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ITER CS Model Coil and CS Insert Test Results

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***Abstract*—The Inner and Outer modules of the Central Solenoid Model Coil (CSMC) were built by US and Japanese home teams in collaboration with European and Russian teams to demonstrate the feasibility of a superconducting Central Solenoid for ITER and other large tokamak reactors. The CSMC mass is about 120 t, OD is about 3.6 m and the stored energy is 640 MJ at 46 kA and peak field of 13 T. Testing of the CSMC and the CS Insert took place at Japan Atomic Energy Research Institute (JAERI) from mid March until mid August 2000. This paper presents the main results of the tests performed.**

***Index Terms*— Critical current, losses, superconducting magnets, instability.**

I. INTRODUCTION

THE CSMC and three insert coils were among the main deliverables from the ITER Engineering Design Activity, which started in 1992.

The 180 t test assembly consists of Inner Module [1], Outer Module [2] and the CS Insert [3] and the supporting structure. This is the largest cable-in-conduit conductor (CICC) magnet ever built with 640 MJ stored energy at 46 kA. It operates at a higher current than any other large superconducting magnet.

The CSMC used a heavy wall conduit, made from Incoloy 908 superalloy, which helped to utilize the superconducting properties of Nb3Sn to the full extent.

The main objectives of the testing were validation of all ITER CSMC specifications, determination of the operational limits and verification of the design criteria for *superconducting magnets* for fusion.

The main goals of the test program were [4]:

1. Produce 13 T peak field in DC and a ramp mode of 0.4 T/s consistent with ITER CS operation with a peak current of 46 kA.
2. Demonstrate operation of the CS Insert in the reverse mode at –40 kA in 13 T
3. Demonstrate a margin of 2 K in a simulated ITER operational scenario.
4. Demonstrate that the CSMC can withstand high voltage discharge in a ITER relevant discharge mode, including 5-s detection time.
5. Demonstrate stable operation of leads and joints.
6. Study *losses*, ramp rate limitation, stability against thermal disturbances, quench propagation and thermohydraulic characteristics and sensitivity to the cyclic operation.

The CSMC and the CS Insert were installed in the CSMC Test Facility at JAERI [5] in October 1999. From April 11 to August 18, 2000 the CSMC and the CS Insert were under test with current. About 350 experimental runs were performed in these tests. More than 400 sensors were used to acquire data and the amount of information stored during the test campaign is huge. This paper presents some of the first post-test analysis results.

II. COOLDOWN AND THERMOHYDRAULICS

The cool down started on March 13 and the coils became superconducting on April 4 with the first charging of the coil on April 11.

This cool down time in general was in line with the prediction of 600 hours, limited by the tie rod temperature.

A typical flow distribution through the conductors in the CSMC is reasonably uniform as shown in Fig. 1.

The supercritical pump provided a very steady flow with total capacity in excess of 500 g/s. Most of the experiments were conducted with a flow distribution close to the one shown in Fig. 1, however, elevated temperature measurements sometimes required lower flow – down to 2 g/s in the conductors which were heated.

III. DC PERFORMANCE OF THE CSMC AND THE CS INSERT

A. CSMC

The DC tests were planned to reveal if the available technology is capable of producing a magnet, which would fully utilize the superconductor property in a very high field and stress environment.

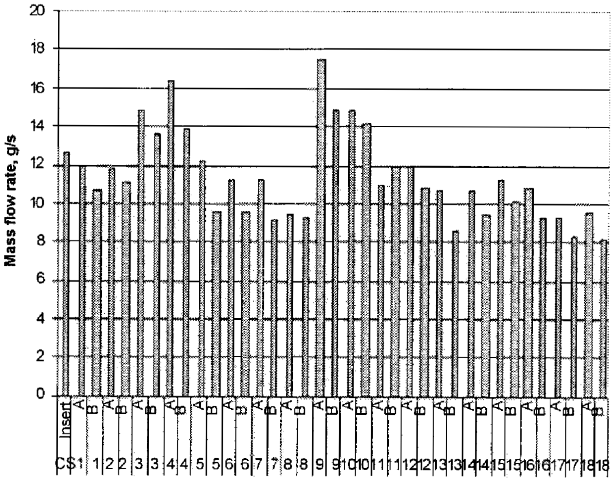

Fig. 1. Helium mass flow distribution in the CSMC and the CS Insert

The first charge to the full current of 46 kA took place on

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April 19 without training. Several charges to 46 kA at elevated temperature of 5.3 K were performed later to demonstrate that the magnet designed with 2 K margin is capable of reaching 100% of its rated current with no problem.

