Applications of Superconductivity

Larger and stronger magnets for Big Science: Colliders, detectors and more...

Erwin Bielert
A little bit of history…

Dewar: all vibrations stop at zero Kelvin and thus electrons can move through the atomic lattice without resistance.

Matthiessen: resistance is dominated by impurities and dislocations inside the atomic lattice and therefore resistance should be finite at low temperatures and towards zero Kelvin.

Kelvin: all movement stops, also the electrons, therefore, no current can be present, which is represented as an infinitely large resistance.

Fundamental physics questions require the need for new technologies:
How do we reach such low temperatures?!
A little bit of history... continued

1877: liquefaction of air by Cailletet (FR) and independently Pictet (CH)

1883: liquefaction of oxygen by Wroblewski and Olszewski (PL)

1898: liquefaction of hydrogen by Dewar (UK)

1908: liquefaction of helium by Kamerlingh Onnes (NL)

1911: resistance measurement of Mercury cooled by liquid helium
1913, Heike Kamerlingh Onnes:  
“for his investigations on the properties of matter at low temperatures that led, inter alia, to the production of liquid helium”

1962, Lev Landau:  
“for his pioneering theories for condensed matter, especially liquid helium”

1972, John Bardeen, Leon Cooper and John Robert Schriefer:  
“for their jointly developed theory of superconductivity, usually called the BCS theory”

1973, Leo Esaki and Ivar Glaever, jointly with Brian Josephson:  
“for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors respectively” and “For his theoretical predictions of the properties of a super current through a tunnel barrier, in particular those phenomena that are generally known as the Josephson effects”

1987, Georg Bednorz and Alexander Mueller:  
“for their important break-through in the discovery of superconductivity in ceramic materials”

2003, Alexi Abrikosov, Vitaly Ginzburg and Anthony Leggett:  
“for pioneering contributions to the theory of superconductors and superfluids”
A dream was born: let’s make a 10 T magnet!

1912: first superconducting Lead coil

“The 10 T magnet project was stopped when it was observed that superconductivity in Hg and Pb was destroyed by the presence of an external magnetic field as small as 500 Gauss (0.05 T)”

It took about 50 years to understand why it was not possible to make strong superconducting magnets. Only in the 1960s the first real superconducting coils were available.
Perfect diamagnetism due to the fact that persistent screening currents flow at the surface of the superconductor as to oppose the externally applied magnetic field: i.e. in the bulk of the material there is no magnetic field, the field is expelled.

Note that diamagnetism in normal metals rather has to do with orbital spin of electrons.

Perfect conductors without any resistance, would also prevent any *change* of magnetic flux due to ordinary electromagnetic induction, but for superconductors there is more going on...
Meissner – Ochsenfeld effect
Meissner – Ochsenfeld effect
Critical field

Solid line is the superconductor and the dashed line the normal metal.
Type I and Type II superconductors

\[ B_c \approx B_c(0) \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right] \]

**Mercury**

- Type I
  - \( B_c = 0.041 \text{ T} \)
  - Normal
  - Superconductor \( T_c = 4.15 \text{ K} \)

**Niobium-Tin**

- Type II
  - \( B_{c2} = 24.5 \text{ T} \)
  - Normal
  - Mixture of normal and superconducting
  - \( T_c = 18 \text{ K} \)

- Type I
  - \( B_{c1} = 0.19 \text{ T} \)
  - Normal
  - Superconductor
Vortices can move under the action of forces, flux creep and even flux jumps might occur. Due to a better understanding at the microscopic level, pinning centers can be introduced. Material science is of utmost importance for the development of future superconductors.
Magnetic field goes down with increased distance from current source... to have high magnetic fields, currents need to be close!
Superconducting magnets: why bother at all?

Magnetic field scales with number of turns, current and permeability.

The ingredients for a strong magnet are clear: Many turns with high current and a iron core.

Problems and difficulties:
- Iron saturates
- Current causes Ohmic heating (V=IR, P=VI)

Practical limitation of normal conducting, water cooled magnets is 2 T.
Recipe for increased current densities

Precipitates in alloys, microstructure of Nb-Ti

Thin filaments in a wire
Modern superconductors: practical for magnets

- **YBCO** for DC magnets of 17-40 T, expensive, cost must come down for large scale use
- **Minimum practical current density**
- **BSCCO-2212** for DC magnets of 17-40 T provided cost reduced
- **MgB₂** not for high field magnets but for niche market 1-5 T, 4-20 K
- **Nb₃Sn** for magnets of 9-20 T
- **NbTi**, still the workhorse for 1-9 T at 2-4 K

![Graph showing Jₐ (A/mm²) vs. Applied Field (T) for various superconductors including YBCO, MgB₂, Nb₃Sn, NbTi, and BSCCO-2212.](image-url)
Scaling of current with volume: huge currents!

