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Investigations on NbTi superconducting racetrack coils under pulsed-current excitations

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Abstract. One of the key issues in the technology of superconductors is the protection against quenches. When designing a superconductor as a magnet, a coil or even current leads, the design should be made such that the superconductor withstands all operational conditions, especially those occurring rapidly, as fast discharges or pulsed loads. A model for a superconducting racetrack coil based on NbTi winding is investigated under pulsed transport current conditions (zero external field) utilizing finite element analysis within the Simulia Opera platform. A pulse duration of a few milliseconds and a peak current exceeding 1 kA is yielded by discharging a capacitor into an RLC circuit that includes the superconductor coil as an element. A quench multi-physics analysis has been performed comprising both thermal and electromagnetic solutions. The transition to normal state and quench occurrence has agreed with the expected critical curve together with the load-line estimated for the existing coil geometry.

1. Introduction

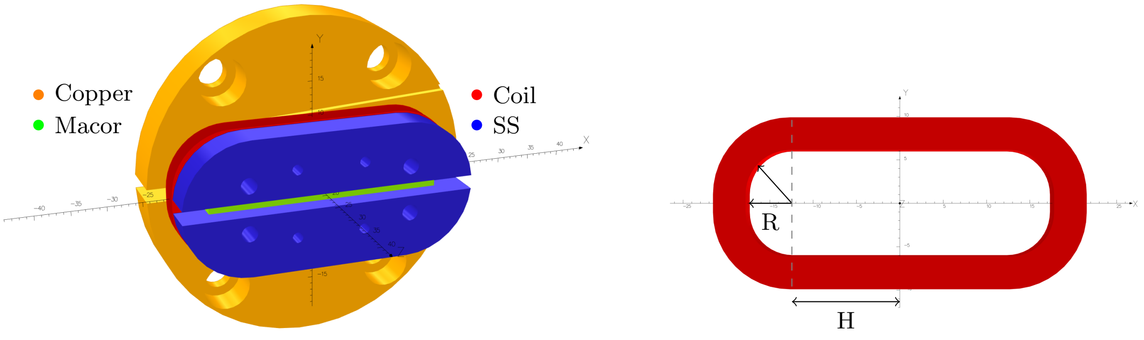
There has been a strong interest in utilizing magnets in alternating field applications since the early days of superconducting magnet technology [1]. The pulsed current measurement not only enables characterizing a superconductor (SC) transition to normal (as in typical DC or AC measurement techniques) but also provides the ability to reach high field levels over short periods of time, thus reducing the power and the heat generated in the SC sample.

As a step towards understanding the electromagnetic and thermal processes in a pulsed SC, a model for a racetrack coil based on the winding of the low-temperature superconductor NbTi (one of the SC choices used in conventional pulsed magnets) has been investigated by finite element modeling using Simulia Opera [2].

In this paper, the rapid transport current characteristics in the zero applied field condition (self field only) have been studied by exciting the SC coil through a pulsed waveform featuring a rise time below 0.2 ms and a peak value that exceeds the critical current level. The second section describes the 3D model of the racetrack coil along with other different parts modeled in the coil design. Details on the assigned settings together with electromagnetic and thermal results obtained from a quench analysis are given in the third and fourth sections.

2. Design of the SC coil

An illustration for the different parts in the coil's 3D model is presented in figure 1. The design of the SC coil is based on a racetrack geometry wound around a copper core. Two non-magnetic stainless steel (SS) parts are used for supporting the winding structure. A Macor ceramic plate is used as an insulator between conductive domains. The racetrack coil has a half length and a bending radius of 12.5 mm and 5 mm, respectively. The coil has four layers with 18 turns in total. The general motivation behind the overall 3D geometry is linked to some existing sample coils used for SC damage studies [3].



(a) (b)

Figure 1: 3D drawing of the model of the SC coil. Markers in the legend indicate different parts by their color (a). 2D drawing in the xy plane for the racetrack coil. The symbols H and R show the coil's half length and arc radius, respectively (b).

