Superconductors for the FCC in a 10 year perspective – a view from the February 2015 LT/HFSW (Low Temperature High Field Superconductor Workshop)

David Larbalestier
ASC-NHMFL-FSU

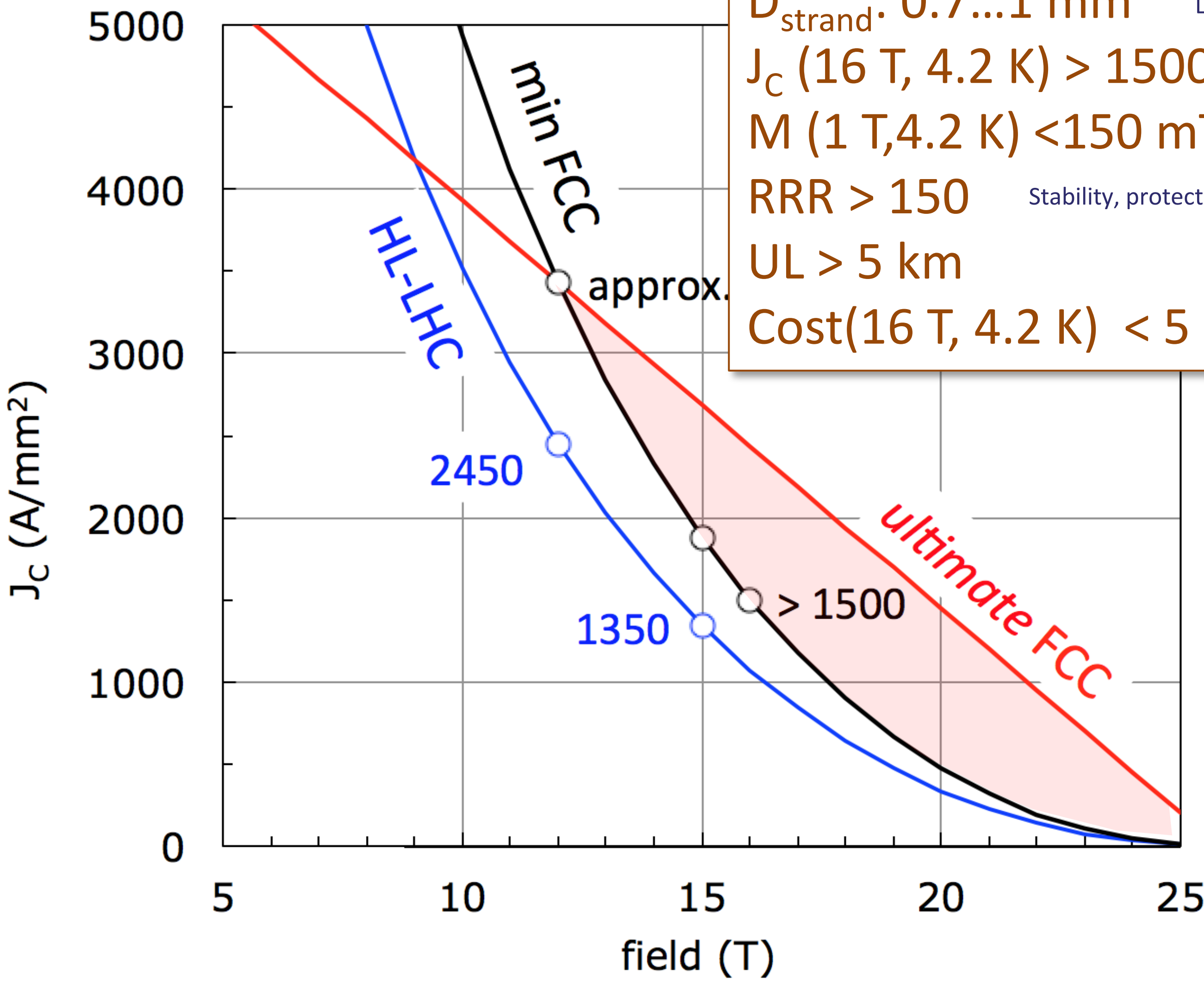
With special thanks to Mike Sumption (OSU), Venkat Selvamanickam (TcSUH), Danko van der Laan (ACT), Yibing Huang and Mike Field (OST) and my colleagues at FSU, especially Peter Lee, Jianyi Jiang, Ulf Trociewitz and Eric Hellstrom and the LTSW session chairs Arup Ghosh, Dave Sutter, Bruce Strauss, Ken Marken, Dan Dietderich and Lance Cooley)

Opportunities

Material	Threats	Opportunities
Nb_3Sn	Low margin	High pinning, fine grain drives up Jc to FCC targets, scale up drives costs down
Bi-2212	High cost and complexity in use	The first HTS wire that looks like an LTS wire
MgB_2	Low H_{c2} makes in-field use marginal, low sc fraction makes J_E low	H_{c2} engineering makes a magnet conductor and low cost pulls MRI applications
Fe-based $(K,Ba)Fe_2As_2$ (122)	Low connectivity cannot be resolved in round wire form	GB impurity effects get resolved, Jc rises and huge H_{c2} drive applications
REBCO	High cost, dependence on markets beyond magnets makes manufacture uneconomic, and tape form	CORC provides twisted, MF cable with small bend radii and high J_E – thicker REBCO, thinner substrates drive down $/kA.m

Homework set by the organizers

FCC Nb_3Sn performance targets



D_{strand}: 0.7…1 mm Large cables, **cabling !**
J_C (16 T, 4.2 K) > 1500 A/mm^2
M (1 T,4.2 K) <150 mT (D_{fil} < 20 μm) Field quality
RRR > 150 Stability, protection
UL > 5 km
Cost(16 T, 4.2 K) < 5 USD/kA m ITER material cost per kg

All single parameters are in reach, their combination is the challenge !

Ultimate Nb_3Sn ? Pursue the idea of improved high field pinning (q=1)
(D. Dietrich and R. Scanlan, A. Godeke)

Comment on the Home Work

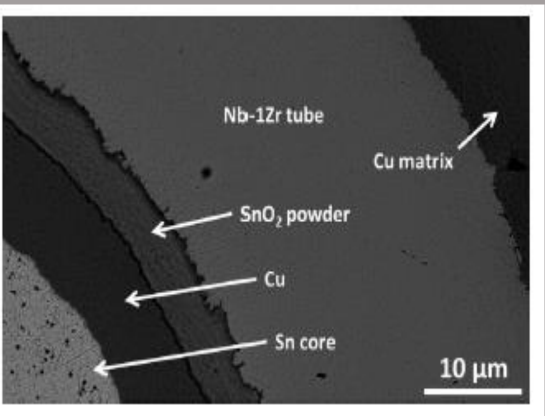
- At first sight the Jc target (J_C (16 T, 4.2 K) > 1500 A/mm^2) is the most daunting, but D_{fil} < 20 μm and cost(16 T, 4.2 K) < 5 $/kA.m surely complicate life!
- But HiLumi production is teaching us a lot about high Sn routes
- Recent R&D results at OSU and Hypertech are showing that Jc targets are not insane!

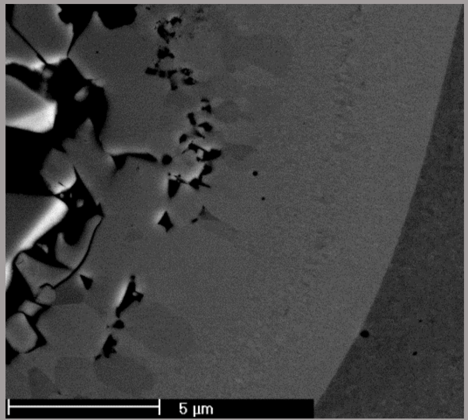
What are the Limits of J_c in Nb_3Sn Strands?

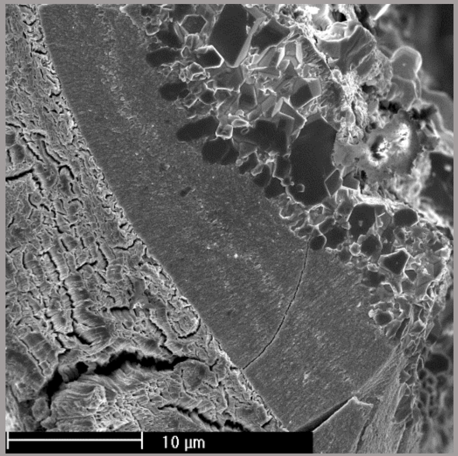
- New Tube Type Strand -- Idea to use internal oxidation of Nb-Zr to reduce grain size (following Zeitlin, but using an effective oxygen source and path). *Strand manufactured by Hyper Tech Inc.*

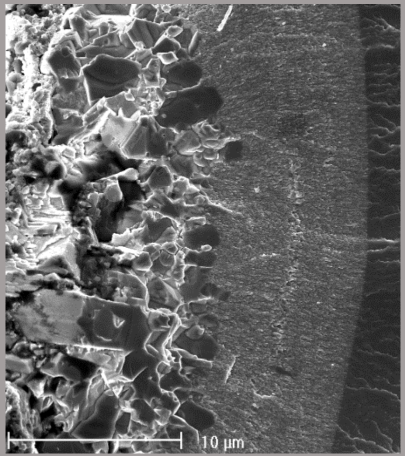
The Ohio State University
M. D. Sumption
X. Xu
E. W. Collings

Hyper Tech,
X. Peng

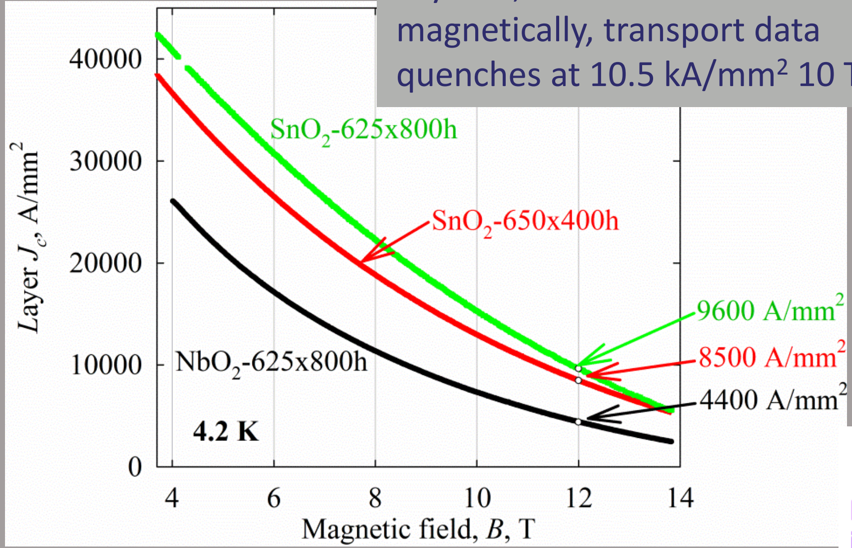


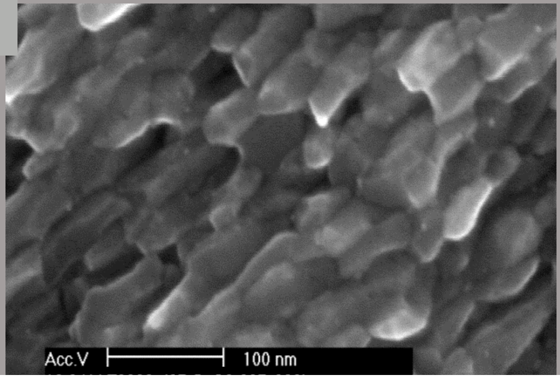


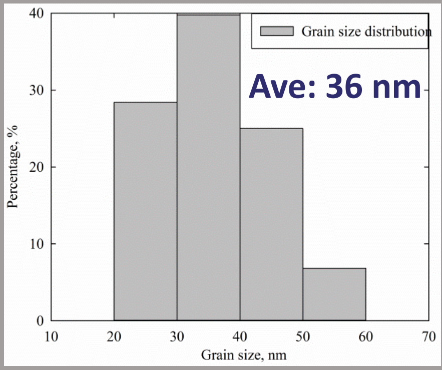




Layer Jc, measured magnetically, transport data quenches at 10.5 kA/mm^2 10 T







APPLIED PHYSICS LETTERS **104**, 082602 (2014)

