Summary of the Test Results of ITER Conductors in SULTAN

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Abstract. After completing the qualification tests of the ITER cable-in-conduit conductors (CICC), the tests of samples from the series manufacture are running in the SULTAN test facility in Villigen, Switzerland. The key test for the conductor samples is the current sharing temperature, T_{cs}, at the nominal operating field and current, i.e. the maximum temperature at which the conductors operate before developing an electric field of 10 µV/m. All the TF samples fulfilled the ITER requirement of $T_{cs} \geq 5.8$ K after 1000 load cycles. The T_{cs} results have a broad scattering among the suppliers, from 5.8 K up to 6.6 K.

The assembly of the Nb_3Sn based CICC samples (for TF and CS coils) is carried out at CRPP. The NbTi CICC samples (for PF, CC and bus bars) are assembled at the suppliers, with a U-bend replacing the bottom joint. The poor performance of some Main Busbar (MB) conductor samples, caused by poor sample assembly, triggered the effort to assemble a MB sample at CRPP with solder filled terminations and a bottom joint. The superior test results of the MB-CRPP sample, closely matching the performance assessment carried out using 3-D field distribution and *n*-index behavior was a successful achievement of the last year of operation.

According to the Procurement Arrangement for the ITER coils, the winding companies must qualify the joint and termination manufacture by SULTAN samples. The first joint sample tested in SULTAN was a TF joint from EU, followed by a Correction Coil (CC) joint sample from China. Other joint samples are being assembled in USA (Central Solenoid), in Russia (PF1), in EU (PF2 - PF5) and in China (PF6).

All the ITER coils use the "twin box" design for joints, except the Central Solenoid. At the first test in SULTAN of a twin-box TF joint sample in 2013, an unexpected resistance increase was observed after an accidental dump of the SULTAN field, causing a large field transient parallel to the joint contact surface, with large eddy currents and electromagnetic loads at the pressure-contact between strand bundle and copper plate of the twin box. The resistance requirement for the TF joint was still fulfilled after the dump. The initial performance of the joint sample for Correction Coil conductor was not satisfactory and a second qualification sample is being prepared.

1. Introduction

Since May 2012 the SULTAN test facility at Villigen, Switzerland, is leased to the ITER Organization (IO) by a contract with CRPP to test the superconducting cables for the ITER magnets. The results of the conductor tests in SULTAN are part of the acceptance tests for the Procurement Arrangements (PA) with the ITER Domestic Agencies, (DA). For each

TABLE I: CONDUCTOR SAMPLES TESTED IN SULTAN – September 2010 to September 2014

Supplier	TF	CS	PF1/6	PF2/3/4	PF5	MainBus	CC	CCBus
CN	4			3	3	4	5	3
EU	5	2	2					
JA	5	5						
KO	6	1						
RF	4							

conductor type and each industrial supplier, the test plan includes the Supplier Qualification (SQ), based on extensive tests of conductor sections cut from a short length production, the Process Qualification (PQ) phase, with conductor specimens cut from a > 100 m long production unit, and Production tests for specimens cut from the actual production.

The Nb_3Sn conductor samples are assembled at CRPP from two 3.5 m long conductor sections, joined at one end by the "bottom joint" and connected to the other hand to the current source [1-3]. The operating current and the background field are obviously the same in the two conductor sections of a sample, but the operating temperature can be set independently in the two conductors, allowing to test individually the current sharing temperature, T_{cs}, of the two conductor sections. In the NbTi conductor samples assembled at the DAs with a U-bend instead of a bottom joint, only one conductor section is used and tested in one sample.

Disregarding the test of the ITER Model Coil conductors in the past century, the test of the first ITER conductor samples started in 2007 with R&D and prototype samples. The number of samples tested in the last four years (September 2010 to September 2014) is listed in Table I according to the type of conductor and the DA where the conductor is manufactured. The list includes also three CS type samples with variation of layout. The longer test period, 8 weeks, was used for the CS sample CSJA6 in 2014.

