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Production and installation study of the ITER PF4 in-pit feeder

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HIGHLIGHTS

- Explosive bonding is used to connect the OFE copper with steel box.
- During production process, alignment method is applied to ensure the precision relative positions of the busbar joints.
- The assembly sequence of the PF4 in-pit feeder is developed with minimum clearance of 31 mm.
- Copper shims are used to compensate the gap between busbar joints.

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ABSTRACT

The PF4 in-pit feeder includes the In-Cryostat-Feeder (ICF) and Cryostat-Feed-Through (CFT), with busbars being their key components. The relative positions of the busbar terminal joints are measured by using a laser tracker and adjusted by positioning tools. The busbars are not fixed on the separate plate until the position errors meet the manufacture tolerances. The CFT has a 2.38° penetration angle relative to the ground and will be installed firstly. The position of the connection interface between the CFT and its lifting tool is analyzed, and to reduce the total deformation and keep the assembly precision of the joints the straight part of the CFT needs to be supported. The ICF has the most critical assembly operation space, as it must be installed on its temporary support in a temporary position. After the PF4 coil has been installed the ICF will be moved to its final position. To guarantee the 30 mm safety assembly clearance provided by ITER, the collision analysis of the ICF is performed, which demonstrates that the assembly procedures are feasible.

1. Introduction

The ITER tokamak contains powerful superconducting magnets to generate, stabilize and control the deuterium–tritium plasma, feeders are life-line for them [1,6]. The PF feeders can convey the cryogenic cooling and electrical power to coils as well as the instrumentation channels needed to operate and monitor the function of the PF coils [3]. There are six poloidal field (PF) feeders for six PF magnets, and the units are distributed around the tokamak (Fig. 1).

Three of them are at the lower level and the others at the upper level. The PF4 feeder consists of an in-pit feeder and an out-pit feeder. The in-pit feeder includes CFT and ICF, which connects the out-pit feeder and the PF4 coil with busbar joints. CFT and ICF are connected by a gimbal. The outside of the PF4 feeder is room temperature, and the busbars are cooled by helium which have temperature of near 4.5 K. In order to reduce thermal radiation heat loads onto the busbar system, an 80 K thermal shield is designed between the outer tube and the busbars [11]. When the PF4 magnet is working, the electromagnetic force will make it generate displacements in radial and toroidal directions. With the adjustment of the gimbal those displacements can be absorbed. The total weight of the PF4 in-pit feeder is about 20 tonn.

2. The production and industrial fabrication of the PF4 in-pit feeder

Before the final assembly of the PF4 in-pit feeder on the tokamak, the ICF and CFT have been produced and fabricated in the factory. The main components of ICF and CFT are busbars, cooling pipes, instrumentation pipes, pipe supports and outer tubes, etc (Fig. 2).

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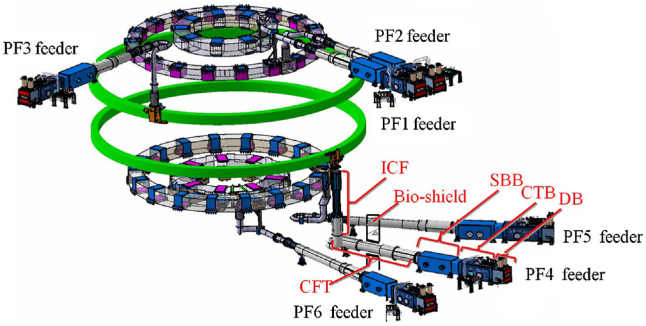

Fig. 1. Layout of ITER PF feeders.

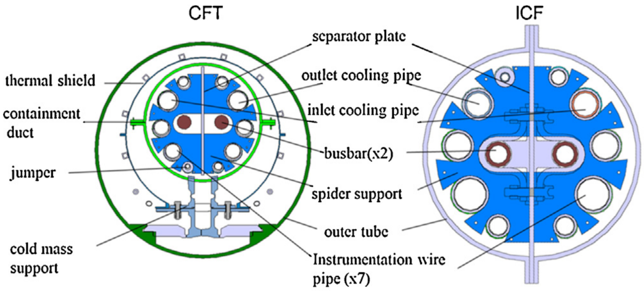

Fig. 2. Cross sections of PF4 feeder CFT and ICF.

