100 Years of Superconductivity
50 Years of Superconducting Magnets

Martin N Wilson

11th April 1911

Heike Kammerlingh Onnes Notebook #56

‘Kwik nagenoeg nul’
quick silver near enough zero

1st November 1961

International Conference at MIT on
High Magnetic Fields

sketch of HKO by his brother Menso Kammerlingh Onnes
Serendipity - but only after years of preparation

1882  HKO appointed professor of experimental physics at university of Leiden.
      - mission: test Van der Waals molecular theory of gases
      - motto: 'through measurement to knowledge'
      - cryogenic laboratory - a cold factory ⇒ big science

1892  oxygen liquefier ⇒ 14 litres/hour

1901  Leiden laboratory workshops
      organized as an instrument makers school
      - the 'blue collar boys'
      - a modern laboratory

1906  hydrogen liquefier ⇒ 4 litres/hour

1908  helium liquefier ⇒ 0.28 litres/hour

1910  first measurements on resistivity
The Leiden helium liquefier

1908 0.28 liquid litres helium per hour

1911 addition of side arm cryostat with stirrer for experiments

1912 improved version liquefies 0.5 litres per hour
1911: Resistivity at low temperature

- very different predictions of what might happen

- need high purity to see variations at very low temperature

- Leiden had expertise in purifying Hg by multiple distillation

- but nobody expected this!

(from HKO Nobel lecture)
Superconductivity

‘.....something unexpected occurred.
The disappearance did not take place gradually
but abruptly. ...... less than a thousand millionth part’

‘.....mercury at 4.2 has entered a new
state which ............... can be called the
state of superconductivity’  

HKO Nobel Lecture
**Persistent currents**

lead coil with shorted terminals
impose magnetic field when warm
cool the coil
remove field - induces current
measure field from current
back off with a resistive coil
no change for hours - persistent current

'It is uncanny to see .......... You can feel, almost tangibly how the ring of electrons in the wire turns around, around, around - slowly and almost without friction'

*P Ehrenfest*

**are they really currents?**

*yes!*
Magnets

' ............ bearing on the problem of producing intense magnetic field
.......a great number of Ampere windings can be located in a very
small space without ........ heat being developed......'

Communication from the Physical Laboratory University of Leiden Sept 1913

' ............ 100,000 Gauss could then be obtained by a coil of say 30
centimetres in diameter and the cooling with helium would require a
plant which could be realized in Leiden with a relatively modest
support............'

Third International Congress of Refrigeration, Chicago Sept 1913

' ............ In field above this threshold value, a relatively large magnetic
resistance arises at once.....'

'Thus an unexpected difficulty ............. faced us. The discovery of the
strange property which causes this made up for the difficulties
involved.'

Nobel Prize Acceptance Lecture, Stockholm Dec 1913
1930s: magnetic properties

1933: Meissner (& Ochsenfeld) effect

- cool down superconductor in magnetic field
- at the critical temperature $\theta_c$ the field is pushed out
- increase the field - field is kept out
- increase the field some more - superconductivity is extinguished and the field jumps in
- decrease the field - it's pushed out again

1935: London theory

- within a superconductor
  \[ \nabla^2 B = B / \lambda \]
  \[ \lambda^2 = m / 2e^2 \mu_0 n_c \]

  *where $m$ = mass electron, $e$ = charge electron, $n_c$ = density of carriers*

- so at the boundary
  \[ B = B_o \exp (-x/\lambda) \]
  \[ \lambda = \text{London penetration depth} \]
1930: Alloys

- at the Kammerlingh Onnes Laboratory, Keesom and de Haas showed that some alloys, eg PbBi, remain superconducting up to much higher fields than mercury, and lead.

1933: Magnets

- Mendelssohn in Oxford made a small PbBi solenoid for adiabatic demagnetization work
- it didn't work
- in retrospect ‘.....the only explanation I can offer is that the solenoid was not made from drawn wire but cut from a cast cylinder.'
1930s: magnetic properties

1937: Type 2 superconductors

- at Kharkov, Ukraine, Shubnikov showed that some materials show a more complicated Meissner effect
- field expelled at critical temperature
- increasing field penetrates partly at the lower critical field $H_{c1}$
- superconductivity not destroyed until (much higher) field $H_{c2}$
- fully reversible - state of thermodynamic equilibrium

Magnetization

(magnetic moment per unit volume)

Type 1: diamagnetic up to $B_c$ then resistive

Type 2: diamagnetic up to $B_{c1}$ then partially diamagnetic up to $B_{c2}$ then resistive

more alloy additions $\Rightarrow$ lower $B_{c1}$ higher $B_{c2}$
1954: the first superconducting magnet

George Yntema University Illinois magnet for adiabatic demagnetization

got niobium data from Schoenberg's book

but didn't read '....superconducting solenoids....but none of these possibilities could be realized because (high) critical field is characteristic of a very small fraction of the alloy...'

hard annealed

for quench protection
1961: MIT Conference on High Magnetic Fields

- 4.3T NbZr solenoid
- 5.5T NbZr solenoid
- 2.5T superferric racetrack with Nb$_3$Sn or NbZr windings
- 1.5T MoRe solenoid

Magnets in cryostats for the first time.
**1961: MIT Conference on High Magnetic Fields**

**Nb₃Sn: a brittle intermetallic compound**

- draw down Nb tube filled with Nb & Sn powder then heat to ~1000°C
  
  JE Kunzler, Bell Labs

- measured in pulsed high field
  
  HR Hart et al GE Research Labs

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Bernd Matthias found Nb₃Sn and probably more new superconductors than anyone else.
John Hulm did much of the early work on NbTi at Westinghouse.