In the current study, the SC wire is similar to the strand used in the LHC main dipole. Table 1 summarizes the general parameters of the SC strand. Φ_{wire} and Φ_{overall} represent the non-insulated and the insulated wire diameters, respectively. The copper to superconductor filling factor is given by Cu/SC.

Table 1: SC Strand's Specifications.

Parameter	NbTi
Φ_{wire}	0.825 mm
Φ_{overall}	0.955 mm
Cu/SC	1.95
Insulation	Kapton

The coil is assigned with volume meshed properties with filament size of 0.3 mm. To help properly tracking the temperature rise in the axial and radial directions, along which thermal rises occur over small distances, an anisotropic mesh having a size factor of 0.1 is defined resulting in a maximum size of 30 µm in the coil's transverse plane. For the current driving source, the coil is set to be a circuit element to enable pulsed excitation later.

3. Quench analysis

A quench computational analysis has been made in order to understand the thermal and electromagnetic processes when the SC coil is subject to a pulsed transport current. The analysis has been performed in a quench multi-physics mode. By this mode, values for both electromagnetic fields and temperatures are shared at each time step. Magnetic fields are being calculated by the Transient Electromagnetic (TE) solver which is running concurrently with the thermal solver, therefore, including eddy current effects in the surrounding conducting domains.

The adaptive time stepping has been used for the TE analysis with a span of 3 milliseconds and a maximum error in time stepping of 0.01%. The model is assumed to be initially cooled at a fixed temperature of 4.2 K. The analysis has been carried out on a two-socket workstation, with 16 cores per processor and a RAM total capacity of 120 GB. The study total computational time was about 3 days. Further details on the thermal and TE solvers' settings are given in the next subsections.

3.1. Thermal settings

The thermal and TE settings are based on the strand's main parameters as shown in table 1, where the wire is composed of three materials: the SC, the copper matrix and the insulation. The specific heat capacity of the strand C_{strand} as a function of temperature T is defined according to:

$$C_{\text{strand}} = \frac{C_{\text{sc}}(T)\theta_{\text{sc}}\rho_{\text{sc}} + C_{\text{cu}}(T)\theta_{\text{cu}}\rho_{\text{cu}}}{\rho_{\text{bulk}}}\,, \tag{1}$$

with C, θ and ρ denoting, for each constituent, its specific heat capacity, filling factor and mass density, respectively. The bulk mass density ρ_{bulk} is given by:

$$\rho_{\text{bulk}} = \theta_{\text{sc}}\rho_{\text{sc}} + \theta_{\text{cu}}\rho_{\text{cu}}\,. \tag{2}$$

An anisotropic thermal conductivity $\mathrm{K}(T)$ is assumed for the strand. In the azimuthal direction, the strand constituents are conceived thermally as parallel resistances, hence, the thermal conductivity in this direction reads:

$$\mathrm{K}_{\phi}(T) = \mathrm{K}_{\text{sc}}(T)\theta_{\text{sc}} + \mathrm{K}_{\text{cu}}(T)\theta_{\text{cu}}\,. \tag{3}$$

In contrast, for the axial and radial directions, resistances are in series and thermal conductivity is mainly governed by that of the insulation ($\mathrm{K}_{\text{ins}}(T)$). By applying the homogenization method [4], the thermal conductivity in the radial and axial directions reads:

$$\mathrm{K}_{r,z}(T) = \frac{d + \Phi_{\text{wire}}}{\frac{d}{\mathrm{K}_{\text{ins}}(T)} + \frac{\Phi_{\text{wire}}}{\mathrm{K}_{\text{sc}}(T)\theta_{\text{sc}} + \mathrm{K}_{\text{cu}}(T)\theta_{\text{cu}}}}\,, \tag{4}$$

where d is the insulation total thickness. As can be seen from (4), and because thermal conductivity of copper is orders of magnitude greater than that for insulation, the second fraction in the denominator can be dropped and (4) is reduced to $\simeq \mathrm{K}_{\text{ins}}(T)\frac{\Phi_{\text{overall}}}{d}$.

