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Superconductivity

IN SUMMARY

- **PROCESS AND TECHNOLOGY STATUS –** Superconductivity is the ability of certain metals, alloys and ceramic materials to let electrical current flow with no electrical resistance and energy dissipation. Superconductivity appears at below a certain (critical) temperature, which is between 30K and 120K (-243°C and -153°C) for high-temperature superconductors (HTS) and below 20K (-253°C) for the low-temperature superconductors (LTS). Superconducting properties disappear if the temperature rises above the critical value, but also in the presence of high current density or strong external magnetic fields. The critical values of temperature, magnetic field and current density are specific characteristics of each superconductor material. Almost all of today's superconductors are based on Nb (niobium) and Nb-alloys LTS wires, which have already reached a high level of industrialization. LTS use is common practice in the production of small superconducting magnets for medical diagnostics (magnetic resonance imaging, MRI), in research applications, and in large superconducting magnets for world-scale experimental facilities (nuclear fusion, particle accelerators and detectors for high-energy physics). At present, LTS represent a commercially available technology while ceramic HTS are still under development. HTS research has been recently boosted by new discoveries and focuses on the complex ceramic HTS materials and their production process. Advanced cryogenics plays a key technical and economic role in superconductivity, and may drive important developments.

- **PERFORMANCE & COSTS –** Superconductors offer several advantages over conventional electrical conductors. They enable the manufacturing of components (e.g., high-field magnets) that could not be feasible using conventional conductors. The energy saving due to the absence of electrical resistance more than compensates for the energy required to maintain superconductors' operation temperature. Superconducting devices are typically 50% smaller and lighter than equivalent conventional components and their manufacturing process generate no incremental emissions of greenhouse gases. Their cooling is ensured by non-flammable liquid nitrogen or helium, as opposed to flammable and/or toxic oil coolant used in high-performance conventional components. Apart from the cooling system, the typical cost of LTS per unit of carried electrical current (€/m-A) is at least than ten times lower than the cost of an equivalent conventional conductor. All these advantages translate into technical and economic benefits. Nevertheless, considering the cost of superconductors' cooling system, superconductivity is not yet economically competitive with conventional conductors in most applications, and its economic convenience must be assessed by cost/benefits analyses on case–by-case basis.

- **POTENTIAL AND BARRIERS –** Research and MRI applications account for almost all today's global superconductivity market (some € 4 billion in 2007), with MRI being by far the dominant commercial application. Research and MRI are expected to also play a central role in the future market and to constantly grow up to € 4.5 billion by 2013. However, HTS materials and new applications may offer important new business opportunities. Emerging fields could be large-scale applications for power production and transportation, electronic devices for information and communication technologies (ICT), and new medical applications such as ultra-high resolution systems for MRI. HTS cost-to-performance ratio as well as cost and technical development of commercial cooling systems for both LTS and HTS are currently the main barriers to large superconductivity deployment. These obstacles could be overcame by technical advances by the end of this decade and give rise to new start-up markets which could reach some € 0.6 billion by 2013. The identification of niche markets and pilot customers as well as ramping up the existing production facilities are important elements for market deployment. However, the lesson learned from other material-based technologies imply that the large deployment of superconductors will take considerable additional time.

PROCESS AND TECHNOLOGY STATUS – Certain metals, metal-alloys and ceramic materials (superconducting materials) allow direct electrical current to flow with no electrical resistance and no energy dissipation if they are cooled below a certain temperature (critical or transition temperature). Superconductivity disappears if the temperature rises, but also in the presence of high current density or strong external magnetic fields. Critical temperature, magnetic field and current density are peculiar properties of each superconducting materials. Superconductivity was discovered in 1911. The very low temperatures required by superconductors - and the cost of achieving and maintaining such temperatures - hampered the deployment of early applications. Superconducting technology was originally developed for research and technology development (RTD), and for military applications. Yet in the 1980s, superconductivity could only be achieved with low-temperature superconductors (LTS) at temperatures close to the helium liquefaction temperature (4.2K). In 1986, a new class of materials (ceramic cuprates) was discovered, having superconductivity transition at temperatures between 30K and 120K (high temperature superconductors, HTS). These materials need cheaper and simpler cooling systems, but consists of complex ceramics and require high-tech and quality-controlled production processes. Research and discovery of novel superconductors are actively pursued. In 2001, magnesium diboride (MgB_2) has been found to offer

