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The ITER Magnets: Design and Construction Status

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***Abstract*— The ITER magnet procurement is now well underway. The magnet systems consist of 4 superconducting coil sets (toroidal field (TF), poloidal field (PF), central solenoid (CS) and correction coils (CC)) which use both NbTi and Nb_3Sn-based conductors. The magnets sit at the core of the ITER machine and are tightly integrated with each other and the main vacuum vessel. The total weight of the system is about 10000 t, of which about 500 t are Nb_3Sn strands and 250 t, NbTi. The reaction of the magnetic forces is a delicate balance that requires tight control of tolerances and the use of high-strength, fatigue-resistance steel forgings. Integration and support of the coils and their supplies, while maintaining the necessary tolerances and clearance gaps, have been completed in steps, the last being the inclusion of the feeder systems. Twenty-one procurement agreements have now been signed with 6 of the ITER Domestic Agencies for all of the magnets together with the supporting feeder subsystems. All of them except one (for the CS coils) are so-called Build to Print agreements where the IO provides the detailed design including full three-dimensional CAD models. The production of the first components is underway (about 175 t of Nb_3Sn strand was finished by July 2011) and manufacturing prototypes of TF coil components are being completed. The paper will present a design overview and the manufacturing status.**

***Index Terms*—Magnetic confinement, Superconducting magnets, Fusion reactors**

I. Magnet Requirements

A. Operational Performance

THE function of the ITER magnets, Fig 1, is to form, control and drive the tokamak plasma [1]. For this purpose, the Toroidal Field (TF) coils will provide a steady field of 5.30T at a radius of 6.20m. The Central Solenoid (CS) and Poloidal Field (PF) coils will be capable of 30000 inductively driven 15MA plasma pulses with a burn duration of about 400s. Hybrid and non-inductive plasmas will also be within the coil capabilities (where the plasma current duration is extended by non-inductive current drive methods), with burn durations up to 12000s. An extensive database of plasma scenarios (coil currents and plasma details) has been simulated and is used to confirm the coil capabilities [2]. The CS and PF coils are designed also for feedback control of plasma disturbances at frequencies up to the 100Hz range.

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In terms of the number of operational cycles for other conditions, the coil system is designed for 100 cooldown and warm-up cycles, 1,000 TF charging cycles, 50 TF fast discharges and 10 TF quenches. A fast discharge of the CS or PF coils is less onerous than the reference inductive plasma cycle and so no extra limits are imposed.

Achieving reliable quench detection for the coils [3] is critical for successful operation, not only because of the obvious need to protect against coil damage but because false positives will interrupt machine availability, especially of the TF coils. The magnet quench detection system will be able to distinguish between superconductor quench and the electromagnetic perturbations caused by a plasma disruption with a reliability of >90% for the CS, Correction Coils (CC) and PF coils and >99.9% for the TF coils. The quench detection system of the coils (particularly the TF) must be designed to allow possible tuning during commissioning as experience with plasma behaviour is obtained. The magnets need not be ready for further operation (i.e. completely recooled) until 96hrs after a fast discharge of the TF system. In the event of a fast discharge of only CS, PF or CC, the magnets will be re-cooled ready for further operation within 2hrs. In the event of a fast discharge of any or all of the magnets, the Helium expelled from the system will be collected and stored. There is negligible expulsion from CS, PF or CC during a fast discharge but, due to eddy current heating of the radial plates, almost all the TF helium is expelled as the temperature rises to about 50-60K.

The magnet system cooldown will not occur at any time faster than 1K/h and the maximum temperature difference between inlet and outlet supplies will be 50 K. It will be demonstrated by analysis that the maximum temperature differences inside the modules and structure do not exceed 50 K. Cooldown from RT to 4K will be achieved within 30 days.

B. Tolerances

Tolerances are essentially in any real engineering component and affect the ITER coils in three ways. Firstly, the departure from ideal shapes and locations of the coils generates so called 'error field'. Approximately, the allowable departure from axisymmetry of either toroidal or poloidal field is about $3x10^{-4}$ T [4]. The correction coils are placed and sized so that they can correct the most significant error modes in the poloidal field (up to mode 3 in either poloidal or toroidal directions). The two main sources of the error field are the unpaired lengths of busbars that are required to connect the coil terminals to the main cryostat feeders, though it is second order. The second source (more significant) arises from coil positioning errors. Secondly, the penalty for allowing increased tolerances is generally that high strength structural material is lost, replaced by weak filler material. A margin of 10% is allowed in the design between maximum allowable stresses and those calculated by stress analysis for the ideal geometry, to allow for geometric imperfections. Thirdly, the coils and their connections must all fit together when installed in the cryostat, maintain minimum clearances (generally a minimum gap of 50mm is required between components with independent flexing) during operation between themselves and also to surrounding components such as the Vacuum Vessel.

Detailed and self-consistent tolerances have been developed for all the magnet components, considering these three requirements and the various manufacturing operations. Costs are reduced by avoiding tight tolerances and a balance has to be maintained between performance and latitude allowed to suppliers.

