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Testing short samples of ITER conductors and projection of their performance in ITER magnets

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Abstract

Qualification of the ITER conductor is absolutely necessary. Testing large scale conductors is expensive and time consuming. To test straight 3-4m long samples in a bore of a split solenoid is a relatively economical way in comparison with fabrication of a coil to be tested in a bore of a background field solenoid. However, testing short sample may give ambiguous results due to different constraints in current redistribution in the cable or other end effects which are not present in the large magnet. This paper discusses processes taking place in the ITER conductor, conditions when conductor performance could be distorted and possible signal processing to deduce behaviour of ITER conductors in ITER magnets from the test data.

Introduction

It was known from the very beginning of the CICC (Cable-in-Conduit Conductor) development that the performance of the large conductor is not always equivalent to the sum of the performances of the strands which it is comprised of. Testing of the short samples became a very important R&D activity to verify and qualify performance of large CICC in general and of ITER conductors in particular. Two facilities were built in the world in the late 80-s to test short samples of the CICC up to the fields of 11.5-13 T with the high field region of 0.3-0.45 m. One facility was FENIX, at LLNL, USA, which ceased operations in 1994. Another facility, SULTAN at PSI, Switzerland is the only facility still in operation for full scale ITER short conductors tests.

Although testing at SULTAN gives very valuable results about performance of the conductor, there are some features in the experimental set up and sample preparation that make interpretation of the test results difficult and ambiguous.

The SULTAN samples are about 3.5 m long and the magnetic field area is about 0.4 m long, which is marginal for ITER conductors. The short length of the magnetic field has two major concerns for projecting of the SULTAN test results to the conductor performance in a large magnet. First, the voltage generating length in the SULTAN is short in comparison with the one in the ITER magnet, which limits the total voltage available for making the current distribution uniform [1]. Second, the length of the magnetic field is comparable with the twist pitch of the last stage subcable, which means that some strands do not see high magnetic field and therefore will carry higher current than if they were in a magnet, where all strands are exposed to peak magnetic field.

In recent tests [2], the ITER conductor samples showed growth of the voltage from the very start of current charging. Such behaviour is inconsistent with a superconducting transition and needs to be explained by other mechanisms. It requires strong assumptions to make interpretations and projections to the behaviour of the conductor in ITER magnets. This type of behaviour was observed in few cases before in previous tests, but that observation did not draw much attention then, since the criterion was typically set at 100 μV/m or even at a quench current. The current sharing temperature T_{cs} definition for ITER conductor qualification are set at a lower

level of the electrical field, 10μV/m, and that makes the determination of the T_{cs} very sensitive to the assumptions about superconducting transition and noise.

This paper discusses electrical field development in the short sample with nonuniform distribution, possible mechanisms resulting in distortions of the superconducting transition of the CICC and signal processing approaches to convert measured voltage into voltage of a CICC with uniform current distribution.

Measurements of the transitions in ITER CICCs

Figure 1 shows a typical voltage growth of the ITER CICC tested at SULTAN when current is far away from the critical current and presumably all superconducting strands are fully superconducting.

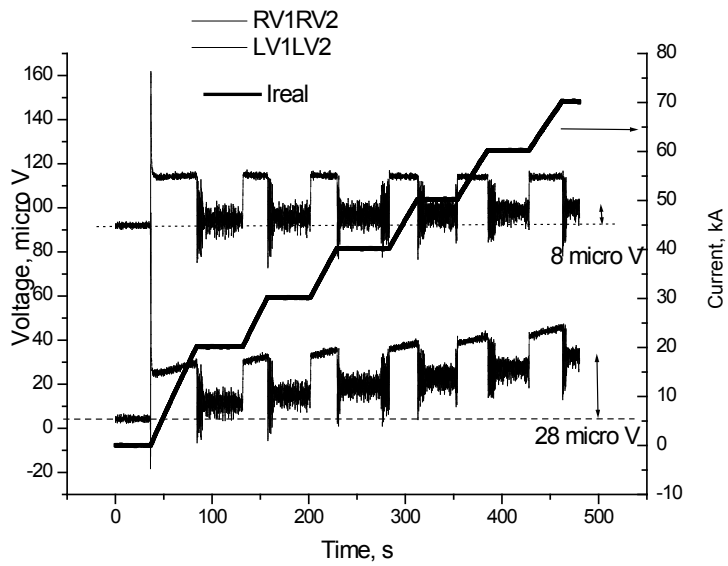

Figure 1. Voltage – growth versus time in the TFAS1 CICC far away from critical surface (B=0). Right leg voltage is the top signal; the left leg voltage is at the bottom.

