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Functional specification

LHC HTS CURRENT LEADS

Abstract

This Functional Specification describes the electrical and cryogenic requirements, the thermo-electrical performance and the interfaces of the High Temperature Superconducting (HTS) current leads used to power the LHC superconducting magnets. It identifies also the signals derived from the leads relevant for cryogenic control and for protection of the resistive and HTS sections. The detailed design of the lead mechanical interfaces is the subject of separate Interface Specification documents [1], [2], [3].

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History of Changes

Rev. No.	Date	Pages	Description of Changes
0.1	2002-07-18	All	Submission for approval
0.2	2003-03-18	All	Modification of total number of leads according to machine layout version 6.4 (section 1.2)
			Definition of lead operation with temperature of inlet gas varying between 4.5 K and 20 K (section 3.3.1.1)
			Change of operating temperature of HTS component in stand-by operation (section 3.3.1.2)
			Definition of instrumentation in leads (section 6.2)
			Definition of shipping conditions and transport requirements (section 10)
	2003-03-19	All	Re-formulation of sections 3.3, 3.3.2 and 7.3 taking into account the comments of AT/ACR-IN
	2003-07-11		Request from AT/ACR-IN of change in baseline: reduction of maximum allowed pressure drop in 20 K helium circuit from 50 mbar to 30 mbar (section 5.1.2)
1.0	2003-07-16	All	Released version

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1. INTRODUCTION

1.1 HTS CURRENT LEADS

The LHC will be equipped with about 3300 current leads in total. About 2100 leads are resistive (60 A ad 120 A leads needed for the powering of corrector dipoles, Inner Triplet sextupole, octupole and dodecapole correctors) while about 1200 incorporate a section with HTS (High Temperature Superconducting) material.

Powering the superconducting magnet circuits of the LHC will require feeding about 3.4 MA into the "cold mass" of the machine. Conventional self-cooled leads would conduct about 1.1 W/kA into the liquid helium. The availability of 20 K helium gas in the cryogenic system makes the use of HTS materials attractive: the gas can be used to cool the resistive upper section of the lead allowing the lower HTS section to operate at temperatures between 4.5 K and 50 K, ideal for presently available HTS materials.

The use of HTS material incorporated in the lower part of the lead allows a reduction of heat load into the liquid helium by a factor of about 10 if compared to conventional self-cooled leads. The corresponding reduction in total cooling power is about a factor of 3.

1.2 NUMBER OF LEADS AND CURRENT RATINGS

Table 1.1 summarises the total number of HTS leads required for the LHC operation (N_{TOT}) and their correspondent ultimate current (I_{ULT}) (machine layout version 6.4).

I_{ULT} (A)	N_{TOT}	LOCATION OF LEADS
600	692	DFBM (20), DFBL (44), DFBA (628)
3900	54	DFBL(12), DFBM(42)
4650	9	DFBM
4655	24	DFBL
4670	8	DFBL
4650	9	DFBA
5820	138	DFBA
6533	16	DFBM
13000	64	DFBA

Table 1.1: Number of HTS leads

There are in addition 40 HTS leads, associated with the 8 DFBX units, which are part of the U.S. supply [4].

1.3 LOCATION OF CURRENT LEADS

The HTS leads or lead assemblies will be mounted in four different types of cryostats with the following designations: DFBA, DFBM, DFBL and DFBX.

The DFBA cryostats contain the HTS leads used to power the magnets in the so-called "continuos" cryostats.

The DFBM-DFBL cryostats contain the HTS leads used to power the stand-alone magnets in the LSS with the exception of the Inner Triplets.

The DFBX cryostats contain the HTS leads, supplied by the US collaboration, powering the Inner Triplets in IP 1, IP 2, IP 5 and IP 8, including D1' s in IP 2 and IP 8.

1.4 ARRANGEMENTS OF THE LEADS

The HTS leads to be purchased by CERN are classified into three types, according to their nominal current carrying capability (see section 2.2): 600 A, 6000 A and 13000 A leads.

The 6000 A and the 13000 A current leads are supplied as single units. The 600 A current leads are supplied incorporated on a common flange in a group of 4.

