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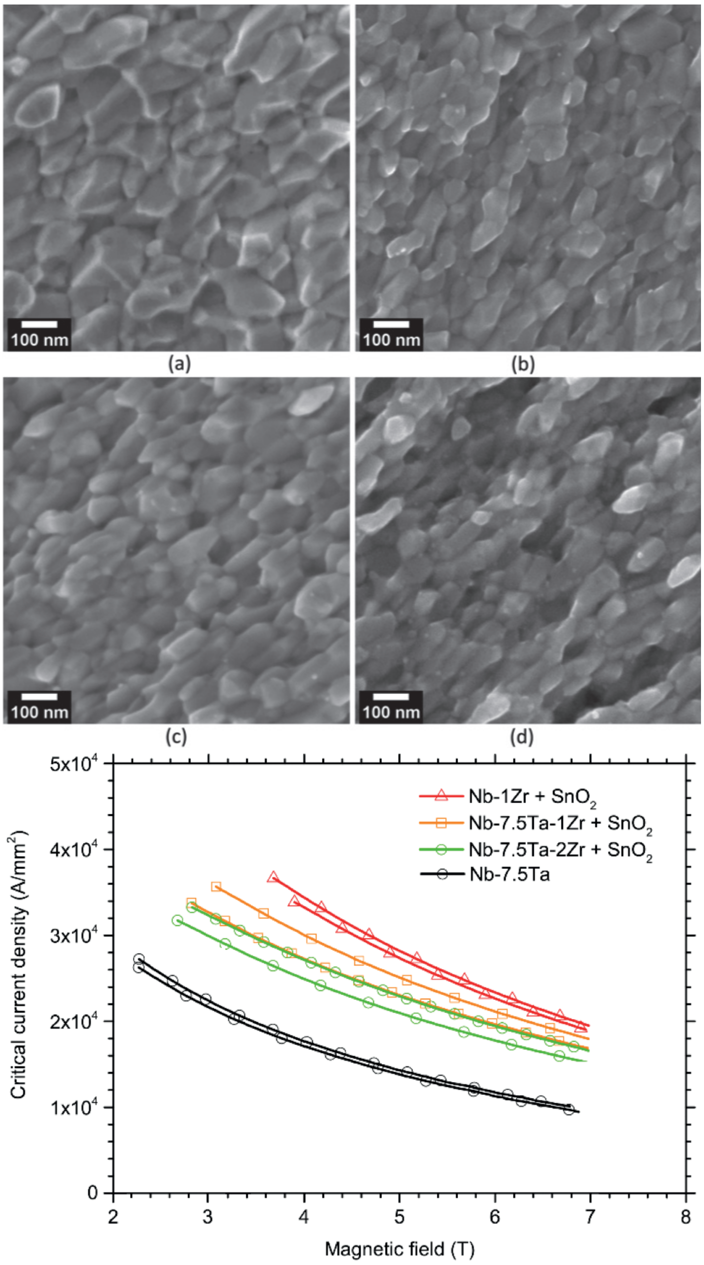
The search for new physics beyond the Standard Model is driving the High Energy Physics (HEP) community to conceive novel experiments based on a highest-energy hadron collider with a centre-of-mass collision energy of 100 TeV [1]. One of the main challenges in view of this Future Circular Collider (FCC) is the development of high-field superconducting accelerator magnets. Assuming a ring circumference of 100 km, the dipole field needed to reach 100 TeV must be about 16 T (the energy at the collision is given by E[TeV] = $3 \cdot 10^{-4} \cdot B \cdot R$, where B is the intensity of the magnetic field and R is the radius of the ring, both in SI units). Such a field level is about twice that of the Nb-Ti magnets installed in the Large Hadron Collider (LHC), which represent the end-of-the-line in terms of performance of accelerator magnets based on this material. Nb_3Sn is the superconducting material poised to take the place of Nb-Ti as the next step in accelerator magnet technology. High temperature superconductors (HTS) also have promising properties, with high in-field critical current density that indicate the potential for 20 T-range accelerator magnets. However, FCC would require superconducting materials in massive quantities, an estimate of 10000 tons in a time frame of 30 years. Even if we extrapolate with optimism the present industrial capabilities of about 1 ton/year, HTS cannot represent a credible option. Over the last two decades, high-field Nb_3Sn magnet technology has made great progresses thanks to the ITER conductor development [2] and various R&D programs funded by the European Commission and the US Department of Energy [3,4]. The first milestone for Nb_3Sn applications in HEP research programs will be achieved with the installation of the Nb_3Sn dipole and quadrupole magnets built for the High-Luminosity upgrade of the LHC (HL-LHC) at CERN [5]. These will be the first Nb_3Sn magnets ever operating in a particle accelerator and thus represent an important test bench in the perspective of the FCC developments.

