Hierarchical Co-simulation Interface for the Simulation of Transient Effects in Superconducting Accelerator Circuits

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ABSTRACT

Superconducting high-field magnets are one of the main components of modern high-energy particle accelerators. Due to the considerable energy stored in the magnetic field, a transition of a small cable volume from the normal conducting to the superconducting state, also known as a quench, may result in an uncontrolled release of the energy as Ohmic losses and possibly in catastrophic damage in the magnet and circuit.

To prevent this scenario, a detailed study of electro-thermal transient effects such as quench initiation, propagation, interaction with electrical circuits and their powering control systems, etc., has to be carried out. However, a consistent simulation of those transient effects poses considerable challenges. Firstly, a superconducting magnet model is composed of several coupled physical domains, i.e. electrical, magnetic, thermal, and mechanical, all governed by non-linear equations [1] with highly non-linear material properties. Secondly, the dynamic behavior of the coupled physical domains is characterized by time constants ranging from microseconds (quench initiation) to minutes (current discharge in large superconducting circuits). Thirdly, the transient effects span over a wide range of geometric scales, from sub-millimeter resolution required to track the quench front in a superconducting cable to kilometers-long superconducting circuits with over 100 teen-meter-long magnets.

In this contribution we present the coupling interfaces of the STEAM (Simulation of Transient Effects in Accelerator Magnets) framework. The foundation of the STEAM framework is a set of dedicated models implemented as automated workflows with appropriate commercial solvers [2, 3, 4, 5], namely FEM (Finite Element Method) models for 1D and 2D field problems and network models for electrical circuits and control algorithms. On top of that, there are three coupling interfaces allowing for a cooperative execution of those models. Controller-circuit coupling enables exchanging information between a current controller with voltage as a control signal in an electrical circuit. The field-circuit coupling provides an interface between an electro-thermal FEM model of a magnet and an electrical circuit [6]. Mesh-based coupling allows for the interpolation and exchange of results between FEM models of different mesh [7]. The three interfaces can have multiple instances in a single co-simulation. They are combined together in a hierarchical way and activated based on the transient evolution in the superconducting circuit.

An analysis of the energy flow between coupled physical domains is carried out in order to determine an efficient coupling scheme and communication interval [8, 9]. Hierarchical co-simulation interface of the STEAM framework opens new ways for simulating transient effects in superconducting magnets beyond the capabilities of existing monolithic simulation tools [10, 11, 12]. The presentation will be concluded with results of the STEAM application to the simulation of the quench initiation, propagation and protection in a main bending magnet of the LHC (Large Hadron Collider) [13] as well as a discussion of performance and future developments.

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