R&D on 52kA HTS Trial Current Lead for ITER

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Abstract. ASIPP has the experience of design and fabrication of 16kA HTSCLS those are successfully used in EAST Tokamak. The aim of the 52kA trial lead is to develop 45/52kA CS/PF HTS current lead prototype for the ITER project. Different from former HTSCL structure 52kA HTSCL current lead not only consists of conventional helium cooled heat exchanger, HTS module using InnoST tapes and NbTi low temperature superconductor (LTS) module but also a helium cooled copper transition and a binary shunt made of S.S and PSnCu. 52kA HTS current lead was tested in the EAST Tokamak facility at ASIPP. Some test results are also presented and analyzed on the rear of the paper.

1. Introduction

ITER has a total of 60 current leads (CLs) including 24 for the 45/52kA CS/PF coils. HTS current leads (HTSCLs) are applied on ITER current leads because they can reduce heat loads at 4.5K and cooling power consumption about 2/3 comparison with conventional current leads. All ITER leads would require ~700W refrigeration at 4.5 K and 150 g/s helium at 50 K with the proposed HTS design. The electrical power savings is about 2.5 MW[1]. At CERN, 600A~13000A HTSCLs have been successfully used in the Large Hadron Collider (LHC)[2]. In 2002-2004 EU Fusion Development Programme, FZK and CRPP successfully developed and tested a first 70kA HTS current lead as a demonstrator for ITER[3]. China has responsibility for the procurement of all ITER current leads. The 52kA of PF nominal current, 50K helium cooling, 65K/5K of HTS warm/cold end temperature and 25kV of high voltage (HV) level are based on ITER magnet design requirements. This paper reports the structure design and test results of the 52kA HTS trial current lead done by ASIPP feeder current lead group base on ITER current leads technique criteria.

2. 52kA HTSCL Design

2.1. Functional Specification of the ITER PF HTSCL

ITER current leads transfer the power to the coils on the background magnetic field. They are also the cryogenic to room temperature transitions. In the ITER feeder functional specification the requirements on current capacity, HV insulation, heat loads, quench detection/ protection and so on are detail discussed. Table I gives an excerpt of this specification, listing the main operational parameters.

2.2 Structure Design

The 52kA trial current lead consists of five parts: a) the foil stack heat exchanger (HEX) connecting to room temperature termination; b) the HTS module containing 90 HTS stacks and cylinder binary shunt; c) 60K copper transition connecting HTS module and the HEX; d) the electric insulator flange; e) the LTS module with twin box design. FIG.1 shows the design of the 52kA trial lead.

TABLE I: FUNCTIONAL SPECIFICATION FOR PF LEADS.

Parameter	Value
Current (kA)	52
Operating temperature of bottom – top of HEX[1] (K)	65 - 300
Operating temperature of bottom – top of HTS (K)	4.5 - 65
Temperature margin according to 1uV/cm criterion (K)	10
Maximum design voltage (kV)	25
Max heat load / lead at cold end (W)	12, excluding joint
Max joint resistance HEX-HTS (nΩ)	10
Max joint resistance HTS-LTS (nΩ)	1
Max joint resistance LTS-busbar (nΩ)	2
Hot spot max temperature (K)	200
Burnout time[2] include 2s quench detect delay(s)	16
LOFA time[3] (s)	300
Insulation	double, Paschen-hard