A field of 16 T in a dipole configuration translates into a requirement of a minimum critical current density, J_c, of more than 1500 A/mm^2 at 16 T and 4.2 K [6], which is a target currently beyond state-of-the-art for commercial Nb_3Sn wires [7,8]. The work reported here is motivated by the need to push Nb_3Sn technology towards its ultimate performance in view of achieving and exceeding the requirements of the FCC study. The in-field critical current capabilities for any type-II superconductor rely on its ability to impede vortex motion, i.e. to pin the vortex lines into the material. This ability is given by the presence of the so-called pinning centers, features in the material that interact attractively with individual vortices. Grain boundaries represent the primary pinning centers in Nb_3Sn: higher current densities are thus obtained in materials that have finer grains. In the present day high-performance wires, Nb_3Sn has average grain sizes of typically 100 - 200 nm [9,10]. The Group of Applied Superconductivity at UNIGE is working in close collaboration



Top: SEM images of Nb_3Sn grains at fractured surfaces from samples based on (a) Nb-7.5Ta (reference), (b) Nb-1Zr+SnO_2, (c) Nb-7.5Ta-1Zr+SnO_2 and (d) Nb-7.5Ta-2Zr+SnO_2. The refinement of the grain size in the samples containing Zr is evident.
Bottom: Enhancement of the critical current densities (at 4.2 K) of samples based on Nb-Zr and Nb-Ta-Zr with an oxygen source compared to reference samples based on Nb-7.5Ta without an oxygen source.

with CERN to the development of methods for refining the grain size of Nb_3Sn with processes scalable to the industrial production of wires. The inhibition of the grain growth in the presence of oxide nanoparticles and, in particular, the so-called internal oxidation method [11] appear to be the most promising avenues. The key ingredient for the internal oxidation is the use as a precursor of Nb-alloys containing a small percentage of Zr. The composite wires prepared at UNIGE, made of Nb-alloy, Sn and Cu, contain also a core of powdered metal oxide (SnO_2 or CuO). During the heat treatment the metal powder is reduced and oxygen diffuses into the Nb-alloy where it oxidizes the highly reactive Zr. For this to work, the Gibbs free energy of formation of the metal oxide that acts as an oxygen source needs to be higher than those of ZrO_2. As a result, very fine particles of ZrO_2 are formed that inhibit the growth of the Nb_3Sn during the reaction of Nb with Sn. Custom Nb-alloys containing Zr and Ta were produced and tested to combine the increase in the critical current density because of the reduced grain growth to high upper critical fields because of the presence of Ta, which is a well-known dopant for increasing B_{c2}. The results are summarized in the figure. The internal oxidation of Zr led to a finer grain structure, the lowest average grain sizes being close to 50 nm, and superior critical current densities. Moreover, the combined presence of Ta and Zr led also to a record value of 29.2 T at 4.2 K for the upper critical field [12]. The transfer of the present results to prototype multifilamentary wire is ongoing.

This activity is part of the CHART initiative. Since 2015, CHART, which stands for “Swiss Accelerator Research & Technology”, has been bringing together the Swiss leading forces in the R&D of superconductor technology for accelerators under the auspices of the State Secretariat for Education, Research and Innovation (SERI). This interdisciplinary collaboration includes researchers from the Paul Scherrer Institute (PSI), the two Federal Institutes of Technology in Zurich and Lausanne, the University of Geneva and, of course, CERN, and one of its main goals is the design, construction and test of a 16 T dipole prototype.

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