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Correction coil and magnet feeder lessons learned

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Abstract

China has contributed to the manufacturing of the Error Field Correction Coils (CC) and the Magnet Feeders for ITER (International Thermonuclear Experimental Reactor). The manufacturing projects have been carried by ASIPP (Institute of Plasma Physics Chinese Academy of Sciences). In this paper, the lessons learned from these two manufacturing projects will be described with special focus on some key manufacturing processes. These experiences gained from the work carried so far in CC and magnet feeder manufacturing and testing are very valuable not only for the remaining manufacturing tasks of these two projects, but also for similar systems of other Tokamak fusion device.

Keywords: magnet feeders, error field correction coils, Paschen test, superconducting joint, special welding

(Some figures may appear in colour only in the online journal)

1. Introduction

ITER is equipped with a set of 18 Superconducting Error Field Correction Coils (CCs). These are located in three groups of six: at the top, bottom and outer side of the vacuum vessel, as shown in figure 1(*a*). The purpose of these coils is to correct the effects of the asymmetries caused by coil manufacturing and assembly tolerances on the plasma. By driving electric currents in these CCs, magnetic fields can be created that restore plasma symmetry.

There are 31 feeders (26 for magnets) arranged in a circle at both the lower and upper levels of the ITER tokamak building, as shown in figure 1(*b*), to convey electrical power and cryogenic coolant to the superconducting magnets. All magnet feeders are made of three main segments with coil terminal box (CTB), cryostat feedthrough (CTF) and in-cryostat feeder (ICF) [1–4].

Until September 2023, about 90% of CC and 80% of feeders manufacturing tasks have been completed. Most of the components of these two systems have been delivered to the ITER site and already been installed to the Tokamak Hall. This paper will introduce the key technical challenges and experiences in the manufacturing phase from the following aspects.

2. CC lessons learned

2.1. CC Helium nozzle welding

The CC were winded by single conductor. To avoid the big flow resistance and temperature variation in the coil, a multi-channel approach of supercritical helium (SHe) was

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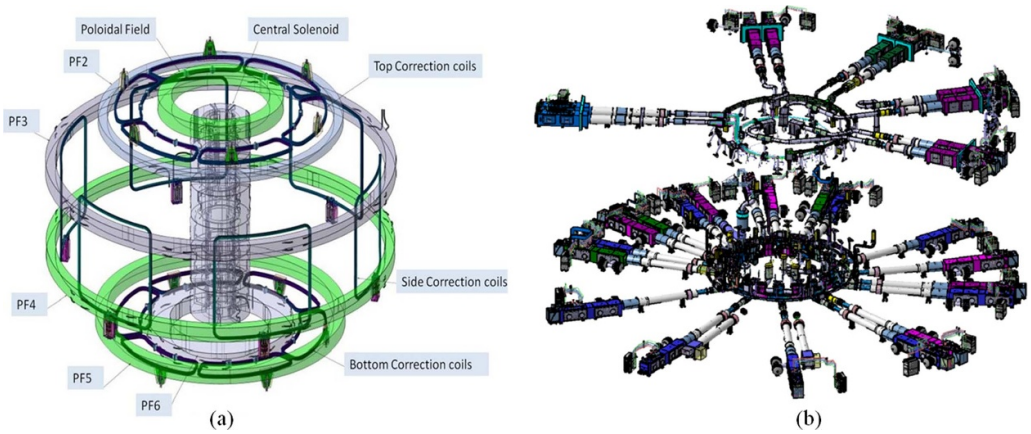


Figure 1. (*a*) Layout of the (18) ITER error field correction coils. (*b*) Layout of the (31) ITER feeders.