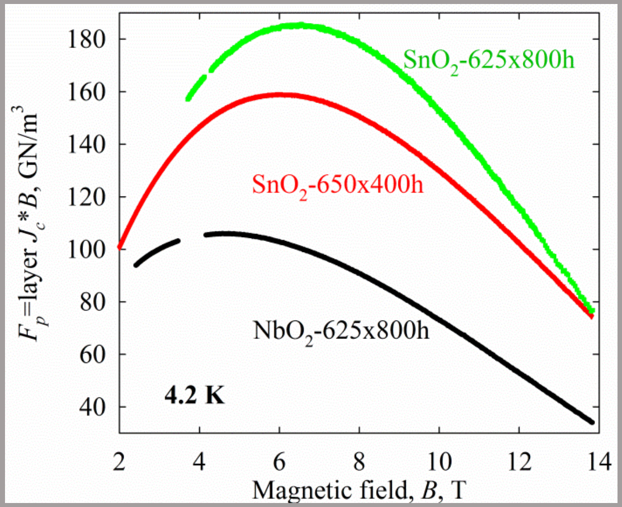
Refinement of Nb_3Sn grain size by the generation of ZrO_2 precipitates in Nb_3Sn wires

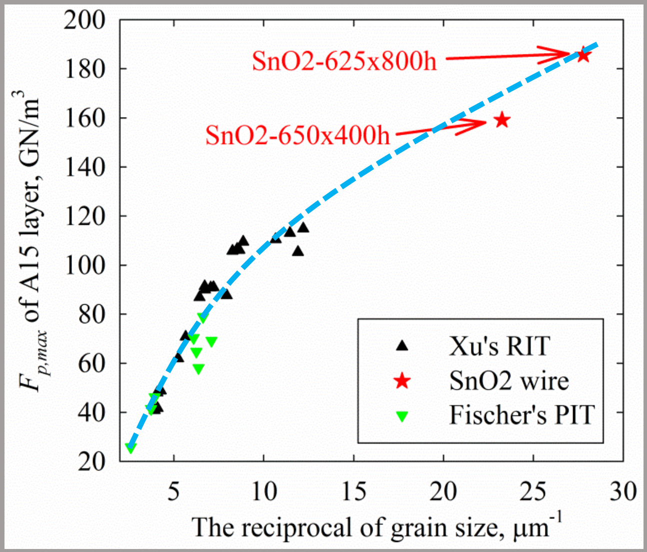
X. Xu,[1,a)] M. Sumption,[1] X. Peng,[2] and E. W. Collings[1]
[1]*Department of Materials Science and Engineering, The Ohio State University, Columbus, Ohio 43210, USA*
[2]*Hyper Tech Research Incorporated, 539 Industrial Mile Road, Columbus, Ohio 43228, USA*

Hyper Tech

THE OHIO STATE UNIVERSITY

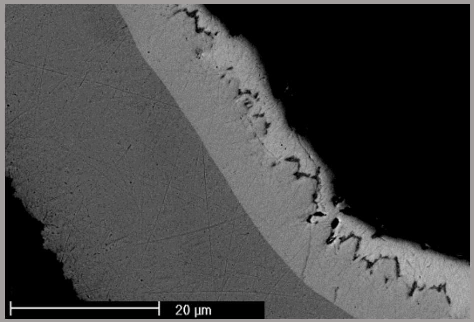
F_p-B curves of Internal oxidation strands



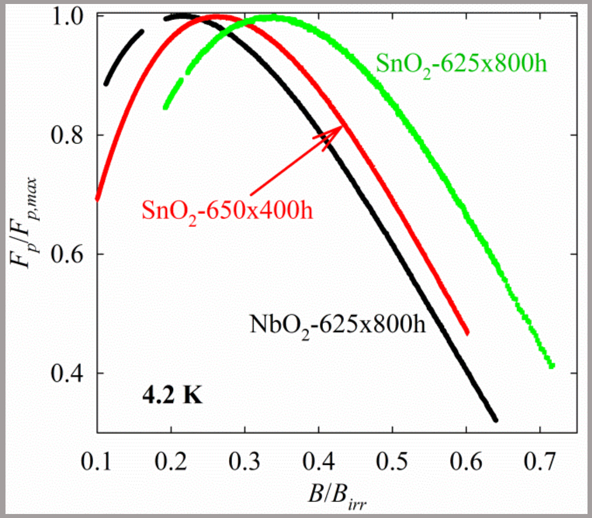


For SnO2-625x800h, two causes for increase in 12 T Jc:

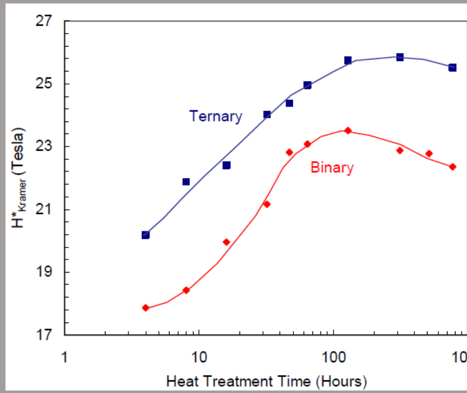
1. Increase in $F_{p,max}$.
2. Some shift of Fp-B peaks.

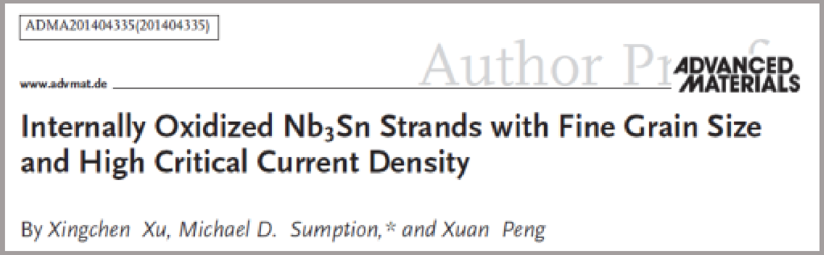


B_{irr} was obtained by fitting the F_p-B curve using F_p=Kb^p(1-b)^q, where b=B/B_{irr}.



	B_{irr}, T	Grain size, nm	F_p-B peak
NbO_2 - 625 °C	20.9	~90	0.22B_{irr}
SnO_2 - 650 °C	23	45	0.26B_{irr}
SnO_2 - 625 °C	~20	36	0.34B_{irr}




ADMA201404335(201404335)

www.advmat.de

Author Proof

ADVANCED MATERIALS

Internally Oxidized Nb_3Sn Strands with Fine Grain Size and High Critical Current Density

By Xingchen Xu, Michael D. Sumption,* and Xuan Peng

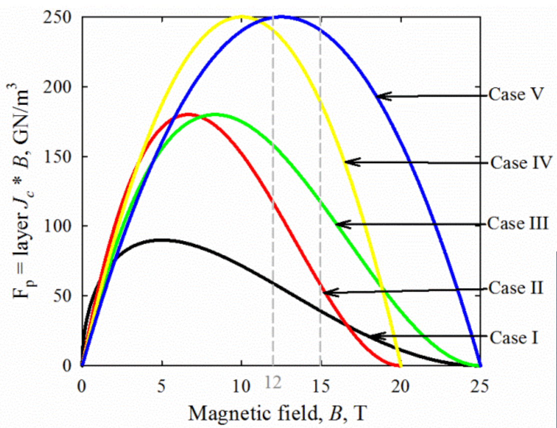
Further improvements:

1. Ti additions => B_{irr}↑
2. Higher Zr contents => smaller grain sizes?

Hyper Tech

CSMM Center for Superconducting & Magnetic Materials

THE OHIO STATE UNIVERSITY



What are the limits of J_c in Nb_3Sn?
Maybe these (if everything works out)……

Engineering J_c and I_c for the five different cases:

		I. Present state-of-the-art RRP strands	II. The wire with SnO_2 - 625 C / 800h	III. Only improve B_{irr} to 25 T by Ti doping, etc.	IV. Only refine the grain size to 25 nm	V. Both improve the B_{irr} to 25 T and refine the grain size down to 25 nm
Grain size, nm		100 - 120	36	36	25	25
F_p-B peak		$0.2B_{irr}$	$0.34B_{irr}$	$0.34B_{irr}$	$0.5B_{irr}$	$0.5B_{irr}$
$F_{p,max}$, GN/m^3		~90	180	180	~250	~250
B_{irr}, T		25	20	25	20	25
12 T	Layer J_c, A/mm^2	5,000	9,600	16,400	20,000	20,800
	Non-Cu J_c, A/mm^2	3,000	5,760	9,840	12,000	12,480
	Engineering J_c, A/mm^2	1,600	3,050	5,200	6,360	6,600
	I_c, A	800	1,530	2,620	3,200	3,320
15 T	Layer J_c, A/mm^2	2,700	3,800	7,800	12,500	16,000
	Non-Cu J_c, A/mm^2	1,600	2,280	4,680	7,500	9,600
	Engineering J_c, A/mm^2	850	1,210	2,480	4,000	5,100
	I_c, A	430	610	1,250	2,000	2,560

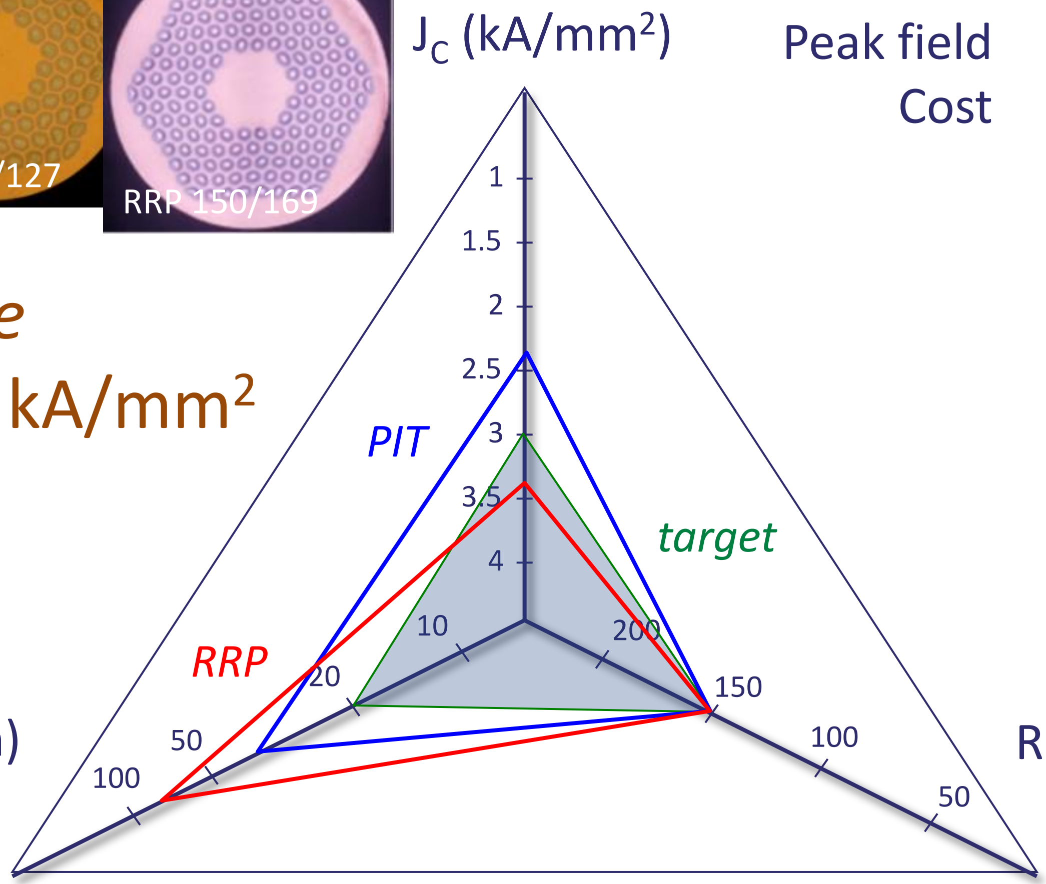
Note: Assuming all the five cases have the same Nb_3Sn area fraction with the state-of-the-art RRP strands:

- the Nb_3Sn area fraction in a subelement is 60%,
- the non-Cu area fraction in a strand is 0.53,
- the wire diameter is 0.8 mm.

