Effect of joint quality on conductor short sample performance

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Abstract. Full size conductor short samples for the International Thermonuclear Experimental Reactor (ITER) are composed of two straight conductors connected together at one end, and to the facility current leads at the other ends. The quality of these electrical connections was early suspected to play a role in the measurement of the conductor performance, which has been confirmed by recent test results. In order to investigate this phenomenon, CEA developed an experimental program, within EFDA task ELRES, to study the effect of well calibrated joint defects on subsize NbTi conductor performances. Two types of NbTi strands associated with two different cable void fractions were used in order to vary the interstrand resistances. Experimental results clearly show that joint defects degrade measured conductor critical currents, except when sufficiently low interstrand resistances allow a possible current redistribution among strands. Analysis of Hall probe signals show evidence of current redistribution among subcables during the tests.

1. Introduction

Full size conductor short samples are planned to be used in the conductors qualification program of the International Thermonuclear Experimental Reactor (ITER). Each sample is composed of two straight conductors connected together at one end, and to the facility current leads at the other ends. The quality of these electrical connections was early suspected to play a role in the measurement of the conductor performance [1], which has been confirmed by recent test results [2], [3]. To investigate quantitatively this phenomenon, CEA developed an experimental program, within EFDA task ELRES, to study the effect of well calibrated joint defects on subsize NbTi conductor performances. Two types of NbTi strands associated with two different cable void fractions were used in order to vary the interstrand resistances. Experimental results clearly show that joint defects degrade measured conductor critical currents, except when sufficiently low interstrand resistances allow a possible current redistribution among strands. Analysis of Hall probe signals show evidence of current redistribution among subcables during the tests.

2. Description of the samples

Each ELRES sample is composed of two straight conductors (called legs) connected at their bottom ends through a joint and having each at its top end a termination to connect the sample to the facility current leads (see figure 1). The sample is tested in the vertical position.

Two different NbTi strands, 0.81 mm in diameter, were used in the ELRES conductors, the AL strand with an internal 10 µm CuNi barrier fabricated by Alstom (France), and the EM strand with a 1 µm Ni plating fabricated by Europa Metalli (Italy). They have the same NbTi areas (i.e. 35% of the total strand area) but different copper/non copper ratios (1.54 for AL, and 1.9 for EM). They are the same strands as the ones used in the full-size sample called PF-FSJS [2]. The cross-sections and the critical transport properties of these strands can be found in [2] and [4], respectively.
The ELRES conductors are subsize cable-in-conduits made of a multi-stage cable composed of: 3x3x3x4 = 108 identical strands embedded in a square steel jacket (see figure 2). One type of conductor (C36) has a 36% void fraction, and the other (C32) has a 32% void. The cabling patterns are identical and the last cabling twist pitches are ranging from 165 mm to 180 mm for a specification of 170 mm. Taking into account the strand and the cable types, there are finally 4 different types of conductor (called C36-AL, C36-EM, C32-AL, and C32-EM).

The bottom joint is made according to the CEA twin box concept [5] (see figure 3). The top joints are also fabricated using a copper-steel joint box, but the cable is subdivided into its main 4 subcables, each of them being soldered with PbSn onto the copper sole inside the joint box.

In order to study the effect of joint defects on the conductor characteristics, the bottom joint of the sample is “degraded” by insulating a given proportion (0%, 25%, and 50%) of the connected area into the joint box. This insulation is performed in a symmetric way in the two legs. Table 1 defines the names of the samples, the conductors used, and the corresponding joint insulated areas.

| Sample name | ELRES-0 | ELRES-1 | ELRES-2 | ELRES-1c | ELRES-2c |
|-------------|---------|---------|---------|----------|----------|
| Left leg    | C36-AL  | C36-AL  | C36-AL  | C32-AL   | C32-AL   |
| Right leg   | C36-EM  | C36-EM  | C36-EM  | C32-EM   | C32-EM   |
| Joint defect| 0%      | 25%     | 50%     | 25%      | 50%      |

There are 3 measured voltage drops per leg (see figure 1): V1-V2 giving the voltage drop over 170 mm (one average final twist pitch length), V5-V7 giving the “same” voltage drop but measured on the opposite conductor side, and V2-V8 giving the half joint resistance (including about 160 mm of conductor). The background magnetic field extends over an effective length of 425 mm including...
110 mm above V1, 170 mm between V1 and V2, and 145 mm below V2, the bottom joint itself is in a negligible field. There are 5 temperature sensors, 2 on each leg (T<sub>up</sub> upstream V1, and T<sub>down</sub> downstream V2), and one (T<sub>out</sub>) at the common helium outlet, downstream the joint. Last, there are on each leg 2 sets of 4-quadrant Hall probes each (oriented so as to pick the radial field component), one set upstream V1 and one set downstream V2.

