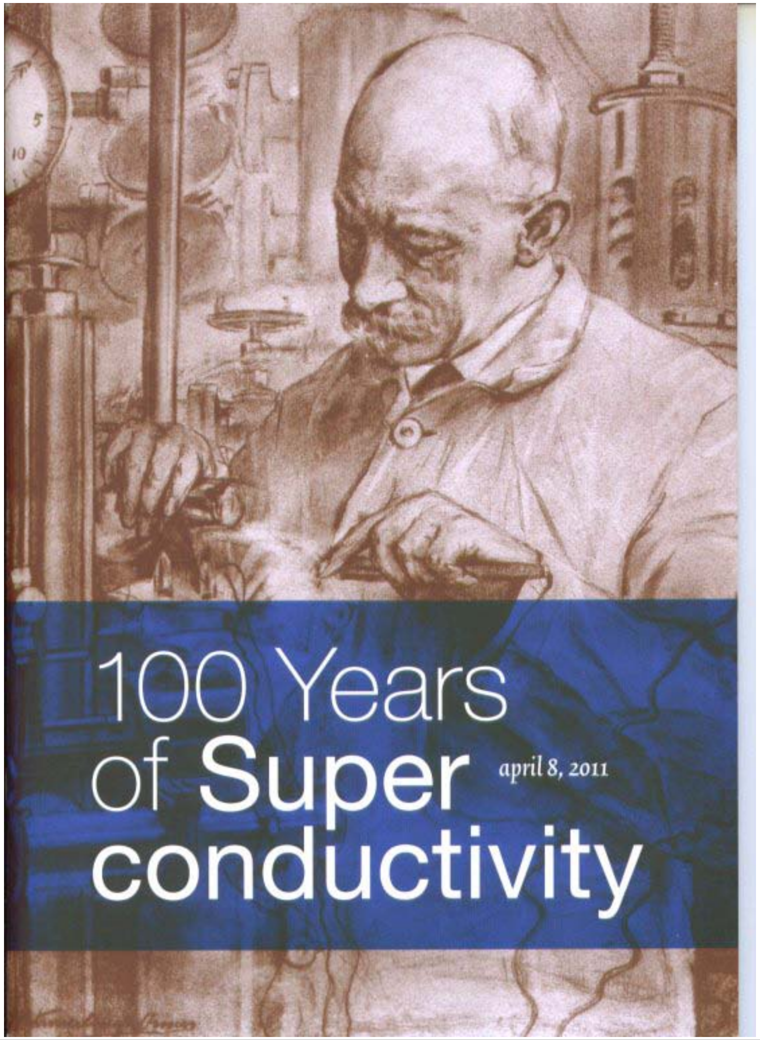
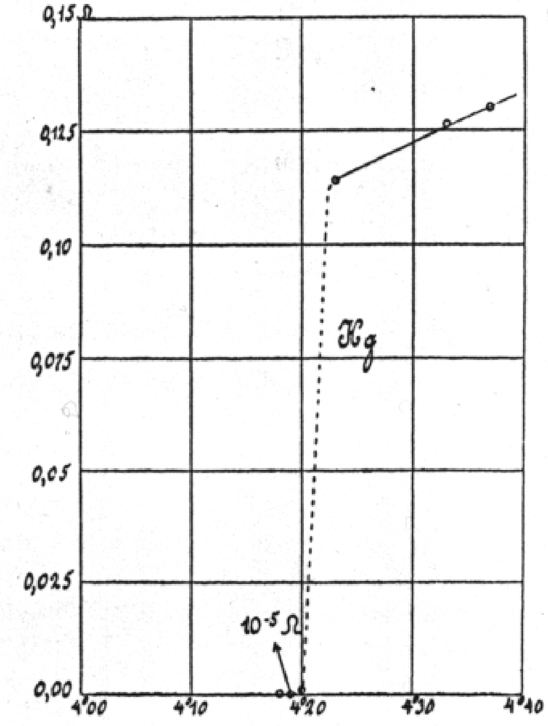
Superconductivity at 100: what about the next century?





David Larbalestier

Applied Superconductivity Center

National High Magnetic Field Laboratory

Florida State University

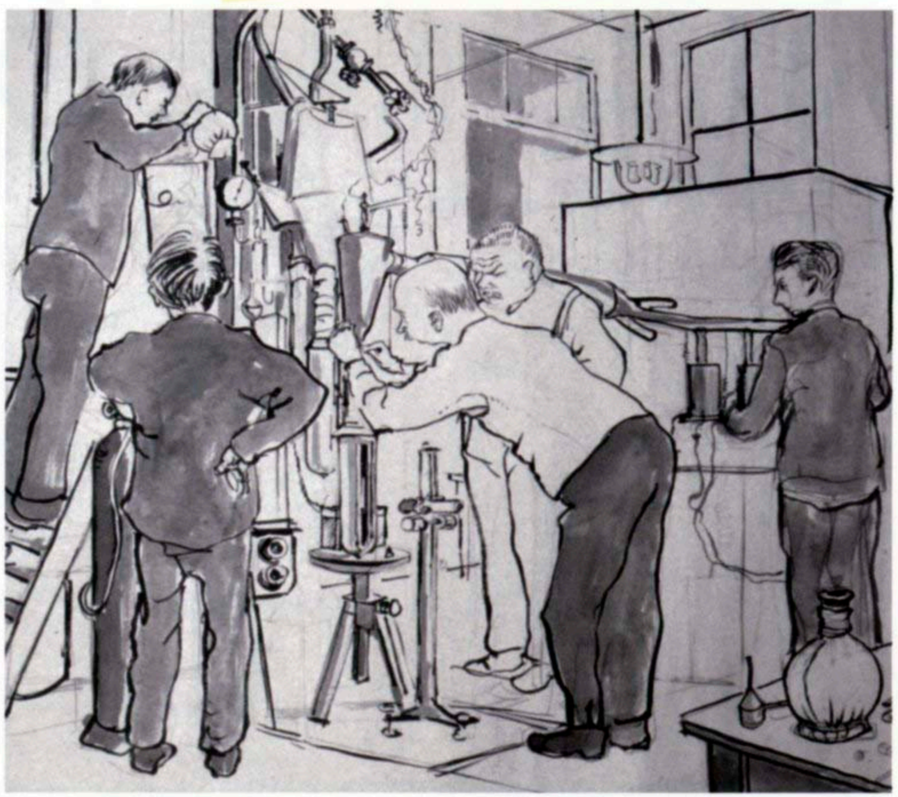
American Physical Society, April Meeting

Centennial of Superconductivity - J2

Anaheim, CA

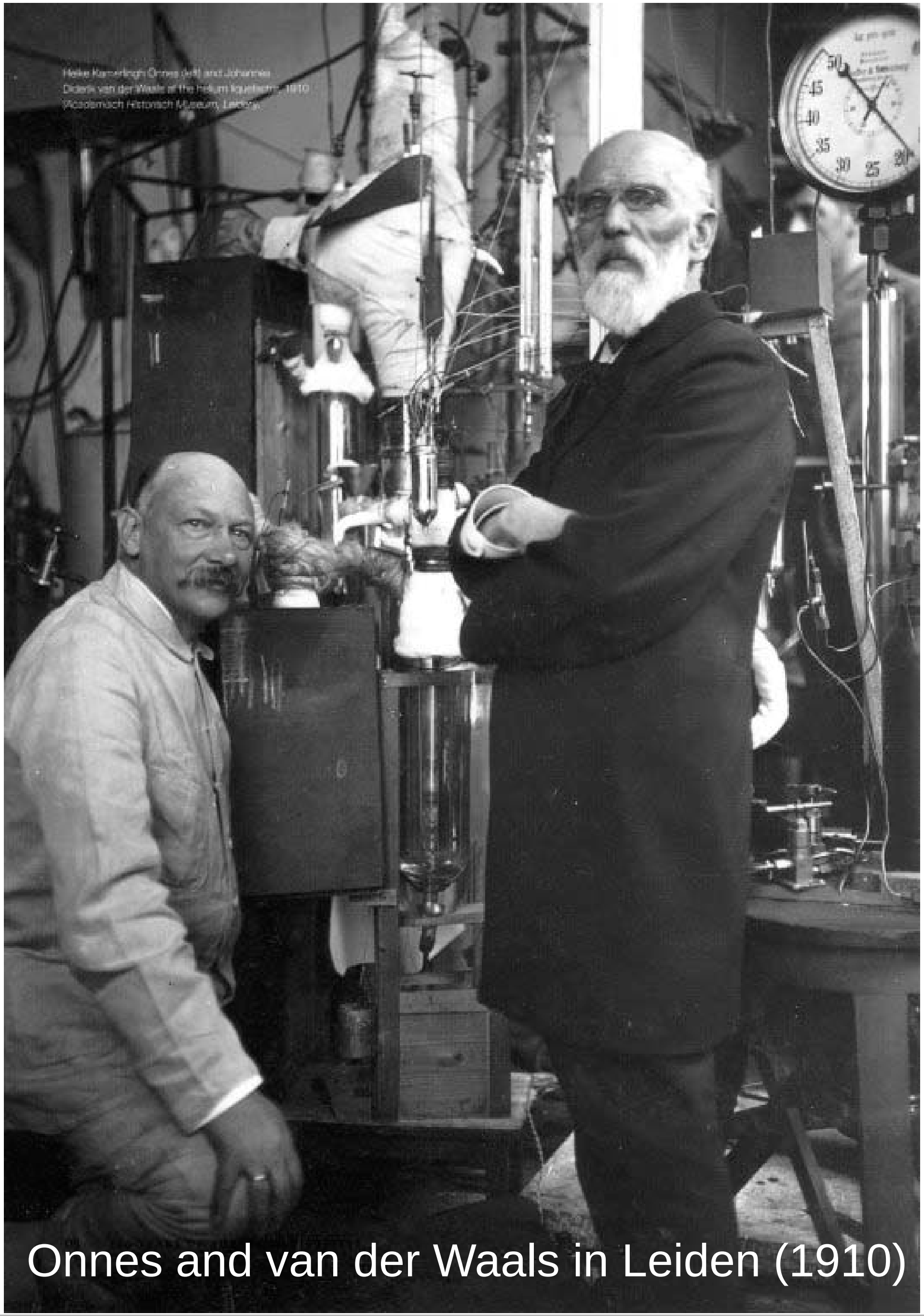
May 1, 2011

Onnes in Leiden 1882- 1926



Flim, Kesselring and trainee instrument-makers at the helium liquefactor. Drawing by Harm Kamerlingh Onnes, ca. 1920 *(Museum Boerhaave)*.

Onnes was appointed in 1882 at the age of 29 and published nothing for 10 years



Onnes and van der Waals in Leiden (1910)

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)

Application

- 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 in Nb_3Sn finally discovered (Kunzler, Buehler, Hsu and Wernick)
- 1960s – superconducting magnet technology took off

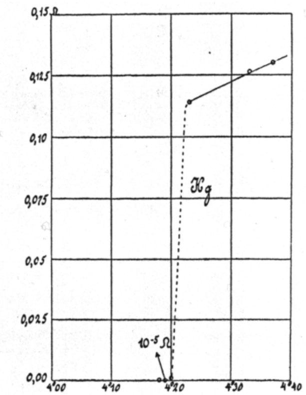
A historical perspective….Onnes in Chicago 1913 (IIR)

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. . . .



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.

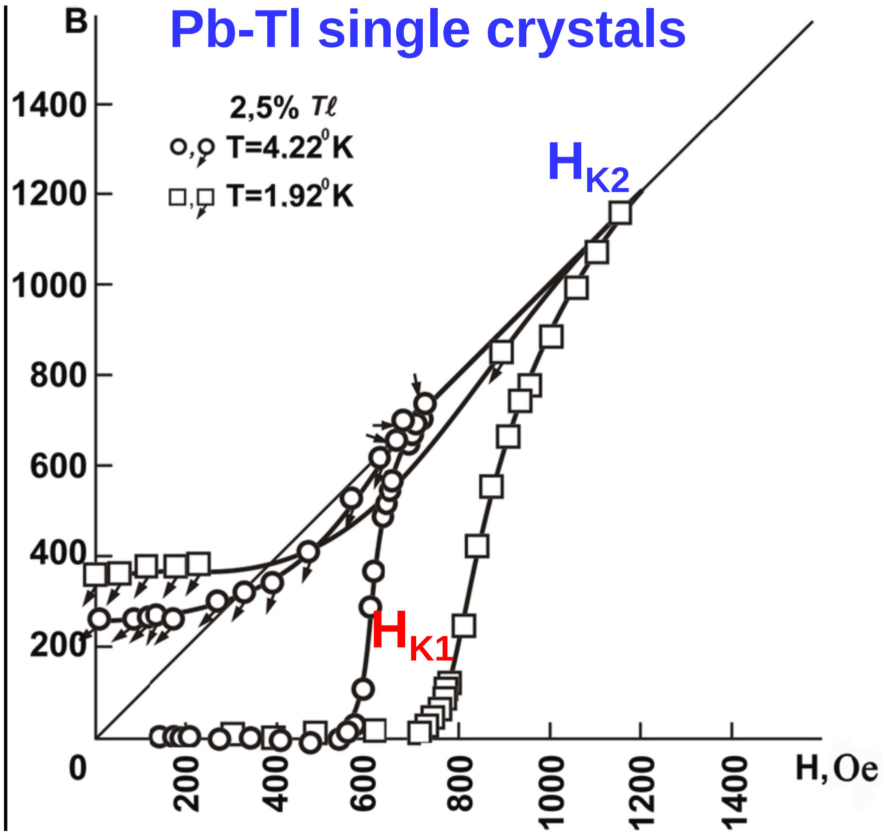
The insulation of the wire was obtained by putting silk between the windings, which being soaked by the liquid helium brought the windings as much as possible into contact with the bath. The coil proved to bear a current of 0.8 ampere without losing its superconductivity. There may have been bad places in the wire, where heat was developed which could not be withdrawn and which locally warmed the wire above the vanishing point of resistance. . . .

