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**Dissertation Thesis Abstract** 

# Advanced superconducting conductors for fault current limiters

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#### Abstract

Resistive type of superconducting fault current limiter (SFCL) potentially offers attractive properties for fault current limitation in high voltage transmission. The evolution of renewables rediscovered interest in high voltage direct current (HVDC) transmission for long distances. The existing protection systems are at their operational limits and novel ways of electric grid protection are in demand. Second generation (2G) coated conductors (CC) with their ability of nonlinear transition from superconducting to a highly resistive state are interesting adept for mitigating prospective fault currents  $(I_{pf})$  to acceptable levels. However, during the fault current and consecutive coated conductor quench, considerable Joule losses are dissipated. The critical current  $(I_c)$  of the superconductor, as the most sensitive component of CC, can be degraded by a temperature of a few hundred Kelvins (~480 K). The thesis investigates the concept of coated conductor enhancement by a modification with an electrically insulating high  $c_p$  (EIHC) layer. At first, FEM numerical model was developed to study the performance of the short (100 mm), uniform coated conductor under influence of DC-current limitation in the circuit with constant voltage (CV) power supply. The comparison of the unmodified CC and coated conductors modified by "metallic shunt" and EIHC layer is presented. Then the experimental apparatus is developed to test a coated conductor behavior in specified DC-current limitation conditions. The results on 100 mm long samples are presented. The thesis continues with statistical analysis of the effect of the critical current homogeneity on the current limitation performance of coated conductors modified by the EIHC layer, as the primarily studied concept. The results indicate a correlation between EIHC modification effectiveness and coated conductor critical current inhomogeneity. Artificially induced quench evolution on the CC surface in both unmodified and modified samples is experimentally studied by a high-speed monochromatic-light sensitive camera. The results show a significantly larger normal zone in samples modified by the EIHC layer, which improves heat transfer and reduces the temperature in localized hot-spot. The samples enhanced by the EIHC layer survived repeated quench, while the  $I_c$  of unmodified reference degraded at similar conditions. In the next step, the sample with  $I_c$  inhomogeneities inherited during fabrication is studied in a controlled DC-current limitation experiment in the circuit with a CV power supply. The thesis additionally investigates the effect of initial ambient temperature on coated conductor performance during current limitation and the effect of DC-current pulse rate on  $I_c$  degradation of CC.

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#### **1. Introduction**

The concept of the Resistive type of Superconducting Fault Current Limiter (R-SFCL) introduces attractive physical characteristics thanks to the superconductor nonlinear phase transition accompanied by a steep increase in resistivity. It is especially promising for protecting the upcoming high voltage direct current (HVDC) transmission lines, where the existing protective systems are reaching their operational limits.

One class of the promising superconducting conductors for R-SFCL are the second generation (2G) high-temperature superconductors (HTS), based on *Rare Earth*-Barium-Copper-Oxide (*REBCO*), also known as coated conductors (CC). R-SFCL for HVDC in the current range of tens of thousands of amperes requires coated conductor lengths in tens to hundreds of meters. However, one of the major obstacles for coated conductor large-scale utilization is its fabrication cost. Two approaches allow cost reduction of CC:

- a. Increasing the electric fields resilience of CC
- b. Increasing the current carrying capacity of CC

A superconductor in nominal DC operation transports current without resistance. A fault current, exceeding the critical current, causes the transition to normal state and rise of the electric field. Joule resistive losses dissipate in CC and increase the coated conductor temperature. Highenough temperature (~480 K) can cause the degradation of superconductor  $I_c$ . The standard architecture of commercially fabricated CC usually allows coated conductor transition to the normal state (quench) without degradation at relatively low electric fields. However, necessary coated conductor length reduction leads to higher electric fields because the nominal net voltage is distributed along a shorter length. A higher electric field leads to higher heat dissipated in normal state. Therefore, a change in the 2G HTS design for the current limitation at high electric fields is necessary. The primary focus of the thesis is an investigation of coated conductor modification by an electrically insulating, high thermal capacity (EIHC) layer.

The secondary approach utilizes the superconductor critical current ( $I_c$ ) - temperature (T) dependence. In case, where we would need two parallel CC we can potentially use one conductor with a higher critical current. The  $I_c$ -T dependence of the CC allows an increase of critical current. Lower ambient temperature increases the coated conductor ability to transport superconducting current approximately by a factor of two via a reduction of the temperature by only ~12 K (from liquid nitrogen (LN<sub>2</sub>) temperature at atmospheric pressure of 77 K to the sub-cooled temperature of 65 K).

Are modified coated conductors able to withstand the target electric fields of 100-150 Vm<sup>-1</sup> during DC-current pulse? How will longitudinal  $I_c$  inhomogeneity affect the current limitation? What is the effect of the EIHC modification on the DC-current limitation performance of coated conductor? How will sub-cooling of LN<sub>2</sub>, affect coated conductor ability to limit currents without degradation of  $I_c$ ? These are the basic questions that the thesis endeavors to answer.

The author implemented several methods in the thesis to answer the laid questions. For coated conductor characterization (measurement of volt-ampere characteristic (I-V)) the DC pulse characterization instrumentation was developed. A newly designed, unique experimental

apparatus for DC-current limitation experiments with constant voltage (CV) power supply served for experimental testing of coated conductors in conditions of DC-current limitation. The DCcurrent limitation apparatus allowed us to study the effect of the current ramp rate on  $I_c$ degradation. Later, high-speed optical imagining of the fluorescent layer covering the surface of the CC was implemented to study the local  $I_c$  hot-spot and its effect on the current limitation performance of coated conductor modified by the EIHC. In addition to experimental techniques, the numerical FEM model served for better understanding and evaluation of processes in CC, and the possibility to predict coated conductor behavior during DC-current limitation.

#### 2. Resistive Type of Superconducting Fault Current Limiter (R-SFCL)

Generally, the electrical grid operates in two states: *steady* and *transient*. Steady operation is the desired state when the grid is within designed limits. In the ideal case, the grid impedance is zero, in the real case as low as technically viable. The nominal transient operation occurs during switching or other necessary temporary alternations, which are standardly also within designed limits. However, an integral part of each system is also the *faulty transient state*. In a fault state, ideally, the grid impedance is infinitely high. In practice, the prospective fault current  $I_{pf}$  [A] magnitude can reach 10 – 100 times [1] of nominal current  $I_{nom}$  for several tens to hundreds of milliseconds. Then it is interrupted either by an effective protective system or by physical limitations of the grid (thermal or mechanical damage). Components in the power systems must be able to withstand fault currents for this period.

