Progress of the ITER Central Solenoid Model Coil Program

H. Tsuji 1), K. Okuno 2), R. Thome 3), E. Salpietro 4), S. Egorov 5), N. Martovetsky 6),
M. Ricci 7), R. Zanino 8), G. Zahn 9), A. Martinez 10), G. Vecsey 11), K. Arai 12),
T. Ishigooka 13), T. Kato 1), T. Ando 1), Y. Takahashi 1), H. Nakajima 1), T. Hiyama 1),
M. Sugimoto 1), N. Hosogane 1), M. Matsukawa 1), Y. Miura 1), T. Terakado 1), J. Okano 1),
K. Shimada 1), M. Yamashita 1), T. Isono 1), N. Koizumi 1), K. Kawano 1), M. Oshikiri 1),
Y. Nunoya 1), K. Matsui 1), Y. Tsuchiya 1), G. Nishijima 1), H. Kubo 1), T. Shimba 1),
E. Hara 1), K. Imahashi 1), Y. Uno 1), T. Ohuchi 1), K. Ohtsu 1), J. Okayama 1), T. Kawasaki
1), M. Kawabe 1), S. Seki 1), K. Takano 1), Y. Takaya 1), F. Tajiri 1), F. Tsutsumi 1),
T. Nakamura 1), H. Hanawa 1), H. Wakabayashi 1), T. Shimizu 1), K. Kuramochi 1),
T. Omine 1), T. Tamiya 1), J. Harada 1), K. Nishii 1), M. Huguet 2), N. Mitchell 2),
D. Bessette 2), J. Minervini 3), R. Vieira 3), P. Michael 3), M. Takayasu 3), G. Bevilacqua 4),
R. Maix 4), R. Manahan 6), R. Jayakumar 6), L. Savoldi 8), W. Herz 9), A. Ninomiya 13)

1) Japan Atomic Energy Research Institute (JAERI), Naka, Japan
2) ITER Joint Central Team, Naka, Japan
3) Massachusetts Institute of Technology, Cambridge, MA, USA
4) European Fusion Development Agreement, Garching, Germany
5) D. V. Efremov Scientific Research Institute, St. Petersburg, Russia
6) Lawrence Livermore National Laboratory, Livermore, USA
7) ENEA C. R. Frascati, Frascati, Italy
8) Politecnico di Torino, Torino, Italy
9) Forschungszentrum Karlsruhe , Eggenstein-Leopoldshafen, Germany
10) CEA Cadarache, St-Paul-Lez-Durance, France
11) Ecole Polytechnique Federale de Lausanne, Villigen, Suisse
12) Electrotechnical Laboratory, Tsukuba, Japan
13) Seikei University, Musashino, Japan

e-mail contact of main author: tsuji@naka.jaeri.go.jp

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 cool down and charging tests were successfully carried out by international test and operation teams. In pulsed charging tests, where the original goal was 0.4T/s up to 13T, the CS Model Coil and the CS Insert Coil achieved ramp rates of 0.6T/s and 1.2T/s up to 13T, 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 we are now ready to construct the ITER coils with confidence.

1. Introduction

In the ITER Central Solenoid (CS) Model Coil Program, 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 Outer Module as shown in Fig. 1. A CS Insert Coil is placed in the inner bore of the CS Model Coil. Also indicated in Fig. 1 are two other insert coils: Nb_3Sn toroidal field (TF) Insert Coil and Nb_3Al Insert Coil which can also be placed for testing in the inner bore of the CS Model Coil.
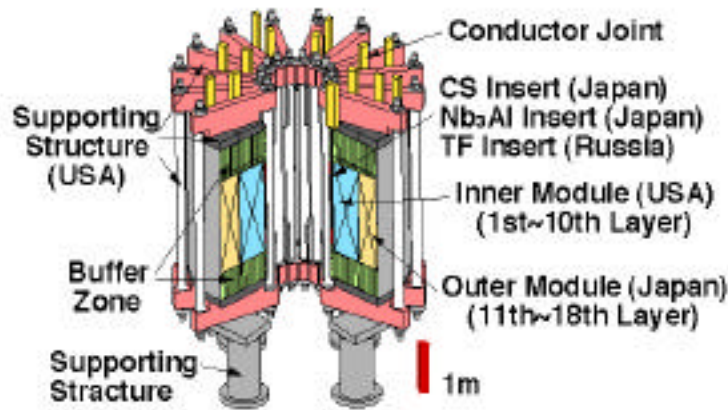
FIG. 1   CS Model Coil and Insert Coils

