ELSEVIER

Fusion Engineering and Design 56–57 (2001) 59–70

Fusion Engineering and Design

www.elsevier.com/locate/fusengdes

First test results for the ITER central solenoid model coil

T. Kato [a,*], H. Tsuji [a], T. Ando [a], Y. Takahashi [a], H. Nakajima [a], M. Sugimoto [a], T. Isono [a], N. Koizumi [a], K. Kawano [a], M. Oshikiri [a], K. Hamada [a], Y. Nunoya [a], K. Matsui [a], T. Shinba [a], Y. Tsuchiya [a], G. Nishijima [a], H. Kubo [a], E. Hara [a], H. Hanawa [a], K. Imahashi [a], K. Ootsu [a], Y. Uno [a], T. Oouchi [a], J. Okayama [a], T. Kawasaki [a], M. Kawabe [a], S. Seki [a], K. Takano [a], Y. Takaya [a], F. Tajiri [a], A. Tsutsumi [a], T. Nakanura [a], H. Hanawa [a], H. Wakabayashi [a], K. Nishii [a], N. Hosogane [a], M. Matsukawa [a], Y. Miura [a], T. Terakado [a], J. Okano [a], K. Shimada [a], M. Yamashita [a], K. Arai [b], T. Ishigouoka [c], A. Ninomiya [c], K. Okuno [d], D. Bessete [d], H. Takigami [d], N. Martovetsky [e], P. Michael [f], M. Takayasu [f], M. Ricci [g], R. Zanino [h], L. Savoldi [h], G. Zahn [i], A. Martinez [j], R. Maix [k]

[a] *Naka Fusion Research Establishment, JAERI, 801-1, Mukouyama, Naka-machi, Naka-gun, Ibaraki, 311-0193, Japan*
[b] *Electrotechnical Laboratory, 1-1-4, Umezono, Tsukuba-shi, Ibaraki, 305-8568, Japan*
[c] *Seikei University, 3-3-1, Kichijyouji-kita, Musashino-shi, Tokyo, 180-8633, Japan*
[d] *ITER Naka JCT, 801-1, Mukouyama, Naka-machi, Naka-gun, Ibaraki-ken, 311-0193, Japan*
[e] *LLNL, L-641, 7000 East Ave., Livermore, CA 94550, USA*
[f] *MIT PSFC, 185 Albany Street, NW 22-129, Cambridge, MA 02139, USA*
[g] *Association Euratom–ENEA C.R. Frascati, C.P. 65, 00044 Frascati, Italy*
[h] *Politecnico, 24, corso Duca degli Abruzzi, 10129 Turin, Italy*
[i] *Accosiation Euratom-FZK, Forschungszentrum, D-76344 Karlsruhe, Germany*
[j] *Accosiation Euratom-CEA/Cadarache, F-13108 Saint Paul Lez Durance, France*
[k] *EFDA-CSU Garching, MPI, Boltzmannstr. 2, D-85748 Garching, Germany*

Abstract

The largest pulsed superconducting coils ever built, the Central Solenoid (CS) Model Coil and Central Solenoid Insert Coil were successfully developed and tested by international collaboration under the R&D activity of the International Thermonuclear Experimental Reactor (ITER), demonstrating and validating the engineering design criteria of the ITER Central Solenoid coil. The typical achievement is to charge the coil up to the operation current of 46 kA, and the maximum magnetic field to 13 T with a swift rump rate of 0.6 T/s without quench. The typical stored energy of the coil reached during the tests was 640 MJ that is 21 times larger than any other superconducting pulsed coils ever built. The test have shown that the high current cable in conduit conductor technology is indeed

* Corresponding author. Tel.: +81-29-270-7544; fax: +81-29-270-7579.
E-mail address: kato@naka.jaeri.go.jp (T. Kato).

PII: S0920-3796(01)00235-6

applicable to the ITER coils and could accomplish all the requirements of current sharing temperature, AC losses, ramp rate limitation, quench behavior and 10 000-cycle operation.

Keywords: Superconducting coils; ITER; Central Solenoid coil

1. Introduction

The ITER Central Solenoid (CS) Model Coil Program [1] has been carried out since 1992 as one of the largest R&D programs in the ITER Engineering Design Activity in an international collaboration among the ITER Joint Central Team (JCT), EU, Japan, Russia and US. In the program, the CS Model Coil (CSMC) and the CS Insert have been developed and tested in order to verify the magnet technology that will allow the ITER magnets to be built with confidence. It is expected to provide the validation of design and analysis tools, the demonstration of industrial manufacturing methods, the performance of each component integrated in the magnet and the demonstration of reliable operation.

Fabrication of the CSMC and CS Insert adopted a commingle-fabrication task sharing; all participants shared the fabrication of the Nb_3Sn cable-in-conduit superconducting cables (24.6 tons). The US provided Incoloy 908 [2] as a conductor jacket material. The EU assembled the cables and the jacket into the conductors. The US assembled the CSMC Inner Module (10 layers) [3], and Japan assembled the Outer Module (eight layers) [4] and the CS Insert (one layer) [5]. Their configuration and major parameters are shown in Fig. 1 and Table 1, respectively. The CSMC is the largest pulsed superconducting magnet ever built

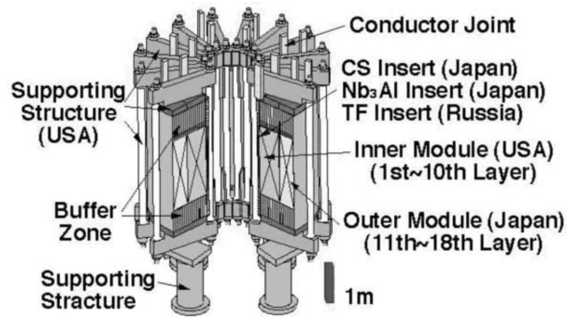

Fig. 1. Configuration of the CS Model Coil and the CS Insert.

