Superconductivity Centenary

Noble Science among Nobelists and even a King

Jarl-Thure Eriksson
13.6.2011
The discovery of superconductivity on April 8, 1911

Historic diagram of Kamerling Onnes, 26 October 1911

Kamerling Onnes 1853-1926, together with Johannes van der Waals, 1837-1923, in front of Onnes’ cryostat at Leiden.


The cooling system was based on the use of liquified common gases at several temperature stages.

Source: Dirk van Delft, Peter Kes, The discovery of superconductivity, American Institute of Physics, 2010
Historic notes

Onnes’ Notebook for April 8, 1911:
“Mercury’s resistance practically zero.”

Gilles Holst, 1886-1968
- the student (25) who assisted Onnes in measuring the resistance of mercury around the critical point 4.2 K
- later esteemed radio tube developer at Philips

Source: Dirk van Delft, Peter Kes, The discovery of superconductivity, American Institute of Physics, 2010
The laboratory team of Kamerling Onnes

Garret Flim, chief technician

Myth 1: The “blue boy” messed up the measurements. Onnes considered the first results as a system disturbance.

Reality: Gilles Holst did the measurements and Onnes made the historical notes himself.

Myth 2: Onnes placed a short-circuited SC coil in a dewar bottle, travelled to a conference in England and showed the existence of a magnetic field due to the persistent current.

Reality: In 1914 Onnes succeeded in producing a persistent current in a SC mercury ring conductor. In 1932 Garret Flim demonstrated the same phenomenon to the Royal Institution in London.

The first Solvay conference in Brussels in 1911.

Onnes presented the Hg-resistance drop curve at 4.2 K only a couple of weeks after the measurement in October.

In the back row to the right: Rutherford, Onnes, Einstein and Langevin.
The Meissner effect

The physics of superconductors was almost a mystery until the 30ies.

Walther Meissner and Robert Ochsenfeld were the first to investigate the magnetic field in and around a SC body.

In 1933 Meissner found that the field was completely expelled from the bulk material.

Walther Meissner, 1882-1974
Early theories

The two-fluid model, 1934
C.J. Gorter, H.B.G. Casimir

- two components of conduction charge carriers, "fluids", $n_n$ and $n_s$,
- the density of $n_s$ increases with decreasing temperature, $n_s$ vanishes at $T_c$,
- the "superfluid" component is an ordered condensed state with zero entropy; hence incapable of transporting heat.

The London equations in 1935
Fritz London, 1900-1954

- an electromagnetic approach to SC,
- describes the penetration of the magnetic field into a superconductor in the Meissner state,
- defines one form of penetration depth $\lambda$.

The Ginzburg-Landau theory 1950
Vitaly Ginzburg (1916-2009), Lev Landau (1908-1968), Nobel in 1962

- a phenomenological explanation of SC based on thermodynamics, i.e. the Landau second-order phase transition theory, lacks microscopic description,
- defines a correlation length $\xi$, which describes the average life length of SC "charges",
- the ratio between the correlation length and the penetration depth (different from London's def.) is related to $B_{C1}$ and $B_{C2}$.

\[ \lambda \equiv \sqrt{\frac{mc^2}{4\pi n_s e^2}}. \]
The history of superconducting materials

Source: DolTPoMS, Dept. of Material Science, University of Cambridge
Two types of superconductivity

Type I: Pure metals, only Meissner state superconduction.

Type II: Compounds (Nb$_3$Sn), alloys (Nb-Ti), Meissner state and a mixed state comprising flux vortices.

Type II superconductor

Quantum flux, fluxon: 
\[ \Phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15} \text{Vs} \]
Abrikosov Vortex Lattice

Alexei Abrikosov, * 1928

- Seminal paper in 1957
- Based on the Ginzburg-Landau theory
- Quantized flux vortices
- Proposed square lattice, in reality triangular
- Nobel Prize 2003

First decoration picture of vortices by Essmann and Traeuble (1967).
Source: Abrilovos's Nobel Lecture, 2003

Ginzburg received the Nobel Prize together with Abrikosov in 2003.
BCS theory of superconductivity, 1957

Named after John Bardeen, Leon Cooper and Robert Schrieffer

- first microscopic theory, i.e. a theory explaining the phenomenon in quantum mechanical terms,
- electrons are tied together forming Cooper pairs,
- an energy gap between the pair and the atomic lattice prevents thermal interaction, as a result electron pairs can move without releasing energy to the lattice,
- the theory works only at low temperatures and for elements, simple compounds and alloys, it has not been successful for HiTc superconductors.