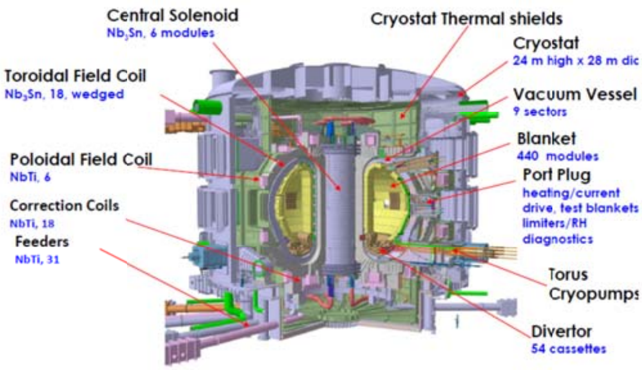

Fig. 1. Overview of ITER and the Magnet System

C. *Nuclear heating*

The design decision was made during the ITER Engineering Design Activity (1993-2001) to limit the nuclear heating from the reference 500MW plasma to 14kW, a level comparable with that of the AC losses, in the range 10-20kW when averaged over a 1800s plasma cycle. This is compatible with the cable-in-conduit conductor design with a central cooling channel, prevents the nuclear heating dominating the cryoplant size and assists in smoothing the cryoplant loads (as AC losses concentrate in the ramp up and ramp down times when there is no nuclear heating). At the same time, some options are available to operate with extra nuclear heat loads if nuclear heating predictions turn out to be inaccurate. This is achieved by adjusting the cryoplant operating conditions and/or the plasma pulsing rate (i.e. trading of nuclear vs AC losses).

D. *Helium cooling*

The coils are cooled with supercritical Helium at an inlet temperature of 4.5K (corresponding to a heat exchanger bath at 4.2K). This temperature provides good heat capacity of the helium flow and matches both Nb_3Sn operation in the range 12-13T (for the TF and CS coils) and NbTi operation up to 6T for the PF.

For any set of coils, the heat exchanger bath may be reduced from 4.2K to 3.8K to allow the capability to correct possible faults or design/analysis errors discovered in operation (for example, an underestimate of the nuclear heating or a drop in conductor current sharing temperature).

E. *Safety*

Because of the severe effect of magnet faults on the overall machine availability, and the difficulty of repair, there are multiple monitoring and protection systems built into the design. These include inherent features, detection/monitoring systems (that operate continuously while the coils are charged), and testing systems (that are applied periodically when plasma pulsing is interrupted or when the magnets are discharged). Particular attention is paid to reducing the probability of potential cascade sequences, where the existence of an initial fault increases the probability of others (for example, heat from a short degrades a protection barrier or increases local voltages), and common mode faults where several components (due for example to a common manufacturing error) have the same initial fault.

From the safety viewpoint the magnets contain high forces and high stored and mobile energy. So there exists theoretical potential to impact neighbouring systems which include tritium confinement barriers, either by heating or by impact. Studies have shown that all magnet faults are confined with the magnet system with the possible exception of an undetected coil quench (when >10kg of liquid metal may be sprayed on to the vacuum vessel). A separate safety class quench detection system has been included for the TF coils, located outside the cryostat in the Helium lines, fully independent (pressure based) and separated from the normal quench detection system, to prevent such an initiating event.

F. *Operational Margins and Performance Verification*

The coils have been designed with superconducting margins based on the results from the ITER model coil program in the EDA phase of the project, supplemented and updated by tests on short conductor samples. The margins, in terms of allowed degradation of the superconductor that can occur before the machine operation is compromised, are conservative. They typically allow for a 30% loss of superconductor area while maintaining the full operation temperature margin of 0.7K. Since superconductor degradation is also generally associated with a more gradual superconducting transition (the so-called n value), the full operation can be maintained beyond this level of degradation if the coil cooling is increased.

Margins also exist to cover uncertainties in the coil operating conditions, particularly for nuclear heating and plasma disruptions.

G. *Repair*

Some in-situ repair possibilities are built into the magnet system, as follows:

In situ repair (in all cases hands-on access is required, possibly with local removal of the thermal shield):

- Retightening of the CS precompression structure. A loss of 5% of the initial precompression is required to be within the design capability. Above this the situation must be reviewed and operating window restrictions may be imposed until retightening can be scheduled.
- Retightening of the TF Precompression rings. A loss of 5% of the initial pretension is required to be within the design capability. A review is required if operation is continued with a higher loss.
- Retightening of bolts on TF gravity support plates, CC support plates and PF coil clamps
- Bridging of a failed PF double pancake
- Repair of He pipes and He inlets in the CS bore and at TF and PF coil terminals

Removal (medium difficulty):

- Extraction of CS stack (no removal of feeders/coils)
- Removal and replacement of TF Precompression rings (this requires removal of the CS)
- Removal of PF1
- Replacement of inner poloidal keys (partial removal of CS and PF1/6 coils)

Removal (high difficulty):

- Removal of a TF coil
- Removal of PF2

To ease removal of the CS (which may be required for replacing the Precompression Rings) the upper connections of the CS to the feeders are aligned to allow the CS stack to be lifted vertically once the joints are opened, without removal of the feeders.

Because of the long timescale and high cost of manufacturing replacement coils once manufacturing is complete and tooling is dismantled, one spare CS module and one spare TF coil are included in the procurement. It is as a result a requirement that all CS modules are interchangeable.

Certain large components can only be placed in the lower cryostat during assembly. Therefore, 3 spare precompression rings and jumpers for the PF coil double pancake bridging are stored below the tokamak assembly in case of need.

II. System Overview and Integration

The overall operational requirements of the magnets define the basic functionality but obviously leave open many design choices, many of which affect also the design of the rest of the machine. The following section gives a brief summary of the final design choices. More details are given in [5].

The magnet system for ITER consists of 18 TF coils, a CS coil stack with 6 coil modules, six PF coils and 18 Correction Coils (CC), Fig 1 and Table 1. The 18 TF coils determine the basic toroidal segmentation of the machine and were chosen to meet the requirements of access ports (both number and size) and the ripple at the plasma edge.

