Key Engineering Features of the ITER-FEAT Magnet System and Implications for the R&D Programme

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Abstract. The magnet design of the new ITER-FEAT machine comprises 18 Toroidal Field (TF) coils, a Central Solenoid (CS), 6 Poloidal Field (PF) coils and Correction Coils (CCs). A key driver of this new design is the requirement to generate and control plasmas with a relatively high elongation (k_{95} = 1.7) and a relatively high triangularity (δ_{95} = 0.35). This has lead to a design where the CS is vertically segmented and self-standing and the TF coils are wedged along their inboard legs. Another important design driver is to achieve a high operational reliability of the magnets, and this has resulted in several unconventional designs, and in particular, the use of conductors supported in radial plates for the winding pack of the TF coils. A key mechanical issue is the cyclic loading of the TF coil cases due to the out-of-plane loads which result from the interaction of the TF coil current and the poloidal field. These loads are resisted by a combination of shear keys and "pre-compression" rings able to provide a centripetal preload at assembly. The fatigue life of the CS conductor jacket is another issue as it determines the CS performance in terms of the flux generation. Two jacket materials and designs are under study. Since 1993, the ITER magnet R&D programme has been focussed on the manufacture and testing of a CS and a TF model coil. During its testing, the CS model coil has successfully achieved all its performance targets in DC and AC operations. The manufacture of the TF model coil is complete. The manufacture of segments of the full scale TF coil case is another important and successful part of this programme and is near completion. New R&D effort is now being initiated to cover specific aspects of the ITER-FEAT design.

1. Introduction

The ITER-FEAT machine is a tokamak with a nominal plasma major radius of 6.2 m and a plasma minor radius of 2 m. The nominal plasma current is 15 MA and the toroidal field at the major radius is 5.3 T. The project goals are to achieve extended burn, for a duration of about 400 s, in inductively-driven plasmas with the ratio of fusion power to auxiliary power (Q) of at least 10 and to aim at demonstrating steady-state operation using non-inductive current drive with Q of at least 5. In addition to these physics goals, the technological objectives are to demonstrate the availability and integration of essential fusion technologies and to test components of a future reactor. Tritium breeding blanket modules are to be tested with an average neutron flux of at least 0.5 MW/m^2 and a neutron fluence of at least 0.3 MW.a/m^2 [1]. These programme objectives require operational flexibility to allow the optimization of performance and the possible future use of new, more advanced, plasma scenarios [2]. An example of this operational flexibility, which is important for the magnet design, is the requirement to be able to operate at a plasma current of 17 MA, albeit with a reduced inductive burn duration.

A key driver of the ITER-FEAT magnet design is to generate and control [3] plasmas with a relatively high elongation k_{95} of about 1.7 and a relatively high triangularity, δ_{95} of 0.35. These plasma-shaping specifications are more demanding than those of the 1998 ITER design [4] and have made it necessary to adopt a design where the CS is vertically segmented into several electrically independent modules in order provide non-uniform current distributions along the vertical axis. These CS modules, six modules in total, require electrical connections which can be located only in an annular gap between the TF coils and the CS. The consequences of the need for independent CS modules and the gap for connections are that the CS must become a pancake-wound, free-standing coil subject to high cyclic tensile stresses. With such a CS design, the TF coils must be self supporting against their centripetal load and, therefore, must be wedged along their inboard legs. These are the main differences between the ITER-FEAT and the 1998 magnet designs where the CS was monolithic and layer-wound, and the TF coils were bucked on the CS [5].

Another important design driver, common to the ITER-FEAT and the 1998 designs, is the need to achieve a high operational reliability of the magnet system. Reliability considerations, and in particular the reliability of the coil insulation, have been given a high priority, considering the size and cost of the magnets and also the difficulties involved in the replacement of any coil. As a result, certain unconventional design features of the 1998 design have been maintained, and in particular, the use of conductors supported in radial plates for the winding pack of the TF coils, and the use of double-turn insulation for the PF coils.

This article focuses on the description of the most distinctive features of the ITER magnet system: the key mechanical issues of the TF coil structure, the TF winding pack design, the CS conductor jacket and the PF coil design. The status and achievements of ongoing R&D is reviewed and new R&D requirements for ITER-FEAT are described.