Fig.1 - Multi-wire LTS for nuclear fusion facilities (ENEA, Italy)

Tab. 1 - Properties of Superconductors

- Zero resistance to direct current
- High current density
- Low resistance at high frequency
- Low signal dispersion
- High sensitivity to magnetic field
- No penetration of externally applied magnetic field
- Rapid single flux quantum transfer
- Close to speed of light signal transmission

performance between those of LTS and HTS, with a transition temperature at around 30K. A novel class of superconductive materials, the iron arsenides (FeAs), with transition temperature of about 55K, has been discovered in 2008. The capability of carrying high current density with zero electrical resistance offers the opportunity of lowering losses in electricity transmission, reducing size, weight and cost – and improving performance - of electrical coils, magnets, motors, generators, and electronic devices. As a consequence, superconductivity offers unique functions and performance improvements in a number of components for power generation and transmission, medical equipment, information and communication technology and industrial processes. The special properties of the superconductor materials (Tab. 1) enable important applications in key market sectors: ● Low resistance at high frequency and low signal dispersion play a fundamental role for microwave components and in communication technologies; ● High sensitivity to magnetic fields makes it possible to produce superconductive sensors with a sensing capability 1000 times higher than conventional devices; ● The capability of driving off external magnetic fields holds the potential for applications in magnetic levitation systems for transportation; ● Important applications in digital electronics and high speed computing derive from other peculiar superconductor properties such as the Josephson effect and the sharp transition to superconducting status. A comprehensive list of superconductivity applications is provided in Tab. 2 and 3. Superconductor materials and their critical temperatures are shown in Fig. 2. Boosted by the growing demand for sustainable technologies and most efficient use of resources, the integration of superconductors in end-use technologies is one of the technology challenges of the 21st century. Superconductor technology can in fact provide cost-efficient and environmentally desirable solutions to many current and future needs. (Tabs 2 and 3).

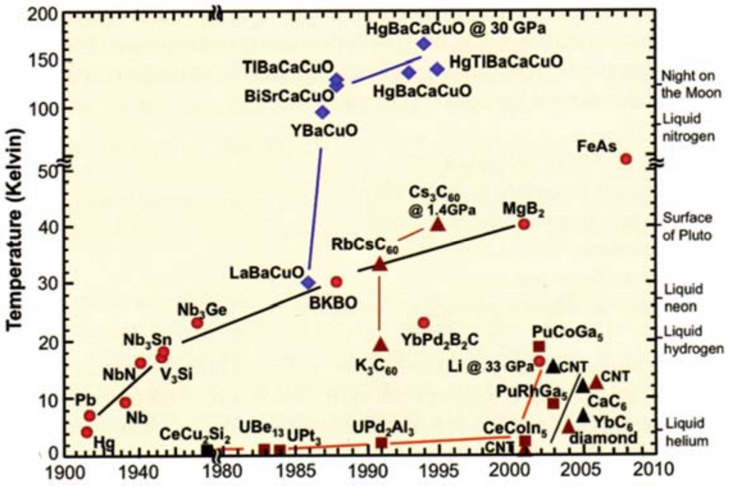

Fig. 2 – Superconducting Materials (Source: CCAS)

■ **Current Applications** - At present, high-field magnets, with high current density and zero DC resistance are mostly used in research and technology development **(RTD)** and in biomedical applications such as the magnetic resonance imaging **(MRI)**. Over the past decades, the extraordinary development of the cooling systems made it possible the introduction of superconducting magnets in MRI and enabled impressive improvements in the image resolution for medical diagnosis (Fig. 3). MRI is currently the largest market for LTS wires while LTS magnets are the dominant technology for MRI. LTS magnets are also used for research devices and for large-scale, high-field magnetic systems used in nuclear fusion and high-energy physics facilities (particle accelerators and detectors). Current application fields also include electronics and industrial processes. An example of industrial application is the magnetic separation of kaolin clay where the use of superconductors enables a 95% reduction of energy use. Examples of electronic applications are outstandingly sharp and low-noise microwave filters used in radio communication systems, and superconducting quantum interference devices (SQUIDs) based on weakly coupled Josephson junctions.

