Design and Technology Preparation for the ITER HTSCL

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***Abstract*—ASIPP will supply for ITER all the current leads. There are three types of high temperature superconducting (HTS) current leads designed to carry 68 kA, 55 kA, or 10 kA to the ITER magnets. Different from the trial leads manufactured and tested in Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP), some critical technologies were qualified before the manufacturing of the ITER leads could commence, including: 1) welding, brazing, and soldering qualification; 2) fin type heat exchanger (HEX) with tight assembly tolerance; 3) low temperature superconducting (LTS) linker with cables soldered to the 5 K copper terminal; 4) instrumentation mock-up for the temperature and voltage test. In this paper, the outcome of these qualification activities will be reported together with the plans for the series production planning and development.**

***Index Terms*—Current lead, heat exchanger, mock-up, NbTi, qualification.**

I. Introduction

TO POWER the ITER magnets 60 high temperature superconducting (HTS) current leads have been developed [1]–[3] and finally designed [4] to supply current and also connect them to the room temperature power supply. In 2010, the ITER Feeder Procurement Agreement (PA) was signed by China domestic agency (CNDA). ASIPP finally won the manufacture and test contract of ITER Feeder including the high temperature superconducting current leads (HTSCLs). To supply qualified HTSCLs for ITER 3 staged activities are defined in PA: Stage I, documents preparation; Stage II, mock-up and prototype qualification and Stage III, series production. After one and half years of preparation, a large number of documents were approved by ITER organization (IO) including the manufacture and inspection plan (MIP), manufacture plan (MP), quality plan (QP), procedures and so on. To qualify the critical technologies 9 mock-ups (Fig. 1) are defined and should be qualified before manufacturing of the current lead prototype: 1) Toroidal field (TF) HTSCL electron beam welding (EBW) mock-up; 2) TF HTSCL HEX mock-up; 3) TF HTSCL low temperature superconducting (LTS) linker mock-up; 4) TF HTSCL insulation mock-up; 5) Correction coil (CC) HTSCL EBW mock-up; 6) CC HTSCL HEX mock-up; 7) CC HTSCL LTS linker mock-up; 8) CC HTSCL insulation mock-up; and 9) CC HTSCL instrumentation mock-up.

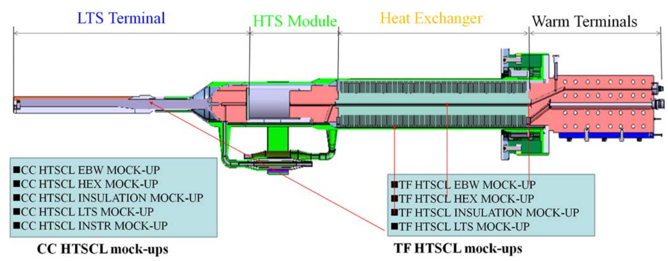

Fig. 1. HTSCL and mock-ups.

In 2013, ASIPP plans to finish the manufacture and test on seven mock-ups before October, except for the TF and CC HTSCL insulation mock-ups.

II. Welding Qualification

The current lead is made of copper and stainless steel (S.S) components. The copper conveys the current from the room temperature busbar to the LTS conductor and exchanges the Joule heat with the coolant at the same time. The main function of the S.S components is mechanical support, supplying or exhausting of the coolant. The current lead is mainly composed of a room temperature (RT) terminal, heat exchanger, HTS module and LTS module. The HTS module is a structure of HTS stacks soldered to the shunt. The LTS module consists of an LTS cable soldered to a cold copper terminal. The RT terminal and HTS shunt are brazed components of copper and S.S. The main components, including the RT terminal, heat exchanger and HTS module, are electron beam (EB) welded to be main frame of the current lead. So tig welding, brazing, EB welding and soldering are the critical technologies that construct the current lead. Before the mock-up and prototype manufacture, these welding technologies are qualified. The tig welding is qualified by the third party HPi Verification Services Ltd according to the ISO 15617 standard. But the vacuum brazing, soldering, and copper EB welding are the technologies for which there is no completely defined standard to support the qualification work. So, the qualifications or the acceptance criteria of these welding are discussed and finally approved by IO.