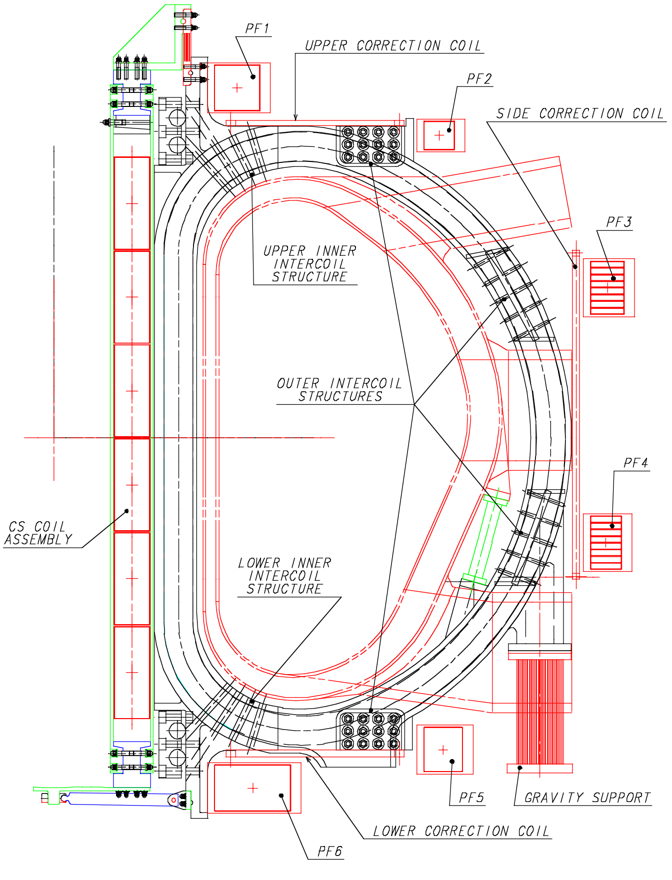

FIG. 1. Elevation of ITER.

2. General Description of the ITER FEAT Magnet System

An elevation of ITER is shown in Figure 1. The magnet system for ITER consists of 18 TF coils, a CS, six PF coils and three sets of CCs. The magnet and structures are surrounded by thermal shields, which intercepts radiation from surfaces at temperatures well above cryogenic temperatures, and are contained inside a cryostat, which provides the vacuum for thermal insulation. The thermal shields and cryostat are not shown in Figure 1.

All magnet structures are designed for 30,000 tokamak pulses at full field and nominal plasma current. The structures are also compatible with limited 17 MA operation without reducing the specified number of 15 MA pulses. The TF coil winding packs are enclosed in cases which constitute the main structural component of the magnet system. The loads which are resisted by the TF coil cases include the forces acting on the TF coils themselves, the vertical loads on the PF coils, the net vertical loads on the CS and the loads on the vacuum vessel which can occur during vertical displacement events of the plasma. This arrangement results in a compact design since loads

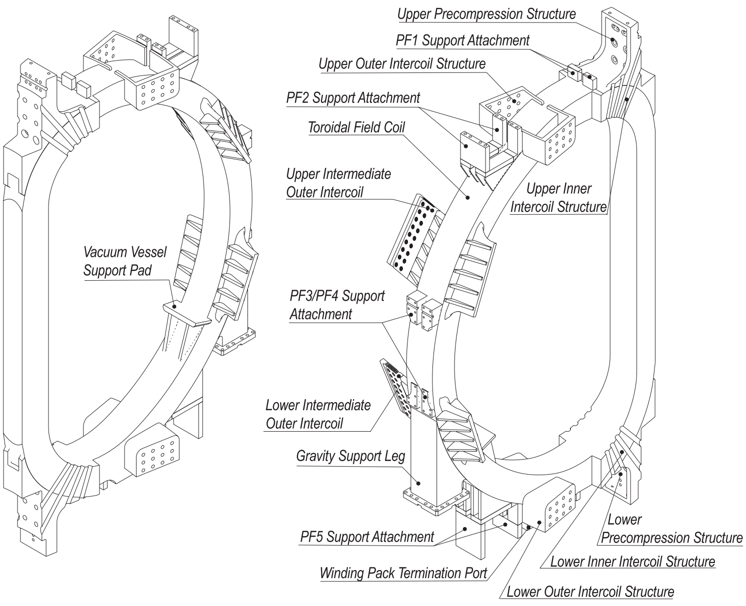

FIG. 2. 3-D view of the TF coil case.

internal to the tokamak assembly are taken up by the TF coil cases without load transmission to external structures. Figure 2 shows a TF coil case with all structural attachments.

