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Quench behavior of High-Temperature Superconductor tapes for power applications

A strategy toward resilience

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Zusammenfassung

Hochtemperatursupraleiter (HTS) können in flüssigem Stickstoff (77 K) supraleitend sein und bergen immense Versprechen für unsere Zukunft. Sie können disruptive Technologien wie Kernfusion, verlustfreie Stromübertragung, Geräte zur Krebsbehandlung und Technologien für den zukünftigen Transport ermöglichen. In den vergangenen Jahren haben sich die numerischen Modelle zur Beschreibung des elektrischen Widerstands von kommerziellen REBCO-Bändern für Geräte, die nahe und oberhalb des kritischen Stroms arbeiten, als nicht genau oder sehr empirisch erwiesen. Der spezifische Widerstand in diesem Bereich ist in der Tat nicht sehr gut bekannt. Der Mangel an diesem Wissen ist ein wesentliches Problem bei der Entwicklung von hochwertigen Simulationswerkzeugen. Die grösste Herausforderung bei der Ermittlung solcher Eigenschaften liegt in der Tatsache, dass bei $I > I_c$ Erwärmungseffekte und thermische Instabilitäten den Leiter schnell zerstören können, wenn nichts zu seinem Schutz unternommen wird. Darüber hinaus ist es aufgrund der Stromaufteilung zwischen den Schichten schwierig, die Menge des von der supraleitenden Schicht geführten Stroms und damit ihren spezifischen Widerstand zu kennen. Die vorliegende Arbeit zielt darauf ab, den überkritischen Strombereich besser zu verstehen, indem ultraschnelle gepulste Strommessungen, die an HTS REBCO-basierten beschichteten Leitern durchgeführt wurden, mit Finite-Elemente-Modellierung kombiniert werden. Die experimentellen Aktivitäten wurden grösstenteils an der EPFL und zum Teil an PM und KIT durchgeführt. Die Modellierungsaktivitäten wurden zwischen EPFL und KIT durchgeführt. Das Hauptergebnis ist eine Widerstandsbeziehung, die den überkritischen Strombereich beschreibt und in numerischen Simulationen von REBCO-Bändern verwendet werden kann. Der Bericht veranschaulicht eine Post-Processing-Methode, die auf dem sogenannten Uniform-Current-Modell (UC) basiert, um den spezifischen Widerstand des REBCO-Materials im überkritischen Bereich aus experimentellen Messungen abzuschätzen. Gepulste Strommessungen von so kurzen 15 μs und mit Stromstärken bis zu $I=5\ I_c$ wurden im Flüssigstickstoffbad (77 K) an Proben verschiedener Hersteller durchgeführt, ohne die Bänder zu beschädigen. Es werden Ergebnisse präsentiert, die mit einer Nachbearbeitungsmethode erzielt wurden, die auf der Regulierung der Daten basiert, um die experimentellen Messungen zu behandeln, die im überkritischen Strombereich extrahiert wurden. Die Ergebnisse dieser Technik ist eine Nachschlagetabelle, die mit interessierten Partnern geteilt und anschliessend in der numerischen Modellierung verwendet werden kann.

Schliesslich eine experimentelle Validierung des überkritischen Strommodells präsentiert. Das Modell wird verwendet, um zu zeigen, dass für den Fall eines supraleitenden Fehlerstrombegrenzers, unter Verwendung des Potenzgesetz-Modells zur Modellierung seiner elektrothermischen Reaktion das Gerät schneller abschaltet als mit dem überkritischen Modell. Zusammenfassend lässt sich sagen, dass diese Arbeit helfen kann, die Verwendung von supraleitendem Material sowie die Menge des Stabilisators zu optimieren. Noch interessanter ist, dass sie die Untersuchung des überkritischen Stromregimes eröffnet, ein neuer spannender Aspekt der kommerziellen REBCO-Bänder.

Résumé

Les supraconducteurs à haute température critique (HTS) peuvent être supraconducteurs dans l'azote liquide 77 K, ce qui est porteur d'immenses promesses pour notre avenir. Ils peuvent permettre la mise en œuvre de technologies de rupture telles que la fusion nucléaire, la transmission d'énergie sans perte, les dispositifs pour le traitement du cancer et les technologies pour les transports futurs. Ces dernières années, les modèles numériques permettant de décrire la résistivité électrique des rubans commerciaux de REBCO pour les appareils fonctionnant à proximité et au-dessus du courant critique, se sont révélés peu précis ou très empiriques. En fait, la résistivité dans ce régime n'est pas très bien connue. Cette méconnaissance est un problème important pour le développement d'outils de simulation de qualité. La principale difficulté pour mesurer de telles propriétés réside dans le fait que lorsque $I > I_c$, les effets de chauffage peuvent rapidement détruire le conducteur si rien n'est fait pour le protéger. De plus, en raison du partage du courant entre les différentes couches constitutives, il est difficile de connaître la quantité de courant transporté par la seule couche supraconductrice et donc sa résistivité. Le présent travail vise à obtenir une meilleure connaissance du régime de courant surcritique en combinant des mesures de courant pulsé ultra-rapide effectuées sur des conducteurs en rubans à couche mince à base de HTS REBCO avec de la modélisation par éléments finis. Les activités expérimentales ont été menées principalement à l'EPFL et en partie au PM et au KIT. Les activités de modélisation ont été réalisées entre l'EPFL et le KIT. Le résultat principal est une relation pour la résistivité décrivant le régime de courant surcritique à utiliser dans les simulations numériques des rubans REBCO. Le rapport illustre une méthode de post-traitement basée sur le modèle dit de courant uniforme (UC) pour estimer avec précision la résistivité du matériau REBCO dans le régime surcritique à partir de mesures expérimentales. Des mesures de courant pulsé aussi brèves que 15 μs et avec une magnitude de courant allant jusqu'à $I = 5\,I_c$ ont été effectuées dans un bain d'azote liquide (77 K) sur des échantillons de différents fabricants, sans endommager les rubans. Nous présentons une méthode de post-traitement basée sur la régularisation des données pour traiter les mesures expérimentales faites dans le régime de courant surcritique. De cette technique résulte une table de référence qui peut être partagée avec tout partenaire intéressé pour leur utilisation dans la modélisation numérique impliquant des rubans supraconducteurs. Le modèle a été validé expérimentalement et utilisé pour montrer que dans le cas d'un limiteur de courant de défaut supraconducteur, les simulations montrent que lorsque le modèle de loi de puissance est utilisé le limiteur surchauffe plus rapidement qu'avec le modèle surcritique. En conclusion, ces travaux peuvent contribuer à étendre l'utilisation des supraconducteurs par l'optimisation de leur stabilisation. Plus intéressant encore, il ouvre l'étude du régime de courant surcritique, un nouvel aspect passionnant des rubans commerciaux de REBCO.