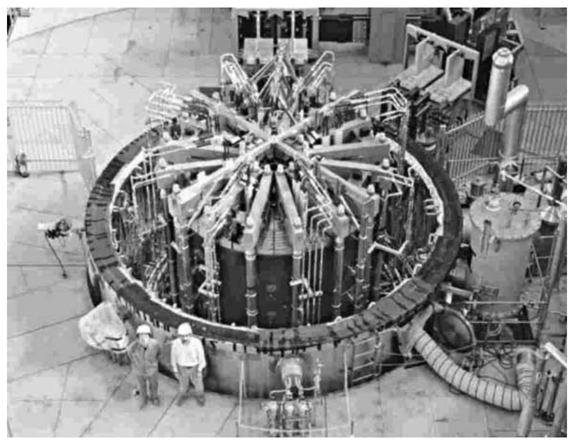

Fig. 2. CS Model Coil and CS Insert after completion of installation.

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

	ITER-CS		CS Insert	CSMC inner module	CSMC outer module
Maximum field (T)	12.8	13.5	13	13	
Operating current (kA)	45	40.5	40	46	46
Outer diameter (m)	4.15		1.57	2.71	3.62
Height (m)	2.0×6		1.80[a]	1.80[a]	1.80[a]
Weight (t)	840		7.7	49.3	52
Stored energy (MJ)	6000		11	640	

[a] Conductor winding pack only.

with a stored energy of 640 MJ, at the operational current of 46 kA. Japan assembled these coil components coaxially as the CSMC and CS Insert in around 5 months within a 6.5-m diameter and 9.5-m high vacuum tank, as shown in Fig. 2, at the CSMC Test Facility [6] located at the Japan Atomic Energy Research Institute, Naka.

The cooldown of the coil system (total cold mass of 180 tons) was initiated by the end of November 1999 but a cold leak was detected at a coil temperature of around 20 K after around 500 h. Then the cooldown was cancelled, followed by warming up the coil. After the leak was repaired, the cooldown was resumed on March 13, 2000. The electric performance test was started in April and was successfully completed on August 18, followed by the coil warm-up which was finished by the end of August. The test implemented a total of about 350 charging runs and around 400 sensors continuously monitored the coil performance by the computer data acquisition system, accumulating a huge amount of test data. The cryogenic system also provided a stable 4-K condition through the test campaign without any problems. This paper introduces the test program, typical achieved operation, and the results of preliminary analysis.

2. Test program

The test program, the first mission of the CSMC and CS Insert electrical experiment, consists of the following three categories: DC test operation, AC test operation, and cyclic test for the CS Insert up to 10 000 cycles. The major test items in each category are listed in Table 2.

The coil operating current pattern depends on the power supply capacity. A DC power supply system consisting of one 50 kA/15 V and two 30 kA/12 V power supplies was used for the DC test operation and the cyclic test. A ramp-up and -down rate of 1 kA/min (16.7 A/s) was chosen for the CSMC based on the coil inductance. In the case of the CS Insert, 5 kA/min (83.3 A/s) was selected when the CSMC maintained the back-up field of 12.5 T but 5 to 6.5 kA/s was used for the cyclic test when the CSMC was operated in persistent mode with 44.5 kA. The AC test operation used the JT-60 power supply system [7], which has two kinds of power supply, namely, F-power supply (45 kA–1.5 kV with available operation time of 70 s) and V-power supply (50 kA–4.5 kV with 15 s). The F-power supply provided the rated pulse operation such as the ramp-up to 46 kA (13 T for the CSMC) at the ramp rate of 0.4 T/s, flat top of 5 s, followed by the ramp-down to zero at 0.7 T/s. The V-power supply has high current and voltage capacity but a short operation time of 15 s and was used for the operation pattern such as higher ramp-up rate operation from 1 to 2 T/s, flat top 1 s, followed by the fast discharge with the coil dump. Accordingly, the ramp-up rate was

Table 2
Concretely implemented test items

Test item	Brief outline
DC test operation	
(1) 13-T demonstration	Demonstration and verification to produce 13-T peak field with 46 kA
(2) 13-T with 2-K margin	Demonstration of 13-T operation with temperature margin of 2 K
(3) Shearing temperature	To measure shearing temperature (T_{cs}) for 1st layer, 11th layer and CS Insert
(4) AC losses	To measure AC losses by manual dump, changing the dump time constant
(5) Joint performance	Evaluation of the 40 conductor joints, measuring their resistances
(6) Stability and quench	To observe stability and quench behavior, induced by intentional disturbance
AC test operation	
(1) 0.4 T/s demonstration	Demonstration of 0.4 T/s trapezoid operation, producing 13-T peak field
(2) AC demonstration	Demonstration of several AC operation patterns
(3) AC losses	To measure AC losses with the trapezoid operation pattern
(4) Ramp-rate limitation	To observe the stability behavior, changing the coil ramp rate
Cyclic test for the CS insert	
(1) Cyclic test	To perform cyclic operation (0–40 kA) for the CS Insert up to 10 000 cycles
(2) Shearing temperature	To check degradation due to cycles, measuring T_{cs} after specified cycles

restricted in the ranges of 0.4–0.6 and 1.0–2.0 T/s.

The following sections in the paper introduce the test results obtained from preliminary analysis: (1) typical demonstrated operation, (2) current shearing temperature (T_{cs}) measurement, (3) AC losses measurement, (4) ramp rate limitation, (5) quench characteristics, and (6) T_{cs} performance of CS Insert and cyclic test.

