T_{cs} Degradation of ITER TF Samples due to Fast Current Discharges

Kamil Sedlak, Pierluigi Bruzzone, Boris Stepanov, Neil Mitchell, Vladimir Tronza, Alexander Vostner

***Abstract*— Direct current (DC) tests performed in the past on the conductor samples of the toroidal field (TF) ITER coils revealed degradation of current sharing temperature, T_{cs}. The degradation progresses with repetitive electromagnetic (EM) loading, and also with thermal cycles between 4.5 K and room temperature. This feature was observed on short samples in SULTAN test facility (EPFL-SPC, Switzerland) as well as in TF Insert Coil tests in CSMC test facility (Naka, Japan).**

We present three independent observations suggesting that initiation of sample quench followed by a fast current discharge, which normally complements every I_c and T_{cs} test in both SULTAN and CSMC, enhances the T_{cs} degradation rate. The exact mechanism of this contribution to the degradation remains unidentified.

***Index Terms*—TF coils, conductor testing, degradation, quench.**

I. ITER TF Sample Degradation

Several large cable-in-conduit conductors (CICC) based on Nb_3Sn exhibit degradation of the DC performance, typically a drop in T_{cs}, when the CICC is exposed to repetitive electromagnetic (EM) load or warm-up-cool-down (WUCD) cycles. The performance degradation was observed also in ITER TF and CS conductor samples [1]-[3]. In the latter case, the problem was mitigated by changing the pitch sequence in the CS cable design [4], [5].

The ITER CICC performance degradation has attracted attention from both experimentalists and theoreticians. The most recent findings and discussion on this topics are summarized in [6], [7] and [8]. In its introductory section, the reference [8] summarizes 38 publications somehow related to the degradation issue.

The degradation due to EM load is induced by repetitive current charging/discharging in the operating magnetic field. The T_{cs} degradation is largest during the first ~10 EM cycles, and gets smaller afterwards. The level of degradation observed in TF conductors with identical layout depends on conductor manufacturer. Practically no degradation is observed in conductors produced in Chepetsk Mechanical Plant, Russian Federation.

To study the degradation due to WUCD cycles is more time consuming, as one thermal cycle lasts several days, compared to a few minutes for the EM cycle. A former study [9] concluded that even though there was a visible degradation observed after the first thermal cycle, the following ten or more additional WUCD cycles, without EM loading between them, did not further deteriorate conductor performance. This might seem to be contradicted by recent TF Insert Coil tests performed in Naka [10], where every subsequent thermal cycle led to a visible T_{cs} degradation. The apparent inconsistency of the two observations is interpreted such that the degradation is present only when WUCD is combined with EM cycling, which was the case in [10] but not in [9].

Very recently, a “conditioning” or “training effect” of TF conductors has been suggested in [6]. The authors claim that the level of ITER TF conductor degradation depends on history of conductor (EM and thermal) cycling, and that it is possible to reduce the level of degradation by a suitable sequence of loading.

We come up with a new phenomenon co-responsible for the sample degradation. We observe that the degradation is enhanced (or accelerated) by the “very fast current dumps” that usually conclude any DC test in both SULTAN test facility [11] and Model Coil test facility in Naka [12], [13]. The reasons for this claim are based on three independent observations presented in sections III-V.

II. T_{CS} and I_C Tests in SULTAN

Before coming to the main topic of the paper, we briefly describe direct current (DC) tests in SULTAN. In the I_c run, first the requested field value and temperature are set, and then the current is ramped up slowly (100 A/s) until the electric field significantly exceeds the critical electric field traditionally set to E_c=10 µV/m. In the T_{cs} run, first current is ramped up in steps to the requested operating value, and then the temperature is slowly increased in steps, again until the electric field significantly exceeds E_c. A typical I_c and T_{cs} run last 30 and 100 minutes, respectively.

Normally, both I_c and T_{cs} tests in SULTAN end up with a voltage take-off. Due to the working principle of superconducting transformer delivering current to the sample, which interrupts current whenever the resistive voltage in the sample exceeds ~100 mV, the current discharges exponentially to zero very quickly after the quench initiation. A typical current dump of ITER TF SULTAN sample in nominal test conditions

(Corresponding author: Kamil Sedlak. e-mail: kamil.sedlak@psi.ch)
K. Sedlak, P. Bruzzone, and B. Stepanov are with École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-5232 Villigen PSI, Switzerland.
N. Mitchell, V. Tronza and A. Vostner are with with the ITER Organization, 13115 Saint Paul lez Durance, France.

