The NHMFL HTS Coil and Conductor Development Program - Presentation to Muon Accelerator Program May 10, 2013

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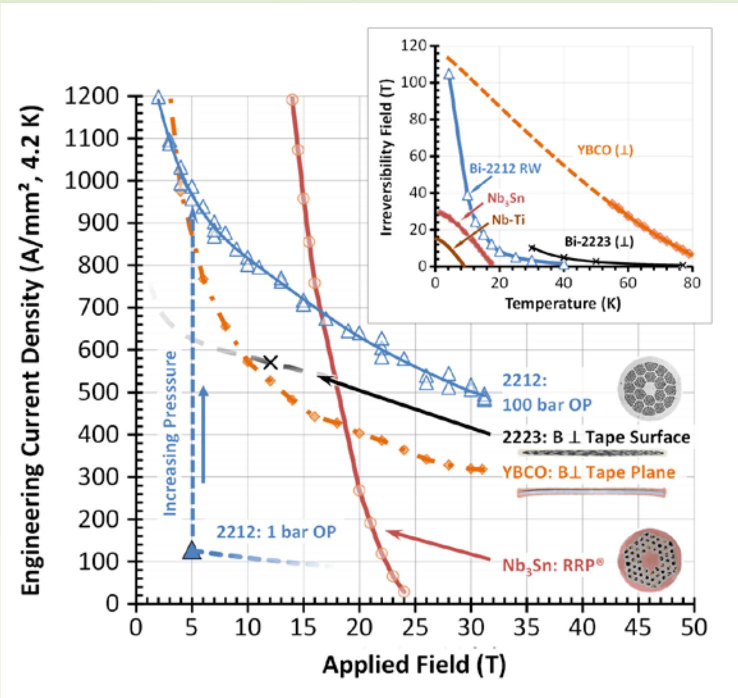
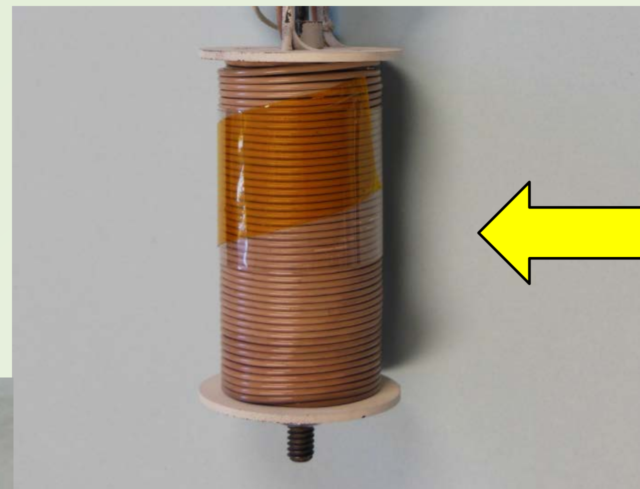
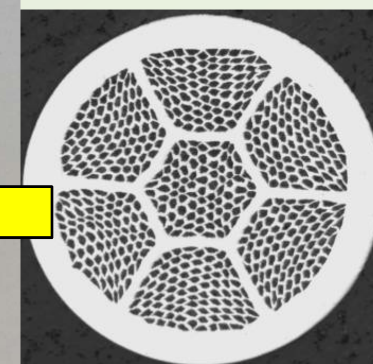
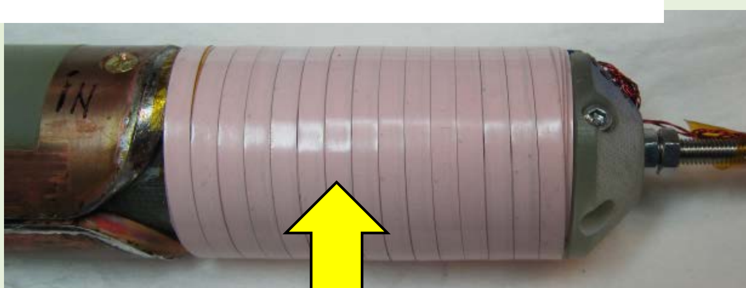


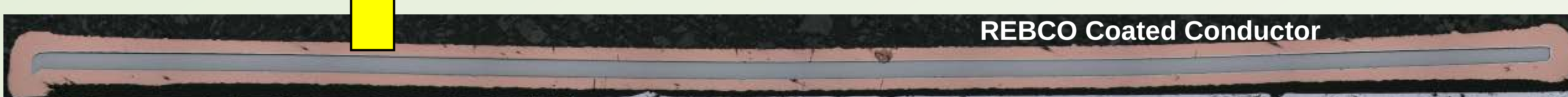




34T (in 31T) – Bi-2212



35T (in 31T) – REBCO coated conductor



Presentation outline

- The global drivers of the MagLab program
  - The mission from NSF and recent NRC panels – COHMAG (2004) and MagSci (2013)
- MagLab team
  - Science and engineering, R&D and project foci
- MagLab goals
  - HTS magnets for users
  - Collaboration with others interested in advancing HTS technologies
- A Coupled conductor-coil focus
  - REBCO
  - Bi-2212
- Outlook
  - Major new accomplishments not possible with LTS are now in prospect
  - Possible perils can be avoided by good collaborations

The Global Context is provided by COHMAG- Opportunities in High Magnetic Field Science – 2004

- **Grand magnet challenges:**
  - 30T NMR (All SC)
  - 60T Hybrid (R + SC)
  - 100T Long Pulse (R)

All require materials *in conductor forms that were not available in 2004*

They now are!

- **Means:**
  - ***….the involved communities [users and magnet builders] should cooperate to establish a consortium whose objective would be to address the fundamental materials science and engineering problems that will have to be solved…….. COHMAG report 2004***

And in 2013 by a new NRC study MagSci – High Magnetic Field Science and technology – under review now

..and locally by user demands, the power bill, and the NSF budget….

- Provides the world's highest magnetic fields
  - 45T DC in hybrid, 32 mm warm bore
  - Purely resistive magnets: 35T in 32 mm warm bore, 31 T in 50 mm bore and 19T in 195 mm warm bore
- 20 MW resistive magnet ~$1500/hr at full power (7.5c/kWhr)

MagLab team formed in 2007-2010

- Cross-divisional effort in ASC and MS&T
  - Applied Superconductivity Center (left Wisconsin in 2006) and Magnet Science and Technology
- 32 T all superconducting magnet is in construction
  - Project leader **Huub Weijers**, designer **Denis Markiewicz**, conductor characterization lead **Dmytro Abraimov**
- HTS R&D effort
  - REBCO characterization (leader **Jan Jaroszynski**)
  - 2212 conductor (leaders **DCL, Eric Hellstrom, Jianyi Jiang and Fumitake Kametani** in strong collaboration with BSCCo – Bismuth Strand and Cable Collaboration – BNL (**Ghosh**) –FNAL (**Shen** and **Cooley**) –LBNL (**Godeke**) – NHMFL and CDP (**Dietderich**))
  - High homogeneity REBCO and 2212 coil construction – leader **Ulf Trociewitz**

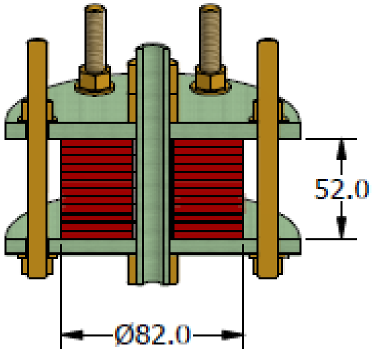
Funding:

32 T is supported by a Major Research Instrumentation award of NSF and by the NSF core grant to the NHMFL

Bi-2212 conductor work is supported by DOE-HEP through a university grant

HTS coil work (REBCO and 2212) is supported on the NSF core grant

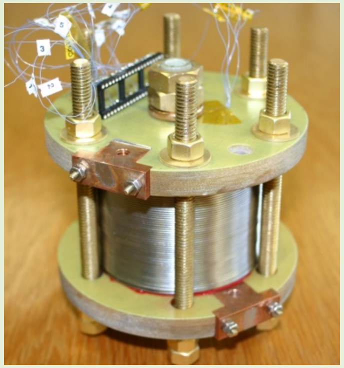
REBCO Test Coils: 2007-2009

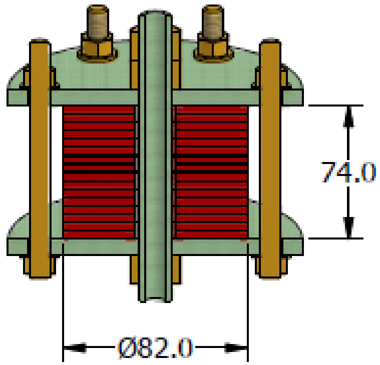


SuperPower I.

Bmax = 26.8 T

ΔB = 7.8 T

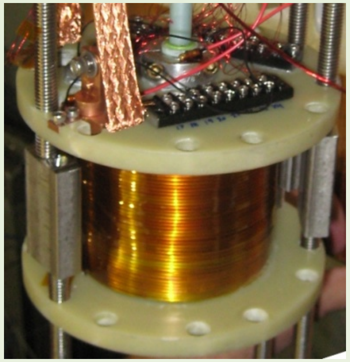


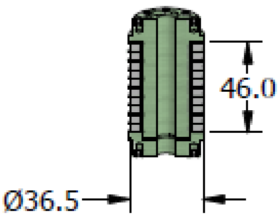


SuperPower II.