Possible rosy scenario: 6x increase in Jc at 15 T

Meanwhile the practical HiLumi Nb_3Sn wire is in sight

Performance
Peak field
Cost



Practical wire

$J_C(12T) > 2.5$ kA/mm^2

$D_{fil} < 50$ μm

RRR > 150

Magnetization
Field Quality
Stability

Stability
Protection

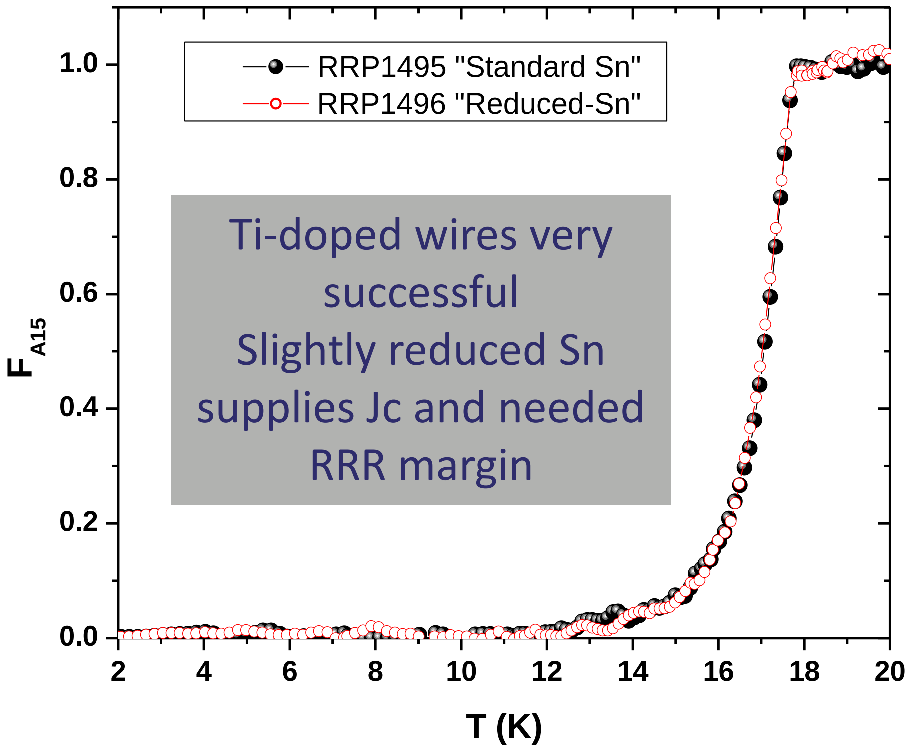
Luca Bottura (CERN) – 2013 MT23 talk – OST RRP and BEST PIT are vying for supremacy

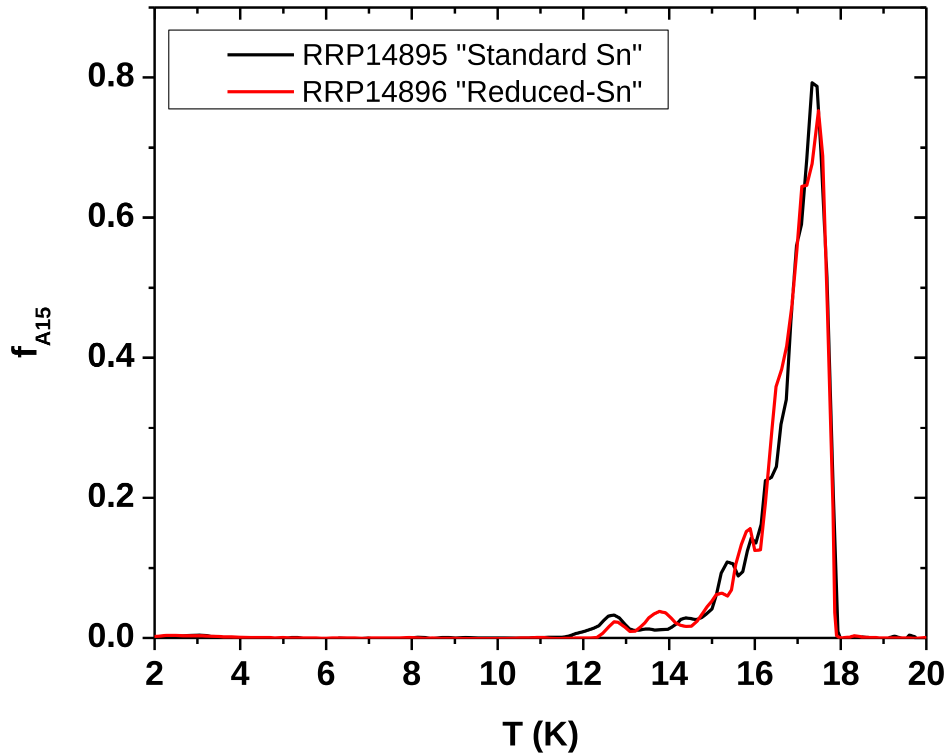
The FCC charge – Bottura March 23 talk

Task	Key targets	Description
Nb_3Sn	D_{strand}: 0.7…1 mm J_C (16 T, 4.2 K) > 1500 A/mm^2 DM (1 T,4.2 K) <150 mT (D_{fil} < 20 μm) RRR > 150 UL > 5 km	Develop conductor for **increased J_C** with respect to HL-LHC specifications, maintain high RRR, reduce magnetization, increase stability, withstand cabling
LTS cost	Cost(16 T, 4.2 K) < 5 $/kA m	Perform cost analysis and identify drivers Process innovation and potential for industrialization to increase yield and UL, **reduce cost**
HTS	J_E (20 T, 4.2 K) > 600 A/mm^2 UL > 100 m	Develop long length homogeneous YBCO tape and BSCCO wires, develop high current cables
Quench	Quench propagation speed and temperature limits characterization	Understand quench regimes and quench limits for LTS and HTS materials

For a real wire, not just Jc, not just $/kA.m but $d_{filament}$, piece length – in short everything – so progress towards the real targets of HiLumi is still vital

The A15 T_c-distribution is now very sharp



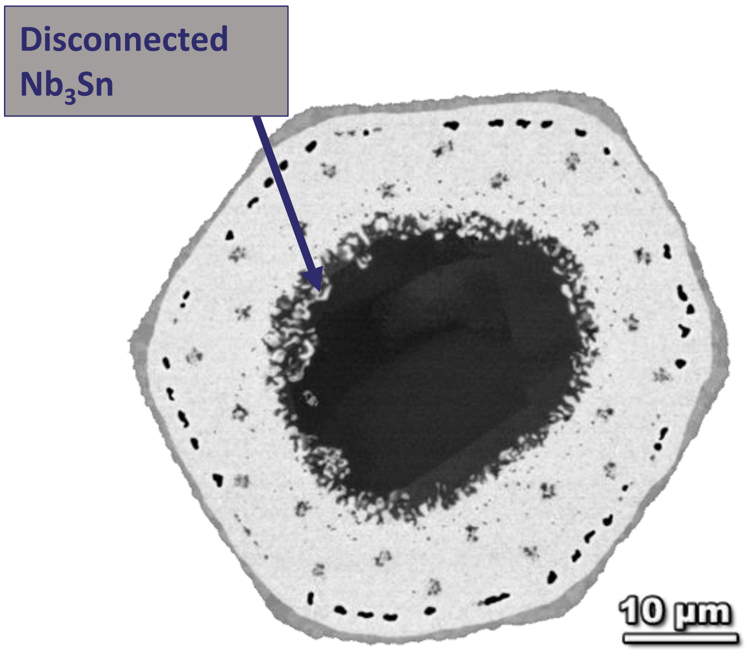


- The two wires almost overlap each other
- There is no A15 with T_c below ~12 K

OST RRP HiLumi wires reacted by A Ghosh (LARP) analyzed by Chiara Tarantini

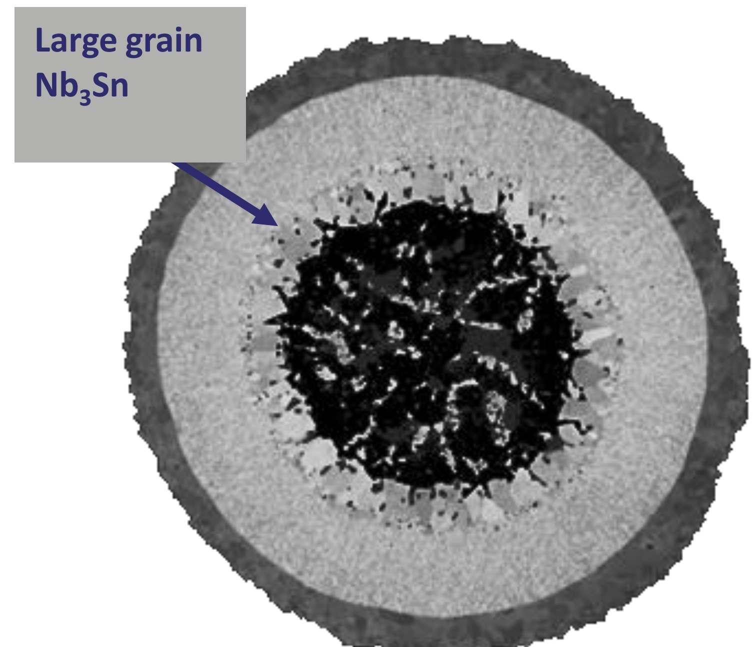
New goal is to maximize the A15 and ensure that it carries current

- In fact a significant Nb_3Sn fraction is lost as large grain or is disconnected A15 in the core and does not contribute to J_c.



RRP images by C. Sanabria (ASC)

Fully reacted RRP filament showing signficant disconnected Nb_3Sn due to dissolution (a result of **high Sn phases** in contact with Nb).



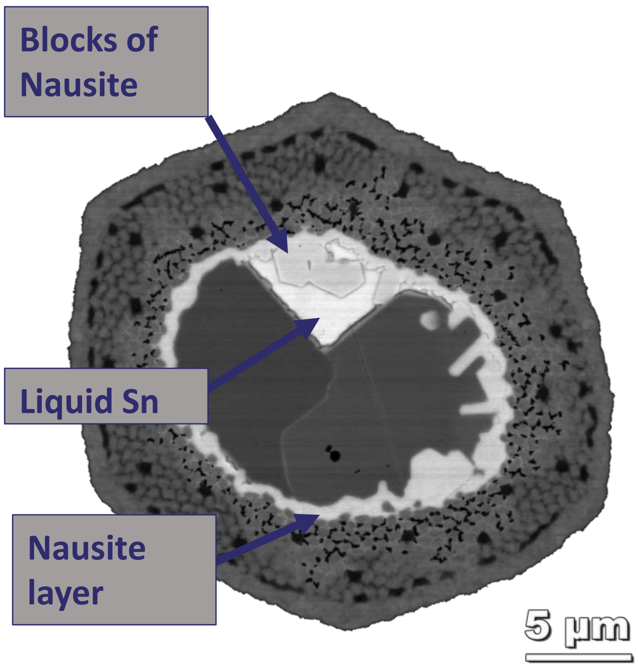
PIT images by C. Segal (ASC)

Fully reacted PIT filament showing a substantial amount of large grain Nb_3Sn due to **high Sn phases** in contact with Nb.

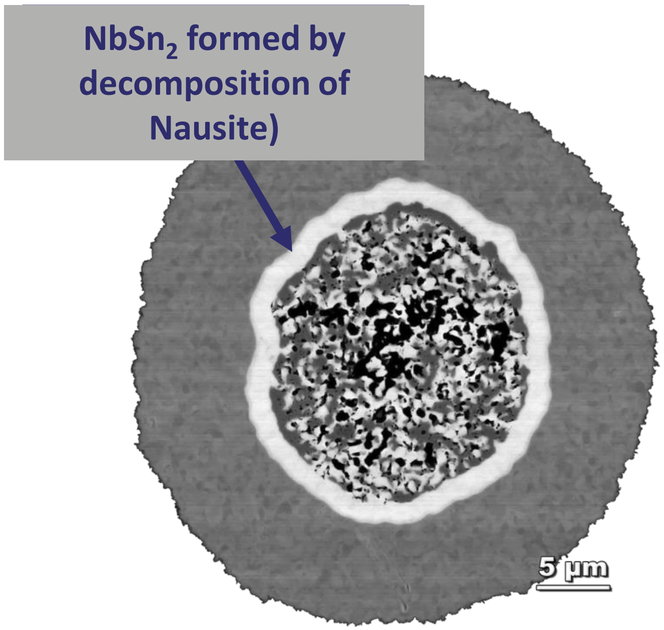
Events **below 600°C** are responsible for Large Grain and Dissolution

HiLumi conductors

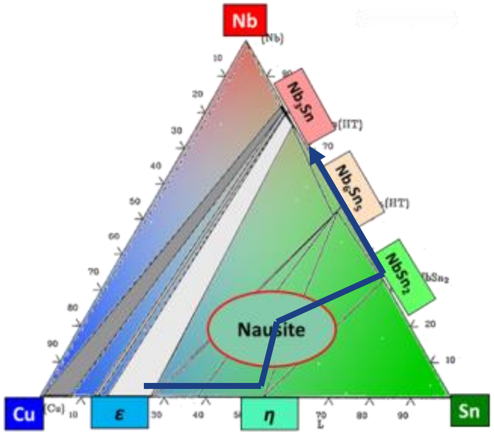
- The Sn-Nb-Cu Nausite phase is **responsible** for useless Large Grain A15 and Dissolution of filament(s) into the core



RRP filament quenched from 545°C. These blocks of Nausite are responsible for **Disconnected Nb_3Sn**



PIT filament quenched at 575°C. These blocks of $NbSn_2$ (previously Nausite) are responsible for **Large Grain Nb_3Sn**



