

Results of ITER Superconducting Magnet R&D

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Abstract

The ITER magnets are among the most time-critical of the tokamak components. Over the last two years, as well as finalising the magnet design, the final elements of the magnet R&D have been completed. These elements include the resolution of the Nb3Sn strand performance degradation reported for some conductor samples, the PF conductor performance demonstration in the PF insert coil, the CS conductor jacket, the studies of radiation resistant insulation, a basic demonstration of the performance of the uniaxial glass fibre pre-compression rings (an important element in the TF coil out of plane support) and 68 kA HTS current leads.

The focus of the work is now moving to qualification of components made under industrial conditions, the qualification of processes and tooling and the fabrication process optimisation to reduce costs. First in this respect are the fabrication routes for the TF coil radial plates and structures, and the design/manufacture of the TF coil winding, transfer and insulation tooling. Overall the progress in the work shows that a satisfactory performance of Nb3Sn conductor could be reached; and the manufacture feasibility of the ITER magnet is confirmed.

1, Introduction

The ITER magnet system consists of 18 Toroidal Field (TF) coils, a 6-module Central Solenoid (CS) coil, 6 Poloidal Field (PF) coils, 9 pairs of Correction Coils (CC) as well as 31 feeders for the magnet power, cooling and instrumentation supply[1] [2].

Both TF and CS coils operate at high fields and use Nb3Sn-type superconductor. The PF coils and CCs use NbTi superconductor, all coils are cooled with 4.5 K supercritical helium. The conductor is a cable-in-conduit conductor with a circular multistage cable around a small central cooling spiral tube. The operating currents are 40-45 kA for the CS, 45-55kA for the PF coils and 68 kA for the TF coils. The CC coils use 10 kA conductor without central cooling tube. Each coil is connected through a feeder to the current leads and valves located outside the main cryostat and bio-shield in the coil terminal boxes (CTBs), ITER has a total of 60 current leads using high temperature superconductor (HTS). The R&D for ITER magnet technology, especially the conductor development has been ongoing for years.

2, TF conductor

The TF and CS model coils were the most important ITER magnet R&D activity, successfully completed and tested at the end of the EDA in 2000-2003. The model coil program showed that, although Nb3Sn conductors could provide the required performance, there was some degradation of the strand performance within the cable, which needed to be addressed. The ITER conductors were modified accordingly to provide an extra margin to compensate the degradation. However, following this, some short sample measurements seemed to show a more dramatic fall off in performance compared to strand behaviour and the degradation increasing with cycling. The degradation is clearly related to transverse loads on cables, either local or cumulative.

An urgent R&D programme was launched in 2006 and carried out by CN, EU, KO, JA, RF, US DAs as well as directly funded IO contracts PSI/CRPP in the last two years. The main objectives of the program are: -1- to investigate early results that suggest TF conductor will not meet performance requirements, and -2- to confirm that the TF conductor can provide the required performance under the applied operating conditions (especially as regards magnetic loads).

The degradation has been traced to filament fracture under the local and cumulative magnetic loads in the cable. Tests on strands to simulate loads in cables have been done by Twente University and the effect of bending and pinching was investigated. The results of strands from different suppliers show a wide variation in sensitivity with the internal tin strand appearing more sensitive. Work by FSU confirmed the correlation with filament fracture.