1.5 EQUIPMENT CODE

The following equipment code is adopted:

13000 A	**600 A**	**6000 A**
DFLAS	DFLBS	DFLCS

Table 1.2: Equipment code

1.6 MASS OF CURRENT LEADS

The 600 A current lead assembly has a mass of about 40 kg, while for a single 6000 A and 13000 A current lead the mass amounts to about 50 kg and 70 kg respectively.

1.7 OVERALL DIMENSIONS

Each lead has a maximum overall length of 1.5 m. The outer diameter of the insulating mounting flange is 218 mm for the 13000 A current lead and 255 mm for the assembly of four 600 A current leads. The external diameter of the lead envelope is about 128 mm for the 13000 A current leads and 50 mm for each 600 A current lead. Detailed information on the size of the components is given in separate documents [1], [2], [3].

2. ELECTRICAL REQUIREMENTS

2.1 LEAD FUNCTION

The HTS current leads are designed to power the LHC superconducting magnets. They operate in a range of temperature between 295 K±5 K and 4.5 K. They provide the electrical link between the warm cables from/to the power converter and the low temperature superconducting bus bar bringing the current from/to the cryo-magnets (see Fig. 1).

2.2 CURRENT RATINGS OF THE LEADS FOR THE LHC MACHINE

The CERN supplied HTS current leads for the LHC machine will be ordered in three series covering different ranges of ultimate current (I_{ULT}):

- 600 A HTS leads (I_{ULT} = 600 A),
- 6000 A HTS leads (3900 A ≤ I_{ULT} ≤ 6533),
- 13000 A HTS leads (I_{ULT} =13000 A).

The rating of each series of current leads indicates the maximum current (I_{MAX}) that the leads are designed to transport in steady state operation while the temperature at the top of the HTS is maintained at its operating value (see section 3.3.1.1).

The 6000 A leads will be used to cover the current range from 3900 A to 6533 A**.**

The total number of leads (N_{TOT}) required for the LHC machine for different current ratings is listed in Table 2.1.

LEAD CURRENT RATING (A)	600	6000	13000
N_{TOT}	692*	258	64

Table 2.1: Total number of leads required for different current ratings

2.3 ELECTRICAL INSULATION OF CURRENT LEADS

The lead consists of a live envelope containing the resistive heat exchanger and the HTS element. An insulating flange at room temperature provides the electrical insulation between the lead body and the cryostat flange. The electrical insulation of the 4.5 K-20 K gas inlet port and of the room temperature gas recovery port is made via ceramic insulators. Two insulating fibre-glass envelopes cover respectively the HTS element and part of the resistive heat exchanger (see Fig.1).