Summary

High-Temperature Superconductors (HTS) can be superconducting in liquid nitrogen (77 K), holding immense promises for our future. They can enable disruptive technologies such as nuclear fusion, lossless power transmission, cancer treatment devices, and technologies for future transportation. In the past years, the numerical models to describe the electrical resistivity of REBCO commercial tapes for devices working near and above the critical current, have been shown to be not accurate or very empirical. The resistivity in this regime in fact, is not very well known. The lack of this knowledge is a significant issue in developing quality simulation tools. The major challenge in retrieving such properties lies in the fact that when $I > I_c$, heating effects and thermal instabilities can quickly destroy the conductor if nothing is done to protect it. Moreover, due to the current sharing between the layers, it is difficult to know the amount of current carried by the superconducting layer, and hence, its resistivity. The present work aims to understand better the overcritical current regime combining ultra-fast pulsed current measurements performed on HTS REBCO based coated conductors with Finite Element Modeling. The experimental activities were carried out mostly at EPFL and in part at PM and KIT. The modeling activities were carried out between EPFL and KIT. The major result is a resistivity relationship describing the overcritical current regime to be used in numerical simulations of REBCO tapes. The report illustrates a post-processing method based on the so-called Uniform Current (UC) model to estimate the REBCO material's resistivity in the overcritical from experimental measurements. Pulsed current measurements as short 15 μs and with current magnitude up to $I = 5\,I_c$ were performed in liquid nitrogen bath (77 K) on samples from various manufacturer, without damaging the tapes. We present the results obtained using a post-processing method based on regularization of data to treat the experimental measurements extracted in the overcritical current regime. The output of this technique is a look-up table that can be shared with interested partners and used in numerical modeling afterwards.

Finally, we present and experimental validation of the overcritical current model. The model is then used to show that for the case of a superconducting fault current limiter when the power-law model is used to model its electro-thermal response, the device quenches faster than with the overcritical model. In conclusion, this work can help optimize the use of superconducting material as well as the the amount of stabilizer. More interestingly, it opens the study of the overcritical current regime, a new exciting aspect of REBCO commercial tapes.

Main findings

In the framework of the Ph.D. research, the major scientific achievements include:

- The development of a post-processing method based on the so-called Uniform Current (UC) model to estimate the resistivity of the HTS in the overcritical current regime from experimental measurements with an accuracy below 10 %;
- The formulation of a Non-Linear Least Squares optimization method. This method aimed to find the silver layer thickness's best-approximated values and its electrical resistivity temperature dependence. The method was used to minimize the uncertainties on such parameters and reduce the error of the calculated quantities (temperature, current, resistivity) related to such uncertainties;
- The use of *non-parametric constrained regularization methods* (Data Regularization) to treat the experimental measurements extracted in the overcritical current regime. The output of this technique is a look-up table that can be shared with interested partners and used in numerical modeling afterwards;
- The proposal of the overcritical current model, an alternative to the power-law model, to describe the overcritical current regime ($I > Ic$), based on experimental measurements obtained as outlined above. The model was validated experimentally with measurements performed at EPFL and KIT, and it was used to show that for the case of a superconducting fault current limiter when the power-law model is used to model its electrothermal response, the device quenches faster than with the overcritical model;

The lack of good knowledge in the overcritical current regime is a major issue in developing quality simulation tools for optimizing the design of superconducting devices working near and above the critical current. This work can be very useful to optimize the use of superconducting material as well as the amount of stabilizer. More interestingly, it opens the study of the overcritical current regime, a new exciting aspect of REBCO commercial tapes.

Contents

Abbreviations

PCM	Pulsed Current Measurements
SFOE	Swiss Federal Office of Energy
HTS	High Temperature Superconductor
FEA	Finite Element Analysis
EPFL	École Polytechnique de Lausanne
PM	Polytechnique de Montréal
KIT	Karlsruhe Institute of Technology

1 Introduction

1.1 Background information and current situation

The use of power applications will be of paramount relevance in future grids, for instance superconducting fault current limiters (SFCL) will be used in the grids with the aim of protecting them from electrical faults. A good knowledge of all the material properties and their temperature dependence is critical in simulating a superconducting device. However, if on the one hand the electrical and thermal properties of materials constituting the HTS tapes such as silver, copper or Hastelloy can be found in literature, on the other hand it is difficult to have an accurate knowledge of the over-critical current resistivity ($I > I_c$) for the superconducting material. The major challenge in retrieving the overcritical current resistivity lies in the fact that as soon as the transport current (I) in a HTS conductor becomes higher than its macroscopic critical current (I_c), heating effects and thermal instabilities occur and quickly destroy the conductor if nothing is done to protect it. Another challenge is due to the inter-layer current sharing occurring among the materials that constitute the tape.

A SFCL is an application where the overcritical current regime is a key knowledge. Many works studying the electro-thermal behaviour of RSFCL during a fault used a power law in the flux creep regime [18,19], and some of them used a piece-wise power-law in which the flux-flow was considered as a flux-creep region with a lower n-value [25]. In these cases, widely used models such as the critical state model or the power-law model are not always reliable. To the best of the authors' knowledge, the over-critical current resistivity of an HTS commercial coated conductor has never been characterized experimentally to be used as a model to study by simulation its impact in superconducting application.

1.2 Purpose of the project

Improve the knowledge on HTS tapes in resistivity regions difficult to characterize, namely the overcritical current regime.

1.3 Objectives

Developing a procedure that combines fast-pulsed current measurements (PCM) and FEA to extract the over-critical current resistivity curve [3] In this contribution we present the entire procedure followed to extract the HTS tapes resistivity, which comprises the experimental pulsed current measurements (PCM) on HTS tapes and an extensive use of numerical analysis to extract, reconstruct and validate the HTS tapes resistivity.

