Manufacture and Test of the ITER TF Type HTS Current Lead Prototypes

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***Abstract*—High temperature superconducting current leads (HTS-CL) are designed to supply the current to the large superconducting ITER magnets for the operation with reduced heat load to the cryogenic system. The Toroidal field (TF) current leads are the largest with a current capacity of 68 kA each. The Institute of Plasma Physics of the Chinese Academy of Sciences (ASIPP) is responsible for the supply of the current leads based on a design jointly developed with the ITER organization. Before the supply of the TF HTS-CL series, a pair of prototypes was manufactured in 2014 by ASIPP and associated manufacturers according to previously qualified manufacturing procedures. Rigorous quality control measures were developed and applied in preparation for series manufacturing. To verify compliance of the prototypes with the ITER specification, thorough testing was conducted in 2015. The test items under particular scrutiny were: the pressure drop in the counter-flow heat exchanger, the loss of flow accident test after steady state operation at 68 kA current, the so-called overheating time of the HTS module following an induced quench, the electrical resistances of the soldered joints inside the lead assembly (i.e., the low temperature superconducting (LTS) to busbar and the HTS to LTS joints), and the conduction heat load per lead to the 4.5 K end. In this paper, the main manufacturing steps are discussed, and test results are presented and discussed.**

***Index Terms*—Bi-2223, current lead, heat exchanger, NbTi.**

I. Introduction

One of the key technologies of the ITER fusion experiment, are the HTS current leads. They convey the large currents to the ITER superconducting magnets at a minimum heat load from the room temperature to the 4.5 K stages. The ITER coil system requires a total of 60 HTS current leads to transfer 50 GJ of stored energy into the largest superconducting magnets ever built: 18 for the TF coils (68 kA), 12 for the Central Solenoid (CS) coils (46 kA), 12 for the Poloidal Field (PF) coils (55 kA) and 18 for the Correction Coils (CC) (10 kA) [1].

The Institute of Plasma Physics of the Chinese Academy of Sciences (ASIPP) developed the ITER trial leads [2]–[5] from 2007, based on the successful delivery of 15 kA HTS current leads for the EAST Tokamak [6]. The so-called "demonstrator" 70 kA HTS current lead was also designed and tested by KIT (EU) [7]. Over a thousand HTS current leads were successfully manufactured at CERN for the Large Hadron Collider (LHC) [8]. Based on the previous development the ITER leads were finally designed in 2011 in cooperation with the HTS-CL working group [9]. After the qualification of the critical technologies on mock-ups [10], ASIPP completed the qualification program with the fabrication of two 68 kA TF-type current lead prototypes without insulation, which were made in 2014 and tested in 2015, as reported here.

TABLE I
Main Parameters of the TF Current Lead

RT terminal		HTS module	
Contact area to flexible busbar	0.19 m^2	Length of stack	430 mm
Current density	1.8 A/mm^2	Diameter of shunt	148 mm
Helium cooling	40.26 cm^2	Shunt steel cross-sectional area	2732 mm^2
HX module		**LTS module**	
Length	951 mm	LTS type	NbTi
Current density	10.5 A/mm^2	NbTi strands	900
Number of fins	151	Strand Cu/NCu ratio	2.3
Diameter of fins	188 mm	LTS-Cu cone joint length	120 mm
Fin thickness/gap	3/3 mm	LTS-box joint length	450 mm
HTS module		**Insulation**	
Number of HTS stacks	90	Type	Pre-preg (Pp)/Kapton tapes, 50% overlap
Number of tapes / stack	8	Composition	2 layers Pp+9 layers Pp/Kapt+2 layers Pp
Ic of each stack	>820 A	Thickness	6 mm

II. Manufacture of the Prototypes

The critical manufacture technologies of the prototypes include: 1) machining of the fin type Heat eXchanger (HX); 2) soldering of stacks and stack-shunt soldering; 3) soldering of the LTS linker and twin box joint; 4) Electron Beam Welding (EBW) for integration; 5) honed tube and instrumentation assembly; 6) Room Temperature (RT) flange assembly. Table I summarizes the main parameters of a TF-type lead. Note that the high voltage insulation, a critical component, is not discussed further in this paper. The insulation was qualified separately through specialized mock-ups [11].

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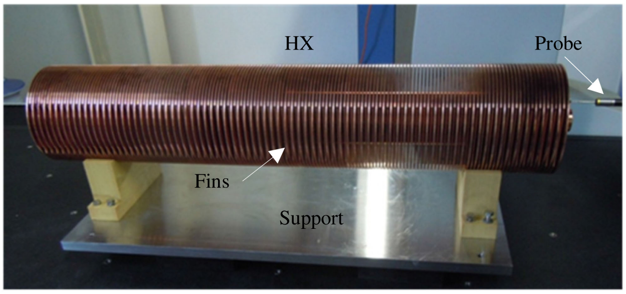


Fig. 1. Fin type heat exchanger (HX) in the CMM for test.