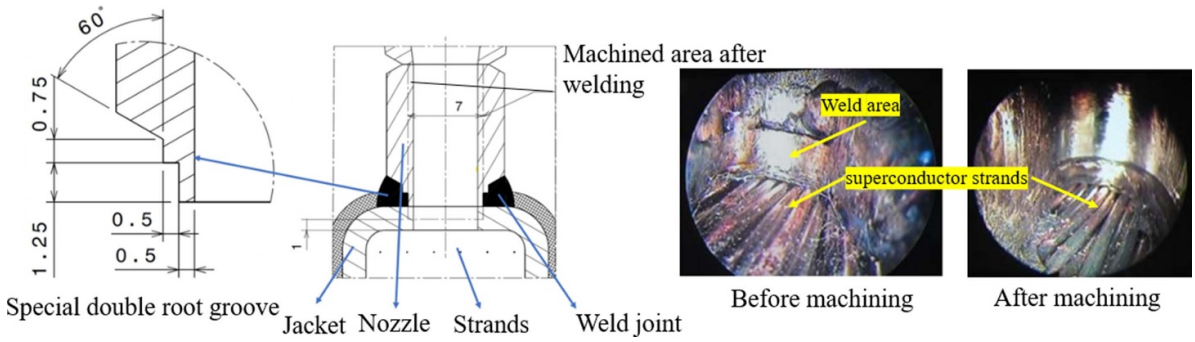


Figure 2. CC He nozzle welding sketch.

designed by welding the inlet/outlet nozzles (SS 316 l) on the adjacent layer jackets. All bottom and top CC are identical in design and construction with four inlets and five outlets. All side CC are identical layout with two inlets and three outlets [5]. And the structure of helium nozzle itself is same on each CC (as shown in figure 2).

Fracture assessment was performed based on ASTM E 399 and E 813-89 standards with 1.5 safety factor. The Helium nozzle shall be survived after 60 000 cycled loading fatigue test in 'strain driven' mode with strain range 0.09% $\sim$ 0.18% at 4.5 K (These requirements are based on expected values during operation). During the TIG welding process the temperature of superconductor strands shall be limited below 250 °C. Special double root face groove was used to control the deformation. Most of the deformation will happened on the first root (1.25 $\times$ 0.5 mm), and this root area will be machined off after welding to improve the surface quality, as shown in figure 2.

Every duration of welding must be less than 5 s, and until the temperature dropped below 50 °C (the interval time is about 5 mins) the welding can be continued. A special cooling block (water-cooling) was designed to control the temperature during the welding process, the structure of cooling block is shown in figure 3.

Large quantities of welding tests were performed to find suitable welding structure and process parameters in the qualification phase of production. On the testing mock-up, there were four thermal couples placed around weld joint, thermal couples 1–4 were inserted into conductor. The thermal couple 5 measured ambient temperature as a control group. The results showed that the maximum temperature could be controlled less than 135 °C. The curves and the layout of thermal couples are shown in figure 4.

2.2. CC terminal service box (TSB) SS pipe insulation

TSB contains the interfaces between electrified and non-electrified pipes. In this area, all the pipelines shall be connected by insulation breaks and insulated (The requirements are 3 kV for DC HV (Direct Current High Voltage) test and 1.5 kV with leak current below 20 μA for Paschen test), as shown in figure 5. Normally, insulation is wrapped using GK tape composed of pre-preg (which needs to be cured by heating to 80 °C–90 °C) and Kapton tape. Due to space limitations, the heating device cannot be used. Therefore, the wet wrapping process was performed, where the dry glass fiber tape was manually impregnated and compounded with Kapton tape, then wrapped and cured at room temperature. At present, 12 CC (all bottom and top CC) passed the DC HV test and Paschen test successfully. This experience showed that wet wrapping process of insulation was not only suitable for coil TSB, but also suitable for coil onsite installation process to solve the space limitation issue.

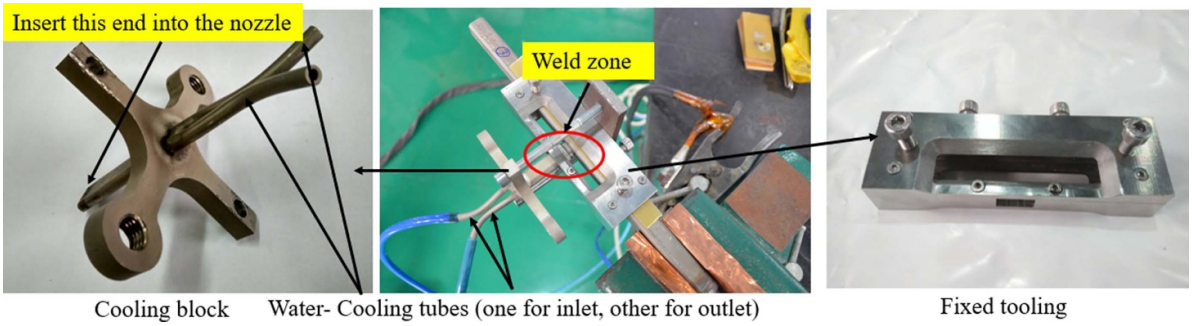


Figure 3. The structure of cooling block.

