Superconductivity as a key technology from small electronics to large magnet applications

Academia – Industry matching event – Fostering collaborations in Superconductivity
May 27th- 28th 2013, Madrid, Spain

Prof. Dr.-Ing. Mathias Noe
Institute for Technical Physics, Karlsruhe Institute of Technology, Germany
Superconductivity as a key technology from small electronics to large magnet applications

Acknowledgement

All colleagues working in this field

All members of CIGRE WG D1.38

All members of IEA Implementing Agreement for a Cooperative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector

And all members of ITEP at KIT
Superconductivity as a key technology from small electronics to large magnet applications

- Medicine
- Science
- Energy
- Engineering
- Transport
- Electronics
Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event

- Cyclotrons
  - MRI applications
- Fusion
  - Wind generators
- Medicine
- Science
- Energy
- Engineering
- Transport
- Electronics
- Accelerator magnets
- Particle detectors magn.
  - Supercond. cavities
- SQUIDS for biomedicine
Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event
In red – topics covered by my presentation

- Cyclotrons
- MRI applications

- Fusion
- Wind generators
- Power applications

- Levitation

- Accelerator magnets
- Particle detectors
- Magn. Supercond. cavities
- High field magnets

- SQUIDS for biomedicine
- Detectors

- Medicine

- Science

- Energy

- Engineering

- Transport

- Electronics
Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event
In red – topics covered by my presentation

- Cyclotrons
  - MRI applications

- Fusion
  - Wind generators
  - Power applications

- Levitation

- Accelerator magnets
- Particle detectors magn.
- Supercond. cavities
- High field magnets

- State-of-the-Art
- Highlights
- Research Directions

- Magnetic separation
- Magnetic heating

- SQUIDS for biomedicine
- Detectors
Motivation
What is the advantage of superconductivity?

Superconductivity offers

- Highest current densities, at zero DC resistance and at high magnetic fields
- Peculiar magnetic behaviour with Meissner-Ochsenfeld effect and flux pinning
- Josephson effect
**Motivation**

**Technical Superconductors – Key towards Applications**

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$ [K]</th>
<th>$B_{c2}$ [T]</th>
<th>Short name</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>9.3</td>
<td>14.5</td>
<td>NbTi</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>18.3</td>
<td>27.9</td>
<td>Nb$_3$Sn</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>$\sim$ 39 K</td>
<td>17</td>
<td>MgB$_2$</td>
</tr>
<tr>
<td>Bi$_{2-x}$Pb$_x$Sr$_2$Ca$_2$Cu$_3$O$_y$ (y = 8 ÷ 10)</td>
<td>$\sim$ 110</td>
<td>$&gt; 100$</td>
<td>Bi 2223 (1G)</td>
</tr>
<tr>
<td>Bi$_2$Sr$_2$CaCu$_2$O$_y$ (y = 8 ÷ 10)</td>
<td>$\sim$ 80</td>
<td>$&gt; 100$</td>
<td>Bi 2212</td>
</tr>
<tr>
<td>REBa$_2$Cu$_3$O$<em>7$$</em>{-x}$ (RE: Y, or other rare earth elements)</td>
<td>$\sim$ 90</td>
<td>$&gt; 100$</td>
<td>Y 123 (2G)</td>
</tr>
</tbody>
</table>

*NbTi*  
*Nb$_3$Sn*  
*MgB$_2$*  
*Bi 2223-1G*  
*ReBCO123-2G*
Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event
In red – topics covered by my presentation

Cyclotrons
MRI applications

Fusion
Wind generators
Power applications

Levitation

Accelerator magnets
Particle detectors magn.
Supercond. cavities
High field magnets

Magnetic separation
Magnetic heating

SQUIDS for biomedicine
Detectors

Medicine
Science
Energy
Engineering
Transport
Electronics
Superconducting High Field Magnets
Energy Efficiency

20 T Bitter-Magnet

- Water cooling
  - 10 °C
  - 300 m³/h
  - 12 bar

- $B_0 = 20$ T
  - $\phi = 185$ mm

Power Supply

- 6 MW (20 kA, 300 V)

20 T NTSL-Magnet (KIT)

- Cooling Power
  - < 15 kW

Superconductivity enables a considerable increase in energy efficiency.
Superconducting High Field Magnets
State-of-the-Art

Hybrid magnets
(LTS as background and resistive insert)

<table>
<thead>
<tr>
<th>Location</th>
<th>Field (T)</th>
<th>Power (MW)</th>
<th>Bore (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tallahassee</td>
<td>45</td>
<td>30</td>
<td>32</td>
</tr>
<tr>
<td>Tsukuba</td>
<td>37</td>
<td>15</td>
<td>32</td>
</tr>
<tr>
<td>Sendai</td>
<td>31</td>
<td>7</td>
<td>32</td>
</tr>
<tr>
<td>Nijmegen</td>
<td>45</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>Grenoble</td>
<td>42</td>
<td>22.5</td>
<td>34</td>
</tr>
<tr>
<td>Hefei</td>
<td>40</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>Berlin</td>
<td>25</td>
<td>4</td>
<td>50</td>
</tr>
</tbody>
</table>

Under construction

Source: Mark Bird, Progress in High Field Magnets, MT21, Hefei 2009

Superconducting High Field Magnets
Materials and their maximum Field applicability

Source: Peter J. Lee, NHFML, Tallahassee
Superconducting High Field Magnets
State-of-the-Art of HTS Magnets

<table>
<thead>
<tr>
<th>Year</th>
<th>HTS</th>
<th>$B_A + B_{HTS} = B_{tot}$ (T)</th>
<th>$J_{ave}$ (A/mm$^2$)</th>
<th>Stress (MPa)$^*$</th>
<th>Stress (MPa)$^{**}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>BSCCO</td>
<td>20+5=25</td>
<td>89</td>
<td>125</td>
<td>175</td>
</tr>
<tr>
<td>2008</td>
<td>BSCCO</td>
<td>20+2=22</td>
<td>92</td>
<td>69</td>
<td>109</td>
</tr>
<tr>
<td>2008</td>
<td>BSCCO</td>
<td>31+1=31</td>
<td>80</td>
<td>47</td>
<td>89</td>
</tr>
<tr>
<td>2007</td>
<td>YBCO</td>
<td>17+7.8=26.8</td>
<td>259</td>
<td>215</td>
<td>382</td>
</tr>
<tr>
<td>2008</td>
<td>YBCO</td>
<td>31+2.8=33.8</td>
<td>460</td>
<td>245</td>
<td>324</td>
</tr>
<tr>
<td>2009</td>
<td>YBCO</td>
<td>20+7.2=27.2</td>
<td>211</td>
<td>185</td>
<td>314</td>
</tr>
<tr>
<td>2009</td>
<td>YBCO</td>
<td>220+0.1=20.1</td>
<td>241</td>
<td>392</td>
<td>~611</td>
</tr>
</tbody>
</table>

