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Analysis of the quench propagation along Nb$_3$Sn Rutherford cables with the THELMA code. Part II: Model predictions and comparison with experimental results

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ABSTRACT

To improve the technology of the new generation of accelerator magnets, prototypes are being manufactured and tested in several laboratories. In parallel, many numerical analyses are being carried out to predict the magnets behaviour and interpret the experimental results. This paper focuses on the quench propagation velocity, which is a crucial parameter as regards the energy dissipation along the magnet conductor. The THELMA code, originally developed for cable-in-conduit conductors for fusion magnets, has been used to study such quench propagation. To this purpose, new code modules have been added to describe the Rutherford cable geometry, the material non-linear thermal properties and to describe the thermal conduction problem in transient regime. THELMA can describe the Rutherford cable at the strand level, modelling both the electrical and thermal contact resistances between strands and enabling the analysis of the effects of local hot spots and quench heaters. This paper describes the model application to a sample of Short Model Coil tested at CERN: a comparison is made between the experimental results and the model prediction, showing a good agreement. A comparison is also made with the prediction of the most common analytical models, which give large inaccuracies when dealing with low n-index cables like Nb$_3$Sn cables.

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1. Introduction

In the case of a quench, the Nb$_3$Sn accelerator magnets of the new generation, like those to be installed in HL-LHC, will store magnetic energy sufficient to cause a detrimental overheating if the magnets protections will not operate properly. In order to better understand and predict the magnets behaviour as regards this and other aspects, a set of prototypes have been and are being manufactured and tested in several laboratories [1]. This fundamental experimental investigation is complemented by numerical analyses carried out with special-purpose and commercial codes, which describe the magnet and its conductor at different detail levels. In this framework, the THELMA code, originally developed for cable-in-conduit conductors for fusion magnets, has been empowered with the target to study also the accelerator magnets made with Rutherford cables. To this purpose, a new geometrical model for the Rutherford cable was implemented. Coupled with the new thermal model recently developed to predict the performances of NAFASSY magnet conductor [2], this feature permits the electromagnetic-thermal analysis of segments of Rutherford cable in magnetic field in transient regime.

Thanks to the availability of many experimental data collected by CERN SM/18 test laboratories, the quench propagation along Rutherford cables could be selected for a first validation of both these code new modules, being the material non linear thermal behaviour a key factor in this phenomenon. As a benchmark, the experimental results obtained from one of the Short Model Coil prototypes have been used. The prototype considered is Short Model Coil 3 (SMC3), a short racetrack coil made with Nb$_3$Sn cable, developed in the frame of the Next European Dipole Joint Research Activity, a collaboration between CEA, CERN, SFTC with the technical support of LBNL [3,4]. This project was a part of the European EUCARD project, for the development of particle accelerators in order to achieve a higher luminosity and larger beam energies [5]. The target of this subszie coil was to achieve a magnetic field of 12 T on the conductor: this was actually confirmed by the ramped current training tests, carried out in 2011, which showed the coil capability to reach 12.5 T at 1.9 K after training.
This paper is mainly focused on a validation of the THELMA new models against the experimental data. In addition, an opportunity is also taken to review some usual analytical models of the quench propagation along a superconductor and to compare their predictions with the results obtained experimentally and with THELMA.

In the paper the relevant experimental aspects and results are described, while the details of the geometrical and thermal models formulation are presented in the companion paper [6].

2. Analytical formulae for the quench propagation velocity

Before describing SMC3 and its tests, a summary of three commonly used analytical models of the quench propagation is given. These analytical models assume a monodimensional cable geometry, describing the cable as a solid homogeneous material cooled by a helium bath with constant temperature or in adiabatic conditions [7–9]. The temperature profile along the conductor is supposed to propagate as a wave travelling at the quench propagation velocity \( v_q \) without modifying its shape. The heat current balance equation, written with respect to a reference axis with coordinate \( z \) travelling together with the temperature wave, is:

\[
d\frac{d}{dz}\left(k \frac{dT}{dz}\right) + v_q \gamma c_r \frac{dT}{dz} + G(T, J) = 0.
\]