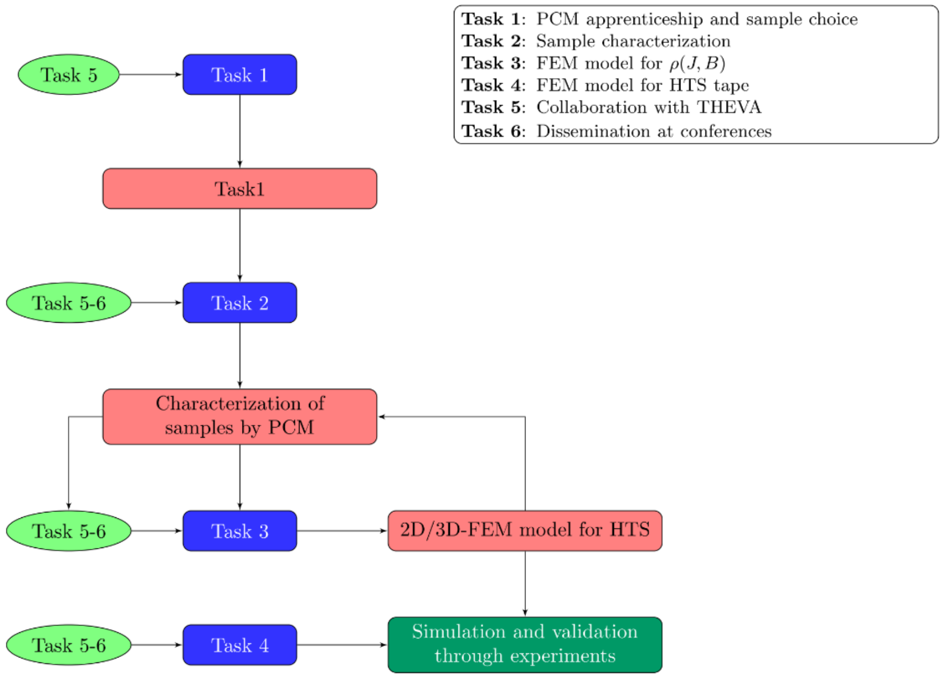
Finally, development of 2D and 3D electro-thermal and magneto-thermal models to evaluate the measured resistivity in a relevant case scenario involving practical applications.

2 Description of facility

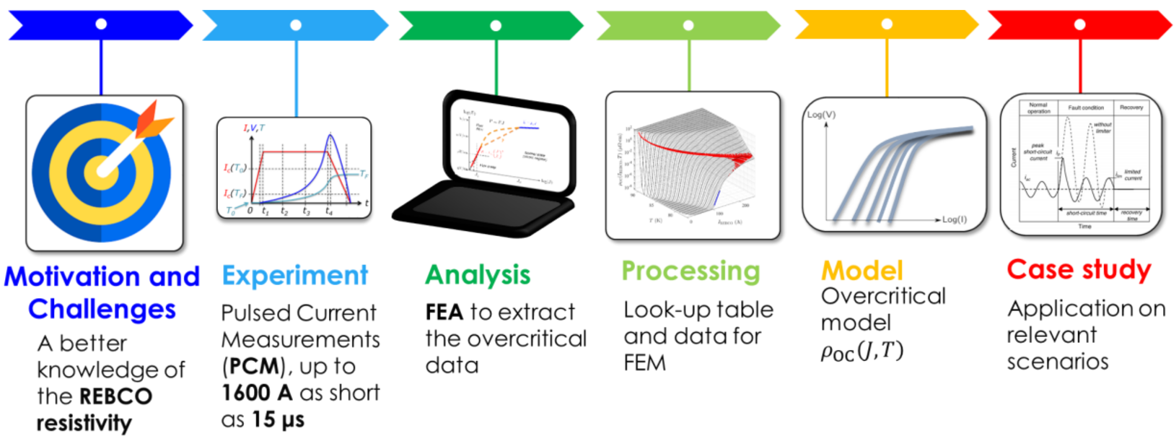
The Lab is situated at EPFL, in the Computer Science Building (BC). The experimental setup is constituted by a custom developed pulsed current measurement (PCM) system, a glass cryostat, an electromagnet surrounding the cryostat and able to produce a field up to 0.4 T. Since LN2 is used as a cryogenic fluid, the measurements are carried out at 77 K. In the last year a vacuum pump has been implemented. By pumping the vacuum on the LN2 it is possible to change the boiling point of the LN2 down to 65 K. This allow us to perform the measurements between 65 K and 77 K.

3 Procedures and methodology

In this report we will refer to the PhD thesis proposal submitted at EPFL during the exam for the final admission at the doctoral school. In particular, we will refer at the tasks present in the flow chart drawn for this work and presented here.



Alongside the tasks, the main outcome has been the development of a procedure that combines the experimental characterization with numerical methods (finite element analysis, uncertainty analysis and regularization of the data) to obtain a suitable set of data to be used in computer modeling.



- Experiment: The samples characterized so far are ReBCO commercial coated conductors, with and without copper stabilizer. It is not excluded that in future other typologies samples will be measured. The characterization is carried out by using PCM technique. With pulses up to 1.6 kA as short as 15 µs we characterize the samples in the overcritical current regime without damaging the tapes.

- FEA Analysis: Due complex phenomena such as current sharing among the layers and spatial disuniformities of the electric field, temperature and current density, the use of FEA techniques is necessary to retrieve the resistivity of the YBCO. A thermal + current sharing model (2D UC model) has been developed to obtain the overcritical current curves. Further validations through FEA are required. To validate the resistivity curves, further models are developed by simulating the experiment and the voltage curves obtained. One of the most critical aspect of the 2D UC model is its sensitivity to the input parameters. Understanding how the uncertainties and sensitivities of the input parameters (geometry and material properties) are affecting the quantities of interest (current sharing among layers, temperature in the domains and resistivity) has been necessary to obtain reliable overcritical curves. The uncertainties on geometrical and material parameters of the HTS tapes impose limits on our confidence in the response or output of the 2D UC thermal model. We perform a sensitivity analysis that describes how sensitive the quantities of interest are to the variation of individual input parameters. Since there might be multiple input parameters, a sensitivity analysis helps determining which ones drives the majority of the variation in the outcome and hence to exclude others. Finally, an uncertainty analysis using FEA is carried out, describing the range of possible outcomes given a set of inputs with uncertainty.

- Regularization of the curves: In order to the use the overcritical data in modelling, the creation of a suitable resistivity surface is of paramount importance. However, due to collinearity and lack of data, a simple interpolation performed by most commercial software can be ill-posed or affected by overfitting. To address this problem, we process the overcritical data through regularization of the data, which can be thought as a process of adding information in order to solve an ill-posed problem or to prevent overfitting. The detailed description of this technique goes beyond the scope of the paper and will be published in future.