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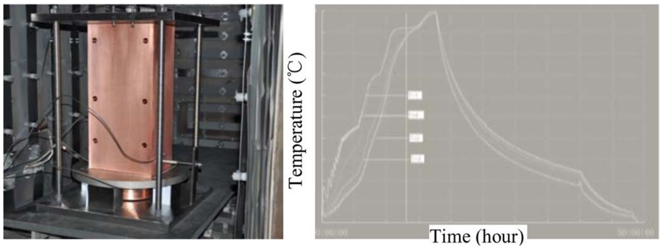

Fig. 2. Brazing qualification for RT terminal of TF lead.

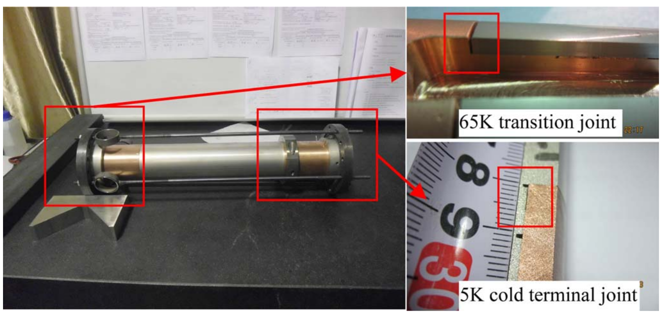

Fig. 3. Brazing qualification for shunt of CC lead.

A. Brazing Qualification

There are two major brazed subassemblies, RT terminal and HTS shunt, to be brazing qualified before the current lead prototype manufacture. The main part of RT terminal, which is a big copper terminal, connects the power supply flexible plate and the heat exchanger. The other S.S tubes and flange are brazed to the copper terminal. The HTS module is a structure of stacks soldered on the shunt in a rectangular array. Before the soldering of the HTS stacks, the shunt is brazed from the 65 K copper transition, S.S cylinder and 5 K copper terminal. The HTS shunt conveys current from the copper exchanger to HTS stacks and LTS cable. The S.S cylinder can share the current when the HTS stacks quench.

Because the brazing quality relates to the mass of the component, the real size terminal and shunt are designed for the qualification. The tools, brazing process and temperature control for the brazing qualification will be applied in future real leads. The main function of the brazing is for the vacuum and pressure leak resistance. So, all the brazed joints are vacuum or pressure leak tested at real operation pressure. The tensile stress test is performed on the shunt, because the gravity will give rise to a bending moment here on the operation when the current lead is horizontally placed.

The TF RT terminal and shunt are vertically placed in the vacuum furnace (Fig. 2). The thermocouples are mounted on the different S.S and couple parts to detect the temperature of different parts and material. Before the melting point of the filler, many temperature stabilizing steps for 30 minutes to 1 hour are held. At the beginning of the brazing, there is an obvious temperature difference between different parts, because of the difference of the mass and specific heat capacity.

Different than the TF lead shunt, CC lead shunt is horizontally put in the furnace. On the first brazing, both S.S-Cu brazing joints failed (Fig. 3). Half of the 65 K transition circular joint is not brazed.

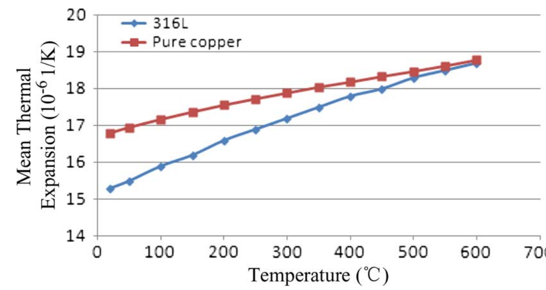

Fig. 4. Thermal expansion difference between pure copper and S.S.

TABLE I
EB WELDING QUALIFICATION

Test	Operation standard/procedure	Acceptance criterion
Visual test	EN 970	ISO 13919-1, Level B
Thermal shock	KY-FD-ZY-025[a]	No crack
Leak test	KY-FD-ZY-010[b]	Allowable leak rate $<10^{-9}$pa.m^3/s at 0.7 MPa
Metallography test	ASTM sectionⅨ2010 QB-180	ISO 13919-1, Level B
Tensile test	ASTM sectionⅨ2010 QB-153	≧180MPa

The reasons are analyzed that the loads on the four screws were not uniform. The 5 K cold terminal is a copper cylinder outside covering the steel. The defect is on the longitudinal line. The defects appear because of the different thermal expansion (Fig. 4). When the shunt is heated to be greater than 800 °C, the gap between the copper and the S.S reaches 0.5 mm. No capillary could be developed for the brazing. So, on the second round brazing qualification this joint was changed to be steel outside, and a torque wrench was used to control the tension in the tie rods.