(1)

where \( \gamma c_r \) is the volumetric specific heat (J/m\(^3\)K), \( k \) is the thermal conductivity (W/mK), \( J \) is the engineering transport current density and \( G(T, J) \) is the generation function, corresponding to the losses in the conductor per unit of volume at the given current density (W/m\(^3\)) [7]. This equation is non linear, so that simplifying hypotheses had to be made to get an analytical solution or, at least, an estimation of \( v_q \). The first assumption in [7–9] is that the whole conductor can be represented as a superconducting (SC) region adjacent to a normal conducting region, with different material properties. The transition occurs at temperature \( T_{tr} \), called transition temperature, corresponding to the losses in the conductor per unit of volume at the given temperature (W/m\(^3\)) [7]. This equation is non linear, so that simplifying hypotheses had to be made to get an analytical solution or, at least, an estimation of \( v_q \). The first assumption in [7–9] is that the whole conductor can be represented as a superconducting (SC) region adjacent to a normal conducting region, with different material properties. The transition occurs at temperature \( T_{tr} \), called transition temperature, corresponding to the losses in the conductor per unit of volume at the given temperature (W/m\(^3\)) [7].

In general, one may express \( T_v \) as:

\[
T_v = T_g + x_v (T_c - T_g),
\]

(7)

with 0 < \( x_v \) < 1. In his model, Wilson proposes a linear dependence of \( g \) with \( T \) [7], which gives \( x_v = 1/2 \) (Fig. 1 left). An alternative approach is to consider the current in the stabilizing copper linear with the temperature in the current-sharing regime [10], which corresponds to a quadratic \( g(T) \) and gives \( x_v = 2/3 \) (Fig. 1 right). An evaluation of the optimum \( x_v \) value is given below, on the basis of the comparison between measured and analytically computed velocities.

3. The Short Model Coil 3

SMC3 is formed by two double pancake racetrack coils, each pancake (layer) being made of 21 turns divided into 3 groups of 17, 2 and 2 turns. A view of the impregnated coil, with its instrumentation wirings is shown in Fig. 2. The coil cable is of Rutherford type, made of 14 Nb3Sn PIT Bruker-EAS strands with a diameter of 1.25 mm and a Cu/non Cu ratio 1.25. The cable has a transposition pitch of 60 mm and a rectangular cross-Section 10 mm wide and 2.2 mm thick. The cable RRR is between 70 and 80 and the short sample critical current is 15,400 A at 4.2 K and 18,500 A at 1.9 K. The critical current measured on extracted and virgin strands at 10 T gave respectively 1563 A and 1868 A, which gives a critical current degradation of 16.3%. The cable is insulated with a thin ceramic layer, locally reinforced with a glass tape and surrounded by a fibreglass sleeve. The finished coil is vacuum impregnated with epoxy resin. The coil is inserted in an iron yoke suitably shaped to achieve the maximum magnetic field in the central straight part of the coil, which is 150 mm long. The field profile is improved also by spacers between the turns groups at the coil ends. An external aluminium ring applies a mechanical preload on the coil thanks to the differential thermal contraction. The preload can be adjusted by means of suitable bladders, keys and longitudinal rods [11].
3.1. Experimental set-up

As far as the electromagnetic measurements are concerned, the magnetic field is measured by a Hall probe per coil, while the voltage distribution along the coil conductor is measured by means of eight voltage taps per coil layer. These taps are suitably arranged in order to measure the voltage along the innermost turn of each layer, along the layer jump and along a set of turns located in the coil lower field zone. Inside the coil, the voltage taps connections have been realised with the printed boards technique: thin traces of coupled steel and copper traces are obtained on a polyimide sheet. Other traces in the same sheet connect the Hall probe, the coil strain gauges and two spot heaters. The voltages along the conductor are measured as differences between these taps signals, so that 15 longitudinal voltage signals are available. A schematic of the voltage taps location on the two layers of each coil is shown in Fig. 3.

