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Viewpoint

High critical current nanocomposite $REBa_2Cu_3O_7$ (RE = rare earth) tapes: towards a new era of ultra-high field magnetism

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This is a viewpoint on the letter by G Majkic *et al* (2018 *Supercond. Sci. Technol.* **31** 10LT01).

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

Achieving practical ways of uniaxial texture development was achieved relatively quickly 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 the development of Kamerlingh Onnes' dreams, the performances achieved were not attractive enough. A second generation of conductors was required and they were indeed discovered based on the HTS phase with the lowest anisotropy and the most promising performance: $REBa_2Cu_3O_7$ (REBCO), where RE = rare earth. The 'miracle' advancement was to define tricks allowing REBCO epitaxial layers to grow on top of metallic substrates: the coated conductor (CC) was born [1, 2]. This discovery was a quantum leap in approaching Kamerlingh Onnes's dreams and it has become the strongest driving force in creating an HTS industry. For several power applications (e.g. cables, fault current limiters), CCs already have the required performance and market penetration, and it is now essentially a matter of reducing the € kA^{-1} m^{-1} ratio, 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 of Kamerlingh Onnes' dreams, was another issue! In the 1960s the superconductivity industry was associated with 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 from these magnets. Medicine (MRI), chemistry (NMR), high energy physics (HEP), fusion and 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 Kamerlingh Onnes' dream. The high magnetic fields achieved with LTS using the elusive liquid He could now be easily generated with liquid N_2 or cryocoolers. Additionally, ultra-high fields (UHF) would now become accessible through cooling with liquid He [1, 2].

Again, however, a revolution in materials science was necessary to materialize such a 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 $BaZrO_3$ (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 kilometer lengths, something never made before!

In nanoelectronics 'top-down' manufacturing approaches are the rule (nanolithography for instance) at the centimeter scale of devices. It was clear that these costly technologies could not be afforded in HTS CC manufacturing. The alternative was a lower cost 'bottom-up' manufacturing approach (eventually leading to self-assembly) but up to now this has only been made a reality at centimeter lengths. Could we imagine that it could become feasible at the required industrial scale? Intensive HTS research and development at the laboratory and industrial scales in recent years have demonstrated that nanocomposite materials can be indeed prepared in kilometer lengths [6]. These advances are a giant step, not only initiating a new era of UHF magnetism, but also reinforcing the idea that large scale nanotechnological applications are manageable. As a major demonstration of the opening of this new era of UHF magnetism, we should mention the 32.5 T all-superconducting magnet recently demonstrated at the National High Magnetic Field Laboratory in Tallahassee, Florida, a technological achievement already pointing towards a new world record for a continuous field magnet (45 T at present) [7].

The letter 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 manufacturing have consolidated the availability of high quality CCs. The total REBCO film thickness has been continuously increasing, the control of the APC 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 at present 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 at 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 five times larger than Nb_3Sn 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 matched 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_e is twice as high as 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 MOCVD processing approach allowing the increase of 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 CCs and wire developments and so the future availability of magnets in the range of 25–30 T appears closer on the horizon.

There is no doubt that the new era of UHF magnetism opens a very promising prospective for a broad range of new scientific discoveries. For instance, the most challenging accelerator project in HEP (the Future Circular Collider) and the next generation of fusion reactors beyond ITER are planning to use UHF-HTS magnets. Even more so, 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 far-reaching advances in the comprehension of complex matter at the atomic and molecular scale to be made.

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