Both CS and TF coils operate at high field and use Nb3Sn-type superconductor. The PF coils and CCs use NbTi superconductor. All coils are cooled with supercritical Helium with a coil inlet temperature of 4.5 K. The conductor is a cable-in-conduit conductor with a circular multistage cable consisting of about 1000 strands cabled around a small central cooling spiral tube. The cable is contained in a circular jacket for the TF coils or a jacket with an outer square section for the other coils. The operating currents are 40-45 kA for the CS, 45-55kA for the PF coils and 68 kA for the TF coils. The CCs use a reduced size conductor, 16kA, with about 300 strands and without the central cooling channel.

The coil electrical insulation system is composed of multiple layers of polyimide film-glass impregnated with epoxy resin (a radiation hard cyanate ester based resin in the case of the TF coils). Epoxy-glass and filled epoxy resin is used extensively to fill tolerance gaps.

The TF coil case encloses the winding pack and is the main structural component of the magnet system [6]. The TF coil inboard legs are wedged all along their side walls in operation, with friction playing an important role in supporting the out-of-plane magnetic forces. In the curved regions above and below the inboard leg, the coils are structurally linked by means of three upper and three lower precompression rings formed from unidirectional bonded glass fibre and by four upper and four lower sets of poloidal shear keys arranged normal to the coil centreline. In the outboard region, the out-of-plane support is provided by four sets of Outer Intercoil Structures (OIS) integrated with the TF coil cases and positioned around the perimeter within the constraints provided by the access ducts to the vacuum vessel. The OIS form four toroidal rings and act as shear panels in combination with the TF coil cases. The TF conductor is contained in grooves on each side of flat D shaped steel radial plates. Seven DPs are assembled together to form the winding pack of one TF coil.

The CS assembly [7] consists of a vertical stack of six independent winding pack modules, which is supported from the bottom of the TF coils through its pre-load structure. The pre-load structure consists of a set of toroidally segmented tie-plates located at the inner and outer diameters of the coil stack. It provides axial pressure on the stack through key blocks . The CS modules use a square section jacket which is self-supporting against the radial and vertical magnetic forces.

The six PF coils (PF1 to PF6) [8, 9], are attached to the TF coil cases through flexible plates or sliding supports allowing radial displacements. The square conductor provides the coil structural support.

Outside the TF coils, and mounted on their cases, are located three independent sets of CC [10], each consisting of six coils arranged around the toroidal circumference above, at and below the equator. Within each set, pairs of coils on opposite sides of the machine are connected in series.

The coil supplies (helium, current and instrumentation [11]) are grouped into feeder ducts [12, 13] that run from outside the cryostat, initially within cryostat extensions and then inside the main cryostat, largely above and below the coils. The valves, current leads and instrumentation cubicles are placed in galleries just outside the bioshield [14]. The current leads make use of HTS technology [15].

TABLE 1 COIL MAIN PARAMETERS

Parameters	TF	CS	PF
Number of coils	18	6	6
Number of turns per coil or WP	134	549	115-459
Stored magnetic energy GJ	41GJ	7	4
Maximum operating current kA	68	45	45
Nominal peak field T	11.8	13.0	6.0
Electrical discharge time constant*s	15	11.5	18
Conductor total length m	82260	36114	63142
Coil total weight (with case and structures) t	298 (1 coil)	954 (all)	2163 (all)
S/C strand total weight t	410	104	240
Winding Pack weight t	110	688	1361
Coil Case weight t	188t	NA	NA
Centring force per coil	403MN	NA	NA
Vertical force per coil, max MN	NA	327	160
In plane bursting force per half coil MN (max for CS and for each PF)	205	220	43,13,30, 19,64,54
Length of the coil centerline m	34.1	10.7	25-75
WP Conductor length	4570m	6019	6009-14067
Conductor Unit Length Range m	760/ 415	903/601	387-879
Cross section of the steel at TF inboard mid plane (jacket + RP, case) or in coil section (CS, PF) m^2	0.562	0.86	0.44,0.2 0.32,0.29 0.37,0.82
He mass flow rate in conductor g/s	8	8	8-14
He mass flow rate of structures kg/s	2.5	←	←

*Note that this is the overall thermal equivalent exponential value as temperature dependent resistors are used and there is a detection delay time

III. ASSEMBLY

This section is a brief summary of the main assembly steps.

The lower PF coils (P5 and P6) and the lower Correction Coils (CCs) are the first coils to be placed in position, on temporary supports at the bottom of the cryostat. Various elements of the support structure are also put in position at this time (such as the lower precompression rings and the gravity supports). The feeders for the side and lower correction coils (the lower header rings) are also positioned.

The TF coils are assembled in pairs in the assembly hall at the ITER site as part of a 1/9 vacuum vessel sector complete with its thermal shield, Fig 2. The tightly toleranced interface regions between the two coils will have been precision machined in the factory but additional shimming can be provided as required. The upper and lower OIS acts as the reference surface and joint to link the coils for this operation. Each coil has a thin 'sandwich' of insulation, contained between two steel sheets, that is fixed to one of the coil wedging surfaces (welded or bonded) during manufacturing, and shims can be attached by welds to the outer sheet. Slots for the shear keys are oversized to allow the use of slot liners which are custom machined to achieve a tight fit of the shear keys in those liners.