2.1. The busbars (with joints) fabrication

ITER PF4 feeder superconducting busbars use NbTi superconductor which adopt Cable in Conduit Conductor (CICC) cable design concept as in the ITER magnets. The CICC is cooled internally with supercritical helium at 0.6 MPa and 4.5 K [3,5,10]. Each of the PF4 feeder CFT busbars is about 10 m in length, and it has seven bends. There are a total of five different bending radiuses. The two busbars of the ICF are identical with their length around 3.6 m, and they have four bends with different bending radii. At the two ends of the busbars of the PF4 feeder CFT or ICF are busbar joints. The above bends are bended by using the bending dies which have the same radius as the busbars'. The manufacture tolerances of the busbars are ±0.5 mm in length and ±0.01° in angle which are very strict to guarantee the accurate positions of the busbar joints. When one bend is finished, it will be measured and then corrected, and all of those bends should be produced like that one by one. This can avoid large cumulative errors at the last bended section.

The busbar joint used on the PF4 feeder is called a twin-box joint, and the section of the joint is as shown in Fig. 3. The "Oxygen Free Electrolytic" (OFE) copper sole, which has high conductivity [4], is connected with the steel box by an explosive bonding process. Before the connection of joint and cable the conductor should have the pretreatment process of jacket removing, nickel coating removing and strand tinning. The joint box needs preparation work also, which contains the OFE copper sole explosive bonding and its inner surface tinning electrolytic process. The coating material of the above tinning process is 63Sn/37Pb whose melting point is 183 °C. The cable end shall be inserted into the termination box and the cover shall be placed on top of the cable. The joint is then heated to 200 °C to keep the solder (63Sn/37Pb) melted, then compressed by applying the necessary pressure to move the cover down until it fits to its final designed position (~2MN are needed). Then the pressure should continue while the heating is stopped, and laser welding should be used to bond the cover and the box together. After finishing the assembly, the termination box shall be leak tested to ensure a leak level <10^{-9} Pa m^3 s^{-1}.

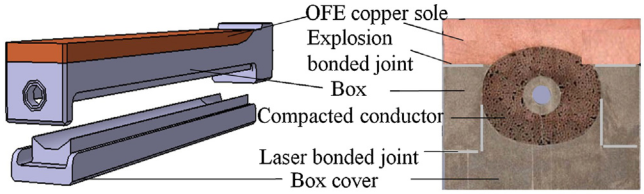

Fig. 3. Components and connection of PF4 feeder busbar joint.

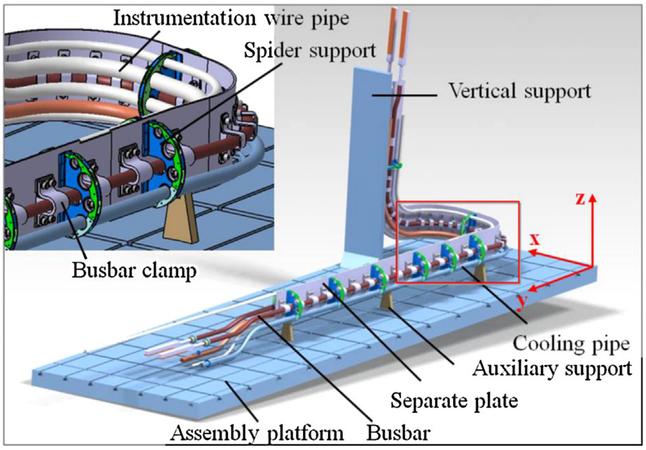

Fig. 4. Assembly platform and coordinate system for CFT assembly.

2.2. The CFT (ICF) final fabrication in factory

The basic final fabrication process of CFT can be summarized as follows: (a) install the separate plate, (b) install the lower busbar clamps, (c) install the busbars, (d) assemble the spider supports and install all the instrumentation wire pipes and cooling pipes, (e) connect the containment duct, (f) install thermal shield and cold mass supports, (g) install the outer tube.

