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Design of the HTS Current Leads for ITER

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Abstract

Following the design, fabrication and test of a series of trial leads, designs of the three types of current leads required for ITER have been developed, and targeted trials of specific features are in progress on the way to fabrication and testing of prototype units. These leads are of the hybrid type with a cold section based on the use of high temperature superconductor (HTS) and a resistive section cooled by forced flow of helium gas, optimized for operation at 68 kA, 55 kA and 10 kA. The leads incorporate relevant features of the large series of current leads developed and constructed for the CERN-LHC, relevant features of the trial leads built for ITER, and additional features required to fully satisfy the exigent constraints of ITER with regard to cooling, insulation, and interfaces to feeder and powering systems. In this report a description of the design of the leads is presented, together with plans for the preparation of prototype manufacture and testing at ASIPP.

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***Abstract*—Following the design, fabrication and test of a series of trial leads, designs of the three types of current leads required for ITER have been developed, and targeted trials of specific features are in progress on the way to fabrication and testing of prototype units. These leads are of the hybrid type with a cold section based on the use of high temperature superconductor (HTS) and a resistive section cooled by forced flow of helium gas, optimized for operation at 68 kA, 55 kA and 10 kA. The leads incorporate relevant features of the large series of current leads developed and constructed for the CERN-LHC, relevant features of the trial leads built for ITER, and additional features required to fully satisfy the exigent constraints of ITER with regard to cooling, insulation, and interfaces to feeder and powering systems. In this report a description of the design of the leads is presented, together with plans for the preparation of prototype manufacture and testing at ASIPP.**

***Index Terms*—Bi-2223, current leads, fusion, ITER.**

I. INTRODUCTION

THE manufacture of the ITER feeder system, including the current leads, has been allocated by the Chinese Domestic Agency (CNDA) to the Institute of Plasma Physics (ASIPP) in Hefei. In advance of the granting a Purchase Authorization for these components, this Institute, supported by the ITER Organization (IO), developed, constructed and tested trial HTS leads rated at the required currents. As well as incorporating experience from the EAST project, this development relied on technology proven for other HTS lead projects, in particular the 70 kA demonstrator lead made by KIT [1], the JAEA program [2], and the success of the large production of such leads for the LHC at CERN [3], which led to the adoption of HTS technology for the ITER leads. Test results on trial leads in December 2008 and January 2010 [4, 5] showed that major parameters approached the IO requirements on heat loads and the time required for discharge between fault detection and runaway overheating. The work to develop the trial HTS leads was periodically reviewed by a Working Group of external experts that helped with the transfer of important technology. The relative success of the program gave confidence to the scientists in ASIPP, and provided a useful basis for proceeding with the next phase.

This report is structured as follows. First the main features of the current leads are presented. In the following section the parameters of major components of the leads are described in some detail. The treatment of protection is presented in the fourth section. This is followed by sections on preparations for the manufacture and cold testing of the prototypes.

II. PRINCIPAL DESIGN FEATURES OF THE LEADS

ITER requires current leads to feed the toroidal field (TF) coils (eighteen units rated at 68 kA), the central solenoid (CS) and poloidal field (PF) coils (twenty-four units rated at 55 kA) and the correction coil (CC) coils (eighteen units rated at 10 kA). The heat load from the leads into the 5 K environment is reduced by a factor of 5 due to the use of HTS technology. The main features of the leads are summarized as follows:

1. Use of a fin-type heat exchanger (HEX) with zigzag coolant flow in the non-superconducting section. This follows a specific recommendation of a 2010 review;
2. The HTS module is made of stacks of HTS tape soldered to a stainless steel shunt;
3. A transition section between HEX and HTS modules provides thermal inertia in case of coolant loss;
4. Electron beam welding (EBW) is used to weld the HEX ends to warm terminal and transition section;
5. The conductor linking the cold end of the HTS module to the twin-box joint consists of the same Nb-Ti and copper wires that are used for the Nb-Ti busbar;
6. The mechanical support of the lead to the coil terminal box (CTB) is separated from the vacuum seal and Paschen-tight electrical insulation;
7. The warm terminal includes a heat exchanger to ensure exiting He gas is at ambient temperature;
8. Instrumentation wiring is brought out through a central hole in the HEX and room temperature terminal. This hole also serves to pump the local vacuum that surrounds and protects the HTS components;
9. The warm terminal design for the 68 and 55 kA leads includes a bolt-on water-cooled heat exchanger.
10. The techniques proposed for the manufacture will be tested and proven in representative mock-ups.