The assembled 1/9 machine segments are transferred to the pit in the tokamak hall, Fig 2. The vault structure of the TF coil inboard legs is built up circumferentially, with correction of the accumulated assembly error by shims every 3 pairs if necessary (although the intention is that the coils are machined accurately enough to avoid shimming at assembly).

The upper and lower OIS structures again act as reference surfaces for the assembly operation. Once the vault structure is complete, the remaining OIS keys are installed. After the OIS panel structure linking the outer legs is complete, the upper and lower precompression rings are installed and pre-tensioned. The ring pretensioning can be adjusted to compensate for any settling effects. Retensioning, if necessary, can be performed with the CS in-situ.

All Corrections Coils (lower, side and upper) are then attached to the TF coil cases. The PF coil installation starts with a survey of the support positions on the TF coil cases. If required, appropriate shims are prepared and installed before the PF coils are attached to the TF coils.

Coil current centre alignment could be done on the basis of the geometry of the winding pack, measured at the final stages of manufacturing. However, direct measurement of the locus of the current centre line is expected to be possible at room temperature with a small AC current in the coil to an accuracy better than 1mm. A prototype system is being developed [6].

The feeder installation (apart from the CC header ring) is the next step in the magnet assembly. Those under the machine are either lowered into position through the bore of the TF coils or brought in through the side ports.

Finally, the CS is assembled outside, complete with its preload structure and all terminals and cooling pipes. It is then lowered into the inner bore of the TF coils and attached to the supports at the bottom of the TF coil inboard legs.

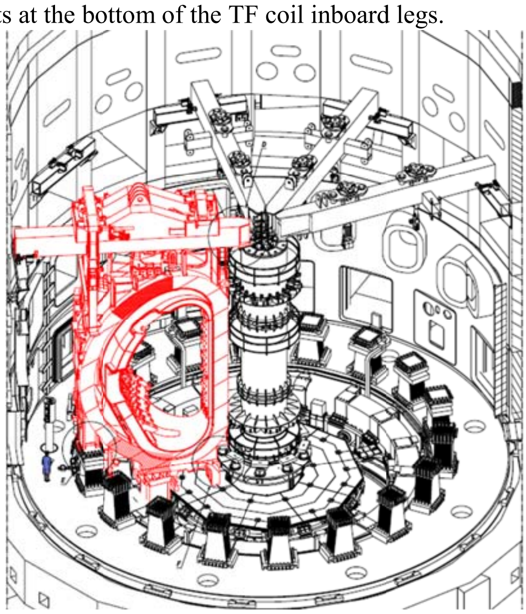

Fig. 2. 1/9 VV segment and 2 TF coils, with temporary supports, inside the cryostat

IV. Manufacturing

In this section we give a brief description of the manufacturing operations for the main components. This is the reference scheme originally foreseen for the coils and for which the design is optimised. Individual Domestic Agencies, responsible for the procurement, may adjust this in the interests of cost reduction.

A. Conductor

The components of the conductor are the superconducting strands, copper wires, an open spiral that forms the central cooling channel, steel wraps for AC loss barriers to cable substages and for protection of the final cable, and extruded sections of the jacket (either circular for the TF coils or a square outer section with a circular hole for the CS a nd PF. The manufacturing is illustrated in Fig 3 [16]. The strands and copper wires are cabled to a multistage circular cable, the final substage of which has 6 'petals'. The 7-11m jacket sections, 1-2mm oversize on the cable, are butt welded together to form a full unit length (this process allows easy weld inspection and testing) before the cable is pulled into it. The jacket is then compacted by rolling, onto the cable. The process requires careful control of dimensional tolerances so that the cable can fit the jacket with a 1-2mm clearance and a pulling force <5t, without excessive compaction that is detrimental to the jacket mechanical properties (it has to wi thstand the Nb_3Sn heat treatment without grain boundary sensitisation).

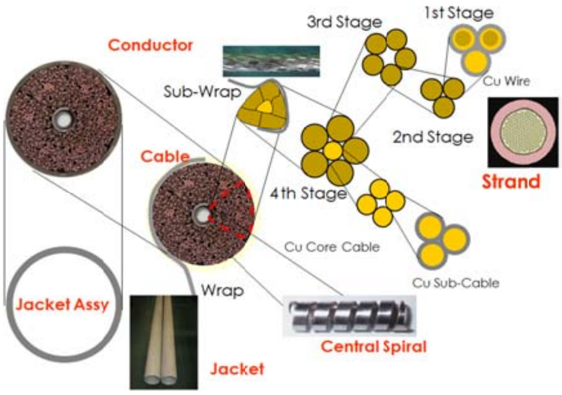

Fig. 3. Steps in Conductor Manufacturing Process

B. TF Coil Winding Pack

The conductor is wound into a mould holding the shape of the conductor during the reaction heat treatment [17, 18]. During the manufacture of the TF Model Coil, it was found that the conductor may experience a permanent elongation after the heat treatment up to 0.05%. During heat treatment, the conductor is held flat by clamps but is allowed to move radially. The initial winding dimensions must take account of this possible change in length after heat treatment so that the reacted conductor can fit in the RP grooves.

Once the DP is wound but before heat treatment, the conductor jacket at the i nner transition region is opened and the helium inlet formed. The conductor terminations are also formed after winding but before heat treatment of the conductor. They consist of the terminals (2 per WP) and the DP to DP joints (6 per WP).

The conductors are then heat treated (about 650°C for 200hrs) in a furnace with a controlled inert atmosphere. After heat treatment, the top and bottom single pancakes are moved vertically up and down respectively to create a gap b etween them and allow the removal of the mould. The RP is then inserted between the two separated pancakes as shown in Fig 4. The removal of the mould and the insertion of the RP are complex operations requiring a purpose-designed handling tooling and a special set of insertion movements. The allowable maximum strain on the conductor (±0.1%) limits the pancake separation.