Beside the conductor samples, two samples of electrical connections (joints) have been tested, one TFjoint prepared by the European coil manufacturer and one CCjoint prepared by the Chinese coil manufacturer. More joint samples are planned in the next period, for all kind of coils and all coil manufacturers.

2. Status of the TF Conductor Test

As reported in [1], the TF conductors suffer of performance degradation upon cyclic loading. The T_{cs} test at 68 kA and 10.79 T background field (leading to 11.15 T "effective field", as in the ITER TF coils) is carried out immediately after the first cool-down, "initial", after 1000 load cycles at nominal current, "final", and after a warm-up / cool-down cycle to room temperature, "wucd". The specified current sharing temperature is $T_{cs} \geq 5.7\ K + 0.1\ K$ after 1000 load cycles (no thermal cycle).

Two features affect the performance evolution for Nb_3Sn based CICC [4-5]: the relaxation of the initial thermal strain due to settling in the strand bundle upon operating loads and the filament breakage due to local bending of the strands upon transverse load. In the TF conductors with "long" cable pitch sequence, the filament breakage dominates over the strain relaxation and the net performance change is a degradation of the T_{cs}. Another evidence of filament breakage is the reduction of the index n of the superconducting transition in the voltage-current characteristic [6], defined by

$$E = E_0\left(J/J_c\right)^n \quad (1)$$

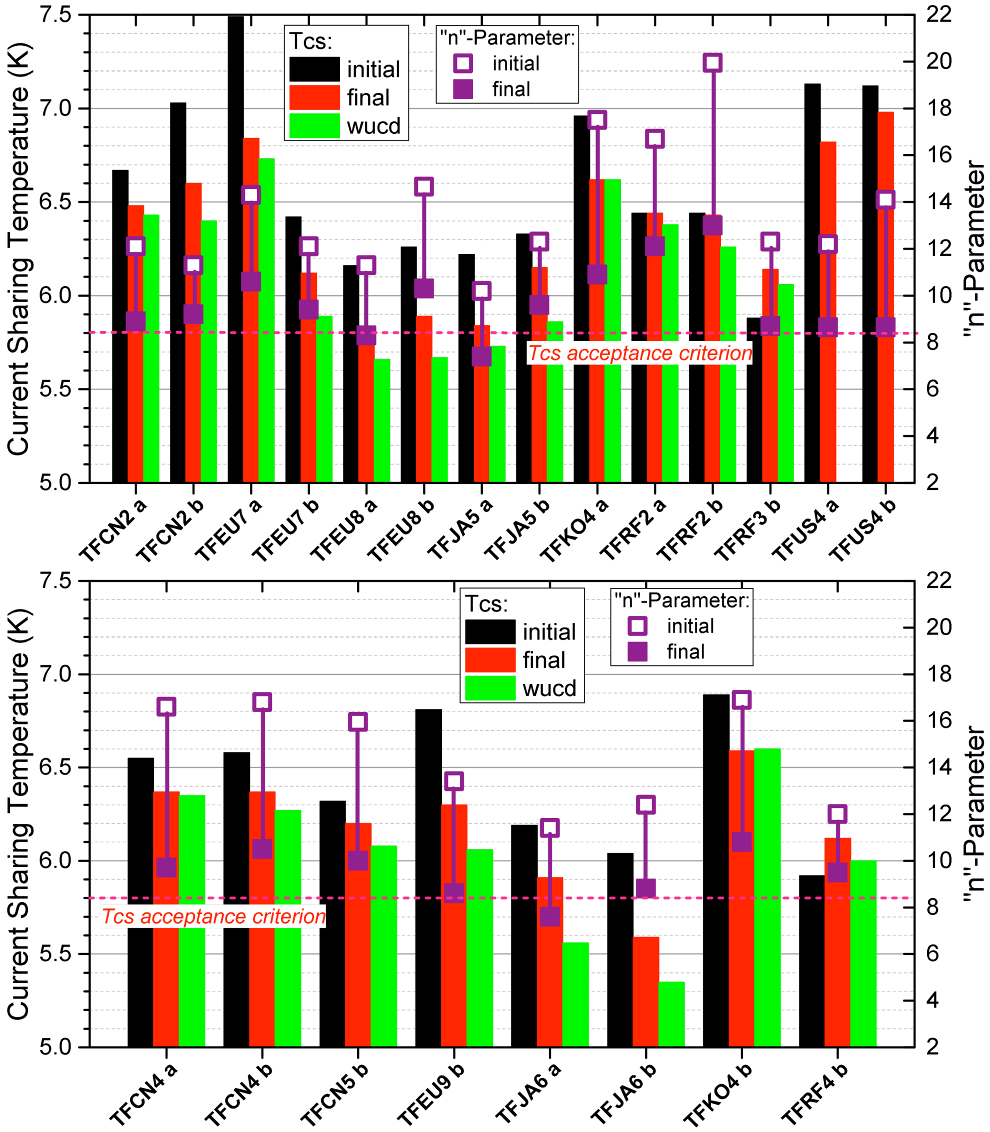

FIG. 1. T_{cs} and n index results for the SQ (top) and PQ (bottom) phase of TF conductors

