Progress of the ITER central solenoid model coil programme

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Abstract. The world's largest pulsed superconducting coil was successfully tested by charging up to 13 T and 46 kA with a stored energy of 640 MJ. The ITER central solenoid (CS) model coil and CS insert coil were developed and fabricated through an international collaboration, and their cooldown and charging tests were successfully carried out by international test and operation teams. In pulsed charging tests, where the original goal was 0.4 T/s up to 13 T, the CS model coil and the CS insert coil achieved ramp rates to 13 T of 0.6 T/s and 1.2 T/s, respectively. In addition, the CS insert coil was charged and discharged 10 003 times in the 13 T background field of the CS model coil and no degradation of the operational temperature margin directly coming from this cyclic operation was observed. These test results fulfilled all the goals of CS model coil development by confirming the validity of the engineering design and demonstrating that the ITER coils can now be constructed with confidence.

1. Introduction

In the ITER central solenoid (CS) model coil programme, the CS model coil and the CS insert coil have been developed so as to confirm the validity of the engineering design of the ITER Nb_3Sn CS coil and to develop technologies to fabricate the ITER CS coil. This international collaboration began in 1992. The CS model coil is composed of an inner module and an outer module, as shown in Fig. 1. A CS insert

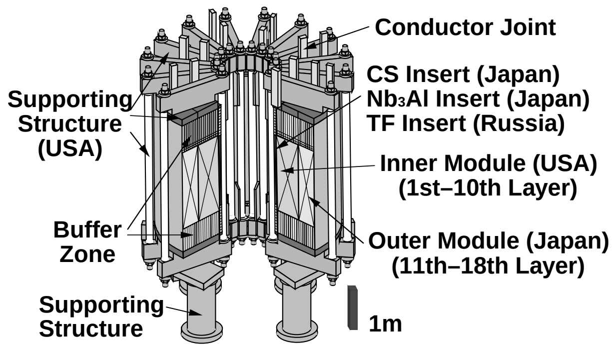

Figure 1. CS model coil and insert coils.

coil is placed in the inner bore of the CS model coil. Also indicated in Fig. 1 are two other insert coils, the Nb_3Sn toroidal field (TF) insert coil and the Nb_3Al insert coil, which can also be placed for testing in the inner bore of the CS model coil.

The purpose of the latter two insert coils is to measure the superconducting performance of the conductors developed for the ITER TF coil under the 12 T background field of the CS model coil. The Nb_3Sn TF insert coil and the Nb_3Al insert coil are now being fabricated by the Russian Home Team and the Japanese Home Team of the ITER project, respectively.

Table 1 shows the designed performance of the CS model coil and CS insert coil together with the required performance of the ITER CS coil. The essential feature of the ITER CS coil is to be operated in pulsed mode so as to induce and control a plasma current of about 15 MA. Therefore the target performance of the CS model coil and CS insert coil as pulsed coils was selected as a charging ramp rate of +0.4 T/s up to 13 T and a discharging ramp rate of −1.2 T/s from 13 T. The pulsed field losses generated during pulsed operation make this a difficult design point not previously demonstrated on this scale in superconducting magnet technology. The largest pulsed coil before the CS model coil programme operated at up to 7 T with a stored energy of 30 MJ.

2. Development and fabrication of the CS model coil and CS insert coil

The first step of this challenge to superconducting magnet technology was initiated by the development of Nb_3Sn strands with a high critical current density at 13 T and with a low pulsed field loss. For the strand to be used in the conductor wound in the high field layers, the development target was to realize a critical current density of higher than 550 A/mm^2 at the reference field of 12 T and a pulsed loss of less than 200 mJ/cm^3 for a bipolar magnetic field swing between +3 T and −3 T. Before the start of this development, the fabrication of a Nb_3Sn strand with a critical current density of higher than 550 A/mm^2 was possible; however, the pulsed loss due to superconducting hysteresis loss was typically much greater than 200 mJ/cm^3. The development of this advanced strand was carried out by reducing the diameter of the Nb_3Sn filaments to below 4 μm, taking special care to reduce the electromagnetic coupling between filaments. Figure 2 shows one of the successfully developed strands containing, in a core with a diameter of 0.51 mm, 8037 Nb_3Sn filaments each with a diameter of 2.7 μm. The superconducting core was separated by a Ta barrier so that the resistivity of the Cu stabilizer would not be increased by the diffusion of Sn. Before the cabling of 1152 strands, each strand

