Progress in Design and Fabrication of Current and Helium Feeding System for JT-60SA Superconducting Coils

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Abstract. To realize JT-60SA of the largest superconducting tokamak device in the world, the current feeder, helium piping and control system have been designed. In order to reduce the reaction force of support, crank shaped feeder and piping were designed. The crank shaped feeder reduces the reaction force of support to 10% of zigzag shaped feeder. Because of the limited space in torus hall, many interfaces of feeder and piping are located at upper part of tokamak. Feeders and piping have to manage large displacement of interface by adding bending. One box type electrical joint was developed with good reproducibility of electrical resistance below 3 mΩ even though different connecting positions and manufactures. Five coil terminal boxes, eleven valve boxes, components of cryoline and control system were manufactured already. These components will be installed in torus hall in 2019.

1. Introduction

The JT-60 Super Advanced (JT-60SA) consists of 18 Toroidal Field (TF) coils and 10 Poroidal Field (PF) coils including a Central Solenoid (CS) with 4 modules, and 6 Equilibrium Field (EF) coils as shown in FIG. 1 [1, 2]. The stored energy of TF coils and cold mass are 1.06 GJ and 750 ton, respectively. It means that the JT-60SA is the largest superconducting fusion device before ITER. Coil Terminal Boxes (CTB), feeders, superconductor for PF feeders, Valve Boxes (VB), Cryoline and magnet control system are procured by Japan. High Temperature Superconductor Current Leads (HTS CLs) and superconductor for TF feeder are procured by
Europe. This paper overviews the progress about the design and manufacturing of the current and helium feeding system.

2. Current and Helium feeding system

Coils are charged with currents through feeders that are connected to the current leads in CTBs located around the cryostat [2]. Feeders in large fusion devices like LHD, W7-X, KSTAR and EAST are introduced from the bottom of cryostat. However, the space for feeders and cooling pipes below JT-60SA is not enough because the center of plasma is fixed at 8 m from building floor to use the existing heating system. Therefore, many feeders and pipes are introduced from the top of cryostat. The space in the torus hall is also limited by the existing devices. Thus, 26 current leads are installed in 5 CTBs separately located around the Cryostat (see FIG. 2). HTS CLs are used to reduce the refrigerator power consumption [3]. Normal conducting busbars from power supply are connected to the warm end of HTS CLs. Feeders consisting of NbTi superconductors are connected to the cold ends of HTS CLs, and are routed to main cryostat. Feeders in CTB are connected to the in-cryostat feeders through mid joints in the vicinity of cryostat wall. The in-cryostat feeders are connected to the terminal joints of coils. FIG. 3 shows the cross section of feeder conductors. TF and PF feeders are manufactured from TF coil conductor and EF coil conductor, respectively [4, 5]. The current of TF and PF coils are 25.7 kA and 20 kA, respectively. Since the maximum allowable magnetic field of HTS CL is 33 mT, HTS CLs have to be 7 m away from the cryostat wall. It means that current feeder in CTB shrinks about 21 mm by cooling to 4 K. The maximum allowable horizontal force of HTS CL is 560 N. The feeder supports were adapted to keep forces on HTS CL within the allowable ones. [6]. Five CTBs were already manufactured by October 2018.

The JT-60SA helium refrigerator system (9 kW at 4.5 K) supplies helium to cold components through 5 piping loops: TFC (4.4 K), PFC (4.4 K), Cryopump (3.7 K), Thermal Shield (TS) (80 K), and HTS CL (50 K) [7]. The auxiliary cold box of refrigerator is placed on a room called the cryogenic hall, next to the torus hall. Cryoline connects the auxiliary cold box and cryostat as shown in FIG. 4. Helium from refrigerator flows to coils through cryoline, VB and in-cryostat piping.
The cryoline with 44 m in length is a bundle of helium pipes (see FIG. 5). Cryoline with vacuum barrier was required to prevent the leakage of tritium produced by DD reactions to outside the torus hall. The vacuum barrier is located near the middle of cryoline in a longitudinal direction. Cryoline has two bypass valves to control the mass flow to the TF winding pack (TFWP) and TF casing individually. Cryoline is connected to the upper part of cryostat. The vertical displacement of cryostat by vacuum pumping is -5 mm. The maximum relative displacement between the cryostat and the common stage by earthquake is 15 mm in radial direction. The outer pipe has bellows to manage displacement. Three types of supports for helium pipes were designed not to destroy the vacuum barrier and bypass valves by thermal shrinkage of pipes as shown in FIG. 6. The first is the guide support which allows the longitudinal movement of pipes. Pipes just through the holes on GFRP plate. The weight of pipes are supported, but pipes can move longitudinally. The second is the anchor support which prevent the movement of pipes completely. Collar are attached on pipes to stop the movement of pipes. The third one is the vertical support which allows the longitudinal and horizontal movement of pipes. Holes on GFRP plate have space horizontally. Pipes can move both longitudinally and horizontally. The anchor support are installed at the nearest position to the cryostat not to pull the pipes in cryostat and at vertical part outside torus hall to support the weight. Vertical supports were installed around corner of the cryoline.

