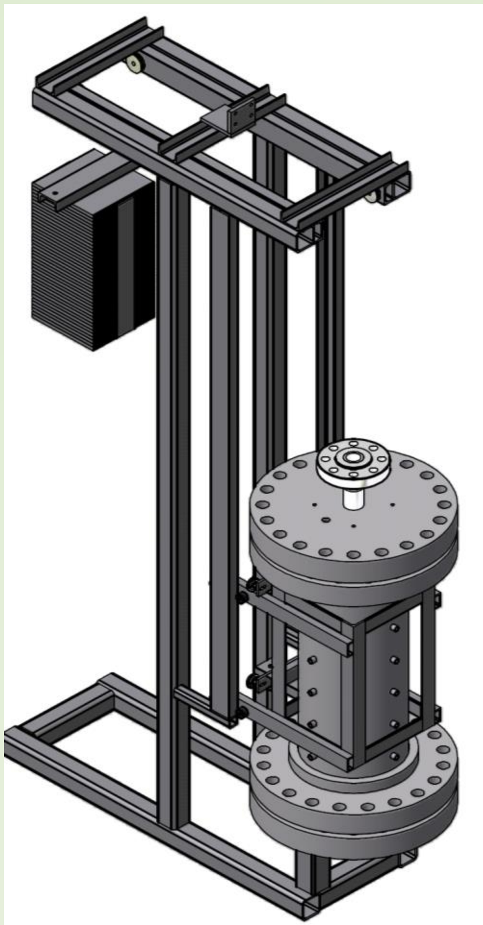
2212 (25% sc)

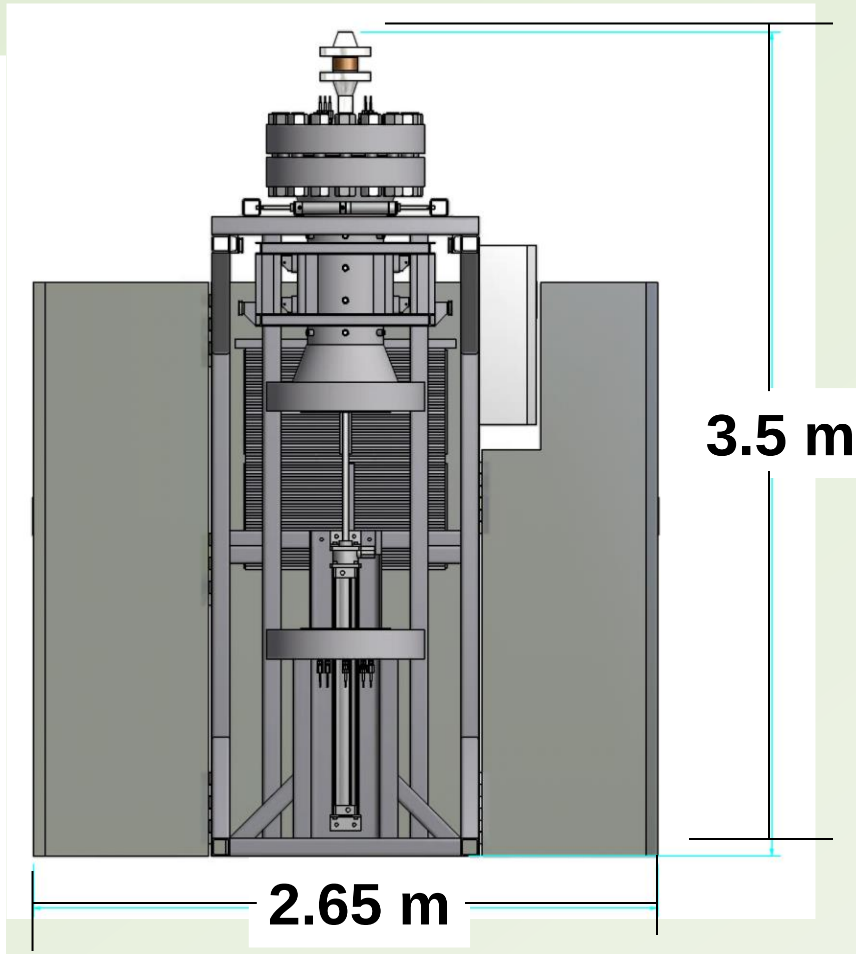


REBCO coated conductor (1% sc)

100 bar OP furnace for large coils

Hot Zone:
17 cm ϕ, 50 cm



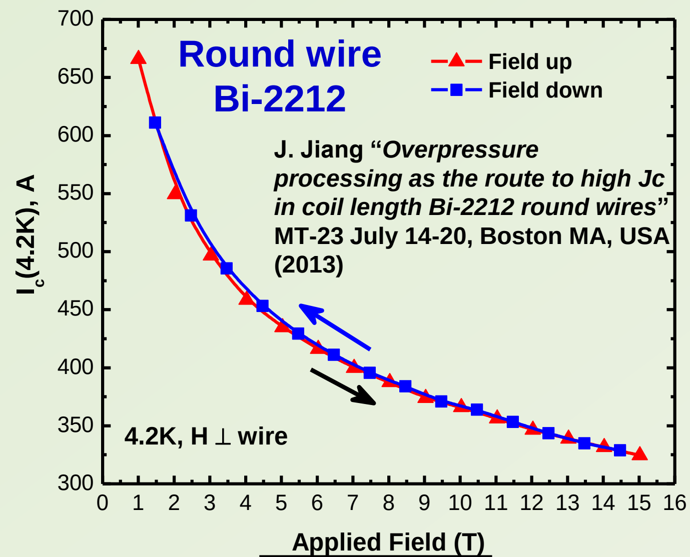


Delivered Dec. 2013
Final installation underway

Hellstrom on Friday morning

Higher J_c in round wire (RW) 2212? Almost certainly: so far J_c raised mainly by connectivity enhancement…