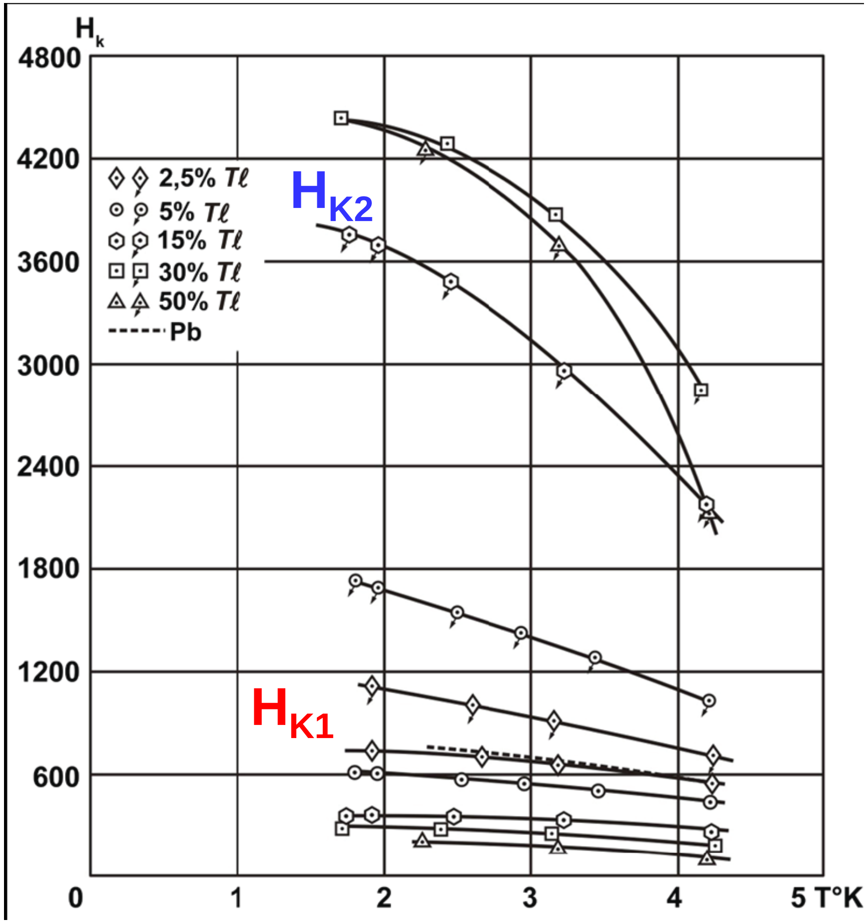
I think it will be possible to come to a higher current density . . . if we secure better heat conduction from the bad places in the wire to the liquid helium. . . . In a coil of bare lead wire wound on a copper tube the current will take its way, when the whole is cooled to 1.5 K. practically exclusively through the windings of the superconductor. If the projected contrivance succeeds and the current through the coil can be brought to 8 amperes . . . we shall approach to a field of 10 000 gauss. The solution of the problem of obtaining a field of 100 000 gauss could then be obtained by a coil of say 30 centimeters in diameter and the cooling with helium would require a plant which could be realized in Leiden with a relatively modest financial support. . . . When all outstanding questions will have been studied and all difficulties overcome, the miniature coil referred to may prove to be the prototype of magnetic coils without iron, by which in future much stronger and . . . more extensive fields may be realized than are at present reached in the interferrum of the strongest electromagnets. As we may trust in an accelerated development of experimental science this future ought not to be far away.

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

1936: Type II Superconductivity discovered – and unappreciated

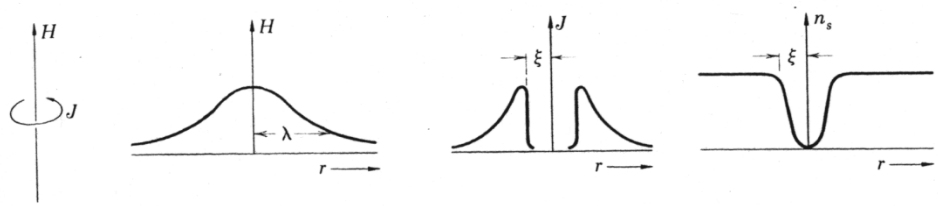




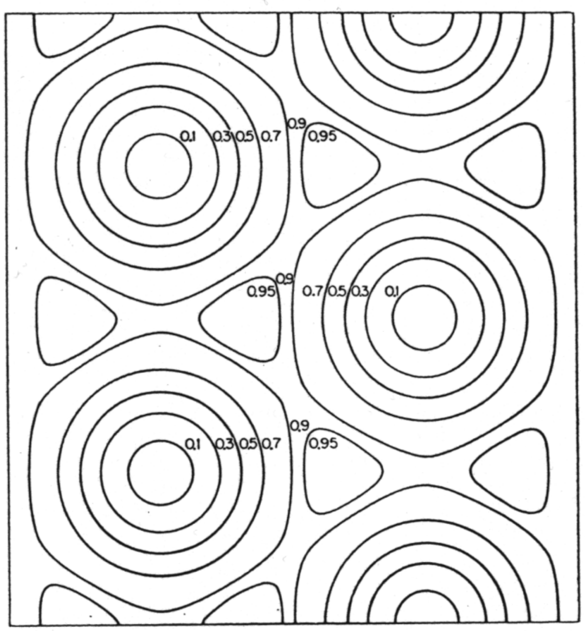
Shubnikov returned to Kharkov from Leiden to start single crystal alloy studies – persistence of superconductivity beyond the Meissner state - then imprisoned and shot

L.V.Shubnikov et al., *Zh. Exper. Teor. Fiz. (USSR)* **7**, 221 (1937)
L.W.Schubnikow et al., *Sondernummer Phys.Z.Sowiet. Arbeiten auf dem Gebiete tiefer Temperaturen,* 39 (1936); *Phys.Z.Sowiet.* **10**, 165 (1936).

Early 1950's: Abrikosov: what if $\kappa = \lambda/\xi$ becomes very large?



- **Two characteristic lengths**
  - coherence length ξ, the pairing length of the superconducting pair
  - penetration depth λ, the length over which the screening currents for the vortex flow
- **Vortices have defined properties in superconductors**
  - normal core dia, ~2ξ
  - each vortex contains a flux quantum ϕ_0 currents flow at J_d over dia of 2λ
  - vortex separation $a_0 = 1.08(\phi_0/B)^{0.5}$



$H_{c2} = \phi/2\pi\xi^2$

$\phi_0 = h/2e = 2.07 \times 10^{-15}$ Wb

B/B_{c2} (=b) ~ 0.2

A.A.Abrikosov, *Sov.Phys.JETP.* **5**, 1174 (1957).

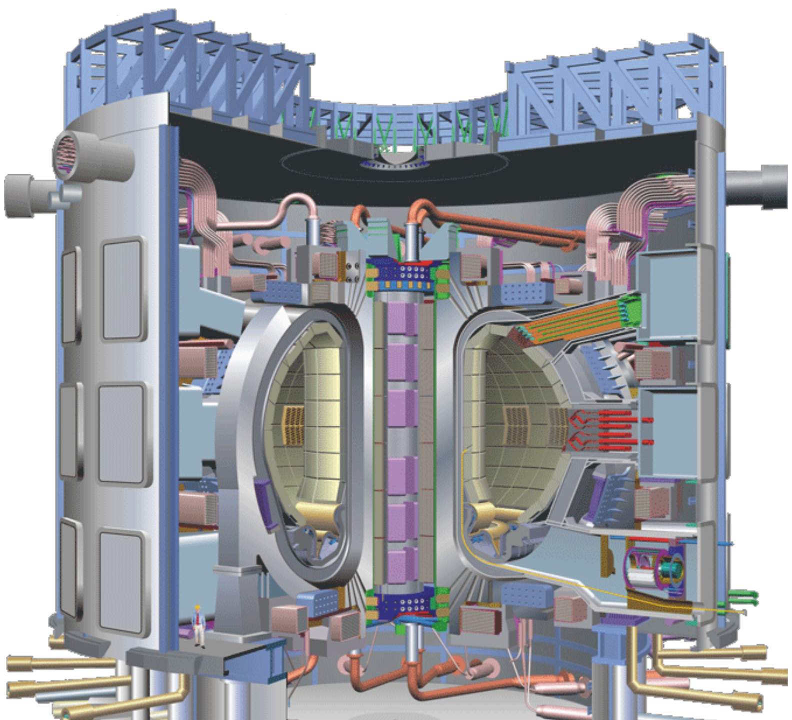
Decisive experiment only in 1961

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

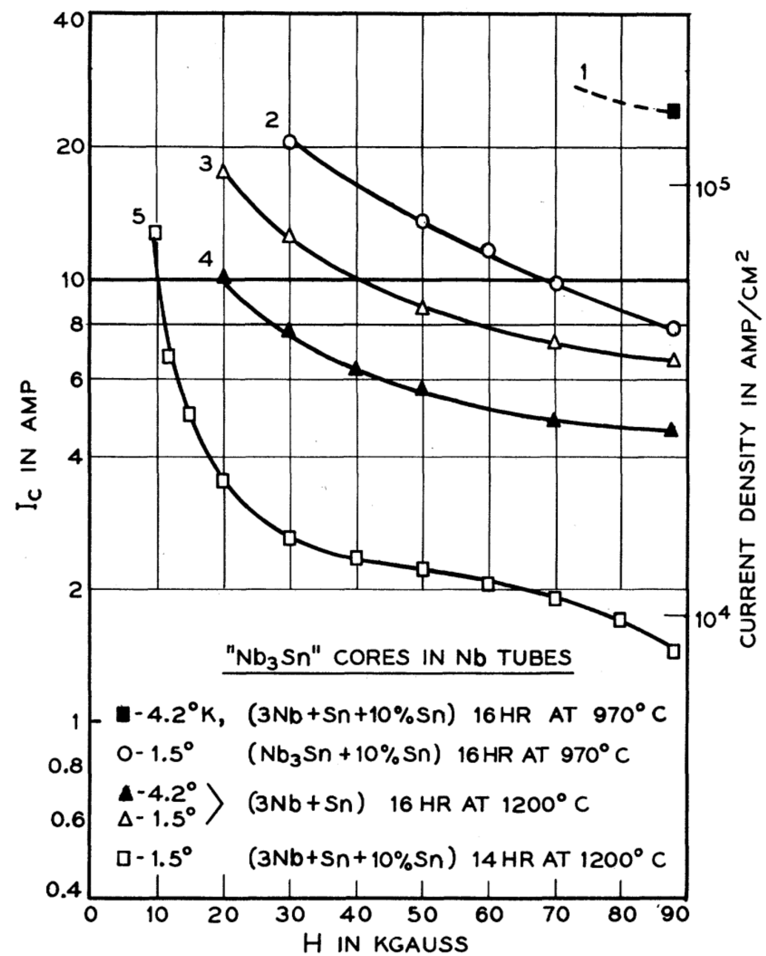
J. E. Kunzler, E. Buehler, F. S. L. Hsu, and J. H. Wernick
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received January 9, 1961)