3. Typical demonstrated operations

Typical demonstrated operations are listed in Table 3. Three of the most typical operations are as follows: (1) Operating scenario of the ITER CS coil requests the maximum field change of -1.2 T/s from 13 T, simulating the plasma breakdown phase. To prove such operating scenario, the CSMC was fast discharged from 13 T with a time constant of 8.5 s, corresponding to a field change of -1.5 T/s (DC-3 in Table 3). Measured coil current, temperature and pressure in this condition are shown in Fig. 3. The operation was successfully achieved, the peak pressure and the maximum temperature rise at the outlet of the innermost-turn conductor, mainly induced by AC losses, were observed to be 0.9 MPa and 6.7 K, respectively. (2) The fastest pulse operation of the CSMC is to ramp up to 46 kA, 13 T with a trapezoid pattern at 0.6 T/s (AC-6 in Table 3) as shown in Fig. 4. This shows 1.5 times faster ramp-rate than the rated ramp-rate of 0.4 T/s. The outlet temperature of the innermost-turn conductor increased from 4.5 to 6.4 K ($\Delta T = 1.9$ K) due to AC losses and two temperature peaks such as 5.3 and 5.7 K were observed in the inlet temperature profile. It is supposed that the generated AC losses stopped the helium flow at the inlet and then such peaks appeared. (3) The CS Insert was charged up to 13 T by a ramp-up rate of as high as 1.2 T/s (ACI-7 in Table 3) as shown in Fig. 5. The coil outlet temperature increased to 5.4 K ($\Delta T = 0.9$ K), which is a half as small as the 0.6-T/s CSMC operation. Accordingly, the AC losses of the CS Insert are around half of the AC losses of the CSMC. The temperature rise at the conductor center was also observed to have a peak of around 6.1 K, still showing a temperature margin of about 1.5 K against the current shearing temperature at 13 T of around 7.6 K. Note that the conductor center temperature could not measure at the time from the beginning of charge to the end of flat top due to large noise induced by the power supply in AC operation.

The successfully demonstrated operations have brought the following results.

1. The CSMC and the CS Insert obviously satisfy the ITER CS coil design criteria.
2. ITER CS coil operation scenario is completely demonstrated.
3. Up to 4.8 kV was practically applied to the CSMC without any problems.
4. Both the CSMC and the CS Insert could operate beyond their rated condition. In particular, the CS Insert was able to operate up to 13 T with the ramp-up rate of 1.2 T/s.
5. The trapezoid operations generating 13 T at the ramp rates of 0.4 and 0.5 T/s with an inlet temperature of 6.5 K for the CSMC and for the CS Insert were successfully achieved, respectively.
6. Both the CSMC and CS Insert were revealed to be very stable pulsed coils.
7. Developed conductor joints (measured average resistance of 2 nΩ at 46 kA) satisfied the ITER R&D target (less than 6.5 nΩ at 46 kA).

4. Current sharing temperature (T_{cs}) measurement

Current sharing temperature (T_{cs}) is one of the important test objectives to determine superconducting properties of the conductor used in both the CSMC and CS Insert, which will provide and determine a degradation of the superconducting properties and a required I_c margin through the coil fabrication. The T_{cs} measurements were carried out for the specific layer conductors, namely, the 1st layer and the 11th layer of the CSMC, and the CS Insert (one layer coil). The 1st layer is the innermost layer of the CSMC inner module, generating a peak field of 13 T at the center of its conductor length, and the 11th layer is the innermost layer of the CSMC outer module, generating a maximum field of 6.5 T at both end of its

Table 3
List of typical demonstrated operations

No.	Outline of the operation
DC operation of the CSMC	
DC1	Ramp-up to the nominal current of 46 kA and generation of a maximum field of 13 T (stored energy 640 MJ) with an inlet temperature of 4.5 K. No coil quench occurred, even in the first run
DC2	Ramp-up to 13 T with elevated inlet temperatures of 5.3 and 6.3 K to the innermost turn (highest field layer) without quench
DC3	Fast discharge from 13 T with a time constant of 8.5 s, corresponding to a field change of −1.5 T/s, to simulate the operation of ITER CS at plasma breakdown phase
DC4	Fast discharge from 13 T with a time constant of 5.3 s (shortest), corresponding to the maximum-field change of 2.5 T/s. The peak voltage of the coil terminals was around 4800 kV
DC-5	All the 37 conductor joints (35 interlayer joints and two terminal joints) worked as designed, generating around 4 W per joint at a current of 46 kA
AC operation of the CSMC	
AC1	Ramp-up to 46 kA, 13 T, with an inlet temperature of 4.5 K at a ramp rate of 0.4 T/s, flat top of 5 s, followed by ramp-down to zero at 0.7 T/s
AC2	Ramp-up to 46 kA, 13 T, with an inlet temperature of 4.5 K at a ramp rate of 0.4 T/s, flat top of 5 s, followed by a fast discharge with a time constant of 8.5 s (1.5 T/s)
AC3	Ramp-up to 46 kA, 13 T, in 26 s (0.5 T/s), flat top of 5 s, ramp-down to 41 kA in 2 s (0.7 T/s), flat top of 5 s, followed by ramp-down to zero in 18 s (0.6 T/s)
AC4	Bipolar operation of zero to −11 kA in 6 s, 2 s flat top, −11 kA to +35 kA in 40 s, 4 s flat top, and ramp-down in 19 s
AC5	Ramp-up to 46 kA, 13 T, with inlet temperatures of 6.0 and 6.5 K at 0.4 T/s, flat top of 5 s, followed by ramp-down to zero at 0.4 T/s. A quench occurred at around 45 kA during the ramp-up in the 6.5-K operation
AC6	Ramp-up to 46 kA, 13 T, with an inlet temperature of 4.5 and 6.5 K at 0.6 T/s, flat top of 10 s, followed by ramp-down to zero at 0.6 T/s. A quench occurred at around 41 kA during the ramp-up in the 6.5-K operation
DC operation of the CS Insert	
DCI-1	Ramp-up to the nominal current of 40 kA and generation of a maximum field of 13 T with a back-up field from the CSMC and an inlet temperature of 4.5 K. No quench occurred, even in the first run
DCI-1	Ramp-up to 13 T with a back-up field from the CSMC and an inlet temperature of 5.3 and 6.8 K without quench
AC operation of the CS Insert	
ACI-1	Ramp-up to 44.3 kA, 13 T, with an inlet temperature of 4.5 K at a ramp rate of 0.4 T/s, flat top of 5 s, followed by ramp-down to zero at 0.7 T/s
ACI-2	Ramp-up to 44.3 kA, 13 T, with an inlet temperature of 4.5 K at a ramp rate of 0.4 T/s, flat top of 5 s, followed by fast discharge with a time constant of 10 s, corresponding to a field change of 1.3 T/s, to simulate the operation of ITER CS at plasma breakdown phase
ACI-3	Ramp-up to 44.3 kA, 13 T, in 26 s (0.5 T/s), flat top of 5 s, ramp-down to 39 kA in 2 s (0.7 T/s), flat top of 5 s, followed by ramp-down to zero in 18 s (0.6 T/s)
ACI-4	Bipolar operation of zero to −11 kA in 5.4 s, 5 s flat top, −11 to +44.3 kA in 40.5 s, 5 s flat top, and ramp-down in 14.3 s
ACI-5	Ramp-up to 44.3 kA, 13 T, with an inlet temperatures of 4.5 K at 0.6 T/s, flat top of 5 s, followed by ramp-down to zero at 0.6 T/s
ACI-6	Ramp-up to 44.3 kA, 13 T, with an inlet temperatures of 6.5 K at 0.5 T/s, flat top of 5 s, followed by ramp-down to zero at 0.5 T/s
ACI-7	Ramp-up to 44.3 kA, 13 T, with inlet temperatures of 4.5 K at 1.2 T/s, flat top of 1 s, followed by fast discharge from with a time constant of 10 s. A quench occurred at around 44 kA from the CSMC during ramp-up