- Overpressure processing removes gas bubbles but leaves high angle GBs in place
  - However no hysteretic signature of weak links as is quite obvious in Bi-2223
  - Does this mean that high angle GBs do not block current in 2212 as all expectations from 2223 would suggest?
- Recall that Bi-2212 is the first HTS conductor like an LTS conductor
  - twisted, multifilament, round, good normal conductor in parallel – no Diffusion Barrier needed
- Bi-2212 round wire development is an ongoing effort of US BSCCo (Bismuth Strand and Cable Collaboration
  - at ASC-NHMFL, BNL, FNAL and LBNL with OST and Nexans (under CERN support) in association with EUCARD2



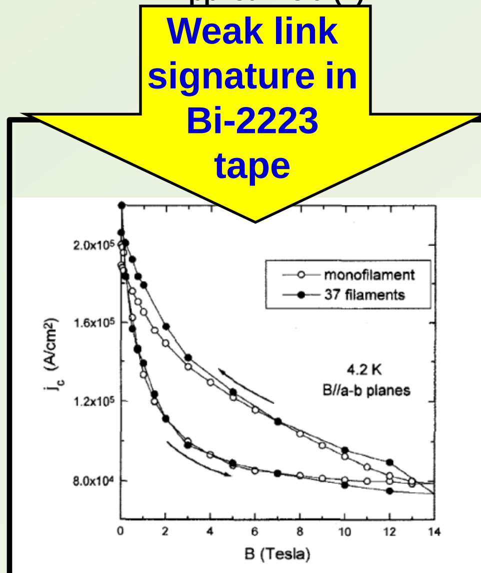
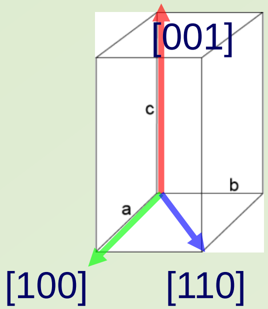
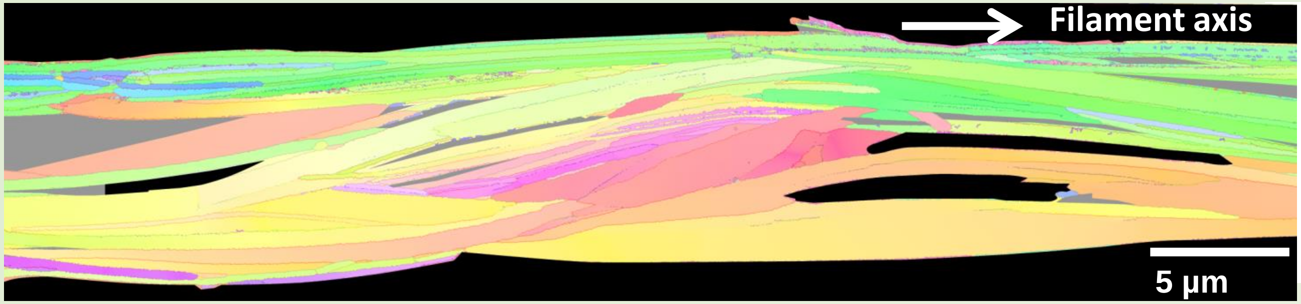


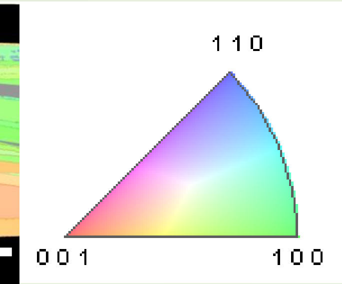
Fig. 4. Critical current densities as a function of the field and of its history at 4.2 K for both mono- and multifilamentary tapes.

[Ref. **] Martin *et al.*, *IEEE Trans. Appl. Supercond.*, (1997)

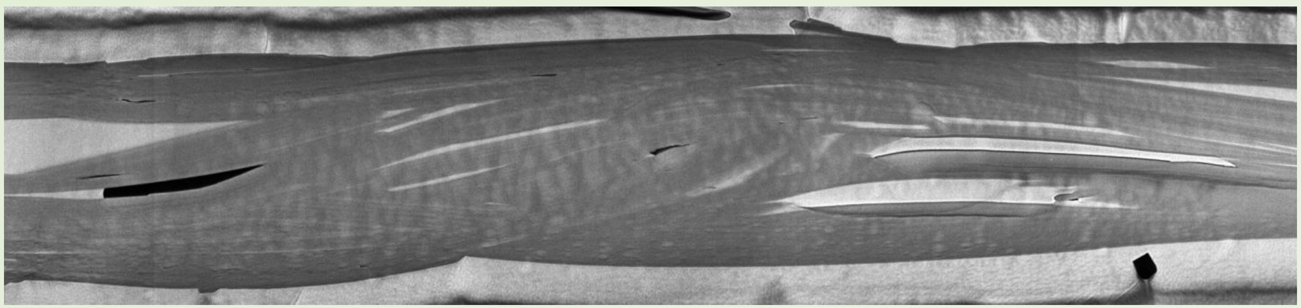
Bi-2212 connectivity is far from perfect







