A Numerical Study of Quench in the NHMFL 32 T Magnet

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***Abstract*—The National High Magnetic Field Laboratory (NHMFL), Tallahassee, FL, USA, has developed, built, tested, and commissioned a 32 T all-superconducting user magnet system combining two series-connected high-field high-temperature superconductor (HTS) nested inner coils (insert) wound with SuperPower, Inc. REBCO tapes and a low temperature superconducting (LTS) outer magnet (outsert) composed of five coils (subdivided into 17 electrical sections). Protected-quench tests were performed at the NHMFL to analyze the reliability of the 32 T magnet during the superconducting-to-normal transition. The quench tests were performed at different values of transport current both in the HTS insert and in the LTS outsert. The University of Bologna, in collaboration with the NHMFL, has developed a quasi-3-D FE model suited for the analysis of quench in HTS magnets. The model was previously applied to the analysis of the experimental results of the quench tests carried out on the prototype coils, manufactured in the framework of the 32 T magnet R&D activities. In this paper, the numerical model is applied to analyze the quench initiation and propagation in the 32 T HTS insert. The dump of the transport current during quench is computed and compared with the experimental result. The most stressed regions within the insert windings are identified.**

***Index Terms*—HTS, quench, large scale application of superconductivity, high field magnets, FEA, computer simulation.**

I. Introduction

THE R&D activity at the NHMFL for the development of the 32 T magnet started in 2007 with the development of the SuperPower small test coils generated up to 8 T in a background magnetic field of 19 T provided by a resistive magnet (the grand total of 27 T). The first tests on larger prototypes, incorporating all main features of the future magnet HTS coils, were performed during the years 2012-2015. In 2015, the prototypes were tested in the actual LTS outsert built by Oxford Instrument, Inc. In 2017, the first tests on the final configuration of the 32 T magnet were performed [1]–[4].

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The full-scale modelling of up-to-date HTS magnets calls for addressing at least the following challenges: first, the conductor high aspect-ratio, i.e., kilometers in length (about 10 km for the 32 T magnet HTS insert) versus the remarkably small thickness (the REBCO tapes are 0.1 mm thick); second the need to solve a coupled thermal, electromagnetic (and electric circuit) problem. In 2016, a quasi-3 D FE model was proposed by the University of Bologna in collaboration with the NHMFL to solve these challenges. The code was validated first by analyzing the test results of the prototype coils. Particularly, the quench propagation was studied in the insert prototypes in self-field and in a background magnetic flux density of 15 T generated by a large bore resistive magnet of the NHMFL [5]. Then, the insert prototypes coupled with the actual LTS outsert were analyzed to determine the overall specific quench behavior of coupled HTS and LTS magnets [6].

In this study, the quasi-3 D FE model is extended to include appropriately the structure of the entire 32 T magnet. Two test cases are selected to be simulated. In the first case, the HTS insert is analyzed during a protected quench without including the LTS outsert at all (Self-Field Quench Test). In the second case, the transition in the HTS insert is studied as if a quench occurs first in the LTS outsert (Half-Energy Quench Test). The contribution of different pancakes of the insert to the transition is presented along with the entire insert quench behavior analysis results.

II. The 32 T Magnet Structure

As described in [1] and [2], the 32 T magnet is composed of a 15 T large-bore LTS multi-coil outer magnet (outsert) and a two-nested-coil REBCO insert assembled from double pancakes/modules to generate an additional field of 17 T, see Table I. The insert inner coil, Coil 1, comprises 20 modules (i.e., 40 pancakes), whereas the insert outer coil, Coil 2, consists of 36 modules (72 pancakes).

The LTS Outer magnet and its cryostat are provided by the Oxford Instruments, Inc. The LTS outsert quench protection system consists of both a classic passive diode-resistor network and an active system with a quench detection and power units and quench protection heaters embedded in the winding. The outsert quench protection can also be triggered manually by a TTL signal from the quench detection unit of the REBCO insert. The outsert winding is composed of 17 electrical sections, featuring an operating current of 268 A and a self-inductance of 194 H.

TABLE I
HTS INSERT COILS TECHNICAL PARAMETERS [1]

	Coil 1	Coil 2
Inner Radius [mm]	20	82
Outer Radius [mm]	70	116
Height [mm]	178	318
Number of pancakes	40	72
Operative Current [A]	174	174
Conductor length [km]	2.9	6.8
Inductance [H]	2.6	9.9
Field contribution [T]	10.7	6.3

As detailed in [2], the insert pancakes are wound with an uninsulated 4-mm wide REBCO tape co-wound with a sol-gel-insulated stainless steel strip as a turn-to-turn insulation [7]. The pancake-to-pancake insulation within a module represents a 0.25 mm thick G-10 sheet. The quench protection heaters are embedded between the modules and sandwiched between thin layers of Kapton and G-10. The heaters are designed to be sufficiently powerful to ignite normal zone in most of the modules promptly and thus protect reliably the insert coils in a number of case scenarios [8], [9]. The insert detection unit monitors voltages between different sections of the insert coils (balance voltages) and is set to trigger at 100 mV, and/or by a TTL signal from the outsert quench detection system.

