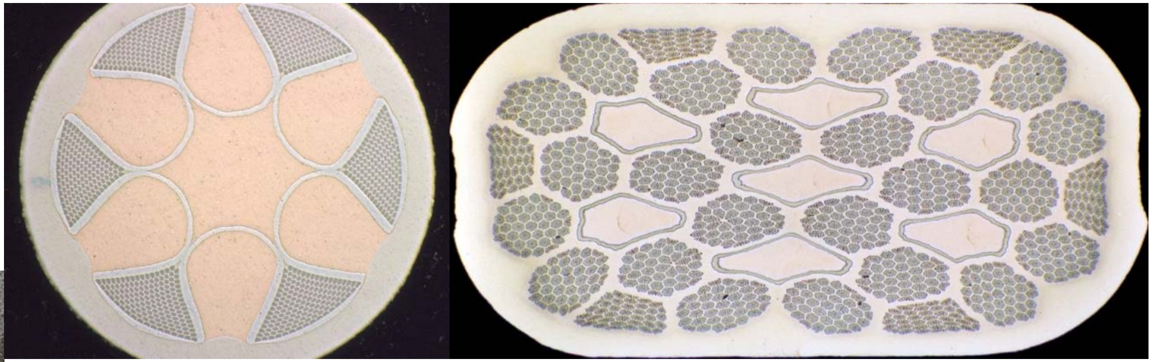
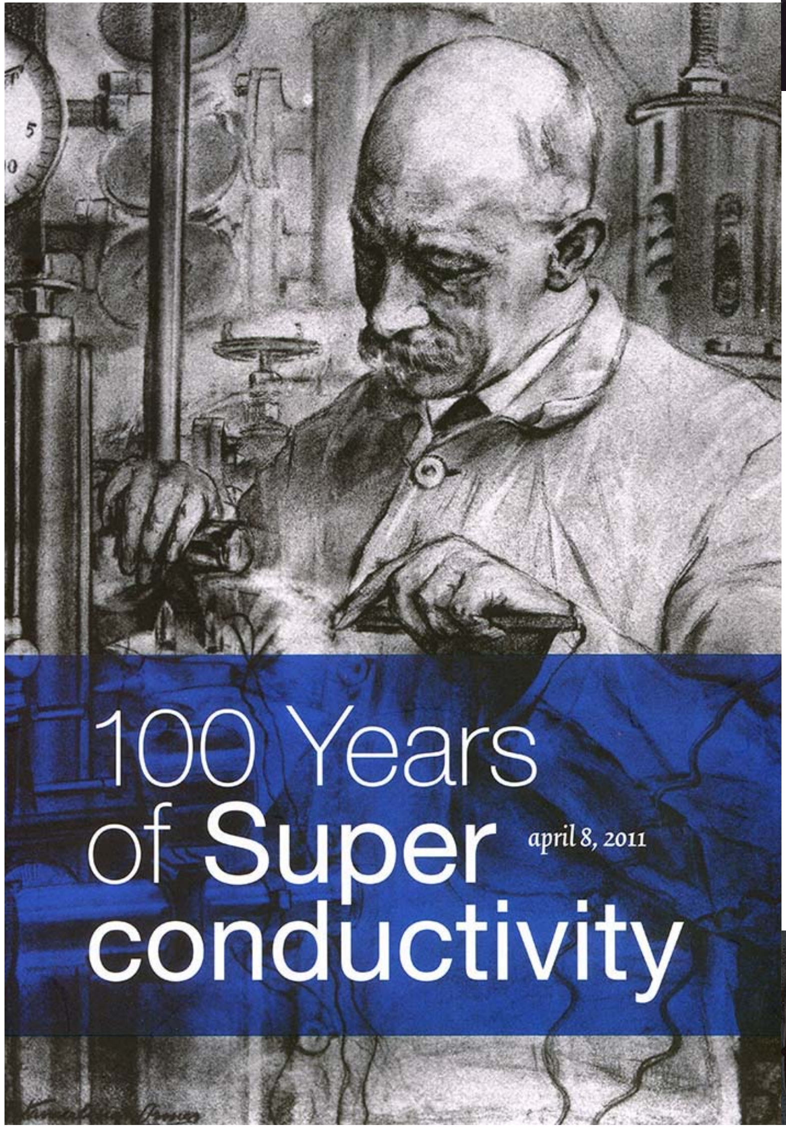
# Conductors from Superconductors





**David Larbalestier* and Peter J Lee**

Applied Superconductivity Center

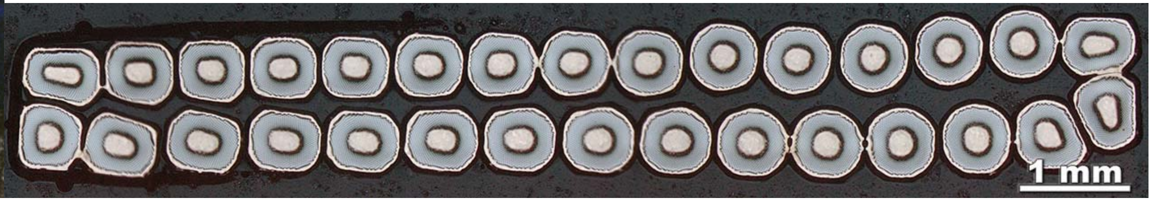
National High Magnetic Field Laboratory

Florida State University

**The Centennial Meeting on Superconductivity**

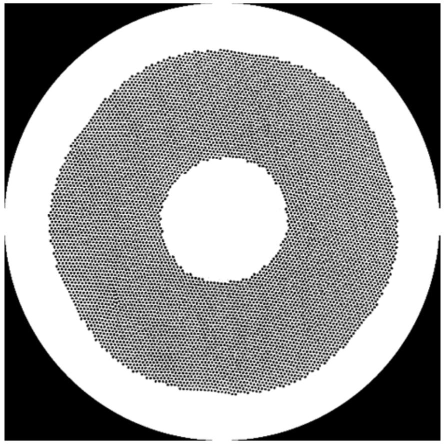
The Hague, The Netherlands, September 21, 2011

Grateful acknowledgement especially to DOE (HEP and OFES), ITER-IO and NSF-DMR for long term support
*IEEE Advisory Council on Superconductivity Distinguished Lecturer

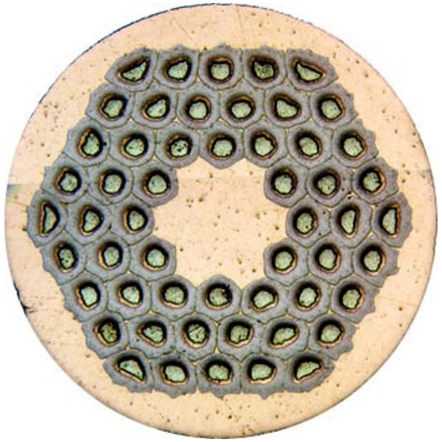


# My talk in one slide

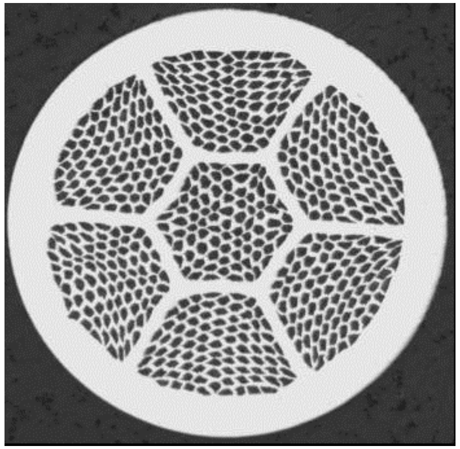
- Thousands of superconductors – 6 conductors - 2011
- Magnets are the “killer ap” - 1913
- The great silence – 1936-1961
- The explosion of applications – 1961-1987
- The explosion of high Tc – 1987 on
- The future………………..?



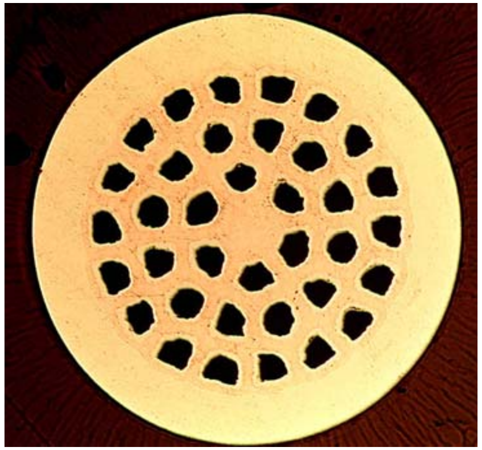
Nb47Ti



Internal Sn $Nb_3Sn$

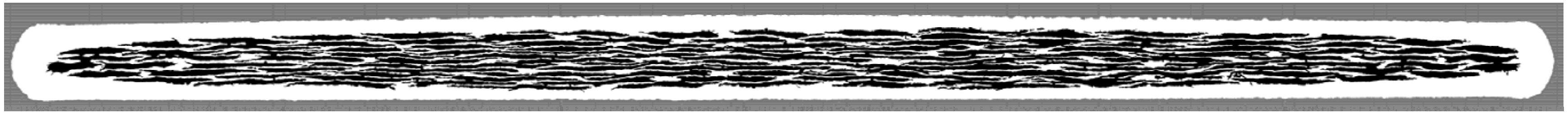


Bi-2212

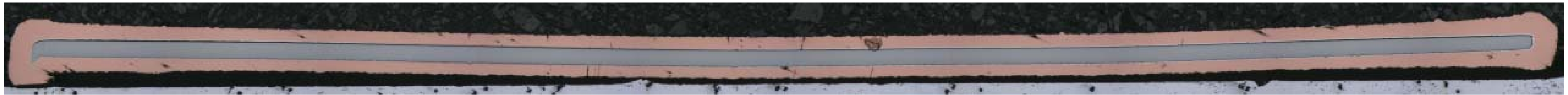


$MgB_2$

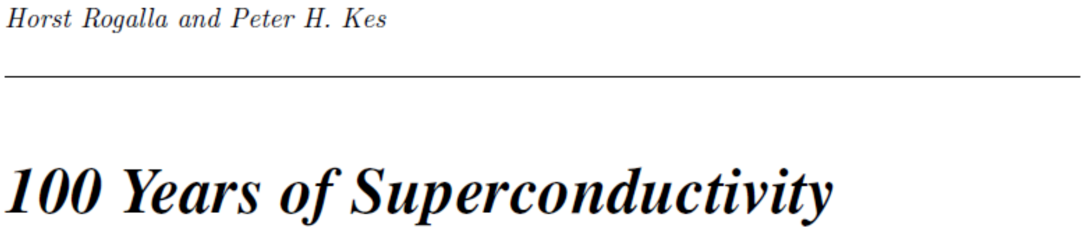
**Magnet wires should be long, strong, stable, affordable, have high critical current density, high upper critical field and preferably round**



Bi-2223

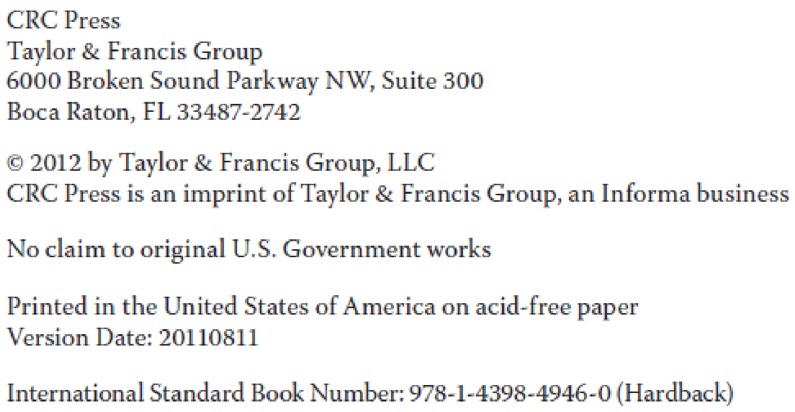


REBaCuO coated conductor



*Horst Rogalla and Peter H. Kes*

# *100 Years of Superconductivity*



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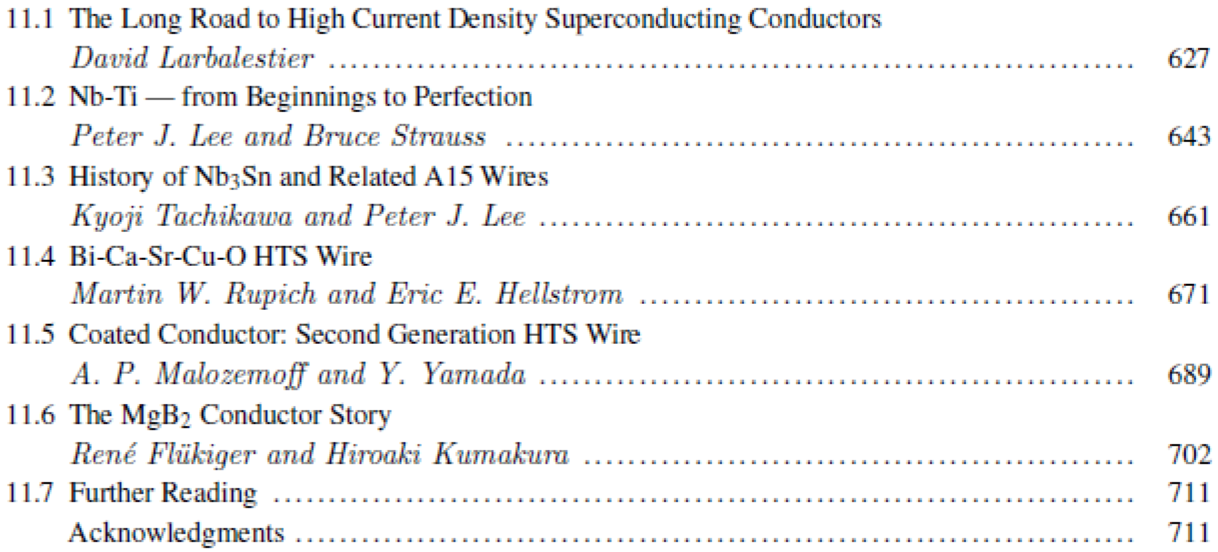
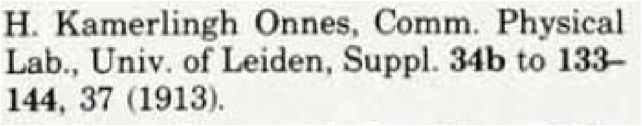
## Chapter 11: Wires and Tapes

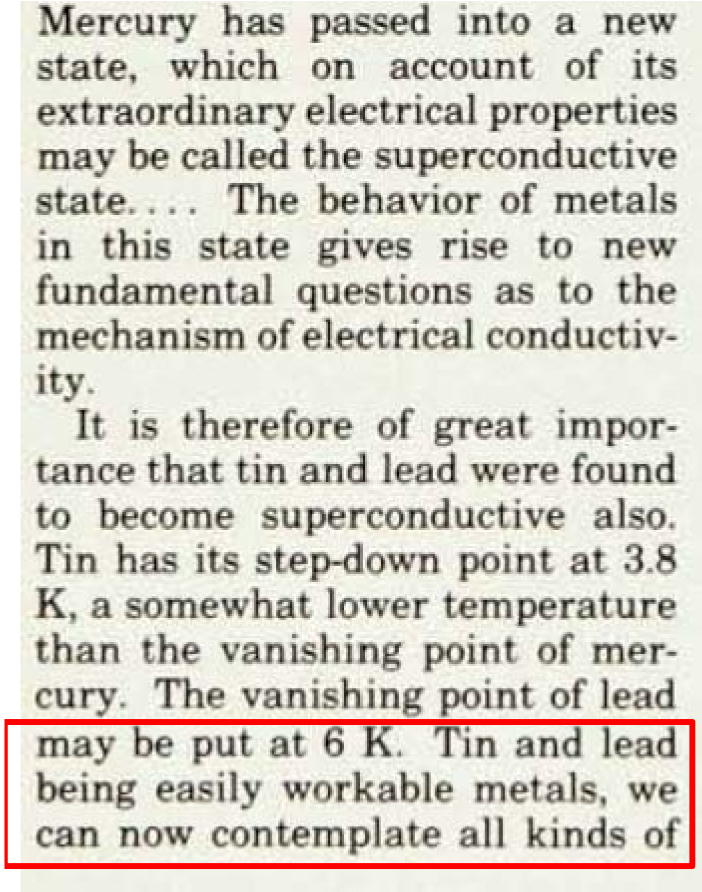
**Editor: David Larbalestier**



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

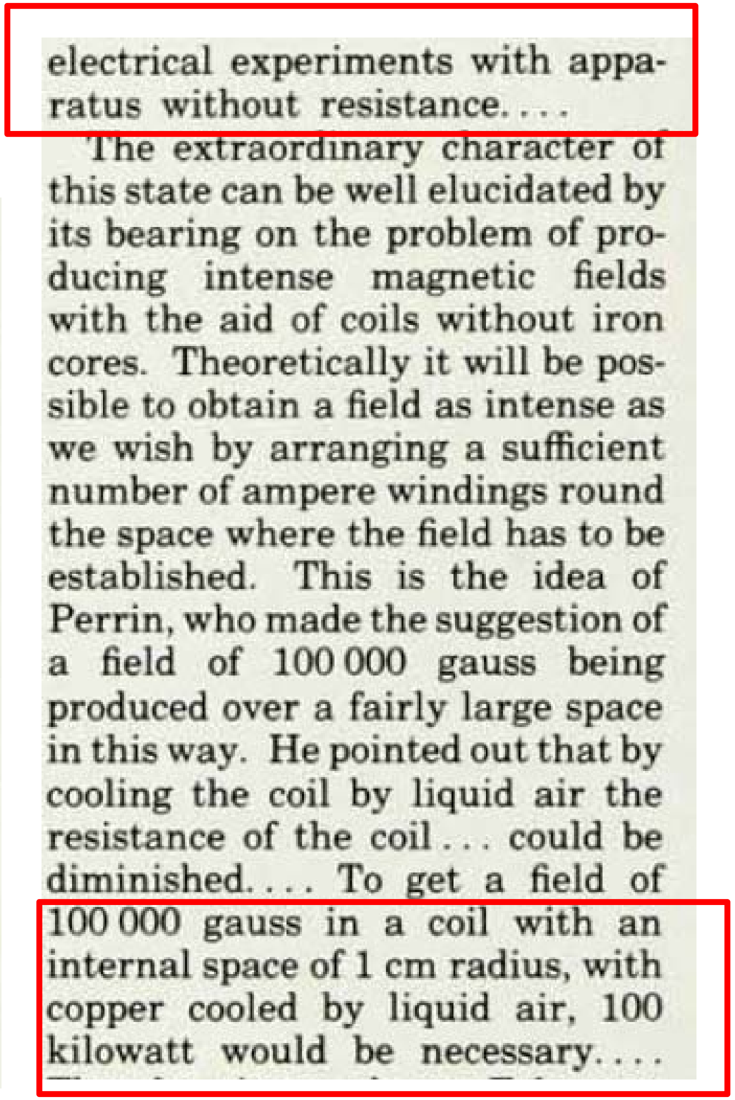


H. Kamerlingh Onnes, Comm. Physical Lab., Univ. of Leiden, Suppl. **34b** to **133–144**, 37 (1913).



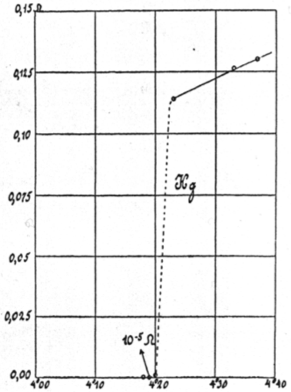
Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state. . . . The behavior of metals in this state gives rise to new fundamental questions as to the mechanism of electrical conductivity.