* 173 assemblies of four current leads

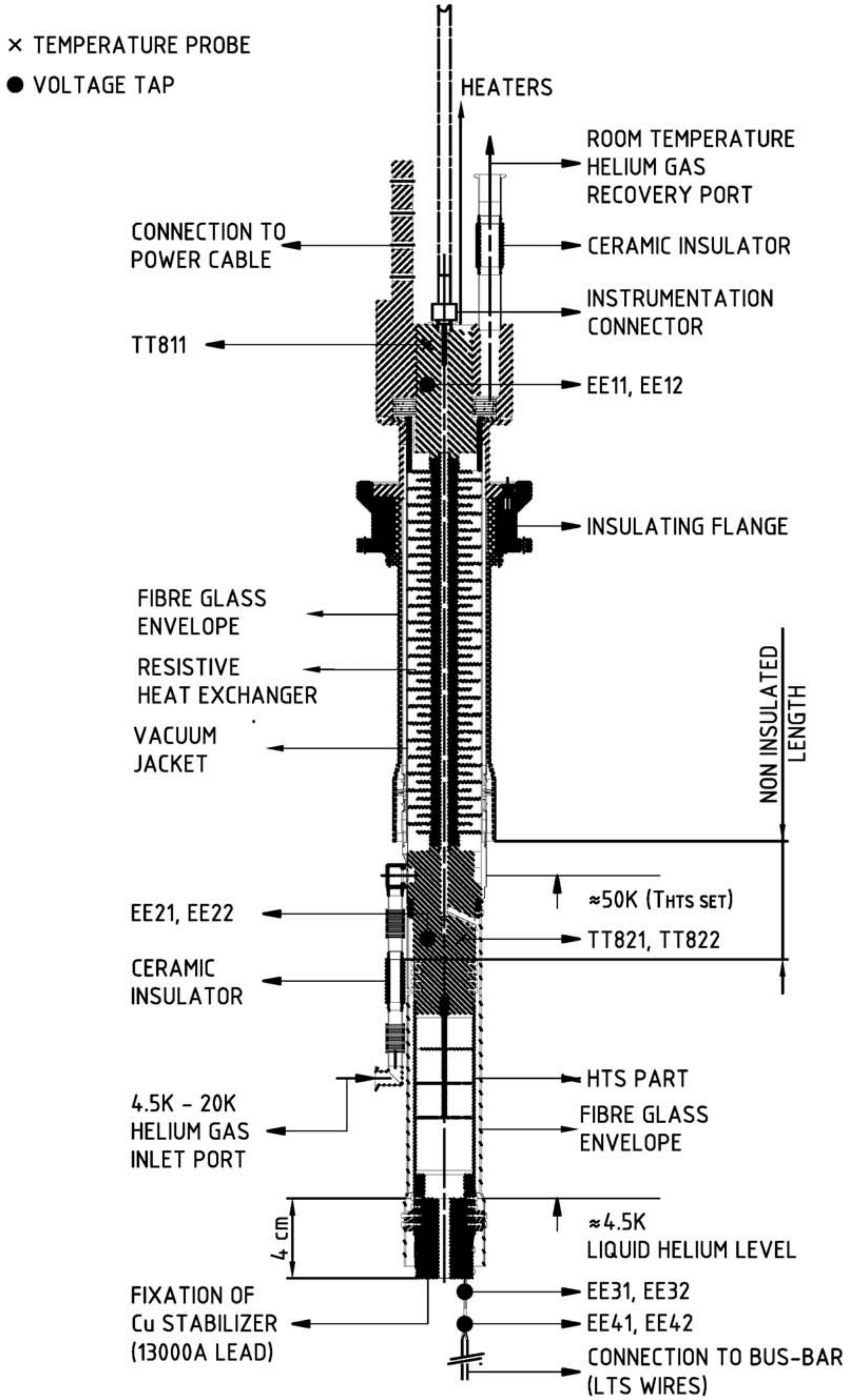

Fig.1: Lead schematic

3. CRYOGENIC REQUIREMENTS

3.1 COOLING SCHEME

The HTS current lead consists of a resistive heat exchanger and an HTS part (see Fig.1). The resistive heat exchanger is cooled using the nominally 20 K helium gas (see section 3.3.1.1) at 0.13 MPa absolute pressure from the DFB pipe DH. It operates between room temperature and the operating temperature of the HTS (T_{HTS}) and its cryogenic envelope is thermally insulated from the cryostat environment via a vacuum jacket. The HTS part operates between this T_{HTS} level and 4.5 K. The HTS cold end dips into liquid helium (4.5 K) and is self-cooled by the vapour created by the heat conducted into the bath. The 20 K circuit and the 4.5 K circuit are hydraulically separated at the warm end of the HTS. A warm cryogenic valve controls the nominally 20 K helium flow of each lead to maintain at a fixed temperature the top of the HTS section (see sections 3.3.1.1 and 3.3.1.2). The resistive part of the lead is designed to work stably (stable temperature profile with maximum temperature of the resistive heat exchanger never exceeding room temperature) at all currents up to I_{MAX} when this temperature is thus controlled. The gas escaping at the warm end of the HTS stays in the helium vessel and is recovered with the cryostat boil-off.

3.2 CRYOGEN REQUIREMENTS

The leads operation requires:

- Helium gas, at a temperature lower than 25 K (0.13 MPa), for the cooling of the resistive part,
- Liquid helium at 4.5 K covering the cold end of the HTS (see section 7.6).

3.3 GAS FLOW AND CONTROL

A room temperature helium valve is required for each lead. The total number of control valves (N_V) and the corresponding helium mass flow rate (m_{20K}) are summarised in Table 3.1.

The valve, which controls the nominally 20 K helium flow, is temperature controlled by a platinum sensor incorporated at the top end of the HTS part (TT821 or TT822 in Fig.1). The helium flow is controlled to maintain the temperature at the top end of the HTS at fixed values both in stand-by operations and in operation with current (see section 3.3.1).

It should be possible to implement a control of the flow as a function of current.

