Superconductivity
Physics and
Potential Applications in Aeronautics

Dr. rer. nat. Jürgen Steinwandel
Executive Expert Energy & Propulsion
Airbus Group CTO- AGI TX6 Ottobrunn/Munich
March 2015
Table of Content

1. Introduction (History and basic physical principles)
2. Principles of Theoretical Physics for Superconductivity
3. Overview Superconductors and Cooling Technologies
4. Hybrid- Electric Powertrains in Aircraft
5. Superconducting Cables
6. Superconducting Electric Machines
7. Expectations for Superconducting Components/Subsystems in Aircraft
1. Introduction (History and some basic Physical Principles) /1

1911: Discovery of the effect by Heike Kamerlingh - Onnes ; Leiden Low Temperature Physics Department. Noble Price 1913.

Measurements using Mercury (Hg) with 4,2 K transition temperature.

Physical nature of Superconductivity:

- Cooperative macroscopic quantum effect leading to a:
  - 2nd order phase transition (Fermi gas to Bose Einstein gas & condensation)
  
- Free lattice electrons (Fermions; spin 1/2h are coupled via lattice phonon interaction to so- called Cooper pairs consisting of two electrons with antiparallel spin vectors (intrinsic angular momentum), which results into a Boson having spin 0. This is a switch in the quantum statistics from Fermi- Dirac (Spin 1/2h, e.g. electrons) to Bose-Einstein (Spin 0 or 1,2…, e.g. Cooper pairs, lattice phonons, photons….). Description possible via one general wave function.

Theoretical Physics models for Superconductivity and related phenomena

- F. London/H London (1935) Theory superconductivity
- J. Bardeen/L.Cooper/J. Schrieffer-BCS-Theory (1957), Nobel prize (1972)
1. Introduction (History and some basic Physical Principles)

1933: Discovery of the Meissner - Ochsenfeld- Effect
(W. Meissner and R. Ochsenfeld; Low Temperature Physics Department Physikalisch - Technische Reichsanstalt Berlin.

Classification of Superconductors:

**Superconductors of first order (Showing a M-O- effect).**

- Magnetization

  \[ M = \begin{cases} 0 & H < H_c \\ \text{linear} & H > H_c \end{cases} \]

  Meissner- Phase (well below 1 Tesla)

  Examples: Hg; Pb; Al. In general mostly elements

**Superconductors of second/third order (Showing no M-O- effect).**

- Magnetization:

  \[ M = \begin{cases} 0 & H < H_c \\ \text{linear} & H > H_c \end{cases} \]

  Shubnikov- Phase (up to 50 Tesla for third order)

  Examples: NbTi; Nb3Sn, MgB2 (mostly intermetallics), but also: e.g. YBCO (HTS)

Ideal superconductor in a magnetic field
Superconductor of 1st order
“ideal diamagnet”

However:
No absolute ideal behavior in reality, but described by the London penetration

\[ \lambda_L = \sqrt{\frac{\mu_0 \lambda}{4\pi \mu}} = \sqrt{\frac{mc^2}{4\pi n_s e^2 \mu}} \]

Analogy: Skin effect for high frequency currents/electric fields
1986: Discovery of High Temperature Superconductors (HTS)
J.G. Bednorz and K.A. Müller. IBM Research Institute Rüschlikon/CH
Nobel Prize 1987
Transition Temperature: 32K (original published value)

Chemical Physics Nature:
• Perovskit (Oxide Ceramics); (La,Ba)2CuO4
• Electrically non-conductive above transition temperature (isolator)
• Oxygen-Ion conduction at high temperatures (> 800 °C, SOFC relevant)

Preparation of ceramic HTS superconductors (basics):
• Solid state thermochemical reaction with oxide powder component mixing, calcination and subsequent sintering to form bodies.
• Solution chemistry processes like reaction spray, freeze drying, sol-gel
• Typical calcination temperatures: 600°C-950°C
• Typical sintering temperatures (depending on powder morphology: and pressure (e.g. hot isostatic): up to 1100 °C
2. Principles of Theoretical Physics for Superconductivity

Theory of Bardeen, Cooper and Shrieffer (BCS)

- Based on Drude- Lorentz free electron gas

Free lattice electrons (Fermions; spin $\frac{1}{2}$h are coupled via lattice phonon interaction to Cooper pairs consisting of two electrons with antiparallel spin vectors, which results into a Boson having spin 0. This is a switch in the quantum statistics from Fermi-Dirac (Spin $\frac{1}{2}$h, e.g. electrons) to Bose-Einstein (Spin 0). Only the BE statistics describes superconductivity adequately!

- Strictly valid for metallic superconductors (low temperature) only. It is, however, assumed that the BCS theory is also valid for HTS.

Problem: binding energy of a Cooper pair is about $1/1000$ eV (for comparison: a chemical bond energy is $2 – 5$ eV). Stability at higher temperatures questionable.