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

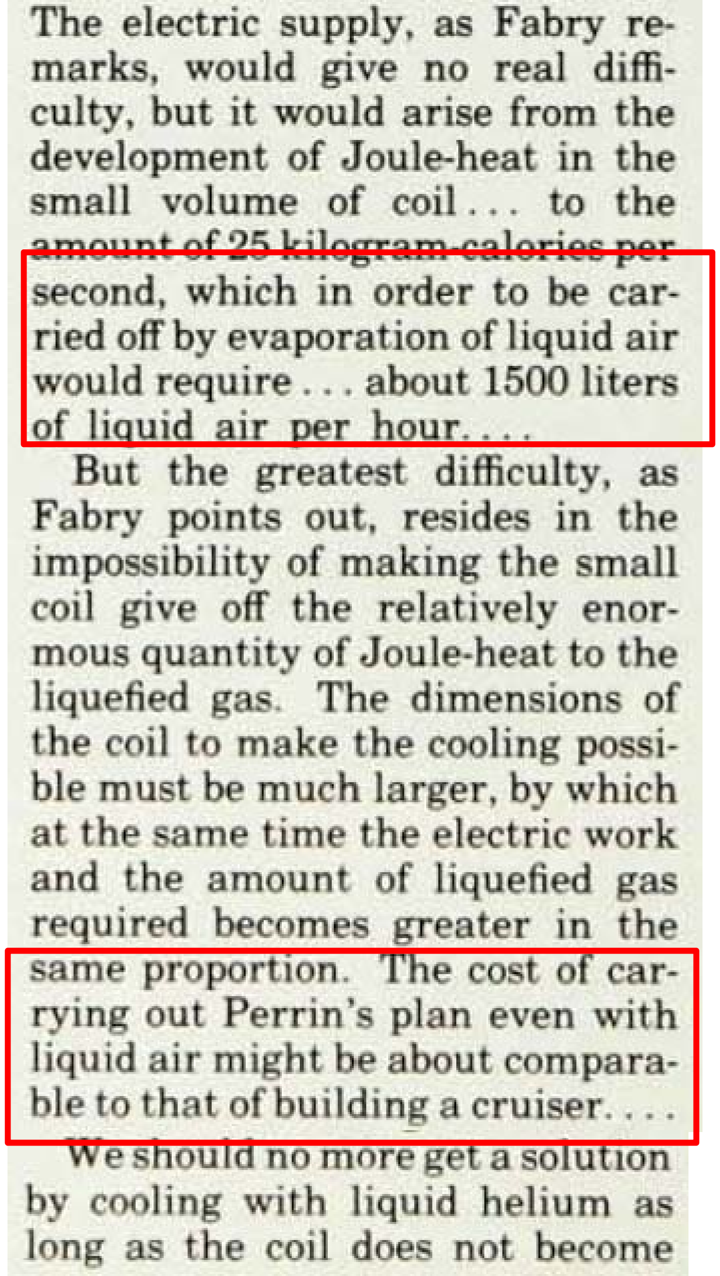


electrical experiments with apparatus without resistance. . . .

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. . . .



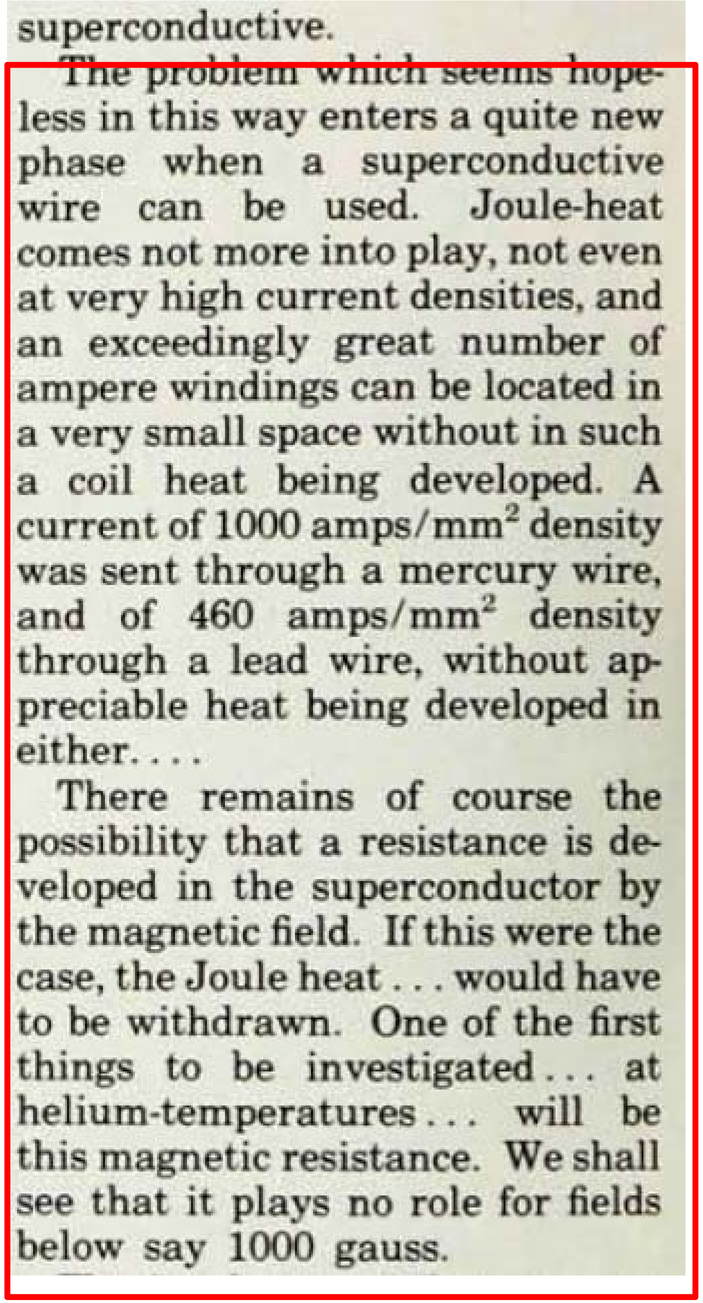
*Actually Keesom gave the talk as Kamerlingh Onnes was indisposed



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. . . .

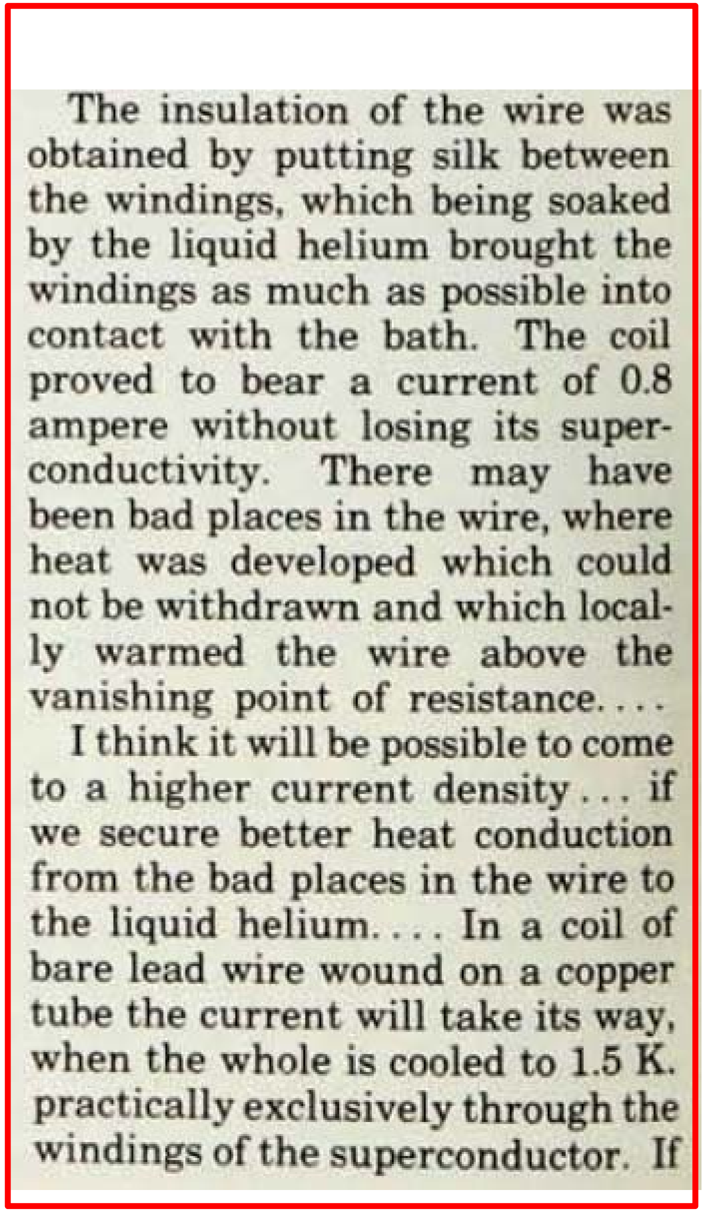
We should no more get a solution by cooling with liquid helium as long as the coil does not become



superconductive.

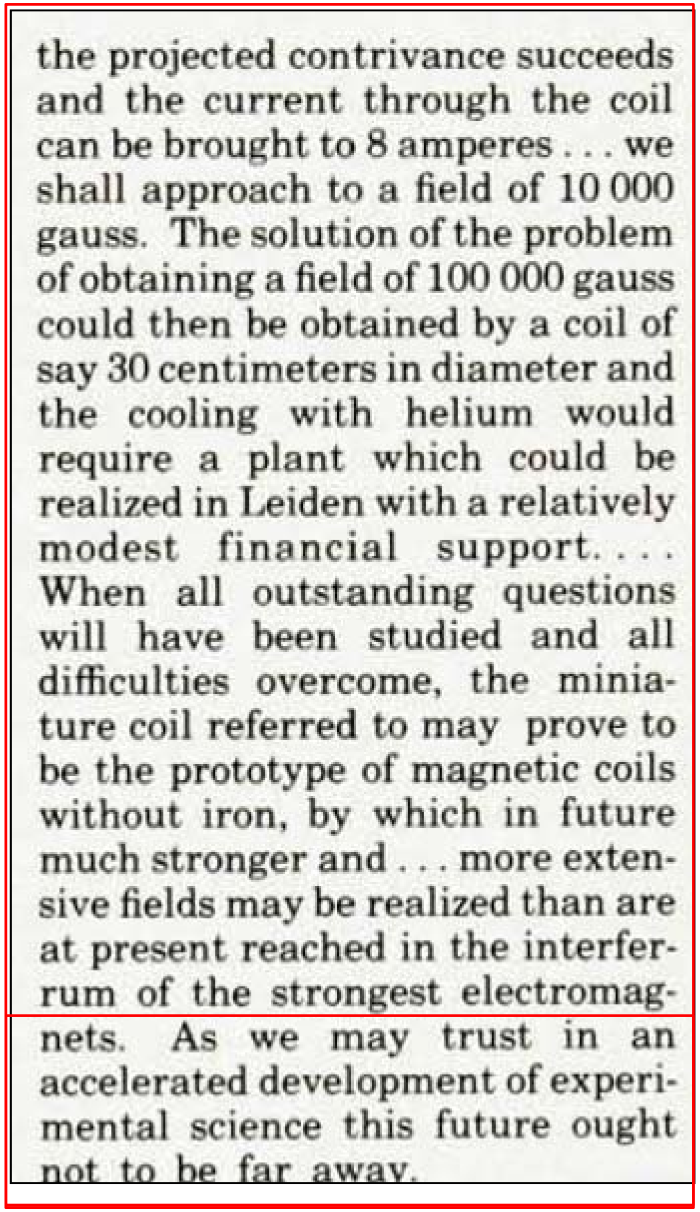
The problem which seems hopeless in this way enters a quite new phase when a superconductive wire can be used. Joule-heat comes not more into play, not even at very high current densities, and an exceedingly great number of ampere windings can be located in a very small space without in such a coil heat 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.



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

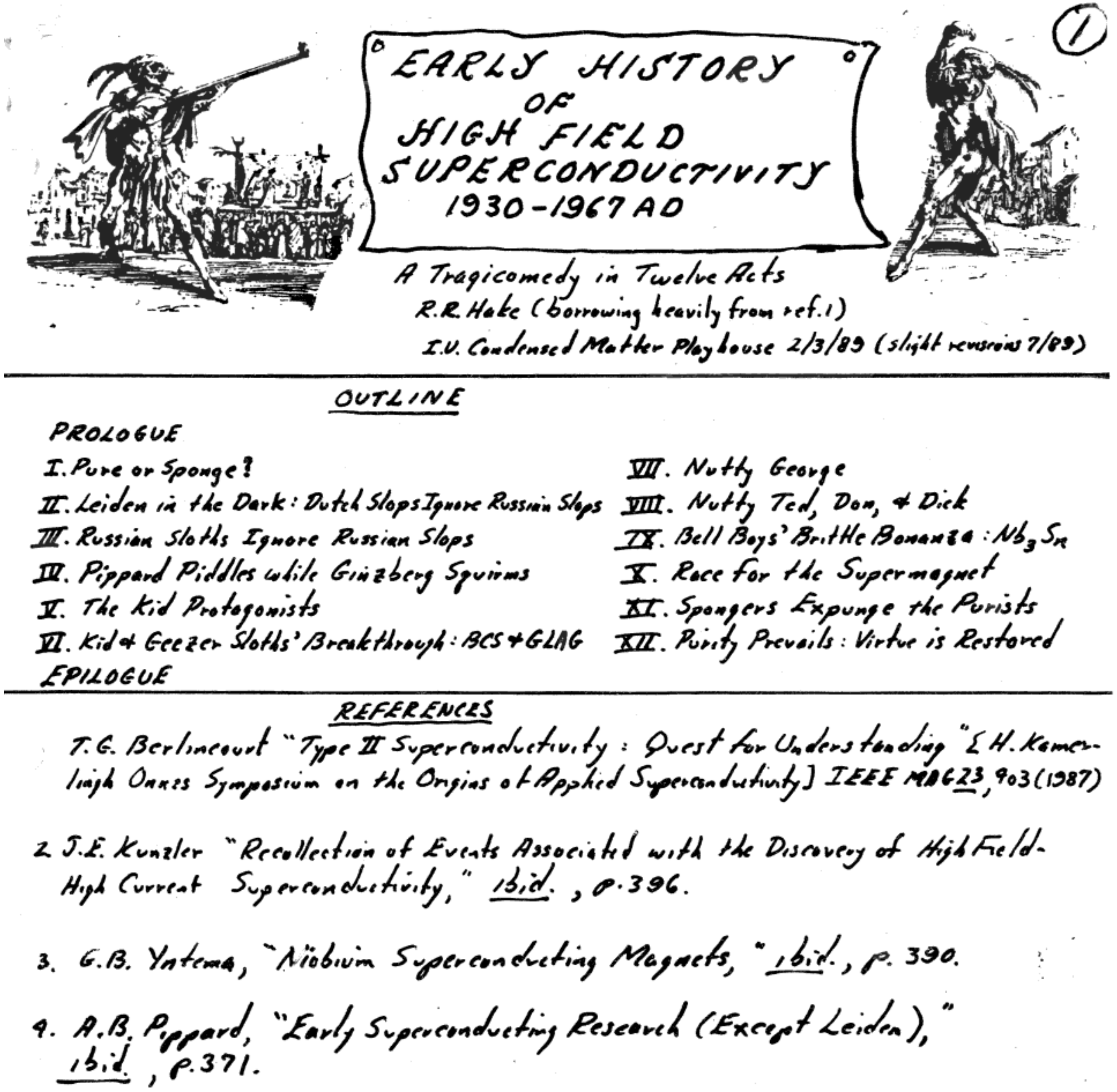


the projected contrivance succeeds and the current through the coil can be brought to 8 amperes . . . we shall approach to a field of 10 000 gauss. The solution of the problem of obtaining a field of 100 000 gauss could then be obtained by a coil of say 30 centimeters in diameter and the cooling with 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

# The great silence: 1914-1961



①

EARLY HISTORY
OF
HIGH FIELD
SUPERCONDUCTIVITY
1930-1967 AD

A Tragicomedy in Twelve Acts
R.R. Hake (borrowing heavily from ref. 1)
I.U. Condensed Matter Playhouse 2/3/89 (slight revisions 7/89)

OUTLINE

PROLOGUE

I. Pure or Sponge?
II. Leiden in the Dark: Dutch Slops Ignore Russian Slops
III. Russian Sloths Ignore Russian Slops
IV. Pippard Piddles while Ginzberg Squirms
V. The Kid Protogonists
VI. Kid + Geezer Sloths' Breakthrough: BCS + GLAG
VII. Nutty George
VIII. Nutty Ted, Don, + Dick
IX. Bell Boys' Brittle Bonanza: $Nb_3Sn$
X. Race for the Supermagnet
XI. Spongers Expunge the Purists
XII. Purity Prevails: Virtue is Restored

EPILOGUE

REFERENCES

T.G. Berlincourt "Type II Superconductivity: Quest for Understanding" [H. Kamerlingh Onnes Symposium on the Origins of Applied Superconductivity] IEEE MAG 23, 903 (1987)

2. J.E. Kunzler "Recollection of Events Associated with the Discovery of High Field-High Current Superconductivity," ibid., p. 396.

3. G.B. Yntema, "Niobium Superconducting Magnets," ibid., p. 390.

4. A.B. Pippard, "Early Superconducting Research (Except Leiden)," ibid., p. 371.

# The Dick Hake Story (U. of Indiana and Atomics International)

# ACT I. PURE OR SPONGE?

W.J. de Haas & J. Voogd, Commun. Phys. Lab
U. Leiden #208b (1930); *ibid.* #214b (1931)

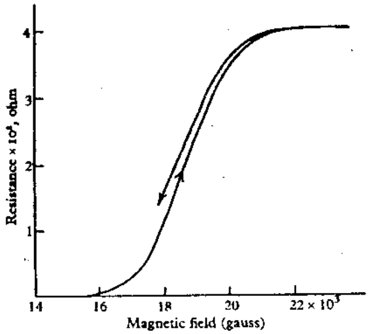


Fig. 14. Restoration of resistance of Pb-Bi eutectic by a magnetic field at 4·2° K. (de Haas and Voogd, 1930).

[Attempt
technolo
applicat
producti
H-fields
conducti
Solenoids
(1935) on
(1935)

## Early Ideas on High-Field Superconducti

I. Could be bulk property of HOMOGENEOU
(**PURE**) materials associated with negati
interphase surface energy:

H. London, Proc. Roy. Soc. (London) A152, 65
C.J. Gorter, Physica 2, 449 (1935)
(says $H_{max} \simeq \frac{\lambda}{\xi} H_c$) ← Thermodynamic Cr
Gorter's "minimum superconductor" i same as GL coher

II K. Mendellsohn Proc. Roy Soc. (London) A152, 34

"We think that all experimental results so far obta on IMPURE "(our caps + underline) metals and on a can be explained by their INHOMOGENEITY (us causes the formation of a **SPONGE** of higher value."