Further investigations of the problems found in short samples suggest that these are sometimes related to the sample itself rather than the conductor design. Between 2006 and 2008 a large database of conductor tests (both full-size ITER and sub-size) clearly indicate that large SULTAN samples are sensitive to the joint current distribution, even if the joint resistance is low overall, and this effect is sufficient in some cases to result in an incorrect degradation assessment. The biggest accomplishment in TF conductor R&D during the last two years, however, is that it was clearly shown that long twist pitches can improve conductor performance. The cable design has therefore been adjusted with longer twist pitch in the inner cabling stages, while at the same time, the sample joint was improved by solder filling. The instrumentation of the SULTAN sample was also modified in order to provide a better base for both the electrical and calorimetric assessments of Tcs. Up to now, 9 prototype TF conductor samples (with 18 different conductor legs) have been tested. Fig. 1 shows the test results of SULTAN samples, the V pair (No1-3) is for the samples tested earlier and V star (No4-8) is the result with the modified instrumentation. The poor performance of sample 6 was caused by an obvious mistake in sample preparation. Sufficient ‘good samples’ were found to demonstrate that all strands perform adequately in the reference configurations with margin (i.e. target Tcs >6 K, required 5.7 K). Fig 2 shows a sample Tcs change with the cycling load [2] [3].

New analysis codes able to simulate the impact of the joints were developed. However, since the joint non-uniformity is not known, it is not possible to reconstruct the sc performance of a sample distorted by current non-uniformity. All “suspicious” samples are being remade with new joints and are being re-tested.

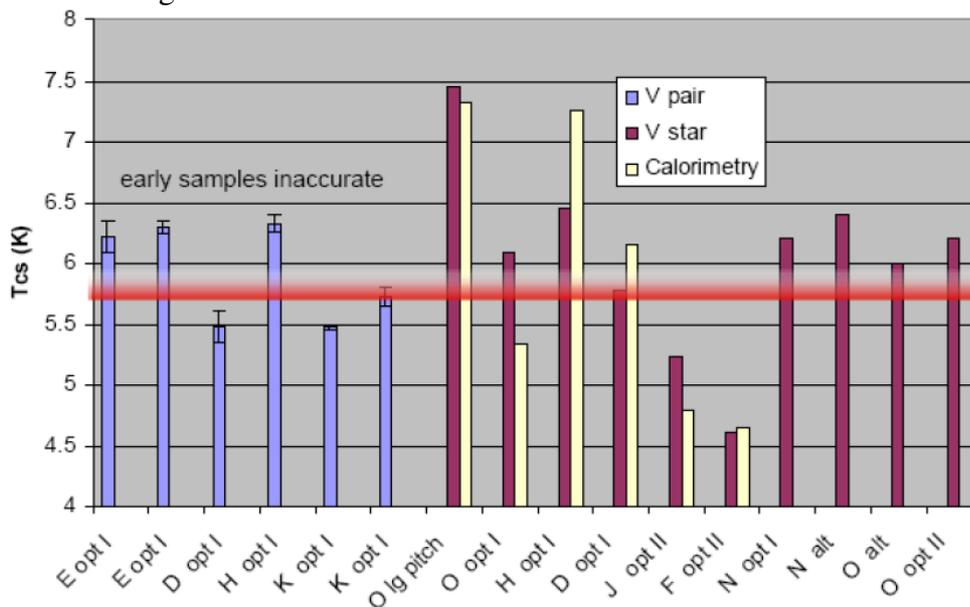


Fig 1 Test results of SULTAN samples (after 1000 cycles)