Resistive type of superconducting fault current limiter (R-SFCL) is a device connected in series with the system that limits the excessive currents. The R-SFCL functions on introducing superconducting elements to the grid, which in nominal operation has very low (in AC transmission) or zero (in DC transmission) losses. In a normal state, the *REBCO* is practically an insulator, and the current flows only through the thin metallic layers of the coated conductor. When connected in the series with the protected circuitry, it reduces the magnitude of the fault current. Resistive losses dissipating in the coated conductor must be efficiently transferred from the coated conductor. *Currently, existing R-SFCLs are capable to withstand* ~50 Vm<sup>-1</sup>. In the thesis, we investigate the possibility to enhance coated conductors to limit 100-150 Vm<sup>-1</sup>. The R-SCFCL in high voltage transmission is a complementary device to existing circuit breakers. It reduces the fault current magnitude, which reduces the severity of the fault and mitigates uncoupling by a circuit breaker. A considerable amount of energy dissipates in the CC during the fault current quench.



Fig. 2.1 Simplified scheme of resistive FCL

Because of *REBCO*  $I_c$  susceptibility to degradation under excessive temperature, the maximum temperature in coated conductor must be maintained below a certain threshold for a certain period. The oxygen diffusion from the REBCO [2] causes  $I_c$  degradation [3]. An additional source of mechanical degradation of the coated conductor is the different thermal expansion coefficients.

The main design parameters for DC R-SFCL are:

- The nominal voltage,  $V_{nom}[V]$ , the nominal current  $I_{nom}[A]$
- The prospective fault current  $I_{pf}$  [A], fault duration  $t_{pf}$  [ms] (in this work, standard 50 ms)
- Maximum quench temperature  $T_{Q\_MAX}$  [K]
- Coolant (ambient) operating temperature  $T_0$  [K]
- Cost (material, cooling maintenance)

Nominal current  $I_{nom}$  is lower than the critical current of coated conductor  $I_c$ . Nominal voltage depends on the grid. The prospective fault current  $I_{pf}$  [A] is the current which would be in the circuit without current limitation. The necessary length of coated conductors depends on the maximal electric field which can coated conductor withstand during the quench  $E_{Q_MAX}$  [Vm<sup>-1</sup>]. The fault duration  $t_{pf}$  together with dissipated energy, which is the product of current and electric field, determines the coated conductor temperature at the end of the fault current. The ambient temperature determines the critical current of coated conductors.

#### 3. Second Generation (2G) Coated Conductors (CC)

The *RE*BCO superconductor is from the cuprate family. The first two letters in the acronym stand for rare-earth, which expresses the possibility of substitution by different rare earth elements. Because of the wide use of Yttrium, we sometimes refer to *RE*BCO coated conductors as YBCO. Fig. 3.1 shows an illustration of the YBCO orthorhombic crystal lattice. The a-b plain conductivity is higher than c plane conductivity, therefore the crystal arrangements effort in coated conductor tapes corresponds to that.



Fig. 3.1 Illustration of YBCO crystal lattice [4]

Researchers and manufacturers are working on achieving the highest current densities possible. Critical current density in a single *RE*BCO crystal reaches ~10 kAmm<sup>-2</sup> (at 4.2 k and self-field) [5]. The  $B_{c2}$  of YBCO is estimated to be more than 110 T (at 4.2 K) [6]. The critical temperature is ~92 K, well above 77.3 K (Liquid Nitrogen (LN<sub>2</sub>) boiling temperature at 101 kPa). The samples presented in this work have a thickness of superconducting layers of 1.1 µm (SuperPower manufacturer) and 3.3 µm (Theva manufacturer).

The structure of the second generation (2G) coated conductor (CC) comprises a substrate layer (Hastelloy, stainless steel, etc.) on which, depending on the fabrication method, is a series of buffer layers deposited. On top of the buffer layer is situated superconducting layer. A silver overlayer additionally covers this composition of layers. The most common stabilizer material is copper.



Fig. 3.2 Illustration of REBCO coated conductor prepared by MOCVD [7]

#### 4. Summary of State-of-the-Art CC Modification Concepts

The section briefly summarizes novel concepts for modification of 2G coated conductors for use in R-SFCL.

**Current Flow Diverter (CFD)** [8], [9]: The main purpose is to accelerate normal zone propagation velocity by redirecting the current flow from the superconductor. It increases current transfer length and improves the spatial distribution of heat generation across the CC. In this concept, the architecture of 2G HTS coated conductors is changed by inserting a highly resistive layer at the interface of the superconductor and stabilizer in the central part of the CC on the interface of *REBCO* and silver overlayer (Fig. 4.1 (a)). This way during the quench, a current flowing from superconductor to metallic stabilizer is forced to elude the resistive layer.



Fig. 4.1 (a) Illustration of current flow path [8]

(b) CC modified by CFD [9]

*REBCO* on the sapphire substrate [10], [11], [12]: The concept builds on a physical property of sapphire (corundum - Al<sub>2</sub>O<sub>3</sub> [13]) monocrystal structure. The sapphire is substrate material, replacing Hastelloy or other standard materials. It has an exceptionally high specific heat capacity  $c_p$ =761 J kg<sup>-1</sup>K<sup>-1</sup> (@294 K) [13]. The fundamental problem with the use of Sapphire as a substrate is its crystalline structure. It deforms the crystal lattice of *REBCO*, which causes the formation of misalignments, which practically reduces the *I<sub>c</sub>*. Currently it is not expected to bend such conductors to pancakes or solenoids (as is a consideration with other concepts).

**Metallic shunt on standard 2G HTS tape** [14]: Let us call the metal modification "a shunt". Coated conductor modified by additional metallic layer is supposed to improve longitudinal heating of the coated conductor to achieve a more uniform transition to the normal state and avoid the formation of hotspots during quench. It also reduces the electric field load of CC. Hastelloy has high resistivity, and it is an identical material, as is the CC substrate. It allows avoiding the thermal contraction difference between CC and Hastelloy shunt. The drawback is the relatively high cost of the Hastelloy and (Ni-Sn) solderThe metallic shunt (Hastelloy, stainless steel) is soldered on the surface of the CC sample from the side of HTS. The thickness of the metallic shunt

is around 500  $\mu$ m, which makes it relatively stiff and hard to bend. The Ni-Sn soft solder has approximately 5-10  $\mu$ m, depending on the quality of the soldering technique.

#### 5. Electrically Insulating High $c_p$ (EIHC) Modification

The term EIHC generalizes the idea of using electrically insulating epoxy material with a high thermal capacity to increase the total thermal capacity of the modified CC. The layer acts as a "heat reservoir" for heat dissipated in the CC, without generating additional heat as metallic shunt does. It practically does not affect conducting cross-section of the CC as metallic shunt does, so the current after during the quench is as low as the structure of the original CC allows.