The current sharing temperature (T_{cs}) and the critical current measurements were carried out on the conductor 1a, 11a and the CS Insert.

1) Conductors 1a and 11a T_{cs}.

Current sharing temperature T_{cs} and *critical current* I_c measurements at DC conditions showed that the superconducting properties of layer 1, and of conductor 1a in particular, follow the ITER design guidance [6] based on L. Summers correlation [7]. Fig. 2 shows DC results measured on the layer 1. As seen from Fig.2, the current sharing measurement at constant current is consistent with the critical current measurement at a fixed temperature, which is evidence that the conductor properties reach its ultimate limit. The fitting parameters, describing the properties of the layer 1a are: jc= 593 A/mm^2 @4.2K, 12T, e=-0.25%, Tc0m=18K, Bc20m=28T).

These fitting parameters show that the CSMC conductor exceeds the specified strand current density at 12T and 4.2 K of 550 A/mm^2. The cable experienced a very low strain in the conductor resulting in high jc because of Incoloy 908 conduit and a proper design.

2) Layer 11a

Measurement results of layer 11a are summarized in Fig. 3. The critical current of layer 11a shows higher parameters than expected from the strand specifications or from the short sample data, which are higher than the specifications. Also, it was noted that the measured data do not fit well into a L. Summers correlation [7] within a reasonable range of parameters. It is possible, that since the conductor 11a has a mixture of two different strands (Hitachi and Furukawa), the behavior of the Tcs in a mixed cable is different than for a single strand cable. These facts are yet to be analyzed in more detail. Nevertheless, it seems clear that conductor 11a does not show any sign of degradation.

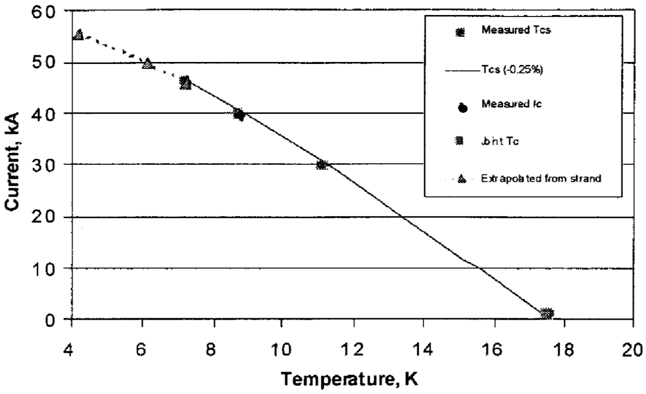

Fig. 2. Results of the DC tests on the layer 1 and a fitting curve [6].

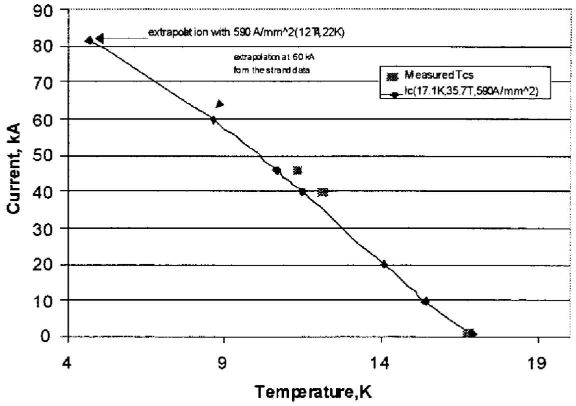

Fig. 3. Current sharing measurements on the conductor 11a

3) CS Insert

The T_{cs} and I_c were measured on the CS Insert in 13T by varying background field from the CSMC. The T_{cs} at 13T and 40kA, (nominal operation conditions of ITER-EDA) was 7.7K.

That satisfies the requirement of the temperature margin of 2K for the maximum operating temperature of 5.3K. The measurement results slightly exceed the ITER design guidance as shown in Fig. 4. However, j_c in a strand sample heat treated with the CS Insert was higher than 550A/mm2 of the ITER design guidance. Also, the strain in Nb3Sn strand is expected to be less than -0.25% assumed in Fig.4 due electro-magnetic force. Although these factors require more detailed analysis, it is clear that the CS Insert show small or no degradation as well.