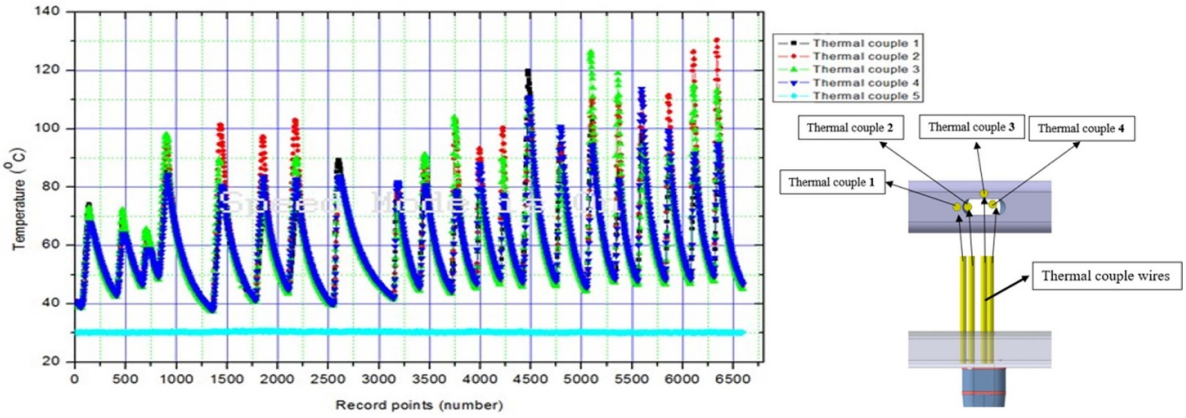


Figure 4. Strands temperature curves of Helium nozzle welding and the layout of thermal couples on testing mock-up.

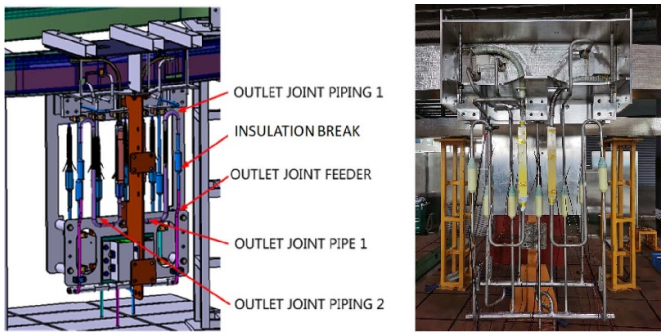


Figure 5. BCC TSB pipeline's structure.

2.3. HV signal wires' passing through

HV signal wires are used to detect the HV signals on the CC at 4.5 K temperature. The abnormal signals will activate the ITER Magnet Quench Protection System. The installation of the HV signal wires is critical for the CC magnet systems.

The CC ground insulation thickness is 4 mm with four layers Glass-Kapton-Glass (GKG) plus one layer glass tape (The requirements are 3 kV for DC HV test and 1.5 kV with leak current below 20 μA for Paschen test). Limited by installation space, the length of the HV signal wires' passing through area should be as short as possible, and the risk of damage to the signal wires also need to be considered at the same time. After investigation and tests, the HV signal wires' passing through structure was defined that it is 200 mm length with 50 mm length on each layer, and shrinkable tube was applied at HV signal wires passing through area to protect HV wires from resin pollution, as shown in figure 6.

To reduce the risk for online installation, all HV signal wires installations were made offline on individual components (as shown in figure 6 right picture). And all the completed components had to pass the 3 kV DC HV test and 1.5 kV Paschen test at room temperature after 80 K to 300 K thermal cycling (1 time), then they were connected with pipelines.