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



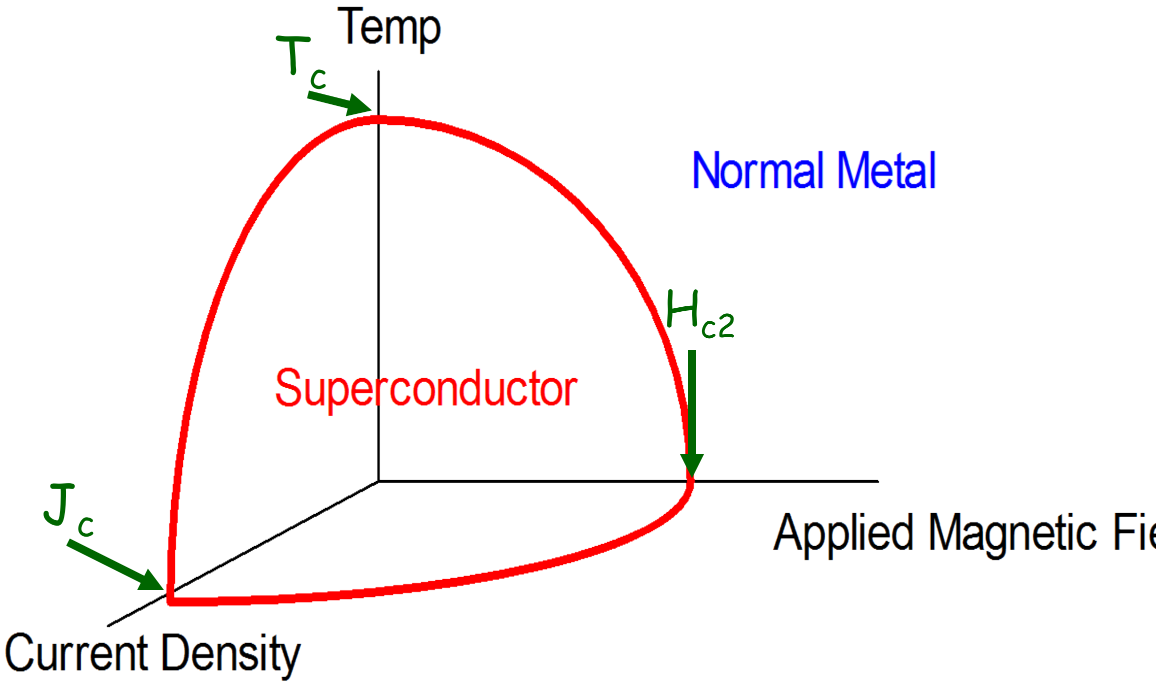
ITER uses 600 tonnes of Nb_3Sn



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

Magnets depend much more on high Jc and Hc2 than high Tc

- Critical Parameters
  - Critical Temperature, T_c
  - Critical Magnetic Field, H_{c2}
  - Critical Current Density, J_c
- But for HTS, H_{c2} is not the phase boundary
  - Thermal fluctuations make the dissipation line lie far below H_{c2} at an irreversibility field H*

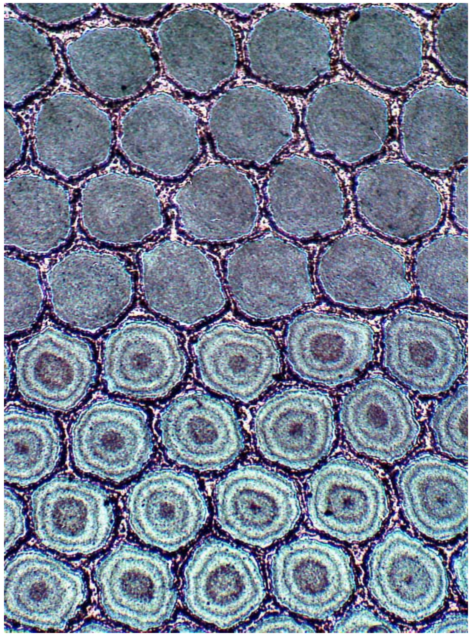


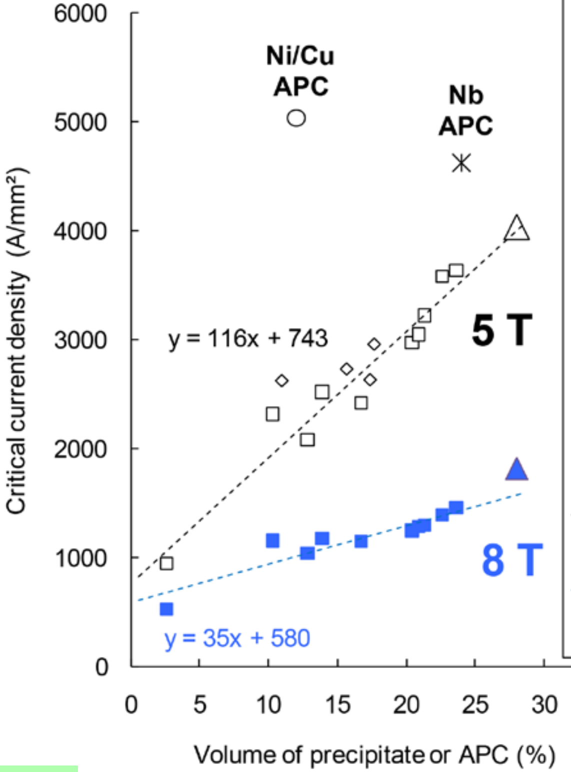
T_c, H_{c2}, H* relatively fixed for any given material, J_c highly dependent on specific sample!

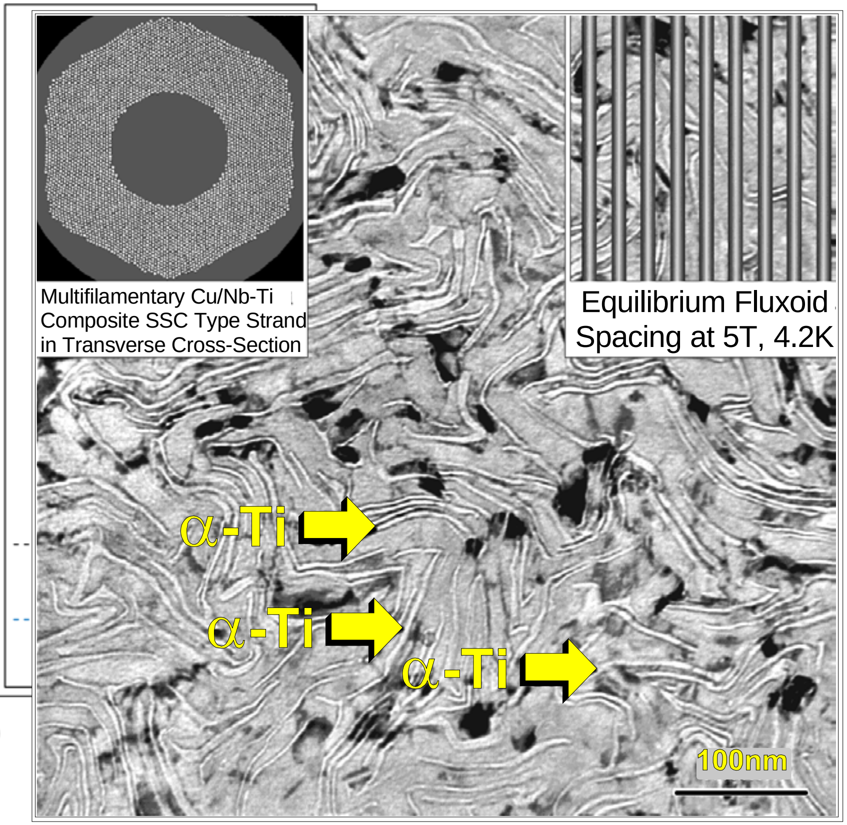
Optimal Nb- Ti properties developed by understanding the processing- nanostructure- J_c feedback cycle

Start with homogeneous Nb-Ti

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



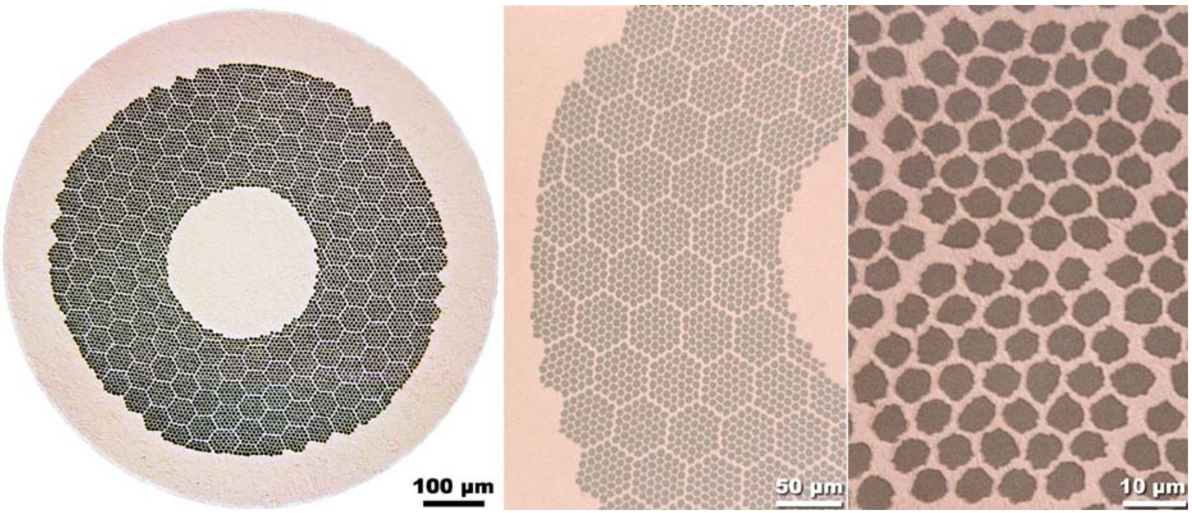




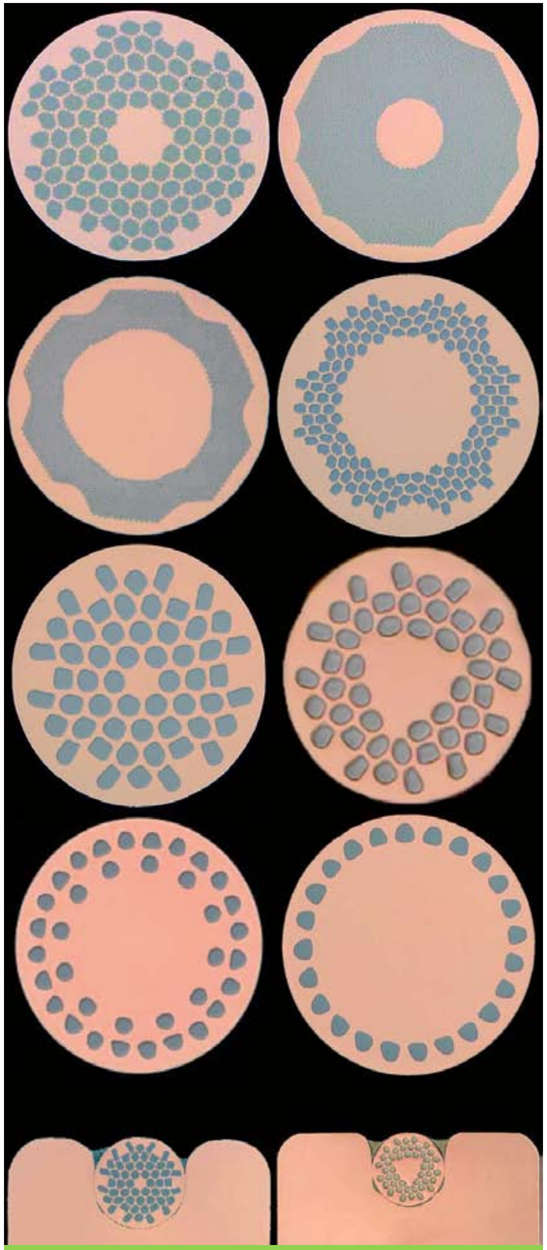
Images by Peter Lee, NHMFL

Nb- Ti created the superconducting magnet industry – accelerators in the forefront – MRI the sustaining market

- Conductors of almost any architecture
- With truly optimized properties



LHC conductors by Luvata



Some of the BEST conductors

Superconducting MRI Magnets are the ongoing volume driver for wire and magnets…

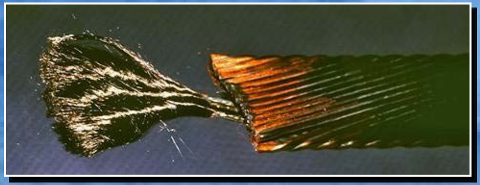
Closed (1- 3 Tesla) and open (0.3T) MRI magnets both use Nb- Ti with a transition temperature (T_c) of only 9K, ~- 450F.