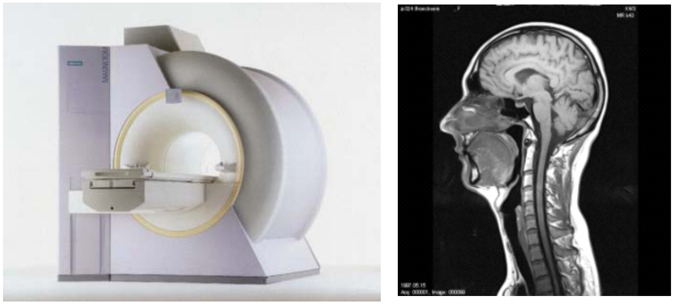

Fig. 3 - MRI Device and Output

SQUIDs are able to monitor magnetic fields billion times weaker than the earth magnetic field. They are used for monitoring and recording heart and brain functions. Notably, multi-channel SQUIDs for magneto-cardiogram (MCG) and magneto-encephalogram (MEG) devices have been developed by improving the sensitivity of LTS SQUIDs above a few fT/(Hz)1/2. Abnormal current distribution in ischemic hearts and propagation pathways for arrhythmias are thus easily detected. ■ **Applications under Development** - Superconductors with ultralow losses in alternate current (AC) are under development for power applications such as electricity transmission, large transformers and motors. They could enable large energy savings if compared to existing technologies. The technical feasibility of these applications has already been demonstrated. HTS multi-channel SQUIDs are under development for next-generation electronic devices to save space and provide mobility. A large R&D effort is devoted to quantum computers based on SQUIDs and Josephson junctions. Much faster than existing computers, quantum computers could solve problems with exponential complexity in polynomial times, with important consequences in cryptanalysis and in both civilian and military security applications. ■ **Cryogenics** plays a key role in superconductivity development and deployment. Costly and energy-consuming cryo-coolers are needed to provide reliable, low-temperature cooling at typical temperatures of 4.2K, 20K, 27K and 77K (helium, hydrogen, neon and nitrogen

Please send comments to dellacorte@frascati.enea.it (author) and giorgio.simbolotti@sede.enea.it (TB coordinator) liquefaction temperatures, respectively). Cryogenics and low-temperature materials science are therefore fundamental for the future of superconductivity. Moreover, superconducting devices require non-superconducting materials and components with optimal mechanical, thermal and electrical properties at low temperatures.

Tab.2 - Large-Scale Applications of Superconductivity

Application	Major Technical Features
Power Cables	higher current densities, smaller cable diameters, lower transmission losses
Current Limiters	highly non-linear super-normal conductor transition, self controlled current limitation
Transformers	higher current densities, smaller size, lower weight, lower losses
Motors/Generators	higher current densities, higher magnetic fields, smaller size, low weight & losses
Magnets for RTD, Magnetic Energy Storage, Magnetic Separation, NMR Spectroscopy, MRI, Magnetic Levitation	higher current densities, higher and ultra-higher magnetic fields, higher magnetic field gradients, smaller size, lower weight, lower losses, persistent currents, ultra-high temporal field stabilities, stronger levitation forces, larger air gaps
Cavities for Accelerators	lower surface resistance, higher quality factors, higher microwave-power handling
Magnetic Bearings (based on HTS bulk materials)	higher current densities, lower losses, stronger levitation forces, self-controlled autostable levitation

