Multi-physics modeling of metal-insulated REBCO magnets with screening currents

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Abstract—**The design of REBCO high temperature superconducting (HTS) ultra-high-field magnets requires fast and accurate multi-physics modelling (electromagnetic, thermal and mechanical). This contribution presents a novel computationally-efficient multi-physics method that takes screening currents into account. We apply this method to a REBCO insert within a 19 T / 150 mm bore low-temperature superconducting (LTS) magnet. We analyze the electro-thermal quench behavior, the thermal stress during quench, and the axial force on the LTS due to quench in the HTS insert. Results suggest that AC loss from screening currents speed-up electrothermal quench.**

Keywords—High magnetic field magnets, metal-insulated coils, multi-physics modeling of high temperature superconductors.

REBCO HTS coils are very promising for ultra-high-field magnets. Enabling currents between turns highly improves the reliability against thermal quench, such as in no insulation and metal-insulation windings. During quench, thermal gradients could also increase stress, hence this effect needs to be under control. Thus, the design of ultra-high-field magnets requires fast and accurate multi-physics modelling, where the electromagnetic, thermal and mechanical properties interact. This contribution presents a novel multi-physics method that takes screening currents into account. We also apply this method to a 32 T magnet consisting of the REBCO insert of NOUGAT [1] within a 19 T / 150 mm bore low-temperature superconducting (LTS) magnet by Oxford Instruments. Apart from the electro-thermal behavior and the stress during quench, we also analyze the axial force on the LTS due to quench in the HTS insert.

The REBCO insert, which is based on NOUGAT [1] consists on 18 pancakes made of 290 turns of 6 mm wide tape.

We use the same electrical properties of all the materials within the REBCO coated conductor tapes and the co-wound stainless-steel as in [2], which depend on the magnetic field, $\mathbf{B}$, and temperature, T. Particularly, the REBCO layer is assumed to follow a power-law relation between the electric field and current density with exponent $n = 30$ and critical current density $J_c(\mathbf{B}, T)$ obtained from fitting experiments of Fujikura tape. We also consider a contact resistance between tapes in the radial direction of 10^{-6} Ωm^2. The thermal properties of all layers are the same as those given in [3], where the thermal conductivities and capacities depend on temperature. For the mechanical properties, we take the elastic moduli and thermal expansion coefficients of [4]. We assume that all materials are elastic, hence there is no plastic deformation.

The insert is charged at a rate of 1 A/s in the full 19 T background field from the LTS outsert until it reaches a plateau at 314.3 A. To model accidental damage, a degradation of Jc to 0.1 times its original value is applied to turns 41-50 of the bottom pancake 157.15 s after the end of the ramp. We also consider a voltage limitation of the HTS source of 1 V.

This work presents a novel multi-physics numerical method that combines electromagnetic, thermal, and mechanical models. The electromagnetic and thermal models interact to each other as in [5], while the electro-thermal model interacts with the mechanical model only one way: the Lorentz force and temperature from the electro-thermal model are the input for the mechanical model. The electromagnetic model is based on the Minimum Eletromagnetic Entropy Production (MEMEP) and takes both angular and radial currents of the REBCO insert into account using an axi-symmetric approach [2]. In addition, we also take screening currents into account, as well as voltage limitation of the current source. For the thermal model, we use our own implementation in C++ of finite differences [3]. Finally, we implement the mechanical model by means of MATLAB, using our own finite-element approach [6]. For all models, we consider homogenized properties for high computational speed [2], [3], [6]. The computing time of the electrothermal model is of a few hours.

Results show that before J_c damage significant screening currents are present in all pancakes (Fig. 1). After degradation, temperature increases at the damaged turns and their neighbors due to: (a) Joule heating caused by over-critical current and transfer to radial currents; (b) local change of magnetic field, which causes AC loss at the neighboring turns. Since the