Figure 1 shows voltage in both legs of the sample and the current that is charged in steps with a wait period between steps. While current is changing, the voltage signal contains an uncertain inductive component; therefore only at dI/dt=0 we can judge about voltage in the conductor.

The left leg (with voltage taps LV1-LV2 located on the conductor one twist pitch apart in the high field region) shows 8 μV at 70 kA and the right leg shows 28 μV. Since the critical electrical field criteria is 10 μV/m and the length between the voltage taps is 0.45 m, which translates into 4.5 μV, it is obvious that without some credible and verifiable method to eliminate signals that are irrelevant to performance the measurements are useless.

During voltage measurements and while trying to determine a temperature or current where the voltage corresponds to the "critical" current criteria of 10 μV/m these effects need to be taken into account and removed. The question is: having a voltage versus temperature or current transition measured in SULTAN is it possible to project behaviour of the CICC in ITER magnet? If yes, what is the way to do it? If not, what needs to be done to the sample and instrumentation to measure a "true" transition?

This paper addresses the first question. We will discuss the latter later in a separate paper. In brief, to achieve a uniform current distribution the transverse resistance between the strands

should be sufficiently low that at the level of 4.5 μV the current could redistribute to become uniform. In this paper we review some proposed signal processing to significantly reduce or to eliminate the signals which are not associated with the real transition of the superconductor in order to project it to the conditions of a magnet where we expect uniform current distribution in the cable and all voltage along the conductor is the resistive transition.

The methods to eliminate irrelevant signals are the following:

I. Subtract the linear Ohmic signal IRo from the Volt-Ampere Characteristic (VAC) by finding an appropriate effective Ro from the experiment. The Ro can be negative or positive, sheer matter of luck. In the case of Volt-Temperature Characteristic (VTC) the artificial voltage signal is taken by also subtracting the voltage IRo, this time the current is constant. In practice it is the analyst's discretion to pick the temperature where the resistance of the superconductor is considered to be zero. The corresponding voltage is then subtracted as "parasitic" value in addition to the usual instrumentation offset. Figure 2 shows an example of a VTC at 70 kA.