Table 1. Major parameters of the coil modules compared with those of the ITER CS coil

	ITER CS		CS insert	CS model coil inner module	CS model coil outer module
Maximum field (T)	12.8	13.5	13	13	7.3
Operating current (kA)	45	40.5	40	46	46
Outer diameter (m)	4.15		1.57	2.71	3.62
Height (m)	2 (6 modules)		2.80	2.80	2.80
Weight (t)	840[a]		7.7	49.3	52
Stored energy (MJ)	6000		11	640	

[a] Including support structure.

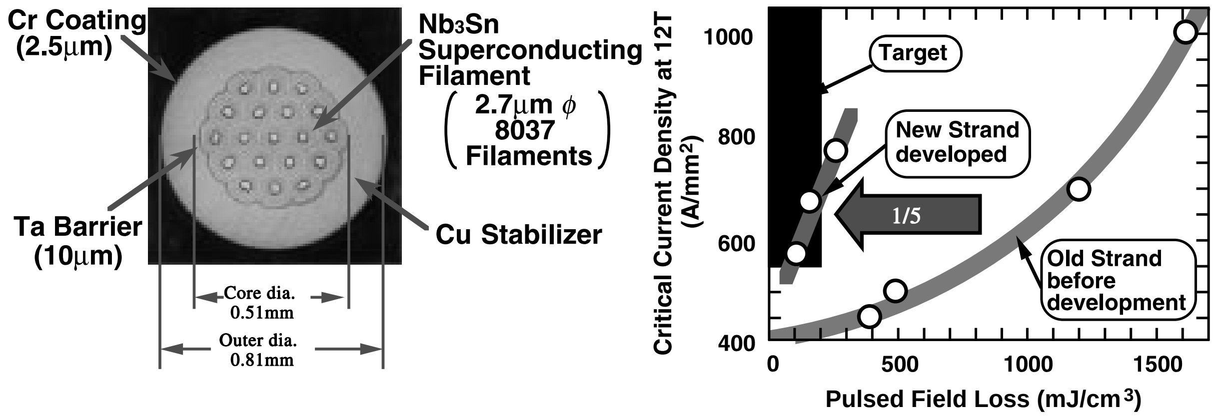

Figure 2. Nb_3Sn strand developed for the CS coil and its improvement in pulsed field loss.

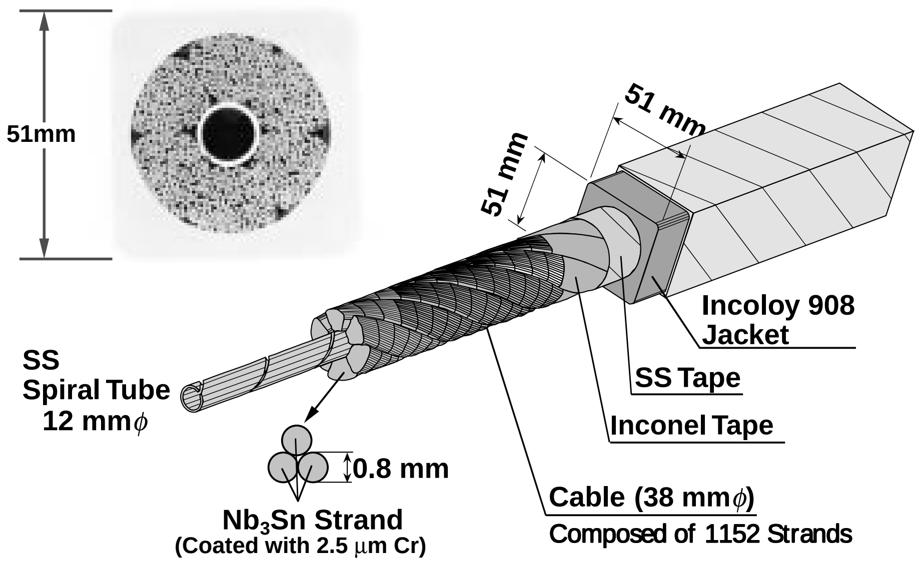

Figure 3. Configuration and cross-section of the conductor developed for the CS coil.