IV. JOINTS

The joints in any high current magnet like the CSMC and the CS Insert are very important elements, which could have become the limiting factor in the CSMC overall performance. Two types of the 46 kA joints for the CSMC were developed and tested during an extensive R&D program [8,9]: a lap joint and a butt joint. The requirements to have a low resistance, low DC and AC *losses* and high reliability in a high field and high dB/dt environment made the joints quite complicated. Only a few cryogenic tests on prototypes were carried out to verify the joints performance in the R&D effort and some improvements were made. The production effort of the CSMC exceeded the R&D production by an order of magnitude and since during the R&D stage we had a few joints, which failed to meet the

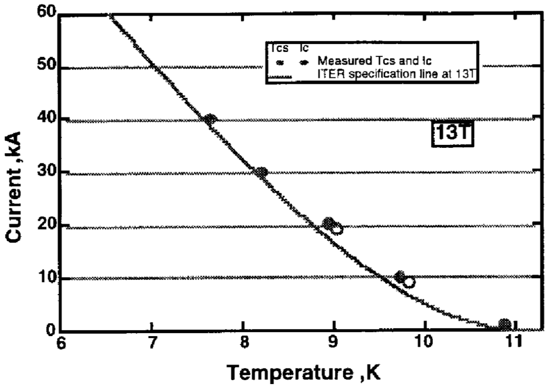

Fig. 4. Current sharing and critical current measurements on the CS Insert Coil.

specifications, there was a concern about possibility of a sub-standard joint in the test assembly. The CSMC testing was truly a verification test that provided very valuable data on the joint performance in the large magnet.

The R&D effort on the joints showed, that electrical measurements made across the joints indicated a significantly lower heat generation than the real heat generation in the joint measured by calorimetry. This was caused by the current distribution near the joint in the relatively short test samples. In the CSMC it was expected that the current distribution would be more favorable due to the longer distance between joints.

Fig. 5 shows resistance of the joints measured by two independent ways – by electrical and by calorimetric methods.

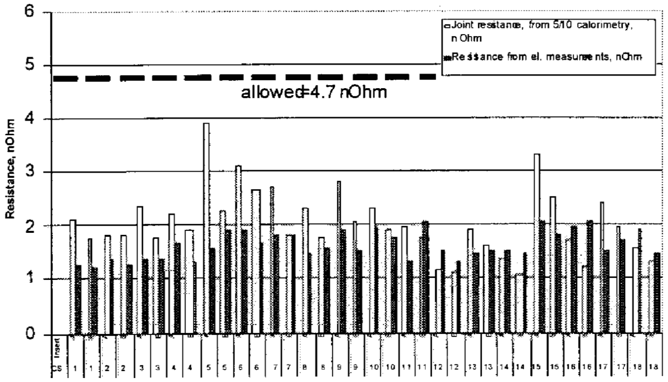

Fig. 5 Joint resistances in the CSMC and the CS Insert measured by electrical and calorimetry methods at 46 kA

It is seen that both joint designs (lap joints in layers 1-10 and butt joints in layers 11-18) provided resistances below the specifications in a quite reproducible manner. The two methods give very consistent and close results, much closer than in the short sample measurements during the R&D on the joints.

These results make the R&D effort on the joints a big success and show that the high current, low resistance, low loss joints can be built in an industrial environment reliably. In no test runs at 4.5 K, did the joints cause a quench or limit performance.

V. AC LOSSES

Loss measurements in the CSMC and the CS Insert were one of the most important elements of the Test Program. It was known from previous experiments that the short sample loss measurements do not always represent the *losses* in the magnet [10]. The scatter in the loss measurements on the short samples of relevant subscale and full-scale ITER conductors during the R&D effort was very significant. The coupling loss time constant varied from several milliseconds to 30-50 ms per unit of strand volume [11-13]. It also varied greatly depending on mechanical load on the conductor and number of test cycles. In a 1-m OD CIC NbSn magnet test it was noticed that the *losses* decreased significantly as a result of the charge cycles [14], the same results were observed in the conductor samples [15]. Looking for this effect, the *losses* in CSMC and the CS Insert were measured periodically starting from the first shots till the very end of the test campaign. Many interesting phenomena were observed during the AC loss measurements, here we are presenting only a few major results.

A. *Hysteresis losses.*

The hysteresis *losses* in the conductors were measured in very slow ramps (dI/dt=1 kA/min) and were in line with expectations from the strand data. The IGC strand, used in the layers 5-8, and the Mitsubishi strand in the layers 10, 15 and 16, which were made by the internal tin process, showed lower than expected hysteresis *losses*, which makes the internal tin strand a viable candidate for any layers, including the inner layers of the Central Solenoid for a future fusion machine.

B. *Coupling losses*

The coupling loss time constants for all conductors in the CSMC and the CS Inserts deduced from the 18 s discharge from 36.8 kA on June 26 are shown in Fig.6.

