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ITER Central Solenoid Insert Test Results

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***Abstract*—The ITER Central Solenoid (CS) is a highly stressed magnet that must provide 30 thousand plasma cycles under the ITER prescribed maximum operating conditions. To verify performance of the ITER CS conductor in conditions close to those for the ITER CS, the CS Insert was built under a US-Japan collaboration. The Insert was tested in the aperture of the CSMC facility in Naka, Japan, during the first half of 2015. A magnetic field of up to 13 T and a transport current of up to 60 kA provided a wide range of parameters to characterize the conductor. The CS Insert has been tested under direct charge and reverse charge, which allowed a wide range of strain variation and provided valuable data for characterization of the CS conductor performance at different strain levels.**

The CS Insert test program had several important goals:

1. **Measure the temperature margin of the CS conductor at the relevant ITER CS operational conditions**
2. **Study the effects of electromagnetic forces and strain in the cable on CS conductor performance**
3. **Study the effects of the warmup and cooldown cycles on CS conductor performance**
4. **Compare conductor performance in the CS Insert with the performance of the CS conductor in a straight hairpin configuration (hoop strain free) tested in the SULTAN facility**
5. **Measure the maximum temperature rise of the cable as a result of quench**

The main results of the CS Insert testing are presented and discussed.

***Index Terms*—Superconducting magnets, voltage measurement, loss measurement, degradation, performance**

I. Introduction

The Central Solenoid (CS) will be provided to ITER by the US ITER Domestic Agency. The conductor is supplied by the Japanese Domestic Agency. The CS conductor was qualified in the SULTAN test facility [1], where a short piece of conductor was placed in a background field of 10.85 T, a current was introduced into the conductor, and the temperature was slowly increased. Then the conductor went through electromagnetic (EM) load cycles and warmups and cooldowns to simulate ITER operating conditions. In the past, the CS conductor experienced a significant degradation during the EM cycles and the warmups. It was assumed and then confirmed [2] that the reason for the degradation was broken superconducting filaments due to the EM forces in the cable. The degradation threatened the ITER mission of 30,000 full cycles and therefore was treated as a high priority by the ITER community. It led to a new cabling pattern [3]. The new layout, which has much tighter twist pitches in the subcables proved to have no degradation in SULTAN tests and was adopted for the CS. This new conductor was used for the CS Insert fabrication.

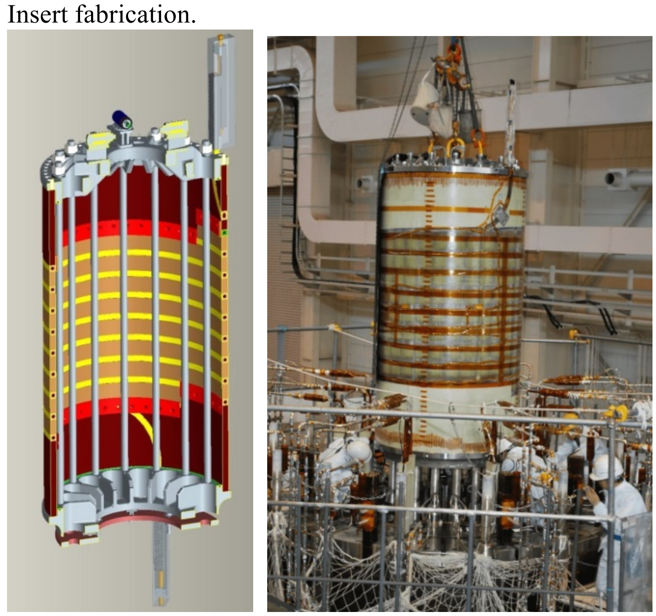

Fig. 1. CSI cross section (left) and installation of the CSI into the test facility (right)

Overall responsibility for the CS Insert (CSI) Project rests with US ITER. The CSI was designed by US ITER, built by Mitsubishi Electric Company under Japanese Domestic Agency supervision, and tested by the Japan Atomic Energy Agency Operating Group. An international Testing Group controlled the testing procedure and analyzed the test data.

