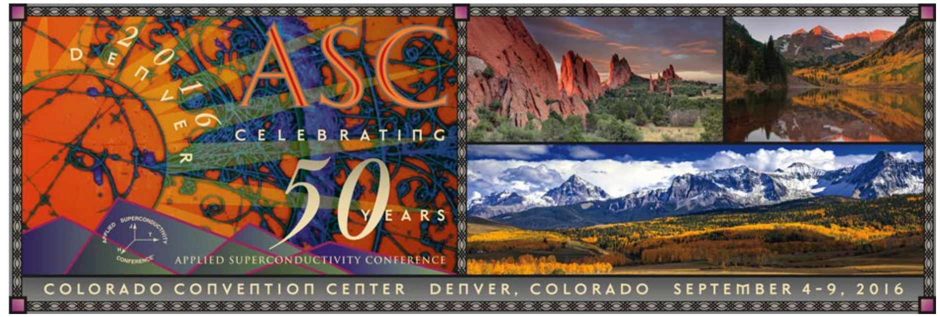
IEEE/CSC & ESAS EUROPEAN SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2016.
Plenary presentation 1PL-01 given at ASC 2016; Denver,Colorado,USA, September 4 – 9, 2016.

NATIONAL HIGH MAGNETIC FIELD LABORATORY



Superconductors for the Future – from the Perspective of the Past

David Larbalestier*

September 5, 2016

*Support by NSF core grant, DOE-High Energy Physics (HEP) , CERN, NIH and DOE-SBIR

Material shown here drawn from a wide variety of MagLab staff and students in the Applied Superconductivity Center, Magnet Science and Technology Division and the NMR program and collaborations with FNAL, LBNL, BNL in the BSCCo partnership, SuperPower (REBCO) , Oxford Superconductor Technology (2212) and Solid Materials Solutions (2212)

Thanks to many colleagues who shared insights with me on many aspects, some of whom are cited *in situ* and especially Peter Lee, Eric Hellstrom, Seungyong Hahn, Fumitake Kametani, Jianyi Jiang, Ulf Trociewitz and finally Lance Cooley with whom I have had many cost and technical discussions

Personal comments

- My first ASC was the 1974 ASC in Oakbrook IL when I was a postdoc at Rutherford Lab in Martin Wilson's group
- Have never missed an ASC – so ASC has been central to my career
- Wilson's group was a magnet group and I learned that conductor development had to serve the product – but also that no magnet was ever better than its conductor (and often much worse)
- Until 1987, magnets were the (only) product of superconducting conductors
- With the discovery of superconductivity above 77 K, product push took a central stage in the ASC community
- 29 years after HTS and 42 years since my first ASC, where are we?

I want to explore the future of conductors from this perspective

Principal Themes

How do we make a potential superconductor "real"?

"Real" implies applications that can deliver orders and keep a conductor manufacturer in business………….

- LTS – Nb-47Ti, Nb_3Sn
- HTS – REBCO, Bi-2223, Bi-2212
- MTS – MgB_2
- Anything else?
  - The MTS K-122 $(K,Ba/Sr)Fe_2As_2$
  - H – solid H_3S or H-charged Pd
  - The elusive Room Temperature Superconductor

LTS – low temperature superconductor: T_c <20 K
MTS – medium temperature superconductor: T_c > 20 K < 77 K
HTS – high temperature superconductor: T_c > 77 K

Where should we concentrate going forward?

High field superconductivity was a complete surprise in 1960!

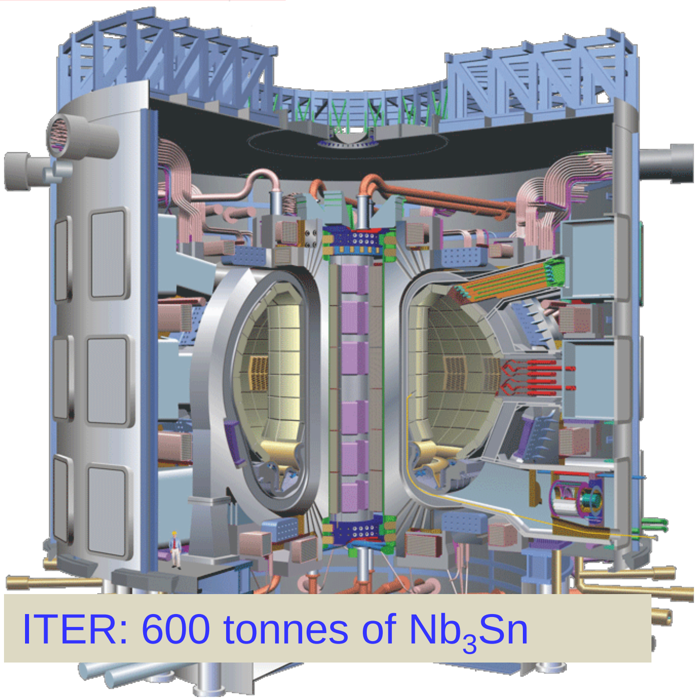
SUPERCONDUCTIVITY IN Nb_3Sn AT HIGH CURRENT DENSITY IN A MAGNETIC FIELD OF 88 kgauss

J. E. Kunzler, E. Buehler, F. S. L. Hsu, and J. H. Wernick
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received January 9, 1961)

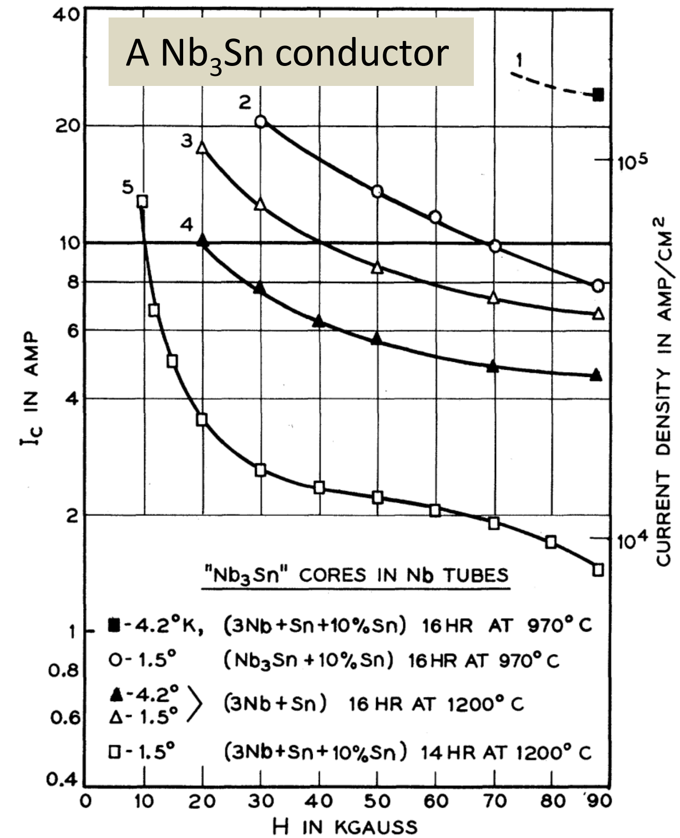
We have observed superconductivity in Nb_3Sn at average current densities exceeding 100 000 amperes/cm² in magnetic fields as large as 88 kgauss. The nature of the variation of the critical current (the maximum current at a given field for which there is no energy dissipation) with magnetic field shows that superconductivity extends to still higher fields. Existing theory does not account for these observations. In addition to some remarkable implications concerning superconductivity, these observations suggest the feasibility of constructing superconducting solenoid magnets capable of fields approaching 100 kgauss, such as are desired as laboratory facilities and for containing plasmas for nuclear fusion reactions.[1,2]

The highest values of critical magnetic fields previously reported for high current densities

89



ITER: 600 tonnes of Nb_3Sn



Phys Rev Letts **6**, 89 (1961), submitted **January 9, 1961**, published **February 1, 1961**!

Sometimes magnets happen fast…

The November 1961 Magnet Technology Conference at MIT

BRIT. J. APPL. PHYS., 1962, VOL. 13

International Conference on High Magnetic Fields, Massachusetts Institute of Technology, November 1961

Who	Field	Material	Bore
Bell	6.9 T	Nb_3Sn	0.25”
Atomics International	5.9 T	Nb-25Zr	0.5”
Westinghouse	5.6 T	Nb-25Zr	0.15”

From discovery to a 7 T magnet in 12 months!
No wonder Parkinson was wondering whether conferences were needed!

Concluding remarks

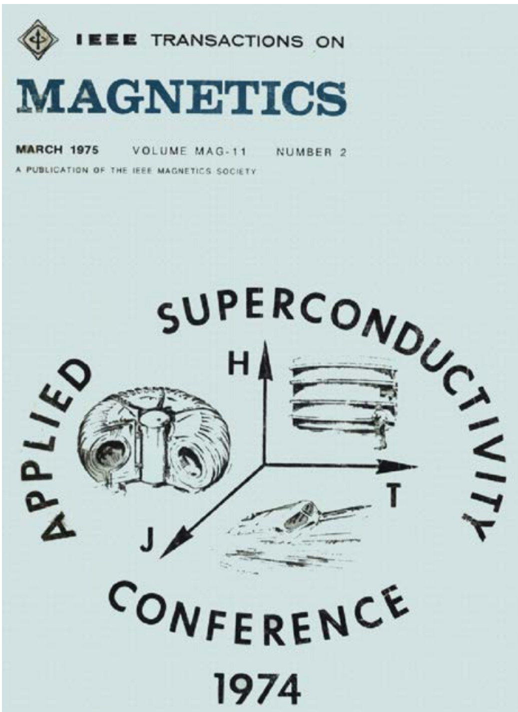
After any conference of this type it is often asked if there should be another. The argument against conferences in which the common factor linking sessions is a technique is that they cover far too wide a field or multiplicity of fields. This can be true but is a factor under the control of the organizers. With this particular conference the 'net' was perhaps too widely spread. However, the conference could hardly avoid being a success owing to the sessions involved with high critical field superconductors which are fairly new in their application to the generation of high fields and on which a very great deal of active work is in progress. This topic was wisely left to the last, after review of all the other fields of application and methods of generating high fields.

In applying steady high magnetic fields to physical experiments and in equipment there have seemed to be two barriers. The first is a cost barrier at which fields easily achievable with iron cooled magnets are passed (about 30 kG); the second is the barrier set by the strength of materials, which at present seems to be at about 250 to 300 kG. The first of these is being finally swept away with the advent of superconducting solenoids and the second will soon be approached in several laboratories, probably simultaneously.

Ministry of Aviation,
Royal Radar Establishment,
St. Andrews Road,
Great Malvern,
Worcs.

D. H. PARKINSON
20th June 1962

The 1974 proceedings: Bubble Chambers (HEP), Tokamaks and MagLev on the cover



1974 Applied Superconductivity Conference

SEPTEMBER 30–OCTOBER 1,2 1974
ARGONNE NATIONAL LAB — Argonne, Ill.
NATIONAL ACCELERATOR LAB — Batavia, Ill.

EXECUTIVE COMMITTEE

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Publications
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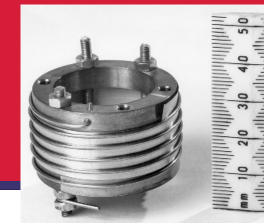
Aluminum Company of America

Strong DOE (AEC then) interest and some of the 1974 organizers are still active: Bruce Strauss, John Rowell and Ted Geballe

Harwell-made wire, Rutherford-made coils were my first ASC presentations



IEEE Transactions on Magnetics, vol. MAG-11, no. 2, March 1975

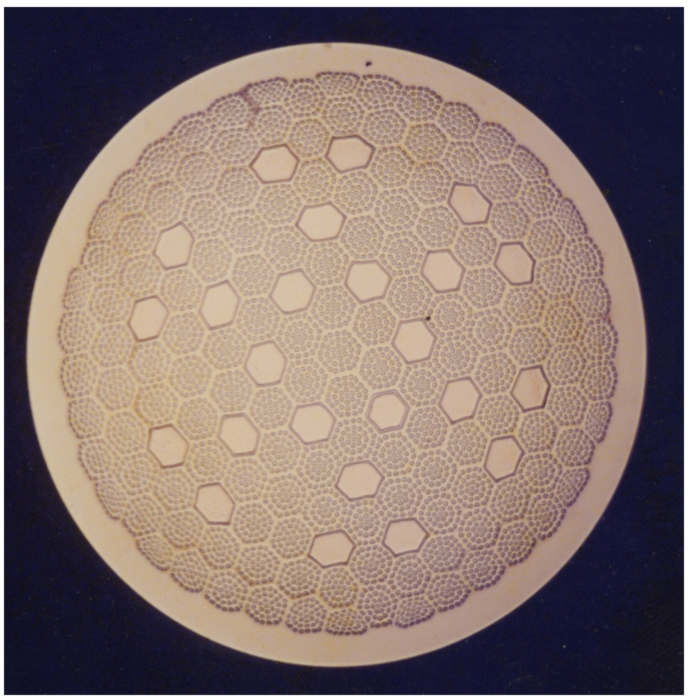
MULTIFILAMENTARY NIOBIUM TIN MAGNET CONDUCTORS

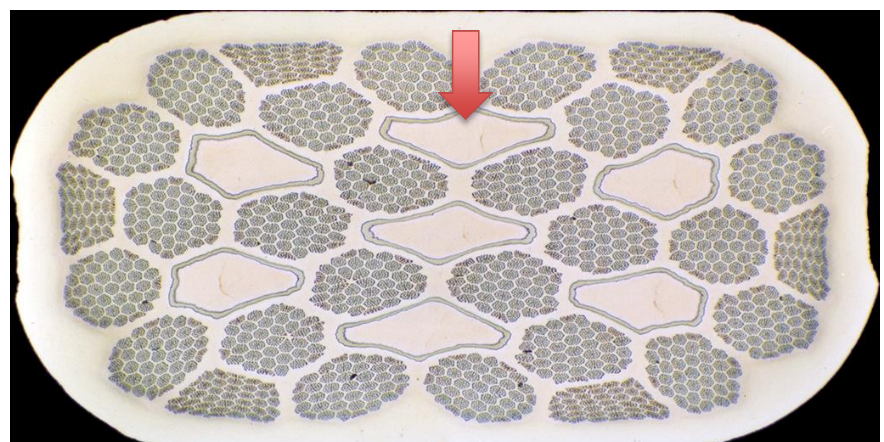
D.C. Larbalestier,+ P.E. Madsen,* J.A. Lee,*
M.N. Wilson,+ J.P. Charlesworth.*

The "ITER" barrel is actually a Rutherford barrel

An extraordinary collaboration between the groups of Jimmy Lee at Harwell and Martin Wilson at Rutherford Lab

Diffusion barriers were very difficult – notice the (small amount) of pure Cu protected by Ta barriers



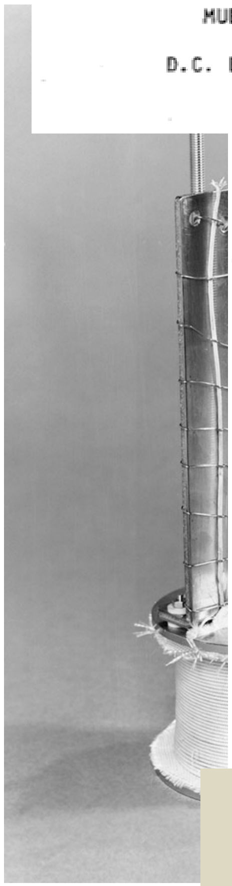


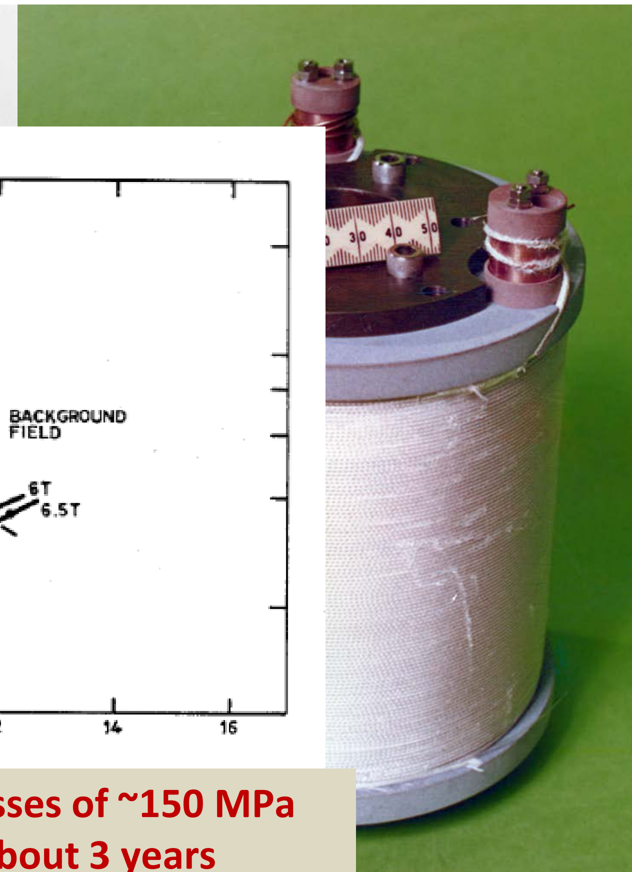
We made about 15 coils in 2 years, achieving highly stable 12 T fields accessible in 10-15 minute ramps

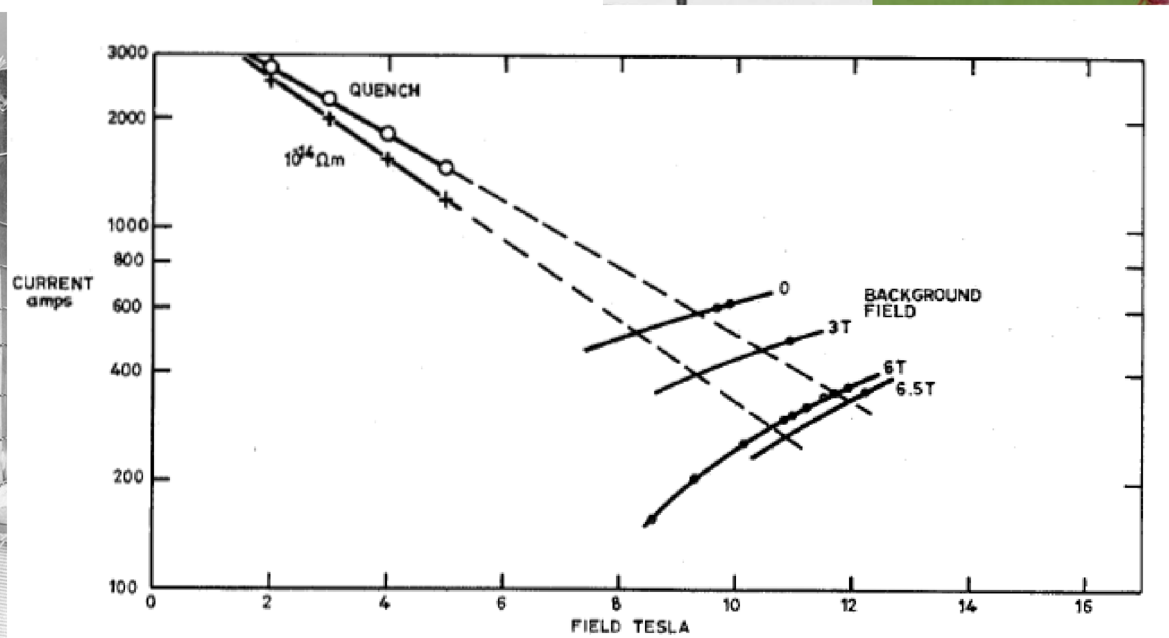
IEEE Transactions on Magnetics, vol. MAG-11, no. 2, March 1975

