Upgrade and Commissioning of the SULTAN Facility to Host Quench Experiments on HTS High Current Conductors

Ortensia Dicuonzo, Rui Kang, Kamil Sedlak, Boris Stepanov, Davide Uglietti, Rainer Wesche, and Pierluigi Bruzzone

***Abstract*—High Temperature Superconductors (HTS) are promising materials for future fusion magnets. One of HTS conductors' main issues is the quench protection: the quench develops much slower than in LTS, delaying the quench detection by voltage monitoring and causing a massive temperature increase before detection. The Swiss Plasma Center (SPC), with the support of EUROFusion, has upgraded the SULTAN facility to test large current conductors during the whole quench evolution. The 100 kA superconducting transformer has been replaced by an 18 kA direct power supply, which allows sustaining the operating current in the sample during a quench. Five HTS conductors have been manufactured at SPC: they are sub-size of the HTS high-current cables designed by the group for an HTS high current high field cable proposed for EU-DEMO Central Solenoid (CS) hybrid magnet. Every conductor has a specific feature. The aim is to compare the quench behavior of the five conductors "parametrically". The commissioning of the upgraded facility and the preliminary results of the measurements are presented in this work.**

***Index Terms*—HTS, Quench, TSTC, SULTAN.**

I. Introduction

HTS are appealing for the Tokamak based nuclear fusion reactor, thanks to the capability to carry high current at high magnetic field with higher thermal stability than the convectional Low Temperature Superconductors (LTS). For this reason, the SPC is investigating the possibility of using HTS conductors in a CS hybrid magnet concept for the EU DEMO [1].

To operate a magnet safely, it is crucial to design a reliable quench detection system. If it is based on voltage monitoring, it could be trouble for HTS magnets: the normal zone propagation velocity is about one/two orders of magnitude slower than LTS [2] due to the high temperature margin. Therefore, when the quench is detected, the hot-spot temperature may have reached very high values, able to damage, even to burn, the magnet.

Consequently, the quench in HTS is less probable than LTS but more dangerous if it occurs.

Till this moment, to the best of our knowledge, the quench evolution in high current cables was addressed, especially by multi-physics codes [3]–[6]. Experimentally, it was studied mostly on low current conductors [7] and just a few experiments were performed on high current cables [8]. In [9], only the initial quench phase could be investigated, but it was impossible to study its full evolution: the SULTAN superconducting transformer, which routinely charges the sample, can work with a sample resistance of a few nΩ. As soon as the sample's resistivity increases, which is the case during the quench, the transformer switches off.

As a consequence, for the quench experiment presented in this work, the facility had to be upgraded. Previous quench experiments were performed in SULTAN, with more time-consuming and unsuitable for HTS cables [10]. After replacing the transformer with a power supply, it is now possible to experimentally study the quench evolution and propagation in HTS high current cables (forced-flow, up to 15 kA) in high field. Besides, just three working days are needed to switch the SULTAN facility from ordinary to "Quench Experiment" operation.

II. Upgrade of SULTAN for HTS Cable Quench Experiments

A. Sample Holder

The most important feature of the upgrade is integrating the 18 kA, 10 V power supply to sustain the current during the quench evolution. The sample is connected to the power supply through 15 kA current leads (integrated with the sample holder, see Fig. 1a)) and copper bus bars.

The current leads can carry a maximum of 15 kA due to space restriction in the sample holder. They consist of an HTS module (made of ReBCO tapes, 10 mm wide, manufactured by Shanghai Superconducting Technologies, SST [11]) and a heat exchanger. The heat exchanger is a bundle of thin copper wires (0.1 mm diameter).