III. MODEL DESCRIPTION

The electromagnetic-thermal quasi-3 D FE quench model of the insert HTS coils is coupled with the magnet lumped-parameter electrical circuit model that also describes the inductive coupling between the dual coil insert and the multi-section outsert. A detailed description of the model is provided in [5], [6].

A. Thermal Model

In the quasi-3 D FE approach, each pancake is modeled as a 2 D element based on the assumption that the temperature is uniformly distributed along the axial direction within a given pancake. Given the symmetry conditions of the pancake geometry and of the heater configuration [6], the 2 D FE mesh only covers one-half surface of the pancake. At each node of the mesh, a set of heat balance equations is written for the array of temperature $T_i(x, y, t)$, corresponding to the time t and to the position of the *i*-th pancake given by the coordinates x, y. The heat balance equation for the *i*-th pancake ($i = 1 \ldots 40$ or 72) is as follows:

$$\rho C_p(T_i)\,\frac{\partial T_i}{\partial t} - \nabla\cdot(\mathbf{K}(T_i)\,\nabla T_i) = \frac{J^2(t)}{\sigma_i(T_i, B_i, J)} + Q_i^z(x, y, t) + Q_i^{heater}(x, y, t) \quad (1)$$

where ρ is the homogenized density, C_p the homogenized specific heat, $\mathbf{K}$ the tensor of anisotropic thermal conductivity, σ_i the homogenized electrical conductivity in the circumferential direction, Q_i^{heater} the heater pulse power and Q_i^z the axial heat exchange between adjacent pancakes computed as:

$$Q_i^z(x, y, t) = \frac{T_{i+1} - T_i}{V_P\left(R^{G10}_{i,i+i} + R_{cz}\right)} - \frac{T_i - T_{i-1}}{V_P\left(R^{G10}_{i,i-i} + R_{cz}\right)} \quad (2)$$

where V_P is the pancake volume, $R^{G10}_{i,i-i}$ is the G-10 thermal resistance between pancakes i and $i-1$, R_{cz} is the thermal contact resistance between a given pancake and the adjacent G-10 layer.

Adiabatic boundary conditions are applied on the external surface of each coil and a uniform temperature distribution over both coils of the insert at 4.2 K is set as the initial condition [10].

B. Homogenization Procedure

The superconducting tape and its insulation are represented through a homogeneous material with anisotropic physical properties. The applied homogenization procedure enables one to determine the circumferential electrical conductivity in azimuthal direction. Based on the same approach, both circumferential and transversal thermal conductivities are computed [5], [6].

The electrical conductivity in the circumferential direction σ is calculated as a function of the position assuming all the multiple layers of the tape layered structure to be in parallel [5]. A nonlinear power law is used as a constitutive electric characteristic of the superconducting layer, with the critical current expressed as a function of temperature T, magnetic flux density B, and field angle θ with respect to the tape surface. The critical surface is described through the parametrization provided in [11]–[13].

The radial and axial components of the magnetic flux density vector are computed in each node of the 2 D mesh and at each time step during the simulations through a 2 D numerical method [13].

C. Insert-Outsert Inductive Coupling Model

The current I_{op} in the HTS insert circuit is obtained by solving the electric circuit equation including the inductive coupling between the insert and the outsert:

$$V_0(t) = \left(R_{NZ}^{coil1}(t) + R_{NZ}^{coil2}(t) + R_j\right) I_{op}(t) + L\frac{dI_{op}}{dt}(t) + \sum_{j=1}^{17} M_j^{in}\frac{dI_j}{dt}(t) \quad (3)$$

where L is the self-inductance of the insert (composed of the two series connected coils); M_j^{in} the mutual inductance between the insert and the *j*-th electrical section of the multi-section outsert; I_j is the current in the *j*-th section of the outsert; V_0 is the overall voltage on the insert, which is kept constant during the quench; R_{NZ}^{coil1} and R_{NZ}^{coil2} are the total resistances of the insert's Coils 1 and Coil 2.

