EDITORIAL

Introduction to the focus on superconductivity for energy

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Introduction to the focus on superconductivity for energy

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1. Introduction

After a century from their discovery, superconducting materials are used in several fields and their applications for energy are a revolutionary dare. A huge amount of work has been done to face this challenge, and nowadays superconducting power cables, high field magnets, and power devices (such as transformers, motors, magnetic-energy storage, fault current limiters) are a genuine fact.

The international conference ‘Superconductivity for Energy’, held in Paestum (Italy) on May 2014, had a resounding success, with more than 100 participants, 50 talks, and about 30 poster presentations, with several world experts as invited speakers. It was organized in the framework of the NAFASSY (NAtional FAcility for Superconducting SYstems) project, recently funded by the Italian Ministry of University and Research to realize a facility for measuring power devices and superconducting materials in high magnetic fields at low temperatures. In the following, we provide a brief overview of the main topics discussed in the special issue.

2. Superconducting materials

Superconducting materials represent a great opportunity for the development of high efficiency power devices, magnetic energy storage and power transmission lines, as well as energy production in the context of thermonuclear fusion [1]. The main features that make superconductors competitive for large scale applications are the high power density and low losses, which allow diminishing volume and weight of superconductive devices, compared to the standard ones. For a proper commercial exploitation, besides the highest current carrying capability in high magnetic fields, superconducting materials should meet several engineering requirements: good uniformity, mechanical strength and stability, long length and low ac losses [2]. However, affordability is always a primary concern for these products.

From a practical point of view, the main challenge for a superconductor is not just to achieve the highest critical temperature \( T_c \), but also the highest critical current density \( J_c \). The maximum possible value of \( J_c \) is the depairing current density \( J_{dp} \), which is mostly predetermined by the microscopic material properties. On the other hand, \( J_c \) is dominated by extrinsic defects of the material [3, 4], due to the growth technique as well as to the artificial creation of defects into the material, so that great efforts have been devoted to improve the performance of superconductors by acting on effective novel pinning mechanisms [5–8]. Moreover, the dissipationless property and the stability of the superconducting state are affected in the dissipative regime, characterized by a current density \( J \) with \( J_c < J < J_{dp} \) [9–11].

The production of superconducting magnets for fusion machines still employs conventional low temperature superconductors (LTS), Nb₃Sn and NbTi [12, 13],...
Table 1. Material parameters for power applications.

<table>
<thead>
<tr>
<th>Superconducting material</th>
<th>$J_e$ ($10^3$ A mm$^{-2}$)</th>
<th>$H_{irr}$ (T)</th>
<th>Fabrication Techniques</th>
<th>Commercial metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>1@4.2 K, 5 T [15]</td>
<td>10.5@4.2 K [4]</td>
<td>Extrusion of copper clad NbTi</td>
<td>0.5–10 US$/KA m</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>2@4.2 K, 10 T [15]</td>
<td>24@4.2 K [4]</td>
<td>Bronze and internal tin processes</td>
<td>3–50 US$/KA m</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>0.5@4.2 K, 5 T [15]</td>
<td>15@20 K [4]</td>
<td>PIT</td>
<td>Cost comparable to LTS for production &gt;10$^9$ Km/year</td>
</tr>
<tr>
<td>REBCO</td>
<td>0.6@4.2 K, 10 T [15]</td>
<td>25@60 K [4]</td>
<td>PLD, MOCVD, CSD, thermal and e-beam evaporation</td>
<td>350 ($I_c \times L$ (A Km) @77 K, 0 T) [4]</td>
</tr>
<tr>
<td>BSCCO 2212</td>
<td>0.8@4.2 K, 10 T [15]</td>
<td>5@30 K [20]</td>
<td>PIT</td>
<td>450 ($I_c \times L$ (A Km) @77 K, 0 T) [4]</td>
</tr>
<tr>
<td>BSCCO 2223</td>
<td>0.5@4.2 K, 10 T [15]</td>
<td>12@30 K [14]</td>
<td>PIT with rolling process</td>
<td>200 ($I_c \times L$ (A Km) @77 K, 0 T) in lengths up to 1500 m [27]</td>
</tr>
<tr>
<td>FeSeTe (11 family)</td>
<td>0.2@4.2 K, 0 T [25]</td>
<td>43@4.2 K [20]</td>
<td>PLD, RABiTS</td>
<td>n.a.</td>
</tr>
</tbody>
</table>
while high temperature superconductors (HTS) are becoming a promising alternative in power technology due to the development of second generation coated conductors [14–17]. In addition, the manufacturing of MgB₂ superconducting wires is an industrial reality, matching the requirements of several applications, such as MRI magnets, rotating machines and fault current limiters [18, 19]. Moreover, the discovery of a new class of superconducting materials, the iron-based compounds, boosted the potential of superconductivity for energy applications, due to their promising properties with respect to the different mechanisms limiting the current in HTS, i.e. the very small coherence length causing a poor grain connectivity, the anisotropy and the variety of chemical composition [20–23]. In particular, iron-based materials can sustain large currents at high magnetic fields up to 30 T [24–26] and can be operative in a wide temperature region (20 K–60 K) by using cryocoolers as the refrigeration technique.

