Thermally Activated ReBCO Switches for Charging High-Current Magnets

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***Abstract*—Aiming at design improvements for the International Axion Observatory, alternative options for powering of the 20-kA magnet are under consideration. Use of high-temperature superconductors in a transformer–rectifier system cooled by a single stage cryocooler at 40 K–50 K level is a promising option, which allows to avoid massive movable bus bars, current leads, and related services. The overall efficiency of such a magnet powering system is determined by the characteristics of high-current switches, which have to operate in a fast synchronous manner. We studied the performance of thermally activated superconducting switches made of adjusted 4-mm-wide ReBCO tapes, using etching of the tapes in a $FeCl_3$ bath to increase their resistance in normal state and to prepare low-mass heaters perfectly matching the tape surface. First experimental results on the "off" state performance and time constants of the switches, when toggling between "on" and "off" states, are presented. Finally, we discuss a conceptual design of an all-ReBCO rectifier system comprising a superconducting transformer and thermally activated switches, which can be scaled up for charging large magnet systems like particle detector magnets where slow charging is feasible.**

***Index Terms*—ReBCO tapes, etching, high current switches.**

I. Introduction

LARGE scale superconducting magnets are often designed based on high current cables, operating at tens of kA, in order to reduce the self-inductance of the windings and simplify their protection against quench. However, this leads to a relatively high heat load on the cryogenic system originating from the interface between room temperature power supply and magnet busbars. In the case of IAXO [1], which is aimed at a search for solar axions, a 22 m long/660 MJ NbTi magnet is designed using 8 racetrack coils operating at 12 kA and 8 detector bores placed between them in a toroidal geometry. Here, use of a room temperature power supply with massive busbars is even more complicated, because the magnet system has to rotate on a platform 360° horizontally and ±25° vertically. In addition, use of crycoolers may be necessary depending on the cryogenic environment at a local site, which further supports the requirement of minimized heat load. Hence, use of a superconducting rectifier [2], [3], an alternative method for magnet charging, is under consideration for the project.

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Currently, this technology is used in some detector magnets [4], [5], which are essentially operated in stationary mode and thus slow magnet charging is applicable. Basically, a superconducting transformer in a combination with high-current switches are used such that a voltage from the secondary coil is applied with the same polarity to the load coil by toggling the switches every half-cycle correspondingly. Therefore, the efficiency of charging is defined by the power loss in the open switch, which is inversely proportional to its resistance in the normal state, and by how fast the switches can be toggled between 'on' and 'off' states. Note also that high-current superconducting switches are of general interest for large scale superconducting magnets from a quench protection point of view [6], [7].

While sufficient performance of rectifiers can be achieved using LTS switches, with the open state resistance typically in the range of tens to hundreds mΩ, the use of HTS switches is appealing because of the possibility to operate at elevated temperatures, for example connected to a cryostat thermal shield or cryocooler first stage. This results in a more efficient removal of heat load and high stability margin in a closed state. Considering ReBCO tapes in particular, their resistance in normal state is also promising if the amount of stabilizing material can be minimized. In the limit of copper and silver layers removed from a 12 mm-width ReBCO tape with 45 μm thick Hastelloy, the resistance is estimated as high as 1.9 Ωm^{-1} at 100 K.

In this work, we aim at the development of high-current ReBCO switches operating in conduction cooling condition. In the following section, we discuss the methodology used to increase the resistance of ReBCO tapes in the normal state. Then, we report on the first measurements on such switches, conduction cooled at 77 K. Finally, the technical aspects of an all-ReBCO based rectifier demonstrator are outlined.

II. Etching of ReBCO Tape

The effect of chemical reactions between iron chloride $FeCl_3$ and coated conductors on the performance of 4 mm-width tapes has been investigated. Our results are based on SuperPower 4 mm wide tapes, but are expected to be largely valid also for similar ReBCO tapes of other companies. The tapes are partly immersed in a $FeCl_3$ bath in order to etch its stabilizing layers comprising copper and silver over a specified length, aiming at increase of electrical resistance in the normal state of the treated section in the tape, while preserving the original composition at the tape terminations to avoid difficulties with joints.