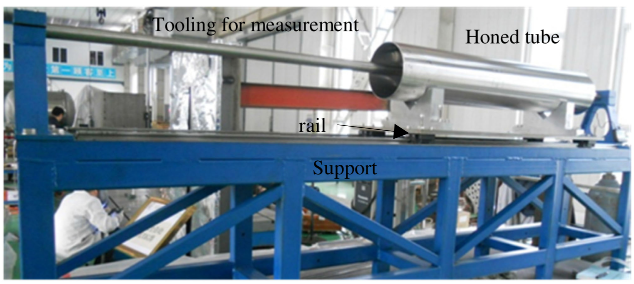


Fig. 2. Measuring the HX cover tube.

A. Fin Type HX

Tight machining tolerances are required to limit the bypass flow of helium between outer tube and the finned HX core. Machining the 151 finely-spaced fins with the specified tolerances required a 5-axis CNC, thereby also reducing the machining time to ∼1 week, from 3 months for a normal lathe. The dimensional checks (Fig. 1) were made with a Coordinate Measuring Machine (CMM). The tolerance achieved on the diameter of the fins ranged from -0.038 mm to +0.015 mm. The straightness was within 0.077 mm. The close-fitting tube was honed to provide a smooth surface (arithmetical mean deviation of the profile Ra < 0.8 mm) and straightness < 0.07 mm (Fig. 2).

B. Soldering of Stacks and Stack-to-Shunt Soldering

The stacks of HTS tapes were vacuum-soldered from 8 layers of SEI (Sumitomo) Bi-2223 tape using Sn-3.8Ag-0.7Cu (melting point 217 °C), soldered at ∼240 °C. The critical current of each tape in self-field and 77 K was more than 160 A. The critical current of the stacks was measured in 77 K liquid nitrogen (LN_2) and self-field. The minimum critical current reached 820 A (Fig. 3).

The HTS stacks were soldered on the shunt using Sn63Pb37 foil after the twin box joint assembly (see Section C below). Using a large vacuum furnace the pressure was kept below 0.1 Pa and temperature distribution kept uniform through radiation heating. Three temperature sensors were mounted on the shunt close to the stacks. The recorded temperatures showed only a 3° temperature difference.

C. LTS Linker and Twin Box Joint

The LTS cable is in fact a ∼1 m long piece of the same busbar that connects the leads to the coil terminals through the ITER feeders. It is of the Cable-In-Conduit-Conductor (CICC) type and made with NbTi superconducting strands [12]. The Nickel coating from the strands was removed. After pre-tinning and

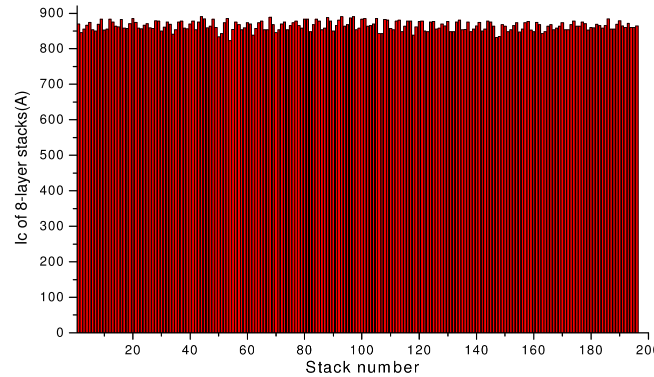


Fig. 3. Critical currents of the 180 stacks (plus spares) for two leads.

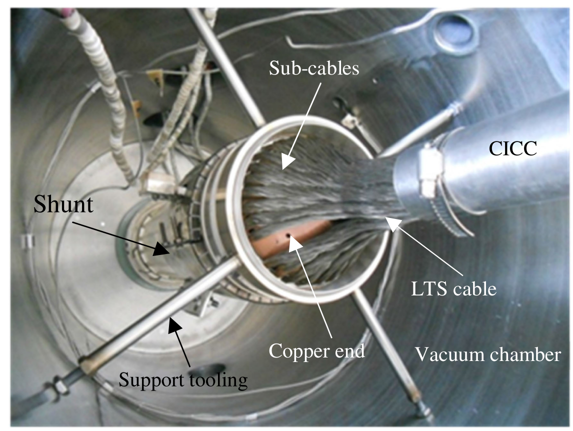


Fig. 4. Soldering of the LTS linker to the shunt.

molding with Sn-3.8Ag-0.7Cu, the 18 sub-cables were inserted and re-flow soldered into pre-cleaned blind holes in the copper end (or 5 K terminal) of the shunt. A special vacuum pressure technology was developed, consisting of soldering in vacuum, with pressure applied at the end to compress the liquid solder and obtain homogeneous filling. This operation was performed before soldering the stacks to the shunt - the higher melting point Sn-Ag solder not melting in the subsequent soldering (Section B above).