- Modelling in relevant case scenario: The development of 2D and 3D electro-thermal models will help in evaluating how the overcritical current curves impact relevant scenarios such as SFCL. We recently showed by simulation whether and to what extent using such resistivity instead of the widely utilized power-law resistivity affects the thermal and electromagnetic performance of the tapes in the practical case of a SFCL [7].

4 Results and discussion

4.1 Task 1: PCM apprenticeship and sample choice

In order to learn the basic use of the ultra fast source, I spent 2 months in Montreal at the École Polytechnique de Montréal (PM) under the supervision of Prof. Frédéric Sirois (July-August 2017).

4.2 Task 2: Sample characterization

Commercial available coated conductors from THEVA, SuNAM, SuperPower and SuperOx have been measured in liquid nitrogen (77 K). The samples are from 4 mm to 12 mm wide tape and 10 cm long (Ag Stabilizer). The sample characterization is a Task that will cover the entire PhD thesis. However, we stopped the experimental activities mid 2020.

4.3 Task 3: Post processing methods for ρ(J,T) (FEA+ Data Regularization)

FEM simulations are fundamental, and the state of the art in modelling superconductors has several possibilities. Using a model known as “Uniform Current” (UC) model, the resistivity is extracted [2]. The resistivity calculated with the UC model is processed using the technique known as Regularization of Data. Figure 1 presents the overcritical resistivity $\rho_{OC}(I,T)$ surface obtained from two experimental data sets corresponding to samples SP01 and SP02 from SuperPower, both 4 mm wide and 10 cm long REBCO tapes with 1 µm silver stabilizer having I_c (77 K and self-field) and T of 90 A / 92 K and 63 A / 88 K respectively.

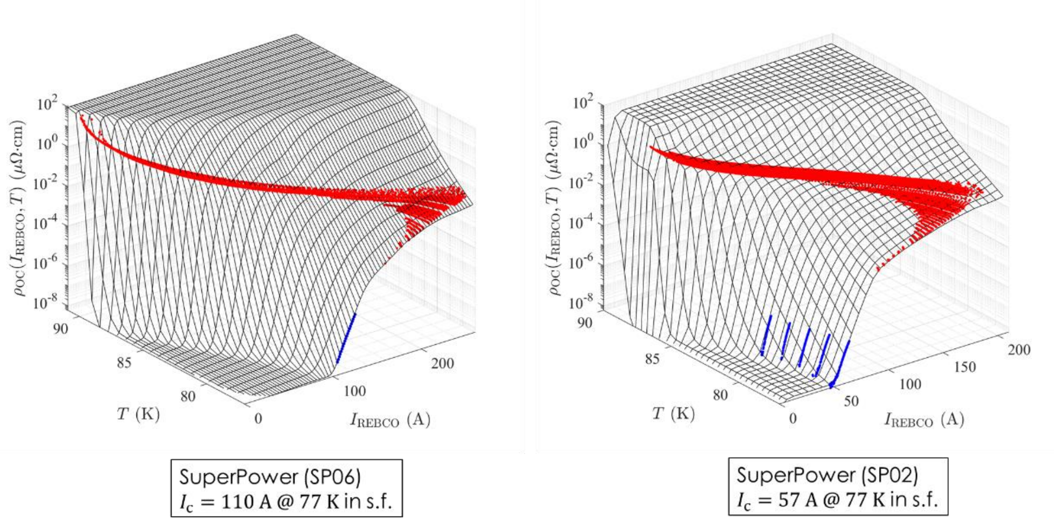


Figure-1 Post-processed data in form of look-up tables.

To have further insight of the importance of those data, it is useful to compare those widely used formulations such as the power-law. In Figure 2(left) we compare, for three different temperatures, the resistivity of the REBCO as described by the conventional power law (dashed lines) and the overcritical curves obtained by regularization of the data (continuous line). The constant yellow line at $0.1\ m\Omega \cdot cm$ is the normal state resistivity of the REBCO at 92 K while the black scattered points are the experimental measurements. The difference between $\rho_{OC}(I,T)$ and $\rho_{PWL}(I,T)$ for the same current is striking. This difference, for real coated conductors, is mitigated by the presence of a stabilizer such as the silver (or copper). In Figure 2(right), the resistivity of the silver is represented as a constant line at $0.2\ \mu\Omega \cdot cm$. The silver acts as a parallel resistor and the overall resistivity of the tape is lower than the one of the single REBCO layer.

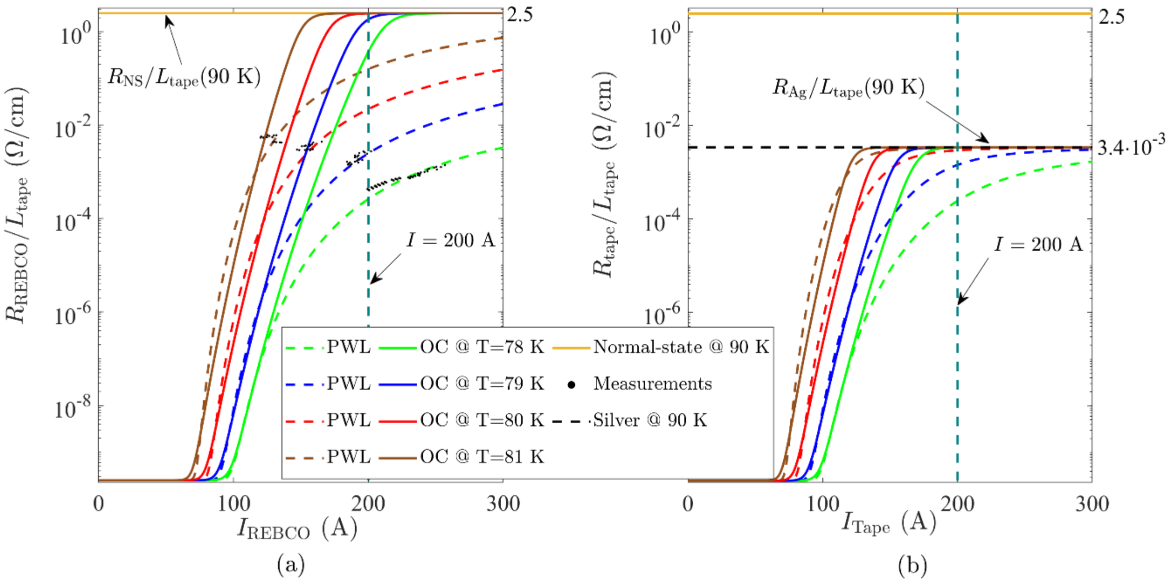


Figure-2 Comparison between the power-law and the overcritical resistivity models in term of resistance per unit length for (a) REBCO and (b) overall tape.