Bmax = 27 T

ΔB = 7 T

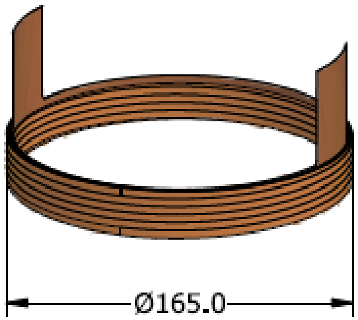




NHMFL I.

Bmax = 33.8 T

ΔB = 2.8 T



NHMFL II.

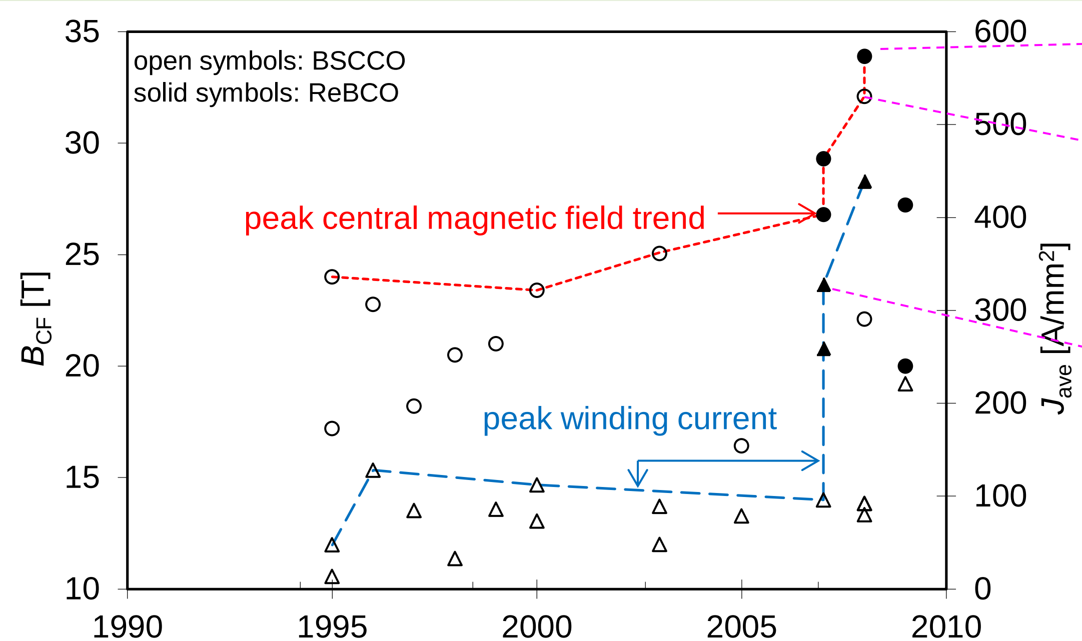
Bmax = 20.4 T

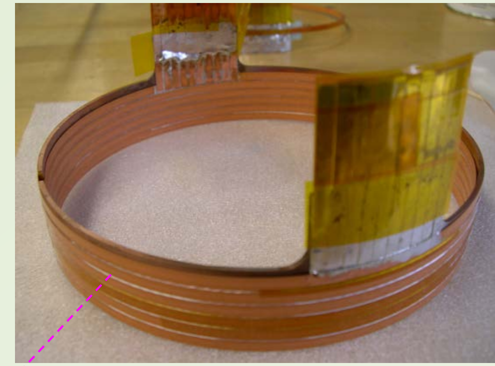
ΔB = 0.4 T

These coils made with cooperation of SuperPower (Drew Hazelton and V. Selvamanickam) showed that REBCO tapes were excellent for small high field coils. They allowed us to propose a 32 T user magnet to NSF in 2010.

HTS insert coil trends – ’09 update

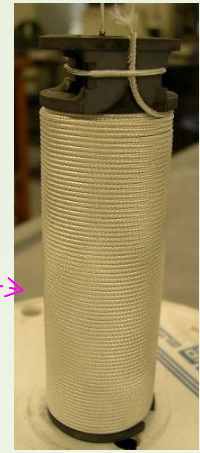
year		$B_A+B_{HTS}=B_{total}$ [T]	J_{ave} [A/mm^2]	Stress [MPa] $J_{ave} x B_A x R_{max}$	Stress [MPa] $J_e x B_A x R_{max}$
2003	BSCCO	20+5=25 T(tape)	89	125	175
2008	BSCCO	20+2=22 T(wire)	92	69	109
2008	BSCCO	31+1=31 T (wire)	80	47	89
2007	YBCO- SP	19+7.8=26.8 T	259	215	382
2008	YBCO-NHMFL	31+2.8=33.8 T	460	245	324
2009	YBCO -SP	20+7.2=27.2	211	185	314
2009	YBCO-NHMFL (strain limited)	20+0.1= 20.1	241	392	~611





