J. Plasma Fusion Res. SERIES, Vol. 9 (2010)

Design and Construction of JT-60SA Superconducting Magnet System

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(Received: 4 November 2009 / Accepted: 9 February 2010)

The upgrade of JT-60U magnet system to superconducting coils (JT-60SA) is progressing by both parties of Japanese government and European commission (EU) in the framework of the Broader Approach agreement. The magnet system for JT-60SA consists of 18 Toroidal Field (TF) coils, a Central Solenoid (CS) with four modules, six Equilibrium Field (EF) coils. The TF coil case encloses the winding pack and is the main structural component of the magnet system. The CS consists of four independent winding pack modules, which is support from the bottom of the TF coils. The six EF coils are attached to the TF coil cases through supports with flexible plates allowing radial displacements. The feeder system is connected from each coil to the helium refrigerator and the power supply. High temperature superconducting current leads are installed in the coil terminal box connecting to the cryostat. The TF coils and HTS leads are provided by EU. CS, EF coils and feeder system are prepared by Japan. The construction of CS and EF coils was started in 2008 in Japan.

Keywords: fusion, magnet, superconducting, JT-60, broader approach

1. Introduction

The agreement between the Government of Japan and the European Atomic Energy Community for the Joint Implementation of the Broader Approach Activities in the Field of Fusion Energy Research was signed on February 5, 2007. This so-called "Broader Approach" materializes the privileged partnership of Japan and EURATOM in the field of fusion energy research. Japan and EURATOM will work together on three individual projects under this agreement to accelerate the realization of fusion energy as a clean and sustainable energy source for the 21st century. The JT-60 tokamak will be upgraded to an advanced superconducting tokamak JT-60SA (JT-60 Super Advanced) [1, 2], and be operated under the framework of this Agreement as a "satellite" facility for ITER. The Satellite Tokamak Programme is expected to develop operating scenarios and to address key physics issues for an efficient start up of ITER experimentation and for research towards the fusion DEMO reactor.

After the conceptual design report [3, 4], it was recognized that the superconducting magnet baseline design presented some cost issues. There were a number of reasons for cost issues arising with the JT-60SA design. In the TF magnet, there were larger than expected cost of winding, significant increase in amount of superconducting strand to obtain a sufficiently large temperature margin under large nuclear heating. In the PF magnet, there were larger than expected cost of conductor materials and numbers of coils for unrealistic plasma operation. The cryogenic system had uncertainties in the design including reasonable sizing of cryoplant distribution and the main equipment, and amount of heats loads.

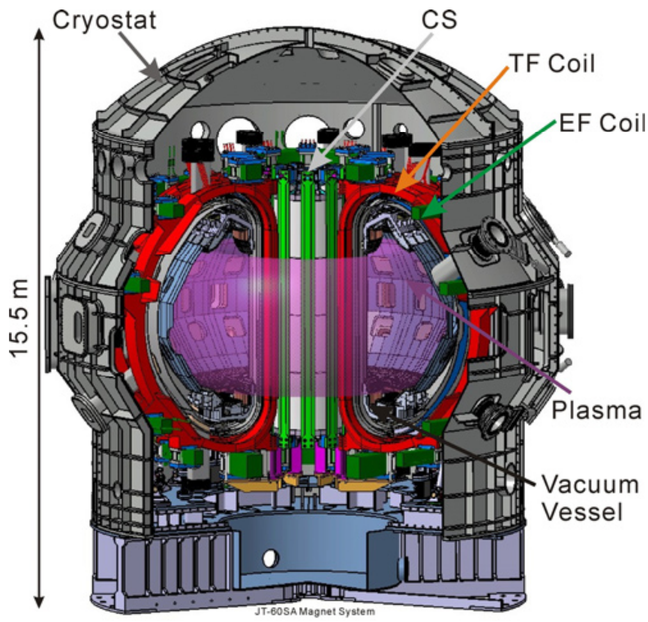

Fig. 1 JT-60SA basic device

The re-baselining of the machine has been completed to reduce the manufacturing cost [1]. All the scientific missions for the JT-60SA project can be achieved with the low cost designed machine. Main reductions for the magnet design are toroidal field, number of PF coils and neutron heating.