B. EBW Qualification and Mock-up

To weld the main components of the current lead and convey the current, EB welding was chosen because of its: 1) larger welding depth; 2) narrow heat-affected zone. The larger welding depth will decrease the current density on the joint section. The narrow heat affect zoom will give least deviation on the copper residual resistance ratio (RRR) value and keep the HTS stacks on safety temperature during welding.

The tests and reference for the qualification are in Table I. The tensile strength ranges from 194 to 205 MPa of the 4 samples. The metallographical photos prove the welding depth is larger than the defined value, and no void can be found in the joint (Fig. 5). For EB welding of copper material there is no applicable acceptance criterion. The standard ISO 13919 part 1 for S.S EB welding joint is referenced and agreed by IO for the copper EB welding joint here (Table I). Level B, the strictest quality, is applied.

The EBW mock-up is welded from two short size real copper parts. The fins on the mock-up are the feature of the real HEX. After welding, the deformation of the fins can be inspected. To monitor the temperature on the HTS stacks the thermaxes are pasted on the right position of the mock-up. The max temperature during welding can be recorded on it. The recorded

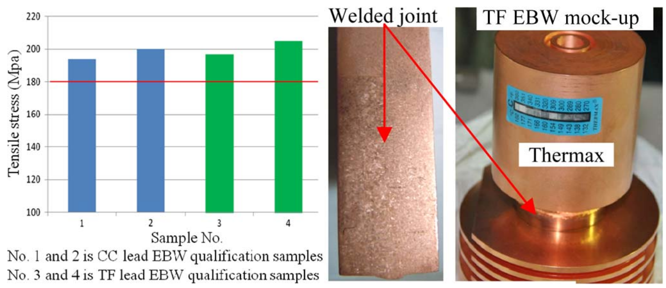

Fig. 5. Tensile and metallography test of EBW joint.

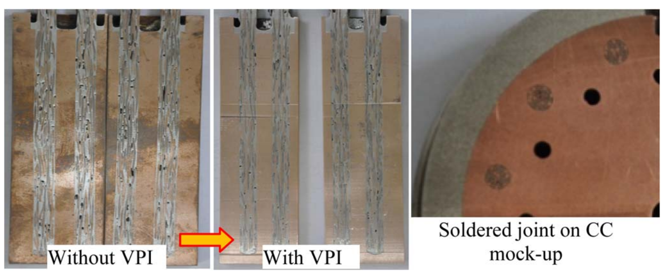

Fig. 6. Soldered samples and soldered joint on CC mock-up.

maximum temperature 171 °C is less than the melting point 183 °C of 63 Sn-Pb solder for the stacks soldered to the shunt (Fig. 5).

C. Soldering Qualification

The LTS cable is soldered to the cold copper terminal and the twin box. The joint resistance is the critical criteria for the acceptance of the soldering. The LTS cable is twisted from copper wire and NbTi strands. Before the soldering of the copper wires and NbTi strands, the nickel is removed. The solder joint of the cold copper terminal and LTS cable is a full soldered joint. The filler fills all the voids between the wires and stands in the hole. But the joint between the cable and twin box is for the surface contact soldering. The voids in the cable are for helium flow. Given the different soldering requirements, different nickel methods are applied. To fill all the voids in the cable, all the nickel on the wires and strands have to be removed. The chemical method is the best solution. The mechanical method is more suitable for the nickel removing of the cable for the twin box soldering joint, because no caustic solutions or alien material are involved.

After tinning, the cable is pressed in the module to be the right size. The soldering of the cable into the hole is a special challenge, because: 1) the blind hole is not good for the solder extension; and 2) the voids in the cable are not easy to be filled. Tinning of the copper hole and cable is applied that is useful for the filler extension. To fill the voids the soldering with vacuum pressure impregnating (VPI) technology is developed. With VPI method the void fraction is much less (Fig. 6), and the cable is solidly anchored in the copper sample. Less than 2.5 nΩ of this joint on ITER CC lead is required. Given the maximum joint resistance 16.3 nΩ (Fig. 7) on the samples 0.68 nΩ can be achieved on real lead. It proves that this joint design is acceptable.