The cold terminal of the lead (joint box) was machined from an explosion-bonded stainless steel-copper bimetallic plate after bending and heat treatment. Once the cable was assembled into the joint box, the cover was TIG welded under pressure for closure. A temperature sensor, mounted on the outside of the box near the welding position (and moving with the weld), was used to ensure that the temperature would not exceed a safe level for the superconducting cable inside. The maximum temperature was 170 °C. From experience with the LTS linker mock-up it was known that there is only a ∼5 °C temperature difference between the cable and the outer surface of the box. Sn63Pb37 solder foils placed between cable and copper sole were melted during stack-to-shunt soldering in the vacuum furnace (see Section B).

D. EBW for Integration

The RT terminal, HX and HTS-shunt/LTS-linker assemblies are then joined by Electron Beam Welding (EBW), as pioneered for the CERN leads [8], for its major advantages: 1) large welding depth (needed to conduct the high currents through it), and 2) narrow heat affected zone (very convenient given the many

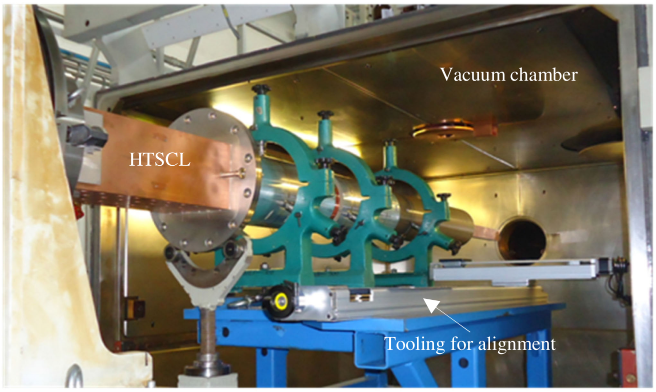
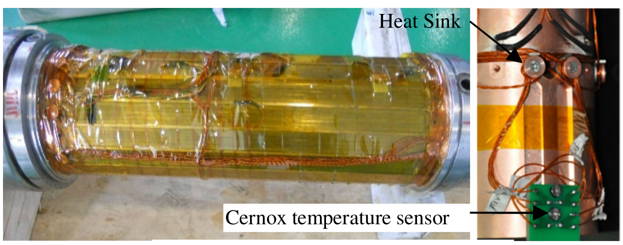


Fig. 5. EBW of the prototypes.



HTS module sample for sensor assembly

Fig. 6. Instrumentation on prototype.

solder joints of the shunt-LTS-linker and also to limit impact on the Cu RRR). A special tool was developed for the alignment of the three subassemblies (Fig. 5). For the EB welding the tolerance on alignment of the subassemblies was <0.1 mm. The joints were welded to a depth of 30 mm or more to carry the 68 kA current. The maximum temperature was less than 171 °C on the HTS stacks, as shown with the electron beam welding mock-up [10]. This is a safe temperature for the stacks that were soldered to the shunt using Sn63Pb37.

E. Honed Tube and Instrumentation Assembly

Because of the tight tolerance on the machined HX core and honed tube, the honed tube was heated to 180 °C to avoid jamming during assembly. This ensured a minimum clearance of 0.25 mm. The successful assembly took only a few seconds.

After the assembly and closure welding of the honed tube, the HTS module and LTS linker were equipped with temperature sensors and voltage taps. PT100 temperature sensors were used at the warm end of the HTS module; Cernox temperature sensors for its cold end as well as the LTS linker. Cylindrical-type PT100 and Cernox sensors were inserted in holes and conductive grease was used to fill the gaps. Before passing the wires through the central channel leading up to the RT terminal, they were wrapped around heat sinks for thermalization and to provide mechanical strain relief (Fig. 6). All the sensor circuits were doubled for redundancy.

