The ITER Central Solenoid

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***Abstract*— The Central Solenoid for the International Thermonuclear Experimental Reactor (ITER), a fusion tokamak experiment with the goal of generating 500 MW of fusion power with high gain (Q>10), must provide most of the volt-seconds needed to induce and sustain a 15 MA plasma for burn times of > 400 s. The 6.4 GJ Central Solenoid design requires a 45 kA conductor and has a peak field of 13 T. The Central Solenoid consists of six pancake-wound modules, stacked vertically, and held in axial compression by an external structure. The five-stage cable has 1/3 copper and 2/3 advanced Nb3Sn strands in a thick superalloy conduit and is cooled by the forced-flow of supercritical helium through the cable space. Key design issues include the qualification of a conduit with adequate fatigue strength, avoiding filament damage from transverse Lorentz loads, eliminating axial tension in the winding insulation, and qualification of space-saving intramodule butt joints.**

Keywords- fusion reactors, ITER, superconducting magnets, superconductors, cable in conduit

I. INTRODUCTION

THE International Thermonuclear Experimental Reactor (ITER) is the flagship project of the world fusion program [1]. This superconducting tokamak reactor has the goal of generating 500 MW of fusion power with long burn times (300-500 s), a Q (fusion/external heating power) higher than 10, and steady-state discharges with Q>5. Success in ITER should enable a fusion demonstration power plant. The nominal ITER plasma has a current of 15 MA with a capability of 17 MA. The plasma current is induced by a superconducting, air-core transformer primary, called the Central Solenoid (CS). The CS coils must initiate, ramp-up, and sustain the plasma, during the entire burn, then ramp it down in a controlled manner. To do this, a volt-second swing of 277 Wb must be achieved by a combination of the CS and a separate Poloidal Field (PF) system that shapes the plasma. In order to generate the volt-seconds needed in the available space, a peak flux density of 13 T is required in the CS coils, along with a stored energy of 6.4 GJ [2], [3]. Inducing the plasma rapidly enough to balance losses requires field ramping up to 1.3 T/s.

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The Central Solenoid system appears as six rectangular winding pack cross-sections about the vertical axis in Fig. 1. The 15 MA plasma is induced in the large D-shaped vacuum vessel.

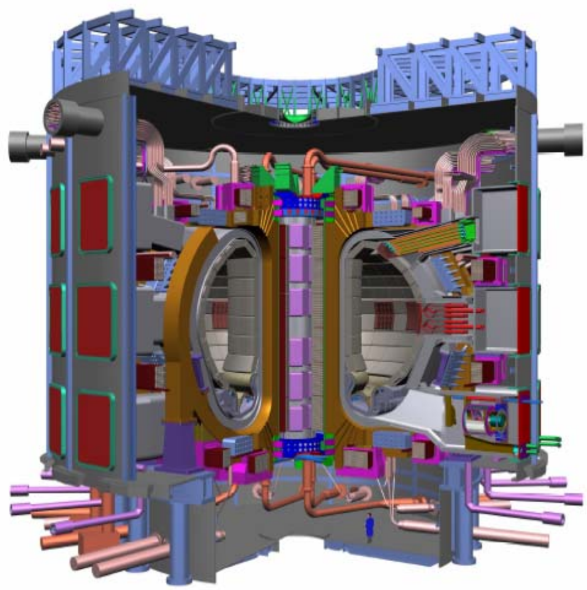

Fig. 1. The ITER tokamak nuclear island. Central Solenoid six modules at vertical axis

II. CENTRAL SOLENOID SYSTEM DESCRIPTION

A. *Overall CS System*

The six coils in the Central Solenoid system are ramped up and down in a complex scenario, in order to induce and control the tokamak plasma. The reference 15 MA scenario with a 300 s plasma flattop and an 1800 s duty cycle [2], [3] is shown in Fig. 2.

