An Open Source Workflow for the Multiphysical Simulation of Quenches in Superconducting Accelerator Magnets

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ABSTRACT

The Large Hadron Collider is a particle accelerator for high-energy particle physics at CERN, in Switzerland. Here, low-temperature superconducting magnets are responsible of controlling the orbit of the relativistic particle beams by means of intense electromagnetic forces. If temperature, current or the magnetic flux density exceed a critical surface, superconductors quench, i.e., the material becomes resistive. Eventually, as a consequence of the losses, the magnet may be significantly damaged. Therefore, being able to accurately simulate the magnetic field of those superconducting magnets is not only important for their design and optimisation, but also crucial for their operability and protection.

The quasistatic field [1] can be described on a domain Ω by the partial differential equation

$$\boldsymbol{\sigma}\frac{\partial \mathbf{A}}{\partial t} + \nabla \times (\boldsymbol{\nu}\nabla \times \mathbf{A}) = \boldsymbol{\chi} i, \tag{1}$$

with boundary and initial conditions for the magnetic vector potential $\mathbf{A}$, where $\boldsymbol{\sigma}$ and $\boldsymbol{\nu}$ denote conductivity and reluctivity, respectively. The current density $\mathbf{J}_\mathrm{s} = \boldsymbol{\chi} i(t)$ is expressed by a winding function $\boldsymbol{\chi}$ and a scalar current i. The temperature is given by the heat equation

$$\rho C_\mathrm{p}\frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = P_\mathrm{s} + P_\mathrm{Joule}, \tag{2}$$

where ρ is the mass density, C_p the heat capacity, k the thermal conductivity and T the temperature. The Joule losses P_Joule are defined as $P_\mathrm{Joule} = q_\mathrm{flag}\,\sigma^{-1}\|\mathbf{J}_\mathrm{s}\|^2$ and are activated in case of a quench by the sigmoid-type activation function q_flag that depends on time, the magnetic flux density $\mathbf{B} = \nabla \times \mathbf{A}$ and current density $\mathbf{J}_\mathrm{s}$. The power density $P_\mathrm{s}(\mathbf{A})$ links the heat equation with the electromagnetic fields. In case of quenching, i.e., $q_\mathrm{flag} > 0$, the superconducting coils have a resistance with the voltage drop

$$v = \frac{\mathrm{d}}{\mathrm{d}t}\Phi + \mathbf{R}_\mathrm{t} i \text{ with } \mathbf{R}_\mathrm{t} = \int_\Omega \boldsymbol{\chi}^\top q_\mathrm{flag}\sigma^{-1}\boldsymbol{\chi}\,\mathrm{d}\Omega. \tag{3}$$

The resistance $\mathbf{R}_\mathrm{t}$ inherits the dependencies on t, $\mathbf{B}$ and $\mathbf{J}_\mathrm{s}$. In order to numerically approximate the solution of the equations above, the finite element method is used. The majority of implementations in the accelerator community is based on proprietary finite element solvers. In this contribution we discuss an improved model and its implementation within the opensource software GetDP [2].

REFERENCES

[1] Bortot, L. et al. A 2-D Finite-Element Model for Electrothermal Transients in Accelerator Magnets. *IEEE Trans. Magn.* (2018) **54(3)**:7000404.

[2] Geuzaine, C. GetDP: a general finite-element solver for the de Rham complex. *PAMM* (2007) **7**:1010603–1010604.