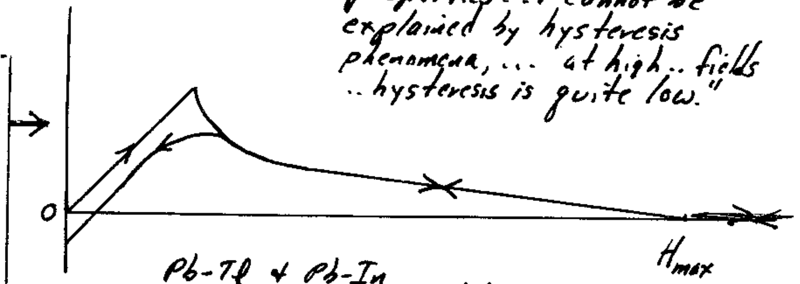
## III. THE CRUCIAL EXPERIMENT.

⑤

L.V. Shubnikov, V.I. Khotkevich, J.D. Shepelev, J.N. Rjabinin, J. Exptl. Theoret. Phys. (USSR) 7, 221 (1937) [Portions were reported in English!: J.N. Rjabinin and L.V. Shubnikov, Nature 135, 581 (1935); Phys. Z. Sowjet 7, 122 (1935).]

"Such unusual magnetic properties... cannot be explained by hysteresis phenomena, ... at high.. fields ..hysteresis is quite low."

This work ignored for 20 YEARS until Abrikosov compared this date with his theory in 1957!!



Pb-Tl & Pb-In
Single Phase Single Crystals

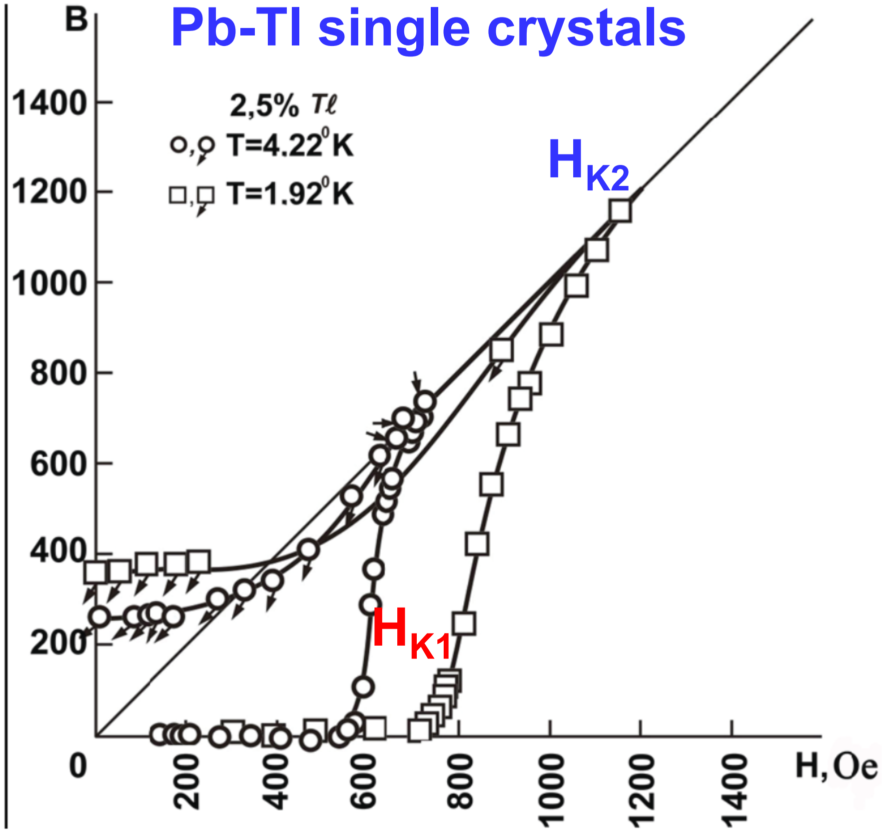
Shubnikov *et al.* said:

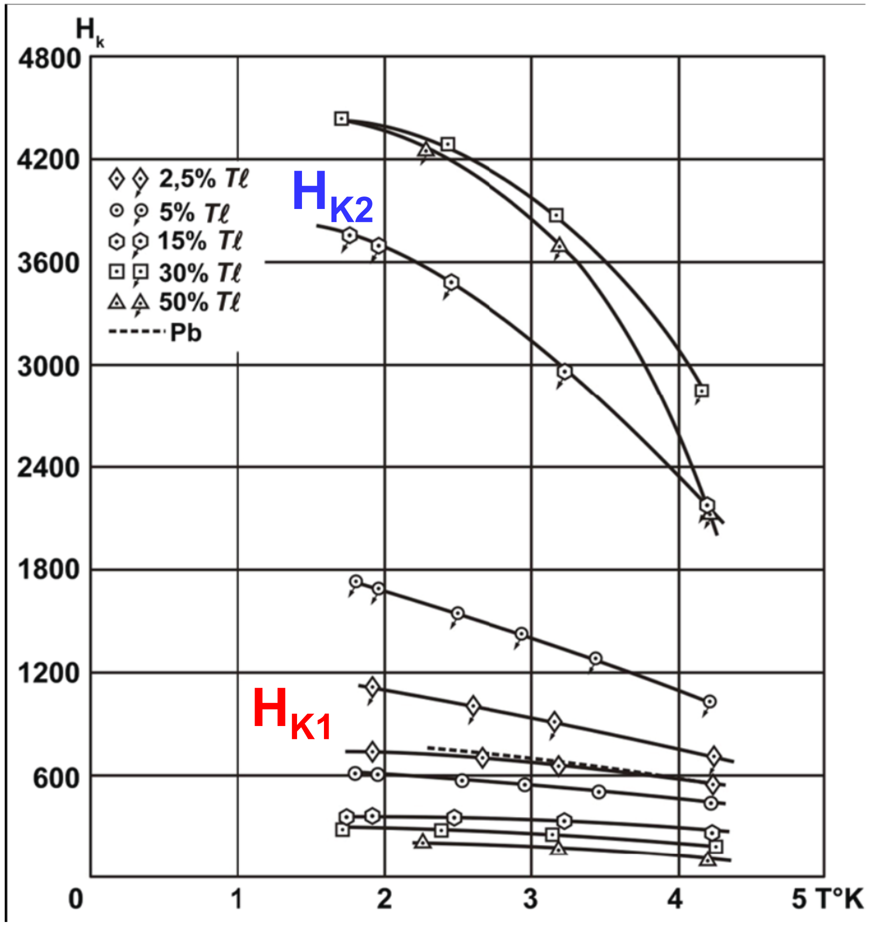
1. $\int M dH$ = Superconducting state condensation energy
2. Even though Hmax exceeds $H_c$ of pure metals, the condensation energies are are comparable and depend on T in the same way
3. The zero-field specific heat jump in an alloy superconductor should be comparable to that of a pure superconductor, (and not have gigantic value, expected if complete flux expulsion existed up to Hmax).

BUT SHUBNIKOV *et al.* "FAILED TO EXPLOIT THEIR NEWFOUND UNDERSTADING"... (making) "no mention of the Gorter-H. London theory.... "nor of the Mendelssohn SPONGE..." T.G. Berlincourt

# 1936: Type II Superconductivity discovered – and unappreciated

**Pb-Tl single crystals**

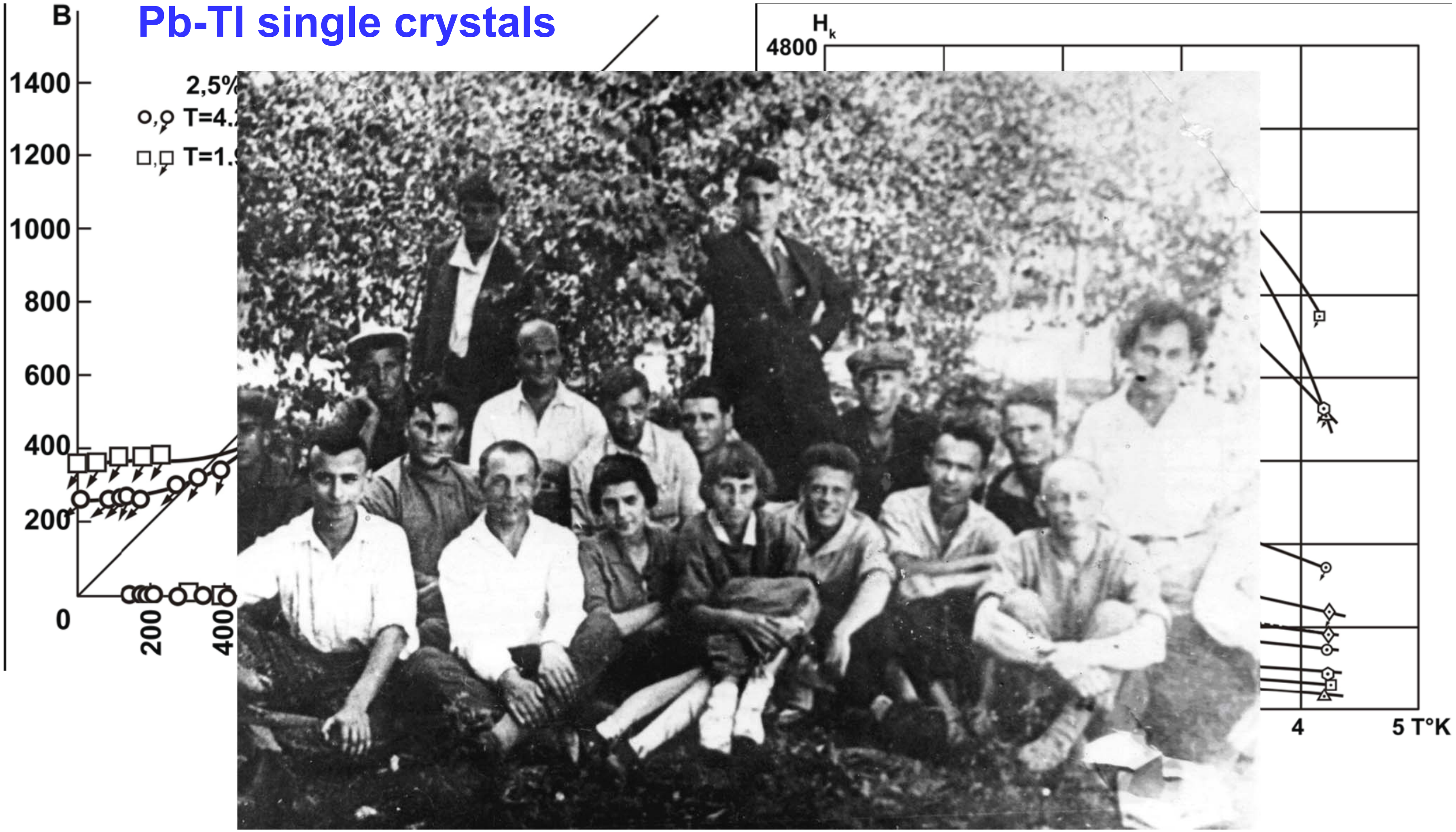




L.V.Shubnikov et al., *Zh. Exper. Teor. Fiz. (USSR)* **7**, 221 (1937)
L.W.Schubnikow et al., *Sondernummer Phys.Z.Sowiet. Arbeiten auf dem Gebiete tiefer Temperaturen,* 39 (1936); *Phys.Z.Sowiet.* **10**, 165 (1936)
A.G. Shepelev, In: Superconductor (ed. A.M. Luiz), Sciyo, Rijeka (2010), p.17; http://www.intechopen.com/books/show/title/superconductor.

# 1936: Type II Superconductivity discovered – and unappreciated

**Pb-Tl single crystals**



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

## ACT III. RUSSIAN SLOTHS IGNORE RUSSIA

V.L. Ginzburg and L.D. Landau, Zh. Eks
i Teor. Fiz. 20, 1064 (1950).

"It has not been necessary to investiga the nature of the state which occur when $k > 1/\sqrt{2}$, since from the experimental data . . . . it follows $k \ll 1$." [Apparently oblivious o Schubnikov *et al.*!

K. Mendelssohn to T.G. Berlincourt

"It was extremely nice of you to send me a copy of your own paper, as well as a translation of Shubnikov's paper published in 1937. This is indeed of considerable help in assessing the earlier developments. At that time the Stalin Purge was only beginning, and I was very puzzled at the blanks I drew in trying to get in touch with Shubnikov. In 1957 Landau introduced me in Moscow to Shubnikov's widow, Olga Trapeznikova, who also is a physicist. She told me that her husband had just been exonerated posthumously from all charges. This made it possible for Abrikosov to refer to Shubnikov's papers, since up to then Soviet etiquette required that anyone who had disappeared in the purges had never lived."

(According to Balabekyan, (1966) Sh was unjustly arrested in 19 sentenced to 10 years impri and died in 1945.)

## ACT IV. PIPPARD PIDDLES WHILE GINZBURG SQUIRMS

In 1951-53 Pippard used intuitive ideas to explain that a short electron mean free path would lead to negative surface energy. He was aware of GL-theory and the Gorter - H. London ideas.

PIPPARD IS VERY SMART!

WHY DIDN'T PIPPARD PUT IT ALL TOGETHER?

"So in the early 1950's there was a certain amount of conflict which wasn't helped, incidentally, by the fact that Ginzburg kept on writing small papers in which he said it would be much better if we interpreted the electronic charge as not being exactly e, but e times a small numerical factor which might be as large as 2! He didn't say it was exactly 2; instead he wanted to introduce a fudge factor of (say) 1.6, and Landau kept on telling him he couldn't just put in arbitrary numbers, and muttered darkly about gauge invariance going wrong if you did."

A.B. Pippard in
"Historical Context of
Josephson's Discovery"
in SQUIDS + Machines (Plenum, 1977) p.1.

# ACT V. THE KID AND GEEZER SLOT TEAM UP FOR SOME BREAK BCS AND GLAG

NOBEL PRIZE WINNING MICROSCOPIC THEORY OF SUPECON

J. Bardeen, L.N. Cooper, J.R. Schrieffe

Phys. Rev. 108, 1175 (1957)

L.P. Gor'kov, Zh. Eksperim. i Teor. Fiz

1918 (1959); Sov. Phys. JETP 9,

1364 (1959)

[In "dirty limit" $H_{c2}(T=0) = (\text{const.})$

GLAG: Ginzburg, Landau, Abrikosov,

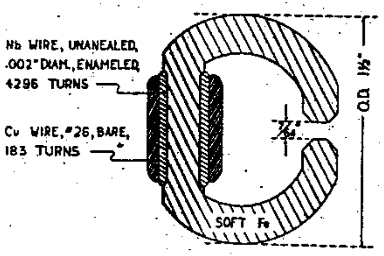
The basic theory of high-field superconductivity (except for the paramagnetic limitation) is in place in 1959 but virtually ignored until 1962!

# ACT VII. NUTTY GEORGE

G.B. Yntema, Phys. Rev. 98, 1197 (1955)

Also (unaware of Yntema): S.H. Autler, Bull. Am. Phys. Soc. 4, 413 (1959)

FIRST SUPERCONDUCTING-WIRE MAGNET



0.71 Tesla

Cold-drawn Nb wire

Figure 2. Electromagnet with superconducting niobium windings, horizontal cross-section. Magnet constructed at University of Illinois in 1954.

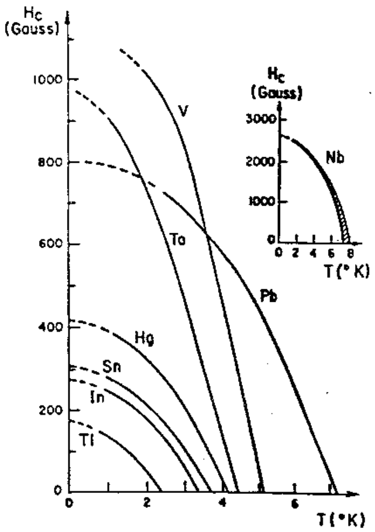


Figure 1. Critical fields as functions of temperature. Traced from figure compiled by D. Shoenberg, 1952 (Ref. 1).

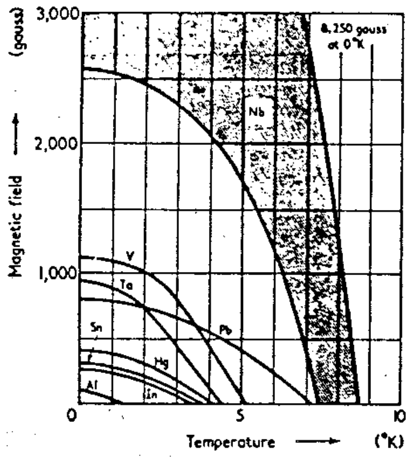
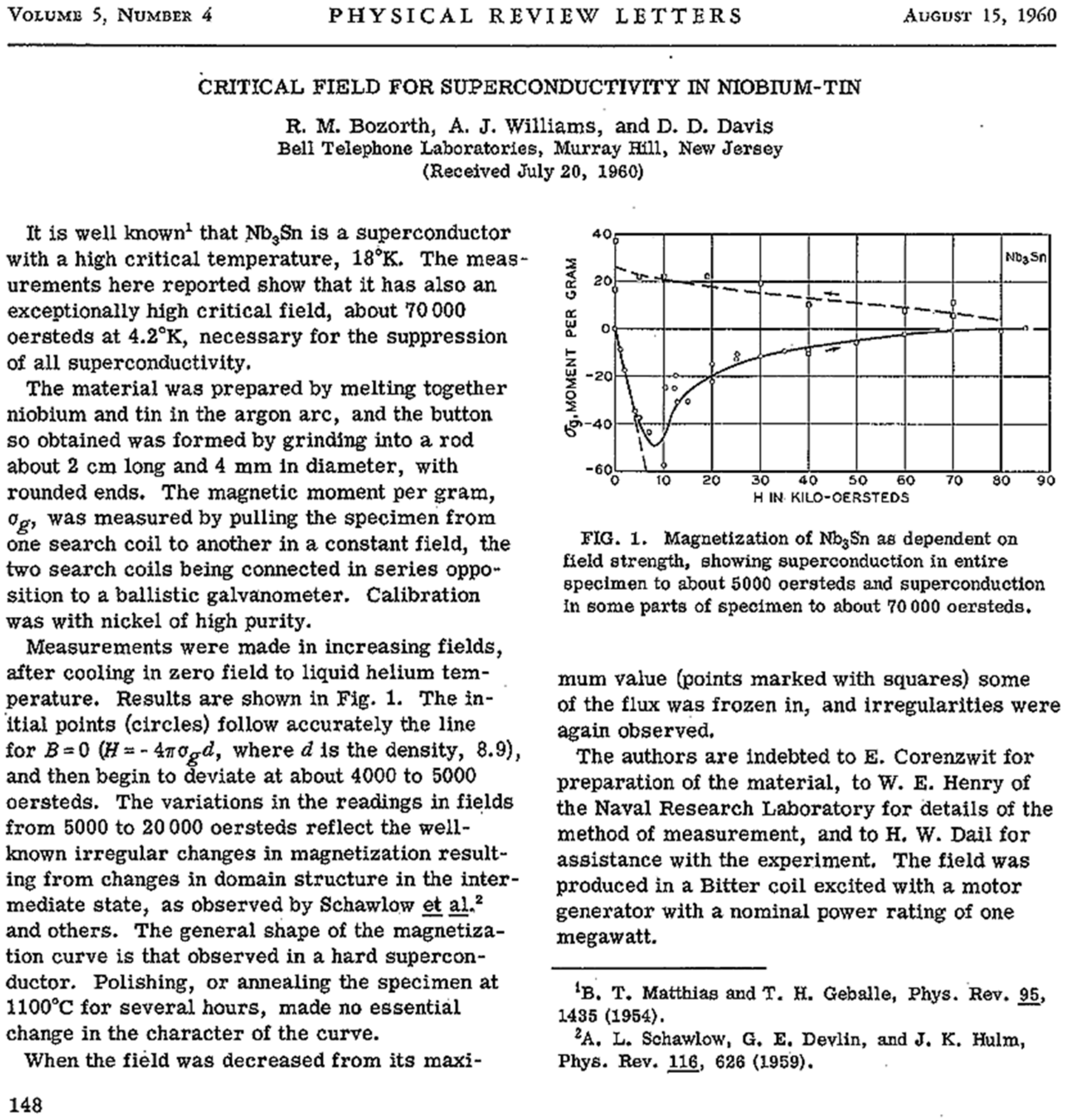


Figure 8. Critical fields as functions of temperature. The shaded area shown for niobium illustrates the variation in reported values. Compiled by V. D. Arp and R. H. Kropschot, 1960 (Ref. 18).