A complete 68 kA lead is shown in Fig. 1; the design concept for the 55 kA and 10 kA leads is similar. The current is delivered from the power converters by a water-cooled aluminium busbar system and is connected to the copper terminal of the lead via flexible copper links. The

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bus system and terminal are insulated from ground, and in case of a fast discharge of a magnet the lead potential can reach up to 20 kV for the TF, CS and PF circuits, and up to 10 kV for the CC circuits. The insulation is therefore designed to allow for testing at 30 kV and 15 kV to ground respectively. The current flows from the terminal through the heat exchanger that is cooled by a counter-flow of helium gas entering at its lower extremity at 50 K, where it is connected to a copper block (the transition section), which provides thermal inertia, and the HTS section. The HTS section consists of a number of stacks of Bi-2223 tape soldered to a stainless steel cylinder that provides mechanical support for the tape stacks and an electrical shunt. In normal operation there is no Joule heating in the HTS section, and as it is located in a vacuum environment the heat flux is determined by the temperature of the extremities (65 K and 5 K) and the thermal conductivity of the section. The latter is minimized by using Ag-5%Au alloy for the matrix of the HTS tape. The cold end of the HTS section is connected to Nb-Ti and copper wires, the same in dimension and total number as in the corresponding superconducting busbar in the feeder, via a supercritical helium cooled copper cap. The low temperature superconductor (LTS) conductors are grouped into a terminal ("half-joint") that allows connection to the feeder busbar via a standard ITER "twin-box" joint [6]. The HTS section is shrouded by a local evacuated cylinder onto which the insulation is wrapped. High voltage insulating breaks are provided to isolate the lead from the pipework supplying the incoming 50 K helium and exiting 5 K helium gas. These breaks are integrated into the lead as shown in Fig. 1. The break for the warm gas exiting the lead is installed separately in the vicinity of the terminals. Temperature sensors are installed at the warm end of the HTS section: these serve to control the 50 K He flow in order to maintain the temperature of 65 K. Voltage taps provide signals for protection. Within the evacuated CTB the leads are enveloped in a hermetic, Paschen-tight, multi-layer insulating sheath, the external surface of which is covered with a ground plane of conductive paint.

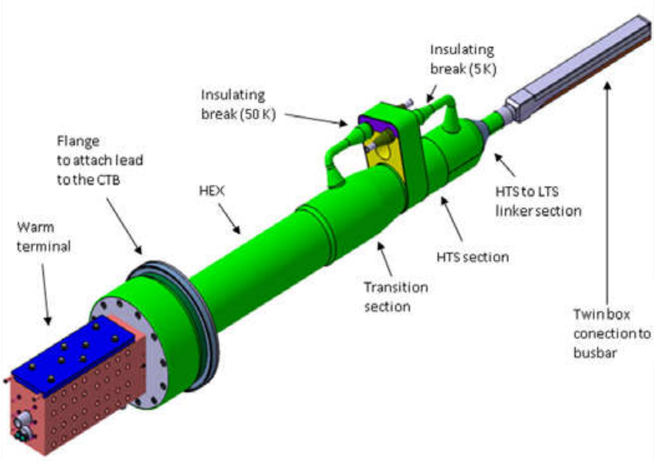

Fig. 1. CAD view of the 68 kA lead for the TF coils. The total length is 3.2 m.

III. DETAILS OF MAJOR COMPONENTS OF THE ITER LEADS

A. *The HTS Section*

For use in current leads it is found to be practical to use the fragile Bi-2223 tape in the form of stacks. For the trial leads ASIPP applied successfully [7] the technology of vacuum soldering the tapes that had been previously developed at CERN for the LHC leads [8], and there was no need to change this component substantially. For the 68 kA leads each stack consists of 12 tapes; for the 55 kA leads there are 10 tapes per stack. The 4 mm wide tape is specified to carry at least 100 A in self-field at 77 K. For both of these lead types there are 90 stacks, grouped in fives, located in 18 grooves around the periphery of the 148 mm diameter stainless steel shunt tube. Copper terminals are brazed to the ends of the shunt. The tapes are soldered into stacks using Sn-3.8%Ag-0.7%Cu at 225°C, and the stacks are soldered into the grooves using lead-tin eutectic at 185°C. The overlap with the copper terminal is 71 mm at the 5 K and 49 mm at the 65 K end; the length of the shunt between the terminals is 310 mm. The 10 kA lead uses 36 stacks of 4 tapes arranged in pairs in 18 grooves around a 76 mm diameter shunt tube; the contact length is 55 mm at the cold end and 45 mm at the warm end, and between the terminals there is 310 mm. The arrangement for the large leads is illustrated in Fig. 2 and Fig. 3.