Tab.3 - Electronics Applications of Superconductivity

Application	Major Technical Features
High Frequency Sensor Coils for NMR	lower resistive losses, higher quality factors, smaller size
Microwave Filters for Wireless Communication	lower surface resistance, smaller size, lower transmission losses, higher quality factors
Resonator for Oscillators & other passive microwave devices	lower resistive losses, higher quality factors, lower transmission losses, smaller size
Far-Infrared Bolometers	highly non-linear super-normal conductor transition, higher irradiation-mediated temperature sensitivities
Microwave Detectors	highly non-linear junction characteristic, higher conversion efficiency for frequency-mixing
X-Ray Detectors	lower particle excitation energies, higher photon energy resolution
SQUID Sensors for RTD, Medical Diagnosis and non Destructive Testing SQUID Amplifiers	persistent currents, quantum interference effects, ultra-high magnetic field sensitivities, low-noise low-signal amplification
Voltage Standards for Metrology & Industry	voltage steps in microwave irradiated junction arrays, quantum precision output voltages
Digital Circuit & Microprocessors	persistent current, single flux quantum signal levels, ultra-fast ultra-low power data transfer & processing

PERFORMANCE & COSTS – Superconductors offer varied advantages over conventional electrical conductors. They enable the manufacturing of components (e.g., high-field magnets) that would be unfeasible using conventional conductors. The energy saving due to the absence of electrical resistance more than compensates for the energy requested to maintain the low operation temperature. Superconductors are typically smaller and lighter than equivalent conventional components. Their manufacturing process generate no incremental emissions of greenhouse gases. They are cooled by non-flammable fluids such as liquid nitrogen or inert helium, as opposed to flammable and/or toxic oil coolant used for high-performance conventional components. However, in most applications, superconductivity is not yet economically competitive because of the high cost of the cooling system to operate superconductors at low temperature. The technical-economic advantages of using superconductors must be assessed by cost/benefits analysis on case-by-case basis. Typical superconductors costs (at zero magnetic field and relevant operating temperature) are as follows:

- Commercial 100-Ampere NbTi LTS wire: € 0.03/m;
- Best practice 100-Ampere Nb_3Sn LTS wire: € 0.12/m;
- Most promising 100-Ampere YBCO HTS wire: € 30/m.

In other words, the cost of commercial NbTi superconducting wires capable to carry a 100-A current is €0.03/m. For comparison, the cost of an equivalent, 100-Ampere conventional copper wires is about €7.5/m. In spite of the large superconductor advantage, the high additional cost of the cooling system still makes the use of conventional conductors more convenient in most commercial applications (e.g., electricity transmission in electrical devices and networks). Cost, however, is not the sole criterion for using superconductors. Other benefits can be found in the reduced size and weight (typically 50%) of components as a result of the high superconductor current density (up to 10^5 A·/mm^2), in the lower energy losses, in the improved performance and stability. Magnetic fields of tens of tesla, as required in nuclear fusion (10^7 times higher than the earth magnetic field) could not be achieved using conventional conductors. Similarly, the high MRI resolution obtained from using superconducting magnets could not be achieved by conventional magnets. As far as cooling is concerned, new-generation cryo-coolers have proved to be maintenance-free for long periods (years). However, their production scale is still limited, and cost per cooling Watt is still high and sensitive to the refrigeration volume and temperature range. Pulse tube cryocoolers represent a promising, reliable and low-cost option. Their typical cost for 5-W refrigeration power in the temperature range 33K-77K is in the order of $3000 (some $600/W). Of course, the larger the market the faster the technology learning and cost reduction.

POTENTIAL AND BARRIERS – According to the Consortium of European Companies for Superconductivity Use, (Conectus, 2007), the current global superconductivity market including MRI and small/large systems for research applications (RTD) amounts to some € 4 billion per year (2007) and is expected to grow by some 10% by 2013 (Fig. 4). Niche markets for HTS are also expected to grow. These projections include traditional applications and emerging innovation in traditional applications. They do not actually include potential new business opportunities based on new superconducting materials and applications such as quantum interference effects already used in a new class of ultra-fast and ultra-low-power-consumption superconductors for electronic components. In the future, these components could play important roles in areas where traditional semiconductor-