VB contains valves and sensors to control the helium flow. Eleven VBs are installed around the cryostat. Dimensions of VB body are 2 m height and 1.4 m in the outer diameter. Almost all cold helium lines from refrigerator are firstly into VBs through cryoline and upper In-cryostat piping, which is placed above the superconducting coils. Pipes for pressure taps, orifice plates, and temperature sensors are installed at the pipes in VB for measurement of pressure, the flow rate, and the temperature of helium. In-cryostat piping made by SS316L are categorized to 5 types: upper, middle, and lower main piping and upper and lower branch
piping. Upper main piping is composed of manifolds and pipes supported by the cryostat top lid and connects cryoline and upper VBs or CTBs. Middle main piping is installed in the bore of CS and supported by the cryostat top lid and the cryostat base. It connects upper and lower main piping. Lower main piping is supported by the cryostat base and connects middle main piping and lower VBs or CTBs. Upper and lower branch piping are supported by superconducting coils and the cryostat, and connects VBs and superconducting coils or TS.

The refrigerator was already installed on-site and passed acceptance tests in November 2016 [8]. The manufacturing of cryoline was finished by February 2018. The manufacturing of 11 VBs were finished in 2017.

A measurement and control system is required to operate the system efficiently and safely [9]. About 3000 signals have to be treated for magnet system. A supervising system called magnet controller was developed. FIG. 7 Shows the signal system of magnet controller. Feature of the magnet controller are 1) achievement of an efficient cooling sequence to cool down the TF coil by controlling the TFWP bypass valve, 2) reduction of TF casing pressure loss by the TF casing bypass valve, 3) redundant design of quench detectors and detection circuits to secure reliability, 4) trigger of slow discharge as much as possible before fast discharge is triggered by quench to minimize the magnet temperature rise, allowing fast recovery of the superconducting magnet system for the next pulse operation.

Unlike the other loops such as the PF coils and TS, the TF loop

FIG. 7. Schematic of signal system of Magnet Controller

FIG. 8. Bypass valve position in TF loop at start of cooldown, and end of cool down
has a unique flow schematic. The TF coil consists of the winding pack and the casing as shown in FIG. 8. WP and casing is connected in series. The series connection allows to use the winding flow rate to cool also the casing. The magnet controller splits the total mass flow from the refrigerator to the TFWP and the casing by controlling the bypass valve. At ambient temperature when the cool down starts, the total flow from the refrigerator cannot pass the TFWP due to its large pressure loss. The magnet controller bypasses the excess mass flow by opening the TFWP bypass valve. When the TF is getting colder and its pressure loss is reduced enough, the TFWP bypass valve will be fully closed. The casing bypass allows to keep the pressure drop in casings low by providing an additional route of helium flow. If the WP and the casing are independently cooled or connected in parallel, another circulator or a larger-sized circulator would have been needed. The manufacturing and testing of magnet controller was finished in March 2018.

3. Crank shaped feeder in CTB and He piping in CS

In the initial design, feeders in CTB were zigzag shape because of its easy manufacturability. However, it was found by finite element method (FEM) structure analysis that the strain in fixed support caused by thermal shrinkage of feeder is large. The strain was not changed even though the increment of number of zigzag from 3 to 4. Thus, the investigation of spring constant for several feeder shapes was conducted by FEM structure analysis as shown in FIG. 9. The right hand edge of feeder was fixed, then, the left hand side of feeder was pulled 10 mm. The spring constant was calculated from the reaction force at right hand edge and 10 mm in displacement. It was confirmed that the spring constant of 3 zigzags (FIG. 9(a)) and 4 zigzags (FIG. 9(b)) are in the same level. Spring constants of U shape (FIG. 9(c)) and crank shape (FIG. 9(d)) were about 10% of zigzag shapes. Finally, crank shape was selected because of its easier manufacturability than U shape [6].

Middle main piping in the bore of CS consists of 4 pipes. Top and bottom part of middle main piping are supported by support structure connected to the cryostat. The cryostat is deformed by the evacuation of cryostat. Thus, the connecting point of piping is moved by evacuation. The vertical displacement of top and bottom is -6.1 and 0.7 mm, respectively. Support structures are also shrunk by cooling. The displacement of connecting part for middle main piping were evaluated as 2.1 mm for upper

![FIG. 9. The spring constant of each feeder shape in CTB](image)

![FIG. 10. The comparison of the reaction force for upper and lower support by dead weight and cooling of pipe.](image)
and -5.1 mm for lower. The middle main pipes are initially designed as S shaped bending structure. However, it was found by FEM structure analysis that the reaction force by dead weight and cooling of pipe is large. The shape was changed into crank shape like the feeder in CTB. FIG. 10 shows the reaction force by one pipe. The reaction force for upper support was reduced to 49%.