- 0.0001 m³ HF insert model
  ~ 200 A

- 2 m³ MRI magnet
  200-800 A @ 1-3 T, ~10 MJ

- 25 m³ ATLAS solenoid
  8 kA @ 2T, 40 MJ

- 50 m³ LHC dipole
  12 kA @ 8.3 T

- 400 m³ HEF detector magnet
  20 kA @ 4 T, 2.6 GJ

- 1000 m³ ITER magnets
  40-70 kA @ 10-13 T, 50 GJ
Large current asks for cables rather than wires.
A magnet can only meet high standards, if the cable used to wind the coils is of the best quality imaginable. But the cable will only perform correctly if the wires are designed properly and this goes all the way down to the most fundamental understanding of the superconducting material itself.
Applications: wind turbines

Fig. 1: Envision OC-1 turbine (E120-3.6 MW) installed Thyboron, Denmark. EcoSwing will replace pink parts by an HT1 generator and an innovative power converter.

Expected Key Benefits
- Generator Weight: -40%
- Generator Length: -22%
- Generator Cost: -40%
  (mature market)
- Nacelle Weight: -25%

A EU Horizon 2020 project by Envision, ECO5, Jeumont, Delta, Theva, SHI, DNV GL Energy, Fraunhofer Institute & University of Twente.
Applications: power lines

Coordinated by TenneT (Dutch TSO)

- 3.4 km long
- 64 / 110 kV; 150MVA
- Feasibility
- Cost-effectiveness
- Reliability & reparability
Applications: nuclear fusion

Caderache, France: building site
Applications: MRI

Largest market for superconducting material
Applications: accelerators

Collision energy:

\[ E_{\text{TeV}} \approx 0.3 B_T R_{\text{km}} \]

9 T & 4.6 km \Rightarrow 14 \text{ TeV}
Applications: detectors

\[
\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3 BL^2 \sqrt{N+4}}
\]
LHC magnets
Oersted, Ampère, Biot-Savart
Bending and focussing
No superconductivity, no Higgs…

The Large Hadron Collider could not be realized without exclusive use of superconductivity and high quality magnets.

- Nb/Cu cavities for acceleration
- ATLAS and CMS detector magnets
- 1232 dipoles magnets for bending
- 386 quadrupole magnets for focusing
- ~6000 correction magnets
- Insertion and Final Focusing magnets

No Higgs without Superconductivity!

Fundamental physics questions require the need for new technologies…
CMS and ATLAS: fundamentally different magnets
ATLAS: extreme use of superconductors

1 Barrel Toroid and 2 End Cap Toroids and 1 Central Solenoid
generate 2 T for the inner detector and ~1 T for the muon detectors

21 m diameter and 25 m long
8300 m³ volume with field

170 t superconductor
320 t magnets
7000 t detector
90 km superconductor

20.4 kA at 4.1 T
1.6 GJ stored energy
4.7 K conduction cooled
9 yrs of construction 1998-2007

By far the largest trio of toroids ever built!
ATLAS subsystems

Solenoid 2 T at 7.83 kA
2.4 m bore x 5.3 m long
39 MJ at 2 T, 7.73 kA

Barrel Toroid integration

8 25x5 m² long/wide coils
1.1 GJ at 4 T, 20.4 kA

End Cap Toroids
20.4 kA, 4.1 T, 250 MJ
140 t cold mass
Transport of ATLAS magnets

Solenoid insertion

100 tons Barrel Toroid coil

250 tons, 15 m height, 5 m wide
Applications: MRI

First (1912) & Largest ever built (2007)
from 0.05 m to 25 m
Possible accelerators of the future

ILC in Japan:
International Linear Collider

But no need for many magnets...
Possible accelerators of the future

CLIC:
Compact Linear Collider

Yet again:
not many magnets required...
Possible accelerators of the future

CepC/SppC in China:
Circular Electron Proton Collider
Super Proton Proton Collider
Possible accelerators of the future

**FCC:**
Future Circular Collider

100 TeV c.o.m.
100 km circumference
16 T magnets -> how?
Remember this one?

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FCC target

- LHC
- High Luminosity
- FCC
- FCC Target: 1500 A/mm²

Graph showing $J_c$ at 4.2 K (A/mm²) vs Field (T):
- $J_c$ values:
  - 3000 A/mm²
  - 2000 A/mm²
  - 1000 A/mm²

Microstructures:
- Lattice: 50 nm
- Filament: 20 μm
- Wire: 1 mm
Upscaling of production

Future Circular Collider

For comparison:

ITER uses only
200 t NbTi and
500 t Nb₃Sn!

<table>
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<th>LHC</th>
<th>HE-LHC</th>
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<td>33 TeV</td>
<td>100 TeV</td>
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<tr>
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<td>3000 t</td>
<td>9000 t</td>
<td>6000 t</td>
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<td>700 t</td>
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<td><strong>20 T</strong></td>
<td><strong>20 T</strong></td>
<td><strong>16 T</strong></td>
</tr>
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</table>
FCC-hh: cavern
Possible future detector systems: FCC-hh
FCC-hh: baseline

Design:
• Main solenoid with 4 T in a 10 m free bore
• Forward solenoids, to extend the bending capacity for high eta particles
• Attractive force between solenoids need to be handled with tie rods (60 MN inwards)

Result:
• Relatively simple cold-mass structure, a scaling-up of existing and proven designs
• Stored energy: 13.9 GJ
• Significant stray field in main cavern, since no return yoke, nor shielding coil present (cost reduction)
Possible future detector systems: FCC-hh