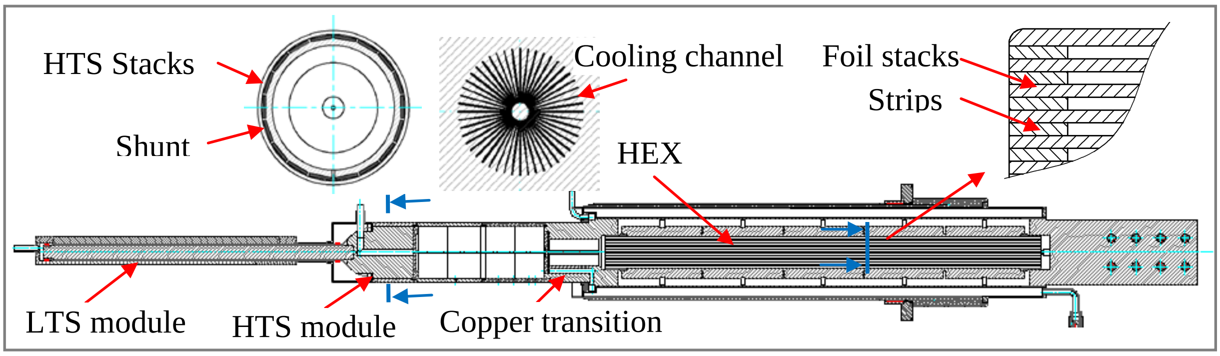

FIG. 1. 52kA HTS Current Lead.

a) Heat Exchanger

52kA trial lead HEX consists of 140 Cu foil stacks and 280 Cu strips those space the stacks on two sides. Top and bottom S.S plate cover the HEX to bundle the stacks and strips, which are also the heat sinks (See FIG. 2). The advantages of the foil stack HEX are high hP value, lower pressure drop, less material and lower helium flow. Current carrier, the fins, has big enough surface to exchange the heat with the helium. The average heat transfer parameter hP 14000 W/K/m of the design will lower the mass flow to 3.182 g/s of 50 K GHe. The estimated efficiency is 99.6%. Table II lists the main geometrical parameters of the 52kA HTS-CL HEX design, which are optimized for RRR 50. The calculated and optimized HEX voltage drop is 79 mV, and the 65K heat leak is 12.14W. The calculated pressure drop, except the pressure drop in pipes and transition, is ~0.02bar far below the specified limit. But the foil stack HEX is the larger contact resistance because of the soldering of the HEX to two ends. In the next prototype current leads electron beam welding will instead of the soldering to decrease the joint resistance.

[1] HEX is heat exchanger of the current leads.
[2] Burn-out time is defined as time needed to reach the hot spot temperature at full current after a quench.
[3] LOFA time is defined as time needed to reach max HEX voltage after a loss of flow accident in HEX cooling.

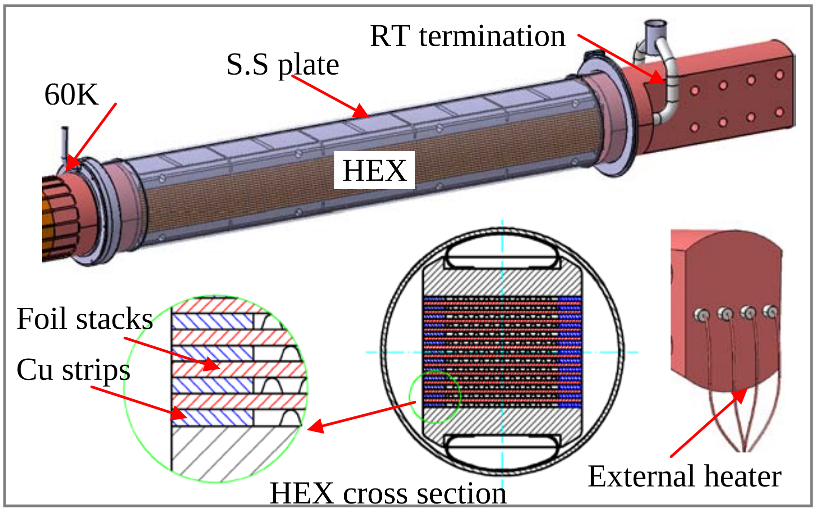

FIG. 2. 52kA Trial Lead Heat Exchanger.

The room temperature (RT) termination is a Cu rod connected to 8 cooled cables. 4 embed external heaters are to prevent freezing in the low current or off-duty operation. An active water cooling termination will be designed on the prototype leads to keep the termination room temperature.