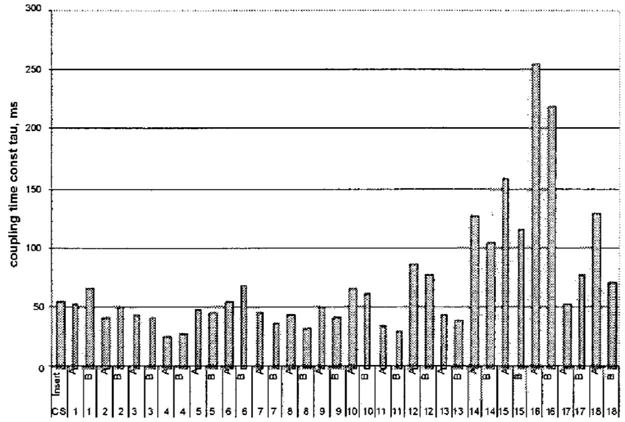

Fig. 6. Coupling time constant in the CSMC and CS Insert

The coupling *losses* in the CSMC showed several interesting features:

- Most of the conductors, except the CS Insert show significant and more or less monotonic reduction in *losses* (factor of 2 to 3 from the virgin state) with time and number of cycles.
- The coupling loss constant for Inner Module conductors is noticeably lower than for the Outer Module conductors, especially for the layers 14-16.

One of the possible explanations for the loss reduction is the electromagnetic load on the cable, which breaks the low resistance links between strands. Trying to find a quantitative correlation between number of cycles and the coupling *losses*, we introduced a term for the equivalent elapsed number of cycles Np. The Np equals to the summation of $(B_i/B_1)(I_p/46)^2$ values, , where (B_i/B_1) is the ratio between the average field in the layer "i"and in the layer 1, I_p[kA] is the peak current in each test run. So, for example, a charge to 23 kA would contribute in the first layer 0.25 to the Np, while full charge to 46 kA will contribute 1, respectively smaller in the outer layers. Fig. 7 shows a correlation for the Inner Module selected layers, all of which seem to follow the same pattern. The Outer Module conductors demonstrate similar seemingly universal features.

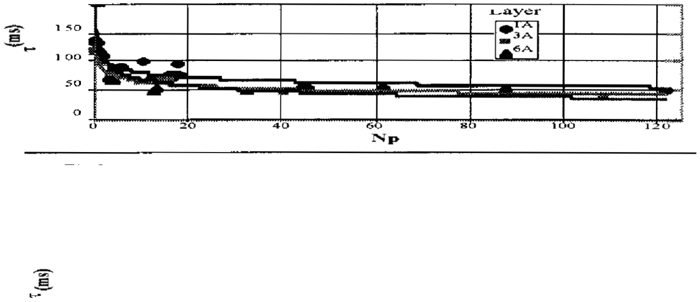

Fig.7. Reduction of the coupling loss with number of equivalent cycles (see text for details)

VI. RAMP RATE LIMITATION

The nominal ramp for the CSMC design was 0.4 T/s for a charge to 13 T. The pre-test analyses predicted that the maximum ramp rate, which the CSMC and the CS Insert would be able to withstand with no margin was 1.2 T/s.

The CS Insert withstood the 1.2 T/s ramp to 13 T, while CSMC conductor 1b quenched in that run at about 11.8 T due to slightly higher and less uniform *losses* than in the CS Insert. This is very close to the pre-test analysis prediction.

The CSMC was successfully charged to 38 kA at 1.9 T/s and CS Insert had to be warmed to 6.5 K to quench it at 40 kA and 1.9 T/s ramp. To establish if quench in the CSMC at high dB/dt results from instability or from simple heating due to *losses*, we tried to calculate the maximum temperature in the conductor at the moment of the quench. We used no-quench runs and the outlet/inlet data for the analysis. Fig. 8 shows the result of this analysis, which shows that the *losses* and corresponding heating are mostly responsible for the quench and electromagnetic *instability* and non-uniform current distribution in the conductor play a small role up to 0.6 T/s, although the deviation from the DC performance starts to grow at higher dB/dt rates. These results and many other successful runs simulating the ITER operation scenarios, including plasma initiation, disruptions and much more severe conditions showed that the CSMC had relatively low ramp rate sensitivity up to 2 T/s.