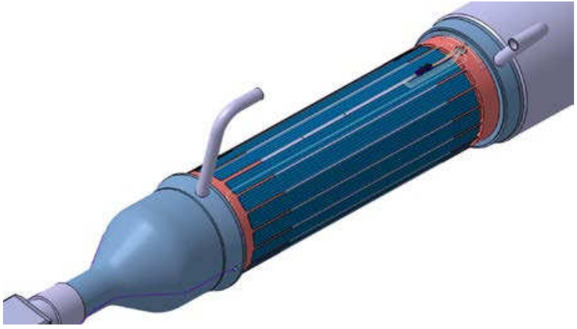

Fig. 2. CAD view of HTS stacks as mounted on 55 kA and 68 kA leads.

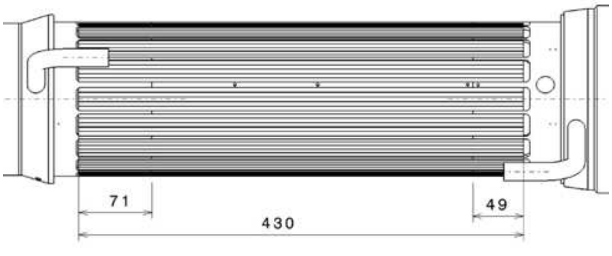

Fig. 3. Side view of stacks mounted on the shunt for the high current leads.

B. *The Main Heat Exchanger (HEX)*

The design of the HEX is crucial for satisfactory operation of the leads. An important advantage of the fin type heat exchanger is that correct performance is assured if measurable mechanical tolerances are adhered to. Following very positive experience at CERN with production runs of several hundred HTS leads for the LHC [9], it was decided to adopt this design concept for the ITER leads. The heat exchangers for the three lead types have therefore been optimized using 1-, 2- and 3-D computational models to give the parameters summarized in

Table I. The fin thickness is 3 mm, as is the spacing between fins; feasibility of machining has been demonstrated at ASIPP. The cut dimension in the table is the depth of the segment that is removed to permit optimized flow. The HEX for the 55 kA current lead is illustrated in Fig. 4 and Fig. 5. The cooling helium gas is confined to follow the zigzag path along the heat exchanger by the enveloping, 3 mm thick, stainless steel tube that is shown in the figures. A tight fit between tube and heat exchanger provided uniform performance for the CERN leads, and has been shown on a full scale mock-up to be also feasible for the large ITER leads. The central hole (diameter 16 mm for the large leads, 10 mm for the 10 kA leads) is a channel for the instrumentation wires and for evacuating the protective volume of the HTS section. As for the LHC leads, electron beam welding technology is chosen for the electrical joints at the ends of the HEX.

TABLE I PARAMETERS OF THE HEAT EXCHANGERS

Dimension	10 kA	55 kA	68 kA
Length (mm)	900	950	950
Ø Fins (mm)	110	174	188
Ø Core (mm)	39.3	82.6	92.4
Cut (mm)	10	13	15

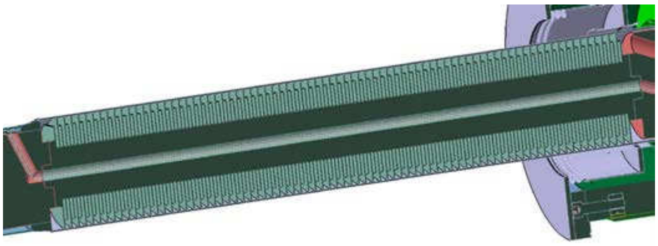

Fig. 4. CAD view of the HEX for the 55 kA lead.

