Toward FCC-hh and future colliders:
Exploration of high field magnet technology at CEA-Paris Saclay

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Nb_3Sn magnets are the cornerstone of the HL-LHC upgrade and the reliable performance of Nb_3sn high field dipoles will be the prerequisite for the construction of a 100 TeV collider such as FCC-hh. Despite the major progress made in preparation of HL-LHC, our community knows that a structured effort is still required to go from the implementation of a few Nb_3Sn magnets in HL-LHC to several thousands of them in FCC-hh. Whereas Nb_3Sn stays the most relevant route to achieve the 16 T frontier, some questions need to be addressed going from conductor characterization, to magnet design aspects and operation of these magnets. Here are some examples of key topics to pursue and/or address for upcoming designs:

1. Integrated Modeling aiming at conciliating topical simulation (quench, mechanical) as well as multiscale approach
2. Electrical, thermal and mechanical conductor characterization: from strand to coil samples
3. Technological development to ensure conductor integrity during coil fabrication
4. Technological development on insulation system for electrical integrity
5. Understanding of trade-off between conductor volume optimization and mechanical stress level
6. Accounting for I_c reduction due to stress at the magnet design stage
7. Accounting for mechanical stresses developed during a quench
8. Development of graded technology (coil fabrication, Nb_3Sn-Nb_3Sn joints…)
9. Development of reliable, series-oriented coil fabrication process and support structure
10. Understanding of training sources and explore solution to reduce it (innovative magnet design, improved impregnation system…)
11. Technological development of quench detection techniques and protection system
12. Development of diagnostics techniques from magnet assembly to operation

Addressing these numerous challenges requires strong synergy between European and International labs and call for a well-defined strategy. Coordination has to be improved to maximize the chance to master all relevant technologies for FCC-hh. Along this line, it is of paramount importance to discuss the key challenges and results on Nb_3Sn accelerator magnets at the technical and scientific level. Since 2017, a workshop dedicated to Nb_3Sn magnet technology is organized regularly by CERN and CEA Paris Saclay [1-2]. All technology aspects are discussed. The role of this workshop should be pushed forward to strengthen collaboration between laboratories.

From a design stand point, with FCC-hh as an objective, the EuroCircol design study [3] led by CERN and associating various European labs including CEA Paris-Saclay has been completed. This study was looking at various configurations to achieve 16 T in a double 50 mm aperture magnet. Graded compact efficient magnet cross-sections have been proposed. CEA was in charge of the study of the block option [4]. Based on this design and within a bilateral collaboration agreement between CEA and CERN, CEA is contributing specifically to item #8 by being responsible for the development of a single aperture demonstrator [5].

This long term goal (~8 years) is built upon a step-by-step strategy starting with a first model called Research Racetrack Dipole Development. This magnet is composed of two racetrack coils assembled in a shell-based support structure (aka bladders and keys structure). The main objective of this magnet is to be a test bed for grading technology. In order to minimize the amount of conductor used in this technology demonstrator, a single layer layout has been chosen. Several challenges have to be faced. Some of them concern the possible dimensional changes of the two different cables and the support of the conductor leads exiting the coil since the joint between the two grades of cable are made outside. The definition of a clear development plan through mock-ups and characterization is required to ensure success of this demonstrator. A PhD thesis was launched in 2019 to understand the behavior of the Nb_3Sn during its heat treatment, as well as the associated dimensional changes, in order to include this constraint during the early stage of a magnet design [6, 7].
As mentioned above, it is also important to develop numerical approaches to support magnet construction and understand performance. As a contribution to item #1, CEA Paris-Saclay has been working on a multi-scale model combined with experimental characterization [8]. This thorough and detailed work needs time to bloom but appears essential to our deep understanding of Nb_3Sn magnet behavior.

Beyond Nb_3Sn, the use of HTS is the other key challenge of our community. Muon colliders or 150 TeV FCC-hh require very high field magnets (> 20 T) for which HTS conductors are necessary.
CEA Paris-Saclay has a long history of HTS magnet development: from HTS inserts for accelerator technology to insert for high magnetic field application.
In the framework of the European Coordination for Accelerator Research and Development (EUCARD) and EUCARD-2, CEA Paris-Saclay is contributing to the development of small magnets or inserts. These models allow the definition of the fabrication process and the exploration of practical difficulties related to HTS conductor. As of today, the EUCARD insert reached 5.4 T at 4.4 K [9] and the Eucard2 cosθ aiming at producing 5 T in a 40 mm aperture is under assembly before test in stand-alone configuration [10].
In addition to the development of reliable coil fabrication technology, it is well known that the use of HTS will lie first in our ability to protect and operate HTS coils safely. The limited quench propagation velocity leads to possible coil destruction. As part of the quest toward very high magnetic field, and in order to alleviate the protection issue, CEA Paris-Saclay has been investigating innovative winding techniques such as Non Insulation (NI) and Metal-as-Insulation (MI) techniques demonstrating "built-in" self-protection features. Recent results [11] obtained in collaboration with LNCMI in Grenoble, France show promising results and encourage pursuit of this R&D effort.
Besides the protection question, as another example of challenges to face, we know that HTS conductor such as REBCO tape develop large screening currents when subjected to orthogonal magnetic field, causing problematic magnetic field distortion and reducing main field. CEA Paris-Saclay has led some research to investigate techniques aiming at reducing the effects of screening current induced fields [12]. Efforts need to be sustained in that direction to ensure satisfying performance in accelerator application.

Overall, challenges on both Nb_3Sn and HTS implementation are wide. Reinforced synergy between European and International laboratories as well as information exchange between various application fields remains necessary for the development of reliable, accelerator ready high field magnets.

References

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