The inboard straight legs of the TF coils are wedged to sustain the centering forces. Friction forces at the wedge are able to sustain locally the out-of-plane loads which result from the interaction of the TF coil current with the poloidal magnetic field. At the inboard curved regions of the TF coils, the out-of-plane loads are supported by shear keys which are located between adjacent TF coil cases. In these regions, the coils are linked by means of two upper and two lower pre-compression rings formed from unidirectional glass fibre. The radial centripetal loads provided by these rings ensure that the shear keys operate under toroidal pressure. Along the outboard contour of the TF coil cases, the coils are connected by structures, the Outer Intercoil Structures (OISs), which form four toroidal belts. The top and bottom OISs are box structures consisting of two main shear panels linked by insulated adjustable shear keys. The main function of these OISs is to provide mechanical rigidity during the assembly of the coils. The two OISs above and below the equatorial ports, consist of shear panels which provide torsional rigidity against out-of-plane loads. There is low voltage electrical insulation toroidally between TF coils in the inboard leg wedged region and at the interfaces of the shear keys and OIS connecting elements.

The CS assembly consists of a stack of six electrically independent modules. Six modules are sufficient to generate the full range of plasma scenarios and shapes. The modules are pancake wound with the helium coolant inlets located at the inner diameter of each pancake. Coolant outlets and pancake to pancake joints are located at the outer diameter and superconducting bus-bar connections run vertically in the gap between the CS and the TF coils. The CS stack is hung from the top of the TF coils through its pre-load structure. This pre-load structure, which consists of a set of tie-plates located outside and inside the coil stack, provides axial pressure on the stack, thus avoiding any separation between modules during operation. The CS coil stack is self supporting against the coil radial forces and most of the vertical forces, with the support to the TF coils reacting only the weight and net vertical components resulting from up-down asymmetry of the poloidal field configuration.

The six PF coils (PF1 to PF6) are attached to the TF coil cases through flexible plates allowing radial displacements. The PF coils provide suitable magnetic fields for the plasma equilibrium and control, and their position and size have been optimised accordingly, within the constraints imposed by the access and pumping ducts to the in-vessel components. Because of operational reliability and availability requirements, the PF coil conductor is provided with double-turn insulation. The coils are also provided with some redundant ampere-turn capability. These features are described in section 6.

Outside the TF coils, three independent sets of CCs are located above, at, and below the equator. Each set consists of six coils arranged around the torus. These coils are used to correct error fields, particularly those with toroidal asymmetry, arising from positioning errors in the coils and ferromagnetic materials, and to stabilise plasma resistive wall modes.

All ITER-FEAT coils are superconducting. The CS and TF coils operate at high field and use Nb_3Sn superconductor. The PF coils and CCs operate at lower field and use NbTi superconductor. All coils are cooled with supercritical helium in the range 4.4 - 4.7K.

The weight of the whole machine is supported by 18 gravity supports of laminated construction so as to be flexible in the radial direction while retaining high azimuthal rigidity. At their lower ends, these supports connect to a stiff toroidal ring which is an integral part of the cryostat structure. The Vacuum Vessel is supported by similar supports to TF coil cases. These supports can resist loads resulting from seismic motion.

All TF coils, the CS and the upper outer PF coils are designed to be removable from the machine in case of a major fault. Individual double pancakes of the PF coils may be disconnected and by-passed in-situ in case of fault, since the PF coils have accessible joints located on their external side. In addition, the cryostat design allows the lower (trapped) PF coils to be rewound in situ under the machine.

Table I lists some of the main magnet parameters.

TAB. I: OVERALL MAGNET SYSTEM PARAMETERS

Number of TF coils	18
Magnetic energy in TF coils (GJ)	~ 41
MA.t in TF coils	164
TF coil current (kA)	68
Maximum field in TF coils (T)	11.8
Centering force per TF coil (MN)	403
Vertical force per half TF coil (MN)	205
TF coils discharge time constant (s)	11
MA.t in CS	134
CS current, initial magnetization, [end-of-burn] (kA)	41.5, [45.2]
CS peak field, initial magnetization, [end-of-burn] (T)	13.5, [12.8]
CS discharge time constant (s)	7.5
MA.t in PF coils	60.5
PF coil current, normal operation, [backup mode] (kA)	45, [52]
PF coils discharge time constant (s)	14
Correction coil current (kA)	7.5
Weight of TF coils including structures (t)	5,362
Weight of CS including structures (t)	1,041
Weight of PF coils including clamps (t)	2,595
Weight of CCs including clamps (t)	80
Total weight of magnet system (t)	~ 9,078

