The JT-60SA Superconducting Magnet System

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Abstract. The JT-60SA experiment is one of the three projects to be undertaken in Japan as part of the Broader Approach Agreement, conducted jointly by Europe and Japan, and complementing the construction of ITER in Europe. The superconducting magnet system for JT-60SA consists of 18 Toroidal Field (TF) coils, a Central Solenoid (CS) and six Equilibrium Field (EF) coils. The TF magnet generates the field to confine charged particles in the plasma, the CS provides the inductive flux to ramp up plasma current and contribute to plasma shaping and the EF coils provide the position equilibrium of plasma current and the plasma vertical stability. The six EF coils are attached to the TF coil cases through supports with flexible plates allowing radial displacements. The CS assembly is supported from the bottom of the TF coils through its pre-load structure. The design status of the JT-60SA superconducting magnetic system is reviewed.

1. Introduction

The mission of the JT-60SA experiment is to contribute to the early realization of fusion energy by addressing key physics issues for ITER and DEMO. The main scope of JT-60SA operation is to explore the steady-state plasma regimes in high-beta configurations. One central objective is to reach the long-pulse duration domain with 100 second plasma shots. The reference scenarios include ITER-like configurations [1].

The superconducting magnet system for JT-60SA consists of 18 Toroidal Field (TF) coils, a Central Solenoid (CS) and six Equilibrium Field (EF) coils as shown in figure 1[2].

The TF magnet generates the field to confine charged particles in the plasma, the CS provides the inductive flux to ramp up plasma current and contribute to plasma shaping and the EF coils provide the position equilibrium of plasma current and the plasma vertical stability. The TF coil case encloses the winding pack and is the main structural component of the magnet system [3]. The six EF coils are attached to the TF coil cases through supports with flexible plates allowing radial displacements. The CS assembly is supported from the bottom of the TF coils through its pre-load structure [4] [5].

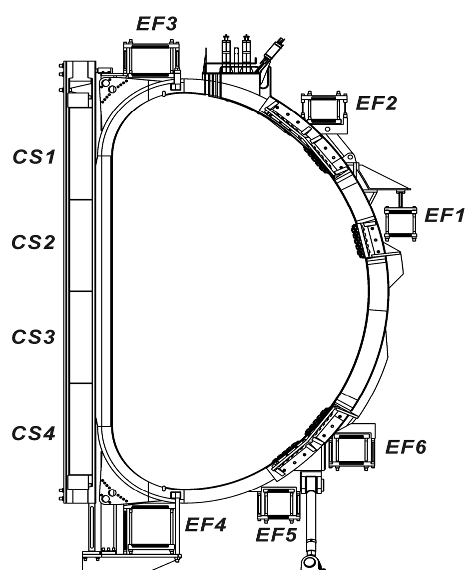

Figure 1: Cross-section view of the JT-60SA TF, EF and CS magnet systems

2. Toroidal Field Magnet

The main magnetic confinement of the JT-60SA experiment is provided by a set of 18 coils, D-shaped so as to be nearly free of bending moments when loaded by self field magnetic pressures. The 18 coils are wedged together over their straight section to support in-plane centralising forces. Overturning moments on the coils are supported by keys between the casings in the upper and lower inboard curved regions, which are pre-compressed by toroidal bolts during assembly. In the outer region a conceptually new outer intercoil structure (OIS) has been designed, supporting the casings against out-of-plane loads. Adjacent OIS components are connected toroidally by bolted shear plates, forming a rigid toroidal structure to support all 18 TF coils. Since the OIS is detached from the coil casings, it also allows some in-plane expansion of the coils. The TF coils are supported by a kinematic gravity support which is bolted to the cryostat base structures allowing the TF coils to shrink radially during cool-down. Each of these supports has a cryogenically-cooled thermal barrier connected to the thermal shield of the vacuum vessel. The main parameters of the TF magnet are given table 1. Low voltage electrical insulation is placed between the TF coils in the wedged region at the straight leg, and additionally between the OIS shear panels, limiting the circulation of currents in the structure during the dynamic operation of the device.