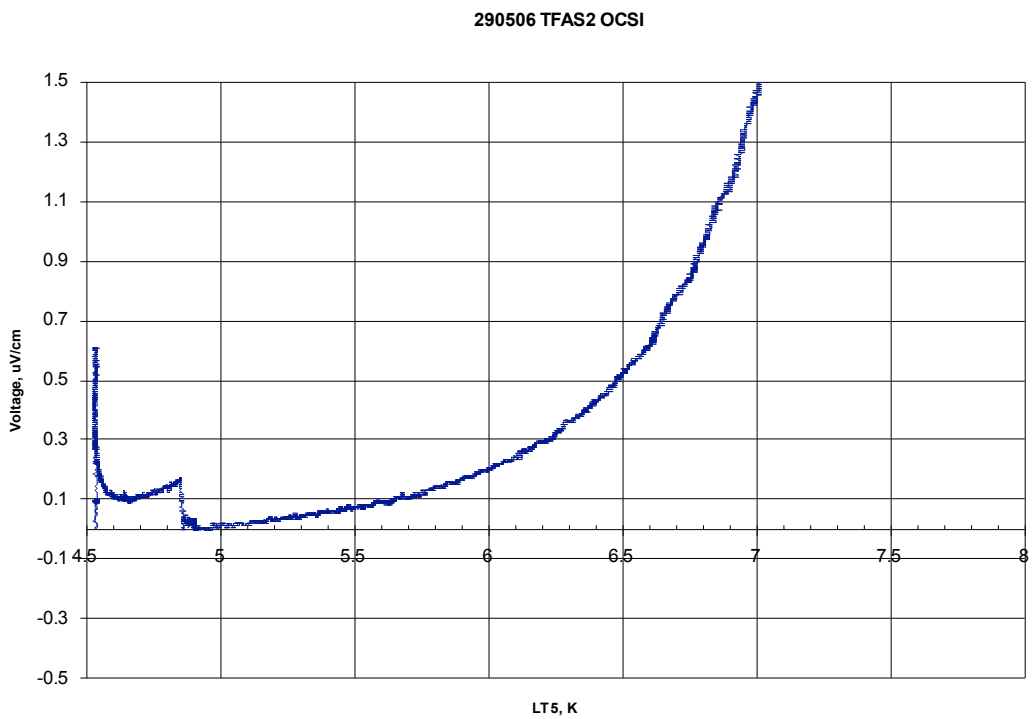

Figure 2. A typical VTC of an ITER class CICC.

In this case, the "zero" resistance is elected to be at 4.9 K. This choice is critical in determination of the Tcs. But there is a very weak justification to this selection and therefore there is a high probability of an error.

II. The second method to eliminate the noise is to take multiple measurements of voltages at the same cross section where the original voltage taps are and average their readings to obtain more representative voltages of the cable.

III. The third method is to assume that the transition of CICC into resistive state has an exponential growth versus temperature and versus current as:

$$E = E_c \exp\left[\frac{I - I_{cs}}{I_o} + \frac{T - T_{cs}}{T_o}\right] \quad (1)$$

Then selection of a zero offset must be based on the best fitting of the (1) to the experiment at highest practical electrical fields, where effects of the current redistribution are the lowest, but not too high, where self heating effect are too high and thermal take off starts.

IV. The fourth method is to use calorimetric measurements for voltage averaging. This method is based on the thermal balance equilibrium expressed as:

$$MC_p(T_{out} - T_{in}) = \int EIdx \quad (2)$$

The difference of the temperatures upstream and downstream are sensitive only to the heat generated in between them and some analysts believe that it allows eliminating parasitic signals associated with nonuniform current distribution originated from the joints.

To analyze these approaches we will use a simplified model of superconducting cable.

Two layer model of the conductor

There is a general agreement in the community that distortion in the superconducting transitions occur due to nonuniform distribution of the current in the cable.

Numerous studies performed in the past and recently [3, 4] used a network of resistances and inductances to simulate behaviour of the conductor in SULTAN facility. These models help to explore wide possibilities of the parameters, but the essence of the mechanisms could be more easily explained by a simple two layer model, shown in figure 3.

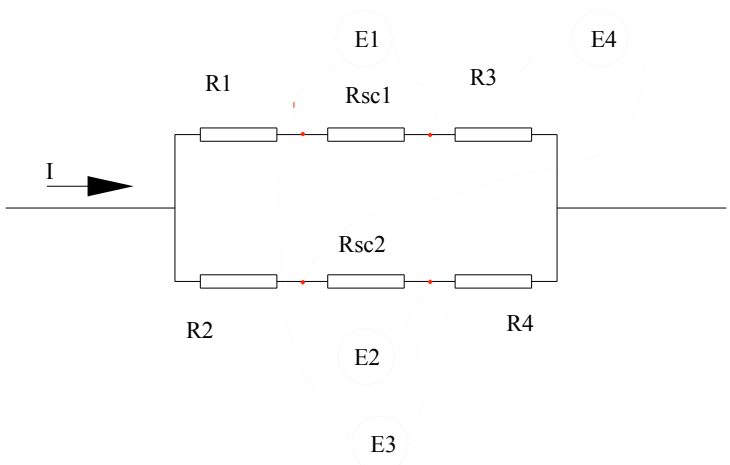

Figure 3. A simple two layer model of the conductor.