3.2. TE settings

The electrical conductivity of the strand in the normal state is defined to be that of copper scaled by its volume filling ratio. For the superconducting state, the critical current I_c is given by:

$$I_{\text{c}} = J_{\text{c}} A_{\text{wire}} \theta_{\text{sc}}\,, \tag{5}$$

with A_{wire} for the wire cross sectional area. The parameterization of Bottura [5] has been used to describe the critical current density J_{c} of NbTi as a function of temperature and magnetic flux density B:

$$J_{\text{c,NbTi}}(T, B) = J_{\text{ref}} \frac{C_0}{B} \left[b\right]^{\alpha} \left[1 - b\right]^{\beta} \left[1 - t^n\right]^{\gamma}. \tag{6}$$

The reduced field and reduced temperature b and t are given by $\frac{B}{B_{\text{c2}}(T)}$ and $\frac{T}{T_{\text{c0}}}$, respectively. T_{c0} is the critical temperature at zero field. The upper critical field $B_{\text{c2}}(T)$ as a function of temperature is given by:

$$B_{\text{c2}}(T) = B_{\text{c20}} \left[1 - t^n\right], \tag{7}$$

where B_{c20} is the upper critical field at zero temperature. The values of the free parameters J_{ref}, α, β, n and γ are taken from [6].

As stated before, the SC coil is assigned as a winding circuit element. The current delivered to the coil comes as a result of the damped oscillations occurring in the electrical circuit. The values of lumped elements chosen in the circuit are: 9.76 mF and 195 V for the capacitance and the initial voltage on the capacitor, 0.143 Ω for the series resistor and a high impedance for the circuit switch.

4. Results

To reduce computational efforts, one single pulse has been applied over a span of 3 milliseconds. The generated pulse wave-form is shown in figure 2. A rising time of 0.165 ms and a peak current of 1202 A have been reached. The dashed line indicates the moment when transition to normal state occurs.