2. Requirements for Superconducting Magnet System

Main mission of JT-60SA is to support and

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supplement ITER toward DEMO. The JT-60SA will be the largest superconducting Tokamak to be built before the ITER Tokamak. The operational regimes of JT-60SA are the steady-state and high beta condition for more than 100 seconds. The JT-60SA has an enhanced flexibility in lower aspect ratio (A=2.5-3.1) and plasma shape.

The maximum plasma current is 5.5 MA with relatively low aspect ratio plasma and 4.6 MA for ITER shaped plasma. Inductive operation with a 100s flat top will be possible within the total available flux swing of 40 Wb. The heating and current drive system will provide 41 MW (34 MW of neutral beam injection and 7 MW of ECRF). The divertor target is designed to be water-cooled in order to handle heat fluxes up to 15 MW/m^2 for 100 s flat top.

An annual neutron fluence of 1.5x10^{21} neutrons will be subject to the agreement by the responsible legal authority and local government. The cutaway view of JT-60SA is shown in Fig.1. Typical parameters of JT-60SA are shown in Table 1 in comparison with original JT-60U and ITER parameters. The design and operational requirements are defined in Table 2.

3. Design of Superconducting Magnet System

The superconducting magnet system for JT-60SA consists of 18 Toroidal Field (TF) coils, a Central Solenoid (CS), six Equilibrium Field (EF) coils as shown in Table 3 and Fig. 2. The TF coils generate the field to confine charged particles in the plasma, the CS provide the inductive flux to ramp up plasma current and contribute to plasma shaping, the EF coils provide the position equilibrium of plasma current and the plasma vertical stability. The configuration of JT-60SA magnet system is similar to the ITER magnet system [5] because the design bases of these coils have been developed by mainly EU, Russia, US and Japan during the ITER Engineering Design Activity (EDA) phase.

3.1 TF Coils

The TF coil case encloses the winding pack and is the main structural component of the magnet system. 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, Fig. 3.

In the curved regions above and below the inboard leg, the coils are pre-compressed by toroidal bolts and two circular insulated pints. In the outboard region, the out-of-plane support is provided by Outer Intercoil Structures (OIS) [6] separated with the TF coil cases, Fig. 3. The OIS consists of 18 sections that carries a coil and supports it against out of plane loads while allowing limited radial movement due to the in-plane expansion of the coil. There is low voltage electrical insulation toroidally between TF coils in the inboard leg wedged region and between the OIS connecting elements.

Table 1 Major parameters of JT-60SA

	JT-60U	JT-60SA	ITER
Plasma current, Ip (MA)	3.0	5.5	15
Toroidal field, Bt (T)	4.0	2.25	5.3
Major radius Rp (m)	3.4	2.96	6.2
Minor radius ap (m)	0.9	1.18	2.0
Elongation κ	1.8	1.94	1.7
Flat top (s)	15	100	400

Table 2 Operational requirements of JT-60SA magnet system

Ripple of toroidal field	< 1 %
The error magnetic field of toroidal field (Bt)	< 5 x 10^{-4}
Neutron loads	
Peak neutron production rate (n/s)	1.5 x 10^{17}
Margin for nuclear heating calculation	1.5
Insulation dose in TF coil (kGy)	20
Number of operational cycles	
Plasma operation shots	18,000
Plasma disruptions	2,000
TF coil charge	3,000
Superconducting conductor design	
Hot spot temperature during quench (K)	< 200
Temperature margin during operation including plasma disruption (K)	> 1.0
Material requirements of coil case and structure	
Low cobalt (Co) content to reduce activation (wt%)	< 0.05
Permeability of stainless steel	< 1.05