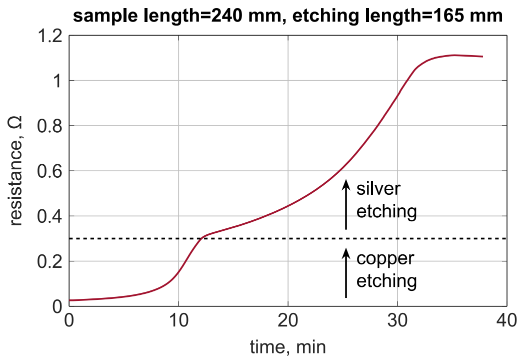

Fig. 1. Evolution of the tape resistance at room temperature of ReBCO 4 mm-wide sample immersed in a $FeCl_3$ bath.

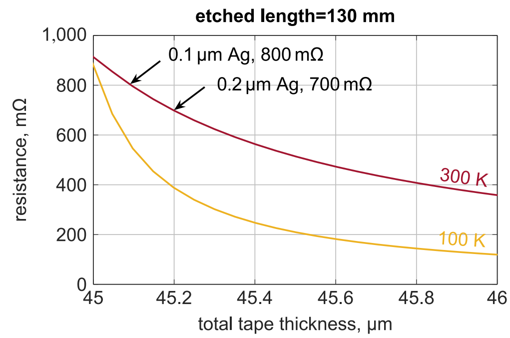

Fig. 2. Resistance of ReBCO 4 mm-wide sample by varying thickness of the silver layers from 0 μm to 1 μm at 100 K and 300 K. Thickness of Hastelloy is set at 45 μm.

First, the etching process was carried out at a certain time duration. While a correlation between etching time and retained critical current of the samples was not observed, it was noted that all the layers in coated conductors, except Hastelloy, can be removed during etching if the samples stay in the bath for at least half an hour or longer. Hence, such simple method is still useful for the purpose of preparing heaters, which are naturally of the same dimensions as the tapes itself. The resistance of such heaters is about 7 mΩ per mm-length for 4 mm-width tapes, practically not depending on the operating temperature. This is a high enough value to provide a heating power per unit surface of $\sim 1 \mathrm{W/cm^2}$ at few ampere of operating current.

Then, the resistance of the tape, while it was immersed in a $FeCl_3$ bath, was measured as a feedback to provide a better control of the etching process. A typical result of the measurements is presented in Fig. 1. It takes about 10 min to etch the 40 $\mu\mathrm{m}$ thick copper layer, while twice as long is necessary for complete etching of the silver layer, which are just few micrometers thick. Thus, the reaction rate with $FeCl_3$ is more than an order of magnitude higher for copper ($\approx 4\,\mu\mathrm{m/min}$) than for silver layers ($\approx 0.1\mu\mathrm{m/min}$). This result is fortunate because any non-uniformities along the copper layer (i.e., variation of its thickness, surface contamination etc) is smoothed out after the etching. Note that for a sample immersed vertically, faster etching was observed at the tape regions located closer to the top of the bath.

A magnetic stirrer is used to speed up the etching process and to ensure uniformity along the tape length. When a threshold resistance is reached, the sample is taken out of the bath and washed in water and hydrogen peroxide, which allows to stop the etching process more efficiently. Using this method, it was possible to reduce the total thickness of the silver coating down to $0.1\mu\mathrm{m}$. As shown in Fig. 2, the tape resistance decreases drastically at 100 K, by about 50%, if a 0.2 $\mu\mathrm{m}$ thick silver layer is left.

The critical current of the samples was measured before and after the etching at 77 K in self-field. A minor decrease of I_c, by less than 5%, is usually present right after the etching, which in most cases is due to the increased steepness of the superconducting transition. No degradation of I_c was found in the measurements performed afterwards, during one week.

If compared with the possibility of ordering ReBCO samples with reduced thickness of stabilizing layers from commercial manufacturers, 'in-house' tape etching provides more flexibility in terms of layer composition along the tape length at practically no extra cost.

III. Test Results at 77 K

Following the method explained, 12 ReBCO tapes were etched up to 0.80 Ω resistance at room temperature over 130 mm length, corresponding to $0.1\mu\mathrm{m}$ thickness of the silver layer. The critical current of each tape was measured before and after the etching, showing on average reduction by 3% from 143 A to 138 A. The tapes were used in the assembly of a high current ReBCO switch. Details of the experimental setup and performed measurements are summarized in the following sections.