Nb- Ti might be replaced by MgB_2 (ASG- Columbus)

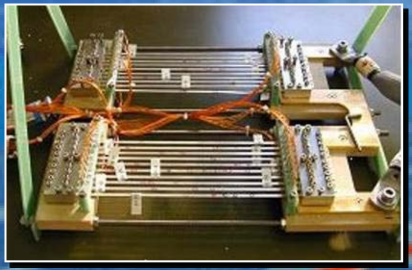
LHC at CERN – LTS enabled by HTS

Mont Blanc

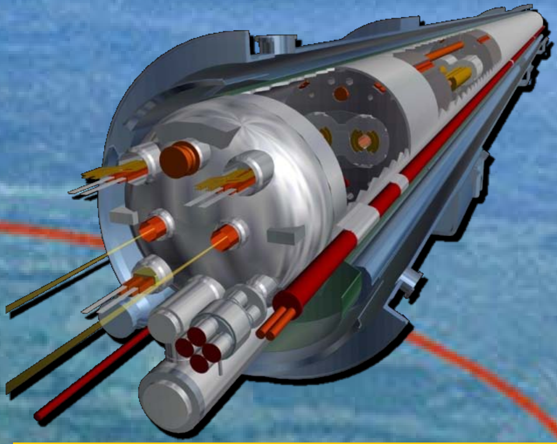
1500 tonnes of LTS SC cables



3286 HTS Leads



1232 SC Dipoles



Lake Geneva

Switzerland

Large Hadron Collider

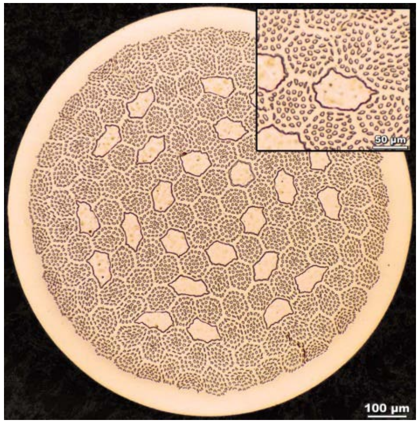
15000 MJ of magnetic energy

27 km Tunnel

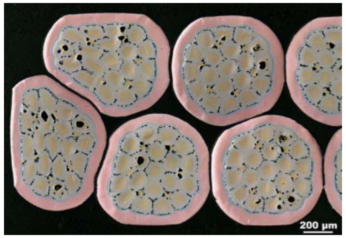
France

- **Nb-Ti at 1.9 K at CERN France/Switzerland**
- **5000 Superconducting Magnets in 27 km tunnel**
- **Beam-steering dipole magnets reach 8.36 T (1.9 K)**

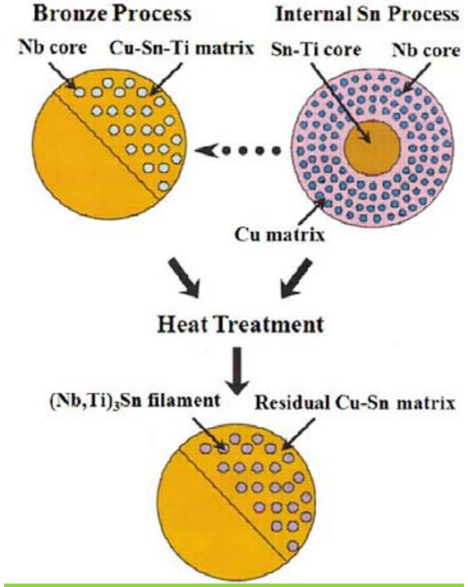
Filamentary Nb_3Sn has evolved over 4 decades

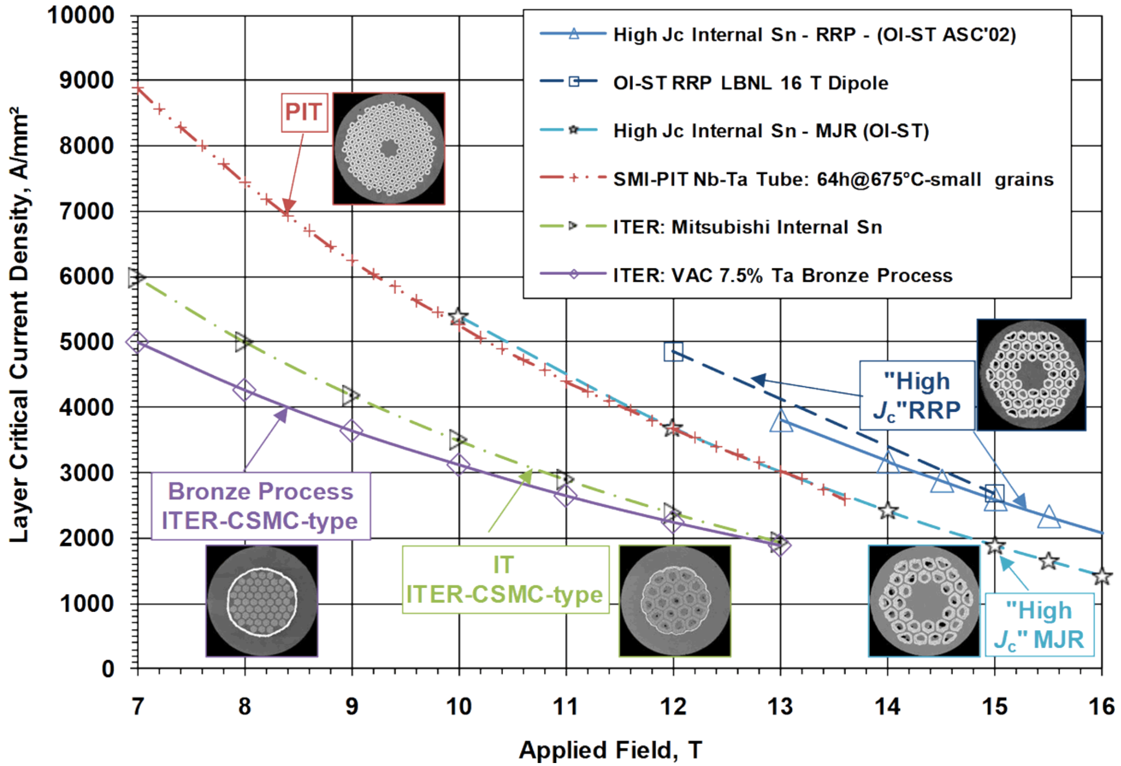


The 1st stabilized conductor (1973) – 12 T magnet use (Harwell-Rutherford)



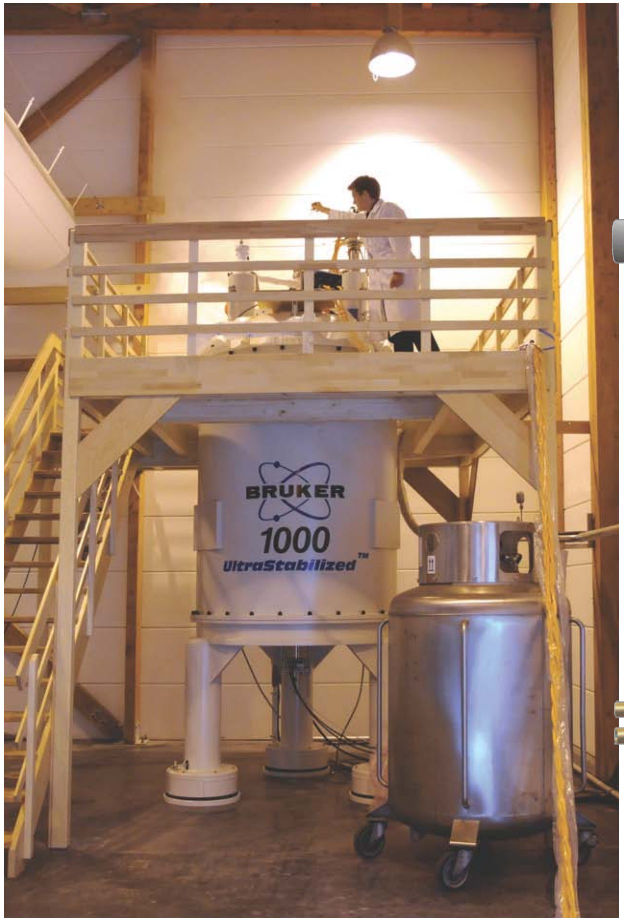
- **Huge advances in the last 10 years under HEP driving for LHC application!**



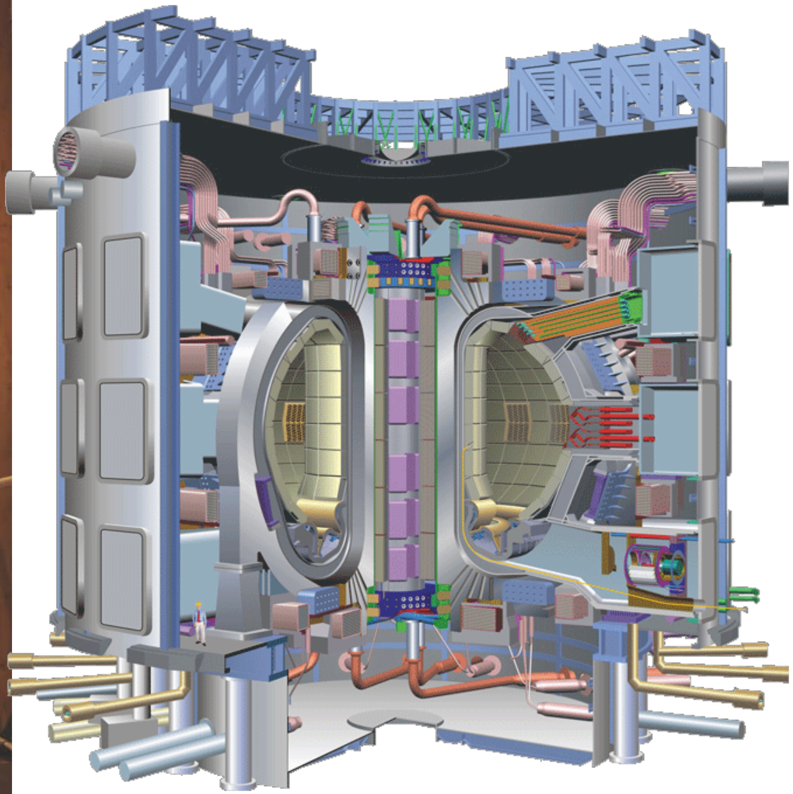


Multiple paths

Nb_3Sn has been driven by NMR, now by ITER and HEP R&D by LHC insertion



1 GHz NMR in Lyon – 23.5 T at 1.8K



13 T Toroidal field and central solenoid coils

- Intersection region quads (LARP) and collimator enablers in LHC upgrade

1986, cuprate superconductivity

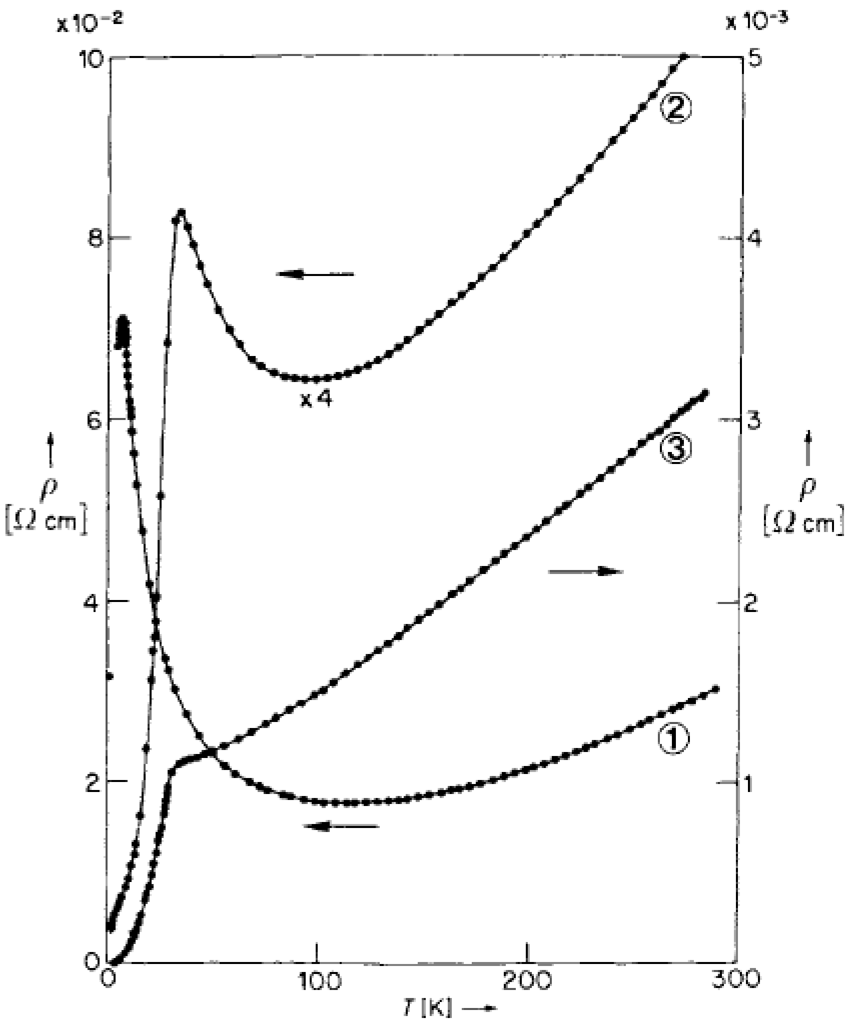


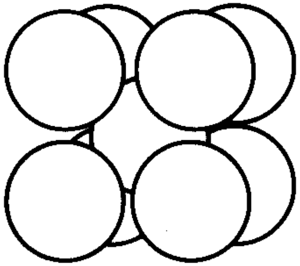
Fig. 1.9. Resistivity as a function of temperature for La_2CuO_{4-y} : Ba samples with three different Ba : La ratios. Curves ①, ②, and ③ correspond to ratios of 0.03, 0.06, and 0.07, respectively (adapted from [1.20]).