Table 3 Overall magnet system parameters

	JT-60SA	ITER
Number of TF coils	18	18
Magnetic energy in TF coils (GJ)	1.06	41
Maximum field in TF coils (T)	5.65	11.8
Centering force per TF coil (MN)	22.6	403
Vertical force per half TF coil (MN)	13.6	205
CS peak field (T)	8.9	13.5
Total weight of magnet system (tons)	~ 700	~ 10,100

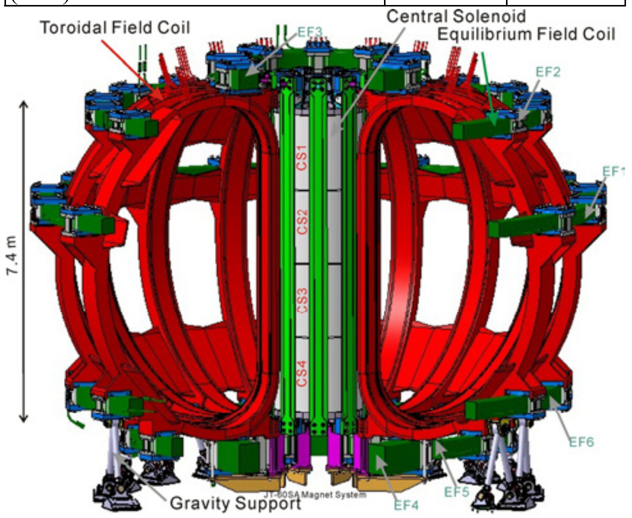

Fig. 2 Magnet system of the JT-60SA

The TF coil pancake and terminal joint are located at the top of the coil just out-board of the vertical ports. The winding consists of six double pancakes. The helium cooling inlets is located on the inner cross-over and all the joints and manifolds are covered in a protective case extension above the coil case.

The V-shape gravity supports are bolted to the cryostat base and TF case, with link elements (plain spherical bearings) to allow radial displacements. Each TF coil is electrically insulated from its own support. The magnets are supported fully independently of the vessel and associated components. The main electromagnetic parameters of the TF coils are given in Table 4.

3.2 Central Solenoid

The CS assembly consists of a vertical stack of four independent winding pack modules, Table 4, which is support from the bottom of the TF coils through its pre-load structure [7]. At the top, there is a sliding connection to provide a locating mechanism and support against dynamic horizontal forces. This pre-compression structure provides axial pressure on the stack. It consists of a set of tie-plates located at inner and outer diameters of the coil stack. The number of CS modules is selected to satisfy the plasma shaping requirements and minimize current leads. The modules can be energized independently. The busbars, joints and cooling pipes are placed outside the coils. TF coil supports the weight and net vertical component resulting from up-down asymmetry of the poloidal field configuration.

The CS pre-compression structure consist of the lower flange, the upper flange a set of tie-plates buffer plates wedge and connecting bolts. The flanges are split into 9 sectors linked by electrical insulated bolted joints to reduce AC loss during pulsing of the machine. The induced voltage across the insulated joints is low (< 10 V). The outside tie plate region needs to have at least 30 % open space in the toroidal direction for the joints current leads and helium pipe arrangement. The preload structure is designed so that it can restrain the maximum vertical separating load of acting on the end modules of the stack as well as the maximum inward compression when all coils push towards the axis without overall gap developing between coil or coils and end flanges Fig. 4. The butt joints [8] are located at the coil outer diameter and are embedded within the winding pack.

The individual coil modules are identical but rotated and inverted to form the stack, with individual interface plates bonded during tacking. Each winding is formed from six octa-pancakes and one quadra-pancake with helium inlets at all joints/helium outlets on the outer surface. In case of JT-60SA, it is difficult to use inner bore space (0.8 m diameter) for helium headers and insulation breaks. The conductor is cooled from inlet located at outer surface via high field region to outlet at

Table 4 Parameters for the TF coils and CS

	TFC	CS
Number of coils	18	4
Weight including structures (tons)	370	92
Winding Size (m)	D shape bore : R:3.98 x H:6.92, Winding dR:0.144, dT:0.341	Rc: 0.824, Winding dR: 0.340, dZ: 1.585
Coil current (MA)	1.85	11.1
Number of turns	72	549
Nominal peak field (T)	5.65	8.9
Total conductor length (km)	24.4	11.5
Ground/Terminal voltage (kV)	1.4 / 2.8 (6 coils in series)	10 / 10
No. of current lead pairs	3	4