*$J_{ave} \cdot B_A \cdot R_{max}$

**$J_E \cdot B_A \cdot R_{max}$

Source: Mark Bird, Progress in High Field Magnets, MT21, Hefei 2009

2.8 T in 31 T = 33.8 T
SuperPower YBCO in NHMFL coil (OD=3.5 cm)

Many activities to develop HTS magnets and magnet inserts.
Superconducting High Field Magnets
Examples of Further HTS Magnet Objectives

NHFML 32 T all superconducting solenoid
BNL 35 T hybrid solenoid (HTS and NbTi)
KIT > 28 T HTS solenoid insert for NMR

<table>
<thead>
<tr>
<th>Total field</th>
<th>32 T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field inner YBCO coils</td>
<td>17 T</td>
</tr>
<tr>
<td>Field outer LTS coils</td>
<td>15 T</td>
</tr>
<tr>
<td>Cold inner bore</td>
<td>32 mm</td>
</tr>
<tr>
<td>Field uniformity</td>
<td>5x10^{-4} 1cm DSV</td>
</tr>
<tr>
<td>Current</td>
<td>172 A</td>
</tr>
<tr>
<td>Inductance</td>
<td>619 H</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>9.15 MJ</td>
</tr>
</tbody>
</table>

Source: NHFML, Tallahassee, US
Superconducting High Field Magnets

Application of 2G HTS Tapes in first commercial R&D Magnets

<table>
<thead>
<tr>
<th>Specification</th>
<th>Specification Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central field at 4.2 K</td>
<td>20 T</td>
</tr>
<tr>
<td>Central field at 2 K</td>
<td>22 T</td>
</tr>
<tr>
<td>Max. op. current</td>
<td>200 A</td>
</tr>
<tr>
<td>Inductance</td>
<td>100 H</td>
</tr>
<tr>
<td>0 to 18 T</td>
<td>20 min</td>
</tr>
<tr>
<td>18 T to B_{max}</td>
<td>17 min</td>
</tr>
<tr>
<td>Central field homogeneity</td>
<td>0.1 % in 10 mm</td>
</tr>
<tr>
<td>Clear central bore</td>
<td>30 mm</td>
</tr>
<tr>
<td>Overall diameter</td>
<td>350 mm</td>
</tr>
<tr>
<td>Overall height</td>
<td>650 mm</td>
</tr>
</tbody>
</table>

Source: www.cryogenic.co.uk
Superconducting High Field Magnets
Recent progress in Bi2112 by swaging

Reduction of Gas Bubbles and Improved Critical Current Density in Bi-2212 Round Wire by Swaging
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013 6400206
Superconducting High Field Magnets
Research Direction

• Develop HTS inserts for high field magnets
  • Coil winding
  • Stability (electrical, mechanical)
  • Quench detection
  • Conductor concept
  • Homogeneity
  • Cryogenics
  • ...

• Increase magnetic fields (far) beyond 20 T in fully superconducting magnets
• Improve material properties at high fields

HTS will increase the magnetic field of superconducting magnets or will enable more compact magnets.
Superconducting High Field Magnets
Economic Feasibility of High Temperature Superconductors?

<table>
<thead>
<tr>
<th></th>
<th>4.2 K, 6 T</th>
<th>4.2 K, 10 T</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi wire</td>
<td>2.5 $/kA m</td>
<td>20 $/kA m</td>
</tr>
<tr>
<td>0.85 mm diameter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu/Sc 1.3/1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filaments 54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>YBCO tape</td>
<td>125 $/kA m</td>
<td>150 $/kA m</td>
</tr>
<tr>
<td>4 mm tape width</td>
<td>33 $/kA m</td>
<td></td>
</tr>
</tbody>
</table>

Today's cost assumptions:
NbTi 200 $/kg
YBCO 30 $/m

A replacement of LTS by HTS wire in permanent magnets seems technically feasible but will take place commercially only if HTS competes price performance ratio of LTS.
Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event
In red – topics covered by my presentation

Cyclotrons
MRI applications

Fusion
Wind generators
Power applications

Levitation

Medicine

Science

Energy

Engineering

Transport

Electronics

Accelerator magnets
Particle detectors
Supercond. cavities
High field magnets

Magnetic separation
Magnetic heating

SQUIDS for biomedicine
Detectors

M. Noe

Academia – Industry matching event – Fostering collaborations in Superconductivity
May 27th- 28th 2013, Madrid, Spain
Superconducting AC Cables

Benefits of Superconducting Cables

• Higher power or lower voltage at same or smaller diameter
• Simplified network structures by reducing the number of voltage levels
• Reduce number of substations especially in urban areas
• Simplified right of way because of small cable diameter (3 in 1 design)
• Economic benefits in comparison to high voltage equipment
• No electromagnetic outer fields
• Simplified admission procedure of medium voltage cables in comparison to high voltage cables