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 Nb_3Al Insert Coil are now being fabricated by the Russian Home Team and 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 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 were 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 13T.   The pulsed field losses generated during pulsed operation make this a difficult design point not previously demonstrated in this scale in superconducting magnet technology. The largest pulsed coil before the CS Model Coil Program operated 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 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

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

	ITER-CS		CS Insert	CSMC Inner Module	CSMC Outer Module
Maximum Field	12.8 T	13.5 T	13 T	13 T	7.3 T
Operating Current	45 kA	40.5 kA	40 kA	46 kA	46 kA
Outer Diameter	4.15 m		1.57 m	2.71 m	3.62 m
Height	2 m x 6*		2.80 m	2.80 m	2.80 m
Weight	840 ton**		7.7 ton	49.3 ton	52 ton
Stored Energy	6 GJ		11 MJ	640 MJ	

* 6 modules   ** including support structure
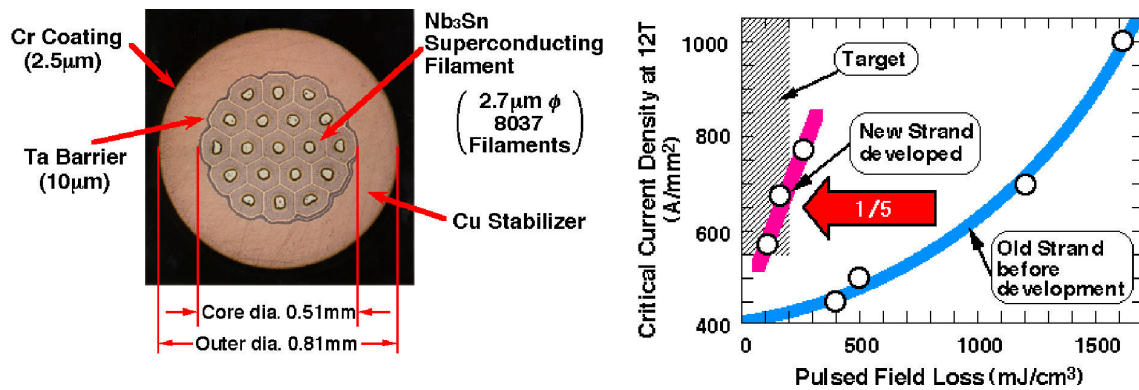
FIG. 2   *A Nb₃Sn strand developed for the CS coil and its improvement in pulsed field loss*