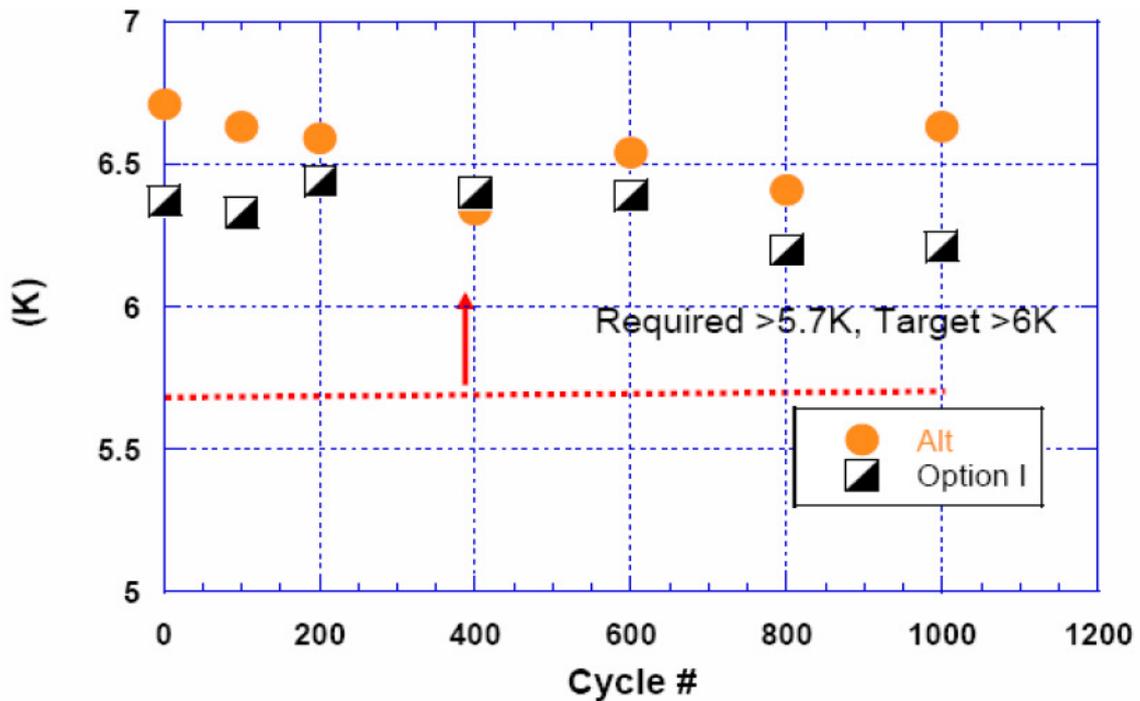


Fig 2 Current sharing temperature vs. cycle

3, PF Insert Test (EU, JA, RF DAs)

Still on the conductor, the NbTi used in the PF coils has received less attention but is equally critical in enabling ITER to achieve the required plasma performance. The PFI conductor (very similar to conductor of PF1 and PF6) short sample tests in SULTAN had shown that above a current threshold (30 to 40 kA), the quench current was much below the expected strand critical current. Meanwhile there is a requirement to increase the capability of PF coils. The new requirements on 15 MA plasma operating window proposed in scientific reviews of the ITER physics capability, ask for higher current and magnetic field, significant changes to the PF coil system (table 1), requiring extensive re-design of conductor and coils. The main change with respect to the original design (table 2) is a reduction in the Cu: non Cu ratio of the low field conductors (PF2 to PF5), increasing the superconducting area in the conductor and ensuring sufficient temperature margin [4]. At the same time, we have to control the conductor AC losses in the cable to limit the temperature increase due to pulse operation of the conductor. The maximal magnetic field requirement for PF6 is at the limit of the range of capability of NbTi conductor in normal operation condition and sub-cooling may be needed.

Coil	Base line	I, kA	B, T	N
PF2	2001	41	4	106
	2008	55 / 55	4.8 / 5.0	115.2
PF5	2001	45	5	216.8
	2008	52 / 33	5.7 / 6.0	216.8
PF6	2001	45	6	424.4
	2008	52*/41*	6.8*/7.0*	459.4

Table 1 PF requirement (“*” sub-cooling)

Conductor version	SC: Cu	A mm ²		SC strand	
		SC	Cu		
PF2 3, 4	2001	1:6.9	45.3	430.8	864
	2008	1:2.3	90.3	424.7	720
PF5	2001	1:4.4	80.5	422.3	1080
	2008	1:2.3	144.8	370.5	1152

Table 2 Main change of PF2-5 conductor

The Poloidal Field Conductor Insert (PFI) coil is a single layer solenoid completed in 2007 and tested in the bore of the CSMC facility (Fig.3) in Naka in July 2008 [5]. This insert coil tested a long length of conductor very close to that used in the PF1 and PF6 coils as a demonstration of the conductor and joint technology that will be applied to the ITER PF coils and to confirm that the design margin for these coils is adequate to achieve the peak PF6 operating conditions and that the AC losses fall within the expected range of values.