3. Magnet feeder lessons learned

3.1. The special welding of thin-walled helium pipes on the superconducting jacket

To achieve the highest mechanical property between the jacket of superconductor and joint, the full penetration butt welding is required. But the overheating will degrade the superconductivity of strands. And because of the multi-strand cable and 0.1 mm stainless steel foil wrapping underneath the jacket (as shown in figure 6), there were no proper NDT (Non-destructive testing) methods to do volume inspection of welds after welding. So only the process control can be used to ensure welding quality. During the qualification phase, ASIPP performed serial trials to achieve the full penetration welding and

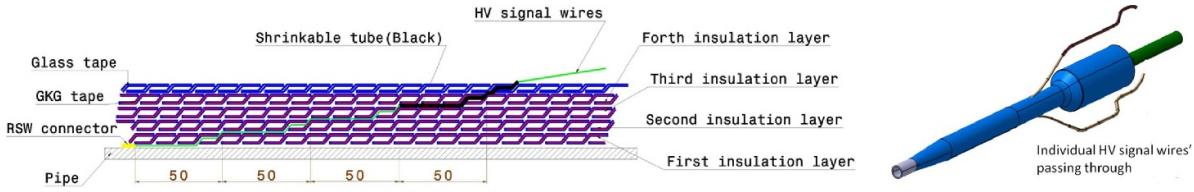


Figure 6. Scheme of the HV signal wires' passing through in the insulation (red—polyimide film, blue—glass tape).

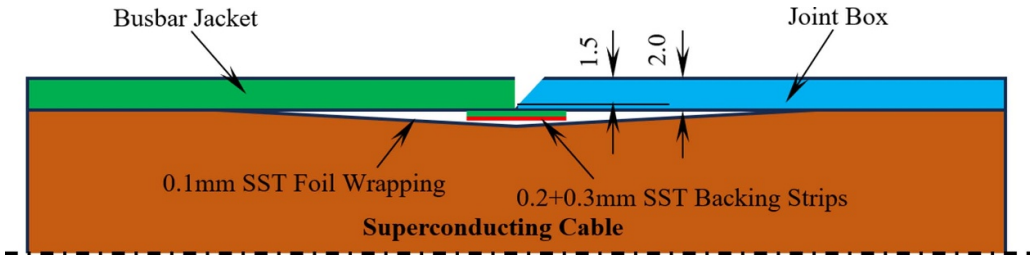


Figure 7. Final configuration of butt-welding seam.

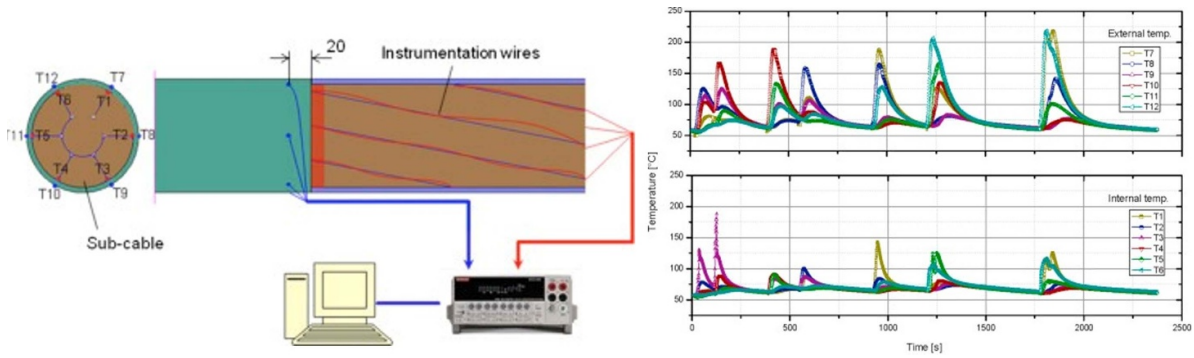


Figure 8. The temperature measuring points distribution and curves. 6 internal thermocouples (T1–T6) uniformly distributed in circumference underneath the welding seam and 6 external ones (T7–T12) 20 mm outer away from the welding seam. Reprinted from [6], Copyright (2015), with permission from Elsevier.

control the cable temperature below 250 °C. The final strategy is to insert 0.2 + 0.3 stainless steel strips (as shown in figure 7) to isolate the welding heat and perform the welding according to the qualified parameters. The detailed qualification processes are shown in [6]. It proved that during the whole welding processes the cable temperature was lower than 190 °C, the temperature measuring points distribution and curves are shown in figure 8. For this special welding process, a PPS (Production Proof Sampling) welding should be performed before the production welding, and the welder must be qualified in advance and invalid if more than three consecutive months of non-practice of the welding. The visual test, penetration test and radiographic test shall be performed to the PPS welding seam.