Formation of Cooper pairs:
While moving an electron deforms the lattice of atoms by attracting them towards the path.
Higher positive charge density attracts another electron, which couples itself to the first electron.
In practice a very dynamic process involving a great number of electrons.

Leon Cooper, *1930, Nobel Prize in Physics 1972 (together with Bardeen and Schrieffer)
Shots from Gräftåvallen, Sweden, June 1988

John Bardeen, 1908-1991
Nobel Prize in Physics 1956, invention of the transistor
Nobel Prize in Physics 1972, theory of superconductivity

Robert Schrieffer, *1931
Nobel Prize in Physics 1972, theory of superconductivity

Philip W. Anderson, *1923
Nobel Prize in Physics 1977, electronic structure of magnetic and disordered solids

Photos: JTE
**Nb$_3$Sn/Cu SC wire**

Magnet manufacturing with use of superconductors on base of Nb3Sn/Cu demands much more complex technology connected with baking out of a ready magnet at high temperature in vacuum or inert gas.

Three main processes of fabricating Nb$_3$Sn wires:
- Bronze process
- Internal Sn process
- Powder in tube (PIT) process

Source: Nikolay Mezentsev, Joint US-CERN-Japan-Russia Accelerator School, 6-16 April 2011

\[
\frac{B_{C2}(T,\varepsilon)}{B_{C20}(\varepsilon)} = \left[ 1 - \left( \frac{T}{T_{CO}(\varepsilon)} \right)^2 \right] \cdot \left[ 1 - 0.31 \cdot \left( \frac{T}{T_{CO}(\varepsilon)} \right)^2 \right] \cdot \left[ 1 - 1.77 \ln \left( \frac{T}{T_{CO}(\varepsilon)} \right) \right]
\]

- \(B_{C20} = 30T\) critical field at \(T=0K\)
- \(T_{CO} = 18K\) critical temperature at \(B=0T\)

\[
a = 900 \text{ for compressive deformation} \\
a = 1250 \text{ for tensile deformation}
\]

Comparison of NbTi and Nb$_3$Sn

Joint US-CERN-Japan-Russia Accelerator School, 6-16 April 2011
# TABLE 1. Large Scale Applications of Superconductivity

<table>
<thead>
<tr>
<th>Energy Production</th>
<th>Approximate Year for Earliest Commercial Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion</td>
<td>2000</td>
</tr>
<tr>
<td>MHD</td>
<td>1985</td>
</tr>
<tr>
<td>Energy Storage</td>
<td></td>
</tr>
<tr>
<td>Magnetic</td>
<td>1980</td>
</tr>
<tr>
<td>Energy Transformation</td>
<td></td>
</tr>
<tr>
<td>AC Generators and Motors</td>
<td>1980</td>
</tr>
<tr>
<td>DC Generators and Motors</td>
<td>1980</td>
</tr>
<tr>
<td>Transformers</td>
<td>?</td>
</tr>
<tr>
<td>Energy Transmission</td>
<td></td>
</tr>
<tr>
<td>DC Cables</td>
<td>1990</td>
</tr>
<tr>
<td>AC Cables</td>
<td>1990</td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
</tr>
<tr>
<td>High Speed Ground Transport</td>
<td>1980</td>
</tr>
<tr>
<td>(Passengers and/or Freight)</td>
<td></td>
</tr>
<tr>
<td>Space Craft Launch</td>
<td>1980</td>
</tr>
<tr>
<td>Industrial Processing</td>
<td></td>
</tr>
<tr>
<td>Separation (Ore, Recycling)</td>
<td>1980</td>
</tr>
<tr>
<td>Water Filtration</td>
<td>1980</td>
</tr>
<tr>
<td>Effect on Chemical, Metallurgical Reactions</td>
<td>?</td>
</tr>
</tbody>
</table>

Source: J Powell in SC Machines and Devices, NatoAdv Study Institute, 1973
Bubble chambers were important instruments in high energy physics during the latter part of 1900.