- Although wires have no macroscopic texture, local growth-induced texture at filament-level is strong



- Filaments are not yet phase-pure either and 2nd phase must block supercurrent even if high-angle GBs do not

Kametani et al. (ASC-NHMFL) in preparation EUCAS 2013

SWOT – getting HTS into the big time

Strengths

- High Jc at B impossible for Nb
- Proof of principle to 35T so far
- Insulation technologies for both REBCO and 2212
- Strong industry in CC manufacture and broad interest

Opportunities

- MagSci magnets
- HEP machines – MAP and LHC
- 35-40 T POP in 31 T in view
- Solution NMR demonstrations with 2212 or REBCO
- Collaborations with multiple sectors

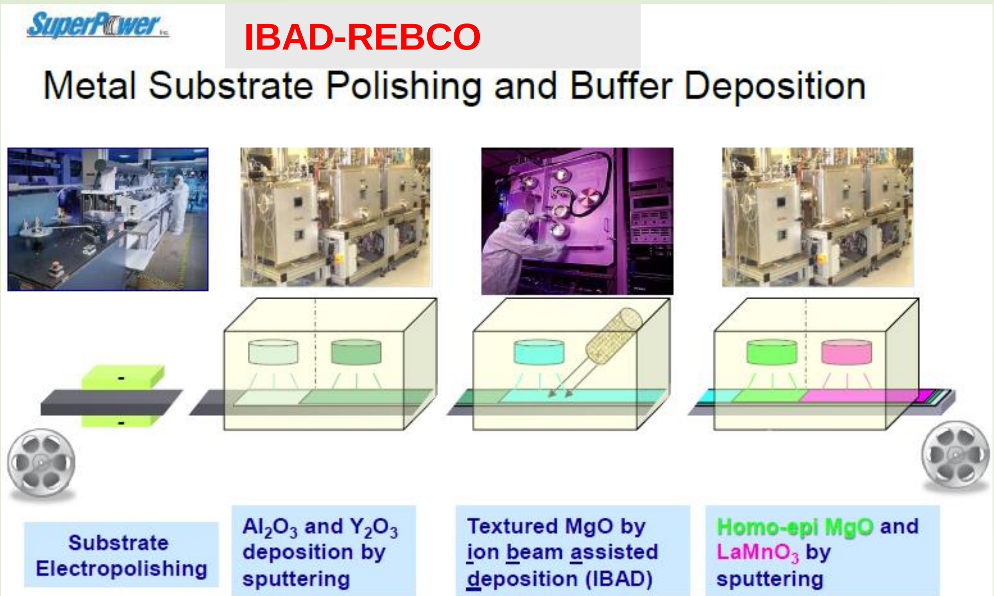
Weaknesses

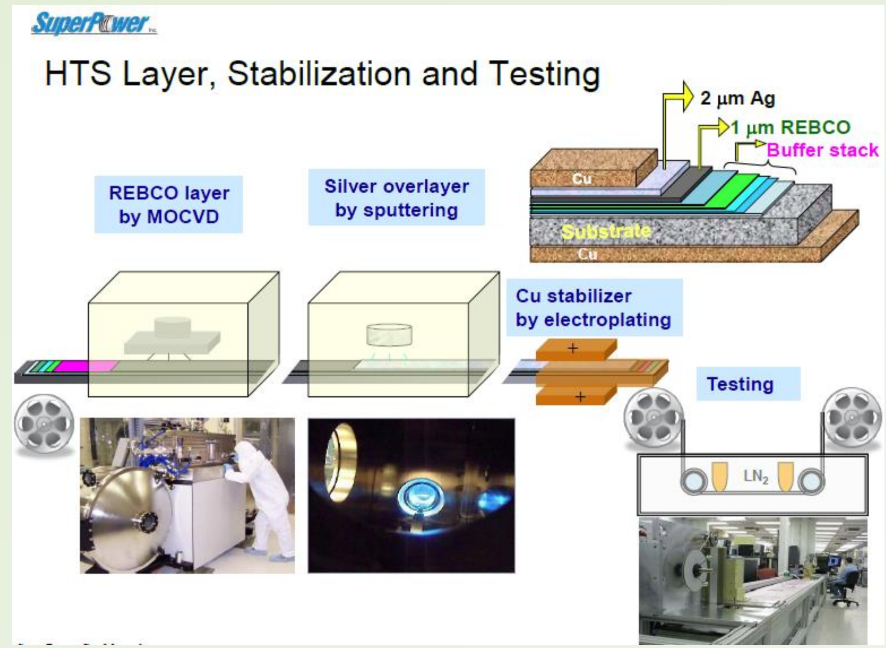
- Conductors are $$$ - $75-100/m
- Defect rich!
- REBCO is very capital and team expensive
- Good 2212 requires 20-100 bar HT