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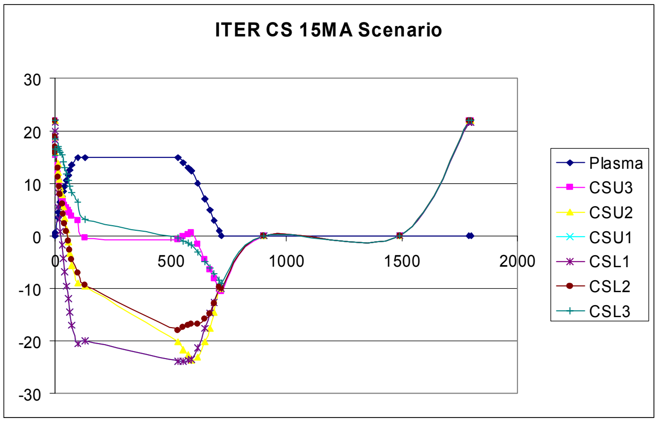

Fig. 2: CS Currents (MAT) vs. Time (s) for ITER 15 MA Scenario

The six module Central Solenoid Stack has a diameter of 4.16 m and a height of over 12 m. The dimensions of an individual Central Solenoid module are listed in Table I.

TABLE I
CENTRAL SOLENOID MODULE MAJOR DIMENSIONS

Parameter	Units	Value
R_1	(m)	1.36
R_2	(m)	2.08
H	(m)	2.075
NI	(MAT)	24.66
nturns		548
npancakes		40
nlayers		14
$L_{conductor}$	(km)	5.94

The peak flux density in the Central Solenoid is 13 T and the peak conductor current is 45 T with a flux density of 12.6 T. The coil is ramped moderately rapidly with a peak ramp rate of 1.3 T/s. The overall stored energy of the Central Solenoid, as a stand-alone system is 6 GJ. Major performance values of the Central Solenoid system are listed in Table II.

TABLE II
CENTRAL SOLENOID MAJOR PERFORMANCE VALUES

Parameter	*Units*	*Value*
B_{max}	(T)	13
I_{cond}	(kA)	45
dB/dt	(T/s)	1.3
W_m	(GJ)	6.4
V-s swing	(Wb)	277*
M_{wp}	(tonne)	600
L_{cond}	(km)	35.6
$M_{Nb3Strand}$	(tonne)	138**
$M_{conduit}$	(tonne)	470**

* including. PF
** 7 modules, purchased

The CS system is supported from the top of the TF coil system by the CS Upper Supports, as shown in Fig. 3. Nine vertical precompression straps are used to compensate for cooldown and current distributions during part of the scenario that would put some of the CS interpancake insulation in tension. In order to get precompression during cooldown, the steel precompression straps have a higher coefficient-of-expansion (COE) than the winding pack. To obtain additional compression, the use of preheating during assembly or epoxy-inflated bladders are being considered. The precompression straps are bolted to a spring assembly that controls the strap tension, before cooldown. There are three pairs apiece of copper coil termination flags above and below the CS winding stack, carrying current to the upper and lower modules, respectively.