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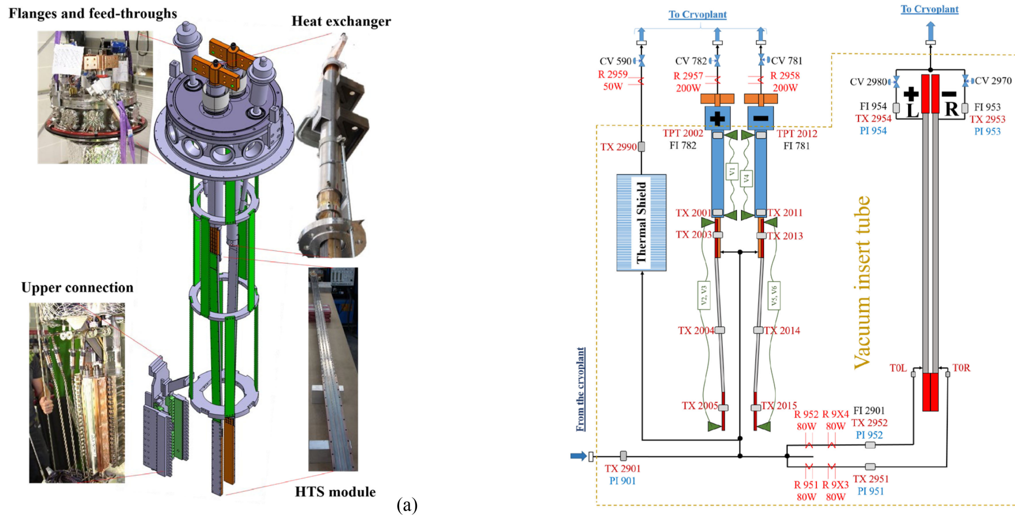


Fig. 1. a) The CAD drawing of the sample holder with the original parts highlighted. b) The sketch of the cooling circuit of the sample holder and the sample. Here the acronym meanings. FI: mass flow meter. TX: temperature sensor. CV: control valve. PI: pressure sensor. R and RX: heater. V: voltage taps.

The sample holder is also equipped with new flanges (with feed-throughs) and with a thermal shield.

A quench detection and protection system independently monitor both the sample and the HTS current leads. The quench protection system of the HTS current leads has a fast reaction. The usual SULTAN test sample does not have a quench protection system because of the very modest power of mW order. Instead, in the quench experiment, the power supply can provide up to 30 kW. Therefore, the conductors are protected by switching off the power supply when the voltage exceeds a certain threshold, anyway high enough to be able to observe the quench evolution. Besides, an emergency button can be pressed manually by the test crew.

B. Cooling Circuit

In Fig. 1b), the cooling circuit of the sample (made of two conductors, called "legs") and sample holder is shown. The fresh He coming from the cryoplant, is split into three branches: to the sample, the thermal shield, and the current leads. The sample branch then is divided once more in two: each leg is cooled independently. The inlet pressure in the sample is 10 bar. Two heaters per leg are attached to the He pipe upstream to the inlet. These heaters are used to heat up the helium that triggers the quench in the conductors. The mass flow rate is measured at the outlet. The inlet and outlet pressure are measured too. An extra mass flow meter is installed at the left leg inlet to measure the backflow. The mass flow of helium cooling the current leads is adjusted to the current. It cools down the heat exchanger and the upper part of the HTS module. Therefore, the HTS module is cooled by heat conduction from the sample at the bottom and by direct cooling at the top. In other words, the HTS adapter, whose maximum tolerable temperature is 40 K, separates the heat exchanger and the test conductor thermally.

The Helium provided by the cryoplant slightly heats up before it reaches the test well. The minimum inlet temperature of the sample is about 6 K at the maximum mass flow rate. The commissioning of the upgraded SULTAN was successful.

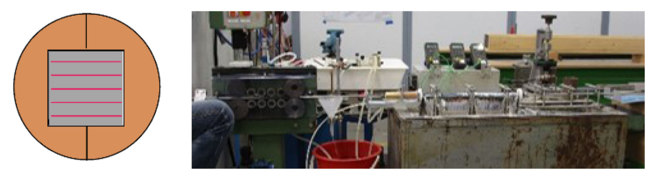


Fig. 2 a) cross section of the strand. b) the fountain solder bath used to solder the strand.

III. The SPC Quench Experiment Conductors

A. Conductors

The conductors are the sub-size of the Twisted Stack Soldered Conductor (TSTC) designed in [12], in the sense that the critical current should not exceed 15 kA at 11 T. The copper and steel cross sections are scaled-down as well [3]. The stack of HTS tapes is encapsulated in the groove of two half-cylindrical copper shells. The final cylindrical assembly is called "strand" (Fig. 2a)). The strand is then twisted (twist pitch 400 mm) and soldered by $Sn_{40}Pb_{60}$ [13]. Compared to the original technique: a fountain solder bath is used (Fig. 2b)).