MULTIFILAMENTARY NIOBIUM TIN SOLENOIDS

D.C. Larbalestier,* V.W. Edwards,* J.A. Lee,†
C.A. Scott,* M.N. Wilson.*



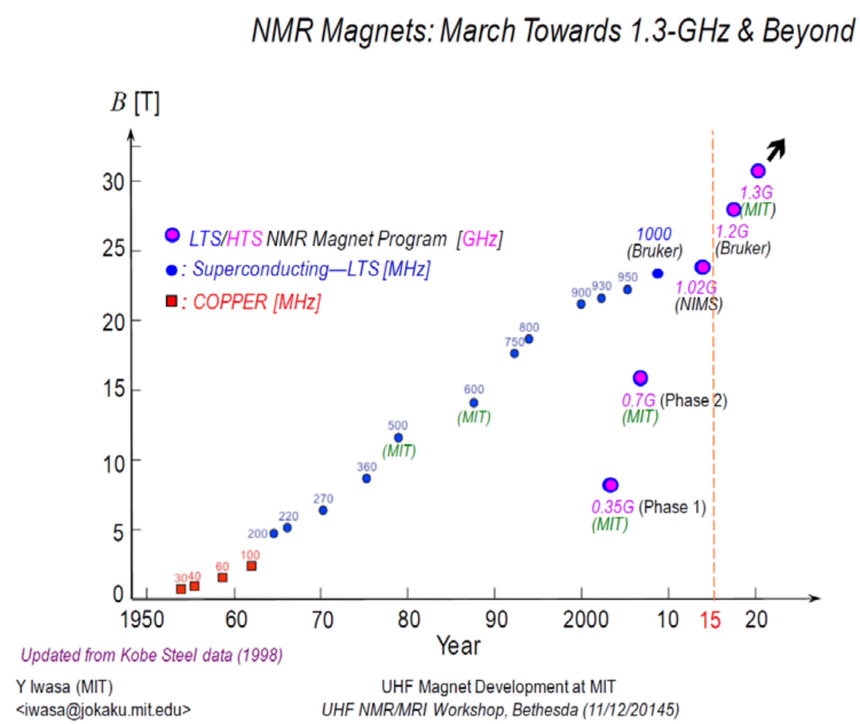




Quench at 130% of short sample at hoop stresses of ~150 MPa
Primitive conductors to real magnets in about 3 years

Important project pulls for Nb_3Sn

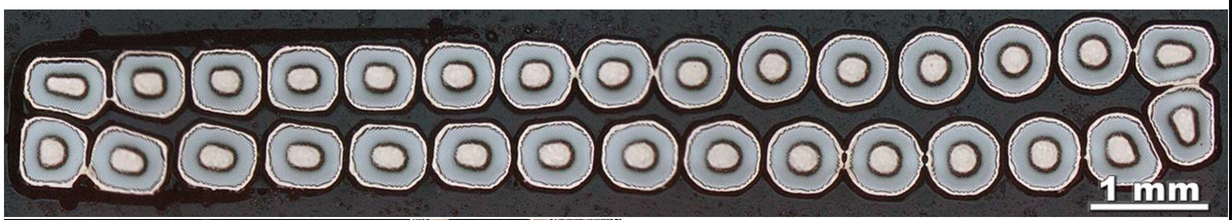
- NMR magnets above 360 MHz
- General lab magnets – 15-22 T 50 mm bore
- Fusion, 600 t for ITER
- The need for accelerator magnets with B> 8 T

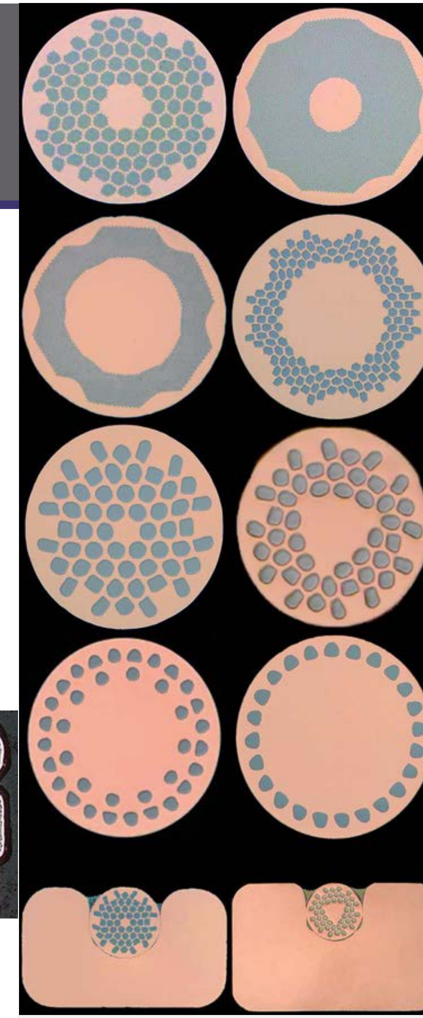


42 years later, there is still a substantial market for Nb_3Sn and further needs and opportunities to completely understand it.
But NMR at > 1 GHz can only be done with HTS insert coils

The Conductor Zoo

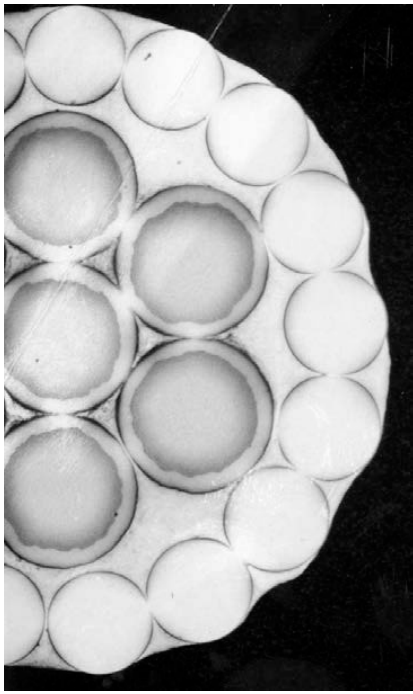
- Real conductors are needed in all sorts of form, size, current carrying capacity and normal metal protection amount
- And often need to be cabled



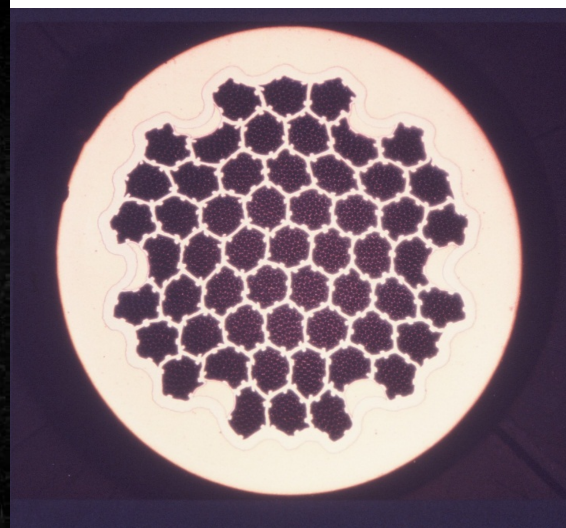


Nb-Ti strand and monolith cross-sections just from one manufacturer: Bruker EST (Courtesy Manfred Thoener)

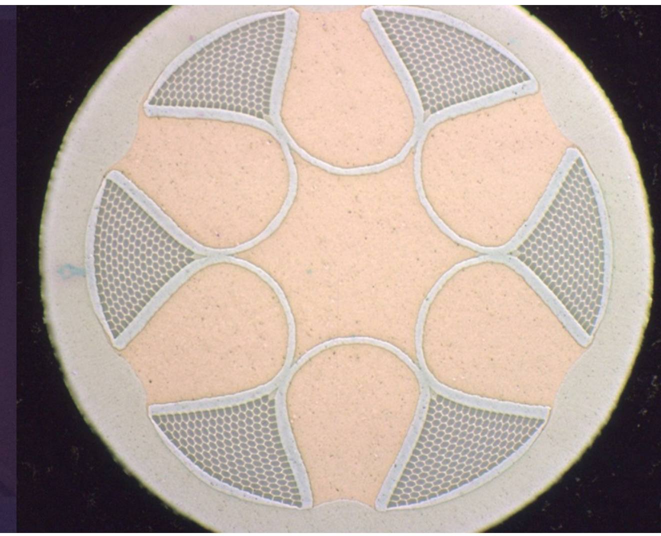
Nb-Ti architectures developed rapidly in the 1960's and 1970's



Atomics International: Cabled Monofilament ~1965



Rutherford Lab/IMI twisted multifilament ~1967

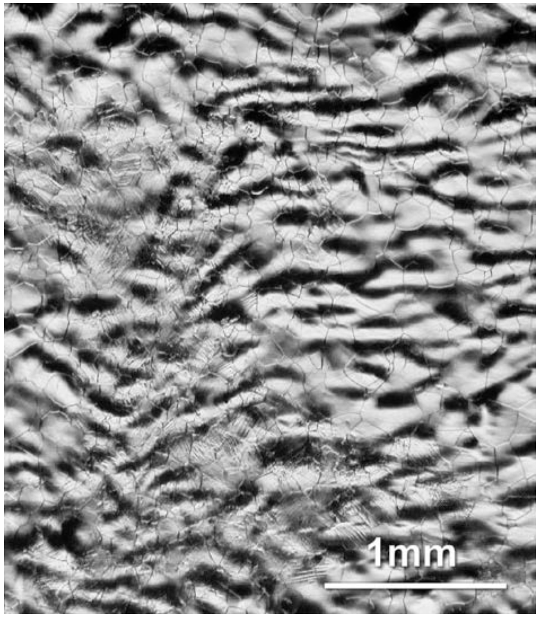


Tulip conductor for POLO by Vacuumschmelze ~1978

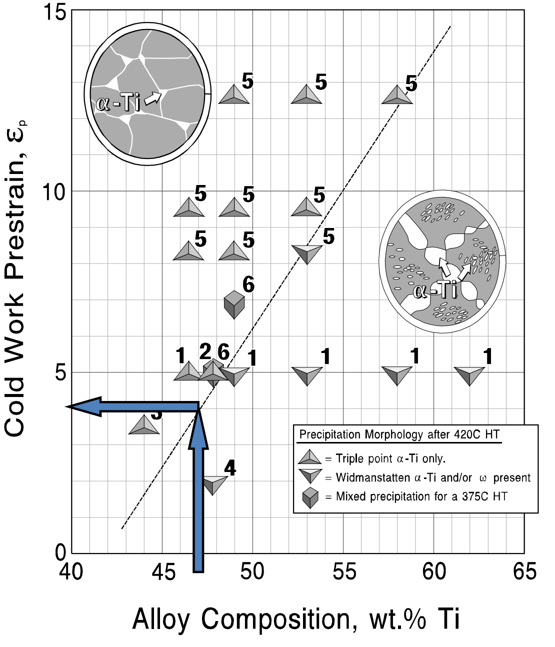
From flux-jump unstable prone to the first multifilament, twisted and electromagnetically stable, fast-ramp conductors to mixed matrix, plasma-instability stable conductors of great beauty

Hi Ho Nb-Ti: the path to very high J_c . . .

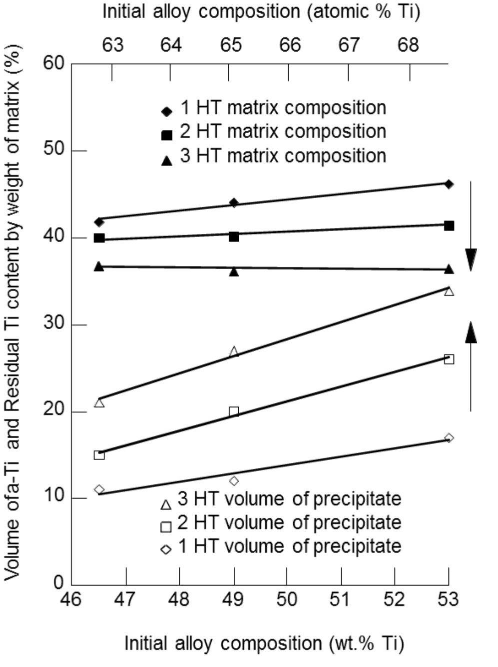
Hi Ho – high homogeneity – without large compositional variations left behind from the melt



Micro-chemical inhomogeneities led to huge local variations in a-Ti precipitation. Starting about 1985, the Nb-Ti workshop engaged industry, magnet builders and scientists in working out the process relationships



Precipitation morphology Sensitive to Composition and Strain, 1988



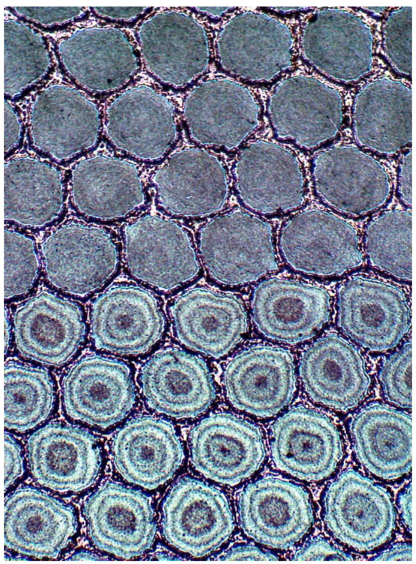
Precipitation Rate Sensitive to Composition and number of Heat Treatments (HT), 1988

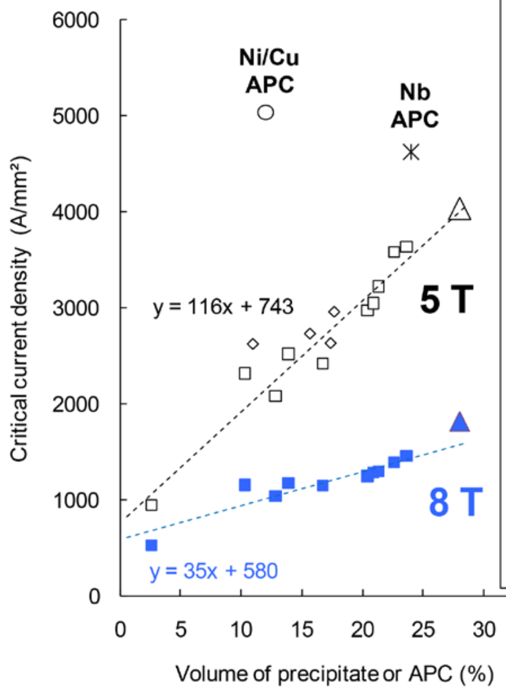
Understanding α-Ti precipitation and formation of nanoscale ribbons by drawing steps between HT led to predictable, non Black Magic HT, high J_c and today's commodity conductor

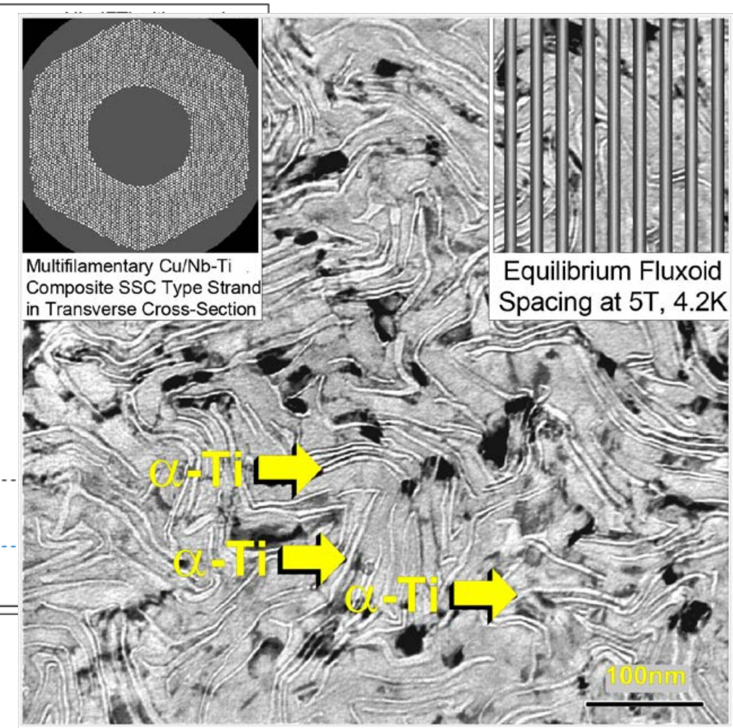
Optimal Nb-Ti properties developed by understanding the processing-nanostructure-J_c feedback cycle

Start with homogeneous Nb-Ti

Precipitate 20-25vol.% α-Ti to pin vortex cores



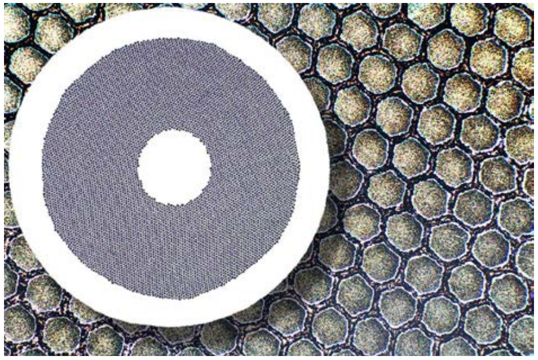




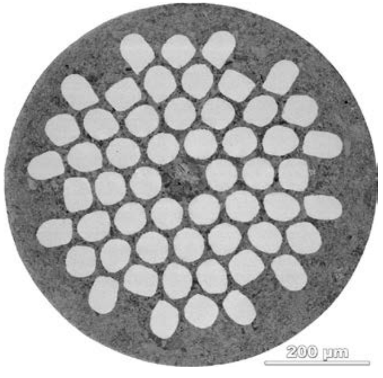
Tremendous support by Wah Chang (Bill McDonald especially)

Micro- and nano-structural view by Peter Lee, more pins than vortices (AJ vortices) – Gurevich and Cooley PRB **50**, 13 563 (1994)