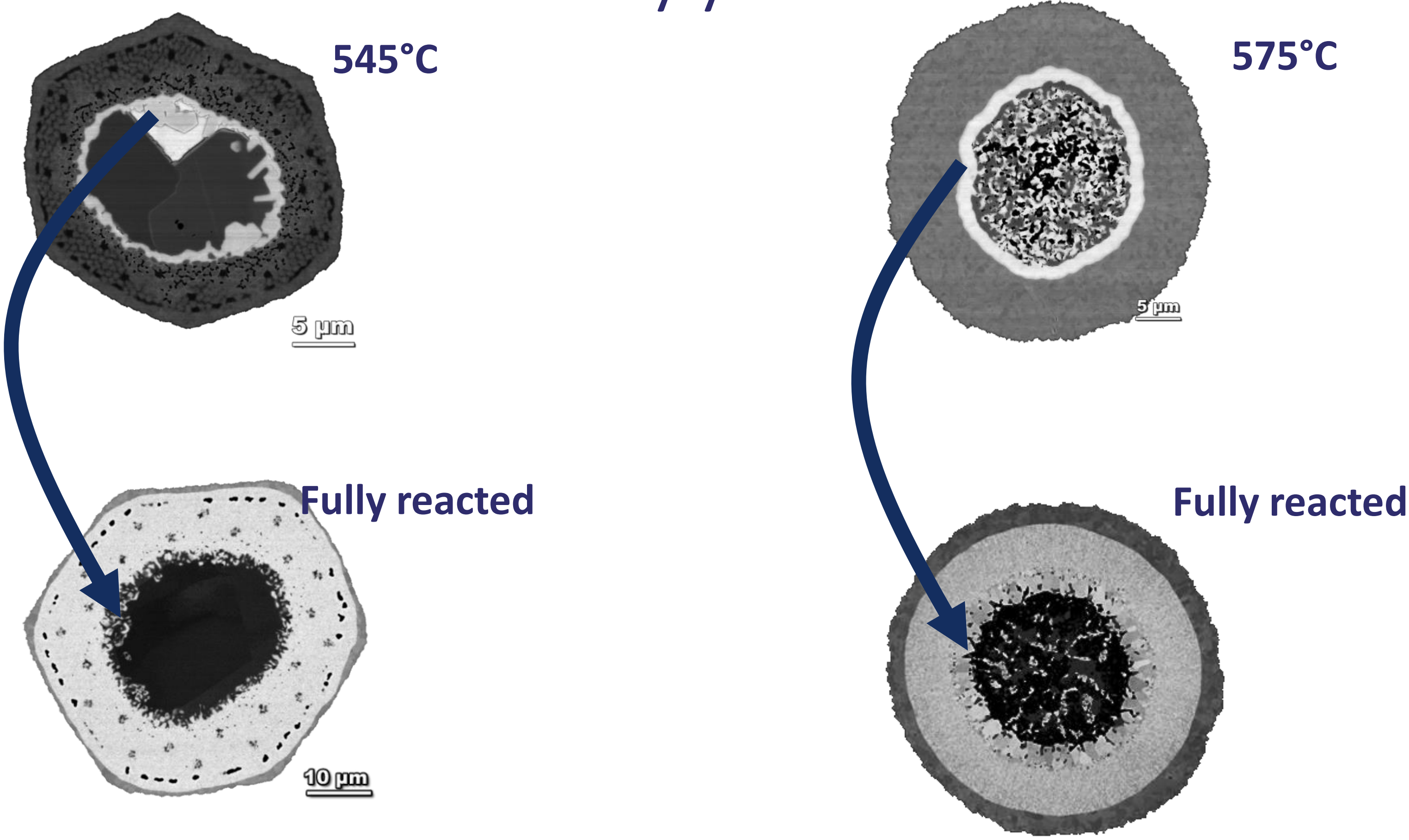
Phase diagram adapted from Villars [2], Pong [3] and [1] Scheuerlein

Nausite exists between ~350°C and ~550°C

Now being appreciated that much similarity of reaction path in PIT and RRP

1) C. Scheuerlein, *et. al.*, *J. Phys.: Conf. Ser.*, vol. 234, no. 2, p. 022032, Jun. 2010.
2) Handbook of Ternary Alloy Phase Diagrams, P. Villars, A. Prince and H Okamoto, eds., ASM International, 9757 (1995).
3) I. Pong, et al. *Supercond. Sci. Technol.*, vol. 26, no. 10, p. 105002, Oct. 2013.

The **lower temperature events** have been overlooked for many years



… It is time to understand **what is happening** here!

We believe that this is the key to removing variabilities in RRP performance and in further enhancing PIT performance – and would be vital too for oxide-pinned fine grain Nb_3Sn too

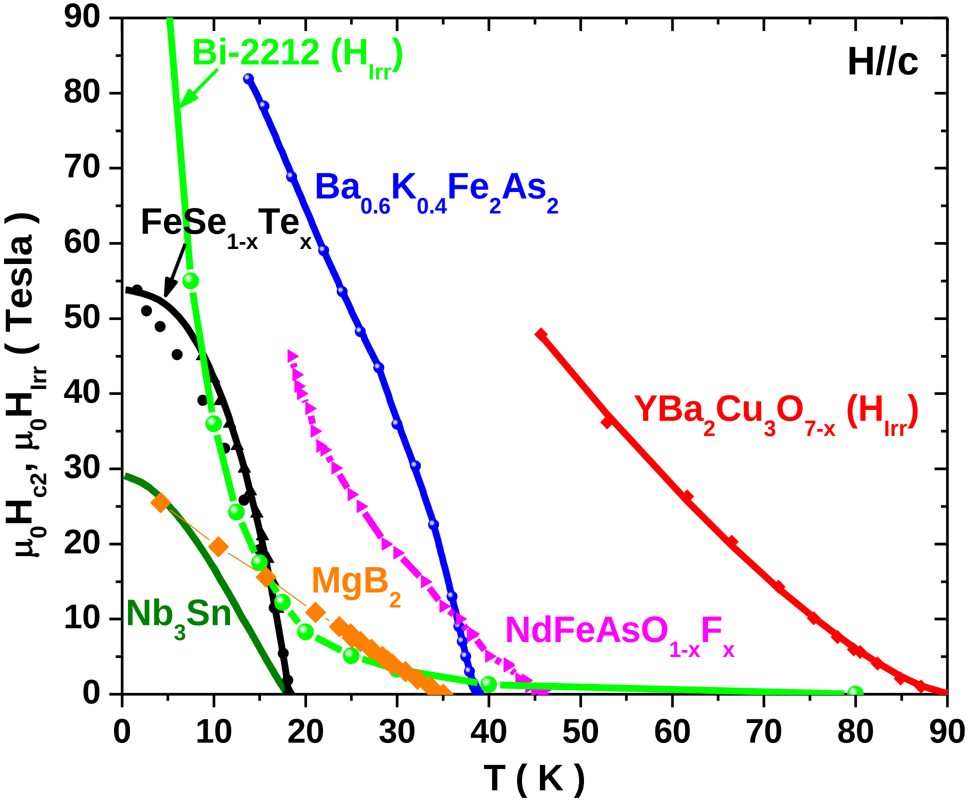
My view of Nb_3Sn

- **Still work to do** – even though HiLumi performance seems to be asymptotic
  - Today's action is on manufacturing variables – they are forcing us to confront what we do not yet understand
    - They are also the route to lower $/kA.m
  - The reaction pathway(s) are still poorly understood (Pong, Lee and Sanabria session 3 LTSW)
  - A new POP of small grain size and oxide pinning has been provided by OSU (Xu and Sumption)
    - Potential for 6x increase of Jc at 15 T
    - But is it fabricable in FM form? Definitely interesting work.

Does even 6x Jc provide enough stability margin for 16 T dipoles (no increase in ΔT)?

If not Nb_3Sn, then what?

Primary requirement is higher H_{c2} or H_{irr}



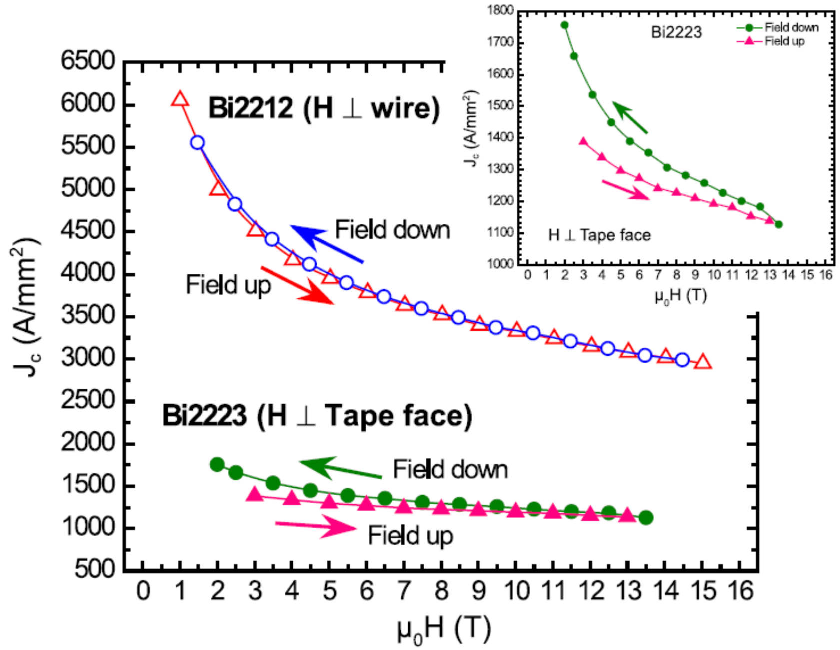
- Multiple materials possible
  - Bi-2212
  - MgB_2
  - REBCO
  - Fe-base (FeSe,Te or especially 122)

….and also that GB problems do not excessively complicate product form

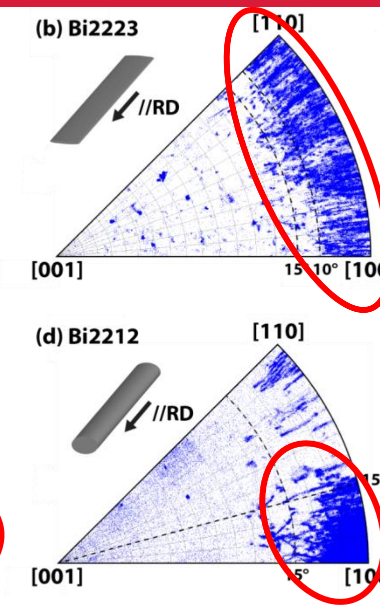
The GB problem

- All low carrier density materials (HTS cuprates and Fe-based superconductors) suffer from some blocking of current at GBs
  - Higher doping levels raise the carrier density and allow higher Jc
  - YBCO and Bi-2223 were the first HTS materials to become conductors – neither allows much overdoping
  - Bi-2212 optimizes in a lower Tc, overdoped state
  - Fe-based superconductors seem to show same behavior as cuprates but to a less marked degree

Bi-2212 appears to be biaxially textured



Bi-2223: self-organized in-plane texture much less effective than Bi-2212 only uniaxial texture



Bi-2212: self-organized in-plane texture due to melt texturing

Biaxial growth texture!