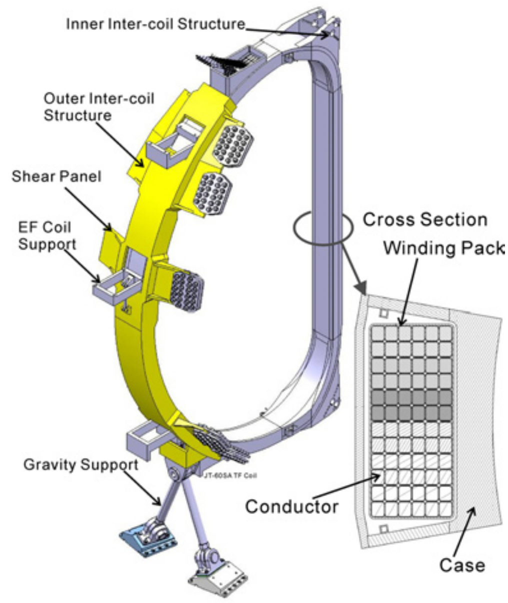

Fig. 3 TF coil with outer inter-coil structure

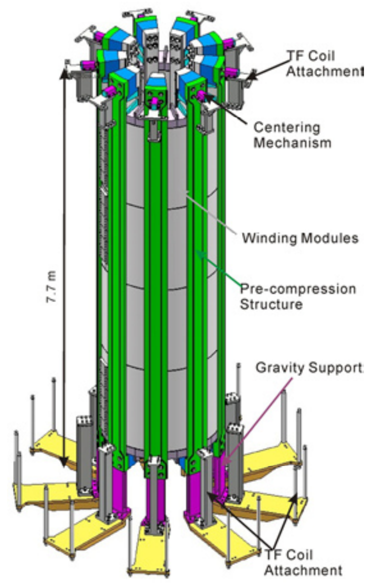

Fig. 4 CS assembly

outer surface. All cooling pipes are lead to top and bottom of CS assembly to connect headers through electrical insulations.

3.3 EF Coils

The six EF coils (EF1 to EF6) are attached to the TF coil cases through flexible plates supports allowing radial displacements. The EF coil positions and sizes (Table 5) have been optimized for the plasma requirements, within the constraints imposed by the access and ports around the vacuum vessel. The EF3, EF4, EF5 winding packs can use the standard double pancake winding with joints only on the outside of winding and helium inlets at the inner cross-over. The EF1, EF2, EF6 winding pack shall use the singe pancake winding with joints located on both inside and outside of winding because their conductor length are beyond manufacturing limit (600 m), and the magnetic field on inner and outer surface of winding becomes similar level.

For EF coils, the winding pack consists of a stack of pancakes enclosed in a common ground insulation wrap. For these pancakes in EF coils, handshake type joints (Fig. 5) are adopted for assembly requirements. Large diameter EF coils (EF1, EF2, EF5 and EF6) shall be manufactured directly on-site in Naka, because of the difficulties associated to their ground transportation.

The top and bottom of EF winding pack is supported between the clamp plates. Two clamp plates shall be tighten by long stud bolts to keep pressure during cool down and magnetic loads. Four corners of the winding pack have the peak stress during pre-compression at room temperature. Clamp plate shaped with the cubic function of distance from the centre line of the clamp plate can reduce peak stress in the winding pack [9].

3.4 Conductor

All conductors for TF, CS and EF coils are cooled with supercritical helium with a coil inlet temperature of 4.5 K. All conductors are type of a cable-in-conduit (CIC) conductor with a circular multistage cable.