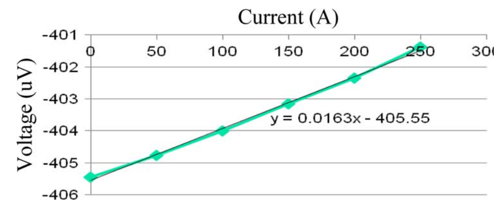

Fig. 7. Joint resistance test profile.

III. HEX Mock-Up

The fin type HEX makes the coolant flow in Zig-Zag manner. The assembly tolerance is very critical to assure the correct performance of the HEX. CERN has a very large number of positive experiences on the production and runs of several hundred HTS leads for the LHC [5], [6]. The H7/g6 assembly tolerance is also introduced to the ITER current lead. To improve the assembly of the close-fitting tube and heat exchanger, the tube is honed to a nice finished surface.

The HEX mock-up is a real size of the HEX and honed tube. Two ends are sealed by tig welding. The coolant is supplied and exhausted from the tube. The pressure drop can be tested after the assembly.

The TF lead HEX core after machining is $\phi 188^{-0.014}_{-0.041}$. The TF lead honed tube is with a tolerance of -0.045 to 0. The CC lead HEX core is $\phi 110^{+0.02}_{-0.07}$. The CC lead honed tube has a tolerance of -0.04 to -0.02. The transition fit is chosen, because assembly with heated tube is applied. After heating the tube to about 180 °C, the diameter increases by 0.25 mm for CC HEX, and 0.43 mm for TF HEX, which should allow smooth assembly. Both the TF HEX and tube are the right size but the surface of the tube is not smooth without the honing because the precision boring easily available in the workshop of the supplier. The worse surface quality will be a risk for the assembly. The honing of the tube will be applied on the TF tube.

The CC HEX and tube are ready for the assembly. The diameter and surface quality of the tube are very good after the honing. The minimum 0.044 mm gap between the CC HEX core and the tube can be calculated after the heating of the tube. So, in principle, the assembly of the HEX core and heated tube should be no trouble. But unfortunately on the first assembly, the HEX got stuck during assembly because of the incorrect tooling. The tooling fix the HEX core on the floor, and the tube is assembled on a vertical rail on the tooling (Fig. 8). So the tube can only slide on the rail.

The success of the assembly with this tooling should be based on the condition that the HEX core and tube are same line coaxial. It means: 1) the axes of the core and tube are on the position; and 2) both the core and tube should be vertical. Given $0.0028°$ deviation, the maximum disalignment will be $903 \times \sin 0.0028° = 0.044$ mm on one end. It is obvious that this tooling is not so accurate. So, the tooling is the main reason for the parts getting stick.

After the analysis of the reason for the stick, the 2nd HEX assembled by manual method was a success (Fig. 8). The tube can adapt to the HEX core during the assembly. The pressure drop of the CC HEX mock-up will be tested next month.

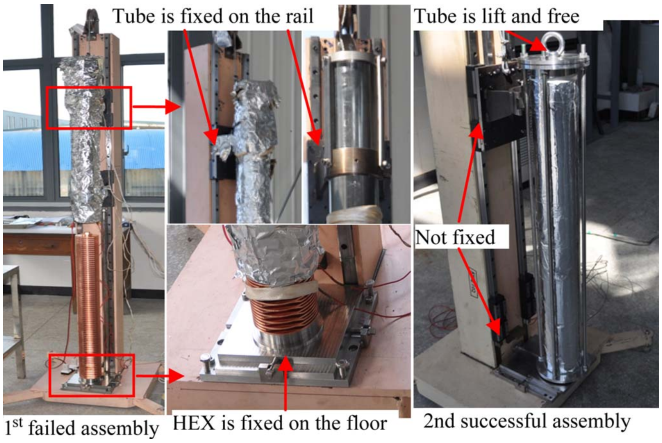

Fig. 8. Assembly of CC HEX mock-up.

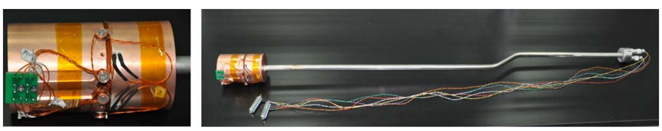

Fig. 9. Instrumentation mock-up.