was coated with 2.5 μm of Cr to increase the contact resistance between strands. In addition, each subcable with 192 strands was wrapped in inconel tape. By increasing the resistivity between strands or between subcables, as shown in Fig. 3, the pulsed loss due to coupling current under a pulsed field was successfully reduced. The cable of 1152 Nb_3Sn strands is protected by a thick jacket of Incoloy 908, which has a similar thermal expansion rate and ensures the minimum strain between the activation temperature of 923 K to produce Nb_3Sn and the operation temperature of 4.5 K. Incoloy 908 has a potential problem of cracking due to stress accelerated grain boundary oxidization during activation heat treatment; however, the technology to avoid this critical problem was established. The CS conductor jacketed by the European Home Team was shipped to the USA for fabrication of the CS model coil inner module and to Japan for fabrication of the CS model coil outer module and the CS insert coil. These three coil modules were successfully fabricated by the end of 1999 [1–3]. The installation and assembly of these coils took place at the Naka Fusion Research Establishment of JAERI, as shown in Figs 4–6, through the collaboration of the Japanese Home Team and the US Home Team. Five months were required to prepare this system, which has a cryogenic weight of 180 t, for testing. The weight includes supporting

Figure 4. CS model coil inner module.

Figure 5. CS model coil outer module.

structures to give a compressive preloading of 9000 t to the coils.

3. Test of the CS model coil and CS insert coil

The purposes of the test of the CS model coil and CS insert coil were to:

(a) Demonstrate a reliable cooldown to 4 K in 480 h without any damage to insulators;
(b) Confirm the DC performance of the CS model coil by charging up to 13 T, 46 kA with a stored energy of 640 MJ, and of the CS insert coil by charging up to 13 T, 40 kA;
(c) Achieve pulsed charging performance by a ramp rate of +0.4 T/s to 13 T and discharging performance by a ramp rate of −1.2 T/s from 13 T for both coils;
(d) Measure the operational temperature margin for both coils;
(e) Perform and demonstrate a cyclic charging of the CS insert coil for 10 000 cycles.

Figure 6. Installation of the CS insert coil into the inner bore of the CS model coil.

3.1. Initial cooldown

Initial cooldown of the CS model coil and the CS insert coil was started in March 2000 by keeping the

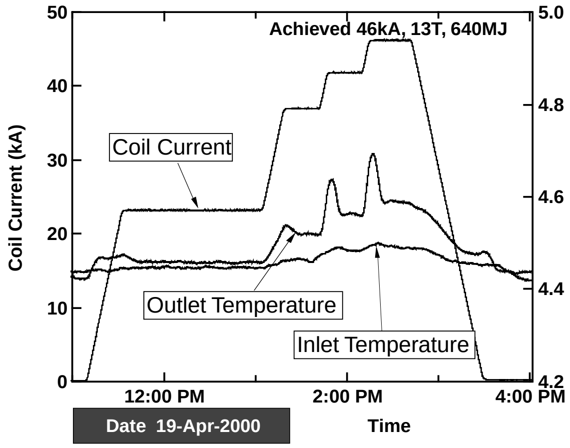

Figure 7. First DC charging of the CS model coil up to 46 kA, 13 T.

temperature difference between outlet helium and inlet helium within 50 K. A typical distribution of helium mass flow rate was 50 g/s to the inner module, 50 g/s to the outer module, 15 g/s to the CS insert coil, 50 g/s to the supporting structures as shown in Fig. 1, and 15 g/s to the 4 K base structure, for a total flow rate of 180 g/s. The cooldown time was about 500 h and was mainly determined by the cooldown rate of the supporting structures. All the coil modules showed a clear superconducting transition at 17.5 K. No degradation of the electrical insulation of the coils was found. Finally the coil system was connected to a 4 K supercritical helium circulation pump with a capacity of 800 g/s and the coils were ready for a charging test. The steady state heat load including this helium pump was about 960 W at 4.5 K.

