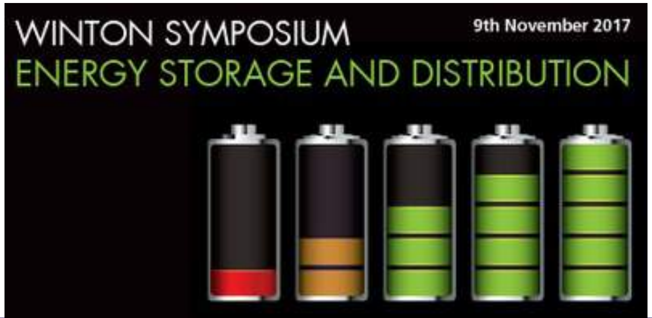
NATIONAL HIGH MAGNETIC FIELD LABORATORY



Prospects for the use of superconductors for energy storage and distribution

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November 9, 2017

The Winton Symposium on Energy Storage and Distribution

Cavendish Laboratory, U. of Cambridge UK

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*Material shown here drawn from a wide variety of internal MagLab staff and students. Special thanks to Huub Weijers (32 T project leader), Seungyong Hahn (No insulation project leader), Ulf Trociewitz (Bi-2212 coil project leader), and Scott Marshall (Bi-2223 coil project leader)

High Temperature Superconductors (HTS):Can they be useful for SMES and other green energy applications?

- The technical answer is yes – validated with both LTS materials in the 1960s and 1970s with HTS from the 1990s to today
- Economically the present answer is NO

- **The missing link is an affordable, inexpensive conductor that can compete with Cu and Fe**
- **In the last 10 years, HTS conductors are showing that they can produce high magnetic fields quite impossible with any low temperature superconductor (LTS)**
- **The "killer app" for superconductors is the generation of high magnetic fields or low fields in large volumes**

Time lines of Superconductivity

- **Science**

- 1911 – discovery
- 1932 – Meissner effect
- 1936-7 – the vital influence of allowing a pure metal (Shubnikov)
- 1950 – phenomenological theory (Ginzburg and Landau)
- 1957 – BCS theory – electron-phonon basis for superconductivity
- 1957 – vortex state in high κ superconductors (Abrikosov)
- 1986 – superconductivity in cuprates (Bednorz and Muller)
- ……………superconductivity everywhere (at low temperatures)

- **Applications**

- 1913 – vision of a 10 T superconducting magnet (Onnes) – dashed by 1914
- 1936 - Signs in Kharkov of path to higher field superconductivity
- 1961 – High current density in high fields finally discovered in Nb_3Sn (Kunzler, Buehler, Hsu and Wernick)
- 1960s – superconducting magnet technology took off
- 2000s – widespread application of HTS (in the LHC, all the LTS magnets are powered by HTS current leads)

Superconducting applications had a 50 year germination

A historical perspective….Kammerlingh Onnes in Chicago 1913 (IIR)

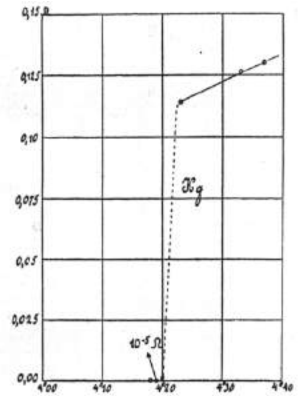
H. Kamerlingh Onnes, Comm. Physical Lab., Univ. of Leiden, Suppl. **34b** to **133–144**, 37 (1913).

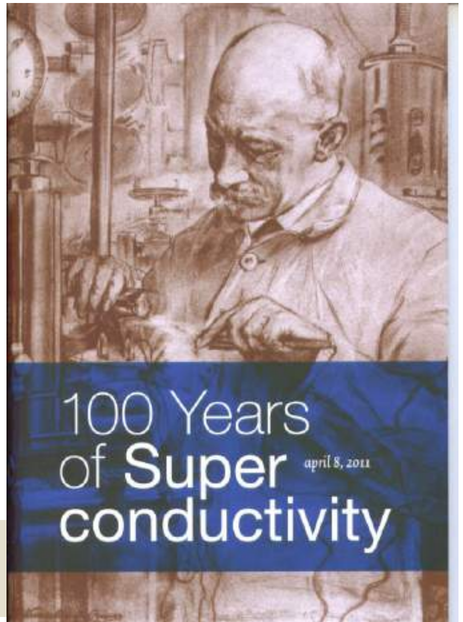
Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state. . . . The behavior of metals in this state gives rise to new fundamental questions as to the mechanism of electrical conductivity.

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. . . .

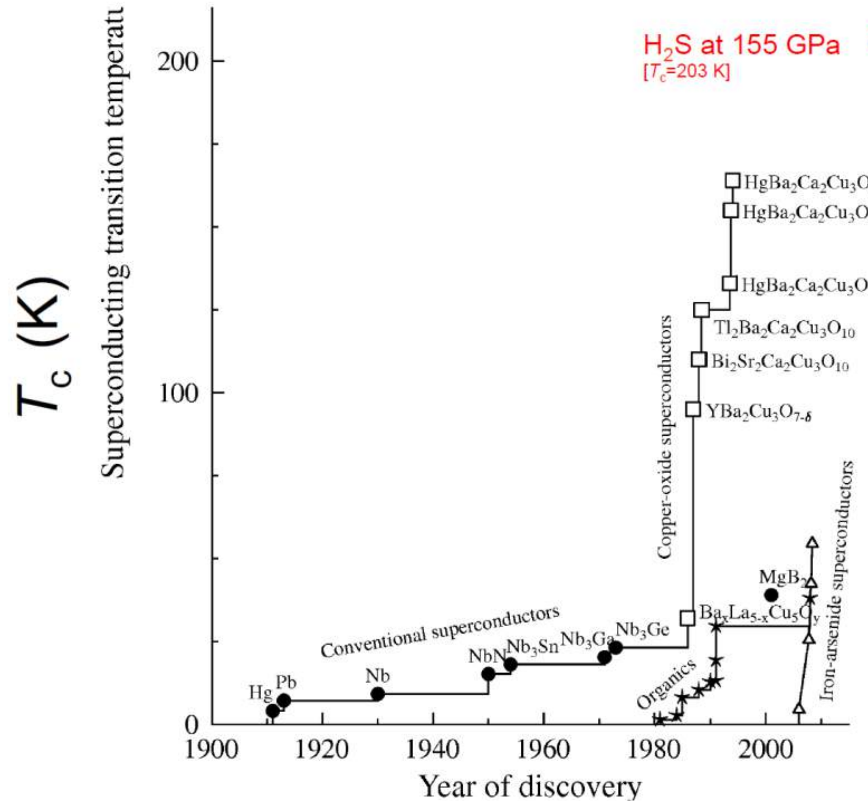


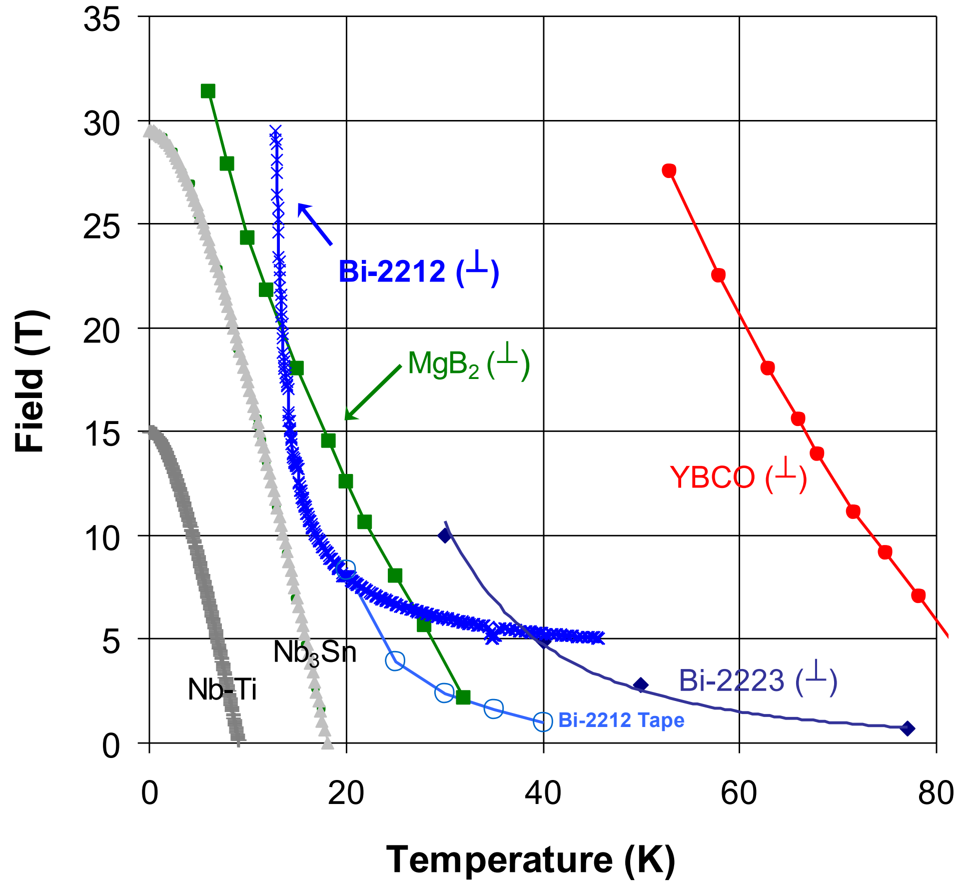


Onnes in 1913...........................!

- The conception of a 10 T magnet
  - The impossibility of doing this with Cu cooled by liquid air (as expensive as a warship)
  - The possibility of doing it with superconductor (1000 A/mm^2 with a Hg wire, 460 A/mm^2 with a Pb wire
  - Silk insulation allowed easy He permeation
  - Sn coated on a strong constantan wire
- A little problem!
  - Resistance developed at 0.8 A, not 20 A
  - 48 years had to go by before the path to high field superconducting magnets was cleared

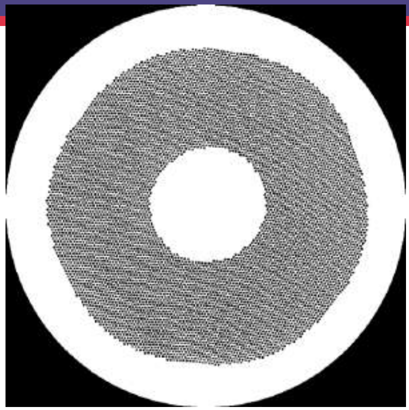
Transition temperature T_c, Upper Critical Field H_{c2} and Superconducting critical current density J_c define applications



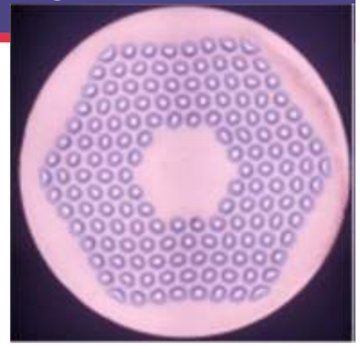


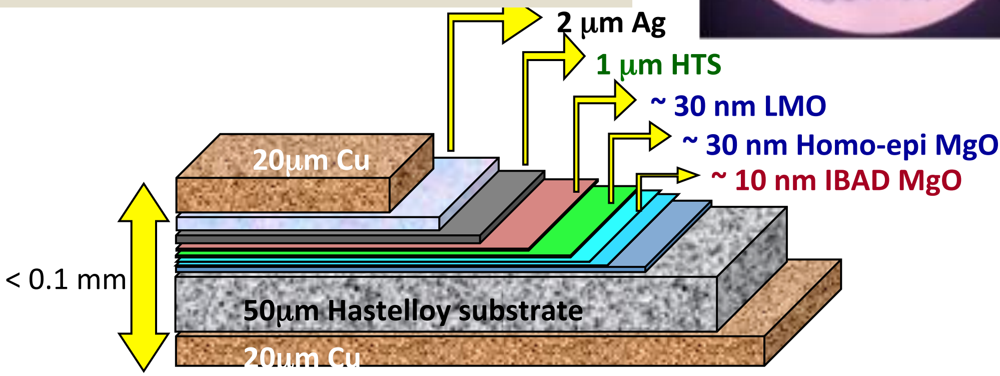
>95% of present superconducting technology is Nb-Ti and Nb_3Sn – HTS is possible but conductor availability and cost is the issue

Available conductor choices today



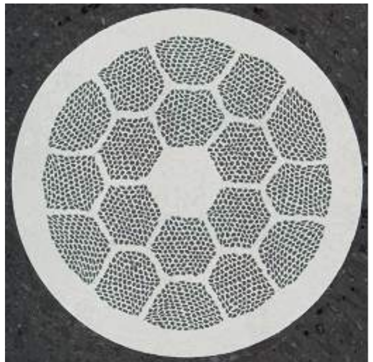
2. RRP (150/169 design) very high J_c Nb_3Sn conductor- thousands of few μm dia. Nb filaments in pure Cu converted to ~ 40 μm filaments after reaction with Sn cores, easily cabled to make 10-20 kA conductors





