

Characteristic Timescales for the Operation of HTS CICCs in Compact Fusion Reactors

Original

Characteristic Timescales for the Operation of HTS CICCs in Compact Fusion Reactors / Breschi, M., Savoldi, L., Cavallucci, L.. - In: IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY. - ISSN 1051-8223. - ELETTRONICO. - 35:5(2025), pp. 1-5. [10.1109/TASC.2025.3554466]

Availability:

This version is available at: 11583/3015116 since: 2026-09-02T16:12:55Z

Publisher:

Institute of Electrical and Electronics Engineers Inc.

Published

DOI:10.1109/TASC.2025.3554466

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

Characteristic timescales for the operation of HTS CICC in compact fusion reactors

Marco Breschi, *Senior Member, IEEE*, Laura Savoldi, *Member, IEEE*, Lorenzo Cavallucci, Luca Bottura

Abstract— In this work we address the shift from Low Temperature Superconductor (LTS) to High Temperature Superconductor (HTS) magnets presently occurring in the development of machines for controlled thermonuclear fusion with magnetic confinement. This shift implies several new challenges, which cannot be ignored in the design and modelling of the future HTS magnets. In this work, we identify the modelling needs driven by the adoption of HTS cables and coils technology for fusion machines. In particular, the characteristic times characterizing the development of the main physical phenomena occurring in HTS tapes, stacks and conductors are derived. These characteristic times in turn have a significant impact on the requirements of strong or weak coupling between different physics in the modelling of HTS magnets.

Index Terms— HTS, slotted core, quench, fusion cable, compact reactor.

I. INTRODUCTION

AN overview of the different options currently under discussion among the candidates to produce electricity from fusion power broadly shows two main lines of thoughts, as far as the generation of the required magnetic field is concerned. On the one hand, several national roadmaps to fusion rely on tokamak designs obtained scaling up ITER, i.e. based on LTS superconducting magnets, and considering the use of HTS only as an option to increase the flux swing generated by the Central Solenoid. This line has a time horizon of several decades, and numerical tools for the multifaceted modelling of superconducting magnets, from micro-scale to system level is quite established [1-10]. On the other hand, a flourishing of private companies is betting on the use of HTS magnets to achieve commercial fusion power on a much earlier time horizon. The higher magnetic field, made possible by HTS, allows moving to more compact designs. A variety of solutions is in development, spanning from D-shaped, non-insulated coils wound with stacked HTS tapes, as foreseen in the ARC tokamak [11], to non-planar coils obtained by laser direct patterning over cylinders coated with HTS films for stellarators [12]. The layout of these HTS coils is unprecedented, and available tools may be no longer optimal, nor even suitable.

This work has been partly carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

The shift to HTS allows also in principle to increase the operating temperature from 4.5 K to, say, 20 K, which allows achieving much higher cooling efficiencies. The materials at 20 K also exhibit different properties than at 4.5 K, especially as far as the heat capacity of solids is concerned, showing much higher values. These variations significantly modify the heat inventory, with the solids gaining a substantial role at 20 K with respect to the cryogenic fluid. It should be recalled that at 4.5 K most of the enthalpy available is provided by the supercritical helium, while the solids heat capacity is extremely low. The differences in characteristic times between LTS and HTS conductors refer to both the cable architecture and the material properties. Such differences concern both the development of solely electromagnetic or thermal transients and the evolution of coupled thermal – electrical phenomena, such as in the case of quench.

In this work we address the issue of the shift from LTS to HTS, identifying part of the modelling needs driven by the adoption of HTS conductor and coil technology for fusion machines. Based on a representative case study of a slotted-core conductor, the characteristic times for the development of the main physical phenomena occurring in HTS tapes, stacks and conductors are derived. Some of the differences with respect to LTS are related to the different tape, wire or conductor architecture, while others depend on different material properties, as the operating temperature could be pushed to 20 K, if a full HTS magnet design is pursued.