Picture: nkt cables
# Superconducting AC Cables

## State-of-the-Art of HTS AC Cables

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Place/Country/Year</th>
<th>Type</th>
<th>Data</th>
<th>HTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innopower</td>
<td>Yunnan, CN, 2004</td>
<td>WD</td>
<td>35 kV, 2 kA, 33 m, 3-ph.</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Sumitomo</td>
<td>Albany, US, 2006</td>
<td>CD</td>
<td>34.5 kV, 800 A, 350 m, 3-ph.</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Ultera</td>
<td>Columbus, US, 2006</td>
<td>CD</td>
<td>13.2 kV, 3 kA, 200 m, 3-ph.</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Sumitomo</td>
<td>Gochang, KR, 2006</td>
<td>CD</td>
<td>22.9 kV, 1.25 kA, 100 m, 3-ph.</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>LS Cable</td>
<td>Gochang, KR, 2007</td>
<td>CD</td>
<td>22.9 kV, 1.26 kA, 100 m, 3-ph.</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Sumitomo</td>
<td>Albany, US, 2007</td>
<td>CD</td>
<td>34.5 kV, 800 A, 30 m, 3-ph.</td>
<td>YBCO</td>
</tr>
<tr>
<td>Nexans</td>
<td>Hannover, D, 2007</td>
<td>CD</td>
<td>138 kV, 1.8 kA, 30 m, 1-ph.</td>
<td>YBCO</td>
</tr>
<tr>
<td>Nexans</td>
<td>Long Island, US, 2008</td>
<td>CD</td>
<td>138 kV, 1.8 kA, 600 m, 3-ph.</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Nexans</td>
<td>Spain, 2008</td>
<td>CD</td>
<td>10 kV, 1 kA, 30 m, 1-ph.</td>
<td>YBCO</td>
</tr>
<tr>
<td>Sumitomo</td>
<td>Chubu U., JP, 2010</td>
<td>CD</td>
<td>10 kV, 3 kA DC, 20 m, 200 m</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>VNIKIP</td>
<td>Moscow, RU, 2010</td>
<td>CD</td>
<td>20 kV, 1.4 kA, 200 m</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Nexans</td>
<td>Long Island, US, 2011</td>
<td>CD</td>
<td>138 kV, 2.4 kA, 600 m, 1-ph.</td>
<td>YBCO</td>
</tr>
<tr>
<td>LS Cable</td>
<td>Gochang, KR, 2011</td>
<td>CD</td>
<td>154 kV, 1 GVA, 100 m, 3-ph.</td>
<td>YBCO</td>
</tr>
<tr>
<td>LS Cable</td>
<td>Seoul, KR, 2011</td>
<td>CD</td>
<td>22.9 kV, 50 MVA, 400 m, 3-ph.</td>
<td>YBCO</td>
</tr>
<tr>
<td>Sumitomo</td>
<td>TEPCO, JP, 2012</td>
<td>CD</td>
<td>66 kV, 5 kA, 15 m</td>
<td>YBCO</td>
</tr>
<tr>
<td>Furukawa</td>
<td>TEPCO, JP, 2012</td>
<td>CD</td>
<td>275 kV, 3 kA, 30 m</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Sumitomo</td>
<td>Yokohama, JP, 2012</td>
<td>CD</td>
<td>66 kV, 200 MVA, 240 m, 3-ph.</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Ultera</td>
<td>New York, US, 2015</td>
<td>CD</td>
<td>13.8 kV, 4 kA, 170 m, 3-ph.</td>
<td>YBCO</td>
</tr>
<tr>
<td>Nexans</td>
<td>Essen, Germany, 2013</td>
<td>CD</td>
<td>10 kV, 40 MVA, 1000 m, 3 ph.</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>LS Cable</td>
<td>Jeju Island, Korea, 2014</td>
<td>CD</td>
<td>154 kV, 2.25 kA, 500 m, 3 ph.</td>
<td>YBCO</td>
</tr>
</tbody>
</table>
Superconducting AC Cables
State-of-the-Art of HTS AC Cable Field Tests

Maximum rated current of conventional cables in air

275 kV, 3 kA, Japan

Three phases coaxial
1 phase in 1 cryostat
3 phases in 1 cryostat
In red warm dielectric

Current_{RMS} / kA

Phase-Phase Voltage / kV_{RMS}
Superconducting AC Cables
State-of-the-Art of HTS AC Cable Field Tests

Maximum rated current of conventional cables in ground

275 kV, 3 kA, Japan

Three phases coaxial
1 phase in 1 cryostat
3 phases in 1 cryostat
In red warm dielectric

- 275 kV, 3 kA, Japan

- 5 phases in 1 cryostat

- 3 phases in 1 cryostat

- In red warm dielectric
Superconducting AC Cables
State-of-the-Art

Columbus
- **Ultera**
  - 13.2 kV, 3 kA, 200 m
  - Triaxial\(^\text{TM}\) Design
  - BSCCO 2223
  - Energized 2006
  - High reliability

LIPA
- **Nexans**
  - 138 kV, 2.4 kA, 600 m
  - Single coaxial design
  - BSCCO 2223
  - Energized 2008

Gochang
- **LS Cable**
  - 22.9 kV, 50 MVA, 100 m
  - BSCCO 2223
  - Energized 2007
  - 500 m field test with YBCO in 2011
**Superconducting DC Cables**

**State-of-the-Art**

**DC Cable in Japan**

- Chubu University
- 10 kV, 1.2 kA, 200 m
- Energized 2010

**DC Cable in Russia**

- Customer: General Grid Company
- 20 kV, 2.5 kA, 2500 m
- First full scale sample in 2013
- Cable laying in 2015
- Experimental operation in 2016

---

V.E. Sytnikov, et. al. "HTS DC Cable line project: on-going activities in Russia". IEEE/CSC & ESAS European Superconductivity News Forum (ESNF) No. 23 January 2013
Superconducting DC Cables

Applications

**Industry high current lines**

*Picture: Vision Electric*

**Connect renewables**

*Picture: J. Minervini, MIT*

**Supply data centers**

*Picture: J. Minervini, MIT*

**Grounding of HVDC Lines**

*Picture: Nexans*

**Larger power, long distance transmission**

*Picture: C. Rubbia, IASS*

**Degaussing of ships**

*Picture: B. Fitzpatrick, HTS Peerreview2010*
Superconducting Cables
Research Direction

• Lower cost and higher performance of HTS material
• Improved reliability and availability of the cooling system
• Improved thermal insulation at reduced cost
• Work on standards
  • CIGRE Technical brochure available in 2013
• Demonstrate reliability and availability in long-term field installations

Superconducting cables are very close to commercialization.


Superconducting Rotating Machines

Benefits

**Smaller volume and weight**
- Half the weight and volume
- Two times higher power density

**Less resources**
- Higher efficiency
- Less material

**Improved operation parameters**
- Lower voltage drop ($x_d \sim 0.2\sim 0.3$ p.u.)
- Higher stability
- Higher torque and dynamics
- Higher ratio of breakdown torque to nominal torque
- More reactive power

Enables new drive and generator systems

---

**Conventional synchronous machine**

- $B = 2$ T
- $A_1 = 2$ p.u.
- $P = 4$ p.u.

**Losses**
- $P_{Cu,stat} = 2$ p.u.
- $P_{Cu,rot} = 0$ p.u. + $P_{Cool}$
- $P_{Fe} = 0.6$ p.u.

---

**Superconducting synchronous machine**

- $B = 2$ T
- $A_1 = 2$ p.u.
- $P = 4$ p.u.
Superconducting Rotating Machines
For which Application?