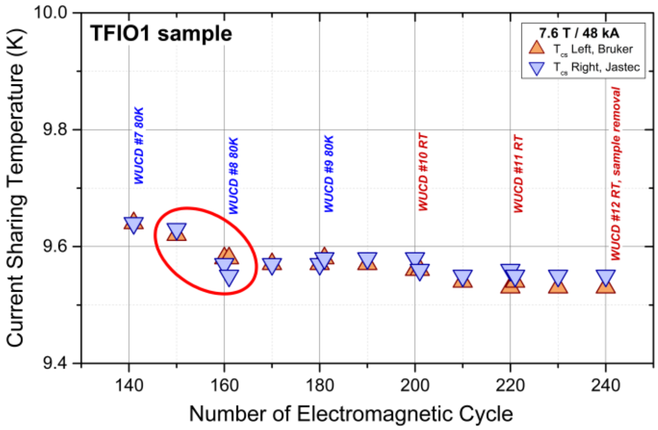

Fig. 1. T_{cs} evolution of TFIO 1 sample. Sample quench happened in the left conductor section (Bruker) at the end of T_{cs} run at 150 EM cycles. Affected is the subsequent T_{cs} at 160 cycles. The T_{cs} drops by 40 and 60 mK in the two conductor sections, respectively.

(10.8T, 68kA) lasts 0.4 s. The temperature in the sample reaches ~30 K. In special cases, if required, the voltage take-off at the end of the SULTAN test can be avoided. For simplicity, we sometimes call the voltage take-off as "sample quench", even though the quench is not fully developed, i.e. it is suppressed in its initial phase by the fast current dump.

III. Measurement of ITER TFIO1 Sample in SULTAN

In 2017, ITER Organization launched a dedicated test campaign [6], whose goal was to look for thresholds for the onset of the WUCD-EM degradation and investigate the differences between conductors produced by different manufacturers. The operating field and current were gradually increased during the test campaigns, and many thermal cycles were performed. The results of the test campaign are presented in [6]. Here we present just one particular observation, demonstrated in Fig. 1, which shows the evolution of T_{cs} measured at 7.6 T and 48 kA. This corresponds to 70 % of the nominal operating current and to 50 % of the nominal EM load. After every 10 EM cycles, a T_{cs} measurement was done, and after every three T_{cs} measurements a WUCD cycle, either to 80 K or to room temperature, was performed.

During the TFIO testing, unlike in the usual SULTAN test campaigns, we tried to avoid the voltage take-off at the end of T_{cs} runs. When the electric field in the sample significantly exceeded the usual criterion of E_c =10 μV/m, the sample current was ramped down slowly, with a ramp rate -300 A/s or slower.

The T_{cs} measurement after 150 EM cycles, however, finished with an unintentional voltage take-off and fast discharge, due to the instability of the inlet temperature during the last temperature step of the test. The T_{cs} measured at 150 EM cycles cannot be influenced by the quench that happened at its very end, but the next T_{cs} measurement, taken at 160 EM cycles could be. And indeed, one can see a drop in T_{cs} at 160 EM cycles in Fig. 1. The T_{cs} drop is observed already before WUCD to 80 K, which was performed after 160 EM cycles. This observation represents the first hint that the performance drop can be a consequence of the preceding voltage take-off followed by the fast current discharge.

IV. Analysis of the Degradation on Many ITER TF Samples

Many ITER TF samples have been tested in SULTAN in past years. One of the interesting results of these tests was the T_{cs} evolution along 1000 EM cycles, in which most of the TF samples exhibited DC performance degradation.

The conductor production and testing was divided into four phases. During the initial phases, up to the pre-production phase III, a typical test campaign lasted three weeks, and the number of DC tests (i.e. T_{cs} and I_c runs) along the EM cycling was higher compared to the final production phase IV lasting just two weeks. This allows us to compare the total drop of T_{cs} during 1000 EM cycles as a function of the total number of sample quenches between the initial T_{cs} (T_{cs} #1) and final T_{cs} after cycling (T_{cs} #1000) performed before any WUCD. Typically, 7 DC tests were done between the first and last T_{cs} measurement in the phase III campaigns, compared to only 4 DC tests for samples in the phase IV. Every DC test ended up by a sample quench.