Threats

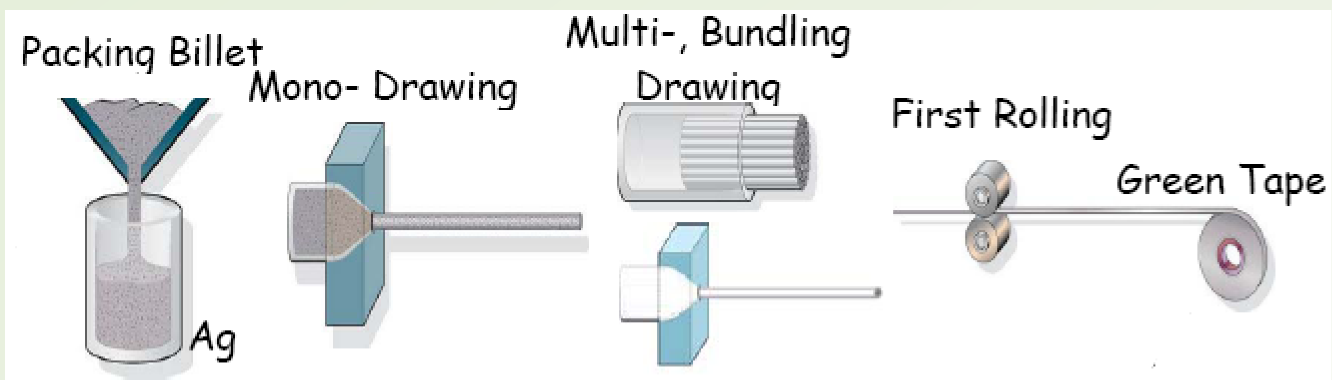
- REBCO cannot be sustained by magnet projects and is at risk if electric utility demand disappears
- Overenthusiasm without proper support

REBCO and 2212 (or 2223) are two manufacturing routes quite different in scale and cost



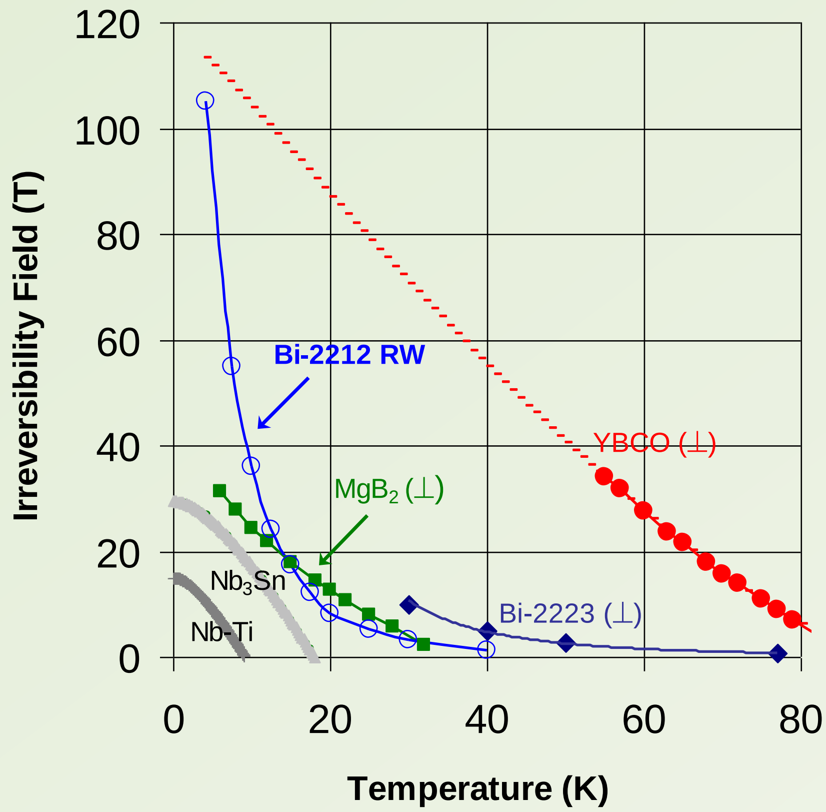


Powder in tube: 2212 and 2223 Can use standard metal fabrication lines developed for MRI, NMR, ITER, HEP