The test programme includes the characterization of the conductor DC and AC performances at the PF1 and PF6 operating conditions, the tracking of sudden quenches, the intermediate joint resistance and the AC loss characteristics of the conductor and variations with cycling.

The consistency among different types of measurements of the same critical point is excellent. and the results clearly show that the quench point (in terms of temperature, current or field) is very close to the expected conductor performance obtained as the sum of the critical current of the single strands evaluated at the peak field in the conductor (Fig. 4).



Fig.3 PFI coil installed in CSMC

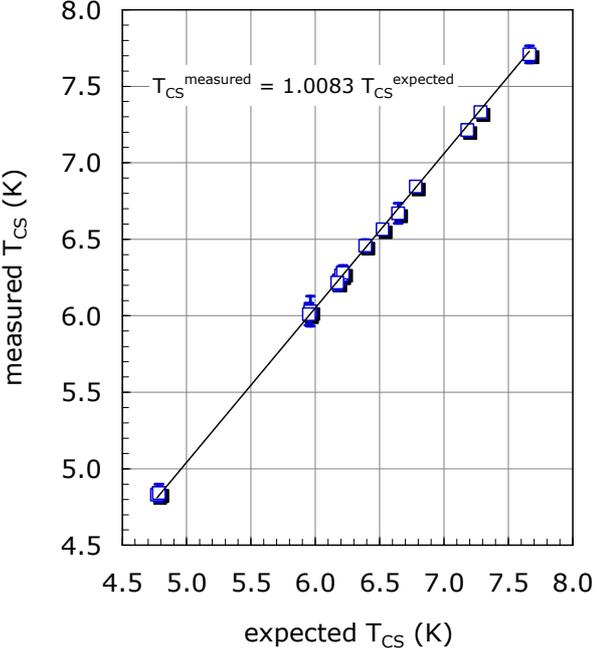


Fig.4 Measured quench temperature vs. expected current sharing temperature

The asymptotic value of the coupling loss constant $n\tau$ is of the order less than 50 ms, in the range of the value expected and well within the range acceptable from the point of view of heat removal.

The PF insert coil performance was excellent, exceeded that of short samples by up to 0.5 K and much better than required to meet the PF coil performance requirements. The test results provide evidence that the PF conductor will perform better than designed, and suggest that subcooling (although included within the design capability) may not be required

4, The CS conductor

CS conductor has somewhat lower magnetic loads than the TF and the superconducting performance is not expected to be such a critical issue. However, the coil relies on the conductor jacket for structural support and a special steel, JK2LB[6], is being developed for this purpose. 400 meters of conductor jacket made from JK2LB steel is being procured by IO for US and will be used for winding trials in the US. At the same time, JA has carried out some trial manufacturing with a dummy Cu cable conductor (Fig 5) and is preparing a CPQS (SULTAN sample Fig 6) to be tested next spring. Considering that the SULTAN test sample

can not simulate the hoop strain effect, IO (in agreement with JA and US) is proposing a modification of the CSMC facility at JAEA to test conductor loops and to enable simulation of hoop strain effects.