The TF coils use NbTi superconductor for 5.65 T. The TF conductor is a CIC conductor with a circular multistage cable consisting of 486 strands cabled without central spiral. The number of superconducting strands is designed to ensure a minimum temperature margin of 1.2 K in normal operating conditions and 1.0 K after a plasma disruption. The nickel (Ni) coating on strand or CuNi barrier embedded inside the strand is employed for reducing AC loss. The operating current is 25.7 kA for the TF coils as shown in Table 6. The TF conductor is similar to the EF conductor without a central hole, but outer dimension (22 mm x 26 mm) is not square in order to optimum its winding pack (6 double pancakes with 6 turns) shape in the TF coil case as shown in Fig. 3.

The CS operates at high field and use Nb_3Sn superconductor. The CS conductor consists of a circular multistage cable consisting of about 324 strands cabled around a small central cooling spiral. The number of superconducting strands is designed to ensure a minimum

Table 5 Parameters for EF coils

	EF1	EF2	EF3	EF4	EF5	EF6
Winding radius(m)	5.819	4.621	1.919	1.919	3.914	5.054
Winding width (m)	0.343	0.370	0.556	0.556	0.315	0.370
Winding height(m)	0.347	0.347	0.441	0.625	0.403	0.403
Coil current (MA)	2.84	3.08	4.94	7.06	3.04	3.60
Conductor current (kA)	20.0	←	←	←	←	←
Peak field (T)	4.8	4.8	6.2	6.2	4.8	4.8
Operating temp. (K)	4.8	4.8	5.0	5.0	4.8	4.8
Number of turns	142	154	247	353	152	180
Conductor length (m)	439	378	434	434	541	413
Ground voltage (kV)	10	←	←	←	←	←

Table 6 Conductor parameters for TF coils and CS

Coil	TF	CS
Type of strands	NbTi	Nb_3Sn
Operating current (kA)	25.7	20.0
Nominal peak field (T)	5.65	8.9
Operating temperature (K)	4.9	5.1
Discharge time constant (s)	10	6
Delay time (s)	2	2
No. of SC strands/Cu strands	324 / 162	216 / 108
Local void fraction (%)	32	34
Cable dimensions (mm)	18.0 x 22.0	Φ21.0
Central hole (id x od) (mm)	non	7 x 9
Conductor dimensions (mm)	22.0 x 26.0	27.9x 27.9
Jacket material	SS316L	SS316LN
Max. length of conductor (m)	228	352

Table 7 Conductor parameters for the EF coils

Conductor type	EF-H	EF-L
No. of EF coils	3, 4	1, 2, 5, 6
Type of strand	NbTi	←
Operating current (kA)	20.0	←
Nominal peak field (T)	6.2	4.8
Operating temperature (K)	5.0	4.8
Number of SC/Cu strands	450 / 0	216 / 108
Local void fraction (%)	34	←
Cable dimensions (mm)	21.8	19.1
Central hole (id x od) (mm)	7 x 9	←
Conductor ex. size (mm)	27.7	25.0
Jacket material	SS316L	SS316L

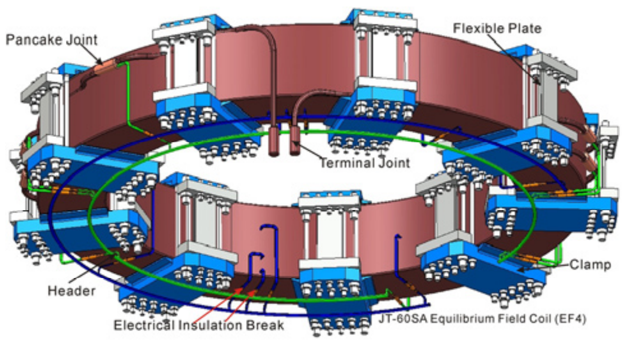

Fig. 5 EF4 Coil

temperature margin of 1.0 K in normal pulse operating conditions. The Cr plating provides a contact resistance barrier to reduce the large coupling currents while still allowing current redistribution. The central spiral is required to improve extraction of the large amount of heat associated to the ac loss during the break down phase. The cable in installed in the square jacket with a circular hole. The material of the CS jacket is a modified SS316 to service through Nb_3Sn heat treatment (650℃ - 100h). The operating currents are 20 kA as shown in Table 6 and Fig. 6.