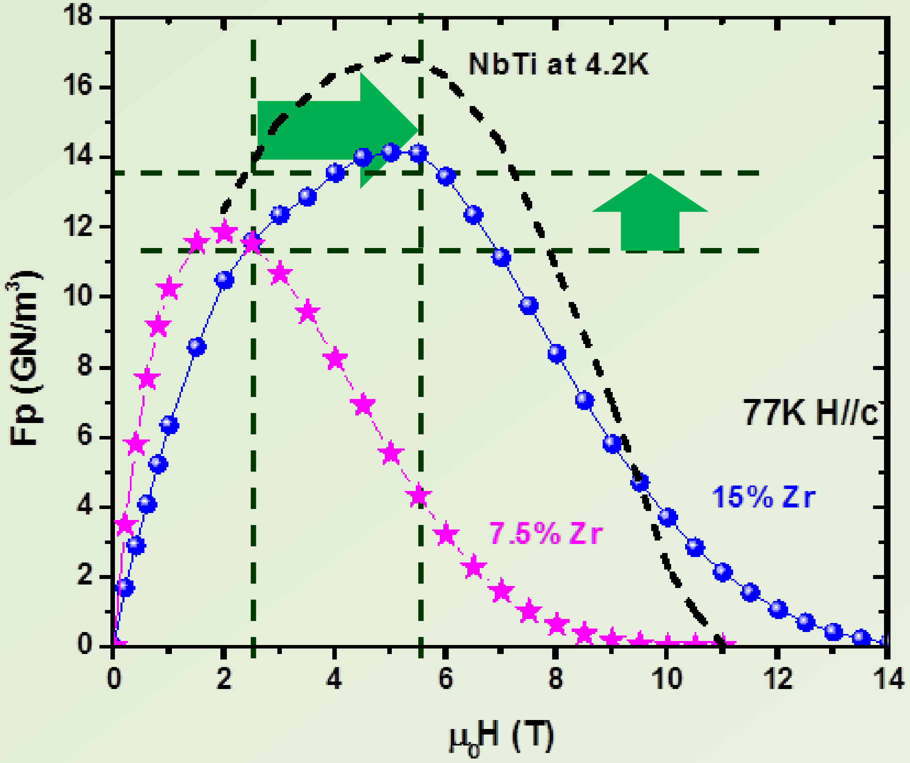


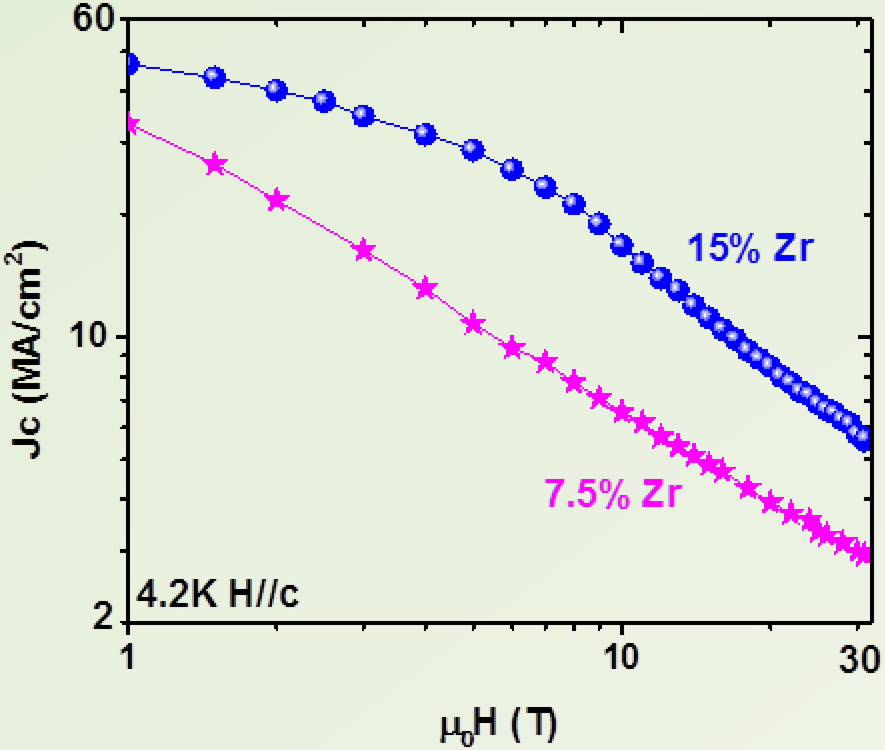
What about Coated Conductors?

- They have a huge temperature advantage to offset their lack of filamentization and rather inflexible designs
- How could one get to a high J_E conductor in the liquid N_2 regime?



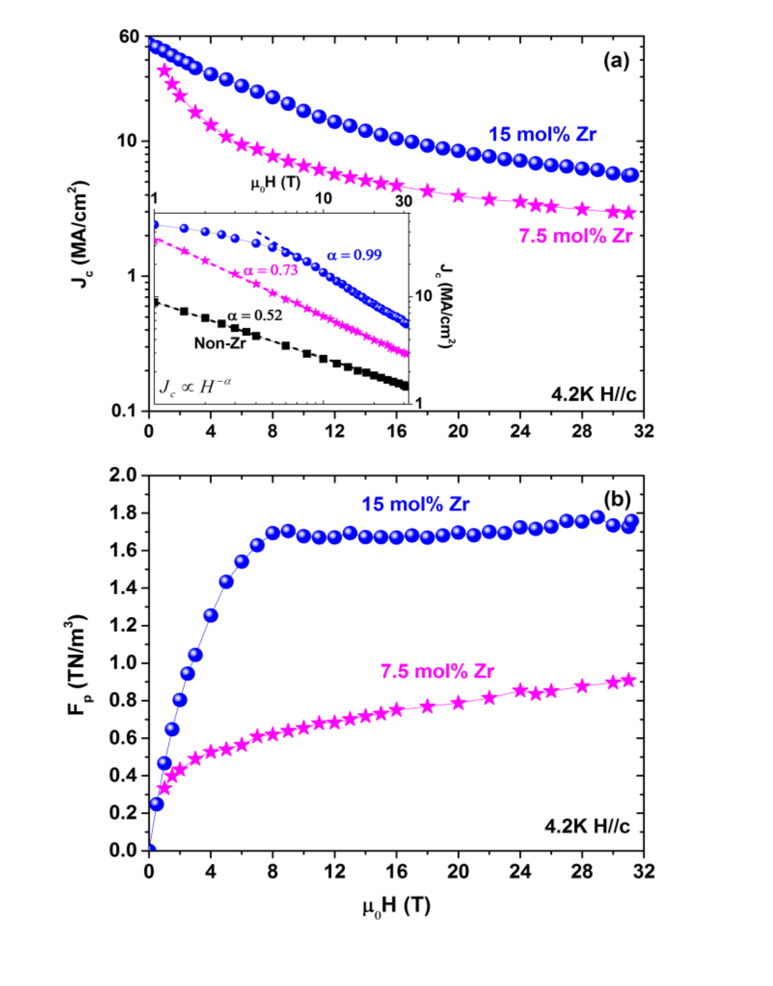
REBCO vortex pinning engineering works – MOCVD on IBAD substrates compatible with e.g. Cable on Round Cores (CORC)