4.4 Task 4 : FEM model for HTS Tapes

We evaluated to what extent using the overcritical current model instead of the power-law model impacts the electrothermal response of a REBCO tape. For this purpose, we used the overcritical current model described above to study the simple case of a superconducting fault current limiter (SFCL). In order to verify the correctness of the overcritical resistivity model obtained above, and also to study the behavior of REBCO tapes in various quench scenarios, we used a 1-D thermal finite element model (temperature variation across the thickness of the tape) coupled with an electric circuit model (current sharing between the various layers of the tape). We assume that the simulated tape's electrical and thermal properties do not vary significantly along its width and length. This means that the simulated tape has uniform properties (width and length) and that with this simple model, one cannot investigate the impact of defects and hot-spots on the RSFCL behavior. The model is nevertheless sufficiently accurate to study short samples. The details of the model can be found in [7].

Fault current measurements in a liquid nitrogen bath (77 K) were performed at KIT (AC faults) and EPFL (DC faults) on SuperPower samples coming from the same batch of the SP06 sample. The power-law model as well as the overcritical current model was implemented in the model found in [7]. AC fault current measurements ranging from 1.4 Ic to 5 Ic and in a liquid nitrogen bath (77 K) were performed on a tape called SP06b at KIT. The SP06b sample was 30cm long, obtained from the same spool as the SP06 sample (1.1 µm of surrounding silver stabilizer). The critical current of SP06b was Ic =118 A at 77 K in self-field conditions. The measurements were carried out with the help and collaboration of Dr. Kudymow and Dr. Batista De Sousa.

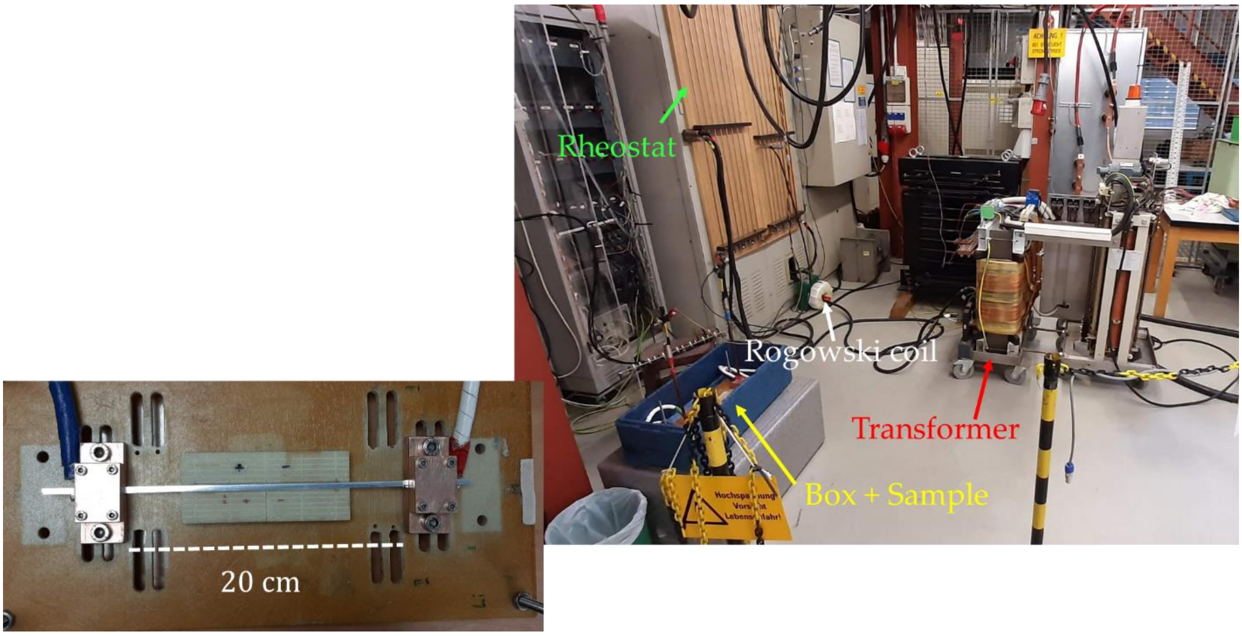


Figure-3 Picture of the sample holder and experimental setup utilized at KIT.

The experimental setup is schematically represented in Figure 3. A low impedance transformer provided the voltage source, while the fault resistance was controlled using a rheostat. We measured the current in the circuit with a Rogowski coil (indicated with a white arrow in Figure 3). Finally, we measured the voltage with the help of voltage taps installed on the sample, separated by a distance of 20 cm each. The voltage taps were located on the top of the copper block, as shown in Figure 3. The voltage limitations tests, for increasing prospective fault, are presented in Figure 4 (next page). In Figure 4 (a) the prospective current was Ipeak = 1.4Ic = 165 A, while the limited peak current was of Ipeak = 162 A. In Figure 4 (e) the prospective current was Ipeak = 4.8Ic =566 A, while the limited peak current was of Ipeak =189A. It is noteworthy to observe that the tape worked as a very good SFCL.

The most significant difference between the models is present for low overcurrent transients (low prospective, current fault). For high prospective fault current, the overcritical current model and the power-law model have similar behaviors.