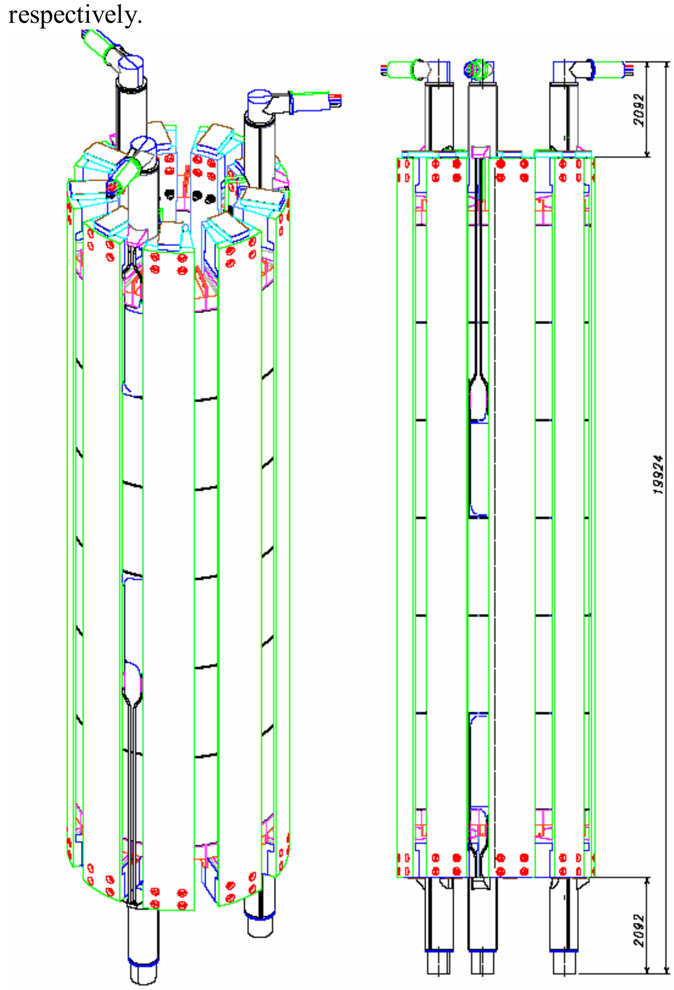

Fig. 3: Isometric and elevation views of CS system

Six identical modules, indexed 60 degrees between each module, are stacked to form the CS module assembly. Each module consists of six "hexa" pancakes and one "quad," where the hexes and quads are 4 and 6 pancake submodules. There are external joints between the hex pancakes and between the final hex and the quad

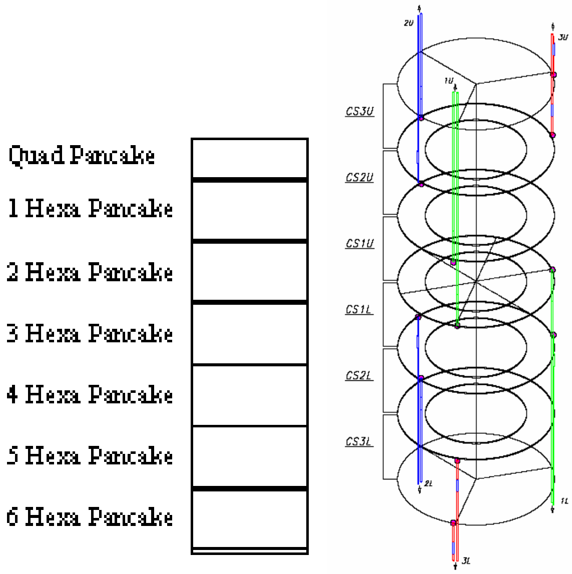

Fig. 4: Pancake module and lead arrangements in Central Solenoid

All current terminals are on the outside of the coil in the low field region and head away from the machine equator, as shown in Figs. 4-5. There is a termination joint at exactly the same distance from each coil winding pack, so that all of the CS modules will be interchangeable, allowing the use of a universal spare coil.