In principle, since the geometry of the voltage taps connections cannot be exactly the same as the corresponding coil conductor segment, an inductive coupling exists between the whole coil and the voltage connections. This may be important during the quench early phase, when the differential voltage signals used to detect the quench are below the rated threshold and the coil current is slowly decreasing, due to the power supply progressive loading. However, it was shown that the inductive effect removal was worthwhile only for voltage measurements over the coil longest segments, made of several turns, while the shortest segments (as the one used here) showed almost negligible effects.

The voltage data used in this analysis have been collected from two training campaigns at a temperature of 4.2 and 1.9 K, in which the coil was fed with ramps of current at a ramp rate of 10 or 20 A/s. During training, two plateau current values have been reached, at 95% and 92% of the load line, respectively at 4.2 and 1.9 K, which correspond to 12.5 T on the conductor. The large majority of the quenches was detected in the straight part of the innermost turn, between taps 102 and 72 (see Fig. 3), located in the coil 1 lower layer. The distance between these taps is 13 cm.

The quench propagation velocity was measured with the Time-of-Flight (ToF) method, which is based on the measurement of the voltage along one or three consecutive coil segments [12,13]. As an example, Fig. 4 left shows the voltages over the straight coil segment 102-72 and the two adjacent segments 62-102 and 72-71 during a quench at 14,053 A at 1.9 K. In these measurements, the quench velocity has been determined as

\[
\nu_{\text{ToF}} = \frac{\text{dtaps}}{(t_1 + t_2)},
\]

where \(d_{\text{taps}}\) is the distance between the voltage taps across the coil conductor segment. The values of \(t_1\) and \(t_2\) have been determined on the basis of a visual analysis of the waveforms, in order to unambiguously state the resistive voltage increase and to detect the presence of possible quench precursor spikes. The typical voltage threshold adopted in a pulse like that of Fig. 4, left, is of the order of 5 mV.

Some experimental values obtained from quenches initiated along 72-102 section are reported in Fig. 4 right, for tests at 4.2 and 1.9 K. This figure reports the propagation velocity as a function of the final current reached during the ramp-up, when quench occurred.
4. Comparison between measurements and analytical models

The $v_q$ values measured from SMC3 have been compared with the predictions given by the analytical models (3)–(5), considering two values for both the SC initial temperature $T_0$ (1.9 and 4.2 K), and $x_{tr}$ (1/2 and 2/3). For the calculation, the same material property models used in THELMA have been adopted [14]. Fig. 5 reports the computed $T_c$ and $T_g$ as a function of the transport current. The $T_r$ values corresponding to $x_{tr} = 1/2$ and 2/3 are also reported, showing that, for large currents, the difference between them can be even larger than one K.

The comparison between the measured $v_q$ and the value computed with the analytical models is presented in Fig. 6. As a general result, in the case of SMC3 the analytical formulae tend to overestimate the velocity and give more accurate values when a higher SC initial temperature is present and $x_{tr} = 2/3$. While Wilson formula (3) is clearly less accurate, being the result of very strong model simplifications, Dresner formula (5) gives the most accurate

Fig. 4. Left: voltages over the straight segment 102-72 and the two adjacent segments during a quench at 14,053 A. Right: quench propagation velocity along coil segment 72-102 as a function of the final current reached during the ramp-up.

Fig. 5. Computed critical temperature $T_c$ and generation temperature $T_g$ for SMC1 conductor. The transition temperatures corresponding to a linear and a quadratic approximation for the generation function are also reported.
predictions at low $\alpha_T$, being essentially as accurate as Whetstone and Roos formula (4) if $\alpha_T = 2/3$. Since the volumetric heat capacity is proportional to $T^3$ in this temperature range [14], the use of lower $\alpha_T$ involves smaller averaged $c_v$ in (3) and $D$ in (4) and (5). The results obtained seem therefore to outline the strong influence of the calorimetric properties SC material in the proximity of the transition temperature.

5. The THELMA model

The THELMA model for the analysis of the quench propagation considers the 15 cm long coil straight part which includes the 72-102 coil segment. Identical cable segments, but with different locations in the coil, have also been parametrically considered, as described below. The Rutherford cable has been described with the new geometrical model, which gives the input data for both the thermal (TH) and electromagnetic (EM) coupled models. Adiabatic conditions have been assumed for the cable, since the insulation thermal diffusivity is usually much smaller than in the conductor [15]. Therefore, in this first model, the insulation heat capacitance has not been taken into account and the inter-strand heat transfer is possible through the inter-strand thermal conductances. A discretisation step of 1 mm has been adopted along the cable, to guarantee the model results convergence and to be consistent with the cross-over contact length, which is about 1–2 mm. A pictorial view of the modelled coil part is given in Fig. 7.