- 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

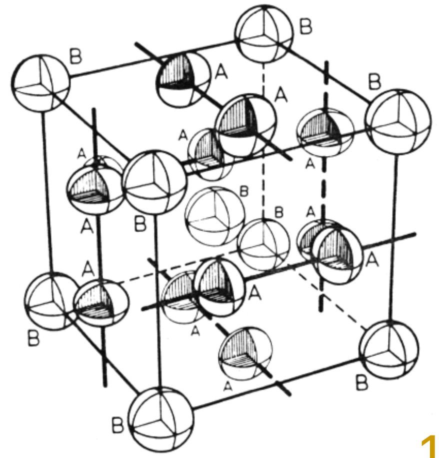
- **Superconductivity induced by doping carriers into an insulating anti- ferromagnetic state**
- **Non- Fermi liquid behavior, but strong correlations that still prevent any generally accepted model for superconductivity in the cuprates**

Higher T_c – greater complexity

Nb-Ti

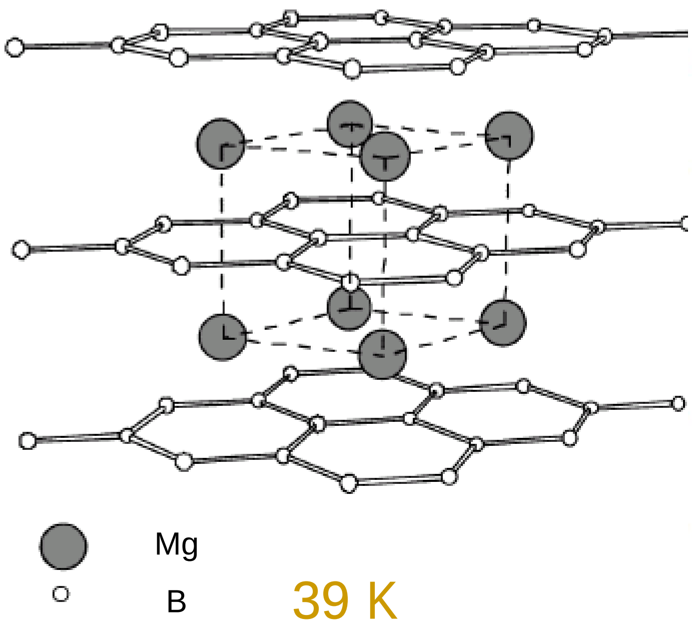


9 K



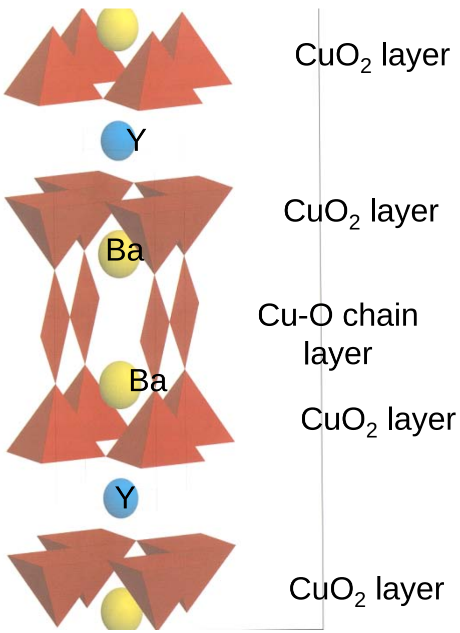
Nb_3Sn

18-23 K



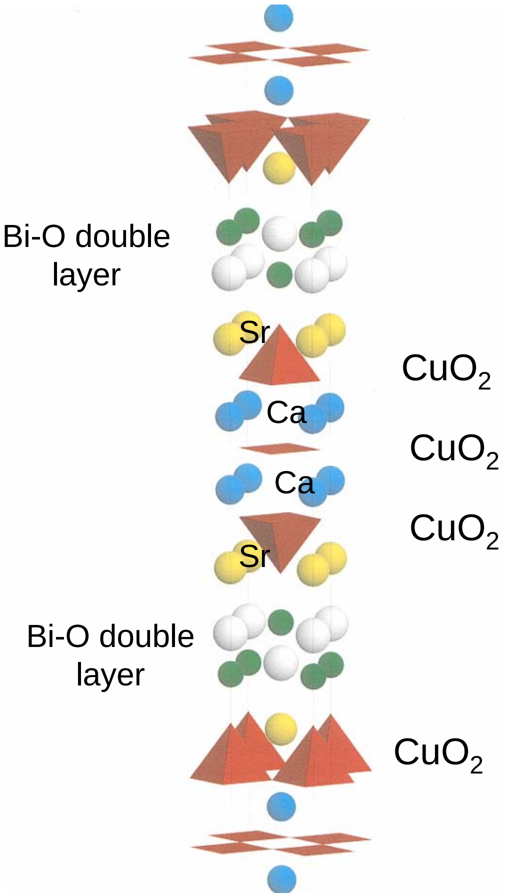
39 K

MgB_2



92-95 K

YBCO



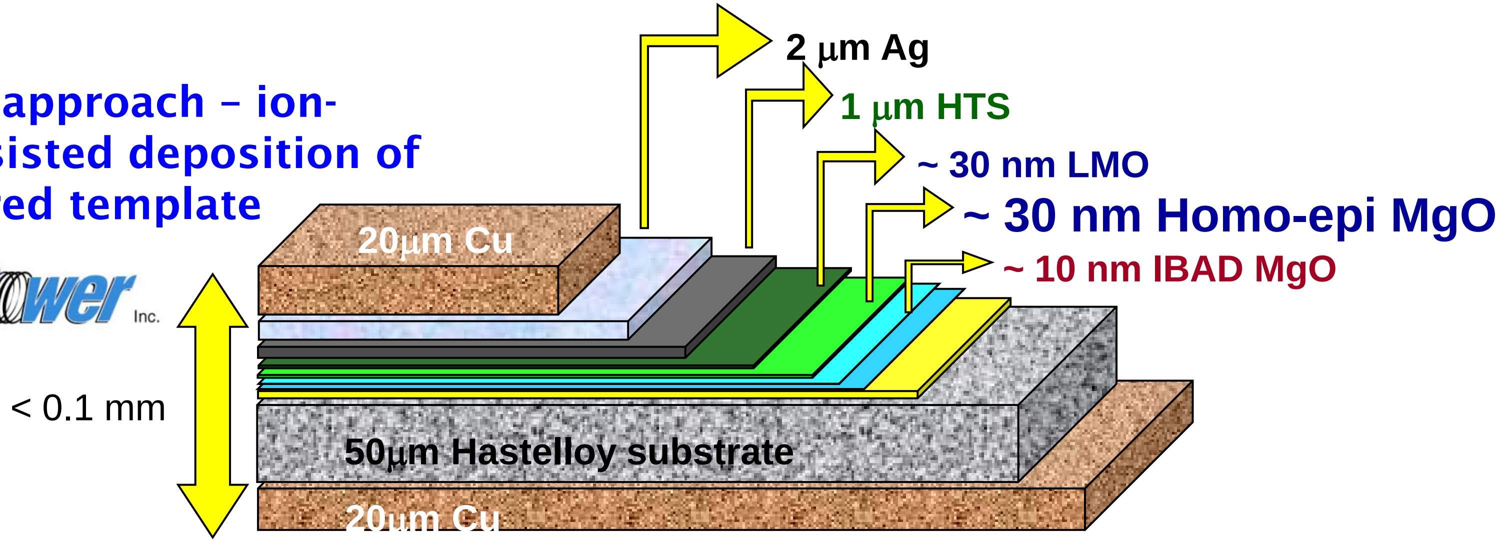
110 K

Bi-2223

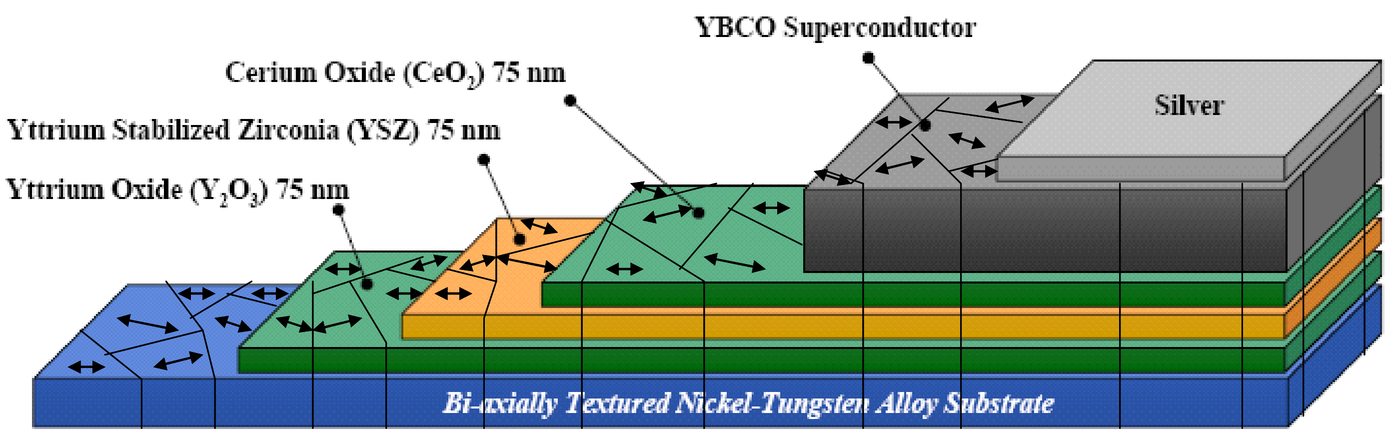
GB obstruction forced development of coated conductors of YBCO: "single crystals by the mile"

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

SuperPower Inc.



Production now in 100-500 m lengths



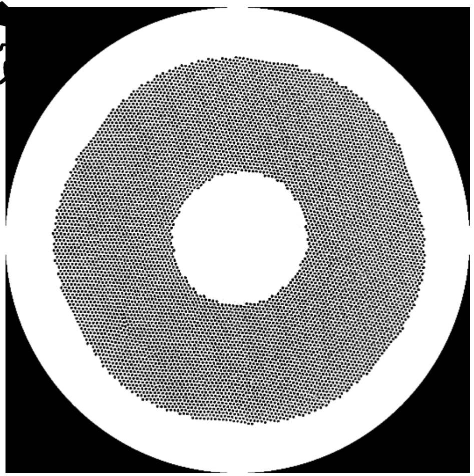
American Superconductor™

One example of electric utility applications…high power cables

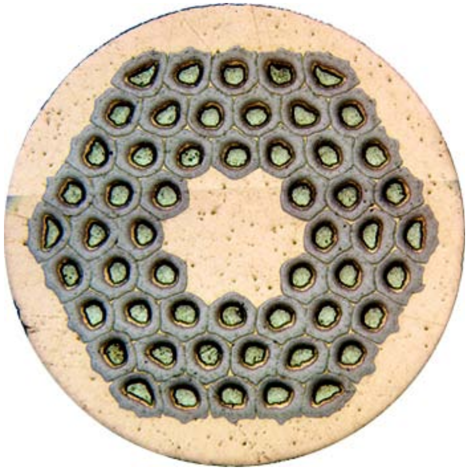
Cu, HTS 1000 A equivalents

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

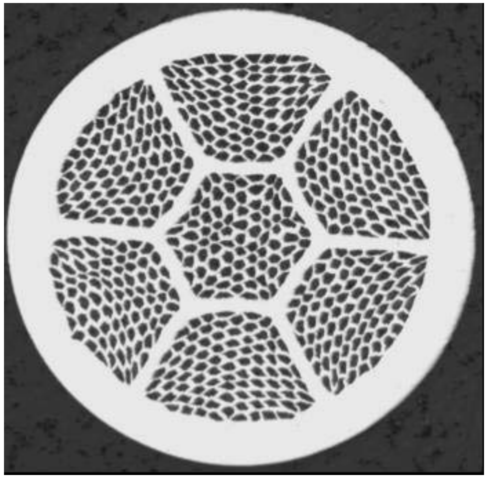
American Superconductor · LIPA · Nexans · AIR LIQUIDE



Nb47Ti (OST)

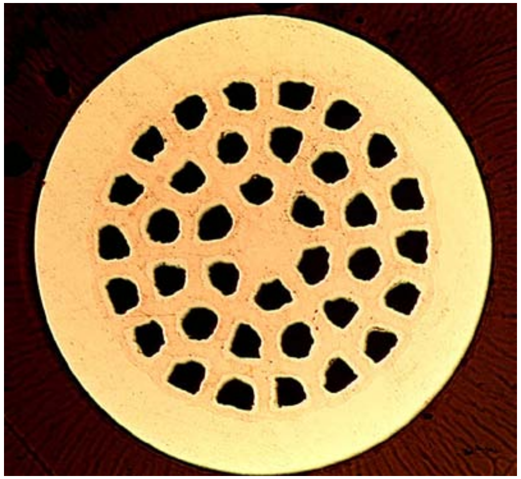


Internal Sn Nb_3Sn (OST)