# Almost there in July 1960……



VOLUME 5, NUMBER 4 PHYSICAL REVIEW LETTERS AUGUST 15, 1960

## CRITICAL FIELD FOR SUPERCONDUCTIVITY IN NIOBIUM-TIN

R. M. Bozorth, A. J. Williams, and D. D. Davis
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received July 20, 1960)

It is well known[1] that Nb$_3$Sn is a superconductor with a high critical temperature, 18°K. The measurements here reported show that it has also an exceptionally high critical field, about 70 000 oersteds at 4.2°K, necessary for the suppression of all superconductivity.

The material was prepared by melting together niobium and tin in the argon arc, and the button so obtained was formed by grinding into a rod about 2 cm long and 4 mm in diameter, with rounded ends. The magnetic moment per gram, $\sigma_g$, was measured by pulling the specimen from one search coil to another in a constant field, the two search coils being connected in series opposition to a ballistic galvanometer. Calibration was with nickel of high purity.

Measurements were made in increasing fields, after cooling in zero field to liquid helium temperature. Results are shown in Fig. 1. The initial points (circles) follow accurately the line for $B=0$ ($H=-4\pi\sigma_g d$, where $d$ is the density, 8.9), and then begin to deviate at about 4000 to 5000 oersteds. The variations in the readings in fields from 5000 to 20 000 oersteds reflect the well-known irregular changes in magnetization resulting from changes in domain structure in the intermediate state, as observed by Schawlow *et al.*[2] and others. The general shape of the magnetization curve is that observed in a hard superconductor. Polishing, or annealing the specimen at 1100°C for several hours, made no essential change in the character of the curve.

FIG. 1. Magnetization of Nb$_3$Sn as dependent on field strength, showing superconduction in entire specimen to about 5000 oersteds and superconduction in some parts of specimen to about 70 000 oersteds.

When the field was decreased from its maximum value (points marked with squares) some of the flux was frozen in, and irregularities were again observed.

The authors are indebted to E. Corenzwit for preparation of the material, to W. E. Henry of the Naval Research Laboratory for details of the method of measurement, and to H. W. Dail for assistance with the experiment. The field was produced in a Bitter coil excited with a motor generator with a nominal power rating of one megawatt.

---

[1] B. T. Matthias and T. H. Geballe, Phys. Rev. 95, 1435 (1954).

[2] A. L. Schawlow, G. E. Devlin, and J. K. Hulm, Phys. Rev. 116, 626 (1959).

# Almost there in July 1960……

VOLUME 5, NUMBER 4 PHYSICAL REVI

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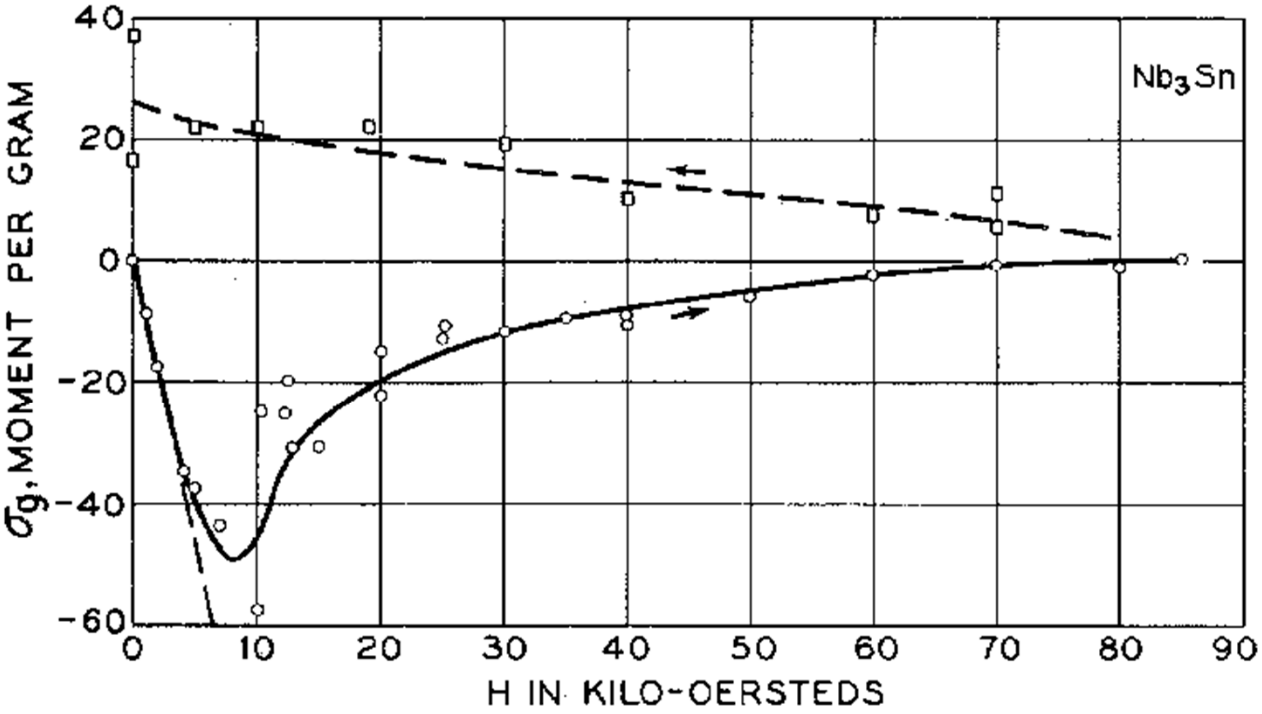
R. M. Bozorth, A. J. Will
Bell Telephone Laboratories,
(Received July

It is well known[1] that $Nb_3Sn$ is a superconductor with a high critical temperature, 18°K. The measurements here reported show that it has also an exceptionally high critical field, about 70 000 oersteds at 4.2°K, necessary for the suppression of all superconductivity.

The material was prepared by melting together niobium and tin in the argon arc, and the button so obtained was formed by grinding into a rod about 2 cm long and 4 mm in diameter, with rounded ends. The magnetic moment per gram, $\sigma_g$, was measured by pulling the specimen from one search coil to another in a constant field, the two search coils being connected in series opposition to a ballistic galvanometer. Calibration was with nickel of high purity.

Measurements were made in increasing fields, after cooling in zero field to liquid helium temperature. Results are shown in Fig. 1. The initial points (circles) follow accurately the line for $B = 0$ ($H = -4\pi\sigma_g d$, where $d$ is the density, 8.9), and then begin to deviate at about 4000 to 5000 oersteds. The variations in the readings in fields from 5000 to 20 000 oersteds reflect the well-known irregular changes in magnetization resulting from changes in domain structure in the intermediate state, as observed by Schawlow et al.[2] and others. The general shape of the magnetization curve is that observed in a hard superconductor. Polishing, or annealing the specimen at 1100°C for several hours, made no essential change in the character of the curve.

When the field was decreased from its maximum value (points marked with squares) some of the flux was frozen in, and irregularities were again observed.



The authors are indebted to E. Corenzwit for preparation of the material, to W. E. Henry of the Naval Research Laboratory for details of the method of measurement, and to H. W. Dail for assistance with the experiment. The field was produced in a Bitter coil excited with a motor generator with a nominal power rating of one megawatt.

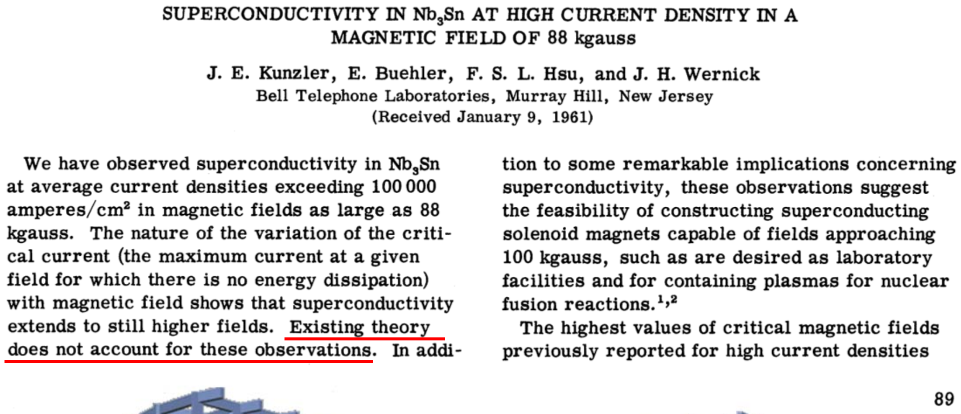
---

[1] B. T. Matthias and T. H. Geballe, Phys. Rev. 95, 1435 (1954).

[2] A. L. Schawlow, G. E. Devlin, and J. K. Hulm, Phys. Rev. 116, 626 (1959).

A one page PRL – but no Bean Model yet, no way to relate magnetization hysteresis to Jc

# Decisive experiment only in late 1960



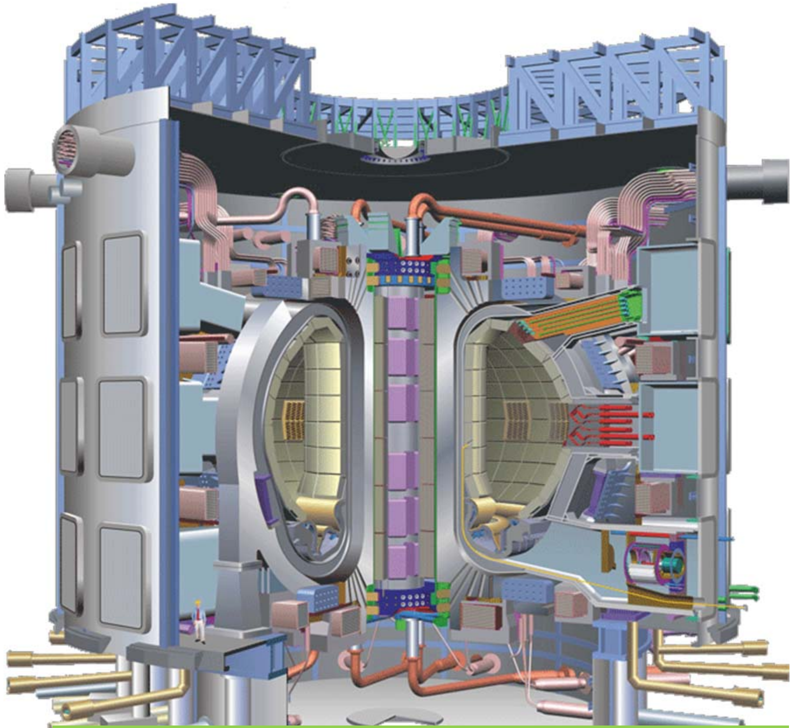
SUPERCONDUCTIVITY IN $Nb_3Sn$ AT HIGH CURRENT DENSITY IN A MAGNETIC FIELD OF 88 kgauss

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

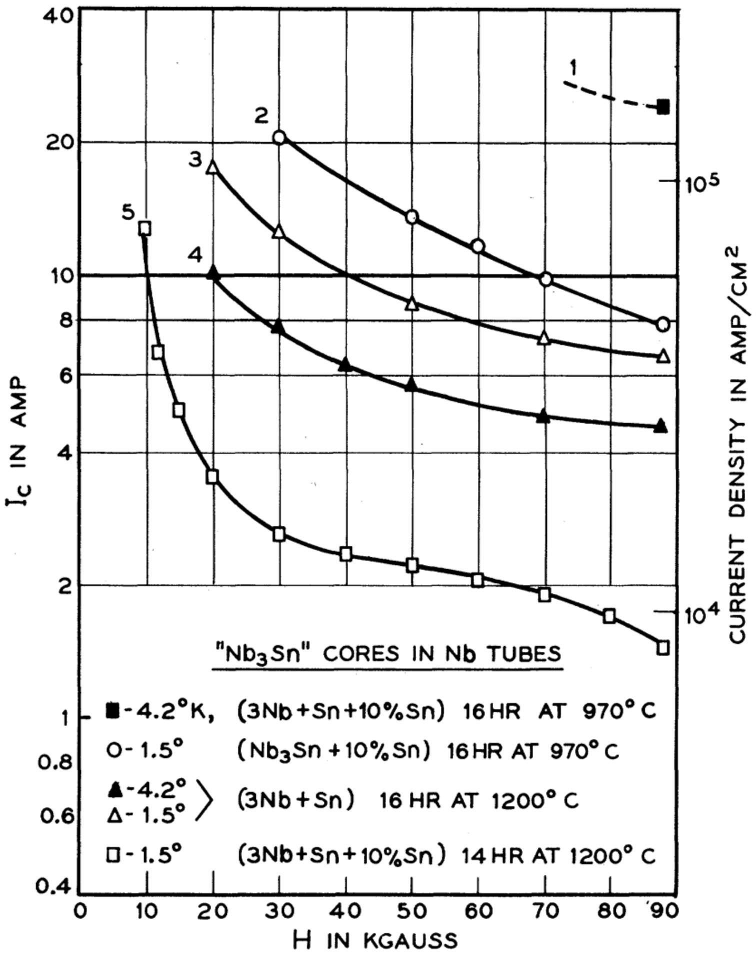
We have observed superconductivity in $Nb_3Sn$ at average current densities exceeding 100 000 amperes/cm² in magnetic fields as large as 88 kgauss. The nature of the variation of the critical current (the maximum current at a given field for which there is no energy dissipation) with magnetic field shows 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

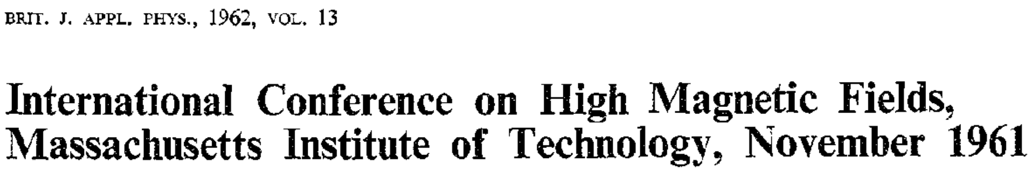


ITER uses 600 tonnes of $Nb_3Sn$



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

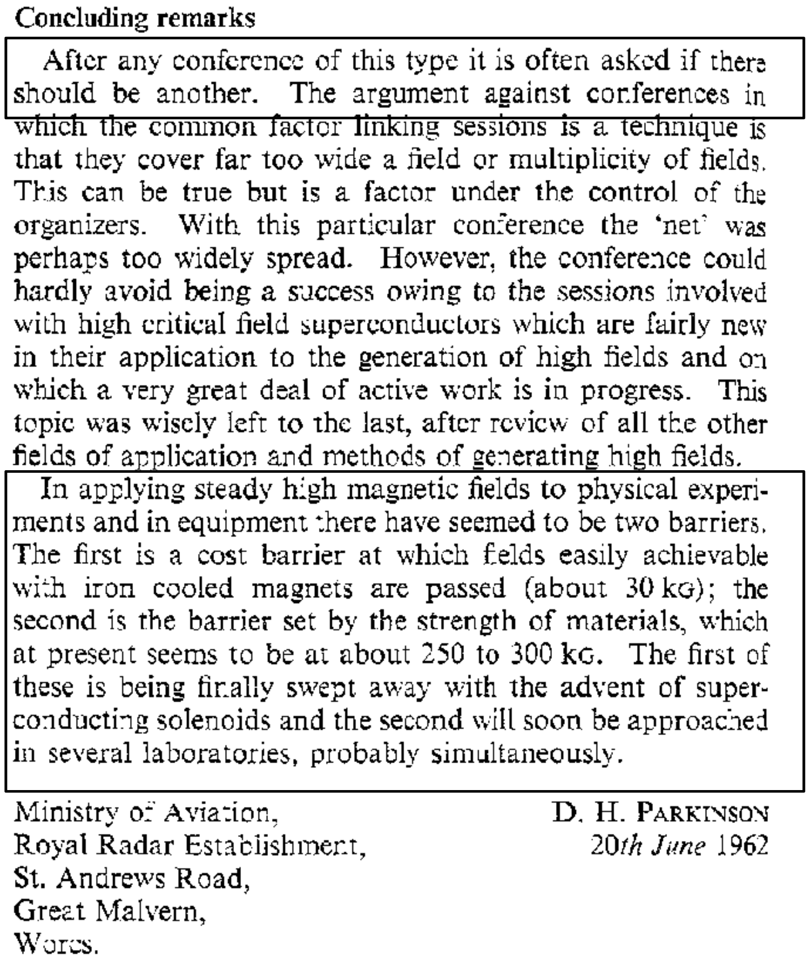
# The November1961 magnet Technology Conference at MIT



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$_3$Sn | 0.25” |
| Atomics International | 5.9 T | Nb25Zr | 0.5” |
| Westinghouse | 5.6 T | Nb25Zr | 0.15” |



**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.

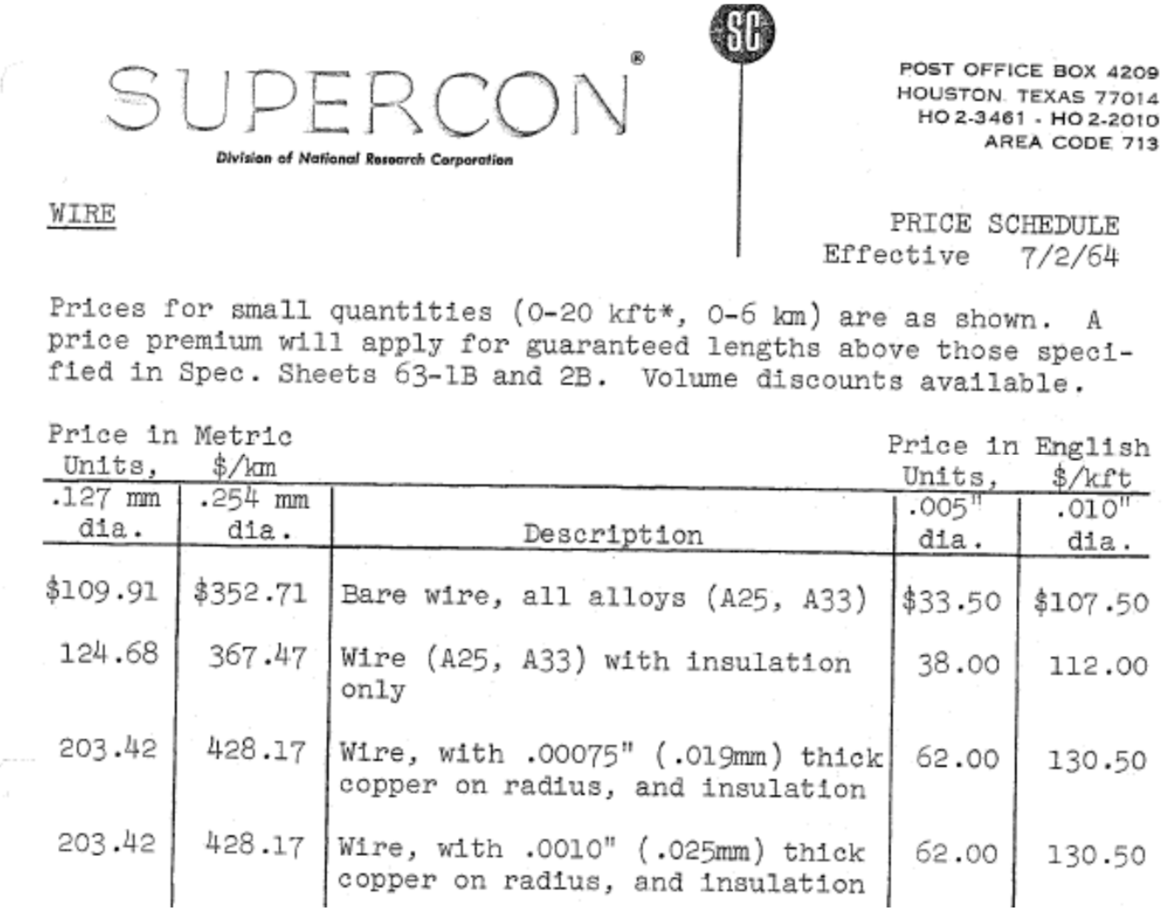
Ministry of Aviation,
Royal Radar Establishment,
St. Andrews Road,
Great Malvern,
Worcs.