4. In-cryostat feeder and piping at upper part

Feeders and piping have to withstand the gravity, thermal contraction by cooling, displacement of cryostat by vacuuming, displacement of coils by cooling and operation and earthquake. For the component supported from the ground, the displacement of lower part is generally smaller than that of higher part. Therefore, interfaces between components and cooling pipes are willing to be placed lower part. For JT-60SA current and helium feeding system, however, almost all

FIG. 11. Displacement of TF coils by cooling and plasma operation.

FIG. 12. Design and stress of He piping between EF2 and VB06.

FIG. 13. In-cryostat feeders from CT03 (a) and CT02 (b).
interfaces between cold components and cooling pipes are placed on the top of components because of limited space. *FIG. 11* shows the displacement of TFC terminal by cooling and electromagnetic force at end of burn of plasma scenario. The terminal is moved -38 mm in vertical direction, -8 mm in radial direction by cooling and 11 mm in toroidal direction by plasma operation. *FIG. 12* shows the result example of a structural analysis of helium piping from VB06 to EF2. In the case of old design, piping was routed by shortest distance consisting of two bending of toroidal and vertical direction. The maximum stress of piping was 582 MPa which is much larger than the design allowable stress of 350 MPa. In the present design, two bending was added horizontally. The stress was reduced to 251 MPa. This kind of additional bending was added for all upper piping between upper VB and coils. The in-cryostat feeders with bending shape for flexibility were also designed to allow coil displacements. *FIG. 13* shows the in-cryostat feeder connecting from CT03 and CT02.

5. Development of the one box joint for feeder

Terminal joints of PF coils and mid joints of TF and PF feeders are the lap type joints connected by solder. The allowable electrical resistance in joint is <5nΩ. *FIG. 14* shows the schematic drawing of joint. The feeder cable are connected. After removing the nickel coating of NbTi strands and copper (Cu) wires. Cable, Cu saddle and cable were soldered and clamped by SS clamp with bolts. The connecting length was 160 mm for PF and 300 mm for TF which is equal to the final twist pitch of cables. The joint is surrounded by stainless steel can. The void fraction and pressing force of cable during soldering are 25% and 140 kN, respectively.

In order to check the reproducibility of electrical resistance and manufacturability of joint, several sample were tested. Because the direction of terminal joint is vertical, it was required to confirm that the solder connection can be done appropriately. Three short samples to test the electrical resistance with relevant external magnetic field were produced. These samples were installed in the superconducting coil at National Institute for Fusion Science (NIFS) [10]. Another test was conducted using the real CTB. First manufactured CTB is for TF coils, jumper NbTi conductor was connected to the one pair of feeder in CTB. The company for tokamak assembly conducted this connection for

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<tr>
<th>TABLE II: Results of conductor joint test</th>
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<tr>
<td>Conductor type</td>
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</tr>
<tr>
<td>Connecting condition</td>
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<tr>
<td>Connecting company</td>
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<tr>
<td>Current (kA)</td>
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<td>Temperature (K)</td>
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<td>External magnetic field (T)</td>
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<td>Joint resistance (nΩ)</td>
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their training Table II shows the overview of joint testing. The joint connections were conducted different company. The measured electrical resistance is also shown in Table II. The joint resistance was derived from electrical current and voltage between voltage taps installed at both ends of joint. All tests shows the electrical resistance below 5 nΩ. The electrical resistance is from 1.0 to 2.8 nΩ indicating that the sufficient reproducibility.

6. Summary

Design of JT-60SA current and helium feeding system has been established and following results were obtained.

(1) In order to reduce the reaction force of fixed support in CTB and support of middle main piping, crank shaped feeder and piping were designed. Thanks to the crank shaped feeder reaction force of fixed support was reduced to 10% of zigzag shaped feeder.

(2) Because of the limited space in torus hall, many interface of feeder and piping are located at upper part of tokamak. Feeders and piping have to manage large displacement of interface. The design of feeder and piping were conducted carefully using FEM structural analysis. The additional bending of feeder and piping are required to reduce the stress below design criteria.

(3) One box type electrical joint was designed for mid joint and terminal joint. To confirm the reproducibility of electrical resistance by different connecting positions and manufactures, several joint testing were conducted. Measured electrical resistance was from 1.0 to 2.8 nΩ which is lower than the criteria of 5 nΩ indicating that the sufficient reproducibility.

References