Figure 3 represents a simplest model of a leg in the SULTAN facility. The Rsc1 and Rsc2 represent nonlinear resistances of the superconductor strands, and R1-R4 are constant resistances representing joint resistances at both ends of the leg. This model helps to explain why negative voltages could be measured along the CICC. First of all, it is clear that the joints from both ends of the sample contribute into the current distribution, not only the geometrically closest joint.

Before the superconductor develops any resistance, the current is shared in accordance with the resistances R1-R4. Then, if the voltage taps of voltmeters are sitting on the different strands, like for the E3 and E4, one of the voltmeters E3 or E4 would be positive and one would be

negative before resistance appears in the superconductor. The two voltmeters attached to the same strand, E1 and E2 will obviously show positive voltages. So, in general, it is more likely to pick positive voltages than negative, but observation of a negative signal is a sure sign of the nonuniform current distribution. However, when the resistance of the superconductor becomes comparable or greater than scatter of resistances in the joint, then all the voltages in figure 1 will become positive and effect of the joints becomes reduced or negligible. If resistances R1-R4 are larger than Rsc1 and Rsc2 and have a significant scatter, the current distribution will be nonuniform. To give a scale of possible nonuniformity we can use the following typical values. The voltage drop on the joints (in figure 1 it is simulated by R1-R4 resistances) at joint resistance of 1 nOhm and current of 70 kA is 70 μV, while determination of the critical current takes place at 4.5 μV. Very often one or both joints in SULTAN are at the level of 2-8 nOhm, which gives even higher possibility of nonuniform current distribution. Thus, in the worst case scenario, when the scatter of the joint resistances is large, the resistance of the superconductor at 10 μV/m may not be sufficient for uniform current distribution.

Using this simple model, we can check the ideas proposed to eliminate non uniform distribution effects.

I. Subtracting a constant resistance.

Subtracting an Ohmic term IRo from the voltage gives an impression that it is a legitimate operation, since it gives a zero voltage at currents and temperatures far from the critical surface, just as one would expect from a “clean” superconducting transition. However, when the current sharing starts, the current redistributes and as a result the correction that needs to be made to get the correct voltage becomes nonlinear.

Figure 4 represents a VTC of the model shown in figure 3. Each layer has a Tcs=6 K and joint resistances values shown in figure 4 for each strand carrying 70 A.