Fig. 5.1 Concept of CC modification by application of EIHC layer [15]

The EIHC layer presented in this work is a low-cost epoxy resin Stycast. Stycast is a well-known material in cryogenic applications such as encapsulation of magnets. Its adhesiveness makes it easily applicable on the surface of CC. After hardening, it remains sufficiently flexible up to 400 µm thickness [15].



Fig. 5.2 Specific heat of EIHC layer affected by different filler materials [16]

For thermal stabilization, Stycast (EIHC) has high specific thermal capacity and conductivity, and its thermal expansion should be similar to thermal expansion [15] of the CC substrate (Hastelloy) to prevent delamination because of high-temperature gradients. The specific heat, as well as thermal expansion of the EIHC, are adjustable by the appropriate filler materials.

#### 6. The Numerical and Experimental Methods

#### Numerical FEM 3D model:

The section presents a 3D numerical model developed for a calculation of a coated conductor under the influence of DC pulse, causing quench. In the model, the quench is uniform along the sample. The model was built in COMSOL Multiphysics® 5.4. The CC is in series with the model of the circuit, simulating experimental conditions. The model solves coupled partial differential equations for heat transfer and dynamic transport current.

The CC represents uniform, rectangular layers, stacked on top of each other. The critical current at 77.3 K is 550 A with n = 19. The width of CC is 12 mm, and the finite length is 76 mm. On top of the 50  $\mu$ m substrate is the 3  $\mu$ m thick superconductor. A silver overlayer from all sides covers the superconductor and substrate. The silver overlayer is 2  $\mu$ m thick from the side of the superconductor, while 1.8  $\mu$ m thick from the substrate side. The initial ambient temperature is 77.3 K. Heat transfer from solid CC to liquid LN<sub>2</sub> defines the heat transfer coefficient.



Fig. 6.1 Illustration of CC cross-section in the simulation

To optimize computation time, the mesh is built of hexahedral elements. A typical tetrahedron is also a viable option, but the computational time is generally longer. There are 10 elements across coated conductor width. Then, particular layers of the coated conductor have a different number of elements according to the thickness of the layer. Because of superconductor layer is thin, there are two elements. Two rows of elements are also in silver overlayer layers. The resistive interlayer between *RE*BCO and silver represents 2D virtual boundary [17]. The thickness of the layer is only a scalar value for the calculation of heat transfer. The buffer layer between substrate and *RE*BCO is also represented as a boundary without the third dimension (thickness). The substrate thickness is divided into 5 elements due to its higher thickness. Modification layers (EIHC, Hastelloy,

stainless steel) have 5-20 elements depending on the thickness of modification. The Comsol offers several solvers for FEM numerical calculation. The results in the thesis were calculated using a parallel sparse direct time-dependent solver MUMPS.

The model includes a simulation of an electrical circuit with parameters similar to experimental apparatus: The voltage of the DC power supply is 10 V, the resistance of the circuit is 6 m $\Omega$ , and the inductance of the circuit is 3  $\mu$ H. The model of the coated conductor is virtually connected with the model of our experimental circuit.

#### **Experimental methods: DC-current limitation experiment**

The section describes the experimental apparatus for the investigation of the *RE*BCO coated current and electric field evolution during the DC-current limitation. The transport current measurement is based on the four-point measurement method. An LN<sub>2</sub> bath cools the sample and sub-cooling is through the evacuation of evaporated nitrogen gas from the cryostat. We can set the range of ambient temperatures of the LN<sub>2</sub> bath from below the freezing point of the Nitrogen (63.1 K) up to boiling temperature at atmospheric pressure (77.3–77.4 K). The temperature of the bath measures the Cernox® sensor at one point ~ 20 mm away from the surface of the sample. The Cernox® sensor response is not sufficiently fast enough to directly measure sample temperature during the DC-current limitation experiment. The sample temperature can be indirectly evaluated from its known resistance – temperature R(T) dependence.

The current flowing through the sample is calculated from the voltage recorded on calibrated measurement resistor connected in series with the sample. The circuit is switched on and off by a synchronized signal send to MOS FET transistors in the Solid-state switch.



Fig. 5.1 a.) Scheme circuit of experimental setup,

b.) Current and electric field in the sample [18]

We use it as a DC power supply set NiCd accumulators. The accumulators have a rated current up to 2500 A (tested up to 1500 A) and voltage of ~1.3 V per cell, in total up to 70 V (tested 15 V). The required supply voltage sets a connection of an appropriate number of cells in series. Then the voltage seen by the sample is :

$$V_{sample} = V_{ACC} - V_{circuit} - V_{Rcircuit}$$
(5.1)

, where  $V_{sample}$  [V] is the voltage measured on the sample,  $V_{ACC}$  [V] is the voltage across battery leads,  $V_{circuit}$  [V] is the voltage drop on the circuit and  $V_{Rcircuit}$  [V] is the voltage on an adjustable resistor with discreet positions. It sets up maximal current peak amplitude. The rate of current rise tunes with circuit inductance  $L_{circuit}$  [µH].



Fig. 5.2 The current rise rate changed by circuit inductance

#### 7. Results of Numerical Calculation of Uniform Coated Conductors

The section summarizes DC-current limitation simulation on reference coated conductor and coated conductors modified by metallic shunt and EIHC layer.

#### **Reference Sample:**

Fig. 6.1 presents calculated I(t), E(t) evolution in the unmodified, ideal, uniform reference coated conductor. Calculations are for standard current limitation conditions - 50 ms pulse at 120 Vm<sup>-1</sup>. The peak amplitude of the electric field calculated on the sample, observed at approximately 1 ms, depends on several CC parameters: the n-factor and resistance of the *REBCO* - silver overlayer interface and metallic layers surrounding the superconductor. Fig. 6.2 shows current development calculated in separate CC layers and the total current flowing through the conductor (black curve). As expected, the current distribution after the complete transition depends on metallic layer resistances. The maximum current peak  $I_q$  [A] in the uniform superconductor is a function of the

applied electric field together with superconductors n-factor and the substrate and silver overlayer resistance. The critical current of the superconductor measured at static and/or pulse characterization is deep below the maximum current reached during the quench  $I_q$  [A].