The sub-size cables are made of a strand triplet, whose twist pitch is 1000 mm. As shown in Table I, five conductors were manufactured. Four of them are based on ReBCO tapes. The first conductor, the "reference" one (#1), has twisted and soldered strands. The second one (#2) has twisted but not-soldered strands (tapes are not soldered together). The third (#3) has soldered, not-twisted strands, with the tapes wide face perpendicular to the magnetic field. The fourth (#4) is solder-filled ($\sim$135 mm^2 of solder) in the space between strands and steel jacket, and the fifth conductor (#5) is like the first one, just made of BSCCO 2223 tapes.

The He cross section in all the conductors is 93 mm^2. It is in direct contact with the strands, flowing between them in all the conductor design, except for conductor #4, where there is a dedicated channel. The ReBCO tapes (50 μm Hastelloy substrate, 10 μm copper per side, width of 3 mm, 25 tapes/stack)

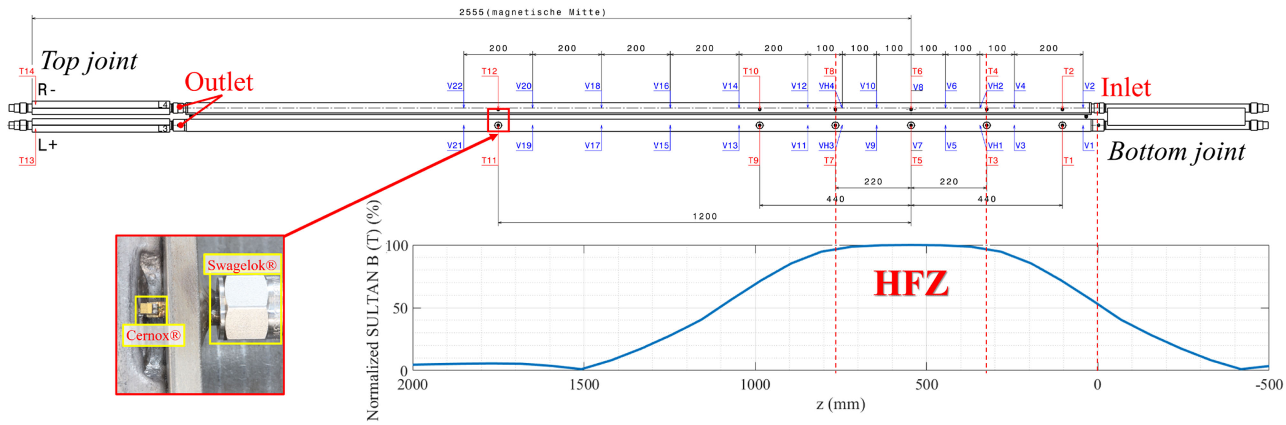
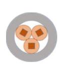
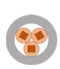
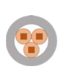
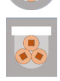


Fig. 3. sketch of the sample instrumentation and the Sultan magnetic field distribution along the sample length. The zero of the z coordinate is placed at the He inlet of the sample. The HFZ is highlighted. Voltage taps in blue, temperature sensors in red. The He sensor is shown. It is placed in conductor #4. During the solder filling step, some space was left for the sensors. First, six holes were drilled in the jacket. Then a protruding threaded part was welded. Afterwards, the sensors were inserted in the holes and fixed (and leak-tight) by screwing a Swagelok fitting [17]. In this way, the Cernox sensor measures the temperature of the flowing helium.

TABLE I
SUMMARY OF THE CONDUCTORS FOR THE QUENCH EXPERIMENT

	Conductor	SULTAN Sample	Copper cross section (mm^2)	Steel cross section (mm^2)
	Reference (#1)	#1 and #3	136	715
	Not-Soldered (#2)	#1	136	715
	Not-Twisted (#3)	#2	136	715
	Solder-filled (#4)	#2	136	652
	BSCCO (#5)	#3	109	715

were purchased from SST [11], while the BSCCO tapes (not reinforced material, width of 4.3 mm, 19 tapes/stack) were supplied by SUMITOMO ELECTRIC [14]. The copper shells are not-annealed and the tape face is perpendicular to the split line. Only the touching contacts between the copper shells are soldered in the not-soldered strands, not the inner space where the tapes are placed. Instead, the ends of the strands are filled by the same solder as used in the termination of the conductor.