The quest for the best material is strictly related to the particular application. Table 1 summarizes useful parameters to discriminate which material can be the right candidate at the different working conditions in terms of temperature and magnetic fields. Although the parameter list is far from complete, other specific information can be found in the references [2, 4, 14, 15, 20, 24–26].

In table 1, \( J_E \) is the engineering critical current density, i.e. the current density in the whole conductor cross section [15]; \( H_{irr} \) is the field at which the bulk critical current density goes to zero [26].

It is well known that choosing the right material on the basis of the highest values of the critical current density is not good practice. Indeed the cost efficiency as well as the ease of the growth technique can make a great difference for commercial production. The isotropy of the superconducting material plays a crucial role, too. For most demanding power devices, tape geometry is still valuable for high mechanical strength, but detrimental in almost all other aspects in comparison to round wires [16]. Concerning the limiting mechanisms to the high current superconductivity, the grain boundary problem seems to be solvable in the new class of iron-based superconductors. Despite a small coherence length, some iron-based compounds (such as the 11-family) show high connectivity even at high angle grain boundaries, as well as a low anisotropy factor \( \gamma = 1.4 \) [22]. However, iron-based superconductors, while scientifically relevant, are not commercially available.

### 3. Power devices

Superconducting power devices include high efficiency transformers, motors, fault current limiters and magnetic energy storage, characterized by compactness and energy saving. However, the market penetration of superconducting devices is strictly related to their capability to overcome the performances (at reasonable costs) of existing electrical devices [28].

#### 3.1. Superconducting fault current limiters

The stability of the electric power system is essential and the superconducting fault current limiter (SFCL) is a very strong enabling technology. Nowadays, the grid is vulnerable to unexpected faults. A SFCL is an innovative technology that can prevent the occurrence of fault currents in power grids, protecting equipment from very large short-circuit currents.

Inductive, resistive and saturable core SCFLs are the three possible solutions. Comprehensive reviews of all possible types of limiter are reported in [29, 30]. Concerning the saturable core FCLs, industrial R&D activity is focusing on limiters for application at the medium voltage level as well as on the high voltage
level by applying BSCCO-2223 tapes for winding, MgB$_2$ appearing as a good candidate for future applications.

The resistive FCL gives important advantages with respect to the saturated core one due to compact size, weight and lower cost. The challenge is devoted to the application of second generation coated conductors, which can ensure high resistivity in quenched condition and protection against hot spots. Industrial R&D activities worldwide concern with the realization of (long) coated conductors with high resistivity substrate for resistive limiters.

Inductive SFCLs are naturally less compact for the presence of a ferromagnetic circuit. Their realization requires a shorter length, although they behave quite robustly against hot-spot formation. Due to such properties, inductive SFCLs are interesting in medium voltage grids. However, the need for relatively large HTS bulk cylinders for secondaries is considered a hard task, and a reason why after a magnetic shielding SFCL demonstration on 1997 [31], only recently have bulk tubes been replaced by BSCCO [32] and/or coated conductor [33] tapes, which overcome that problem.

3.2. Superconducting magnetic energy storage (SMES)

SMES is an energy storage system with large capacity, long life, fast charging speed, and high efficiency up to 95% [34] and it allows improving the performance of the distributed power generation system. An important advancement for the SMES technology is based on HTS, and in particular on their capability of smoothing the active power [35], giving better transient stability [36], increasing the power quality [37] and allowing incorporation to ac side as well as to dc side of distributed generation systems. Great effort has been made worldwide to develop SMES [38, 39] based either on LTS (allowing large capacity systems up to 100 MJ), mostly on NbTi [40–42], or HTS (to get systems typically limited to few MJ capacity) mostly Bismuth based cuprates (Bi-2212 and Bi-2223) [43–45].

