



Electromagnetic and Thermal Modeling of High-Performance REBCO Magnets

The performance of High Critical Temperature (HTS) superconducting materials, particularly REBCO, enables the development of exceptional applications such as very high-field magnets. Their use in very large-scale devices, such as fusion machines, is now being considered. The operating conditions of the conductor can be extreme, with average current densities exceeding 1000 A/mm^2 under magnetic fields beyond 20 T. The study of the behavior of these materials and their implementation in applications is supported in France by the PEPR SupraFusion project. This large-scale collaboration brings together all the stakeholders in applied superconductivity (CNRS, CEA, and several universities) and will provide the framework for this thesis.

To enable reliable design of HTS superconducting devices, a detailed understanding of material behavior is essential, which requires the development of appropriate modeling tools. The properties of these materials demand that numerical tools address complex, nonlinear, and multiphysics problems over a wide range of operating temperatures and magnetic fields.

HTS conductors are available in the form of thin layers (a few microns thick) deposited on wide tapes (a few millimeters wide). Representing complete, potentially large-scale applications that use conductors composed of multiple such tapes is a considerable challenge, as the current distribution is highly non-uniform both between tapes and within each individual tape.

A first modeling tool has been developed at G2Elab within the MIPSE platform (MAGE team) to predict and interpret the evolution of current density distribution in windings. This allows for highly precise prediction of voltage evolution as well as the magnetic field produced. This tool is based on an innovative approach: a finite volume method formulation that strongly ensures the conservation of flux and currents, as well as a natural coupling with electrical circuits. Its main advantage is that it requires a lighter mesh compared to the classical finite element method, as only the active regions (i.e., conductive and/or magnetic regions) need to be discretized. Additionally, this approach ensures excellent conservation of electric currents and easily represents the interaction of the device with its power supply circuit. Recent developments have added efficient matrix compression tools, resulting in a considerable gain in efficiency.

The objective of this thesis will be to contribute to the development of modeling tools for superconducting applications within the MIPSE platform, both in 2D axisymmetric and 3D. This thesis will be conducted in close collaboration between researchers working on superconducting applications at G2Elab (MADEA) and the Néel Institute, and researchers working on electromagnetic modeling at G2Elab within the MAGE team.

- **The first objective** will be to couple the existing 2D and 3D electromagnetic models with a thermal model to account for the temperature dependence of the $E(J)$ behavior law and to study its impact on the behavior of conductors and their applications. This will allow for the evaluation of transient losses in REBCO superconducting coils, as well as the study of thermal runaway dynamics when the critical current is locally exceeded (quench phenomenon). The targeted applications range from very compact high-field magnets to multi-tape cables used in very large-scale applications such as fusion magnets. Validations will be carried out in collaboration with other French



(GeePs, Green) or international laboratories developing such tools, as well as through comparison with experimental data obtained within the team on simple cases.

- **The second objective** will be to use these modeling tools to improve the analysis of complex experimental data from the team's parallel experimental characterization activities in Grenoble. The PhD student will participate in measurement campaigns and may propose additional measurements to further validate the models. The models will also be applied to simulate devices developed by PEPR SupraFusion partners, particularly at the CEA for very high-current conductors, as well as in other international collaborations.
- **Finally, an exploration** will be conducted to account for local effects in very large-scale windings using a multi-scale approach: 3D modeling at the conductor scale could allow for the definition of equivalent behavior laws, which can then be applied to macroscopic winding models where the conductor structure is not detailed.

Supervisors : Arnaud Badel, Alexandre Zampa, Brahim Ramdane, Gérard Meunier (director)

Contact : arnaud.badel@neel.cnrs.fr, alexandre.zampa@neel.cnrs.fr

Place of work : G2Elab and Institut Néel, CNRS, rue des Martyrs, Grenoble, France

Salary : 2300 E/month (before tax)