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Multiphysics modeling of superconducting cables for application in nuclear fusion

By

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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Abstract

The recent concept of compact fusion reactors has catalyzed a paradigm shift in the large-scale applications of high-temperature superconductors (HTS), creating fresh prospects for innovation. However, this accelerated progress has also introduced a spectrum of complex challenges, ranging from the degradation of material properties due to intense neutron and secondary particle fluxes to intricate engineering constraints in magnet design and long-term reliability. Addressing these issues necessitates a profound comprehension of the structural, thermal, and magnetic behavior of superconductors under fusion-relevant conditions, where both multiphysics and multiscale effects play a fundamental role.

In light of this, the present dissertation is dedicated to the in-depth modeling of (primarily) second-generation high-temperature superconductors (2G HTS), with a particular emphasis on their structural integrity, thermo-magnetic thresholds, and overall resilience in irradiation-rich environments. Given the inherently multiscale nature of the problem, an appropriate selection of computational strategies - including a hierarchical modeling approach, cross-platform software synergy, and systematically derived variational methods - is imperative. In parallel, employing well-suited approximations, such as thin-shell techniques or homogenized representations, ensures an accurate depiction of superconducting material responses. These methodologies are essential in high-dimensional simulations, where computational feasibility must be balanced with physical accuracy. The multiscale approach is leveraged not only to optimize numerical efficiency but also to establish a direct link between microscopic physical mechanisms - spanning diverse spatial and temporal scales - and macroscopic observables. Simultaneously, the multiphysics perspective facilitates an independent yet interrelated examination of superconducting and thermal properties, elucidating their temperature-dependent behavior and their mutual interactions under realistic operational conditions.

All computational results presented here have been obtained using the commercial software COMSOL Multiphysics®, a versatile environment that enables smooth coordination between built-in modules and user-defined equations while maintaining interoperability with external simulation environments. Within this modeling paradigm, Finite Element Method (FEM) serves as a robust computational framework for capturing the nonlinear and nonlocal behavior of superconductors across a wide array of conditions, providing critical insights into their response to external perturbations. With these considerations in mind, the core of this work is structured around four key research objectives:

- Characterizing and quantifying the influence of engineered and unintended structural features on the current-carrying performance and electromagnetic response of HTS materials. The analysis is designed to accelerate the experimental characterization process by leveraging high-fidelity numerical simulations. By utilizing a constrained set of experimental data, primarily derived from magneto-optical imaging (MOI), these simulations enable the precise calibration of constitutive material laws while expediting the optimization of operational parameters. This approach enhances the design and refinement of 2G HTS tapes for fusion magnet applications, streamlining the pathway toward material performance improvement.
- Assessing the impact of local ion-beam heating on experimentally observed variations in the critical current density, J_c. Unlike neutrons, which primarily induce radiation damage via hard-sphere collisions with atomic nuclei, ions engage in Coulomb interactions with both nuclei and electrons. Notably, $\sim$ MeV ions predominantly transfer energy to atomic electrons, inducing significant localized heating via ionization. To quantify these effects, experimental observations are supplemented with high-resolution thermal simulations of the irradiation process at the tape scale. The model captures the thermal response across fine spatial (nm–μm) and temporal (fs–ms) scales following individual charged particle impacts. To extend the analysis toward macroscopic steady-state behavior, repeated impacts are simulated at randomized locations on the tape, finally followed by the incorporation of a spatially and temporally averaged model. This methodology transcends conventional steady-state approaches, offering deeper insight into local energy deposition dynamics and rapid thermal transients.

- Expanding the analysis to a more application-relevant scenario by examining the cryostability of superconducting cables. This investigation assesses the cable capacity to dissipate excess heat while retaining its superconducting characteristics under the combined influence of primary and secondary particle-induced damage, heating, and electromagnetic self-field interactions during routine operation. The study begins with an unshielded configuration to pinpoint critical weaknesses, and subsequently guiding the design of a more resilient system.

- Exploring the feasibility of superconducting technologies for neutron detection in nuclear security applications. Starting from a proof-of-concept configuration, this research proposes an optimization strategy to enhance detector performance, evolving from discrete particle detection to continuous neutron flux monitoring. Taking advantage of the unique electromagnetic properties of superconducting materials, the study aims to refine detection sensitivity and resolution, ultimately contributing to the development of advanced, real-time neutron sensors.

Beyond presenting an extensive analysis of the thermomagnetic behavior of HTS materials under intense radiation exposure, this dissertation offers crucial insights into the operational constraints and failure mechanisms of superconductors in compact fusion systems. Furthermore, it provides a systematic approach to the effective application of FEM-based simulations, ensuring precise and computationally efficient modeling tailored to specific engineering challenges.