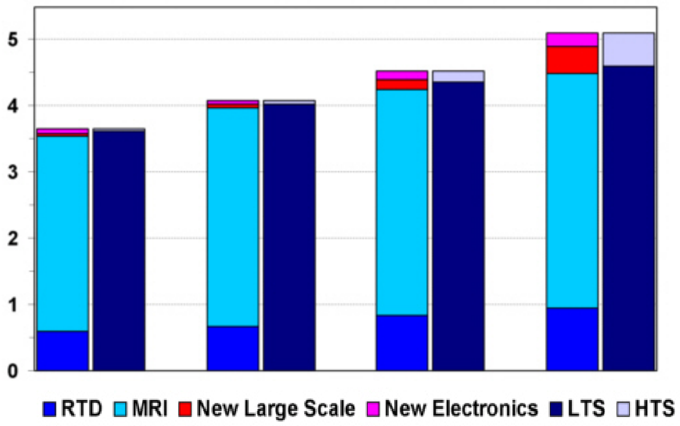

Fig.4 – Superconductivity Global Market (billion €) (Source: Conectus, 2007)

based components have reached their performance limits. Moreover, superconductors could replace copper and permanent magnets in new-design stators, rotors and transformers with improved performance and reliability, and reduced energy losses and weight. It is estimated that a 10-MW wind turbine using HTS technology could weigh one third of a conventional wind generator with equivalent power. Further prospective applications include information and communication technologies, industrial processes, transportation, and medical applications. It is estimated that around the end of the current decade, technical development and cost reduction will prepare the economical basis for new markets. Large deployment however requires the identification of niche markets and pilot customers, improved price-to-performance ratio and large-scale production facilities. LTS and HTS materials will compete in the emerging markets. At present, HTS materials are used in a few applications as their performance and cost are not yet comparable with those of LTS or conventional conductors. Superconductivity development is following the typical pattern of other material-based technologies such as transistors, semiconductors and optical fibers. These technologies entailed high uncertainty and development risk, and took a few decades to move from labs to market. A key role for superconductivity is thus played by public-private partnerships to ensure funding and risk sharing, and parallel progress in related fields, such as cryogenics.

References and Further Information

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Major R&D and Commercial Players

■ Berkeley LAB www.lbl.gov/ ■ CEA www.cea.fr ■ ENEA, www.enea.it ■ FzK www.fzk.de/ ■ Los Alamos National Labs www.lanl.gov/ ■ MIT – PSFC www.psfc.mit.edu/ ■ NHMFL www.nhmfl.gov ■ Alstom, www.power.alstom.com ■ American Superconductors www.amsc.com/ ■ Hypres www.hypres.com/ ■ Sumitomo Electrics www.sei.co.jp/ ■ SuperPower Inc www.superpower-inc.com/ ■ Oxford Instruments www.oxinst.com/Pages/home.aspx ■ Southwire www.southwire.com/ ■ Bruker Advanced Superc www.advancedsupercon.com/ ■ LUVATA www.luvata.com

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Antonio Della Corte is Senior Researcher and Superconductivity Division Head at the ENEA Frascati National Labs. He leads a group of 20 professionals and 10 technicians and holds responsibilities at international level in the design and manufacturing of superconducting coils and devices, notably for nuclear magnetic fusion applications, applied superconductivity and cryogenics. Her is in charge of collaborations with major international organisations such as the European Fusion Development Agreement (EFDA), the ITER project and CERN. He is either leading author or co-author of more than 50 scientific articles and papers on international journals. He also serves as a referee for relevant international publications and papers. He holds a University Degree in Mechanical Engineering.

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Information on ENEA Activities

Processes and Technologies Developed by ENEA (motivation)

■ **New-concept superconductor joints -** ENEA has developed and patented an innovative process to join CICC (Cable-In Conduit Conductor) superconducting cables. Advantages of the new concept are low-space occupancy, low-price and easy manufacturing vs. traditional processes. The new joint has been successfully adopted in the European Fusion Development Agreement (EFDA) DIPOLE superconducting magnet and is being considered for application in superconducting ITER coils. ■ **YBCO Chemical Deposition -** Chemical deposition methods (notably, MOD technique with TFA precursors) are promising low-cost and industrially scalable approaches for YBCO coated conductors. Funded by EFDA, a modified TFA-MOD method is being studied at ENEA to optimize the process and shorten the production time, with unchanged performance.

