High critical current nanocomposite $\text{REBa}_2\text{Cu}_3\text{O}_7$ (RE=Rare Earth) tapes: towards a new era of ultra-high field magnetism

Xavier Obradors

Institut de Ciència de Materials de Barcelona, CSIC

Center of Excellence “Severo Ochoa”

Campus Universitat Autònoma de Barcelona, 08193 Bellaterra, Catalonia , Spain

The discovery of high temperature superconductors (HTS) in cuprate oxides more than 30 years ago opened an unprecedented scientific challenge with huge potential for transforming in a reality two dreams of Kamerlingh Onnes: to transmit electricity without losses and generate huge magnetic fields. Transforming this potential in a reality, however, required revolutions in Materials Science. To make useful the HTS in power applications or in high field magnetism one needs to achieve high critical current conductors and transforming brittle ceramic materials, as the HTS cuprates, in practical conductors: a huge challenge. Even worst, the brittle ceramics should be manufactured in km lengths having, additionally, uniaxial or biaxial texture to minimize the deleterious effects of the grain boundaries! This had never been done before in any material!

Achieving practical ways of uniaxial texture development was quite soon achieved through thermomechanical treatments and this lead to the first generation (1G) of HTS conductors (Bi2212 and Bi2223 tapes) [1]. Although these 1G conductors helped to advance in the development of the Onnes’ dreams, the performances achieved were not attractive enough. A second generation (2G) of conductors was required and they were indeed discovered based on the HTS phase with the lowest anisotropy and the most promising performances: $\text{REBa}_2\text{Cu}_3\text{O}_7$, with RE=Rare Earth (REBCO). The “miracle” was to define tricks allowing to grow REBCO epitaxial layers on top of metallic substrates: the coated conductor (CC) was born [1, 2]. This discovery was a quantum leap in approaching the Onnes’s dreams and it has become the strongest driving force to create a HTS industry. For several power applications (cable, fault current limiter) the CCs have already the required performances and market penetration is essentially a matter of reducing the ratio €/kA m, i.e. the cost of producing 1 m of CC divided by the maximum current it can carry without dissipation.

High field magnetism, the second Onnes’s dream was another issue! In the sixties of the 20th century the superconductivity industry appeared associated to the first superconducting magnets made available with the discovery of hard superconducting wires, i.e. Low Temperature Superconductors (LTS), such as NbTi and Nb_3Sn . It was actually the birth of a new era of high field magnetism and science and technology has widely benefited since then of these magnets: Medicine (MRI), Chemistry (NMR), High Energy Physics (HEP), Fusion, Condensed Matter Physics, are scientific disciplines which would be completely different without such LTS materials.

Now HTS discovery could open a new era of high and ultra-high magnetism, a second quantum leap in the Onnes's dream. The high magnetic fields achieved with LTS using the elusive liquid He would be now easily generated with liquid N₂ or cryocoolers. Additionally, ultra-high fields (UHF) would now become accessible cooling with liquid He [1, 2].

Again, however, a revolution in Materials Science was necessary to materialize such dream. Here the challenge was to generate REBCO CCs having a high density of artificial pinning centers (APC), for instance non-superconducting phases such as BaZrO₃ (BZO) with nanometric dimensions, i.e. in the range of the coherence length of HTS [3 - 5]. It was necessary to implement nanotechnological solutions at km lengths, something never made before!

In Nanoelectronics the "Top-down" manufacturing approaches are the rule (nanolithography for instance) at the cm scale of the devices. It was clear that these costly technologies could not be afforded in HTS CCs manufacturing. The alternative was a lower cost "Bottom-up" manufacturing approach (eventually leading to self-assembly) but this was only made a reality at cm lengths up to now. Could we imagine that it could become feasible at the required industrial scale? Intensive HTS R&D at the laboratory and industrial scales in recent years have demonstrated that nanocomposite materials can be indeed prepared in km lengths [6]. These advances are a giant step, not only initiating a new era of UHF magnetism, they also reinforce the idea that large scale nanotechnological applications are manageable. As a major demonstration of the opening to this new era of UHF magnetism, we should mention the 32.5 T all-superconducting magnet recently demonstrated at NHFML in Tallahassee, a technological achievement already pointing towards a new world record for continuous field magnet (45 T at present) [7].