F. Room Temperature Flange Assembly

A special design allows decoupling the vacuum tightness and mechanical support functions of the RT flange assembly. The vacuum tightness is provided by a stainless steel ring embedded into a composite insulation overwrap and welded to a bellows. The mechanical loads are taken up by an insulating G10 cylinder, sandwiched between two steel flanges to which the cylinder is affixed with bolts and cross-dowels (one of the flanges is part of the brazed terminal assembly). The temperature of the fiberglass composite was controlled to be <80 °C during welding of the bellows to the ring to avoid softening (the insulation is cured at 80 °C). Insulation was also wrapped on the outside of the assembly to avoid bolt-to-bolt tracking discharge over the cylinder surface.

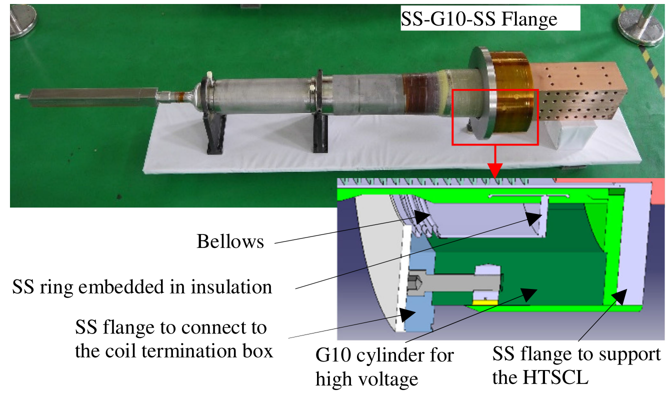


Fig. 7. TF HTSCL prototype.

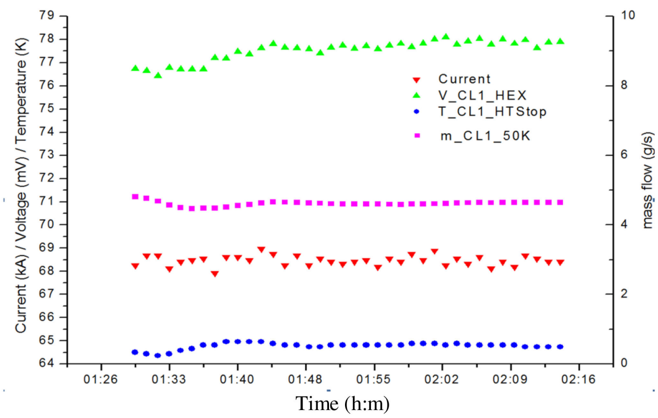


Fig. 8. Steady state operation with 68 kA current for prototype 1.

III. Test Results

The prototypes were tested at ASIPP using an ITER supplied control system, a so-called mini-CODAC prototype. The two prototypes were connected through a superconducting link (the so-called U-bend) via twin box joints. After cooling down for about 24 hrs they were tested in steady state operation at the 68 kA design current for about 2 hours (Fig. 8). The RT terminal temperature was kept steady at about 300 K via a combination of helium gas and water cooling and electrical heaters. The temperature at the top of the HTS section (T_CL1_HTStop) was maintained at about 65 K by feedback control of the 50 K flow through the HX. The HX voltage (V_CL1_HEX) reached steady state after about 1 hour. The steady state 50 K He flow rate (m_CL1_50 K) is 4.65 g/s, which is as expected from calculation [13]. The pressure drop from the inlet 50 K helium to the outlet 300 K helium is 1.1 bar under normal operation condition, also

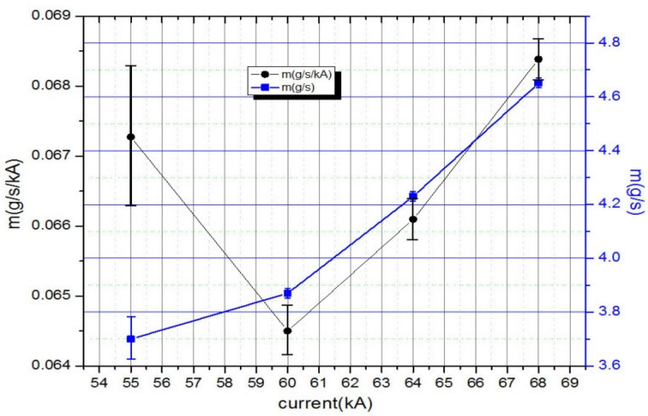


Fig. 9. Mass flow for different currents for prototype 1.