The n index is not a function of operating strain [7], but only of the critical current density, J_c, in the strand. In NbTi based CICC, the n index is identical in the free-standing strand and in the CICC for the same J_c. However, in the TF conductors the n index is smaller than in the free-standing strand and decreases after cyclic loading [1].

The results for the TF conductors of the SQ and PQ phases are gathered in Fig. 1. The drop of T_{cs} is well correlated to the drop of n index. In the TF conductors from Russia (RF), the drop of n is small, suggesting a limited amount of filament breakage: in the RF conductors of PQ and series production, the T_{cs} performance is rather stable - the beneficial strain relaxation is balanced by the limited strand breakage. The better performance of the RF conductors under cyclic load is likely not due to the robustness of the strand, but to the frictional properties of the Cr plating applied by the Russian vendor, which may promote the sliding at the strand crossovers and mitigate the local strand bending.

The SQ phase was completed in 2012. As October 2014, the PQ phase is completed for all but one DA. The series production tests are carried out according to a sampling scheme dictated by IO: about one third of the 126 TF production lengths are tested in SULTAN. As October 2014, the Korean DA has completed the series production test. Only one DA has yet to start the series production tests. The results of the series production samples are gathered in Fig. 2.

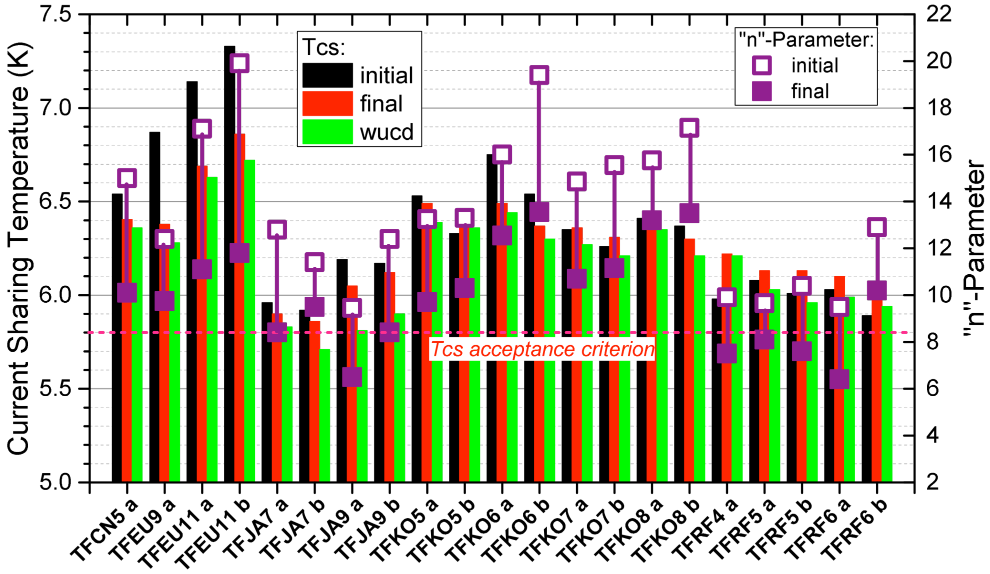

FIG. 2. Results of T_{cs} *and n index for the TF conductor samples from the series production.*