TABLE II: FOIL STACKS HEX PARAMETERS.

Parameter	**Value**
Effective Length, HEX (mm)	1000
60/300 K joint section (mm^2)	4980
Cu current density, HEX (A/mm^2)	8.2
Foil stacks thickness (mm)	0.25
Foil stacks width (mm)	110
Cu strips thickness (mm)	0.25
Cu strips width (mm)	15.7
Wet diameter (mm)	22200
hp at 60K/300K (W/Km)	8033/25910

b) HTS Module

HTS module is designed to be a cylinder and consists of HTS stacks, shunt/support and two OFHC (oxygen-free high conduction) copper ends as FIG.3 shows.

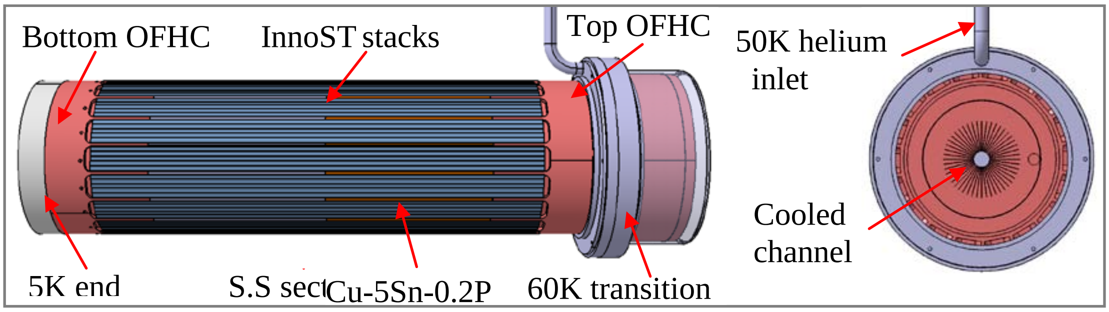

FIG. 3. Binary Shunt and InnoST Stacks.

Current carrying capacity, safety, low joint resistance, and low heat leak must be satisfied on the design. These criteria are listed in table I. The binary shunt includes the S.S and Cu-5Sn-0.2P bronze cylinder. The parameters are included in table III. The S.S material is low thermal conductivity that can decrease 5K heat load. The Cu-5Sn-0.2P bronze (for the warm section) cylinders can prolong the burnout time after HTS quench. The shunt containing 18 grooves to accommodate the stacks, which is much easier to be machined and soldered with stacks after being vacuum brazed with the bottom Cu cylinder of cold end and 60 K Cu transition. 90 stacks with each stack having 12~14 layers of HTS tapes are made by InnoST. The average critical current of the stacks at 77K and self field is 624.5A. The stacks are connected in parallel due to a lower perpendicular field.

TABLE III: HTS MODULE PARAMETERS.

Parameter	**Bronze**	**SS**	**Cu (bottom/top)**	**Stacks**
Length (mm)	151	158	55/50	410
Cross section (cm^2)	24.2	24.2	24.2/161.6	11.9

c) 60K Copper Transition

The transition section between the HTS stacks and HEX, 60K HEX-HTS transition (see FIG.3), has an inner cooled channel with the hPw ~ 1900 W/K-m cooled by 50K inlet helium. It results in ~10 K temperature difference between T52-HEX100% and T52-50KHeIn. If we tried to make T52-HEX100% ~65K, the inlet helium temperature (T52-50KHeIn) must rise up to ~55 K. The 5K temperature difference will greatly prolong the LOFA time. It needs 60s when T52-HEX100% ramp up from 65K to 70K which can be concluded from the LOFA test result shown in FIG.3. The LOFA starts when the temperatures reached 65 K at the HEX cold end and 316 K at the warm end. The lower transition temperature also decreases the heat load. The heat leak calculated is 12.14 W for transition temperature at 60 K and 13W at 65K.

