Overview of Applied superconductivity and applications

Fig. 1: levitation of a NdFeB magnet using a nitrogen-cooled HTS bulk [matchrockets.com].
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Superconductivity

- Superconductivity is characterized by the absence of a measurable resistance under certain conditions (theoretically the total absence of resistance). The term was first introduced in 1911 by Heike Kamerlingh Onnes after the discovery of the first type-I superconductor, Mercury. He received the Nobel prize in 1913 for its work on helium liquefaction.

- Two theories of superconductivity prevail:
  - The macroscopic Ginzburg-Landau theory (Vitaly Lazarevich Ginzburg, Nobel laureate 2003),
  - The microscopic BCS theory (Bardeen-Cooper-Schrieffer, Noble laureates 1972).

Onnes (1853-1926), Dutch physicist [Wikipedia].
Ginzburg (1916-2009), Russian physicist [Wikipedia].
Leon Neil Cooper (1930-), American physicist [Wikipedia].
John Robert Schrieffer (1931-), American physicist [Wikipedia].
Timeline of superconductivity

- The following figure shows the timeline of technological progresses which led to the current state-of-the-art superconductors.

- After the capacity of producing liquid helium was achieved, many superconductors were discovered. However, it took nearly 50 years to migrate to the industrial sector.

- Out of the many found superconductors, only a few led to practical applications.

Fig. 1: A timeline of superconductor discovery and their applications [Wikipedia] [Gurevich].
Advantages

- Superconductors can carry a large amount of current for a given cross-section area without measurable resistance.

- The absence of Joule dissipation allows to transfer power without losses.

- Fig. 2 compares the resistivity of common conductors such as copper, aluminum and silver to a commercial superconductor.

- Table 1 gives an example of transport current capacity of copper and NbTi wires having same diameter equal to 1 mm. Whereas copper wires are operated at room temperature, NbTi wires must be cooled down to 4.2 K [lecture 1 document].

<table>
<thead>
<tr>
<th></th>
<th>Current (A)</th>
</tr>
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<tbody>
<tr>
<td>NbTi</td>
<td>4000</td>
</tr>
<tr>
<td>Copper</td>
<td>16</td>
</tr>
<tr>
<td>Ratio</td>
<td>250</td>
</tr>
</tbody>
</table>

Tab. 1: Transport current comparison.

Fig. 2: Comparison of resistivity versus temperature between common-used electrical materials and commercial YBCO coated conductor provided by American Superconductor Corporation in 2006 [Trillaud].
Drawbacks

- Transferring power without losses is a strong motivation to develop superconductors in order to supersede conventional materials used in power distribution.

- To this date, the main application of superconductivity remains high energy physics and medicine. The cost is mitigated by the necessity to achieve strong magnetic fields.

- Two main issues must be addressed to allow superconductivity to increase its commercial potential:
  - Simplification of the manufacturing process (reducing cost, increasing batch length, homogenization of quality),
  - Cryogenic system (reducing cost, ensuring safety, increasing efficiency).
Bunch of applications

- **Medicine:**
  - MRI

- **Science:**
  - Physics (accelerators: LHC, fusion: ITER, microgravity).
  - Chemistry (NMR).
  - Characterization (SQUID).

- **Power applications:**
  - Distribution (power cables)
  - Power devices (transformers, UPS, energy storage, …)

- **Electronics:**
  - Communications
  - Sensors
  - Signal processing

- **Transportations:**
  - Trains (MagLev)
  - Ships (cloaking hull, propulsion)

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Fig. 3: from top left to bottom right. NMR 900 MHz (Bruker EST), MRI 1.5 T (GE), Shanghai MagLev train, hall 1 of LHC tunnel [Google Images].
Power applications: HTS power cable

- Various available technologies:
  - Warm and cold insulation
  - One phase per conductor or 3 phases per conductor

- Advantages over conventional cables:
  - Higher energy density (1 HTS cable against 3 to 5 conventional cables)
  - Subterranean cables benefiting from existing sites
  - No electromagnetic pollution
  - No heating issue

- Disadvantages:
  - Cost of material (~$200/kA-m)
  - Need for cryogen (LHe, hydrogen, LN$_2$, etc.)