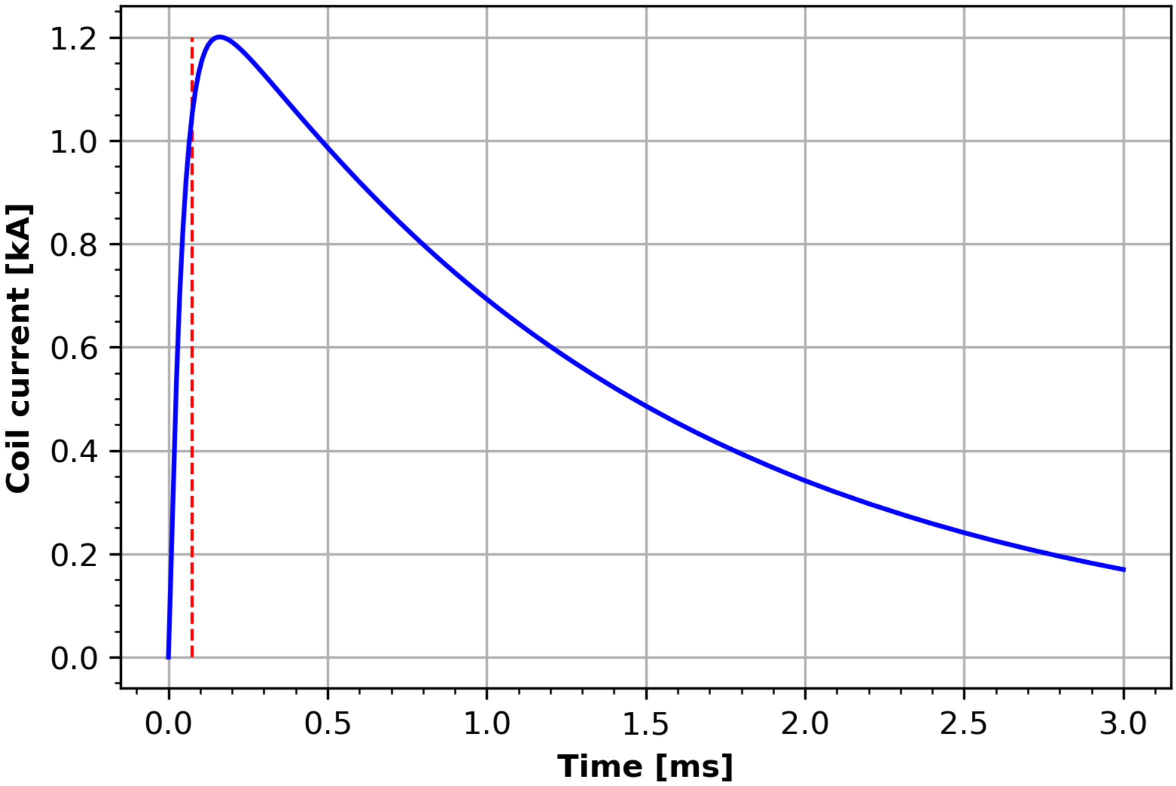


Figure 2: Generated pulse wave-form. The dashed line indicates the time when transition to normal state occurs.

With the applied pulse features, the coil has experienced a transition into the normal state when the transport current exceeded the critical value. Figure 3 shows the transient behavior of the coil's resistance and temperature during the pulse time. In the upper panel, temporal variations of the coil's resistance and the coil's maximum temperature are shown. The quench occurred around the time of 75 µs with a quench current of 1.05 kA. The lower panel in figure 3 shows the critical current of NbTi as a function of the B field at a fixed temperature of 4.2 K according to Bottura [5], together with the load-line estimated for the existing coil geometry.

Clearly, one can see that the quench occurrence agrees with the expected critical current to be around 1 kA as the intersection with the load-line manifests.