II. HTS CONDUCTORS: ANALYSED CONFIGURATION

The analysis of the characteristic times of the main electromagnetic, thermal and hydraulic phenomena occurring in LTS conductors was presented in [13], with reference to stability studies of Cable in Conduit Conductors. For the analysis of the characteristic times in a typical HTS fusion magnet, in this study we select the configuration of the SEctor-ASsembled (SECAS) conductor based on BRAided STacks (BRAST). This conductor was recently developed for fusion magnet applications at the ENEA Frascati laboratory of Applied Superconductivity [14]. The conductor, shown in Fig. 1, consists of 6 sub-cables, each composed of a copper slotted core including a stack of 10 REBCO conductors. The REBCO tapes stack is included in a braid of copper wires adopted to

M. Breschi and L. Cavallucci are with the Dipartimento di Ingegneria dell'Energia Elettrica e dell'Informazione “G. Marconi”, Alma Mater Studiorum, Università di Bologna, Italy (corresponding author: marco.breschi@unibo.it) and with Istituto Nazionale di Fisica Nucleare, Bologna (Italy).

L. Savoldi is with the Dipartimento Energia “Galileo Ferraris”, Politecnico di Torino (Italy), and with Istituto Nazionale di Fisica Nucleare, Genoa (Italy). L. Bottura is with CERN, Geneva, Switzerland.

increase the cable mechanical flexibility while providing a further amount of copper for stabilization in case of quench. The supercritical helium flows inside a central channel, partially separated from the copper sectors by a stainless-steel spiral (see Fig. 1b). An outer steel jacket provides mechanical reinforcement to the conductor.

To identify the main electrical, thermal and hydraulic characteristics times of the SECAS HTS fusion conductors, several simplifying assumptions have been made. First, to compare the impact of different possible operating temperatures for HTS magnets, the computations were performed both at 4.5 K and at 20 K. The magnetic field, which affects the material properties, was set in the range from 1 T to 13 T. Even though HTS magnets can work up to 20 T and beyond, this choice was made to allow a fair comparison of the results obtained at 4.5 K for HTS conductors with those previously obtained for the LTS ones [13]. The RRR of the slotted Cu sector was set from 100 to 300, while the RRR in the Cu stabilizer of the REBCO tape is set variable over a smaller range, from 20 to 30. Electrical and thermal contact resistances were varied in a range of measured values. A heated region of length L is considered for the calculation of the time constants during a superconducting to normal transition, with $L \sim 0.1$ m.

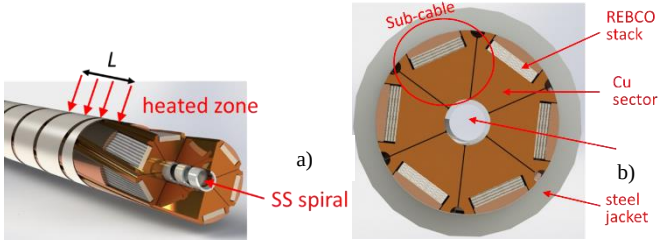


Fig. 1. a) 3D view and b) cross section of a typical SECAS conductor as manufactured by ENEA (from [18]).

III. THERMAL PHENOMENA ANALYSIS

A. Thermal phenomena characteristic times

The characteristic times of thermal phenomena occurring inside a SECAS conductor can be subdivided into two main categories: the time of heat diffusion inside a homogeneous, or piecewise homogeneous material, and the time of heat transfer

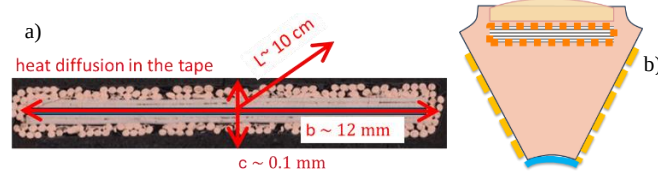


Fig. 2. a) Cross section of a typical a) REBCO tape and b) copper sector in a SECAS conductor for fusion magnets.