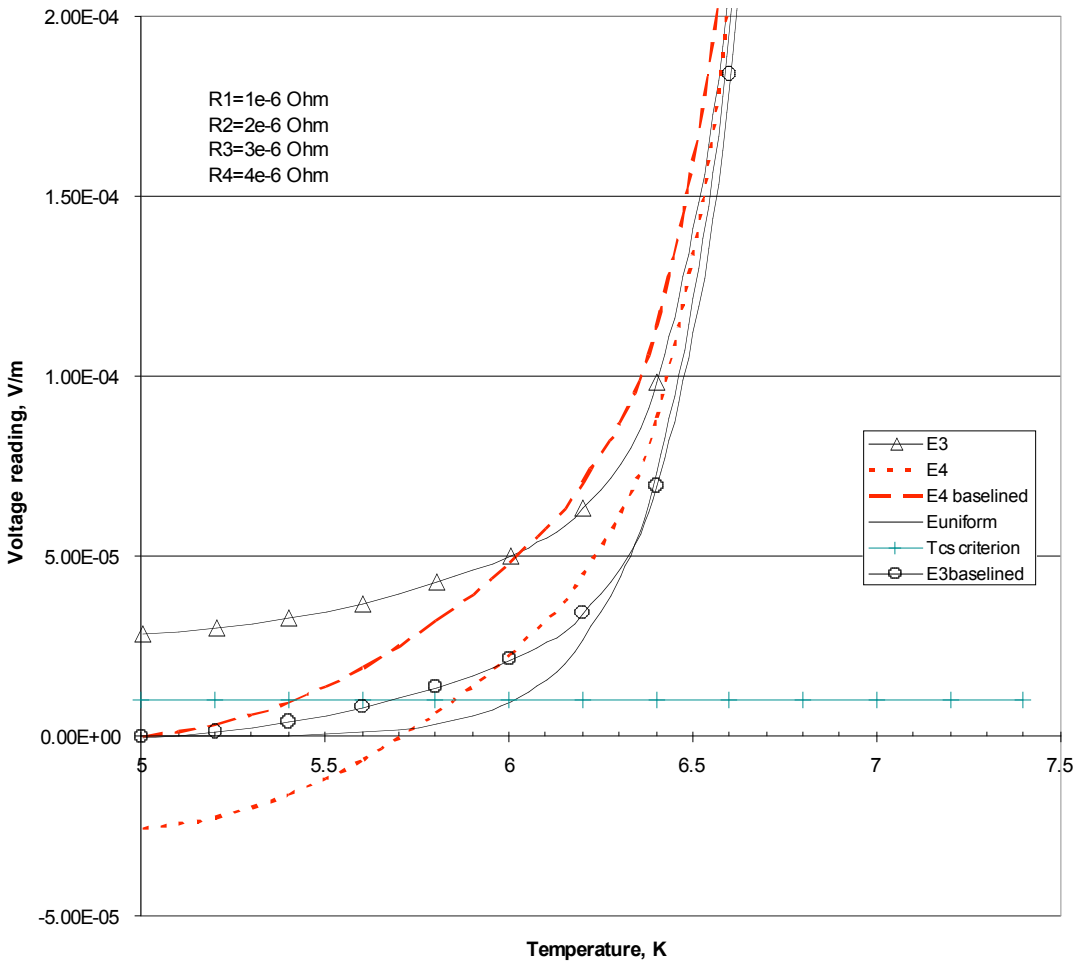

Figure 4. VTC of the two layer model with nonuniform current distribution

We are not showing the voltmeters E1 and E2 readings for clarity and also due to the fact that it is unlikely that voltage taps will sit on the same strand. After base lining the zero at, say, 5 K, voltmeters E3 and E4 will both show the Tcs significantly lower than for the conductor in the condition of a large magnet, where the current distribution is uniform. This is a counter intuitive result, but it points out that if the current distribution is not uniform, the intuitive practice of subtracting an Ohmic component in general is unsubstantiated. It does not convert the test data into voltage for uniform current distribution. The reason is that when resistance of the superconductor grows, it tends to uniformly distribute the current itself. Then the correction, which ignores this, becomes an error.

II. Averaging voltage over the number of measurements on the same base

In this method, the idea is that if many random voltage measurements between two conductor cross sections involving different strands are made and averaged. If there is similar probability of negative or positive voltages in the parameters area far from critical surface (defined at 10 μV/m), this approach would seem as a step in the right direction. However the weight of these voltages is different. Since resistance of a superconductor is very nonlinear with the current, the voltages in the strands with higher than average current will overwhelm the other voltages in the cross

section and as a result will show higher voltages than a CICC with a uniform distribution would show.

Figure 5 shows an averaging of all voltmeters in figure 3 and it is clear that at a low level of voltages the averaging is not very accurate representation of the uniform current distribution and shows things worse than at uniform current distribution.