3.2. Special connection processes for superconducting joint

The original guideline in ITER PA (Procurement Arrangement) for bonding the cable & joint box and the twin boxes (see the right picture in figure 9) is tinning at different temperature (240 °C and 216 °C) sequentially. To keep the bonding of cable & joint box, the twin boxes tinning temperature shall be controlled less than 186 °C which is too low to get perfect tinning quality. To solve this issue, ASIPP designed an indium wires compression connection strategy. Wrap the Φ1.2 mm indium wires around the copper insert uniformly and then compress the indium wires by the twin boxes to designed thickness (0.2 mm, the goal is to fill the gap between the twin boxes with compressed indium), as shown in figure 9. By this strategy, the twin boxes can be bonded together at room temperature and no heating process so that the bonding quality is easy to control and no flux pollution during the installation process. This connection process was qualified and already applied to the onsite joints installation [7, 8].

After the indium wires compression connection, the next step is insulation wrapping of twin boxes. The insulation material and main-structure are same with Feeder busbar insulation which is wrapped with pre-preg and GK (pre-preg and kapton compounding) layers. The first qualification was performed with one time wrapping and vacuum bag curing but it failed. After destructive test, some Paschen channels between HV wires & insulation were found because of weak bonding insulation layers. Then ASIPP preformed a multi-stage

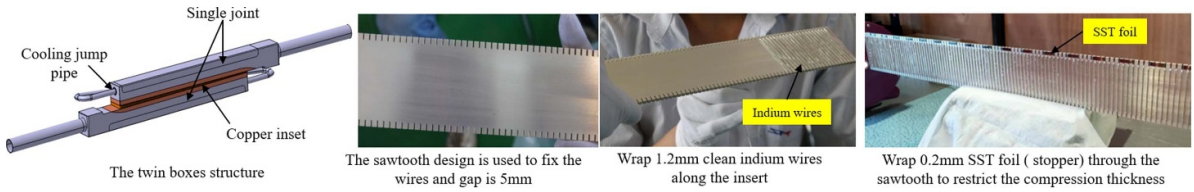


Figure 9. Indium wires on the copper insert (copper insert was silver plated to prevent the oxidation).

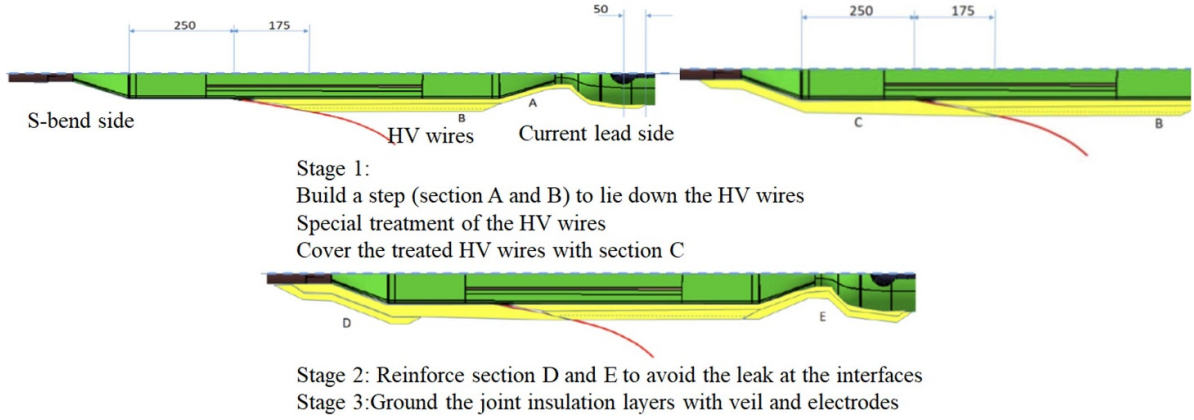


Figure 10. Sketch of joint insulation.