IV. Instrumentation Mock-Up

On the real current, lead there are temperature sensors and voltage taps mounted to detect the temperature from cold to warm terminal and the voltage drop of different module during operation. The operation control will depend on the feedback signal.

These sensors and voltage taps will be enclosed in the envelope of the current lead. After welding and insulation, there will be a very large risk and sacrifice to open it for repairing. It is also not accessible for repairing during normal operation. So the quality of these sensors and the assembly must be very stable for long operation.

The instrumentation mock-up is to simulate the assembly of these sensor and voltage taps and threading of the instrumentation wire though the circuitous internal tunnel. The mock-up is thermally shocked from LN_2 temperature to room temperature for five cycles and tested after every circle in a water and ice mixture.

The cylinder PT100 is inserted in the hole in the copper transition. The heat conductive grease is used to fill the gap. A PC board covers the sensor and two probes are soldered to the PC board. Four instrumentation wires are soldered to the PC board. Before passing the wires through the tunnel, all the wires are wrapped around the heat sink to eliminate thermoelectric force and give mechanical support for the wire (Fig. 9).

A back-up of all the sensor and voltage taps is prepared. When one of the sensors does not work, the test system can quickly do the exchanging and get the feedback signal from the other loop.

V. LTS Linker Mock-Up

The LTS linker mock-up is mainly composed of the LTS cable, 5 K terminal, and the twin box. It will demonstrate the technologies of bimetal plate bonding, bending, heat treatment and machining, tinning, welding soldering of twin box, nickel removing and tinning of the cable, etc.

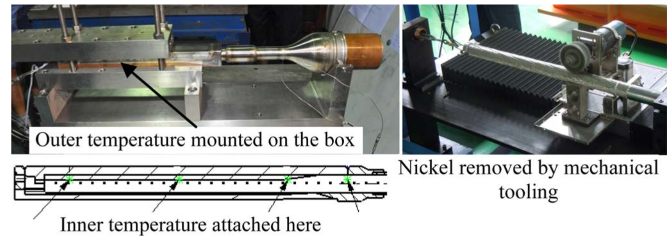

Fig. 10. LTS linker mock-up.

The LTS cable is from the CICC conductor. The jacket and nickel on the cables will be removed. To avoid damage of the NbTi strands, special tooling is developed. Both the mechanical and chemical methods are used for the nickel removing. The reasons are described in Section II soldering qualification. The pickling, passivation, water washing and ultrasonic cleaning are applied. The conductivity ratio of the cleaning water tested $0.1 \sim 1$ which is acceptable. The special tooling is designed for the mechanical nickel removing (Fig. 10). The nylon brush is machined to be tangent to the cable. The cable is stretched during the operation. The rotation and moving speed of the brush are controlled. The surface quality of the cable is compared with a prepared sample after every operation. After chemical or mechanical nickel removing the cable will be stored in a bag filled with dry N_2 gas.

The joint box is machined from an explosion-bonded S.S-copper bimetal plate. After the ultrasonic test, bending, heat treatment, penetration test, machining on CNC, tinning and leak test, the twin box is ready. After the assembly of the cable, the twin box is tig welded under pressure and soldered with Sn63Pb37. Argon gas is blown into the box during the welding and soldering for the protection of the cable. The thermocouples are attached to the cable in the box and mounted on the outside of the box. The recorded temperature of the thermocouples outside can be used as a reference in future series production. During the tinning, welding, and soldering, the accumulated time should be less than 2 h with temperature greater than 200 °C. Temperature greater than 250 °C is prohibited.

VI. Conclusion

On phase II, there are nine mock-ups and three pairs of prototypes to be developed before series production. All the EBW mock-up and instrumentation mock-up are finished. The CC HEX mock-up is also successful assembled. The pressure drop will be tested next month. The tube on TF HEX mock-up is on honing. The critical technologies, soldering of the LTS cable to the copper terminal on LTS linker mock-up, is developed. The explosion bonded bimetal plate is bent and is now being machined. The insulation mock-up is on hold until the stable shear stress.

The machining of prototypes will start in 2013 after the qualification of all the mock-ups. The series production may start next year.

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