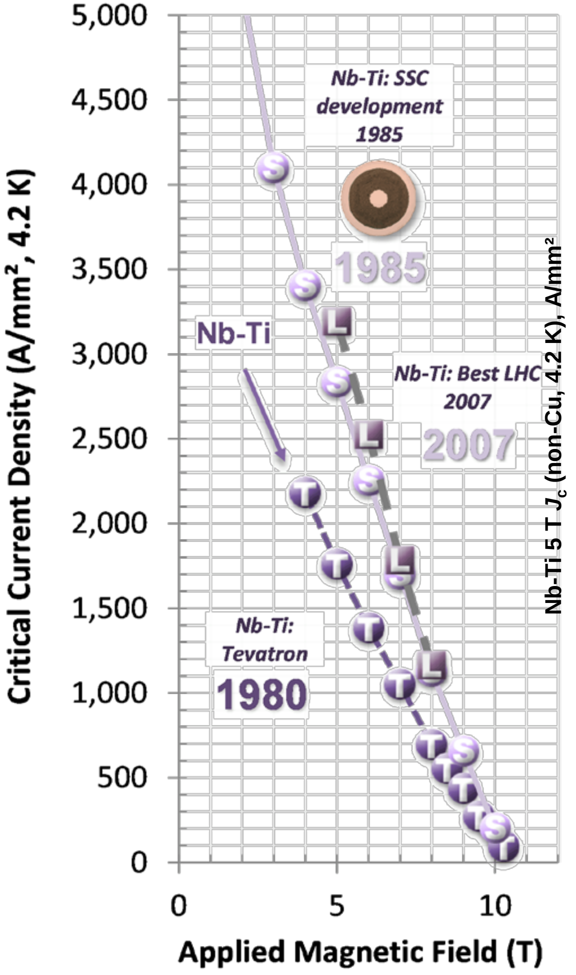
Nb-Ti: a commodity today after removing inhomogeneity

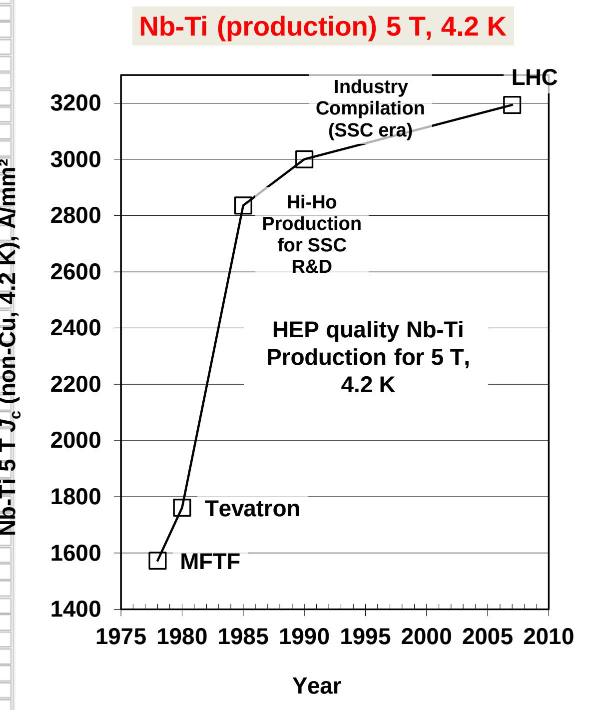


Refined for ~8 μm filament SSC use – later LHC use too



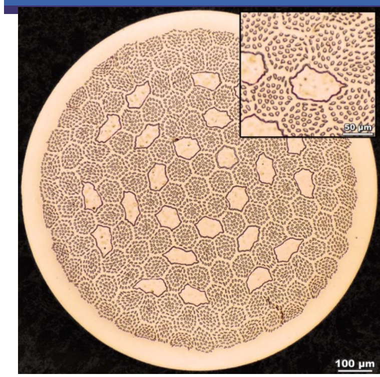
MRI strand



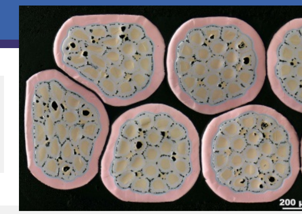


3500 A/mm² at 5 T demonstrated in R&D billets in mid 80s

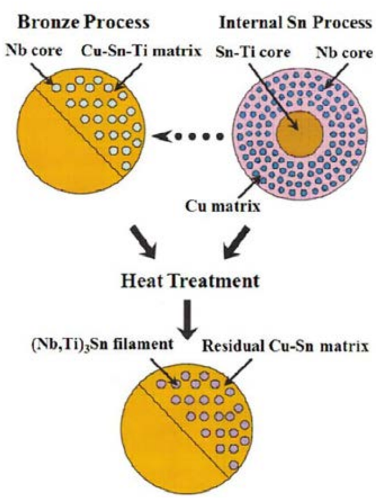
Filamentary Nb_3Sn has evolved strongly over 4 decades

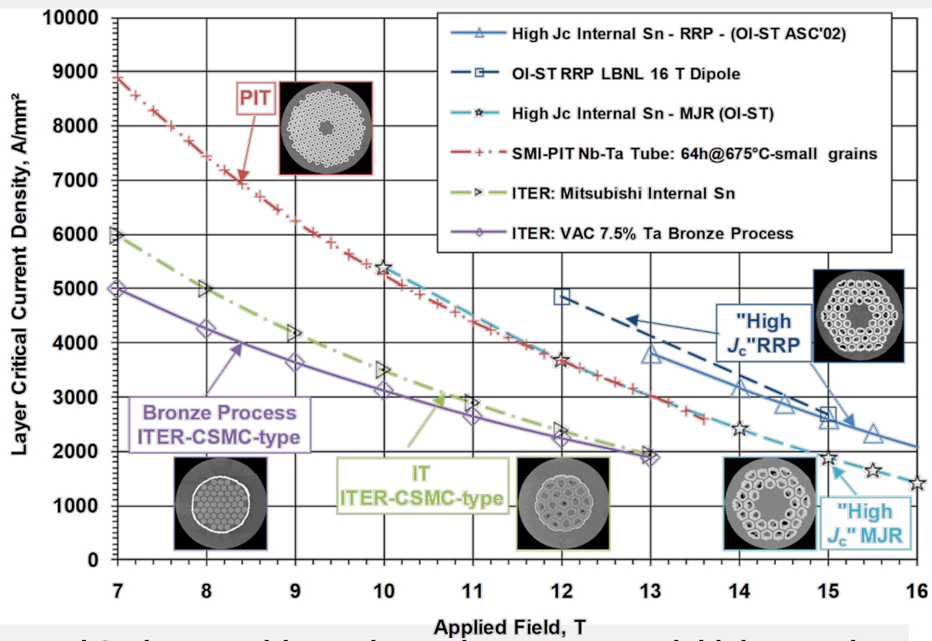


The 1st stabilized conductor (1973) – 12 T magnets and later NMR use (Harwell-Rutherford bronze route)



Huge advances in 2000's with internal Sn routes for much higher J_c in the last 10 years under HEP driving for LHC application!

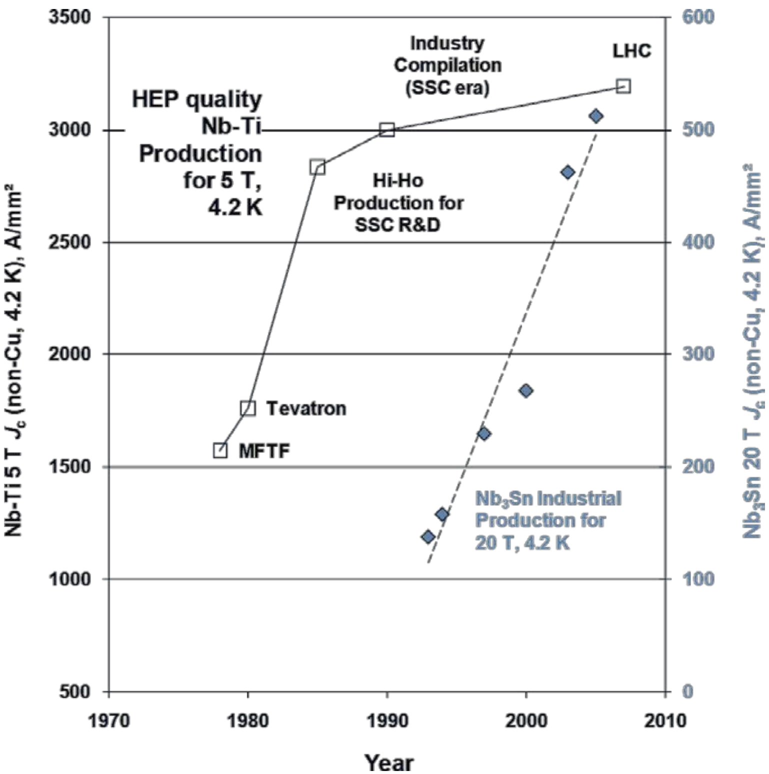




Multiple routes (bronze, external then internal Sn (RRP, PIT) have shown the route to much higher J_c – in the layer and the total cross-section

The challenge of Nb_3Sn today

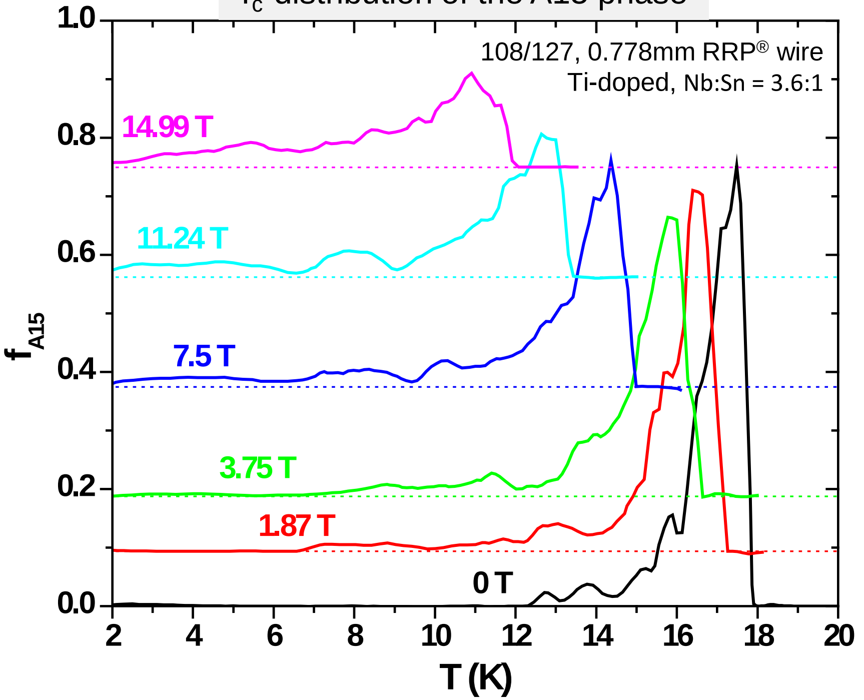
- **Economical fabrication**
  - Large scale bronze (extrusion, many in process anneals, large composition gradients in the Nb_3Sn_{1-x} or smaller scale internal Sn routes (extrusion not possible, few or no anneals, much higher Sn:Cu ratio and smaller A15 composition gradients
- **The highest possible J_c/J_E is required for Hadron Colliders**
  - Use ALL of the Nb and Sn in the package to make Nb_3Sn
  - Most stoichiometric A15 possible
  - Finest possible grain size (<50 nm)



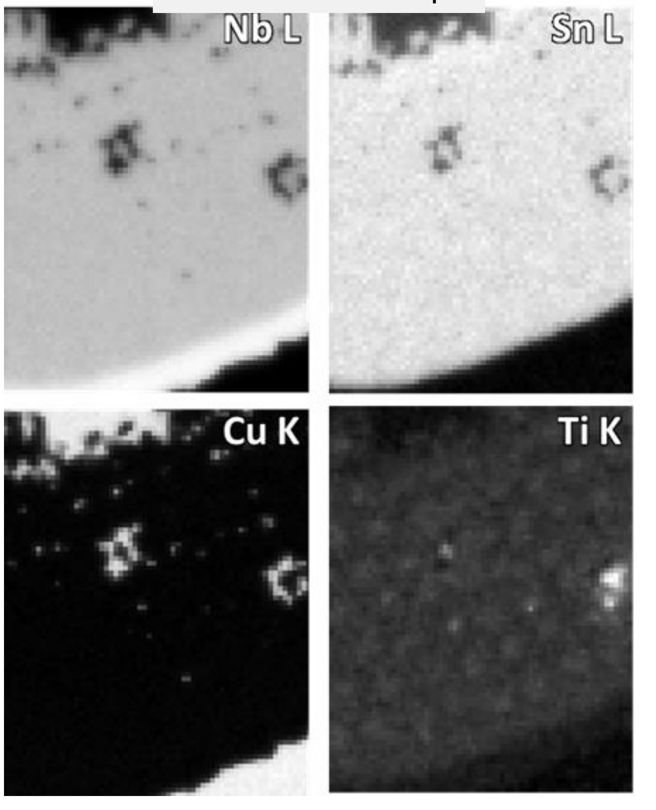
Avoid composition gradients, make strong vortex pinning and maximize the amount of A15 formed from the Nb-Sn-Cu-Ti/Ta mix

But, A15 is still inhomogeneous in the very best RRP wires

T_c-distribution of the A15 phase



EDS chemical maps



T_c as low as 12 K in "optimized" A15 layer

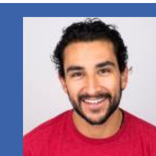
Broad, 15 T Tc distributions mean that only part of the layer is carrying current at high fields

Chemical inhomogeneity in the A15 layer

C. Tarantini *et al.*, Appl. Phys. Lett. 108, 042603 (2016)

4MOr2A-02, Thurs. 3.15 PM

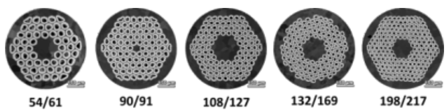
Restacked-Rod Process® Nb_3Sn: Past, Present and Future



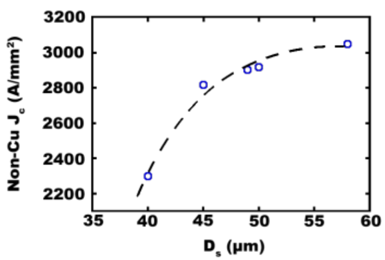
see 4MOr2A-04

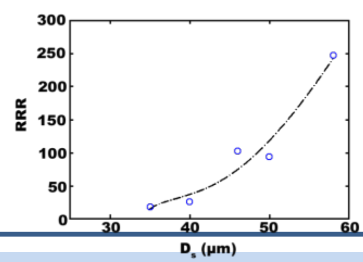
Past

1 Significant processing improvement over the last 10 years…



2 Low RRR and low J_c in small D_s is a long known issue, but has become more pressing as low D_s and high yield billets are demanded.



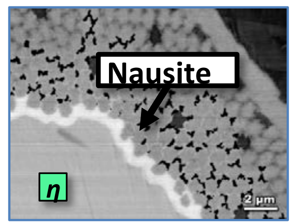


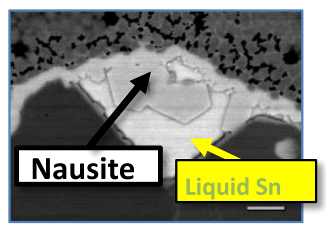
Field *et al. IEEE Trans Appl Supercond* **24**, 1–5 (2014).

Present

1 In 2014 OST found an important source of RRR degradation. RRR was improved about 30%.

2 In collaboration we found that one source of I_c reduction is the formation of the ternary Sn-Nb-Cu phase (Nausite):





Nausite → $NbSn_2$→ Nb_3Sn

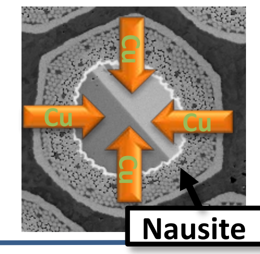
Nb_3Sn formed via this reaction path is often large grained and poorly connected.

Low performing billets are related to excessive production of Nausite.

3 But, Nausite can be used to our advantage

Controlling Nausite growth we can use it to draw more Cu into the core and prevent liquefaction.

J_c in small subelement wires has improved significantly (see 4MOr2A-04)



PhD student Sanabria (FSU) with Field (OST) and Ghosh (BNL)

Future

1. The 50 µm D_s "brick wall" that has haunted RRP® for over 6 years has been breached.
2. A new heat treatment is required for small D_s wires.
3. Understanding the mixing dwells is of paramount importance in order to use Nausite intelligently and avoid wasting Nb_3Sn to disconnection.
4. After optimizing the mixing stages, a similar study will be done for the final stage to improve A15 homogeneity .

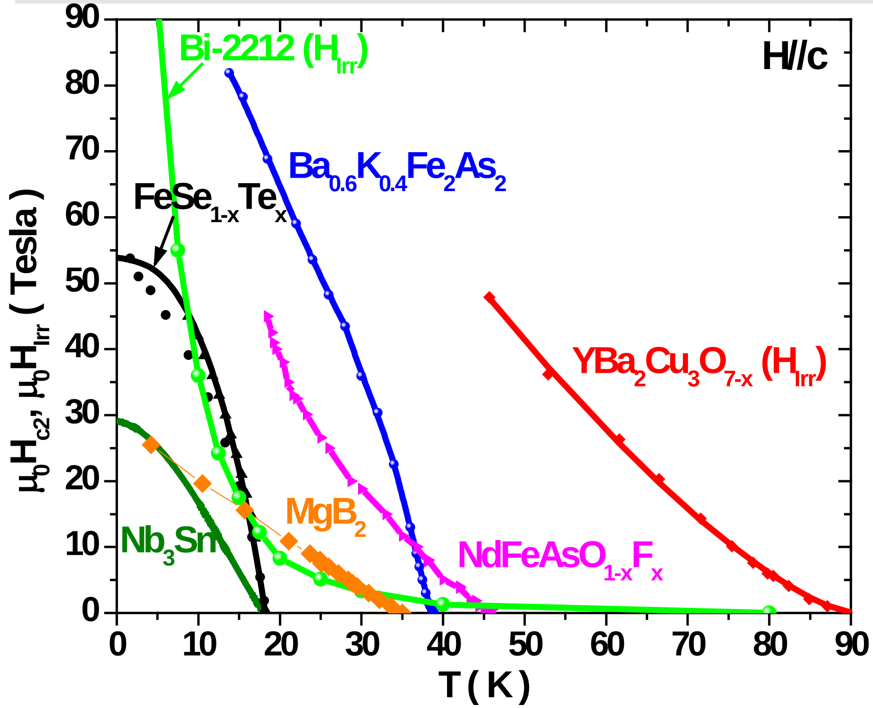
LTS Summary

- Basic processing-Jc relationships for Nb47wt.%Ti have been known for more than 25 years –the workhorse superconductor
- By contrast Nb_3Sn keeps developing because each route has pluses and minuses
  - FCC or an LHC upgrade that needs 16 T dipoles is major stimulus for continuing synergistic conductor-magnet R&D

We always use Nb-Ti unless we can't!

If not Nb_3Sn, then what?

Why? Higher H_{c2} or H_{irr} than Nb_3Sn at 4 K or operation well above 4 K. Is HTS really an **HTemperatureS** or an **HFieldS (HTS or HFS)**?