The corresponding comparison is shown in Fig. 2. The T_{cs} performance drop, expressed as

$$\Delta T_{cs} = T_{cs}\,\#1000 - T_{cs}\,\#1$$

is plotted as a function of the number of sample quenches between the T_{cs} #1 and T_{cs} #1000. There seems to be a trend in the TF samples for the most manufactures – the more DC tests (sample quenches) were performed between the first and 1000th EM cycle, the larger is the T_{cs} degradation. The trend is not visible in CNTF and USTF samples, presumably due to low statistics of measurements in phase III, and in RFTF samples, in which T_{cs} improves with EM cycling instead of degrading.

The trend present in the data represents a second hint that the sample quenches enhance the observed T_{cs} degradation.

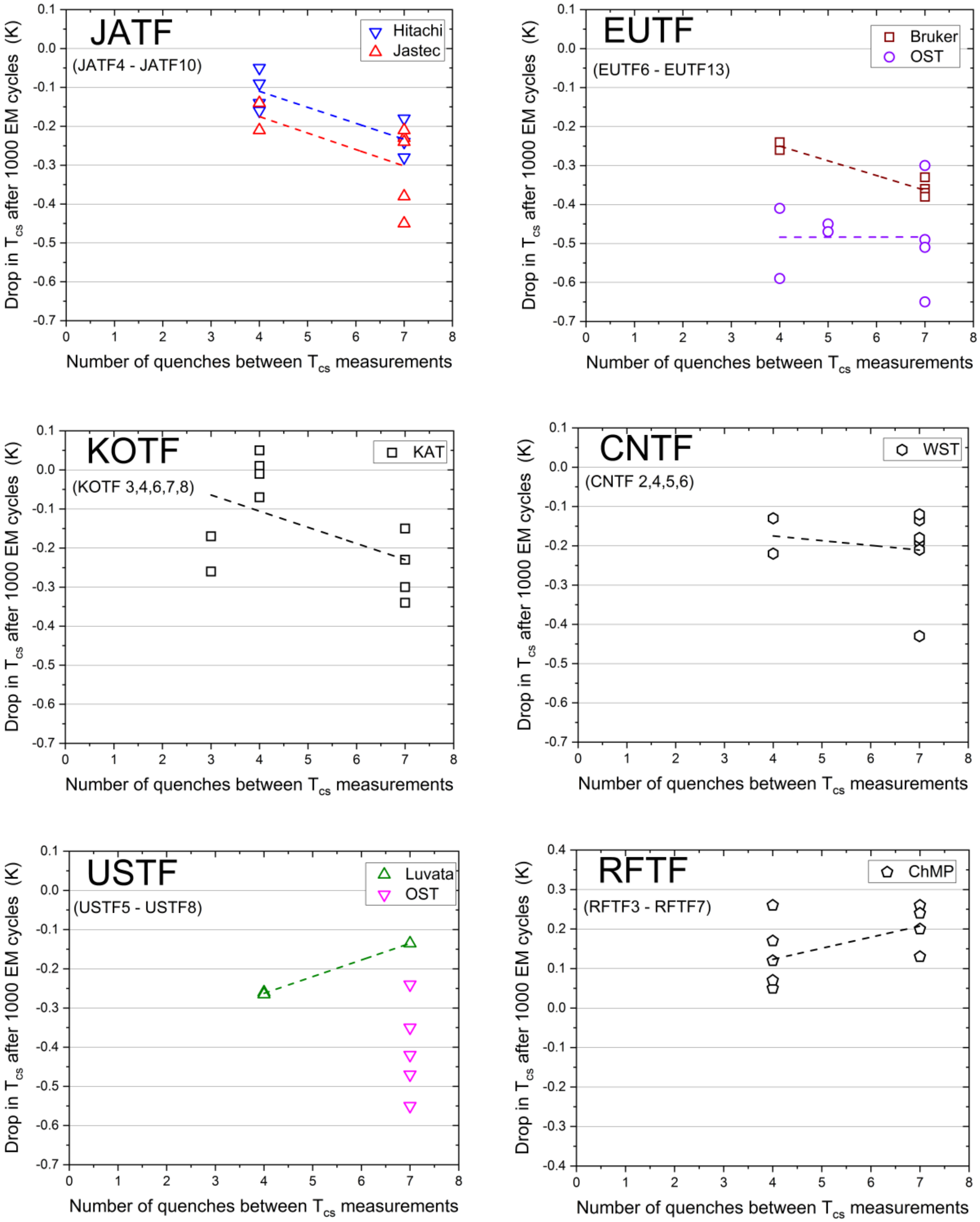

Fig. 2 T_{cs} performance drop after 1000 EM cycles ($\Delta T_{cs} = T_{cs}$ #1000 – T_{cs} #1) as a function of intermediate DC tests, which is equal to the number of intermediate sample quenches. Note that T_{cs} of the samples of Russian Federation behaves differently – the DC performance did not degrade but rather improved during EM cyclic loading. The dashed lines indicate linear fits.