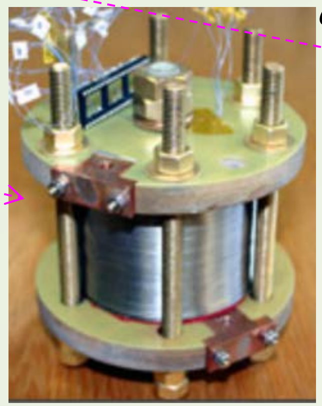
ϕ 163 mm

ϕ 39 mm



Bi-2212

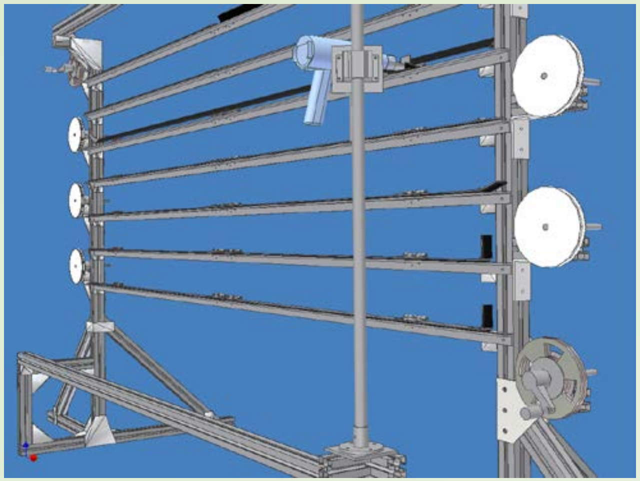
ϕ 38 mm

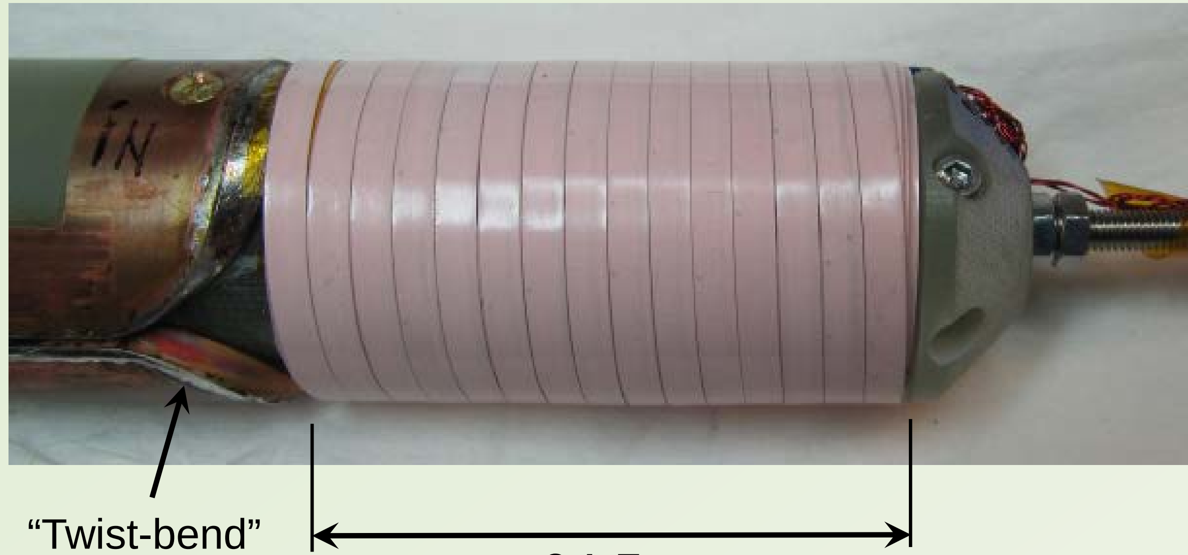


YBCO SP 2007 ϕ 87 mm

REBCO Layer Wound High Field Coil

Conductor insulation facility



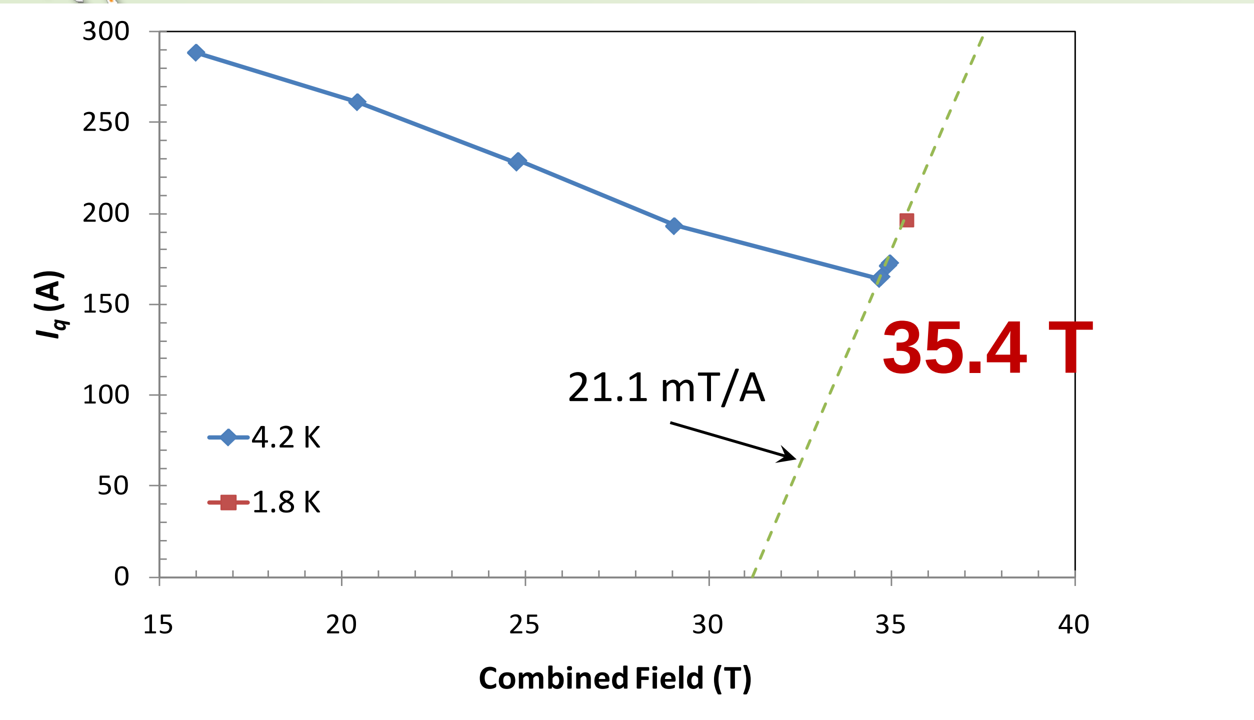


- Wet layer-wound, epoxy filled
- no splices
- thin walled polyester heat-shrink tube insulated conductor
- Coil instrumented with array of voltage taps every 5 – 10 layers

Conductor & Coil			EM Properties	
Cond. Width [mm]:	4.02		Operating Current [A]:	200
Cond. Thickness [mm]:	0.096		Je (Engineering) [A/mm^2]:	518.24
			Jw (Winding) [A/mm^2]:	308.93
Inner Radius [mm]:	7.16		B(0,0) [mT]:	4221.01
Outer Radius [mm]:	18.92		Coil Constant (0,0) [mT/A]:	21.11
Height [mm]:	64.52		L [mH]:	8.90
Layers [-]:	80		Total Field Energy [J]:	187.92
turns/Layer [-]:	14.65			
turns total [-]:	1172			
Cond. Length [m]:	96.03			

Trociewitz, Dalban-Canassy et al. APL 2011

Field Generation and Coil Load Line



- World record field – 35.4 T
- Some signs of limiting a low Ic point in conductor – stimulated us to pursue length-dependent Ic
- Fully insulated and robust

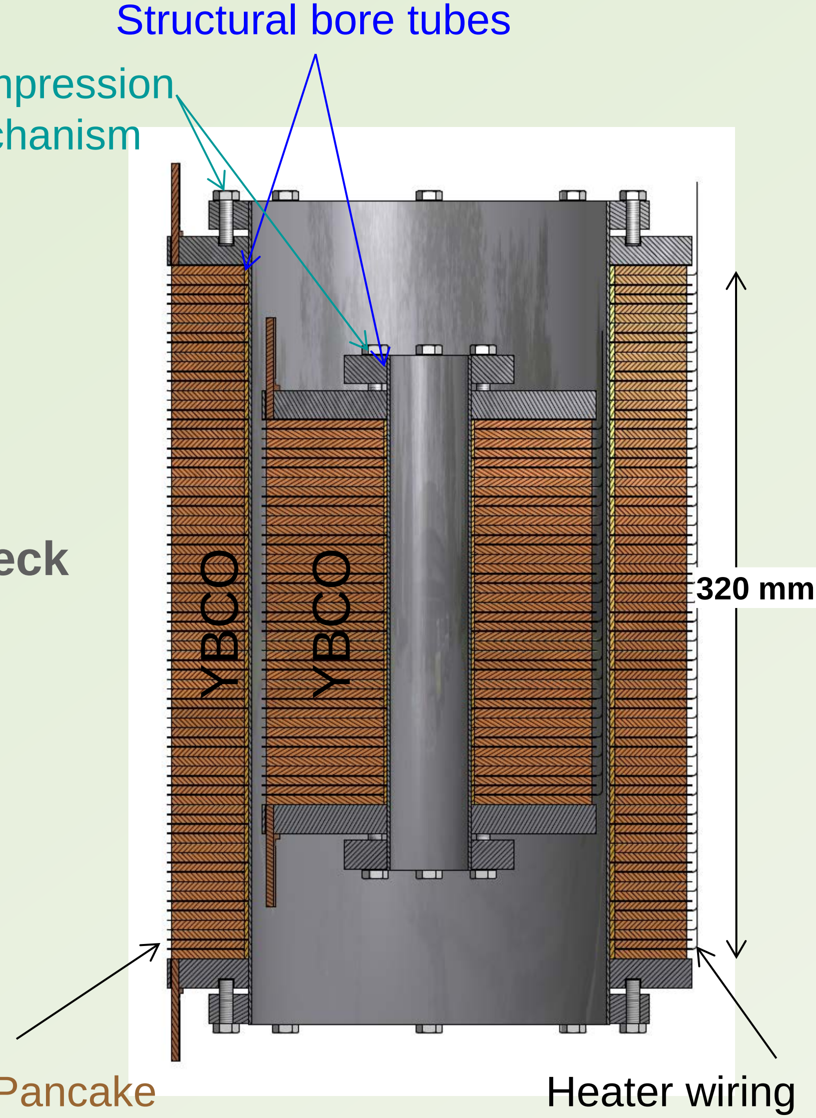
- **4.2 T Field increment achieved in 31.2 T background field**
- **Coil did not degrade even under repeated fast thermo-cycling**
- **Showed that stress levels >340 MPa and conductor current density J_e ~500 A/mm^2 are possible**
- **Introducing layer decoupling during coil manufacturing, bypasses transverse stress weakness**

Trociewitz, Dalban-Canassy et al. APL 2011

32 T Overview

- **Commercial Supply:**
  - 15 T, 250 mm bore Nb_3Sn/NbTi "outsert"
  - cryostat
- **In-House development:**
  - 17 T, 32 mm cold bore YBCO coils
  - YBCO tape characterization & quality check
  - Insulation technology
  - Coil winding technology
  - Joint technology
  - Quench analysis & protection
- **Choices so far**
  - Pancakes, not layer-winding
  - Dry, i.e. no epoxy
  - 4 mm wide tape, 50 μm Cu plating
  - Insulation on co-wound steel strip
  - Quench heaters for protection

Weijers and Markiewicz : LTSW 2012 talk



J_{ave}	188 A/mm^2
Inductance	18 H
DP Modules 20+36	
Turns	10,255+11,368
Conductor	2.9+7.0 km

Status of 32 T now

- **Design is stable,**
  - $I_{op} \leq 0.7 \cdot I_c$, $\sigma_{hoop} \leq 400$ MPa, $J_{ave}=188$ A/mm^2, $J_{Cu} = 420$ A/mm^2
- **Coil winding, joint, cross-over, termination procedures well developed** **(updating and formal documentation ongoing)**
- **Insulation development complete**
  - Commercial sol-gel Silica with added Alumina on co-wound stainless steel reinforcement tape **(2-3 μm layer)**
- **Conductor characterization transitioning into Quality Assurance: (4 K I_c specifications, 14 parameters total)**
- **Repeated tests on sc. test coils in 20 T background**
  - >100 dumps after quench initiation and quenches
- **AC (ramp-) loss and Quench codes in use** **(underway)**
- **Outsert +cryostat is on order** **(21-30 months for delivery)**
- **Working on first of two prototype coils**
  - (full-featured, radially full size, limited height)

Weijers: LTSW 2012 talk

More extended tests of a 6 module 20/70 coil in March 2013 were successful – outer 82/116 now in design