TABLE IV: 60K TRANSITION PARAMETERS.

Transition length (mm)	Cooling channel length (mm)	Cu current density (A/mm^2)	Channel gap (mm)	Wet diameter (mm)	hp at 60K (W/K-m)
180	120	3.1	0.18	2700	1900

d) Insulation and Flange

During coil fast discharges HV will appear on the current leads. For safety all current leads should withstand a 30 kV test voltage. FIG.4 shows the insulation structure.

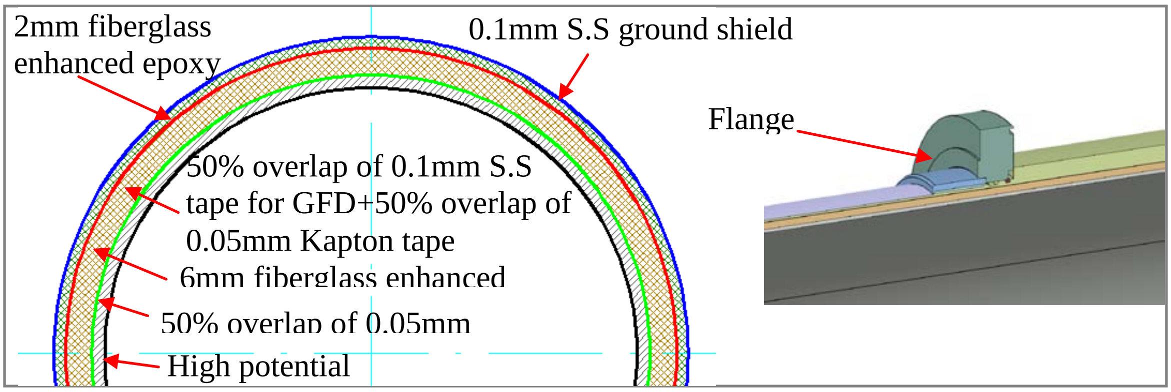

FIG.4. Insulation and Flange

The basic insulation design is as follows: high potential shield + 50% overlapping 0.05 mm Kapton tape + 6mm fiberglass enhanced epoxy resin + 0.1 mm SS mid shield (ground fault detector or GFD) + 50% overlapping 0.05 mm Kapton tape + 2 mm fiberglass enhanced epoxy resin + 0.1 mm SS ground shield. Dielectric properties of polyimide film and epoxy resin are listed in Table V.Two layers of polyimide tape overlap can withstand 30kV test voltage and 6 mm glass-epoxy layer can withstand 100 kV voltage can be concluded from the table. So the basic double insulation design of the lead has plenty of margins. The S.S flange is glued to the insulation layer that follows the 68 kA trial lead[4].

TABLE V: DIELECTRIC PROPERTIES OF POLYIMIDE FILM AND EPOXY RESIN

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Material	Dielectric strength (kV/mm)	Dielectric strength in air (kV/mm)	Relative permittivity
Fiber-glass epoxy resin	18	3.3(for dry air)	4.5
Polyimide (Kapton)	100~190	-	3.1

e) LTS Module

The LTS module consists of two components: link joint between the LTS and the HTS module, twin box joint between the lead and the busbar as FIG.5 shows.