from a conductor part to an adjacent one, considering these parts to be at a uniform temperature. As for the first type of characteristic times, the sketch of the heat diffusion is shown in Fig. 2. Estimations of the heat diffusion characteristic times inside the tape and the Cu sector can be obtained with the following formula, based on the thermal diffusivity $\frac{k}{\rho c_p}$:

$$\tau_{heat\ diffusion} \sim \frac{\rho c_p}{k} L^2 \quad (1)$$

where k is the thermal conductivity of the material (a volume-weighted average of the various layers properties in the case of the REBCO tape), c_p the specific heat at constant pressure (mass-weighted for the REBCO tape) and ρ the density of the material. The parameter L is the characteristic length of heat diffusion in the various directions (see Fig. 1a) for the tape. The results obtained with (1) are reported in Table I for a typical 12 mm wide REBCO tape, with a thickness of about 0.1 mm, with a heated length of 0.1 m, and for the typical Cu sector of the SECAS conductor. It can be noted that at 20 K the characteristic timescales are longer than at 4.5 K in view of the larger specific heat, that increases more rapidly than the thermal conductivity in this temperature range. As expected, the time diffusion over the tape cross section occurs faster than over the much larger cross section of the Cu sector. As for the characteristic time of heat transfer between different parts of the conductor, the following contacts have been considered: tape-to-tape, stack-to-Cu sector and Cu-sector to Cu-sector. The calculation of the heat transfer characteristic time is based on the following formula, to be adapted to the various cases analysed:

$$\tau_{heat\ transfer} \sim \frac{\rho c_p A}{HTC_{eq} L_c} \quad (2)$$

where A indicates the cross section of the object from which the heat transfer starts, L_c the length of the contact and HTC_{eq} is the equivalent heat transfer coefficient, i.e. the reciprocal of the equivalent contact thermal resistance $R_{contact}$. A sketch of the heat transfer contacts analysed is shown in Fig. 3, which also reports the equivalent heat transfer coefficient HTC_{eq} and $R_{contact}$ between the couples of solids under analysis. The characteristic times, reported in Table II, indicate that the longest heat transfer time is the one from sub-cable to sub-cable, which may reach rather high values at 20 K (around 1 s).

TABLE I. CHARACTERISTIC HEAT DIFFUSION TIMES

Propagation direction	4.5 K	20 K
Tape*: L	0.01 s	0.4 s
Tape: b	200 μ s	6 ms
Tape: c	3 μ s	0.1 ms
Cu sector	100 – 600 μ s	3 ms ÷ 0.01 s

*The propagation directions for the tape are shown in Fig. 2a.

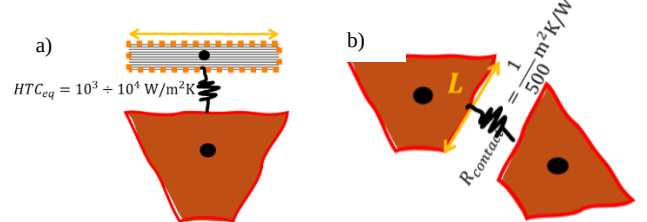


Fig. 3. Sketch of the heat transfer between a) REBCO tapes stack and Cu-sector and b) Sub-cable to -Sub-cable.

B. Suitability of lumped parameter thermal models

To assess the suitability of applying a lumped parameter thermal model for the analysis of the SECAS conductor, considering the tape stacks or the sectors as isothermal, the Biot number can be used as a useful indicator. It provides the ratio of the thermal resistance encountered by the heat conduction inside a bulk of homogeneous material to the thermal contact

resistance found at the material surface by the heat flow in the passage from such material to the adjacent ones.

TABLE II. CHARACTERISTIC HEAT TRANSFER TIMES

Contact	4.5 K	20 K
Tape to tape	0.2 ms	20 ms
Stack-to-Cu sector	1 ms	0.4 s
Sub-cable to sub-cable: c	0.02 s	1 s

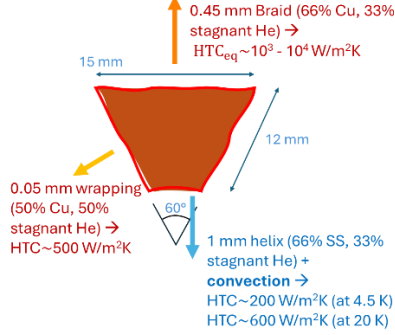


Fig. 4. Sketch of a Cu-sector of the SECAS conductor with typical heat transfer coefficients for thermal contact with other conductor parts.