D. H. PARKINSON
*20th June* 1962

# 1962: The 1st European coil

$I_c$ = 17 A, $B_{max}$ ~ 4 T

# Superconductor price list - 1964



SUPERCON®

Division of National Research Corporation

POST OFFICE BOX 4209
HOUSTON, TEXAS 77014
HO 2-3461 - HO 2-2010
AREA CODE 713

WIRE

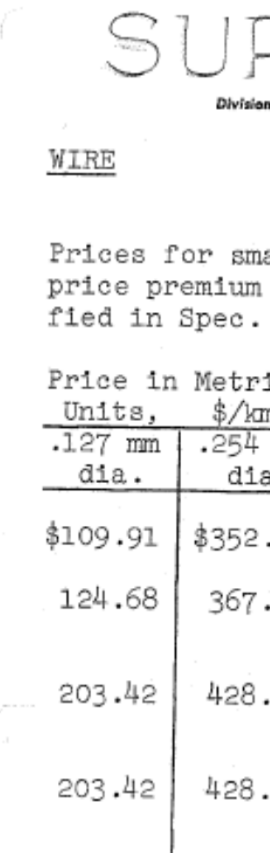
PRICE SCHEDULE
Effective 7/2/64

Prices for small quantities (0-20 kft*, 0-6 km) are as shown. A price premium will apply for guaranteed lengths above those specified in Spec. Sheets 63-1B and 2B. Volume discounts available.

| Price in Metric Units, $/km | | | Price in English Units, $/kft | |
|---|---|---|---|---|
| .127 mm dia. | .254 mm dia. | Description | .005" dia. | .010" dia. |
| $109.91 | $352.71 | Bare wire, all alloys (A25, A33) | $33.50 | $107.50 |
| 124.68 | 367.47 | Wire (A25, A33) with insulation only | 38.00 | 112.00 |
| 203.42 | 428.17 | Wire, with .00075" (.019mm) thick copper on radius, and insulation | 62.00 | 130.50 |
| 203.42 | 428.17 | Wire, with .0010" (.025mm) thick copper on radius, and insulation | 62.00 | 130.50 |

# Superconductor price list - 1964

$100/1000 feet ~ $150/kA-m with inflation factor of 10 and Ic ~20 A



SUI

Division

WIRE

Prices for sma
price premium
fied in Spec.

| Price in Metri<br>Units, | $/km |
|---|---|
| .127 mm<br>dia. | .254<br>dia |
| $109.91 | $352. |
| 124.68 | 367. |
| 203.42 | 428. |
| 203.42 | 428. |

## *We made these Superconducting Magnets to throw away*

Because short-sample performance doesn't prove that a superconductor will perform properly in your magnet, we make, test, and discard superconducting magnets from every heat of SUPERCON wire.

We test these magnets as the last step in our completely integrated production process. We melt our own ingots, draw the wire, apply copper plating and insulation, and carefully check every step with an intensive quality-control program.

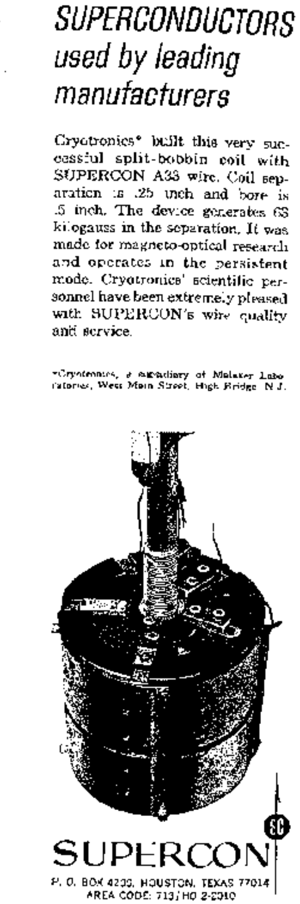
This complete in-house control means that you get ductile copper-plated wire you can wind and rewind, wire with insulation that passes the standard NEMA test. SUPERCON wire comes to you ready to wind, with no further processing necessary.

You can also get valuable counsel from experienced SUPERCON engineers in designing superconducting devices. For example, we would be glad to suggest what current densities you might reasonably expect in unusual geometries.

If you're thinking of making a magnet yourself (we don't make magnets commercially), you'll want to write for our catalog. It gives you guaranteed specifications, and magnet design and winding instructions.

SUPERCON

POST OFFICE BOX 4209, HOUSTON, TEXAS 77014/AREA CODE: 713/HO 2-2010



## *SUPERCONDUCTORS used by leading manufacturers*

Cryotronics* built this very successful split-bobbin coil with SUPERCON A33 wire. Coil separation is .25 inch and bore is .5 inch. The device generates 63 kilogauss in the separation. It was made for magneto-optical research and operates in the persistent mode. Cryotronics' scientific personnel have been extremely pleased with SUPERCON's wire quality and service.

*Cryotronics, a subsidiary of Malaker Laboratories, West Main Street, High Bridge, N.J.

SUPERCON

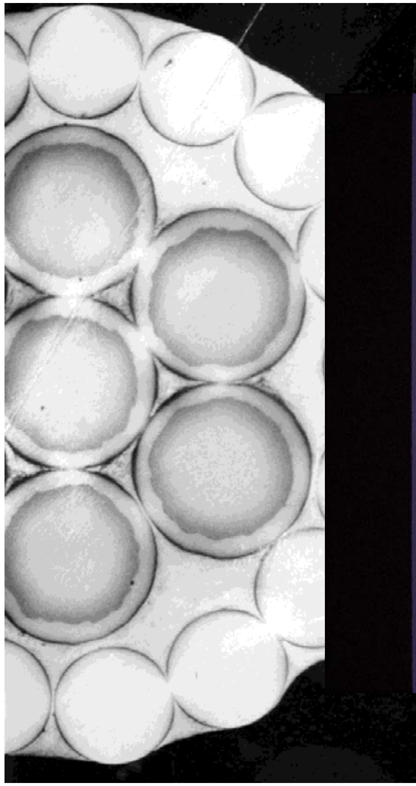
P. O. BOX 4209, HOUSTON, TEXAS 77014
AREA CODE: 713/HO 2-2010

**6.3 T split, 0.5" bore**

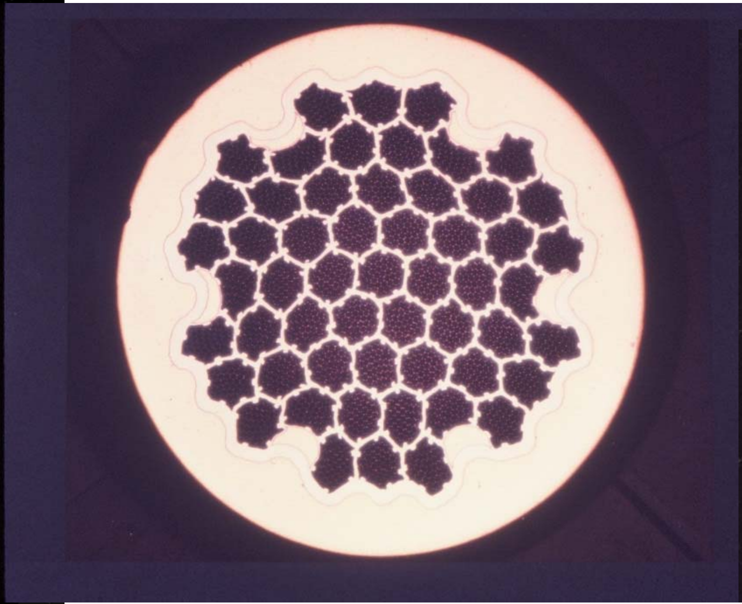
# Real conductors…..

- Stabilizing with copper was very important………….
  - Protect magnets at quench
  - Prevent instabilities
- Fine filaments could be intrinsically stable…………..
  - But only if twisted…..
- All of this came together at the Brookhaven Summer School in 1968
  - Accelerator dreams flourished

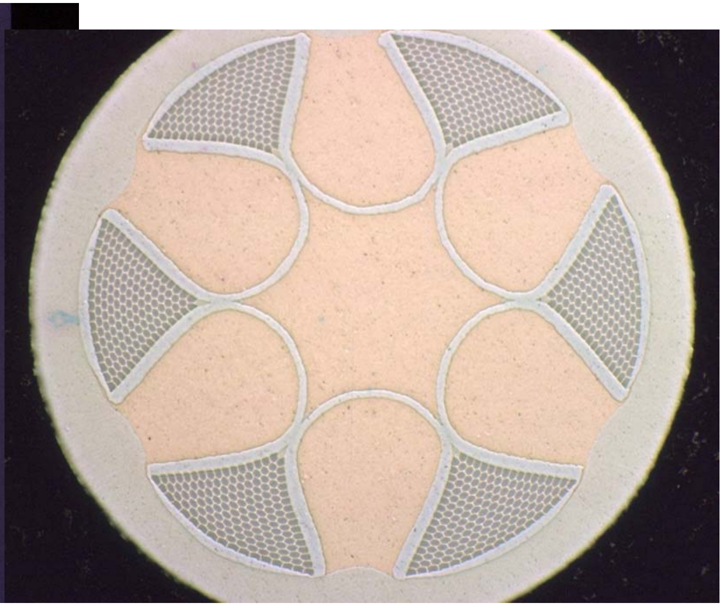
# Nb-Ti developments were rapid



Atomics International:
Cabled Monofilament
~1965

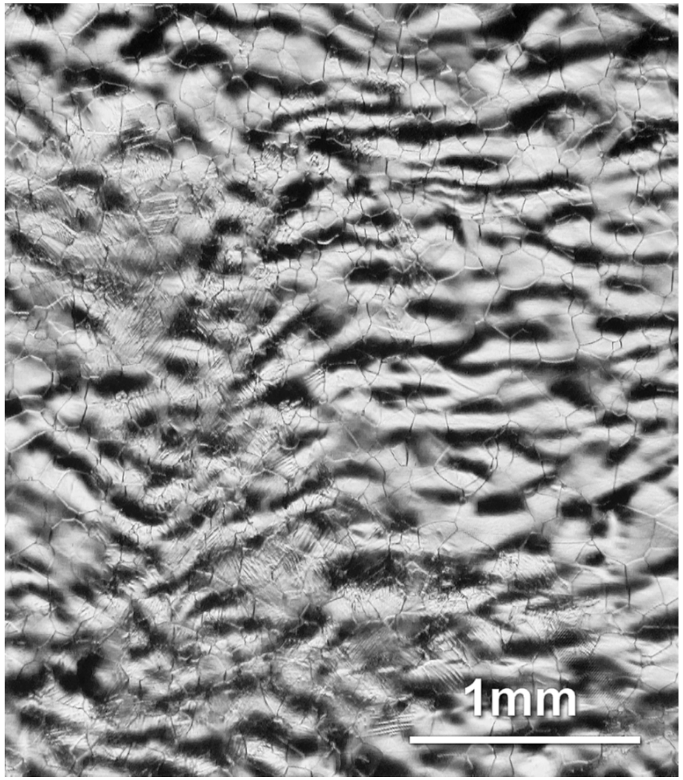


Rutherford Lab/IMI
twisted multifilament
~1967

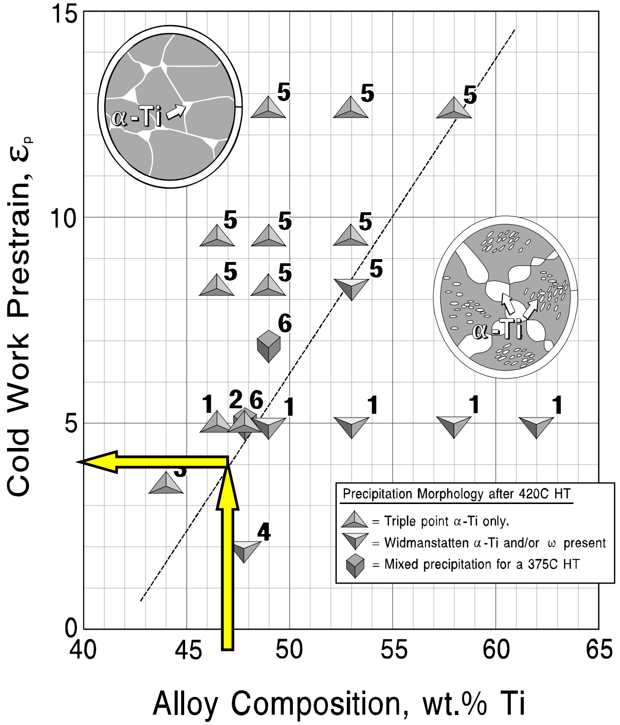


Tulip conductor for
POLO by
Vacuumschmelze
~1978

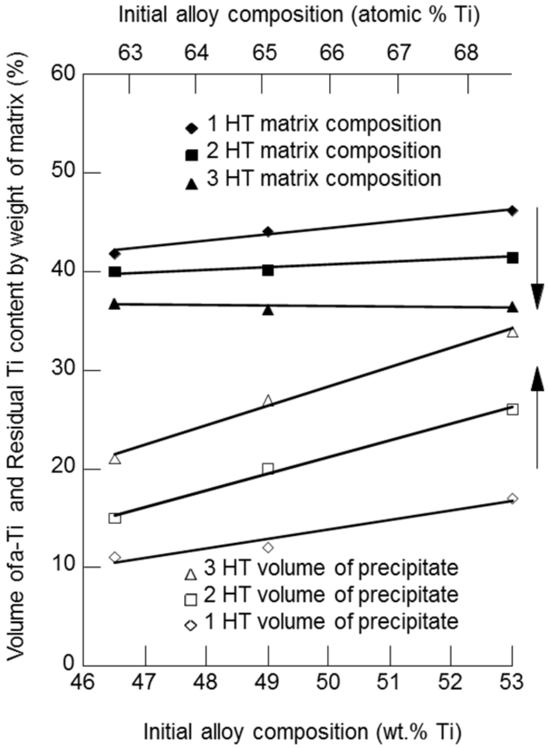
# Hi Ho Nb-Ti: the path to very high Jc……………



Micro-chemical inhomogeneity in a Nb-Ti alloy revealed using a composition sensitive etch. About 1980



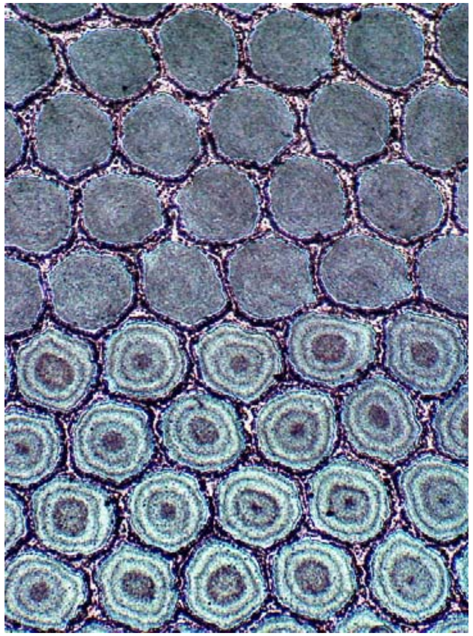
Precipitation morphology Sensitive to Composition and Strain.

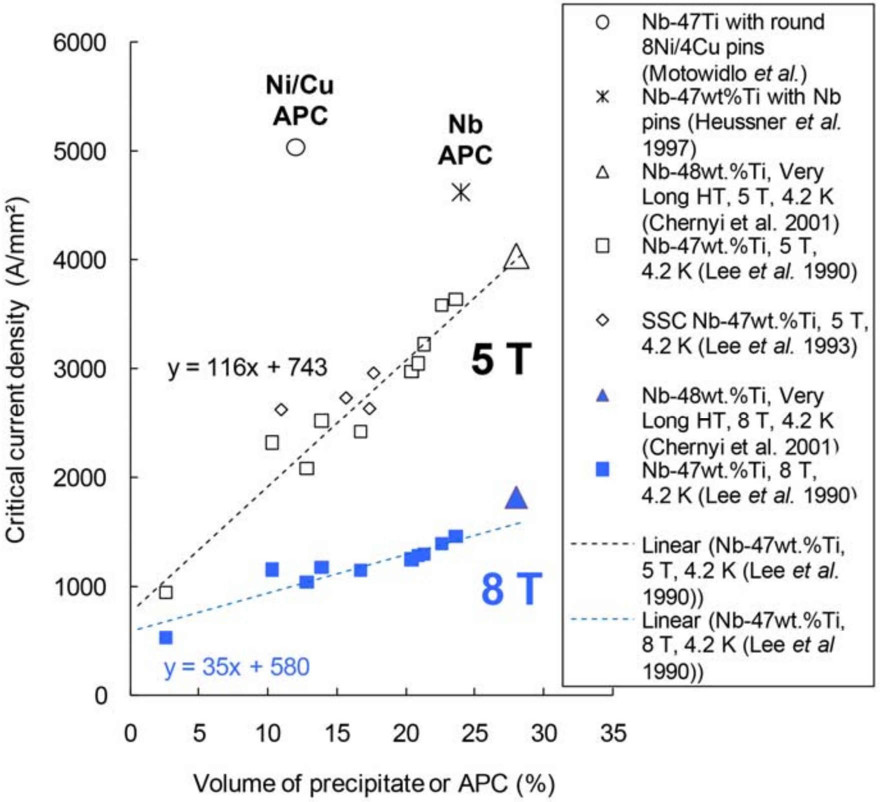


Precipitation Rate Sensitive to Composition and number of HTs.