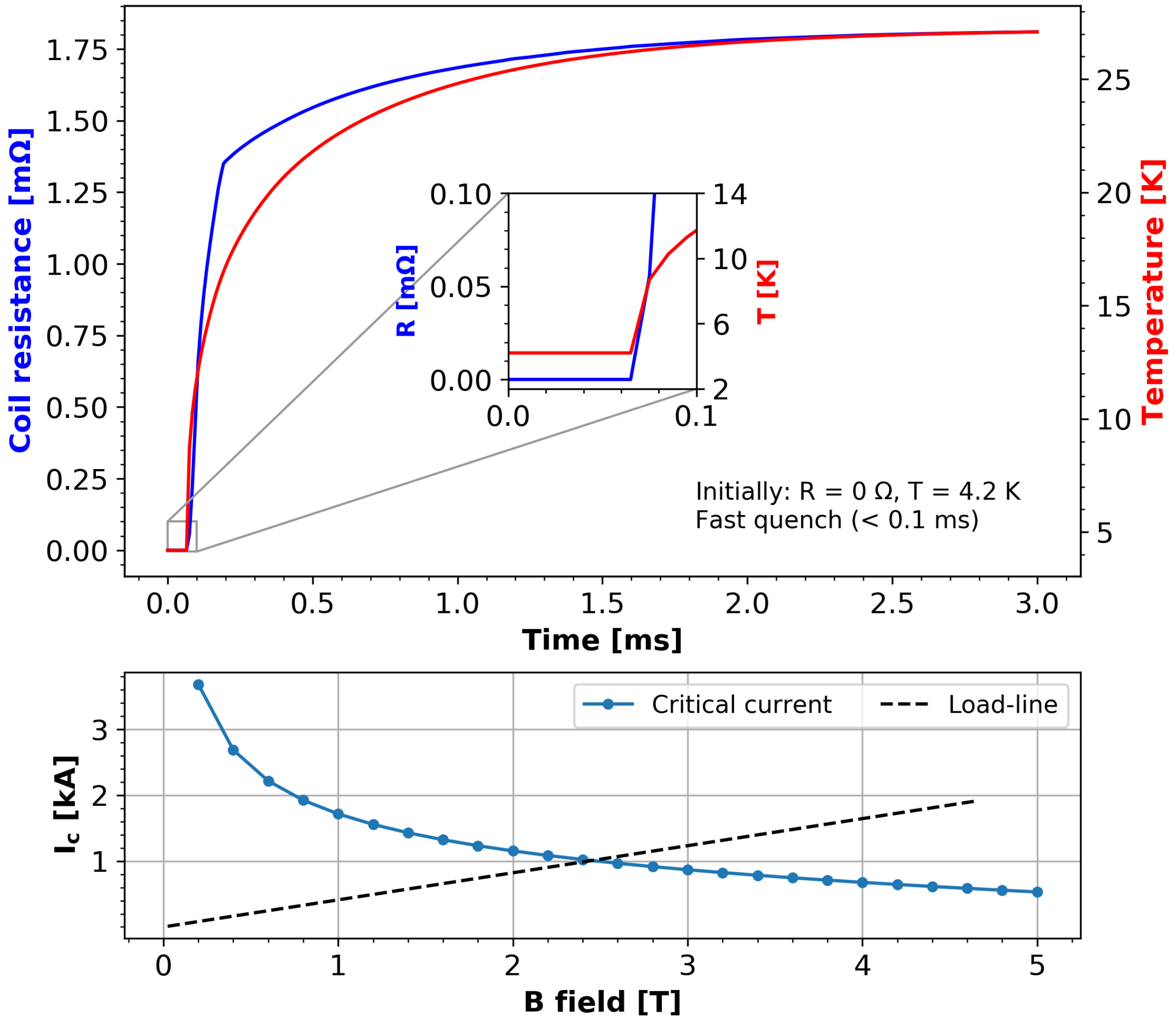
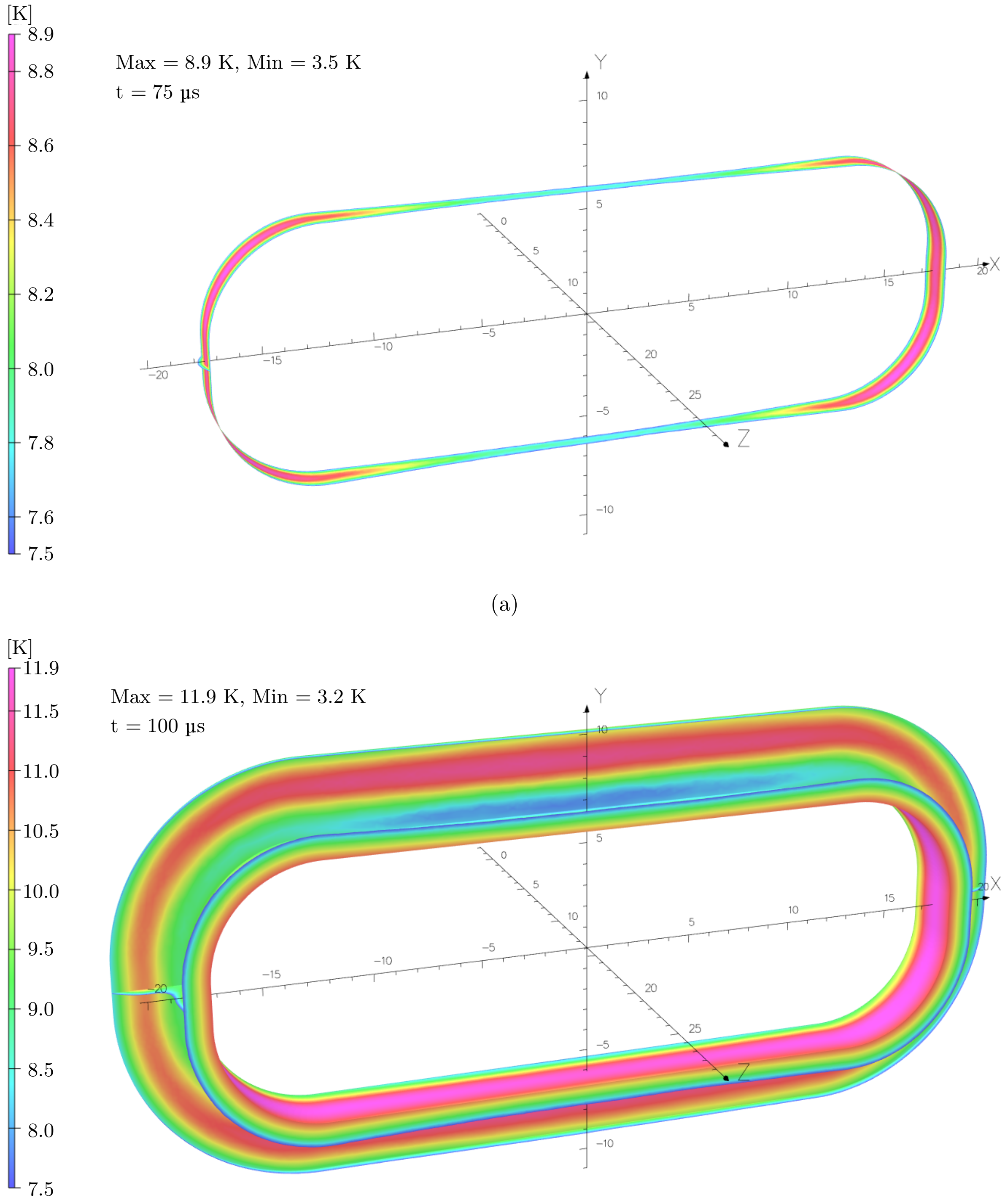