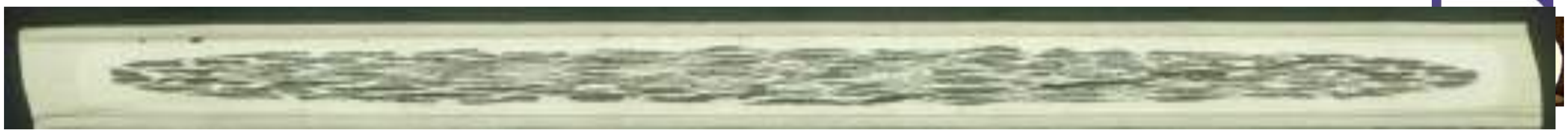
1. Nb47Ti conductor- thousands of 8 μm dia. Nb47Ti filaments in pure Cu, easily cabled to operate at 10-100 kA

4. REBCO coated conductor – highest J_c obtained by biaxial texture developed by epitaxial multilayer growth



5. Bi-2212 – high J_c in isotropic form without macroscopic texture! The first HTS conductor like an LTS conductor.

3. Bi-2223 – the first HTS conductor – high J_c requires uniaxial texture developed by deformation and reaction



My point of view

- I have been in the development and applications of superconductors (almost) my whole career
  - 1965-1970 worked on basics of superconducting materials for PhD at Imperial
  - 1972-1976 Rutherford Laboratory Superconducting Magnet Research Group (Goal – superconducting dipole magnets for the next CERN accelerator (SPS) – achieved about 2006 in the LHC
  - 1976-2006 University of Wisconsin Madison – first the Diurnal Superconducting Magnetic Energy Storage (SMES) Program, then the much broader Applied Superconductivity Center
  - 2006- now: The National High Magnetic Field Laboratory at Florida State University which has the world's highest DC power for high magnetic field generation (56 MW) and the highest fields (45 T in a hybrid 11 T large bore superconducting magnet and a 28 MW 31 T resistive magnet) – now aiming for superconductors to take over

In the 70s and 80s I worked on SMES and post 1987 received strong support for electric utility applications up to cancellation of the US program in 2011

Diurnal SMES at Wisconsin

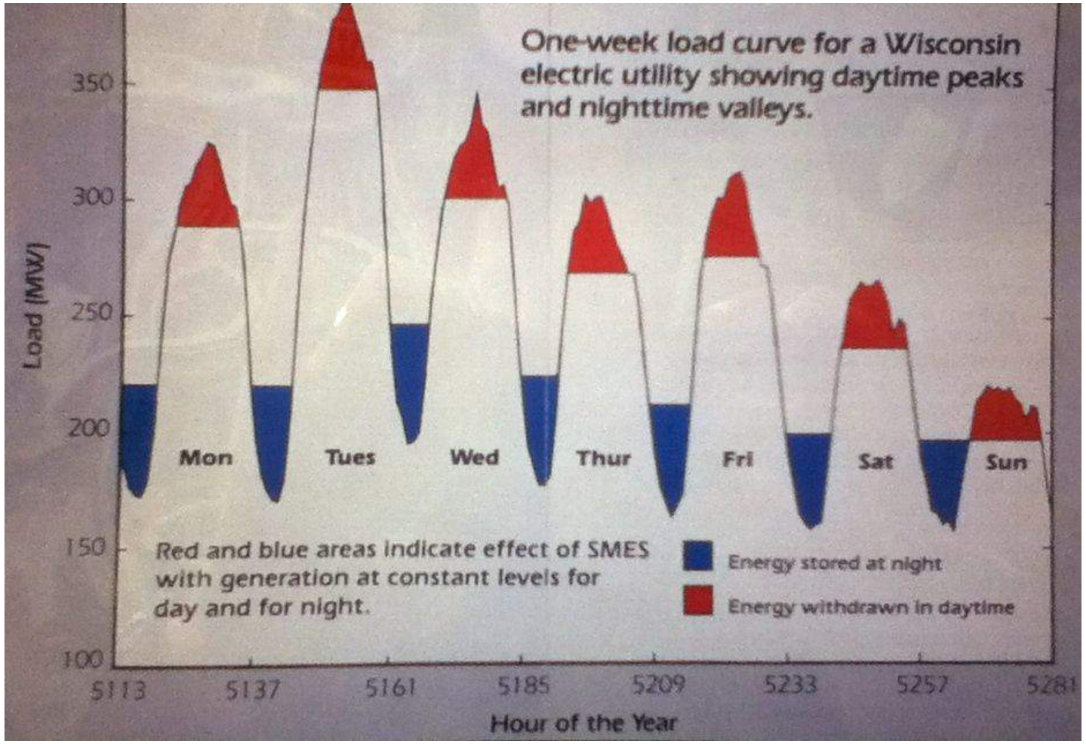
- Superconducting magnet
  - stored energy = 0.5 LI^2 = $B^2/2\mu_0$
- Power Conditioning System
  - round trip efficiency ~90%
- Cryogenic Vacuum Enclosure
  - Maintains the superconducting state
- Structural Support
  - reacts the Lorentz forces
- Energy scaling with size is attractive
  - $E \approx \text{Volume}^{2/3}$

A football-stadium sized superconducting magnet

Conception (supported by WI utilities) was to store 5000-10,000 MWHr diurnally to prevent cycling the ouput power of baseload nuclear and coal plants

Essential elements of the Wisconsin SMES design

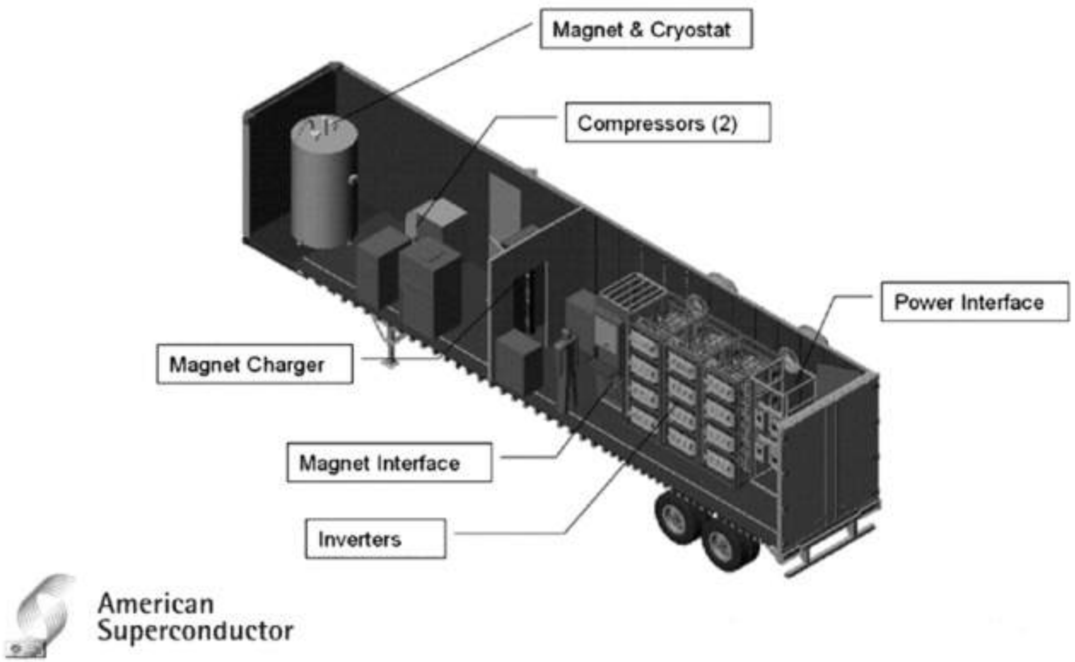
- The utilities were run by engineers and they were interested
- Flexible and generous R&D support for a decade to work on the basis ideas
- 100 kA Nb-Ti superconductor cooled by superfluid He at 1.8 K
- Forces transmitted to granite bedrock by optimized composite supports



The SMES was conceived as a system but construction costs ensured that no real diurnal system could be built

Much smaller system stability SMES were designed and built

- About a dozen D-SMES units were built by AMSC in the late 1990s and early 2000s for local system stabilization
- 3 MJ delivering about 1 MW for 1-2 secs to mitigate power dropouts
- All in self-contained 40 foot trailer
- He cooled Nb-Ti magnet (HTS too high cost)



Small, system-stabilization SMES seemed to offer major benefits as MW UPS for a few seconds, but……..

THE HTS Era: 1986 to today

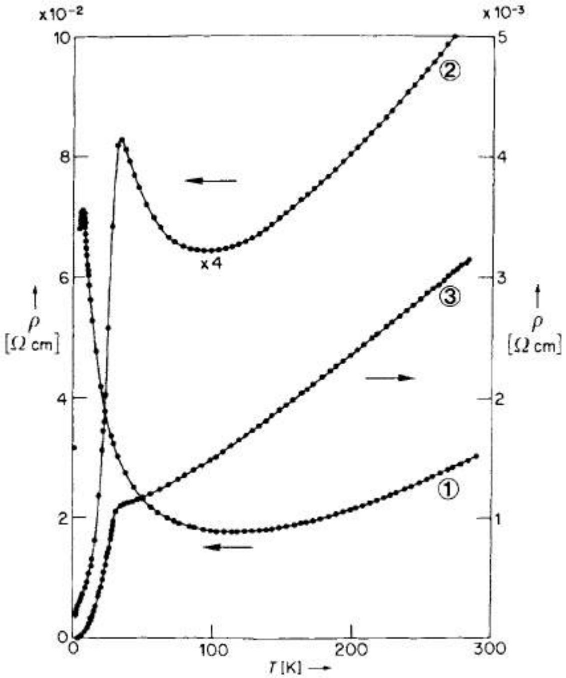


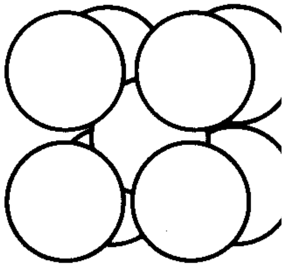
Fig. 1.9. Resistivity as a function of temperature for La_2CuO_{4-y} : Ba samples with three different Ba : La ratios. Curves ①, ②, and ③ correspond to ratios of 0.03, 0.06, and 0.07, respectively (adapted from [1.20]).

- POSSIBLE HIGH-TC SUPERCONDUCTIVITY IN THE BA-LA-CU-O SYSTEM
  BEDNORZ JG, MULLER KA
  Z FUR PHYSIK B-CONDENSED MATTER   64, 189-193
  1986 , Times Cited: ~8000

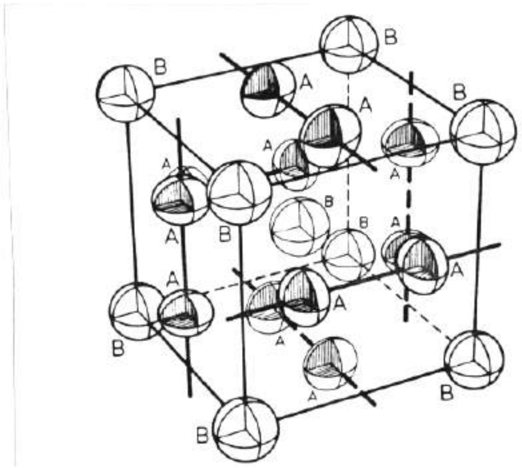
“Superconductivity, once a dead end, becomes the hottest thing in physics” - Time Magazine,   11 May 1987

