Series Production of 13 kA Current Leads with Dry and Compact Warm Terminals

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For the LHC magnet test benches 13 pairs of conventional helium vapour-cooled 13 kA current leads are required. The current leads have been designed and built by industry. Attention was given to economical and reliable design and to a design of the warm terminal in order to avoid any condensation. Three pairs of them were tested at CERN. The dry warm terminal enables voltage test at 4.1 kV at cold condition. The paper describes construction details and compares calculated and measured values of the main parameters.

INTRODUCTION

For the LHC magnet test benches [1] 13 pairs of conventional helium vapour-cooled 13 kA current leads are required. The current leads are operating at 4.5 K saturated liquid helium. Table 1 summarises the design parameters of leads.

Table 1 Design parameters of the current leads

Nominal current	13 kA DC
Maximum current (Imax) for 10 minutes	15 kA DC
Leakage current at 4.1 kV DC at normal working condition	$<10^{-6}$ A
Design pressure	2 MPa
Working pressure	0.12 MPa
Total pressure drop at maximum current	<10 kPa
Heat load at nominal current at self cooling condition	<1.2 W/kA (0.80 g/s)
Heat load in Stand By (I=0 A) at self cooling condition	<10 W (0.51 g/s)
Insert length	1910 mm
Insert diameter	<100 mm
Time of coolant gas flow interruption at Imax without quench	>60s
Warm terminal at any working condition	compact and dry

For series production the vacuum brazing technology as well as the principle of the warm terminal was similar for the 13 pairs of 13 kA current leads discussed in this paper as for 26 pairs of 600 A current leads described in [2]. Including test leads, one of 600 A and one of 13 kA, 80 in total were built. Principle of the lead optimisation is given in [2]. We will describe the various elements and the performance of the leads.

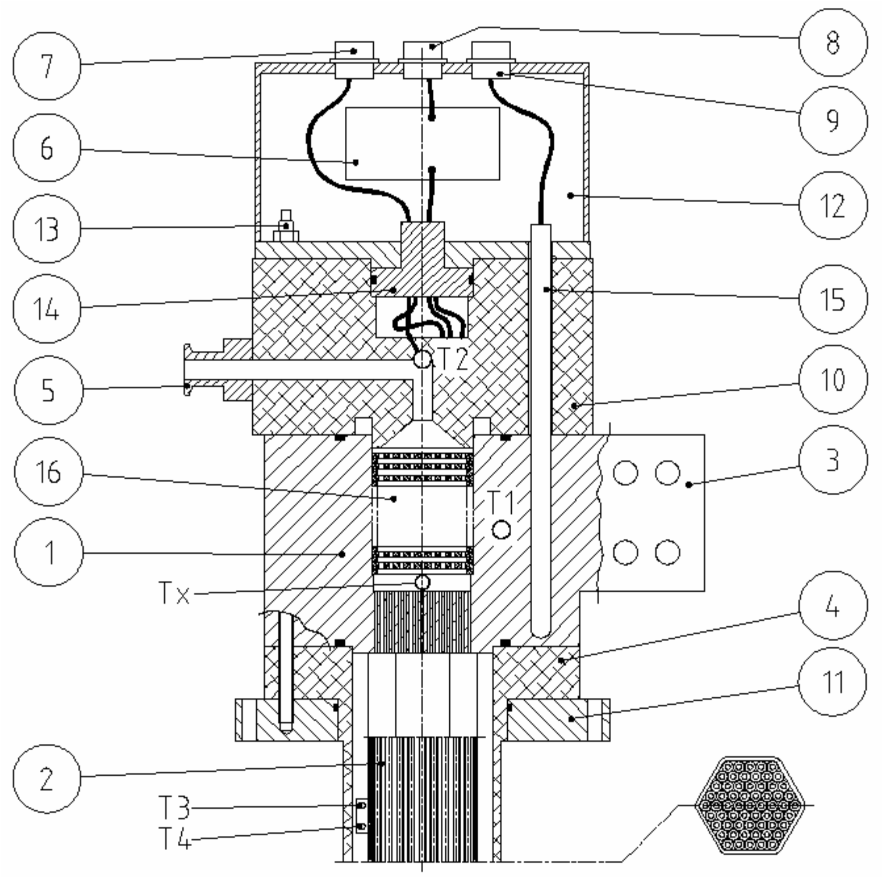
DESCRIPTION OF THE LEAD

The lead consists of the warm terminal, the main heat exchanger, the cold terminal, electrical insulation and instrumentation.

Warm terminal

A schema of the warm terminal is shown in Figure 1.
A massive silver plated copper (SE-Cu) part (1) equipped with an electrical terminal (3) for water-cooled cables is vacuum brazed to 61 copper pipes housed by the hexagonal tube of the main heat exchanger (2). The copper part of the terminal is electrically insulated from the cryostat by a glass fibre ground isolator (4). The outlet gas tapping (5) as well as temperature transmitters (6) including electrical connectors (7) for high voltage taps, (8) for thermometers and (9) for heaters are insulated from copper part of the warm terminal by a massive glass fibre insulator (10).

Figure 1 Scheme of the warm terminal



The whole sandwich, including connecting stainless steel flange (11), ground insulator, copper part, massive insulator and electrical box (12) are bolted together with electrically insulated double-end stud bolts (13) and sealed by O-rings in between.

Heating element

In order to keep the warm terminals at ambient temperature at any working condition five heating elements (15) of 250 W each are installed directly into the warm terminal. Ceramic heaters (Al_20_3) provide excellent electrical insulation while heat transfer is good. The small remaining gap between the warm terminal and the ceramic heater is filled with a heat conductivity compound to ensure a good heat transfer.