3. The TF Coil Structure: Key Issues, Design Solutions and R&D Requirements

Wedged support at the TF coil inboard legs

All along their inboard legs, the coil cases are wedged over their full radial thickness. About 40% of the centring force is reacted through the winding pack of the coil and 60% is reacted by the case. The wedging surfaces must be accurately matched to achieve the required magnetic alignment and reduce stress peaks under the large toroidal wedging pressure of about 590 MPa at the “nose” of the coil cases. Machining of the wedging surfaces will ensure that deviations from flatness have only long wavelength and do not result in localized peak stress. Systematic errors, in particular on the wedge angle, could result in significant stress intensification and must be kept within tolerable limits. Analysis has shown that the wedged surfaces must lie within a tolerance band of 0.2 mm to keep the stress intensification factor within 1.2 which is acceptable. These tight mechanical dimensional tolerances are considered to be achievable by precision machining. Insulation is required between coils to avoid eddy currents. The insulation will consist of a thin layer of epoxy-glass or ceramic coating which must resist the essentially static compressive load of 590 MPa. R&D activities have been initiated to cover this new requirement.

Inner Intercoil Structure

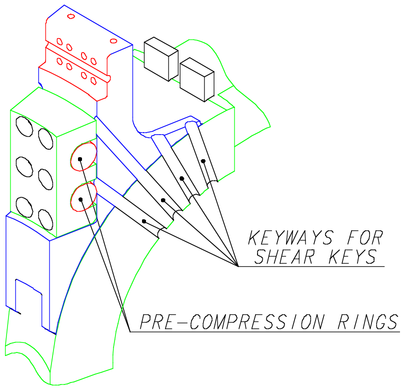

FIG. 3. Inner intercoil structure.

The Inner Intercoil Structures (IISs) are situated at the inboard curved regions, immediately above and below the inboard straight leg of the TF coils. These regions are particularly critical because this is where the out-of-plane loads are highest and the space available for structures is restricted between the TF coils. At each IIS, the cyclic out-of-plane loads are resisted by a set of four shear keys between the coils (Figure 3). The keys run normal to the coil centreline in key slots machined in the coil case which is locally thickened. The keys prevent the development of torsion in the cases which can make a large contribution to the case tensile stresses. At the same time, the relative flexibility of the case in bending gives an almost uniform poloidal distribution of load on the four keys. The shear load per key is in the range of 15 to 19 MN. R&D to verify the shear strength of keys has been initiated.

In the inboard curved region, the coil cases tend to separate on charging due to the overall radial expansion of the coil. Although small, the radial movement is sufficient to create a toroidal gap of about 0.5 mm between key and key slot. During plasma operation, the shear loads acting on the keys tend to increase this gap to more than 1 mm. In order to suppress this undesirable effect, and ensure that the keys do not become loose in their slots, the TF coils are put under a centripetal pre-load at assembly. This pre-load is provided by two pre-compression rings at the top and at the bottom of the TF coil inboard legs. The rings are tensioned at assembly and the load is transmitted by radial bolts to the TF coils which are therefore put into toroidal compression. Analysis shows that with a radial centripetal pre-load of 60-70 MN per TF coil, the toroidal separation in the key region is almost completely eliminated. To be effective, these pre-compression rings need to have a significantly lower elastic modulus than that of the case, so that the pre-compression is not sensitive to assembly tolerances. The rings must be made of a high strength and insulating material. A material which satisfies these requirements is an unidirectional glass fibre-epoxy composite which can be made using a wet glass fibre (S-glass) filament winding technique. The stresses in the rings are limited by pre-tensioning at room temperature since the material is stronger at 4K. There are no significant extra stresses due to the out-of-plane movements of the TF coils. Table II summarises the main requirements for the rings. R&D activities are under discussion to establish the allowable stress and creep behaviour of unidirectional glass fibre composites.

TAB. II: MECHANICAL PARAMETERS FOR PRE-COMPRESSION RINGS

Material	**Tensile stress (MPa)**	**Cross-sectional area of two rings (m^2)**	**Radial displacement to apply pre-compression (mm)**
Fibre Glass	~ 450	0.22	~ 20

The pre-compression rings increase the overall stiffness of the IIS and contribute to lowering stresses in this region. Table III illustrates the structural improvement provided by the pre-compression rings at the most critical area which is just in front of the shear keys at the lower curved region. A fatigue life assessment using Linear Elastic Fracture Mechanics (LEFM) has shown that without the pre-compression rings, the reduction in fatigue life is about 50%.