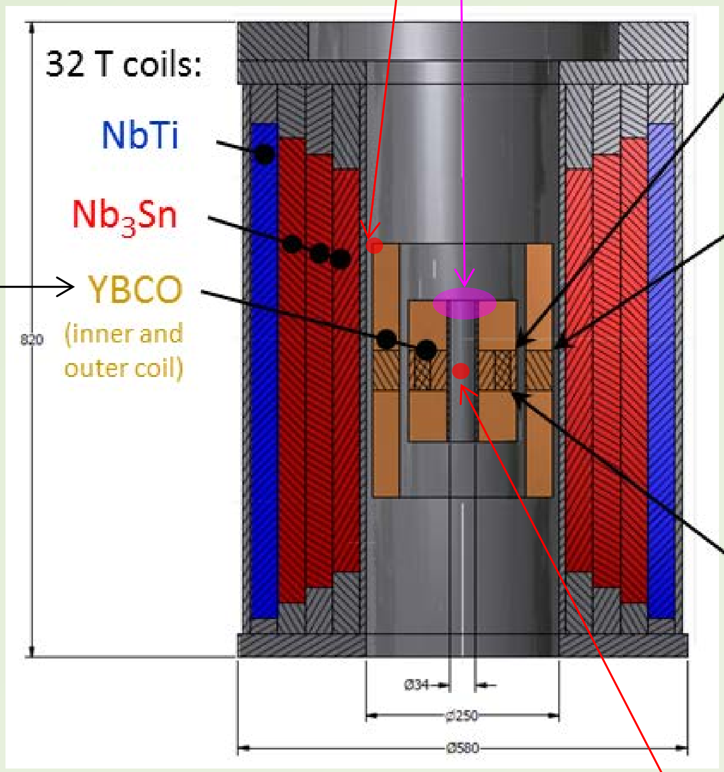
Critical aspects of 32 T design

Most restrictive condition: B = 16 T, angle ϕ = 18°

$-B_z{*}dB_z/dz_{max}$ = ~5000 T^2/m: windings may be **poorly cooled** in area where $-B_z{*}dB_z/dz_{max}$ exceeds 2100 T^2/m

(gas bubbles get trapped)

10 km of
4 x 0.15 mm
REBCO tape



20/70 Inner prototype coil (under construction, 1st test in December 2012

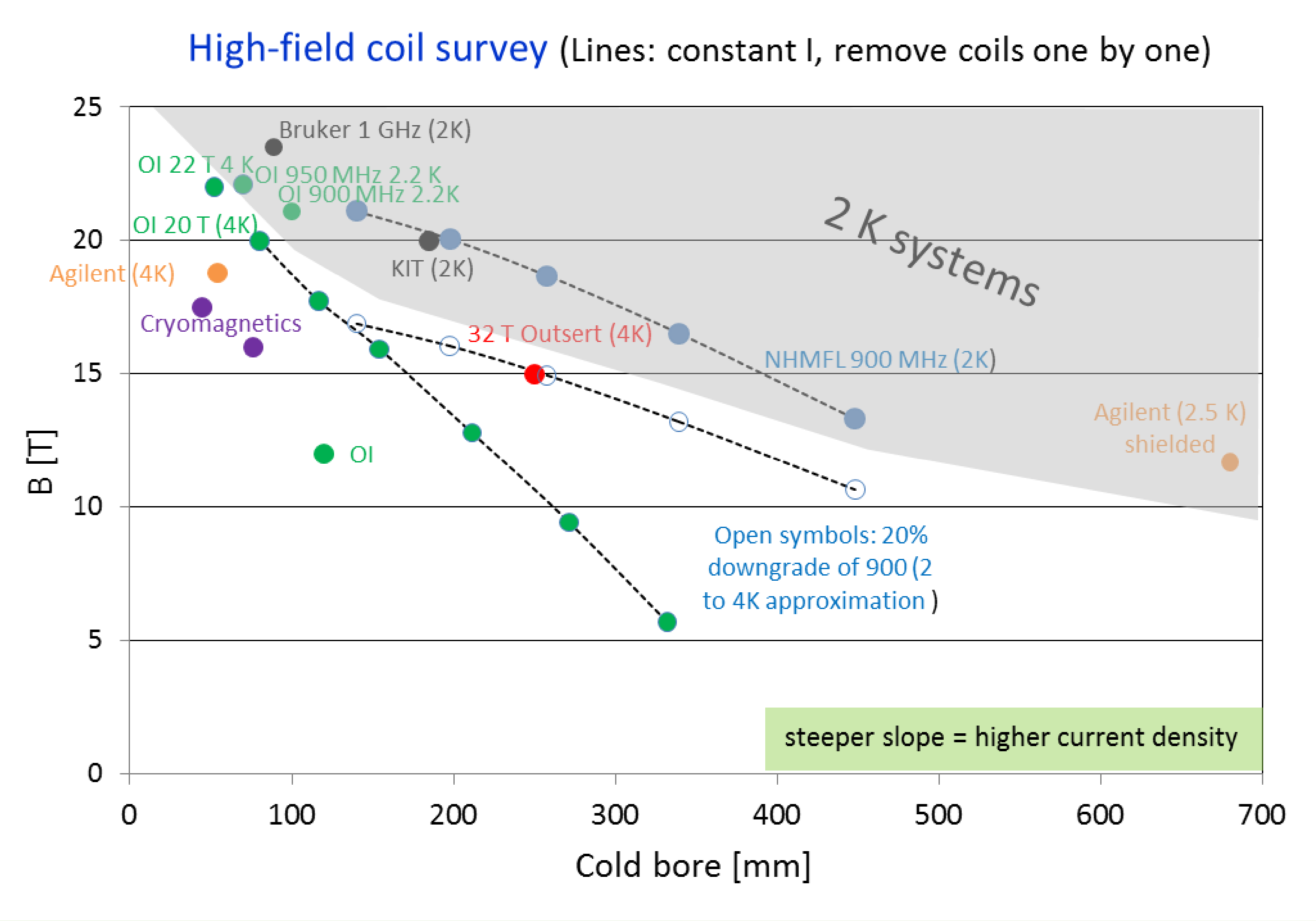
82/116 Outer prototype coil (1st test scheduled for April 2013)

42/62 test coil (Tested in August 2011, January 2012)

32 T, 500 ppm in 10 mm DSV

Translation of these aspects to conductor specification has been complex

LTS outsert magnet is an expensive challenge

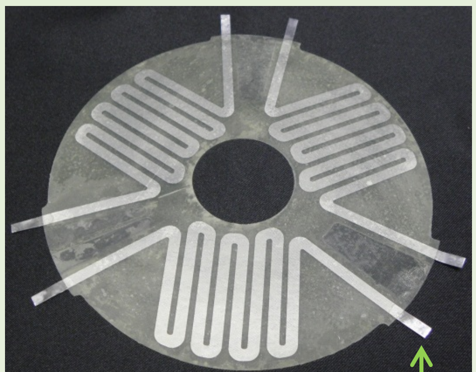


- **15 T in 250 mm is at limit of previous 4 K systems**

HTS Quench management

- **Active quench protection heaters** (NZP is slow but not zero, κ_{axial} a factor)
- **Voltage based quench detection**
  - 10 mV normal zones recover
- **Refinement ongoing**

Quench heater design by Markiewicz

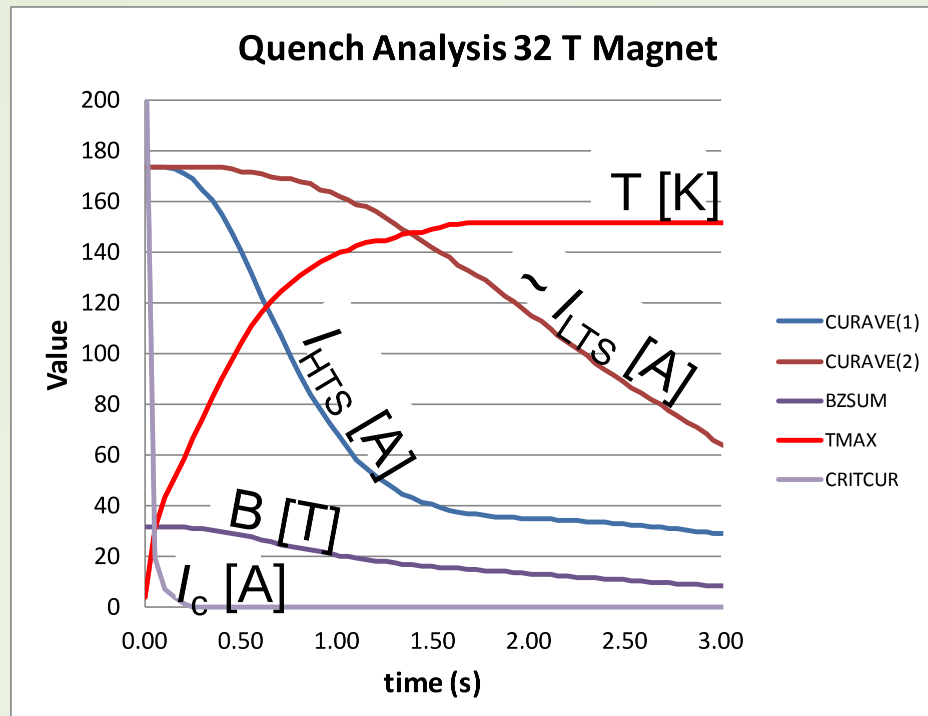


Heater element

Heater terminal tabs

Model for assembly practice

Example of quench code run



Why insulation for 32 T?