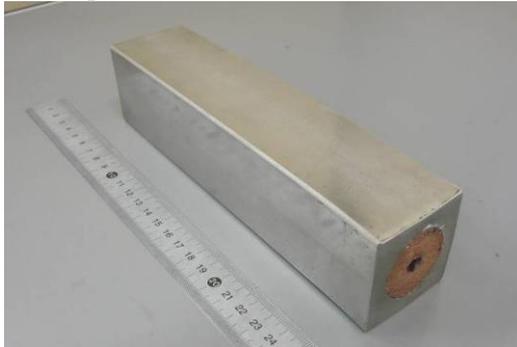


Fig.5 CS dummy conductor

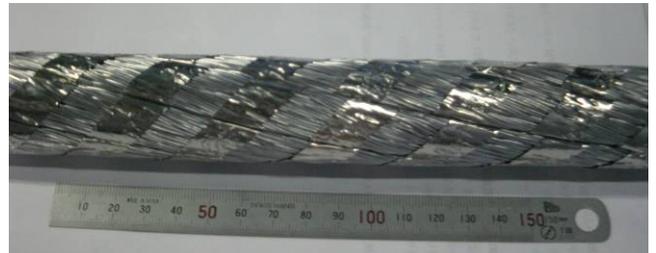


Fig 6 CS cable

5, Radiation Resistant Insulation (EUDA, ATI, CEA)

On the insulation, we well know that the epoxy resin is at the limits of its radiation resistance at the ITER fluence level of 10 MGy (10^{22} n/m²) therefore a new radiation resistant resin based on Cyanate ester has been selected for the TF coils and large scale impregnation trials are underway to demonstrate its compatibility with industrial usage. This resin will provide a radiation life of over 20MGy, twice the original ITER requirement. The Cyanate ester resins are expensive but the cost could be reduced by blending with epoxy.

There are two main R&D issues:-1- the incorrect curing of cyanate ester can lead to exothermic runaway reaction, and -2- the pot life of the resin is very important for the impregnation quality of big size ITER coils. The resin should have enough fluidity and 24-48 hours pot life is required. Impregnation of a TF winding section under industrial conditions has been performed to demonstrate that the reaction can be controlled (Fig 7). The sample fabrication shows that the high steel to resin ratio makes exothermic reaction easy to control, and the pot life of blended CE can be unlimited practically. The characterization of epoxy – CE blend samples shows that blended CE (60 %CE, 40% epoxy) can offer the same radiation resistance, and achieve about two times the ITER design basis with much lower price [7]. Fig 8 shows the Epoxy and Ep oxy -Cyanate Ester Blends radiation resistance test results.

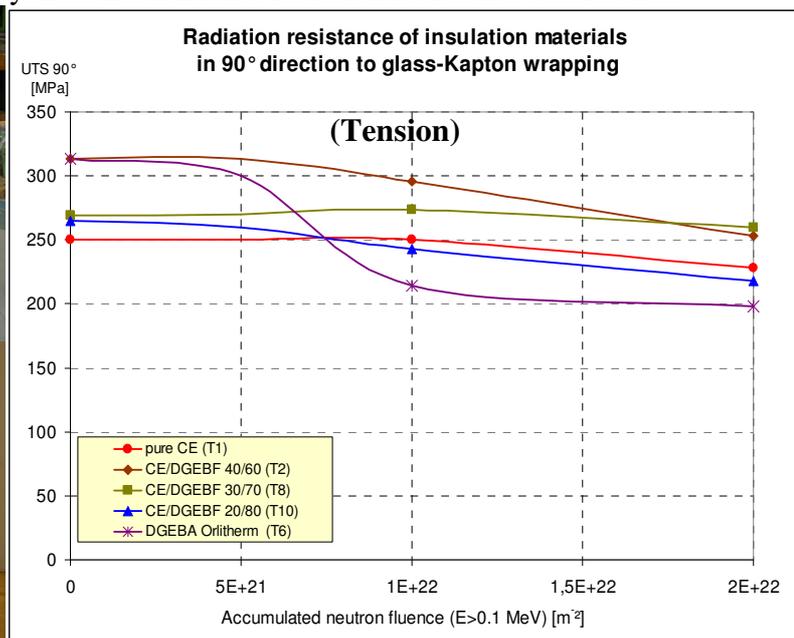


Fig. 7 Epoxy-CE blend sample

Fig. 8 Epoxy-Cyanate Ester blends radiation resistance

6. Precompression Ring R&D (EU and ENEA Frascati)

A critical element of the TF coil structural support system are the pre-compression rings that are used to pre-compress the poloidal keys at top and bottom of the inner straight leg of the TF coils, suppressing gap opening and greatly reducing the cyclic fatigue stresses. These rings are made of impregnated uniaxial glass fibre and are pretensioned at room temperature up to about 300-400MPa.