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$_3$Sn strand with critical current density higher than 550 A/mm^2 was possible, however the pulsed loss due to superconducting hysteresis loss was typically much bigger that 200 mJ/cm^3. The development of this advanced strand was carried out by reducing the diameter of the Nb$_3$Sn filaments below 4 microns, taking special care to reduce the electromagnetic coupling between filaments.   Fig. 2 shows one of the successfully developed strand containing, in a core with a diameter of 0.51 mm, 8037 Nb$_3$Sn filaments each with a diameter of 2.7 microns. 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 cabling of 1152 strands, each strand was coated by 2.5-micron Cr to increase the contact resistance between strands.   In addition, each sub-cable with 192 strands was wrapped by Inconel tape.   By increasing the resistivity between stands or between sub-cables as shown in Fig. 3, the pulsed loss due to coupling current under pulsed field was successfully reduced.   The cable of 1152 Nb$_3$Sn strands is protected by a thick jacket of Incoloy 908 which has a similar thermal expansion rate and assures the minimum strain between the activation temperature of 923 K to produce
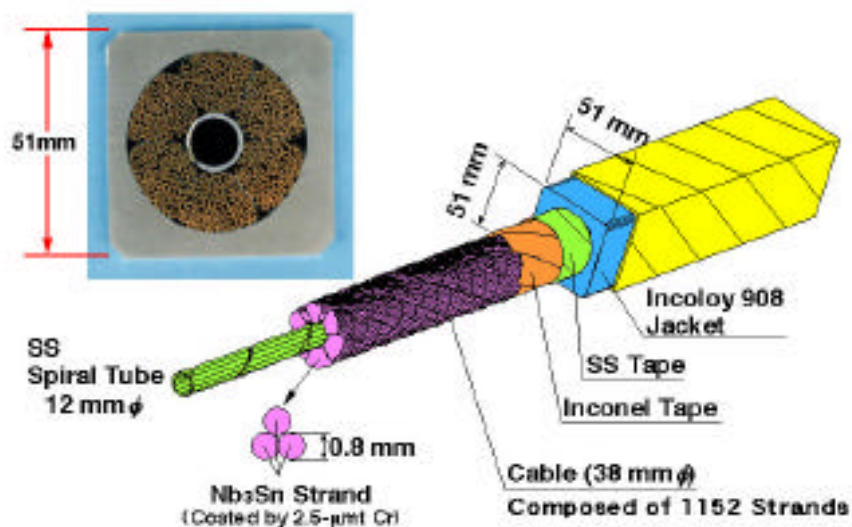

FIG. 3   *Configuration and cross section of the conductor developed for the CS coil*

FIG. 4 CS Model Coil Inner Module

FIG. 5 CS Model Coil Outer Module

Nb$_3$Sn and the operation temperature of 4.5K. 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 European Team was shipped to the USA for fabrication of the CS Model Coil Inner Module and to Japan to fabricate the CS Model Coil Outer Module and the CS Insert Coil. These three coil modules were successfully fabricated by 1999 [1, 2, 3]. The installation and assembly of these coils took place at Naka Fusion Research Establishment of JAERI as shown in Figs. 4, 5 and 6 by collaboration of Japanese Team and USA Team. This installation work took 5 months to prepare this system with a cryogenic weight of 180 tons for testing. The weight includes supporting structures to give a compressive pre-loading of 9000 tons to the coils.

FIG. 6   Installation of the CS Insert Coil into the inner bore of the CS Model Coil

3. Test of the CS Model Coil and CS Insert Coil

The purposes of the test of the CS Model Coil and the CS Insert Coil were as follows;
(a) Demonstrate a reliable cool-down to 4K without any damage to insulators in 480 hours
(b) Confirm 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 up to 13T, 40 kA.
(c) Achieve pulsed charging performance by a ramp rate of +0.4 T/s to 13T and discharging
    performance by a ramp rate of –1.2 T/s from 13 T for both of the coils
(d) Measure operational temperature margin for both of the coils
(e) Perform and demonstrate a cyclic charging of the CS Insert for 10,000 times

3.1 Initial Cool-down

Initial cool-down of the CS Model Coil and the CS Insert Coil was started in March 2000 by
keeping the 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 Outer
one, 15 g/s to the CS Insert Coil, 50 g/s to 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. A cool-down time of about 500 hours
was experienced mainly determined by the cool-down 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 became ready
for a charging test. Steady state heat load including this helium pump was about 960 W at
4.5K.