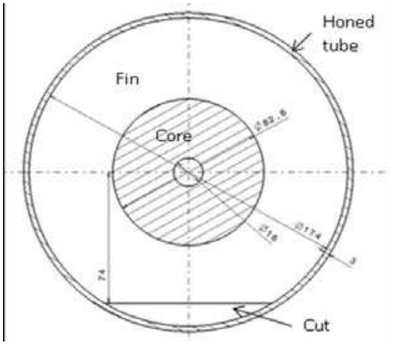

Fig. 5. Cross-section of the HEX of the 55 kA lead.

C. The LTS Linker

The linker connects electrically the cold end of the lead to the twin box joint and thence to the feeder busbar. For all the large current circuits the feeder busbar is the same cable-in-conduit conductor (CICC) made up of 900 strands of Nb-Ti conductor cabled together with 450 strands of copper around a core of 72 additional copper strands. The copper strands serve to stabilize the conductor. The linker is comprised of the same strands, which are grouped at the lead end in 30 sub-cables of 45 strands (30 Nb-Ti and 15 copper) and connected to the cold end of the HTS section via the copper end block (see Fig. 6 and Fig. 7). The central group of 72 copper strands goes straight into the centre of the block. This connection is made with Sn-3.8Ag-0.7Cu solder before vacuum soldering the HTS stacks (with Pb-Sn eutectic) to the vacuum-brazed shunt assembly. The contact length is 120 mm. At the busbar end the sub-cables are combined into a standard cable leading into the half-joint for connection in the twin-box. The CC linker is similar, but uses 12 sub-cables of 27 strands from the CC busbar.

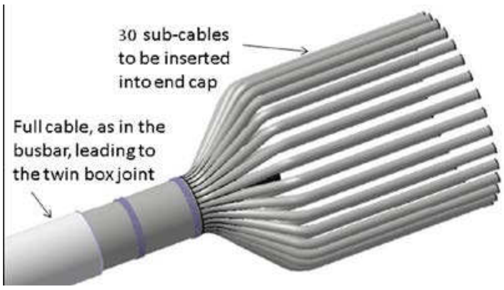

Fig. 6. CAD drawing of the linker.

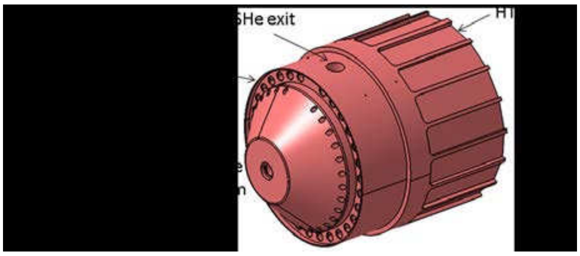

Fig. 7. Drawing of the cold end of the lead into which the linker is soldered.

D. The Room Temperature Terminals

The leads are equipped with large copper terminals of rectangular cross-section for connection to the room temperature busbars as shown in Fig. 1. A cross-section of the terminal of the 68 kA lead is shown in Fig. 8. The size of this terminal is 460 mm (long) x 230 mm (high) x 170 mm thick.

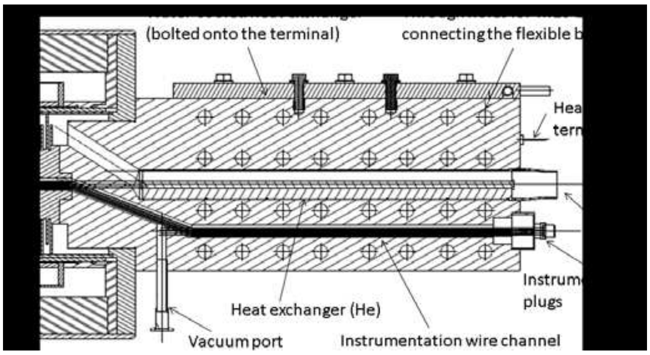

Fig. 8. Cross-section of the 68 kA lead terminal.

The helium gas heat exchanger in the terminal is made by wire cutting fins in a copper rod (see Fig. 9). It is brazed to the terminal. Its function, in conjunction with 6 x 500 W local heaters, is to warm the exiting cold gas to room temperature when the current is low. It also serves to cool the terminal should it overheat due to excessive dissipation in the contacts when the current is high. For the 55 and 68 kA leads a water-cooled heat exchanger is also included to stabilize the temperature of terminals. It is made of copper with brazed stainless steel piping to be compatible with the cooling circuit.