5.1. Electromagnetic model

Although the tests were carried out with a slow ramp of current, in the simulations a constant cable transport current is assumed and the quench is triggered by a heat pulse as described below. The transport current is supposed to be evenly applied at the ends of the cable strands; nevertheless, this current is free to redistribute among and along the strands during the quench propagation, due to electromagnetic and thermal coupling. As a
consequence of this, possible current initial imbalances among the cable strands are neglected. These assumptions are considered reasonable, due to the very small current ramp rate and to the very short time intervals over which the quench propagation develops in the cable segment considered.

The EM model represents the cable with a distributed parameters non linear network [16,17]. This model makes use of the inter-strand contact conductances per unit of length, which are automatically computed starting from the cable geometry.

To implement the EM model boundary conditions, two sets of equal constant current generators with two polygons of lumped inter-strand resistances have been considered at both ends, so that the current redistribution is possible even at the strands ends.

To describe the SC non linear electrical behaviour, the Twente/ITER strand scaling law has been considered [18], with the parameters reported in Table 1 [19]. An applied strain \( \varepsilon_{applied} = -0.2\% \) has been considered, as a consequence of cabling and coil manufacture. The field – current characteristic is considered in terms of power law in which the \( n \)-index is assumed variable with the strand critical current \( I_c \) [20]:

\[
E = E_c \left( \frac{I}{I_c} \right)^n,
\]

\( n = 1 + r f'_c = 1 + 2.20 f'^{0.47} \).

The \( r \) and \( s \) parameters adopted in this equation come from a typical PIT strand [21], albeit with a different diameter (0.81 vs. 1.25 mm). For this reason, \( r \) has been suitably re-scaled in order to have the same \( n \) value for the same non-Cu \( J_c \). The strand Cu resistivity is supposed to depend on magnetic field and temperature according to the NIST model [14], with a RRR = 75. The adjacent and cross-over contact electrical resistances used as a starting point to compute the THELMA EM contact resistances were \( R_e = 9.4 \mu \Omega \) and \( R_s = 1 \) mQ [22], which correspond to the THELMA distributed and spot contact resistances \( R_e = 10.4 \mu \Omega \) and \( R_s = 0.5 \) mQ, determined as described in detail in [6].

### 5.2. Thermal model

The THELMA TH model can take into account the dependence of the thermal contact conductance on temperature [23]. In the absence of more specific data, the values of coated NbTi interstrand contact conductances reported in [24] as a function of temperature (4–10 K) have been considered as a reference. In these measurements, a sample made of a stack of parallel strands is considered, so that no cross-over contacts and only distributed contacts are present. Therefore, the measured heat conductivity (in [24] called 1/Wm = ISTC) corresponds directly to the series of two strand distributed thermal conductances. A numerical fit has been determined from these data, giving:

\[
G_d = \alpha T^0 = 0.545 T^{1.54} \text{W/m K.}
\]

From these values, an estimation of the spot thermal contact conductance has been done by considering the inter-strand spot contact as a distributed contact as long as the strand diameter.

In the TH network, the heat pulse used to trigger the quench is applied by a trapezoidal heat current generator connected between a strand thermal node, located at the cable middle length, and the thermal mass node. This is acceptable since our analysis aims at the evaluation of the quench propagation velocity and is not intended for the detection of the quench causes or the estimation of the quench minimum energy. The heat pulse amplitude and total duration range respectively from 0.1 to few mJ and from less than one up to few ms. In this way the quench propagation can be studied not only along the cable, but also at the cable cross-section level.