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

Start with homogeneous Nb-Ti



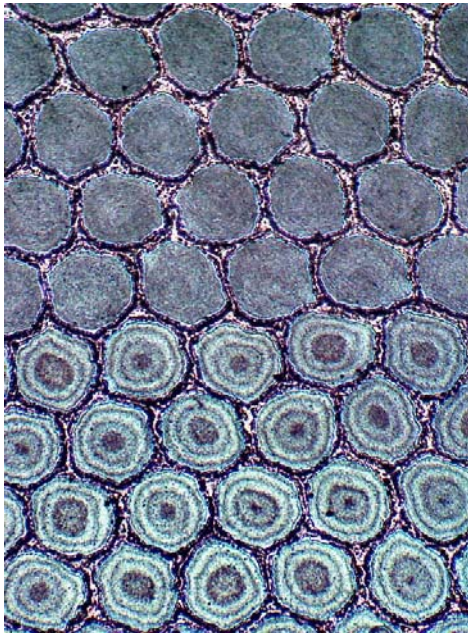


Tremendous support by Wah Chang (Bill McDonald especially)

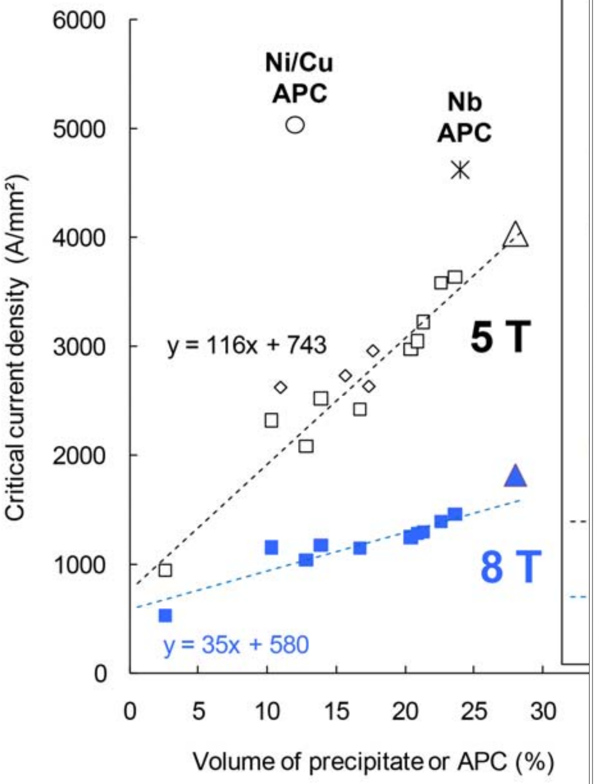
# Optimal Nb-Ti properties developed by understanding the processing-nanostructure-$J_c$ feedback cycle

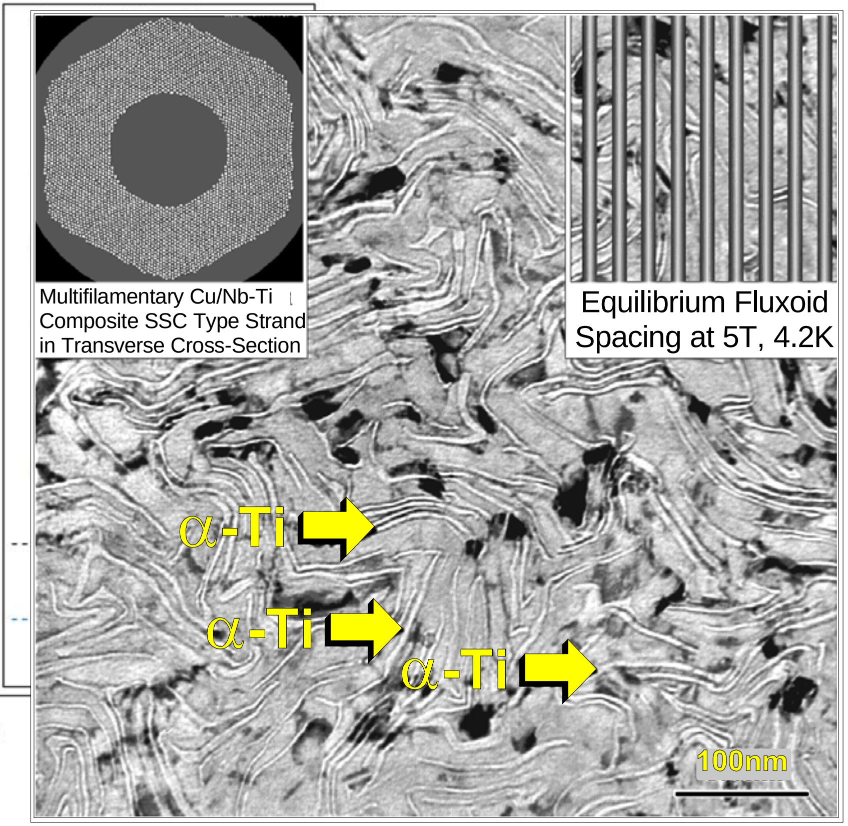
Start with homogeneous Nb-Ti

Precipitate 20-25vol.% $\alpha$-Ti to pin vortex cores



Tremendous support by Wah Chang (Bill McDonald especially)

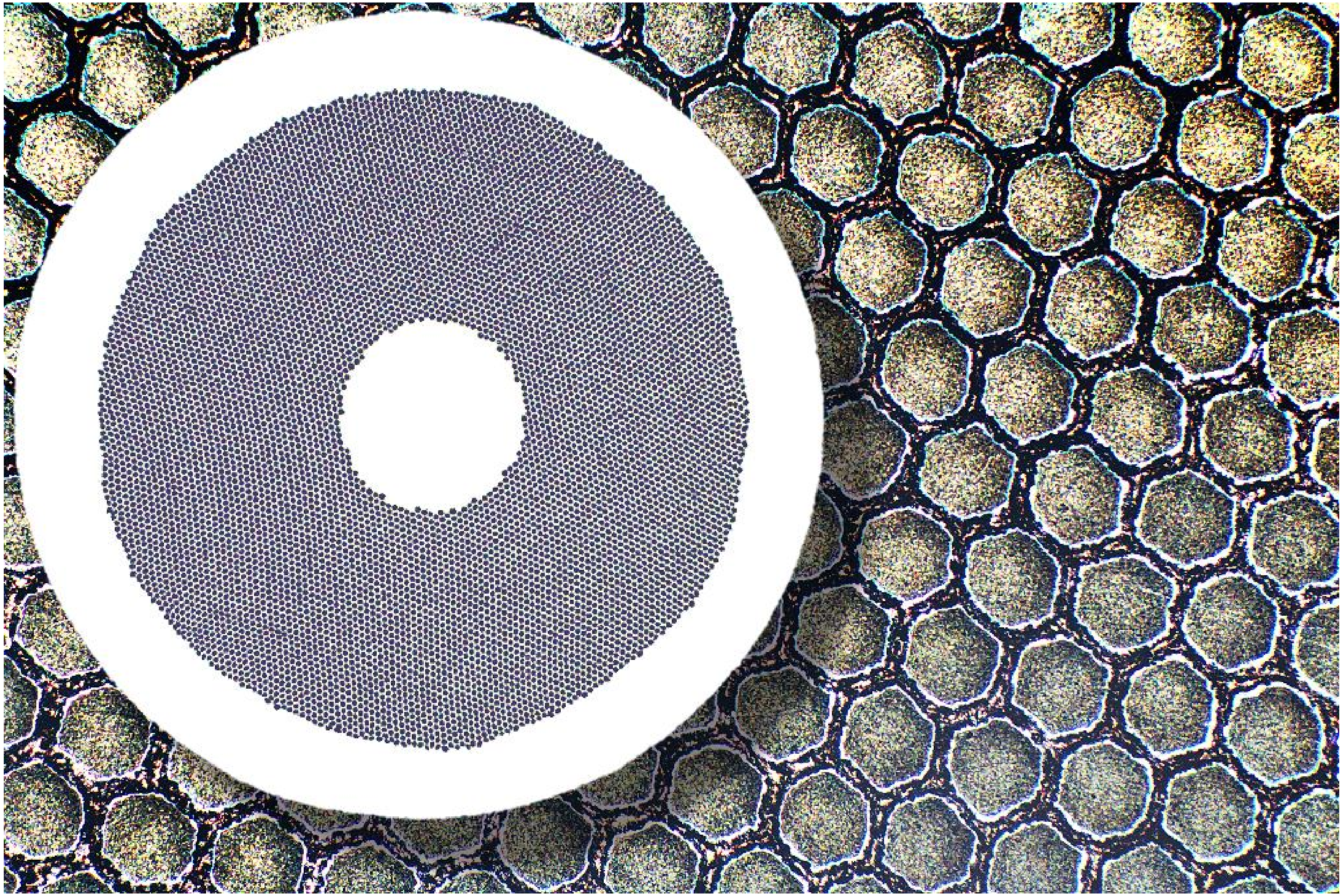




# Nb-Ti – big Industry…

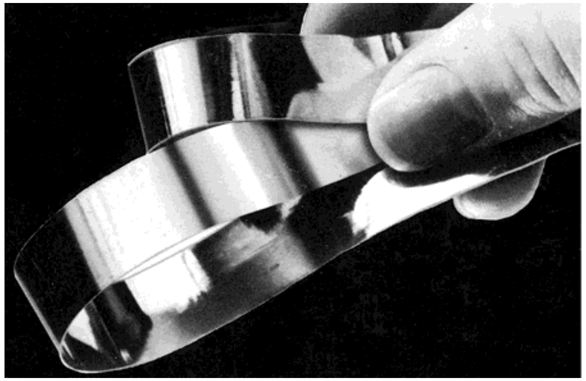
# Nb-Ti – big Industry…

# SSC Nb-Ti - 1987

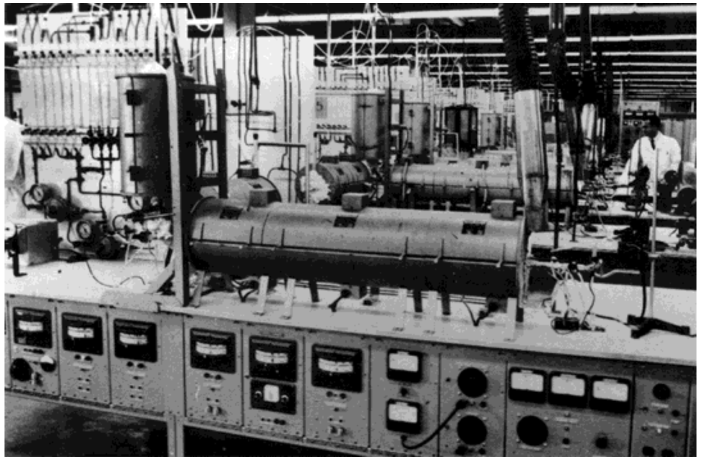


# The $Nb_3Sn$ story…..

- In spite of Kunzler's wire, tape dominated the 1960's
- But in the 1970's the ability to make first $V_3Ga$ (Tachikawa) and then $Nb_3Sn$ at about 600C when Cu was present

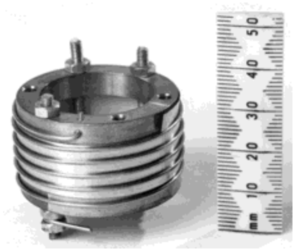


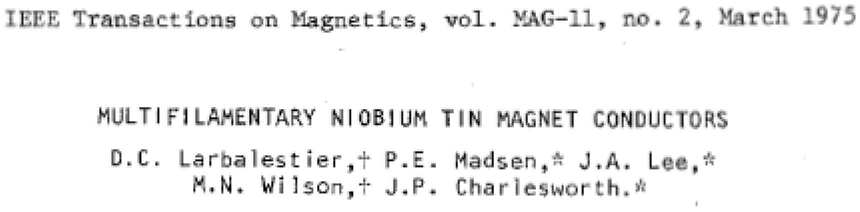
$Nb_3Sn$ tape produced at General Electric using diffusion between a liquid Sn bath and a Nb foil, later the basis of magnets made by Intermagnetics General Corp..



Production facilities for $Nb_3Sn$ wires using the continuous CVD process were established at RCA already in 1966.

# Conductors to coils in short order……………..





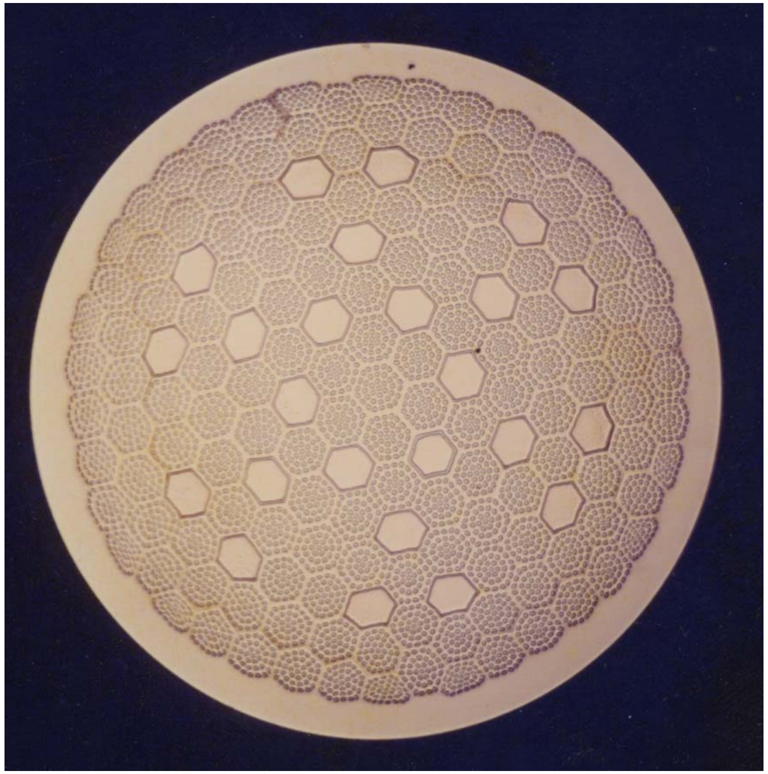
IEEE Transactions on Magnetics, vol. MAG-11, no. 2, March 1975

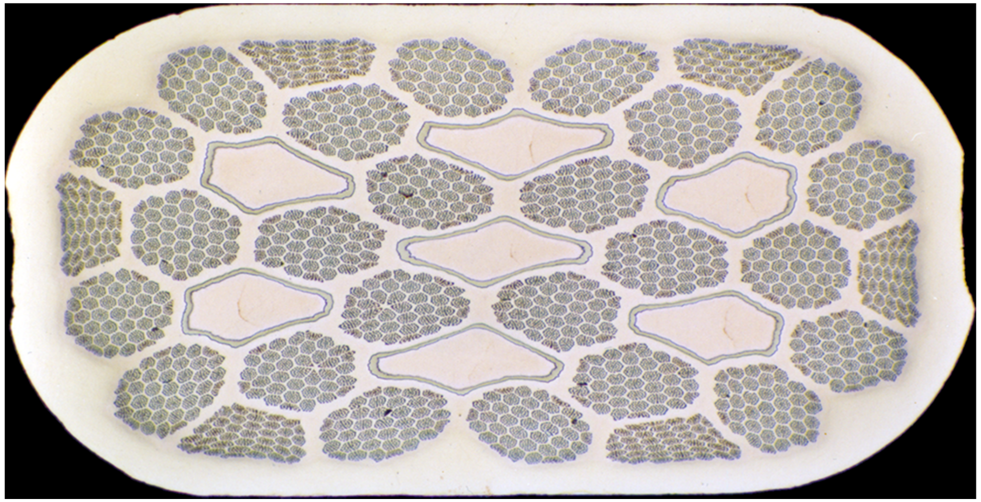
MULTIFILAMENTARY NIOBIUM TIN MAGNET CONDUCTORS

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

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

Diffusion barriers were very difficult – notice the pure Cu protected by Ta barriers



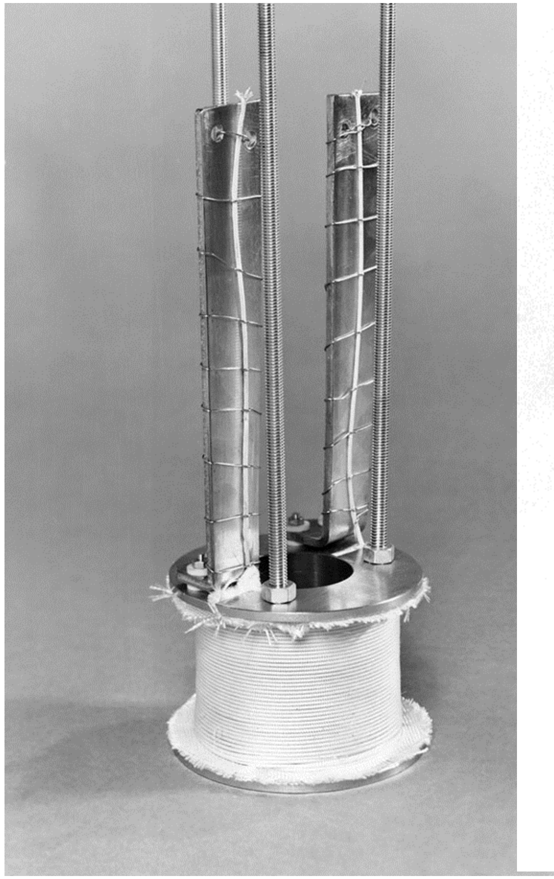


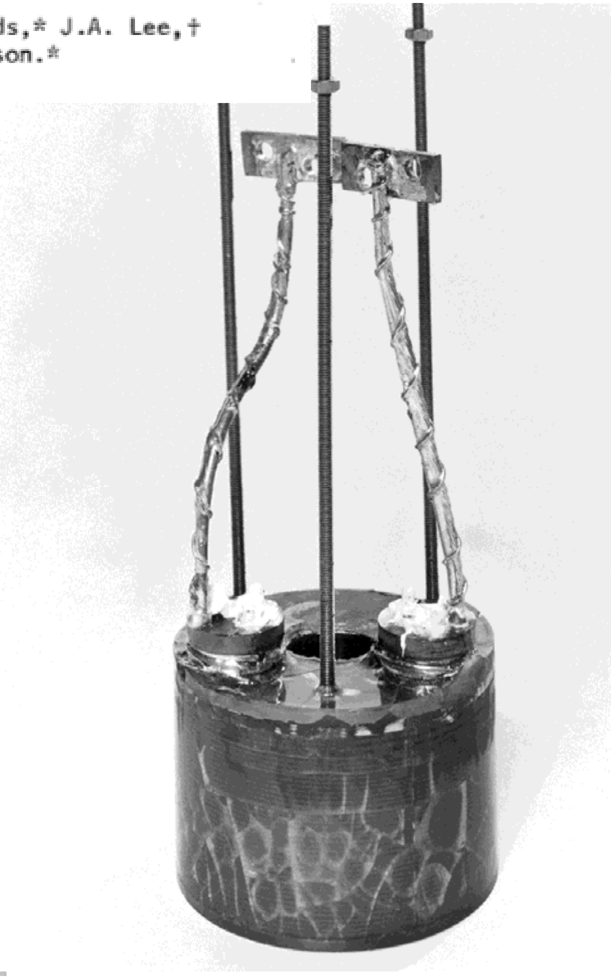
# And here are the coils....

