Superconductivity at 100: what about the next century?

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Onnes was appointed in 1882 at the age of 29 and published nothing for 10 years.
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 $\kappa$ 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$_3$Sn 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/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 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 interferum 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
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)
Early 1950’s: Abrikosov: what if $\kappa = \frac{\lambda}{\xi}$ becomes very large?

- **Two characteristic lengths**
  - coherence length $\xi$, the pairing length of the superconducting pair
  - penetration depth $\lambda$, the length over which the screening currents for the vortex flow

- **Vortices have defined properties in superconductors**
  - normal core dia, $\sim 2\xi$
  - each vortex contains a flux quantum $\phi_0$ currents flow at $J_d$ over dia of $2\lambda$
  - vortex separation $a_0 = 1.08(\phi_0/B)^{0.5}$

$$H_{c2} = \frac{\phi}{2\pi\xi^2}$$
$$\phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15} \text{ Wb}$$
$$B/B_{c2} (=b) \sim 0.2$$

Decisive experiment only in 1961

SUPERCONDUCTIVITY IN Nb$_3$Sn 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$_3$Sn at average current densities exceeding 100,000 amperes/cm$^2$ 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$_3$Sn

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.% $\alpha$-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

1500 tonnes of LTS SC cables

3286 HTS Leads

Large Hadron Collider
15000 MJ of magnetic energy

1232 SC Dipoles

27 km Tunnel

Switzerland

France

Mont Blanc

Lake Geneva

- 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 $\text{Nb}_3\text{Sn}$ 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!
Nb$_3$Sn 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

- 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

9 K

MgB$_2$

18-23 K

YBCO

92-95 K

Bi-2223

9 K

110 K
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

Production now in 100-500 m lengths
One example of electric utility applications...high power cables

- Cables now work at all voltages up to 138 kV and > 500 MVA
Magnet builders prefer round wires

Preferred conductor features:
- Multifilament
- Round or lightly aspected shape with no Jc anisotropy
- Capability to wind in unreacted form while conductor fragility is minimized

Nb47Ti (OST)  Internal Sn Nb₃Sn (OST)  Bi-2212 (OST)  MgB₂ (Hypertech)
HTS will now enable a new generation of magnets -> 30 Tesla
Summary II - HTS Conductor Issues

- $H_{c2}(T)$ much larger than for Nb$_3$Sn
  - 100-120T versus 30T (30T for YBCO at 55K)
  - But, thermal fluctuation effects depress the irreversibility field at which $J_c = 0$ well below $H_{c2}$, except at low $T$

- Grain boundaries easily acquire depressed properties and degrade $J_c$ even for small misorientations of 3-5°
  - 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……
**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
2 (or 3?) viable HTS magnet conductors

- YBCO with phenomenal $J_c$ - $\sim 20 \times 10^6$ A/cm$^2$ at 25T
  - But YBCO is $\sim 1\%$ of cross-section
  - 50% is high strength superalloy

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

- 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, $L \sim 3$ mH
- $ID = 15$ mm, $OD = 38$ mm
- height = 100 mm
- conductor length $\sim 66$ 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 $\sigma_{hoop}$ 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 $\sim 220$ m
- $\Delta B = 1.2$ T at 20 T

Trociewitz, Myers
The Muon Collider Design Study at Fermilab

50 T solenoids are a crucial feature......

Now an approved design activity (MAP)
New Fe-base superconductors have spectacular Jc........

Co-doped BaFe$_2$As$_2$ thin films
The nanocolumns have a square shape with a size of $5\text{-}6\ \text{nm} \sim 2\xi$

Perfect sizes for the pinning centers

Almost perfects structural match between matrix and defects

No buckling around the defects

No degradation of the matrix properties

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, $\text{Ba(Fe}_{1-x}\text{Co}_x\text{)}_2\text{As}_2$ (Co-doped Ba-122) GBs are bad

Grain boundaries are weak linked – but textured growth is working...

Weak-link behavior of grain boundaries in superconducting $\text{Ba(Fe}_{1-x}\text{Co}_x\text{)}_2\text{As}_2$ bicrystals

APPLIED PHYSICS LETTERS 95, 212505 (2009)

Epitaxial Growth of Superconducting $\text{Ba(Fe}_{1-x}\text{Co}_x\text{)}_2\text{As}_2$ Thin Films on Technical Ion Beam Assisted Deposition MgO Substrates

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IFW-Dresden
Applications require conductors

Conductors must be
- Long
- Strong
- Affordable
- Uniform
- Work at high Jc (>1000 A/mm²) 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, Hc2(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…..
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