Higher T_c – greater complexity

Nb-Ti

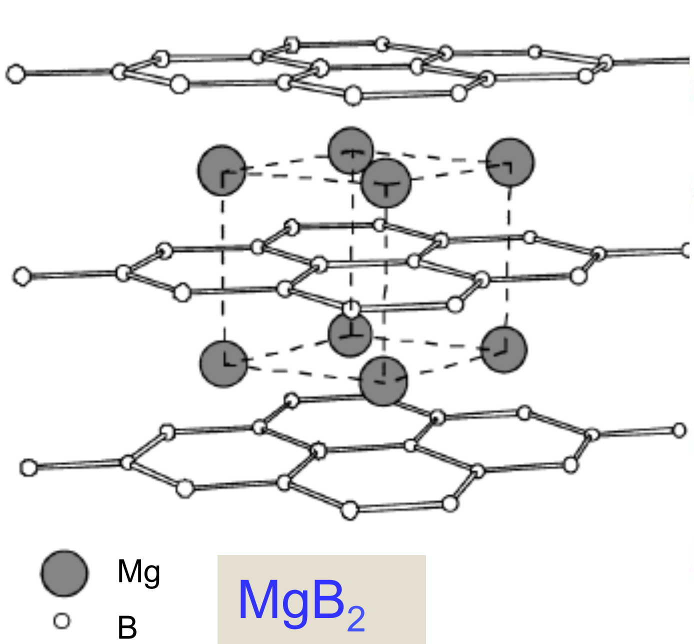


9 K

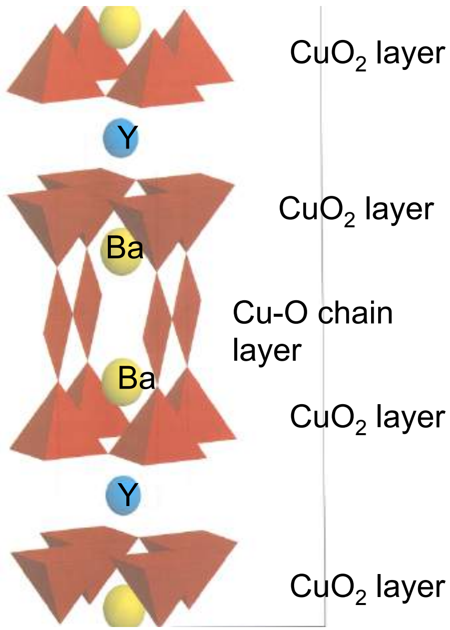


Nb_3Sn

18-23 K

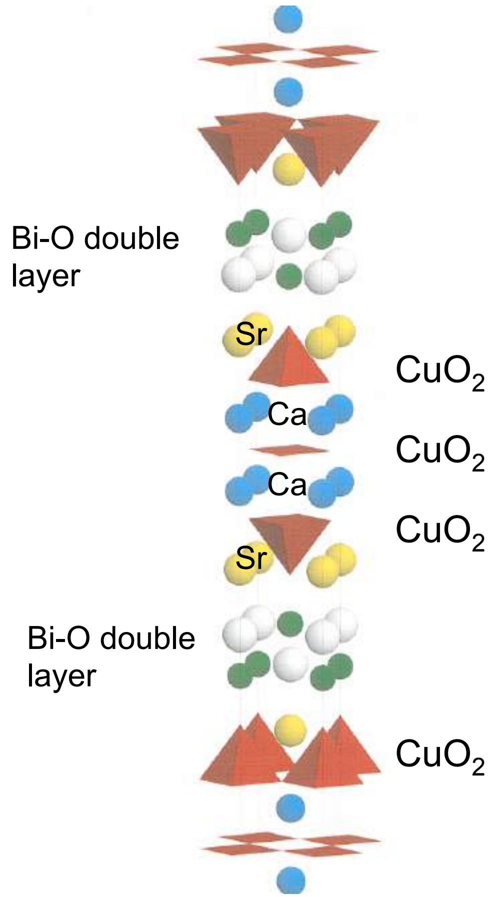


MgB_2



92-95 K

YBCO



110 K

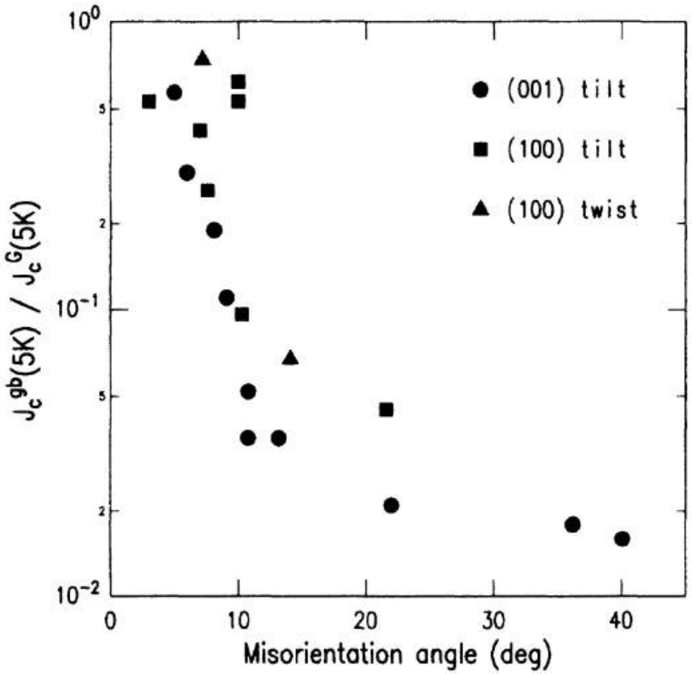
Bi-2223

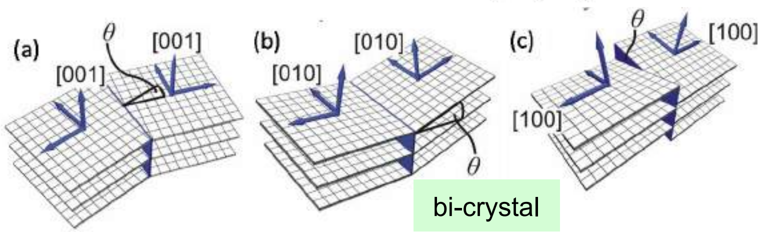
Long length conductors must contain GBs

Cuprate GBs strongly obstruct current

$\xi = \hbar v F / \pi \Delta$, $\Delta \propto Tc$

$\Rightarrow \xi \propto 1/Tc$





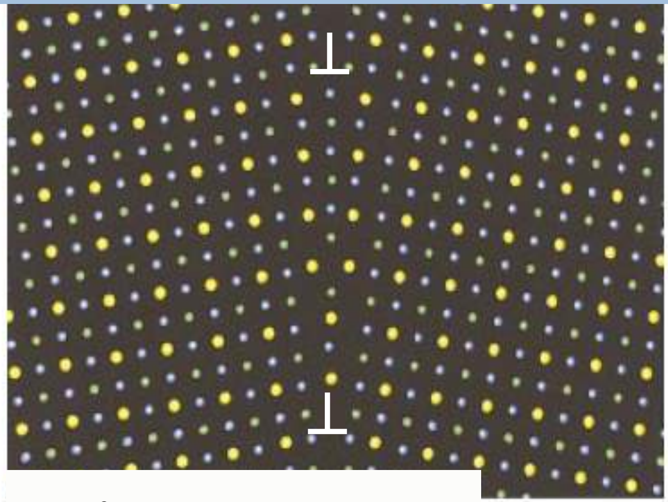
- Small coherence length(nm) makes HTS very sensitive to local defects on nanometer scale

- GB is an obstacle to supercurrent.
- IBM group was the first to demonstrate the significance of grain alignment for REBCO.
- A fast, exponential decay of Jc^{GB} beyond a small critical angle:
  - Planar bi-crystals
  - Critical angle θ_c ~3^o

$$J_c^{GB}(\theta) = J_0 \exp(-\theta / \theta_c)$$

Dimos et al., *PRB, 41(4038), 1991*

Complexity: Strain and charge inhomogeneity at GB

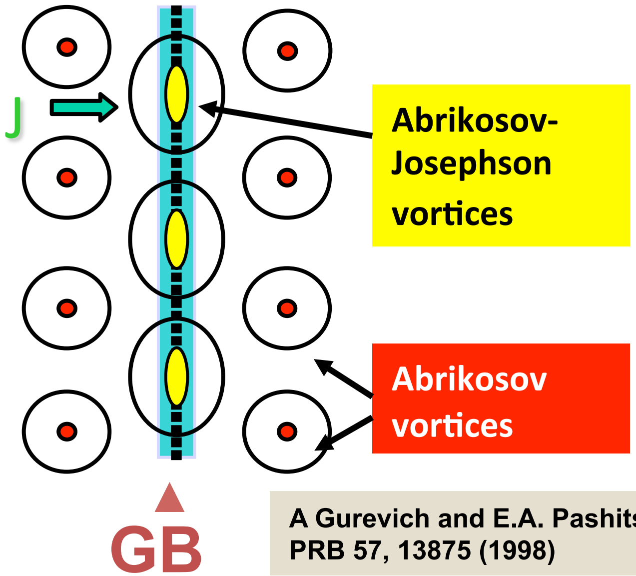


16° [001] tilt grain boundary in YBCO

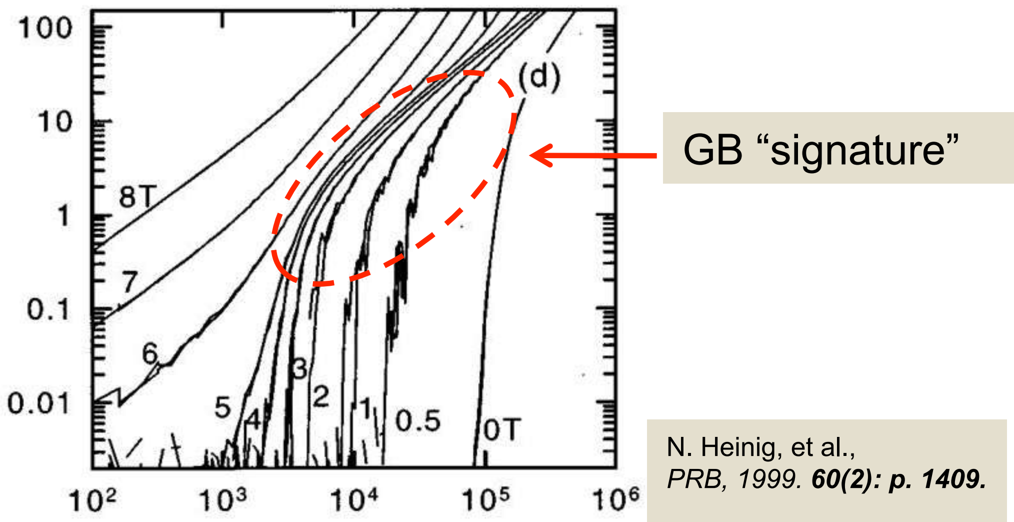
Y/Ba Cu O

Hilgenkamp et al, Rev. Mod. Physics, 74(485), 2002

- GB dislocations:
  - Accommodate misaligned grains
  - Induce strain field, oxygen vacancies and extra charge
- Reduced charge-carrier (hole) density
- Suppressed superconductivity at GB distorts vortex structure and enables easy flux penetration



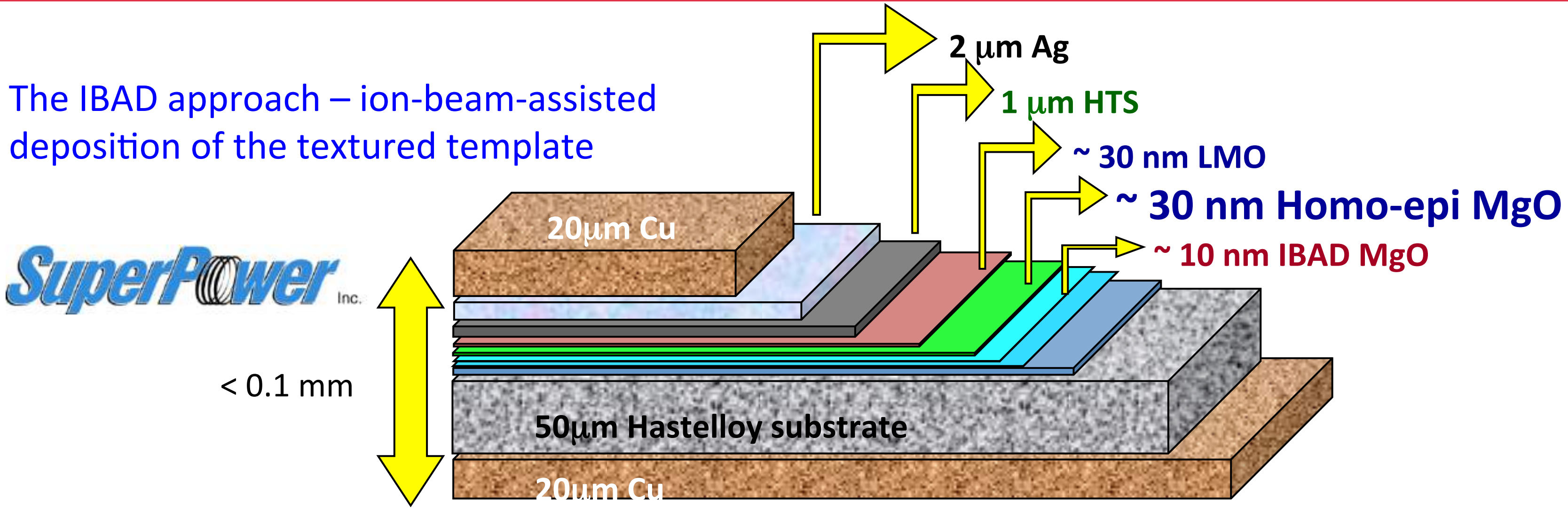
A Gurevich and E.A. Pashitskii, PRB 57, 13875 (1998)



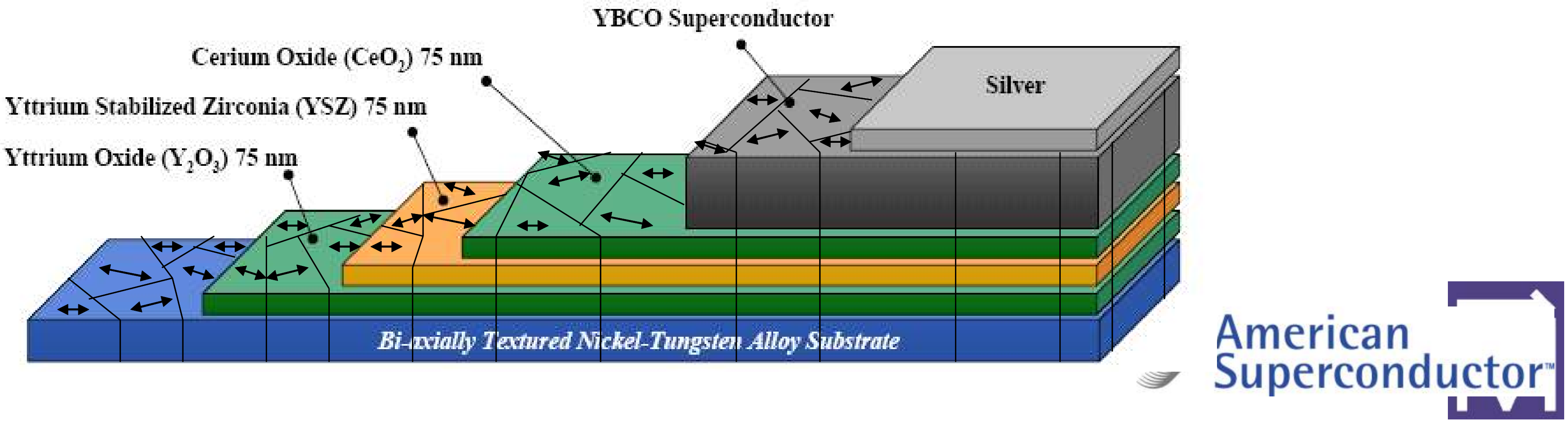
N. Heinig, et al., *PRB, 1999.* ***60(2): p. 1409.***