Fig. 6.1 Calculated electric field development in the reference sample



Fig.6.2 Current distribution in coated conductor layers in the first 3 ms

#### Sample Modified by Soldered Hastelloy:

The subsection presents the electro-thermal numerical calculation of the CC modified by the Hastelloy layer with various thicknesses. Soldered metallic modification of the CC is not in the primary scope of the thesis. The subsection serves only for the comparison of the metallic shunt concept with the EIHC modification. Using the Hastelloy metallic shunt has an advantage over other possible shunts (e.g. Stainless Steel) – it matches the thermal expansion of the CC substrate. The rapid heating because of the fault current limiting process can lead to differences in

temperatures of the superconductor layer, substrate layer, and metallic shunt layer. The significant temperature gradient in different CC layers and metallic shunt leads to delamination and degradation of coated conductor properties. However, the use of the same material as a metallic shunt modification can avoid the extreme differences in thermal expansion. The downside of the use of Hastelloy is its cost.

The bonding of CC and metallic Hastelloy is done with soft Ni-Sn solder. The thickness of the solder layer is constant,  $10 \,\mu$ m; conservatively chosen to consider imperfect manual soldering.



Fig. 6.3 Development of electric field in CC modified by Hastelloy layer

Fig. 6.4 shows the current distribution coated conductor modified by  $100 \mu$ m.The overall magnitude of the current through to the CC is significantly higher compared to the reference sample.

The use of metallic shunt should be chosen with concern to specifically protected grid and its endurance against overcurrents. However, when considering the grid, where nominal current  $I_{nom}$  is always lower than the critical current of 550 A, total current reduction after the initial peak is achieved only by the ~100 µm layer.





On the other side, as is shown in Fig. 6.5, the temperature of the superconductor layer with 100  $\mu$ m Hastelloy shunt after 50 ms is high enough to damage the  $I_c$  of the superconductor by oxygen diffusion [2], [3]. The red curve represents the total current evolution in the reference sample with no modification. As expected, the current in CC modified by Hastelloy is higher after the transition to the normal state. The primary aim of FCL is to limit the current magnitude during the fault current. Considering that  $I_c$  is 550 A, we assume that the nominal operation of the protected part of the circuit is lower than  $I_c$ . We aim to limit currents to magnitudes as close to the operational values as possible. Higher transferred currents increase the risk of damage to the protected part of the grid.

Considering that the thickness of the solder can vary in a broad range, and the thickness of the silver overlayer is also adjustable, the current distribution can be different.



Fig. 6.5 Temperature evolution in superconductor layer of CC modified by Hastelloy of various thicknesses

The results of numerical calculations show a 30% decrease in superconductor layer temperature in CC with homogeneous, isotropic layers modified by 100  $\mu$ m Hastelloy and 10  $\mu$ m thick solder layer at the end of 50 ms pulse. With a Hastelloy layer thicker than 100  $\mu$ m, the temperature is reduced even more. However, in Fig. 6.5 is also visible that the effectiveness of temperature reduction in a superconductor by modification with metallic layer further decreases.

Besides the calculation of CC modified by the Hastelloy, we performed calculations with Stainless Steel. Results are were very similar to the modification by Hastelloy shunt. To avoid redundancy we do not include a standalone subsection.

#### Sample Modified by EIHC layer:

The thesis is focused on the coated conductors modified by the EIHC layer. The EIHC modification of uniform CC behaves differently from an electrical point of view compared to samples modified by Hastelloy.

Using the EIHC layer offers an advantage over metallic shunt modification presented in the previous subsection – an additional binder (soft solder) is not required because of the inherent adhesivity of the epoxy in a fluid state. Because of the insulating character of the high  $c_p$  layer, the total electric field and the current flowing through the CC is practically identical to the reference sample, independent from the thickness of the layer. To avoid duplicity of the presented data, we do not include I(T), E(t) charts. The only expected difference is the temperature of the CC because Joule heat dissipated after the transition to the normal state.

Fig. 6.6 presents temperature development in the homogeneous, isotropic superconductor layer in CC modified by an electrically insulating high  $c_p$  layer.



during the 50 ms DC limit in CC modified by EIHC layer

The calculated effectiveness of heat removal from the superconductor by the EIHC layer is lower compared to the metallic shunts presented in previous sections. The notable result is a saturation of heat removal effectiveness at 500  $\mu$ m EIHC thickness. The phenomenon is visible in Fig. 6.7. However, already 50  $\mu$ m thickness provides a significant reduction of superconductor layer temperature compared to the reference. According to different sources, the degradation of the superconductor layer depends on temperature magnitude and exposure period [3].



Fig. 6.7 Comparison of calculated superconductor layer temperature after 50 ms DC current pulse in CC modified by metallic shunt and EIHC material

To conclude calculated results on uniform coated conductors in section 6, we see that any chosen modification compared to the reference sample, either the metallic or the EIHC decreases the superconductor layer temperature during the standard (DC current limitation at  $120 \text{ Vm}^{-1}$  per 50 ms). The architecture of the reference CC causes a significant electric field peak during the transition to the normal state, which exceeds the desired electric field of  $120 \text{ Vm}^{-1}$  by 40%. We see that the total temperature dissipated at the end of the limitation is lower in coated conductors enhanced with the soldered metallic shunt compared to the EIHC modification.

Calculation shows that the temperature in the superconductor layer of coated conductor modified by the EIHC reaches saturation at a thickness of 500  $\mu$ m and further thickness does not reduce the temperature. In comparison with the metallic shunt, there is also a decrease in superconductor temperature reduction, but up to an investigated thickness of 2000  $\mu$ m, saturation was not reached.

#### 8. Experimental Results of 100 mm Coated Conductors in DC-Current Limitation Experiment

The reference sample is a bare 12 mm wide coated conductor with no stabilizer layer or modification. The length of the samples is 83 mm. The electric field is measured along the ~100 mm length, without knowing the local  $I_c$  inhomogeneities. The critical current of samples was determined by transport DC pulse measurement at 77.3 K.



Fig. 8.1 shows the resistance at room temperature (~294 K) of samples.

The resistance of reference unmodified CC is similar to the sample modified by EIHC (Stycast FT 2850/Catalyst 11 + SiC20wt%) as calculations predicted. As predicted in calculations, modification with the metallic shunt increases the conductive cross-section of the samples, which is manifested in lower resistivity. The thickness of the EIHC layer (for one-sided and from both sides) is ~100  $\mu$ m. Because of the experimental fabrication procedure, the thickness of the EIHC layer varies along with the sample by tens of  $\mu$ m. Besides  $I_c$  and stabilizer inhomogeneities, also non-uniformity of the EIHC layer makes it hard to directly compare calculation with the experimental sample. The technology of metallic shunt fabrication is more mature, and the thickness is sufficiently constant – at 550  $\mu$ m.