SCIENTIFIC REPORTS

SCIENTIFIC REPORTS | 5 : 8285 | DOI: 10.1038/srep08285

OPEN

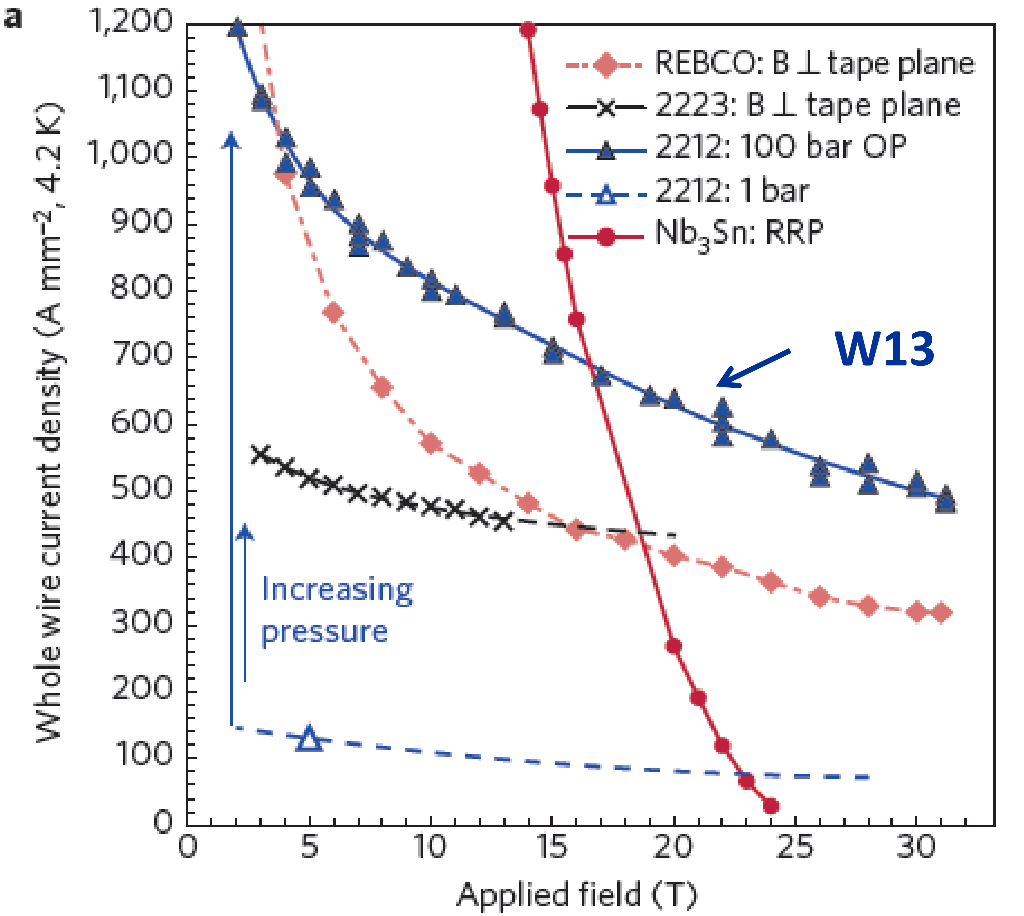
SUBJECT AREAS:
SUPERCONDUCTING PROPERTIES AND MATERIALS
SCANNING ELECTRON MICROSCOPY

Comparison of growth texture in round Bi2212 and flat Bi2223 wires and its relation to high critical current density development

F. Kametani, J. Jiang, M. Matras, D. Abraimov, E. E. Hellstrom & D. C. Larbalestier

Fumitake Kametani, ICMC/CEC Award of Excellence, July 2014 (Enschede NL)

High J_c and J_E are obtained in fully dense OverPressure processed wires (4.2 K, 20 T) J_E = 640 A/mm^2, J_c = 2500 A/mm^2



Larbalestier *et al.*, *Nature Materials* 13, 375 (2014)

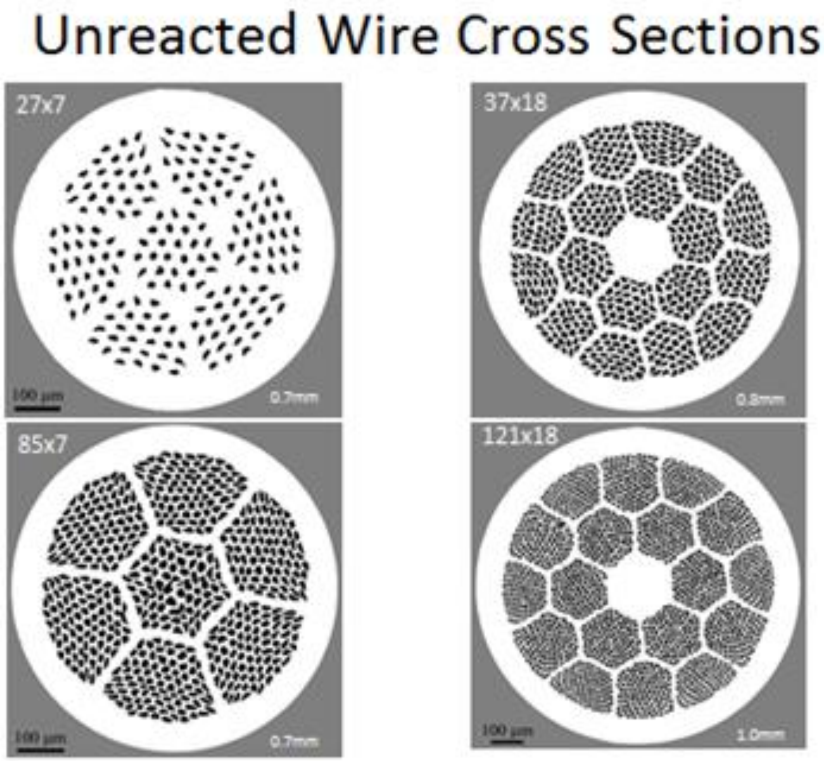
Wires have similar Jc :

- W7 (0.8mm, 37x18, VHFSMC)
- W9 (0.8mm, 37x18, VHFSMC)
- W13 (0.8mm, 37x18, VHFSMC)
- pmm090414 (85x18, CDP)
- pmm120104 (85x18, CDP)
- pmm120822 (121x18, FSU)
- pmm141014 (85x18, MM/OST)

Why are other wires not as good?

- Powder quality varies
- Wire manufacture effects?

OST making wide variety of architectures – all twisted



- Latest CDP scale up wire has provided a single length (800 m at 1.3 mm dia. – 9 kg, twisted with 20 mm pitch)
- FSU Overpressure coil furnace now in operation and 2 coils have been reacted

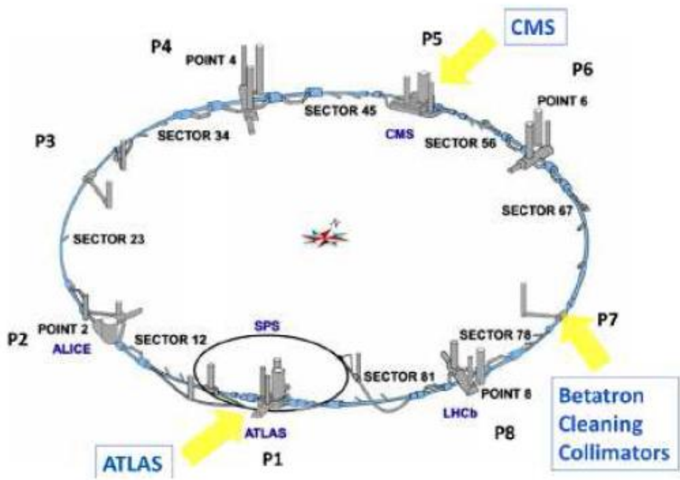
8 T insert coil in 16 T background planned for mid summer (Trociewitz)

MgB_2 conductors for powering cables: CERN related activities

IOP Publishing Superconductor Science and Technology
Supercond. Sci. Technol. 27 (2014) 044024 (7pp) doi:10.1088/0953-2048/27/4/044024

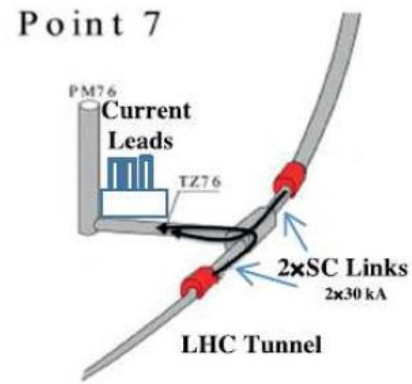
Development of superconducting links for the Large Hadron Collider machine

Amalia Ballarino
CERN, European Organization for Nuclear Research, 1211 Geneva 23, Switzerland

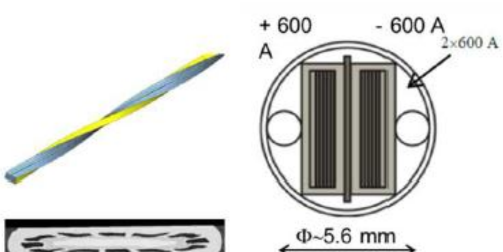


Project related to High luminosity LHC configuration:

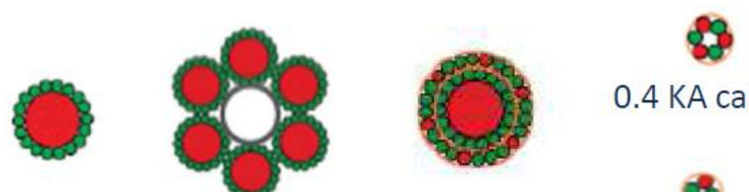
- move the magnet feed boxes out of the tunnel to surface (P1 and P5) or radiation free underground areas (P7)
- feed the magnet with a new cold powering system



Twisted pairs with tapes



Cable configurations with round wires



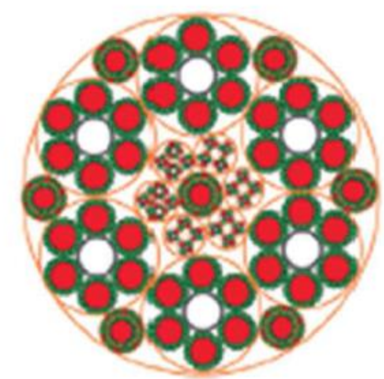
d=6.5mm

20KA cable
d=19.5mm

concentric
2 x 3KA cable
d=8.5mm

0.4 KA cable

0.12 KA cable



165 KA cable assembly
for P1 and P5

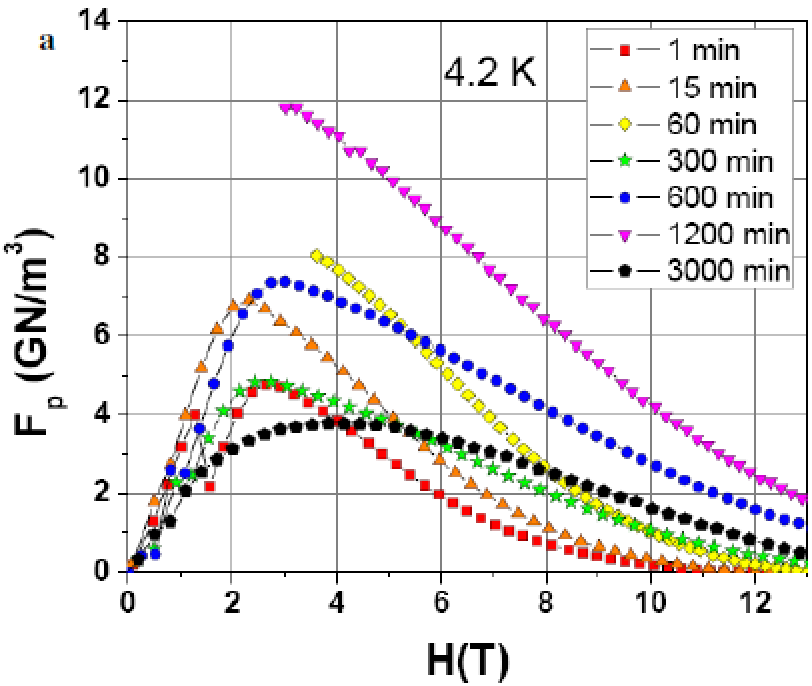
Tonnage manufacturing development of round wire for CERN links

MgB_2 needs a **breakthrough** to become a **high field conductor**

IOP Publishing — Superconductor Science and Technology
Supercond. Sci. Technol. **21** (2008) 035009 (10pp) — doi:10.1088/0953-2048/21/3/035009

Nanoscale grains, high irreversibility field and large critical current density as a function of high-energy ball milling time in C-doped magnesium diboride

B J Senkowicz[1,2], R J Mungall[2], Y Zhu[2], J Jiang[1], P M Voyles[2], E E Hellstrom[1,2] and D C Larbalestier[1]



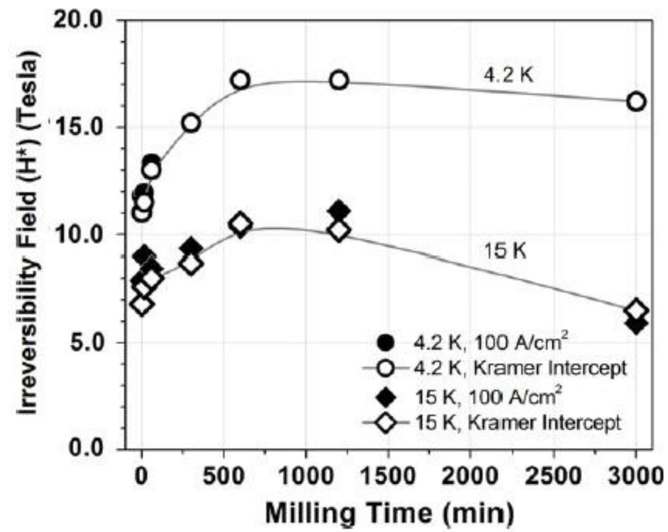


Figure 8. Irreversibility field (H^*) as a function of milling time at 4.2 K (circles) and 15 K (diamonds) using the $J_c = 100$ A cm^{-2} criterion (solid symbols) or a Kramer line intercept (hollow symbols). Lines are a guide to the eye.