3.2. DC charging tests

The DC charging tests of the CS model coil were started in April 2000 by using a 50 kA DC power supply and a circuit breaker for coil protection with a capacity of 50 kA, 10 kV connected to a 1 GJ dump resistor. Quench detection was set at a normal voltage in each layer if a voltage higher than 100 mV continued for more than 1 s. The first charging to 13 T of the CS model coil was carried out with a helium mass flow rate of about 10 g/s for each conductor. As shown in Fig. 7, the coil current was increased stepwise in 3 h and the CS model coil finally reached the goal of 13 T, 46 kA with a stored energy of 640 MJ without any quench in the first trial. In this first charging to 100% current, 37 voltage signs of conductor movements in the innermost layer were observed during the current ramp-up from 90% to 100%. The number of signs under the same condition drastically decreased in the second charging to 100% down to 3 and to zero at the third charging. This means that the microscopic movement of the conductor was completed in the initial two chargings to 100% current and the coil found its mechanically stable structure. The same tendency was observed from the number of major acoustic emissions from the CS model coil, where the number of counts in the first charging to 100% current was 951, which decreased to 416 in the second charging and stayed at around 230 from the fourth charging. The first charging of the CS insert coil up to 13 T and 40 kA under the background field of the CS model coil was also successfully achieved in June 2000 without any quench during the first trial.

The detailed superconducting performance of the coil can be measured by the current sharing temperature (T_{cs}) when the critical current at 13 T is equal to the operating current, 40 kA in the case of the CS insert coil, for example. Figure 8 shows how we measured T_{cs}. We kept the maximum field of 13 T and the operating current of the CS insert coil at 40 kA under the background field of the CS model coil. Then we increased the temperature of the helium flowing into the CS model coil by a resistive heater and measured the normal voltage generated between the terminals of the coil, as shown in Fig. 8. The current sharing temperature is defined when a normal voltage of 0.1 μV/cm of conductor length is generated. The length between the voltage taps attached to the location where a magnetic field of 13 T is generated is 110 cm. In the case shown in Fig. 8, the normal voltage crossed this criterion of 11 μV when the conductor temperature at the same place reached 7.46 K as measured by a high voltage temperature sensor attached to the conductor. The operational margin measured by the CS insert coil at 13 T and 40 kA before the 10^4 cyclic tests was 7.65 K, which corresponds to a temperature margin of 2.3 K compared with the designed operation temperature of 5.3 K. This measured value is sufficiently higher than the temperature margin of 2 K for the original ITER magnet design or of 1 K for the ITER-FEAT magnet design.

3.3. Pulsed charging tests

Pulsed charging tests using the high power supplies of the JAERI tokamak JT-60 were initiated in May 2000. The CS model coil achieved 0.6 T/s up to 13 T and the CS insert coil achieved a swift pulsed

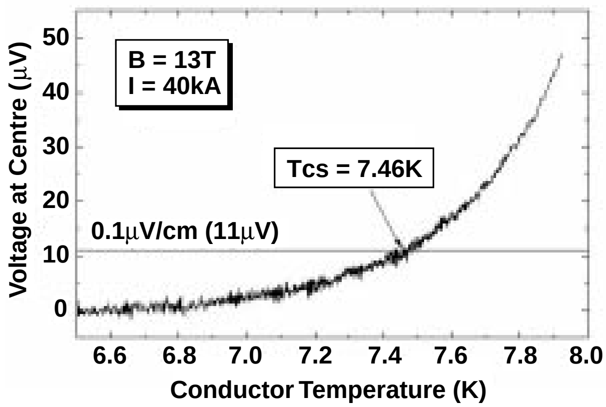

Figure 8. Measurement of the current sharing temperature of the CS insert coil.

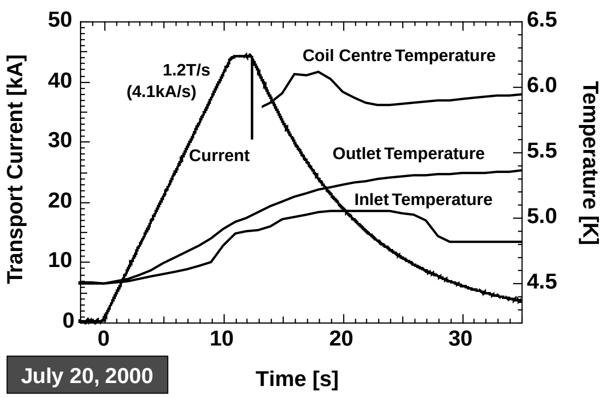

Figure 9. Pulsed charging of the CS insert coil with a ramp rate of 1.2 T/s up to 13 T.

charging of 1.2 T/s up to 13 T without any quench, as shown in Fig. 9. In this swift charging case, the temperature of the conductor at the 13 T location increased to 6.7 K because of pulsed losses. On the basis of the measurement of T_{cs} of the CS insert coil, it was expected that the superconducting state would be maintained up to 7.4 K; therefore the CS insert coil retained its superconducting stability during this 1.2 T/s swift charging.