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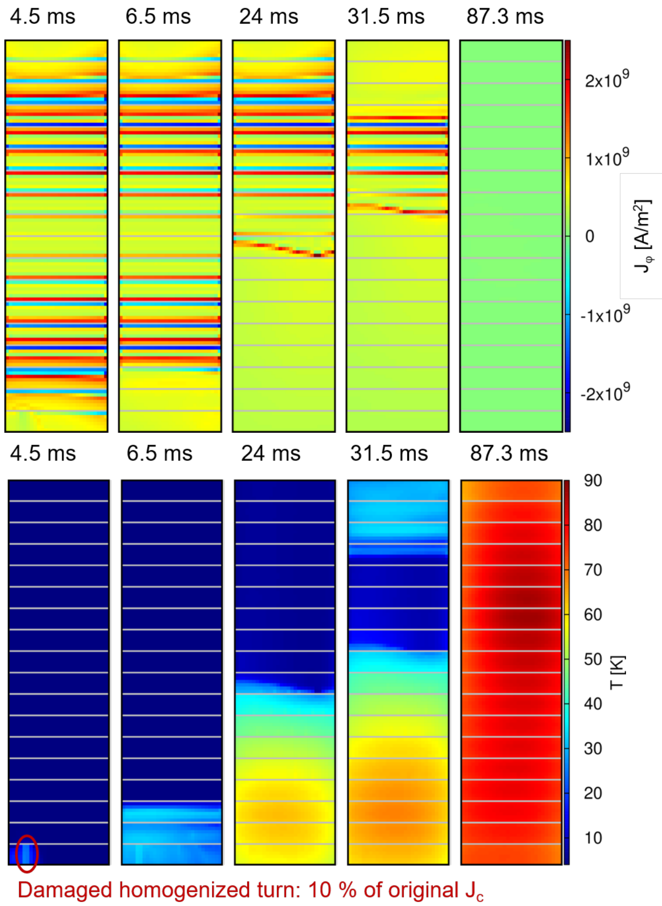

Fig. 1. Cross-section of the modeled REBCO insert (left and right boundaries are the inner and outer radius, respectively) at several times after degradation of turns 41-50 of the bottom pancake, where J_φ is the angular current and T is the temperature.

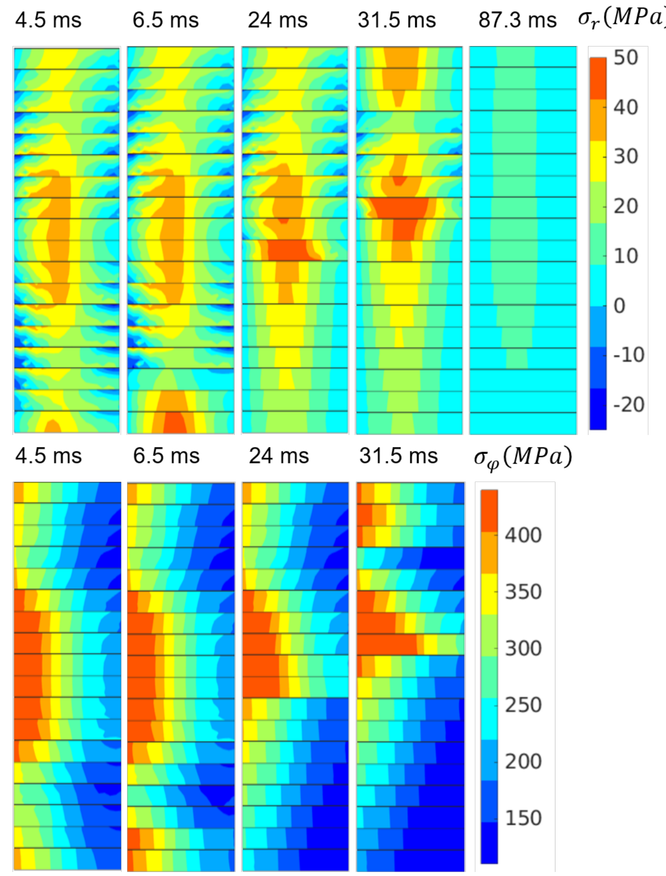

Fig. 2. Radial and angular stress at the cross-section of the REBCO insert at the same configurations as in Fig. 1.

decrease of J_c is sudden, the variation of magnetic field at the neighboring turns is fast, causing significant local AC loss due to screening currents. After a period of time, the quench propagates electrothermally. This quench propagates very fast due to electromagnetic coupling between different turns in a pancake and between several pancakes. Around 30 ms after degradation, the top pancakes also experience electrothermal quench. This is because of the higher current to over critical-current ratio, I/I_c, than the more central pancakes, while the top pancakes also experience change of magnetic flux from the rest of the insert.

Both Lorentz forces and thermal gradients cause stress on the insert (Fig. 2). During electrothermal quench, radial tensile stress increases at the pancakes where there is electrothermal quench, which is due to thermal stress. This means that extra measures should be taken to compensate the radial tensile stress compared to standard operation. These measures could be additional pre-tension winding and overbanding.

Finally, we computed the axial Lorentz force on the LTS insert due to electrothermal quench in the HTS. Indeed, the asymmetric quench causes a significant axial force in the LTS, which needs to be taken into account for the mechanical design of the LTS.

This contribution presented a novel multi-physics numerical method for REBCO inserts that also take screening currents into account. This method is computationally effective and can provide interesting insights regarding ultra-high field magnets.

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