V. Dedicated SULTAN Sample Studies

The observations presented in sections III and IV triggered a dedicated study, whose aim was to investigate the effect of sample quenches (fast current discharges) on the T_{cs} degradation. The study was performed on two "identical" SULTAN samples named TFIO6 and TFIO7. Both samples consist of two conductor sections from the same conductor production batch: the left section Jastec, the right one Bruker, see Table 1. Both Jastec sections were heat-treated together, and so were also the Bruker ones.

Table 1 Conductor sections employed in the SULTAN samples, including ITER ID identifiers.

Sample	Left Section	Right Section
TFIO6	Jastec 81JNC032-2	Bruker 81EAS022
TFIO7	Jastec 81JNC032-8	Bruker 81EAS023

The TFIO6 sample testing started "gently". The initial T_{cs} run has been done without the usual sample quench at the end of run. The second T_{cs} test was performed only after 1000 cycles, also without quench. A sequence of another 14 T_{cs} runs has followed, at the later stage intentionally ending with quenches and interleaved with electromagnetic load cycling and one thermal cycle to room temperature. Table 2 summarizes the test sequence and also the measured T_{cs} .

The TFIO7 sample testing started right from the beginning in the usual manner as an ordinary SULTAN sample, i.e. with sample quench followed by the fast current discharge at the very end of every run. Quenches were intentionally induced alternately in the Jastec and Bruker legs by controlling the helium inlet temperature. (The idea was to see if the degradation is linked to the section, where the quench was induced, but no such correlation was found.) Eleven DC tests were done until the 1000th EM cycle, to be compared to two DC test in TFIO6.

The T_{cs} for both samples are presented in Fig. 3. The two upper plots show directly T_{cs} values, separately for Jastec and Bruker conductors, while in the lower plots the values are normalized to the initial T_{cs} . One would expect the initial T_{cs} being the same in