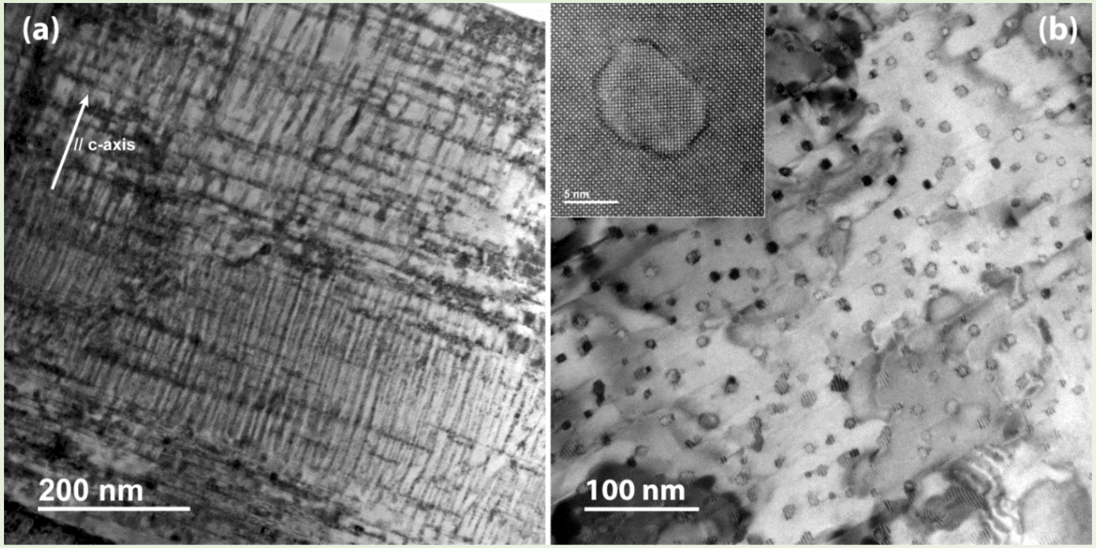




- **Strong recent developments in Selvamanickam group at TcSUH**
  - Strongly enhanced vortex pinning from 4 to 77 K in magnetic fields up to 31 T in a 15 mol% Zr-added (GdY)-Ba-Cu-O superconducting tapes - Xu, Delgado, Khatri, Liu, Selvamanickam (TcSUH) and Abraimov, Jaroszynski, Kametani and Larbalestier (ASC-NHMFL) – Xu et al. , APL-Materials 2, 046111 (2014)

The insulating vortex pins that one would love in Nb_3Sn too..