- 32 T users may ramp often or even non-stop
- $5 \cdot 10^{-4}$ homogeneity and stability in magnetic field are the specifications
- Non-insulated conductor/co-wind would lead to high ramping losses and reduced field quality
  - Quench seems manageable at J_{ave} = 200 A/mm^2 with turn-to-turn insulation
  - At 6 μm thickness per turn it represents only 3% of winding volume

Conductor specification issues

- Geometrical properties
- Mechanical properties
- Electrical properties
  - Normal state properties
  - Superconducting properties
- Magnetic properties

→ + tolerances (uniformity)

Two examples mentioned here

- Environmental
- Traceability and records
  - Materials and production procedures
- Quality Control, Quality Assurance
  - Measurement techniques, procedures, standards
- Handling Non-conformity

Routine for LTS, breaking new ground for HTS conductors

Geometrical uncertainties

- Dimensions and tolerances
- Surface conditions
  - Cleanliness for
    - reliable soldering of joints
    - Application of insulation
  - No pinholes
  - No "deep" scratches (scratches may cause deformation reaching SC layer

32 T conductor specification being developed by Weijers

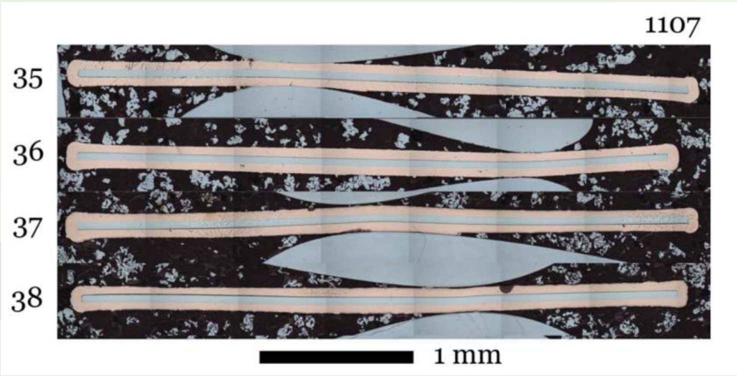
- Trapped He gas leads to poor He cooling
  >> maximize thermal conductivity of windings
  >> Need good radial contact between turns
  >> Need good axial contact between pancakes
- Specify "flatness" of conductor
- Consistent width (over 10 km) important for
  - Axial thermal conductivity
  - Transfer of axial loads in windings
  - Packing factor
- Minimum Cu area for stability
- Minimum Substrate area for strength

Verify each piece length

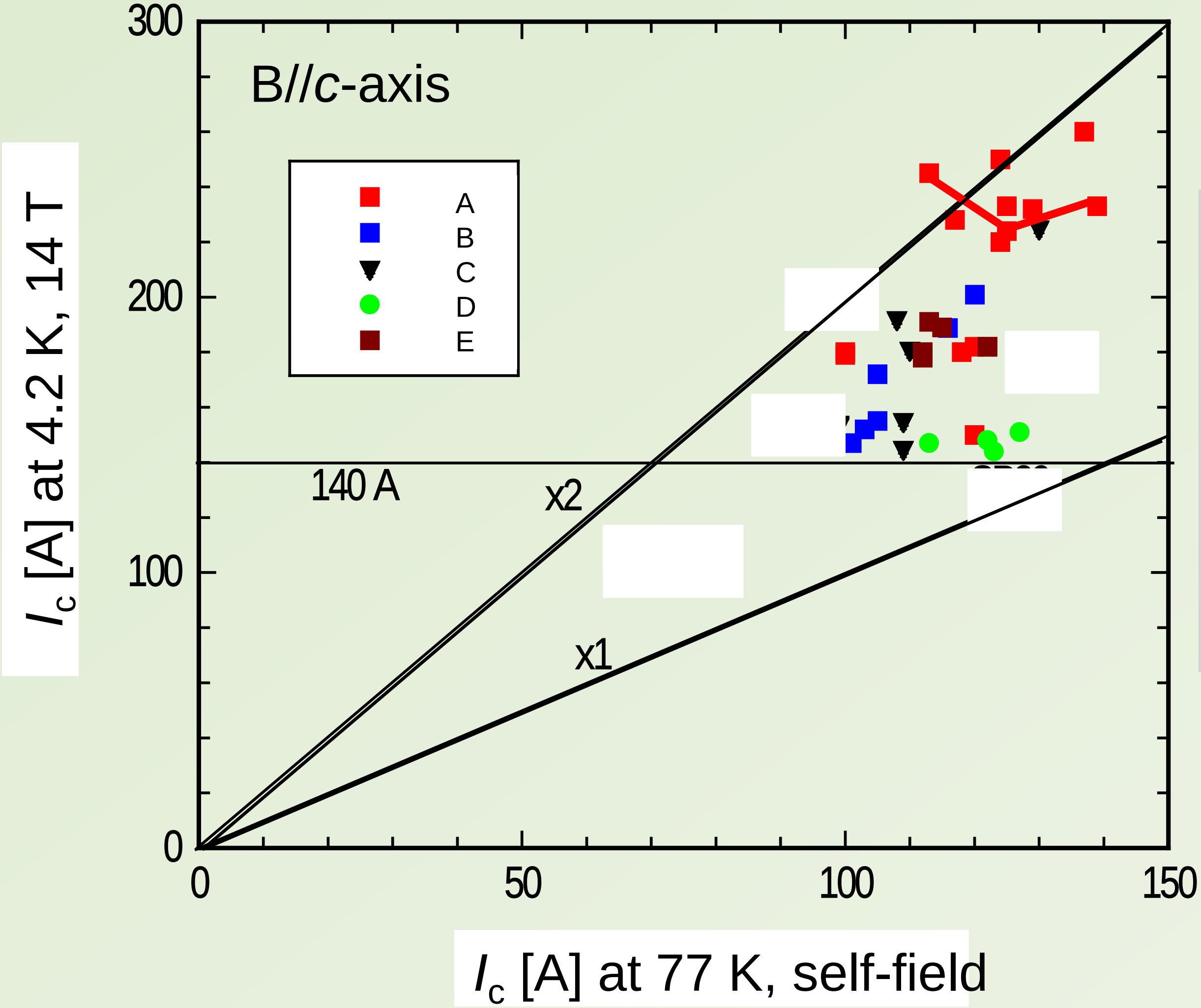
Pancakes need to be firm, flat and consistent in width

Conductors have dog-bone shape

Considerable uncertainty in width



Is the critical current predictable and reproducible? Not yet!



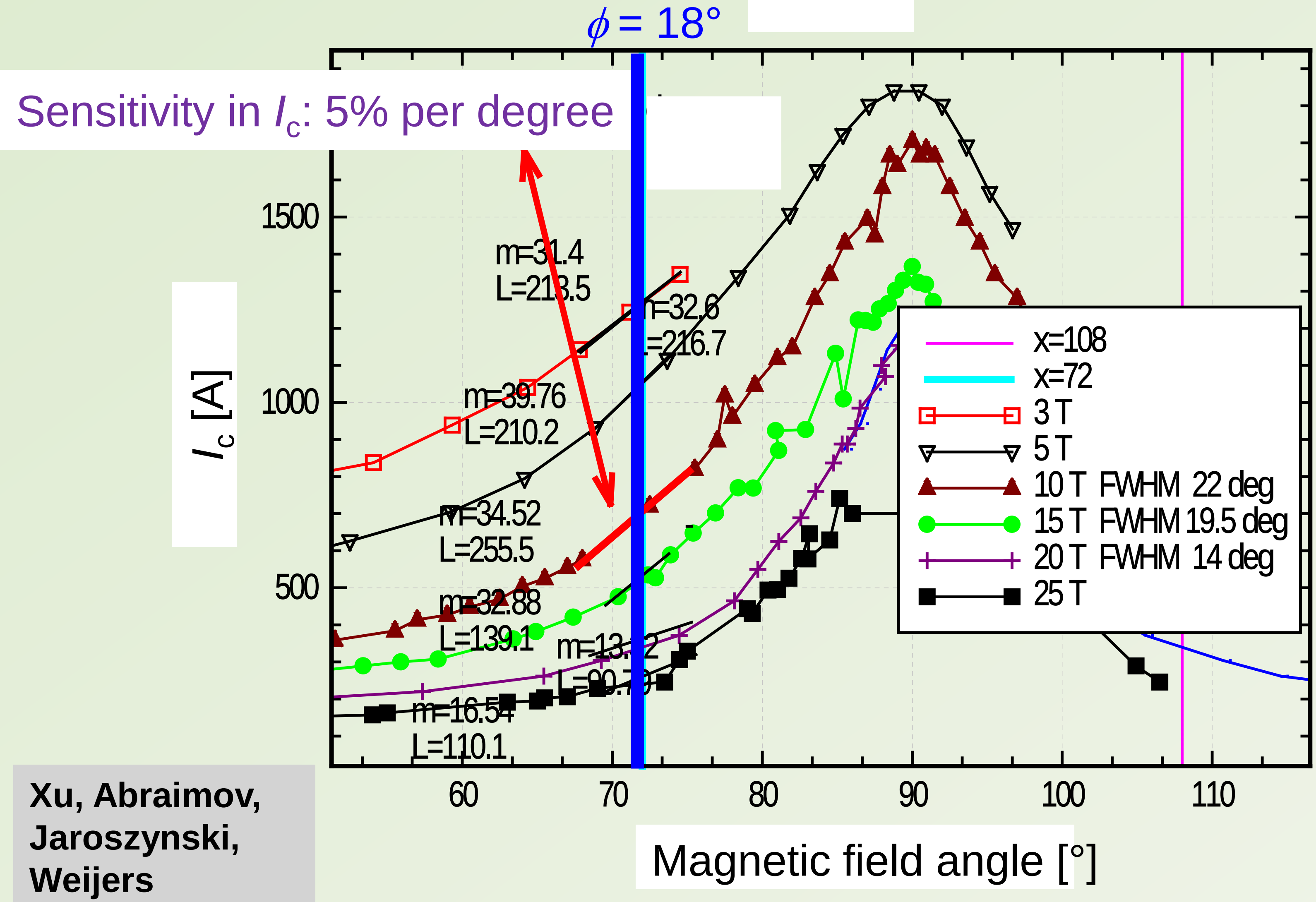
77 K Self-field data is a weak indicator of 4 K, high-field performance