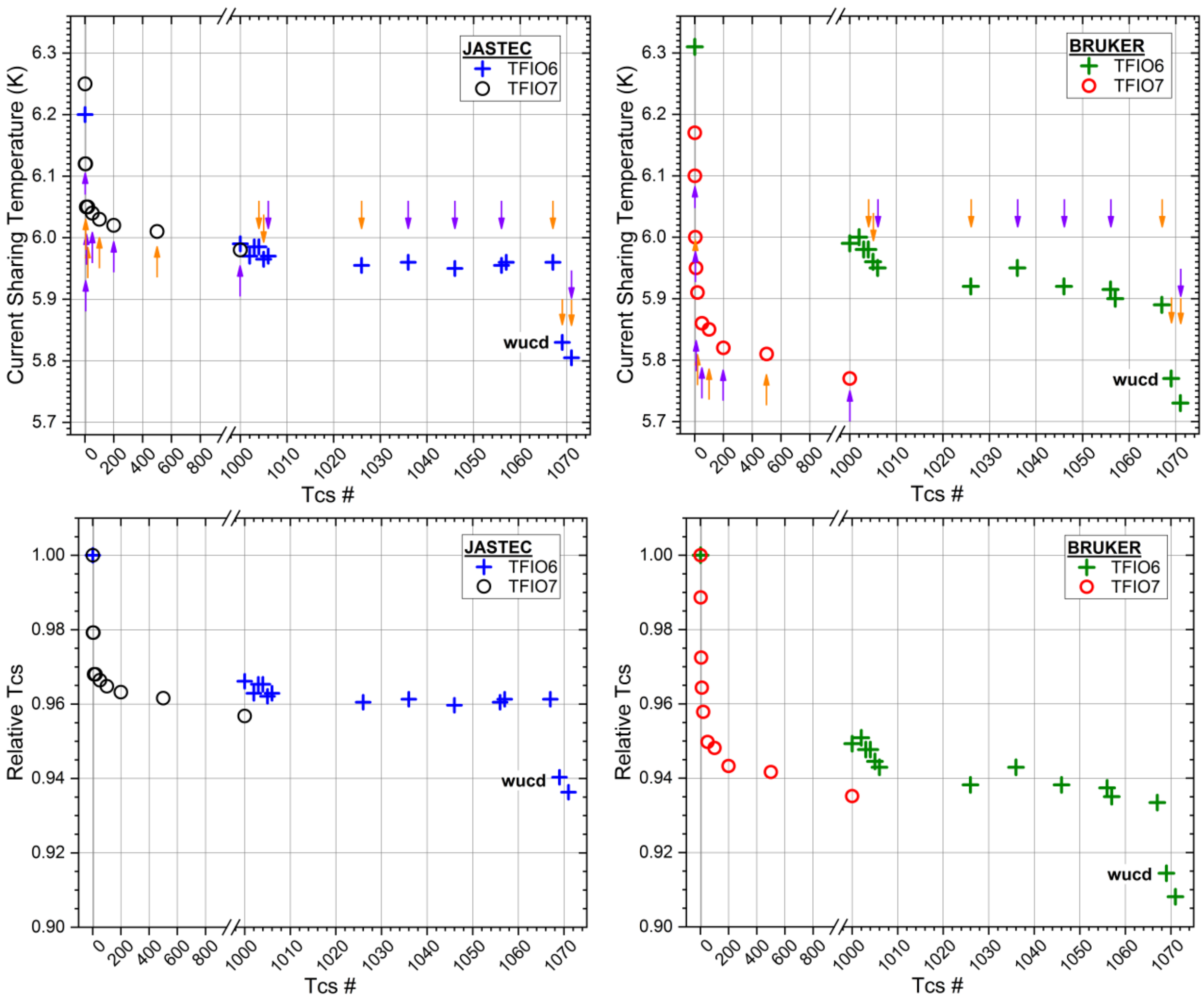

Fig. 3 T_{cs} measured in the TFIO6 and TFIO7 samples (upper plots) and the corresponding relative T_{cs} normalized to T_{cs}#1 (lower plots). The arrows indicate T_{cs} measurements taken after the previous fast current dump in the Jastec (violet) or Bruker (orange) conductor section.

both Jastec sections (as well as same in both Bruker sections), however this is not the case, and the differences are 0.05 K and 0.14 K for the Jastec and Bruker sections, respectively. Small differences in the initial T_{cs} of the ITER TF conductors originating from the same manufacturer were observed in the past.

Table 2 List of T_{cs} runs for the TFIO6 and TFIO7 samples. The comment about quench is related to the quench at the very end of the run, i.e. it may only affect the subsequent test. The two runs with no T_{cs} values are I_c runs.

TFIO6 sample			
Cycle no.	Tcs Jastec	Tcs Bruker	Comment
1	6.2	6.31	no Quench
1000	5.99	5.99	no Quench
1002	5.97	6	no Quench
1003	5.985	5.98	Quench Bruker
1004	5.985	5.98	Quench Bruker
1005	5.965	5.96	Quench Jastec
1006	5.97	5.95	Quench Bruker
1026	5.955	5.92	Quench Jastec
1036	5.96	5.95	Quench Jastec
1046	5.95	5.92	Quench Jastec
1056	5.955	5.915	no Quench
1057	5.96	5.9	Quench Bruker
1067	5.96	5.89	Quench Bruker, WUCD
1069	5.83	5.77	Quench Jastec
1070	-	-	Quench Bruker
1071	5.805	5.73	Quench Jastec

TFIO7 sample			
Cycle no.	Tcs Jastec	Tcs Bruker	Comment
1	6.25	6.17	Quench Jastec
2	6.12	6.1	Quench Bruker
3	-	-	Quench Jastec & Bruker
5	6.12	6	Quench Jastec
10	6.05	5.95	Quench Bruker
20	6.05	5.91	Quench Jastec
51	6.04	5.86	Quench Bruker
100	6.03	5.85	Quench Jastec
200	6.02	5.82	Quench Bruker
500	6.01	5.81	Quench Jastec
1000	5.98	5.77	Quench Bruker

There is a slight difference in the performance drop between the first and 1000th cycle. While T_{cs} in TFIO6 (the conductor that did not experience initial quenches) drops by only 0.21 K (Jastec) and 0.32 K (Bruker), in the TFIO7 (intermediate 10 DC tests followed by sample quenches) T_{cs} drops slightly more, namely by 0.27 K (Jastec) and 0.40 K (Bruker).

In addition, once the DC tests start to be performed on TFIO6 between the cycles no. 1000 and 1067, T_{cs} drops an order of magnitude more than what would correspond to just pure 67 EM cycles. The T_{cs} drops by 0.04 K (Jastec) and 0.10 K (Bruker), while the expected performance drop in both Jastec and Bruker is only around 0.005 K per 67 cycles. (The expected T_{cs} drop is extrapolated from the difference between T_{cs}#500 and T_{cs}#1000 in Table 2.) This clearly shows that the performed DC tests with the fast dump slightly, but observably, degraded T_{cs}.

