# Development of HPC Multiphysics Framework for HTS Magnets in Fusion

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***Keywords—High Temperature Superconductors, Fusion, Multiphysics, High Performance Computing, Edge Finite Element Method.***

## Extended Abstract

High-Temperature Superconductors (HTS) technology show promise for the next generation of fusion devices based on magnetic confinement, enabling higher magnetic fields and current densities, and thus a reduction of overall sizes and running costs due to lower heat load in the cryogenic system. Nevertheless, the use of HTS materials presents some drawbacks concerning quench protection and mechanical stability so that the application in large scale fusion magnets requires the detailed assessment of their thermal, electromagnetic (EM) and mechanical behavior. Computer modeling has played an important role to date in the design of superconducting magnets, but due to the lack of specific tools and to the inherent complexity of such structures, it is often needed either to study the involved phenomena separately or to simulate coupled multiphysics problems on rather simple geometries and models. Our goal is therefore to provide a new High Performance Computing (HPC) unified framework for the multiphysics simulation of HTS devices. The development is intended to build on an existing HPC multiphysics tool and will enable in the near future the design of the most suitable architectures of HTS cables for fusion applications considering mechanical robustness, losses, and quench propagation, detection and protection.

The present abstract is organized as follows: Section I briefly introduces the potential role of HTS technology in Fusion, Section II discusses the current state of simulation tools for HTS and our research objectives, and Section III describes the EM model used to develop a first prototype giving rise to first preliminary results.

## I. HTS Cable Assemblies for Fusion Devices

HTS can withstand high current densities and magnetic fields with wide temperature margins compared to conventional Low-Temperature Superconductors (LTS) at the same operating temperature; therefore they emerge as a reasonable option to be considered in the design of large fusion magnets.

The usual HTS in the form of wires (Bi2212) and tapes (Bi2223, REBCO) can only carry a few hundreds of amperes in high field at low temperature. Since the current of ITER cables and several DEMO designs ranges from 30 kA to 100 kA [1], high current cables with several tens of superconductor wires or tapes need to be assembled in cables for its use in fusion magnets.

Several cable assemblies accounting for the flat geometry of thin REBCO tapes have been proposed for a wide range of applications: the stacked-tape conductor, the Conductor On Round Core (CORC) design [2], and the Roebel cable [3]. The latter two layouts present some features that are not suitable for high field applications [1], but cables based on stacks of REBCO tapes are being considered in some designs of the DEMO (DEMOnstration Fusion Power Station) [4, 5, 6, 7], a nuclear fusion power plant intended to follow the ITER experimental tokamak nuclear fusion reactor by 2050 [8].

## II. State of the Art and Objectives

Since cabling layouts are currently under research [9] in order to optimize the mechanical, thermal and electromagnetic behavior, it is necessary to develop suitable support for magnets and cables design based on multiphysics computer-aided design.

At present, most of the simulation work for superconducting devices is carried out with a large number of in-house codes and commercial softwares due to the existence of various phenomena at different scales that make some tools more appropriate than others depending on the specific physics to be solved. This is further encouraged by the lack of tools able to address the whole picture at a competitive cost both in terms of time and budget.

The project objective is to deliver a HPC unified framework for the multiphysics simulation of large scale HTS devices that, in particular, can be applied to perform a comprehensive analysis of all the physical processes that occur during the operation of superconducting magnets for fusion. This will be achieved by enhancing the current capabilities of Alya multiphysics HPC platform [10] developed at Barcelona Supercomputing Center. More specifically, the project aims at adding to Alya a new electromagnetic module with HTS features that makes use of advanced HPC resources efficiently and that can be coupled to the already existing thermal and mechanical modules.