### 5.3. Iron magnetic model

Presently THELMA takes into account the magnetic field generated by the coil conductor which can be represented with different levels of detail. For SMC3, all the strands of the modelled Rutherford cable segment are individually represented, with possibly non uniform current along their axis, while the rest of the coil is represented by a sequence of solid blocks fed with the transport current [25]. The field contribution of all these blocks is computed with an integral approach assuming a uniform magnetic permeability.

However, for this magnet, iron plays a key role as regards the field profile uniformity along the coil conductor and gives a non negligible contribution to the total field (up to 2 T). To take into account the contribution of iron at the strands locations as a function of the transport current, a ROXIE code 2D model has been developed [26]. A check with a 3D detailed analysis available in literature gave an error of only 0.1 and 0.5 T, respectively at the middle length and at the boundaries of the modelled coil segment [11]. The iron field contribution computed in this way was added to the coil contribution, to compute the material properties and SC scaling law. The impact of this error has been checked through a parametric analysis presented below.

### 6. THELMA model results

The THELMA model of SMC3 takes into account the inter-strand coupling losses and the strand DC (power law) losses. No hysteresis and inter-filament losses have been taken into account. Voltages
and losses are computed starting from the material properties, which are continuously updated on the basis of current density, temperature and magnetic field. In this sense, in THELMA there is no degree of freedom as regards the generation function, which corresponds to the only DC losses. As a comparison with Fig. 1, the results obtained assuming constant $n$ values, showing how lower and lower $n$ indexes are being considered by THELMA with the increasing temperature.

Among the THELMA output data are the current and the temperature distributions along the strands for given time values. As an example, Fig. 9 shows these distributions for a quench at 14 kA and 4.2 K, caused by a trapezoidal heat pulse of 0.125 mJ, lasting 0.3 ms. The left subfigures report the temperature distribution at $t = 0.35$, 1.35 and 2.35 ms after the heat pulse peak, while the right subfigures show the corresponding strands current distribution. At the very beginning of the quench ($\Delta t = 0.35$ ms), a sharp temperature increase is present in the heated strand, close temperature increase is present in the heated strand, close temperature values are present in the two adjacent strands, while the rest of the strands still shows a negligible temperature increase. The current in the heated strand is redistributed to the other strands in a complicated fashion, due to the strands geometry and their contact path. At the heated cable cross-section, the transition is almost completed already at $\Delta t = 1.35$ ms, and two fronts of temperature are propagating towards the cable ends, which are being reached at $\Delta t = 2.35$ ms. It interesting to notice that, while the temperature increase propagates in an almost symmetrical way in both directions, non symmetrical current imbalances are present, due to the strands transposition, which affects the inductive inter-strand coupling. With the increasing temperature, the strand currents imbalances tend become smaller and smaller, being the resistive effect predominant.

6.1. Comparison with the measured velocity values

To comply with the available experimental data, the ToF method has been applied first (8). To this purpose, an array of virtual voltage probes has been considered along the modelled cable, located every cm, thus giving rise to 14 coil segments. The voltage over each coil segment has been computed as the average of the corresponding voltages along the strands. The distance $d_{\text{aps}}$ between the couples of coil segments used to detect the voltage increase was not only the nominal value, 13 cm, but lower distances have been considered as well, as a matter of comparison. The propagation time values $t_1$ and $t_2$ have been computed considering several longitudinal voltage thresholds between 1 mV and 10 mV over the 1 cm coil segment length, to check for possible velocity differences. At the nominal $d_{\text{aps}} = 13$ cm the threshold value affects the results by less than 1 m/s, in agreement with the experimental accuracy of 1:2 m/s. For lower values of $d_{\text{aps}}$, discrepancies up to about 2 m/s can be found, in any case comparable with the experimental accuracy.

The second approach followed for the estimation of $v_\text{ToF}$ is based on the evolution of the computed temperature along the cable, considering the velocity at which a given temperature is propagating along the cable. However, since the strands temperature in the travelling front is not uniform (Fig. 9), different velocities can be obtained from the individual strands. The results show that, if sufficiently long distances are considered for the temperature
propagation (3.5 cm in our simulations), $v_q$ values in excellent agreement with those computed with the ToF method are obtained.