There are many potential applications for HTS rotating machines that differ very much in rating, torque and speed.
## Superconducting Rotating Machines
### State-of-the-Art of large scale Motors and Generators

<table>
<thead>
<tr>
<th>Manufacturer / Country</th>
<th>Machine</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMSC (US)</td>
<td>5 MW demo-motor</td>
<td>2004</td>
</tr>
<tr>
<td></td>
<td>8 MVA, 12 MVA synchronous condenser</td>
<td>2005/2006 (Field test)</td>
</tr>
<tr>
<td></td>
<td>40 MVA generator design study</td>
<td>2006</td>
</tr>
<tr>
<td></td>
<td>36 MW ship propulsion motor</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td>8 MW wind generator design study</td>
<td>2010</td>
</tr>
<tr>
<td>GE (US)</td>
<td>100 MVA utility generator</td>
<td>2006 (discontinued)</td>
</tr>
<tr>
<td></td>
<td>5 MVA homopolar induction motor</td>
<td>2008</td>
</tr>
<tr>
<td>LEI (US)</td>
<td>5 MVA high speed generator</td>
<td>2006</td>
</tr>
<tr>
<td>Reliance Electric (US)</td>
<td>10.5 MVA generator design study</td>
<td>2008</td>
</tr>
<tr>
<td>Kawasaki (JP)</td>
<td>1 MW ship propulsion</td>
<td>200?</td>
</tr>
<tr>
<td>IHI Marine, SEI (JP)</td>
<td>365 kW ship propulsion motor</td>
<td>2007</td>
</tr>
<tr>
<td></td>
<td>2.5 MW ship propulsion motor</td>
<td>2010</td>
</tr>
<tr>
<td>Doosan, KERI (Korea)</td>
<td>1 MVA demo-generator</td>
<td>2007</td>
</tr>
<tr>
<td></td>
<td>5 MW motor ship propulsion</td>
<td>2011</td>
</tr>
<tr>
<td>Siemens (Germany)</td>
<td>4 MVA industrial generator</td>
<td>2008 (Field test)</td>
</tr>
<tr>
<td></td>
<td>4 MW ship propulsion motor</td>
<td>2010</td>
</tr>
<tr>
<td>Convertteam (UK)</td>
<td>1.25 MVA hydro-generator</td>
<td>2010</td>
</tr>
<tr>
<td></td>
<td>500 kW demo-generator</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td>8 MW wind generator design study</td>
<td>2010</td>
</tr>
<tr>
<td>Tecnalia / Acciona (Spain)</td>
<td>500 kW wind generator demonstrator</td>
<td>2016</td>
</tr>
</tbody>
</table>
Superconducting Rotating Machines
State-of-the-Art

Ship Propulsion

AMSC
36.5 MVA, 6 kV
120 rpm
8 poles, 75 tons
Efficiency > 97%
Dimensions: 3.4 m x 4.6 m x 4.1 m

EU „Hydrogenre“ Hydrogenerator

GE/(Converteam)
1.790 MW, 5.25 kV
214 rpm, 77.3 kNm
28 poles, 32.7 tons
4.7 m x 5.2 m x 3.5 m
Test in 2012

Ship Propulsion

Siemens
4 MW, 3.1 kV
120 rpm, 320 kNm
37 tons
50 km HTS
Test in 2010
Superconducting Rotating Machines
Energy Efficiency of HTS Power Generators

Source: High-Temperature Superconductivity for Power Engineering, Materials and Applications, Accompanying Book to the Conference ZIEHL II, Future and Innovation of Power Engineering with High-Temperature-Superconductors, 16-17 March 2010, Bonn, Germany

M. Noe
Academia – Industry matching event – Fostering collaborations in Superconductivity
May 27th-28th 2013, Madrid, Spain
Superconducting Rotating Machines
Energy Efficiency of HTS Power Generators

With an increase in efficiency of 0.5 % a considerable cost saving can be expected.

1) 1 kWh=520 g CO₂ (actual German Energy Mix)
Superconducting Rotating Machines

HTS High Torque Machines for Industry Applications

Data

- Power: 156 kW
- Speed: 57 rpm
- Torque: 26000 Nm
- Efficiency: 99.6 %
- Dynamic: > 10000 rpm/s
- YBCO length: 4 km, 4mm width
- Superconducting stator
- Permanent magnets in rotor

High dynamics and force density with HTS machines
Superconducting Rotating Machines
Research Directions

• Higher performance at lower cost
• Reliable and robust winding concepts
• Efficient and adaptable cooling
• Long-term demonstration in real application (no longer in test labs)
• Many applications
  • Ship propulsion
  • Wind generators
  • Power generators
  • High Torque machines
  • ...

It can be expected, that within the next decade first commercial applications will be in the market. 1)

1) „Status of Development and Field Test Experience with High-Temperature Superconducting Power Equipment, Working Group D1.15, June 2010“
Superconducting Transformer
Benefit of Superconducting Transformers

Manufacturing and transport
• Compact and lightweight (~50 % Reduction)

Environment and Marketing
• Energy savings (~50 % Reduction)
• Resource savings
• Inflammable (no oil)

Operation
• Low short-circuit impedance
  • Higher stability
  • Less voltage drops
  • Less reactive power
• Active current limitation
  • Protection of devices
  • Reduction of investment
## Superconducting Transformers

### State-of-the-Art

<table>
<thead>
<tr>
<th>Country</th>
<th>Inst.</th>
<th>Application</th>
<th>Data</th>
<th>Phase</th>
<th>Year</th>
<th>HTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switzerland</td>
<td>ABB</td>
<td>Distribution</td>
<td>630 kVA/18,42 kV/420 V</td>
<td>3 Dyn11</td>
<td>1996</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Japan</td>
<td>Fuji Electric Kyushu Uni</td>
<td>Demonstrator</td>
<td>500 kVA/6,6 kV/3,3 kV</td>
<td>1</td>
<td>1998</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Germany</td>
<td>Siemens</td>
<td>Demonstrator</td>
<td>100 kVA/5,5 kV/1,1 kV</td>
<td>1</td>
<td>1999</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>USA</td>
<td>Waukesha</td>
<td>Demonstrator</td>
<td>1 MVA/13,8 kV/6,9 kV</td>
<td>1</td>
<td></td>
<td>Bi 2223</td>
</tr>
<tr>
<td>USA</td>
<td>Waukesha</td>
<td>Demonstrator</td>
<td>5 MVA/24,9 kV/4,2 kV</td>
<td>3 Dy</td>
<td></td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Japan</td>
<td>Fuji Electric U Kyushu Uni</td>
<td>Demonstrator</td>
<td>1 MVA/22 kV/6,9 kV</td>
<td>1</td>
<td>&lt; 2001</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Germany</td>
<td>Siemens</td>
<td>Railway</td>
<td>1 MVA/25 kV/1,4 kV</td>
<td>1</td>
<td>2001</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>EU</td>
<td>CNRS</td>
<td>Demonstrator</td>
<td>41 kVA/2050 V/410 V</td>
<td>1</td>
<td>2003</td>
<td>P-YBCO S-Bi 2223</td>
</tr>
<tr>
<td>Korea</td>
<td>U Seoul</td>
<td>Demonstrator</td>
<td>1 MVA/22,9 kV/6,6 kV</td>
<td>1</td>
<td>2004</td>
<td>Bi 2223</td>
</tr>
<tr>
<td>Japan</td>
<td>U Nagoya</td>
<td>Demonstrator</td>
<td>2 MVA/22 kV/6,6 kV</td>
<td>1</td>
<td>2009</td>
<td>P-Bi 2223 S-YBCO</td>
</tr>
<tr>
<td>Germany</td>
<td>KIT</td>
<td>Demonstrator</td>
<td>1 MVA, 20 kV</td>
<td>1</td>
<td>2015</td>
<td>P-Cu/S-YBCO</td>
</tr>
<tr>
<td>USA</td>
<td>Waukesha</td>
<td>Prototype</td>
<td>28 MVA/69 kV</td>
<td>3</td>
<td>2013</td>
<td>YBCO</td>
</tr>
<tr>
<td>Japan</td>
<td>Kyushu</td>
<td>Demonstrator</td>
<td>2 MVA</td>
<td>1</td>
<td>2011</td>
<td>YBCO</td>
</tr>
<tr>
<td>Australia</td>
<td>Callaghan Innovation</td>
<td>Demonstrator</td>
<td>1 MVA</td>
<td>3</td>
<td>2013</td>
<td>YBCO</td>
</tr>
</tbody>
</table>