- Possible ways out:
  - Spin- lattice- Spin magnetic coupling of two electrons
  - Extended quantum mechanical orbital theory
  - Generalized Bose- Einstein condensation (any physical description of superconductivity requires bosons as conducting particles and no Fermions)

\[
P(E) = \begin{cases} 
1 & \frac{1}{e^{(E-\mu)/k_B T} - 1} \quad \mu < 0 \\
\frac{1}{e^{(E-\mu)/k_B T} + 1} \quad \mu = E_F 
\end{cases}
\]
2. Overview Superconductors and Cooling Technologies

Liquid Cooling
- He (liq) for low temperature superconductors
- H2 (liq) for low temperature superconductors
- N2 (liq) for high temperature superconductors
- 1 bar boiling points can be reduced by decreasing pressure
  \(...Future: Cooling liquids like Glycol/Water, Methanol/CO2 ??\)

Cryocoolers (some examples and application)
3. Current and Future Applications for Superconductors

- Superconducting wires and cables
- MAGLEV (Magnetic levitation railway)
- Short cut current limiting devices
- Small and light weight transformers, Generators and Motors
- SMES storage devices (Superconducting Magnetic Energy Storage)
- High performance magnets (particle accelerators and nuclear fusion devices)
- Nuclear magnetic spin tomography (medical diagnostics; Magnetic Resonance Imaging- MRI-)
- SQUID- Sensors for measurements of magnetic properties (Josephson- junction; e.g. medical diagnostics; military applications)

  **SQUID**: Superconducting Quantum Interference Device
- GHz- Microwave circuits for Satellites and mobile transmission
- Miniaturized band filters for TV and earth observation satellites
4. Hybrid-Electric Powertrains in Aircraft

Motivation: Fuel Savings by:
- Increase of overall bypass ratio by multiple fans/propellers
- Boundary layer ingestion to minimize drag (fuselage, wing)

Schematics for fully developed DC serial hybrid electric powertrain (Generator AC/DC conversion required)

Alternatives for electric components/systems
- Conventional (Iron, Copper, Aluminum)
  - Medium voltage (1-10 kV) to reduce weight
  - Current capability: Cu >100 mm²/50A; Al>150 mm²/50A
  - Magnetic Saturation (Fe): ca. 1.6-2.2 Tesla
- Superconductive (HTS)
  - Low (0.2-1 kV) or Medium voltage (1-10 kV)
  - Current capability: HTS >1 mm²/50A
  - Magnetic Induction (HTS): up to 50 Tesla
  - Cables, Generators, Motors

Generator without gear box, turbine shaft match: ca. 5,000 – 10,000 rpm

Fan/propeller drive motors without gear box: Ca. 1,200 – 2,000 rpm (blade tip speed restriction)

Fuel type: Tank

battery

<pilot> Airbus/Rolls Royce E-thrust concept plane Distributed Hybrid-Electric Powertrain temperatures</p>
5. Superconducting Cables

- **First generation**
  - Multifilamentary Bi 2223 tapes.

- **Second generation**
  - YBCO Coated conductor tapes and wire.
  - MgB$_2$
    - Wires with mechanical properties very close to existing material (Cu, Al).

- **Hypertech** (US) and Columbus (Italy) are the most advanced in the manufacture of MgB2 wires. Commercial readiness for some applications, such as for MRI.

- Small scale manufacturing of HTS cables exists (wires + insulation + cryogen channels), probably at a sub-commercial level. Insulation and cryogen channels are likely to dominate overall cable mass and size. **Current assumption in DEAP project is 3 kg/m.**
6. Superconducting Electric Machines

Comparison conventional and HTS electric machine
Proposal Siemens AG
7. Expectations for Superconducting Components in Aircraft

<table>
<thead>
<tr>
<th>Propulsion power cables</th>
<th>Key performance Indicators:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Power / mass ratio</td>
</tr>
<tr>
<td>Short term (5-10 years)</td>
<td>1 kg/km/A</td>
</tr>
<tr>
<td>Mid Term (10 to 15 years)</td>
<td>0.5 kg/km/A</td>
</tr>
<tr>
<td>Long Term (&gt;&gt;15 years)</td>
<td>0.1 kg/km/A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Superconducting electric machines</th>
<th>Power / mass ratio</th>
<th>Efficiency</th>
<th>cont. power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short term (5-10 years)</td>
<td>7-10 kW/kg</td>
<td>99,20%</td>
<td>cont. power</td>
</tr>
<tr>
<td>Mid Term (10 to 15 years)</td>
<td>10-20 kW/kg</td>
<td>99,50%</td>
<td>cont. power</td>
</tr>
<tr>
<td>Long Term (&gt;&gt;15 years)</td>
<td>20-50 kW/kg</td>
<td>99,90%</td>
<td>cont. power</td>
</tr>
</tbody>
</table>

Possible Target Aircraft:  
Regional Aircraft 2025 (1000 nautic miles max)  
Short Range Aircraft 2035 (1000 nautic miles and above)  
Long Range Aircraft: tbd