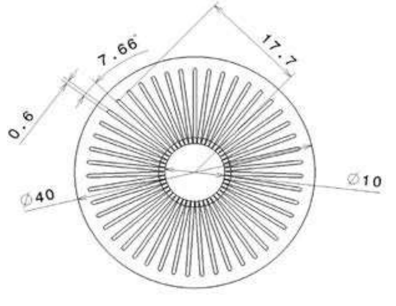

Fig. 9. Cross-section of the helium heat exchanger in the terminal.

E. The Flange Assembly

The flange assembly connecting the lead to the lead box (CTB) must fulfill several functions, namely (i) secure the lead mechanically, (ii) seal the CTB vacuum, (iii) provide Paschen-tight insulation between the lead and the inside of the CTB, and (iv) provide normal HV insulation on the outside. The difficult constraints are (ii) and (iii): these functions are therefore separated from (i) and (iv) as shown in Fig. 10. The volume under the G10 cylinder is not in vacuum, so it is not susceptible to Paschen discharge.

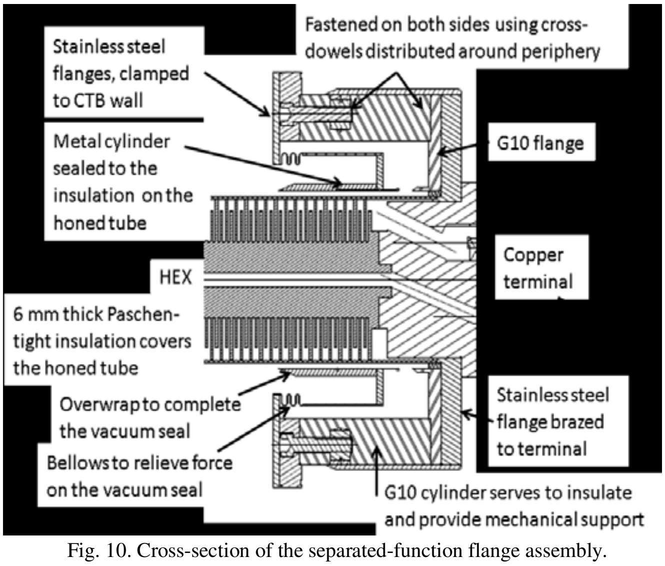

Fig. 10. Cross-section of the separated-function flange assembly.

F. Paschen-tight Insulation

The insulation of the lead consists of thirteen layers of half-overlapped glass-polyimide-glass tape, vacuum impregnated with epoxy. In order to cover hermetically the helium tubes that connect to the insulation breaks, which exit the lead at right angles, conical filling pieces are used to create a smoothly tapered surface for applying the tape, to give the final appearance as shown in Fig. 1.

IV. PROTECTION

The busbar conductors in the feeders contain sufficient stabilization to run without cooling while the magnets are discharged. The time constant of a rapid discharge is 14 s. An initial dwell time of 2 s at full current is assumed, and a safety factor of 2 is applied. The same philosophy is applied to the protection of the current leads. The cross-section of the HTS matrix material together with that of the shunt is such that following resistive transition at the warm end the temperature will not exceed 200 K if full current is passed for 4 s followed by an exponential decay of the current with a time constant of 28 s. The temperature margin of the HTS section is about 15 K. The detection of a resistive transition of the HTS section is via measurement of the voltage drop, with a recommended threshold of 2 mV. Should the voltage across the large HEX exceed 100 mV the current must also be run down. With the above criteria its peak temperature will not exceed 400°C.

V. PREPARATION FOR MANUFACTURE

Before starting manufacture of prototype leads the various technologies and procedures will be tested on simple but representative mock-ups. This concerns the electron beam welding, brazing, soldering, TIG welding, flange assembly, insulation and instrumentation. Fitting the tube over the HEX will be tested before performing the operation on a real lead; the pressure drop through the device will be measured using nitrogen gas at room temperature. The insulation covering the lead will be heat cycled and HV tested on a simulated lead envelope installed in a dedicated vessel evacuated to various levels to verify Paschen-tightness.

VI. COLD TESTING OF THE PROTOTYPES

The final stage of the prototype exercise is the cold testing. The test set-up will simulate the conditions that will obtain in operation at the tokamak. Besides confirming the electrical and thermal performance of the leads in steady state at various currents and in fault conditions, these tests will provide information for the flow control of the 50 K He in transient conditions that will occur when pulsing the magnets.

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

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