After the manufacturing, the strands were tested in liquid nitrogen and self-field. None of the strands, measured in different sections along the length, exhibited an early voltage. The different ReBCO conductors have a critical current in agreement with the value extrapolated from the single-tape measurements, except conductor #1, which shows a value 6% lower I_c. The reason has still to be identified.

After that, the triplet was cabled and inserted in the jacket (an 8.5 mm thick steel tube). Then the jacket was crimped to close the insertion gap. The conductors' termination (length 450 mm) are fabricated inserting the triplet in a copper sleeve, later crimped and filled by Indalloy #282 ($Bi_{57}Sn_{42}Ag_1$ solder) [15], whose melting temperature of 137-139 °C is lower than that of $Sn_{40}Pb_{60}$ (183-191 °C) to ensure that the solder in the strands doesn't melt while the termination is filled. The same solder is selected to fill the solder-filled conductor for its low thermal expansion coefficient: the risk of detachment of the cable + solder body from the jacket during the sample's cooldown is reduced. The He inlet is placed above the bottom termination and the outlet before the upper termination (see Fig. 1b)). The terminations are therefore cooled just by conduction.

B. Sample Instrumentation

The SULTAN sample's two legs are electrically connected in series by a joint at the bottom of the sample (see Fig. 3). At the top, the sample is connected to the current leads. The sample is instrumented with temperature sensors and voltage taps.

The distance of a voltage tap pairs is 100 mm in the High Field Zone (HFZ), whose length is 440 mm, and 200 mm outside. An array of four pairs of voltage taps across the whole HFZ is used to unbiased assess the T_{cs} and I_c, in case of non-equipotentiality, by averaging the signals.

Both the helium and jacket temperature are measured to observe the predicted cross section gradient in [3]. The helium sensors, intrusive into the conductor, and jacket ones are located at the same longitudinal position of the sample, according to instrumentation sketch in Fig. 3. The jacket Cernox [16] sensors are simply glued to the steel. On the solder-filled conductor, they are located on the opposite side of the helium channel, to measure the temperature closer to the strands. In addition, the temperature is measured also in the He inlet, outlet, and at the top termination, for each leg (see Fig. 1b)).

IV. THE TEST PROGRAM

Within a single experiment, the DC performance of the conductors and their quench characteristics can be investigated. The quench experiment has been carried out on the two conductors in separate runs.

During the DC measurements, the I_c and T_{cs} were assessed at different magnetic fields and temperatures, to characterize the conductor and to obtain the data for the $I_c(B,T)$ scaling law. The quench was triggered in two ways: by heat slug and by slowly warm up of the inlet temperature.

The current switch-off criterion is based on temperature. As soon as the maximum temperature among all the sensors overcomes a certain value, the current is damped down. This allows us not to exceed the 150 K temperature limit used for the first two test campaigns. To discharge the current, a fast (200 kA/s) and slow (980 A/s) discharge rates were used.

So far, Sample#1 (conductors #1 and #2) and Sample#2 (conductors #3 and #4) have been tested. Sample#3 (conductors #1 and #5) is assembled and instrumented, and it will be tested by the end of 2020.

V. Results and Discussion

At the maximum field, the I_c values are: $I_{c,\#1}$ (7 K, 10.78 T) = 8.7 kA; $I_{c,\#2}$ (7 K, 10.78 T) = 9.3 kA; $I_{c,\#3}$ (7 K, 10.78 T) = 11 kA; $I_{c,\#4}$ (7 K, 10.78 T) = 11.5 kA. The values for the conductors #2, #3, #4 agree within 8% with the values extrapolated from the measurements on the tapes used for manufacturing. Instead, the I_c of conductor #1, probably degraded during the manufacturing, is about 28% lower than the expected value. Already the liquid nitrogen measurements indicated a lower performance of the conductor #1 compared to the other ones. The difference became even more pronounced in the SULTAN measurements at 7 K and 10.78 T. Further investigations are ongoing.