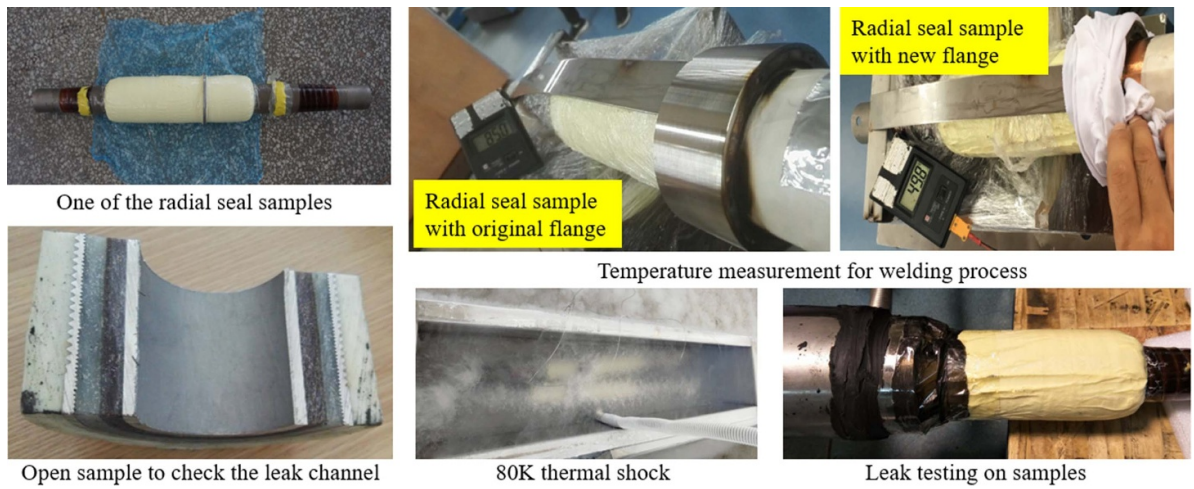


Figure 11. The process studies on radial seal samples. The new radial seal flange can reduce the temperature on the bonding interface between radial seal and insulation from 85 °C to 50 °C. When the screw length of the radial seal more than 80 mm, no leak was found on samples after 80 K thermal shock (5 times before and after welding).

wrapping and curing strategy, as shown in figure 10. For one joint insulation, wrap and cure 3 times to get good bonding results. With the multi-stage insulation strategy all CTB joint insulation have been performed and pass the 30 kV DC (Direct Current) and 15 kV Paschen tests [9]. This strategy is also applied to the onsite joint installation.

3.3. The improvement of the radial seal structure

The radial seal is a very important part which connects the Busbar and the bellows on vacuum barrier. The main body of the radial seal shall be buried in the insulation on Busbar which pass through the vacuum barrier, and the welding flange on radial seal shall be welded with the connection flange of bellows. The radial seal separates the vacuum space between CTB and CFT, and the Busbar axial displacement will be absorbed via bellows during the device operation. The original design was found that the leak rate was very difficult to meet the requirement (1×10^{-8} Pa·m^{3}s^{-1}) after cold test (80 K), there were some micro leakage about 1×10^{-5} Pa·m^{3}s^{-1}. Two main reasons were considered to have caused the leak, one is the welding thermal stress and deformation on welds between radial seal and connection flange of bellows, the other is the thermal contraction during the clod test (80 K) process. To resolve this issue, the R&D (Research and development) were carried out on multiple samples, as shown in figure 11.