These are close to the best bulk form C-doped, fully dense MgB_2 bulks – F_{pmax} (4.2K) = 12 GN/m^3 at 2 T – Nb-Ti achieves 15-20 GN/m^3 at 5 T, H_{irr}(4.2K) ~ 17 T

Higher H_{c2} than Nb_3Sn is attainable in films

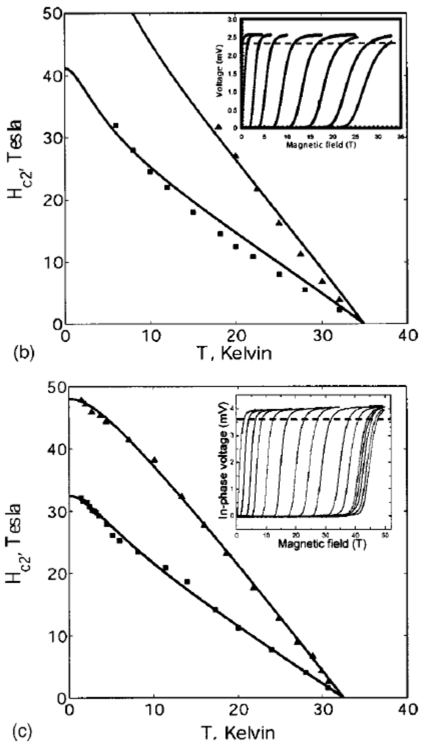


FIG. 2. $H_{c2}^{\parallel}(T)$ (triangles) and $H_{c2}^{\perp}(T)$ (squares) for films G (a), F (b), and D (c). Insets show the raw $R(H)$ traces for $H \parallel ab$. Solid curves are calculated from Eqs. (1) and (2) with fit parameters given in Table I.

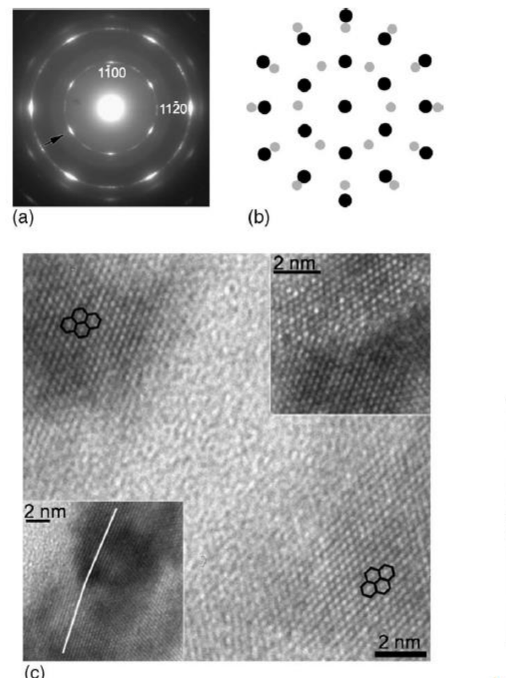


FIG. 1. (a) [0001] zone-axis SAD pattern taken from a plan-view C-d film sample. (b) The model to explain the SAD pattern in (a). (c) HR image taken along [0001] showing an amorphous region between two 30°-rotated MgB_2 grains. The upper-right inset shows a clean boundary between two MgB_2 grains, and the lower-left inset shows two MgB_2 grains with a 4.5° rotation angle with respect to each other.

APPLIED PHYSICS LETTERS **91**, 082513 (2007)

Nanoscale disorder in high critical field, carbon-doped MgB_2 hybrid physical-chemical vapor deposition thin films

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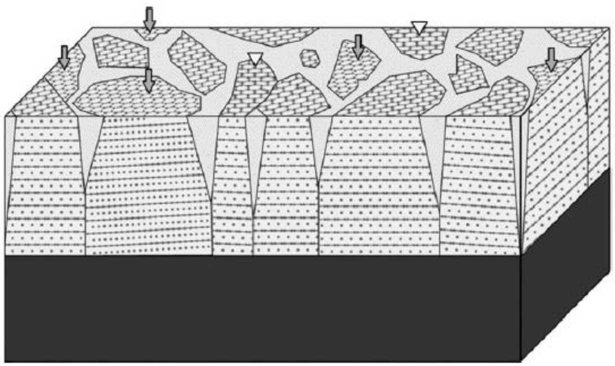


FIG. 4. Schematic drawing showing the microstructure of C-doped films. The arrows indicate grains rotated by 30° and the triangles indicate grains with small-angle rotation about the c axis.

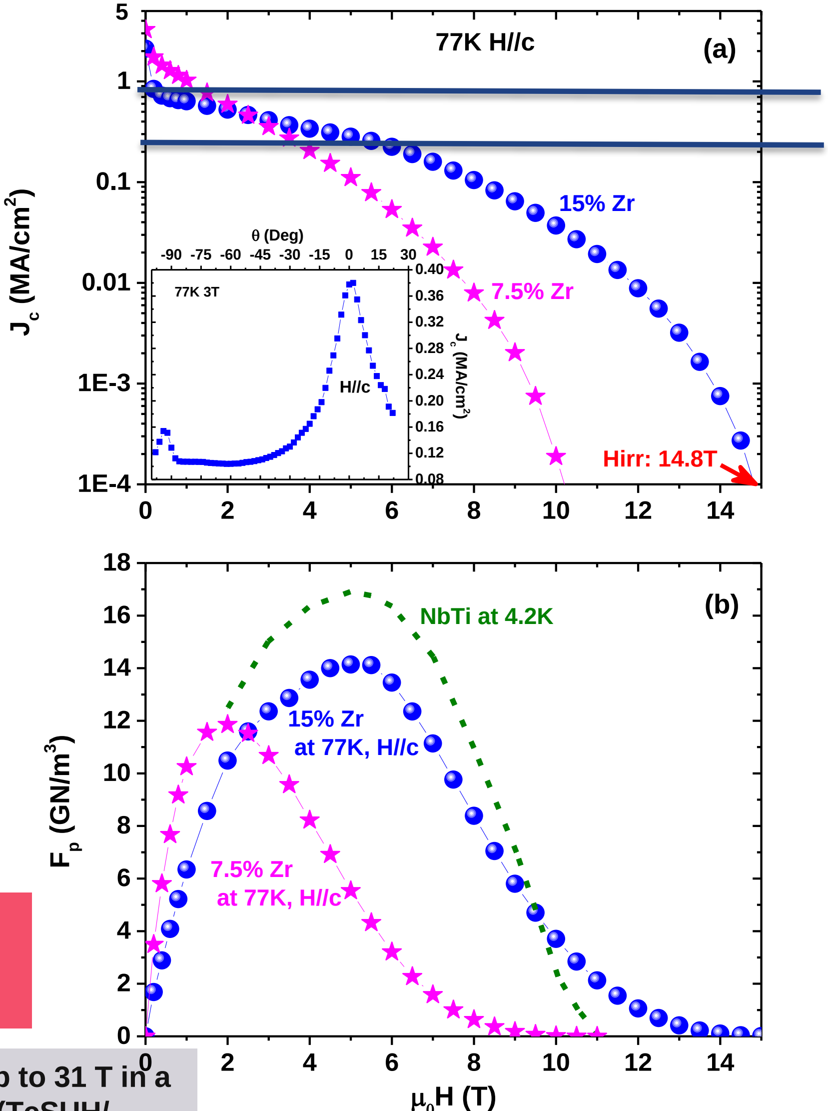
- 40 T H_{c2} and 30-32 K T_c are very attractive –excess intragrain C causes intense scattering which drives up H_{c2} but excess C also almost kills the GB connectivity ensuring low Jc
- Cries out for creative materials science to engineer scattering into bulk form MgB_2

Optimal REBCO vortex pinning engineering works at both 77 and 4 K – How to make CC useful not just at 4K but at 65-77K too?

REBCO absorbs many different types of pin ensuring high J_c: problem is to achieve high J_e, not high J_c

- Standard SuperPower tape has 50μm Hastelloy (but 30 μm is announced) with 1 μm of REBCO and 40 μm of Cu ($t_{nominal}$ = 100 μm)
- New 15Zr with 10^5 A/cm^2 at 8T/77K and H_{irr} = 15 T shows huge potential
- If t_{REBCO} could be 5 μm, Cu 20 μm, Hastelloy 30 μm, J_e (5T, 77K) = 350 A/mm^2 and magnet conductors for 65-77K would be assured

Make Nb-Ti properties the target for 77 K use by REBCO (need non-HEP pull)



- **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, et al. (TcSUH/ ASC-NHMFL collab) – APL- Materials 2, 046111 (2014)**

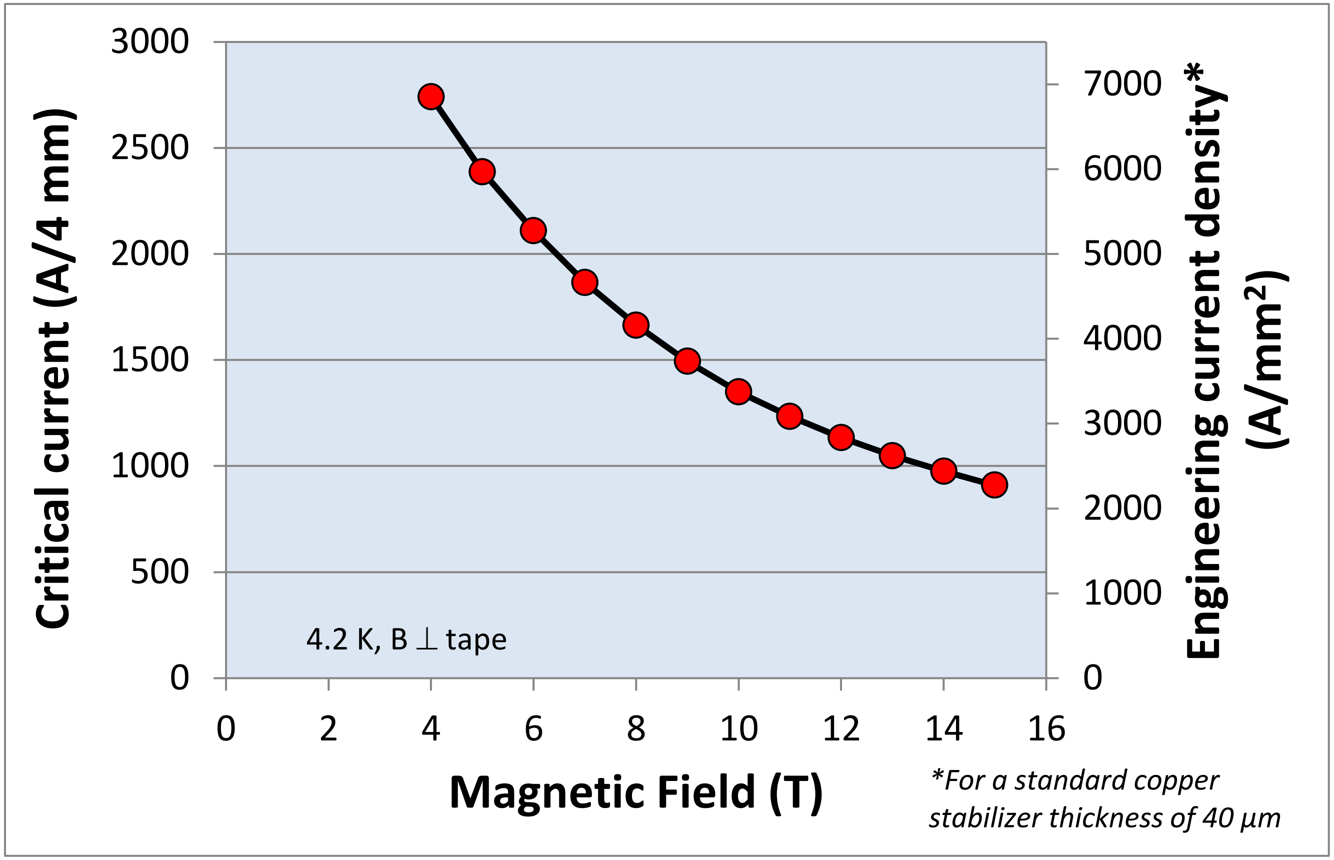
REBCO for HEP magnets in CORC form?