GB obstruction forced development of coated conductors of YBCO: "single crystals by the mile" (Below the 1990-2010 drivers)

The IBAD approach – ion-beam-assisted deposition of the textured template

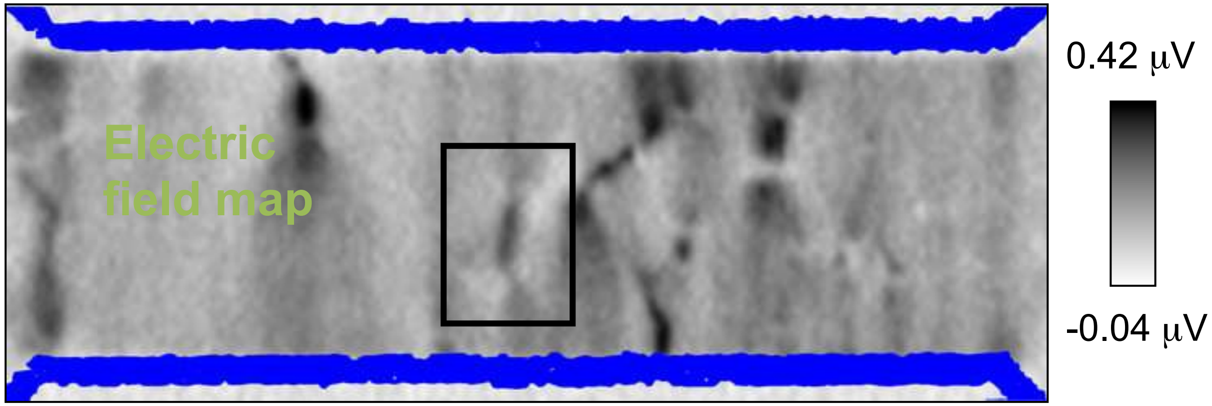


Production in 500-1000 m lengths, delivery rather shorter

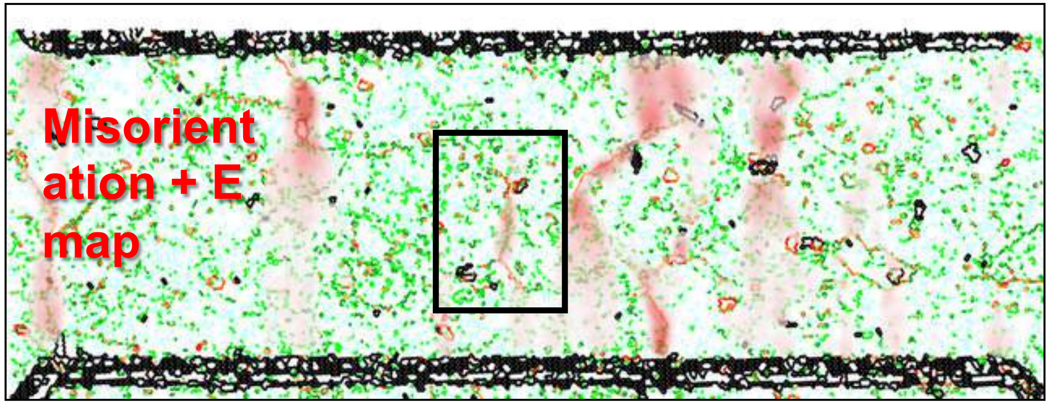


8-10º GBs force current to flow through lower angle GBs

0.8 T,
77K

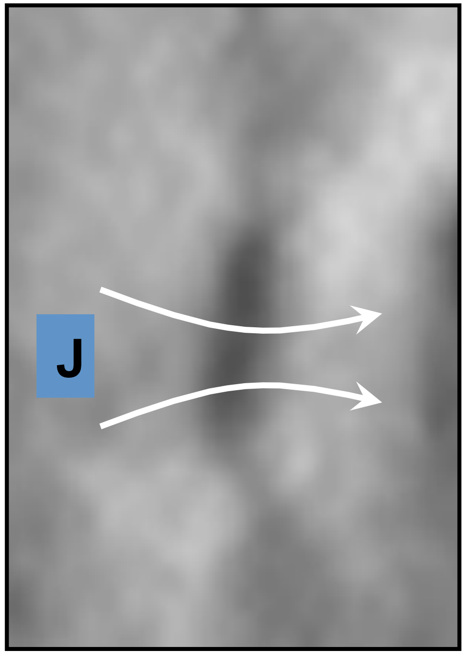


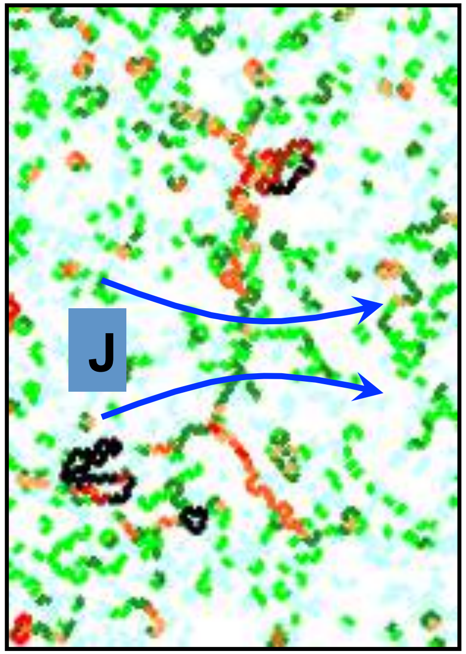
OIM,
E field
map



50 μV

	Min	Max
	2°	3°
	3°	4°
	4°	5°
	5°	6°
	6°	8°
	8°	10°
	10°	12°
	12°	180°





GB dissipation visualized by LT laser imaging

Abraimov

Electric utility application of HTS had great support 1990-2010

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

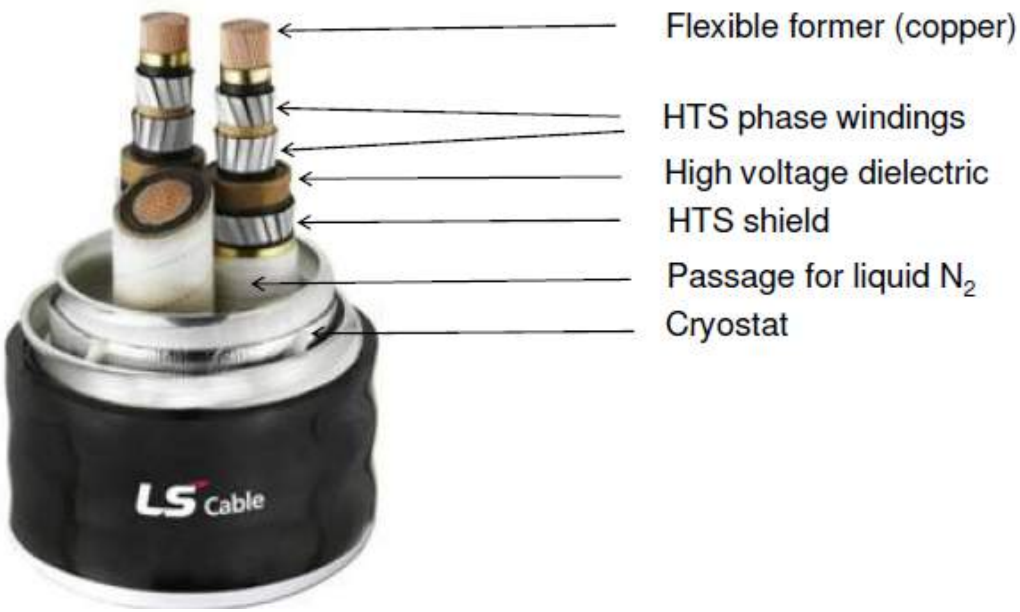
Fig. 1.1. Superconductivity in the electric power system of the future, with widespread use of superconducting generators and motors, fault-current limiters, underground transmission cables, and superconducting magnetic energy storage (Blaugher 1995).

Programs in US, EU, J and later Korea and China developed conductors and all components of the electric system in parallel

One technically successful example of a high power cable

Cu, HTS 1000 A equivalents

- Cables now work at all voltages up to 138 kV and >500 MVA



American Superconductor   LIPA   Nexans   AIR LIQUIDE

2010 DOE message:
Low cost HTS conductor was the promise not fulfilled

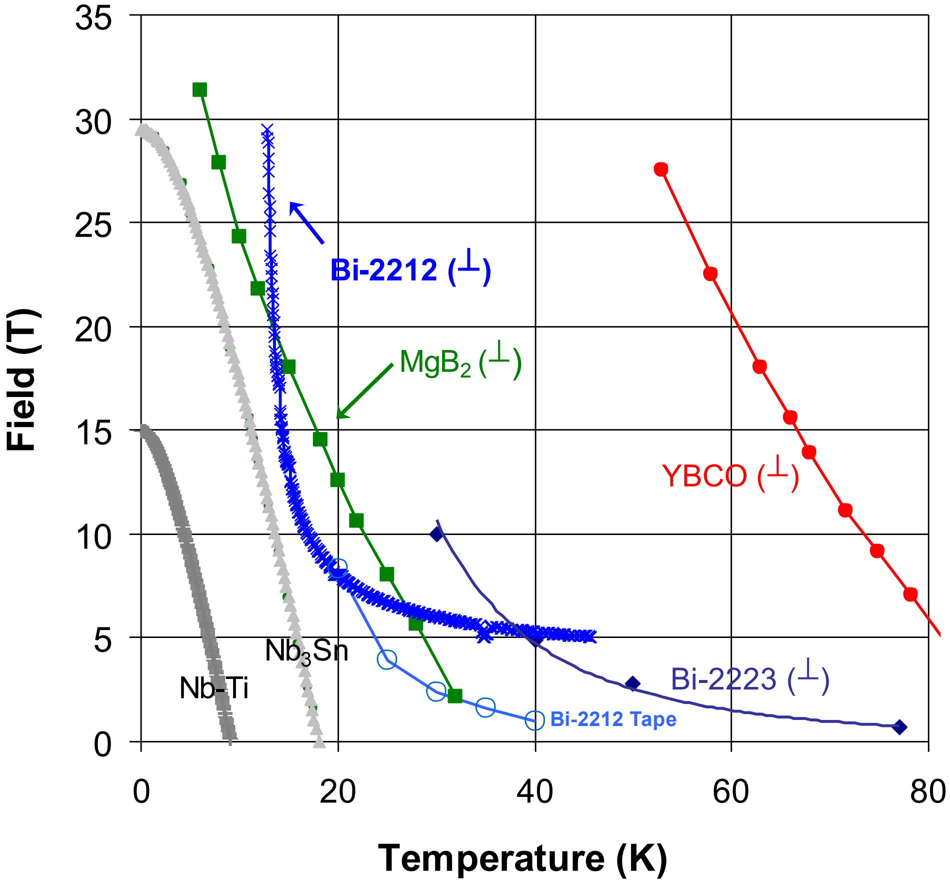
Funding Profile by Subprogram

	FY 2009 Current Appropriation	FY 2009 Current Recovery Act Appropriation	FY 2010 Current Appropriation	FY 2011 Request
Research and Development				
Clean Energy Transmission and Reliability	0	0	38,450	35,000
Smart Grid Research and Development	0	0	32,450	39,293
Energy Storage	0	0	14,000	40,000
Cyber Security for Energy Delivery Systems	0	0	40,000	30,000
High Temperature Superconductivity	23,130	0	0	0
Visualization and Controls	24,461	0	0	0
Energy Storage and Power Electronics	6,368	0	0	0
Renewable and Distributed Systems Integration	29,160	0	0	0
Total, Research and Development	83,119	0	124,900	144,293

Comments: By FY 2011, OE plans to have achieved a critical milestone in the HTS wire complex architecture and multi-step manufacturing process. At that point, the HTS wire research will have reached a termination point that provides meaningful technical value. This, in turn, will enable the orderly closeout of OE-sponsored HTS work with laboratory and industry partners. OE also will partner with the Office of Science in pursuit of room temperature superconductors and transition any remaining superconductivity work at the National Laboratories.

In 2010, DOE zeroed out the program, saying that utilities would not buy HTS devices and thus DOE $ would be better spent searching for a room temperature superconductor

How about HTS magnets as Onnes' "killer app"?