3. DC test results
Current sharing temperature (T<sub>CS</sub>) measurements were performed on all legs. At constant background magnetic field (up to 3.4 T) and current (up to 6 kA), the temperature of one leg was slowly increased up to the quench of this leg. The total (both legs) mass flow rate was fixed at 0.3 g/s which corresponds roughly to 5 g/s (central channel + annular area) in a full size conductor.

3.1. Main issues for testing operation
For all the samples, it was found that the temperature gradient over the sample length (T<sub>up</sub>-T<sub>down</sub>) had to remain below 0.1 K to get consistent measurements of both V1-V2 and V5-V7. The average values between V1-V2 and V5-V7, and between T<sub>up</sub> and T<sub>down</sub> were used to plot the V-T characteristics.

It was also observed that the lower conductor voltage drop V2-V8 systematically raised before V1-V2, although the difference in term of temperature shift was generally low (< 0.1 K). This was attributed to a more non-uniform current distribution closer to the bottom joint and V2-V8 was thus considered as more relevant to a real full-size conductor test.

3.2. Conductor critical currents
As an example, the results of the T<sub>CS</sub> tests at B = 2 T for the lower conductor part (V2-V8= 1.45 μV) are given in figures 4 and 5 for the left leg and the right leg, respectively. Also plotted in each figure is the expected critical current from strand (see “strand”) at applied field. The strand properties are however not accurate as extrapolated from measurements at higher field [4]. It can be seen that the left (AL) leg has almost no degraded performances (ΔT<sub>CS</sub> < 0.1 K) at 25% joint defect, only little (≈ 0.1 K) at 50% joint defect with C32, and significant (> 0.3 K) at 50% joint defect with C36. Overall, the right (EM) leg exhibits already some significant degradation (0.1-0.2 K) at 25% joint defect and still higher (up to 0.3 K above 4 kA) at 50% joint defect whatever is the conductor void fraction.

![Figure 4](image1.png) Critical current of left (AL) leg at 2 T.  

![Figure 5](image2.png) Critical current of right (EM) leg at 2 T.

3.3. Sample characteristics
The half joint resistances were measured on each unheated leg of every sample. Low values were found (2.9 and 1.1 nΩ on the ELRES-0 left and right legs, respectively). Roughly constant (resistance × active area) products were found in all samples with a higher scattering (32% against 13%) in the right leg. These results are qualitatively in agreement with those found on the PF-FSJS [2].
Interstrand resistances were measured on 170 mm spare conductor lengths at all the cabling stage levels. The average inter-subcable resistances were found to be 240, 490, 350, and 70 nΩ.m, in C36-EM, C36-AL, C32-EM, and C32-AL, respectively. The value for C36-EM look unexpectedly too low compared to C32-EM (lower void fraction). However, the much lower value for C32-AL, which was expected (CuNi strands and lower void), explains the good performances of the ELRES-2c (AL) leg.

3.4. Evidence of current redistribution among strands
The 8 subcable currents (4 per leg) at a given location can be computed using the 8 associated Hall probe signals. Examples of results (relative deviation to average value) obtained on ELRES-2c at 2 kA under 3T are presented in figures 6 and 7 (runs are different). One can clearly see the higher current non-uniformity in the right (EM) leg, as well as the earlier current transfer during the transition in the left (AL) leg. Note that the slight oscillations in the EM leg are due to a slight temperature oscillation. A quantitative analysis of the effect of the current redistribution on the voltage drop has still to be performed but it is well-known that improving current distribution decreases voltage drop.

4. Conclusions
Joint defects may degrade significantly the measured conductor performance unless low interstrand resistances allow a possible current redistribution among strands. The interstrand resistance appears to be the key parameter for explaining conductor results since a low joint resistance cannot help to inject current through unconnected strands (compare AL and EM legs with equivalent interstrand resistances).

Absolute (any strand type) joint resistance values cannot be used to characterize joint defects, and even with identical strands, the natural scattering may limit the accuracy of such a determination.

Uneven current distribution among connected strands (due to uneven series resistances) also plays a role on conductor performances in addition to joint defects (see ELRES-1-EM performances).

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