- Multiple materials possible
  - Bi-2212
  - MgB_2
  - REBCO
  - Fe-base (especially K-122)

For LTS we only had to worry about compositional inhomogeneities that vary vortex pinning and H_{c2} – for HTS we always have to worry too about suppression of superconductivity at GBs

HTS conductor constraint

Dimos et al., Phys. Rev. B 41 (1990) 4038

- 1990: IBM bicrystal experiment – exponential drop in Jc(GB) vs. θ
- Very strongly suggested that no conductors would be possible without very strong texture

Suddenly a major focus on avoiding GBs, largely beneficial in Nb-Ti and Nb_3Sn

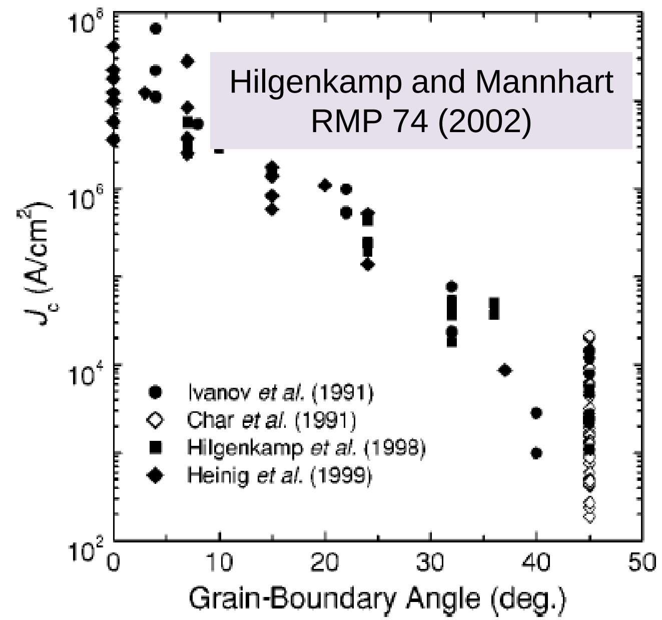


FIG. 30. Critical current densities of [001]-tilt grain boundaries in $YBa_2Cu_3O_{7-\delta}$ films as a function of tilt angle. The data, compiled from the literature as indicated, were measured at 4.2 K, except for those of Ivanov *et al.* (1991). As the latter were measured at 77 K, these current densities were multiplied by a factor of 10.9, which was obtained from the temperature dependence of I_c (see Fig. 36). The data of Char *et al.* were measured with biepitaxial junctions, the others with bicrystal-line junctions.

HTS Conductor History started with Bi22XY

- 1989: monofilaments of Bi-2212 powder melted inside Ag sheathed round wire
- 1989: Ag-sheathed Bi-2223 powder textured by rolling and growth with small amount of liquid
- Both Powder In Tube (PIT) conductors

Key point for both – the weak link signature seen in YBCO thin films was largely absent – a conductor technology was born.

Bi-2223 soon outran Bi-2212 because it could operate at 77K

(Heine, Tenbrink and Thoener APL 55 241 (1989))

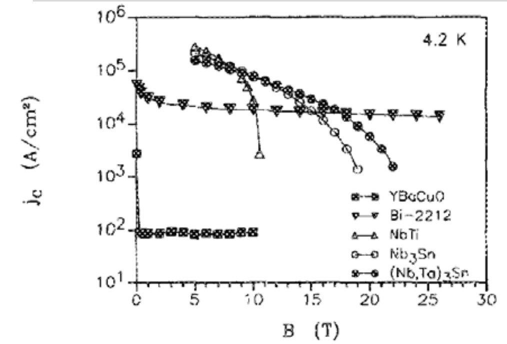


FIG. 2. Critical current density of Bi-2212/Ag and $YBa_2Cu_3O_7$/Ag wires at 4.2 K in comparison with commercial NbTi, Nb_3Sn, and $(Nb,Ta)_3Sn$ multifilamentary wires (noncopper j_c) as produced by Vacuumschmelze.

(Hikata, Sato et al. JJAP Letts. 28, L82 (1989))

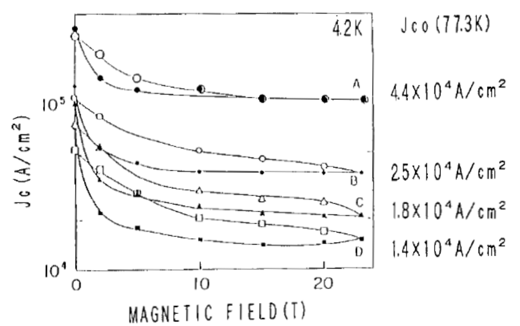
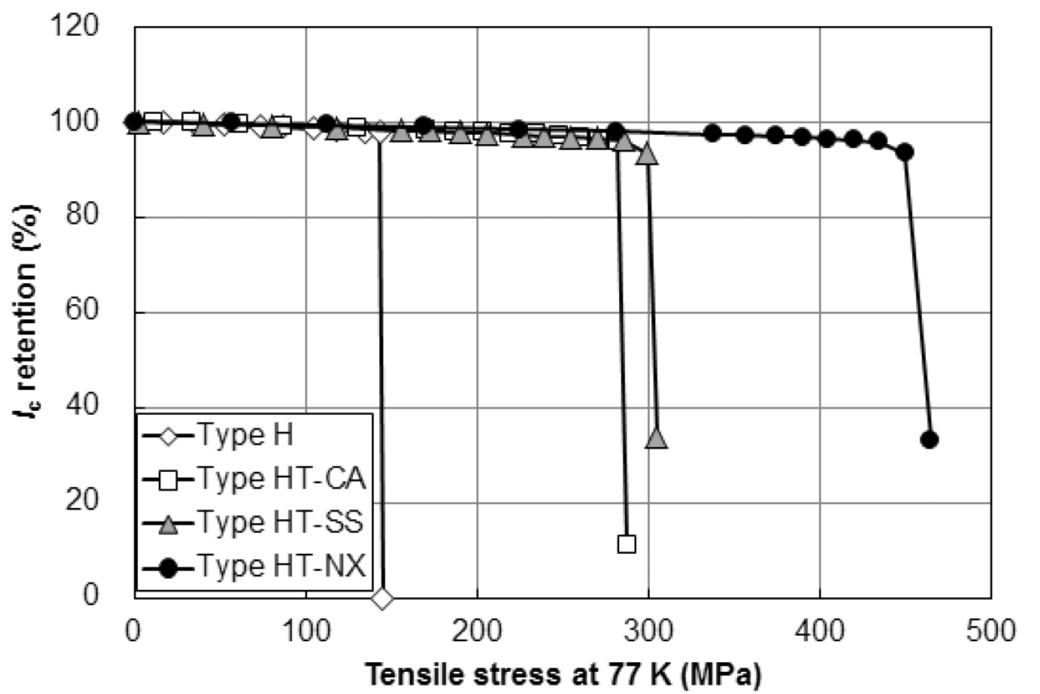
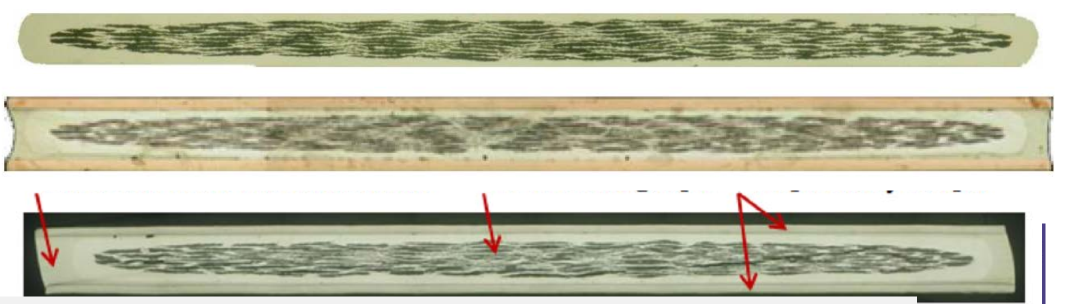


Figure 5. Jc-B properties of silver-sheathed BiPbSrCaCuO wires at 4.2 K.

2223 today: the most mature conductor : limited recent superconducting property advance but clever strength engineering

- Like 2212 with its Ag sheath, the Ag has low E and low Yield strength
- Lamination with Cu, Stainless steel and superalloy greatly increases the stress at which filaments fracture
- Latest Type HT-NX is attractive for high field solenoids
- A problem with 2223 is that it is only uniaxially textured, thus partially weak linked and Jc advances have slowed



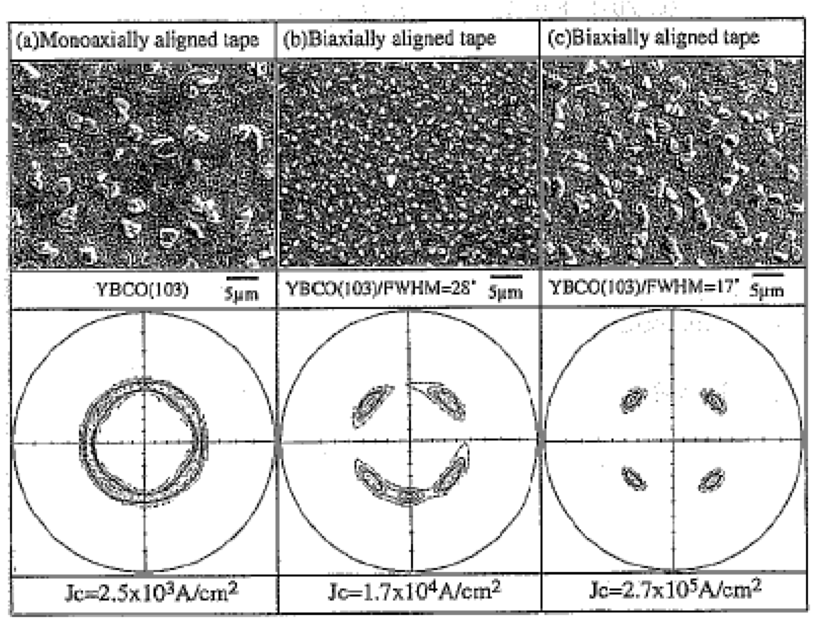


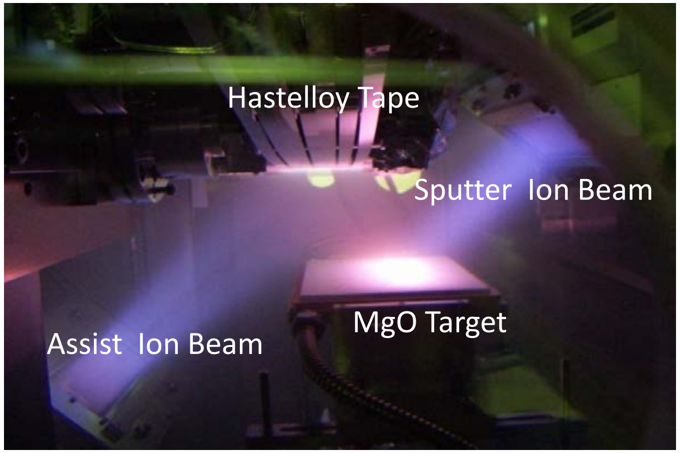
Ch. 2.1 Kobayashi and Ch. 2.3 Otto in Research, Fabrication and Applications of Bi-2223, Ed. Ken-Ichi Sato World Scientific 2016

Coated Conductor Beginnings – Iijima team (Fujikura) only 2 years later (1991)

The low Jc of Bi-2223 (uniaxial texture only of ~15°) encouraged development of biaxially aligned YBCO:

first by Iijima and Fujikura team using YSZ, later and much more effectively using IBAD MgO by the Stanford team





I. Iijima et al., Phys. C 185-189 1959 (1991), Appl. Phys. Lett. 60 (1992) 769; IEEE Trans. Appl. Superconductivity 11 (2001) 2816

“Push” applications of HTS

World Technology Evaluation Center

WTEC

WTEC Panel Report on

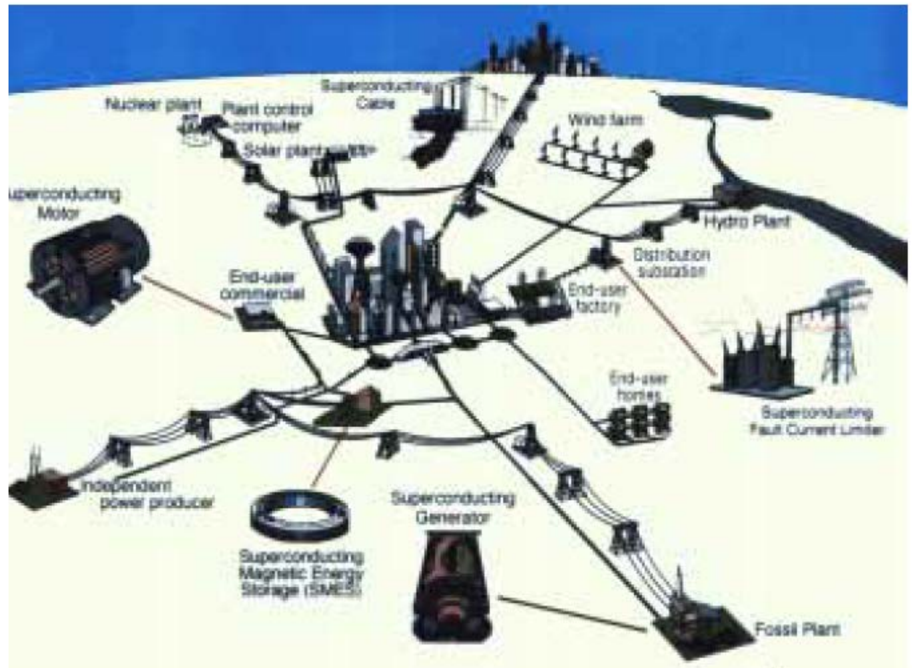
POWER APPLICATIONS OF SUPERCONDUCTIVITY IN JAPAN AND GERMANY

David Larbalestier, Panel Chair
Richard D. Blaugher
Robert E. Schwall
Robert S. Sokolowski
Masaki Suenaga
Jeffrey O. Willis

September 1997

International Technology Research Institute
R.D. Shelton, Director
Geoffrey M. Holdridge, WTEC Director

Loyola College in Maryland
4501 North Charles Street
Baltimore, Maryland 21210-2699



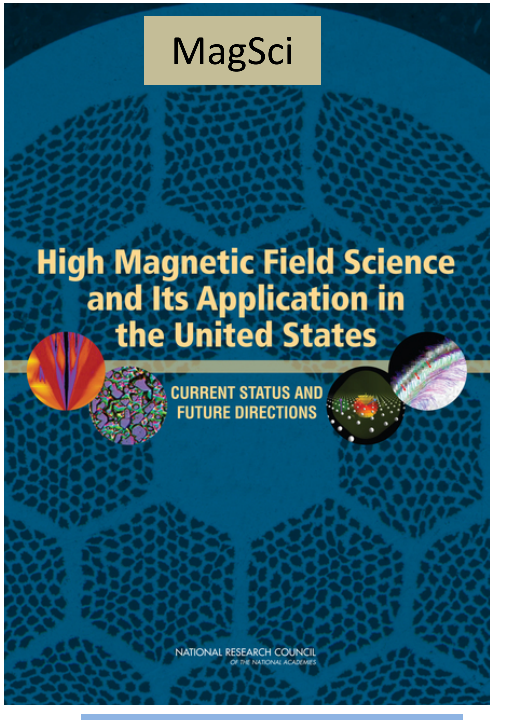
1. Superconductivity in the electric power system of the future, with widespread use of superconducting generators and motors, fault-current limiters, underground transmission cables, and superconducting magnetic energy storage (Blaugher 1995).

1996 WTEC commission was successful in raising the DOE program from about \$25M to \$40M/yr – but lack of utility network orders for HTS led to program cancellation in 2010

National Academy provides a "Pull" project list

MagSci recommendations: MagLab renewal plans

- **Design and build a 40 T all-superconducting magnet**,
- **Design** and build **a 60 T DC hybrid magnet** that will capitalize on the success of the current 45 T hybrid magnet in Tallahassee
- **Design and build** a 150 T pulsed magnet
- Establish at least 3 US 1.2 GHz NMR instruments (thought to be commercial) and **plan for ~1.5 GHz class system development**
- Establish high field (~30 T) facilities at neutron and photon scattering facilities
- Consider regional 32 T superconducting magnets at 3-4 locations optimized for easy user access.
- Construct a 20 T MRI instrument (for R&D with Na, P etc)



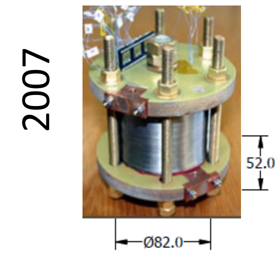
2013 NRC Panel Reinforcing 2004 COHMAG report

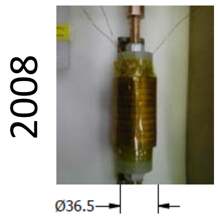
MagLab team formed in 2007-2010 following COHMAG

- **Cross-divisional effort in ASC and MS&T**
  - Applied Superconductivity Center (since 2006) and Magnet Science and Technology
- **32 T all superconducting magnet is about to enter test**
  - Project leader Huub Weijers, designer Denis Markiewicz, conductor characterization lead Dmytro Abraimov
- **HTS R&D effort**
  - REBCO characterization (leaders: Dima Abraimov and 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 (Cooley) –LBNL (Shen and Dietderich) – NHMFL and CDP (Dietderich))
  - High homogeneity REBCO and 2212 coil construction – leader Ulf Trociewitz
  - Strong 2223 prototype NMR coil development – leader Scott Marshall (Arno Godeke)

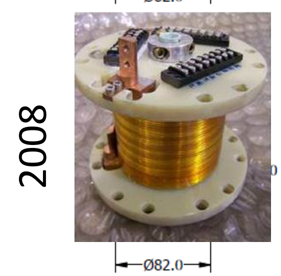
Funding:
32 T is supported by a Major Research Instrumentation award of NSF and by the NSF core grant to the NHMFL
Bi-2212 conductor work is supported by DOE-HEP through a university grant and CERN
HTS coil work (REBCO and 2212) is supported on the NSF core grant