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II. CS Insert Design

The CSI design is described in [4]. Figure 1 shows the CSI cross section and the CSI installation in the test facility. The CSI is a one-layer coil that contains 50 m of CS conductor, separated by G-10 spacers.

The CSI was heavily instrumented in order to monitor voltages, temperature distribution and strain conditions. The instrumentation shown in Figure 2 was also designed to make a close comparison with the SULTAN facility results.

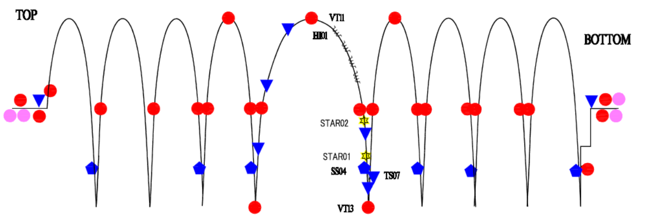

Fig. 2. CSI instrumentation map. VT – voltage taps, SG – strain gauges, T- thermometers and STAR voltage taps are shown.

III. Test Program

The test program was designed to cover the most interesting features in the CSI performance.

It measured all current sharing temperatures (Tcs) and a few critical current (Ic) at the several reference points of the CSI:

(a) Initial magnetization (IM) conditions (40 kA, 13 T peak field)
(b) End of Burn (EOB) conditions (45.1 kA, 12.6 T)
(c) SULTAN test point (45.1 kA, 11.5 T)
(d, e, f, g) 20, 30, 50, 60 kA, 13 T—lower than nominal and elevated current levels
(h, i, j) −30, −40 and −50 kA in 13 T—reverse charges that gave a more compressive load to the conductor

The cycling to 16,000 cycles took place before the elevated and reverse charges. Three warmups were performed after 5000, 8000, and 10000 cycles.

After the elevated current and reverse current charges, we conducted stability runs with the inductive heater. Then we studied propagation of the normal zone and heating of the conductor and the cable as a result of heat deposition during the normal zone propagation and quench. We also measured the Tcs performance of the CSMC that we always monitored in all four previous test campaigns in the CSMC test facility.

IV. CSMC Test Facility

The CSMC test facility was built in 1992–1996 [5] and has had several modifications since then. This facility has unprecedented flexibility in cryogenics, current, magnetic field, and instrumentation that give a unique capability for testing conductors in a wide field of parameter space.

V. CSI Test Results

A. Tcs measurements at the IM simulation

The significance of the IM point is that it is the lowest-temperature margin point over the whole ITER scenario. The Tcs measurements were conducted using two methods: (a) as in the CSI in 2000 [6] and (b) as in the SULTAN facility[1]. In method a, the voltage taps are about 1.16 m away from each other (quarter of the middle turn); and the temperature sensor is selected at the entrance to this region, T07—the sensor with the lowest noise and lowest temperature in the vicinity of the median plane. Method b uses a basis of 450 mm apart but has six sensors circumferentially installed around the conductor cross section to detect nonuniformity [1].

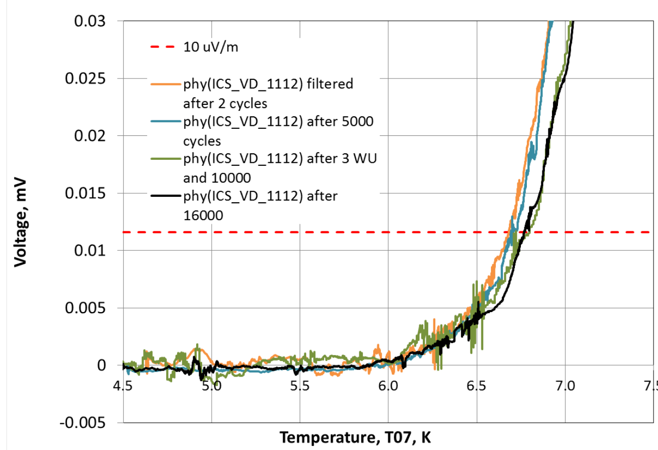

Fig. 2.Tcs for IM simulation, measured by method "a", see text.