LEAD CURRENT RATING (A)	N_V
600	692
6000	258
13000	64

Table 3.1: Total number of warm control valves

3.3.1 TEMPERATURE CONTROL

3.3.1.1 OPERATION WITH CURRENT

For an inlet temperature of the helium gas of 20 K, the temperature at the warm end of the HTS at any current shall be maintained at a set temperature equal to 50 K. As the inlet temperature of the nominally 20 K helium gas depends on the position in the ring - it can vary between 4.5 K and 20 K- it will be necessary to adapt the set points of the temperature at the top of the HTS section ($T_{HTS\ SET}$). This has to be done in order to avoid either over-cooling, which would create condensation or ice formation at the top of the lead with consequent degradation of the electrical insulation and leak tightness of the component, or insufficient cooling with consequent thermal run-away of the resistive and/or HTS part. For each rating of lead the correct control temperature as a function of gas inlet temperature will be provided after type testing on the pre-series. In addition, for those 6000 A leads which are required to operate at up to 6500 A (298 in total), the set points must be adapted to take into account both this and the influence of the gas inlet temperature. Nominal set points in the range 30 K-60 K shall be foreseen.

The tolerance on the set point temperature is ± 2 K.

3.3.1.2 OPERATION IN STAND-BY CONDITIONS

In stand-by conditions, the temperature at the top of the HTS shall be maintained at about 70 K. Lower set point temperatures shall be avoided.

3.3.2 MASS FLOW CONTROL

In case of failure of the temperature sensors, of the associated wiring or of the control system, it should be possible to envisage to control the leads mass flow as a function of current. The dependence of the flow set point on the current for each rating of current lead will be provided after type testing on the leads pre-series.

3.4 NOMINAL PRESSURE OF HYDRAULIC CIRCUITS

The inlet pressure of the 20 K helium gas is 0.13 MPa.
The nominal pressure of the saturated helium bath is 0.133 MPa.

4. ELECTRICAL PERFORMANCE AND DESIGN PARAMETERS

4.1 STEADY STATE OPERATION

The total voltage drop across the lead operating at maximum current and nominal cooling conditions is about 50 mV.

4.2 TRANSIENT OPERATION

The resistive section and the HTS section of the leads are protected independently (see section 7.5).

In case of thermal run-away of the resistive heat exchanger, the total voltage drop across the lead can increase up to 100 mV. Within 5 seconds from the detection of this signal, the magnet or magnets chain must be discharged at its nominal current decay rate.

The leads are designed to safely withstand a quench in the HTS component. This is achieved by incorporating a resistive shunt in parallel to the superconducting element that matches to the longest time constant of the electrical circuit being powered by the leads of each current rating, namely 120 s for the 13000 A leads, 30 s for the 6000 A leads and 20 s for the 600 A leads.

In case of resistive transition of the HTS element, the total voltage drop across the HTS can increase up to 3 mV. Within 5 seconds from the detection of this signal, the discharge of the magnet or magnets chain must start at its nominal current decay rate.

In case of resistive transition of the HTS, the total voltage drop across the lead should never exceed 100 mV.

4.3 INSULATION VOLTAGE TO GROUND

The insulation voltage (U), at cryogenic temperatures, between the cryostat flange (ground) and the current carrying part (warm electrical connection and lead external envelope) is equal to the minimum design withstand voltage of the magnet circuit powered by the leads. The same applies between the helium warm gas recovery port (ground), the 4.5 K-20 K gas inlet port (ground) and the current carrying part (see Fig.1). The insulation test voltage (both polarities) and the maximum leakage current ($I_{LEAKAGE}$) admitted per component are summarised in Table 4.1 [5]. The insulation test voltage of the lead is performed with warm helium gas (295 K ± 5 K, 0.13 MPa) in the resistive heat exchanger and in the cryostat environment.

LEAD CURRENT RATING (A)	U (V)	$I_{LEAKAGE}$ (μA)	Voltage Test duration (s)
600	1500	|3|	30
6000	1300	|10|	30
13000	3100	|20|	120

Table 4.1: Insulation test voltage of current leads (helium @ 295 K ± 5 K, 0.13 MPa)

Two electrical connectors for the instrumentation in the lead (temperature probes and voltage taps are incorporated inside the lead body, see section 6.2) are incorporated at the top of each lead. These connectors are at the same potential as the lead current carrying part.