As the main support of the pipes and busbars, the separate plate is the first part to be assembled during the final fabrication process of the PF4 feeder CFT. The thickness of the plate is 10 mm and it has a U-shaped bend. An assembly platform with a vertical support is designed; many auxiliary supports are fixed on it (Fig. 4). With the sufficient support the deformation of the separate plate is quite small. After that, the busbar clamps (lower clamps) will be installed on the separate plate, and it should not be fixed so as to be adjusted latterly. The positions of two busbar joints of each busbar should be measured and adjusted after assembling. Defining the coordinate system like Fig. 4 shows, 4–6 equispaced-points from the copper surface of two joints are measured to get the relative positions of the two busbar joints, then adjusted to meet their manufacture tolerances. The containment duct and thermal shield are two-halves which are connected by bolts.

The structure and components of ICF is very similar with CFT, and the fabrication processes can be followed as the above ones.

3. The assembly environment and tolerance requirements of PF4 in-pit feeder

3.1. Assembly environment and interfaces

Before the PF4 in-pit feeder installation, the base of the cryostat and the nine toroidal field-vacuum vessel (TF-VV) sectors have been

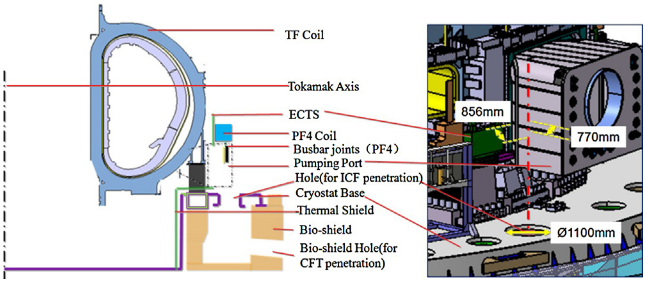

Fig. 5. Assembly environment and interfaces of the PF4 in-pit feeder.

already assembled on their final positions. The six side correction coils (SCC) have been fixed on the TF case by using clamps. Pumping port and equatorial cryostat thermal shield (ECTS) are also installed in their final positions. The hole on the bio-shield with a diameter of 1350 mm and 2.38 degrees tilting angle in which the CFT will be penetrated through confines the space for the CFT assembly. The assembly environment and interfaces of the ICF can be described as follows:

- The Ø 1100 mm hole on the cryostat used for ICF penetration.
- The 856 mm distance between the axis of the cryostat hole (for ICF penetration) and the ECTS.
- The 770 mm distance between the axis of the cryostat hole (for ICF penetration) and the pumping port.
- The interfaces between the ICF and the PF4 coil, CFT in the area of terminal joints.
- The interfaces with its assembly tools (Fig. 5).

3.2. Assembly tolerances requirements

In the PF4 in-pit feeder's assembly, the tolerances of some components of the interfaces are controlled strictly. Those critical interfaces are: the coil terminal joints interfaces and the CFT to bio-shield floor interface.

The busbar joints generate the most of the heat load to the feeder cryo-system and the assembly tolerances have a significant impact on the resistance of the joints [1]. The CFT is connected to its gravity supports and has an incline angle relative to the floor. The installation precision of the CFT influenced its terminal joints' positions obviously, as the CFT has a large size in length.

The tolerance requirements of the main components are shown in Table 1.

Table 1
The tolerance requirements of the main components in PF4 in-pit feeder assembly.

Interface	Item	Value	Comment
Busbar joints	Central offset	±2 mm	One joint referred to the other in width direction
	Central offset	±15 mm	One joint referred to the other in length direction
	Surface gap	+2 mm	Shim thickness between the two joints
CFT—Bio-shield	Inclination	±0.01°	Referred to the horizontal bio-shield floor
CFT gravity supports—Bio-shield	Height	±0.5 mm	Referred to the horizontal bio-shield floor
	Parallelism	0.2 mm	Referred to the horizontal bio-shield floor

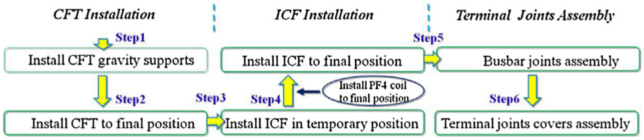

Fig. 6. Assembly scenario of the PF4 in-pit feeder.