Bi-2212 (OST)

Magnet builders prefer round wires



MgB_2 (Hypertech)

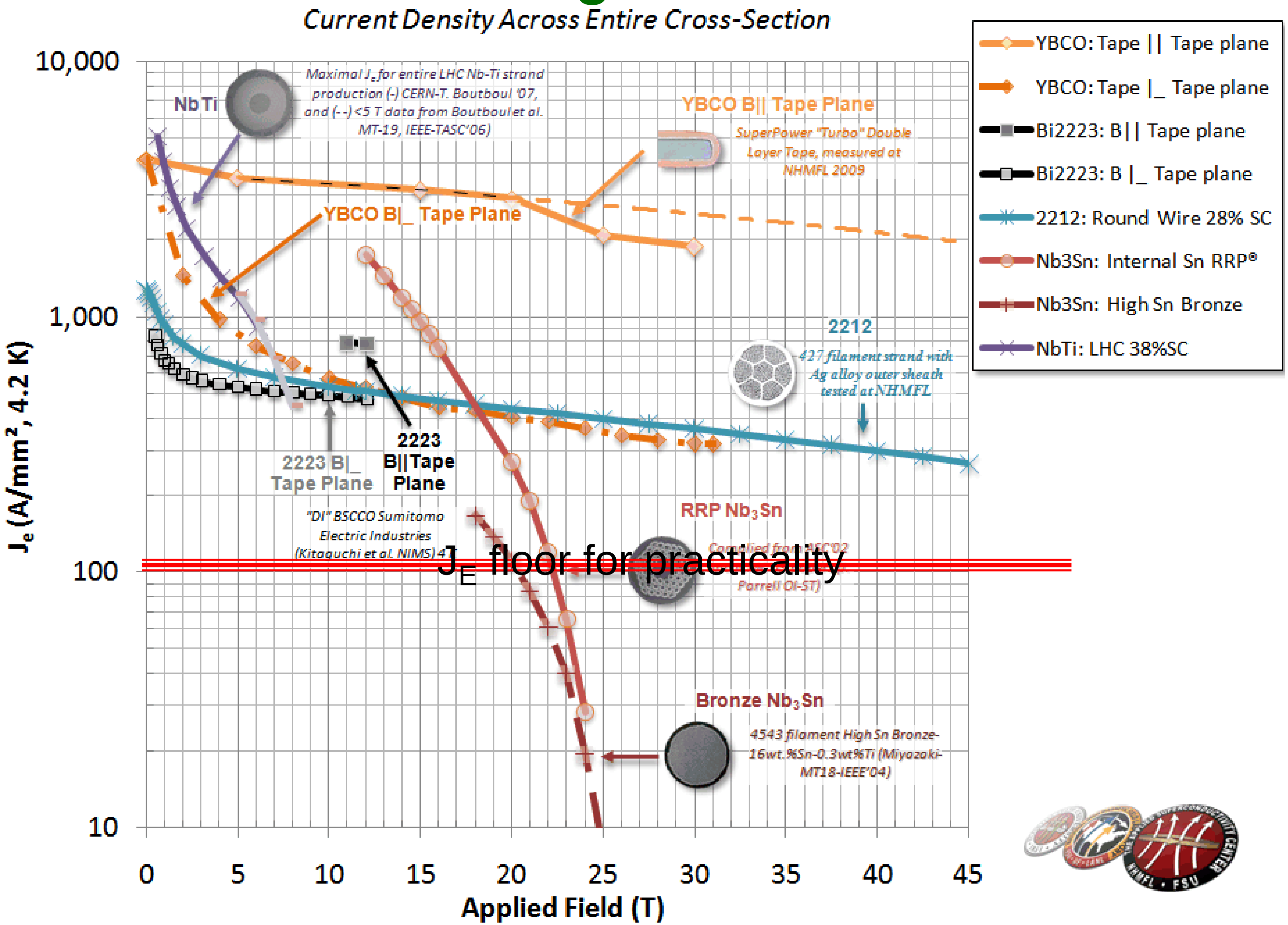
Preferred conductor features:

Multifilament

Round or lightly aspected shape with no Jc anisotropy

Capability to wind in unreacted form while conductor fragility is minimized

HTS will now enable a new generation of magnets - > 30 Tesla



Plot maintained by Peter Lee at: http://magnet.fsu.edu/~lee/plot/plot.htm

Summary II - HTS Conductor Issues

- $H_{c2}(T)$ much larger than for Nb_3Sn
  - 100- 120T versus 30T (30T for YBCO at 55K)
    - But, thermal fluctuation effects depress the irreversibility field at which Jc = 0 well below Hc2, except at low T
- Grain boundaries easily acquire depressed properties and degrade J_c even for small misorientations of 3- 5º
  - Conductors must be fabricated with extreme texture

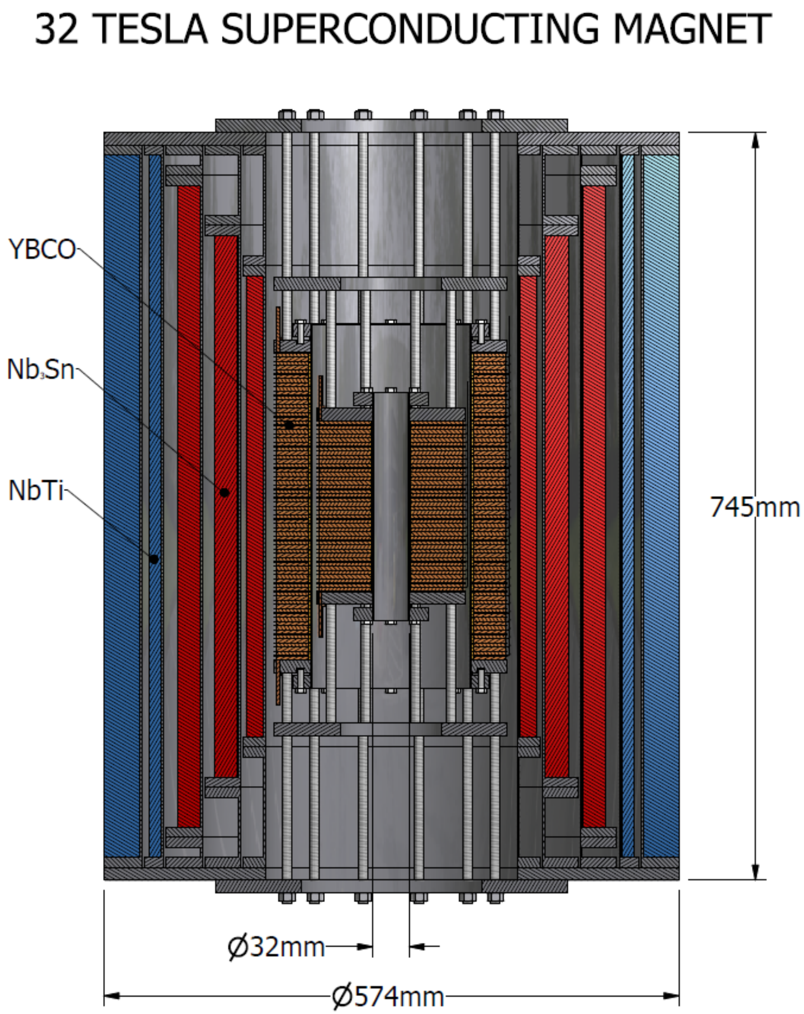
HTS are extremely interesting for high H_{c2}, rather bad from GB property point of view

National Magnet Lab User Facility

- Provides the world's highest DC magnetic fields
  - 45T in hybrid, 32 mm warm bore
  - Purely resistive magnets: 36T in 32 mm warm bore, 31 T in 50 mm bore and 20T in 195 mm warm bore
- 20 MW resistive magnets cost ~$2400/hr at full power
  - Long- time, full- field experiments are very expensive
  - Quantum oscillation, quantum Hall effect, low noise, large signal averaging experiments could run 7 days a week………

32 T Superconducting user magnet: YBCO coated conductor

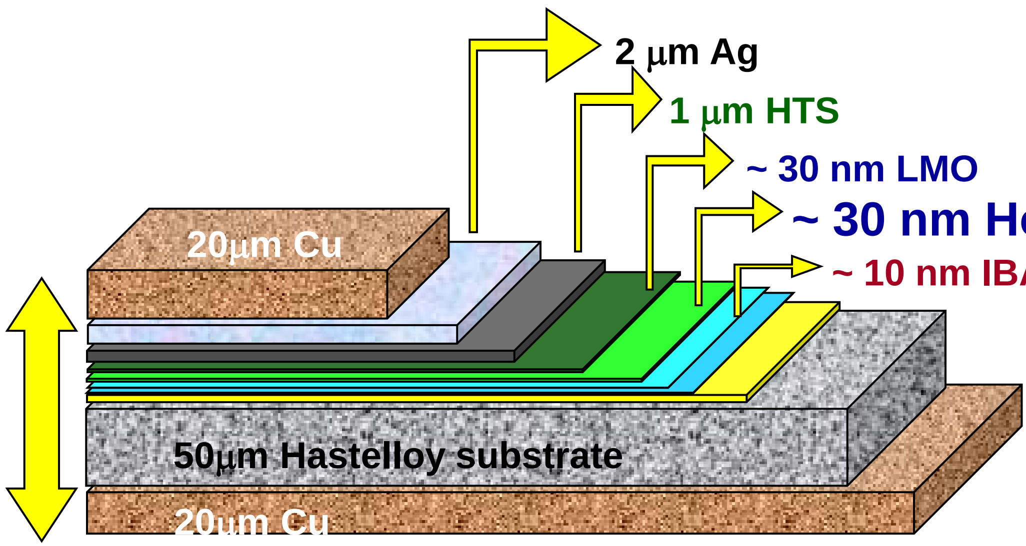
- **Goal:**
  - 32 T, 4.2 K, 32 mm bore, 500 ppm in 10 mm DSV, 1 hour ramp, fitted with dilution refrigerator giving <20 mK
  - On line 2013
- **Funding:**
  - $2M grant from NSF for LTS coils, cryostat, YBCO tape & other components of magnet system
  - Core grant for technology development
  - dilution fridge not yet funded
- **Key Personnel**
  - Huub Weijers, NHMFL, Project lead
  - Denis Markiewicz, NHMFL: Magnet Design
  - David Larbalestier, NHMFL: co- PI, SC Materials
  - Stephen Julian, Univ. of Toronto: co- PI, Science

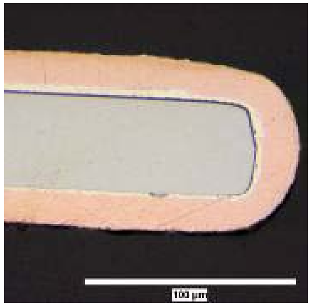


Current	172 A
Inductance	619 H
Stored Energy	9.15 MJ

2 (or3?) viable HTS magnet conductors

- YBCO with phenomenal Jc - ~20 x 10^6 A/cm^2 at 25T
  - But YBCO is ~1% of cross- section
  - 50% is high strength superalloy

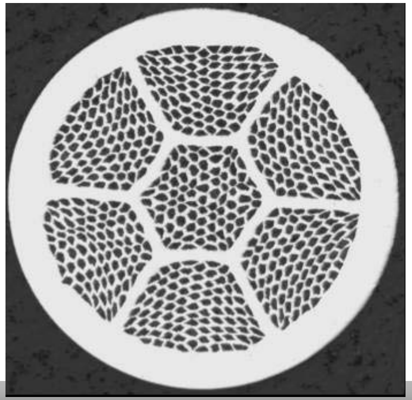




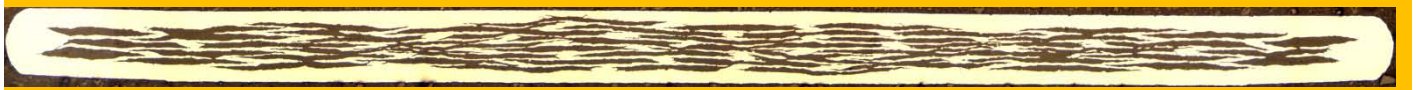
YBCO coated conductor 4 x 0.1 mm

- Round wire Bi- 2212 – the preferred shape for cabling

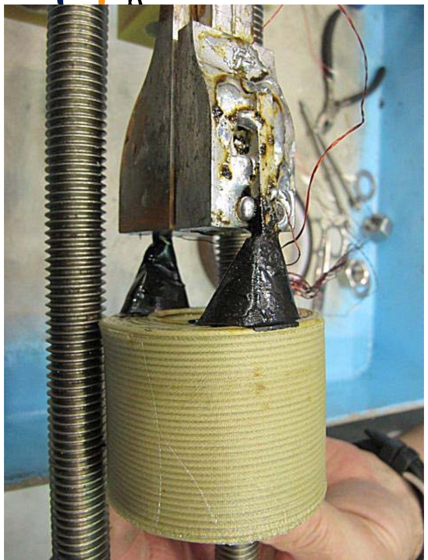
Bi-2212 round wire ~ 1mm dia.