#### **Results on ~100 mm Samples:**

The following charts summarize DC-current limitation experiment results. The experimental result of the DC-current limitation of coated conductor modified from both sides by the EIHC layer is part of the charts, to show improvement compared to the EIHC applied only from the superconductor side. All other presented results are from samples modified only from the side of the superconductor. The constant voltage power supply was set for all measurements that the electric field on the reference sample was standard 120 Vm<sup>-1</sup>. The length of the pulses is 50 ms. The current pulse rate is 5000 As<sup>-1</sup>.

Fig. 8.2 presents electric field evolution in samples over 50 ms pulse. Higher voltage drop is in samples modified by the EIHC, as predicted by calculations. Fig. 8.3 shows the current evolution in the sample over a 50 ms long pulse. The circuit inductance and resistance are constant, as well as power supply voltage. As can be seen, the current magnitude is limited by the EIHC, like the reference sample. In samples modified by metals, current limitation effectiveness is lower by a factor of ~2.5. Considering that nominal current  $I_{nom}$  is always rated lower than minimal value  $I_{c_min}$ , potential circuitry installation would be exposed to the currents more than two times higher than their nominal values throughout the current limitation period. The results are qualitatively



Fig. 8.2 Electric field evolution in different samples

comparable to simulations done on uniform samples. The sudden "jump" in the Stainless Steel curve (~20 ms) and Hastelloy current curve (~13 ms) is probably caused by solder melting. After the experiment, the samples were checked and, in several points, the soft-solder layer was melted and even poured out from the interlayer, leaving void spaces.



Fig. 8.3 Current evolution over time in modified samples

We observed solder melting also in a few other samples with similar metallic modifications. Therefore, we assume that the sudden jump in the current curve, while the electric field curve (Fig. 8.2) is smoothly continuous, is not measurement error but phase change of the solder.



Fig. 8.4 Relative resistance as a function of total Joule heating

Table I. shows the critical current of presented samples before and after the current limitation. The I-V characteristic of the reference is significantly affected by the DC-current limitation experiment. The sample modified by Stainless Steel was completely degraded after a single DC pulse causing a quench. The I-V curve of the sample modified by Hastelloy was not dramatically affected, however, the melting of the solder was observed.

Sample label	<i>I<sub>c</sub></i> at 77.3 K	<i>I</i> <sub>c</sub> at 77.3 K	
	(Before DC-current limitation)	(After	DC-current
		limitation)	
reference	359	249	
EIHC (HTS side)	294	290	
EIHC (both sides)	348	343	
Stainless Steel (SG)	613	0	
Hastelloy	460	449	

Table I.: Ic of modified samples before and after DC-current limitation

The samples modified by the EIHC layer had a slight change in n-factor, while the sample modified from both sides by the EIHC showed no change after the quench induced by DC-current limitation experiment. The reason why the reference sample survived the DC-current limitation can be possibly the better longitudinal  $I_c$  homogeneity compared to the sample modified by Stainless Steel.

To conclude, the experimental results presented in section 7, we compared DC-current limitations on the reference and modified samples. At standard DC-current limitation conditions (120 Vm<sup>-1</sup> per 50 ms) the  $I_c$  of the reference sample is significantly degraded after the first current limitation. The critical current of the sample modified by Stainless Steel was completely degraded and localized melting of the solder was observed. It suggests that there are localized regions with

a higher temperature than the calculation on a uniform sample predicted in the previous section. The sample modified by the Hastelloy shunt survived the single standard DC-current limitation without significant degradation of its  $I_c$ . The sample modified by the EIHC layer (from the side of the superconductor and from both sides) also survived without degradation of  $I_c$ .

#### 9. Analysis of Critical Current Inhomogeneity Effect on Coated Conductor DC-Current Limitation

Two manufacturers produced coated conductors studied in the work, namely German-based company Theva GmbH., and USA-based company SuperPower Inc. The ratio between the total number of studied samples is approx.  $\sim$ 93% (Theva) to  $\sim$ 7% (SuperPower), considering that samples from the Theva company were the only ones modified, therefore studied more intensely. The experimental results presented in the work are only a selected fraction of measured data





Fig. 9.1 presents the results of transport measurements of critical current (at 77.3 K, in self-field) on short Theva samples (80 – 130 mm). Each point in the chart represents the critical current of a single sample before applying any modification or external effect potentially affecting  $I_c$  integrity. Continuous curves represent the batch, or series, of samples cut one by one after each other. The nomenclature of batches for this section will consist of the letter T, followed by a number. Each series is in the context of a time when it was measured (T4: 2017-2018; T6: 2018-2019; T7: 2019; T8: 2019-present days).

Sample series	The standard $I_c$ deviation	Statistical set (n)
	$\sigma_{std} = \sqrt{\sum_{i=1}^{n} \frac{(x_i - x_{mean})^2}{n-1}}$	
T4	46.8	29
T6	209.4	28
T7	85.2	19
T8	45.8	13

Table II.: The critical current deviation of different CC series

Table II. shows standard deviations of selected data series from Fig. 9.1. The critical current deviation in T6, from which the largest number of samples was studied, is 250% higher compared to newer T7, and almost 500% higher compared to the latest T8. Therefore, we conclude significant improvement in the overall  $I_c$  homogeneity of later developed coated conductors. However, it should be emphasized that the curves represent the average transport  $I_c$  measured along the ~100 mm length. The possible incidence of local  $I_c$  inhomogeneities along the lengths shorter than 100 mm samples is not investigated in these experiments.

Let us compare the effectiveness of the EIHC modification on the presented series. The standard modification is by Stycast with SiC filler. However, the SiC ratio differs (10-25%) not only between series but also samples from the same series have slightly different filler ratios. The thickness of the EIHC can vary even on a single sample, because of the early stage method for the EIHC layer application. Therefore, it is not a simple task to rigorously quantify and compare the performance of the EIHC over years (progress in the EIHC application, experimental testing procedures, etc.). However, the samples presented below were tested at the standard experimental condition e.g. the electric field criterion of 120 Vm<sup>-1</sup> of DC-current limitation for 50 ms at 77.3 K (self-field):

Table III. summarizes success rate of EIHC modification at "standard" experimental conditions. Even when the presented samples were not modified by the identical layers (different filler ratio, non-uniformity of EIHC thickness), the statistics indicate a success rate trend.

