Conductors from Superconductors

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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 app” - 1913
- The great silence - 1936-1961
- The explosion of applications - 1961-1987
- The explosion of high Tc - 1987 on
- The future..................?
Magnet wires should be long, strong, stable, affordable, have high critical current density, high upper critical field and preferably round
Chapter 11: Wires and Tapes

Editor: David Larbalestier

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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/mm² density was sent through a mercury wire, and of 460 amps/mm² 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 amperes 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 interfer... 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/mm² with a Hg wire, 460 A/mm² 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
The Dick Hake Story (U. of Indiana and Atomics International)

PROLOGUE
I. Pure or Sponge?

II. Leiden in the Dark: Dutch Ships Ignore Russian Ships

III. Russian Ships Ignore Russian Ships

IV. Pippard Piddles while Ginsberg Squirms

V. The Kid Protagonists

VI. Kid & Ginzburg's Breakthrough: ACS+GINS

EPILLOGUE

REFERENCES


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


**ACT I. PURR OR SPONGE?**

U. Leiden #2086 (1930); ibid. #2446 (1931)

---

**III. THE CRUCIAL EXPERIMENT.**

L.V. Shubnikov, V.I. Khotkevich, J.D. Shepelev,
2, 281 (1937) [Portions were reported in
Englsih: J.N. Rjabinin and L.V. Shubnikov,
Nature 135, 581 (1935); Phys. Z. Sowjet 2, 122(1935)]

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

---

**Early Ideas on High-Field Superconductivity**

I. Could be bulk property of HOMOGENEOUS
(PURE) materials associated with negative
interphase surface energy:

C.J. Gorter, Physica 3, 499 (1935)
(says \( H_{\text{m}} < T \) )


"We think that all experimental results so far obtained on IMPURE (pure copper or silver) metals and on a
few can be explained by their INHOMOGENEITY (us
cause the formation of a SPONGE of higher
value."

---

**Shubnikov et al. said:**

1. \( I_{\text{MDD}} \) = Superconducting state condensation
energy

2. Even though \( I_{\text{MDD}} \) exceeds \( I_{\text{c}} \) of pure
metals, the condensation energies are
comparable and depend on \( T \) in the
same way.

3. The zero-field specific heat jump in
an alloy superconductor should be comparable
in size to that of a pure superconductor and
not have gigantic value expected if
complete flux expulsion existed up to \( H_{\text{max}} \)

But SHUBNIKOV & KOTER  "FELT THEY SNEAKED THERM OF THEIR NEWCOMING
UNDERSTANDING... (making) no mention of the Gorter & London
theory... "not of the Mendelevich SPONGE..." T.G. Berlincourt
1936: Type II Superconductivity discovered - and unappreciated

L.V. Shubnikov et al., Zh. Exper. Teor. Fiz. (USSR) 7, 221 (1937)
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
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 Shubnikov kept on writing small papers in which he said it would be much better if we underestimated the electronic charge as not being exactly e, but a slightly smaller numerical factor which might be as large as 1.8. He didn't say it was exactly 1.8. 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.


"Act III. Russian Sloths Ignore Russia.


"It has not been necessary to investigate the nature of the state which occurs when \( R > 1/\sqrt{\lambda} \) is satisfied, since from the experimental data... it follows \( R < 1 \)." [Pippard, by obituary of Shubnikov et al.]

K. Mendelsohn to T.G. Bermingham;

"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 1950. This is indeed of considerable help to assessing the earlier developments. At that time the Stalin Purge was only beginning, and I was very puzzled at the places I drew in trying to get in touch with Shubnikov. In 1951 Landau introduced me in Moscow to Shubnikov's widow, Olga Tropinezheva, who also is a physicist. She told me that her husband had just been arrested posthumously from abroad. I apologized to Mrs. Tropinezheva to try and understand why, having in mind the links between Gorki and Pippard with the dissection in the paperwork was very likely.

(According to Balabekyan, 1966, Shubnikov was unjustly arrested in 1950, sentenced to 10 years imprisonment and died in 1945.)"
ACT VII. NUTTY GEORGE

G. B. Yacoba, Phys. Rev. 98, 1197 (1955)
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 1964.

Hc (Gauss)

3,000
2,000
1,000

Magnetic field (Gauss)

Temperature (°K)

N40, 45,000 Gauss at 4 K

Figure 4. Critical fields as functions of temperature. The shaded area shown for niobium illustrates the variation in reported values. Compiled by V. D. Aip and D. Shoenberg, 1960 (Ref. 18).

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

Nobel Prize winning microscopic theory of superconductivity
J. Bardeen, L. N. Cooper, J. R. Schrieffer

In “dirty limit” \( H_{c2}(T=0) = (\alpha_{s}H_{c1}/\mu_{B}N) \)

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!
Almost there in July 1960......
Almost there in July 1960......

It is well known that Nb₃Sn 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, \( \mu \), 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 \( B = 0 \) \( H = -4 \pi \rho \), where \( \rho \) 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.¹ 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. Corenswit 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.