Magnets can make fields up to ~2/3 of the transition line

NHMFL 100 mm bore Nb_3Sn 900 MHz NMR/MRI magnet: persistent at 21T (best is now 23 T/1 GHz)

In short, HTS conductors should enable 2 or even 3x LTS magnets

MagLab Hunting License

- MagLab has worked in framework of 2003 and 2013 National Academy reports on High Magnetic Field Science and Technology done under NSF sponsorship
- Our 32 T program framed the MagSci challenges
- Great progress has been made
  - First on the conductor technology
  - Recently on the magnet technology
- Principal effort has been to get a >30 T user magnet built (2009-2017)
- Smaller R&D effort on HTS NMR followed the strong MagSci urgings, starting in 2013

New mechanisms should be devised for funding and siting high-field NMR systems in the United States. To satisfy the likely demand for measurement time in a 1.2 GHz system, at least three such systems should be installed over a 2-year period. These instruments should be located at geographically separated sites, determined through careful consultation with the scientific community based on the estimated costs and the anticipated total and regional demand for such instruments, among other factors, and managed in a manner that maximizes their utility for the broad community. **Moreover, planning for the next-generation instruments, likely a 1.5 or 1.6 GHz class system, should be under**. **way now** to allow for steady progress in instrument development

Key messages:

1. NSF supported a small MagLab HTS program from its beginning – COHMAG allowed it to focus on user magnets – the program got serious after the Applied Superconductivity Center (ASC) moved to the MagLab (2006)
2. DOE (EERE, the HEP and now EERE-AMO again) has supported HTS conductor technology

Multiple MagSci Goals (about $500M in 2013)

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

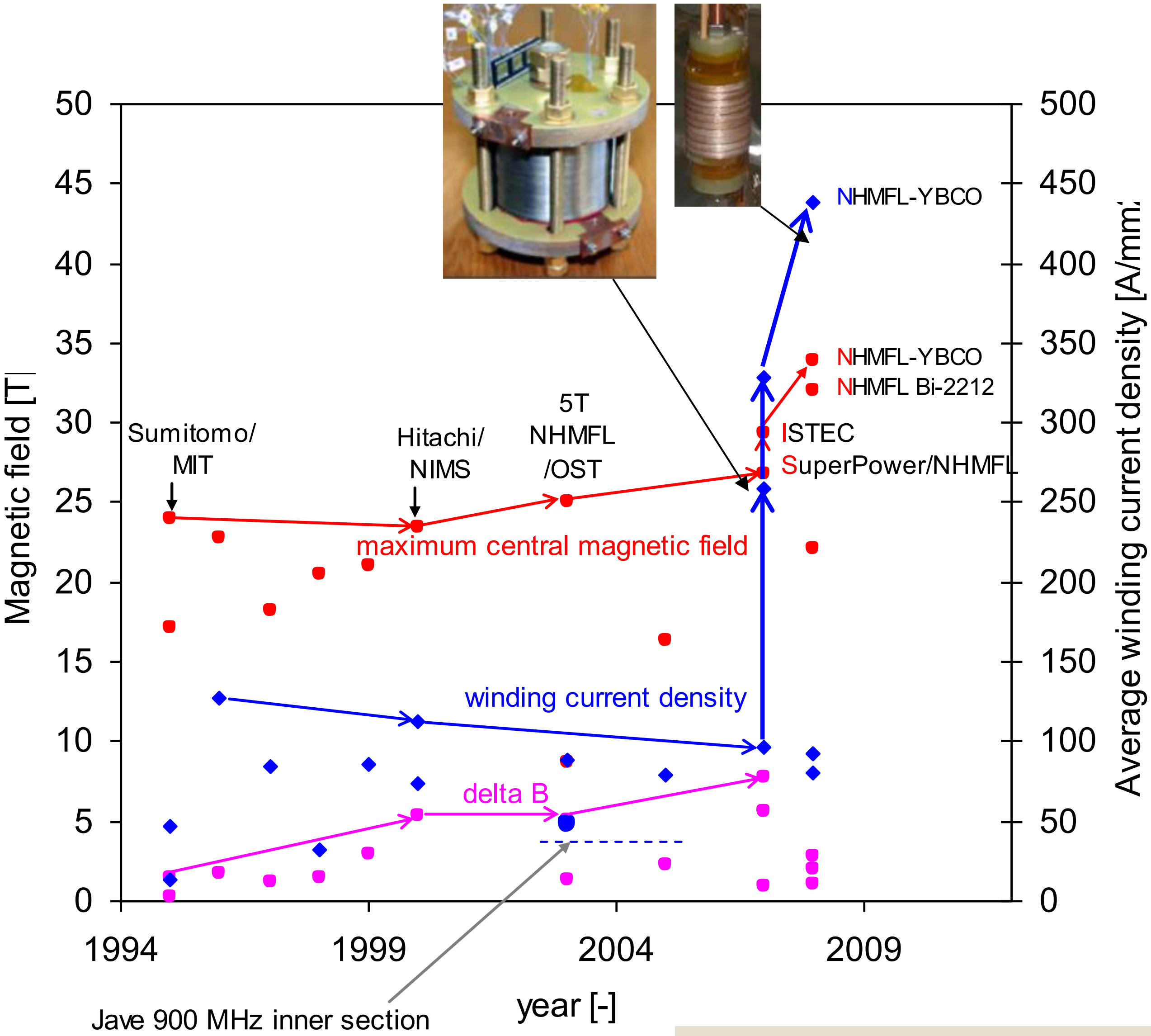
Very strong synergy with HEP goals (future 100 TeV circular hadron collider) and fusion goals (Tokamaks beyond ITER e.g. DEMO or small compact machines) 2016 NSF and DOE workshops have shown a large user base for 25-30 T neutron and photon beamlines

The present MagLab program

- The 32 T User Magnet – a "conservative design"
- R&D magnets
  - Towards 30 T NMR with Bi-2212 and Bi-2223
  - Towards 35-40 T with high J_E NI REBCO
    - Compact 20 T user magnet
    - World record DC field coils (LBC – little big coil inside 31 T resistive magnet at MagLab)
- Proposals to get the $5-20M needed to fulfill such magnet projects
- Lots of R&D on the conductors, still far from perfect

No magnet is ever better than its conductor!

REBCO changed the HTS game in 2007

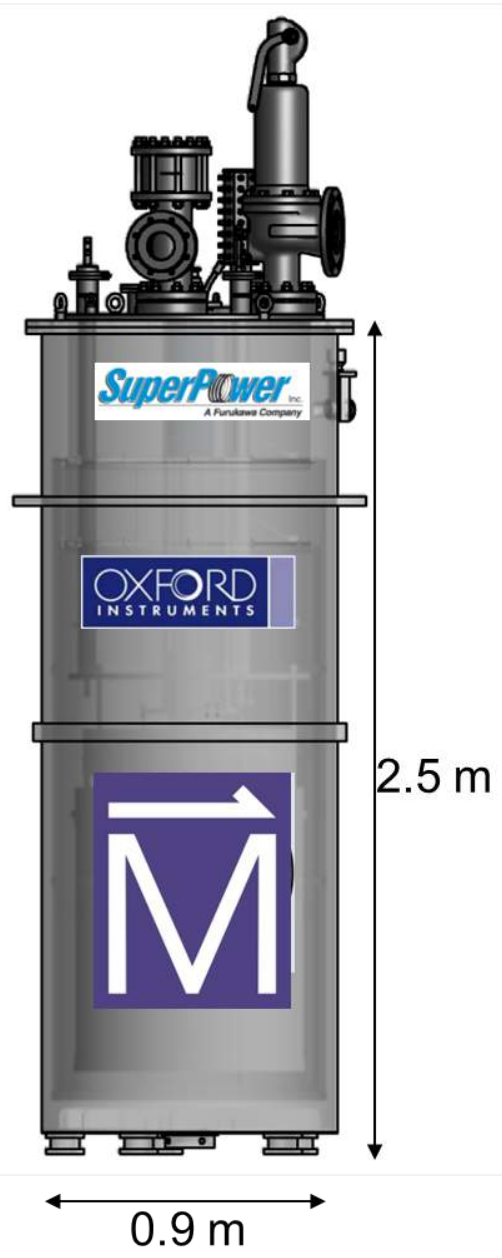


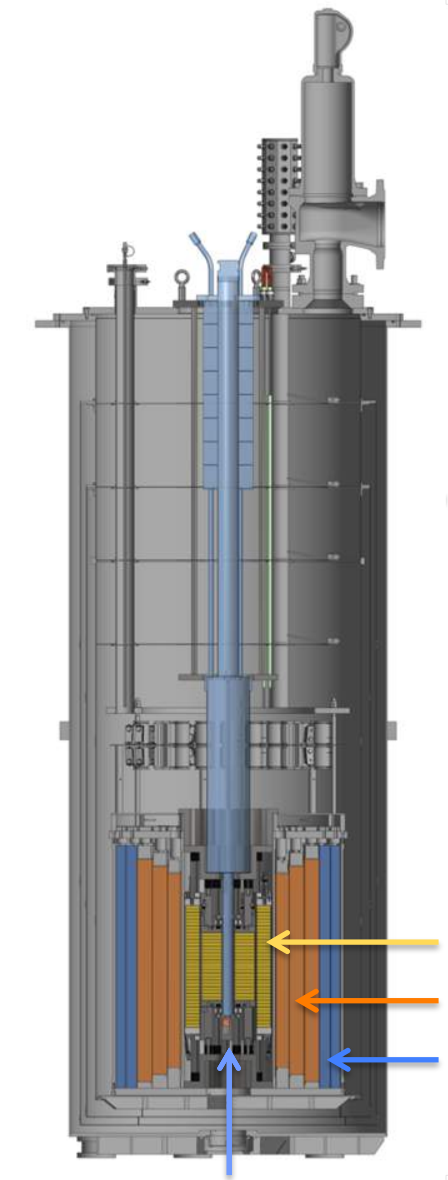
- BSCCO coils (1995-2005
  - Coil size and delta *B* ↗
  - B_{peak} ~ same
  - σ_{peak} ≤ 125 MPa
  - J_{ave} ↘ <100 A/mm2
- 2007 on: REBCO
  - Coil size ↓, delta B ↑
  - B_{peak} ↑↑ 34 T
  - J_{ave} ↑↑ >>200 A/mm^2
  - σ_{peak} > 200 MPa

30 T HTS-LTS magnet then was feasible but conductor was immature

The 27 T, 2007 REBCO SuperPower coil showed huge promise and enabled our 32 T proposal to NSF (2009)

The 32 T user magnet





Key parameters:

Center field	32 T
Clear bore	34 mm
Ramp time	1 hour
Uniformity 1 cm DSV	5×10^{-4}
Operating temperature	4.2 K
Stored energy	8.3 MJ
Expected cycles/20 years	50,000
System weight	2.6 ton

15 T / 250 mm bore LTS magnet
17 T / 34 mm bore REBCO coils
Separately powered, simultaneously ramped

REBCO: 2 double pancake coils
Nb_3Sn coils
NbTi coils

32 T user magnet stores ~8 MJ, ramp rate ~ 1hour

32 T status

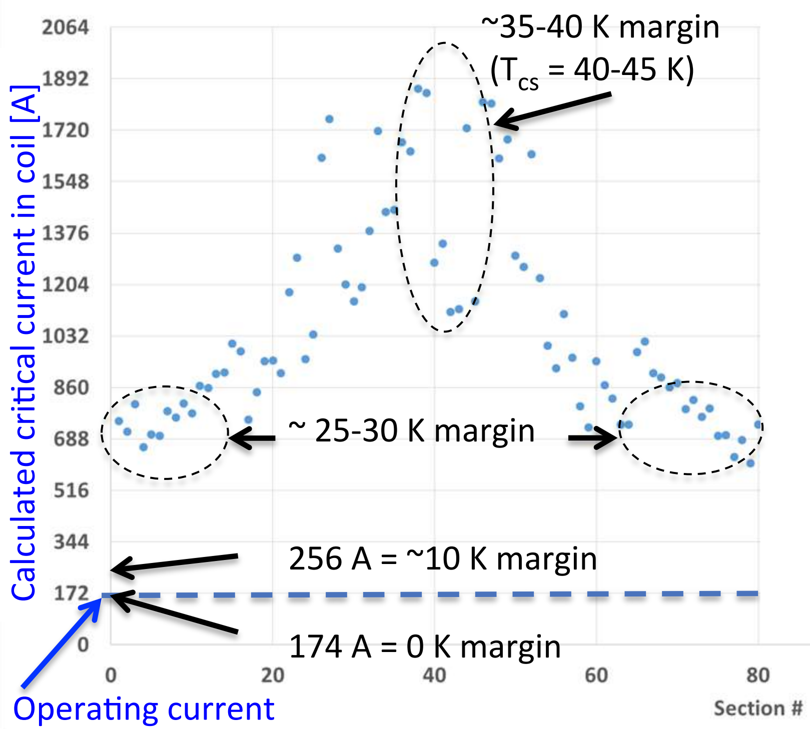
The magnet is still in its commissioning phase: Key Issues

- Quench protection requires quench detection
  - detection in the HTS coils is challenging
- Important complications come from:
  - Using an insulated single strand conductor
  - The large anisotropy of the conductor
  - A high Tc means large energies are needed to drive to the normal state