TAB. III: PRINCIPAL STRESS IN THE TF COIL CASE
IN FRONT OF SHEAR KEYS

	Principal stress (MPa)	**Min/Max stress (R value)**
With Rings	368	0.53
Without Rings	427	0.47

Outer Intercoil Structures

The OISs directly above and below the equator are required to support the out-of-plane forces on the outboard part of the coil. There is a large shear force (in the vertical direction) of about 20 MN acting on each of these OISs. There is also a toroidal tensile load due to the radial expansion of the coil outboard leg. As shown in Table IV, the pre-load provided by the pre-compression rings significantly reduces this toroidal tension to about 8 MN.

TAB IV: TOROIDAL TENSION FORCES (MN)
ACTING ON THE FOUR OISS AT END OF BURN.

	With Rings	**Without Rings**
Upper OIS	5.6	10.5
Upper Friction Joint	8.4	25.3
Lower Friction Joint	0.8	19.4
Lower OIS	6.1	14.4

The poloidal extent of the two equatorial OIS belts is limited by the vertical size of the vacuum vessel ports and, due to this limitation, relatively high cyclic stresses occur at the re-entrant corners where the OISs connect to the TF coil cases. Local structural reinforcements are under study in these regions. In the current design, the OISs consist of shear panels, with a thickness of about 130 mm, protruding from the side walls of the case. Multiple-finger friction joints are then welded to the two adjacent shear panels after survey at assembly. The joints are pre-loaded by two rows of insulated bolts acting on the fingers separated by insulated washers. With the multiple-finger arrangement, the friction surfaces and the shear

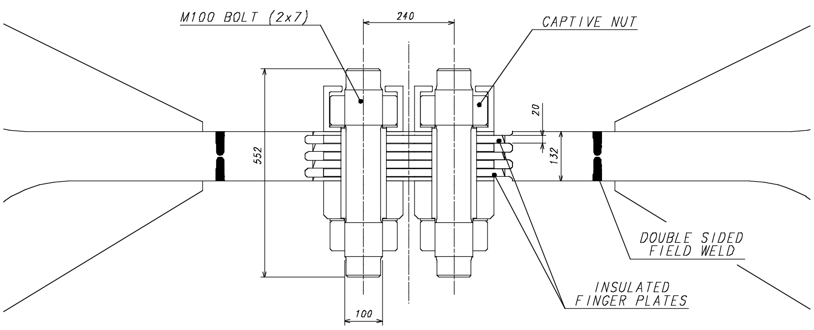

FIG. 4. Cross-section of a friction joint.

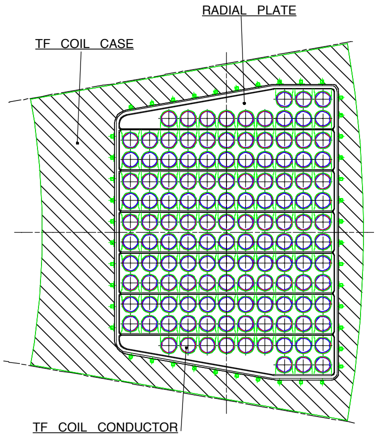

FIG. 5. TF coil winding pack.

capability of each bolt is multiplied by 7. The arrangement of a typical friction joint is shown in Figure 4. The design is being reassessed to see if a pre-welded and keyed/bolted box structure, with a removable central part, can provide adequate out-of-plane support, eliminating in-situ welding.

4. The TF Coil Winding Pack: A Design Driven by Insulation Reliability Considerations

The reference winding pack design is based on the use of circular conductors supported by radial plates, as shown in Figure 5. This design was already used in the 1998 ITER design and has been maintained because of its major advantages in terms of the conductor insulation long-term quality and reliability.

1. A circular outer cross section of the jacket is the optimum shape for applying insulation tapes, resulting in a robust turn insulation. With the circular shape, the turn insulation is not subject to the stress concentration effects which are always present at corners of square conductors.

2. During the magnet operation, the Lorentz forces acting on each conductor are transferred to the plate, without accumulation of forces on the conductor and its insulation. As a result, almost no primary load is applied to the conductor insulation and there is no degradation leading to damage due to mechanical cycling.

3. With circular conductors in radial plates, delamination between the conductor insulation and the radial plate is of no consequence and has no impact on the mechanical or electrical behaviour of the winding pack.

Additional advantages of the radial plate configuration are that it provides a “double insulation” with two physically independent barriers (the turn and the ground insulation) and it gives the capability of detecting impending faults by monitoring the resistance between conductor and radial plate. The considerations above indicate that with this configuration, faults leading to a TF coil short are essentially avoided by design. The radial plate concept has already been fully demonstrated in the TF Model Coil Project [6]. The main drawback, however, is the relatively high manufacturing cost of the radial plates. R&D activities have been initiated to investigate potentially cheaper manufacturing routes.