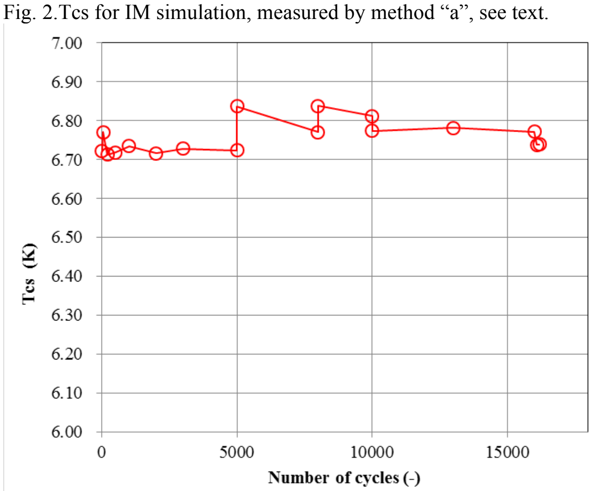

Fig. 3 Evolution of the Tcs for IM simulation defined by method "b".

Both methods gave very similar results, and no nonuniformity was detected, as expected, which gives additional credibility to the results. Figure 2 gives typical V-T transitions and Figure 3 gives the evolution of the Tcs with cycles. As can be seen, the change in Tcs is small and not degrading, which leads to a confident expectation that the CS conductor has sufficient resistance to cycling to fulfill the ITER mission of 30,000 plasma cycles.

B. Tcs measurements at SULTAN operating point

Verification of the SULTAN testing was essential. The CSI cost of construction and testing is more than 30 times of that for SULTAN samples and tests. SULTAN has a much shorter total length and a length in the field and has no hoop strain. During SULTAN testing the ITER community learned how to design the samples to reduce effects of the short length. It was very difficult to convincingly show experimentally that

SULTAN qualification is relevant without comparing these results with a conductor long-length experiment like the CSI. To eliminate uncertainty and validate qualification, it was important to prove that the SULTAN test reflects the real performance of the conductors but without the hoop strain, which had to be accounted for separately using measured strand sensitivity to strain. The theory predicted that the CSI Tcs under SULTAN conditions would be 0.5–0.6 K higher than in SULTAN as a result of the hoop strain of about 0.1%.

Figure 4 shows a comparison of the SULTAN and CSI Tcs results in 10.85 background field and at 45.1 kA current for both cases.

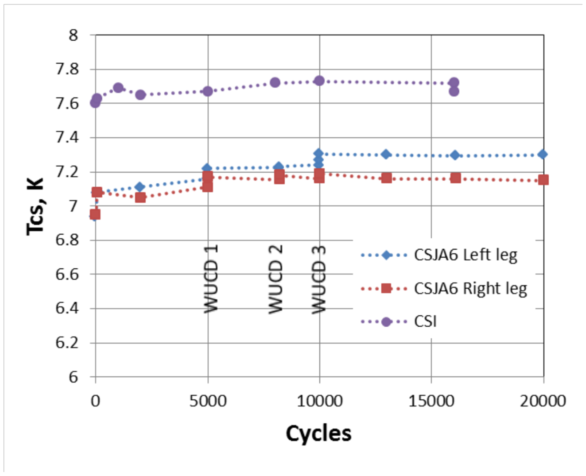

Fig. 4. Comparison of CSI performance in the SULTAN condition simulation. WUCD stands for warmup-cooldown cycle.

These results unambiguously proved the validity of the conductor qualifications in SULTAN facility.

C. Tcs measurements at EOB

Tests under EOB simulation conditions had a higher lateral force than at IM simulation conditions. There was a concern that, because of a large lateral force, the CS conductor behavior would be worse than expected compared with the measurements on the individual strand. We conducted the tests and saw that the EOB performance of the CS conductor was in line with expectations from the strand correlation. The Tcs at EOB varied within 6.80 K and 6.97 K, increasing after cycles and warmups as in the other Tcs cases.