Decisive experiment only in late 1960

SUPERCONDUCTIVITY IN Nb3Sn AT HIGH CURRENT DENSITY IN A MAGNETIC FIELD OF 88 kgauss
J. E. Kurzler, 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 Nb3Sn 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

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

<table>
<thead>
<tr>
<th>Who</th>
<th>Field</th>
<th>Material</th>
<th>Bore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bell</td>
<td>6.9 T</td>
<td>Nb₃Sn</td>
<td>0.25”</td>
</tr>
<tr>
<td>Atomics Internaional</td>
<td>5.9 T</td>
<td>Nb25Zr</td>
<td>0.5”</td>
</tr>
<tr>
<td>Westing house</td>
<td>5.6 T</td>
<td>Nb25Zr</td>
<td>0.15”</td>
</tr>
</tbody>
</table>

**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

\[ I_c = 17 \text{ A}, \quad B_{\text{max}} \sim 4 \text{ T} \]
Superconductor price list - 1964

<table>
<thead>
<tr>
<th>Description</th>
<th>0.005&quot;</th>
<th>0.010&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare wire, all alloys (A25, A33)</td>
<td>$33.50</td>
<td>$107.50</td>
</tr>
<tr>
<td>Wire (A25, A33) with insulation only</td>
<td>38.00</td>
<td>112.00</td>
</tr>
<tr>
<td>Wire, with .00075&quot; (.019mm) thick copper on radius, and insulation</td>
<td>62.00</td>
<td>130.50</td>
</tr>
<tr>
<td>Wire, with .0010&quot; (.025mm) thick copper on radius, and insulation</td>
<td>62.00</td>
<td>130.50</td>
</tr>
</tbody>
</table>
Superconductor price list - 1964

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

We made these Superconducting Magnets to throw away

Because the sample performance doesn't prove that a superconductor will perform properly in your design, we build, test, and discard superconducting magnets from every batch of SUPERCON wire.

We test these magnets on the last step in our completely integrated production centers. We use our own physics, shape the wire, apply superconducting and mechanical coatings, and carefully check every step with an extensive quality assurance program.

The samples shown in this slide are all typical superconducting wires you can work with confidence that ensures the standard NENSA and SUPERCON wire design to exact width or further processing accuracy.

You can also get valuable design experience SUPERCON superconducting device design engineers as designing superconducting devices. For example, we would be glad to support what current densities you might reasonably expect in your applications.

If you're thinking of making a superconducting magnet, you don't need magnets occasionally; you need to work with our catalog. It gives you guaranteed specifications and proven design and fabrication experience.
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)

Equilibrium Fluxoid Spacing at 5T, 4.2K

Multifilamentary Cu/Nb-Ti Composite SSC Type Strand in Transverse Cross-Section

\[
y = 116x + 743
\]

\[
y = 35x + 580
\]

Critical current density (A/mm²) vs. Volume of precipitate or APC (%) at 5T and 8T
Nb- Ti - big Industry...
Nb- Ti – big Industry...
SSC Nb-Ti - 1987
The Nb$_3$Sn story.....

- In spite of Kunzler’s wire, tape dominated the 1960’s
- But in the 1970’s the ability to make first V$_3$Ga (Tachikawa) and then Nb$_3$Sn at about 600C when Cu was present

Nb$_3$Sn 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$_3$Sn wires using the continuous CVD process were established at RCA already in 1966.
Conductors to coils in short order…………….

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....
And here are the coils....
Filamentary $\text{Nb}_3\text{Sn}$ 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!
1986, the 75th Anniversary....

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

Fig. 19: Resistivity as a function of temperature for La$_2$CuO$_{4+x}$: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]).
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)

SuperPower II.  NHMFL II.
Weijers IEEE TAS 20 576 (2010)

2008: 33.8T with pancake coil

- 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, $L \sim 3$ 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

Large OD $\sigma_{\text{hoop}}$ test coil:
- ID = 92.5 mm
- OD = 118.5 mm
- 10 layers, 10 turns
- Bore tube less
- epoxy impregnated
- $\Delta B \sim 0.2$ 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
- $\Delta B = 1.2$ 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 submitted

- **Minimum Ic Condition**
  - \( B = 16.6 \, T \), \( \theta = 16.7^\circ \)
  - \( B = 23.2 \, T \), \( \theta = 9.7^\circ \)

- **Maximum Field**
  - \( B_{\text{max}} = 32.1 \, T \)
  - \( B_{\text{max}} = 21.2 \, T \)


Design by Markiewicz
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 μm 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

<table>
<thead>
<tr>
<th>Conductor &amp; Coil</th>
<th>EM Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cond. Width [mm]: 4.02</td>
<td>Operating Current [A]: 200</td>
</tr>
<tr>
<td>Cond. Thickness [mm]: 0.096</td>
<td>Je (Engineering) [A/mm²]: 518.24</td>
</tr>
<tr>
<td>Inner Radius [mm]: 7.16</td>
<td>Jw (Winding) [A/mm²]: 308.93</td>
</tr>
<tr>
<td>Outer Radius [mm]: 18.92</td>
<td>B(0,0) [mT]: 4221.01</td>
</tr>
<tr>
<td>Height [mm]: 64.52</td>
<td>Coil Constant (0,0) [mT/A]: 21.11</td>
</tr>
<tr>
<td>Layers [-]: 80</td>
<td>L [mH]: 8.90</td>
</tr>
<tr>
<td>turns/Layer [-]: 14.65</td>
<td>Total Field Energy [J]: 187.92</td>
</tr>
<tr>
<td>turns total [-]: 1172</td>
<td></td>
</tr>
<tr>
<td>Cond. Length [m]: 96.03</td>
<td></td>
</tr>
</tbody>
</table>
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

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
Conductor and Coil technologies are intimately linked

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

Conductors
YBCO
2212
2223??
Fe-base??

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