4. Assembly sequence and analysis of the PF4 in-pit feeder

The assembly sequence of the PF4 is divided into three separate processes, the CFT installation, the ICF installation and the terminal joints assembly. The whole assembly sequence is shown in Fig. 6.

4.1. The CFT installation

The two CFT gravity supports are the first components to be assembled. The bottom of the supports is connected to the bio-shield floor by bolts. The bolt holes are designed as a waist type that can adjust the positions of supports conveniently to compensate the manufacture and assembly errors of anchor bolts and the supports. The assembly tolerances of the supports are very strict, and in order to achieve those strict tolerances some shims are inserted between the supports and the floor.

Using a crane to lift and penetrate the CFT into the Ø1350 mm hole on the bio-shield, special lifting tools are needed to keep the balance of the CFT. The size of the lifting tool should be as compact as possible to avoid its collision with the bio-shield during the penetration process. The straight part of it should be bared without attaching points to the lifting tool frame during the penetrating process. The two legs on the bottom of the U-shaped bend part used for their gravity supports' connection can be chosen as the mounting places with its lifting tool. The total deformation of the CFT under gravity force is simulated by ANSYS software, where the two legs are fixed (supported by lifting frame) and the long straight part is free without support (Fig. 7). At the end of the straight part the deformation is 5.6 mm and the maximum deformation occurs at the terminal joints area which reaches to 10.1 mm. The big deformation affects the assembly accuracy of the busbar joints (the parallelism relative to the ground is 0.2 mm). The maximum total deformation of the CFT is within 2 mm.

When the CFT is being transported by its lifting tool before the penetration process, adding auxiliary support on the straight part can reduce the deformation. During the penetration process a guider tool is installed in the hole to protect the outer surface of the CFT which can also play the role as a temporary gravity support. Terminal caps for busbar joints have been designed conceptually by

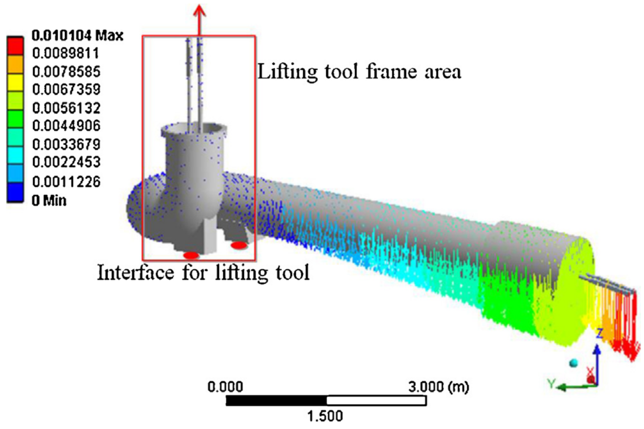

Fig. 7. Total deformation of PF4 CFT when being lifted (without auxiliary tools).

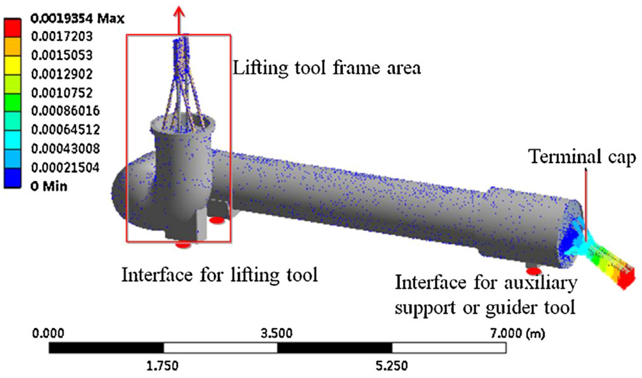

Fig. 8. Total deformation of PF4 CFT when being lifted (with auxiliary tools).