Auxiliary heat exchanger (AHX)

As the permitted leakage current at test voltage of 4.1 kV is low, no humidity on the warm terminal is acceptable. To achieve this, an auxiliary heat exchanger (16) is integrated in the terminal. This exchanger is designed as a perforated plate heat exchanger. Forty-four perforated disks interlaced by silver plated spacers are vacuum brazed in a compact cylinder pressed-in into the terminal copper part. The perforation diameter is 1 mm.

Main heat exchanger (HX)

The body of the heat exchanger consists of 61 copper tubes housed in the hexagonal copper tube all together acting as the conductor. The cooling helium vapour passes externally along the 61 tubes. Material for the conductor is copper (ES-Cu) with a residual resistance ratio (RRR) of 27.

Cold terminal

The copper (OF-Cu) cold terminal of cylindrical shape is vacuum brazed to the copper pipes the hexagonal tube of the main heat exchanger included. The terminal is equipped with a groove and silver plated for high quality soft soldering of superconducting cable. As installation required horizontal soldering in situ a dedicated soldering device and procedure was developed (controlled and constant temperature of the whole soldering area). The surface area of the terminal immersed in liquid helium has been dimensioned to avoid film boiling.

Technology and material check

Modern CNC manufacturing equipment was utilised for cutting operations, which made precise manufacturing possible. This precision allows a high degree of interchangeability between parts before brazing. The vacuum brazing technique was chosen to obtain perfect and long term stable mechanical, thermal and electrical contact. The brazing process is precisely controllable and programmable. There is no temperature gradient in brazing parts. As the brazing material was used alloy Ag-Cu eutectic, melting temperature 780 ^{o}C. Six 13 kA bodies together with twelve 600 A bodies [2] were brazed in one batch. Design of the rig for assembly and test enabled smooth flow during the assembly and test.
The choice of the material is based on two factors. The copper must be oxygen free and possible impurities must have low vapour pressure at brazing temperature. Impurities which tune RRR of copper, must be stable during the brazing process. In our case impurity in copper was phosphorus (about 0.003%). RRR measured before and after brazing shown are nearly identical (27).

High voltage taps

The current lead is equipped with 4 voltage taps. Tap 1 is connected to the warm terminal. Tap 2 is connected to the cold terminal. Tap 3 is prepared to be connected to superconducting bus bar connecting the lead to the magnet coil. Tap 4 is prepared to be connected to the magnet coil. Voltage drop of the current leads is $U_{1-2,}$ resistance of the contact between cold terminal and superconducting cable is given by U_{2-3} while contact resistance between the superconducting bus bar and magnet coil is given by U_{3-4}.

Thermometers

Four current lead thermometers are located as follows. Thermometer T1 measures temperature of the warm terminal, thermometer T2 measures the temperature of outlet gas and thermometers T3 and T4 (redundancy) measure temperature of main exchanger at 90% of exchanger length from cold side where the burn region is expected. Thermometer T1 is installed on the air side. Other three thermometers are located on helium side. All four are connected to the insulated transmitters and further to the connector.

Instrumentation feedthrough

Wires for voltage taps and 3 thermometers pass from the helium side to the air side through a 13-pin feedthrough (14), designed specifically for this purpose. Sufficient distances between live and ground parts ensure that the leakage current at 4.1 kV does not exceed the permitted value.

PERFORMANCE OF THE LEAD

Test conditions and procedure

In order to measure parameters of the current lead a dedicated test set up was designed and built at CERN. The pair of current leads was electrically short-circuited by a superconducting cable and connected to a power supply. The helium level was maintained constant, just below the gas inlet of the main heat exchanger. Heat inleak at self-cooling condition was measured by boil-off method considering that LHe in the cryostat is replaced with cold gas helium, eliminating heat inleak of the cryostat itself and subtracting inleak of resistive connection of the cold terminal/superconducting bus bar. Heat inleak of resistive connection was measured by electrical method; self-heat inleak of the cryostat was measured separately. Only for test purpose one extra thermometer Tx is installed in a tapping between both heat exchangers. T3 monitored at this condition is the future set point of the temperature control at normal working condition.

Results of measurement

In Table 2 are summarised measurement results and the corresponding calculated values.

Table 2 Calculated and measured results

Parameters	Calculated	Measured
Consumption of liquid helium at I=0A [g/s]	0.40	0.52
Consumption of liquid helium at I=13 kA [g/s]	0.75	0.79
Consumption of liquid helium at I=15 kA [g/s]	0.87	0.86
Pressure drop at I=15 kA, total (mainHX) [kPa]	5 (1.7)	2 (0.7)
Leakage current at 4.1 kV DC at working condition [A]	-	16×10^{-9}
Gas outlet temperature Tx at I=0/13/15 kA of the main HX with set point of warm terminal T1=295K [K]	291	289
Gas outlet temperature T2 at I=0/13/15 kA of the auxiliary AHX with set point of warm terminal T1=295K [K]	295	294
T3 at I=0/13/15 kA respectively [K]	140/154/165	134/145/150
Interruption of coolant gas at Imax without any degradation	>60s	>60s

CONCLUSION

Current leads rated to 13 kA continuously and to 15 kA for more than 10 minutes have been constructed by industry and tested. The measurements of the performance indicate that the design is reliable. The glass fibre insulator is robust and cheap and allows optimisation of its geometry. Sophisticated design of the warm terminal avoids any humidity, which ensures the low leakage current. The low leakage current of the leads allows a magnet high voltage test. Elaborated choice of the material and technology was optimised for series production. One pair of the leads installed in one test bench lost signals of T3 and T4 after heavy quench training. Reason will be investigated in near future. All twelve benches using these leads are operational, most of them for more than one year without any problem related to the current leads except in the point mentioned above.

REFERENCES

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