The EF coils use two types of NbTi conductors as shown in Table 7. The cross section of the EF-H conductor is shown in Fig. 7. The nickel (Ni) coating on strand is employed for reducing AC loss. The jackets (SS316L) are compacted and formed from circular tubes. The square formed jackets has enough strength in the EF winding packs because the magnetic compressive pressure in the EF winding pack is much smaller than the CS winding module.

3.5 Feeders

Each coil is electrically connected through an in-cryostat feeder to the current leads located outside the cryostat in the coil terminal boxes (CTBs). The cooling pipes of the winding and structures are connected to valve boxes (VBs). The VBs are installed just outside the cryostat to keep the vertical access of the maintenance for the port. The cryostat, CTBs, VBs and the cryoline are shown in Fig. 8. For a coil, it consists of the feed and return current supply busbars (using NbTi superconductor), the return and supply helium lines and instrumentation lines. The cryoline is a bundle of cryogenic transfer lines with separated vacuum chamber from the helium refrigerator to the cryostat.

A total of 26 current leads using high temperature superconductor (HTS) prepared by EU (Germany) [10] are installed in the CTB. The HTS leads are located under magnetic field 30 mT to optimize amount of HTS materials. The TF coils are connected in six coils series with internal SC busbars and all other coils are connected individually. The HTS material is BSCCO 2223 and Ag-Au stabilizer. The leads consist of a HTS section and a conventional copper section connected together through an electrical joint. The joint and copper are cooled by helium gas at 50 K helium. The cold end of the HTS material is cooled by conduction to the busbar at 4.5 K.

4. Construction of Magnet System

4.1 Manufacturing Conductors and Coils

The construction of CS and EF coils was started in 2008 in Japan. The fabrication of superconducting strand and cable of CS and EF coils were started in 2008. The manufacturing tools for conductor assembly with the butt