TABLE 1: JT-60SA TF Magnet Operating Parameters

Magnetic energy	*1.06 GJ*
Maximum field on conductor	*5.65 T*
Field on plasma axis	*T*
Operating current	*25 kA*
Operating temperature	*~ 4.8 K*
TF system total weight	*~ 370 t*
Maximum voltage versus ground	*1.4 kV*
He mass flow rate / conductor (g/s)	*4*

The superconducting NbTi strands are cabled with copper strands and the cable is inserted in a round 316L jacket. 240 m-long conductors are then compacted to form a rectangular Cable-In-Conduit Conductor (CICC). Characteristics of the conductor are given in table 2. The conductor is cooled by supercritical helium, with a mass flow rate of 4 $g \cdot s^{-1}$. Each winding pack consists of six double pancakes stacked on top of each other and electrically joined by low resistance joints.

TABLE 2: Characteristics of the conductor of the TF magnet

Strand diameter (including resistive barrier)	*0.810 mm*
Critical current per strand at T = 6.1 K and B = 5.65 T	*> 79 A*
Residual Resistivity Ratio of strand (R300/R20)	*> 100*
Non SC/SC ratio of SC strand	*> 1.3*
Number of SC strands	*324*
Number of copper strands	*162*
Winding pattern	*(2 sc +1Cu) x 3 x 3 x 3 x 6*
Twist lengths of the different cabling stages	*45/70/120/190/290 mm*
Cable dimensions	*18 x 22 mm*
Conductor outer dimensions	*22 x 26 mm*

A 1 mm thick layer of insulation is applied to the bare conductor during the winding process. An additional 3 mm layer of ground insulation is applied to the outside of the complete winding pack which is inserted in the casing structure. The casing is thick enough to support all in-plane loads. The out-of-plane loads are supported by the outer intercoil structure which is introduced around the outer region of the coil, as shown in figure 3. Similarly to the casing

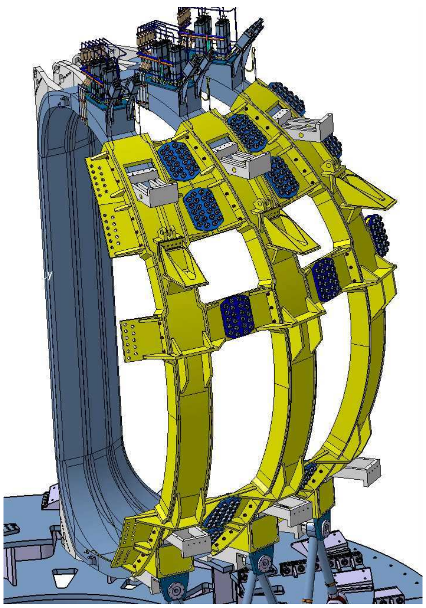

Figure 2: Outer intercoil structure with shear panels

structure, the OIS is constructed from welded plates. It is manufactured in a 'U' shape, which follows the profile of the coil casing in the outer region. Adjacent OIS are bolted together through five shear panels, along the structure as shown in figure 2.

The connection is designed as a friction joint in which the bolts are not loaded by shear. The friction generated in the bolted arrangement is adequate to transfer the shear load.

After completing the shear panel joints, the OIS structure forms a rigid barrel around the outside of the toroidal field magnet system. Any out-of-plane loads are supported by this complete structure such that the maximum toroidal deflection of the complete system during plasma operations remains lower than the design target of 20 mm.

Each coil is supported in the inner region through a pinned and bolted connection at the top and the bottom of the coil and a wedged contact to the adjacent coil, as shown in figure 3. The pins support the shear loads between adjacent coils, while the bolts provide a pre-compression to the region ensuring that the joint does not open during normal operations. The centralizing forces on the coil are supported through contact to the adjacent coils along the full length of the inner wedged region. In addition, this region is insulated with the introduction of an insulating layer along the full length of the wedged region. This insulating layer also acts as an assembly aid as its final thickness can be adjusted to suit the final coil configuration. A cooling channel is included in the casing structure to assist cool-down of the magnet.

The largest stresses in the TFC structures are 450 MPa in the coil case and 544 MPa in the OIS. These values are close to or slightly above the allowable limit for primary membrane stress Sm at the operating temperature, but due to the predominant bending behaviour of the structure, no particular integrity concerns arise. An overview of toroidal displacement and stress intensity for a TFC is given in figure 4. An additional "limit" analysis was carried out in order to study the plastic behaviour of the TF magnet system under a steadily increasing electro-magnetic and gravity load.

All materials defining the structures have been considered as elastic and then plastic (limiting stresses), while strain hardening is neglected. Under these assumptions the occurrence of a plastic hinge followed by an unbounded displacement runaway was investigated. According to the results, the TF magnet system is able to withstand up to 3.5 times the nominal electro-magnetic load without plastic collapse of the structures [9].