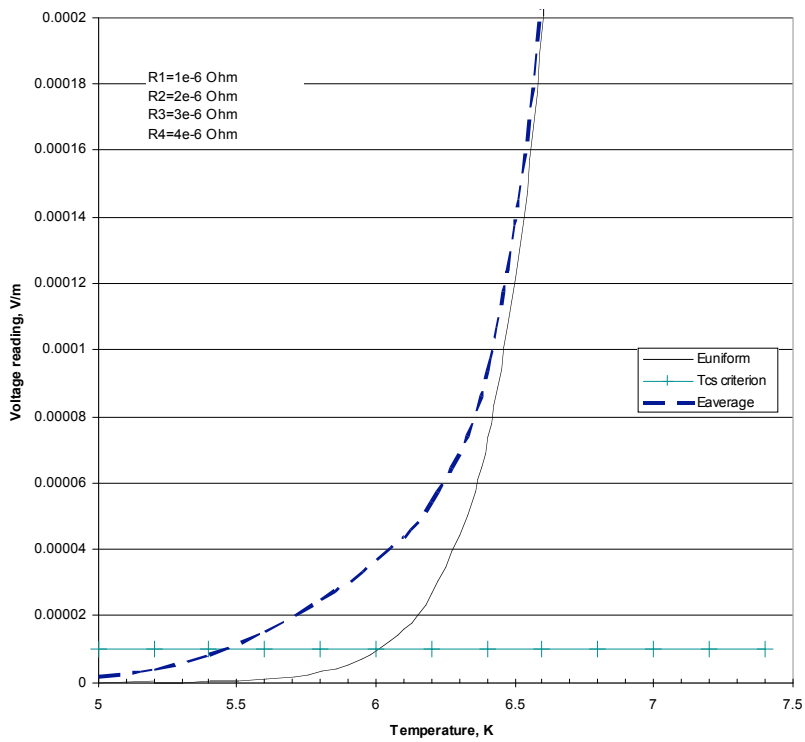

Figure 5. Comparison of average voltage with nonuniform current distribution against uniform electrical field in CICC with uniform distribution.

Thus, voltage averaging, in general, is not an accurate method to predict the behaviour of a cable with uniform current distribution.

III. Assuming exponential transition of the voltage development

Transition of the superconductor into resistive state at low level of electrical field can be described with reasonable practical accuracy as and exponential transition, see equation (1). This type of behaviour was observed in individual strands and in cables, including CICC [5] in conditions when current distribution was made uniform.

The equation (1) is practically indistinguishable from another popular approximation $E=Ec(I/Ic)^N$ if the observed voltage range is 2-3 orders of magnitude or less.

The assumption that the transition is exponential is a strong one, and it affects the processing the data. In a sense, the assumption of Ohm's law is also very essential for measurements of the resistivity of normal metals since it allows elimination of the voltage offset and other parasitic signals.

As we can see from figure 4 and 5, the voltages at higher level approximate uniform distribution, because resistance developed in the strands effectively helps the uniform current distribution.

The procedure of the transition assessment is as follows. We assume that the transition is exponential and plot the VTC or VAC transitions in semi logarithmic coordinates. Since the voltage offset is unknown due to the joint resistances, we are varying the offset value for the transition to find a best fit to the exponential transition.