5. The Central Solenoid: A Design Dominated by the Fatigue Life of the Conductor Jacket

The solenoid is free standing and supports the magnetic loads through structural material within the winding. The main load is the magnetic hoop force, which creates tension in the structural material. Because of its central position in the tokamak, the CS has a major role in driving the radial build while itself forming a fairly minor fraction of the total magnet cost (about 12%). Global optimisation studies have shown that in order to minimize the total cost of the machine, it is preferable to adopt the most compact, high field design option, even if it is not the lowest cost choice for the CS itself. As illustrated in Figure 6, the flux generation in the solenoid is improved by the choice of a high field and the use of the highest allowable tensile stresses in the jacket material. For ITER-FEAT, a peak field of 13.5 T and a tensile peak stress of about 430 MPa have been selected to meet the flux generation requirements. The peak stress is within the fatigue allowable for Incoloy.

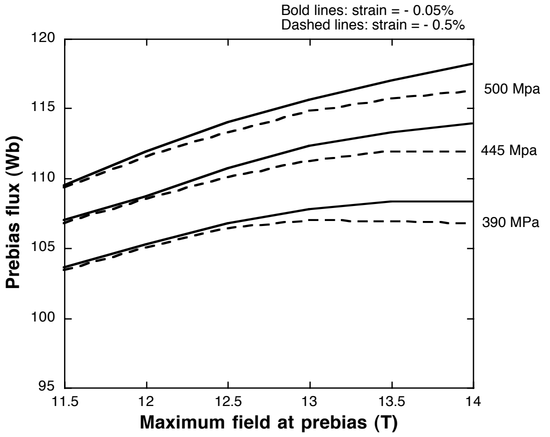

FIG. 6. Prebias flux available from an optimised CS as a function of field, showing variation with allowable peak tension and superconductor strain.

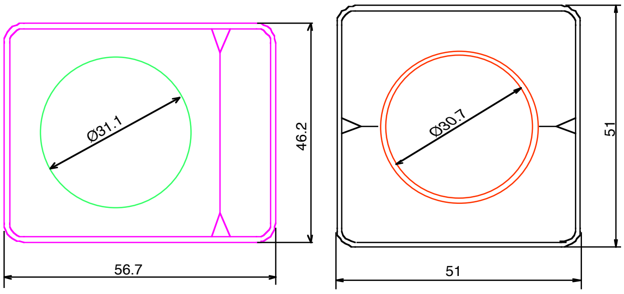

FIG. 7. CS conductor jacket options: Incoloy 908 option (left) with reinforcing strip Double jacket option (Ti-SS) (right).

The requirements for the CS conductor jacket material are, therefore, primarily a high fatigue resistance to stress cycling. There are two basic design options for the CS jacket, as shown in Figure 7, both of which are expected to provide the same flux capability:

1. An extruded, Incoloy 908, jacket with a square outer section. The jacket material is subjected to the Nb_3Sn heat treatment.
2. A double jacket including an inner titanium circular jacket, which undergoes the Nb_3Sn heat treatment, and an outer stainless steel jacket made up of two U-channels which are applied around the inner jacket after the heat treatment.

Incoloy 908 has significant advantages in terms of its very high fatigue resistance and its thermal contraction which matches that of Nb_3Sn. The use of Incoloy has been successfully demonstrated in the CS Model Coil [7]. Incoloy 908 is, however, sensitive to stress accelerated grain boundary oxidation (SAGBO) during the Nb_3Sn heat treatment and requires strict control of the heat treatment atmosphere ($O_2 < 0.1$ ppm) [8]. The double jacket option does not require such strict control procedures for the reaction treatment. For this option, JK2 is proposed as the material of the outer jacket. This material has a coefficient of thermal contraction close to that of Nb_3Sn between room temperature and 4K. However, JK2 is not fully characterised at cryogenic temperature, especially for fatigue properties. R&D activities have been initiated to demonstrate the manufacture of U-channels and to establish the fatigue properties of modified stainless steels, including JK2. To verify allowable stress levels, fatigue testing of both versions of the conductor will also be carried out. At present, Incoloy 908 is selected as the provisional reference solution and the Ti-JK2 option is kept as an alternative solution. The final choice will be based on the R&D results.