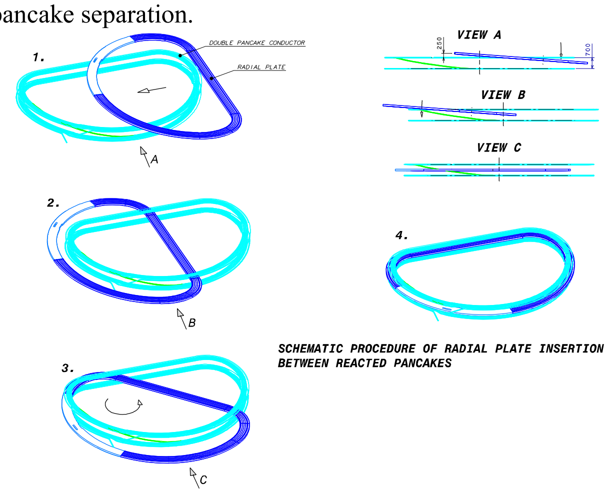

Fig. 4. Transfer of Conductor DP from Mould to Radial Plate

The conductor is then locally lifted to allow the application of the turn insulation. The correct alignment between conductor and RP groove has to be maintained during this process, using marks and adjusting the number of outer glass wraps, to prevent a progressive buildup of misalignment. The width of the RP grooves is adapted to allow a s mooth embedding of the reacted conductor and accommodate winding tolerances and possible permanent elongations of the reacted conductor. The clearance between conductor and groove is 3mm in the upper and lower region and 2mm in the outboard region. The resulting gaps will be filled with glass cloth shims during application of the turn insulation.

The RPs are thick plates made of austenitic stainless steel, type 316LN. The manufacturing process for the RPs relies on machining of plates (produced by hot rolling, forging, or hipping [17, 18]) to form sub-sections which are assembled by welding. The butt welding is simplified by maintaining rectangular butt sections and completing the radial grooves after welding, by local machining. A final machining of the plates is possible in case that the groove needs to be adjusted to fit the final shape of the conductor.

Each jacketed conductor is locked in the RP groove by means of a cover plate (CP). The CPs have holes at 20cm spacing to enable resin flow during the vacuum pressure impregnation (VPI) process. The CPs a re fixed by laser welding with a continuous seam of at least 1mm depth in the outboard leg and at least 2mm depth in the in-board.

The whole DP assembly, with ground and conductor insulation, is then vacuum-pressure impregnated in a mould.

C. TF Structures

Each leg of the TF Coil Case (TFCC) is formed by a sub-assembly of 4 components, with an inner U-section and a closure plate sub-assembly [19].

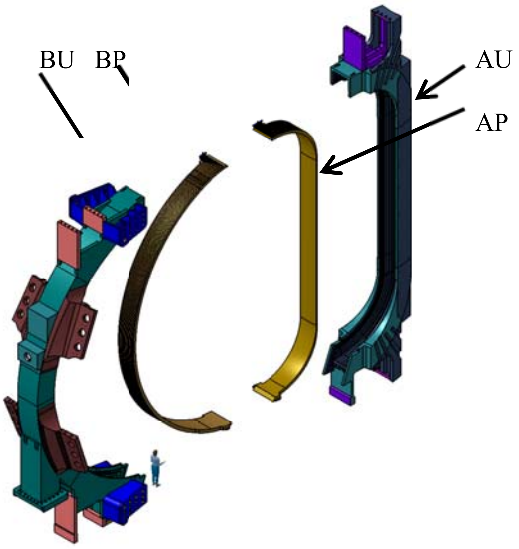

Fig. 5. The 4 Sub-Assemblies of the TF Coil Case

Both U-section sub-assemblies have numerous integral structural attachments such as the Intercoil structures, the pre-compression flanges, the TF coil support leg, and attachments for the CS, PF, CC, vacuum vessel thermal shield (VVTS) supports and machine assembly tooling.

The casing operation comprises three main phases [20]:

- Insertion of the WP into the case;
- Closing by welding the TFCC elements;
- Final impregnation of the TFCC-WP gaps.

The final tolerances acceptable on individual coils are determined by the coil fit during assembly in the cryostat, together with the allowable magnetic field errors and the maintenance of operational clearances. The tolerances on case sections, winding pack and the casing operation are balanced to give maximum manufacturing latitude. The individual subassemblies are built up by a succession of forging, machining, welding and machining steps. The key to cost reduction in this process is a predictable and localized weld distortion so that the number of machining steps, and the amount of overmetal, are minimized and eliminated on the final closure welds.

The AU sub-assembly is the key to maintaining the tolerances. The flat inner surface of the AU sub-assembly will provide precise geometric location and uniform force transfer interface for the winding pack. The base line design requires the installation of a customized shim over the complete interface with a precise flatness and perpendicularity tolerance. The angular faces of the AU sub-assembly are defined with a wedged 20° angle. These faces will define the plane for reference to the current centre line plane of the WP during insertion and they then are used as references for the location of the TF coil in the ITER machine, Fig 6.