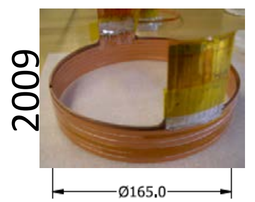
A long REBCO for 32 T verification path





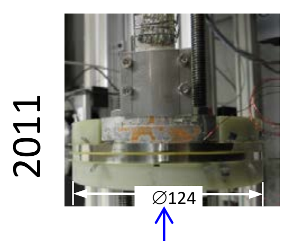
High-B coils
31 T + ΔB





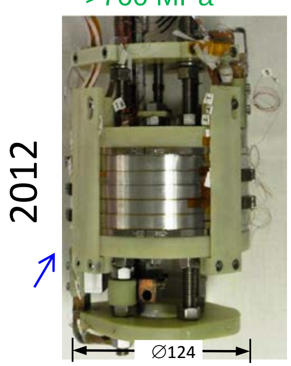
Demonstration inserts
20 T+ ΔB

High Hoop-stress coils
>760 MPa



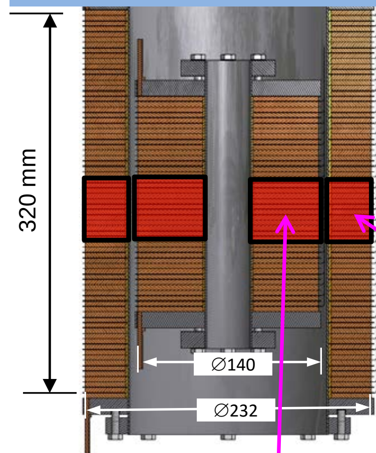
First Quench Heaters

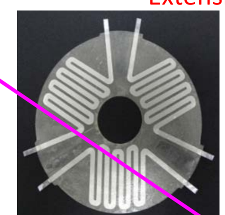
42-62 Mark 1:
1st test coil



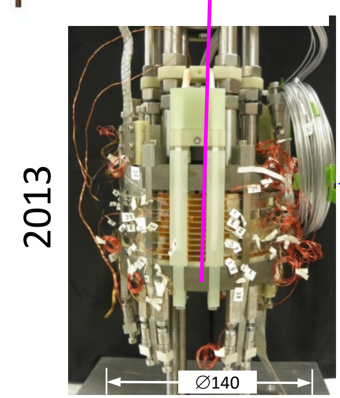
42-62 Mark 2:
2nd test coil

Prototype coils under test
20% of 32 T REBCO coils



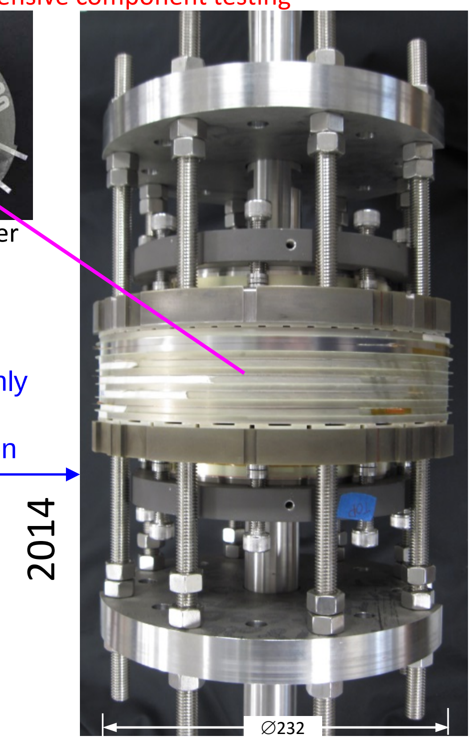


Quench heater



20 - 70:
1st Full-featured Prototype

Heater-only quench protection

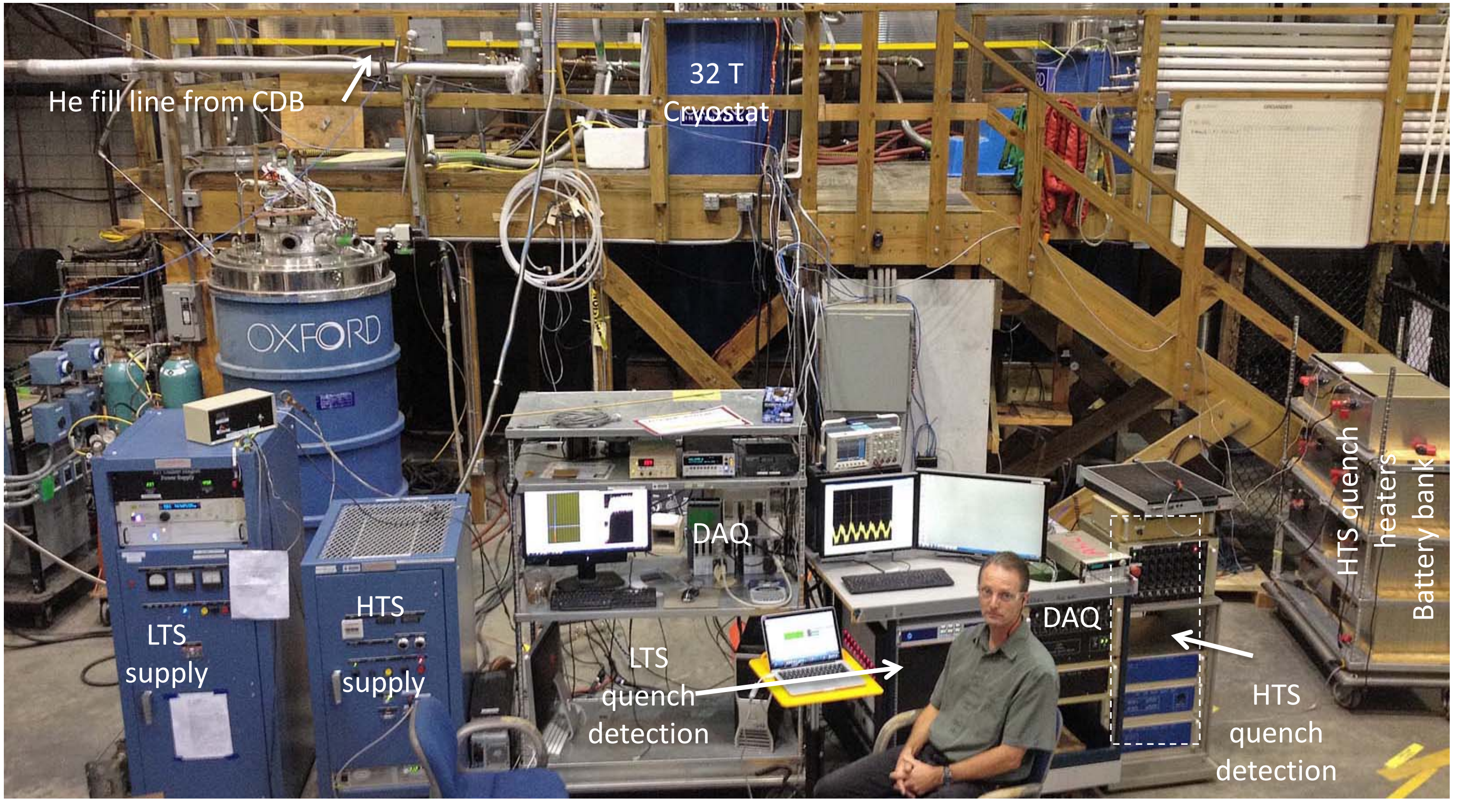


82 - 116:
2nd Full-featured Prototype

Development:

- YBCO tape characterization & QA
- Insulation technology
  - Ceramic on co-wound SS tape
- Coil winding technology
- Joint technology
- Quench protection analysis
- Extensive component testing

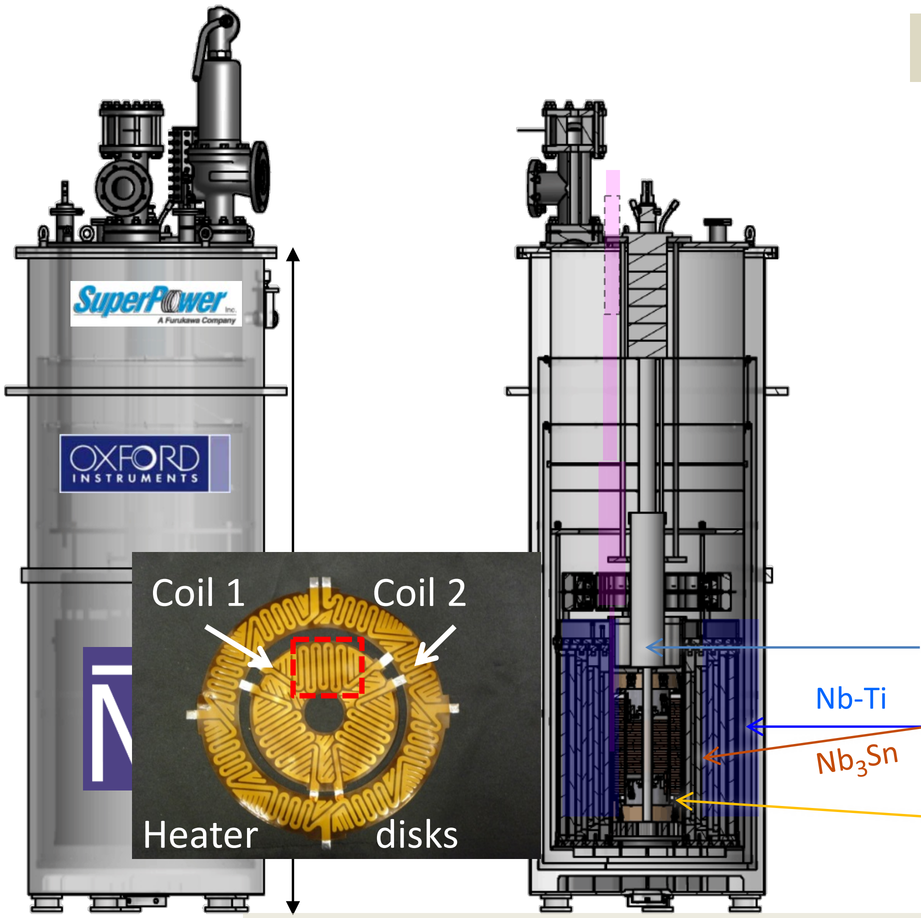
Prototype LTS/HTS integration test with 15 T OI Outsert: June 5, 2015 – 27.0 T achieved



32T project manager Huub Weijers seated at the test station during successful testing of prototype coil after many insert coil and outsert coil quenches

IEEE/CSC & ESAS EUROPEAN SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2016.
Plenary presentation 1PL-01 given at ASC 2016; Denver,Colorado,USA, September 4 – 9, 2016.

The 32 T User Magnet – 2016 Operation (talk today 1LOr2A-06)



0.9 m

Project leader: Huub Weijers

Cold Bore	34 mm
Uniformity 1 cm DSV	$5{\cdot}10^{-4}$
Total inductance	254 H
Stored energy	8.1 MJ
Ramp to 32 T	1 hour
Lifetime cycles	50,000

Mass (total) 2.3 ton

Dilution refrigerator or VTI

15 T / 250 mm bore LTS magnet

17 T REBCO coils (9.4 km of 4 mm wide tape)

17 T REBCO insert nested in 15 T Nb-Ti/Nb_3Sn outsert made by Oxford Instruments – commissioning Fall 2016

IEEE/CSC & ESAS EUROPEAN SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2016.
Plenary presentation 1PL-01 given at ASC 2016; Denver,Colorado,USA, September 4 – 9, 2016.

NI (No Insulation) REBCO Magnets are of Great Interest – 26 T all REBCO Magnet in 2015, 40 T Insert in April 2016

- 32 T has quench protection heaters on every double pancake, fired when "excess" dissipation is detected – operational J_e determined by need to dissipate energy broadly: J_W ~200 A/mm^2 in 32 T
- **Recent No Insulation (NI) REBCO coil achieved 40 T (9.2 T in 31 T) working at 900 A/mm^2 while in He gas at 17 K!**
  - Safe quench without any active quench protection scheme

An earlier Hahn magnet design manufactured at SuNAM was safely quench tested at the MagLab – a 26 T, all-REBCO magnet (260 kJ stored energy at J_e ~ 400 A/mm^2)

The first >40 T superconducting magnet

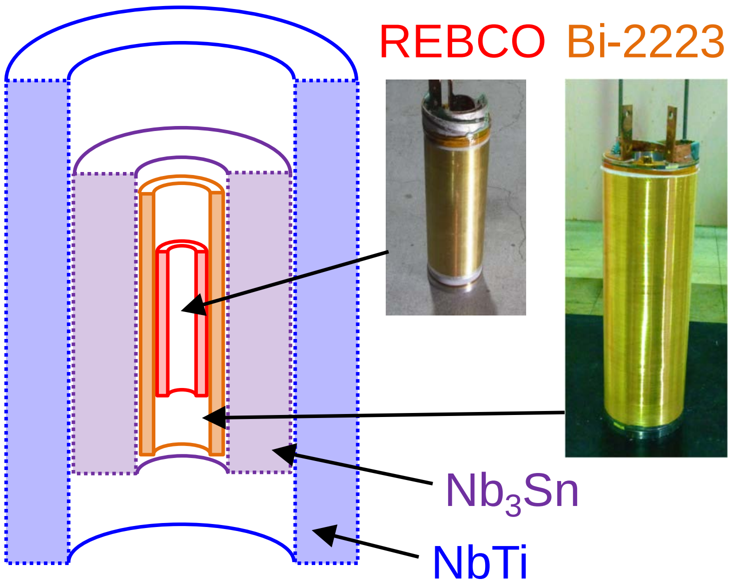
No Insulation REBCO Session: Tuesday 2SpOr3A 4PM Room 201/203

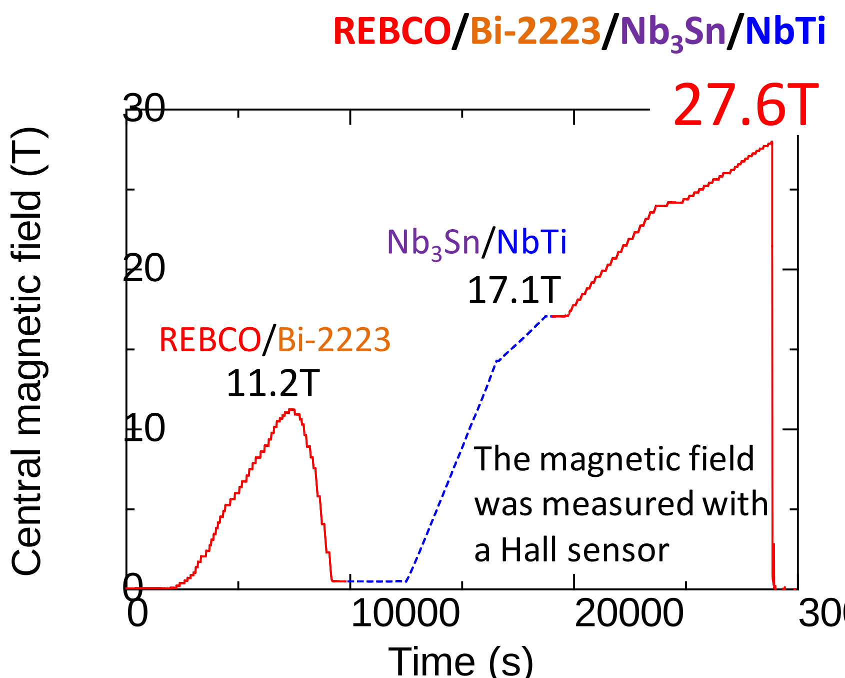
Coil designer Seungyong Hahn

40 T in gas at 17 K with the Kamerlingh Onnes J_E!

27.6 Tesla superconducting magnet; The combination of REBCO, Bi-2223, Nb_3Sn and Nb-Ti

Supported by the JST under the S-INNOVATION program





The world's highest field all-superconducting magnet so far..
Four superconducting technologies needed!

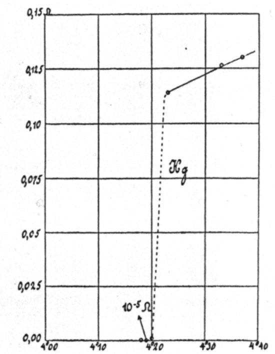
A historical perspective….Onnes in Chicago* 1913 (International Institute of Refrigeration)

H. Kamerlingh Onnes, Comm. Physical Lab., Univ. of Leiden, Suppl. **34b** to 133–144, 37 (1913).

Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state. . . . The behavior of metals in this state gives rise to new fundamental questions as to the mechanism of electrical conductivity.

It is therefore of great importance that tin and lead were found to become superconductive also. Tin has its step-down point at 3.8 K, a somewhat lower temperature than the vanishing point of mercury. The vanishing point of lead may be put at 6 K. Tin and lead being easily workable metals, we can now contemplate all kinds of electrical experiments with apparatus without resistance. . . .

The extraordinary character of this state can be well elucidated by its bearing on the problem of producing intense magnetic fields with the aid of coils without iron cores. Theoretically it will be possible to obtain a field as intense as we wish by arranging a sufficient number of ampere windings round the space where the field has to be established. This is the idea of Perrin, who made the suggestion of a field of 100 000 gauss being produced over a fairly large space in this way. He pointed out that by cooling the coil by liquid air the resistance of the coil . . . could be diminished. . . . To get a field of 100 000 gauss in a coil with an internal space of 1 cm radius, with copper cooled by liquid air, 100 kilowatt would be necessary. . . .



*Actually Keesom gave the talk as Kamerlingh Onnes was indisposed

The electric supply, as Fabry remarks, would give no real difficulty, but it would arise from the development of Joule-heat in the small volume of coil . . . to the amount of 25 kilogram-calories per second, which in order to be carried off by evaporation of liquid air would require . . . about 1500 liters of liquid air per hour. . . .

But the greatest difficulty, as Fabry points out, resides in the impossibility of making the small coil give off the relatively enormous quantity of Joule-heat to the liquefied gas. The dimensions of the coil to make the cooling possible must be much larger, by which at the same time the electric work and the amount of liquefied gas required becomes greater in the same proportion. The cost of carrying out Perrin's plan even with liquid air might be about comparable to that of building a cruiser. . . .

We should no more get a solution by cooling with liquid helium as long as the coil does not become superconductive.

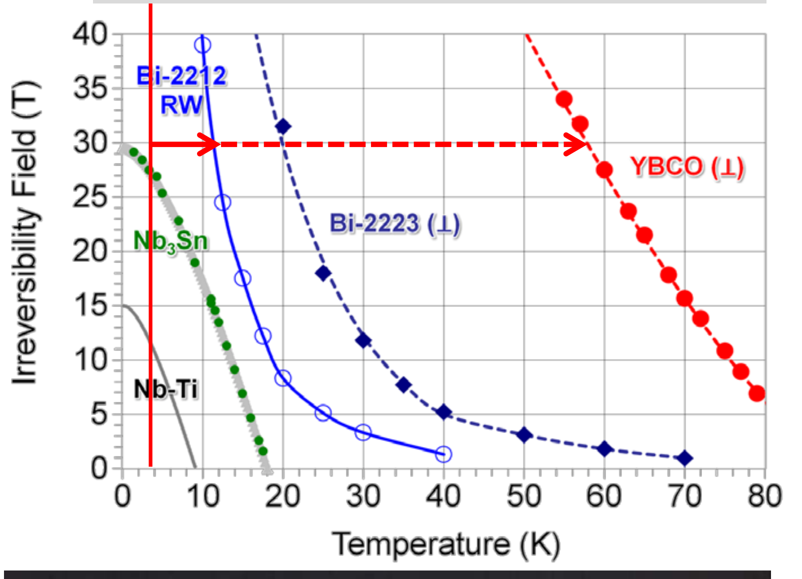
The problem which seems hopeless in this way enters a quite new phase when a superconductive wire can be used. Joule-heat comes not more into play, not even at very high current densities, and an exceedingly great number of ampere windings can be located in a very small space without in such a coil heat being developed. A current of 1000 amps/mm^2 density was sent through a mercury wire, and of 460 amps/mm^2 density through a lead wire, without appreciable heat being developed in either. . . .