Demonstration and Experimental Plants and Facilities

■ **ITER Toroidal Field Model Coil (TFMC) -** ENEA has been a major contributor to the toroidal field model coil (TFMC) for the ITER fusion experimental facility. The TFMC was designed, constructed and tested under the EFDA leadership, in close collaboration with major European superconductivity R&D labs and industry. the TFMC test campaign has confirmed that design and manufacturing process for the ITER TF coils are robust and reliable. The manufacture of these large-size coils using a Nb_3Sn CIC superconductor has been challenging. Many new techniques have been developed to solve technical hurdles according to the ITER design guidelines. ■ **Test Facility for HTS current leads -** ENEA has developed and built a facility for the cryogenic test of HTS current leads to be integrated in the world's largest particle accelerator, the Large Hadron Collider at CERN. These devices are needed to connect the power supplies at room temperature to the SC magnets at 1.9K. Equipped with a suitable data acquisition system, the facility has been designed for the scientific experiment, but it is suitable for industrial-scale tests. A large number (> 300) of components can be tested in a relatively short period.

R&D Objectives and Results (achieved and expected)

■ **R&D on full size conductors for fusion** - Since 20 years, the ENEA Superconductivity Lab is involved in the electro-magnetic and structural characterization of SC wires, sub-cables and films, in the design and manufacturing of superconducting CIC conductors and coils, in designing and testing the ITER model coils (TFMC and CSMC), with participation in all R&D programmes for the ITER magnets (CSMC, TFMC, PF-FSJS and PFCI, TFPRO, etc.), and in basic research on HTS coated conductors and coils. ■ **ENFASI Test Facility -** A new ENEA FAcility for Superconducting Inserts (ENFASI) located at the ENEA Frascati Labs, has been proposed for European financial support in the context of ESFRI Roadmap 2008. In Europe, existing high-field (>12 T) magnetic facilities may test only small samples. The ENFASI project enables testing of large SC conductors and coils, as required for emerging technologies and applications. ■ **SC Power Unit –** A HTS-based superconducting power unit for wind power applications is under investigation. Candidate HTS materials are MgB_2 or last-generation YBCO coated conductors. ■ **YBCO coil -** A YBCO model coil, working at 65-77K is being designed and realized to investigate YBCO performance in view of its application for next-generation fusion magnets.

Human Resources and Budget

18 professionals and 9 technicians working LTS and HTS basic R&D and technologies in varied application fields.

Collaborations and External Funding

ENEA is founder member of the Italian Consortium for Applied Superconductivity (ICAS) between ENEA and industrial partners to promote power application of superconductivity and technology transfer to national industry. The ENEA Superconductivity Lab is also actively participating in the design and construction of the toroidal field coils of the Japanese fusion tokamak JT-60SA, in the context of the international collaboration on fusion between Japan and Europe (Broader Approach). Other major R&D and industrial collaborations include the ITER project; the European organization Fusion for Energy; CERN; ASG Superconductors; Luvata; Criotec; CNR Supermat; EDISON, CRIS, the Italian Universities of Torino, Udine, Bologna, Padova, Tor Vergata, Roma 3; the Universities of Cluj (Romania), Twente (the Netherlands), Geneve (Swisse), Houston (Texas) and the IEE Slovak Academy of Sciences.

National and International Patents, Major Publications, Articles, Conference Participations, citations and web-sites

Patents: ■ Brevetto IT2006RM00429 "Procedimento per la Realizzazione di un Giunto tra Cavi Superconduttori di Tipo CICC a Basso Livello di Ingombro, Bassa Resistenza Elettrica e Basso Costo di Realizzazione", ■ Patent EP0966048 - A1 (21/12/1999) "Non-magnetic metallic substrate for high-temperature superconductors and process for manufacture thereof" ■ Patent WO 2004077581 (10/09/2004) "Method for depositing a film of superconducting material"

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