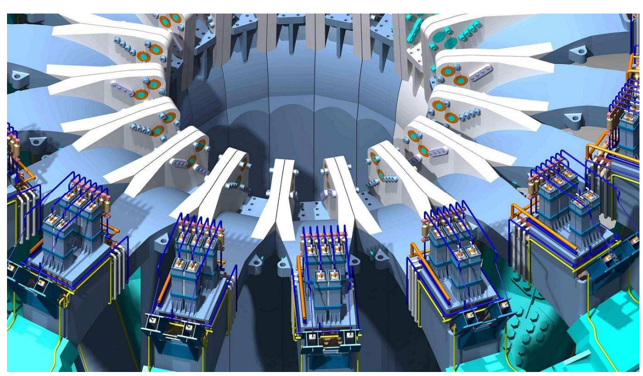

Figure 3: Pinned and bolted connection between adjacent coils

The superconducting strand and conductor specifications were qualified through three samples which were produced and tested between 2008 and 2009 [10][11]. The TF conductor design was found sound with respect to the temperature safety margin (at least 1 K) [12]. The electrical terminals of the coils shall be of the twin-box type. The design of this joint has been qualified by test performed at the SULTAN facility with one of the conductor samples. Conductor and electrical joint design being qualified, tendering procedures were launched. Contract for the strands has been prepared and shall be signed before the end of 2010. Contract for the cabling and jacketing of the conductor shall be placed in 2011.

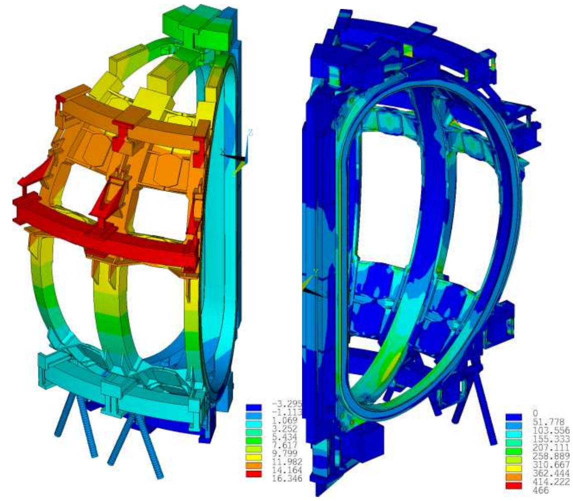

Figure 4: Distribution of toroidal displacement [mm] and stress intensity [MPa] in the magnet system components

As the TF coils will be provided in kind by two voluntary contributors (France and Italy), a common detailed specification for the conductor winding and the coil manufacturing was developed allowing France and Italy to launch their own call for tender procedures. The contracts for the coils manufacturing shall be placed in the first half of 2011.

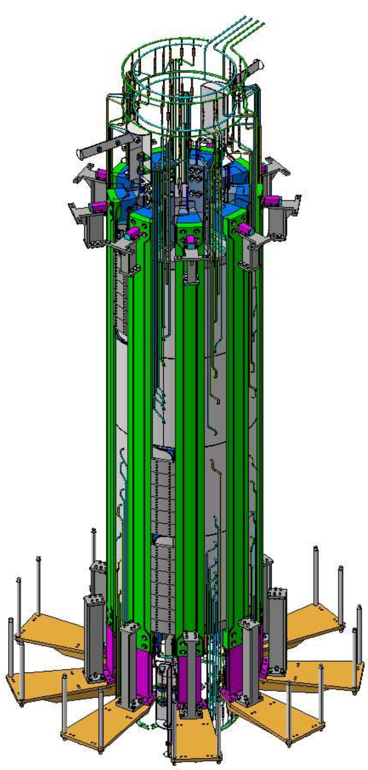

Figure 5: CS system with attachment structures to TF in the bottom area

3. Central Solenoid

The central solenoid (CS) magnet system will provide the flux needed for the first stage of plasma current drive and heating. The CS assembly consists of a vertical stack of four winding pack modules [13]. The coils are electrically independent to ensure maximum flexibility for plasma-shape control. Busbars and joints are placed outside the coils as shown in figure 5. The whole system is supported by the TF magnets through structural links located at the bottom of the assembled system. The main parameters of the CS are given in table 3. The CS pre-load structure, which consists of a set of tie plates located outside and inside the coil stack, provides axial pressure on the stack. The CS stack is self-supporting against the coil radial forces and most of the vertical forces. The lower structural links react only the weight and net vertical components resulting from up-down asymmetry of the poloidal field configuration. The conductor type for the CS modules is a circular cable-in-conduit multistage cable with about 324 Nb_3Sn strands cabled around a small central spiral cooling tube. An extruded jacket