Bi-2223 tapes represent a third possibility exhaustively studied for power applications 30-77K
Now mature – lower J_e than 2212 and YBCO

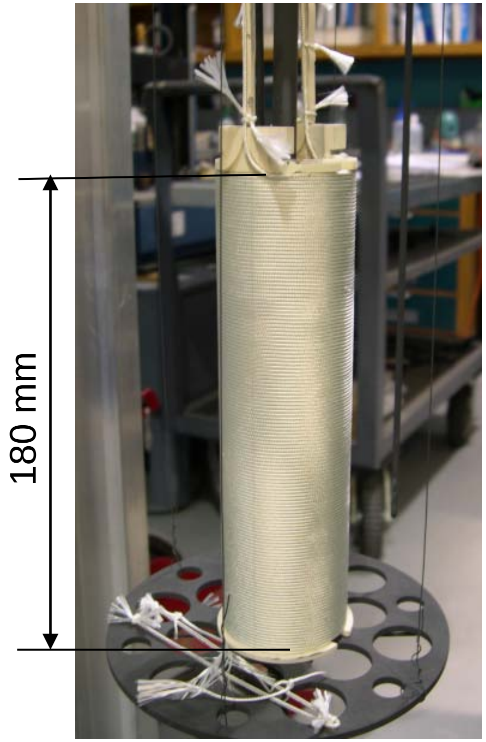


Bi- 2212 Test Coils are advancing



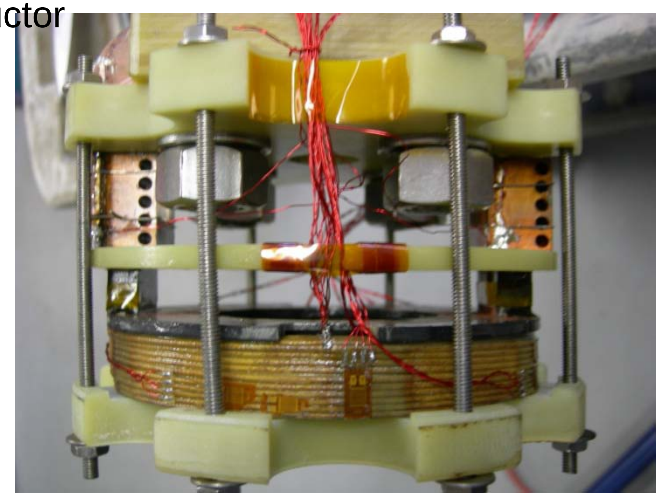
High Field Test coil:

- 10 layers/750 turns, *L* ~ 3 mH
- *ID* = 15 mm, *OD* = 38 mm
- height = 100 mm
- conductor length ~66 m
- *ΔB* = 1.1 T at 31 T
- **first HTS wire-wound coil to go beyond 30 T (32.1 T in 31 T background)**



Bore-tube-free Test Coils:

Minimize chemical interactions with conductor



Large OD σ_{hoop} test coil:

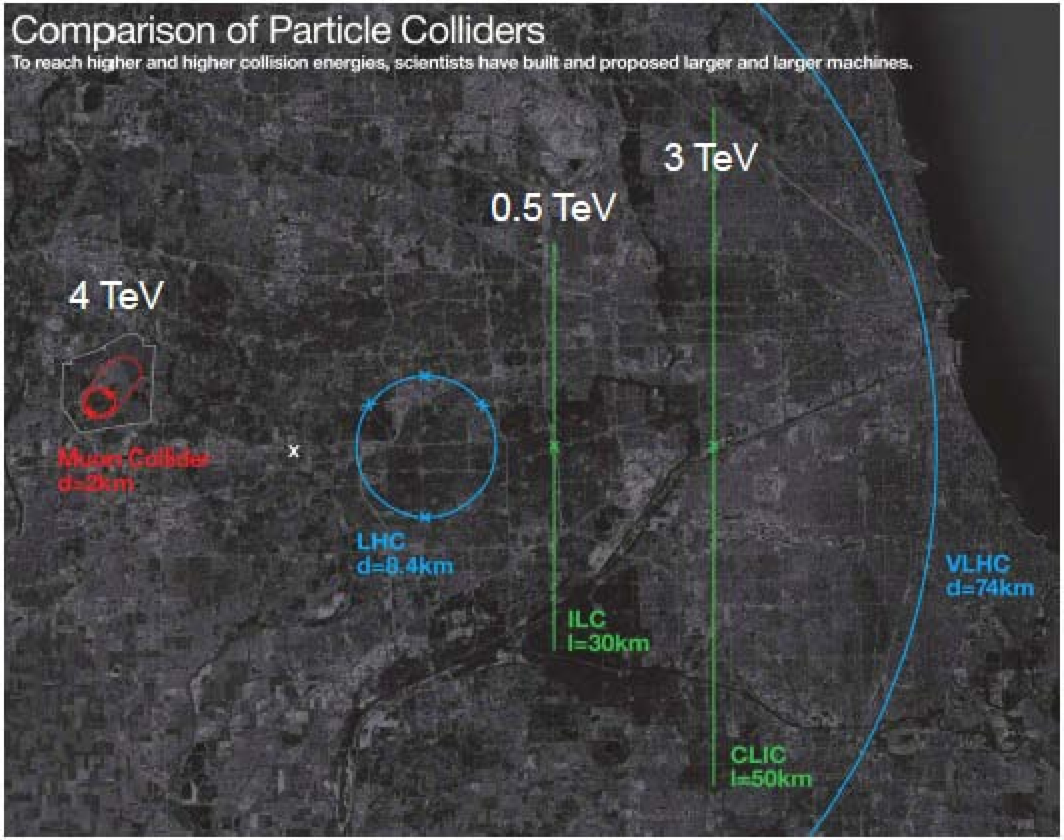
- ID = 92.5 mm
- OD = 118.5 mm
- 10 layers, 10 turns
- Bore tube less
- epoxy impregnated
- ΔB ~ 0.2 T at 20 T

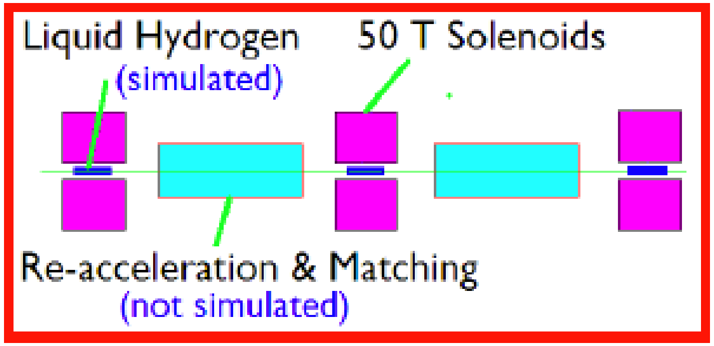
High Field Test coil "7 T inner shell":

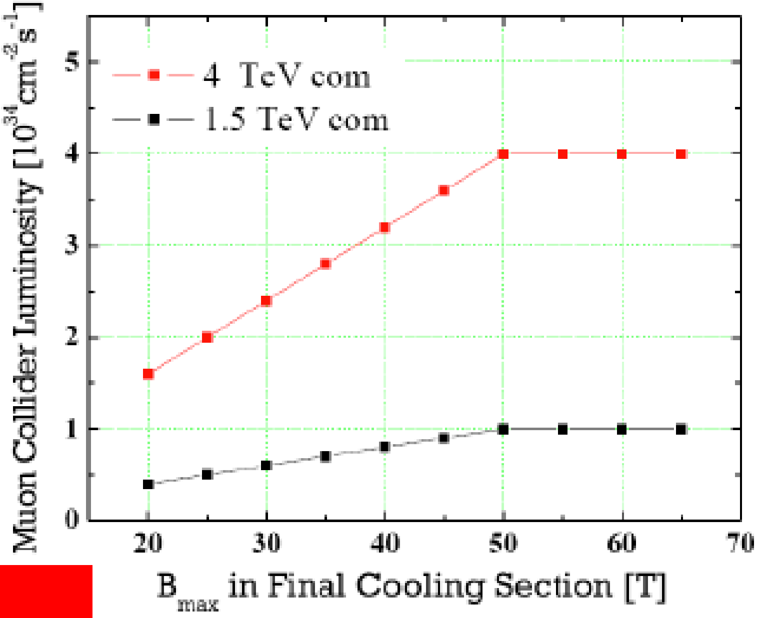
- 10 layers/135 turns, *L* = 14.9 mH
- *ID* = 32.4 mm, *OD* = 57.4 mm
- height = 180 mm
- conductor length ~220 m
- *ΔB* = 1.2 T at 20 T

Trociewitz, Myers

The Muon Collider Design Study at Fermilab



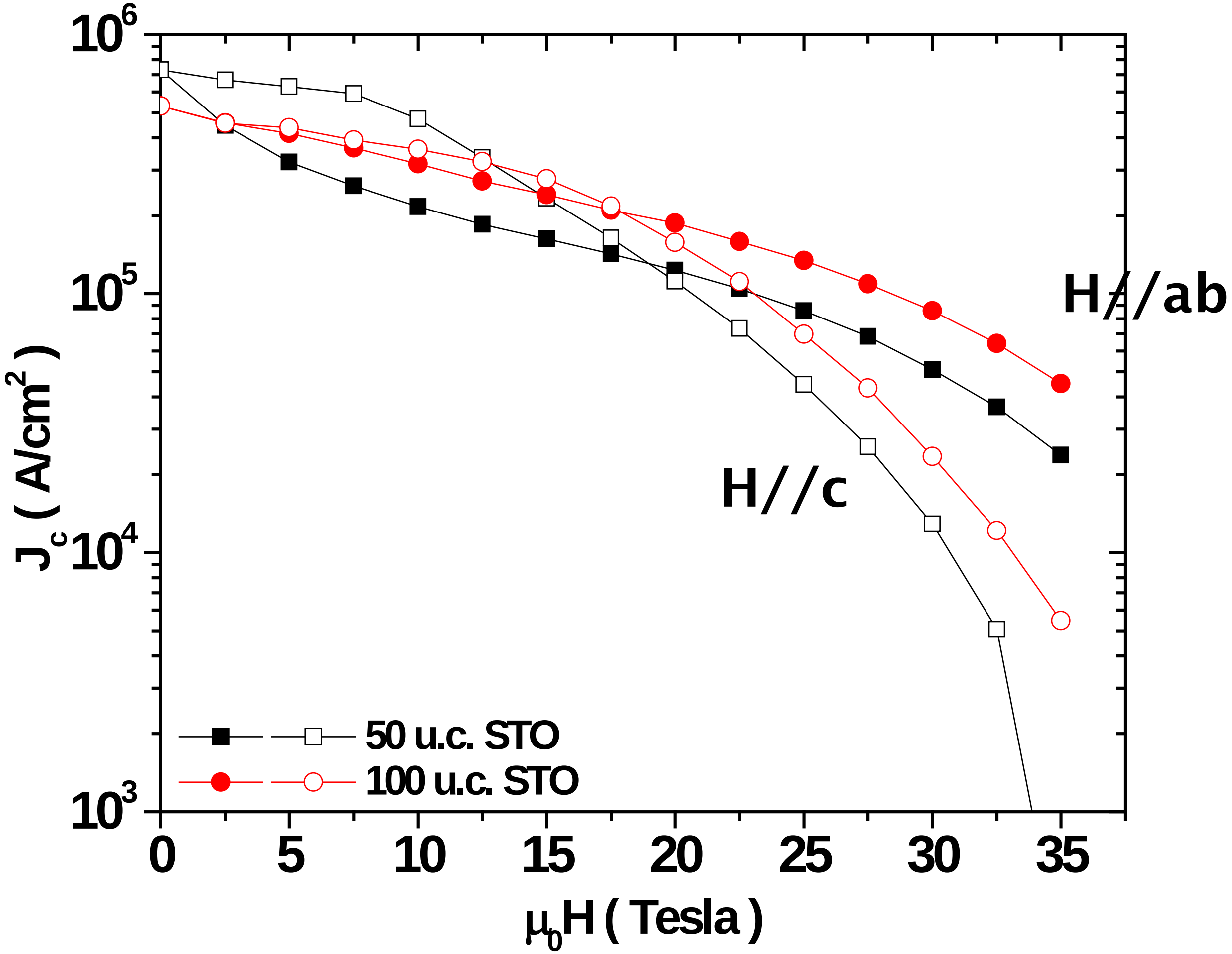




Now an approved design activity (MAP)