Two subsize (1/5 scale) rings (Fig. 9) have been tested [8]. The tests have shown failure at stresses well above 1200 MPa, much higher than the design value of 440MPa (Fig 10), and no creep over 120 days at room temperature at stress levels of 990 MPa. After that, the manufacturing procedure was optimised, and five more rings under fabrication. Higher failure stress is expected



Fig. 9 Subsize pre-compression ring

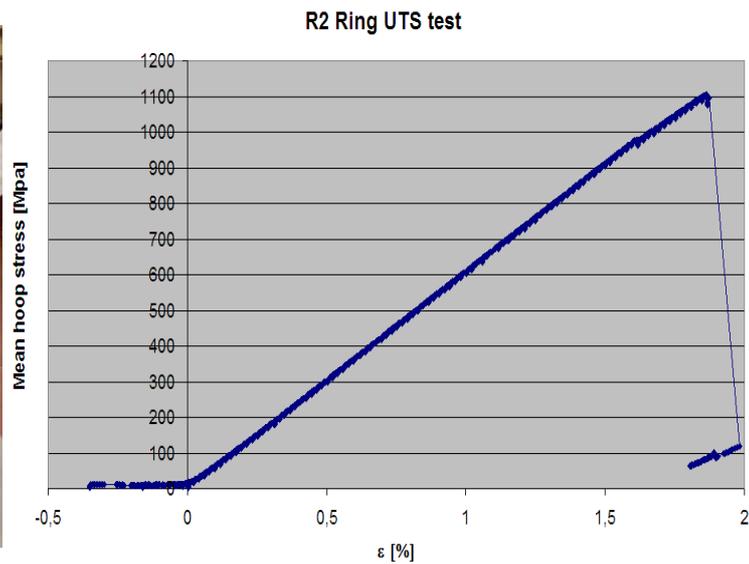


Fig. 10 Test results of R2 ring

7. R&D of TF coil manufacture

The manufacturing optimisation has focused on the TF coil winding, the TF coil radial plates and the TF coil structures. A radial plate is a 14 m × 9 m D-shaped plate having a groove for the conductor on each surface, made of 316LN steel. Tight requirements on dimensional accuracy are required, for example, a flatness of 2 mm over the entire plate. A full scale demonstration on the radial plates manufacturing [9] has been started with industry. In the manufacturing procedures developed so far, seven segments are either machined separately using small milling machines, or formed by laser welding of extruded profiles, and then assembled together by a laser welding machine to form a complete radial plate (fig. 11). The conductor has to be wound to the shape of the groove in the plate with a high degree of accuracy, to enable it to be fitted. A winding machine which achieves the required accuracy has been manufactured and tested. Industrial development of appropriate combinations of forging, welding and machining to minimise costs of the massive steel structures around the winding pack are underway.



Fig 11 Radial plate R&D

8 High Temperature Superconductor (HTS) Current Leads

60 current leads with total nominal current of 2.568 MA are required for ITER magnet system [10]. In the 2001 design conventional current leads cooled by 4.5 K supercritical helium were selected. In order to reduce the load of ITER cryogenic system, HTS leads were proposed and were finally adopted. Compared to the conventional leads, the total electrical power savings generated by the HTS leads in the ITER device will be about 2.5 MW, reducing the operating cost .