TABLE 3: JT-60SA Central Solenoid Operating Parameters

Winding average radius	*0.824 m*
Maximum field on conductor	*8.9 T*
Operating current	*20 kA*
Number of turns	*556*
Operating temperature	*5.1 K*
CS total weight	*92 t*
Maximum voltage vs ground	*5 kV*
He mass flow rate / conductor	*6 g/s*

with a square outer section and a circular hole is adopted for the CS conductor. The conductor parameters are given in table 4. The operating current is 20 kA for the CS. A short length of CS conductor (30m) was recently produced using actual Nb3Sn strands and stainless steel jacket. With the manufacture, in September 2010, of one 350 m-long dummy copper conductor the qualification of the jacketing tooling and manufacture procedures was achieved. Samples for final conductor qualification (current sharing temperature, AC loss) are currently under heat treatment and will be tested in February 2011. Insulation material for the CS was qualified for shear strength at 77 K after gamma-ray irradiation up to 100 kGray. The tooling to manufacture the electrical joints of the CS is commissioned and the manufacturing procedures are under qualification.

To avoid a gap opening due to the repulsive force during operations, the pre-compression force needed is 40.9 MN at room temperature. In the structural analysis with a three-dimensional finite element model in ANSYS, it is confirmed that the latest design of support structure, tie plates and mounting bracket has sufficient mechanical strength, although 316LN with 0.13 to 0.17 wt% of carbon and nitrogen content is adopted. The maximum stress in the jacket is sufficiently small in comparison with the allowable limit for 316LN.

TABLE 4: JT-60SA CS Conductor and Strand Parameters

Material type	*Nb_3Sn*
Strand diameter	*0.82 mm*
Non SC : SC ratio	*1*
Resistive barrier	*Cr plating*
Number of Sc strands	*216*
Number of copper strands	*108*
Cable pattern	*(2SC+1Cu)x3x6x6*
Central spiral outer diameter	*9 mm*
Cable diameter	*21 mm*
Conductor outer dimensions	*27.9 x 27.9 mm^2*

4. Equilibrium Field (EF) Coils

The six equilibrium field coils (EF1 to EF6) are attached to the TF coil cases through flexible plates supports allowing radial displacements. The EF coil positions and sizes have been optimized for the plasma requirements, within the constraints imposed by the access and ports around the vacuum vessel.

TABLE 5: JT-60SA EF Magnet Layout Parameters

	EF1	*EF2*	*EF3*	*EF4*	*EF5*	*EF6*
Winding radius (m)	*5.819*	*4.621*	*1.919*	*1.919*	*3.914*	*5.054*
Number of turns	*142*	*154*	*247*	*353*	*152*	*180*
Maximum field on conductor (T)	*4.8*	*4.8*	*6.2*	*6.2*	*4.8*	*4.8*
Conductor length (m)	*439*	*378*	*434*	*434*	*541*	*413*

As an example, figure 6 shows the general arrangement of the EF4 coil. All EF coils use NbTi strands cooled by supercritical helium. The jacket material is stainless steel SS316L. The EF3 and EF4 coils operate at high field (6.2 T) using high field NbTi superconductor. The EF1, EF2, EF5 and EF6 coils operate at lower field (4.8 T) using lower field NbTi superconductor. The conductor type for EF coils is a circular cable-in-conduit multistage cable with about three hundred strands cabled around a small central spiral cooling tube. A circular jacket with a cable is formed to a rectangular shape. The operating currents are 20 kA for each of the EF coils. The main parameters of the EF coils are given table 5.

To ensure a uniform current distribution in each sub-cable while maintaining AC losses at acceptance level, the transverse resistivity within the cable must be controlled. Therefore, nickel (Ni) coating is applied on the strands of the conductor. The cable is inserted in the jacket by a pull-through, roll down procedure, as for the TF and CS coils. Detailed parameters of the conductors are given in table 6 [14].