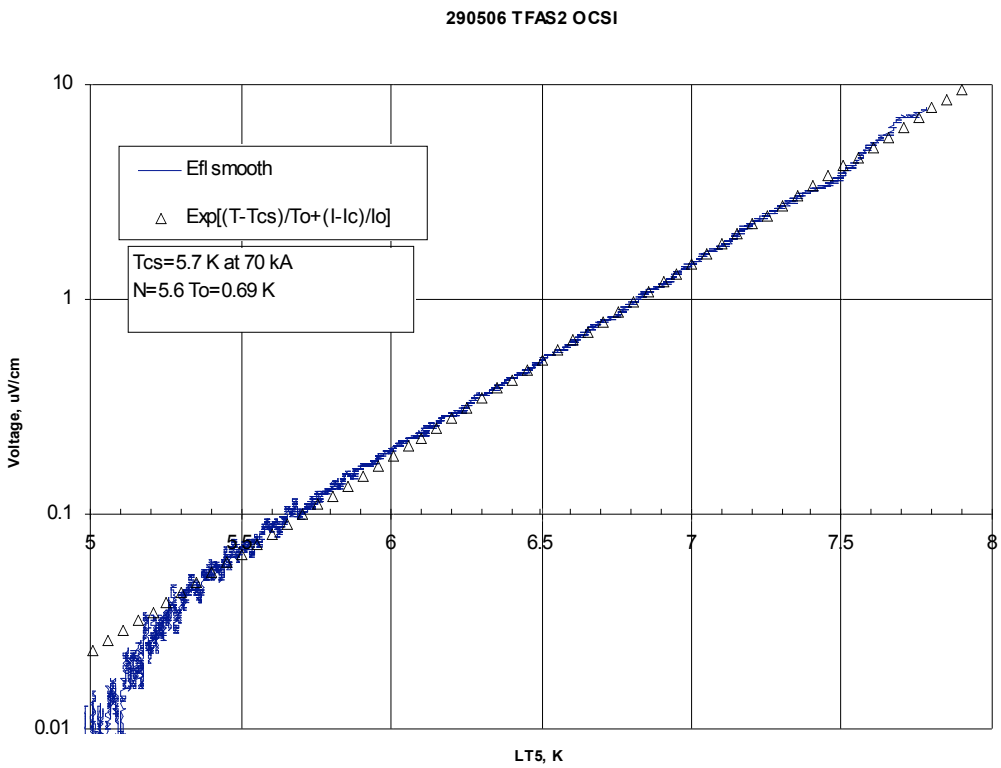

Figure 6. Exponential fit of the VTC transition of a TFAS2 OCSI CICC [2].

An example for TFAS2 OCSI CICC is shown in figure 6. As indicated, after a successful fit, the deviation of the VTC at low fields begins at about 0.05 μV/cm, which is below the criteria of 0.1 μV/cm and therefore it does not affect the determination of the current sharing temperature.

An example of the VTC presumably strongly affected by a nonuniform current distribution is shown in figure 7; here one can see a transition of the OST CICC [2].

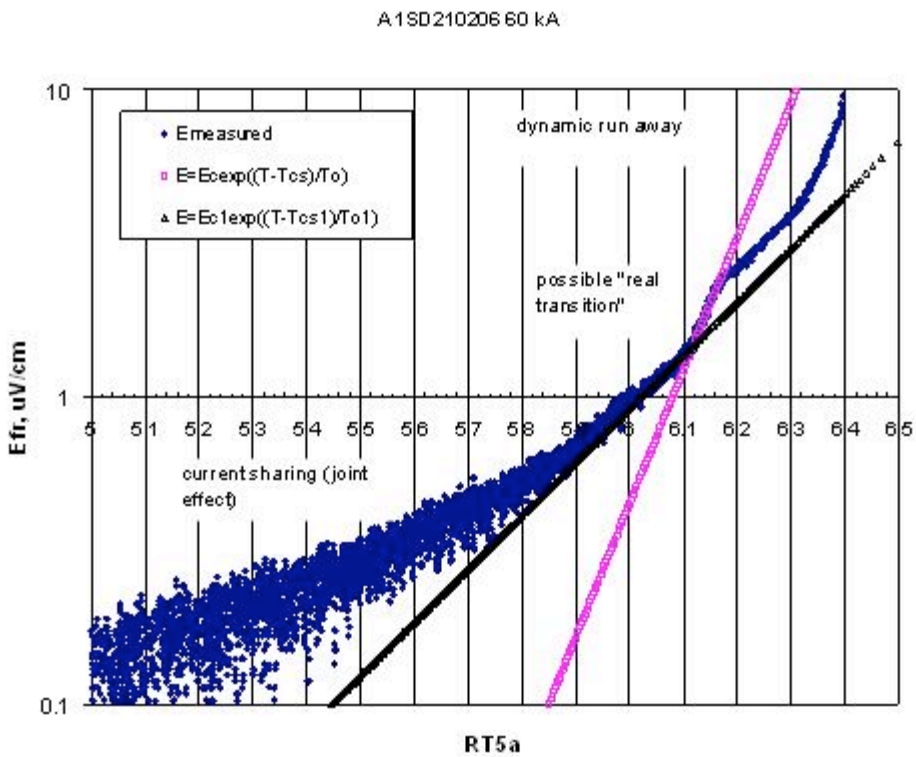

Figure 7. VTC of the OST CICC [2].