- **Active current limitation**
Superconducting Transformers
State-of-the-Art of Current Limiting Transformers

1 MVA Demonstrator
11 kV/415 V
Primary YBCO
Secondary YBCO Roebel cond.
Test in 2013

2 MVA Demonstrator
22kV/6.6 kV
Primary Bi 2223 tapes
Secondary YBCO tapes
Successful test in 2009

28 MVA Prototype
69 kV
Primary and secondary with YBCO tapes
Test planned in 2013
Superconducting Transformers

Applications

In general electricity passes 4-5 transformers from generation to load!
### Superconducting Transformers

#### Energy Efficiency (Example 31.5 MVA Transformer)

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
<th>Capacity GVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>380 kV/220kV</td>
<td>689</td>
<td>311.8</td>
</tr>
<tr>
<td>220 kV/&lt; 220 kV</td>
<td>2612</td>
<td>336.6</td>
</tr>
<tr>
<td>380 kV/&lt; 220 kV</td>
<td>791</td>
<td>215.6</td>
</tr>
</tbody>
</table>

From entsoe, Statistical Yearbook 2008

1) IEA key world energy statistics 2009

- In 2007 the world electricity generation was 19,771 TWh\(^1\).
- The total power loss in Europe is appr. 6.5 %.
- Appr. 40 % of the loss is caused in transformers.

---

From entsoe, Statistical Yearbook 2008

1) IEA key world energy statistics 2009

---

- In 2007 the world electricity generation was 19,771 TWh\(^1\).
- The total power loss in Europe is appr. 6.5 %.
- Appr. 40 % of the loss is caused in transformers.

---

From entsoe, Statistical Yearbook 2008

1) IEA key world energy statistics 2009
Superconducting Transformers

Research Directions

• Develop first large scale demonstrators and prototypes
• Develop wire concepts with reduced AC loss, stability and increased field performance
• Include current limitation (to compensate higher investment cost)
• Develop reliable cryogenic high voltage insulation concepts

Superconducting transformers need further demonstrator and prototype development.
Superconducting Fault Current Limiters
Ideal Fault Current Limiter

- **Fast short-circuit limitation**
- No or small impedance at normal operation
- Fast and automatic recovery
- Fail safe
- Applicable at high voltages
- Cost effective
Ideal Fault Current Limiter

- Fast short-circuit limitation
- **No or small impedance at normal operation**
- Fast and automatic recovery
- Fail safe
- Applicable at high voltages
- Cost effective
Ideal Fault Current Limiter

- Fast short-circuit limitation
- No or small impedance at normal operation
- Fast and automatic recovery
- Fail safe
- Applicable at high voltages
- Cost effective
**Ideal Fault Current Limiter**

- Fast short-circuit limitation
- No or small impedance at normal operation
- Fast and automatic recovery
- Fail safe
- Applicable at high voltages
- Cost effective

**SCFCL**
Superconducting Fault Current Limiters

Economic Benefits

Delay improvement of components and upgrade power systems
  e.g. connect new generation and do not increase short-circuit currents
  e.g. couple busbars to increase renewable generation and keep voltage bandwidths

Lower dimensioning of components, substations and power systems
  e.g. FCL in power system auxiliary

Avoid purchase of power system equipment
  e.g. avoid redundant feeders by coupling power systems

Increase availability and reliability
  e.g. by coupling power systems

Reduce losses and CO₂ emissions
  e.g. equal load distribution with parallel transformers
Superconducting Fault Current Limiters
Successful SCFCL Field Tests until 2000

Phase-Phase Voltage / kV_{RMS}

Current / kA_{RMS}

- Resistive
- DC biased iron core
- Others

Status: 2000

'96
A considerable number of SCFCLs field tests have been performed within the last years.
Superconducting Fault Current Limiters
State-of-the-Art

**Resistive Type**
- 12 kV, 800 A, 120 ms
- YBCO material
- Power system auxiliary
- Energized 2011

**DC Biased Iron Core Type**
- 220 kV, 800 A
- Bi 2223 tapes
- Substation
- Energized 2012

**Hybrid type**
- 22.9 kV, 3 kA
- YBCO tapes
- Substation
- Energized 2011
Superconducting Fault Current Limiters Application Examples

- Bi 2212 bulk
  - 12 kV, 100 A
  - 12 kV, 800 A
  - 12 kV, 400 A
  - Bi 2212 bulk
  - 10 kV, 600 A
  - 10 kV, 2.3 kA
  - Bi 2212 bulk

- YBCO tapes
  - 12 kV, 800 A
  - 20 kV, 1 kA
  - 10 kV, 2.3 kA
  - YBCO tapes

Commercial Projects

www.eccoflow.org
Superconducting Fault Current Limiters

Research Directions

• Develop compact and inexpensive medium voltage SCFCLs
• Develop high voltage SCFCL demonstrators and prototypes
• Demonstrate and improve reliability with long term tests
• Develop tests standards
  • IEEE test guide for FCLs available soon
• Show value proposition and „educate costumer“

SCFCLs are very close to commercialisation.
Superconducting Magnetic Energy Storage Benefits

- Short reaction time (ms)
- Fast charge and discharge
- 0-100 % charging possible
- Independent supply of active and reactive power
- High efficiency
- No degradation
- Environmentally friendly

\[ I = I_0 e^{-\frac{t}{\tau}} \quad \tau = \frac{L}{R} \]