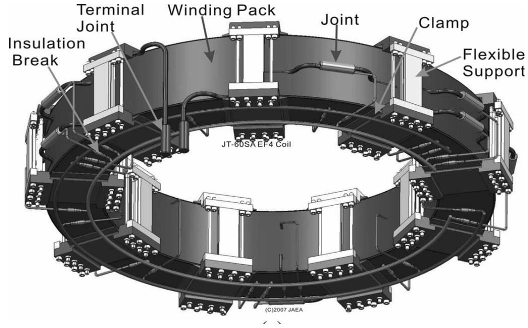

Figure 6: 3D view of EF4

TABLE 6: JT-60SA EF Conductors Parameters

	EF-L (EF1,2,5,6)	EF-H (EF3,4)
Material type	NbTi	
Strand diameter	0.829 mm	
Filament diameter	< 12 μm	
NonSC:SC ratio	2.3	
Resistive barrier	Ni coating	
Number of SC strands	216	450
Number of Cu strands	108	0
Cable pattern	3x5x5x6	
Central spiral outer diameter	9 mm	
Cable dimensions	19.1x19.1 mm	21.8x21.8 mm
Conductor outer dimensions	25.0x25.0 mm	27.7x27.7 mm

Short lengths (30m each) of EF-H and EF-L conductors were produced using actual NbTi strands and stainless steel jacket. Two EF-H copper dummy conductors and nine EF-H superconducting conductors (444 m-long) were produced by July 2010 allowing the qualification of the jacketing tooling and procedures. The current sharing temperature (Tcs) was measured on samples of actual EF-H and EF-L conductors. The Tcs of EF-H and EF-L conductors exceeded the required temperature. The coupling time constant ($n\tau$) of EF-H and EF-L conductors were measured at 90 ms and 80 ms respectively, achieving the EF conductors qualification. Insulation material for the EF coils was qualified for shear strength at 77 K after gamma-ray irradiation up to 100 kGray. One sample electrical joint for the EF conductor was manufactured. The joint resistance was measured between 1.8 and 2.1 nΩ [15]. In order to assess some important values for the design of the JT-60SA magnet system, e.g. AC losses and the required strength of supports, the maximum

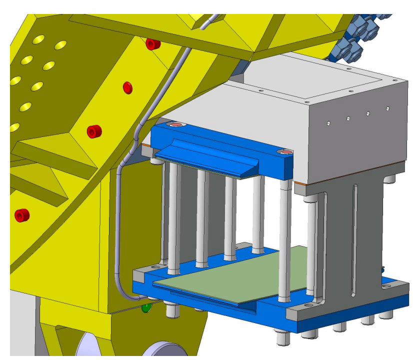

Figure 7: Attachment of the EF4 Coil on a TF coil

TABLE 7: Maximum Field and Vertical Forces for EF Coils

coils	$B_{max}(T)$	*Vertical force : Fz (MN)*	
		Max. Upward	*Max. Downward*
EF1	*3.249*	*5.037*	*9.171*
EF2	*3.460*	*5.546*	*6.647*
EF3	*4.149*	*9.738*	*15.872*
EF4	*5.285*	*15.262*	*23.545*
EF5	*3.408*	*12.838*	*23.822*
EF6	*3.858*	*26.620*	*8.497*

magnetic field and electromagnetic (EM) forces are calculated for each EF coils and CS modules and in a standard plasma scenario. The maximum fields and the maximum vertical EM forces for each EF coils are summarized in table 7. The EF coils are self supporting with regards to the radial magnetic loads. These loads are reacted by hoop tensile stresses in the conductor jacket. The winding pack is clamped between a pair of plates linked by tie-rods (see figure 7). The clamping plates and tie rods can also be used for lifting/handling purposes during EF coil fabrication and installation and they are also used in some of the EF coils to support the coil terminals, outer protection cases and potential breaker. The clamping plates have been designed to minimize stresses in the winding pack ground insulation. The vertical and lateral loads on each EF coil, plus bending moments (due to the residual toroidal field ripple) are transmitted through these plates to the TF coil case. In addition, bending moments due to the TF coil tilting motion are transmitted from the TF coils to the EF coils through these plates.

5. Conclusion

The detailed design of the JT-60SA magnet system, comprising TF magnet, CS and EF coils, was performed in a coordinated way in order to ensure an efficient control of their interfaces. The manufacturing tooling for the CS and EF coils are being installed in the manufacturing facility. With the recent signature of the Procurement Arrangement for the TF magnet, following the ones for the CS and EF magnets, the procurement phase is starting in order to deliver the coils within the general JT-60SA time schedule.

Acknowledgments

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