To evaluate the pulsed loss performance due to coupling current, a coupling loss time constant is usually calculated. The lower the coupling loss time constant, the lower the pulsed loss we can expect in the coil for charging with a high ramp rate. The original design value for the CS conductor was 100 ms. This coupling loss time constant was measured by trapezoidal chargings of the CS insert coil up to 20 kA and for a ramp rate of from 0.2 to 2.0 T/s. A preliminary value of the coupling loss time constant of the CS insert coil was determined to be 115 ± 25 ms.

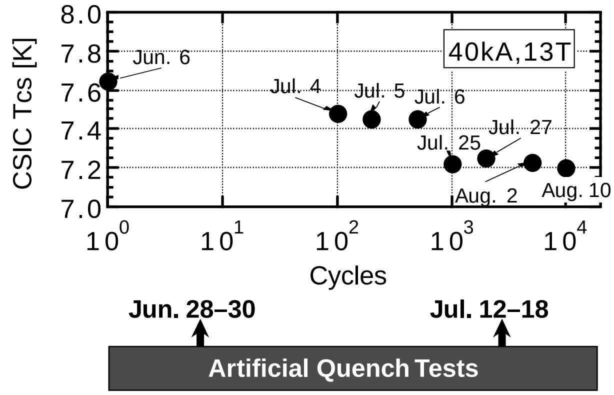

Figure 10. Variation of the current sharing temperature of the CS insert coil.

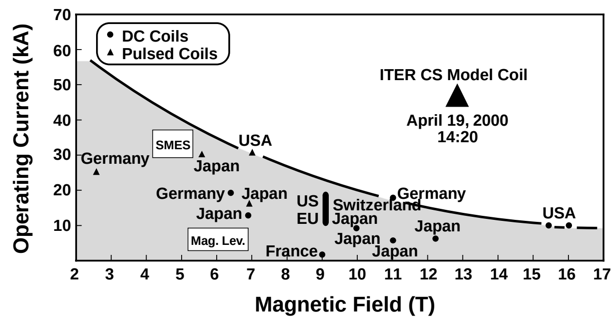

Figure 11. Achieved technology of the ITER CS model coil compared with the previously achieved technology.

With the help of a good operation temperature margin, the CS model coil and the CS insert coil could achieve a ramp rate to 13 T of 0.6 T/s and 1.2 T/s, respectively, without any quench. These values are 1.5 and 3 times higher than the development goal for these coils.

3.4. 10 000 cycle charging test

Under the background field of the CS model coil, charging and discharging between 0 kA, 13 T and 40 kA, 13 T of the CS insert coil were repeated 10 003 times. In this test, we simulated the cyclic operation required for the ITER CS coil. The current sharing temperature as described in Section 3.2 was measured at 13 T and 40 kA before and after 100, 200, 500, 1000, 2000, 5000 and 10 000 cycles. Figure 10 shows the variation of T_{cs} from 7.65 K down to 7.20 K at the end of these tests. This result shows no major degradation of T_{cs} during 100 and 500 cycles, and during 1000 to 10 000 cycles. Test records show that we have carried out artificial quenches of the CS insert coil by using heaters at the points where two drops of T_{cs} are observed in Fig. 10. In these artificial quench tests, the temperature of the conductor measured at its jacket indicated increases of up to around 65 K, suggesting that a much higher temperature might appear in the Nb_3Sn filaments. Therefore the decrease of T_{cs} from 7.65 to 7.20 K, as shown in Fig. 10, is considered to occur owing to the artificial quench tests carried out to measure the quench propagation performance of the coil and not because of cycling under usual conditions.

4. Conclusion

The world's largest pulsed superconducting coil, as shown in Fig. 11, was successfully developed, fabricated and tested. We are now ready to construct the ITER CS coil with confidence.

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