1965: Westinghouse report a 100kg (10T) NbTi solenoid.

NbTi: a ductile alloy

NbTi is now the work horse of the magnet business ~3000 Tonnes pa

better than NbZr at high field

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CERN Centennial Superconductivity Symposium Dec 2011
Understanding superconductivity

1957 BCS Bardeen Cooper & Schrieffer
An effective attraction between pairs of electrons via the lattice promotes a condensed state in which the phases of all the individual wave functions are locked together.

1950 - 1959 GLAG: Ginzburg, Landau, Abrikosov & Gorkov
The behaviour of superconductors is determined by relationship between London penetration depth $\lambda$ and coherence length $\xi$ (distance over which superconducting state can change).

\[
\lambda < \frac{\xi}{\sqrt{2}} \quad \text{Type 1 behaviour} \Rightarrow \text{Meissner effect}
\]

\[
\lambda > \frac{\xi}{\sqrt{2}} \quad \text{Type 2 behaviour} \Rightarrow \text{Shubnikov state}
\]

- in type 2 superconductors field enters as quantized fluxoids with $\phi_o = \frac{h}{2e} = 2 \times 10^{-15}$ Webers

- fluxoids like to distribute uniformly $\Rightarrow$ zero current density in the bulk

- to get bulk current density must force non uniform distribution - flux pinning
Superconductor engineering

**Problem:** magnets do not reach field expected from superconductor properties

**First solution:** cryostabilization, devised by John Stekly 1965

- conductor with copper joined in parallel with superconductor
- well cooled by liquid helium

- current normally flows in superconductor
- if superconductor switches off, current diverts to copper
- Ohmic heating in copper
- heat transferred to helium, temperature falls
- current returns to superconductor

- works well Avco MHD generator ⇒

- but the large amount of copper dilutes current density too much for accelerators, NMR, MRI etc
Practical cryostabilization

Natural convection cooling

Cable in conduit conductor CICC

BEBC at CERN

but low engineering current density
Magnets at high current density

- no need for cryostabilization if we cure the problem of **flux jumping**
- **FJ** is a catastrophic instability of the screening currents which are induced by magnetic field (additional to transport current)

**Flux Jumping Instability**

- screening currents
- temperature rise
- reduced critical current density
- flux motion
- energy dissipation
- temperature rise

- cure flux jumping by weakening a link in the feedback loop
- fine filaments reduce $\Delta \phi$ for a given $-\Delta J_c$
- for NbTi the stable diameter is $\sim 50\mu m$
Magnetization, hysteresis and ac loss

\[ M = \frac{2}{3\pi} J \cdot d_f \]

\( \text{Magnetization M (A/m)} \)

\( \text{Field B (T)} \)

\( \text{Magnetization M (A/m)} \)

\( \text{Field B (T)} \)

\( \text{loop area = ac loss per cycle} \)

\( \text{Field quality in a magnet} \)

\( \text{data on LHC dipoles} \)

Luca Bottura to be published

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1969: Filamentary composite wires

• 'Intrinsically' Stable against Flux Jumping
  high current density in magnets, enables compact windings and high field gradients

• Low ac Losses
  important for synchrotron accelerators, electrical engineering and any application where the field changes

• Low Magnetization
  needed where field quality is important, eg accelerator magnets, NMR spectrometers

• Twisting is essential
  untwisted filaments are magnetically coupled and behave together like a solid wire
  twisted filaments are magnetically decoupled and behave like separate entities
High energy physics: the first technology driver

1967: '…superconductor diameter about $5 \times 10^{-4}$ cm...' PF Smith JD Lewin: Superconducting Proton Synchrotrons: NIMs 52 p298

1970s: GESSS collaboration (Karlsruhe, Rutherford, Saclay)

proposed superconducting magnets for the CERN SPS

D1 Karlsruhe

Rutherford cable

AC4 Rutherford
1984 Tevatron: first superconducting accelerator

Two gifts for accelerator magnet technology

1 porous winding
- Kapton insulation wrap
- no resin against conductor
- liquid helium in contact with wire
- better magnet performance - less training

2 collars
- coils clamped by precision stamped collars, fixed together by rods
- high precision shape
- low eddy currents
Minimum quench energy MQE

- even when flux jumping is eliminated, still get degraded performance
- mechanical energy release as field raised
- make conductor stable against energy release
- quantify conductor stability as minimum energy pulse needed to quench