>> 4 K I_c specification

QA: no reel-reel capability >> sampling only,

Dominant flux pin size and pin morphology differs between 77 K self-field and 4 K, 15^+ T >> somewhat weak correlation

Superconducting I_c anisotropy plays a strong role in magnet design

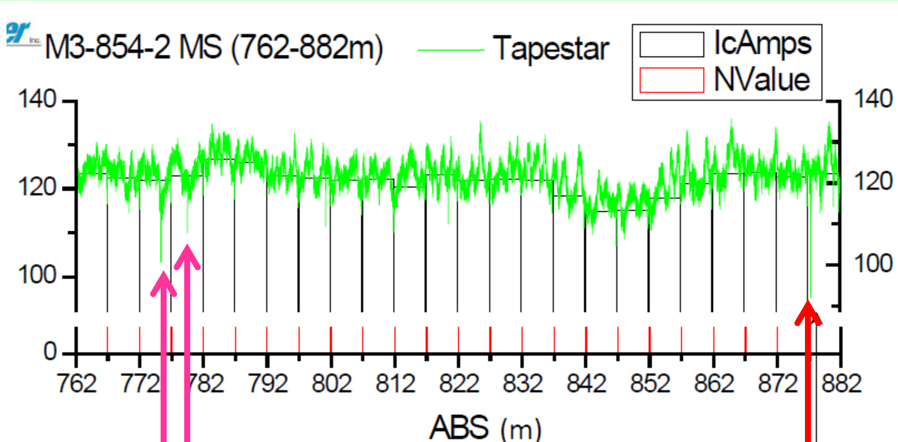


Xu, Abraimov, Jaroszynski, Weijers

Specify I_c at most demanding angle in design to counter potential anisotropy variability

Superconducting length (non) uniformity

Data courtesy of SuperPower



Not detected with LANL device ("Yatestar")

Used in section of coil where quenches originate

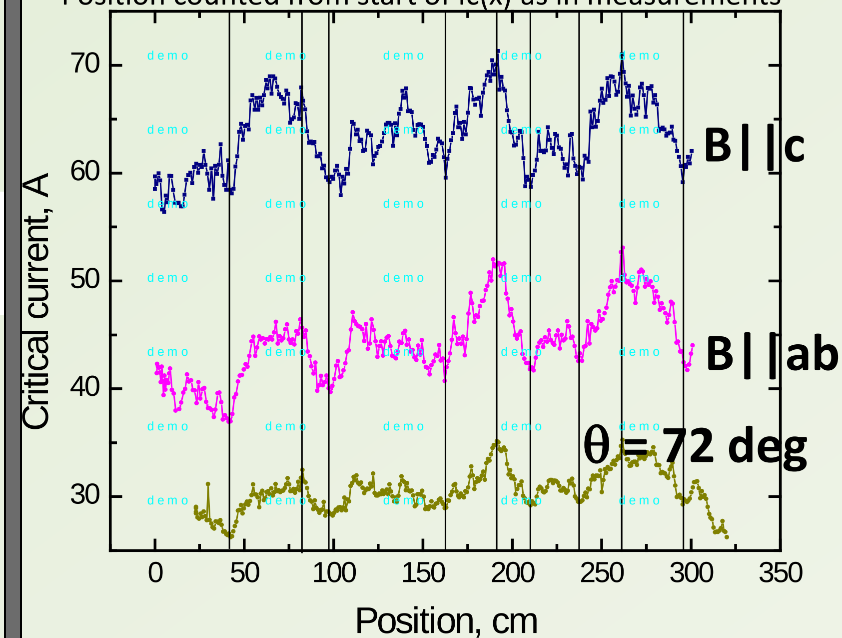
- ***Tapestar:***
- **Magnetization-I_c corresponds well to transport I_c over 5 meters at 77 K**
- **High through-put**
- **Spikes may or may not correlate to physical realities**

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



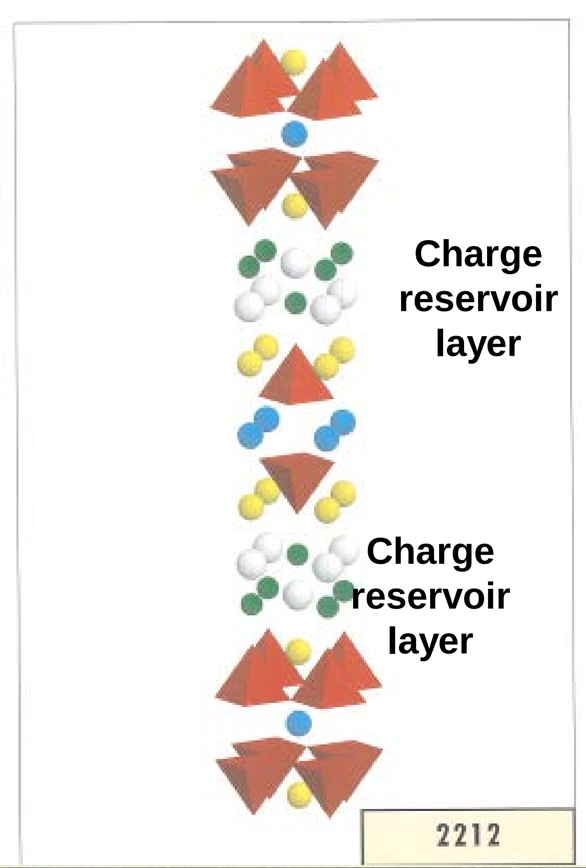
Proto-system built at LANL by Yates Coulter and engineered for 200m lengths at NHMFL by Jan Jaroszynski and John Sinclair, now with Hall probes operating at both 77 and 4 K (Alex Stangl)

Multiple REBCO Proofs of Principle allowed us to…………

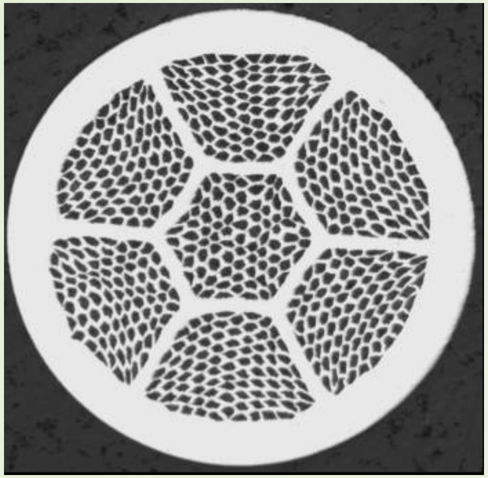
- Concentrate effort on:
  - 32 T construction – early 2015 assembly
  - Extensive characterization of REBCO tapes from SuperPower
  - Layer wound quasi-NMR quality coil – late 2013
    - REBCO is first attempt
    - 2212 will be 2^{nd} attempt when OP furnace is proven
  - Development of round wire Bi-2212 into a full-fledged coil technology (within BSCCo team with DOE-HEP support)

Round wire vs. tape BSCCO Technology

- How can 2212 and 2223 be so different as conductors when they are so similar as structures?