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 higher than 100 mV continued for more than 1 sec. The first charging to 13 T of the CS
Model Coil was carried out with a helium mass flow rate about 10 g/s for each conductor. As
shown in Fig. 7, the coil current was increased step-wise in 3 hours and the CS Model Coil
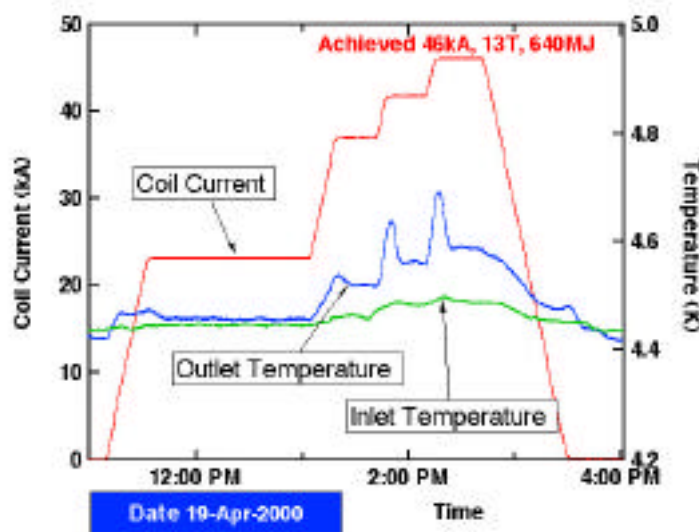

FIG. 7   First DC Charging of the CS Model Coil up to 46kA, 13T

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 inner-most 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 3rd 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 by 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 that was decreased down to 416 in the second charging, and stayed 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 (Tcs) 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 the Tcs. We kept the maximum field of 13 T and the operating current of the CS Insert to be 40 kA under the background field of the CS Model Coil. Then we increased the temperature of 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 (Tcs) is defined when a normal voltage of 0.1 micro-V per cm of the 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 criteria of 11 micro-volt when the conductor temperature at the same place reached 7.46 K 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 to 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 1 K for the ITER-FEAT magnet design.

3.3 Pulsed Charging Test

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 charging of 1.2 T/s up to 13 T without any quench as shown in Fig. 9.
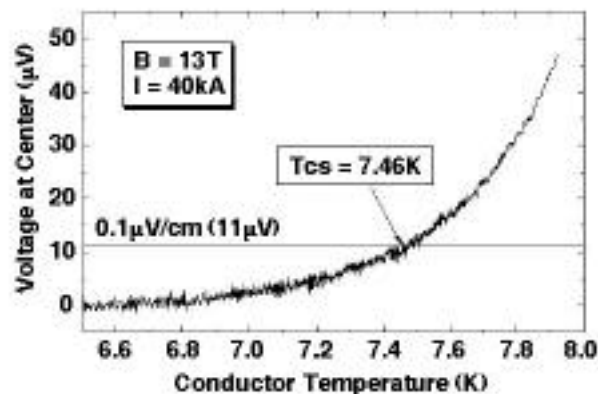

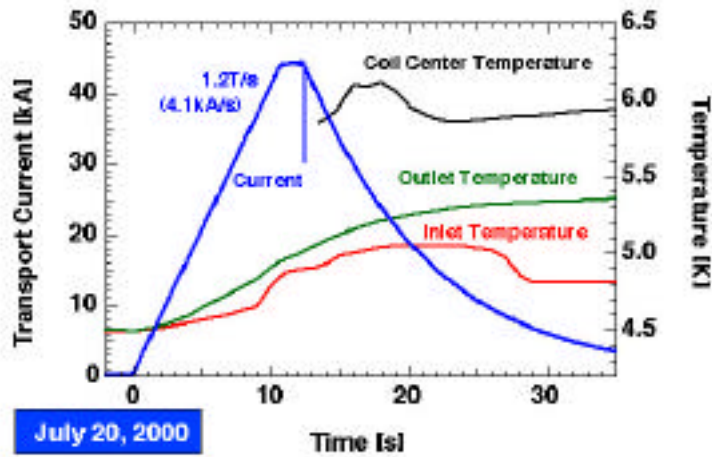FIG. 8   Measurement of the current sharing temperature of the CS Insert Coil

FIG. 9   Pulsed Charging of the CS Insert Coil by a ramp rate of 1.2T/s up to 13T