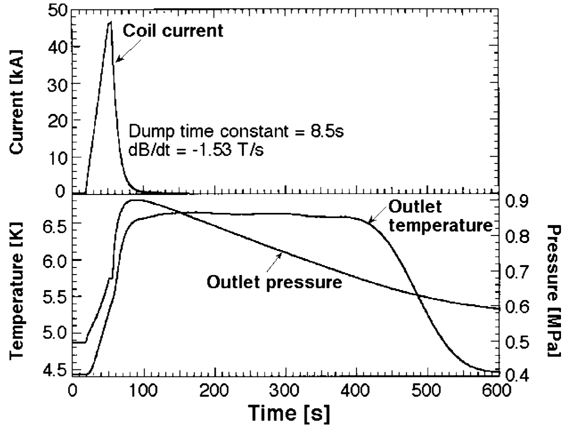

Fig. 3. Fast discharge from 13 T of the CSMC by a field change of more than −1.2 T/s.

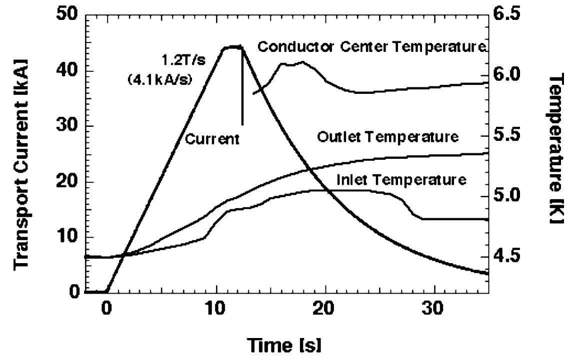

Fig. 5. Successful charging of the CS Insert up to 13 T by a ramp rate of 1.2 T/s.

conductor length. The T_{cs} performance on the CS Insert will be mentioned in the cyclic test section in the paper.

The T_{cs} measurements were done at the specified constant currents of 46, 40, 30 and 1 kA for the 1st layer conductor and 46, 40 and 1 kA for the 11th layer conductor, respectively such that the CSMC was first charged and kept at each specified current and the inlet helium temperature to the specified conductors was gradually increased by the resistive heaters to access the T_{cs}. T_{cs} is defined here as the temperature when the voltage at both ends of the conductor reached 100 μV. In the CSMC, the thermometers were only mounted at both the inlet and outlet of each layer. Then, the temperature through the conductor should have a distribution due to heat diffusion to the adjacent layer. Since an evaluation of such a temperature profile should be required to determine the temperature at the peak field, it was preliminarily supposed to be an average of both the inlet and outlet temperature. In the case of the 11th layer, the peak field appears at both end parts of the conductor. The T_{cs} is almost equal to the inlet temperature. Measured T_{cs} are plotted in Figs. 6 and 7 for the 1st layer and the 11th layer, respectively. An estimated T_{cs} curve for each layer is also superimposed on each graph, which is calculated by the ITER design criteria [8] with the design data (non-copper critical current density of the strand: $J_c = 550$ A/mm^2 at 4.2 K, 12 T, longitudinal strain of Nb_3Sn filament in the strand: $\varepsilon = -0.25\%$, $T_{c0m} = 18$ K, $B_{c20m} = 28$ T). The measured T_{cs} performances for both the 1st and

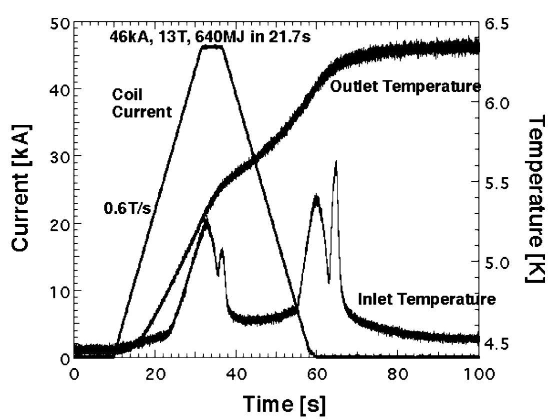

Fig. 4. Fast charging (0.6 T/s) of the CSMC up to 13 T.

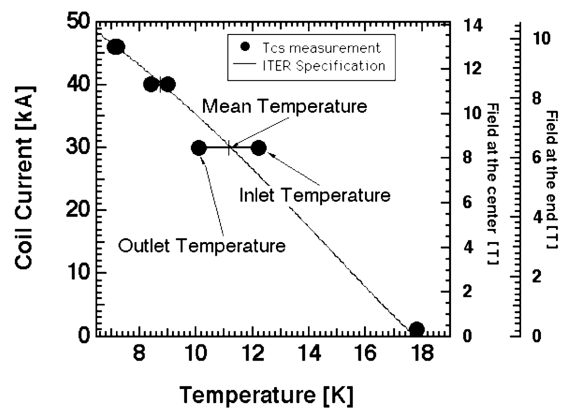

Fig. 6. Measured T_{cs} performance on the 1st layer conductor of the CSMC.