The BEBC Bubble Chamber 3.5 T SC magnet, 1970

Source: CERN
DC Electric Motors: The Fowley Homopolar project

The Fawley Motor

- 3250 hp, 200 rpm,
- designed by IRD in Newcastle upon Tyne,
- installed as a water pump at Fowley power station in 1971,
- tested in 1972,
- project manager: Anthony D. Appleton, SC pioneer.

Source: A.D. Appleton in SC Machines and Devices, NatoAdv Study Institute, 1973
Magnetically Levitated Trains

JNR first levitated test vehicle, 4 passengers

Photo: JT Eriksson, 1974

Magnetic attraction, unstable

Dynamic repulsion, self-stabilizing

JNR Full Scale MAG-LEV train comprising SC technology

Source: Japan National Railways
High Temperature Superconductors

George Bednorz and Alex Müller published the first paper on successful measurements on HiTc superconductors in late 1986. They received a joint Nobel Prize in Physics the next year, 1987.

Characteristics:
- complex structure comprising copper oxides and lanthanides,
- the super-current flows in 2-dimensional planes,
- the break-point between the normal and the SC state is not as clear as for LoTc SCs,
- critical current and critical flux density limit the applications.
The SC onion and the HiTc flop

Notice the highly limiting influence of flux density on current conduction at $T = 0$!
### Forecast of HTS break-through, by item

**Nikkei (Delphi techniques)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Commercial volume M$/y</th>
<th>Probability of b-t by y. 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnets</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRI-tomography</td>
<td>250</td>
<td>100</td>
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<tr>
<td>Wiggles</td>
<td>450</td>
<td>90</td>
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<tr>
<td>Magnetic separation</td>
<td>110</td>
<td>75</td>
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<tr>
<td><strong>Energy systems</strong></td>
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<tr>
<td>Magnetic storage</td>
<td>2,000</td>
<td>70</td>
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<td>Generators</td>
<td>33</td>
<td>56</td>
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<td>Cables</td>
<td>17</td>
<td>52</td>
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<td>Transformers</td>
<td>5 ?</td>
<td>25 ?</td>
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<tr>
<td><strong>Electric energy use</strong></td>
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<tr>
<td>Levitated trains</td>
<td>3,500</td>
<td>100</td>
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<tr>
<td>Magnetic launchers</td>
<td>8</td>
<td>95</td>
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<tr>
<td>Electric machinery</td>
<td>50</td>
<td>52</td>
</tr>
<tr>
<td>Direct ship propulsion</td>
<td>1,100</td>
<td>30</td>
</tr>
<tr>
<td>Electric cars</td>
<td>600</td>
<td>20</td>
</tr>
</tbody>
</table>
Magnetic Resonance Imaging

Typical MRI whole body scanner

MRI scan of metastatic brain tumor

Source: National High Magnetic Field Laboratory, U of Florida

Source: Biology Encyclopedia, Biology Reference
Magnetic Resonance Imaging

SC MRI magnet designed and constructed at Helsinki University of Technology in the late 80ies. Part of an experimental attempt to use phosphorus as the tissue signal base.

Photo: Heikki Collan
Superconductivity in the power sector

- generators
- transformers
- energy storage
- transmission cables

Source: ABB/JT Eriksson
Superconducting Energy Storage, SMES

Toroidal concept of 5000 MWh SMES

Source: U.S. Department of Energy
Generators for power production

- smaller size
- higher efficiency
- small transient reactances meaning fast control properties

Superconducting synchronous generators

<table>
<thead>
<tr>
<th>Country</th>
<th>Company</th>
<th>Power, MVA</th>
<th>Status</th>
</tr>
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<tbody>
<tr>
<td>USA</td>
<td>MIT</td>
<td>10</td>
<td>R&amp;D 1974-80</td>
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<tr>
<td>USSR</td>
<td>All-Union Inst.</td>
<td>20</td>
<td>Tests 1981</td>
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<tr>
<td>USA</td>
<td>General Electric</td>
<td>20</td>
<td>Tests 1982</td>
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<tr>
<td>Japan</td>
<td>Fuji Electric</td>
<td>30</td>
<td>Tests 1983</td>
</tr>
<tr>
<td>Japan</td>
<td>Hitachi</td>
<td>50</td>
<td>Tests 1984</td>
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<tr>
<td>USSR</td>
<td>Elektrosila</td>
<td>300</td>
<td>Rotor, 1980-92</td>
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<tr>
<td>USA</td>
<td>Westinghouse</td>
<td>300</td>
<td>Terminated 1986</td>
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<tr>
<td>Germany</td>
<td>Siemens/KWU</td>
<td>400</td>
<td>Feasibility study 1990-92 Design 1990-94 Tests 1993-94 Design 1994-</td>
</tr>
<tr>
<td>Japan</td>
<td>Msb/Hit/Tos</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>Msb/Hit/Tos</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