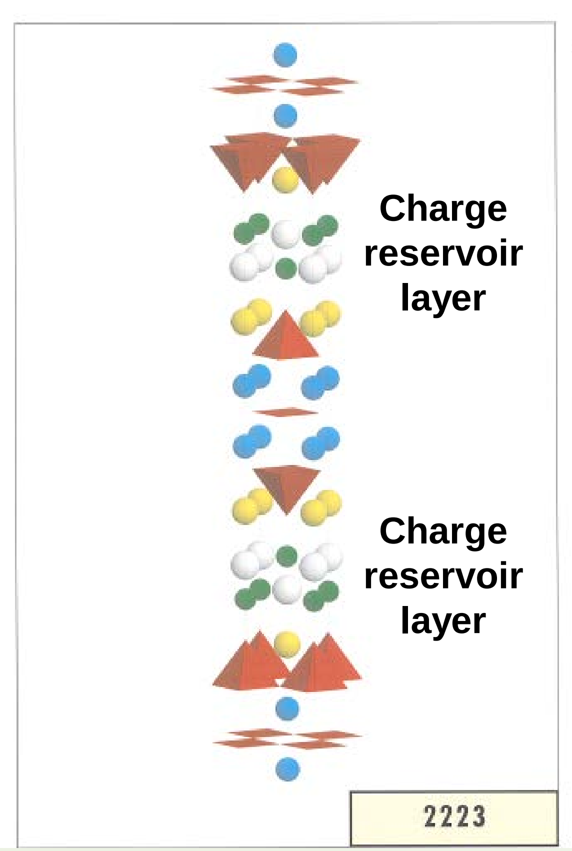


RW - 2212



Versus

tape 2223

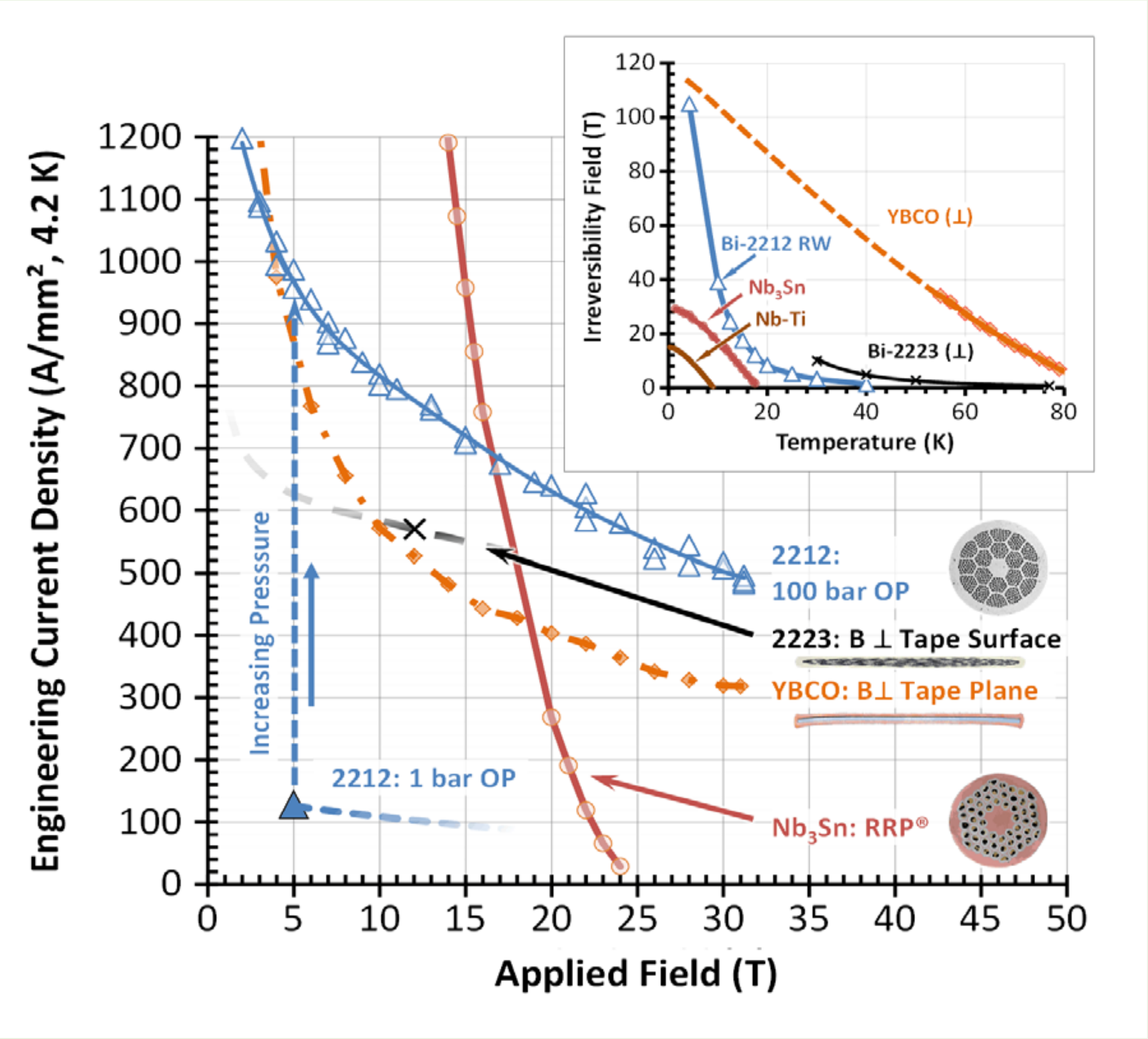


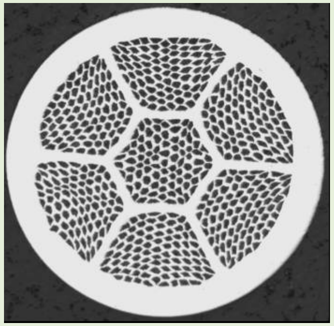
Multifilamentary 2212 has been made for years without much interest

- Why was 2212 round wire ignored?
  - Because, being untextured, it was **obvious (!)** that high angle GBs were producing a connectivity-compromised current path of low Jc……
- ARRA support for a multi-lab collaboration (VHFSMC – DOE-HEP support) in 2010-2012 enabled a much fuller understanding
  - **Principal current limitation is by agglomerated void space in the filaments (bubbles of residual gas) not HAGBs!**
  - Overall conductor J_c of Bi-2212 now exceeds that of any coated conductor when 100 bar overpressure is used to eliminate bubbles

Isotropic, multifilament 2212 has higher conductor J_c than REBCO coated conductor!

- Requires ~100 bar 890˚C processing
- High J_c, high J_e and high J_w has been demonstrated in a coil already (2.4T in 31T)
- Much less field distortion from 2212 than from coated conductors – better for high homogeneity coils
- 7 times increase in long length J_e by removing bubbles

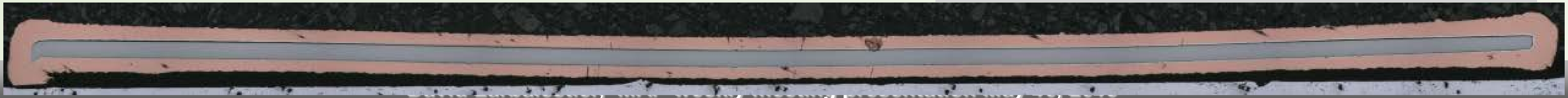




2212

REBCO coated conductor

Larbalestier et al. submitted arXiv 1305.1269

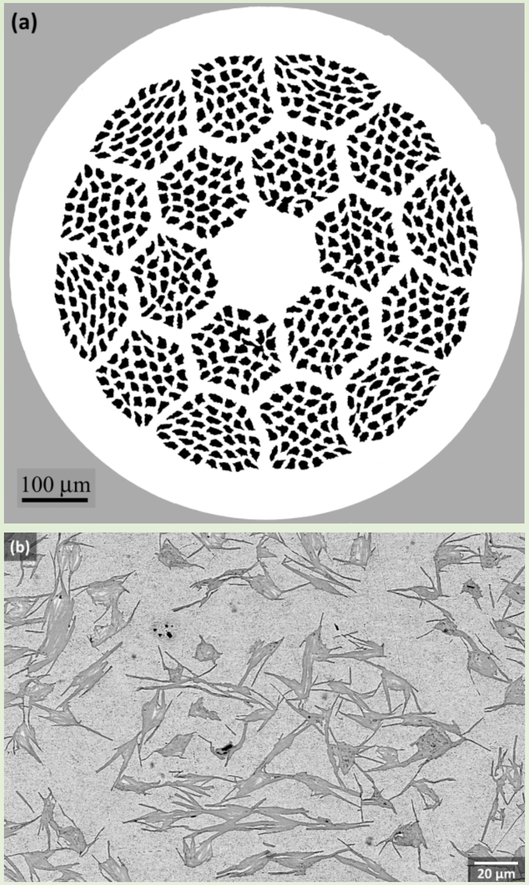


OP furnaces are needed to allow short samples to be translated into coils – NHMFL capabilities

Diameter	Length	Max pressure	Comments
25 mm	15 cm	100-200 bar	Today's workhorse
48 mm	15 cm	25 bar	Commissioning now
45 mm	25 cm	75-120 bar	On order, June delivery
170 mm	50 cm	100 bar	On order, July delivery

