Field-Circuit Coupled Simulation of Magnetothermal Dynamics in an HTS Solenoid

1st Lorenzo Bortot
CERN and TU Darmstadt
Geneva, Switzerland
lorenzo.bortot@cern.ch

2nd Matthias Mentink
CERN
Geneva, Switzerland
matthias.mentink@cern.ch

3rd Arjan Verweij
CERN
Geneva, Switzerland
arjan.verweij@cern.ch

4th Sebastian Schöps
TU Darmstadt
Darmstadt, Germany
sebastian.schoeps@tu-darmstadt.de

***Abstract*—This paper shows the magneto-thermal dynamics of a quench in a HTS solenoid protected by a dump resistor. The analysis is carried out using a field/circuit coupling technique with the waveform relaxation scheme, implemented in the STEAM co-simulation framework. The field model implements a coupled field formulation for superconducting materials combined with solid conductors, and accounts for the dynamics of the solenoid. The circuit model is implemented in a network solver, which accounts for the the supply and protection circuitry. The approach is verified with a monolithic model. It allows for analyzing arbitrarily complex models, such as the circuits of superconducting magnets in particle accelerators.**

Keywords*—*High-temperature superconductors; co-simulation; Field-circuit coupling; magnetization; finite-element analysis; superconducting coils, accelerator magnets.

I. Introduction

High temperature superconducting (HTS) tapes based on ReBCO compounds are potential candidates for future particle physics accelerators. In order to asses the applicability of HTS technology, it is crucial not only to investigate the design of the future HTS magnets, but also to carefully study their dynamic behavior in accelerator circuits which may show collective phenomena (e.g., [1]). Solving this multi-rate and multi-scale problem using monolithic models might lead to unpractical computational time, if high resolution is needed. A possible solution is offered by using a field/circuit simulation strategy, based on the waveform relaxation scheme [2].

In this paper, we propose the co-simulation of a quench event in an HTS solenoid protected by a dump resistor. The field model, implemented using the finite element method, accounts for the magneto-thermal transient occurring in the solenoid by using a coupled field formulation [3] for HTS magnets [4]. The external circuitry is accounted in a SPICE network model. With respect to previous work [5], the field/circuit coupling strategy is extended to the coupled field formulation, in combination with winding functions for solid conductors [6] which are used for the HTS coils. In this way, the co-simulation framework is expanded to include circuits with HTS magnets. In order to verify the approach, the co-simulation is crosschecked with a monolithic simulation. For future studies, more complex models will be considered, including nonlinear circuital elements and advanced protection schemes.

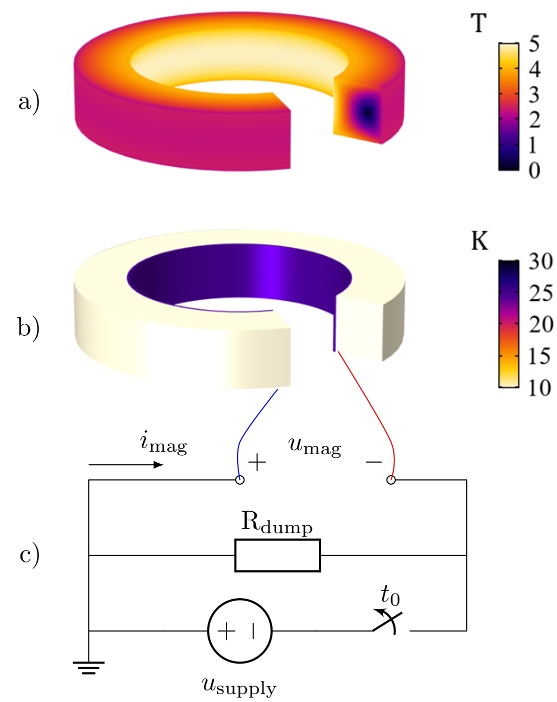

Fig. 1. Field/circuit model of an HTS solenoid. a) Nominal magnetic field, in Tesla. b) Initial temperature distribution, in Kelvin. c) External circuit, including the supply voltage u_{supply} and the dump resistor $\mathrm{R}_{\mathrm{dump}}$. The field/circuit connection is highlighted as a voltage/current port ($u_{\mathrm{mag}}, i_{\mathrm{mag}}$).

II. Case Study: Quench-Back in HTS Solenoid

The relevant parameters for the case-study are reported in Table I. The HTS solenoid is operated at $5\,\mathrm{kA}$ and $10\,\mathrm{K}$, producing a peak field of $5\,\mathrm{T}$ (see Fig. 1a). The initial temperature profile is assumed to be as in Fig. 1b, where the most inner turn reaches $25\,\mathrm{K}$, thus exceeding the current sharing temperature of the tape. At $t = t_0$, the circuit protection is triggered. With respect to Fig. 1c, the power supply is

TABLE I
FIELD QUALITY TESTS: MAIN PARAMETERS

Parameter	Unit	Value
Solenoid inner radius	mm	20
Solenoid outer radius	mm	22
Solenoid Height	mm	10
no. of turns	-	10
Nominal inductance L_d	mH	22.3

disconnected by the switch opening, and the dump resistor $R_{dump} = 0.25\,m\Omega$ is inserted in series with the HTS solenoid. The resistor dissipates the energy stored in the solenoid. The subsequent transient induces dynamic losses which heat up the superconductor in the solenoid. This is the so-called quench-back phenomenon [7], which is beneficial as it contributes to a faster energy dissipation, limiting the peak temperature in the solenoid. This case-study is simulated by means of both, a monolithic approach and a field-circuit coupling strategy based on the waveform relaxation technique.