Detailed report by HW Weijers at EUCAS September 2017

Critical current margin versus quench protection

- Temperature margin goes up during quench as field and current decay
  - Once current decay starts, it becomes harder to drive rest of HTS to normal state
  - Desirable to have large fraction of coil volume with ~ same temperature margin



Coil 1

Temperature margins are much larger in low field conditions

Much more energy must be fired into the quench heaters to protect

- Operating at 70% of I_c would give > 10 K initial temperature margin
- 32 T operates at 33-10% of I_c

Each double pancake has a stainless steel heater triggered by a quench signal from either the LTS outsert or the HTS magnet
130 kJ triggers HTS quench
300 J triggers LTS quench

120 kJ to (partially) quench the HTS magnet, about 250 J to quench the LTS magnet

REBCO beyond 32 T: No Insulation beckons

- 32 T was a significant engineering project
  - Designed “conservatively” so that it would last for 20 years (actual performance limits are only slowly becoming known)
- No Insulation (NI) experiments of Hahn and Iwasa drew our attention for their much higher winding current densities, “solution” to quench problem and smaller, more affordable designs for 30-50 T magnets

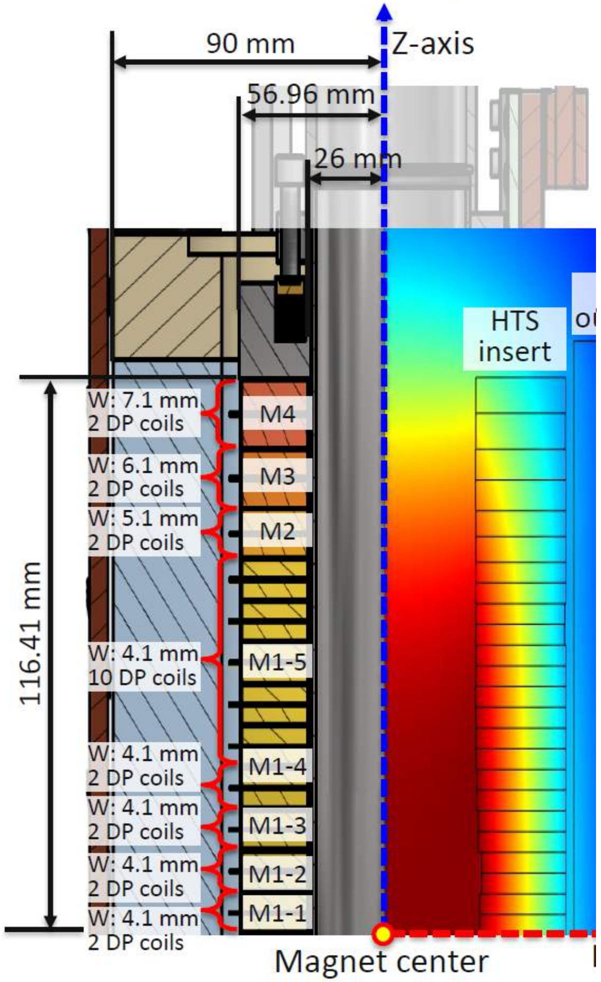
Upgrading an old Oxford 14 T/52 mm bore to 20 T

Key Parameters for 13 T NI Insert Magnet

- Key Parameters

Parameters		Values
REBCO Tape		
Tape width	[mm]	4.1 to 7.1 (Multi width)
Tape thickness	[mm]	0.12 (0.126 ~ 0.117)
REBCO Insert		
Winding inner radius, a_1	[mm]	29.00 to 30.92 (Inner notch)
Winding outer radius, a_2	[mm]	56.96 (OD: 113.92 mm)
Overall height	[mm]	232.81
Number of DP coils		24
Turn per "single" pancake coil		217 to 233
Total REBCO tape	[km]	3.4 (4.1 mm equivalent)
Inductance, L	[H]	2.82
20 T Operation		
Center field	[T]	20.0 (13 T HTS + 7 T LTS)
Operating current I_{op}	[A]	213 (13 T HTS), 80.5 (7 T LTS)
Total inductance of magnet	[H]	36.87 (2.82 (HTS) + 23.37 (LTS) + (2*5.34 (Mutual)))
B1; B2 at 20 T		20.1; 6.4
Magnet constant of 13 T (HTS)	[mT/A]	61.03
Magnet constant of 7 T (LTS)	[mT/A]	86.96
Characteristic resistance, R_c (R_{ct} = 10 μΩ·cm²)	[mΩ]	9.15
Charging time constant (τ)	[sec]	308.20 (=2.82/0.00915)
Storage energy of insert/outsert/total system	[kJ]	64.0/75.7/231

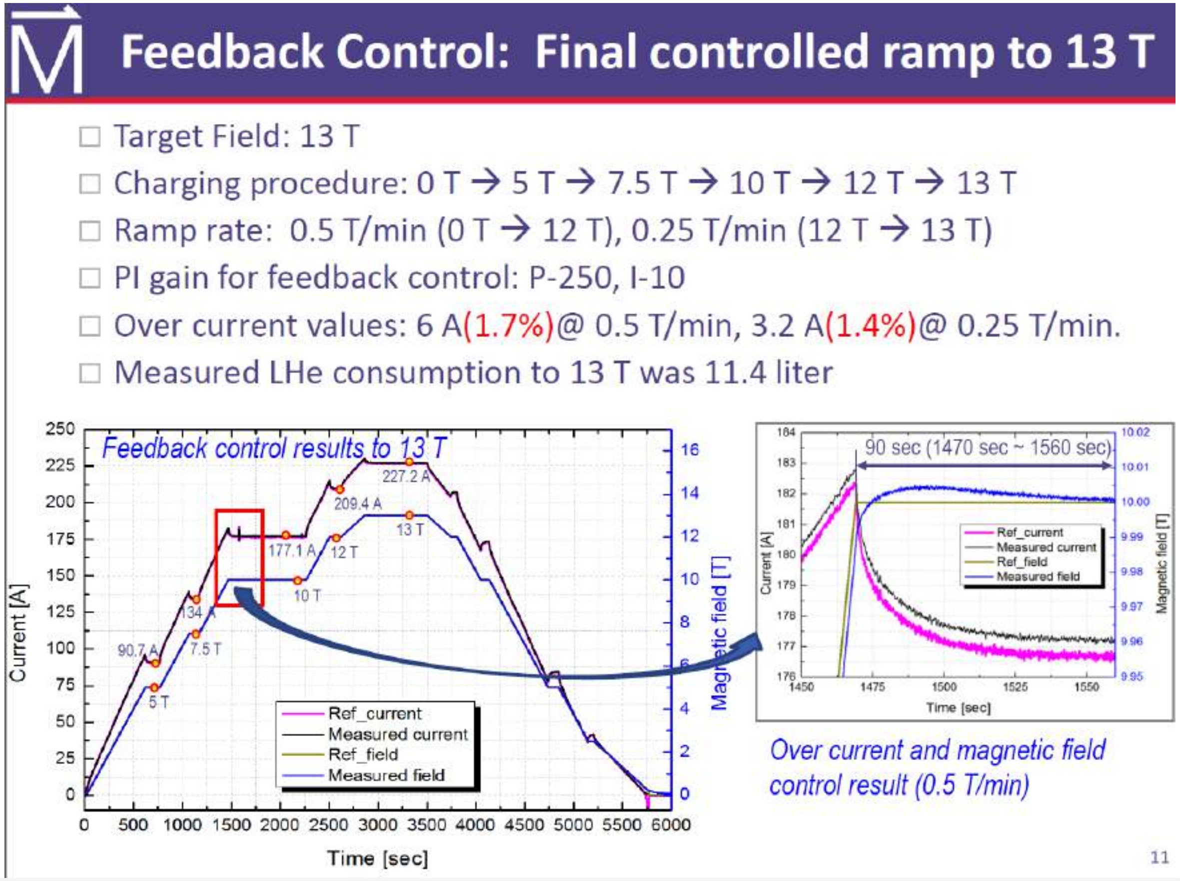
- ½ Structure drawing



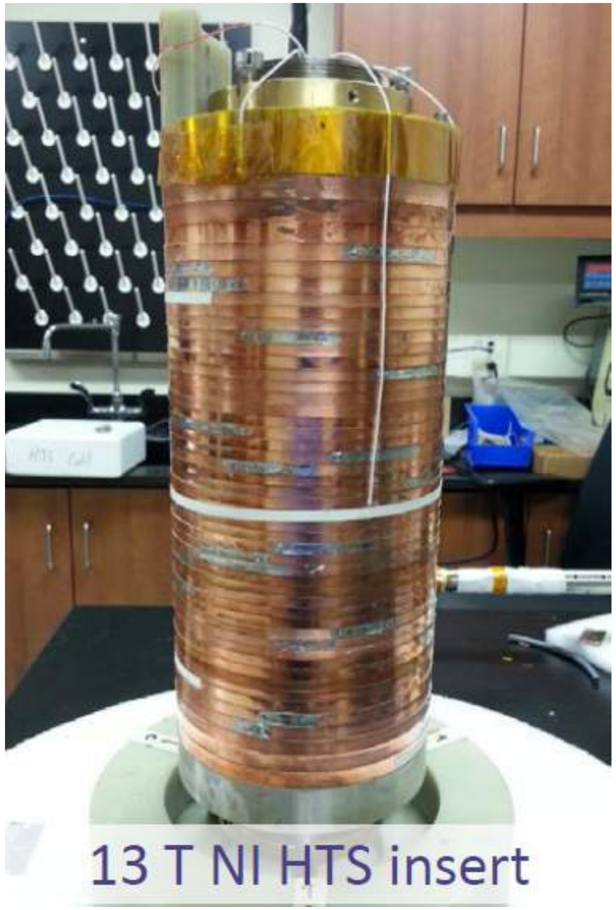
Keep everything except the bad Nb_3Sn inner

Needed about $100K of REBCO coated conductor

Peak field so far: 19 T, limited by LTS magnet



Design by Seungyong Hahn, Conductor by SuNAM



Kwanglok Kim and Kwangmin Kim

- Have demonstrated feedback control to get linear ramp
- NI magnet is very stable, (old) LTS magnet is not
- Concerns about protection of NI magnet against LTS quench without active quench protection
- Retest with more stable Nb-Ti magnet imminent

REBCO beyond 32 T: No Insulation offers huge $J_{winding}$

"Little Big Coil 3 (LBC3)"

- ID: 14 mm; OD: 34 mm; H: 51 mm
- SuperPower 30 um tape
- Tested in a 31 T resistive magnet

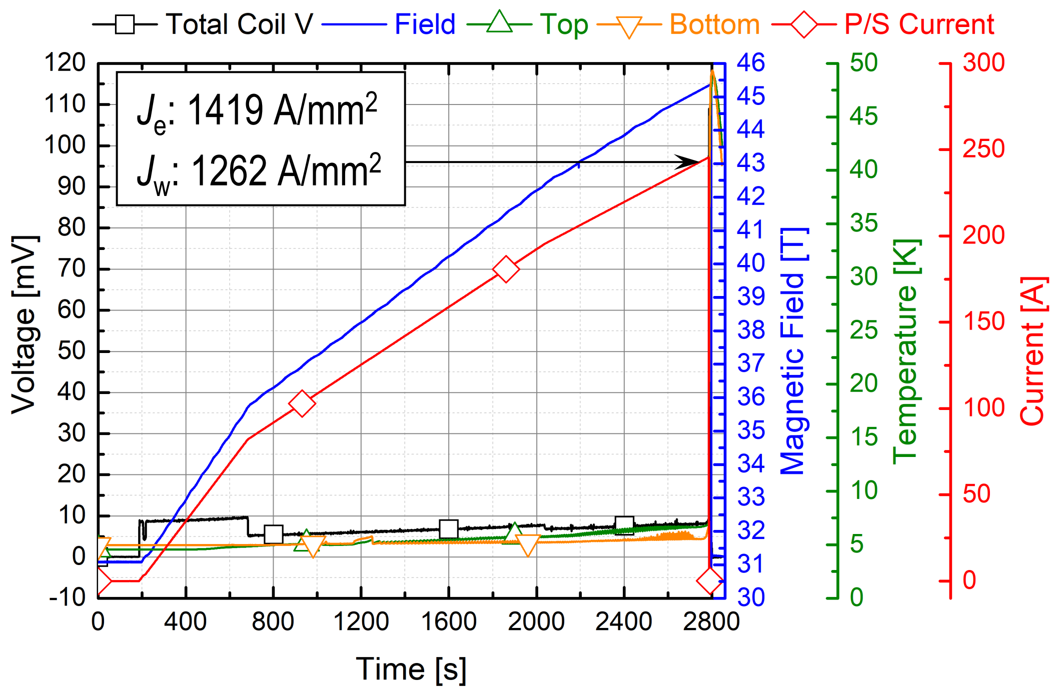
SPC Number	Number of turn	Coil O.D. (mm)
1	229	34.00
2	229	33.95
3	234	34.00
4	229	33.85
5	220	33.83
6	222	33.95
7	222	33.96
8	226	33.75
9	220	33.74
10	229	33.82
11	229	33.84
12	228	34.01