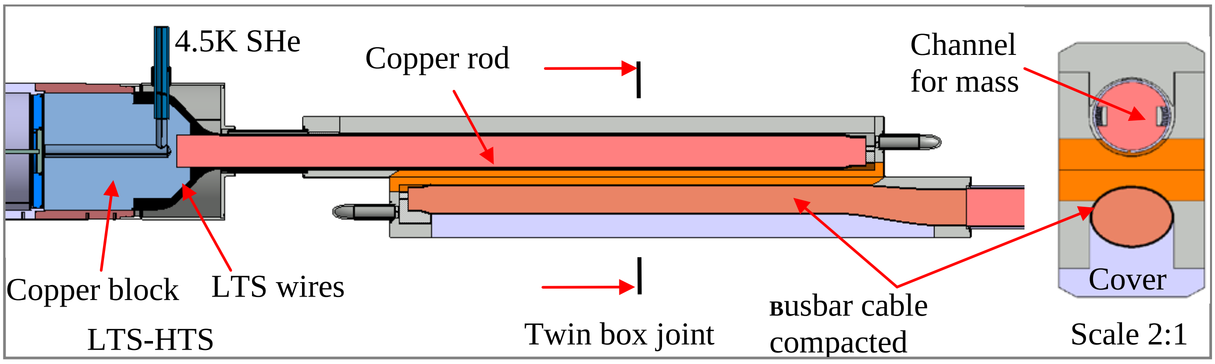

FIG.5. Lts Module

90 NbTi/Cu wires with a cross-section of 2.7mm width and 1mm thickness link 90 HTS stacks. The major parameters of NbTi/Cu wire are listed in Table VI. The wires are soldered into grooves on the copper block firstly (m.p. > 217℃), and rest length of the wires are helically wound on the copper rod. Then this module can be assembled with the box-type joint. Twin box joint of LTS module connect the current lead with the busbar. In order to obtain lower contact resistance the LTS wires and copper plate of the joint must be coated with silver or Sn-Pb solder. The box is closed under 200 ton hydraulic pressures to make the LTS wire tightly contact with copper. 130℃Pb-In-Sn is used to solder the top and bottom boxes together.

TABLE VI: PARAMETERS OF LTS WIRE

Dimension width x thickness (mm)	Critical current at 4.2K and 5T (A)	Noomber of NbTi filament	Diameter of filament (μm)	Twist pitch (mm)	Ratio of copper to non-copper	RRR
2.7 x 1	2200	5400	16	20	1.75:1	80

3. Test Result

For ITER current lead test a current lead test box (CLTB) cryostat was designed and manufactured. A thermal shield in the CLTB was cooled with LN_2. The CLTB contains 52kA and 68kA HTS current leads in it. 52kA current lead constructs a current loop with another 68kA current lead together in the test. The following items have been obtained quantitative results: 1) the current sharing temperatures of HTS modules, 2) the LOFA time and burnout time, 3) the contact resistances and joint resistances and 4) the heat leak via the HTS module. The current sharing temperatures test results under 500μV criterion are plotted in FIG.6. The results show that the temperature margins for the two leads are much higher than 10 K.

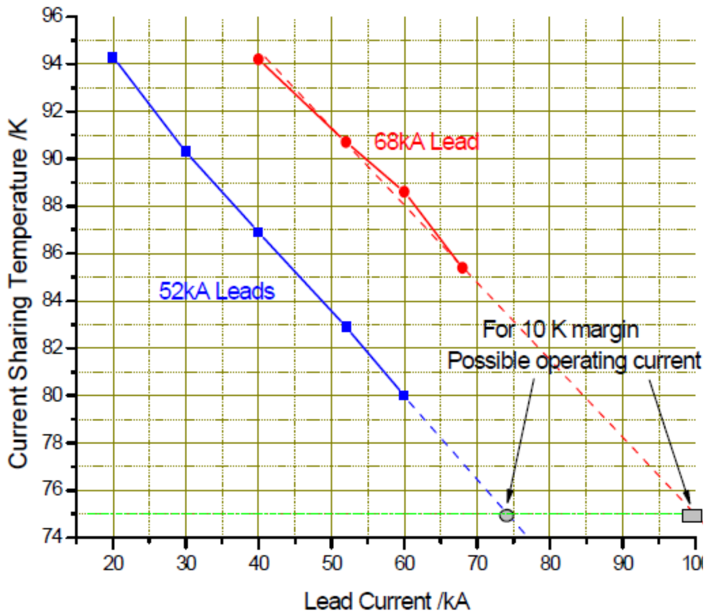

FIG.6. Current Sharing Temperature

The LOFA time should be about 294 seconds (see FIG.8) from the start when the mass flow stops to end where the temperature and voltage ramp up rapidly (0.5 mV criterion). The burnout time is near 22 seconds.