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.*





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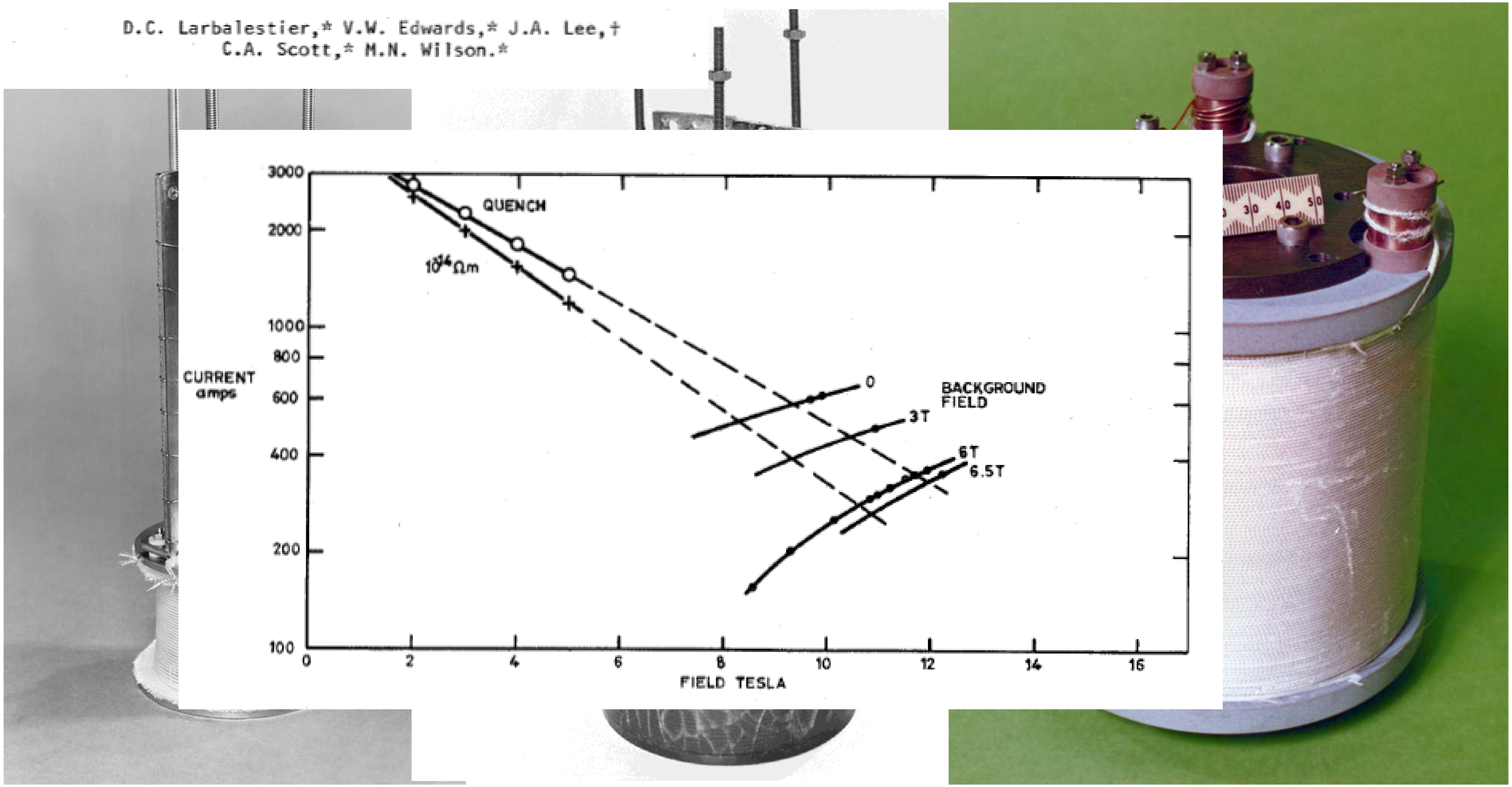
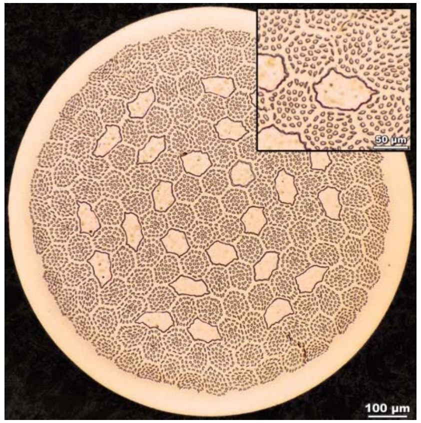
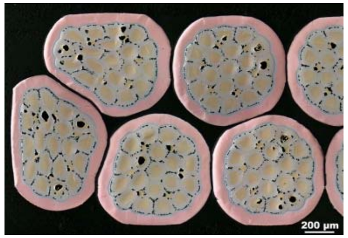


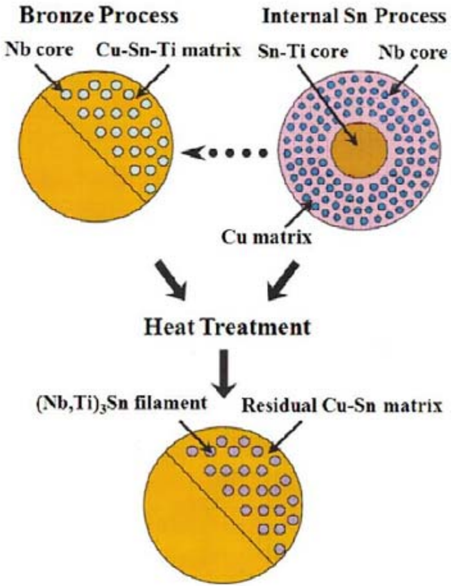
# Filamentary $Nb_3Sn$ has evolved over 4 decades

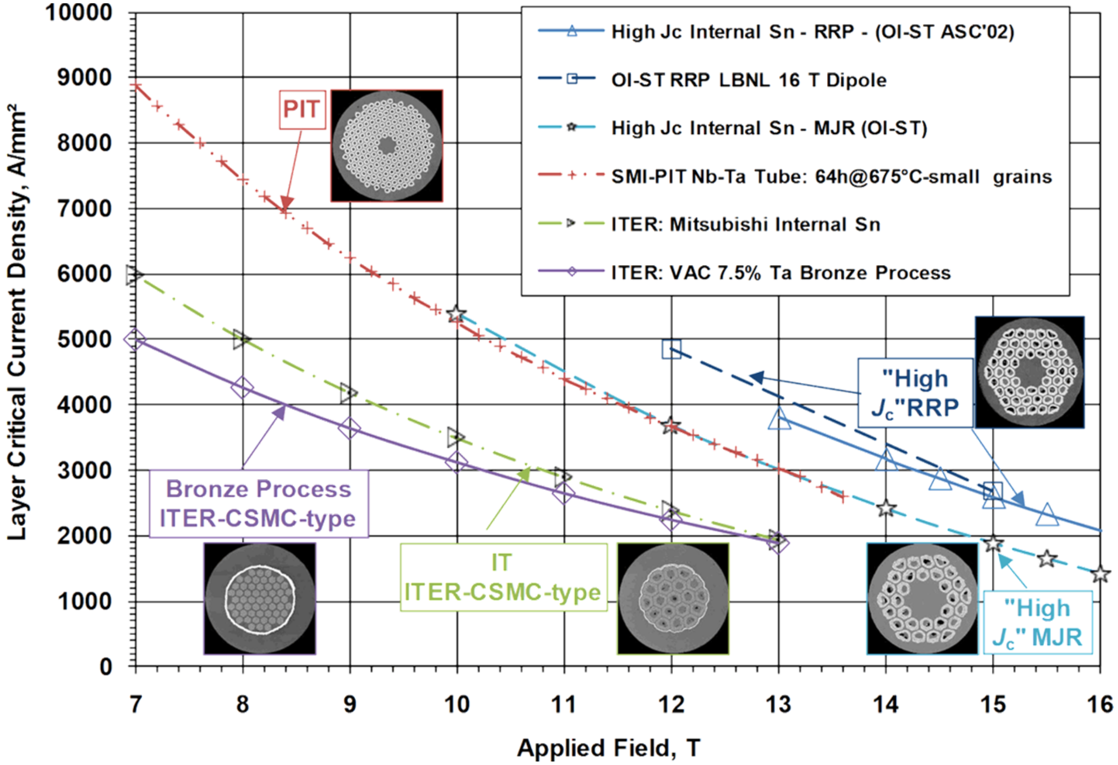


**The 1st stabilized conductor (1973) – 12 T magnet use (Harwell-Rutherford)**



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





**Multiple paths**

# 1986, the 75th Anniversary….

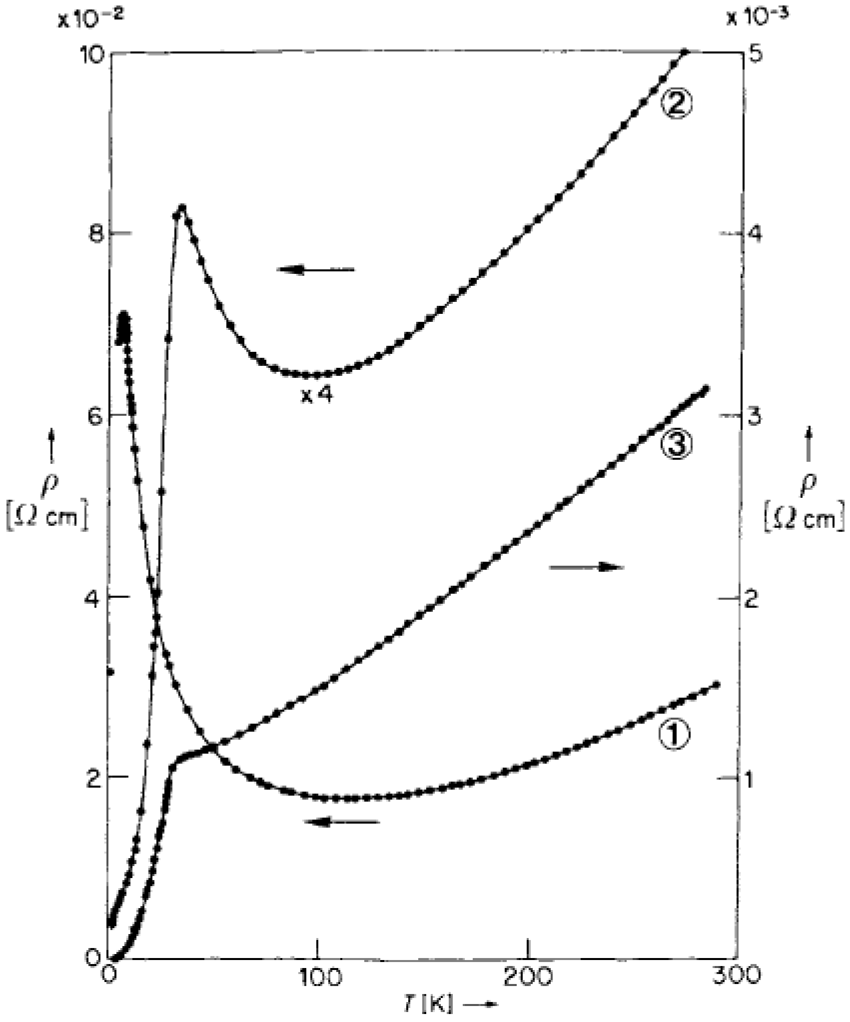


Fig. 1.9. Resistivity as a function of temperature for $La_2CuO_{4-y}$ : Ba samples with three different Ba : La ratios. Curves ①, ②, and ③ correspond to ratios of 0.03, 0.06, and 0.07, respectively (adapted from [1.20]).

- 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

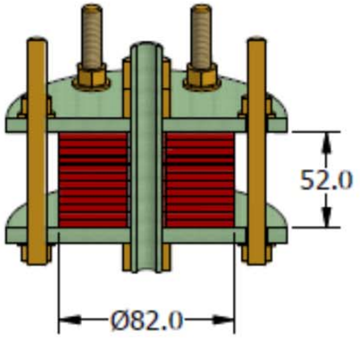
- **Superconductivity induced by doping carriers into an insulating anti-ferromagnetic state**
- **Non-Fermi liquid behavior, but strong correlations that still prevent any generally accepted model for superconductivity in the cuprates**

# National Magnet Lab User Facility

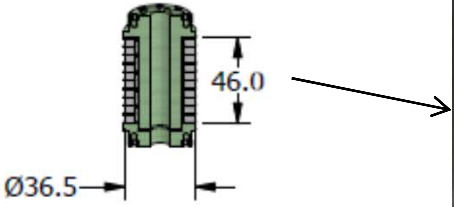
- Provides the world's highest DC magnetic fields
  - 45T in hybrid, 32 mm warm bore
  - Purely resistive magnets: 36T in 32 mm warm bore, 31 T in 50 mm bore and 20T in 195 mm warm bore
- 20 MW resistive magnets cost ~$2000/hr at full power
  - Long-time, full-field experiments are very expensive
  - Quantum oscillation, quantum Hall effect, low noise, large signal averaging experiments could run 7 days a week………

# Continuously higher field REBCO Test Coils

## Early coils in collaboration with SuperPower and subsequent ones built at NHMFL



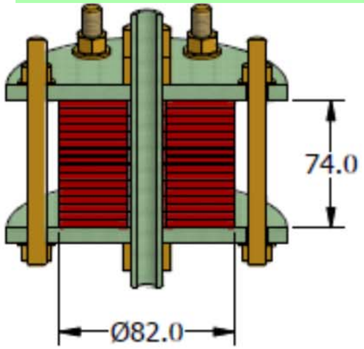
SuperPower I.



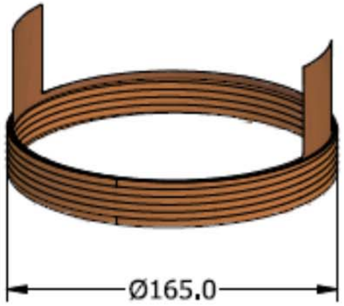
NHMFL I.

Hazelton IEEE TAS 19, 22129 (2009)

2008: 33.8T with pancake coil



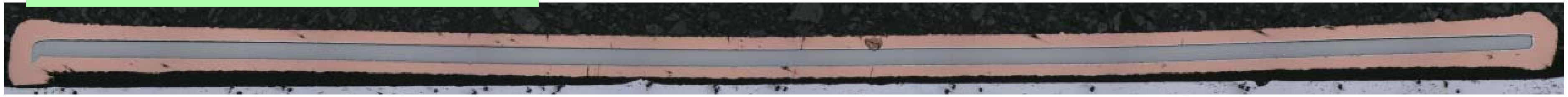
SuperPower II.



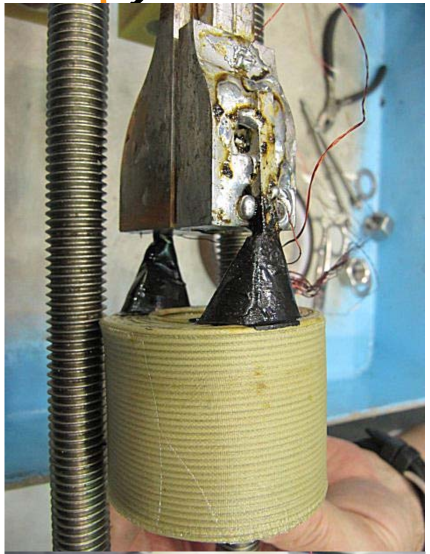
NHMFL II.