When applied to the Cu sector sketched in Fig. 4, the Biot number can be estimated as follows at 4.5 K and 20 K, considering the variability of the Cu thermal conductivity with the magnetic field (up to 20 T) and RRR .

$$Bi(4.5 K) = \frac{\overline{HTC} A}{k P} \sim 0.01 \div 0.08 \quad (3)$$

$$Bi(20 K) = \frac{\overline{HTC} A}{k P} \sim 0.0007 \div 0.02 \quad (4)$$

where $\overline{HTC}$ represents the average heat transfer coefficient encountered by the heat flow in the passage to adjacent materials, and P the perimeter of the overall contact between the Cu sector and the adjacent conductor parts. It should be noted that the Biot number at 4.5 K, which can reach up to 0.08 for a magnetic field of 20 T and $RRR = 100$, is not much lower than 0.1, which is normally considered as a limit for the suitability of application of a lumped parameter thermal model of an object. This means that the temperature gradients across the sector could not be ignored. At 20 K instead, the Biot numbers appear sufficiently lower than 0.1, such justifying the assumption of a lumped representation of the Cu sector, as the temperature differences within it can be considered negligible with respect to the temperature difference between a sector and the adjacent ones.

III. FLUID DYNAMICS OF SUPERCRITICAL HELIUM

The supercritical helium flowing in the central channel of the SECAS conductor can be assumed to have a mass flow rate of few g/s. This implies a velocity in the channel in the order of 0.1 m/s at 4.5 K (and 5 bar) and 0.5 m/s at 20 K (and 20 bar).

For a thermal disturbance length set to $L = 0.1$ m, the

advection time scale can be computed as:

$$\tau_{ad} = \frac{L}{v} \quad (5)$$

The characteristic time of advection over the heated length is about 1 s at 4.5 K, which is much greater than the time required by pressure waves traveling over the same length at the speed of sound ~ 250 m/s. This characteristic time decreases to 0.2 s at 20 K, due to the faster propagation velocity of the supercritical helium at this temperature.

III. ELECTROMAGNETIC PHENOMENA CHARACTERISTIC TIMES

Similarly to the case of the thermal characteristic times, the time constants of the current diffusion and redistribution inside the SECAS conductor can be subdivided into two categories, which correspond to the current diffusion inside an individual conductor part and to the current redistribution from part to part. As for the first type, the analysis of characteristic time is based on the electromagnetic diffusivity $1/\mu_0\sigma$, where σ indicates the electrical conductivity of the material considered and μ_0 the magnetic permeability of vacuum. The characteristic time of current diffusion can thus be determined as:

$$\tau_{current\ diffusion} \sim \mu_0\sigma L^2 \quad (6)$$

The time of current diffusion inside the tape is computed here for the case of tape transitioned to the normal state, and with reference to the diffusion across the tape width. The diffusion essentially occurs in the Cu stabilizer of the tape due to the transition of the superconductor to the normal state. The characteristic time of current diffusion can also be computed for the Cu-sector. The results obtained are reported in Table III. It can be noted in Table III that the temperature does not significantly affect the characteristic times of current diffusion. As for the current redistribution between different parts of the conductor, we consider here the case of redistribution from tape to tape and from sub-cable to sub-cable. The formula adopted for this assessment is taken from [15]:

$$\tau_{current\ transfer} \sim \begin{cases} \frac{2(l-m)}{\pi r} \left(\frac{L_r}{L}\right)^2, & L \ll L_r \\ \frac{2(l-m)}{\pi r}, & L \gg L_r \end{cases} \quad (7)$$

$$L_r = \frac{1}{\sqrt{rg}} \quad (8)$$

where l is the p.u.l. self-inductance of the tape/sub-cable, m the mutual inductance between two tapes/sub-cables, L_r the current redistribution length, r the longitudinal resistivity per unit length, g the contact conductance p.u.l.. The results, also reported in Table III, show that very long current redistribution times can be expected between different sub-cables.