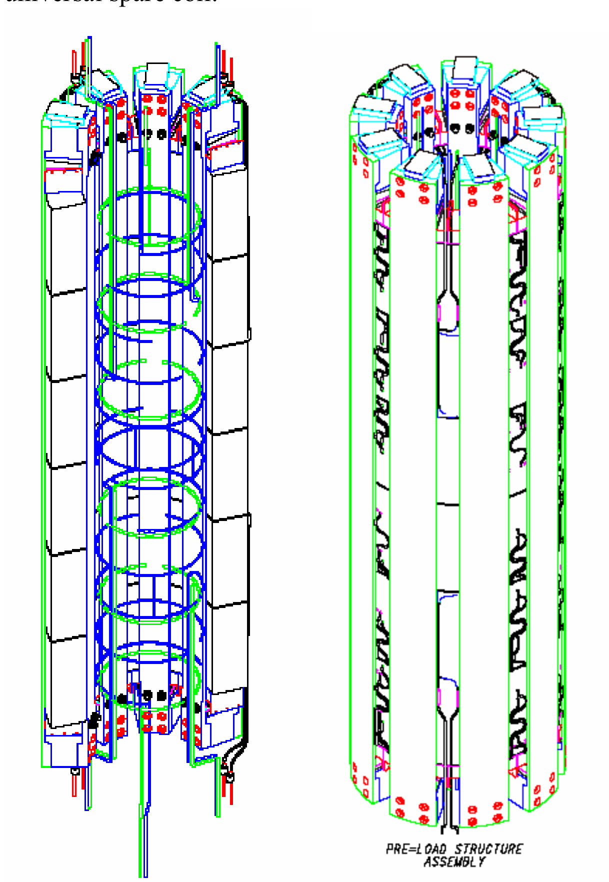

Fig. 5: Inner and outer coolant lines, current leads and preload structure assembly

B. CS Conductor

The CS conductor is an advanced cable-in-conduit (CIC) Nb_3Sn superconductor. Conductor components include the cable itself, consisting of both pure copper and composite superconductor strands, the central cooling tube, the wraps about the cable and final stages, and the Incoloy 908 jacket.

The CS conductors are five stage, 3x3x4x4x6 cables, where the final stage twists 6 'petals' around a central channel. The central channel is an open spiral, allowing helium transfer. It reduces the overall pressure drop and helps maintain stability during final cabling. The final cable stage has a partial steel foil wrap that helps stabilize the cable under transverse loads, and acts as a barrier to coupling currents while allowing helium transfer into the cable. The local void fraction in the petals has been lowered to 33 % to reduce transverse bending. The cable has an outer steel foil wrap to maintain dimensions during spooling and protect the cable during jacketing. The CS conductor dimensions are listed in Table III.

TABLE III
CENTRAL SOLENOID CONDUCTOR DESCRIPTION

Parameter	Units	Value
I_{cond}	(kA)	45
w_{cond}, h_{cond}	(mm)	49.0
nstrands		864
Pattern		3x3x4x4x6
nscstrands		576
ncustrands		288
D_{strand}	(mm)	0.83
Cu/Noncu		1.0

The cables are made of advanced Nb_3Sn strands with higher critical current density than those specified for the ITER Engineering Design Activity [EDA] [4]. The specified J_c in the US strand program is 1,000 A/mm^2 at 12 T and 4.2 K [5], while the EDA HP-II CS specification was 550 A/mm^2 [4]. The Nb_3Sn cables include 1/3 pure copper strands in each first-stage triplet. The copper/noncopper ratio of the Nb_3Sn strands has been reduced from 1.5:1 to 1.0:1, so that the overall critical current of each strand is 2.3 times higher than HP-II. The pure copper strands provide thermal protection during quench, while substantially reducing the cable cost.

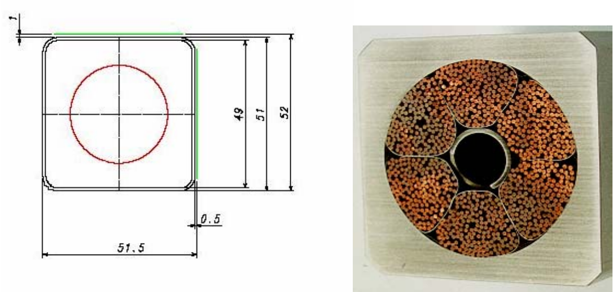

Fig. 6: CS Cable-in-conduit (CIC) superconductor

C. Fabrication

Each hex and quad submodule is wound continuously, in-and-out, with multiroll benders, in order to avoid internal joints. The hex and quad pancakes are then heat treated, after winding, in order to fully react the Nb_3Sn without inducing bending strain in the sensitive reacted strand.