3. Status of the CS Conductor Test

The T_{cs} test for the CS conductor is carried out at 45.1 kA and 10.85 T background field, 1.5 T lower than in operation. The cyclic loading is done at 48.8 kA / 10.85 T, which corresponds to the actual transverse load in operation. The target T_{cs} at the SULTAN test is ≥ 6.5 K.

As October 2014, eight CS conductor samples have been tested in SULTAN, see Fig. 3. The performance of CSJA1, CSJA2 and CSIO1, with "long" pitch sequence, was disappointing: with large number of load cycles and thermal cycles, the degradation was not saturating, leading to unacceptably low T_{cs}. The breakthrough was achieved with the "very short" pitch sequence of CSIO2a [1]. The rigid structure of the first triplet of strands, twisted at 20 mm pitch, withstands the transverse loads without significant bending. Opposite to the TF conductors, the strain relaxation dominates over the filament breakage and the net performance change is an improvement of the T_{cs}, slowly saturating after 20000 cycles.

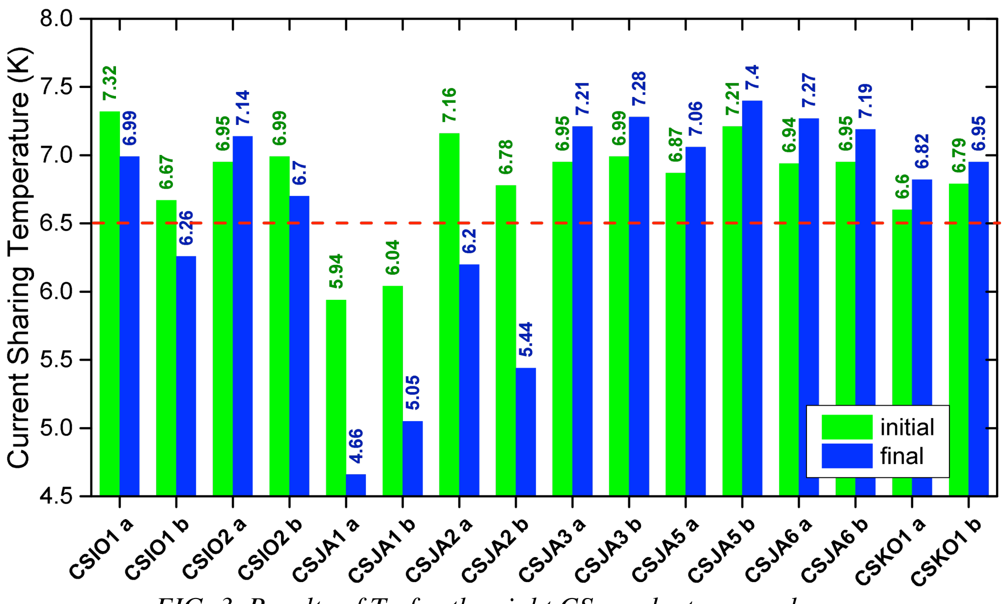

FIG. 3. Results of T_{cs} *for the eight CS conductor samples.*

The good performance of CSIO2a was confirmed in the last two years by the eight conductor sections of CSJA3, CSJA5, CSKO1 and CSJA6, all with the "very short" pitch sequence. Out of the nine conductors, three are made with internal Sn strands from two different suppliers and the other six are bronze strands from three different suppliers, suggesting that the "very short" pitch sequence is effective for both bronze and internal Sn strands.