D. Elevated current tests and reverse charge current tests

The elevated and reverse current tests were designed to extend the range of the hoop strain and see efficiency of the hoop strain to improve Tcs. These tests are strictly speaking outside the operating envelope of the ITER CS and therefore any of the change in performance after these tests should not indicate any problems for the CS. But this was a very unique opportunity to characterize the conductor performance versus strain. As we directly measure the hoop strain by the strain gauges installed on the jacket, we can compare the strain sensitivity of the individual strand and sensitivity of the strain in the jacket to change the Tcs of the conductor.

The strain in the middle of the coil, in the location where we measured the lowest Tcs, is shown in Figure 5. The Tcs points at +60 kA and -60 kA are extrapolated, all the rest are measured. All strain points are measured.

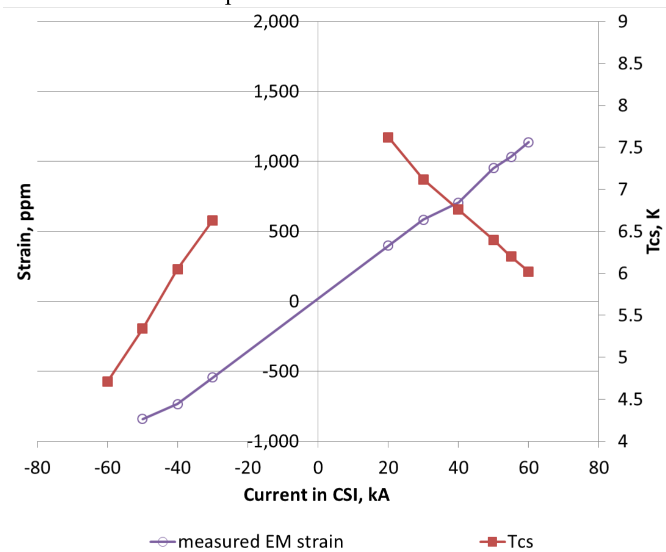

Fig. 5. Tcs and strain in CSI at 13 T peak field on the conductor.

The open circle symbols represent measured strain in the CSI, which is, of course, is the full EM strain.

This data are being processed in order to find how much strain in the jacket is translated into the effective strain in the cable? This is important information for future design evaluation, since Nb3Sn conductor is sensitive to the strain. Preliminary simplified analysis indicates that up to 90% strain in the jacket can be attributed to the cable strain. A thorough analysis will be performed and this indication will be checked in the future in order to find an effective way to describe effect of strain on the conductor properties.

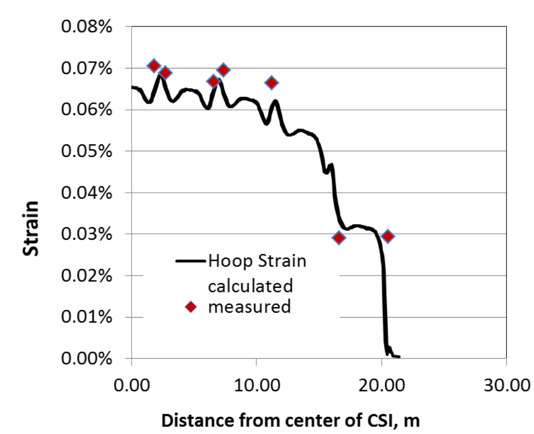

Fig. 6. Strain distribution prediction and measured after 16000 cycles at IM simulation

E. Strain in the CSI

Strain measurements in the magnets are always tricky since we rarely have access to the bare conductor. The strain gauges installed on insulation often give unreliable readings. In the CSI we had a rare opportunity to measure the strain directly on the conductor surface and in the aluminum tie rods that kept the coil in compression. Figure 6 presents the measured strain versus calculated in the CSI conductor, which shows a good agreement. The strain in the tie rods had a significant scatter, but the average value was well in agreement with the prediction.