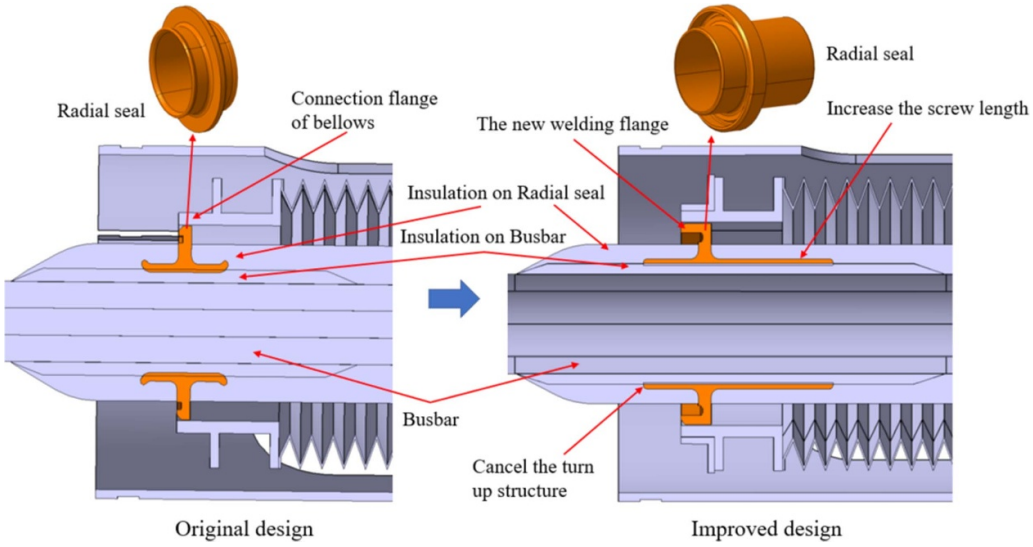


Figure 12. The structure improvement on radial seal.

Base on the R&D results, the new radial seal was designed. The screw length of radial seal was increased to against the thermal shock, and the new welding flange structure can reduce the head load impaction on bonding interface in insulation during welding process, as shown in figure 12. The design improvement made the qualified rate of radial seal leakage reached more than 90%. And leak repair method with resin and wet glass fibers was developed and successfully applied to ensure all products were qualified.

3.4. Research and improvements on Paschen test for the CTB insulation system

In the qualification and the early series product of feeders, two main reasons were found for the failure of the HV test, figure 13 illustrates the location of these factors. First is the improper treatment of the instrumentation wires during joint insulation, such as damaged wires, unsealed wire terminals, and perforated channels along the wire, which leaded to the failures of Paschen test and the discharge occurrences. Second is improper treatment after the cold test of CTB, such as not removing the condensate from the current lead room temperature flange, and the residual helium gas in the insulation break, which caused the degradation of the insulation of the whole CTB.

In view of the above problems, the following measures were taken. In the insulation manufacture stage, increase the penetration distance of the instrumentation wire from the insulation layer, so that the direct contact length between the instrumentation wire and the main insulation is $\geqslant$175 mm. Fill the transition surface around the instrumentation wire with cut pre-preg strips, and seal the instrumentation wire terminals with epoxy resin. At the same time, strengthen the quality control of insulation manufacture. After cold testing, dry the flange section of the current lead, with a maximum baking temperature not exceeding 80 °C. Replace the helium with nitrogen or keep high helium pressure (over 5 bar recommended) to avoid the discharge. After the above methods, all series product of CTB successfully passed the high voltage test.

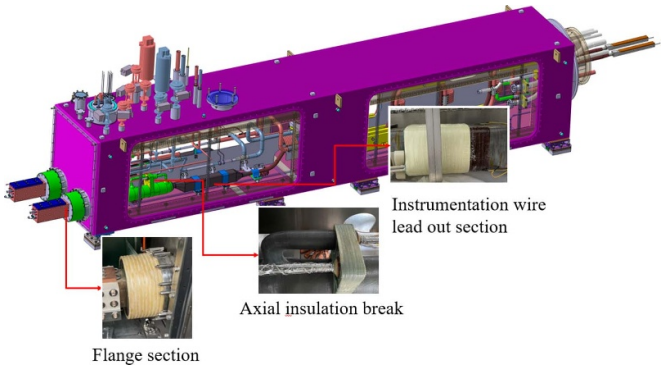


Figure 13. The locations of factors that may cause high voltage testing to failure.

4. Conclusions

All the lessons learned introduced in this paper are focus on the key special manufacture and inspection processes of ITER CC and feeder. These valuable experiences laid a solid foundation for the successful completion of these two projects. Some of them also can provide reference for the onsite installation processes of ITER device, such as the superconducting joints connection between feeder and coil systems, HV electrical testing for onsite insulation system, etc. And these manufacture experiences have high reference value for similar coil and feeder systems of other Tokamak fusion device.

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