The number of load and thermal cycles over the test campaign is not the same for all the samples. The shortest test is for CSJA1, with 6000 load cycles and one warm-up/cool-down. The longest test, lasting eight weeks, is for CSJA6, with 20000 load cycles and four warm-up/cool-down. All the nine conductors with "very short" pitch sequence match the specified T_{cs}. The CS sections for CSJA6 are cut from the series production for the CS3 coil module. The performance evolution of CSJA6 is reported in Fig. 4.

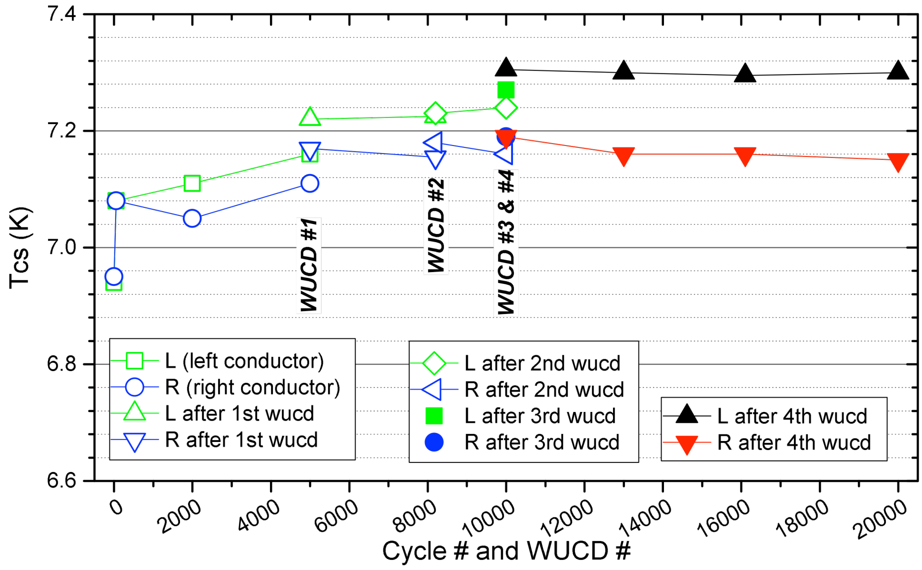

FIG. 4. Results of T_{cs} evolution for CSJA6 over 20000 load cycles and four warm-up/cool-down.