Fig. 4: Different technologies.
Power applications: Fault-current limiter

- Two main topologies:
  - Resistive
  - Inductive

- Advantages over conventional protection systems:
  - Low impedance in no-fault operation
  - Passive system that requires low maintenance
  - Allow service continuation during faults of short durations

- Disadvantages:
  - Cost of material
  - Need for a cryogenic cooling system

Fig. 5: Dramatic example of a fault occurring in power transformer.

Fig. 6: Left: inductive design (Courtesy J. Wolsky 2013). Right: resistive design [Nexans].
**Power applications: SMES**

- **SMES**: Superconducting Magnetic Energy Storage

- 2 topologies:
  - Solenoid (large stray field)
  - Toroidal (larger amount of conductor required)

- **Main applications**:
  - Storage such as batteries, flywheel, etc.
  - Grid stabilization

- **Advantages over conventional systems**:
  - Fast response time
  - No moving mechanical parts
  - Environmental friendly (compared to batteries for energy storage)

- **Disadvantages**:
  - Need for large systems to be of practical use in the power grid
  - Power converter related issues (cost and efficiency)

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Fig. 7: General overview of a SMES system with its power converter [ClimateTech Wiki].

Fig. 8: Largest operated SMES systems [Oregon state].
Power applications: Motors

- Mainly for applications requiring compact light systems such as ships and aircrafts besides large generators (> 6 MW) for off-shore wind power
- A few prototypes have been built and tested
- Two possible configurations:
  - Full superconducting machine (rotor and stator)
  - Hybrid machine, generally the rotor is superconducting
- Competition with permanent magnet machines. Advantage, superconducting conductors require lesser amount of rare earth (cost).

Fig. 9: 3D CAD an hybrid machine [IEEE Spectrum].

Fig. 10: Right: prototype of a 5 MW ship propulsion motor with exciter from American Superconductor Corporation [MaNEP]. Left: superconducting winding in cryostat.
Science: accelerator of particles

- **Main technologies:** Bending and focusing magnets: LHC (>1125 tons of NbTi) [Narlikar]

- **Future technologies in light sources:** Superconducting undulators and wigglers

- **Advantages over conventional technologies:**
  - Allow reaching higher energy beam
  - Most of cases: the only feasible technology (LHC at >7 TeV)

**Light sources: Superconducting Undulators**

Fig. 11: SCU15 for production of high-brilliance X-rays installed in the ANKA storage ring [Phys.org: KIT/ANKA/BNG]

Fig. 12: Preliminary design of the Indian SCU at DAVV, Indore in collaboration with the Institute of Engineering of UNAM (MOU signed in 2015 for a 5 years collaboration).
Present and future Benefits

✔ Betting on expected economical viability, the future benefits are substantial.

✔ A few advantages:
  ✔ Compactness.
  ✔ Lightness.
  ✔ High energy density.
  ✔ Nearly no Joule losses.

✔ Impacts on society:
  ✔ Low maintainability.
  ✔ No visual pollution.
  ✔ Cost effective solutions.
  ✔ Reduction of green house effect.

✔ New technologies focus on energy efficiency and environmental impacts.
Market of superconducting systems

- The contribution of superconductivity to power applications are slowly becoming a reality.
- Power devices made of NbTi wires or BSCCO wires are currently in operation.
- Some commercial products:
  - NMR and MRI magnets.
  - D-SMES (10 systems in the USA including TVA, Alliant Energy and Wisconsin Public Service) [D-SMES brochure].
  - Power cables from prototypes to pre-production systems (China, Denmark, Korea, Japan, Mexico, Spain, Russia).
- Upcoming products:
  - Motors (SeaTitan® wind turbine, ship propulsion engineered by AmSC®).
  - Power distribution (Fault-Current limiters: demonstrators in Germany, China, ...).
- In Mexico, CIDEC (Centro de Investigación y desarrollo CARSO) is the only Mexican company developing and installing superconducting devices in Latin America [Condumex].
The following table summarizes the different commercial superconductors available on the market.

LTS have a fairly well-established niche where the generation of high magnetic field is required. The technology is near its apex and alternative materials are soon needed to go beyond the current state-of-the-art.

HTS conductors are improving constantly. Lengths with better homogeneity increase yearly. However, the cost-performance must drop below $50/kA-m to have a significant commercial impact.

Magnesium diboride is a fairly new superconductor discovered in 2001. Manufacturing techniques remains to be optimized.

Tab. 2: comparison between commercially available conductors.