Sample series	Reference sample	Success rate (120 Vm <sup>-1</sup> for 50 ms at 77.3 K)
T4	degraded $(0.46*I_c)$	80 %
T6	completely degraded	< 50%
T7	completely degraded	without conclusion
T8	degraded $(0.3*I_c)$	100 %

Table III.: The success rate of EIHC modification

The early "relatively homogeneous, low  $I_c$ " series (T4) showed a positive trend of EIHC modification. The later "highly non-homogeneous, high  $I_c$ " series (T6) proved in numerous specified experiments (also various other experiments, which are not included in statistics but are worth mentioning) as irregular and its results unrepeatable. Therefore, the EIHC modification was insufficient in specified fault current conditions. Even samples modified by similar modification

and with very similar average  $I_c$  behaved differently. The last samples, "relatively homogeneous with high  $I_c$ " proved the effectiveness of EIHC modification in specified experimental conditions.

#### 10. Local Quench Observed via High-Speed Fluorescent Optical Imagining

The previous statistical results showed positive effect of EIHC modification on inhomogeneous samples. In this section is investigated the effect of artificially created local critical current minimum to observe dynamics of localized quench. The quench is observed via high speed camera able to record fluorescent light excited on the surface of coated conductor through temperature change. We compare the reference sample, sample modified by the EIHC layer form the side of superconductor and sample modified by EIHC layer from the side of substrate. The experimental method is sufficiently described in [97].

Fig. xx shows illustration of experimental apparatus.



Fig. 10.1 Illustration of measurement setup for quench evolution observation via high-speed camera [97]

#### **Sample Preparation**

The section presents three samples with the same standard architecture; a 12 mm wide Theva sample with a 3  $\mu$ m thick superconductor. The reference sample is coated only by a 2  $\mu$ m silver overlayer, with no modification. We additionally modified the second presented sample with the EIHC layer from the side of the HTS. We also coated the third sample with the EIHC layer but from the side of the Hastelloy substrate ("bottom"). The length of the sample is ~70 mm. A 20 mm copper layer coated the sample endings for current leads. We coated the sample surface from the side of the superconductor with a thermally excitable fluorescent layer – a mixture of the

fluorophore, europium tris (3-(trifluoromethylhydroxymethylene)), and camphorate (EuTFC). The layer serves as an optical indication for NZPV observation. The thermal sensitivity of such coating ranges from 77.3 K to 260 K [97]. The coating was solidified on the sample surface by drying in the oven for two hours at ~90 °C.



Fig. 10.2 Sample holder for high-speed camera quench recording, (a.) Reference sample with no additional coating or copper stabilization, (b.) sample coated with the EIHC from the side of superconductor, and (c.) sample coated with the EIHC from the side of the Hastelloy substrate (the EIHC layer is not visible).

#### **Results**:

Reference sample:



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Sample modified by the EIHC layer:



Fig. 10.3 Comparison of the refereence and the EIHC modified sample

To conclude, the results from experiments presented in the section: the EIHC layer causes approximately two times lower normal zone propagation velocity compared to the reference sample with only a silver overlayer. However, as was shown in the experiment with only the EIHC modification from the superconductor side, the quenched area is 10 to 20 times larger compared to the reference sample. That reduces the density of dissipated energy and at the same time, it increases the heat transfer area to the LN<sub>2</sub>. In the experiment with the EIHC layer applied from the side of the substrate, we observed a reduction in NZPV comparable to the EIHC applied from the HTS side, however, the normal zone area is larger two to four times compared to the reference. Here we have to consider the asymmetry of the coated conductor cross-section. The substrate has a major role in the heat transfer, therefore it limits the effectiveness of the EIHC layer (on the substrate side) on heat dissipation from the superconductor layer.

The critical current of the reference sample significantly degraded after the first quench at 680 A for 12 ms. CC modified by the EIHC layer from the HTS side survived several times longer duration of pulses with no degradation of  $I_c$  The sample modified by EIHC from the substrate side showed degradation of silver overlayer from HTS side but no significant degradation of Ic even after several quenches. The EIHC layer therefore up to some degree enhances coated conductor resilience against the formation of a hotspot.

#### 11. The Effect of Current Rate on Coated Conductor Degradation During DC-Current Limitation

The section investigates the dynamic character of the coated conductor quench induced by the DCcurrent limitation experiment. The subsequent section focuses on the effect of DC pulse rate on the degradation of critical current. It also studies the effect of reduction of the ambient temperature to increase the superconductor current-carrying capacity of the CC. Such temperature reduction can increase the critical current of the CC more than two times. In the subsection is further studied the effect of the current rate on the sample degradation.



Fig. 11.1 Significant *I<sub>c</sub>* degradation during the DC-current limitation at lower temperature [18]

However, was shown recently in [18], the reduction of ambient temperature can lead to coated conductor degradation at the identical DC-current limitation conditions. Fig. 11.1 shows sudden  $I_c$  degradation on a single 6 mm wide sample. The DC-current limitation experiment begins at 77.3 K. The critical current of the coated conductor was measured before and after each DC-current limitation experiment. At the temperature of 66 K, rapid degradation of superconductor critical current during the DC-current limitation occurred.

Table 1V Chedit parameters and initial editent ramp rates [16]		
	Circuit Inductance [µH]	Initial Current Ramp
		Rate [As <sup>-1</sup> ]
Experiment A	3	5000
Experiment B	6	2500

Table IV.: Circuit parameters and initial current ramp rates [18]

We experiment with alternation of current ramp rate to investigate possibility to prevent critical current degradation. To investigate this, we present two experiments with different current ramp rates. Let us call experiment with higher current ramp rate Experiment A. Then the current pulse rate was artificially reduced by increasing circuit inductance (Experiment B). The coated conductor from the same series as in Experiment A was chosen, with a similar average  $I_c$  and n-

factor. The current limitation parameters are the same as data from Experiment A, the initial ambient temperature was set to 66 K. The only difference is the rate of the current pulse. The I-V of the sample in Experiment B with lowered current ramp rate did not change, therefore its critical current did not degrade..



Fig. 11.2 Experimental and calculated evolution of current at a different rate [18]

The results of a numerical calculation in Fig. 11.3 shows temperature development in a uniform sample calculated for conditions corresponding to Experiment A and Experiment B. The results of calculations suggest two important phenomena possibly causing a significant difference of coated conductors DC-current limitation performance in Experiment A and Experiment B. The first observation is that the *temperature rise with a lower current rate is slower* in Calculation B compared to Calculation A. The transition to a normal state has less stepper character with a lower current rate. The second important observation is the initial ambient temperature dependence of the temperature generated by Joule heating. At 66 K, the *temperature development in the CC at 66 K is steeper compared to 77 K for* the identical sample under identical current limitation conditions.

The overal conclusion of the research is that the current rate of the DC-current pulse has a significant effect on the coated conductor's ability to dissipate generated heat during the quench. The initial ambient temperature affects the temperature evolution during the current limitation experiment and can lead to critical current degradation because of higher temperature rise rate during DC current limitation at lower temperature.