Weijers IEEE TAS 20 576 (2010)

- 14.65 avg. turns/layer, 80 layers, 96 m of 4 mm wide tape = 35.5T total
- 4.3 T in 31.2 T background at 196 A and peak hoop stress of >340 MPa
- Trociewitz, Dalban-Canassy, Hilton et al submitted



# Bi-2212 Test Coils are advancing (even with bubbles)

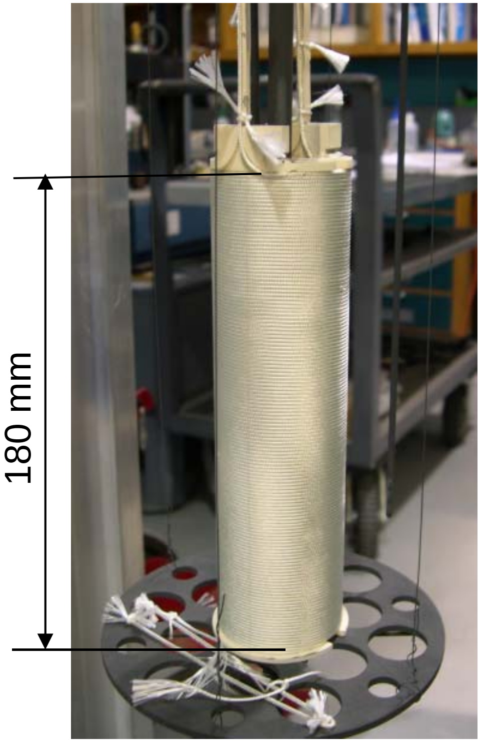


**High Field Test coil:**

- 10 layers/750 turns, $L$ ~ 3 mH
- $ID$ = 15 mm, $OD$ = 38 mm
- height = 100 mm
- conductor length ~66 m
- $\Delta B$ = 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

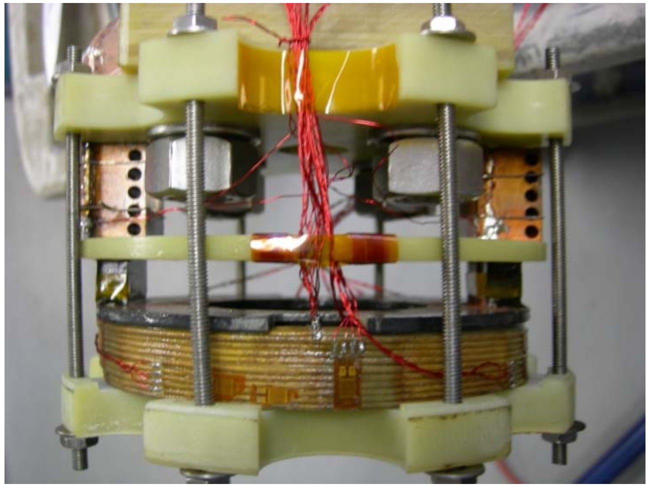


**High Field Test coil "7 T inner shell":**

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

**Large OD $\sigma_{hoop}$ test coil:**

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



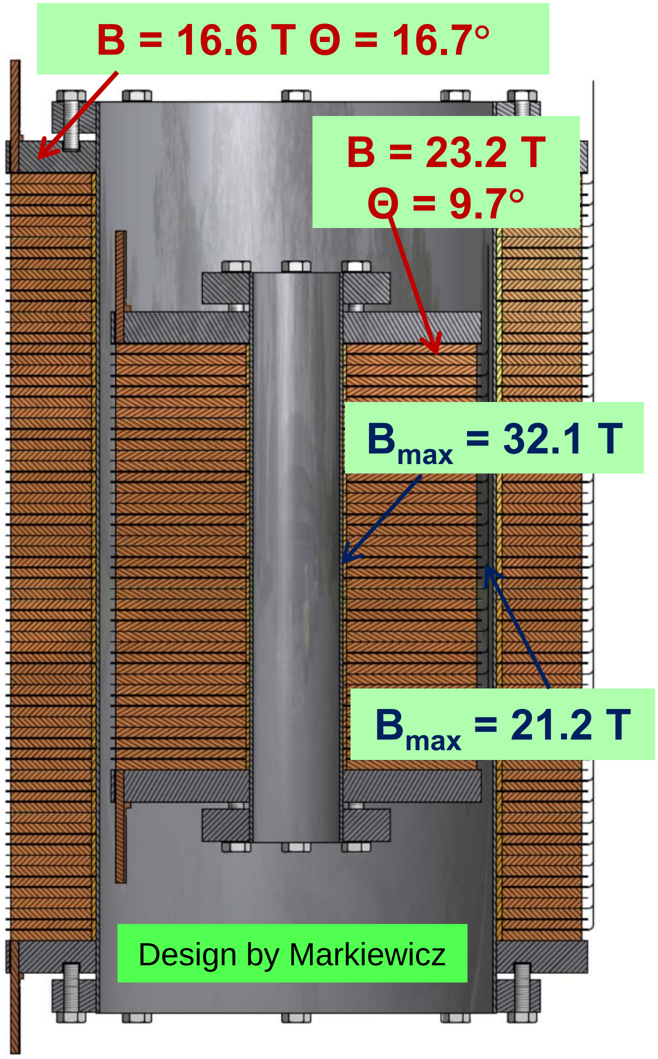
Trociewitz, Myers, Dalban

# 32 T Superconducting user magnet: REBCO 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

Markiewicz et al MT22 submiitted

**Minimum Ic Condition**



Current = 172 A, Inductance = 619 H, Stored Energy = 9.15 MJ

# Insulation with Polyester Shrink Tube

**Problem:**

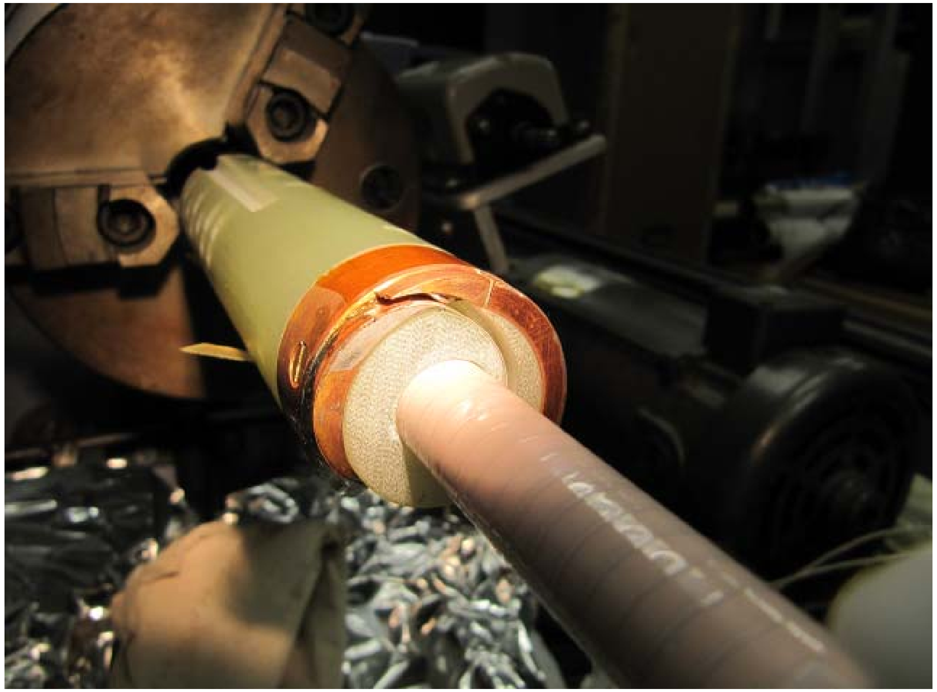
- epoxy impregnation forms solid block
- High risk of delamination of HTS layer while coil contracts during cool down (**Y. Yanagisawa *et. al.***)
- Insulation should mechanically separate conductor from epoxy impregnation

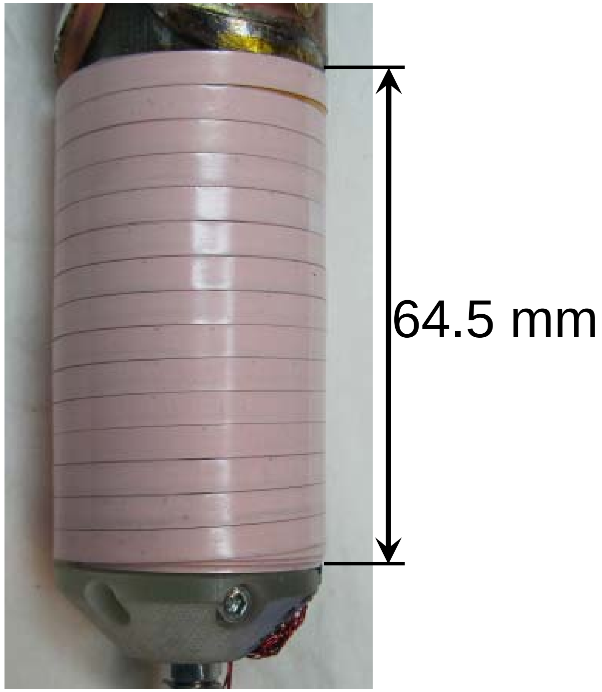
**A solution:**

- thin wall (~20 $\mu$m wall thickness) cryogenically compatible polyester shrink tube
- insulation is applied in 1.22 m long sections with ~ 15 mm overlap between each section
- Full shrinkage achieved at 150 °C

**Mechanized scale up is in progress**

# Y11-02 Coil

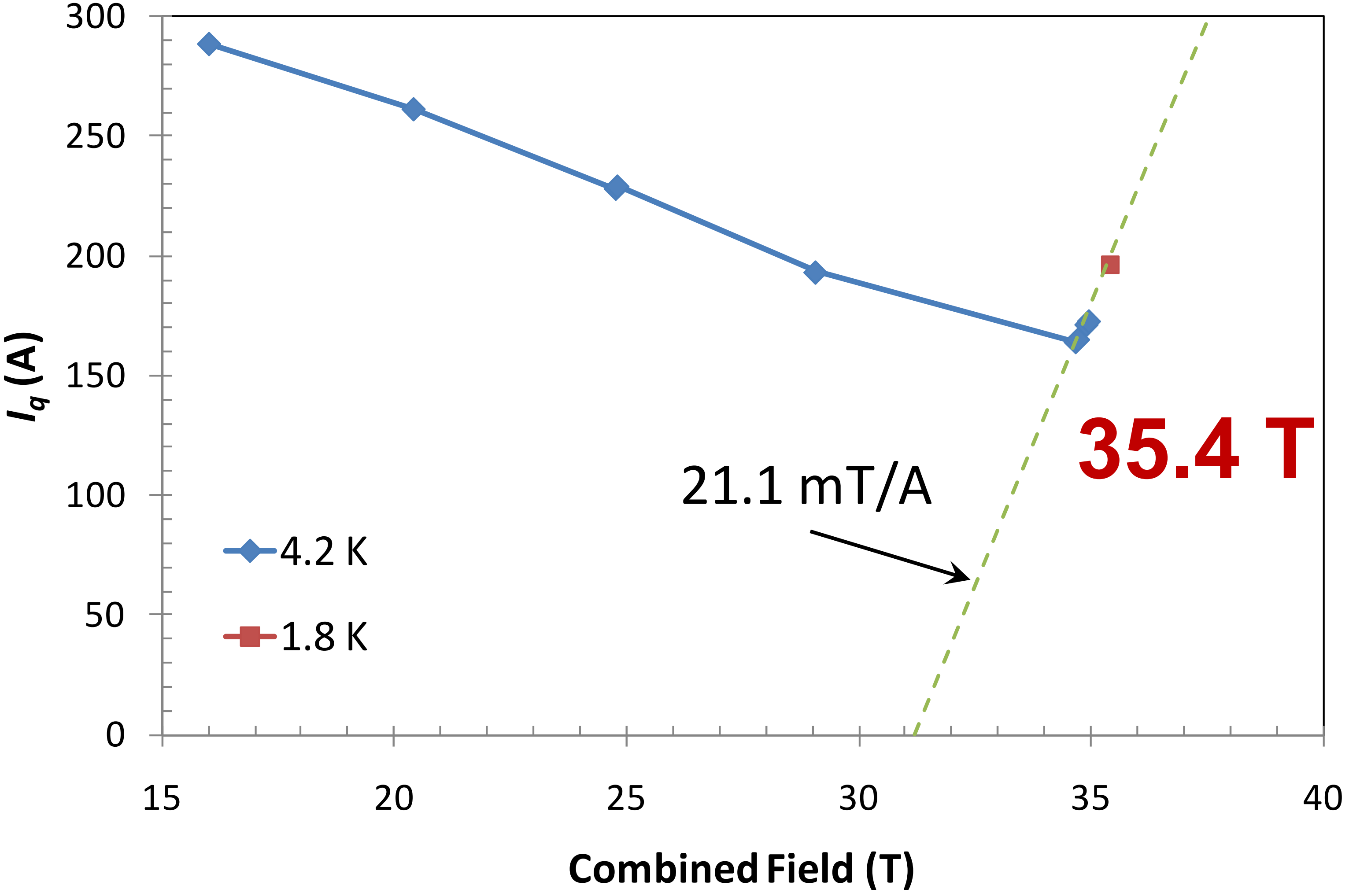




- Wet layer-wound, epoxy filled
- no splices
- Coil instrumented with array of voltage taps; instrumentation sequence: 5 – 10 layers

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

# A new mark for a superconducting coil

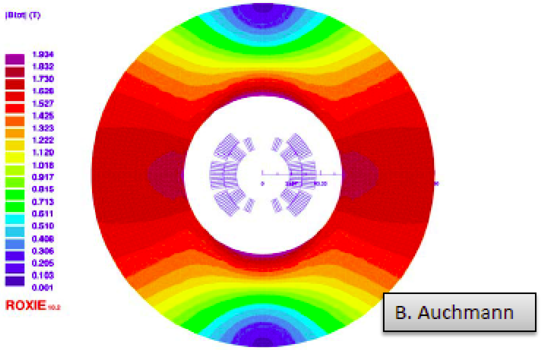


- **4.2 T achieved in 31.2 T background field without any degradation (Trociewitz et al. submitted)**

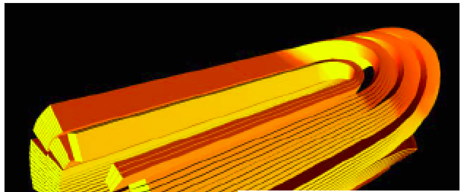
# Program Eucard2 under formation

- Develop 10 kA class HTS accelerator cables
- Test in in a 5 T accelerator quality dipole

# LHC Energy Upgrade

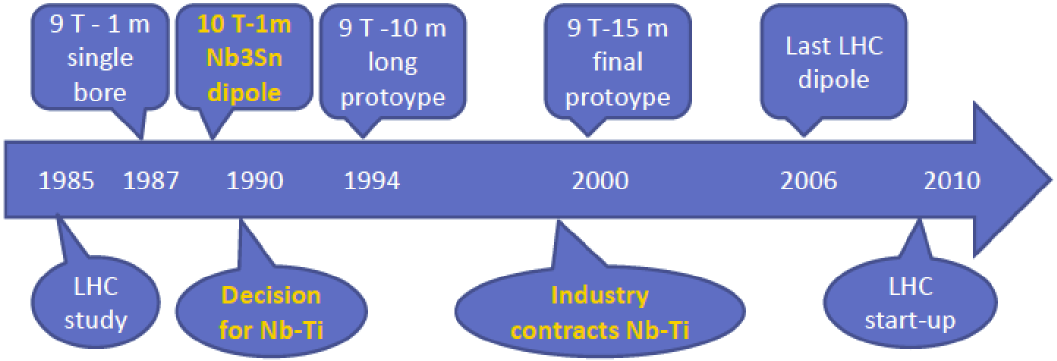


B. Auchmann



## When (if) we have conductor which is the time? LHC timeline

- LHC took 20 years even with Nb-Ti
- The next 5 years are key for HTS for magnets



9 T - 1 m single bore

10 T-1m Nb3Sn dipole

9 T -10 m long protoype

9 T-15 m final protoype

Last LHC dipole

1985 1987 1990 1994 2000 2006 2010

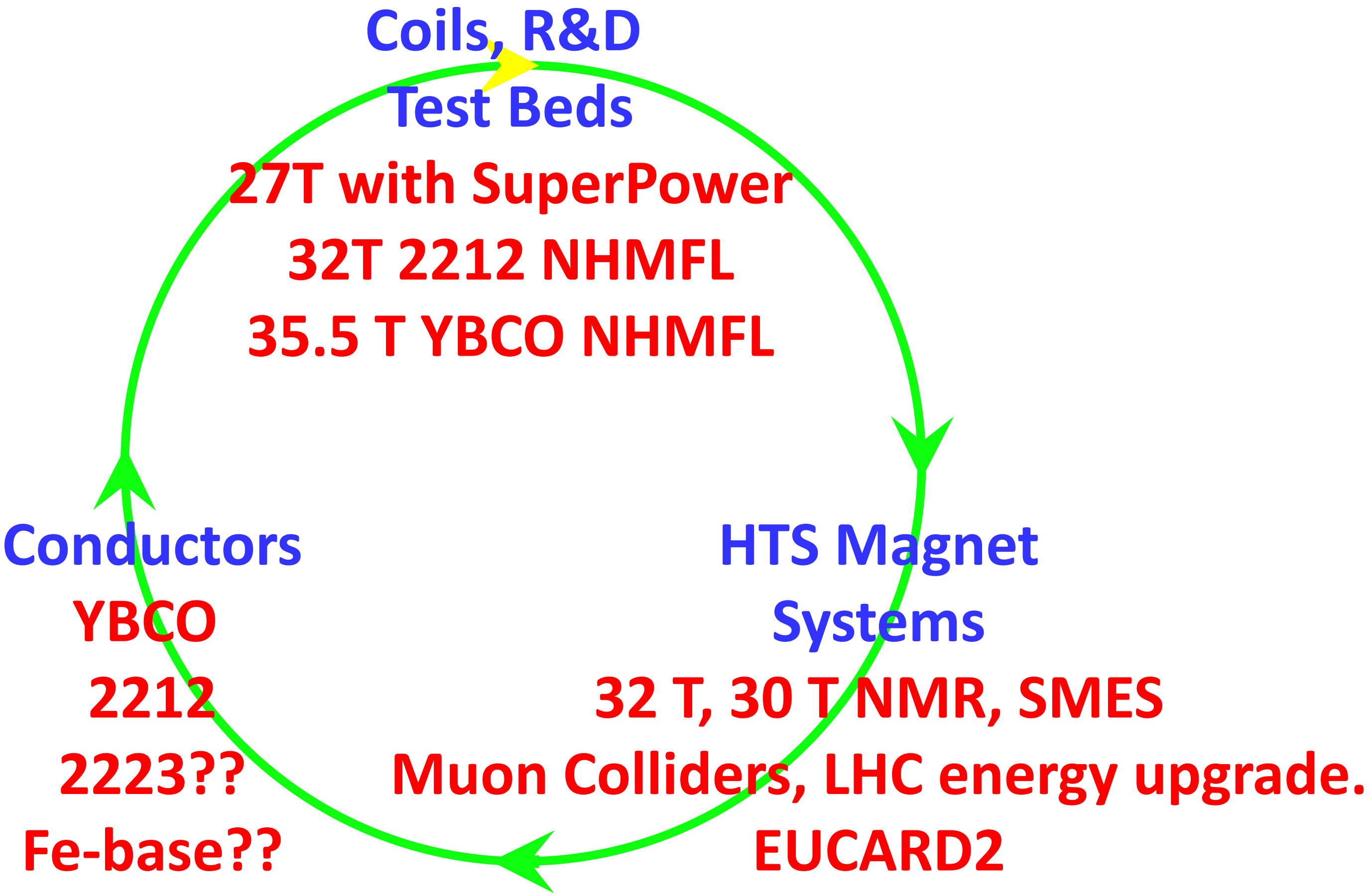
LHC study

Decision for Nb-Ti

Industry contracts Nb-Ti

LHC start-up

# Conductor and Coil technologies are intimately linked



**Coils, R&D**
**Test Beds**
27T with SuperPower
32T 2212 NHMFL
35.5 T YBCO NHMFL

**HTS Magnet Systems**
32 T, 30 T NMR, SMES
Muon Colliders, LHC energy upgrade.
EUCARD2

**Conductors**
YBCO
2212
2223??
Fe-base??

# Our thanks

- To those who have passed us historical material
  - Anatoly Shepelev, Ted Berlincourt, Dick Hake, Martin Wood, Marty Nisenoff, Terry Wong and many others
- To our long term colleagues in the ASC in Madison and Tallahassee
  - Especially more than 50 students, 30 postdocs and 30 sabbatical visitors....
- To the High Energy Physics, Fusion and other applications communities that have supported us well over the long term
- To those who believed in MAKING superconductors
  - especially those at IMI, Harwell, Vacuumschmelze (now BEST), Oxford, SuperPower with whom we have had many productive interactions

# Superconducting Magnets on Wikipedia – needs an update!

- http://en.wikipedia.org/wiki/Superconducting_magnet

**Coil windings**
The coil windings of a superconducting magnet are made of wires or tapes of Type II superconductors (e.g.niobium-titanium or niobium-tin). The wire or tape itself may be made of tiny filaments (about 20 micrometers thick) of superconductor in a copper matrix. The copper is needed to add mechanical stability, and to provide a low resistance path for the large currents in case the temperature rises above $T_c$ or the current rises above $I_c$ and superconductivity is lost. These filaments need to be this small *because in this type of superconductor the current only flows skin-deep.*[*citation needed*] The coil must be carefully designed to withstand (or counteract) magnetic pressure and Lorentz forces that could otherwise cause wire fracture or crushing of insulation between adjacent turns.

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