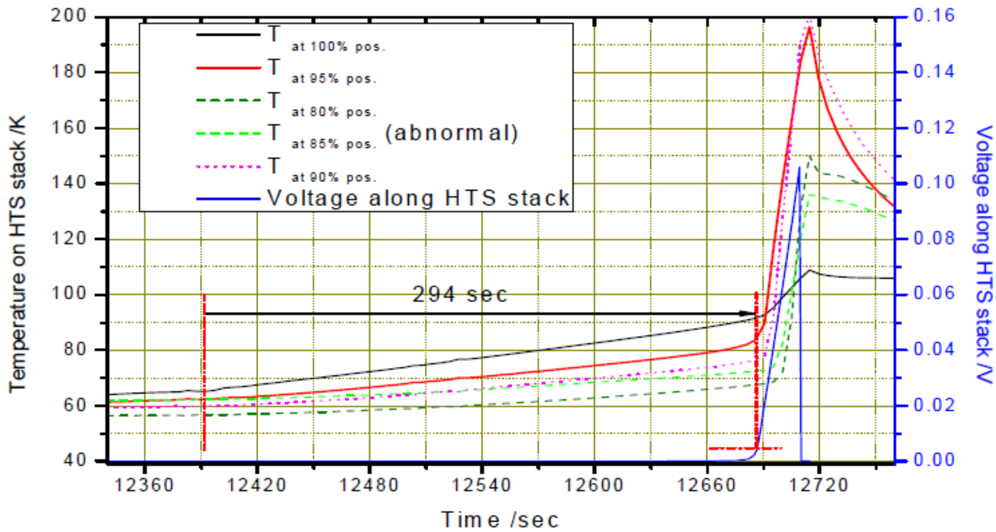

Fig.8. Temperature and Voltage Profiles of LOFA Test

The contact resistance at 52kA operating current is listed in table VII. The contact resistances are < 4.2 nΩat 65 K end, < 1 nΩ for the 5K ends. The twin-box joint resistance are also listed in table VIII: 1.31 nΩ for 52 kA lead which are lower than ITER requirement.

TABLE VII: CONTACT OR JOINT RESISTANCES AT 52KA CURRENT

$R_{\text{LTS-copper cap}}$ (nΩ)	$R_{\text{HTS stack-Cu cap}}$ (nΩ)	$R_{\text{cold end}}$ (nΩ)	$R_{\text{twin-box}}$ (nΩ)	$R_{\text{warm end}}$ (nΩ)
0.13	0.53	0.66	1.31	4.18

The heat leak calculated is 12.14 W for warm end temperature at 60 K. The related data are listed in table VIII.

TABLE VIII: ACQUIRED DATA FOR HEAT LEAK MEASUREMENT OF THE HTS MODULE

$T_{\text{HTS warm end}}$ (K)	T_{SSMid} (K)	$T_{\text{HTS cold}}$ (K)	T_{HeInlet} (K)	Qss (W)	$Q_{\text{HTS stack}}$ (W)	Q_{total} (W)
60	35.36	5.8	50.92	1.67	10.47	12.14

4. Summary

The ITER TF/PF trial current leads have been designed, manufactured and tested in ASIPP. The test results of the contact resistance, burnout time for 52kA current lead are lower than ITER requirements. The LOFA time and heat leak are also very close to the requirements. The cooled copper transition reaches 60K temperature less than 60K of another 68kA current lead that prolongs the LOFA time and also decreases the heat leak.

The CC 10kA current lead fabrication is going on by ASIPP. The insulation HV test and prototype design will be done next step in 2010. The manufacturing procedures and test give the current lead supplier experiences and lesson on the prototype design, fabrication and test.

References

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