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Analysis of the quench propagation along Nb₃Sn 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 Nb₃Sn cables.

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1. Introduction

In the case of a quench, the Nb₃Sn 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 perfor-

mances 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 Nb₃Sn 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 subsize 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.

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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:

$$\frac{d}{dz} \left(k \frac{dT}{dz} \right) + v_q \gamma c_v \frac{dT}{dz} + G(T, J) = 0, \quad (1)$$

where γc_v is the volumetric specific heat (J/m³ K), k is the thermal conductivity (W/m K), 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 temperature (W/m³) [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 boundary between these regions, for which travelling coordinate $z = 0$ is assumed. The material properties are discontinuous at this boundary and $G(T, J)$ is usually expressed as:

$$G(T, J) = \begin{cases} \varrho J^2 & \text{for } T \geq T_{tr} \\ 0 & \text{for } T < T_{tr}, \end{cases} \quad (2)$$

where ϱ is a suitably averaged resistivity of the normal conductor.

In addition to these hypotheses, Wilson assumes constant, albeit suitably averaged, c_v and k , giving this propagation velocity in adiabatic conditions [7]:

$$v_q^W = \frac{\sqrt{k \varrho} J}{\gamma c_v \sqrt{(T_{tr} - T_0)}}, \quad (3)$$

where T_0 is the superconductor initial temperature. More accurate models take into account the dramatic change of material properties across the resistive transition. Whetstone and Roos give an expression that can be rewritten as [9]:

$$v_q^{WR} = \frac{\sqrt{k_{nc} \varrho} J}{\sqrt{\Delta u_s \left[\gamma c_{v_{nc}} - \frac{\Delta u_s}{k_{nc}} \frac{dk_{nc}}{dT} \right]}}, \quad (4)$$

where $\Delta u_s = u_s(T_{tr}) - u_s(T_0)$ is the internal energy variation in the superconductor, k_{nc} and $c_{v_{nc}}$ are respectively the thermal conductivity and specific heat in the normal conductor at temperature T_r .

A similar expression is given by Dresner [8]:

$$v_q^D = \frac{\sqrt{k_{nc} \varrho} J}{\sqrt{\Delta u_s \gamma c_{v_{nc}}}}. \quad (5)$$

The analytical models summarised above are useful for a first estimation of v_q but, when more accurate values are sought, they have

some questionable aspects. In this paper we consider the T_{tr} value, which corresponds to a material sudden transition and in these analytical models regards simultaneously both the thermal properties change and the power generation. In a real SC material, non-negligible losses can take place even at a lower temperature, called *generation temperature* $T_g < T_{tr}$, which can be defined as the temperature at which the critical current is being exceeded by the transport current [7]. The use of (2) corresponds to neglect any possible current sharing regime among SC and stabiliser for $T_g < T < T_{tr}$. For some materials with a sharp transition, like NbTi in some conditions, one can assume $T_g \approx T_c$, so that $T_{tr} \approx T_c$, but this is usually inaccurate for Nb₃Sn cables, characterised by a current-sharing regime that can span over several degrees, with non negligible losses even at very low temperatures, at which the specific heat is quite low. In addition, while T_c depends only on magnetic induction and, possibly, the strain in the conductor, T_g depends also on the transport current.

The optimum T_{tr} can be determined starting from the characteristics of the *normalised generation function* $g(T) = G(T, J)/G(T_c, J)$ on the basis of this averaging condition:

$$g(T_{tr}) = \frac{1}{T_c - T_g} \int_{T_g}^{T_c} g(T) dT. \quad (6)$$

Notice that $g(T_{tr})$ does not depend on the engineering current density. With this condition, the same amount of losses is developed with the continuous transition between T_g and T_c and the sudden transition at T_{tr} .

In general, one may express T_{tr} as:

$$T_{tr} = T_g + \alpha_{tr} (T_c - T_g), \quad (7)$$

with $0 \leq \alpha_{tr} \leq 1$. In his model, Wilson proposes a linear dependence of g with T [7], which gives $\alpha_{tr} = 1/2$ (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 $\alpha_{tr} = 2/3$ (Fig. 1 right). An evaluation of the optimum α_{tr} 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].

Fig. 1. Normalized generation function $g = G(T)/G(T_c)$ as a function of temperature. Left: linear dependence. Right: quadratic dependence.