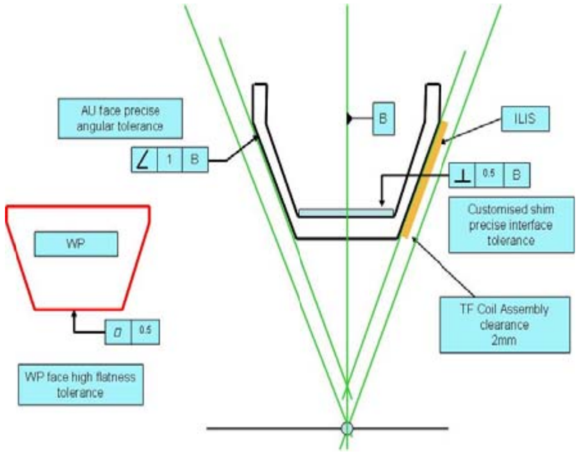

Fig. 6. Key Interfacing Planes and Surfaces on Sector AU

The case sub-assemblies are designed with assembly clearance gaps to the WP. The design clearance will be 7mm (WP angled faces and WP-AU) or 10 mm (WP vs BU–AP–BP). The goal of these clearance gaps is to remove the requirement for tight tolerances on all the WP-TFCC mating surfaces and to allow alignment of the WP relative to the TFCC at insertion. The final geometric location and force transfer between the WP and Case will be achieved by filling the inter-space with a charged epoxy.

The WP will be lowered into the AU element, aligning the WP by means of an overhead bridge crane and three alignment guides. The alignment guides will align the WP while it is slightly lifted over its final position so its weight is still taken from the crane and the guides do not have to apply a large force, Fig 7. Pre-machined G10 shims will be placed on the AU surface to support it.

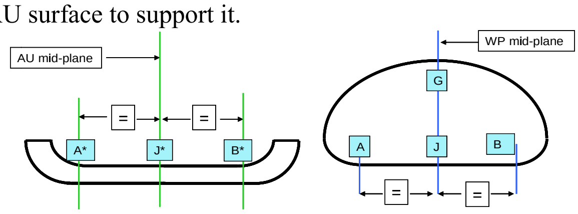

Fig. 7. WP and Case Mid-Planes and Reference Points for WP Insertion in AU Sub-Assembly

The BU sub-assembly will be lifted using tooling and bracing to minimize distortion. The sub-assembly will be lowered over the WP and the interfaces to the AU sub-assembly brought into location. The matching of the weld preparation surfaces will be checked and the geometric location of the BU reference marks surveyed with respect to the AU reference marks and the WP fiducials.

There is a two stage weld sequence. An initial laser root weld of 10–20mm made with the TF coil in the vertical (insertion) orientation. A final structural weld made by the Submerged Arc Method (SAW) with the TF coil rotated to the horizontal position. This weld is to be made after filled resin impregnating the WP to TFCC gap is completely cured.

After welding of the AU-BU interface it will be necessary to block the WP relative to the TFCC structure in order to remove the WP support jigs and braces; this is necessary to insert the final case sub-assemblies AP and BP. At this stage the CCL fiducial marks of the WP will be transferred to the TFCC prior to closing it with the sub-assemblies AP and BP. When fiducial marking transfer is complete, cover plates AP and BP will be installed. The first step will be the laser root welding of the closure plates. After the closing of all welds with laser techniques and the WP-TFCC gap filling by vacuum pressure impregnation with a resin/filler [6], the TFC will be rotated to the horizontal position for completion of the case welding by Submerged Arc Weld (SAW).

D. Gravity Supports

The TFC assembly rests, via 18 Gravity Supports (GS), on a tokamak pedestal ring supported by 18 columns off the concrete floor slab of the tokamak hall. The GS consists of a flexible plate assembly (FPA), clamping bars, studs and bolts, as shown in Fig. 8. The FPA is pre-assembled in the factory from 21 flexible plates (with cooling pipes and thermal shields sections attached), separated by 20 short spacer plates at top and bottom. The FPA components are pressed together at top and bottom between pairs of horizontal pre-stressing bars by tie-rods. The FPA is designed with sufficient pre-compression and friction to prevent both sliding and separation between its components.

The FPA of each GS flexes within allowable stresses to accommodate the radial thermal contraction of the TFC assembly. But the GS is rigid versus cyclic out-of-plane bending caused by TFC torsion during plasma operation, and versus vertical and horizontal forces parallel to the flexible plates due to deadweight, asymmetric plasma VDE and earthquakes. The 18 GS transmit these loads to the pedestal ring, which is an integral part of the cryostat structure.

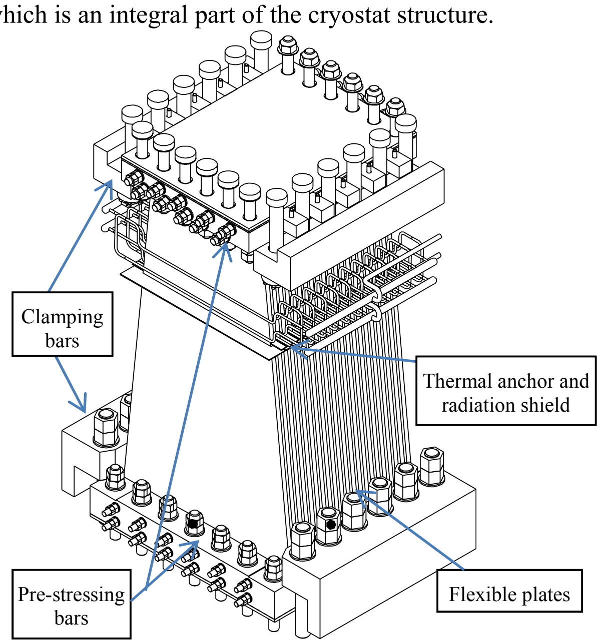

Fig. 8. Details of a Gravity Support

E. PF Coils

A simplified flow diagram of the PF coil manufacturing process is shown in Fig. 9. Starting from the conductor spools, two in hand Double Pancakes (DP) are wound, insulated, vacuum-impregnated with resin, then stacked to form coils, and bonded with a further vacuum impregnation step.