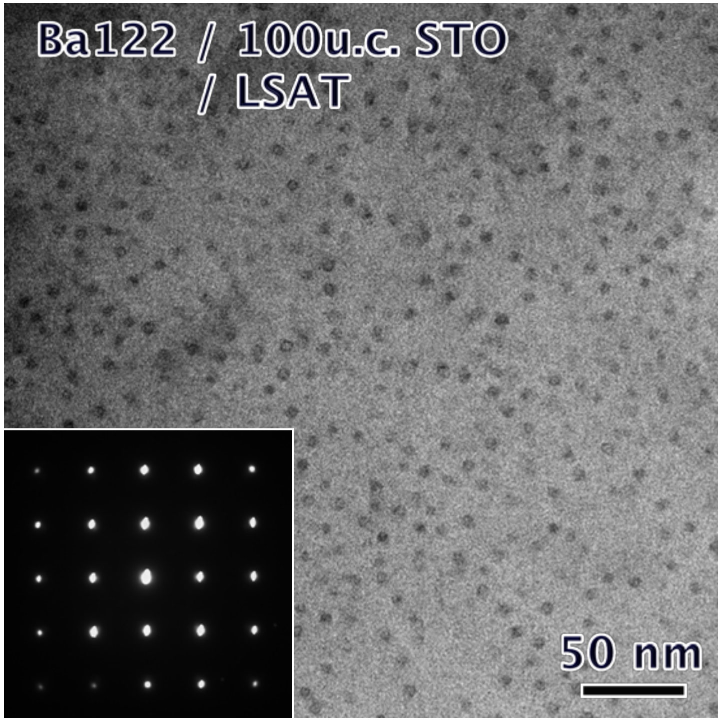
- **50 T solenoids are a crucial feature……**

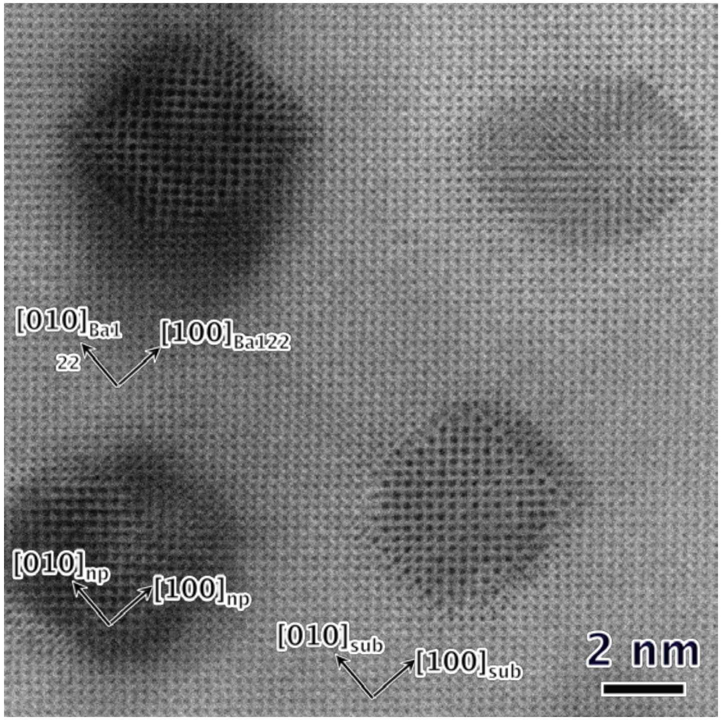
New Fe- base superconductors have spectacular Jc………



Co-doped $BaFe_2As_2$ thin films

Because they have the right nanostructures…





- **The nanocolumns have a square shape with a size of <u>5-6 nm ~ 2ξ</u>**

  <u>Perfect sizes for the pinning centers</u>

- **Almost perfects structural match between matrix and defects**

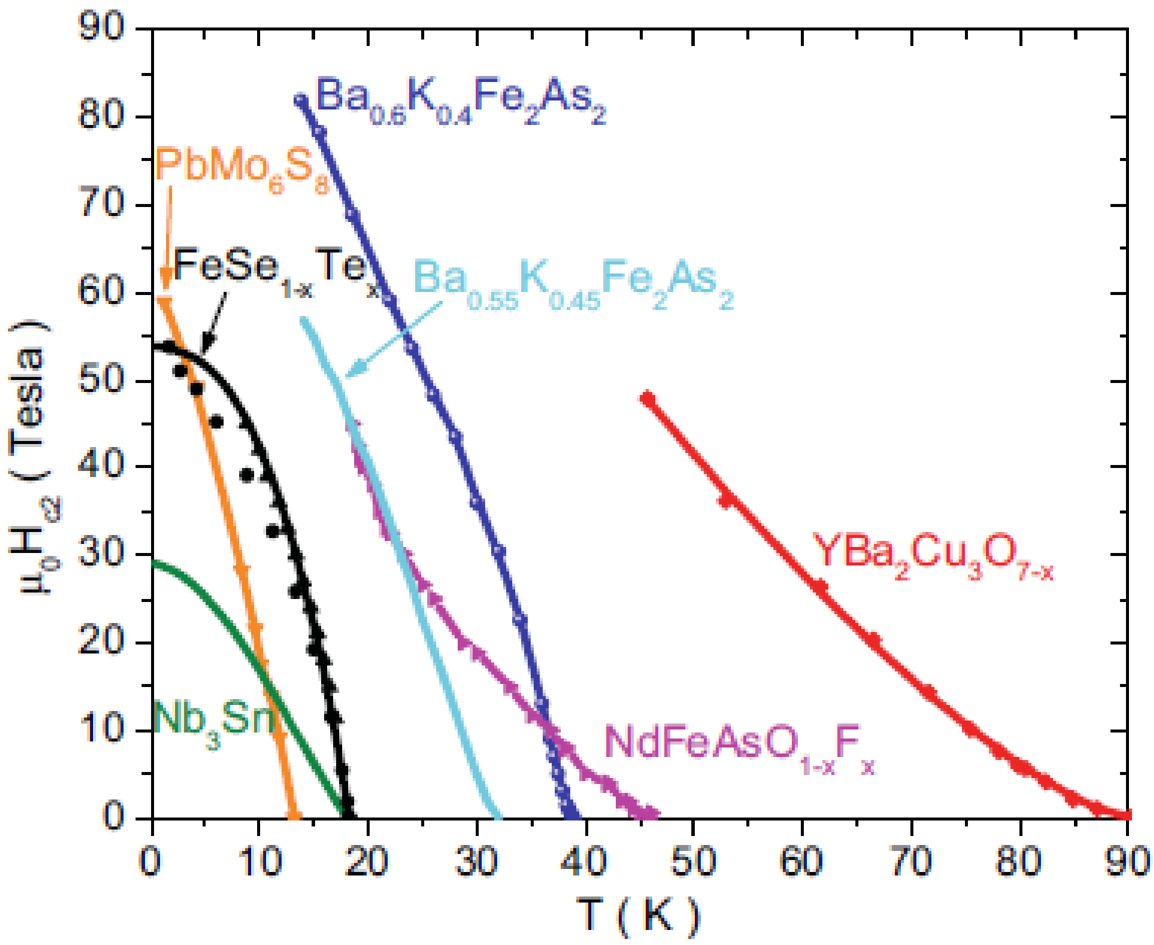
  No buckling around the defects

  <u>No degradation of the matrix properties</u>

Eom (WI), Pan (MI), NHMFL

Y. Zhang et al., Applied Physics Letters 98, 042509

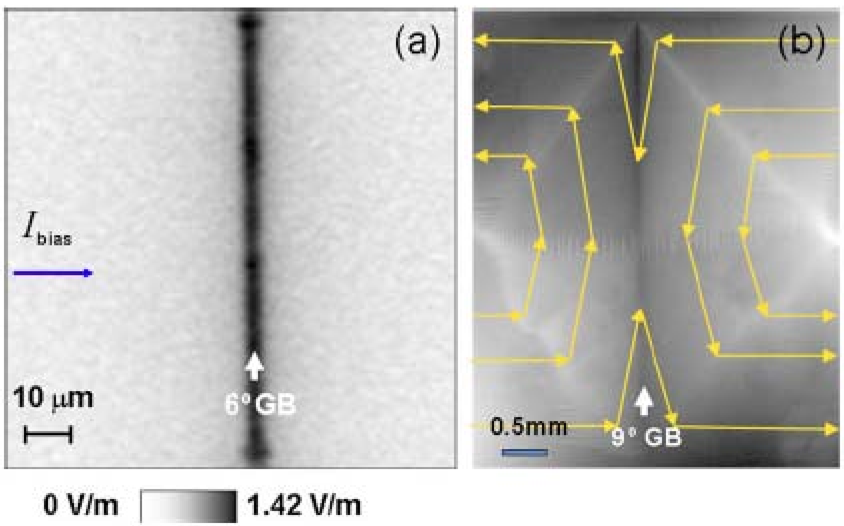
And truly spectacular H_{c2}…

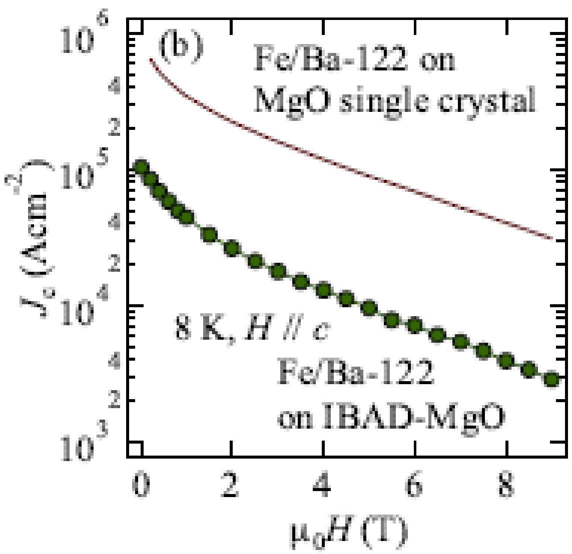


Tarantini et al. submitted (Collaboration with Ferdeghini, Wen)

But, like cuprates, $Ba(Fe_{1-x}Co_x)_2As_2$ (Co- doped Ba- 122) GBs are bad

- Grain boundaries are weak linked – but textured growth is working…





APPLIED PHYSICS LETTERS 95, 212505 (2009)

Weak-link behavior of grain boundaries in superconducting $Ba(Fe_{1-x}Co_x)_2As_2$ bicrystals

S. Lee,[1] J. Jiang,[2,a)] J. D. Weiss,[2] C. M. Folkman,[1] C. W. Bark,[1] C. Tarantini,[2] A. Xu,[2] D. Abraimov,[2] A. Polyanskii,[2] C. T. Nelson,[3] Y. Zhang,[3] S. H. Baek,[1] H. W. Jang,[1] A. Yamamoto,[2] F. Kametani,[2] X. Q. Pan,[3] E. E. Hellstrom,[2] A. Gurevich,[2] C. B. Eom,[1] and D. C. Larbalestier[2]

IFW-Dresden

Epitaxial Growth of Superconducting $Ba(Fe_{1-x}Co_x)_2As_2$ Thin Films on Technical Ion Beam Assisted Deposition MgO Substrates

Kazumasa Iida, Jens Hänisch, Sascha Trommler, Vladimir Matias[1], Silvia Haindl, Fritz Kurth, Irene Lucas del Pozo, Ruben Hühne, Martin Kidszun, Jan Engelmann, Ludwig Schultz, and Bernhard Holzapfel

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[1] Superconductivity Technology Center, Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.A.

Summary - III

- Applications require conductors
- Conductors must be
  - Long
  - Strong
  - Affordable
  - Uniform
  - Work at high Jc (> 1000 A/mm^2) in fields up to at least 10 T
- Preferably have
  - Good grain boundaries
  - No anisotropy
  - Tc well above liquid nitrogen

Today Nb-Ti (Tc = 9K, H_{c2}(4K) 10 T) is the conductor of choice
YBCO (Tc = 92K) is a potential challenger
The search is on for much higher Tc – but that is another story…..

My thanks

- To senior colleagues at the NHMFL
  - especially Alex Gurevich, Eric Hellstrom, Jan Jaroszynski, Jianyi Jiang, Peter Lee, Denis Markiewicz, and Ulf Trociewitz
- To DOE (HEP, Fusion and OETD), ITER, AFOSR and NSF for support
- To the nascent HEP committee with interest in Muon Colliders (Alvin Tollestrup and collaborators at Fermi, LBNL, BNL, NIST, LANL, TAMU)
- To present and former students and postdocs: Zhijun Chen, Aixia Xu, Pei Li, Fumitake Kametani, Akiyasu Yamamoto, David Myers and Tengming Chen some of whose data is here
- To pnictide collaborators in Madison Chang- Beom Eom and Sanghan Lee
- To many industrial collaborators
  - WDG (Terry Holesinger, Ron Feenstra, Marty Rupich, Xiaoping Li, Wei Zhang, Alex Malozemoff)
  - SuperPower (V. Selvamanickam, Yimin Chen, Yi Yuan and Drew Hazelton)
  - OST (Seung Hong, Ken Marken (now LANL), Hanping Miao, Maarten Meinesz, Yibing Huang)
  - Nexans (Mark Rikel)