- Stored Energy: \[ Q = \frac{1}{2} L I^2 \]
- Power: \[ P = U_L I \]
- Energy Density: \[ \frac{Q_{\text{max}}}{V} = \frac{B^2}{2 \mu_0} \]
# Superconducting Magnetic Energy Storage State-of-the-Art

<table>
<thead>
<tr>
<th>Lead Institution</th>
<th>Country</th>
<th>Year</th>
<th>Data</th>
<th>Superconductor</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>KIT</td>
<td>D</td>
<td>1997</td>
<td>320 kVA, 203 kJ</td>
<td>NbTi</td>
<td>Flicker compensation</td>
</tr>
<tr>
<td>AMSC</td>
<td>USA</td>
<td></td>
<td>2 MW, 2,6 MJ</td>
<td>NbTi</td>
<td>Grid stability</td>
</tr>
<tr>
<td>KIT</td>
<td>D</td>
<td>2004</td>
<td>25 MW, 237 kJ</td>
<td>NbTi</td>
<td>Power modulator</td>
</tr>
<tr>
<td>Chubu</td>
<td>J</td>
<td>2004</td>
<td>5 MVA, 5 MJ</td>
<td>NbTi</td>
<td>Voltage stability</td>
</tr>
<tr>
<td>Chubu</td>
<td>J</td>
<td>2004</td>
<td>1 MVA, 1 MJ</td>
<td>Bi 2212</td>
<td>Voltage stability</td>
</tr>
<tr>
<td>KERI</td>
<td>Korea</td>
<td>2005</td>
<td>750 kVA, 3 MJ</td>
<td>NbTi</td>
<td>Power quality</td>
</tr>
<tr>
<td>Ansaldo</td>
<td>I</td>
<td>2005</td>
<td>1 MVA, 1 MJ</td>
<td>NbTi</td>
<td>Voltage stability</td>
</tr>
<tr>
<td>Chubu</td>
<td>J</td>
<td>2007</td>
<td>10 MVA, 19 MJ</td>
<td>NbTi</td>
<td>Load compensation</td>
</tr>
<tr>
<td>CAS</td>
<td>China</td>
<td>2007</td>
<td>0,5 MVA, 1 MJ</td>
<td>Bi 2223</td>
<td>-</td>
</tr>
<tr>
<td>KERI</td>
<td>Korea</td>
<td>2007</td>
<td>600 kJ</td>
<td>Bi 2223</td>
<td>Power-, Voltage quality</td>
</tr>
<tr>
<td>CNRS</td>
<td>F</td>
<td>2008</td>
<td>800 kJ</td>
<td>Bi 2212</td>
<td>Military application</td>
</tr>
<tr>
<td>KERI</td>
<td>Korea</td>
<td>2011</td>
<td>2.5 MJ</td>
<td>YBCO</td>
<td>Power quality</td>
</tr>
<tr>
<td>BNL</td>
<td>USA</td>
<td>2013</td>
<td>3 MJ</td>
<td>YBCO</td>
<td>Grid storage</td>
</tr>
</tbody>
</table>
Superconducting Magnetic Energy Storage
State-of-the-Art of HTS SMES Development

Chubu, Japan
Bridging voltage dips

KERI, Korea
Power quality

CNRS, France
Military application

1 MJ, 1 MW
Bi 2212 tape
500 A,
5 K conduction cooled
Voltage: 2.5 kV

2.5 MJ
YBCO tape, 22 km
550 A
20 K conduction cooled
B_{max} 6.24 T
Test in 2011

814 kJ
Bi 2212 tape
315 A
20 K conduction cooled
Diameter: 300/814 mm
Height: 222 mm
Superconducting Magnetic Energy Storage
Test Experience of HTS SMES for bridging instantaneous voltage dips

SMES have demonstrated their technical feasibility many times.

Source: IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 15, NO. 2, JUNE 2005 1931
Development of MVA Class HTS SMES System for Bridging Instantaneous Voltage Dips
Koji Shikimachi, Hiromi Moriguchi, Naoki Hirano, Shigeo Nagaya, Toshinobu Ito, Junji Inagaki, Satoshi Hanai, Masahiko Takahashi, and Tsutomu Kurusu
Superconducting Magnetic Energy Storage
Research Direction

- Higher field performance at lower cost
- Reduction of AC loss
- Multistrand wires and tapes
- Develop modular SMES systems and hybrid SMES systems

SMES needs significant cost reduction.
Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event
In red – topics covered by my presentation

<table>
<thead>
<tr>
<th>Cyclotrons</th>
<th>Medicine</th>
<th>Accelerator magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRI applications</td>
<td>Science</td>
<td>Particle detectors magn.</td>
</tr>
<tr>
<td>Fusion</td>
<td>Energy</td>
<td>High field magnets</td>
</tr>
<tr>
<td>Wind generators</td>
<td>Engineering</td>
<td>Magnetic separation</td>
</tr>
<tr>
<td>Power applications</td>
<td></td>
<td>Magnetic heating</td>
</tr>
<tr>
<td>Levitation</td>
<td>Transport</td>
<td>SQUIDS for biomedicine</td>
</tr>
<tr>
<td></td>
<td>Electronics</td>
<td>Detectors</td>
</tr>
</tbody>
</table>
Magnetic Separation
High Gradients

Industry solutions are offered for magnetic separation with LTS

Prof. Dr.-Ing. Mathias Noe, KIT „Large Scale Applications of Superconductors“
Magnetic Heating
Motivation

Conventional Heating
Primary coil-AC

![Diagram of Conventional Heating](image)

HTS Magnetic Heating
Primary coil-DC

![Diagram of HTS Magnetic Heating](image)

Technology patented EP1582091, US7339145 (Sinvent AS, Norway)
Magnetic Heating Benefits

Higher Efficiency
Faster Heating
Homogenous Heating

e.g. heating of 1 ton Aluminium with 0.5 MW heating power to 520°C:
  • conventionel 280 kWh
  • HTS magnetic heating 160 kWh

Technology patented EP1582091, US7339145 (Sinvent AS, Norway)
Magnetic Heating
State-of-the-Art

<table>
<thead>
<tr>
<th>Date</th>
<th>Customer</th>
<th>Metal /Size</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept 2007</td>
<td>WeserAlu</td>
<td>Al 6”</td>
<td>Germany</td>
</tr>
<tr>
<td>Mar 2008</td>
<td>Wieland</td>
<td>Cu 16”</td>
<td>Germany</td>
</tr>
<tr>
<td>Jul 2009</td>
<td>Sapa</td>
<td>Al 16”</td>
<td>Italy</td>
</tr>
<tr>
<td>Oct 2009</td>
<td>N.N.</td>
<td>Cu 8”</td>
<td>Germany</td>
</tr>
<tr>
<td>Jan 2010</td>
<td>WeserAlu</td>
<td>Al 9”</td>
<td>Germany</td>
</tr>
</tbody>
</table>