Greater uniformity, longer length, and (much) lower cost

- J_c is quite high enough to get big magnets into trouble at 4 K
- Much longer lengths
  - Delivery on the same scale as manufacture is the path to reduced cost……….<$10/kA-m
- Much thicker films (3-5 μm) would allow 5-15 T technology at 65-77 K by allowing $J_{eng} > 10^3$ A/mm^2 at 5-15 T –
  - this could allow REBCO to take over magnet technology from Nb-Ti (cost $2-5/kA-m) by 65-77 K operation

Selva and Danko talks on Tuesday at LTSW

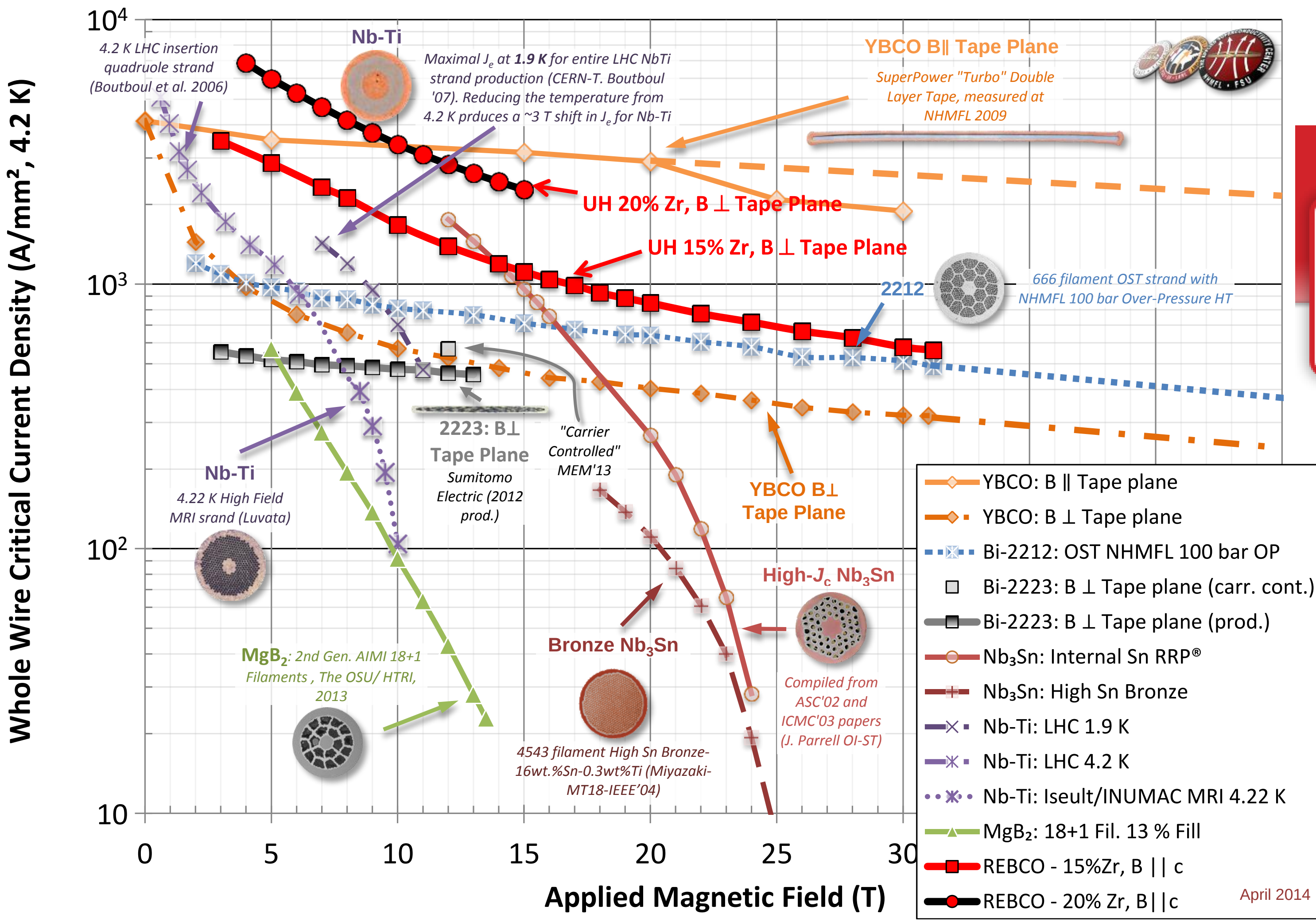
Very high I_c and J_e in 3.3 µm thick 25%Zr tape at 4.2 K



At 4.2 K, 15 T, I_c = 909 A/4mm, J_e = 2273 A/mm^2

Data obtained by Dmytro Abraimov, Van Griffin, David Larbalestier, NHMFL, Feb. 2015

15%Zr & 20%Zr tape performance at 4.2K better than all wires even in field perpendicular to tape



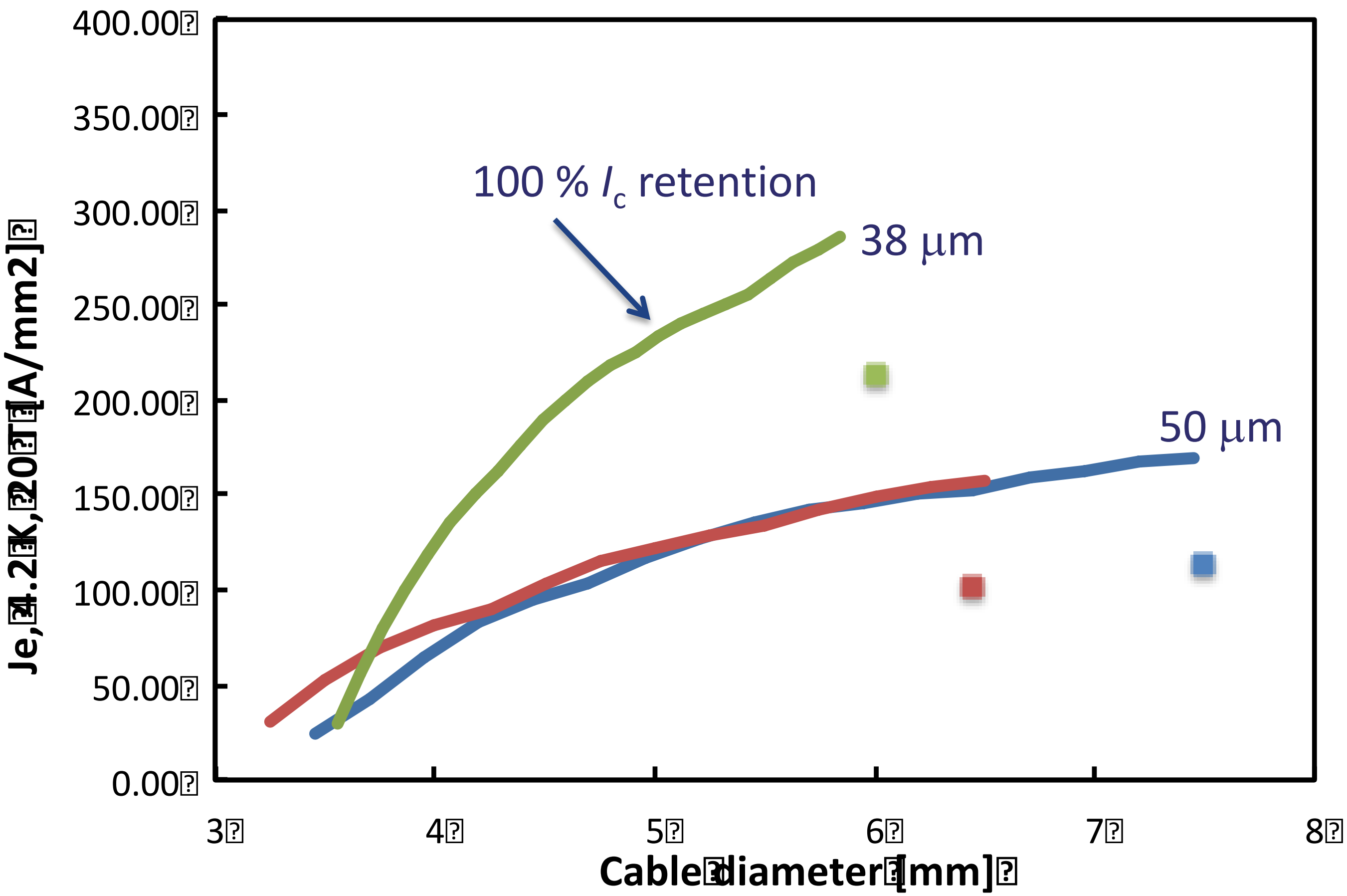
Data maintained by Peter Lee, NHMFL, http://fs.magnet.fsu.edu/~lee/plot/plot.htm
UH data on 15%Zr tapes from *APL Materials* **2,** 046111 (2014)

CORC cable for CERN order

CERN (delivered August 2014):

- 12 meter long
- 38 tapes (4 mm wide, 20 microns of copper)
- 5 mm diameter former

Current status



I_c (20 T) ~ 6 kA.

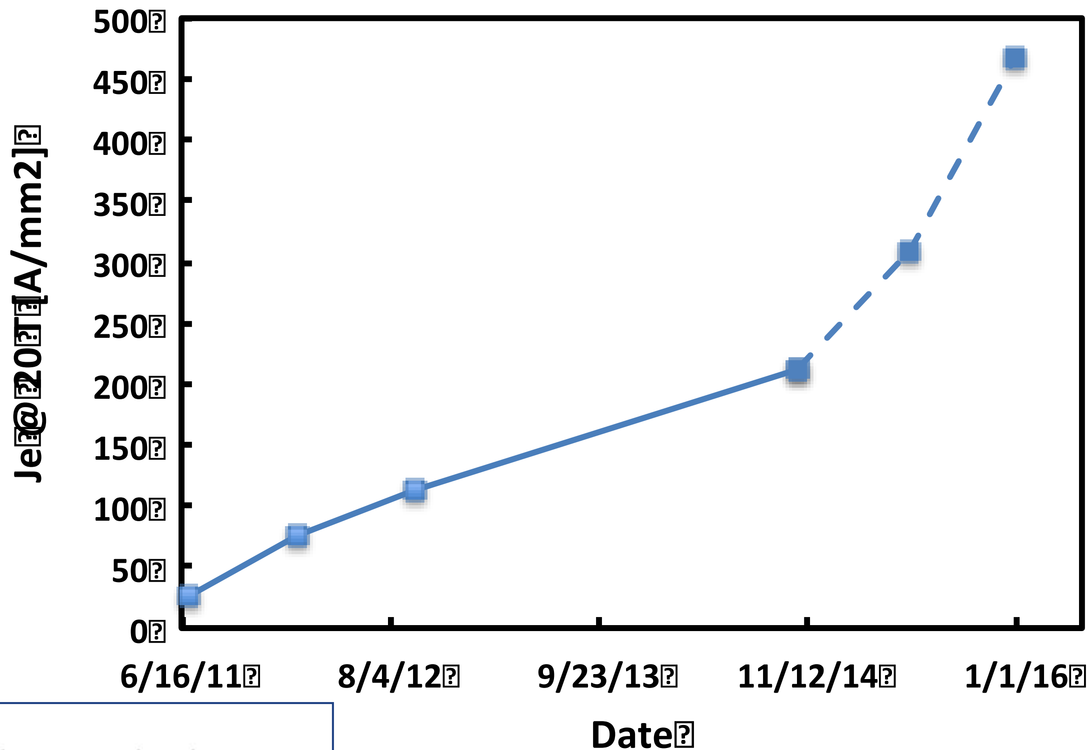
J_e (20 T) = 213 A/mm^2, 75 % I_c retention.

In prospect for 2015

CORC cables are now available, right now, in long lengths:

- I_c up to 7 kA at 20 T
- J_e of 200 A/mm^2 at 20 T
- Cable outer diameter of less than 6.0 mm.

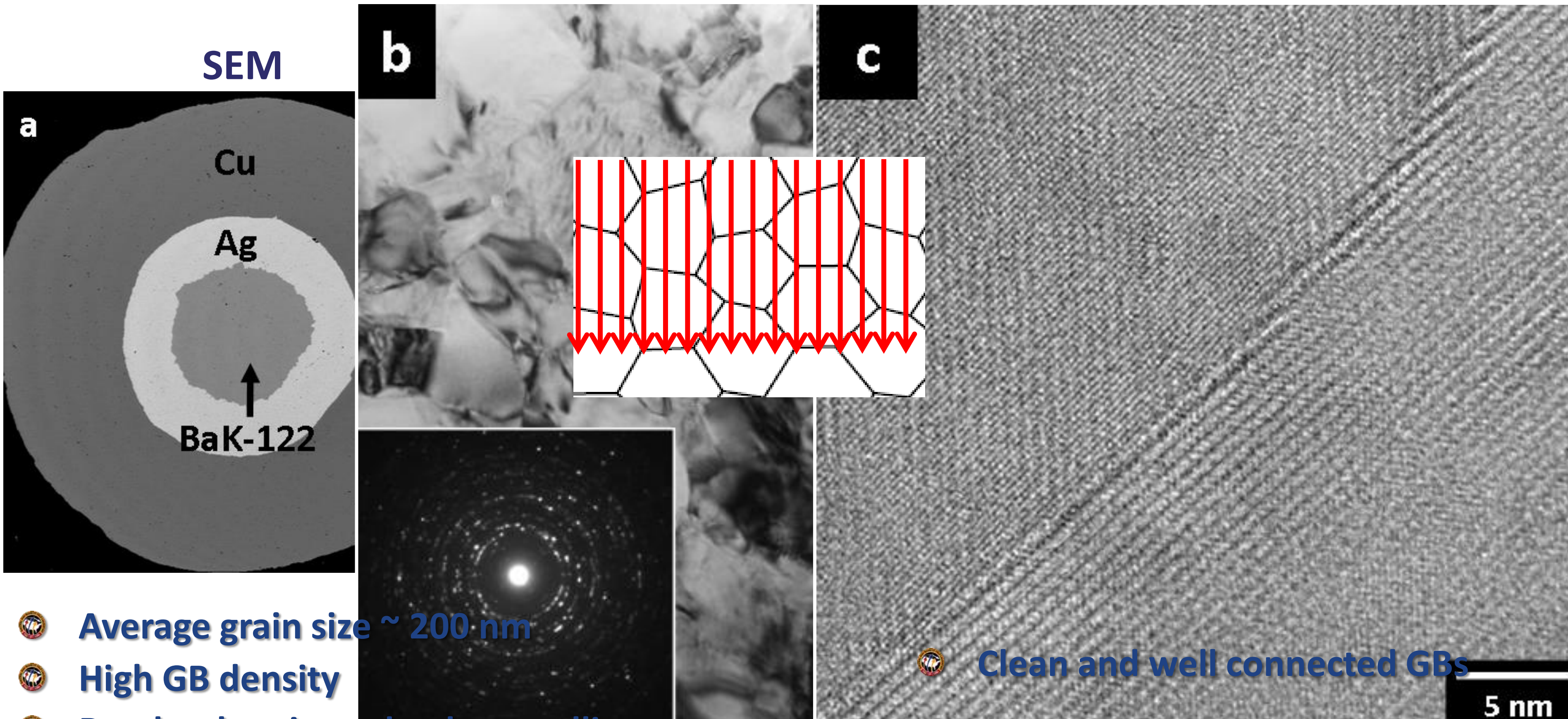
Expected J_e (4.2 K, 20 T) = 400-500 A/mm^2 before the end of 2015!