Fig. 2. View of one impregnated SMC3 coil double pancake. The three turn groups are visible, together with the instrumentation wirings.

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 very 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

$$v_q^{\text{ToF}} = d_{\text{taps}} / (t_1 + t_2), \quad (8)$$

where d_{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.

Fig. 3. Schematic of the voltage probes location on the two layers of each SMC3 coil.

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.

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 α_{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_{tr} values corresponding to $\alpha_{tr} = 1/2$ 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 $\alpha_{tr} = 2/3$. While Wilson formula (3) is clearly less accurate, being the result of very strong model simplifications, Dresner formula (5) gives the most accurate

Fig. 5. Computed critical temperature T_c and generation temperature T_g for SMC3 conductor. The transition temperatures corresponding to a linear and a quadratic approximation for the generation function are also reported.

Fig. 6. Comparison between the experimental and the computed values of quench longitudinal propagation velocity v_q in SMC3 as a function of transport current I_t . Above: results at 1.9 K. Below: results at 4.2 K. The left plots represent the results for $\alpha_{tr} = 1/2$, the right ones for $\alpha_{tr} = 2/3$.

predictions at low α_{tr} , being essentially as accurate as Whetstone and Roos formula (4) if $\alpha_{tr} = 2/3$. Since the volumetric heat capacity is proportional to T^3 in this temperature range [14], the use of lower α_{tr} involves smaller averaged c_v in (3) and Δu_s 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 considered in the parametric analyses, 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.

Fig. 7. Pictorial view of the THELMA model of the SMC3 coil 15 cm long straight part of the innermost turn including 72 and 102 voltage taps.

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

Table 1
Parameters for the SMC3 scaling law.

p	q	C	$B_{c20,max}$ (T)	$T_{c0,max}$ (K)	$C_{n,1}$	$C_{n,2}$	$\varepsilon_{0,a}$ (%)	ε_m (%)
0.5	2	$2.118 \cdot 10^{11}$	29.452	16.973	45.062	4.256	0.286	0

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 $\varepsilon_{appl} = -0.2\%$ 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 (A) [20]:

$$E = E_c \left(\frac{I}{I_c} \right)^n, \quad (9)$$

$$n = 1 + r I_c^s = 1 + 2.20 I_c^{0.47}.$$

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 I_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 $R_a = 9.4 \mu\Omega$ and $R_c = 1 \text{ m}\Omega$ [22], which correspond to the THELMA distributed and spot contact resistances $R_d = 10.4 \text{ n}\Omega \text{ m}$ and $R_s = 0.5 \text{ m}\Omega$, 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 $1/W_{is} = \text{ISTC}$) corresponds directly to the series of two strand distributed thermal conductances. A numerical fit has been determined from these data, giving:

$$G_d = \alpha T^\beta = 0.545 T^{1.54} \text{ W/m K}. \quad (10)$$

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

Fig. 8. Normalized generation function $g = G(T)/G(T_c)$ as a function of temperature computed with THELMA model, with variable n index (solid curve). The dashed lines correspond to generation functions computed with constant n values.

Fig. 9. Quench of the cable at 14 kA and 4.2 K: distribution of strands computed temperatures (left figures) and corresponding distribution of computed currents (right figures) along the 14 strands for different time values Δt after the heat pulse peak.

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, Fig. 8 reports the normalised generation function computed by THELMA for SMC3 at $I_t = 14$ kA. As described above, this curve is computed assuming a variable n index. This figure reports also 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 $\Delta t = 0.35$, 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 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 is 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 to 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_{taps} 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 $d_{taps} = 13$ 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_{taps} , 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_q 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

Fig. 10. Comparison between experimental data and THELMA simulations for $T_0 = 1.9$ K (left) and 4.2 K (right).

Fig. 11. v_q obtained from parametric analyses assuming different constant n (left) and ε (right) values, with $T_0 = 1.9$ K and $I_t = 14$ kA.

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 Nb₃Sn strand strain. The strain affects the critical current which, in turn, affects also the generation temperature T_g . In the reference conditions T_g^{ref} is about 4.6 K. Different levels of applied strain ε_{appl} 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

Fig. 12. Computed v_q as a function of I_t for two more adjacent coil sections, with different background magnetic field. Left: 1.9 K, right: 4.2 K.

expressed again in terms of percent ratio $v_q\%$ 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_q 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 Nb₃Sn 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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