ITER feeder team to limit the deformation in the joint area during the assembly process. Fig. 8 shows the analysis result of PF4 feeder CFT which is supported by an auxiliary support (or guider tool) and protected by two terminal caps. The maximum deformation is 1.9 mm which occurs at the joints area. By modifying the structure of the terminal caps the maximum deformation can be reduced. Detailed design of the lifting tool and auxiliary support is ongoing in Korea.

After the placement of the CFT, use the alignment method to survey the specified points on the busbar joints; if the assembly errors meet the tolerance requirements then fix the CFT on its gravity supports eventually [7].

4.2. The ICF installation

The assembly of the ICF contains two separate processes: install the ICF to its temporary position and to its final position. Confined by assembly space, it is impossible to install the ICF after the PF4 coil is assembled which means the ICF should be installed first and stored in a temporary position. Avoiding clashes is the main principle of the temporary position's being chosen.

When the ICF is installed in its final position, its central axis will coincide with the central axis of its penetration hole. Besides, the surfaces of the busbar joints of the CFT and ICF will contact without gap. In order to avert the interference between busbar joints when the ICF is being penetrated through the hole vertically, the ICF should have a radial offset of 150 mm outwards towards the centre of the tokamak. The ICF is inclined by 10 degrees after lowered to its final height to make the clearance of the busbar joints (CFT&ICF, ICF&PF4) larger. Those movements are performed by using the ICF assembly tool (temporary support) with the assistance of the top crane; all the busbar joints are covered with protection caps during the whole assembly processes. The Degree Of Freedom (DOF) and strokes of the ICF assembly tool is required as Fig. 9 shows, which include: (a) it has a straight line motion along the *Z* axis (parallel with the axis of the tokamak), and the stroke is ±150 mm relative to the final height of the ICF and has a 20 mm margin. (b) It can carry the ICF move in the radial direction and its stroke is +150 mm + 20 mm (margin). (c) It has a + 10° + 1°(margin) rotation in the YOZ plane.

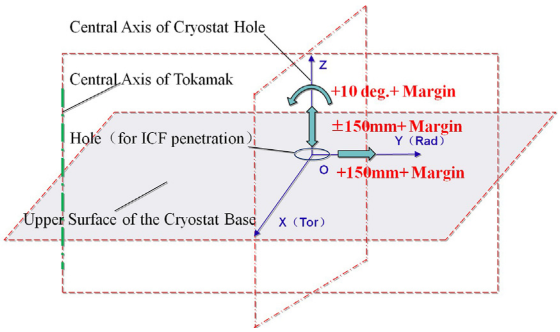

Fig. 9. The function requirements of the ICF assembly tool.

Table 2
The functional requirements of the busbar joints after assembly.

Item	Valve	Comment
Maximum operating current	57 kA [5]	Produce up to ~10 W heating per joint
Peak electromagnetic force	2.7×10^4 N [8,9]	
Busbar joint max resistance (nΩ)	2	
Max average AC loss (%) of joint heating	<10	Affected by the orientation of the joints
Max pressure drop/joint	0.0075 MPa	
He leak rate of weld	10^{-9} Pa m^3 s^{-1}	Without vacuum cup

The purpose of putting the ICF in its temporary position is to wait the PF4 coil's installation. After the PF4 coil is assembled, the ICF turned back to its final position with the reverse movements accordingly.

The assembly space of the ICF is confined by many components. During the PF4 in-pit feeder assembly any of the collision is forbidden especially in the busbar joints areas. To avoid collision caused by swing or vibration when feeder components are being moved, in most of the assembly steps the clearances between feeder and its surrounding components are required larger than 30 mm if 50 mm is impossible to be guaranteed. In the ICF's installation, four places' clearances between the ICF and its surrounding components are supervised. As Fig. 10 shows, those clearances are the minimum distances between: the ICF busbar joint and the terminal joint box of SCC (A–A′), the flange on the ICF and the inner space of the cryostat hole (B–B′), the ICF busbar joint and the CFT busbar joint (C–C′), the ICF busbar joint and the PF4 coil busbar joint (D–D′).