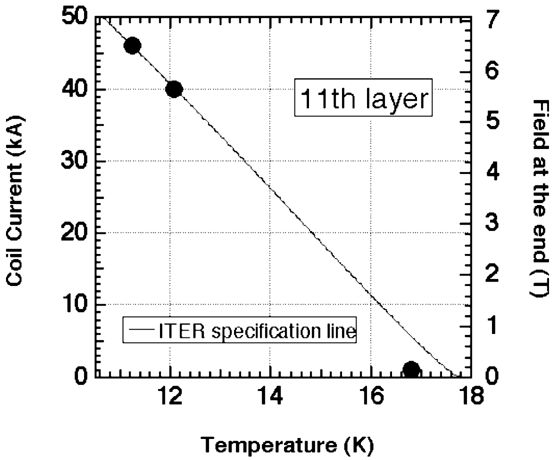

Fig. 7. Measured T_{cs} performance on the 11th layer of the CSMC.

the 11th layer show a good fitting to the design or slightly better than the design, suggesting only small I_c degradation. This, however, is the reason that the actual critical current (J_c) of the used conductor should be slightly better than the design J_c ($J_c = 550$ A/mm^2). Though more detail investigation will be required to determine an exact evaluation of the measured T_{cs} performance, the CSMC clearly verified and satisfied the ITER design criteria on the T_{cs} performance.

5. Measurement of AC losses

This was the first measurement of AC losses for such a large CIC conductor as used in the CSMC and CS Insert that operate at high field and current up to 13 T, 46 kA with long conductor length from 90 to 150 m. Coupling losses for a long and large CIC conductor is of great interest. We therefore try to provide a few of the preliminary results of the measured AC losses for both the CSMC and CS Insert.

First, AC losses for the CSMC were measured by quickly discharging the coil from the specified current such as 23 kA (50% of the rated current), 30 kA (65%) and 36.8 kA (80%), varying the dump time constant from 27 to 5.3 s. AC losses were evaluated by integrating the helium enthalpy measured at the outlet of the conductor for the time until the losses passed through the total length of the conductor. The results are shown in Fig. 8 where the x-axis is chosen as the reverse of the dump time constant. Generally, coupling loss (Q_c) caused by an exponential current dump indicates the following relation:

$$Q_c \propto B_{\max}^2 \cdot \tau_c/(\tau_p + \tau_c) \quad (1)$$

where $B_{\max}$, τ_c and τ_p indicate the maximum magnetic field, coupling time constant of the conductor and dump time constant, respectively. In the figure, losses at each specified current show a linear dependence to the reverse of the dump time constant. Therefore, the coupling time constant of the conductor is much shorter than the dump time constant, suggesting that the conductor should not have a long coupling time constant such as a few tenths of a second that has been reported for the CIC conductor [9]. It was also observed that losses were significantly decreased in accordance with the charging cycles, a phenomenon which has also been reported in the CIC conductor [10,11]. Fig. 9 shows the measured dependence of the AC losses in the 1st layer conductor as a function of run number, which were periodically measured from the beginning of the coil test by the manual dump from 20% current (9.2 kA) with

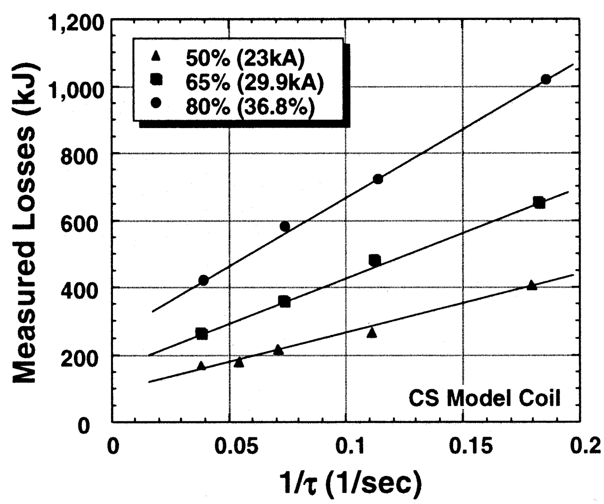

Fig. 8. Measured AC loss performance of the CSMC on its coupling time constant.

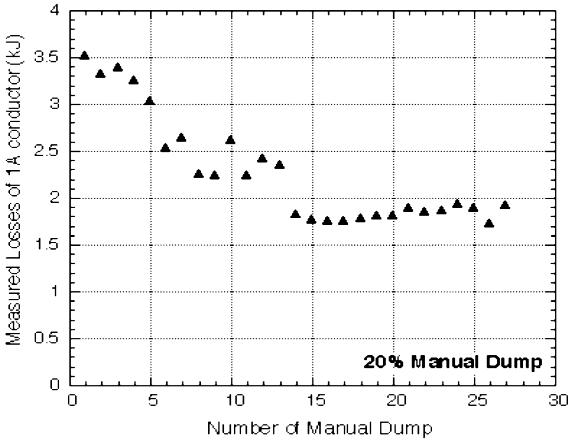

Fig. 9. Decrease of the measured AC losses as a function of number of manual-dumps.

the dump time constant of around 20 s. Note that many runs of up to 100% charging and intentional quench test were involved among such runs. As indicated in the figure, the losses were finally reduced by around a half the value of the initial one. Detail investigation will be required in future to explain the phenomenon but one of the possible explanations for this reduction is to break the low resistance links between strands due to generation of large electromagnetic loads when energizing the coil at the high current regime. A coupling time constant ($n\tau$) for the CS Insert was preliminarily evaluated to be 90–140 ms as shown in Fig. 10, based on measurements during trapezoid current operation where the ramp rate (dB/dt) was varied from 0.2 to 2.0 T/s. When estimating such coupling time constant, hysteresis losses and losses at the joint for each current were assumed to be the value at $dB/dt = 0$ in the figure. The coupling time constant has been found to be much higher than the ITER design reference of 50 ms [8]. However, the CS Insert could be energized to 13 T with the ramp-up rate as high as 1.2 T/s without quench, indicating sufficient margin for the ITER CS coil operation scenario even if the time constant was larger than twice the ITER reference. This result will lead to reducing the coupling time constant determined as the reference.