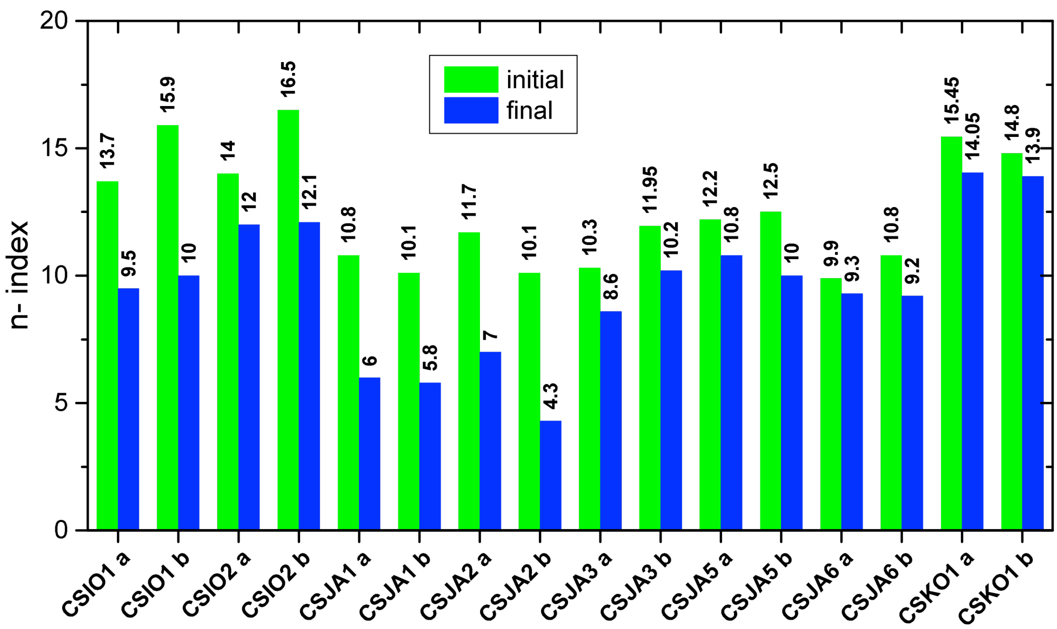

FIG. 5. Results of n index for the eight CS conductor samples.

The results for the n-index are gathered in Fig. 5. The drop of n is much smaller in the conductors with "very short" pitch sequence, but is still measurable, suggesting that some, very limited filament breakage also takes place. It cannot be excluded that over a very large number of load cycles, as for example in an actual fusion plant, with about one million load cycles, an irreversible performance degradation may start. For the ITER CS modules, the planned number of load cycles is up to 60000. A test in SULTAN with up to 60000 load cycles is very demanding. At the rate of about 900 cycles/day, the test duration would be in excess of three months.

4. Status of the NbTi Conductor Test

A total of nine conductor samples have been tested so far for the PF conductors. Two samples, PFEU1 and PFEU2, are for the PF1/6 conductor type, made with Russian cable and assembled in Europe. The PF2/3/4 conductor (four samples) and PF5 conductor (three samples) are assembled in China. Since September 2012, six PF conductor samples have been tested, confirming the results reported in [1] for the three first samples. All samples matches the specified performance, although the T_{cs} definition at 10 µV/m electric field must be replaced by T_q (temperature at the take-off voltage), because the take-off voltage is smaller than 10 µV/m [1].

The performance of the Correction Coil (CC) conductor samples and busbar (CB) samples also match the specification. In the last two years, three CC samples and two CB samples have been tested.

Four Main Busbar (MB) conductor samples were tested between 2011 and 2013. The fifth MB sample is being tested in October 2014. The measured performance of the MBCN1 sample [1] was within the specification, but MBCN2 was about 0.5 K lower, despite the identical layout. The degraded performance of MBCN2 could be explained by a premature quench initiation in the U-bend box: the bending radius of the individual sub-cables in the U-bend can be quite small, as shown in Fig. 6 left, leading to a high self-field generated in some U-bend locations. In this case, the sum of the background field and self-field in the U-bend location can exceed the field in the high-field region. The fact that the quench was initiated in the U-bend, rather than in the SULTAN test region, is supported by a faster temperature increase in front of the high-field region (upstream) than behind it (downstream) during the quench initialization. The MBCN2 sample was modified in China in order to have better control over the individual sub-cable bending path. However, the modified sample, called MBCN3, did not show any improvement of measured T_q. For the MBCN4 sample, the conductor sections were fabricated in China but the joint preparation was done at CRPP, see Fig. 6 right, with a similar layout as for the TF samples.

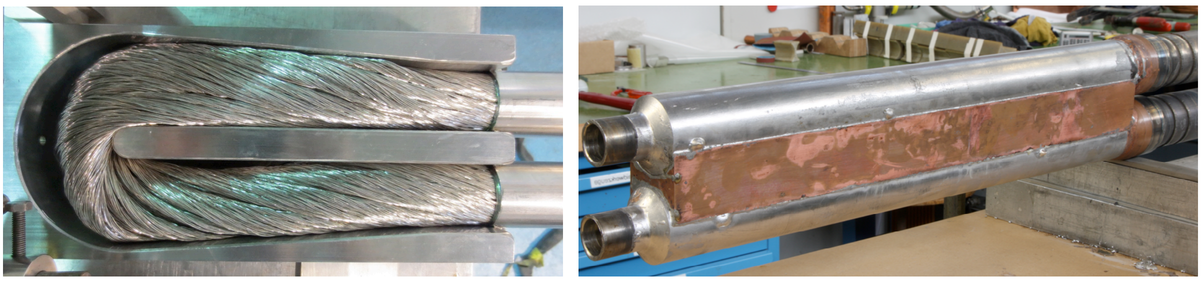

FIG. 6. The U-bend box of MBCN2 (left) and the soldered bottom joint of MBCN4 (right).