Advanced Conductor Technologies LLC
www.advancedconductor.com

Fine-grain K-doped Ba122 polycrystals w/o texture

SEM — TEM — HR-TEM



- Average grain size ~ 200 nm
- High GB density
- Randomly oriented polycrystalline structure with many high-angle GBs
- Clean and well connected GBs

- Clean and well connected GBs
- Average grain size ~ 200 nm

Striking result: $J_c(SF) > 10^5$ A/cm^2 is obtained with a high density of GBs
Stiff vortices must help minimize GB vortex segments

with many high-angle GBs

Nat. Mater. 11, 682 (2012)

APPLIED PHYSICS LETTERS **105**, 162604 (2014)

Evidence for composition variations and impurity segregation at grain boundaries in high current-density polycrystalline K- and Co-doped $BaFe_2As_2$ superconductors

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[2]*Applied Superconductivity Center, National High Magnetic Field Laboratory, Florida State University, Tallahassee, Florida 32310, USA*
[3]*Northwestern University Center for Atom Probe Tomography (NUCAPT), Evanston, Illinois 60208, USA*

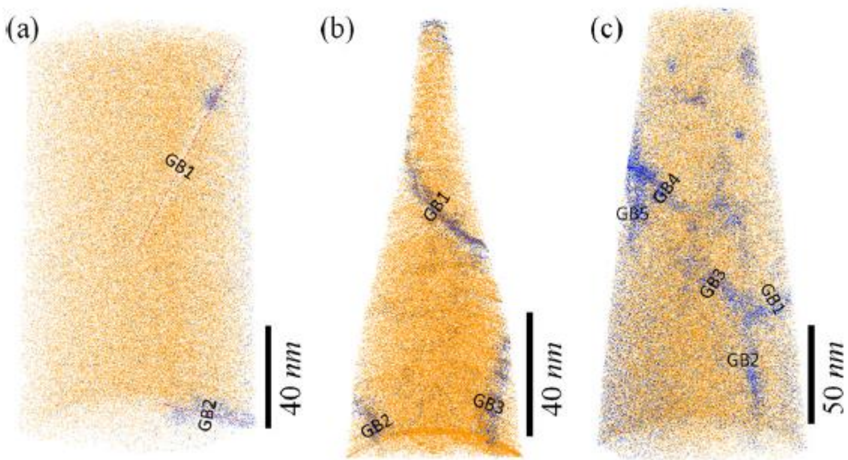

FIG. 2. A 3-D atom-probe tomographic reconstruction of: (a) $(Ba_{0.6}K_{0.4})Fe_2As_2$; (b) $(Ba_{0.4}K_{0.6})Fe_2As_2$; and (c) $Ba(Fe_{0.92}Co_{0.08})_2As_2$ superconductors. Oxygen atoms are in blue and Ba atoms are in orange, other elements are excluded for a clear display of grain boundary segregation. Each dot represents a single atom, but not to scale.

1. These high Jc bulks and wires have significant EXTRINSIC problems
2. Oxygen impurity segregation
3. Significant Fe and As off-stoichiometry at the GB

SCIENTIFIC REPORTS | 4 : 7305 | DOI: 10.1038/srep07305

Development of very high J_c in $Ba(Fe_{1-x}Co_x)_2As_2$ thin films grown on CaF_2

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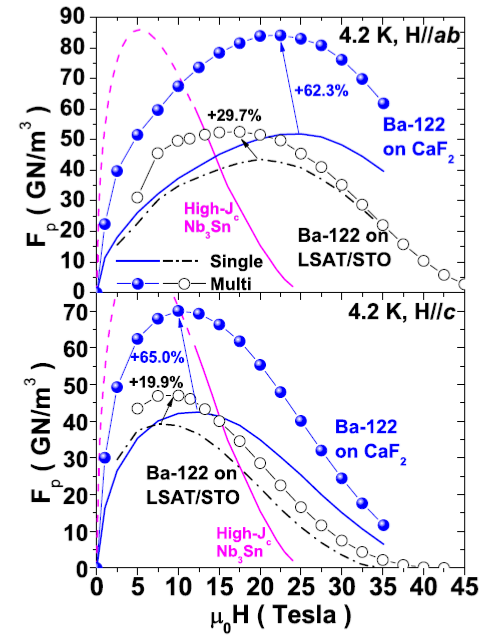
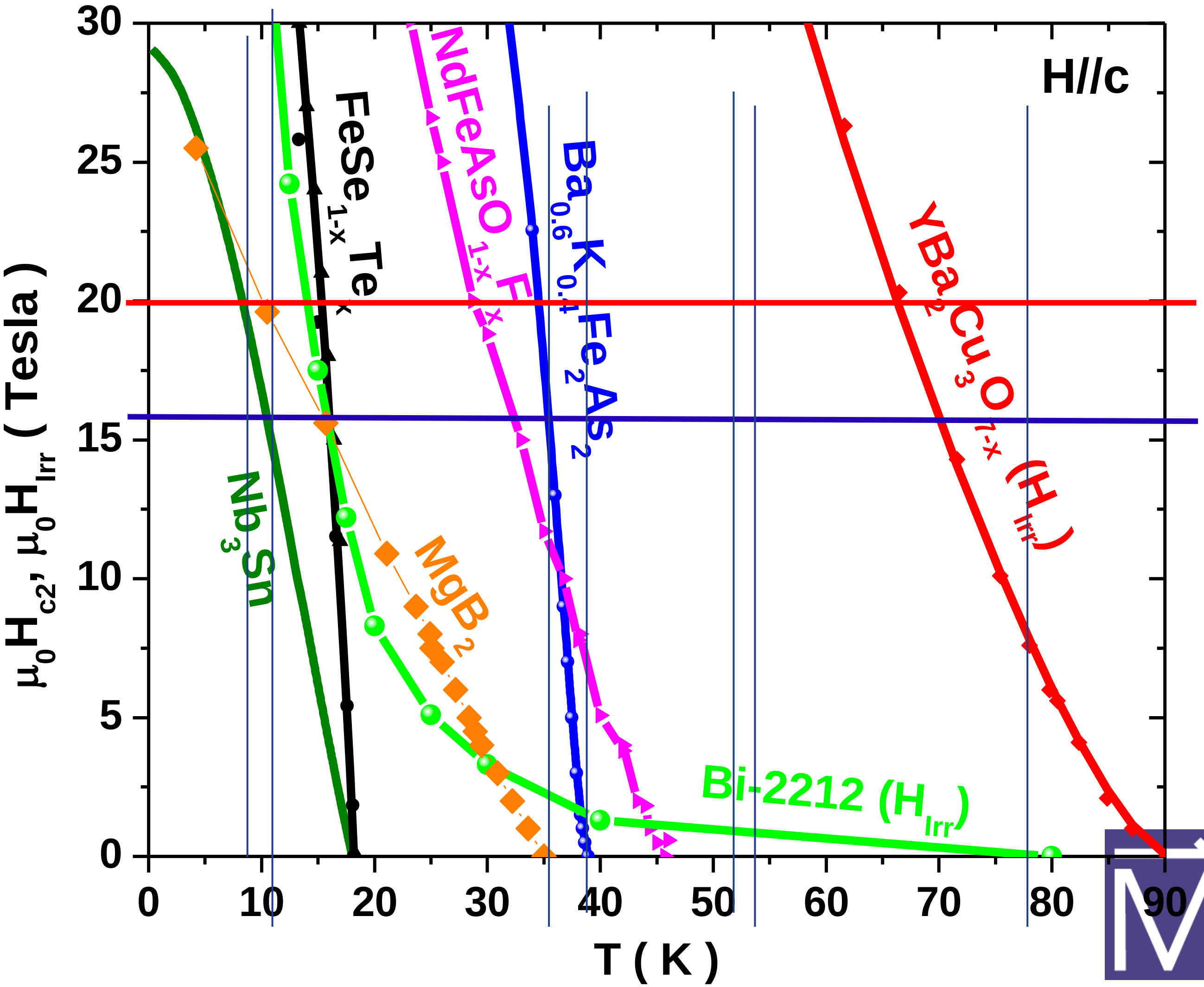


Figure 5 | High-field F_p at 4.2 K for single and multilayer Co-Ba122 films. F_p data along the two main field orientations for the films deposited on on CaF_2 (blue solid lines and symbols) and LSAT/STO (black dashed lines and open symbols). The magenta line represents F_p at 4.2 K of a high-J_c Nb_3Sn wire[39,40].

1. Strong pins accepted – high F_{pmax} and more high field biased than Nb_3Sn
2. Films not bulks
3. The 20 K, not the 38 K 122

A closer look at <30 T range

- The best reason for choosing a new superconductor may be to get more stability margin
- Quench management remains an unresolved issue for many HTS magnets



ΔT and stability margins at 16 and 20 T

Material	Tc(0)	Tc(16T)	Tc(20T)	Enthalpy 4.2 to Tc(16T)	Enthalpy 4.2 to Tc(20T)
Nb_3Sn	18	10.5K	8.5K	3.8 kJ/m^3	2.5 kJ/m^3
MgB_2 *	35-39	16	10.5	10.7	3.8
Bi-2212	80	16	15	10.7	9
BaK122	39	35	34	104	96
YBCO	92	70	66	554	494

Enthalpies are those of Cu and are thus approximations to real conductor properties

The marginal stability of Nb_3Sn is clear enough

MgB_2 assumed to have 30 T perpendicular field H_{c2}, not the 5-17 T of today

Opportunities

Material	Threats	Opportunities
Nb_3Sn	Low margin	High pinning, fine grain drives up Jc to FCC targets, scale up drives costs down
Bi-2212	High cost and complexity in use	The first HTS wire that looks like an LTS wire
MgB_2	Low H_{c2} makes in-field use marginal, low sc fraction makes J_E low	H_{c2} engineering makes a magnet conductor and low cost pulls MRI applications
Fe-based $(K,Ba)Fe_2As_2$ (122)	Low connectivity cannot be resolved in round wire form	GB impurity effects get resolved, Jc rises and huge H_{c2} drive applications
REBCO	High cost, dependence on markets beyond magnets makes manufacture uneconomic, and tape form	CORC provides twisted, MF cable with small bend radii and high J_E – thicker REBCO, thinner substrates drive down $/kA.m

Summary thoughts

- High Jc, small d_{eff} is close to but has not yet been worked out
  - But 16 T dipoles may not be possible if small stability margin cannot be tolerated
  - More magnet science needed!
- Higher Tc and at least 30 T H_{c2} is needed for any Nb_3Sn replacement
  - 2212 shows this in round, FM twisted form
    - Is being made now in km lengths in industry
  - MgB_2 is an interesting dark horse
    - Has the Tc but not yet the H_{c2} – but it might
  - REBCO coated conductor has wonderful Tc, the lowest anisotropy of any cuprate and is being manufactured by several companies world wide
    - Many manufacturing issues and issue of single filament wide-tape screening currents – but very strong vortex pinning and CORC enable high current cables and high J_E
  - A very interesting dark horse is K-doped Fe_2As_2
    - Hc2 of 90 T and Tc of 38 K
    - Pretty high Jc in untextured bulks that have impurity segregations in them
    - Low raw material costs