Cartridge heaters are incorporated inside the top part of each lead to avoid heavy condensation or ice formation when the leads are operating at zero current or at a current lower than the nominal one. These heaters guarantee that the temperature at the top of the lead stays above the dew point in the LHC tunnel (15 °C) on condition that the helium flow in the resistive part of the lead does not exceed the values specified both for stand-by conditions and operation with current (see section 7.3). The heater electrical circuit operates at 24 V. Insulation transformers (220V/24V, one per lead) installed on supporting structure on the DFB will guarantee the insulation at the 4 kV level between the heater circuit and the mains. The maximum power supplied by the heater system is about 1000 W for each 13000 A lead, 500 W for each 6000 A lead and 100 W for each 600 A lead.

5. CRYOGENIC PERFORMANCE AND DESIGN PARAMETERS

5.1 STEADY STATE OPERATION

5.1.1 HELIUM FLOW RATE AND HEAT LOAD

The 4.5 K-20 K helium mass flow (m_{20K}) necessary to operate the leads at zero and maximum current (I_{MAX}) and the correspondent heat load into the liquid helium bath ($Q_{4.5K}$) are summarised in Table 5.1.

LEAD CURRENT RATING (A)	**I=0 A**		**$I=I_{MAX}$**	
	TT821=TT822=70 K		**TT821=TT822=50 K**	
	m_{20K} (g/s)	**$Q_{4.5K}$ (W)**	**m_{20K} (g/s)**	**$Q_{4.5K}$ (W)**
600	≤ 0.015	≤ 0.090	≤ 0.04	≤ 0.090
6000	≤ 0.2	≤ 0.7	≤ 0.39	≤ 0.7
13000	≤ 0.3	≤ 1.5	≤ 0.85	≤ 1.5

Table 5.1: Thermal performance of HTS current leads

5.1.2 HELIUM PRESSURE DROP

The maximum pressure drop of the 4.5 K-20 K helium gas inside the resistive heat exchanger is 3 kPa.

5.2 TRANSIENT OPERATION

The estimated total energy dissipation (E) in case of resistive transition of the HTS in the lead is reported in Table 5.2.

CURRENT RATING (A)	**τ (s)**	**Pmax (W)**	**E (J)**
600	20	6	200
6000	30	51	4500
13000	120	274	25000

Table 5.2: Energy dissipation in case of resistive transition of the HTS

τ= time constant of current decay in the LHC magnet circuit used for calculations

Pmax= maximum power generation

5.3 DESIGN PRESSURE OF HYDRAULIC CIRCUITS

The design pressure of the 20 K and 4.5 K helium circuits is 0.35 MPa.
The 20 K circuit and 4.5 K circuit are specified to be independently pressure tested at 0.45 MPa (pneumatic test).

5.4 LEAK RATE

The integral of leak detected at operating conditions is specified to be:

$\leq 1 \cdot 10^{-5}$ mbar·l·s^{-1} for the 20 K circuit,

$\leq 1 \cdot 10^{-8}$ mbar·l·s^{-1} for the lead vacuum insulation.

6. MECHANICAL, CRYOGENIC AND ELECTRICAL INTERFACES

6.1 DEFINITION OF INTERFACES

The interfaces between the lead and the surrounding environment (see Fig.2) are:

1) mechanical (connection of lead insulating flange to the supporting cryostat flange, connection of the DFB pipe DH to the lead 20 K inlet port, connection of room temperature helium gas port to recovery line),
2) cryogenic (feeding of 20 K helium gas, recovery and control of room temperature helium gas and recovery of gas released at the warm end of the HTS),
3) electrical (connection of the power cables from/to the power converter and connection of cold end of the HTS to the low temperature superconducting bus-bar, acquisition of the lead instrumentation signals).

The design of the interfaces has been made such as to satisfy the geometrical constraints imposed by the integration requirements.

Detailed information on each of these interfaces is given in separate documents [1], [2], [3].