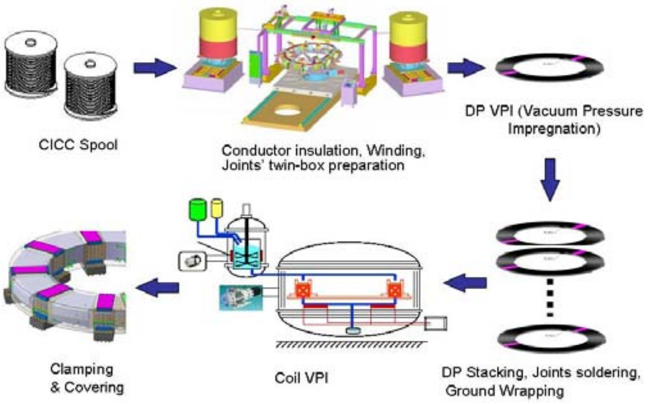

Fig. 9. Simplified flow diagram of the PF coil winding, impregnation, and assembly

Tolerance control is required throughout the manufacturing to ensure that subcomponents interface correctly. The manufacturing scheme has therefore been defined with an allocation of overall tolerances in the coil current centerline position at the different manufacturing stages, and the possibility to allow reductions in position errors during the winding – DP stacking. Assembly errors and manufacturing errors for the PF coils are defined in Fig. 1. The target tolerances for the PF coil winding pack are defined in Table 2.

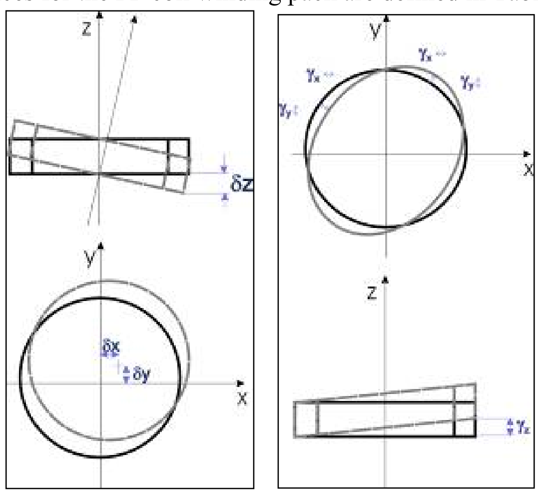

Fig. 10. PF Coil Tolerances

TABLE 2 TARGET TOLERANCES FOR PF COILS IN MM

	Manufacturing			Assembly		
Coil	γx	γy	γz	δx	δy	δz
PF1, 6	± 3	± 3	± 3	± 2	± 2	± 1
PF2, 5	± 3	± 3	± 3	± 2	± 2	± 1
PF3, 4	± 4	± 4	± 3	± 2	± 2	± 1

The shaping of the termination is performed after completion of winding. This operation is needed to allow the proper fitting of the final fillers into the winding pack. To do this, a portion of conductor (about 3 m) is opened, the turn insulation is removed and the joggling is performed by shaped moulds, brought close the winding table.

The winding DP is then placed in a mould and vacuum impregnated with resin. During this process, the conductor ends, which carry the terminations to be used for the joints between double pancakes, must be kept unbonded to the winding pack over a length of typically 5m. This is to provide the required flexibility when the joints are made. These conductor ends are, therefore, provided with an anti-adhesive wrap before impregnation. This wrap is removed after impregnation.

The DP is heated-up to about 80 degrees, by passing current through the conductor. At the same time the resin is put under vacuum, degassed and heated up to 80 degrees. Once the DP is hot it is put under vacuum. The resin flow starts at the lowest point of the DP, in single location, and gets out in the diametrically opposite position, at the highest point of the DP. The resin is forced to face the bottom surface of the DP and to flow through the winding to reach to the surface of it. The DP sides have no resin passages. The whole impregnation is performed slowly, to allow the resin to wet the insulation, to take advantage of the capillary effect and to avoid creating trapped bubbles in the winding.

After the impregnation is complete, the DP is put first at atmospheric pressure and then brought to an overpressure. This helps to reduce and diffuse eventual trapped micro-bubbles of inert atmosphere into the resin bath. Then, with the DP under pressure, the Curing Cycle takes place, for about 24 hours at around 130 degrees.

Eight DPs are assembled together to form the winding pack of PF 1,3,4,5 coil and six and nine DPs are assembled together for PF 2 and 6 winding pack respectively. For handling, the DP is clamped and lifted at a large number of locations by a suitable Jig to avoid local turn deformation and relaxation. A layer of dry glass is placed between the individual DPs to allow resin penetration and bonding during the vacuum impregnation of the ground insulation and to absorb tolerance variations in the gap between the DPs.

Following VPI of the winding pack, cooling pipes for helium inlets and outlets, and manifolds are pre-assembled and connected to the helium inlets and outlets. An insulation break is attached on each inlet and outlet. All cooling pipes are wrapped with individual ground insulation up to the insulation breaks.