6. Ramp rate limitation

The instability induced by fast ramp-up has been reported as one of the unique instabilities for the superconducting pulsed magnet with the CIC conductor [12,13]. Therefore, the existence of a ramp rate dependency of quench or ultimate operation current (ultimate operation magnetic field) was checked as one factor of the pulsed coil stability performance. It was measured on the CS Insert, varying its ramp rate up to 2.0 T/s with trapezoid current operation. Measured data, namely, the achieved magnetic field as a function of ramp rate without quench are plotted in Fig. 11. In the figure, the estimated I_c curve, calculated from the temperature rise due to AC losses with the coupling loss time constant of 100 ms, is also indicated. The data indicated as E and D in the figure can be plotted on or close to the I_c curve and no quenches were observed at a lower regime than the I_c curve, resulting in the conclusion that the CS Insert operation limit should depend on its I_c performance. An effect of higher ramp rate is mainly to increase conductor temperature caused by AC losses and to reduce the temperature margin, namely, the quench current. Unknown instability was not observed through the ramp rate test in the CS Insert.

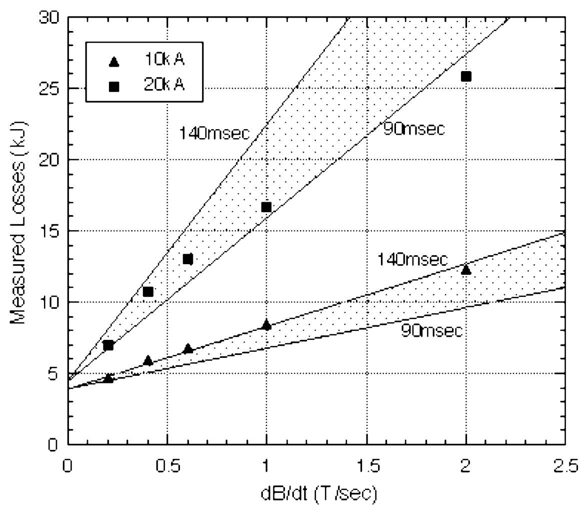

Fig. 10. Evaluation of the coupling time constant ($n\tau$) for the CS Insert.

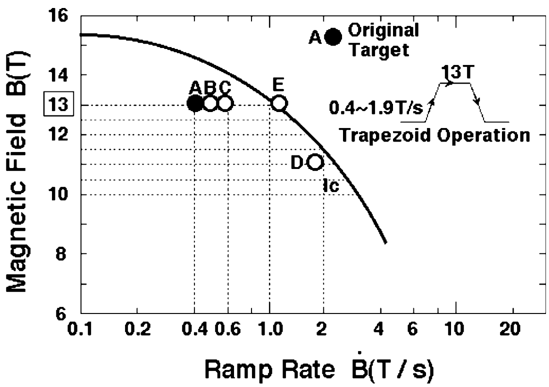

Fig. 11. The magnetic field achieved as a function of ramp rate without quench.

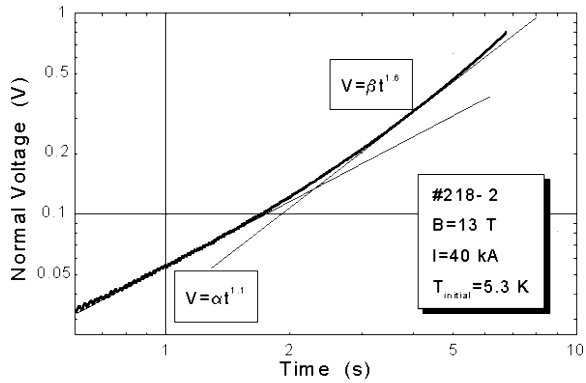

Fig. 12. Measured normal voltage across the conductor.

7. Quench characteristics

To investigate the propagation of the normal zone, and the temperature and pressure rise during quench in the CIC conductor, quench test was performed using the CS Insert. An inductive heater, installed at the highest field region (the center of the conductor) was used to induce the quench. Thermometers and a pressure tap are also mounted at the central region to measure the maximum temperature and pressure rise in the quench. The test was carried out at a field of 13 T, keeping the initial temperature at the conductor center of 5.3 and 6.8 K simulating a 2- and 1.5-K margin, respectively. Furthermore, a delay time to initiate the current dump was controlled up to around 7 s so as to observe the extension of the normal zone. A typical measured behavior of the normal voltage across the conductor at the initial temperature of 5.3 K is shown in Fig. 12. We observed that the voltage increases in proportion to $(\text{time})^{1.1}$ in the first 2 s and $(\text{time})^{1.6}$ after 2 s. The normal zone voltage behavior in the case of 6.8 K shows almost the same tendency. A Joule heating energy is to define the energy generated by the growth of the normal zone until the current dump. It will provide a characteristic to indicate the size of the disturbance induced by the quench. The temperature and pressure rise data through the quench test are arranged as a function of the Joule heating energy as shown in Figs. 13 and 14 for temperature and pressure, respectively. Note that the temperature at the higher regime was evaluated using the resistance of a copper stabilizer. The ITER design criteria determine the hot spot temperature of 150 K assuming a delay time of 5 s. The temperature and pressure rise at the Joule heating energy of 70–80 kJ correspond to the data at the delay time of around 7 s, whose values are read from the figures to be around 85 K and 0.21 MPa, respectively. They are converted to around 90 K and 0.82 MPa in absolute units. Comparison between the hot spot temperature by the ITER design and the measured temperature rise proves that the coil should have sufficient safety margin against the ITER hot spot design criterion. As the end of this session, let us mention the largest quench. It was experienced in the 0.4-T/s pulsed operation with