The resistance of the insert's Coil 1 R_{NZ}^{coil1} is computed through a numerical integration over each pancake volume of Coil 1, with the summation of the contributions from all the

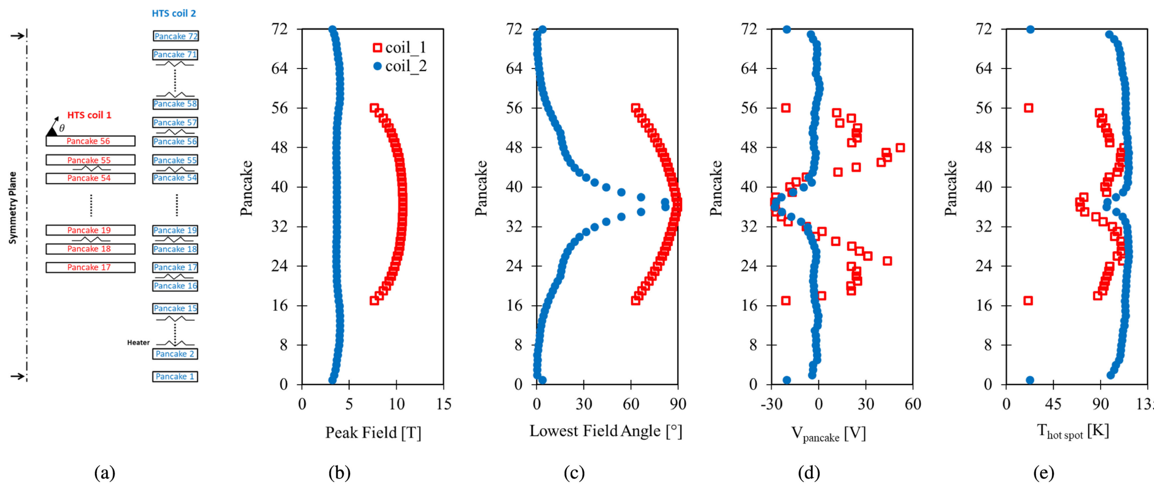

Fig. 1. Results of the Self-Field Quench Test analysis at t = 1.05 s: (a) Sketch of the Self-Field Quench Test. (b) Pancake max. Field distribution. (c) Lowest field angles in the pancakes. (d) Pancake terminal voltages. (e) Hot-spot temperatures.

volumes:

$$R_{NZ}^{coil1}(t) = \frac{2}{I_{op}^2(t)} \sum_{i=17}^{56} \int_{V_i} \frac{J^2(t)}{\sigma_i(T_i(t), x, y)} dV_i \tag{4}$$

where V_i represents the part of the *i*-th pancake in the 2 D model, and the factor 2 accounts for the fact that only half of each pancake is modeled thanks to the aforementioned symmetry condition [6]. The same formulation is adopted for the calculation of R_{NZ}^{coil2}.

IV. Result of Self-Field Quench Test

The quasi-3 D FE model is applied to analyze the HTS insert of the 32 T magnet in the case where the insert is energized alone with 173 A; the outsert is off and its circuit is disconnected. In the test, the heaters between the insert modules (see Fig. 1 a) are fired simultaneously from t = 0.0 s to t =1.0 s.

A. Current Decay

The heat flux introduced by the heaters on the pancakes initiates their transition to the normal state and, as a consequence, the coil current decreases quickly in time. The current decay computed by the quasi-3 D FE model is compared in Fig. 2 with the simulation performed at the NHMFL using a quasi-3D high-accuracy discrete model. The NHMFL discrete model solves the heat conduction equation with a source term which includes appropriately the Joule and index heating, and AC losses as well. This model is based on the discretization of the longitudinal coordinate (along the spiral path of the superconductor) within a given pancake with due regard for the transverse (radial and axial) heat transfer [12], [13].

B. Pancakes Terminal Voltages and Temperatures

By calculating each pancake resistance and the current flowing in it, we can compute the pancake terminal voltages during

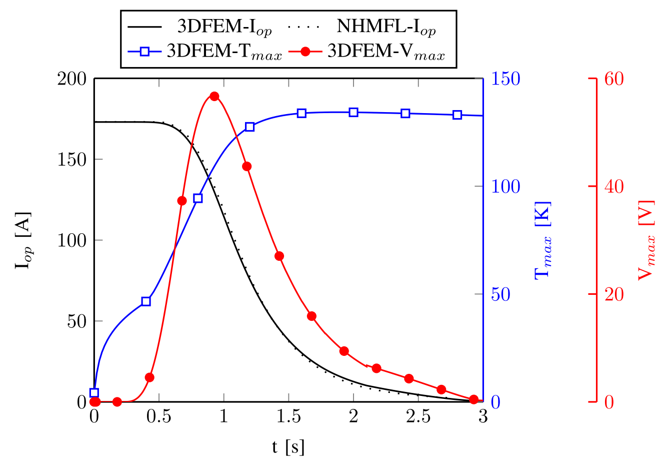

Fig. 2. On the left y-axis, the insert current decay according to the proposed FE model and the NHMFL discrete model. On the right y-axes, maximum pancake terminal voltages (red curve) and hot spot temperature (blue curve) during the Self-Field Quench Test.