The assembly sequence is simulated by DELMIA software, the variation of the above clearances is shown in Fig. 10. When the ICF is in temporary position, the minimum clearance is 31 mm larger than 30 mm which means the assembly sequence is feasible.

4.3. The terminal joints assembly

The terminal joints assembly is the last step of the PF4 in-pit feeder's installation, which includes the busbar joints connection and the covers' assembly of the terminal area. The main operational parameters of the PF4 feeder busbar joints are given in Table 2.

The starting of the busbar joints assembly is after the leak test of the twin-box conductor terminations. Positional adjustment systems are applied to adjust the two boxes' positions in all three directions in agreement with the tolerances shown in Table 1. Due to the assembly error, a gap is common to the joints' surfaces. A custom made three-dimensional shaped copper shim can be inserted between the copper soles. The accuracy of the machining of shim is better than ±0.5 mm and the surface roughness (Ra) of the shim is 1.6–3.2 μm [2]. The busbar can be bended slightly but twist is prohibited completely. The heating temperature in the solder process between joint boxes affects the welding joint between the cable and the joint box. The melting point of the solder between joint boxes should be lower than 183 °C. According to the experiment results from ASIPP, Sn-50Bi-31.2In is a good soldering material for joint boxes welding which has low melting point (100 °C) and low resistance. Weld lateral strips to link the two boxes, which can prevent the stiffness of the S-bend system. Two layers of insulation are wrapped around the area of the connected twin-box. The separate plate is inserted at the terminal joints area and the connected joints are fixed to it by clamps. All pipes are welded at their interfaces

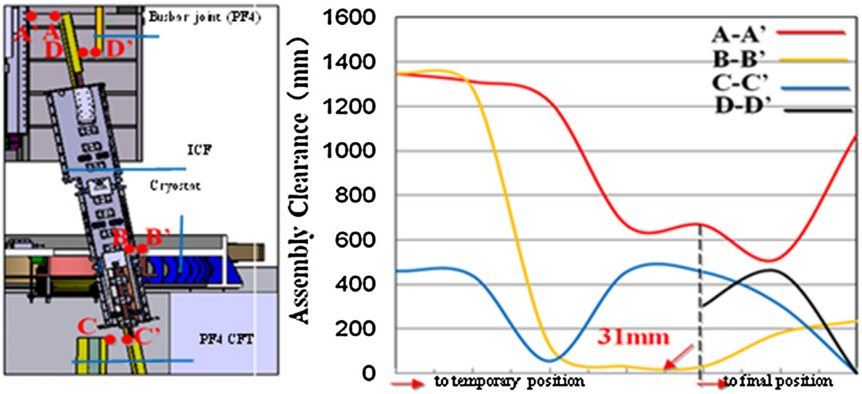

Fig. 10. The supervised areas and their clearances variation during the ICF's assembly.

accordingly. For the terminal joint of the PF4 ICF and the PF4 coil, there is a terminal cover to enclose and protect the connected joints. In the terminal joint area of the ICF and CFT the joints are covered with the middle joint duct. Besides this, the CFT is connected to the cryostat by the transaction of the middle extension conduct and seismic bellows. When all the assembly is finished, a leak test is executed at all welds between the CFT and the cryostat.

5. Conclusions

The PF4 in-pit feeder includes the ICF and CFT. In this paper the production and installation of it is studied. The CFT and ICF are produced in China and then transported to the ITER site to do the final installation. The ICF and CFT have a similar composition structure whose key components are busbars (with joints). In factory the R&D work for the auxiliary production tooling has been started especially for the tools used for busbar bending and joint positioning. The procedures of the PF4 in-pit feeder final assembly and the maximum acceptable error fields are introduced. Some of the assembly tools' function requirements are shown. By measuring the assembly clearances between the ICF and its surrounding components and the calculation of the total deformation of the CFT when it is being lifted, the assembly feasibility is analyzed and demonstrated.

Acknowledgements

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