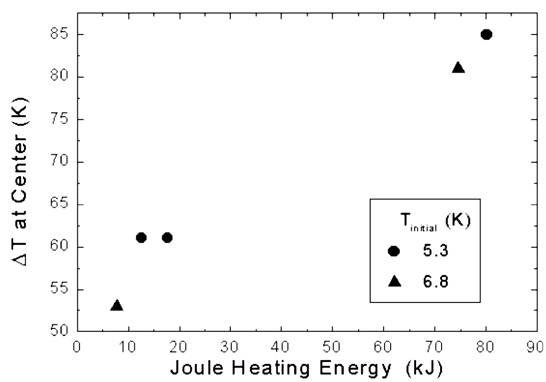

Fig. 13. Temperature rise as a function of the Joule heating energy.

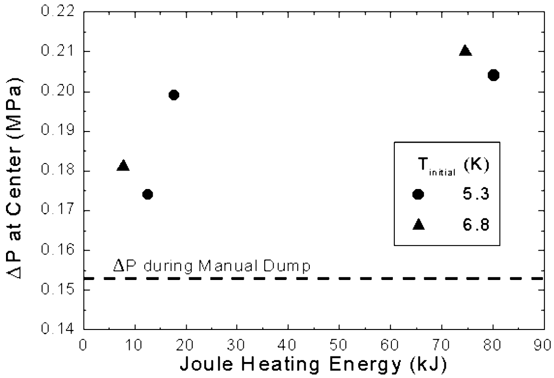

Fig. 14. Pressure rise as a function of the Joule heating energy.

the initial temperature as high as 7.5 K. The quench current reached 43.6 kA. The measured normal voltage across the coil is shown in Fig. 15, showing a rapid voltage increase, reaching 10 V within 1 s. Indeed, the normal zone extended to almost the whole conductor, more than 100 m. The maximum temperature rise was around 65 K. The maximum pressure rise, unfortunately, could not be measured beyond the measurable range of the pressure sensor. But it is supposed to be in the range of 6–7 MPa at the conductor center. The CS Insert and the test facility could withstand such a large quench without any problems.

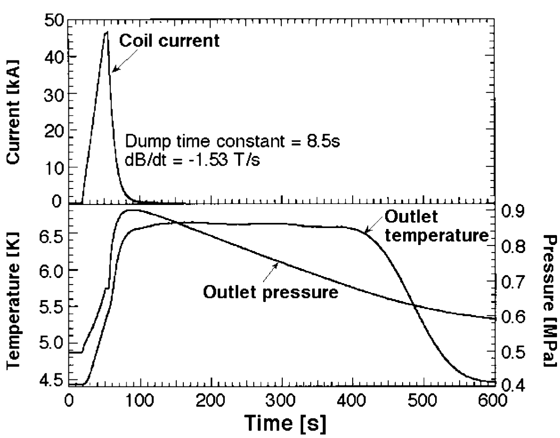

Fig. 15. Measured normal voltage across the coil in the largest quench.

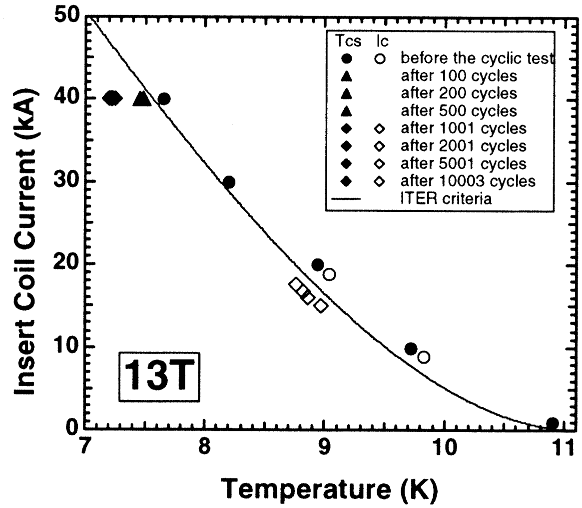

Fig. 16. Measured T_{cs} performance on the CS Insert.

8. T_{cs} of the CS insert and cyclic test

T_{cs} of the CS Insert was investigated in detail since thermometers were mounted at the peak field position, allowed to measure the T_{cs} temperature directly. T_{cs} was measured at the specified current of 40, 30, 20, 10 and 1 kA, respectively. Critical current (I_c) measurement was simultaneously done at both 20 and 10 kA to check that the measured T_{cs} were the same as the I_c measurement. Then the CS Insert has the voltage tap pair located at the center turn with the length of 1.1 m. The T_{cs} and I_c were determined at 11 μV indicating at such voltage tap pair, corresponding to 0.1 μV/cm criterion that is the same voltage defined by the ITER I_c reference. Measured data are plotted in Fig. 16, where the T_{cs} curve calculated by the ITER criteria is superposed. It can be seen that the measured T_{cs} performance satisfies the ITER criteria and shows better T_{cs} than the criteria. The reason is that the actual J_c of the CS Insert should be higher than the J_c defined by the ITER design criteria. Although the actual degradation should be evaluated from the actual J_c of the CS Insert strand, it is a fact that the CS Insert has enough T_{cs} or J_c margin to satisfy the ITER design.

A cyclic test was applied to the CS Insert as one of the crucial tests to reveal fatigue performance

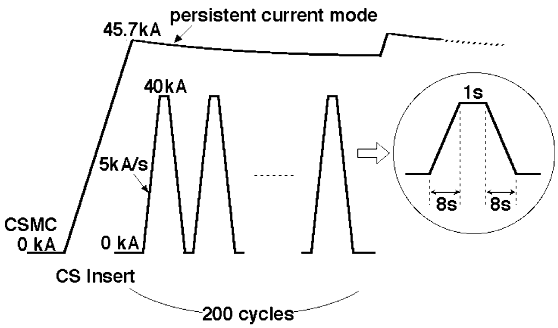

Fig. 17. Operated current pattern of the cyclic test.