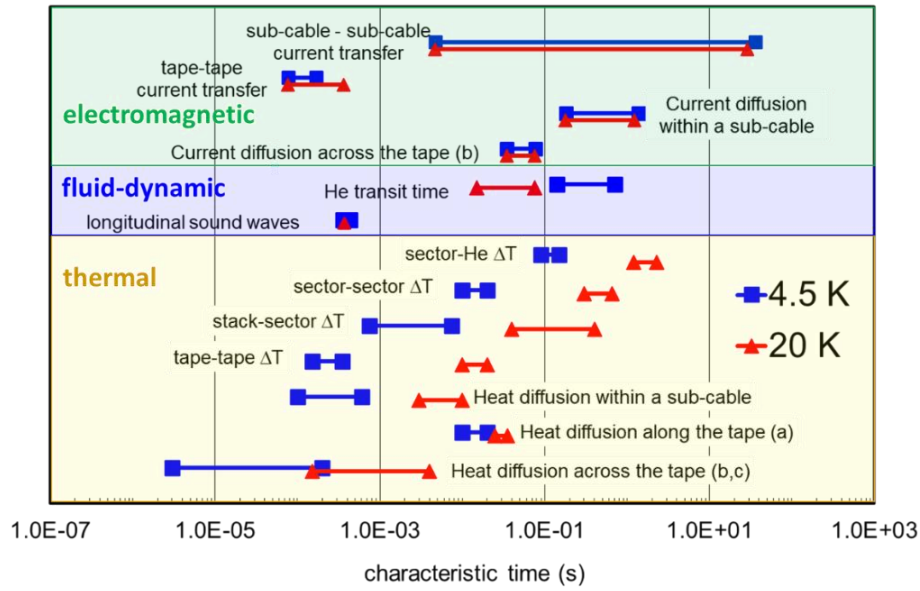


Fig. 5. Characteristic times of the main thermal, fluid/dynamic and electromagnetic phenomena occurring in a typical SECAS - HTS conductor.

TABLE III. CHARACTERISTIC CURRENT DIFFUSION TIMES

Contact	4.5 K	20 K
Across tape width in normal state	0.4 ms $\div$ 0.8 ms	0.4 ms $\div$ 0.8 ms
Cu sector	0.18 s $\div$ 1.4 s	0.18 s $\div$ 1.2 s
Tape-to-tape	80 μ s $\div$ 20 ms	80 μ s $\div$ 40 ms
Sub-cable to sub-cable	5 ms $\div$ 40 s	5 ms $\div$ 40 s

IV. COMPARING LTS AND HTS CONDUCTORS AT 4.5 K

Two results are worth mentioning in the comparison of the characteristic times found for LTS CICC in [13] and in this work for the HTS SECAS, as reported in Table IV. The characteristic time of heat transfer to helium increases significantly from the LTS- CICC to the SECAS-HTS conductor. This can be explained considering that strands in a CICC are in direct contact with the helium, while several contact resistances plus the Cu-sector separate the HTS stack from the central helium channel in the SECAS conductor. Furthermore, the characteristic time of the heat transfer from tape to tape is shorter than that from strand to strand, due to large surface contact between tapes as compared to the local contacts between strands in a CICC.

TABLE IV. CHARACTERISTIC HEAT TRANSFER TIMES AT 4.5 K

Characteristic time	LTS	HTS
Strand to helium / stack to helium	0.1 ms $\div$ 1 ms	$\sim$ 1 ms
strand to strand / tape to tape	4 ms $\div$ 80 s	0.2 ms $\div$ 0.4 ms

V. HTS CONDUCTOR CHARACTERISTIC TIMES

The plot of the thermal, fluid-dynamic and electrical characteristic times obtained for the SECAS conductor is shown in Fig. 5. It can be noted that at 20 K the characteristic times for heat diffusion become larger than at 4.5 K. It is also worth mentioning that the time required for temperature

homogenization in the conductor cross section is not negligible (see for example the stack-Cu sector heat transfer time at 20 K, up to 0.6 s). This result indicates the need to discretize the conductor cross section for an accurate thermal analysis. The only characteristic time that decreases at 20 K is the helium transit time along the heated zone; this is due to the higher velocity of helium at this temperature. No significant impact of temperature is instead found on the electromagnetic time constants, due to the small variation of the electrical conductivity in this temperature range.

It should be noted that in the region of characteristic times from 10^{-4} s to 1 s, which is crucial for thermal stability analysis, the characteristic times of thermal, electrical and hydraulic phenomena are not separated, but rather overlap in various cases. This overlapping is even more pronounced than in the corresponding plot for the LTS conductors [13], which exhibits a larger separation of the time scales. This indicates that a strong coupling between the different physics is required for the analysis of stability and quench in the HTS SECAS conductors.