Insulation is applied after the conductor is reacted, by "unspringing" the pancakes vertically. The turn insulation has a nominal thickness of 1.0 mm around each conductor and is a hybrid system composed typically of two 50% overlapped layers of interleaved glass and polyimide film and one 50% overlapped dry glass layer outside. Additional 1.0 mm thick dry glass layers are placed between pancakes and 0.5 mm strips between turns to help absorb tolerance deviations in flatness, bend radius, twisting, and keystoning.

A specially designed in-line butt joint, similar to the U-joints developed by Japan for the CS Model Coil [6], connects the intramodule hex and quad pancakes. Butt joint preparation precedes the module heat treatment. The steel wrap is removed, the diameter and central hole are reduced, and a copper sleeve is crimped onto the outside of the cable. An exploded view of the butt-joint assembly is shown in Fig. 7. There is a transition region, in which the cable is necked down and the central cooling hole removed, while cooling slots are added to an outside spacer with drain holes for trapped helium. The helium outlet stub is centered on the butt joint itself.

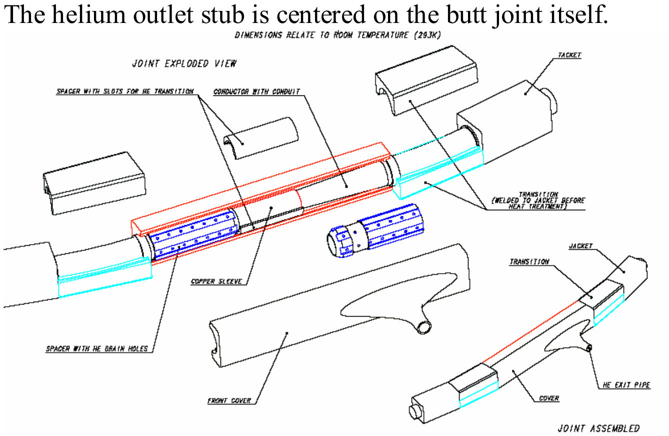

Fig. 7: Intramodule butt joint

D. Cooling

The CS coils are cooled by forced-flow supercritical helium with a nominal inlet state of 4.5 K and 6.5 atm. Helium flows from a high-field inlet through a single pancake and exits at the CS outer radius, so that there are 40 channels in each CS module. This is more efficient than the previous layer-cooled design and holds the temperature in the maximum field turns to 4.7 K. The helium inlet and outlet stubs have recently been redesigned with a reinforced front cover and "compliant" frame in order to eliminate conduit stress risers. The hydraulic cooling requirements vary with time for each modules, but typical values are shown in Table IV:

TABLE IV
HYDRAULIC PARAMETERS, 1 CS MODULE

Parameter	Units	CS Module
nchannels		40
Lchannel	(m)	148.6
Acentral channel	(mm^2)	38.5
Flow Area in annulus	(mm^2)	252.3
Total Flow Area	(mm^2)	290.8
pin	(MPa)	0.66
pout	(MPa)	0.59
Mdot,nom,1 channel	(g/s)	9

III. CONCLUSION

The design of a Central Solenoid system that should be able to satisfy the ITER plasma current and long-burn mission has been completed.

Improvements have been made on the original ITER EDA design, the most important of which is the use of CS modules, allowing more plasma shaping flexibility, the use of a spare, and more efficient cooling. The design has also changed to higher performance Nb_3Sn and conduit material. In-line butt joints reduce space requirements and pulsed losses.

The change to modular design and the associated removal of bucking against the TF system introduces cyclic tension in the conduits and joints as a design issue. Transverse loading of the conductor is another issue, introduced by the Model Coil test results. An active R&D program is underway to resolve remaining design issues.

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