Numerical Modeling for Superconducting Accelerator Magnets

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Advanced modeling tools are currently utilized across the full range of US Magnet Development Program (US-MDP) research activities [1], enabling the design of improved conductors, magnets, and diagnostics. A diverse and challenging set of new modeling tools are required to continue this effort and ultimately improve design time, cost, and performance of future superconducting accelerator magnets. This new development focuses on: (1) simulation of conductor and cable, (2) advanced modeling of interfaces and other potential sources of training in stress-managed designs, (3) modeling of LTS/HTS hybrid magnets, and (4) radiation environment thermal effects on magnets.

1. Simulation of Conductor and Cables

Despite many challenges, several low-field prototype accelerator magnets made from REBCO and Bi-2212 high-temperature superconductor (HTS) were recently built and successfully tested [2-4]. Cabling of the HTS conductor is important for accelerator applications in order to enable high current operation and current sharing around conductor defects. For REBCO cables, improved modeling of steady-state and dynamic current distribution between tapes (current sharing) is critical to further optimize the many different cable geometries being considered. Initial numerical and experimental studies on short REBCO cable lengths are on-going, and largely employ equivalent circuit models. FEM models have also been developed, requiring considerable computational resources. There is a strong need for a "toolbox" of codes, benchmarked by experiment, capable of simulating HTS conductor and cables over a range of required complexity. This will allow for quick, exploratory simulations with broad assumptions, followed by computationally heavy, but more accurate simulations of design points. The challenging non-linearity of HTS, typically modeled using the E-J power law, gives strong motivation to explore the development of codes which leverage HPC resources and/or advanced techniques such as adaptive meshing, domain decomposition, and un-fitted finite elements methods.

The study of Nb_3Sn and/or Bi-2212 Rutherford-type cable manufacturing is a challenging problem in physics and mechanical engineering. The cabling process includes steps of high plastic deformation in order to produce the necessary cable compaction and mechanical stability. Since the strands that compose the cable are initially made of elements (Nb, Sn and Cu for Nb3Sn, and Bi-powder precursor and Ag for Bi-2212) with very different mechanical properties, the problem is one of plastic deformation analysis of a composite material. The purpose of FEM mechanical analyses, coupled to experiments, is to identify upper limits to plastic deformation to avoid irreversible damage, and to understand the influence of the various geometrical parameters in the process [5, 6]. To test the applicability of composite wires to cable fabrication, Nb-Sn wires are flat-rolled to increasing deformations to systematically study such dependence of their properties. FEMs that simulate this mechanical process are used as an aid in designing the wire architecture [7]. Thermal FEM modeling can also be used to optimize wire architecture. The minimum quench energy of Nb_3Sn wires with high specific heat elements was modeled [8] to optimize the location of these special subelements. The same should be done for Bi-2212 conductor. Finally, meso-mechanical FEM models are needed to provide information on local stress and strain states in composite materials [9].

2. Modeling Interfaces in Stress-Managed Designs

HTS and Nb_3Sn conductors considered for high field (>10 T) magnets are strain-sensitive. One promising route to overcoming the strain limits of these materials at high fields is the introduction of mechanical support within the coil itself to prevent accumulation of stress from Lorentz force. Canted-Cosine-Theta (CCT), the Stress-Managed Cosine-Theta (SMCT) and COMB magnet designs utilize this technique [10-12]. As a result of introducing structure in the windings, an increased number of mechanical interfaces exist between the conductor and support structure. De-bonding of these interfaces releases energy and is a potential source of quench training for stress-managed magnets. Early FEM of shear stress at interfaces and experimental results from the CCT program show evidence of this behavior.

Development and application of advanced mechanical interface modeling tools is important to guide design choices within the stress-managed programs and also for interpreting test results. Primarily, implementation of cohesive zone elements or other advanced contact behavior into finite element models can help to determine locations of de-bonding, energy release, and stress-redistribution [13]. Correlation of this modeling with experimental results, especially from CCT subscale program tests designed to probe limits of this behavior, will allow for improved understanding of how interface behavior in stress-managed designs impact training. Ideally, this allows for improved stress-managed magnets through "interface by design", and guide technology development in epoxies and impregnation techniques with the goal of providing feedback on magnet fabrication.

3. Modeling of LTS/HTS Hybrid Magnets

Dynamic simulation of superconducting magnets is critical for the design of protection systems to prevent potentially damaging temperatures and high voltage from developing after magnet quench. Accurate modeling of quench, moreover, enables less conservative magnet designs, reducing development efforts and costs. Modeling these scenarios is challenging due to the many multiscale, multiphysics phenomena which impact magnet behavior. Several different codes, both commercial and in-house, have been developed for these multiphysics problems, and primarily utilized to design quench protection for low-temperature superconducting (LTS) systems [14-17].

Many of these modeling challenges are exacerbated when both HTS and LTS superconducting materials are used in the same magnet [18]. This "hybrid" approach is considered for 15 T + magnet designs where the current carrying capability of HTS at high fields is utilized for the inner-most winding layers. Hybrid magnets are being designed considering HTS and LTS coils as powered in series in a single structure, or considering the HTS coil a removable insert of a larger aperture LTS magnet. To design quench protection for these magnets, a new framework is desired which integrates the relevant HTS behavior with the multiphysics approaches developed for LTS, and which is able to account for magnetic coupling of HTS inserts in LTS magnets. This code would be capable of capturing the different aspects of HTS, including: strong conductor magnetization (likely through use of an E-J power law), anisotropic critical current, large aspect ratio conductors (i.e. tapes), and current sharing within HTS cables. The time dependent, multiphysics nature of these simulations make them already computationally challenging for LTS magnets. With this in mind, it is clear that new modeling frameworks for hybrid magnets should be compatible with efficient use of HPC resources.

4. Modeling of the Radiation Environments and the Associated Thermal Effects on Magnets

The steadily raising bending fields and collision energies of future machines lead to the increased synchrotron radiation load on the ring magnets [19] and the increased radiation load from the collision debris on the IR magnets [20], which lead to degradation of insulation and reduction of the magnet thermal margins. In addition, the renewed interest to muon colliders brings up a whole new set of radiation problems from muons and its decay products, which may require unconventional design approaches, like open-midplane magnets [21]. It is important to continue the development and improvement of the radiation modelling methods and tools along with the thermal modeling of the magnets under the radiation loads to meet the requirements of the new machines [22-23].

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