Parameters		Values
REBCO Tape		
Width; thickness	[mm]	4.03; 0.045
Thickness of substrate; copper	[mm]	0.03; 0.01 (5 μm per side)
E_r; E_θ; E_z	[GPa]	69; 144; 144
95-% I_c retention stress	[MPa]	720 (0.5 % strain)
Little Big Coil		
Winding ID; OD; height	[mm]	14; 34; 51
Number of pancakes		12
Turn per single pancake		226.4 (average)
Total turns of LBC		2717
REBCO tape per pancake	[m]	16.7
Total REBCO length	[m]	200.4
Self Inductance of DP	[mH]	3.66 (DP3) – 4.01 (DP2)
Total inductance	[mH]	50.6
Magnet constant	[mT/A]	60.2 (calculated, actual)
Tape current density (J_t) at 100 A	[A/mm^2]	551
Coil current density (J_e) at 100 A	[A/mm^2]	533
$L_s+\sum L_M$ for DP1 (Top) - DP6(Bottom)	[mH]	7.22; 9.13; 9.14; 9.24; 8.74; 7.14
R_c (R_{ct}=50.0 $\mu\Omega$·cm^2 from 0 T LHe test)	[mΩ]	47.1
τ_c ($=L/R_c$)	[s]	1.07
31 T Background Magnet (Cell 7)		
Overall winding ID; OD; height	[mm]	38; 600;400
Magnet constant	[mT/A]	0.8432
B_c at I_{op} of 37.0 kA	[T]	31.197
Self inductance	[mH]	4.30
Mutual inductance with LBC	[mH]	1.07
Operation		
I_c of DP1 (T) - DP6 (B) at 45.5 T	[A]	576; 505; 526; 513; 502; 577
ϵ_{bend} at $r=a_1$; a_2	[%]	0.21; 0.090
$\epsilon_{mag}(r=a_2)$ at 40 T; 45 T; 48 T	[%]	0.23, 0.40, 0.50
V_{DP}; V_{LBC} at 10 A/min	[mV]	1.2 - 1.5; 8.4
I_{leak} at 10 A/min	[A]	0.2
Overall Joule heating at 10 A/min	[mW]	<10

- Uses 50 mm bore 31T resistive magnet as background
- 12 pancakes with special SuperPower 30 um Hastelloy substrate and 10 um of Cu
- Challenge of He bubble and damage by (random) 31 T magnet trips

LBC3 achieved 14.5 T inside 31 T: 45.5T

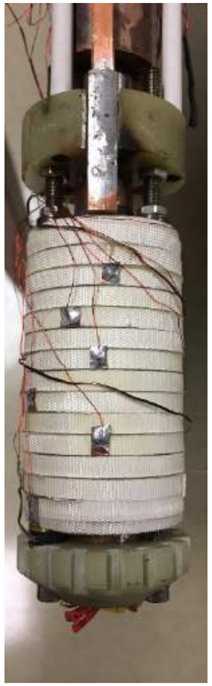
- Coil suffered one trip of 31 T magnet without current
- Then driven to quench at 45.5T
- Some damage noticed
- Magnet was unwound and conductor run through our continuous Ic(77K) measurement device (YateStar)

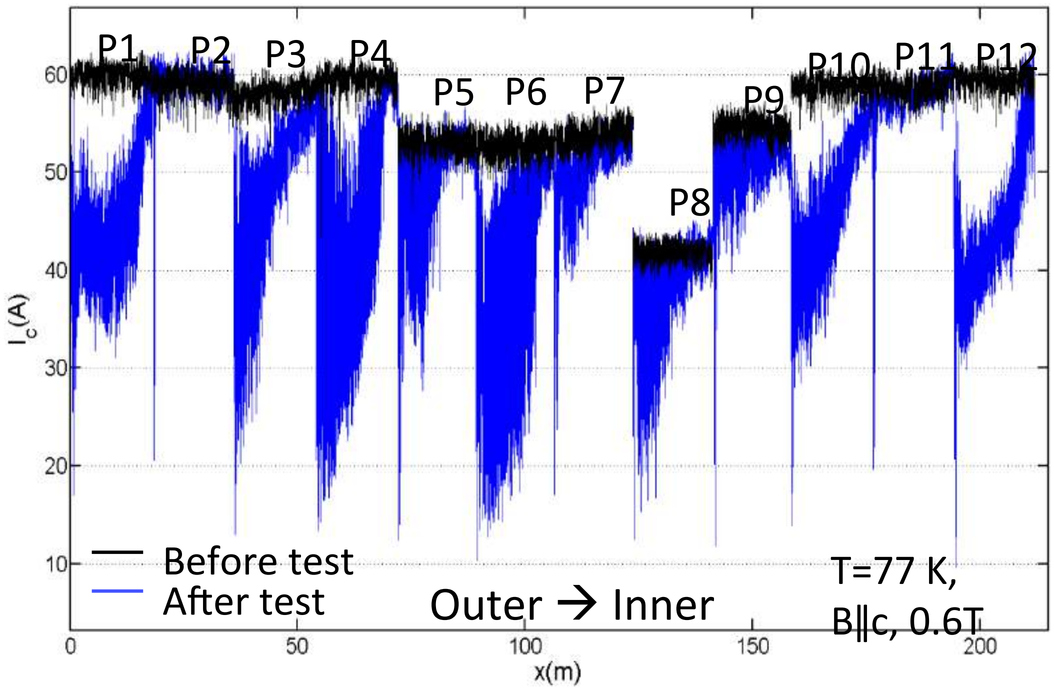


Kwanglok Kim and Kwangmin Kim

See talk by Seungyong Hahn later today

Pre- and post mortem testing of LBC3 in YateStar (at 77K)





Paul Hu PhD

- No visible external damage after test (at left)
- Blue traces show Ic(x) after test, black before
- Most pancakes are damaged but P2 and P11 are (almost) not

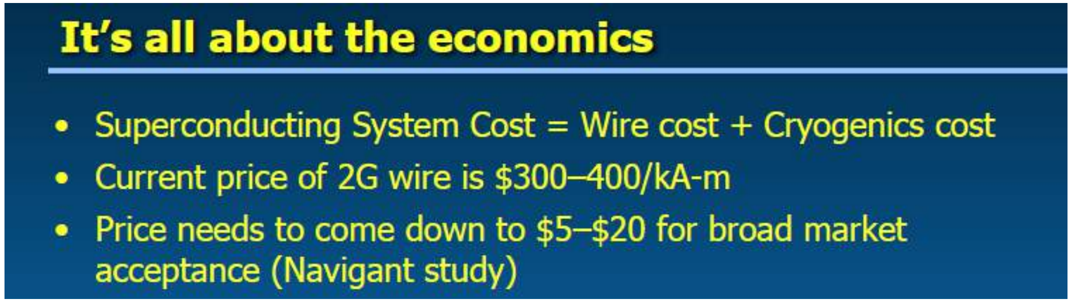
Seems that damage occurred under large forces, especially on slit edges, rather than at quench – is 47 T possible for the next LBC?

Lessons learned from our REBCO coils

- Quenches must – and can - be managed
- NI magnets make quench safer but NI magnets are vulnerable to external energy inputs
  - Nested coils need more work
- The large anisotropy of REBCO (~5) makes quench management more challenging
- Stresses within coils and forces between nested coils need careful analysis
- The conductor manufacture process interacts with the coil performance at the ultra high fields we want
- HTS conductor and their test coils are expensive

The clever materials engineering approach to the cheap conductor of "green energy"

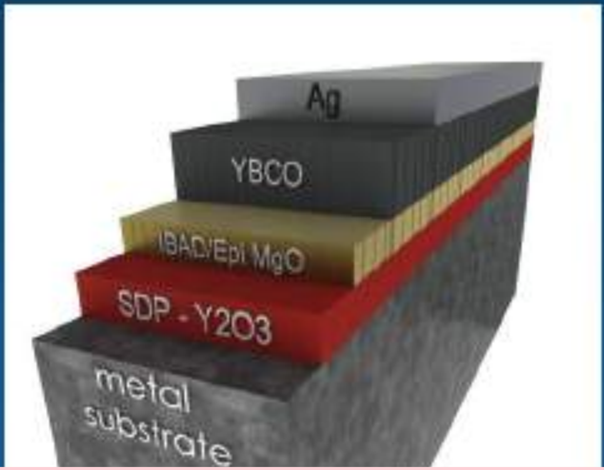
- Uses REBCO, the only HTS conductor capable of operating in liquid nitrogen in fields of several tesla
- Must be made from cheap materials rapidly



Key aspects were worked out at Stanford in 1990s by Bob Hammond and Judith Driscoll (Now Cambridge) and are implemented in the SuNAM (Korea) production of REBCO coated conductor

Cost of embodied materials in a coated conductor

We analyze the following IBAD CC structure (500 A/cm):
Demonstrated at LANL and at STI



- 0.5 μm Ag
- 2 μm YBCO
- 50 nm MgO
- 0.5 μm Y_2O_3
- 50 μm metal tape

Cost of Embodied Materials for 1 kA-m

Layer	Materials cost/kA-m
Ag (0.5 μm)	$ 0.12
YBCO	$ 0.04
IBAD+epi (MgO)	$ 0.0005
SDP layer (Y_2O_3)	$ 0.005
substrate (stainless)	$ 0.08
Total	**$ 0.25**

Key point: raw materials are cheap, clever processing could win out

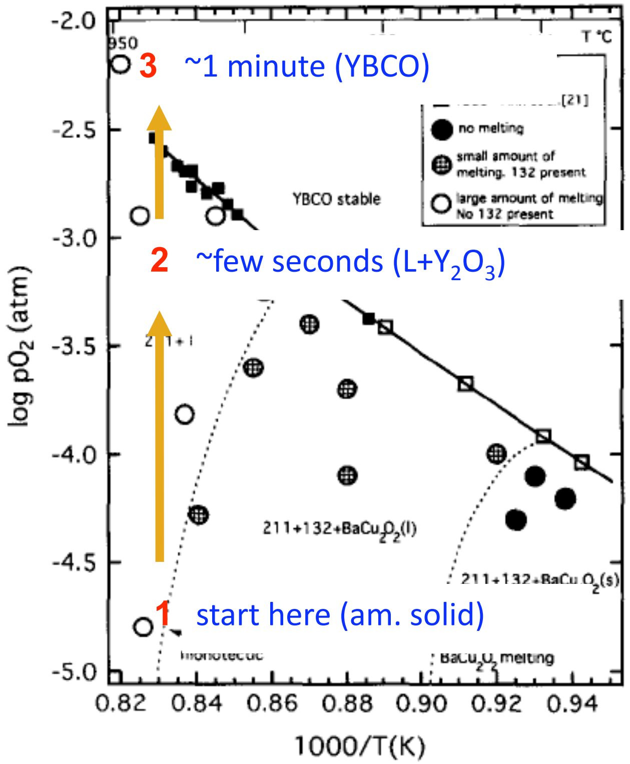
Assume this structure produces **500 A/cm** (2.5 MA/cm^2) in a 2 micron thick YBCO film, LN2 self-field

- If we assume 30% capture efficiency (best case for PVD), ie IBAD, YBCO and Ag, then the raw materials costs are **$0.63/kAm**
- CC cost cannot be lower for this structure and performance

*V. Matias et al *Supercond. Sci. Techn.* **23**, 014018 (2010)

Los Alamos

Liquid growth and pO_2 control in *bulk* for making YBCO faster and at lower temperature



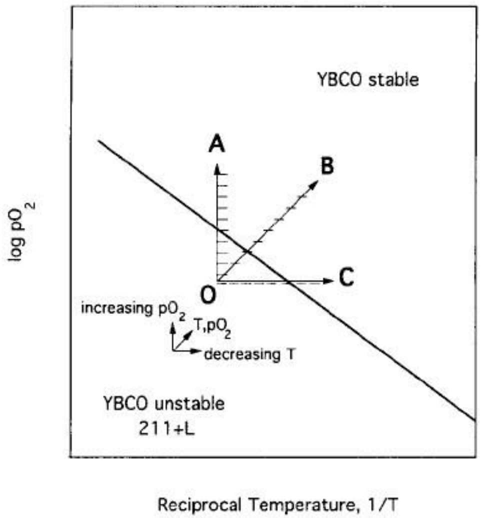


Fig. 2. Possible reduced temperature and pressure melt-processing routes (O to A, B, or C), shown on a schematic stability diagram for YBCO.