F. CS Coils

Conductor winding is shown in Fig. 11. Each conductor length is received on a spool and is used to wind either a hexapancake (HP) or a quadpancake (QP). The conductor is unwound from the spool to pass through a straightening unit before reaching the winding table. The conductor is wound without any insulation, which implies that spacers are regularly inserted between turns and pancakes to account for the further installation of the insulation. Multiple pancake winding with a single length means that winding is alternatively performed inwards and outwards in successive planes, starting and ending on the outside. The winding is circular, which means that the radius of curvature is constant along a turn, with the exception of the joggle area where the conductor is moving from one turn to the next. This is achieved through a short straight section followed by a curved section. Much attention has to be paid to this area since any error in the starting point could impact the geometry of the next turn. The correct bending radius of the conductor in each section is achieved using a set of bending rollers located at the entrance of the winding table. Most of the winding is planar, with the exception of the pancake to pancake transition, performed alternately at the inner and at the outer radius.

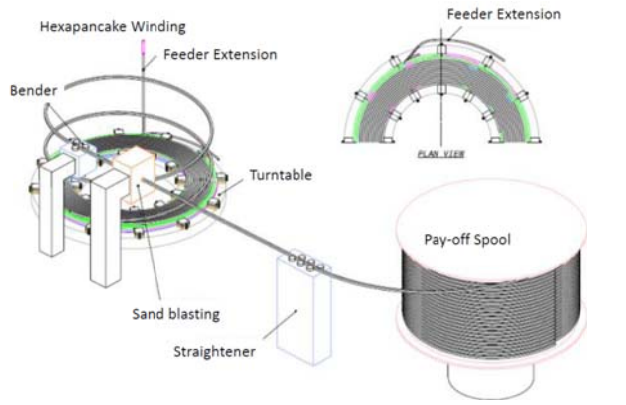

Fig. 11. CS module winding

The location of the He inlets and outlets is only defined after winding the HP or QP once the future location of the inner and outer tie plates is estimated. The conductor jacket is then locally machined in order to insert the prefabricated cover including the He inlet or outlet.

Once the upper terminal is manufactured, a clamping system is installed around the hexapancake or quadpancake and it is transferred to the heat treatment oven to form Nb_3Sn.

The whole stack of wound conductor is clamped and transferred to the insulation station. In order to allow space to install the wrapping tool, the conductor is progressively unsprung by removing the spacers and lowering down the turn to be insulated and putting it in its final position. A continuous control of the position of the insulated turns is performed and interturn and interpancake glass cloth layers inserted to fill the space. The ground insulation is installed around the whole module at the insulation station.

The impregnation mould is installed around the coil. He inlets and outlets are plugged to avoid any penetration of resin during impregnation. Resin is injected inside the mould from bottom to top so as to avoid bubble formation.

18 outer tie-plates and 9 inner tie-plates are manufactured. These tie-plates are either cut from cold worked and shot peened laminated plates or machined out of forged pieces. They can be split into three parts (two ends and a central section) welded together, since the thickness of the ends is larger than that of the central part. The only machined surfaces are the flat surfaces which transmit the load to the keyblocks, and the holes for bolting the tie-plates to the keyblocks.

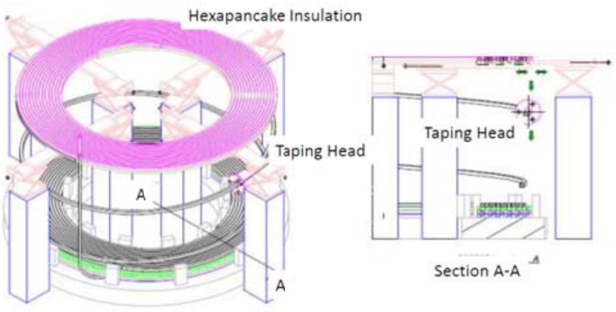

Fig. 12. Installation of the conductor insulation during CS winding

The stacking is performed in the assembly hall and requires the use of a special support able to withstand the weight of the CS plus temporary structures. The support must be very rigid as the key blocks must remain in a plane within 1 mm. The deformation should be such that the stacking of the modules remains perpendicular to the reference plan determined by the keyblocks. Slots are provided in the support to allow vertical movement of the modules with their busbar extensions. A template is first installed on the stacking support to simulate the 9 supports located at the bottom of the TF coils. Then the lower keyblocks are installed and bolted to the stacking support. The G10 buffer plates are installed after having determined the correct thicknesses of the lower and upper ones taking into account the real height of each module. Then they are machined in order to have the CS equatorial plane located with the correct offset to the machine equatorial plan at room temperature. The tolerances for the CS modules are given in Table 3 (see Fig 10 for notation).

TABLE 3: TARGET TOLERANCES FOR THE CS COILS MM

Each CS module	γx	γy	γz
Manufacturing	+/-2	+/-2	+/- 1
	δx	δy	δz
Stack assembly *	+/- 3	+/- 3	+/- 0.5 (CS3L) linearly to +/-2 (CS3U)
Installation **	+/-2	+/-2	+/-0

* Change in δx and δy between adjacent modules < 2 mm
** extra δx, δy identical for all modules at installation

The precompression system is then installed at the top of the CS assembly. A set of supernut bolts is used to apply the precompression by pulling simultaneously on all the tie plates. This is achieved by tightening progressively the bolts so that the tensile load is equal in all tie-plates. When enough gap is provided, shims are inserted between tie-plates and keyblocks. After insertion of the shims and tightening of the horizontal screws, the bolts are unscrewed to release the load on the threads.

V. CONCLUSIONS

The main requirements, design and manufacturing routes for the ITER coil system have been described. Construction of the components is underway and the many technical challenges are being successfully solved.

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