The pancake-wound ITER-FEAT CS design, as opposed to the layer-wound 1998 CS design, includes new features which require some R&D verification. *Helium inlets* are no longer conveniently located at the conductor extremities, but are at the conductor mid-length (in the case of double pancakes). The inlet preparation requires an opening, together with suitable reinforcements, in the wall of the conductor jacket. The helium flow distribution in the superconducting cable also requires verification. The *joints between the CS pancakes* are located in the annular gap between the TF coils and the CS. This exposes the joints at the top and bottom ends of the CS to transverse field that can drive eddy currents across the joint surface. There is little data on the performance of lap joints in this configuration as they did not occur in the 1998 design. Test programmes for these items are under discussion.

6. PF Coil Design: A Design Driven by Reliability and Availability Considerations

The PF coils are pancake wound with NbTi superconductors in square jackets. Because of the operational reliability requirements, especially for the electrical insulation, and the difficulty in replacing a coil, the conductor is provided with double turn insulation. The double turn insulation consists of two insulation layers with a thin metal screen in between. Double pancakes are wound two-in-hand. This arrangement allows detection of an incipient short before it develops into a full short resulting in significant damage to the coil and, as a consequence, the need for a major coil repair or replacement. In the event of the detection of an incipient short in a double pancake, the faulty double pancake must be disconnected and by-passed using bus-bar links. This work is to be carried out hands-on and requires access to the joint regions at the outer diameter of the coils. Following the by-pass of a double pancake, plasma operation can continue at full performance by using the remaining double pancakes at higher current (backup mode). For PF2, PF3, PF4 and PF5, the conductor is designed to allow the backup mode without any need to decrease the conductor operating temperature. In the case of PF1 and PF6 that are operated at higher field, sub-cooling at inlet temperatures below 4.2K would be required.

The use of double turn insulation and the ability to continue operation with a by-passed double pancake should make a major coil repair or replacement unnecessary throughout the life of ITER-FEAT.

Should, however, such major repair be required, the following strategy could be followed:

- The upper coils, PF1 and PF2, can be relatively easily removed from the cryostat. For them, major repair work, or rewinding, should be carried out outside the cryostat.
- For the lower coils, PF5 and PF6, major repair work, including rewinding, should be carried out under the machine inside the cryostat.
- PF3 and PF4 are trapped by the Vacuum Vessel ports and are the most difficult to access and repair. For this reason, their resistance to faults has been enhanced by using double pancakes with individual ground insulation and metal plate separators between double pancakes to limit damage propagation in the event of a fault.

7. A Successful R&D Programme Fully Relevant to ITER-FEAT

The Model Coil Projects were launched in 1993 to drive the development of the ITER full scale conductor, including the manufacturing of strand, cable, conduit and termination, and the conductor R&D in relation to AC losses, stability and joint performance. These projects also drive the supporting R&D programmes on coil manufacturing technologies, including the entire winding process (wind, react, and transfer), electrical insulation and quality assurance. These objectives are still fully relevant for ITER-FEAT.

The total planned production of 29 t of Nb_3Sn strand, from seven different suppliers throughout the four ITER Parties, has been completed and qualified. This reliable production expanded and demonstrated the industrial manufacturing capability which will be required for the production of 480 t of high performance Nb_3Sn strand for ITER-FEAT.

Central Solenoid Model Coil Project [7]

FIG. 8. CS model coil and CS insert installed in the vacuum chamber at the test facility in JAERI Naka. The preload structure (upper beams and tension rods), helium pipes and tops of the coils are visible.

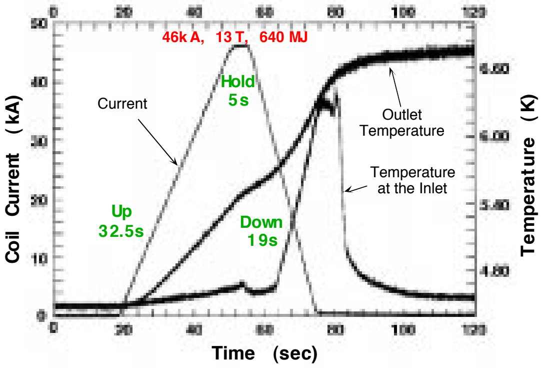

FIG. 9. Ramp-up to 46 kA, 13 T, with an inlet temperature of 4.5 K at a ramp rate of 0.4 T/s, flattop of 5 s, followed by ramp-down to zero at 0.7 T/s. The outlet temperature increased to 6.8 K after the pulse.