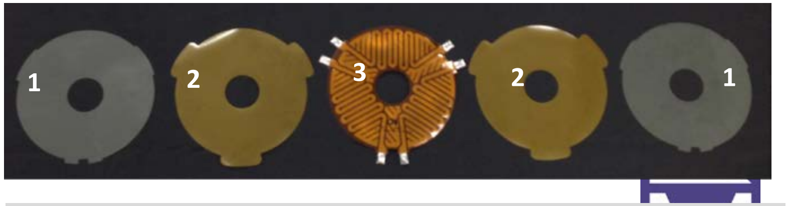
There remains of course the possibility that a resistance is developed in the superconductor by the magnetic field. If this were the case, the Joule heat . . . would have to be withdrawn. One of the first things to be investigated . . . at helium-temperatures . . . will be this magnetic resistance. We shall see that it plays no role for fields below say 1000 gauss.

Danger: Quench Must be Addressed!

- Undetected normal zones can provoke magnet burn up (several significant HTS magnets have burned following spontaneous quenches).
- HTS has high stability but very undesirable slow normal zone propagation velocity.
  - Few m/s for Nb-Ti and Nb_3Sn.
  - <10 cm/s for 2223 and YBCO.
  - **40-100 cm/s for 2212 at 20-30 T (like Nb_3Sn at 15 T)*** *Shen *et al.*, LBNL-NHMFL collaboration
- Quench is being addressed with:
  - NI REBCO – but pancakes only
  - Quench heaters protect 32 T REBCO – much easier in pancakes than layer windings
  - New idea CLIQ (Coupling-Loss Induced Quench) now introduced in US at LBL (Emanuele Ravaioli -Toohig Fellow LBNL)

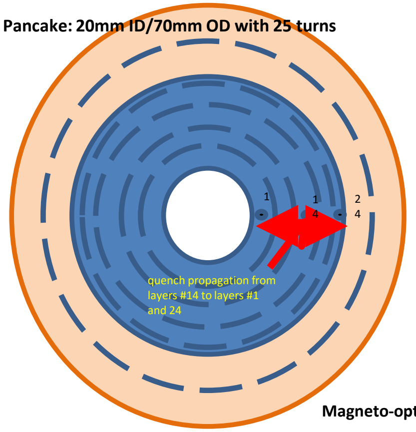
4 K operation requires large heating to drive YBCO to the normal state – lower $H_{irr}(T)$ makes protection easier

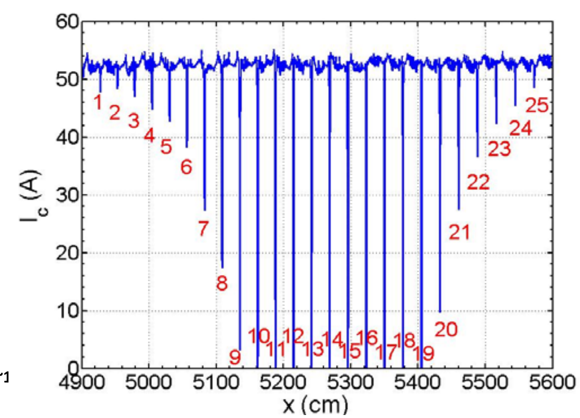




32 T quench heater: 1. G10, 2. Kapton, 3 the SS heaters

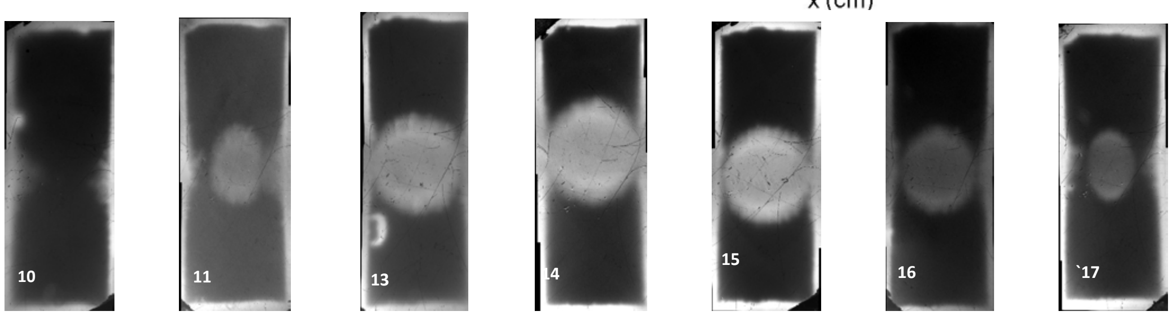
Single Filament, Insulated REBCO Tapes are Vulnerable to Manufacturing Defects and MUST be actively protected as 32 T is





During accelerated 32 T prototype coil fatigue testing in Fall15 at unusually high current and ramp rates, one pancake was damaged – due to low Ic spot??

Magneto-optical images of ~1



Magneto-optical images of the damage zones in layers 10-17 show extremely localized damage – an illustration of very low quench velocities

- 32 T used about 10 km of far from perfect 4 mm wide tape
- A unique MagLab, continuous, in field measurement tool (YateStar) allows understanding positional variation of Ic with 2 cm resolution

Polyanskii 5LOr1A-03 Friday morning

The route to a liquid nitrogen conductor

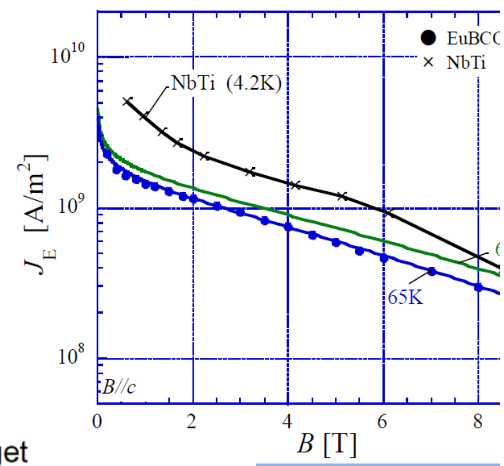
1MOr2C-02

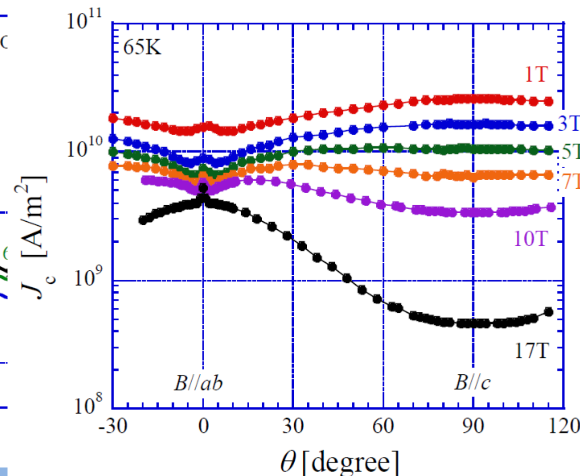
Current Transport Property of $BaHfO_3$ Doped EuBCO Coated Conductor over a wide range of Temperature and Magnetic Field up to 25T

Kyushu University
M. Inoue, K. Takasaki, K. Imamura, T. Suzuki, K. Higashikawa, T. Kiss

AIST
A. Ib, T. Izumi

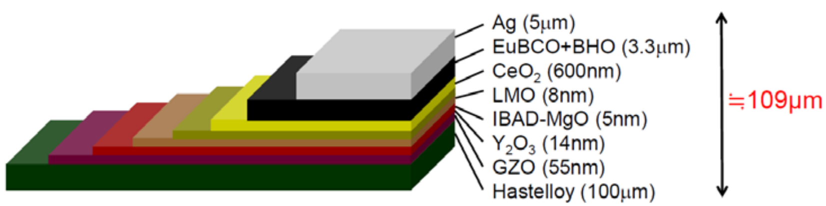
Potential of thinner Hastelloy subst.
100µm -> 50µm





PLD process using BHO doped EuBCO target

Superconducting layer	BHO	thickness	J_c@77K,s.f	I_c@77K,s.f
$EuBa_2Cu_3O_{7-\delta}$+$BaHfO_3$	3.5 mol%	3.3 µm	2.3 MA/cm^2	760 A/cm-w
$GdBa_2Cu_3O_{7-\delta}$+$BaHfO_3$	3.5 mol%	3.2 µm	2.1 MA/cm^2	670 A/cm-w
$GdBa_2Cu_3O_{7-\delta}$	–	2.5 µm	2.3 MA/cm^2	580 A/cm-w

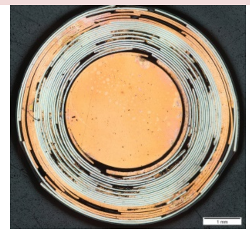


Key points:

- Eu-123 seeds fewer a-axis grains and allows better epitaxial growth
- Avoidance of nanorods means more isotropic pinning
- Demonstration on the 100 m scale
- SuperPower is now delivering 30 mm substrates which enabled MagLab 40 T magnet – very close to Nb-Ti if all combined

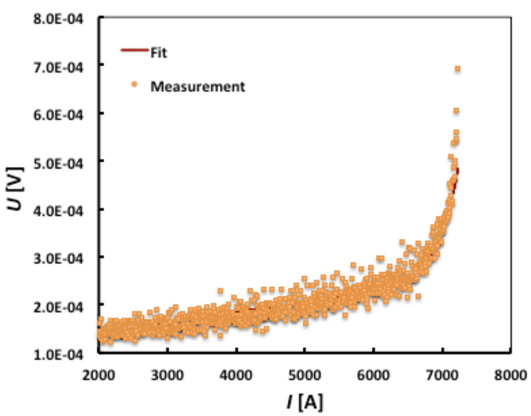
Very compact, high J_E cables (CORC) enabled by 30 μm substrates are now being made

Danko van der Laan advocated the CORC (Conductor on Round Core) as the route to a round, multifilament, twisted REBCO conductor, working closely with SuperPower, the MagLab and others



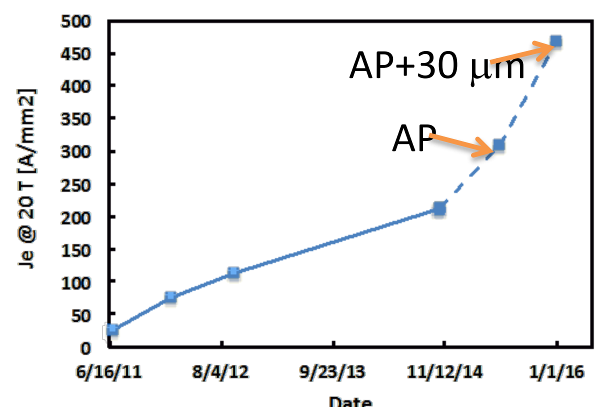
v.D Laan et al. SuST 29 (2016) 055009

Multilayer Barber pole wrap built up in many layers leading to cables capable of kiloamps



J_e (4.2 K, 20 T) = 310 A/mm^2
Achieved at end of 2015

- Enabled by advanced pinning (AP – 15Zr vs. 7.5Zr) tapes
- Enabled by thinner conductor substrates (30 μm vs. 50 μm today))



Latest NHMFL test results

I_c (4.2 K, 17 T) = 7,030 A
J_e (4.2 K, 17 T) = 344 A/mm^2

SuperPower Inc.

Advanced Conductor Technologies LLC
www.advancedconductor.com

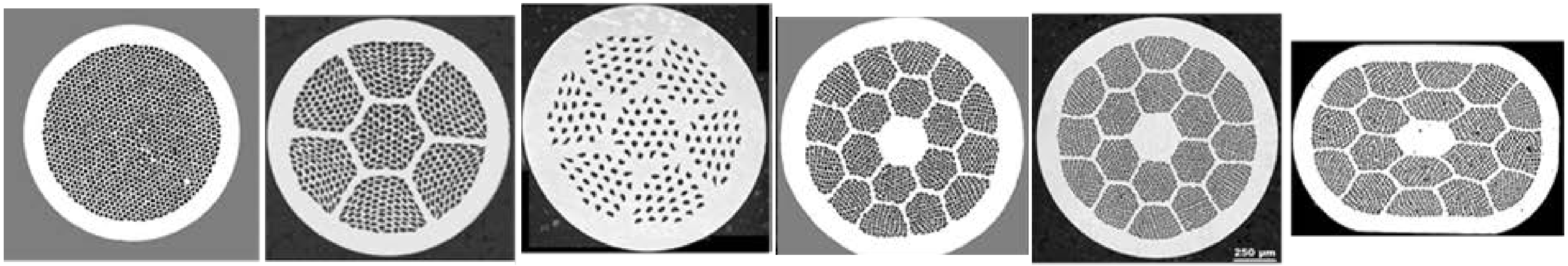
REBCO Coated Conductor Reflections

- Today's REBCO CC is an amazing conductor for high field magnets
  - 40 T today, 3 all superconducting 26-27 T magnets demonstrated in K, J and USA, 32 T expected soon
  - No Insulation (NI) is allowing (small) magnets to operate at the 1000 A/mm^2 level safely
- 4 K magnets deliver "Pull" – but can they deliver profitability?
- 65-77K magnet use for 1-10 T magnets should be the aim
  - Thicker REBCO (3-5 μm), probably liquid-driven routes, thin substrates

Thanks too to Judith Driscoll, Drew Hazelton, Teruo Izumi, SeungHyun Moon, Teresa Puig, Selva Selvamanickam , Alexander Usoskin and Aixia Xu who helped me with these conclusions

Is an HTS tape all that you can get? No!

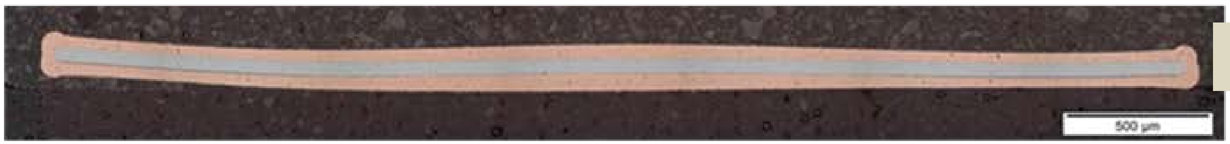
Bi-2212 wires are manufactured in many architectures by Oxford Superconducting Technology



Bi-2223

Sumitomo

REBCO – 32 T conductor



SuperPower

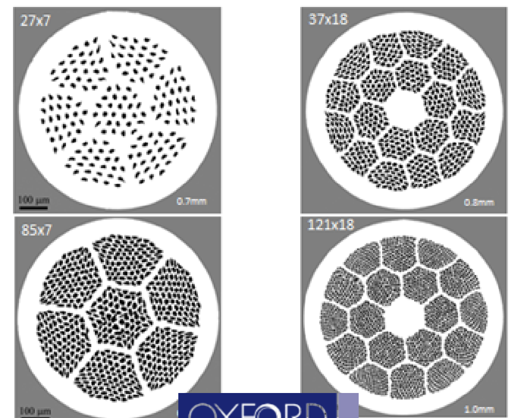
- **W&R technology** (like Nb_3Sn) - Only Bi-2212 allows multiple architectures and arbitrary size and shape – because it is reacted into the superconducting state **AFTER magnet winding**: Much more flexibility with 2212 but making it superconducting is our responsibility
- **R&W technology** - 2223 comes in one size only (but with various strengthening laminate possibilities) and REBCO is slit into variable widths of 1 - 12 mm – both come in the superconducting state
- **R&W technology** - The architectural restrictions on 2223 and REBCO arise from basic properties of grain boundaries and the low carrier density of cuprate superconductors

The price for round wire 2212 is as for Nb_3Sn – you must wind and then react (W&R)

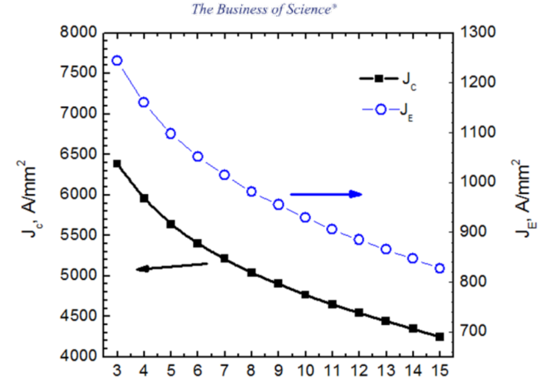
Bi-2212 – key positives

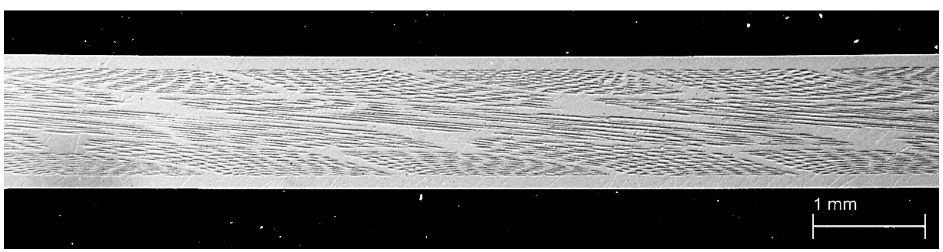
- Round, fine filament (~15 μm), twisted
- Available in multiple architectures
- Made on the same fabrication lines as Nb-Ti and Nb_3Sn
- OST is making single billet piece lengths in multiple architectures (> 1km at 1 mm dia.)
- Does not depend (like REBCO and Bi-2223) on electric utility demand
- Has the highest J_E of any HTS conductor and crosses over with Nb_3Sn at ~ 16 T (but with much bigger ΔT)
- Small coils being fabricated at FSU, FNAL and LBNL under BSCCo partnership