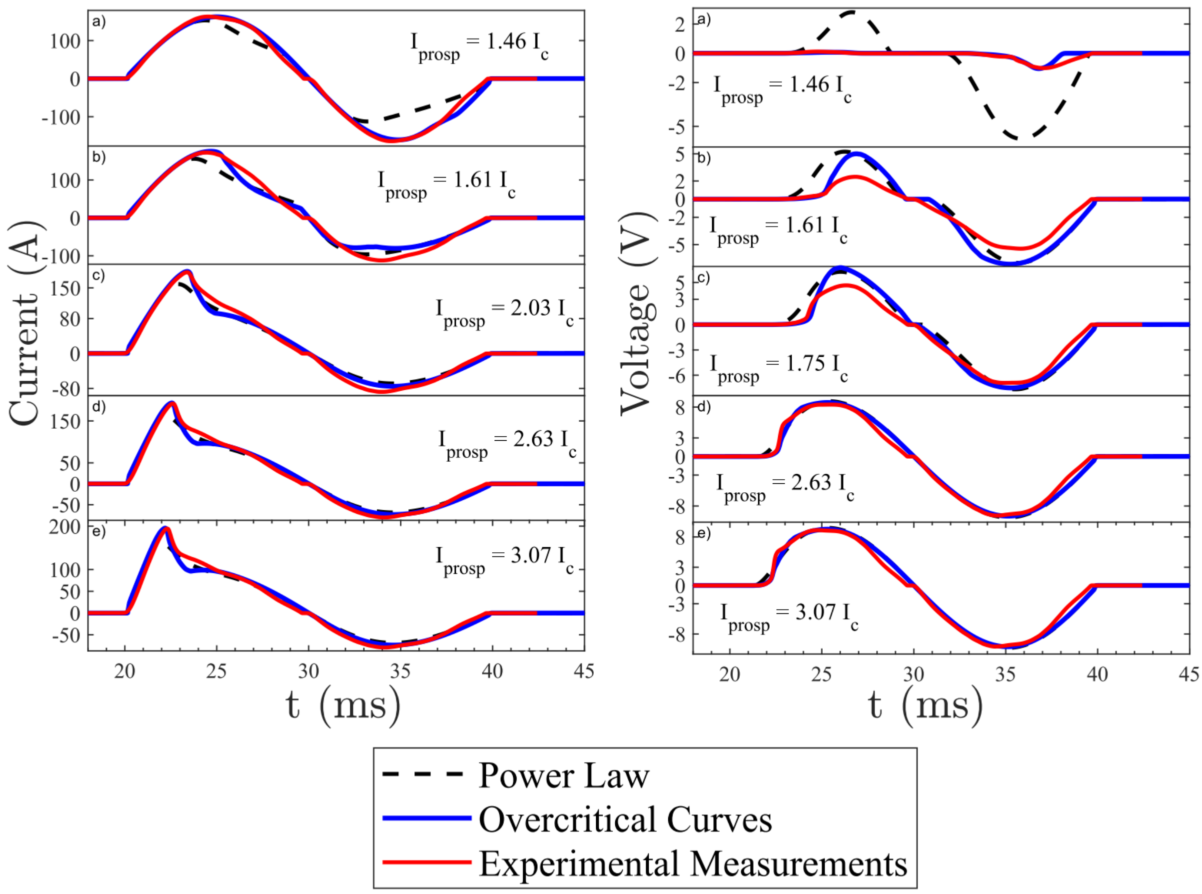


Figure-4 Measurements and simulations of an HTS tape undergoing AC fault current limitation under an increasing applied electric field. The measurements were performed on one sample (SP06b) coming from the same batch as SP06.

Finally, we analyze the impact of using the overcritical current model instead of the power-law model. In particular, we calculate by simulation the temporal evolution of current and temperature in the tape for different homogeneous AC fault current limitation conditions. The model used to simulate AC fault current limitation is presented in [7]. A sinusoidal voltage signal is imposed on the circuit, while a load resistor draws the nominal current from the source. A switch in parallel to the load resistor, when closed, simulates the fault occurring at a given time and draws the fault current through a resistor R_{fault}. In the simulations, V_{peak} =12 V and f =50 Hz. The switch operates at t =20 ms and the short-circuit is cleared after two periods of the sinusoidal voltage source, i.e. t = 60 ms. In Figure 5a, we present the evolution of the total current in the circuit and the current in the REBCO layer (top), the temperature (middle), and the REBCO layer resistivity (bottom). Figure 5a shows the results for I_{fault} = 1.45Ic. The difference in simulation results for low overcurrent transients is remarkable. Even if the first current peak does not change considerably using the overcritical current model instead of the power-law model, the temperature rise is significantly different. With the power-law model, the tape quenches more rapidly, i.e. its temperature reaches Tc =90 K in less than one cycle (see Figure 5a). The difference in the temperature rise obtained when using the overcritical current model instead of the power-law model can be understood by comparing the electrical resistance per unit of length of the of REBCO layer ($R_{\mathrm{REBCO}}(I,T)/L_{\mathrm{tape}}$ in Figure 2 pag. 11), the total resistance per unit of length of the tape

$(R_{\mathrm{tape}}(I,T)/L_{\mathrm{tape}})$ and the total Joule losses in Figure 5b ($\sim R \cdot I^2$). In Figure 5b we compare the total current, the resistance per unit length of the tape and the total Joule losses obtained with the power-law and overcritical current resistivity models. In the gray-shaded area between 23 ms and 29 ms, when the tape is still superconducting, we see that the total current $I_{\mathrm{tot,PWL}}$ is not too different from $I_{\mathrm{tot,OC}}$.

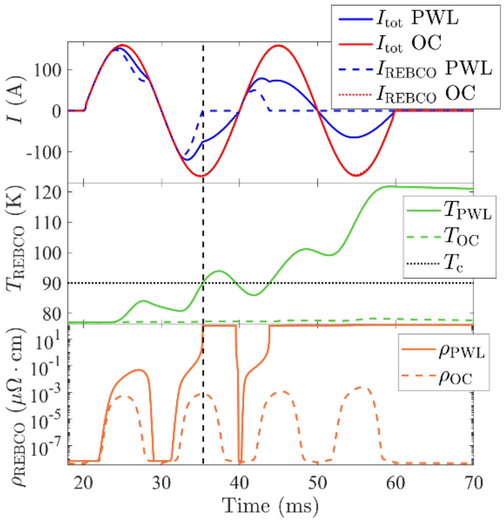


Figure-5a Simulated AC faults on SP06 with the overcritical resistivity model and the power-law model, for 1.45Ic. The black dashed lines indicate the moment where the quench occurs.