<table>
<thead>
<tr>
<th>Material</th>
<th>Length (m)</th>
<th>Price ($/kA-m)</th>
<th>Type</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>&gt;1000 m</td>
<td>$25-$50</td>
<td>Wire, cable, tape</td>
<td>Power applications, science</td>
</tr>
<tr>
<td>LTS</td>
<td>&gt;1000 m</td>
<td>NbTi (8 T, 4.2 K): $4-$6, Nb₃Sn (12 T, 4.2 K): $15-$30</td>
<td>Wire, cable</td>
<td>Science, medicine, power devices</td>
</tr>
<tr>
<td>MTS (MgB₂)</td>
<td>&gt;1000 m</td>
<td>$1 (projection)</td>
<td>Wire, tape</td>
<td>Medicine</td>
</tr>
</tbody>
</table>
Superconductor technologies

- Superconductors need particular manufacturing processes.
- In the following slides, a broad panel of common techniques are introduced. Crystallographic structures, phase diagrams, wire or tape layouts are presented as well.
- In addition to manufacturing processes, special handling is sometime required due to the poor mechanical properties of some superconducting phases.

Fig. 15: Nb₃Sn insulated cable. The filaments of superconductor are visible.
NbTi conductors

Bruker EST (NMR, MRI)

Oxford Instruments (high stabilization)

Outokumpu Poricopper (ITER)

Cable in conduits (fusion)

Aluminum stabilized cable (ATLAS toroid-CERN)

Furukawa Electric (LHC)
Nb₃Sn

NED project (future accelerators)

Supercon Inc. (external stabilization)

Supercon Inc. (internal stabilization)

Bruker EST (rectangular conductor)

Cable stack (Alstom-MSA)

Cable in Conduit (ITER)
BSCCO conductors

BSCCO-2212 (Oxford Instruments)

BSCCO-223/Ag tape

Power cable (Nexans, Endesa and Centre Labein Technalia)

BSCCO-2212 cable (Oxford Instruments)
YBCO conductors

Copper laminated (AmSC®)

Electroplated copper (Superpower Inc.)

Roebel cable

YBCO cable (AmSC® and ORNL)
MgB$_2$ conductors

Mono-filament (Hyper Tech Research, Inc.)

Multi-filaments (Hyper Tech Research, Inc.)

Tape (Columbus Superconductors SpA)

19 strand MgB$_2$/Ti/Cu
Comparison between superconductors

Fig. 16: Comparison of transport current of various superconductors at 4.2 K, self-field [P.J. Lee].
Manufacturers of superconductors

The following list may not be exhaustive. It presents various manufacturers of superconducting wires:

- SuperPower Inc. (http://www.superpower-inc.com/)
- Oxford Instruments (http://www.oxford-instruments.com/Pages/home.aspx)
- American Superconductor Corporation (http://www.amsc.com/).
- Nexans S.A. (http://www.nexans.com/).
- Outokumpu (http://www.outokumpu.com/).
- Bruker EST (http://www.bruker-est.com/).
- Columbus Superconductors SpA (http://www.columbussuperconductors.com/).
Various international projects covering the development of power systems and scientific instruments based on superconducting technology:

- Thermal, mechanical and electromagnetic modelling of HTS bulks for electrical machines (collaboration with the University of Lorraine, Nancy, France)
- Design of a superconducting undulator for a new generation of Free Electron Laser (Memorandum of Understanding with the University of Indore, Indore, India)
- Design of a fault-current limiter for the national power grid (PhD program, collaboration with CEPEL, Brazil, and SupElec, France)
- Design of a HTS power cable in collaboration with Servicio Condumex S.A. (PhD program, on hold)
- Estimation of power losses in large scale superconducting devices (PhD program, collaboration with Karlsruhe Institute of Technology, Germany and the National High Magnetic Field Laboratory, Fl, USA)

Thank you for your attention
References


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- [Wikipedia] Wikipedia:
  - http://en.wikipedia.org/wiki/Meissner_effect


- [Phys.org] SCU15 at ANKA synchrotron radiation facility, Karlsruhe Institute of Technology, Germany

- [Oregon state] Largest SMES. Internet website:
References

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- [IEEE Spectrum]. Internet link:
  http://spectrum.ieee.org/energy/renewables/winner-superconductors-on-the-high-seas
- [AmSc®] (American Superconductor Corporation):
  - http://www.amsc.com/
- [P.J. Lee]:
  - http://www.magnet.fsu.edu/magnettechnology/research/asc/plots.html