## III. FEM Prototype and Preliminary Results

A first standalone prototype has been successfully tested against approximated analytical models, see Fig. 1. We have implemented the 2-D H-formulation of Maxwell's equations to model the highly nonlinear electromagnetic behavior of superconductors,

$$\begin{aligned} \mu\,\partial_t \boldsymbol{H} + \nabla \times (\rho\, \nabla \times \boldsymbol{H}) &= 0 && \text{in } \Omega \times (0, T]\,, \\ \boldsymbol{n} \times \boldsymbol{H} &= \boldsymbol{g}_D && \text{on } \Gamma \times (0, T]\,, \\ \boldsymbol{H}\,(t = 0,\, \boldsymbol{x}) &= \boldsymbol{H}_0\,(\boldsymbol{x}) && \text{in } \Omega. \end{aligned} \quad (1)$$

$\boldsymbol{H}\,(t, \boldsymbol{x})$ is the magnetic field intensity, $\mu$ the magnetic permeability, and $\rho$ the electric resistivity given by a power law in superconducting materials,

$$\rho = \frac{E_c}{J_c} \left( \frac{\| \nabla \times \boldsymbol{H} \|}{J_c} \right)^{n-1}, \quad (2)$$

where $E_c$ is the critical electric field, $J_c$ is the critical current density, and $n$ is the exponent of the power law.

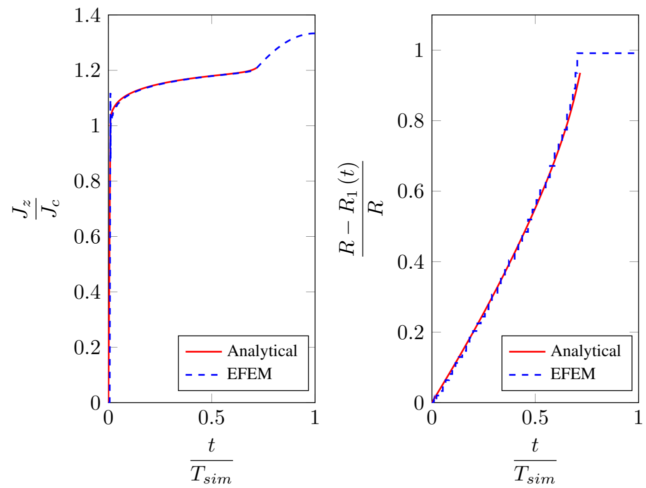


Fig. 1: Magnetization of a superconducting wire, $R = 1\,mm$, $I_c = 300\,A$, $E_c = 1\,\mu V/cm$, $n = 30$, transporting a time-varying current, $I\,(t) = I_0 \sin\,(2\pi f t)$.

Due to the mathematical properties of the problem, the Edge Finite Element Method (EFEM) [11, 12] has been preferred over the classical nodal FE approaches. EFEM is the common approach in the field of numerical modeling for applied superconductivity [13, 14], and will be adopted in the near future to study 3-D geometries and the foreseen coupling with the thermal model.

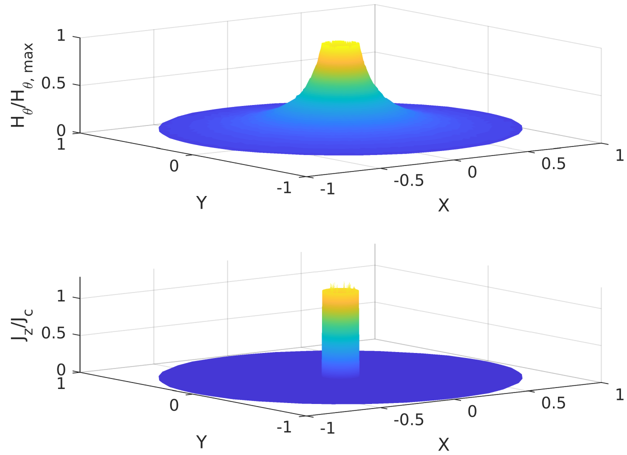


Fig. 2: Magnetic field and current distribution in a superconducting wire surrounded by air.

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**José Lorenzo** received his MSc degree in Industrial Engineering from Universidad de Sevilla, Spain, in 2014. In collaboration with CIEMAT (Madrid, Spain), he joined the Magnets, Superconductors and Cryostats Group at CERN (Geneva, Switzerland), where he worked in the analysis and numerical modeling of quench in $Nb_3Sn$ cables from 2015 to 2017. Later, he has worked at Universidad Autónoma de Madrid, Spain, in the implementation of control for Partial Differential Equations, shape optimization for Fluid Dynamics and mesh morphing techniques.