The 18 HTS leads for the TF coils are operated in DC and all other 42 (CS, PF and CC) HTS current leads are for pulsed operation. High voltage (30kV to ground) and high current (up to 68 kA) is a challenge and requires a development program. The BiSCCO 2223 HTS current leads for the ITER TF magnet system will be based on the previous experience gathered at FZK, CERN and ASIPP. ASIPP plans to approach the prototype HTS current by 2 steps: the goal of the first step is to design and produce a pair of trial leads with technologies readily available in ASIPP and implement the most important functional specifications. Based on the test results of the trial leads, new technologies required for the prototype lead will be developed and all of the functional specification implemented in a second step. The ASIPP/CN is presently manufacturing a pair of HTS trial leads, to be tested in October 2008. Fig 12 shows the trial 68 kA current lead for TF coil

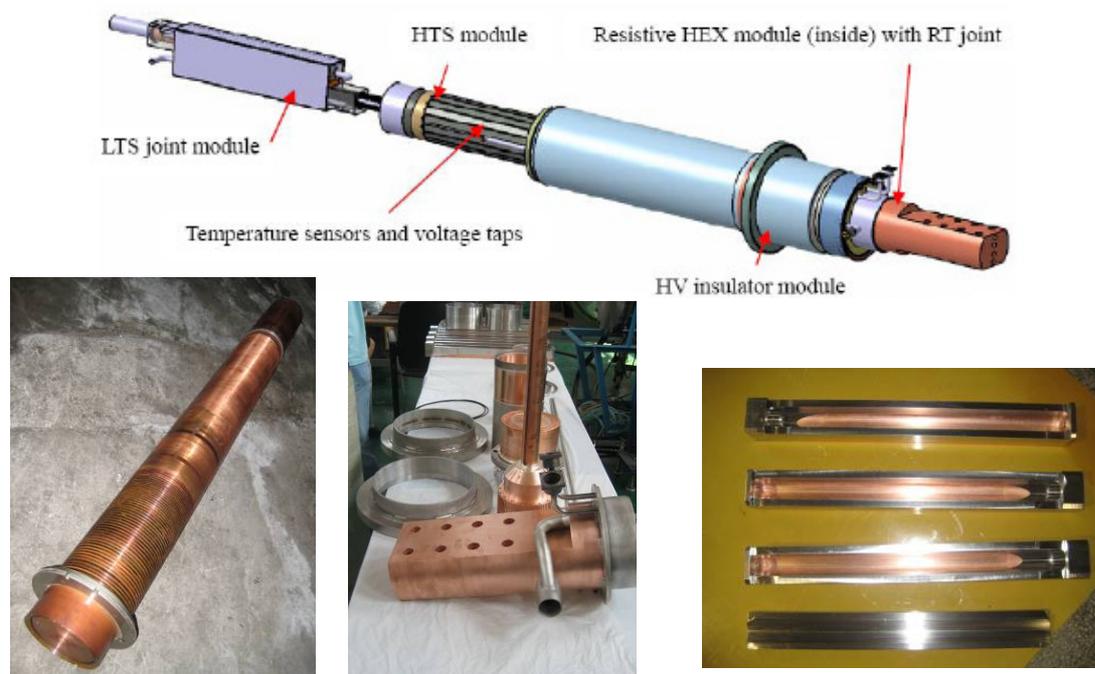


Fig 12 ITER 68 kA TF Trial Lead

9, CONCLUSIONS

The ITER magnet R&D has made very big progress recently. The accumulated data base of SULTAN sample tests have clearly shown that the TF conductor can provide the required performance under the operation conditions. The PFI test demonstrated the conductor and joint technology adopted for PF coils. The conductor DC performance is excellent, the quench point is very close to the expected conductor performance obtained as the sum of the critical current of the single strands evaluated at the peak field in the conductor. The AC loss is as expected and well within the range acceptable. The PFI test results confirmed that the PF conductor can provide the required plasma control ability. The final qualification for CS conductor, high radiation resistance insulation, pre-compression rings, TF coil radial plates as well as HTS current leads is going on, with preliminary results indicating that the key material and technology issues are covered. Basic R&D is completed and the main activity is on prototype testing, detailed design and performance qualification.

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