#### The quench study in local *I<sub>c</sub>* inhomogeneity inherited from the fabrication:

In previous section we observe the effect of the current rate on the coated conductor during DCcurrent limitation. The section presents the performance of unmodified *RE*BCO CC during the DC-current limitation experiment and the effect on regions with the lower critical current originated during its fabrication.



Fig. 10.4 Illustration of 6 mm sample cross-section (not in scale)

The 6 mm wide (SuperPower) sample is selected based on our previous experience with its relatively low  $I_c$  longitudinal inhomogeneity, compared to the T6 Theva series. The average critical current is ~150 A. The Hastelloy substrate is 50 µm thick. A 2 µm thick silver overlayer covers from all sides the superconductor and substrate.



Fig. 10.5 Illustration of  $I_{c_{min}}$  position identified by DC-pulse characterization

(not in scale)

The length of regions closer to the current leads  $(L_1, L_5)$  is 200 mm, and inner regions  $(L_2, L_3, L_4)$  are 160 mm long. After we installed the sample into the sample holder and cryostat, we measured the  $I_c$  of selected regions.

The characterization identifies the  $2^{nd}$  region as weakest at both temperatures. The  $1^{st}$  region is the second weakest. The lowest critical current, together with the highest resistance in a normal state causes the steepest rise of the electric field in the  $2^{nd}$  region.



Fig. 10.6 Longitudinal  $I_c$  homogeneity in static and pulse characterization and resistance at room temperature

After the initial sample characterization, the DC-current limitation experiment was conducted. The ambient temperature of  $LN_2$  in DC-current limitation experiments is 66.0 K. Experiment was done at 10 ms up to 120 Vm<sup>-1</sup>. The aim is to observe regions with lower  $I_c$  during the *DC-current limitation experiment and the effect of the current pulse at current different rates*. The change of the current rate is done by adjustment of circuit inductance Higher circuit inductance causes a

lower current rate. The circuit inductance is also used to represent the difference in the current pulse slope.

*The experimental procedure*: The voltage of the power supply is constant. The set of DC limitation experiments is iterative. The experiment begins at pulses with amplitude lower than  $I_c$ . At constant current amplitude, we changed the slope of the current pulse from lower to higher. After each DC-current limitation, the sample I-V was tested. We chose this approach because of previous experience with fast current change causing damage to the CC. We increased the current magnitude and rate until the first quench of the sample. In Fig. 10.7 a.) there is current evolution in the sample. The black curve represents the last current magnitude when the sample did not quench and the current was not limited by the CC. The 6  $\mu$ H circuit inductance represents a current rate of ~2500 As<sup>-1</sup>. Then we increased the current pulse rate to 5000 As<sup>-1</sup> (3  $\mu$ H). There is a higher current in the second and third DC-current limitation compared to the first pulse. We cannot, therefore, completely rule out the quench initiated by the higher current magnitude. However, the effect of a current rate can be still observed during the quench.



Fig. 10.7 a.) Current evolution, b.) Electric field-time evolution

#### E S T U

Fig. 10.7 b.) shows the electric field in the two quenched regions. The maximum electric field along the sample was set to be  $120 \text{ Vm}^{-1}$ , in case of uniform transition along the sample. However, the local electric field in region 2 is almost two times higher. The "hotspot" has higher electric fields, which leads to higher energy dissipation in the region. The electric field of ~220 Vm<sup>-1</sup> in region 2 was reached in 10 ms pulse. In a standard 50 ms experiment, it would be higher. The density of dissipated energy in the sample is higher due to local inhomogeneity.

Fig. 10.8 a.) presents the I-E dependence of regions 1 and 2. Region 2 reached a complete quench along. The measurement closely demonstrates normal zone propagation from region 2 to region 1. At first, region 1 did not quench because it was limited by region 2. However, because resistive losses are dissipating in region 2, heat propagates to region 1 and causes a complete quench in region 1. Heat evolution originating in region 2 causes the initial slow rise of the electric field in region 1. When the heat propagates through the whole width of the superconductor, there is a complete phase transition in region 1. From electric field evolution in region 1, we estimated the NZPV of this particular 6 mm sample without any modification to be  $\sim 3 \text{ ms}^{-1}$ .



10.8 The log-log scale of quench in regions 1 and 2 at two circuit inductances

Fig. 10.8 b.) shows region 2 measured at two different circuit inductances (current rates). Here we evaluate the change in the n factor of superconductor transition to normal state. We see that at a higher current rise rate (3  $\mu$ H or 5000 As<sup>-1</sup>), there are two times higher n factor compared to 6  $\mu$ H (2500 As<sup>-1</sup>). The difference in current rate change, achieved by variation of circuit inductance shows, that higher current rate change affects the n-factor of the transition. At 5000 As<sup>-1</sup> (3  $\mu$ H), the measured n-factor of transition is 96, while in the experiment with 2500 As<sup>-1</sup> (6  $\mu$ H) the



Fig. 10.9 Location of degraded points in the region 1 and 2.

n-factor is 48. The temperature dependence of the n factor is well known [20], [21], [19] The higher n-factor during the transition suggests higher temperature dissipated in the experiment with a higher pulse current rate.

The two measurements presented in Fig. 10.8 are only two representants out of a total of 34 DCcurrent limitation experiments done on the sample. The results repeated even after partial degradation of the critical current. After the experiment, we observed the exact location of two hotspots causing quench in regions 2,1. It is visible to the naked eye. Fig. 10.9 shows the location on two burned points (of approximately circular shape) on top of the silver overlayer.

To conclude the presented experiment: we showed in a controlled environment the effect of two weaker regions originating in the coated conductor fabrication process in DC-current limitation conditions. The experiment was done in a such manner, that the DC current pulse



induces the quench in only regions with the lowest critical current. In such conditions, the electric field is concentrated in several times the smaller area than expected. It can lead to the degradation of the critical current. At the same time, we showed the effect of the current rate change on a smaller scale compared to section 10.1. We were able to observe the change of the n factor during the transition to the normal state. The change in the n factor suggests the difference in the local temperature of the quenched regions. Additionally, we were able to observe normal zone propagation from region 2 to region 1 and confirm experimentally obtained velocities in section 9.2.3. We can therefore conclude that the current rate during the quench affects the temperature dissipated in the region. The effect has more severe consequences in the case of local critical current inhomogeneities, where it can lead to the density of dissipated energy is higher.

#### 12. Conclusions

The thesis focuses on the investigation of 2G HTS superconducting conductor applicability for DC-current limitation. The objectives derive from the aim to achieve the cost-effectiveness of the coated conductors. To decrease the amount of the conductor, two potentially valid approaches were investigated: enhancement of the coated conductor thermal stability to withstand higher electric fields and increasing the current-carrying capacity to transport higher currents.