Magnetic heating has been started to enter the market **but ...**

**Lessons learned?**
Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event
In red – topics covered by my presentation

Cyclotrons
MRI applications

Fusion
Wind generators
Power applications

Levitation

Accelerator magnets
Particle detectors magn.
Supercond. cavities
High field magnets

Magnetic separation
Magnetic heating

SQUIDS for biomedicine
Detectors

M. Noe
Academia – Industry matching event – Fostering collaborations in Superconductivity
May 27th-28th 2013, Madrid, Spain
Transportation Principles

Electrodynamic levitation

Superconductor (moving)

Major benefits
- Very high speeds
- self guiding at high speed

Superconducting levitation

Superconductor (moving)

Major benefits
- Stable
- passive
- speed independant
Transportation
Electrodynamic Levitation

MLX01

Superconducting magnet and a liquid helium tank on top of it

1977  7 km test line in Miyazaki Prefecture
1996  42.8 km test line in Yamanashi
Nov. 1997  first time speed with more than 500 km per hour
Dec. 2\textsuperscript{nd} 2003  581 km/h – world speed record for all trains
May 18\textsuperscript{th} 2011  Consent on Tokyo – Osaka line (505 km/h)

Extensive test experience with Yamanashi test line.
Transportation Superconducting Levitation

Test vehicle

Vehicle
- Length: 2500 mm
- Width: 1200 mm
- Rated load: 600 kg
- Superconductor: YBCO at 77 K
- Max. acceleration: 1 m/s²
- Speed: 20 km/h

Track
- Track width: 1000 mm
- Length: 80 m
- Curve Radius: 6.5 m
- Field in air gap: 0.6 T
- Air gap: 10 mm

80 m test line in operation at IFW in Dresden since 2011
Transportation
Superconducting Levitation

Supralinear motion

Track width: 600 mm
Air gap: 10–15 mm
Max. acceleration: 2.4 m/s²
Max. speed: 8.6 km/h
Max. payload: One person, up to 120 kg
Magnets: 320 NdFeB magnets

Suprahandling

Dimensions: 2,000 × 2,000 × 1,000 mm
Max. acceleration: 0.70 m/s²
Max. payload: 120 kg (X plane), 60 kg (Y plane)
X-axis: 2 large magnetic rails, 1,800 mm apart
Max. travel: 1,300 mm, Air gap: 10–15 mm
Y-axis: 2 small magnetic rails, 350 mm apart
Max. travel: 1,100 mm, Air gap: 5–10 mm

First products demonstrated at Hannover Fair in 2013
Transportation Superconducting Levitation

A MagLev vehicle track is being built with 200 m and it will connect 2 buildings at Federal University of Rio de Janeiro

Source: Prof. Rubens Andrade
Laboratory for Applied Superconductivity – LASUP
Department of Electric Engineering
Federal University of Rio de Janeiro – COPPE – UFRJ
Transportation
Superconducting Levitation

Test module constructed
Module weights 750 kg
Supports 800 kg load
Linear induction motor
12 m Permanent Magnet Guideway

Source: Prof. Rubens Andrade
Laboratory for Applied Superconductivity – LASUP
Department of Electric Engineering
Federal University of Rio de Janeiro – COPPE – UFRJ
## Status

### Large Scale Energy Applications

<table>
<thead>
<tr>
<th>Technology Demonstration</th>
<th>Prototypes in field operation</th>
<th>First commercial products</th>
<th>Full market entry</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTS Fusion magnets</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HTS Fusion magnets</td>
<td></td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>AC Cable</td>
<td></td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>DC Cable</td>
<td></td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Power generator</td>
<td></td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Ship propulsion</td>
<td></td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Hydro generator</td>
<td></td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Wind generator</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transformer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MV FCL</td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>HV FCL</td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>HTS SMES</td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>LTS SMES</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic separation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic levitation</td>
<td></td>
<td></td>
<td>13</td>
</tr>
</tbody>
</table>
Status
Large Scale Energy Applications
Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event
In red – topics covered by my presentation

- Cyclotrons
- MRI applications
- Fusion
- Wind generators
- Power applications
- Levitation
- Medicine
- Science
- Energy
- Engineering
- Transport
- Electronics
- Accelerator magnets
- Particle detectors
- Magn. Supercond. cavities
- High field magnets
- Magnetic separation
- Magnetic heating
- SQUIDS for biomedicine
- Detectors
Electronic Applications
Overview

Quantum Metrology
- Josephson Voltage Standard

SQUID
- Medicine (MKG, MEG, Pharmacy)
- Geophysical Exploration
- Non-Destructive Testing

Radiation Detectors
- Radio Astronomy
- Medicine, Spectroscopy
- Security

Digital Electronics
- ADC, DAC

Microwave Filters and Resonators

Quantum Computing
Electronic Applications Overview

Quantum Metrology
- Josephson Voltage Standard

SQUID
- Medicine (MKG, MEG, Pharmacy)
- Geophysical Exploration
- Non-Destructive Testing

Radiation Detectors
- Radio Astronomy
- Medicine, Spectroscopy
- Security

Digital Electronics
- ADC, DAC

Microwave Filters and Resonators

Quantum Computing
Electronic Applications
SQUID Sensitivity

Source: Brian Fishbine, SQUID Magnetometry, Los Alamos National Laboratory, 2003

SQUIDS achieve highest magnetic field sensitivity. Applications are in medicine, non destructive testing and geophysics.
# Electronic Applications

## SQUID Magnetometer for Geophysics

### Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitive receiver</td>
<td>for transient electromagnetic measurement</td>
</tr>
<tr>
<td>Record the complete gradient tensor</td>
<td>of the earth magnetic field</td>
</tr>
<tr>
<td>Geomagnetic detection</td>
<td>system for near-surface anomalies</td>
</tr>
</tbody>
</table>

### Purpose

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploration of minerals</td>
<td></td>
</tr>
<tr>
<td>Localises and quantises magnetic objects</td>
<td>under ground or under water</td>
</tr>
<tr>
<td>Three-dimensional geomagnetic mapping</td>
<td>of the ground</td>
</tr>
</tbody>
</table>

SQUIDS are commercial products for geophysics in a growing niche market.

