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Wed-Af-Po.07-07: Transient finite element simulation of superconducting accelerator magnets using thermal thin shell approximation

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The design and operation of superconducting accelerator magnets necessitate accurate knowledge of thermal conditions to ensure their stability and performance. During the operation of these magnets, quench events can lead to complex thermal transients. Their analysis is commonly supported by detailed simulations, for which the finite element (FE) method can be used. The FE method offers robust capabilities for modelling the intricate geometries and material properties of superconducting magnets. However, accelerator magnet geometries can consist of superconducting cables with a high ratio of bare conductor thickness to electric insulation thickness. The thermal gradients across these thin insulation layers must be resolved accurately to ensure the overall validity of the simulation, for which high-quality meshes are required. This leads to many degrees of freedom (DoFs) in a classical FE discretization, resulting in significant computational time requirements, particularly since non-linear material properties are involved.

In this work, we propose to use a thermal thin-shell approximation (TSA) to improve the computational efficiency when solving the heat diffusion equation in two dimensions. The TSA collapses thin electrical insulation surfaces into lines while accurately representing the thermal gradient across the insulation thickness, thereby removing the need for a surface mesh of the insulation. Consequently, this approach significantly reduces the number of required DoFs and the computational time. The TSA method enables the implementation of arbitrary multi-layered insulation regions, including internal heat sources, such as quench heaters (QHs). Furthermore, the TSA allows boundary conditions to approximate cryogenic helium cooling via a temperature-dependent heat transfer coefficient.

In this contribution, we apply the TSA method to compute the thermal transient response of superconducting Large Hadron Collider (LHC) and High-Luminosity LHC (HL-LHC) accelerator magnets. First, the method is verified by comparison with classical FE simulations with meshed surface insulation regions for detailed models of the Nb_3Sn HL-LHC MBH and the Short Model Coil (SMC) dipole magnets. The results show that the TSA approach preserves the solution's accuracy while significantly reducing the computational time, thereby rendering it viable for full-size magnet simulation.

Second, the QH delay computed with the TSA method is compared to measurements. To this end, the thermal transient simulation is coupled to a magnetostatic solution to account for magneto-resistive effects. Third, the full capabilities of the TSA are then showcased in non-linear magneto-thermal simulations of several LHC and HL-LHC superconducting magnets.

The TSA is implemented in the multipole module of the free and open-source Finite Element Quench Simulator (FiQuS). FiQuS provides the superconducting magnet community with access to simulations of superconducting magnets, regardless of their level of expertise in modelling and simulation. The software design of FiQuS provides a user interface that separates the coil design, material composition and powering details from the numerical computing aspect. All presented multipole magnet models are generated programmatically from human-readable input text files, which aids in the reproducibility, traceability and parametrization of the simulations. The input files and source code to recreate the results are shared.

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