F. AC losses

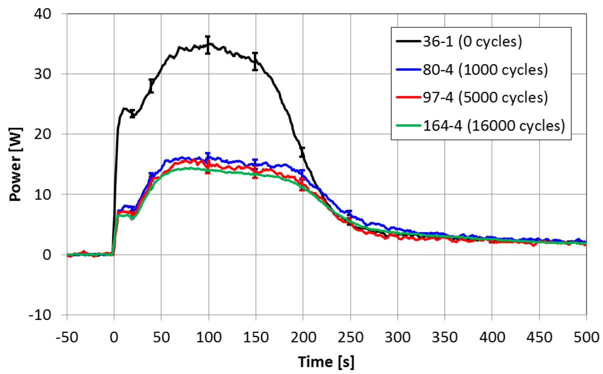

Fig. 7 AC loss during dump from 23 kA, no current in the CSI

The AC loss was measured in different pulse shapes. Figure 7 shows the results of the 23 kA dumps in the test campaign. The hysteresis loss (not shown) agrees with the strand data. The coupling current losses have a loss parameter *ntau* on the level of 100–120 ms after they stabilize after 1,000 cycles, which is several times higher than in the CSI tested in the year 2000 [6]. This may be explained by the tighter cable compaction of the CSI of 2015.

G. Stability measurements

An inductive heater was used to initiate a thermal disturbance on the conductor that would cause a quench. Calibration tests and interpretations are not yet finalized; but the preliminary estimates make it clear that the conductor quench energy is close to the available enthalpy of the conductor, including helium. That suggests that the CS conductor is very stable and has maximum available stability against pulsed disturbances.

H. Quench propagation studies and heating of the cable

The nominal protective discharge of the CS in the event of quench has 1.5 s of the detection time, 0.5 s of the commutation time to open the circuit breaker and an exponential discharge onto the dump resistor with 7.5 s time constant. The heat deposition in the conductor in adiabatic mode is equivalent to the 5.75 s of the normal zone growth at the constant current of 45.1 kA and then immediate discharge to zero current. Quench propagation and maximum heating temperatures were measured in CSI at 45 kA in 12.5T, where the current pulse was close to the constant current and then a very quick discharge. The jacket temperature was measured directly by the temperature sensors on the conductor and the cable temperature was measured by the resistance measurements of the conductor. We deduced the temperature of the cable from known dependence of copper resistance versus temperature. At the longest delay of 7s, a maximum temperature of 200K and 120K were achieved in the cable and the jacket respectively. The cable did not suffer from exceeding the hot spot requirement of 150K, as the Tcs measurements carried at the very end of the test campaign did not reveal any degradation. This additional margin may result in allowing a longer quench detection time, which has still to be quantified. If this 1 s could be added to the recognition of the quench, it would make the quench detection significantly easier and more reliable.

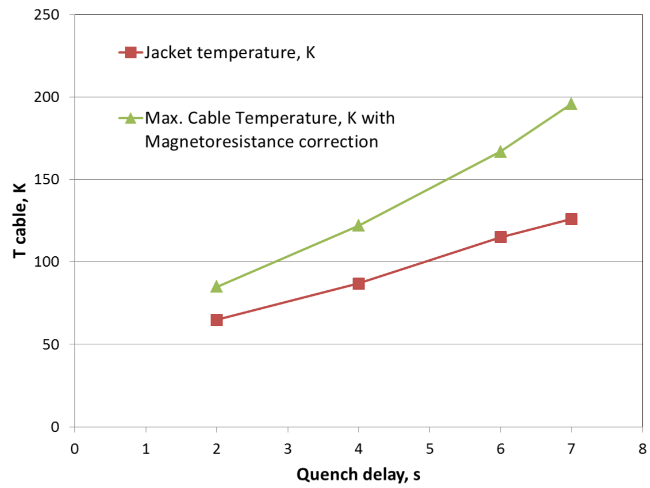

Fig.7 Heating of the cable and the jacket as a result of the quench propagation with delay

The velocity of quench propagation at 45 kA was measured to be 1.2-1.5 m/s, as expected.

VI. Conclusions

The CSI project ensured that the CS will meet the ITER mission requirements, provided very valuable information regarding CS conductor performance and protection, validated the SULTAN testing qualification for ITER, and verified the conductor design.

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