III. NUMERICAL RESULTS AND DISCUSSION

The numerical analysis considers two cases, the first where the quench-back is accounted for, and the second where the whole solenoid is assumed to be normal conducting at $t = t_0$, and labeled as a quench-all case. The purpose of the second case is to obtain an optimal quench protection result that is used to compare the performance of the dump resistor. The numerical results for the monolithic approach are presented, and will be used in the full manuscript for validating the co-simulation approach. The current and temperature dynamics in the solenoid are given in Fig. 2. The current shows an acceleration with respect to an exponential decay (dashed line) $10\,ms$ after the circuit protection is activated. This is due to the quench-back effect. The sudden increase in the DC resistance of the solenoid R_{DC} (see Fig. 3, solid line) increases the decay rate of the current. This effect allows to limit the temperature in the solenoid to a peak value of $320\,K$. It is of interest to observe the behavior of the solenoid differential inductance L_d (see Fig. 3, dashed line), which features an increase by about a factor 3 as the current approaches to zero. This is due to the action of persistent eddy currents in the superconducting material, which trap the magnetic flux within the coil. The values for the ideal quench protection scenario are also shown for reference. In the ideal case, the peak temperature is limited to $100\,K$.

IV. ACKNOWLEDGMENT

This work has been sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 05E15CHA), by the 'Excellence Initiative' of the German Federal and State Governments and by the Graduate School of Computational Engineering at Technische Universität Darmstadt.

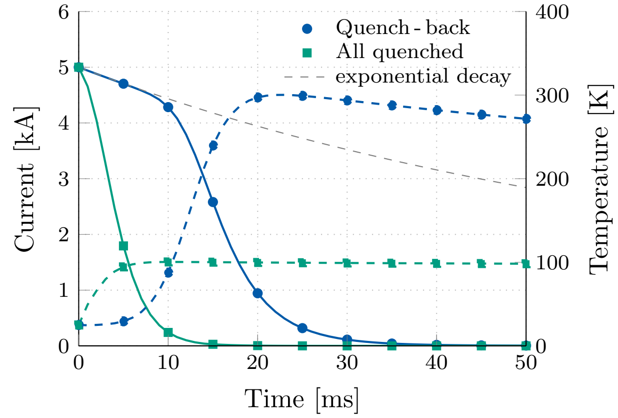

Fig. 2. Current and temperature in the HTS solenoid, reported as continuous and dashed lines, respectively. The markers refer to the case of quench-back (circles) and quench-all (squares) cases, respectively.

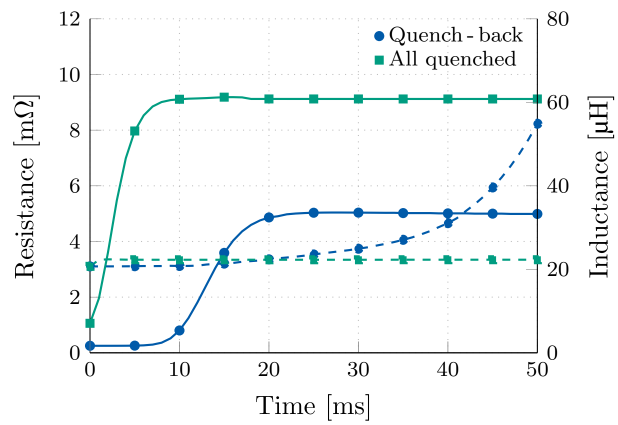

Fig. 3. DC resistance R_{DC} and differential inductance L_d in the HTS solenoid, reported as continuous and dashed lines and referring to the left and right axis, respectively. The markers refer to the case of quench-back (circles) and quench-all (squares) cases, respectively.

REFERENCES

[1] Ravaioli, Emmanuele and others, "Impact of the voltage transients after a fast power abort on the quench detection system in the LHC main dipole chain," IEEE Trans. Appl. Supercond., vol. 22, no. 3, pp. 9002504–9002504, 2012.
[2] Schöps, Sebastian and others, "A cosimulation framework for multirate time integration of field/circuit coupled problems," IEEE Trans. Magn., vol. 46, no. 8, pp. 3233–3236, 2010.
[3] J. Dular and C. Geuzaine and B. Vanderheyden, "Finite Element Formulations for Systems with High-Temperature Superconductors," IEEE Trans. Appl. Supercond., 2019.
[4] Bortot, Lorenzo and others, "A Coupled AH Formulation for Magneto-Thermal Transients in High-Temperature Superconducting Magnets," Accepted for publication on IEEE Trans. Appl. Supercond., arXiv preprint arXiv:1909.03312.
[5] Bortot, Lorenzo and others, "STEAM: A hierarchical cosimulation framework for superconducting accelerator magnet circuits," IEEE Trans. Appl. Supercond., vol. 28, no. 3, pp. 1–6, 2018.
[6] Schöps, S. and others, "Winding functions in transient magnetoquasistatic field-circuit coupled simulations," COMPEL, vol. 32, no. 6, pp. 2063–2083, 2013.
[7] Wilson, Martin N, "Superconducting magnets," Clarendon Press Oxford, 1983.