VI. CONCLUSION

This work provides a spectrum of characteristic times for the development of electrical and thermal phenomena in HTS conductors. Although approximate, such spectrum can provide useful indications for the modeling of electromagnetic, thermo-hydraulic phenomena, especially in terms of the need to couple the different physics.

The characteristic times can also serve as a basis for the development of novel design criteria for HTS magnets. The design of HTS magnets cannot in fact be incrementally based on the LTS magnet design but requires novel approaches, as well as accounting for other multi-physics aspects. As an example, mechanical analysis must be pushed at the tape level, while it was mainly at cable/coil level for the LTS coils. Finally, particle-material interactions at the tape level, which were largely ignored for LTS, become of extreme relevance for the HTS magnets design.

REFERENCES

- [1] L. Bottura, C. Rosso, M. Breschi, "A general model for thermal, hydraulic and electric analysis of superconducting cables," *Cryogenics*, vol. 40, pp. 617-626, 2000.
- [2] L. Savoldi Richard, et.al., "The 4C code for the cryogenic circuit conductor and coil modeling in ITER," *Cryogenics*, vol. 50, pp. 167-176, 2010.
- [3] M. Ciotti, A. Nijhuis, P. L. Ribani, L. Savoldi Richard and R. Zanino, "THELMA code electromagnetic model of ITER superconducting cables and application to the ENEA stability experiment," *Supercond. Sci. Technol.*, vol. 19, no. 10, pp. 987-997, 2006.
- [4] M. Breschi, P. L. Ribani, "Electromagnetic Modeling of the Jacket in Cable-in-Conduit Conductors," *IEEE Trans. Appl. Supercond.*, vol. 18, n. 1, pp. 18 – 28, 2008.
- [5] Q. Le Coz, et al. "TACTICS: overview of a multi-physic analysis tool for fusion magnet design and application to DEMO TF coil," *Cryogenics*, vol. 127, 2022, Art. no. 103553.
- [6] Q. Le Coz, et.al., "Towards a multi-physic platform for fusion magnet design—Application to DEMO TF coil," *Fusion Engineering and Design*, vol. 124, pp. 104-109, 2017.
- [7] E.P.A. van Lanen, A. Nijhuis, "JackPot: A novel model to study the influence of current non-uniformity and cabling patterns in cable-in-conduit conductors," *Cryogenics*, vol. 50, pp. 139-148, 2010.
- [8] H. Bajas, D. Durville and A. Devred, "Finite element modelling of cable-in-conduit conductors," *Supercond. Sci. Technol.*, vol. 25, 2012, Art. no. 054019.
- [9] M. Breschi, P. L. Ribani, H. Bajas and A. Devred, "Modeling of the electro-mechanical behavior of ITER Nb₃Sn cable in conduit conductors," *Supercond. Sci. Technol.*, vol. 25, 2012, Art. no. 054005.
- [10] N. Mitchell, "Modeling of non-uniform current diffusion coupled with thermohydraulic effects in superconducting cables", *Cryogenics*, vol. 40, pp. 637-653, 2000.
- [11] Z. S. Hartwig *et al.*, "The SPARC Toroidal Field Model Coil Program," *IEEE Trans. Appl. Supercond.*, vol. 34, no. 2, pp. 1-16, 2024, Art. no. 0600316.
- [12] <https://renfusion.eu/>
- conductors with and without artificial pinning centers," *Supercond. Sci. Technol.*, vol. 31, 2018, Art. no. 044006.
- [13] L. Bottura, "Modelling stability in superconducting cables." *Physica C: Superconductivity*, vol. 310, no. 1-4, pp. 316 – 326, 1998.
- [14] L. Muzzi et al., "Design and Feasibility Assessment of an HTS Sector Shaped High-Current Conductor for Fusion Coils," *IEEE Trans. App. Supercond.*, vol. 33, no. 5, pp. 1-6, 2023, Art. no. 4200106.
- [15] G. Ries, "Stability in superconducting multistrand cables", *Cryogenics*, vol. 20., pp. 513-519, 1980.