Pictures: Supracon GmbH, Jena, Germany
Electronic Applications
Terahertz Detectors - Security

Various Applications
- Medical Care (Tumor diagnostics)
- Security (detection of hidden weapons, explosives, drugs, etc.)
- Radio-Astronomy
- Remote Sensing and Exploration

Pictures: M. Siegel, KIT
Electronic Applications
Radiation Detectors – Radio Astronomy

Atacama Large Millimeter/submillimeter Array (ALMA)

First light in 2011
5000 meters above sea level
60 12 m antennas

80-900 GHz
10 channel SIS receivers per antenna
1500 SIS mixers

Terahertz detectors have reached maturity in a niche market. All radiotelescopes with more than 100 GHz use superconducting Terahertz detectors.
Electronic Applications
Single Photon Detectors - Principle

Single-photon sensitivity from visible to infrared spectrum, e.g. ultrafast spectroscopy
Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event
In red – topics covered by my presentation

- Cyclotrons
  - MRI applications
- Fusion
  - Wind generators
  - Power applications
- Levitation
- Medicine
- Science
- Energy
- Engineering
- Transport
- Electronics
- Accelerator magnets
- Particle detectors
  - Supercond. cavities
- High field magnets
- Magnetic separation
- Magnetic heating
- SQUIDS for biomedicine
  - Detectors
## Outlook

### Which Material for Large Scale Applications?

<table>
<thead>
<tr>
<th>Magnet Applications</th>
<th>Technology Status</th>
<th>Present Favourite</th>
<th>Future Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRI Magnets</td>
<td>Commercial up to 3 T</td>
<td>NbTi</td>
<td>MgB$_2$, REBCO</td>
</tr>
<tr>
<td>NMR Magnets</td>
<td>Commercial up to 1000 MHz</td>
<td>NbTi, Nb$_3$Sn</td>
<td>REBCO</td>
</tr>
<tr>
<td>Accelerator magnets</td>
<td>In operation up to 9 T</td>
<td>NbTi</td>
<td>Nb$_3$Sn, REBCO, BSCCO</td>
</tr>
<tr>
<td>Fusion magnets</td>
<td>Demonstrator</td>
<td>NbTi, Nb$_3$Sn</td>
<td>REBCO</td>
</tr>
<tr>
<td>R&amp;D and industry magnets</td>
<td>Commercial up to nearly 20 T</td>
<td>NbTi, Nb$_3$Sn</td>
<td>MgB$_2$, REBCO, BSCCO</td>
</tr>
</tbody>
</table>

### Power System Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Technology Status</th>
<th>Present Favourite</th>
<th>Future Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cables</td>
<td>Close to commercialisation</td>
<td>BSCCO, REBCO</td>
<td>MgB$_2$</td>
</tr>
<tr>
<td>Rotating machines</td>
<td>Demonstrators</td>
<td>BSCCO</td>
<td>REBCO, MgB$_2$</td>
</tr>
<tr>
<td>Transformers</td>
<td>Demonstrators</td>
<td>REBCO</td>
<td>-</td>
</tr>
<tr>
<td>Fault current limiters</td>
<td>Close to commercialisation</td>
<td>REBCO, BSCCO</td>
<td>-</td>
</tr>
<tr>
<td>SMES</td>
<td>Prototypes</td>
<td>NbTi</td>
<td>MgB$_2$, REBCO</td>
</tr>
</tbody>
</table>

### Other Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Technology Status</th>
<th>Present Favourite</th>
<th>Future Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current leads</td>
<td>Commercial up to a few kA</td>
<td>BSCCO</td>
<td>REBCO</td>
</tr>
<tr>
<td>Electrodynmic levitation</td>
<td>Demonstrator</td>
<td>NbTi</td>
<td>BSCCO, REBCO</td>
</tr>
<tr>
<td>Superconducting levitation</td>
<td>Demonstrator</td>
<td>REBCO</td>
<td>-</td>
</tr>
</tbody>
</table>
## Outlook

**Which Material for Large Scale Applications?**

<table>
<thead>
<tr>
<th>Magnet Applications</th>
<th>Technology Status</th>
<th>Present Favourite</th>
<th>Future Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRI Magnets</td>
<td>Commercial up to 3 T</td>
<td>NbTi</td>
<td>MgB$_2$, REBCO</td>
</tr>
<tr>
<td>NMR Magnets</td>
<td>Commercial up to 1000 MHz</td>
<td>NbTi, Nb$_3$Sn</td>
<td>REBCO</td>
</tr>
<tr>
<td>Accelerator magnets</td>
<td>In operation up to 9 T</td>
<td>NbTi</td>
<td>Nb$_3$Sn, REBCO, BSCCO</td>
</tr>
<tr>
<td>Fusion magnets</td>
<td>Demonstrator</td>
<td>NbTi, Nb$_3$Sn</td>
<td>REBCO</td>
</tr>
<tr>
<td>R&amp;D and industry magnets</td>
<td>Commercial up to nearly 20 T</td>
<td>NbTi, Nb$_3$Sn</td>
<td>MgB$_2$, REBCO, BSCCO</td>
</tr>
</tbody>
</table>

### Power System Applications

<table>
<thead>
<tr>
<th>Applications</th>
<th>Status</th>
<th>Materials</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cables</td>
<td>Close to commercialisation</td>
<td>BSCCO, REBCO</td>
<td>MgB$_2$</td>
</tr>
<tr>
<td>Rotating machines</td>
<td>Demonstrators</td>
<td>BSCCO</td>
<td>REBCO, MgB$_2$</td>
</tr>
<tr>
<td>Transformers</td>
<td>Demonstrators</td>
<td>REBCO</td>
<td>-</td>
</tr>
<tr>
<td>Fault current limiters</td>
<td>Close to commercialisation</td>
<td>REBCO, BSCCO</td>
<td>-</td>
</tr>
<tr>
<td>SMES</td>
<td>Prototypes</td>
<td>NbTi</td>
<td>MgB$_2$, REBCO</td>
</tr>
</tbody>
</table>

### Other Applications

<table>
<thead>
<tr>
<th>Applications</th>
<th>Status</th>
<th>Materials</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current leads</td>
<td>Commercial up to a few kA</td>
<td>BSCCO</td>
<td>REBCO</td>
</tr>
<tr>
<td>Electrodynamical levitation</td>
<td>Demonstrator</td>
<td>NbTi</td>
<td>BSCCO, REBCO</td>
</tr>
<tr>
<td>Superconducting levitation</td>
<td>Demonstrator</td>
<td>REBCO</td>
<td>-</td>
</tr>
</tbody>
</table>

*Thank you very much for your attention!*
Outlook
What does Superconductivity needs in the Future?

I never did anything by accident, nor did any of my inventions come by accident, they came by work.
Thomas Alva Edison

Anything that won’t sell I don’t want to invent. Its sale is proof of utility and utility is success.
Thomas Alva Edison

Hard work + Sales = Success

Thank you very much for your attention!