The result for MBCN4, see Table II, is the best of all MB samples and closely matches the analytical assessment made in [8] based on the scaling law for the strand I_c, the 3D self field map and the index *n*.

TABLE II: T_{CS} PERFORMANCE FOR MB SAMPLES.

Sample	MBCN1	MBCN2	MBCN3	MBCN4
T_{cs}(3.22T, 45.5kA)	6.95 K	6.51 K	6.45 K	7.02 K

The experience with the MB samples shows that the U-bend box layout, with poor control of the individual strand bending and related self field, may compromise the sample performance at high current and low background field. It has been agreed that the next MB samples will be assembled at CRPP with the bottom joint.

5. Test of the TF and CC Joints

A sample of TF inter-pancake joint, prepared at the European industry, was tested in 2013 and 2014. The joint resistance fulfills the specification, R ≤ 3 nΩ at 2 T and 68 kA. However, the strong dependence of R on the operating current and background field suggests that the pressure contacts between strand bundle and copper plate are strong inhomogeneous, with early saturation of the few low resistance contacts. A field transient on the joint, caused by a fast discharge of the SULTAN field, produced unexpected resistance increase, in the range of 20%, due to the electromagnetic loads pushing the strand bundle away from the copper plate and thus weakening the contacts [9].

A sample of the CC joint, prepared in China, was tested in summer 2014. The very high resistance, exceeding the spec by an order of magnitude, suggests pollution of the contact between strand bundle and copper plate. Post mortem investigation are carried out in China and a new sample is expected within the end of 2014.

6. Outlook in the Test Activity of next Period

The test operation in SULTAN run smoothly during the ITER tests, without discontinuity, except the planned, yearly maintenance of the cryo-plant. The flow of samples was carefully coordinated by IO and very few idle weeks occurred because of lack of samples to be tested. However, the duration of the leasing contract for SULTAN test needs to be extended: the test needs for the CS conductors exceeds the initially assumed demand because more strand suppliers are qualified and the test duration (10000 load cycles) requested long campaigns. Further on, the need of qualification tests for joints was not accounted in the initial estimate and, last, a fraction of the conductor production is delayed, e.g. the CS conductor in Japan, the PF conductor in Europe and the TF conductors in USA.

The extension of the contract for tests in SULTAN beyond 2015 is being negotiated between IO and the DAs with an updated cost sharing. The use of the EDIPO test facility [10] may also be considered for the CS conductors, as EDIPO provides a higher background field than SULTAN, matching the actual operating field of the ITER CS.

7. Conclusion

The test of the ITER conductor samples in SULTAN progresses smoothly to full satisfaction of all the parties. The test of the TF conductor production approaches the final phase, with over 70% of the planned samples already tested, without rejection. The developmental samples of CS conductor in 2012 and the extended tests with up to 20000 load cycles in 2014 have identified the suitable cable layout to withstand the lifetime of the ITER CS. The test of the CS samples will be likely completed in 2016. For the NbTi conductors, the sample layout with U-bend box has shown its limitation at low field and high current: next samples of the Main Busbar conductor will be prepared with the well proven layout of the bottom joint instead of the U-bend. The qualification test of joint samples, prepared at the industry has just started: although the joint layout is not new, the behavior under transient field and the technology transfer to the industry are not obvious, as suggested by the first results. An intensive qualification phase for the joints prepared at the industry in EU, China, USA, Japan and Russia is the next crucial task.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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