the tests:

$$\Delta V_i(t) = R_i(t) I_{op}(t) + \sum_{j=1}^{N} M_{ij} \frac{dI_{op}}{dt} \tag{5}$$

where ΔV_i is the terminal voltage of the *i*-th pancake, R_i is the resistance of the *i*-th pancake, and M_{ij} is the mutual inductance between the *i*-th and *j*-th pancakes.

In Fig. 1 b the peak field of each pancake is shown at 1.05 s, after the heat pulse end. The peak field is 10.7 T and 4.0 T for the Coil 1 and Coil 2 respectively. The field angle (Fig. 1 c) is rather uniform in Coil 1 in a range between 60 ° and 90 ° while spreads between 0 ° and 90 ° in Coil 2.

In Fig. 1 d the terminal voltage distribution throughout the pancakes is shown. The pancakes of Coil 2 are dominated by the inductive effect (negative pancake voltage). The development of quench in the insert is determined by the transition of Coil 1 rather than by that of Coil 2. Two pancakes, #17 and #56, which

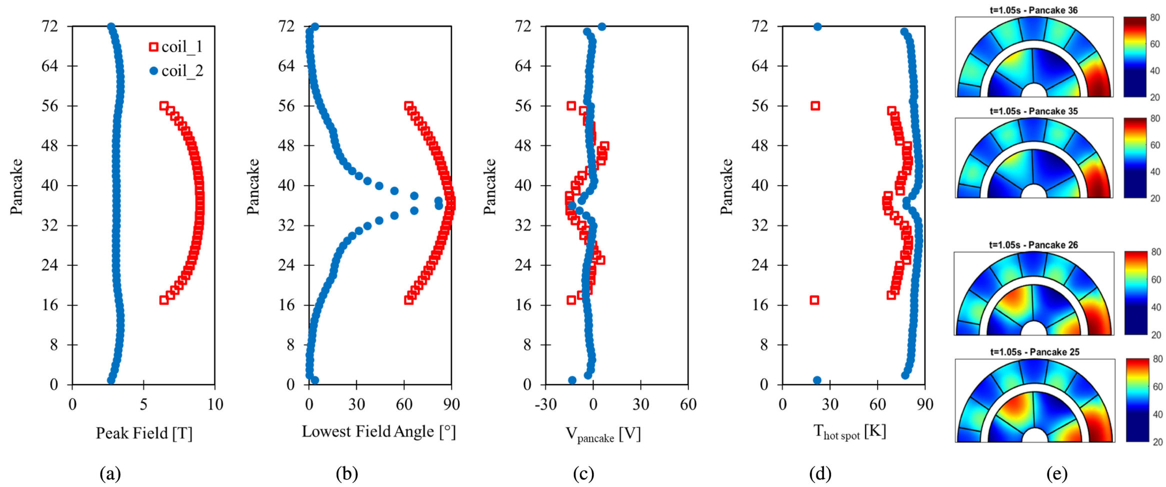

Fig. 3. Results of the Half-Energy Quench Test analysis at $t = 1.05$ s: (a) Pancake max. Field distribution. (b) Lowest field angles in the pancakes. (c) Pancake terminal voltages. (d) Hot-spot temperatures. (e) Temperature distribution over pancakes #25, #26, #35, #36.

are at the upper and lower positions of Coil 1, are not directly in contact with the heaters and hence their terminal voltages are dominated by the inductive effect. In Coil 1, the resistive effect (positive pancake voltages) is predominant in the pancakes from #18 to #31 and from #43 to #55. The pancakes in the central zone of the magnet, namely from #32 to #42, subjected to the most intense magnetic flux density, are dominated by the inductive coupling. The result confirms the conclusion drawn in [5] and [6], i.e. the most dangerous locations derive from the trade off between magnetic field and field angle. The maximum terminal voltage of each pancake is detailed in Fig. 2 (right axes) during the quench test.

The results of the pancake terminal voltages are confirmed by the hot spot temperature reached in each pancake (see Fig. 1 e). In Coil 1, the pancakes from #25 to #32 and from #42 to #48 are more thermally stressed then the pancakes #36 and #37 in the central region of the magnet. In Fig. 2 (right axis), the hot spot temperature development in time of the whole magnet is shown. The peak temperature approximates 130 K.