Unreacted Wire Cross Sections



OXFORD INSTRUMENTS
The Business of Science



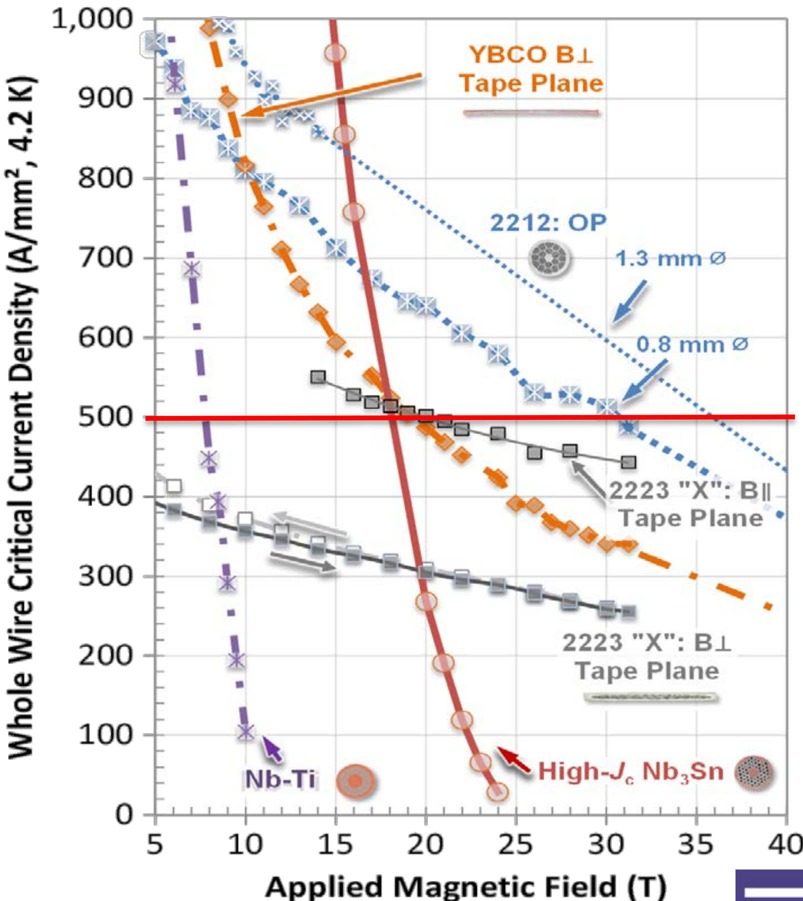


Native superconducting joint: Peng Chen 4L-OrB-02

OST 1 km long 1 mm dia wire with outstanding J_c and J_E: Jiang 1MOr-04 !0:00 AM today, Huang same session

Magnets Require High Conductor Current Density J_E, not just High J_c in the Superconducting Layer

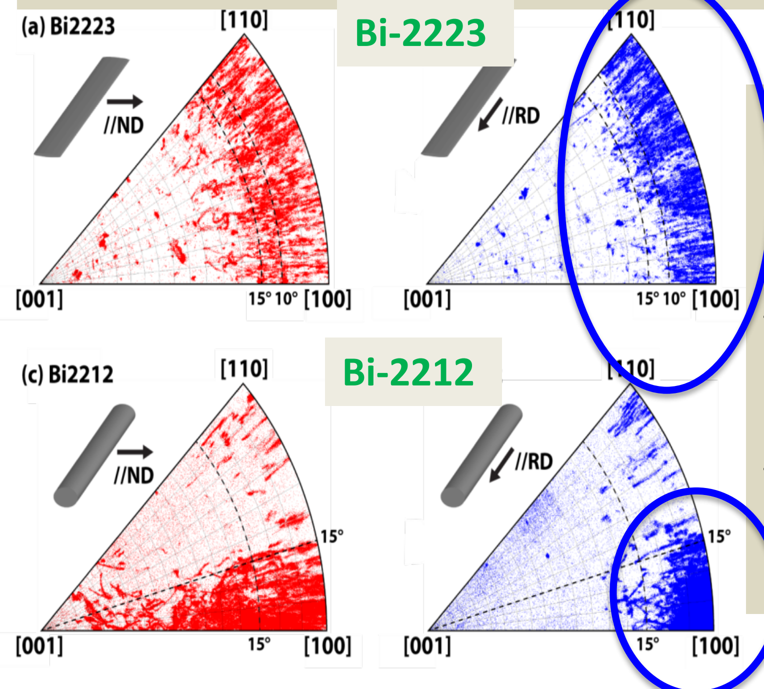
- Highest J_c is in quasi-single crystal REBCO but smallest fill factor too (~1% *vs.* 25 - 40%)
- Whole wire J_E values ~ 500 A/mm² needed for small bore magnets
  - All 3 HTS wires can offer this
- Enhancing connectivity is 90% of the game for HTS conductor technologies
  - Avoid grain boundaries
  - Avoid manufacturing defects, especially in REBCO



Bi-2212 minimizes High Angle Grain Boundary density by self-alignment in the melt

- Classic IBM experiments (1988) showed that grain misorientations $\theta > 3 - 5^{\circ}$ greatly degraded connectivity
- Complex, high-texture fabrication processes were developed to deliver high J_c
  - "Single crystal by the 100 m" for REBCO – strong biaxial texture by thin film growth processes
  - Weak uniaxial texture for Bi-2223 – metal working
  - **Biaxial growth texture for Bi-2212 allows wire to be made on standard LTS fabrication lines**

Kametani *et al.*, Sci Rep 5, 8285 (2015)



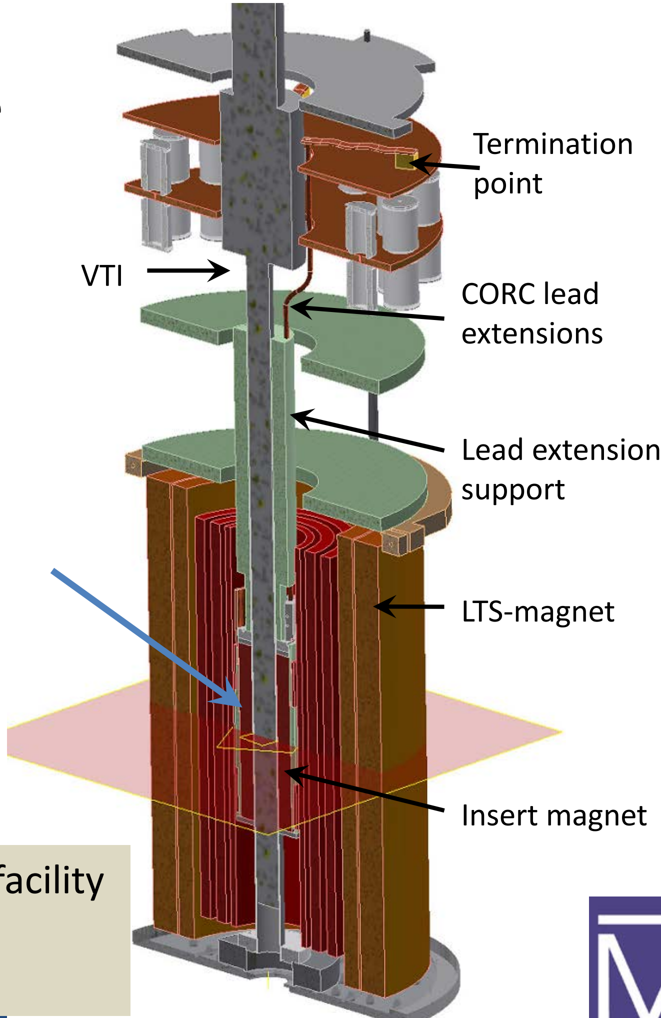
Much smaller distribution of θ in 2212 than in 2223 – but REBCO is the champion (3 - 5°)

Bi-2212 develops high J_c for two reasons:

1. Melting 2212 inside its Ag sheath generates a biaxial texture of ~15°
2. Overdoping is possible in 2212, allowing higher GB superfluid density

NMR and accelerator magnets are a strong pull for 2212

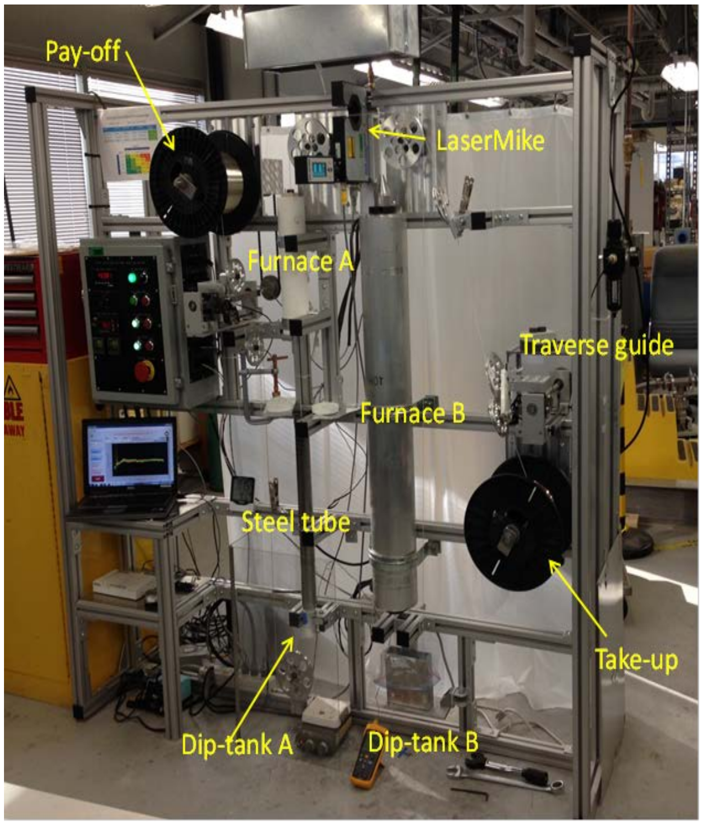
- They are multifilament wires with much lower magnetizations than wide tape, single filament REBCO CC
  - **Suitable for homogeneous magnets like NMR or accelerator magnets (2212 only)**
- A major drive of MagSci is for HTS NMR at fields up to 1.6 GHz
- We have established an HTS NMR Testbed with a 115 mm bore 17 T Nb-Ti/Nb_3Sn magnet – IMPDHAMA
- 2212 and 2223 inserts for up to ~24 T (1 GHz) are being constructed now



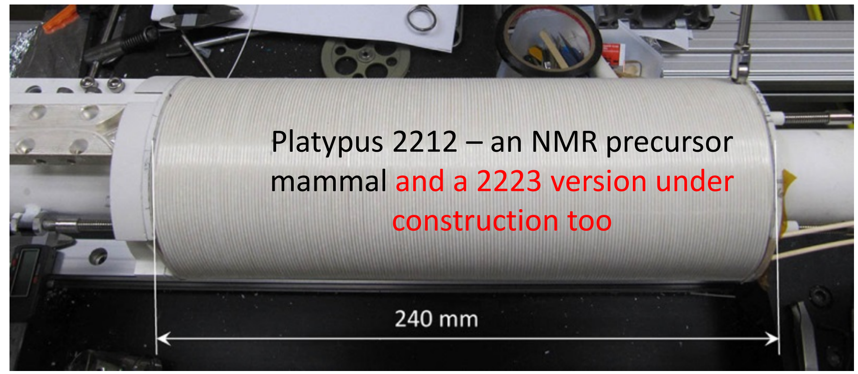
Ulf Trociewitz/Bill Brey Project leaders of IMPDHAMA facility
Ulf Trociewitz Project leader 2212 Platypus
Scott Marshall Project leader 2223 Platypus

Wind and React 2212 requires us to Insulate and React it Ourselves – Most Technology Now in Hand

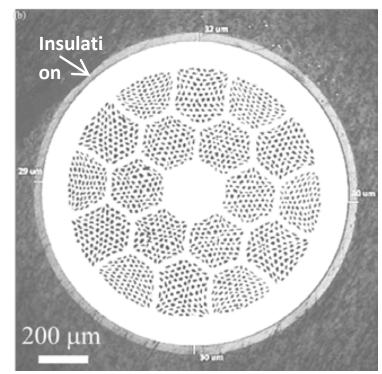
Bi-2212: W&R technology



NHMFL Insulation line (Jun Lu)



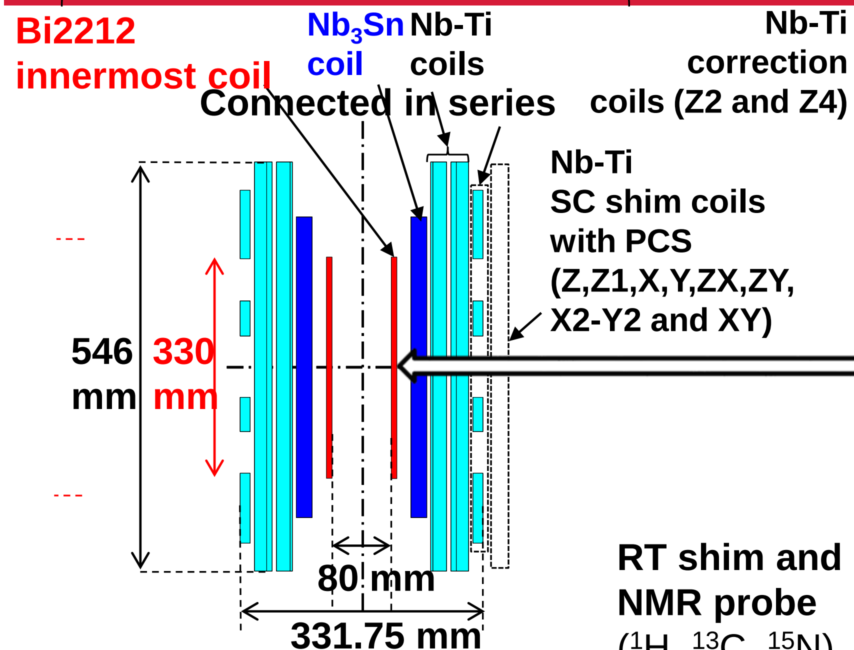
- Insulation is vital – but must withstand 890°C reaction
- 1 km lengths now being coated reliably



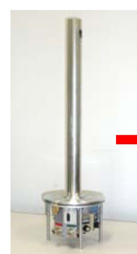
25 µm TiO_2 coating

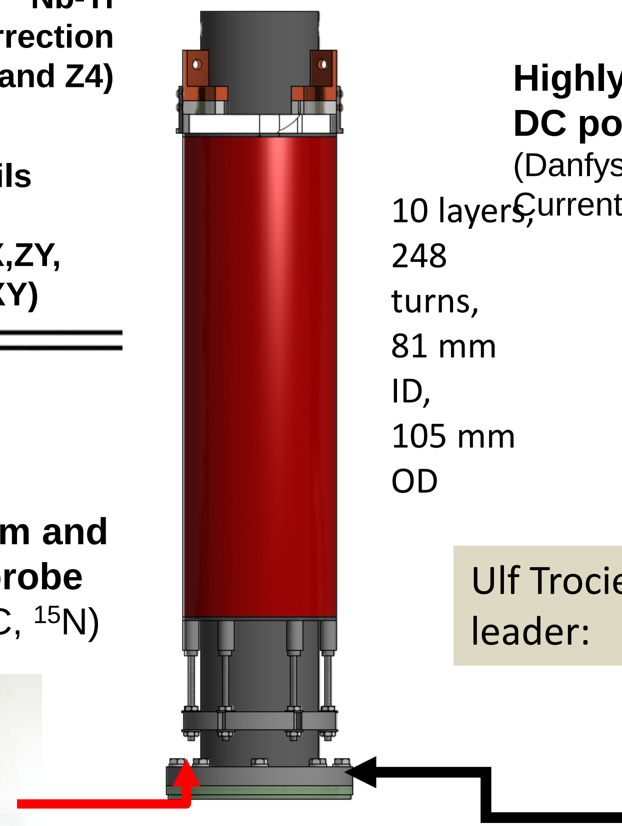
Presentations by Jun Lu, Trociewitz, Peng Chen Bosque and Hilton

Bi-2212 Insert for RIKEN 400 MHz Solution NMR System is in heat treatment (R of W&R)



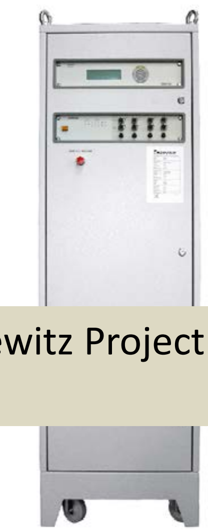
RT shim and NMR probe
(^{1}H, ^{13}C, ^{15}N)





10 layers,
248
turns,
81 mm
ID,
105 mm
OD

Highly stabilized DC power supply
(Danfysik)
Current stability <1ppm



Ulf Trociewitz Project leader:

- Uses ~730 m of Bi-2212 round wire made by OST in one length
- Components are in production, expected delivery October 2016

Operated in driven mode
The field fluctuation is stabilized using field-frequency lock

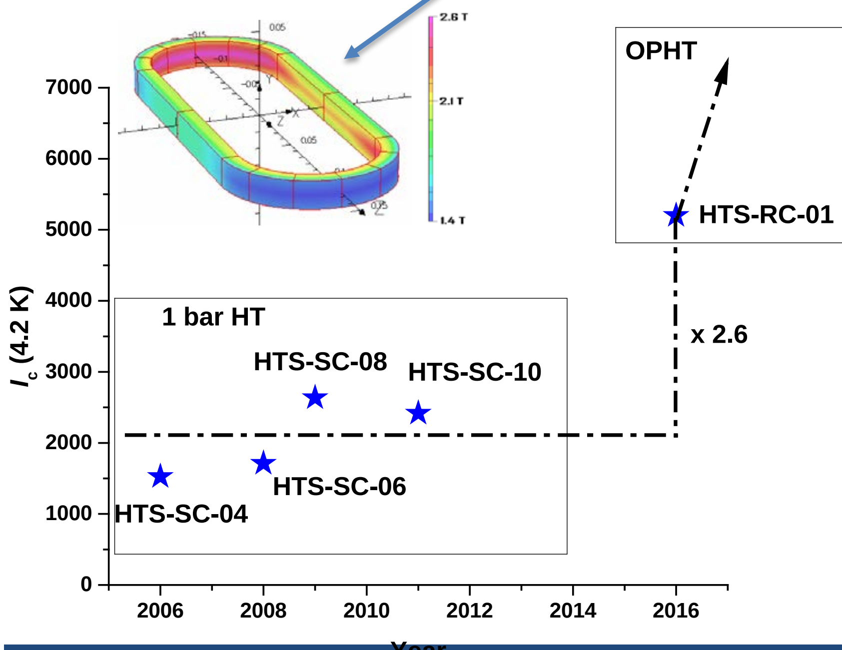
Bi-2212 accelerator magnets with 3 times higher Ic after 50 bar OP (Tengming Shen 1LROr2B-04

LBNL HTS-RC-1 (5.2 kA, 86% SSL, J_{cable}=470 A/mm^2, J_e=640A/mm^2, 140 m conductor, 18 lbs coil thermal mass, dimensions: 37 cm x 12 cm x 3.1 cm)

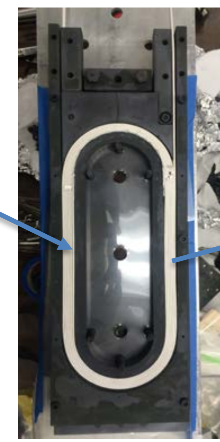
Rutherford cable breaks 5 kA barrier.

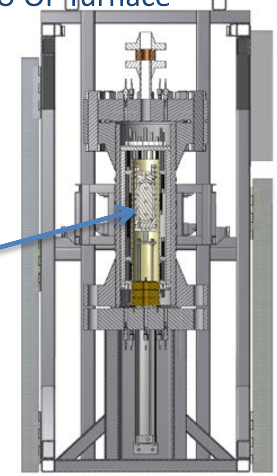
OPHT demonstrated to develop high J_c in coils.