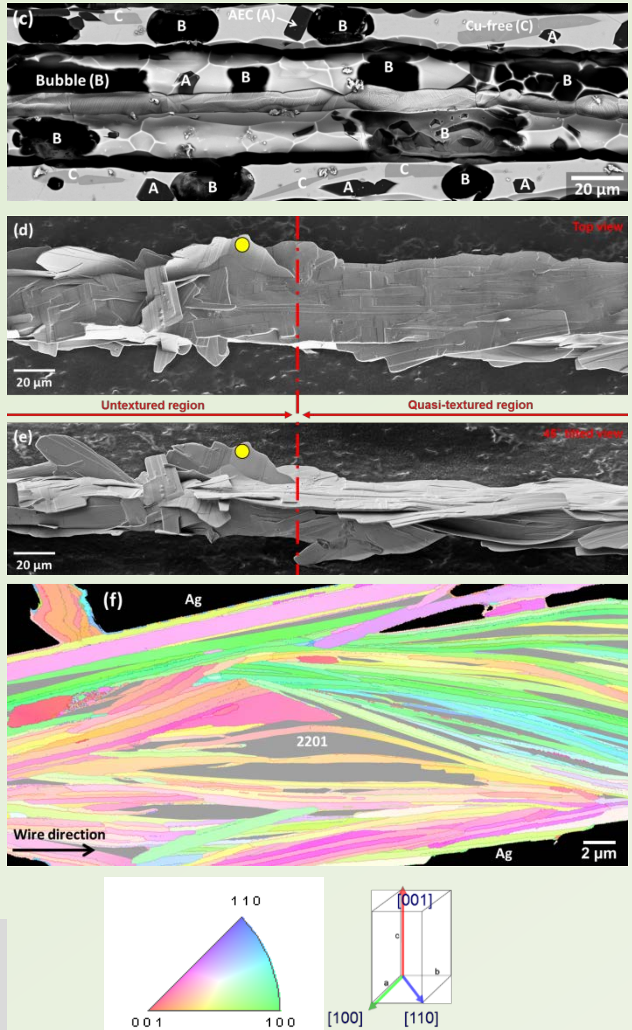
- Capabilities are available to all in BSCCo and many samples have been shared with LBNL and FNAL
- FNAL is designing a 100 bar capability for straight Rutherford Cables suitable for reacting 2212 cable designed for test in FRESCA at CERN

2212 Filaments contain many HAGBs – and (without bubbles) have high Jc



Kametani and Jiang arXiv 1305.1269

Transverse section images



Longitudinal section images

Polished sections of filaments in their surrounding Ag

Exposed filaments show their plate-like nature and frequent strong misalignments.

EBSD images show some local texture and significant 2nd phase content within filaments

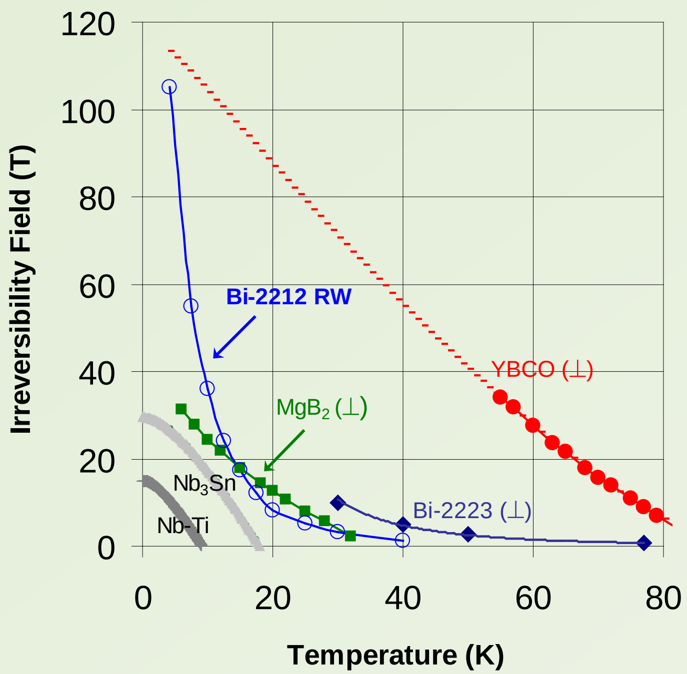
The filaments cannot be fully connected – yet do have high Jc

Outlook is very positive

- More than 35 T (in 31T) with REBCO has been safely and reproducibly generated
  - All superconducting 32 T magnet is under construction and should be ready for NHMFL users in 2015 (highest field LTS magnet is 23.5T)
- Although HTS conductors are MUCH more complex than Nb-Ti or Nb_3Sn, we are getting a handle on their properties
- Very strong collaboration is in place with wire vendors (SuperPower and OST) and planned users in Accelerator labs
  - BSCCo unites Fermilab, LBNL, BNL and NHMFL on 2212
  - CERN is linked to BSCCo through EUCARD2 task 10 20 T magnet aspect of LHC energy upgrade

The case for a long term R&D effort

- **Magnet-pull focus**
  - NMR HTS coil
  - 40 T small HTS coil (31 T background)
  - Accelerator demands (MAP, LHC)
  - Finding the limits (stress, energy density, quench….)
- **Conductor-pull focus**
  - YBCO coated conductors are evolving rapidly driven by 40-77K, 0-3 T use – what about 4 K, 20-40 T properties?
  - Bi-2212 is round wire and multifilament – but has intrinsically poor vortex pinning due to large electronic anisotropy



- **2212 and YBCO have 3 times the critical fields of Nb_3Sn but their conductor technology is still primitive….**
- **What we really want are the vortex pinning properties of YBCO and the grain boundary properties of 2212**
- **Why not………..?**

Some recent relevant papers

Planar GBs in YBCO

- Gurevich, A., Rzchowski, M. S., Daniels, G., Patnaik, S., Hinaus, B. M., Carillo, F., Tafuri, F., and Larbalestier, D. C., “Flux Flow of Abrikosov-Josephson Vortices Along Grain Boundaries in High-Temperature Superconductors,” *Physical Review Letters.* Vol. 88, No. 9, 2002, 097001-1-4.
- Song, X., Daniels, G., Feldmann, D.M., Gurevich, A., and Larbalestier, D.C., "Electromagnetic, Atomic-Structure and Chemistry Changes Induced by Ca-doping of Low Angle YBCO Grain Boundaries," *Nature Materials*, Vol.4, 2005, pp.470-475.

Non-planar GBs in YBCO

- Feldmann, D. M., Holesinger, T. G., Cantoni, C., Feenstra, R., Nelson, N. A., Larbalestier, D. C., Verebelyi, D. T., Li, X., Rupich, M., “Comparative Study of Grain Orientations and Grain Boundary Networks for $YBa_2Cu_3O_{7-x}$ Films Deposited by Metalorganic and Pulsed Laser Deposition on Biaxially Textured Ni W Substrates,” *Journal of Materials Research*, 21, 2006, 923-934.
- D. M. Feldmann, T. G. Holesinger, R. Feenstra, C. Cantoni, W. Zhang, M. Rupich, X. Li, J. H. Durrell, A. Gurevich and D. C. Larbalestier, “Mechanisms for enhanced supercurrent across meandered grain boundaries in high-temperature superconductors”, J. of Appl. Physics 102, 083192 (2007).
- D. C. van der Laan, T.J. Haugan, P.N. Barnes, D. Abraimov, F. Kametani, D. C. Larbalestier and M.W. Rupich, “Effect of strain on grains and grain boundaries in $YBa_2Cu_3O_{7-x}$ coated conductors”, Supercond. Sci. Tech., 23, 014004 (2010).

Bi-2212 wires without macroscopic texture

- T. Shen, J. Jiang, A. Yamamoto, U. P. Trociewitz, J. Schwartz, E.E. Hellstrom, and D.C. Larbalestier, “Development of high critical current density in untextured round-wire, multifilamentary $Bi_2Sr_2CaCu_2O_x$ round-wire by strong overdoping”, Appl. Phys. Letts., 95, 152516 (2009).
- Fumitake Kametani, Tengming Shen, J. Jiang, C. Scheuerlein, M. Di Michiel, Y. Huang, H. Miao, J. A. Parrell, E. E. Hellstrom, and D. C. Larbalestier, “Bubble formation within filaments of melt-processed Bi-2212 wires and its strongly negative effect on the critical current density”, Superconductor Science and Technology, 24, 075009 (2011)
- D. C. Larbalestier[1], J. Jiang[1], U. P. Trociewitz[1], F. Kametani[1], C. Scheuerlein[2], M. Dalban-Canassy[1], M. Matras[1], P. Chen[1], N. C. Craig[1], P. J. Lee[1] and E. E. Hellstrom[1], submitted to Nature Materials, arXiv 1305.1269.

High Field coils

- H.W. Weijers, U.P. Trociewitz, W.D. Markiewicz, J. Jiang, D. Myers, E. E. Hellstrom, A. Xu, J. Jaroszynski, P. Noyes, Y. Viouchkov, and D. C. Larbalestier, “High field magnets with HTS Conductors”, *IEEE Transactions on Applied Superconductivity*, 20, 576 (2010).
- Ulf P. Trociewitz, Matthieu Dalban-Canassy, Muriel Hannion, David K. Hilton, Jan Jaroszynski, Patrick Noyes, Youri Viouchkov, Hubertus W. Weijers, and David C. Larbalestier “35.4 T field generated using a layer-wound superconducting coil made of $(RE)Ba_2Cu_3O_{7-x}$ (RE = rare earth) coated conductor”, *Applied Physics Letters*, 99, 202506 (2011).
- W. Denis Markiewicz, David C. Larbalestier, Hubertus W. Weijers, Adam J. Voran, Ken W. Pickard, William R. Sheppard, Jan Jaroszynski, Aixia Xu, Robert P. Walsh, Jun Lu, Andrew V. Gavrilin, and Patrick D. Noyes, *IEEE Transactions on Applied Superconductivity*, 22, 4300704 (2012)
- M. Dalban-Canassy, D.A. Myers, U.P. Trociewitz, J. Jiang, E.E. Hellstrom, Y. Viouchkov, and D.C. Larbalestier, “Study of the local variation of critical current in Ag-alloy clad, round-wire $Bi_2Sr_2CaCu_2O_{8-x}$ multi-layer solenoids”, *Superconductor Science & Technology*, 25, 115015 (2012).