This plot shows a significant effect of the current redistribution judging by strong distortion from the exponential transition. We identified possible explanations of the low E area as a current redistribution affected by the joint. The high E area, unstable run away, is the area when the thermal equilibrium can not be maintained any longer since. The intermediate area is the presumably a “real” transition. But unfortunately, we can clearly identify one exponential transition. There are two slops with approximately exponential transition. There is no way to say from figure 7 which slope is the real transition, but in both cases the Tcs is significantly higher than what one would conclude from the “raw” transition, crossing the 0.1 μV/cm criterion below 5 K. Such a sample can not be used as a qualification sample and there is seems to be no processing which could convert the measured data into performance of the CICC in the magnet. Thus, the exponential fit procedure seems to have a more solid basis for processing the test results and converting the data into useable assessment of the CICC at uniform distribution. But even this method can not recover severe nonuniform distribution cases and it can not predict in advance at what level of electrical field the CICC has a uniform current distribution.

IV. Calorimetric measurements

The idea of calorimetric measurement of the average voltage in the sample is based on the intent to eliminate effect of the joint on voltage measurements in the high field area. Indeed, using calorimetry equation (2) we measure only heat associated with resistances of the superconductor strands in between two temperature sensors. Away from the critical surface there is no heat generation in the high field zone even at nonuniform distribution and this is attractive feature. But if distribution of the current is not uniform, the heat generation will also be different from the uniform distribution, although there will be some averaging.

Let’s imagine that we have a cable of two strands carrying a nonuniform current, modelled by figure 3 and we detect the heat generated by these strands away from joints and convert them into the average electrical field.

Let the current in the first strand to be I1, in the second I2 and the total current is:

$$I_1 + I_2 = 2I_{ave} \qquad (3)$$

Where I_{ave} is the average current that each strand would carry if the distribution would be uniform.

The electrical field in the strand could be described by (2).

Due to non-linearity of the superconducting transition the heat generation in the cable with nonuniform current distribution will be greater than in a cable with uniform distribution. This easily follows from the equation (4), where left side is the heat at a nonuniform distribution and the right side is the heat generated at a uniform current distribution.

$$E_c \exp[\frac{I_1 - I_c}{I_o}]I_1 + E_c \exp[\frac{I_2 - I_c}{I_o}]I_2 > 2E_c \exp[\frac{I_{ave} - I_c}{I_o}]I_{ave} \qquad (4)$$

Therefore, calorimetry can eliminate the heat generated in the joints but can not make the distribution of the current uniform. Consequently, the electrical field determined by calorimetry will also be higher than for a uniform distribution. Thus, calorimetry can not solve the problem of nonuniform current distribution. At high levels of the electrical fields the calorimetric measurements should coincide with the electrical measurements. If so, projection to the low electrical fields should be done on the basis of extrapolation of the exponential VTC transition, not on the basis of the calorimetric measurements.

Inability to correct nonuniform current distribution is the fundamental problem of the calorimetric measurements. There are other practical features that make calorimetric measurements questionable. First of all, the sensitivity of the electrical field measurements is about 1 μV/m. At 70 kA and 4 g/s the sensitivity of the temperature sensor must be about 2 mK, which is extremely challenging and beyond the manufacturer specifications. Also, the temperature measurements require strong assumptions to compensate thermal noise and unexplained tendencies at the level of several milli Kelvin.

In addition to that, the calorimetry works only for the uniform temperature distribution on the level of mK or better, otherwise the error or uncertainty is too large. It becomes sensitive to the distribution of the mass flow in the cross section; in particular, it requires blocking the central channel to avoid cold helium escape from the high field region.

Thus, the calorimetric method is not accurate and is less reliable than extrapolation of the exponential fit from higher magnetic fields into the lower fields.

Conclusion

We used a simple two-layer model to check different techniques of signal processing to convert electrical field measurements of the cables with nonuniform current distribution into performance at uniform current distribution. The most promising procedure is to match the measured voltage assuming an exponential transition at highest practical electrical fields and extrapolate it to the level of the critical electrical field defined as 10 μV/m or 0.1 μV/cm.

But even this method is not always successful. If the effect of the nonuniform distribution is too strong and run away happens before uniform transition sets in, this method has very limited value and a sample can not be used for qualification or prediction of the CICC behaviour in ITER magnets. The other methods used sometimes for SULTAN test assessment, like subtracting an Ohmic signal, averaging or calorimetry do not seem to have a solid substantiation; in general they give erroneous results, unless distribution of the current is uniform when no correction is needed.

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