A. Experimental Setup

Photographs of the assembly, made of two identical sides, and schematic arrangement of the tapes are shown in Fig. 3.

Flat copper blocks, two per each side, are placed on a G10 support plate leaving a small gap in order to avoid a contact between them. The tapes of different lengths (170 mm, 190 mm, 210 mm) were split in four groups and soldered at the terminations such that a staircase arrangement with 10 mm step is formed. The ReBCO side of each tape faces the current leads to minimize the contact resistance. The central region of each side of the assembly is covered with two layers of Kapton over about 130 mm length to insulate it from the etched zone of the tape stacks (see the left picture in figure 3), while still providing conduction cooling to the stacks when the setup is partly immersed in liquid nitrogen from the bottom side (see the right picture in figure 3). The gap size can slightly be adjusted if necessary, to ensure that the tapes stay straight after soldering.

Two heaters are placed in between the two sides of the assembly by matching the location of the stacks. As shown in the right picture in figure 3, they are insulated from the stacks by one Kapton layer. The heaters are made from 4 mm-wide ReBCO tapes by full etching of their central part over 130 mm length, such that the heating power will be deposited only at the etched zone of the tapes, and not at the terminations. The heaters are connected in series. The tapes and heaters are coated

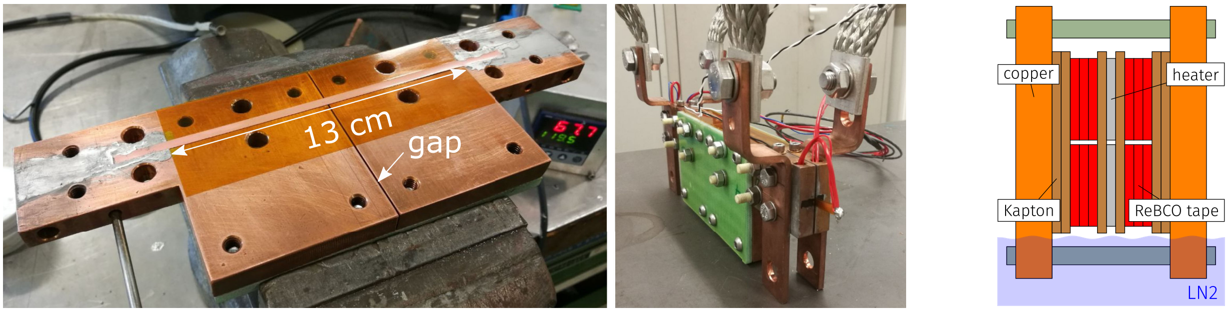

Fig. 3. Left: two photographs of the switch components showing copper blocks, two per each side, used as current leads and as heat sinks, and complete assembly with connected terminations. Right: sketch of the switch cross-section composed of the tape stacks insulated by Kapton layers from the copper blocks on one side and heaters on the other side.

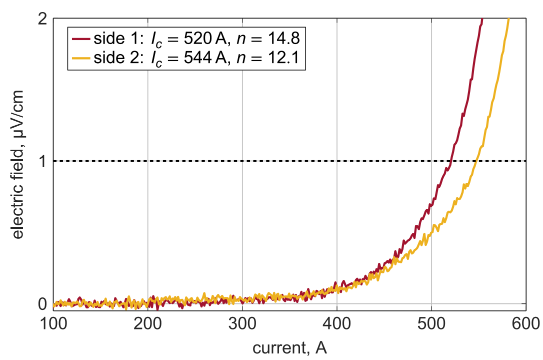

Fig. 4. Voltage-current transition of the switch at 77 K (ohmic contribution from the terminations is subtracted).

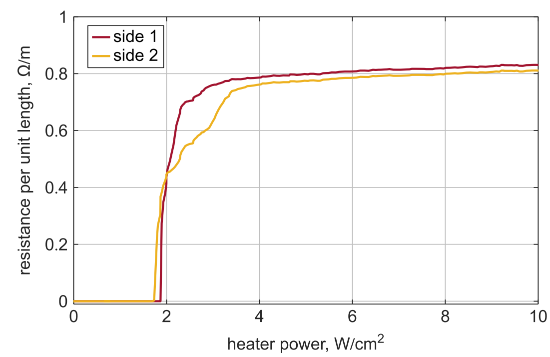

Fig. 5. Resistance of the switches as a function of the surface heater power.