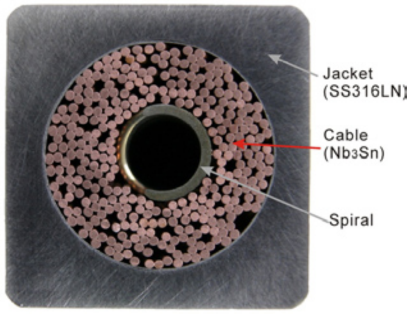

Fig. 6 CS conductor compacted from a round-in-square jacket

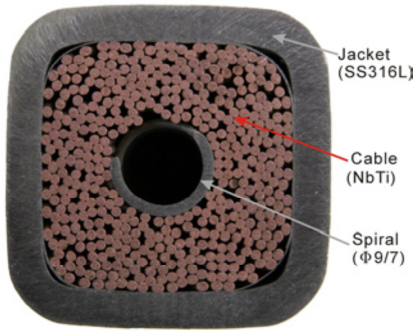

Fig. 7 EF-H conductor compacted from a circular tube

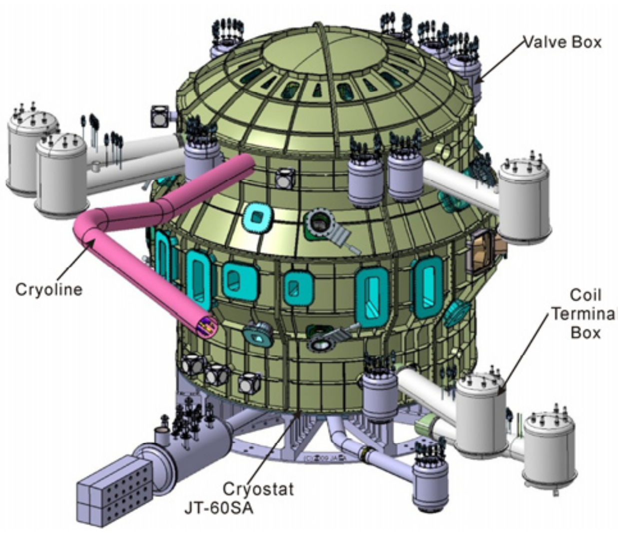

Fig. 8 Cryoline, valve box and coil terminal box

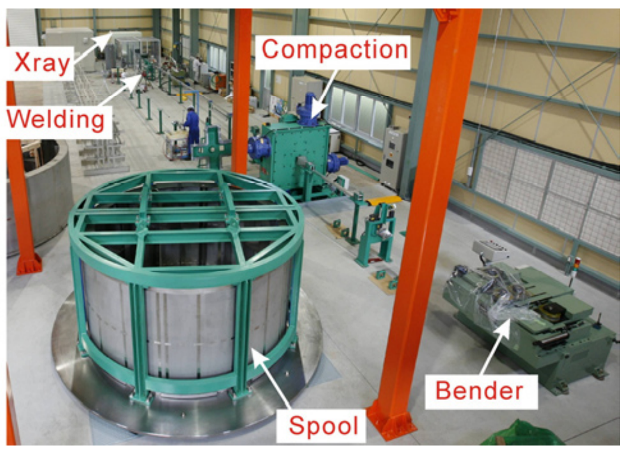

Fig. 9 Conductor assembly facility in Naka site

welder, the cable compaction and the spool have been prepared for the conductor production in Naka site [11] as shown in Fig. 9. A dummy cable (200m length) with copper strands and a superconducting cable (30m) for CS, EF-H and EF-L conductors were fabricated in 2009. The cross section photos of Fig. 6 and Fig.7 are the first production for JT-60SA CS and EF conductor. Dimensions of CS and EF jacket are examined to determine the required void fraction (33%) in cable area after compaction, using three kinds of jackets. For the EF-H jacket, three dimensions circular pipes with outer diameters of 33.5, 33.3 and 33.1 mm, inner diameter of 27.4 mm are compacted to measure the void fraction. The pipe with outer diameter of 33.1 mm was selected for the mass production to meat the void fraction [11].

The constructions of TF coils and HTS leads will start in 2010 in EU after adjustments for interface and administrative issues.

4.2 Verification Tests

The EF conductor is evaluated in JAEA and NIFS facility. The critical current of CIC NbTi conductor with a central spiral of JT-60SA EF-H prototype conductor was measured to satisfy the requirement [12]. The joint resistance of EF conductor was measured to be less than 3 nΩ [13]. The stability and quench propagation are measured to show similar quench propagation [14] to the computer simulation code [15] in the NIFS facility.

The critical current of each strand by the mass production were qualified in their operating condition. The critical current of each superconducting conductor by the mass production will be measured to verify the requirements for temperature margin. Key components of conductor joints and terminal joints will be qualified by 4 K test. The helium inlet and terminals of conductor in winding will be evaluated by the mechanical test. The insulation system will be evaluated by shear strength, irradiation test and the stack samples consist of 4 by 4 winding model. Winding technique and accuracy will be evaluated by a dummy pancake winding using the new winding tools in the coil manufacturing line.

5. Conclusions

The detailed design of PF coil system was completed by summer of 2008. The tools for conductors for CS and EF coils are progressed to qualify the trial conductor fabrication. The manufacturing CS and EF coil is started to design the manufacturing tools. The building for the EF coil manufacturing is completed. The manufacturing for trial sample is progressed to verify the detailed components: inlet, joint and termination.

The detailed design of TF coil system was completed by summer of 2009. The manufacturing of the TF conductor and TF coil fabrication will start in 2010. The assembly of the magnet system, mainly TF coils will be studied to minimize the assembly period. The detailed design of associated components, the thermal shield, the feeder components and quench detection and control system be started in next year.

Acknowledgments

The superconducting cables were manufactured by Furukawa Electric Co. Ltd.. The CS and EF Jackets were produced by Kobe Special Tube Co. Ltd.. The CIC conductors were fabricated by Hitachi Setsubi Engineering Co. Ltd..

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