During the DC assessment of the Sample#1, conductor #2 was accidentally damaged by mistake. Unfortunately, the current at the end of the test was switched off too late and too slow. No further useful data of Sample#1 are available. We will get more information on conductor #1 during the test of Sample#3. Conductor #2 was dismounted and the strands will be measured in liquid nitrogen to evaluate the severity of the damage.

In order to perform the quench experiment on the Sample#2 at 100 A/mm^2 copper current density, relevant for large fusion conductors, the magnetic field was set to 6 T for conductor #3 and 6.5 T for #4.

An example of a quench experiment (see Fig. 4) is reported, where the evolution of the highest He and Ja temperatures and the highest electric field of the conductor #3 and #4 are plotted. The quench was triggered by heat pulse, the current was discharged with the fast discharge rate from 15 kA to zero. The initial mass flow rate is 1.5 g/s. The heat pulse (at the maximum power of the heaters) was very long for both the conductors: 20 s (1.6 kJ) for conductor #4, 15 s (1.2 kJ) for #3. The temperature difference between helium and jacket (at the same electric field, for example, 10 mV/cm) is much lower in conductor #4 than in #3, as qualitatively predicted in [3]. Even though both conductors' maximum temperature is approximately the same, the electric field is higher for conductor #3. For this conductor, this is a sign that the strands' temperature is much higher than the maximum of the measured He and jacket temperatures. In conductor #4, the heat capacity is larger than in the other conductors. Consequently, after the current damp, the temperature goes down smoother. The time to reach the maximum measured temperature after the current damp is longer, namely 11 s, while almost instantaneous in conductor #3. Also, quench evolution is slower: around 46 s for the conductor #3, compared to 96 s for the conductor #4.

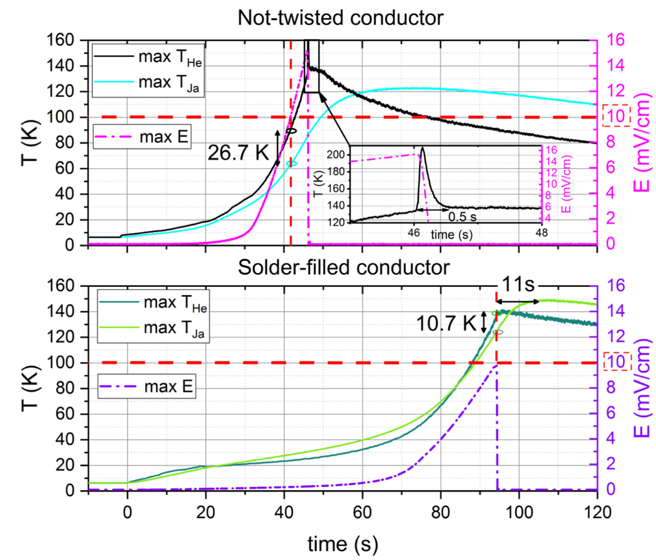


Fig. 4. Temperature and electric field evolution of the not-twisted and solder-filled conductor. Relative time t = 0 when the self-heating starts. T_{He} is the helium temperature. T_{Ja} is the jacket temperature. The dashed red line indicates the chosen electric field at which to compare the T_{He} - T_{Ja} of the two conductors. In the zoom for the conductor #3, the shown peak is just a measurement artifact, presumably due to the inductive voltage on the temperature sensor induced by the rapid change in the self-field during the current damp.

VI. Conclusion

The SULTAN test facility upgrade to host the Quench Experiments on high current conductors up to 15 kA was accomplished successfully.

Five conductors were manufactured and two samples (four conductors) were tested: one ended prematurely due to the damage of one of the leg. The second was carried out thoroughly.

Some preliminary results of the Sample #2, qualitatively in agreement with the prediction published by R. Kang, have been presented, highlighting the different performance of two conductors. Further and more in-depth investigations, namely the detailed analysis of all the cables' experimental results and a comparison with the multi-physics THEA model, are ongoing.

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