V. Result of Half-Energy Quench Test

In the Half-Energy Quench Test, the HTS insert is energized with 122 A current, the outsert with an initial current of 188 A. As in the previous quench test, the heaters between modules are fired simultaneously for 0.8 s. In this case, the induced voltages in the outsert exceed the threshold and the outsert quench protection system is triggered resulting in the outsert discharge.

A. Current Decay

The current decay in the HTS insert due to the normal zone propagation is shown in Fig. 4. The quasi-3 D FE model computation is compared with the experimental results.

B. Pancakes Terminal Voltages and Temperatures

In this quench case, the intervention of the outsert quench protection system results in the outsert discharge and in the

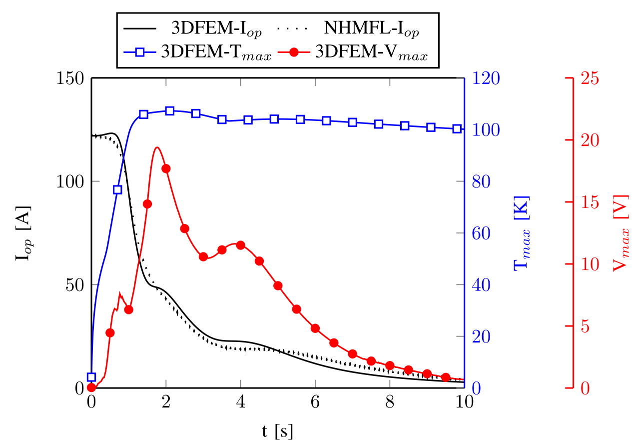

Fig. 4. On the left y-axis, the insert current decay according to the proposed FE model and the NHMFL discrete model. On the right y-axes, maximum pancake terminal voltages (red curve) and hot spot temperature (blue curve) during the Half-Energy Quench Test.

time-varying current in the 17 sections of the outsert. The computation of the pancake terminal voltages ΔV_i requires the introduction of the mutual induction M_{ik}^{out} between the i-th pancake and the k-th sections of the outsert. Then, the pancake terminal voltages $\Delta V_i(t)$ can be computed according to the following relation.

$$\Delta V_i(t) = R_i(t) I_{op}(t) + \sum_{j=1}^{N} M_{ij} \frac{dI_{op}}{dt}(t) + \sum_{k=1}^{17} M_{ik}^{out} \frac{dI_k}{dt}(t) \tag{6}$$

The peak field and the lower field angle of each pancake is shown in Figs. 3 a and 3 b at 1.05 s. In Fig. 3 c the terminal voltage distribution between pancakes is shown. With respect to the Self-Field Quench Test, in this case most of the pancakes of Coil 1 are dominated by the inductive effect. The most dangerous pancakes are not the pancakes in central region of the magnet: pancakes from #35 to #37 are dominated by induction whereas pancakes from #45 to #48 and from #20 to #27 are the most resistive ones. The time evolution of the maximum pancakes terminal voltage of all pancakes is shown in Fig. 4 (right axes).

These results is confirmed by the hot spot temperature and the temperature distribution over the pancake (see Figs. 3 d and 3 e). In Coil 1, the pancakes from #24 to #32 and from #42 to #48 are more thermally stressed then the pancakes #36 and #37 in the central region of the Coil 1. The hot spot temperature development in time of the whole magnet is plotted in Fig. 4 (right axes) during the quench test. A peak temperature of about 110 K is reached.

VI. Conclusion

The main computational efforts involved in the modelling of HTS large scale magnets are the high aspect ratio, the dimension of the magnet and the coupled thermal and electromagnetic problem. In this study, these challenges are solved by different techniques: the anisotropic homogenized material, the reduced dimensionality approach and the implementation of distributed thermal contact resistances between pancakes. These techniques are implemented in the quasi-3 D model which allows analysing the NHMFL 32 T magnet composed of two HTS coils for a total amount of 112 pancakes.

The results of the quasi-3 D model are in agreement both with numerical simulations performed with a different model and with experimental tests. The terminal voltages and the hot spot temperatures of each pancake are computed to study the quench development in the magnet. The results point out the influence of the magnetic flux density and of the field angle on the quench: the combination of both parameters determines the most stressed pancakes. The analysis also shows the dominant effect of Coil 1 on the quench of the global magnet.

The results obtained in the analysis of quench tests confirm the ability of the quasi-3 D model to study the quench in a full scale magnet with a reasonable computational effort.

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