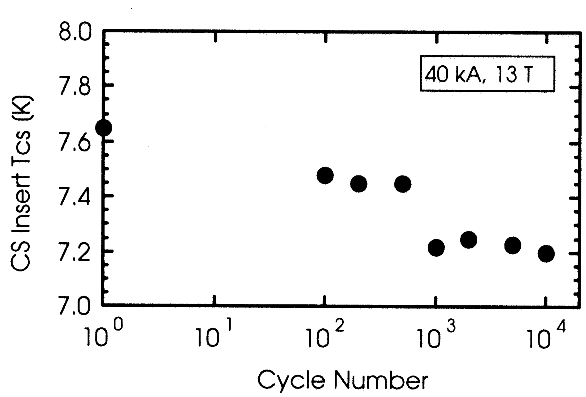

Fig. 18. Measured T_{cs} at 40 kA, 13 T as a function of cycle number.

for a large pulsed magnet with the CIC conductor. The cyclic test was performed by charging the coil current rapidly up and down from 0 to 40 kA in a 13-T background field from the CSMC. Fig. 17 shows the current pattern used. The test cyclically applied a peak electromagnetic force from 0 to 520 kN/m to the central part of the CS Insert conductor and 10 003 cycles were finally achieved. During the test, degradation was checked by measuring T_{cs} after 100, 200, 500, 1001, 2001, 5001 and 10 003 cycles, respectively. T_{cs} degradation was observed and the measured T_{cs} were superimposed in Fig. 16. When the measured T_{cs} at 40 kA, 13 T are re-plotted as a function of cycle number as shown in Fig. 18, it noted that the degradation shows an interesting tendency. Significant degradations occurred at the specified cycle intervals such as between 0 and 100 cycles and between 500 and 1000 cycles, however, the degradation did not appear for the other cycle intervals. It was found that the AC test operation including many of the large quenches were performed between the intervals that indicate the degradation. Accordingly, it suggests that such degradations might be caused not by cycles but by quenches. However, so far we cannot find a reasonable explanation that the degradation should be caused by quenches. Changes of mechanical and electric-insulation stiffness were also monitored through the cyclic test and significant changes of strains and electric insulation resistance did not appear. To conclude, the CS Insert, namely the conductor proposed for the ITER CS coil, can withstand full charge operation up to 10 000 cycles.

Table 4
Summary of the test results compared to the design criteria

Items	R&D target	Achievement	ITER-FEAT design
Operation current (kA)	46	46	42/45
Maximum field (T)	13	13	13.5/12.8
Current ramp-up rate (T/s)	0.027 ($\leq$13 T), 0.4 ($\leq$13 T)[a]	1.2 ($\leq$13 T)	0.1–0.2 ($\leq$8 T), 0.045 ($\leq$13.5 T)
Current ramp-down (T/s)[b]	−1.2 at 13 T	−1.5 at 13 T	−1.2 at 13 T
Hot spot temperature (K)	150 (5-s delay time)	90 (7-s delay time)	150 (2-s delay time)
Fast discharge decay time const. (s)	20	5.3	7.5
AC loss coupling time const. (ms)	25–100	90–140	50
Joint resistance (nΩ)	Less than 6.5	Average 2.0	Less than 4.5

[a] This test program target.
[b] At the plasma breakdown.

9. Conclusion

The CS Model Coil project, continuing over 8 years of international collaboration, has attained a significant milestone here through the first coil test. The CSMC and the CS Insert are obviously proved to satisfy and exceed almost all the ITER CS coil design criteria as shown in Table 4. Finally, we can say that the superconducting magnet technology has now developed to a level that will allow the ITER magnet to be built with confidence.

Acknowledgements

Well over 100 people from many countries and organizations participated in this large and very successful project. The authors are grateful to all who contributed to the project.

References

[1] K. Okuno et al. ITER model coil test program, Proc. MT-15 (1997) 365–368.
[2] F. Wong, et al., Characterization of Incoloy 908 and avoidance of stress accelerated grain boundary oxidation (SAGBO) during ITER model coil fabrication, Fusion Technol. 34 (3 Pt. 2) (1998) 815–821.
[3] R.J. Jayakumar, et al., The USHT-ITER CS model coil program achievements, IEEE Trans. Appl. Supercond. 10 (2000) 560–563.
[4] T. Ando, et al., Completion of the ITER CS model coil—outer module fabrication, IEEE Trans. Appl. Supercond. 9 (1999) 628–631.
[5] M. Sugimoto, et al., Completion of CS insert fabrication, IEEE Trans. Appl. Supercond. 10 (2000) 564–567.
[6] S. Shimamoto, et al., Construction of ITER common test facility for CS model coil, IEEE Trans. Magn. 32 (1996) 3049–3052.
[7] M. Matsukawa, et al., Preparations in the JT-60 power supply for pulse operation test of ITER CS model coil, IEEE Trans. Appl. Supercond. 10 (2000) 1410–1413.
[8] N. Michell et al. ITER design criteria, ITER DDD 1.1-1.3 Appendix C-II (1998) 15.
[9] T. Hamajima, et al., AC loss performance of the 100 kWh SMES model coil, IEEE Trans. Appl. Supercond. 10 (2000) 812–815.
[10] E.P. Balsamo, et al., Direct measurement of the AC loss of an ITER relevant coil, Physica C 310 (1998) 258–261.
[11] A. Nijhuis, et al., Electromagnetic and mechanical characterization of ITER CS-MC conductors affected by transverse cyclic loading, part 1: Interstrand coupling losses, IEEE Trans. Appl. Supercond. 9 (1999) 1069–1072.
[12] T. Ando, et al., The second test results on the Nb3Sn DEMO Poloidal Coil (DPC-EX), Adv. Cryogen. Eng. 39 (1994) 335–341.
[13] M. Steeves, et al., Test results from the Nb3Sn US-Demonstration poloidal coil, Adv. Cryogen. Eng. 37 (1991) 345–354.