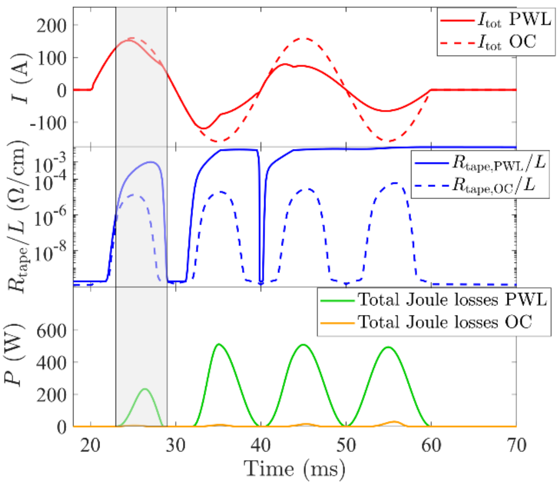


Figure-5b Comparison between the total current (top), resistance per unit length (middle) and Joule losses (bottom) in the RSFCL model using the power-law and overcritical current resistivity models in the AC current limitation case with Ifault = 1.45Ic. The gray-shaded area shows the remarkable difference in term of Joule losses.

4.5 Overall results

All results of this very extensive work are available in detail in the PhD thesis, elaborated and published by Nicolò Riva. See [1] in the publications.

An abstract of the PhD thesis is as well attached in the Appendix.

5 Conclusions

The lack of good knowledge in the overcritical current regime is a major issue in developing quality simulation tools for optimizing the design of superconducting devices working near and above the critical current. This work, especially the possibility of characterizing systematically the overcritical current regime and the formulation of the overcritical current model, could help to optimize the use of superconducting material as well as the amount of stabilizer. More interestingly, it opens the study of the overcritical current regime, a new exciting aspect of REBCO commercial tapes.

6 Outlook and next steps

In the future, an extensive measurement campaign will be necessary, exploring several experimental conditions. A significant limitation of this work in fact, is that only a few experimental conditions were explored. Although many samples from different manufacturers were characterized, no comparative work was carried out (samples with different pinning force/scenarios, higher magnetic field (B > 300 mT, wider temperature range T < 77 K). We plan to assess the impact of using the overcritical current model in other relevant case scenarios like a hotspot scenario in superconducting devices, quench in magnets, or non-insulated coil, or also for screening currents induced stress and for coolant optimization. We are also considering characterizing the REBCO overcritical current regime for other sample typologies like bulks, stacks of tapes, or thin films. Finally, significant work in the physical interpretation of the results should be done.

7 National and international cooperation

As National collaboration we strictly collaborate with SCI-Consulting, a company located close to EPFL. A custom-built amplifier splits the signal into low frequency (LF) and high frequency (HF), necessary in order to protect the delicate DAQ system. This amplifier has been developed and customized from SCI-Consulting, which assist us in the problems due to the device itself.

As International collaboration, we work on an everyday basis with Prof. Frédéric Sirois and Dr. Christian Lacroix from PM. The goal is to keep on improving the experimental setup, initially developed by PM, and to advance together on the knowledge of the overcritical current resistivity.
A collaboration with Prof. Francesco Grilli from KIT has been carried out for developing the models since the beginning. His expertise in FEM Multiphysics simulation is fundamental for our goals. The last year has been spent in Karlsruhe under his supervision, implementing and developing advanced models with commercial and in-house software.
Interested partners such as KIT (Wescley De Sousa), Tampere University (Janne Ruuskanen) and Cambridge (Mark Ainslie) showed their interest in the work carried out. They agreed in using the results we obtain using our resistivity curves in relevant case scenarios where they think the curves can be of impact.
Finally, with a growing interest in modeling and commercializing superconducting devices, the question of how to teach and to explain to students the potential use and benefits of superconductivity has arisen. To help students visualize this, and with the help of Francesco Grilli and Bertrand Dutoit, we recently created a series of web applications using COMSOL Multiphysics.

The models are implemented in the COMSOL Multiphysics environment and distributed as a web application within the project AURORA (le**a**rning s**u**pe**r**c**o**nductivity th**r**ough **a**pps).

The server can be reached at the following link: **https://aurora.epfl.ch/app-lib**

8 Publications

Documents, proceedings and journal articles

[1] N. Riva, *PhD thesis, Quench behavior of High-Temperature Superconductor tapes for power applications, A strategy toward resilience:* 2021, (http://dx.doi.org/10.5075/epfl-thesis-8754)

[2] N. Riva *et al., Study of a Superconducting Magnetic Diverter for the ATHENA X-Ray Space Telescope,* IEEE Transactions on Applied Superconductivity (Volume: 28, Issue: 4, June 2018)

[3] *N. Riva, S. Richard, F. Sirois, C. Lacroix, B. Dutoit, F. Grilli, Isothermal resistivity curves of HTS coated conductors: a synergy between experiments and simulations – 2019 IEEE Transactions on Applied Superconductivity 29 6601705*

[4] N Riva, L. Benedetti, Z. Sajo - *Modeling The Hyperloop With COMSOL Multiphysics®: On The Aerodynamic Design Of The EPFLoop Capsule* – Conference Paper in Lausanne COMSOL Conference 2018

[5] Z Sajò, L.Benedetti, N. Riva - *Modeling The Hyperloop With COMSOL Multiphysics®: On The Pressurized system Of The EPFLoop Capsule* – Conference Paper in Lausanne COMSOL Conference 2018

[6] M Seydoux, N. Riva, et al – Design and manufacturing of a Linear Induction Motor for the 2019 EPFLoop prototype in the framework of the SpaceX Hyperloop competition– Conference Paper in Cambridge COMSOL Conference 2019

[7] N. Riva, F. Sirois, F. Grilli, C. Lacroix, B. Dutoit, *Resistivity of HTS tapes in overcritical current regime: impact on SFCL modeling* – Superconductor Science and Technology, Volume 33, Number 11, 2020

[8] N. Riva, F. Grilli, B. Dutoit, *Superconductors for power applications: an executable and web application to learn about resistive fault current limiters* – European Journal of Physics, (doi.org/10.1088/1361-6404/abf0da)

[9] N. Riva, F. Grilli, F. Sirois, C. Lacroix, A. Akbar and B. Dutoit, *Optimization Method for Extracting Stabilizer Geometry and Properties of REBCO Tapes* – IEEE Transactions on Applied Superconductivity (doi: 10.1109/TASC.2021.3063079.)

[10] A. Akbar, N. Riva, Z. Yang, L. Thevenaz and B. Dutoit, *Fast Hotspot Detection in SFCLs by Exploiting Strain Response in Optical Fiber Sensing*, in *IEEE Transactions on Applied Superconductivity*, doi: 10.1109/TASC.2021.3061346.

[11] N. Riva, F. Sirois, C. Lacroix, J. Giguere, F. Pellerin, F. Grilli, B. Dutoit, *The eta-beta model model: an alternative to the power-law model for numerical simulations of REBCO tapes*, submitted to Superconductor Science and Technology.