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Physica C 241 (1995) 401–413

PHYSICA C

Phase equilibria in the Y–Ba–Cu–O system and melt processing of Ag clad $Y_1Ba_2Cu_3O_{7-x}$ tapes at reduced oxygen partial pressures

J.L. MacManus-Driscoll [a,*], J.C. Bravman [a], R.B. Beyers [b]

niversity, Stanford, CA 94305-2205, USA
in Jose, CA 95120-6099, USA
994

⇓

Partial melting below stability line, at ~930°C for >12 hours

⇓

Increase pO_2, apply temperature gradient and anneal on/just above stability line for >7 days

⇓

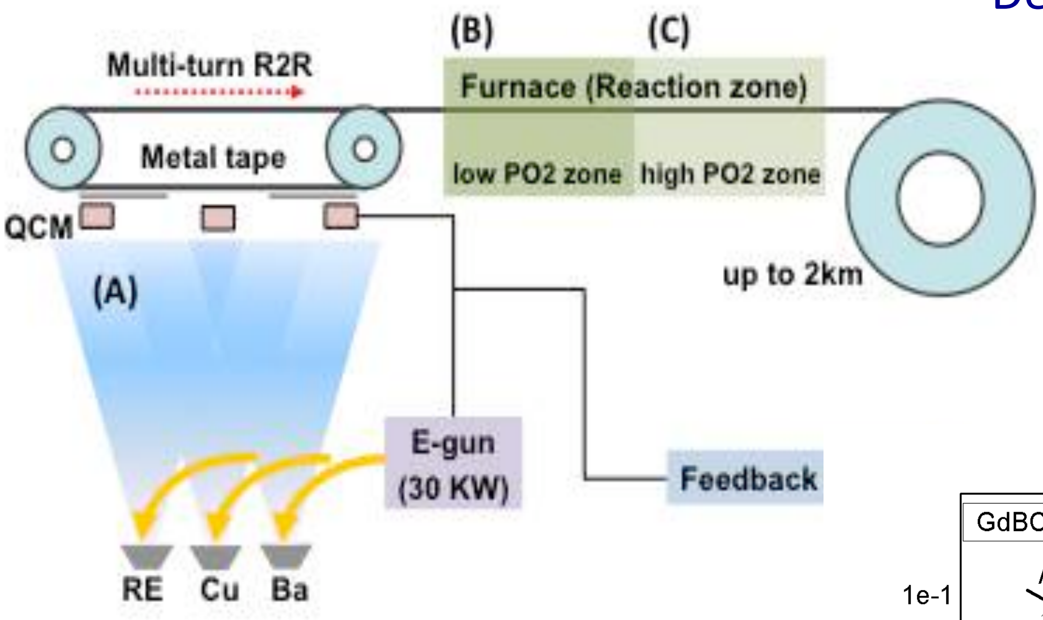
Increase pO_2, and anneal above stability line for >5 days

⇓

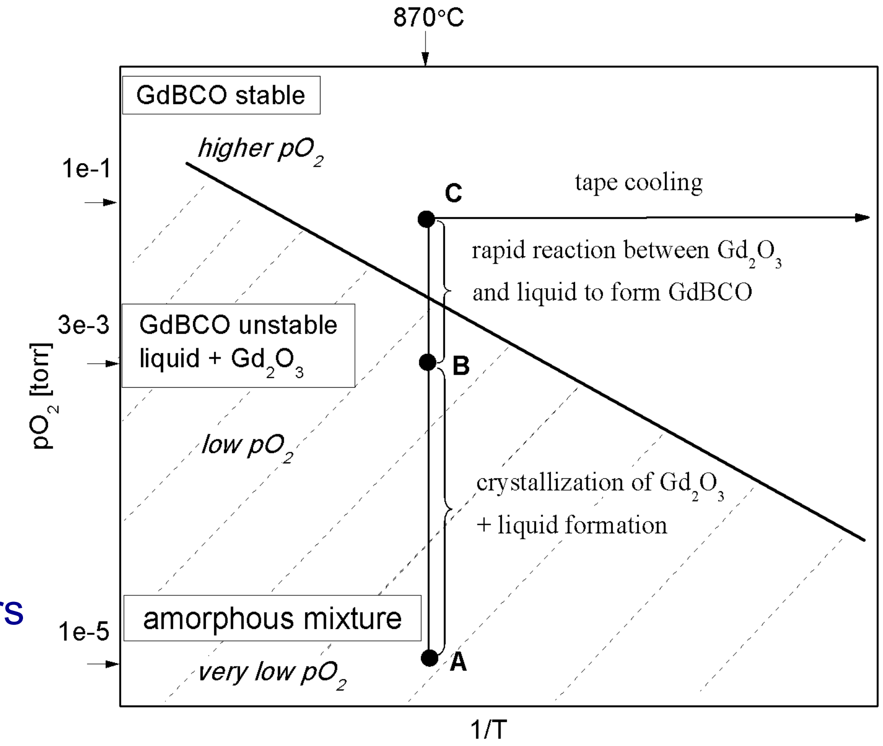
Slow cool, anneal at 500°C in O_2

RCE-DR : Reactive Co-Evaporation by Deposition & Reaction

SuNAM

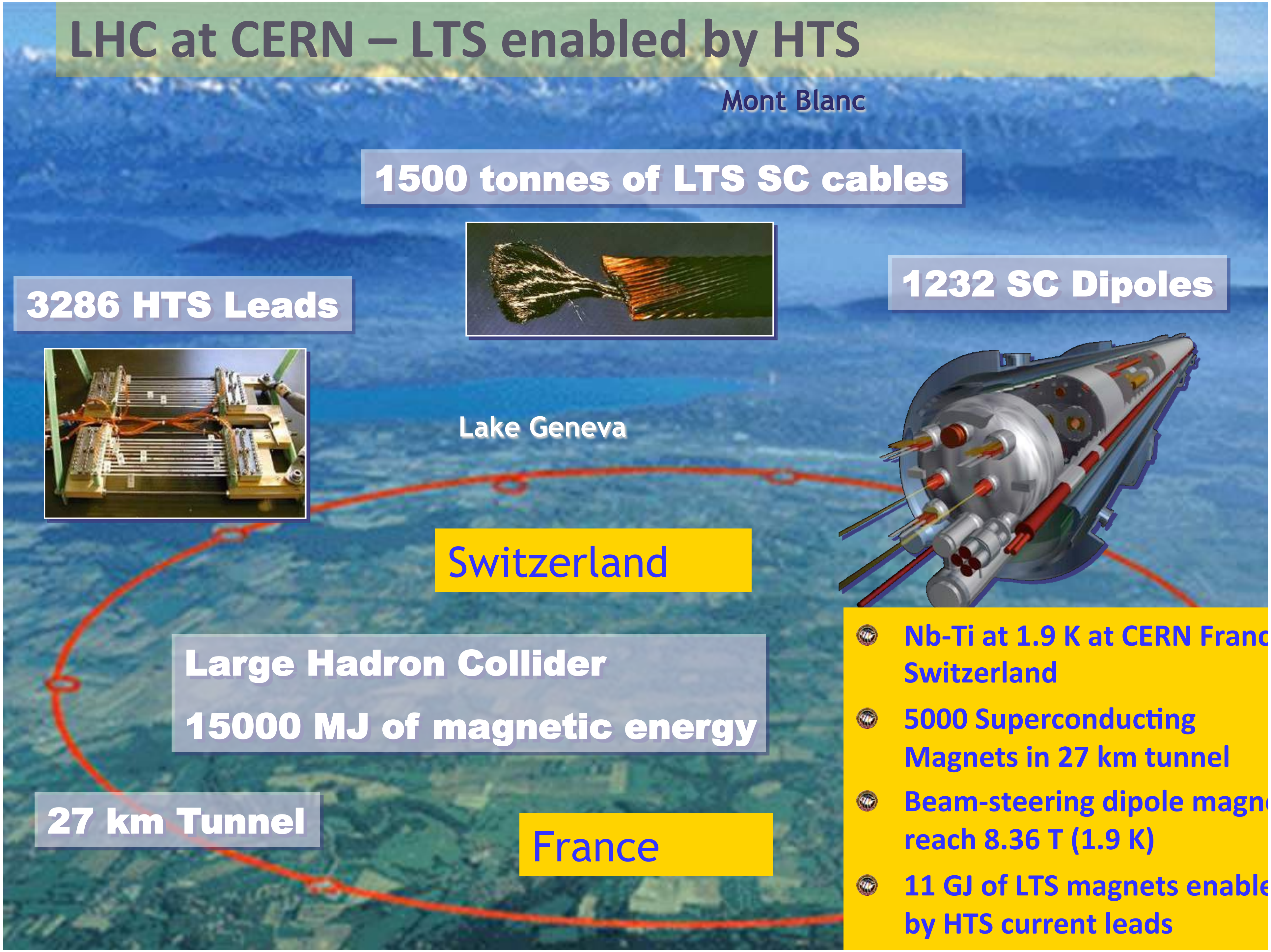


(A) very low PO2 zone: 10^{-5} Torr, amorphous film
(B) lower PO2 zone: 30 mTorr, < 5 sec, Gd2O3 + L
(C) higher PO2 zone: 100 mTorr, <60 Sec, 123 phase



Metal/IBAD MgO/$LaMnO_3$/superconductor
>500 A/cm tapes in 1.0 km lengths in 2 - 5 hours

rate of 0.1μm/min with multi pass deposition
and translation rate of 120 m/hr


LHC at CERN – LTS enabled by HTS
Mont Blanc
1500 tonnes of LTS SC cables
3286 HTS Leads
1232 SC Dipoles
Lake Geneva
Switzerland
Large Hadron Collider
15000 MJ of magnetic energy
27 km Tunnel
France
Nb-Ti at 1.9 K at CERN Franc
Switzerland
5000 Superconducting
Magnets in 27 km tunnel
Beam-steering dipole magn
reach 8.36 T (1.9 K)
11 GJ of LTS magnets enable
by HTS current leads

A REBCO SMES?

- A project driven by ARPA-E at ABB, BNL, SuperPower and TcSUH aimed to use 20-30 T REBCO coils as a high field prototype: $E = B^2/2\mu_0$ [Jm^{-3}]
- Use of a toroidal structure enables full shielding of the field and maximum use of the expensive conductor at its highest J_c when H is parallel to the tape plane and the *ab*-planes of REBCO
- The concepts were tested with 2 nested solenoids that achieved 12.5 T at 27 K

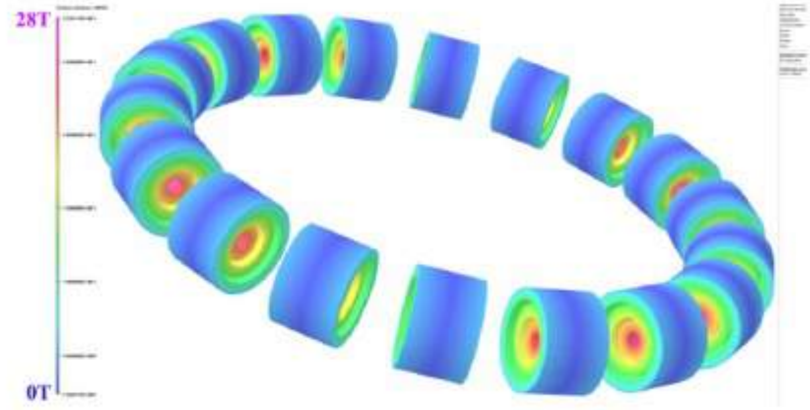


Fig. 2. Toroidal structure containing several modules consisting of HTS pancake coils. Field contours are superimposed over the conductor.

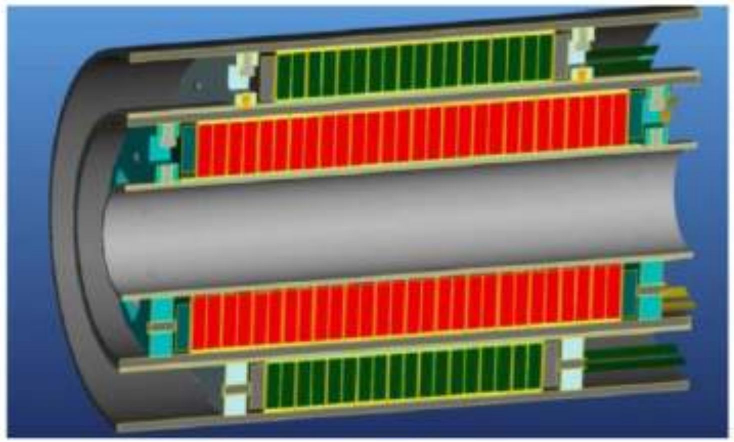


Fig. 4. Basic mechanical model of the SMES structure with inner and outer pancakes, SS support tubes, and end plates.

Gupta *et al.* IEEE Trans. Appl. Supercon. 26 5700208 (2016

Summary thoughts

- Where no price competition exists, HTS is doing fine
  - REBCO now at 45.5 T in insert coils
  - 32 T hybrid LTS (15 T) and HTS (17 T REBCO) is now in final commissioning
  - On a volumetric basis HTS is about 10 times the cost of Nb-Ti (90% of all superconductor) - $80-120K/liter versus ~$5K/liter
  - Bi-2212 and Bi-2223 are competitive at 4 K with REBCO for magnets
- To get into competitive electrotechnology markets where Cu and Fe dominate…………..
  - Clever materials engineering is needed…………

The widespread application of HTS requires clever materials engineering and Cambridge is playing a vital role

Thank You!

David Larbalestier

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- Platypus team led by Ulf Trociewitz with Ernesto Bosque, David Hilton, Youngjae Kim, George Miller and Lamar English and PhD students Peng Chen (now GE) and Daniel Davis and the NMR effort led by Bill Brey
- NI magnet design/construction led by Seungyong Hahn, Tom Painter, Ian Dixon, Kwanglok Kim, Kwangmin Kim and PhD student Kabindra Bhattarai and Kyle Radcliffe
- Conductor design and evaluations led by Dima Abraimov and Jan Jaroszynski
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- The 2223 team led by Scott Marshall
- The BSCCo and OST team led by Tengming Shen (FNAL, now LBL), Arup Ghosh (BNL) and Yibing Huang (OST) and Alex Otto at SMS, with great recent 2212 powder development by Andrew Hunt and the nGimat team
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