Throughout the solution of the thesis, the DC current pulse apparatus for short (100-1000 mm) coated conductor electrical properties characterization (I-V dependence) was developed and standardized for experimental evaluation of coated conductor samples. Simultaneously with the characterization apparatus, the DC-current limitation experimental apparatus with a constant voltage (CV) power supply was built. The DC-current limitation experimental apparatus is used to investigate a short length (standardly ~100 mm, successfully tested up to 700 mm) coated conductor performance during the current limitation in specified conditions. Standard conditions for the DC-current limitation experimental apparatus can artificially alter the current pulse rate. For a dynamic quench investigation, the high-speed camera recording fluorescent light emitted from the surface of the coated conductor is utilized.

The numerical model of coated conductor for investigation of its DC-current limitation performance was developed to complement experimental results. The model includes the simulation of the circuitry for a closer approximation of experimental conditions.

The work presents a novel approach to thermal stabilization of coated conductors for R-SFCL application: Electrically insulating, high thermal capacity modification (EIHC). Numerical and experimental methods investigate the concept.

- The electro-thermal numerical analysis of uniform coated conductors in the constant voltage circuitry under the DC-current pulse  $(I > I_q)$  compares the performance of the reference coated conductor, the coated conductor modified by a metallic shunt (stainless steel, Hastelloy), and the coated conductor modified by the EIHC layer. The electro-thermal numerical calculations show temperature reduction at the end of the 50 ms pulse at 120 Vm<sup>-1</sup> for all selected conductor enhancement methods.
- The DC-current limitation experimental results in section 7 show in some cases good agreement with the numerical calculations on uniform samples. The experimental results on ~100 mm samples have, however, very inconsistent repeatability. A direct correlation between coated conductor critical current longitudinal homogeneity and degradation of the coated conductor  $I_c$  during the DC-current limitation experiment is shown.
- The CC modified by the EIHC suggests that in samples with very high critical current deviation (209.4), the critical current degradation occurs in more than 50% of cases (T6 series). In sample series (T4) with lower critical current deviation (46.8) and at lower critical current magnitudes, the degradation occurs in 20% of samples. In samples fabricated by the most advanced technique (T8), with the most homogeneous longitudinal *I*<sub>c</sub> distribution (45.8) and with the highest *I*<sub>c</sub> magnitude, the degradation of critical current was not observed at identical DC-current limitation conditions.

- The high-speed fluorescence imagining technique was used to observe the artificially induced quench in the reference sample and the samples modified by the EIHC layer. Despite slower normal zone velocity in the coated conductors modified by the EIHC layer, the area of the normal zone in the sample modified by the EIHC layer is 10 20 times larger compared to the reference sample. Heat dissipation in the larger area causes a more uniform quench along the sample and enlarges the heat transfer area.
- At 66 K, a significant critical current degradation during the DC-current limitation experiment was observed. With the support of the numerical modeling, we proposed the explanation that at lower temperatures the longitudinal Ic inhomogeneity together with a higher temperature rise rate results in a locally higher density of dissipated heat.
- The experiment with alternation of the current pulse rate during the DC-current limitation showed, that a higher current rate affects the n factor of the superconductor during the quench. It indirectly suggests that with a higher current rate there is a higher temperature in the superconductor. As we showed, the alternation of the current ramp rate can prevent the degradation of critical current. The effect of the current ramp rate is important especially in CC with higher  $I_c$  longitudinal inhomogeneity with the possibility of localized hotspots, where a higher current ramp rate increases the density of dissipated heat. The results were published in a peer-reviewed journal.

#### **13.** List of Publications

#### Publications in CC database:

- Mošať, M., Šouc, J., Vojenčiak, M., Solovyov, M., Búran, M., and Gömöry, F.: Influence of current change rate during DC current limitation on the coated conductor degradation IEEE Trans. Applied Supercond. 31 (2021) doi: 10.1109/TASC.2021.3068332. (IF 1.962)
- Búran, M., Vojenčiak, M., Mošať, M., Ghabeli, A., Solovyov, M., Pekarčíková, M., Kopera, Ľ., and Gömöry, F.: Impact of a REBCO coated conductor stabilization layer on the fault current limiting functionality, Supercond. Sci Technol. 32 (2019) 095008. (IF 2.489)
- 3. Pekarčíková, M., Mišík, J., Drienovsky, M., Krajčovič, J., Vojenčiak, M., Búran, M., **Mošať**, M., Húlan, T., Skarba, M., Cuninková, E., and Gömöry, F.: Composite heat sink material for superconducting tape in fault current limiter applications, Materials 13 (2020) 1832. (IF 3.057)

#### Publications in SCOPUS database:

 Vojenčiak, M., Mošať, M., Pekarčíková, M., Michalcová, E., and Mišík, J.: Advanced superconducting tapes for high voltage fault current limiters. In: 12<sup>th</sup> Inter. Conf. ELEKTRO 2018. Eds. P. Hockicko et al. Piscataway: IEEE 2018. ISBN: 978-1-5386-4759-2, no. 93.

#### Attendance in international conferences

- 1. **Mošať**, M., Vojenčiak, M., Búran, M., Šouc, J., Pekarčíková, M., and Gömöry, F.: HTS coated conductor current limiting performance at temperatures lower than 77K. In: EUCAS 2019. Glasgow 2019. Výveska.
- 2. **Mošať**, M., Vojenčiak, M., Gömöry, F., Lacroix, C., and Sirois, F.: Importance of stabilization layer homogeneity for coated conductors used in fault current limiter. In: Workshop on Coated Conductors for Applications 2018. Vienna 2018. Výveska.

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- Gömöry, F., Mošať, M., Pardo, E., Vojenčiak, M., Lacroix, C., and Sirois, F.: Electro-thermal modelling for optimization of CC tape in DC fault current limiter. In: 6<sup>th</sup> Inter. Workshop on Numerical Modelling of High Temp. Supercond. Caparica 2018. Výveska.
- 4. Vojenčiak, M., **Mošať**, M., Buran, M., and Gömöry, F.: REBCO coated conductor for fault current limiter application in cryogen free conditions. In: Workshop on Coated Conductors for Applications 2018. Vienna 2018.
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Gömöry, F., **Mošať**, M., and Šouc, J.: Superconducting fault current limiter operating in liquid nitrogen. In: ELEKTRO 2014. Žilina: FEE Univ. Žilina 2014. ISBN 978-1-4799-3721-9. P. 650-653.

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