![Graph showing MQE vs. I/Ic](image)

- open insulation
- Porous metal
- closed insulation
- bare wire

40μJ is a pin dropping 40mm

**single wire measurement 1980**
Superconducting accelerators

Hera

RHIC

LHC

Helios
2020: Really big science - ITER

29m high
28m diameter
23000 tonne
51,000 MJoule
1962: A new industry

Research magnets

NMR spectrometers
NMR Imaging

1979 Oxford Instruments build the world's first superconducting NMR imaging magnet

2011 Siemens Skyra MRI
*CONsortium of European Companies (determined) To Use Superconductivity*
A century of critical temperatures

Woodstock of Physics 1987

Paul Chu

Critical temperature K vs. year

- Pb
- Hg
- Sn
- Nb
- Nb$_3$Sn
- NbZr
- NbTi
- PbMo$_6$S$_8$
- YBCO
- B$_2$212
- B$_2$223
- MgB$_2$
- BaLaCuO

Alex Mueller
Georg Bednortz

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Wonderful materials for magnets

but for two problems

- flux flow resistance
- grain boundary mismatch
Accessible fields for magnets

- B2212
- YBCO
- MgB$_2$
- B2223
- Nb$_3$Sn
- Nb$_3$Al
- NbTi
HTS grain boundary matching

- current can only jump between grains if they are aligned
- must make conductors with all grains aligned to a few degrees
- a single crystal km long!

Textured YBCO tape

- best irreversibility field
- deposit YBCO film on aligned substrate

- OK in high field and at high temperature
HTS - where next?

Existing applications? replace LTS

- reduced cost of cryogenics
  - but modern cryogenics are very efficient
  - typical MRI installation cryogenic cost is only 4% of operating budget

- more convenient cryogenics ⇒ cryo-free magnet systems
  - but two stage cryocoolers work fine at 4K!
  - no coolant gas: uncooled copper leads ⇒ 45 × more heat leak than cooled
  - HTS leads are the essential enabling technology for 4K cryocooler magnets

- current leads: often the largest refrigeration load of a magnet

- High field magnets - research, NMR, HEP?
  - Nb$_3$Sn ⇒ 22T  BSCO & YBCO ⇒ 50T

New Applications?

- in rough environments where cryogenics must be very robust and reliable

- where loss is inherent and causes a large refrigeration load - electrical power engineering

  - refrigeration power demand $\frac{CoP(77K)}{CoP(4K)} \approx 25$
Current leads and cryofree systems

13 kA lead for LHC
(photo CERN)

12 T magnet & dilution refrigerator

7 T split pair

Current lead

photos
Oxford Instruments
**High field inserts**

- **round B2212 wire insert**
  \[ \Rightarrow 22.5T \text{ in } 20T \text{ background} \]

- **coated YBCO tape insert**
  \[ \Rightarrow 33.8T \text{ in } 31T \text{ background} \]

Critical current vs. magnetic field graph:

- **B2212**
- **Nb\text{\textsubscript{3}}Sn**
18 May 2011
Japanese Government authorizes Central Japan Railway Co to proceed with high speed Maglev link from Tokyo to Osaka by 2045 speed 580 kph

2005 B2223 levitation magnet tested on vehicle

2010 coated YBCO tape model levitation magnet

photos CJR and RTRI

Induction heating of aluminium billets

rotate the billet in a dc field
Motors

36.5MW ship propulsion motor
B2223 rotor tested Jan 2009

30kW prototype electric car
Sumitomo Electric Industries

1MW generator & motor (LTS)
IRD 1975
team leader
Tony Appleton
Power transmission

1MVA prototype transformer

630kVA 3 phase transformer at Baiyin China

2 MVA FCL Transformer (Nagoya University)

Inductive Fault Current Limiter (Zenergy)
HTS in engineering - things still to do

1) Cost

- NbTi or Nb$_3$Sn at 4.2K 5T ~ 1€ /kA.m
- Nb$_3$Sn at 4.2K 12T ~ 3€ /kA.m
- B2212 at 4.2K 12T ⇒ ~ 70€ /kA.m

2) AC losses

\[ P = \dot{B} J_c \frac{d}{4} \]

d is width transverse to field

Loss power

Refrigeration power demand

\[ \frac{CoP(77K)}{CoP(4K)} \approx 25 \]

10µm at 4K ⇒ \(\frac{1}{4}\) mm at 77K
1µm at 4K ⇒ 25µm at 77K
A superconducting century

- Liquefy helium
- Superconductivity of mercury
- Magnetic field quenches superconductivity in lead
- PbBi alloy superconducts in 2T
- Meissner effect
- London theory
- Shubnikov measures type 2 behaviour
- First magnet
- BCS and GLAG theories
- Nb₃Sn, NbTi
- MIT Conference on High Magnetic Fields
- First NMR spectrometer
- First MRI
- Tevatron
- BaLaCuO
- YBCO, BSCCO
- YBCO tapes
- LHC