Also the n-values measured in the I_c runs seem to support the conclusion that sample TFIO7 has degraded more than the TFIO6 one, see Table 3. However, it has to be noted that we did not perform an initial I_c measurement for the TFIO6 sample (not to risk a voltage take-off in the initial phase of testing), and therefore we can only compare the n-values at 1001 cycles, and not the relative change between e.g. the 3rd and the 1001st cycle.

Table 3 The n-values of the TFIO6 and TFIO7 samples.

	TFIO 6		TFIO 7	
	Jastec	Bruker	Jastec	Bruker
Cycle #	n-value	n-value	n-value	n-value
3	-	-	11.2	12.4
1001	9.7	12.3	8.3	10.6
1068	9.4	11.3	-	-
1070	9	10.6	-	-

VI. Discussion

We have presented three independent observations that demonstrate enhanced (or accelerated) degradation of T_{cs} due to voltage take-off (quench) followed by the very fast current discharge. Very recently, a difference in T_{cs} degradation has been reported in section 6.2 of [6], where a concept of "conductor conditioning" or "training" was introduced in order to explain the difference in the rate of degradation between the ITER TF conductors of the same manufacturer. By comparing the T_{cs} evolution in TFIO1 and TFI-SULTAN (TF insert-coil sample tested in SULTAN, whose T_{cs} degraded more than that of TFIO1), it was found that "the degradation of the conductor seems to decrease when the conductor is exposed to lower EM loads at the beginning of the testing series before being exposed to the highest EM loads (i.e. a training effect)."

However, also in this case an (alternative) explanation to the different T_{cs} degradation could be related to the sample quenches. While TFI sample was tested in a usual way with sample quenches, quenches were avoided during TFIO1 testing.

What can be the underlying mechanism causing the quench-related degradation? The typical highest temperature observed during the sample quenches in SULTAN is around 25 K. The temperature sensors are located on the steel jacket upstream and downstream of the quenched region (the quench is generally initiated in a 450 mm long high-field zone), and therefore the hot-spot temperature in the cable might marginally exceed 25 K. The degradation due to the thermal expansion of either strands or jacket is therefore hard to believe. It is also unlikely that local AC currents induced by fast current dump could be too high to potentially damage the strands, e.g. by locally induced forces.

The conductor loses its superconducting properties during quench, the resistance of the coupling current loops becomes orders of magnitude higher than in the superconducting state, which substantially suppresses the induced AC loss currents.

We have not found a difference between the degradation of the conductor section, in which the voltage take-off was induced, compared to the second leg. This suggests that the conductor degradation is due to the fast current dump rather than due to the voltage take-off.

In conclusion, we are lacking a solid plausible explanation for the suspected degradation. One might speculate about some load-rate dependent effects in a cable behaving as a non-elastic spring, in which fast varying load induce more total displacement than a slow varying one.

VII. Conclusions

The T_{cs} degradation of ITER TF conductors has evolved into a very complex phenomenon. It clearly depends on the electromagnetic and thermal cycling, and we seem to have some evidence now that it is enhanced also by sample quenches followed by fast current dumps. All these individual factors degrade DC performance of the cable, however the degradation gets clearly increased when these factors act in combination. It even seems that the degradation can be limited by an appropriately chosen sequence of partial EM load and thermal cycling in the initial phase of the coil operation, i.e. by the so-called conditioning/training [6].

The good news for the ITER project is that the reported degradation due to the sample quenches followed by the fast current discharge will not happen in the ITER TF coils that will be under all circumstances discharged slowly ($\tau_{discharge} = 11$ s), even in the case of a real quench. The T_{cs} degradation observed in SULTAN samples and in TF Insert Coil tests are therefore likely slightly overestimating the degradation that we might see during the ITER TF coil operation.

On the other hand, the observation that the voltage take-off (an initial phase of a quench) with the fast current discharge degrade the ITER TF conductor came unexpected. The underlying mechanism is not understood, and we may wonder what will happen in case of a real, fully-developed quench in the ITER TF magnet, when the hot-spot temperature in the cable might reach 250 K during the transient. Surprises in terms of T_{cs} degradation are not excluded, as no quench test with a fully developed temperature rise has ever been performed on the full-size ITER conductor due to non-existing test facility able to do so.

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