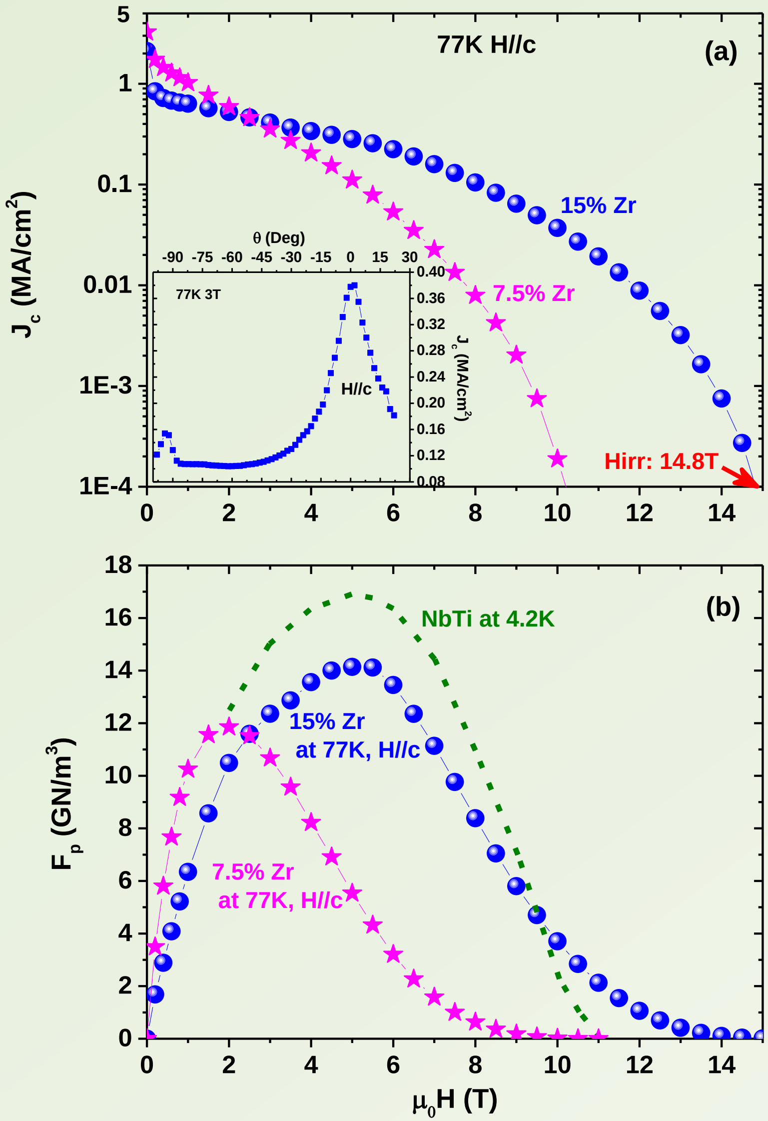


TEM by Kametani ASC-NHMFL

- $BaZrO_3$ and RE_2O_3 pins give REBCO the same J_c properties as Nb-Ti
  - At 77K, not 4.2K
- But layer thickness is 1 μm
  - 3-5 μm REBCO and thinner substrates would go far to equalize J_E too
- Pinning force at 4.2 K now exceeds 1500 GN/m^3, 75 times Nb-Ti

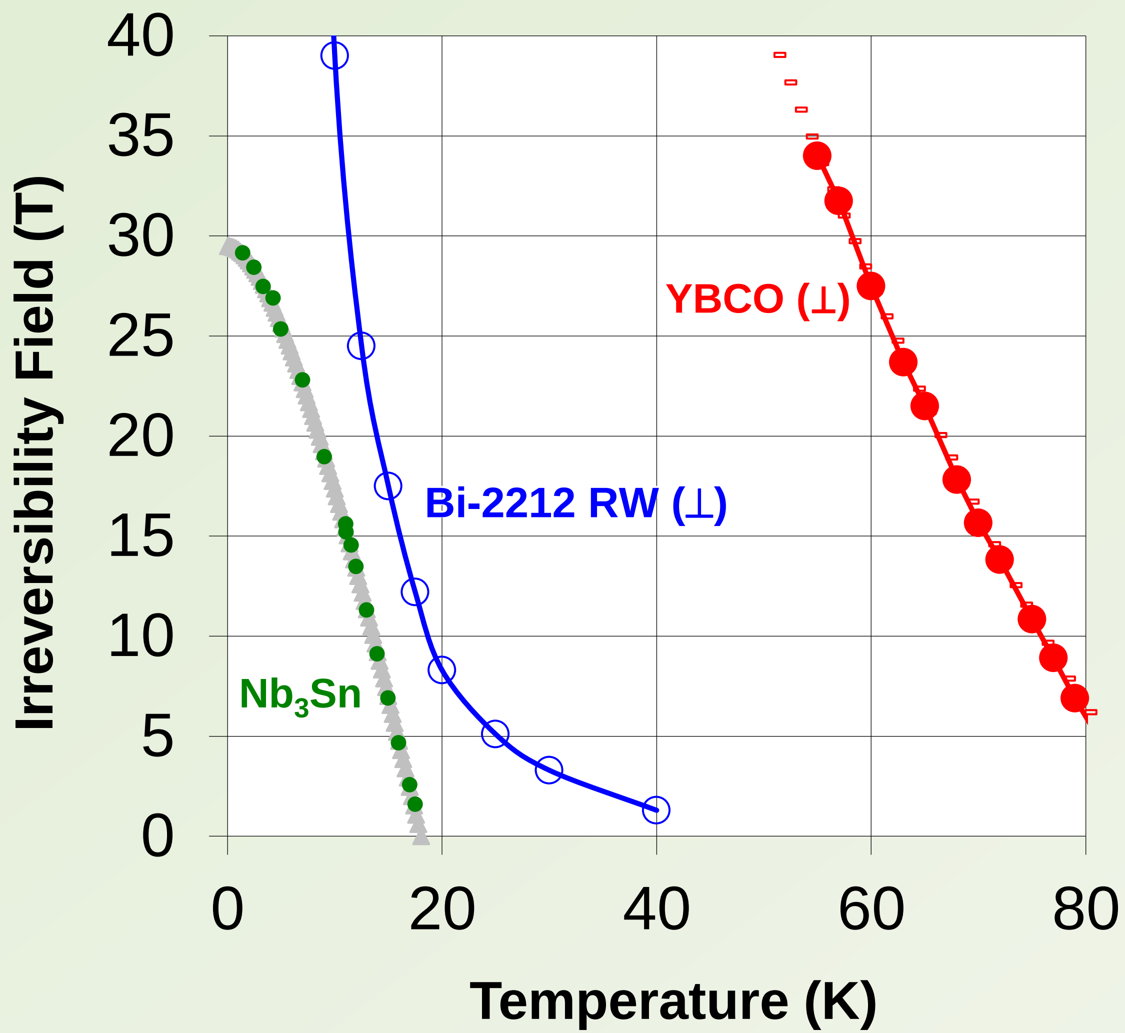
How about 77 K properties?