Oral presentations

[12] N. Riva, S. Richard, F. Sirois, C. Lacroix, B. Dutoit, F. Grilli - Isothermal resistivity curves of HTS coated conductors: a synergy between experiments and simulations - Oral Presentation at MSE Darmstadt 2018 – Available online

[13] N. Riva, S. Richard, F. Sirois, C. Lacroix, B. Dutoit, F. Grilli - Quench behavior of High-Temperature Superconductor tapes for power applications: a strategy toward resilience - Oral Presentation at ASC Seattle 2018

[14] M. Paolone, N. Riva, Z. Sajo, L. - Modeling The Fifth mode of transportation with COMSOL Multiphysics®: On The multyphysics design Of The EPFLoop Capsule Benedetti - Plenary Keynote at Lausanne COMSOL Conference 2018

[15] N. Riva, F. Grilli, F. Sirois, C. Lacroix, B. Dutoit, M. Masse - 1D and 2D finite-element approaches to extract the resistivity of the superconductor material from pulsed current measurements on HTS commercial tapes - Oral Presentation at CHATS Szcezcin 2019

[16] N. Riva, M. Seydoux et al - Design and manufacturing of a Linear Induction Motor for the 2019 EPFLoop prototype in the framework of the SpaceX Hyperloop competition – Presentation in Cambridge COMSOL Conference 2019

[17] L. Benedetti, J. Harray, N. Riva - SpaceX Hyperloop Competition: Fluid Damper Optimization Through CFD & Multi-Body Simulations of The Prototype Dynamic Response to Stochastic Excitation – Presentation in Cambridge COMSOL Conference 2019

[18] N. Riva, F. Grilli, F. Sirois, C. Lacroix, B. Dutoit, W. B. de Sousa - Resistivity of HTS tapes in overcritical current regime: Impact on Superconducting Fault Current Limiter - Oral Presentation at EUCAS 2019 , Glasgow

9 References

[19] F. Sirois, B. Dutoit, C. Lacroix, J.-P. Corbeil, and J. Coulombe, "*Flux flow characteristics of 2G HTS coated conductors measured with microsecond-range pulsed currents*," presented at the 12th European Conference on Applied Superconductivity (EUCAS 2015), Lyon, France, 2015, pp. 1–28.

[20] S. Richard, F. Sirois, C. Lacroix "*Development of a characterization method of the resistance of 2G HTS CCs tapes above Ic in static condition with ultra-fast current pulses*", To be published

[21] F. Grilli, "*Numerical modeling of HTS applications",* 2016 IEEE Trans. Appl. Supercond. 26(3) 500408

[22] F. Sirois, J. Coulombe, F. Roy, B. Dutoit, "*Characterization of the electrical resistance of high temperature superconductor coated conductors at high currents using ultra-fast regulated current pulses"*, Supercond. Sci. Technol. 23, 034018, 2010 [Available online: http://dx.doi.org/10.1088/0953-2048/23/3/034018]

[23] L. Liang et al. , "*Modeling and Experiment of the Current Limiting Performance of a Resistive Superconducting Fault Current Limiter in the Experimental System"*, Supercond. Journal of Superconductivity and Novel Magnetism, 28, 2015

[24] Czerwinski et al. , "*Analysis of Alternating Overcurrent Response of 2G HTS Tape for SFCL"*, IEEE TAS Vol. 3 24 5600104, 2014

[25] Paul et al. , "*Fault current limiter based on high temperature superconductors"*, Physica C: Superconductivity Vol. 354, 2001

10 Appendix

Abstract of the PhD thesis, elaborated and published by Nicolò Riva.

Quench behavior of High-Temperature Superconductor tapes for power applications: A strategy toward resilience

High-Temperature Superconductors (HTS) can be superconducting in liquid nitrogen (77 K), holding immense promises for our future. They can enable disruptive technologies such as nuclear fusion, lossless power transmission, cancer treatment devices, and technologies for future transportation. In the past years, the numerical models to describe the electrical resistivity of REBCO commercial tapes for devices working near and above the critical current, have been shown to be not accurate or very empirical. The resistivity in this regime in fact, is not very well known. The lack of this knowledge is a significant issue in developing quality simulation tools.

The major challenge in retrieving such properties lies in the fact that for $I > I_c$, heating effects and thermal instabilities can quickly destroy the conductor if nothing is done to protect it. Moreover, due to the current sharing between the layers, it is difficult to know the amount of current carried by the superconducting layer, and hence, its resistivity.

The present work aims to understand better the overcritical current regime combining ultra-fast pulsed current measurements performed on HTS REBCO based coated conductors with Finite Element Modeling. The experimental activities were carried out mostly at EPFL and in part at PM and KIT. The modeling activities were carried out between EPFL and KIT. In the framework of my Ph.D. research, major findings include:

- The development of a post-processing method based on the so-called Uniform Current (UC) model to estimate with accuracy the resistivity of the HTS in the overcritical current regime from experimental measurements;
- The development of a post-processing method based on *regularization of data* to treat the experimental measurements extracted in the overcritical current regime. The output of this technique is a look-up table that can be shared with interested partners and used in numerical modeling afterwards;
- The development of the *overcritical current resistivity model*, based on data processed with the Uniform Current model. The overcritical current resistivity model show a remarkable deviation with respect to the widely used power-law model. This results has a practical impact in developing quality simulation tools for optimizing the design of superconducting devices working near and above the critical current;
- The experimental validation of the overcritical current resistivity model. The model was also used to show that, for the case of a superconducting fault current limiter, when the power-law model is used to model its electro-thermal response, the device quenches faster than with the overcritical model. In other words, it was showed how the power-law model leads to a wrong estimation of the temperature's temporal evolution, largely overestimating the maximum temperature of the REBCO layer. When using the overcritical current model, the temperature is much lower.

The lack of good knowledge in the overcritical current regime is a major issue in developing quality simulation tools for optimizing the design of superconducting devices working near and above the critical current. This work can be very useful to optimize the use of superconducting material as well as the amount of stabilizer. More interestingly, it opens the study of the overcritical current regime, an unexplored exciting aspect of REBCO commercial tapes.

Keywords: Resistivity, Modeling, Overcritical current regime, HTS, REBCO, Finite Element Modeling, Pulsed Current Measurements.

Karlsruher Institut für Technologie

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