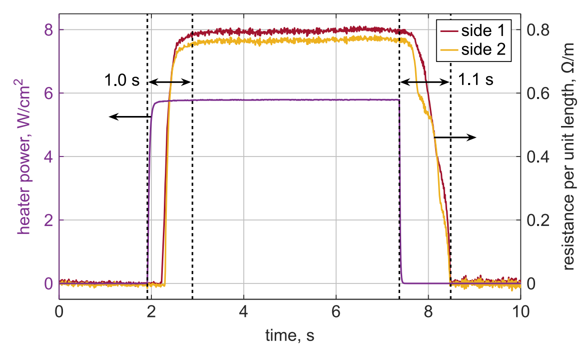

Fig. 6. Response of the switches on the heat pulse applied at 77 K.

with Apiezon grease in order to decrease the thermal resistance between the components.

Such assembly can be tested as one 12-tape switch if the terminations are connected in parallel, or as two 6-tape switches if the terminations are connected in series. Results of the measurements of the latter option are summarized below.

B. DC Tests

The voltage-current transition of the switches has been measured at 77 K. The total resistance at the terminations is $0.39\mu\Omega$ for side 1 and $0.31\mu\Omega$ for side 2, corresponding to a contact resistance $\approx 200\,\mu\Omega\mathrm{mm}^2$. As presented in figure 4, where the linear slope due to the contact resistance was subtracted, the critical current is 520 A for side 1 and 544 A for side 2.

The measured critical current is noticeably lower than expected. Accounting for the self-field effect in the stacks carrying currents in the opposite directions, I_c is estimated at $\approx 740A$, which corresponds to 10% reduction from an algebraic sum of the single tape critical currents, $\approx 830A$. Reasons for a 30% reduction obtained in the measurements are likely not related to the etching of tapes. Instead, the assembly process might be at the origin of the performance degradation, which has to be verified.

The ’off’-state resistance was measured as a function of the surface heater power, see the results in figure 5. The switches are activated starting at $\approx 2\mathrm{W/cm}^2$, showing a weak dependence of the resistance on the heater power at higher values. Obtained data, $\approx 0.8\,\Omega\mathrm{m}^{-1}$, are in agreement with an estimate of the single tape resistance at 100 K for a $0.1\mu\mathrm{m}$ thick silver layer as presented previously in figure 2. The activation power is determined essentially by the cooling power, which is high in this design due to the large volume of cold copper blocks. The activation power can be decreased by reducing the cooling power and/or by increasing the number of the Kapton layers providing thermal insulation between tape stacks and copper.

C. Transient Response

After the heat pulse is applied, activation of the switches is delayed by a time required for heat to propagate and to increase the temperature of the stacks to above their critical temperature, which is about 95 K. As presented in figure 6, it takes about 1.0 s to turn the switches ‘off’ and 1.1 s to recover, in the case

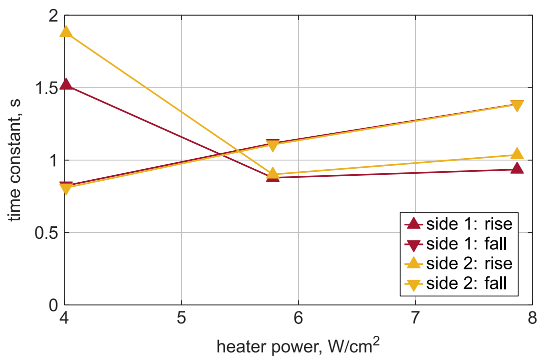

Fig. 7. Rise and fall time constants of the switches as a function of the heater power.