The article in this issue by Majkic et al [8] reports the confirmation of the excellent performances (engineering critical current density at high magnetic fields and liquid He temperature) which can be achieved with CCs prepared by Metal Organic Chemical Vapor Deposition (MOCVD). During recent years a parallel development of advanced approaches in MOCVD, Pulsed Laser Deposition (PLD) and Chemical Solution Deposition (CSD) manufacturing have consolidated the availability of high quality CCs. The total REBCO film thickness has been continuously increasing, the control of the APCs landscape has been mastered and the thickness of the metallic substrates has been reduced [1, 2, 6, 8]. The best vortex pinning performances are achieved up to now with film deposition methods where the two phases of the nanocomposite (REBCO and APC) are simultaneously deposited and grown (PLD and MOCVD). This approach leads to self-assembled BZO nanorods within the YBCO matrix and a strong vortex pinning enhancement which was carefully tuned through thorough analysis of the structure at atomic scale [3 - 5]. Now the group of the University of Houston has demonstrated in short nanocomposite REBCO CC tapes (30 cm) the highest engineering critical current density J_e achieved so far, i.e. J_e values 5 times larger than Nb₃Sn or Bi2212 round wires [9] at 4.2 K and 14 T, even when the magnetic field is applied perpendicular to the REBCO CC tape. This new advance is perfectly well baked by several industrial producers of nanocomposite CCs (Bruker HTS, Superpower Inc and others) with close performances in long lengths (> 600 m) [6, 10]. The new achieved

world record J_c is twice higher than the best values reported so far in CCs and five times higher than the commercial values for CCs. The key advancement of this CC arises from an improved processing MOCVD approach allowing to increase the film thickness up to 4.6 μm while the BZO nanorods keep the structural coherence across the whole film. This achievement will certainly stimulate further advancements in other competing CC and wire developments and so the future availability of magnets in the range of 25 - 30 T appears closer in the horizon.

There's no doubt that the new era of UHF magnetism opens a very promising prospective for a broad elenchus of new scientific discoveries. For instance, the most challenging accelerator project in HEP (Future Circular Collider) and the next generation of fusion reactor beyond ITER are planning to use UHF-HTS magnets. Even more, it is unpredictable how far the scientific knowledge will advance in Condensed Matter Physics, Nanotechnology or Chemistry, for instance, but we are deeply convinced that such new powerful magnets will enable to make drastic advances in the comprehension of complex matter at the atomic and molecular scale.

References

- [1] Larbalestier D C et al 2011 High- T_c superconducting materials for electric power applications *Nature* **414** 368
- [2] Obradors X and Puig T 2014 Coated conductors for power applications: materials challenges *Supercond. Sci. Technol.* **27** 044003
- [3] Foltyn RF et al 2007 Materials science challenges for high-temperature superconducting wire *Nat. Mater.* **6** 631
- [4] Obradors X, Puig T, Palau A, Pomar A, Sandiumenge F, Mele P and Matsumoto K 2011 Nanostructured Superconductors with Efficient Vortex Pinning in “*Comprehensive Nanoscience and Technology*”, Vol. 3, eds Andrews DL, Scholes G and Wiederrecht G (Oxford: Academic Press) p 303
- [5] Matsumoto K and Mele P 2010 Artificial pinning center technology to enhance vortex pinning in YBCO coated conductors *Supercond. Sci. Technol.* **23** 014001
- [6] Usoskin A et al 2018 Double-disordered HTS-coated conductors and their assemblies aimed for ultra-high fields: large area tapes *IEEE Trans. Appl. Supercond.* **28** 6602506
- [7] Weijers HW et al 2016 Progress in the Development and Construction of a 32-T Superconducting Magnet *IEEE Trans. Appl. Supercond.* **26** 4300807;
<https://nationalmaglab.org/news-events/news/mini-magnet-packs-world-record-punch;>
- [8] Majkic G et al 2018 Engineering current density over 5 kA/mm^2 at 4.2 K, 14 T in thick film REBCO tapes *Supercond. Sci. Technol.*
- [9] Larbalestier D C et al 2014 Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T *Nat. Mater.* **13** 375

[10] Senatore et al 2014 Progresses and challenges in the development of high-field solenoidal magnets based on RE123 coated conductors *Supercond. Sci. Technol.* **27** 103001