3.3. Motors

Superconducting motors strongly reduce losses and dimensions with respect to standard motors, allow very high power and torque density, and improve the operation conditions by reducing friction and windage. The development of superconducting motors implementing high-Tc materials have been performed since 90s, however their present boost is favored by the affordable costs of HTS. Different technological solutions have been addressed to realize low-power (based on axial high flux density [46, 47]) in the range 1 W–500 W or high-power motors (based on the flux concentration principle [48]) in the MW range.

4. Superconducting cables and magnets

4.1. Superconducting cables

The use of superconducting cables for large scale applications is conditioned by the possibility to manufacture very long wires (up to kilometers in length) with high values of $J_c$ and critical magnetic field, $H_{c2}$.

Most of the large scale devices rely on NbTi and Nb$_3$Sn superconducting cables, which require liquid helium for cooling. Concerning the superconducting magnets for nuclear fusion reactors, where several sources of heat loads are expected and where large heat dissipation is required, most of the designed solutions are based on CICCs (Cable-In-Conduit Conductors). CICCs are made up by superconducting and copper wires cabled together, inserted inside a stainless steel jacket and cooled by forced-flow supercritical helium that was proven to provide larger stability margins with respect to bath-cooled, liquid helium magnets.
The main disadvantage of CICCs is the limited overall engineering current density, with respect e.g. to conductor solutions based on compact Rutherford cables, as those used in high energy physics magnets, where magnetic field quality, magnet shape, and high engineering $J_c$ represent the main design driving factors [50].

Recently, great attention has been devoted to HTS cables, based on BISCCO wires and ReBCO tapes [49, 51]. Compared to LTS, HTS exhibit higher values of $H_{c2}$, $J_c$, specific heats, thermal conductivities, and lower required refrigeration power (20 K–77 K, depending on the operating magnetic field), which makes them suitable for high field applications above 15 T. In addition, the operation at 20 kA of a multi-wire MgB$_2$ cable, internally cooled at 20 K, has been demonstrated [52]. The possibility to operate superconducting cables at the liquid hydrogen temperature is promising for the development of superconducting power transmission lines, where the hydrogen could serve as coolant, as well as energy carrier in addition to the superconducting cable [53, 54].

Both HTS and medium-temperature superconducting power cables can provide a new way to solve power transmission issues. Several development and demonstration projects have been successfully completed in recent years showing the technical feasibility of the insertion of superconducting cables in the power grid [55]. Benefits of HTS applications in the power grid might become more visible in confined power grids [56].

4.2. Superconducting magnets for fusion reactors

Superconductivity also plays an important role as an enabling technology for nuclear fusion reactors. In a fusion reaction [57], energy is released when two light atomic nuclei (such as the isotopes of hydrogen, deuterium and tritium) are fused together to form one heavier atom and high-speed neutrons. The kinetic energy of the neutrons (17.6 MeV per reaction) is absorbed by the blanket, causing it to heat up. The heat energy is collected by the coolant (water, helium or Li-Pb eutectic) flowing through the blanket and, in a fusion power plant, this energy will be used to generate electricity by conventional methods. To make the fusion process useful as an energy source, the ‘fuel’ must be heated to extreme temperatures over 100 million degrees Celsius and confined for long enough times to approach steady-state regime at sufficiently high density in order to become a plasma. The most promising device for the magnetic confinement is the ‘tokamak’, a Russian word for a torus-shaped magnetic chamber. The need of superconducting magnets for the plasma confinement was recognized since the early development of fusion devices, as summarized in a recent review paper [58]. The international fusion research is following a roadmap to achieve power generation within 30 years, mainly focused on two superconducting tokamaks: ITER and DEMO.

ITER (International Thermonuclear Experimental Reactor) [59] is an international project aiming to confirm that fusion power will be possible on a commercial scale. ITER is a 500 MW fusion reactor with a power amplification $Q=10$. The magnetic system consists of four main subsystems, currently under production [60]:

- 18 toroidal field (TF) coils, which produce the confining/stabilizing toroidal field;
- 6 poloidal field (PF) coils, for positioning the plasma;
- a central solenoid (CS) coil, which induces current in the plasma;
- 18 correction coils (CC), which correct error fields due to manufacturing/assembly imperfections, and stabilize the plasma against resistive wall modes.