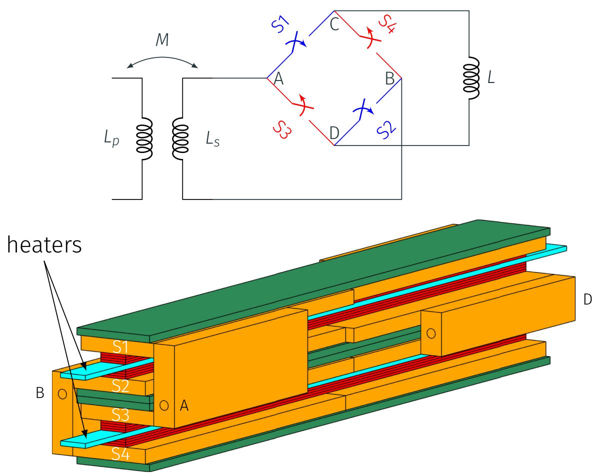

Fig. 8. Top: electrical circuit of a full-wave bridge rectifier. Bottom: sketch of a switch bridge with the components labelled according to the circuit above.

5.8 W/cm^2 is applied, corresponding to 6 A heater current. After this period, the switches are ready for the pumping stage when operating in a rectifier system.

The dependence of the rise and fall time constants of the switches on the heater power is given in figure 7. While the fall time increases monotonically, the rise time first decreases down to about 1 s and then it starts slowly increasing, even though the voltage starts to take off slightly earlier for a higher heater power. This is because the equilibrium temperature of the system increases actually with the heater power. Also note that by definition, the rise time is infinitely long for the minimum activation power of $2\mathrm{W/cm^2}$.

An important feature is that when switches are operated in a rectifier system, the heater can only be used to turn them 'off', but not to keep the state due to voltage applied by the transformer. It leads to leakage current in the open switch, thus the self-heating will prevent the normal zone from collapsing.

IV. Design of the Rectifier Demonstrator

A full-wave bridge rectifier is selected for demonstrating, see the corresponding electrical circuit in figure 8. When comparing with a more common option, a full-wave rectifier with 2 switches and load coil connected at a midpoint of the secondary coil, the following advantages of the bridge type can be outlined:

- Modularity of the switch bridge, i.e., it can be used with already existing superconducting transformers or be combined in parallel or in series;
- Simple design of the transformer secondary coil;
- Potential for faster charging, since the mutual inductance can be highest possible.

The conceptual design of a switch bridge is presented in figure 8 (note the matching labels between the top and bottom pictures), for which the following aspects have been addressed:

- Straightforward manufacturing and assembly of components;
- Convenient use of 4 switches since only 2 heaters are required;
- Minimized self-field effect on I_c due to anti-parallel current flow in neighbouring stacks;
- Long length for connections to the load coil and secondary coil of the transformer;
- Large copper surface to provide conduction cooling conditions.

For the other two main components of the circuit, transformer and load coil, CORC [8] cables will be used. Hence, we aim at demonstrating an all-ReBCO rectifier system operating in a temperature range around 50 K. For this need, a single stage cryocooler will be used providing conduction cooling to transformer and switches.

V. Summary & Outlook

The ReBCO tape etching process is fine-tuned using a magnetic stirrer and tape resistance as a feedback to obtain the desired performance of ReBCO tapes in the normal state. It was possible to remove the copper coating completely and to reduce the total thickness of silver coating down to $0.1\,\mu\mathrm{m}$, resulting in $4.2\,\Omega\mathrm{m}^{-1}$ resistance on a 4 mm single SuperPower tape at 100 K. This performance was tested at 77 K and conduction cooling conditions of the two switches, each containing 6 etched tapes. The time constants of the switches to toggle between 'on' and 'off' states are about 1 s, which is encouraging for further application. The critical currents of the switches, 520 A and 544 A, are noticeably lower than the expected value of 740 A, which is to be further investigated on next samples.

Currently, the main issue to be addressed is how to protect the ReBCO switches in the case of quench, even though it is not likely to happen due to a large temperature margin. Because practically all the stabilizing material is removed, it will be attempted to keep the hot-spot temperature within acceptable limits using high sample rate voltage detection system together with applying protective Schottky diodes, which have a very fast switching action and a low forward voltage drop.

Manufacturing and test of an all-ReBCO rectifier demonstrator is planned as a mid-term goal. The performance of the device will be investigated at temperatures around 50 K using a single stage crycooler. For this purpose, the conceptual design of a switch bridge based on 12 mm width ReBCO tapes was proposed, with 15 tapes per switch required to reach an operating current of 10 kA.

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