In this swift charging case, the temperature of the conductor at the 13-T location increased to 6.7 K because of pulsed losses. Based on the measurement of the current sharing temperature 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 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 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 msec. Being helped by a good operational 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.
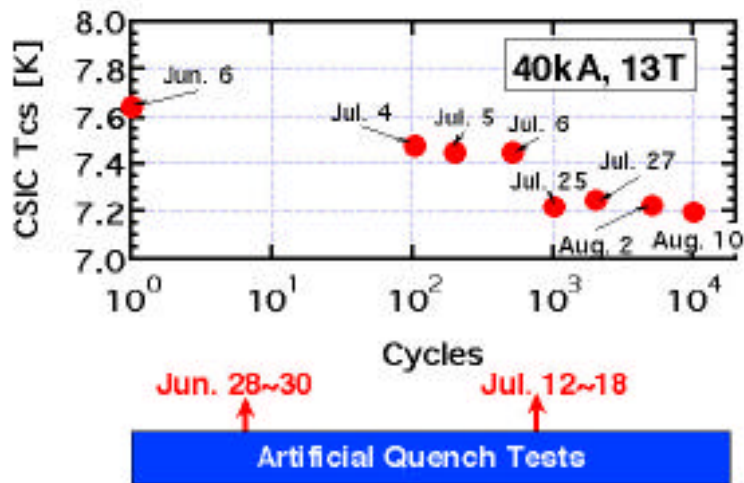

FIG. 10   Variation of the current sharing temperature of the CS Insert Coil

3.4 10,000 Cycle Charging Test

Under the background field of the CS Model Coil, charging and discharging between (0 kA, 13T) and (40 kA, 13 T) of the CS Insert Coil were repeated for 10,003 times.   In this test, we simulated the cyclic operation required for the ITER CS coil. The current sharing temperature as described in 3.2 was measured at 13T and 40 kA before and after 100, 200, 500, 1000, 2000, 5000 and 10,000 cycles. Fig. 10 shows the variation of Tcs from 7.65 K down to 7.20 K at the end of these tests. This result shows no major degradation of Tcs 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 Tcs are observed in Fig. 10.   In these artificial quench tests, conductor temperature measured at its jacket indicated increases up to around 65 K, suggesting that much higher temperature might appear in the Nb_3Sn filaments. Therefore, the decrease of the Tcs from 7.65 K to 7.20K as shown in Fig. 10 is considered to occur due to the artificial quench tests carried out to measure the quench propagation performance of the coil and not by cycling under usual condition.

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 ITER CS coil with confidence.

5. Acknowledgement
The authors appreciate the strong support by Dr. Aymar and Dr. Shimomura to this program as well as the effort by hundreds of colleagues from the world's industries and laboratories who participated in this program.   Without the great effort made by each of them, the CS conductor, the CS Model Coil and CS Insert Coil would never have been developed.

6. References
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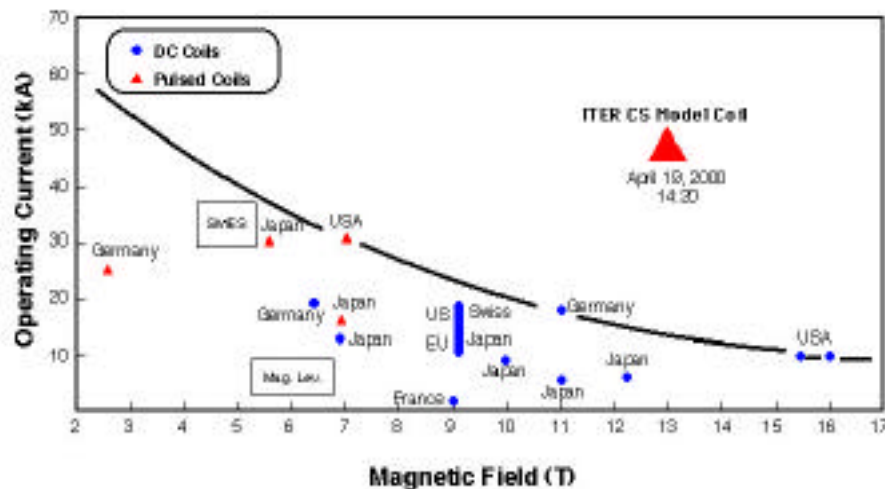[3] M. Sugimoto et al., *ibid,* pp. 564-567

FIG. 11 Achieved technology of the ITER CS Model Coil compared to technology frontier before