Source: U.S. Department of Energy
Source: JTE
Finland
SC ship propulsion for arctic Ice Breakers

Conventional

Superconducting

P = 27 MW

Figure 2. Comparison between a 27 MW conventional (left) icebreaker propulsion system and a superconducting (right) system.

Source: JT Eriksson, PhD thesis 1982
The SUMO Motor, HUT 1979

The SUMO motor was designed and constructed at Helsinki University of Technology between 1977 and 1979.

Maximum performance:

\[ P = 100 \text{ kW} \]
\[ n = 1200 \text{ rpm} \]
\[ I = 12,000 \text{ A} \]
\[ I_F = 150 \text{ A (SC field current)} \]

Photo: Jorma Luomi
The SUMO motor

The homopolar motor concept:
- two static counter-magnetized SC solenoids inside a hollow rotor,
- active armature circuit at room temperature,
- armature conductors consisting of copper shells.

Practical outline and current collection:
- two “auxiliary rotors” at constant speed provide centrifugal force keeping liquid Ga-In in circumferential trenches,
- the armature current is transferred from the stator conductor to the rotor conductor via the liquid metal rings and a “shunt” in the auxiliary rotor - and then back again in the other end of the rotor.
Hands on...

Assembling the SUMO Motor

From the left:
Matti Savelainen
Antero Arkkio
Jorma Luomi
JTE

Photo: VTT

First test run of the SUMO Motor in May 1979

From the left:
JTE
Peter Berglund
Matti Savelainen
Antero Arkkio

Photo: Jorma Luomi
The upgraded synchrotron ring at the MAX-Lab, University of Lund.

Source: MAX-Lab brochure 1996
The emission of synchrotron radiation

1. Bending Magnet
\[ \frac{v_e}{c} < 1 \]

2. Bending Magnet
\[ \frac{v_e}{c} < 1 \]

3. Undulator
\[ \frac{v_e}{c} \leq 1 \]

4. Wigler
\[ \frac{v_e}{c} \leq 1 \]

Source: JT Eriksson
Computer simulation of the emission of SR in a 3-pole wiggler magnet.

Source: Lauri Kettunen, TUT
A SC 3-pole wiggler for the MAX-Lab

Lasse Söderlund and Risto Mikkonen assembling the SC wiggler at TUT.

Photo: Söderlund, Mikkonen
King Karl XVI Gustaf of Sweden initiating the MAX II ring at the Lund facility in 1996.

Upper right: Risto Mikkonen at the planned position of the TUT wiggler. 
Lower right: The TUT wiggler and cryostat delivered to MAX-Lab.

Photos: JTE
Tho Norpas HiTc SC generator

A joint Nordic undertaking starting in 1989.

TUT responsible for design and construction.


\[ P = 1500 \text{ W} \]
\[ V = 400 \text{ V} \]
\[ n = 1500 \text{ rpm} \]
\[ \eta = 95.5\% \]

Photo: TUT, Lasse Söderlund
Tho Norpas HiTc SC generator

General design.

Superconducting field coil (one of four)
Material: BSCCO 2223, American Superconductor Inc.
Turns: 198
Nominal current: 137 A
Max. flux density: 1.0 T
Critical current density over-all: 45 A/mm²

Source: Söderlund, Mikkonen
One more Nobelist

Chen-Ning Yang, *1922

- Nobel Prize in 1957 with T. deLee for work on weak interactions,
- Most well-known for the Yang-Mills theory, a mathematic formulation of the strong force resembling General Relativity equations,
- Was invited to meet with Einstein,
- Appointed Einstein Professor at Princeton University after Einstein’s death in 1955.

Photo JT Eriksson