For the CS model coil, the cabling, jacketing and winding techniques have been established and all these activities have been completed. The heat treatment to react the superconducting alloy without degrading the mechanical properties of the Incoloy 908 jacket, is a critical step which has also been successfully completed. The manufacture and assembly of the inner module (USA), the outer module (Japan), and the insert coil (Japan) were completed before the end of 1999 (Figure 8). In April 2000, the maximum field of 13 T and stored energy of 640 MJ, at a maximum current of 46 kA, have been achieved in the ITER dedicated test facility at Naka-JAERI (Figure 9). This full charge has been followed by a comprehensive test programme including current-sharing temperature measurements, fast ramp-up and discharges, and current and field cycles simulating the ITER CS operation. Although the analysis of the data is not complete, it is already clear that the performance of the CS model coil is according to expectations and meets the full size CS operation conditions. A 10,000 cycles fatigue test of the insert coil has also been completed and results are under evaluation. It must be noted that the size of the CS model coil (3.6 m in diameter and 2 m in height) is almost the same as the size of a ITER CS module (4 m in diameter and 2 m in height) and the maximum field and coil current are also the same.

Toroidal Field (TF) Model Coil Project [6]

FIG. 10. Winding TF model coil conductor into mould

FIG. 11. Forging of inner leg curved section of TF coil case as hollow tube.

For the TF model coil, forging and machining of the radial plates have been completed. Cabling, jacketing, winding, reaction treatment and transfer of the conductor on the radial plates have also been successfully demonstrated (Figure 10). The coil manufacture, including the final impregnation of the winding pack inside the coil case is completed. All this work has been performed in the European Union. The coil testing is expected to start during the first half of 2001. The model coil will be tested first on its own and later in conjunction with the LCT coil [9] in the TOSKA facility at FzK (Germany). With the LCT coil, a field of 9.7 T at 80 kA will be achieved. By comparison, the peak field and the operating current are 11.8 T and 68 kA in ITER-FEAT. The model coil uses a cable similar to the full size TF coil cable and the cross section of the TF model coil is smaller but comparable in size to that of the ITER TF coil.

A test up to 13 T of the TF insert coil with a single layer will be performed in the CS model coil test facility at JAERI. This insert coil will be completed in the Russian Federation this year. A 1 km jacketing test, which exceeds the ITER-FEAT requirements, has been separately demonstrated in the Russian Federation.

For the development of the manufacture of the TF coil case, large forged (Figure 11) and cast pieces (about 30 t and 20 t respectively) have been produced in the EU. The use of forgings and castings is attractive since it is expected to result in significant cost reductions as compared to a manufacture based on welded plates. Investigation of the properties of the forging has revealed values exceeding the requirements of 1000 MPa yield stress and 200 MPam$^{1/2}$ fracture toughness, with low fatigue crack growth rates. The casting also shows properties adequate for the low stress regions of the case (yield stress about 750 MPa). Welding trials have demonstrated successful welding of the cast to forged sections, and have established welding procedures for the case sections and the final closure weld of the half cases.

New R&D activities

New R&D requirements have been identified to improve the database, allow cost reductions and address technology needs specific to the ITER-FEAT design. As already indicated, they cover the insulation materials and shear keys, the pre-compression rings of the TF coil structure, the TF coil winding pack, the materials and manufacturing technology database for the jacket of the CS conductor, and the CS pancake joint performance.

An R&D programme on NbTi conductors and joints for the PF coils is also under preparation. NbTi R&D is not specific to the new ITER design but, due to resource limitations, it was not included in the 1992-1998 R&D programme. The programme should include investigations of strand coatings for AC loss control, AC loss measurements, and testing of conductor and joint samples. The manufacture and testing of a NbTi Insert Coil is an important part of this programme.

6. Conclusions

The ITER-FEAT magnet design is well advanced, design solutions have been identified and are in the process of detailed design. The R&D programme launched in 1993 is near its conclusion. This programme is fully relevant to ITER-FEAT and has confirmed the industrial feasibility of the conductor and the magnets. The experimental results achieved with the CS Model Coil and CS Insert are excellent and confirm the adequacy of the conductor to meet the ITER CS operation conditions. New R&D activities have been launched to facilitate cost reductions and address technology needs specific to the ITER-FEAT design.

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This report is an account of work undertaken within the framework of the ITER EDA Agreement. The views and opinions expressed herein do not necessarily reflect those of the Parties to the ITER EDA Agreement, the IAEA or any agency thereof. Dissemination of the information in this paper is governed by the applicable terms of the ITER EDA Agreement.

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