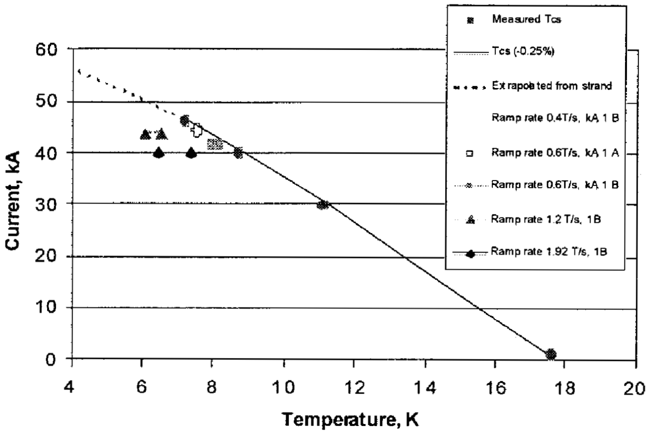

Fig.8 Peak temperature prior to quenches in the pulses versus DC current sharing temperature Tcs

VII. CONCLUSIONS

All of the main goals of the Test Program were achieved. Performance of the CSMC and CS Insert demonstrated that:

1. Large scale, high field magnets can be designed, built and operated with little or no degradation of superconducting properties
2. High performance of the magnet fully justified the additional R&D and fabrication effort spent on the Incoloy 908 jacket used in the CSMC and in the CS Insert.
3. The CSMC R&D and fabrication effort developed the technology to build large fusion magnets with predictable properties for operation in demanding conditions

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REFERENCES

[1] R.J. Jayakumar, J.V. Minervini, J. Wohlwend, N. Martovetsky, R. Thome, "The USHT-ITER CS Model Coil Program Achievements", *IEEE Trans. Appl. Superconductivity*, vol. 10, No 1, pp.560-563, March 2000.

[2] T. Ando, T. Hiyama, Y. Takahashi, et .al, "Completion of the ITER CS Model Coil –Outer Module Fabrication", *ibid*, pp. 568-571.

[3] M. Sugimoto, T.Isono, Y.Nunoya et al, "Completion of CS Insert Fabrication", *ibid*, pp. 564-567

[4] "Test Description Document for ITER Central Solenoid Model Coil", ITER Document, Rev. 3.2, June 1998.

[5] S. Shimamoto, K. Hamada, T. Kato, et al, "Construction of ITER Common Test Facility for CS Model Coil, *IEEE Trans. Mag.*, vol. 32, No. 4, p 3049, July 1996

[6] N. Mitchell et al, "Design Criteria:DDD1.1-1.3 Appendix C: Superconducting Magnet Design Criteria," *ITER N11 DDD 32 97-12-08 W 02, Dec 8, 1997.*

[7] L.T. Summers, M.W. Guinan, J.R. Miller, P.A. Hahn, "A Model for the Prediction of Nb3Sn Critical Current as a Function of Field Temperature, Strain, and Radiation Damage," *IEEE Trans. MAG –27*, No. 2, p.2041, (1991)

[8] N. Martovetsky, J. Jayakumar, R. Manahan, P. Michael et al, "Development and Test of the ITER Conductor Joints for the central solenoid", Presented at the *Annual American Nuclear Society meeting*, Nashville, June 1998

[9] Y. Takahashi, Y. Nunoya, G. Nishijima et al, "Development of 46-kA Nb3Sn Conductor Joint for ITER Model Coils", *IEEE Trans. Appl. Superconductivity*, vol. 10, No 1, pp.580-583, March 2000.

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[10] Takataro Hamajima, Satoshi Hanai, Yoshihiro Wachi, Nicolai Martovetsky et al "Test results of the 100 kWh SMES model coil - AC loss performance," *Cryogenics* 39 (11) (1999) pp. 947-953.

[11] D. Ciazynski, B. Turck, J.L. Duchateau, C. Meuris, "Current Distribution in 40kA NbTi and Nb3Sn Conductors for NET/ITER", *IEEE Trans. Mag.*, vol. 27, No. 2, pp 2194, March 1991

[12] P. Bruzzone, A.M. Fuchs, G. Vecsey, E.Zapretilina, 'Test results for the high field conductor of the ITER Central Solenoid Model Coil" *Presented at CEC conference,* Montreal, July 13-16, 1999.

[13] Y. Takahashi, "Results of the CS conductor JAERI tests", *private communication*

[14] [4] E.P. Balsamo, D.Ciazynski, O.Cicchelli et al, "Direct measurement of the AC loss of an ITER relevant coil", *Physica C* 310 (1998) p.258-261

[15] A. Nijhuis, N.H.W. Noordman, H.H.J. ten Kate et al., "Electromagnetic and Mechanical Characterization of ITER CS-MC Conductors affected by Transverse Cyclic Loading, Part 1: Interstrand Coupling Losses", *IEEE Trans. Appl. Superconductivity*, vol. 9, No 2, pp.1069-1072, June 1999.

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