The conductors for TF and CS coils require about 600 tons of Nb$_2$Sn strands, whereas the PF and CC conductors need around 275 tons of NbTi strands [61].

ITER is being built in Cadarache (France) and the first plasma is foreseen by 2019.
DEMO is a demonstration power plant, supplying fusion electricity to the grid. It is being designed now and will be constructed during ITER operation. If successful, it will be followed by the first generation of commercial fusion power stations.

While ITER is a joint effort, many countries including Europe, China, Korea, Japan, United States and India are already considering their own demonstration facilities as the next step toward commercial fusion power. Although the goals of DEMO are broadly agreed, its design concept is not. Depending partly on the timescale envisaged for its construction, different views on the DEMO design concept have emerged, since some key plasma-related areas are expected to be very different moving from ITER to DEMO [62].

As an example, the Korean project (K-DEMO) is focusing on a tokamak with 6.5 m major radius, a peak toroidal field of 16 T and a toroidal field at plasma centre of 7.72 T [63], whereas the present design of the European tokamak (EU-DEMO) foresees a major radius of 9.0 m, a peak field of 13.6 T and a field at plasma center of 6.8 T [64]. In table 2 the main features of the TF magnetic systems of ITER and EU-DEMO are reported [65]. The challenging requirements of DEMO design open an issue on the superconductive materials to be used for magnets. A clear possibility is to propose high critical current density Nb$_3$Sn strands, but the suitability of HTS for fusion magnets has also been considered [7, 66].

### 4.3. Superconducting test facilities

The R&D activity carried out for fusion projects has also promoted the building of high-field test facilities, suitable for the qualification of superconducting cables and magnets. Presently, the qualification of ITER conductors is carried out at SULTAN test facility [67] located in Switzerland, providing a maximum magnetic field of 12 T on 3.5 m-long straight samples. Other facilities are available for short samples: the European Dipole (EDIPO) [68], having a peak field of 12.5 T; the FBI measurement facility [69] at the Karlsruhe Institute of Technology in Germany having a LTS split coil magnet of 12 T; the 9 T split-coil magnet facility located at National Institute for Fusion Science (NIFS) [70] in Japan and the NHMFL Split Solenoid Facility [71] located in Florida, designed to produce a 14 T field. Other facilities, such as TOSKA in Karlsruhe [72], CEA Facility in Saclay [73] and CSMC in Naka (Japan) [74] are used to test very large coils and are not suitable for testing conductors in high field conditions at affordable costs. In Italy, the NAFASSY facility [75], designed to test long conductors in a peak field of 8 T, is under construction.

<table>
<thead>
<tr>
<th>TF magnet</th>
<th>ITER</th>
<th>EU-DEMO (2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius</td>
<td>6.2 m</td>
<td>9.0 m</td>
</tr>
<tr>
<td>Mean circumference</td>
<td>34.1 m</td>
<td>39.8 m</td>
</tr>
<tr>
<td>Area per TF coil</td>
<td>0.8 m$^2$</td>
<td>2.46 m$^2$</td>
</tr>
<tr>
<td>Field at major radius</td>
<td>5.3 T</td>
<td>6.8 T</td>
</tr>
<tr>
<td>Tot. current in coil</td>
<td>9.1 MA</td>
<td>19.1 MA</td>
</tr>
<tr>
<td>Stored energy/coil</td>
<td>2.28 GJ</td>
<td>9.06 GJ</td>
</tr>
<tr>
<td>Peak Volt. at dump</td>
<td>6.05 kV</td>
<td>9.56 kV</td>
</tr>
<tr>
<td>CICC current</td>
<td>68 kA</td>
<td>82.4 kA</td>
</tr>
<tr>
<td>Peak field on CICC</td>
<td>11.8 T</td>
<td>13.6 T</td>
</tr>
<tr>
<td>e.m. load</td>
<td>816 kN m$^{-1}$</td>
<td>1120 kN m$^{-1}$</td>
</tr>
<tr>
<td>Minimum current sharing temperature</td>
<td>5.7 K</td>
<td>6.5 K</td>
</tr>
</tbody>
</table>
All of the mentioned infrastructures are based on NbTi and/or Nb3Sn magnets. The possibility of sensibly increasing the peak field of superconducting magnets up to 30–40 T relies on the development of HTS coils. Presently, several high-field dc magnets based on REBa2Cu3O7−x have been manufactured [2], but further efforts are required to increase the bore and the high field zone length in order to use these magnets as test facilities for superconductive cables.

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