As done for the analytic models, $v_q$ has been studied as a function of the cable transport current $I_t$ at two initial temperatures $T_0 = 1.9$ and 4.2 K. Fig. 10 shows the comparison between the measured and the computed $v_q$ for both temperatures. In this figure, the measured values are reported as a function of the final current reached during the ramp-up, when quench occurred, while the computed values are reported as a function of the steady-state current assumed for the THELMA run. As it can be seen, the agreement is very good for both temperatures, and this is particularly important, since the only model parameter changed between the two cases, for a given transport current, is the initial temperature. The magnetic field is automatically determined starting from the transport current. In the end, comparing this figure with Fig. 6, one can see that, at both temperatures, the code gives much more accurate velocity predictions, compared with analytical models.

6.2. Parametric analyses

To better understand the model sensitivity to the material and boundary conditions, a set of parametric analyses has also been carried out. As a reference for all them, a transport current $I_t = 14$ kA and a temperature $T = 1.9$ K, corresponding to $v_q = 20.6$ m/s, have been considered. In each analysis, one model parameter has been changed in turn with respect to its reference value.

The first analysis deals with the $n$ value: a set of $v_q$ values have been computed from simulations made assuming constant $n$ values ranging from 10 to 100, instead of a variable $n$ computed by means of Eq. (9). The results are reported in Fig. 11 left, in which the propagation velocity as a function of $n$ is plotted in terms of percent ratio with respect to the reference value. This curve shows that the computed $v_q$ is associated with relatively high $n(I_c)$ values, as expected for the PIT SMC3 strand. However, it must be said that, in general, $v_q$ is appreciably affected by $n$ index only if the conductor current is very high (10–15 kA), due to the larger current sharing regime.

The second evaluated aspect is the dependence of $I_c$ in the Nb$_3$Sn strand strain. The strain affects the critical current which, in turn, affects also the generation temperature $T_g$. In the reference conditions $T_{g0}^{ref}$ is about 4.6 K. Different levels of applied strain $\varepsilon_{appt}$ between $-0.4\%$ and $0\%$ have been considered, with the results presented in Fig. 11 right, where $T_g$ and the propagation velocity are reported as a function of $\varepsilon$. In this figure the velocity is
expressed again in terms of percent ratio \( v_p \% \) with respect to the reference value. As it can be seen, the generation temperature corresponding to the applied strain has a remarkable change, ranging between 3.3 and 5.2 K, with corresponding velocity changes up to 40%.

The last parameter considered in the analysis is the magnetic field. The aim of this analysis is to check the \( v_p \) changes for field variations comparable with those met along 102-72 segment as a consequence of the iron 3D geometry. To this purpose, the quench propagation has been studied along two more adjacent coil straight segments 61-51 (with highest peak field: \( B_{61-51} = 12.8 \) T) and 112-52 (lower peak field \( B_{112-52} = 11.6 \) T). The results are presented in Fig. 12, where they are compared with the measured values in 102-72 section. As in the case of \( n \) value parametric variation, differences can be observed at large \( I_t \) values, while negligible variations are present for lower current.

7. Conclusions

The analysis of the quench longitudinal propagation in the Nb3-Sn prototype coil SMC3 has been presented. This analysis makes use of the new THELMA thermal model, coupled with the existing electromagnetic module. As far as the longitudinal quench propagation is concerned, a very good correspondence is present between measured and computed values, which shows not only the accuracy of the electromagnetic and thermal coupled models in this case, but also the correctness of the material properties description. The results obtained from three commonly used analytical models of the quench longitudinal propagation have also been discussed, on the one hand showing the importance of a correct definition of the models transition temperature and, on the other hand, the THELMA model better accuracy.

Further model important developments are going to be implemented in THELMA, namely the model of insulating layers, which will permit the effects of coil insulation to be taken into account, to study also the quench transverse propagation and the cable heaters efficiency as regards the quench protection.

THELMA can model Rutherford cables at a very detailed level. However, to carry out reliable results, a deep knowledge of the material properties of the modelled materials is of paramount importance, together with the accurate measurement of the contact thermal and electrical resistances between strands. Alternatively, THELMA can be used as an analysis tool for the determination of these parameters starting from a set of experiments parametrically modelled with the code.

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