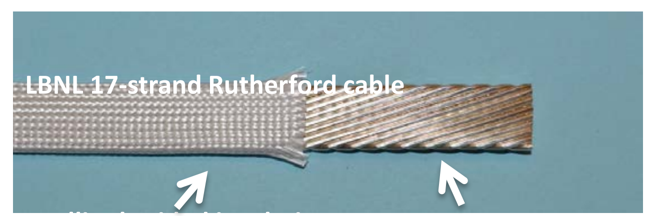
2-layer racetrack coil based on 17-strand Rutherford cable



LBNL RC-1 in FSU OP furnace

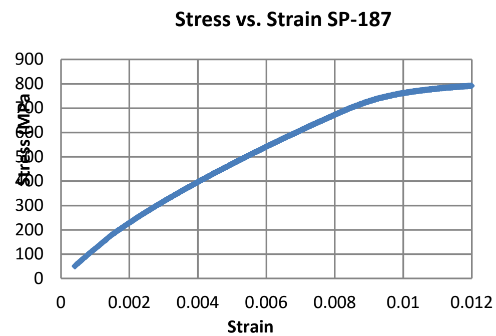






Good Stress/Strain Tolerance vital: Available in REBCO and 2223 – 2212 in Development

REBCO Coated Conductor

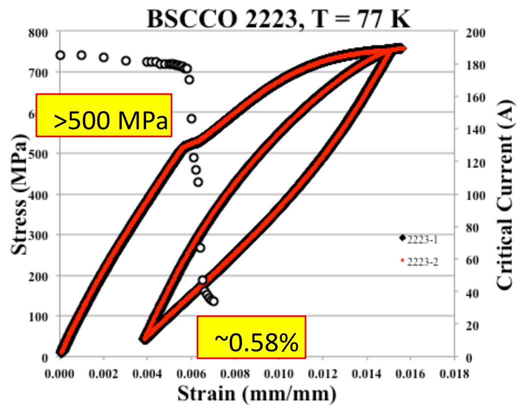


σ(ε) for 32 T REBCO

32 T operates at ~400 MPa at ε = 0.4%

Weijers et al. MT24 IEEE TAS subm.

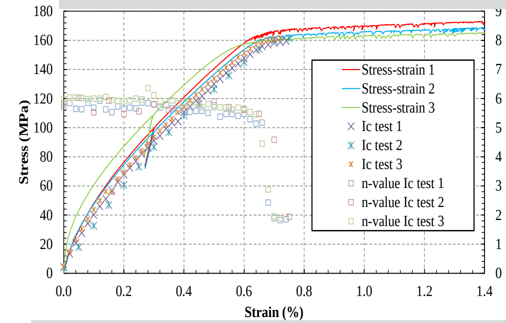
Strong 2223 (2223NX)



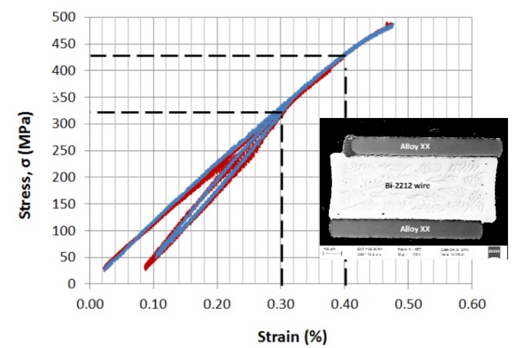
Excellent high field performance shown by Godeke *et al.* (MagLab 10/15 and Yanagisawa *et al.* SuST 2015

2212

Round, unstrengthened 2212 wire



Bjoerstad and Scheuerlein, *SuST (2015)*



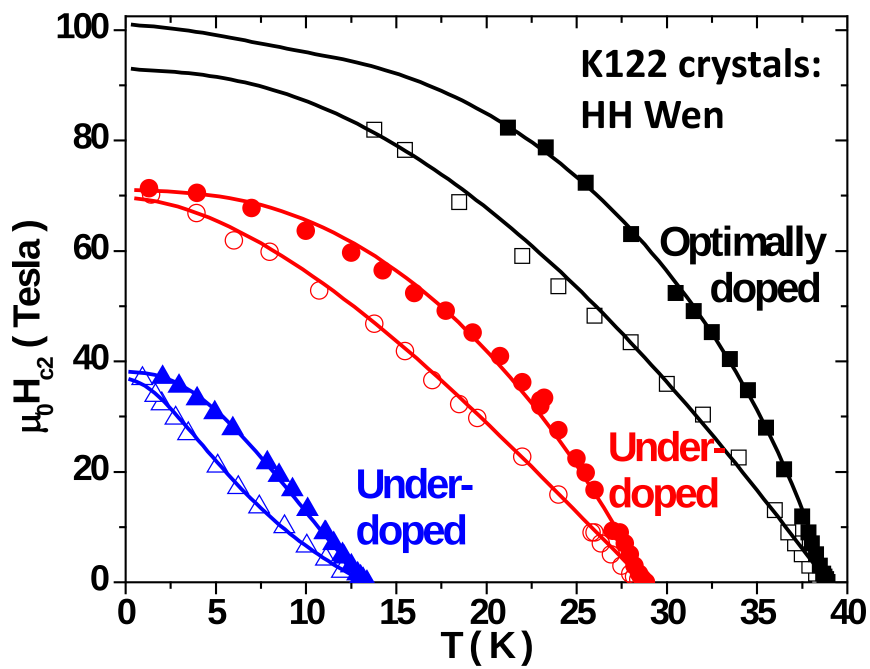
Stress for ε = 0.4% raised from 120 to 425 MPa

M. Boebinger, R. Walsh

Key message: REBCO is inherently very strong, 2223 has recently been greatly strengthened, 2212 strengthening now being prototyped, similar to lamination of 2223 (Alex Otto, Solid Materials Solutions)

And now for something different….

Tarantini et al. PRB 86, 214504 (2012)



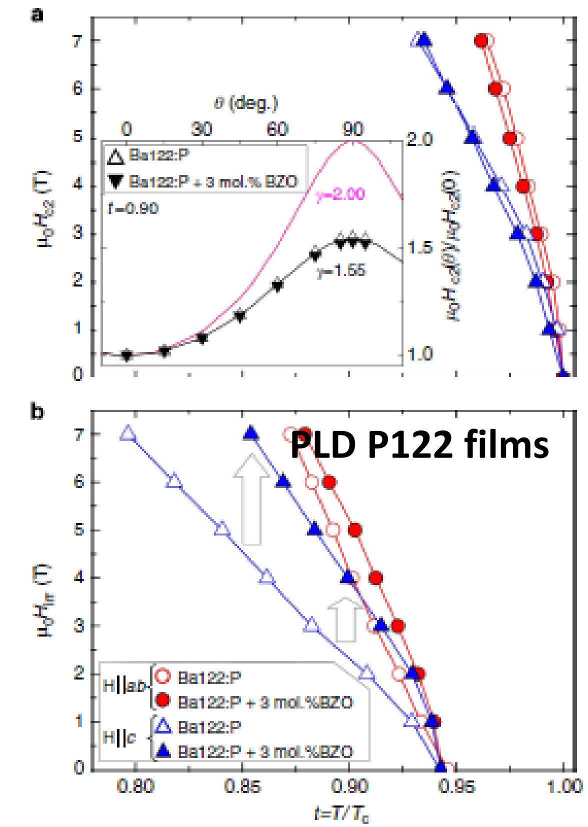
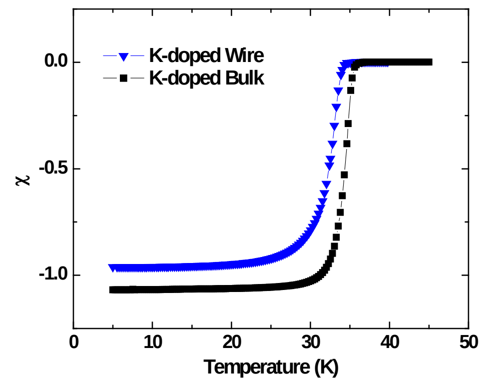


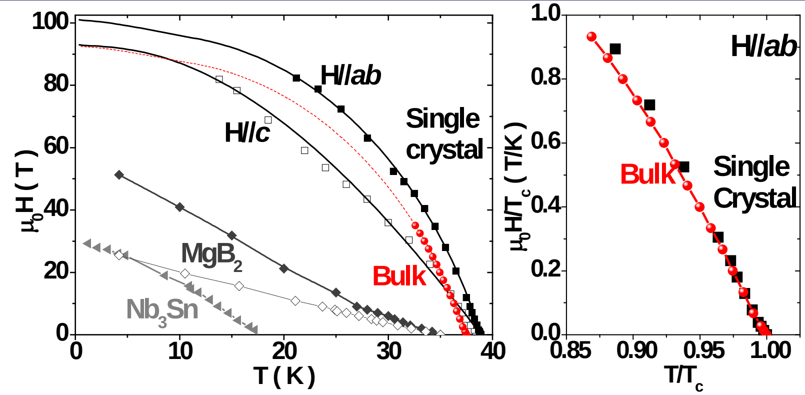
Figure 3 | Upper critical field $H_{c2}(T)$ and irreversibility field $H_{irr}(T)$. (**a**) Normalized temperature ($t = T/T_c$) dependence of H_{c2} for Ba122:P and Ba122:P + 3mol.%BZO films at **H**||c and **H**||ab. Inset: angular dependence of H_{c2} at $t = 0.90$ for Ba122:P and Ba122:P + 3mol.%BZO films follow a curve consistent with $\gamma \sim 1.55$. (**b**) Normalized temperature dependence of H_{irr} at **H**||c and **H**||ab.

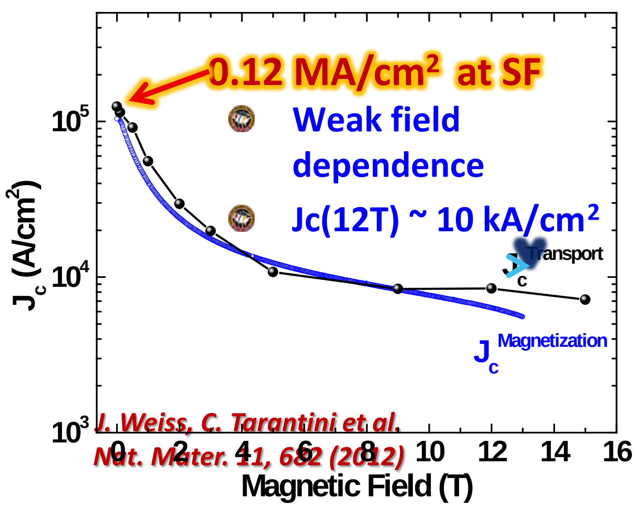
Miura et al. Nat. Comm. Doi 10.1038 (2013)

- **Gamma ~1.1 for K-122 and 1.55 for P-122**
- **High vortex pinning too**

K-Ba122: Very high H_{c2} and high J_c in dense and untextured bulks and wires







259 filament wire

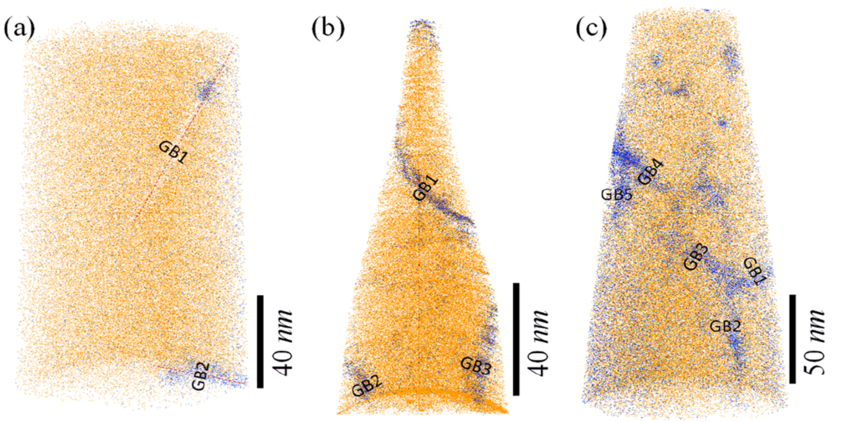
Higher Jc values obtained by Ma et al (IEE-CAS) and Gao et al. (NIMS)
- But on textured tapes

Is K-122 the route to an affordable, high-field Superconducting Conductor?

Present HTS conductors are several times more expensive than LTS conductors

Raw material costs of K-122 conductor are much less than any Nb-base conductor
K-122 must be Wind and React (like Nb_3Sn) – but reaction is at 600°C
Challenge: plenty of vortex pinning in 122 compounds – is the poor GB connectivity intrinsic or extrinsic?

Kim *et al* .APL 105 162604 (2014) (FSU-NWU collaboration)
Weiss *et al.* Nat. Matls. 11, 682 (2012)



Atom probe microscopy on high Jc $((Ba_{0.6}K_{0.4})Fe_2As_2$ showing strong O segregation to GBs **(blue highlights)** – a clear sign of impurity blocking of connectivity across GBs that causes the macroscopic Jc to be much les than the vortex pinning Jc

And finally MgB_2

Superconducting Links Characteristics (1/3)

LHC P7

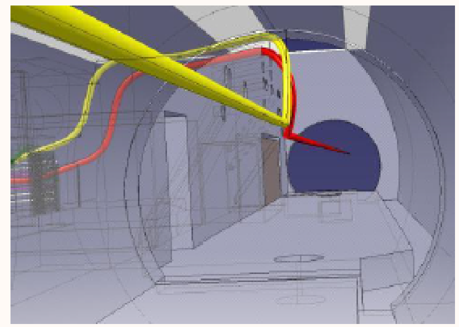
2 Links, Each ~ 500 m long

50 Cables per link rated at 600 A

|Itot| = 30 kA

Removal of LHC cryostats from tunnel

Underground installation



LHC P1 and P5

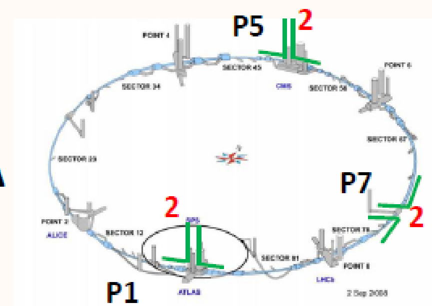
2+2 Links, Each ~ 300 m long

42 Cables per link rated at up to 20 kA

|Itot| = 150 kA

Upgrade of Hi-Luminosity Triplets

Surface Installation



A. Ballarino, CERN

Paestum, 15-19 May 2014

Current links for the LHC can be done with today's MgB_2 affordably

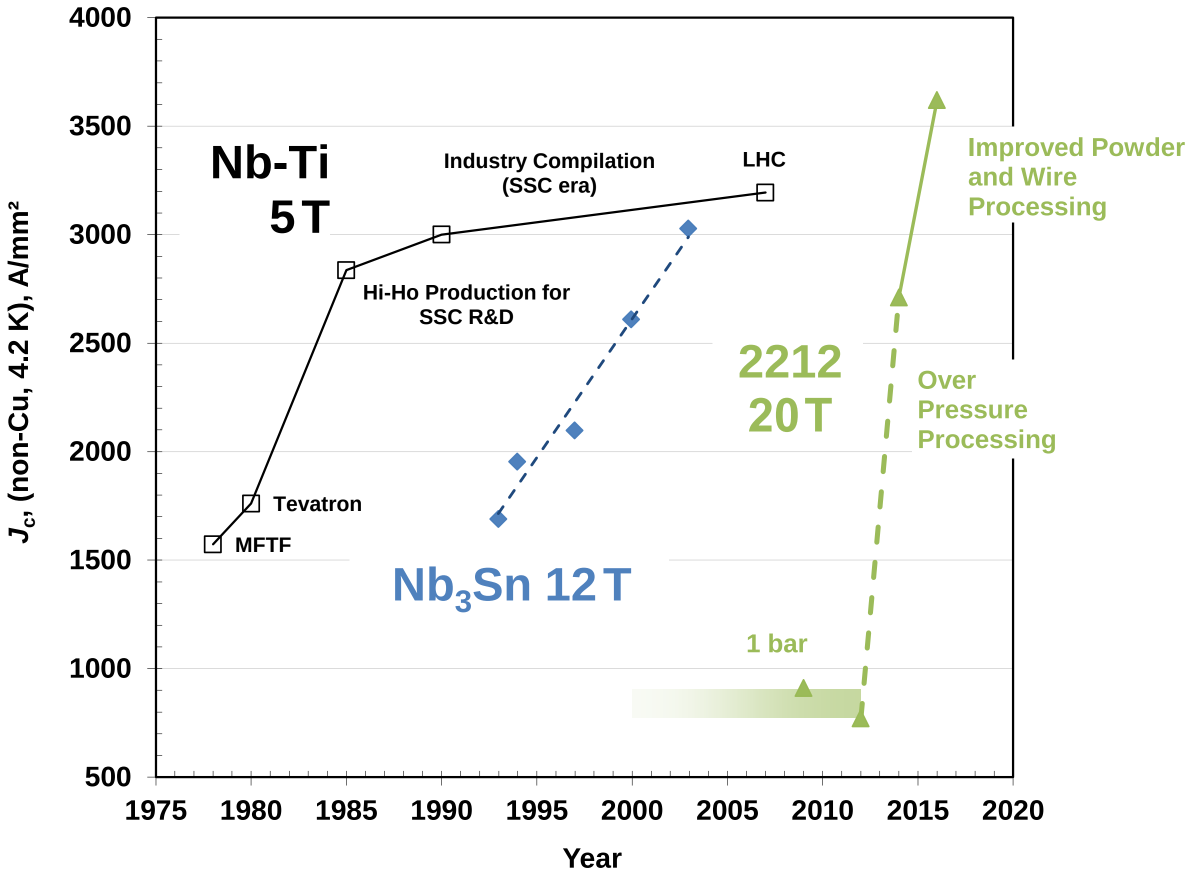
Where would I put my money?

- Nb-Ti and Nb_3Sn for sure
- HTS still demands faith in the future
  - REBCO for ultra-high field magnets, especially NI where quench problem may be solved
  - 2212 as a round wire HTS technology that is challenging but now close to full magnet demonstration
- K,Ba/$SrFe_2As_2$ as potentially the isotropic, affordable, multifilament round wire that can extend Nb_3Sn or even replace it if present connectivity issues are just GB impurity issues
  - And MgB_2 too if I could attain the high H_{c2} of Penn State films into bulks!

Affordable conductors and working science-magnet-manufacturer links are the key to success – more magnets, not just conductor lengths are needed!

Electric utility PULL would be the game changer for HTS

What is the next high field superconductor for this plot?



My Thanks

- To the long term conductor manufacturers like Oxford, Bruker, Luvata, IGC, SuperPower, AMSC, Furukawa, Fujikura, Hitachi, Mitsubishi, Kobe Steel, Columbus, SuNAM
- To more than 50 PhD students who have taken up the challenge of understanding conductor materials in ASC
- Especially to the HEP community for more than 35 years of continuous support to me (and even longer to the field)
  - And especially to Dave Sutter of Advanced Accelerator R&D at DOE-HEP who had a truly long term vision for superconductivity and accelerators
- To NSF, the MagLab and Greg Boebinger who cheerfully took up the challenge of supporting new generations of high field superconducting magnets in 2005 after COHMAG reported