- Standard SuperPower tape has 50μm Hastelloy (but now 30 μm is announced) with 1 μm of REBCO and 40 μm of Cu ($t_{nominal}$ = 100 μm)
- 10^5 A/cm² at 8T/77K and H_{irr} = 15 T show huge potential
- If t_{REBCO} could be 5 μm, not 1 μm, magnet conductors at 65-77K would be assured

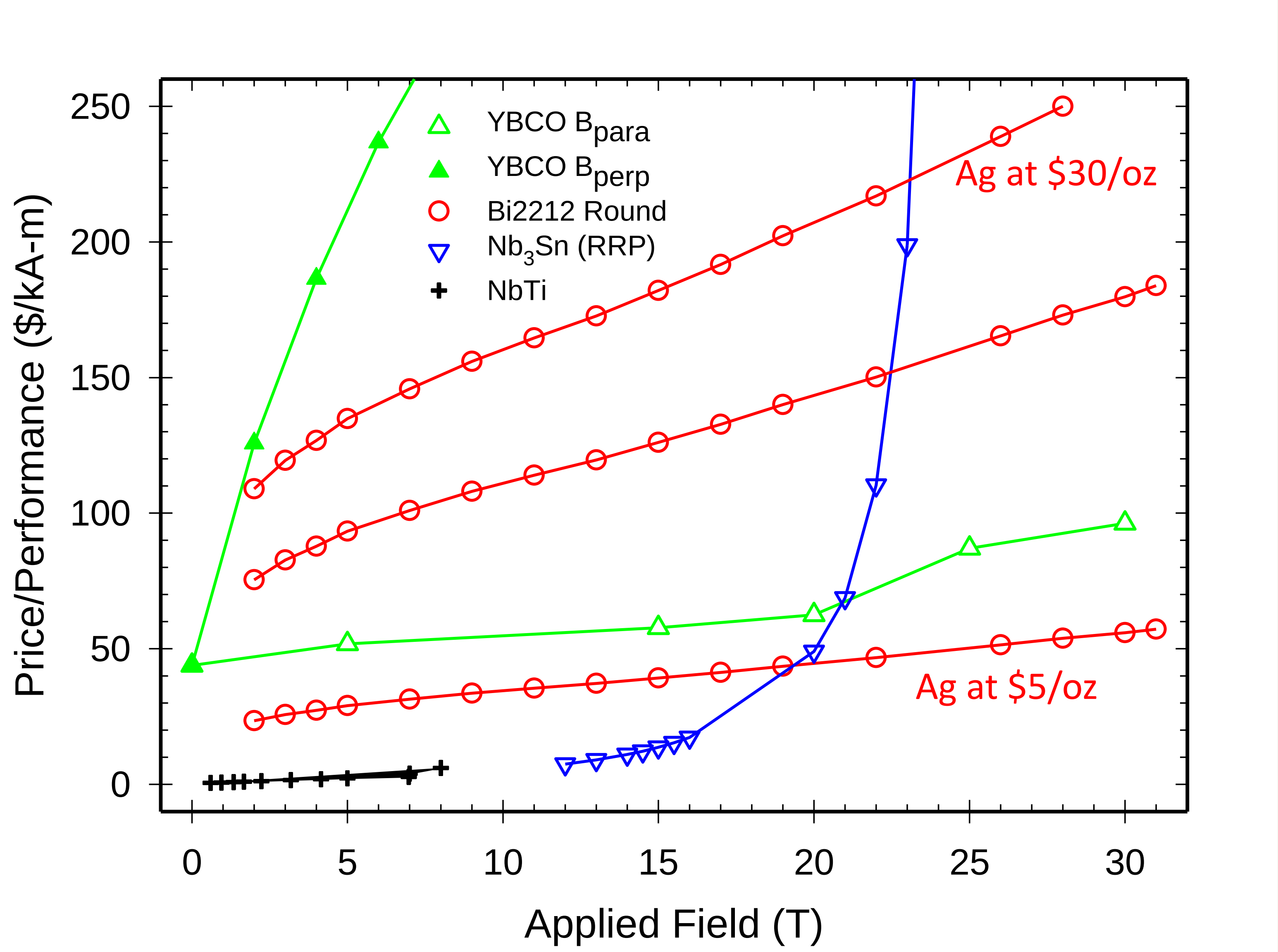


H_{irr} for Nb_3Sn, 2212 and REBCO

- Too much stability complicates quench protection
- No accelerator magnet has exceeded 15 T yet
- 2212 and REBCO have that capability but 2212 may be easier to protect



Price/Performance with Ag at $5-30/oz



Calculations by Strauss and Marken (S4E Paestum May 2014

Final message

- HTS conductors have now enabled fields of >35 T, more than 50% more than the highest LTS magnet
- We now have 3 HTS conductors, each with distinct attributes
  - Bi-2223 – 2 km lengths
  - REBCO Coated conductors – highest $H_{irr}(T)$
  - Bi-2212 – round wire and multifilament and highest J_e at 4 K
- We have applications pull to insert HTS into real magnets
  - A new market beyond the electric utility industry
- A new concerted effort to make round wire multifilament REBCO could be transformational for all superconducting magnet technology
  - Meanwhile, do the best with what we have – REBCO CC tape, 2223 tape and now round wire 2212!

Summary