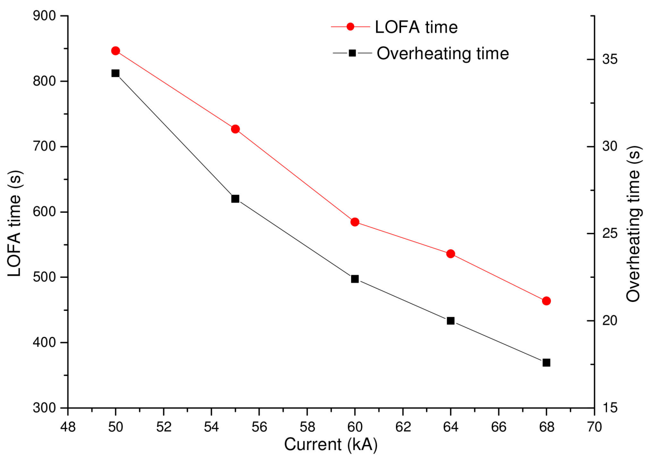


Fig. 10. LOFA and overheating time for the prototype 1.

as expected. The mass flow for operation at different currents is shown in Fig. 9. The minimum specific mass flow rate per kA current is at 60 kA current operation. This indicates that the optimum current for this prototype is a bit less than 68 kA. This is also consistent with the fact that the HX voltage is somewhat higher than expected at 68 kA.

After steady state operation the LOFA test was initiated by stopping the 50 K He flow. The time it takes until quench is defined as LOFA time. Here, 1 mV in the HTS is defined as the threshold of the quench detection. The LOFA condition was tested for different currents. At 68 kA the LOFA time for both prototypes is greater than 450 s.

The time (at full current) from the trigger of the quench protection system to the time when the HTS has reached 200 K is defined as the "overheating time". It is specified by ITER to be larger than 15 s. After ~10 s, when the interlock system was triggered by a 100 mV threshold and the current removed, the hot spot temperature on the HTS had only reached about 100 K. The OH time data in Fig. 10 were obtained from extrapolation of the experimental temperature/time graphs to 200 K.

The heat conduction to the 5 K end through the HTS shunt was measured (Fig. 11). An indirect method was used, inferring the heat load from the comparison of the measured temperature profile along the HTS shunt with a calculated profile for the shunt and HTS geometry and thermal conductivity with the

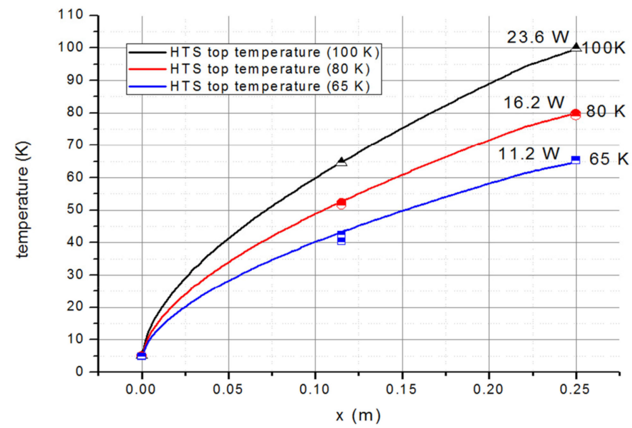


Fig. 11. Heat load to the 5 K end of prototype 1.

TABLE II
JOINT RESISTANCE SUMMARY OF TF PROTOTYPES

	R_HX-HTS	R_HTS-LTS	R_Twinbox
specified	<10 nΩ at 65 K	<1 nΩ	<2 nΩ
CL1	5.14 nΩ	0.14 nΩ	0.37 nΩ
CL2	5.26 nΩ	0.44 nΩ	0.26 nΩ

heat flux as adjustment parameter. The heat load estimated by this method is 11.2 W, i.e., less than the ITER limit of 15 W.

The joint resistance is summarized in Table II. The measurement is the average of two, taken for opposite current polarities of the power supply. The resistance of the HTS-LTS covers the joint of HTS-5 K copper end and 5 K copper end-LTS. The twin box joint resistance includes the joint of LTS-copper sole and between the two boxes using Indium sheet.

IV. CONCLUSION

Two TF 68 kA current lead prototypes were manufactured and tested at ASIPP as the final qualification before the series production. The HTS stacks and LTS cables were joined to the current leads by vacuum soldering. The three main subassemblies - RT terminal, HX core and shunt/LTS-linker, were integrated by EB welding. The HX core and the honed tube are assembled with extremely tight tolerances. The prototypes were tested at 68 kA in steady state, followed by a LOFA test and quench. The measured steady state mass flow rate 4.65 g/s and 1.1 bar pressure drop in the HX are as expected from calculation. After cutting off the 50 K He flow it takes more than 450 s before the quench ensues (LOFA time) and the overheating time is at least 15 s. All the joint resistances are well within the specified bounds. The shunt heat conduction measured as 11.2 W is below 15 W. Therefore all parameters meet the ITER requirements. The insulation was qualified separately and is discussed in a different paper.

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Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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