Figure 3: Resistance and hot spot temperature of the NbTi coil over the pulse time. A magnifying inset is showing the moment when the coil switches to resistive mode around 75 µs (upper panel). The critical current of NbTi as a function of the B field at a fixed temperature of 4.2 K together with the load-line estimated for the existing coil geometry (lower panel).

Figure 4 shows how the quench propagates through the coil at different times. The local distributions of the coil's temperature at the times 75 µs (upper panel) and 100 µs (lower panel) are shown. A constraint on the minimum temperature set to 7.5 K is made to demonstrate the temperature evolution. Values of the coil's hot and cold spots at each time are indicated. As can be seen from figure 4, at an early stage, at the time of 75 µs when the quench occurs, the temperature rise is propagating in the azimuthal direction. It can also be seen that the hot spot is initiated at the arcs' locations. In addition, when hot spots begin to form, the local temperature of distant coil parts starts to decrease. Later after the start of the quench, at the time of 100 µs, the temperature rise starts developing radially and axially. From the temporal local temperatures, a clear asymmetric quench can be seen, as would be expected, from the



(a)

(b)

Figure 4: Local distribution for the coil's temperature at the times 75 µs (a) and 100 µs (b). Values of the coil's hot and cold spots at each time are indicated. A constraint on the minimum temperature set to 7.5 K is made to demonstrate the quench propagation in different directions.

effect of conduction heating caused by eddy currents on the surface of the surrounding copper core.

5. Summary

In this paper, computational modeling for a low temperature superconducting racetrack coil with NbTi winding has been presented. A quench coupled solver within Simulia Opera has been used as an analysis tool featuring both thermal and transient electromagnetic processes simultaneously. The model has been investigated under pulsed transport current excitation with a few milliseconds duration and a peak current around 1.2 kA. The quench has been observed when the transport current exceeded the critical value. As a result of conduction heating caused by eddy currents in the surrounding copper core, an asymmetric quench has been observed. A similar recent investigation has been carried out on a Nb_3Sn model. As a follow up, an experimental implementation of the proposed pulse method for an in-situ testing is envisaged.

6. References

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