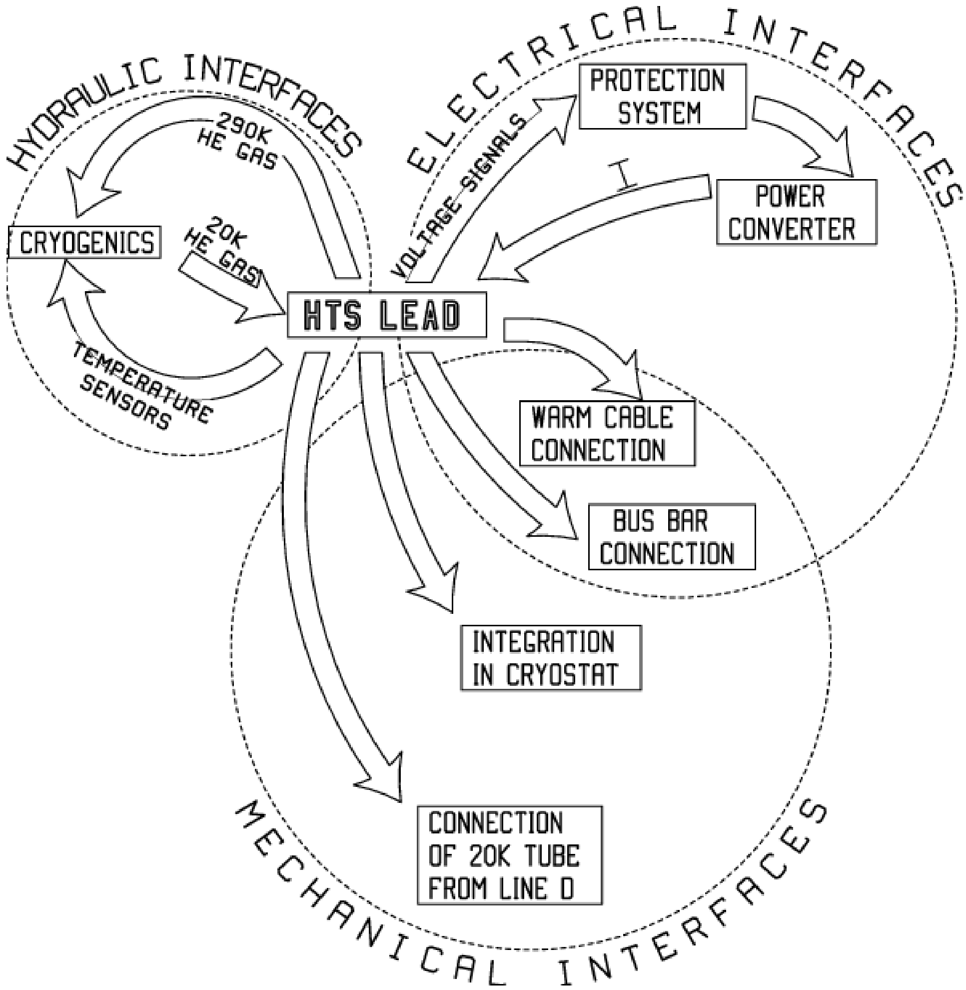

Fig.2: General interfaces of HTS current leads

6.2 INSTRUMENTATION IN CURRENT LEADS

Instrumentation (voltage taps and temperature probes) is incorporated in the lead for:

•Control of the 20 K helium flow,

•Independent protection of both the resistive heat exchanger and the HTS part.

Two additional voltage taps are made available for the protection of the magnets circuit.

Each current lead of any current rating is equipped with the same type and number of instrumentation signals. These signals consist of (see Fig.1):

1) <u>eight voltage signal wires</u> located at:

•Warm end of resistive heat exchanger (EE11, EE12),

•Warm end of HTS (EE21, EE22),

- Cold end of HTS (EE31, EE32),
- Low temperature superconducting wires (EE41, EE42);

2) <u>three platinum resistance thermometers</u> (Pt100 IEC) located at:

- Warm end of resistive heat exchanger (TT811),
- Warm end of HTS (TT821, TT822).

The voltage taps in any position on the lead and the temperature sensors at the warm end of the HTS are doubled to allow redundancy.

The purpose of the voltage signals is as follows:

- The voltage EE11-EE21 (or EE12-EE22) is for the protection of the resistive heat exchanger,
- The voltage EE21-EE31 (or EE22-EE32) is for the protection of the HTS part,
- The voltage tap EE41 (or EE42) is provided for the protection of the magnet circuit.

The purpose of the temperature sensors is as follows:

- TT821 (or TT822) is for the control of the 20 K helium flow,
- TT811 is for monitoring the temperature at the top of the lead and verifying the integrity of the lead heating system.

A 16-pin instrumentation connector is incorporated in the top terminal of each lead. It is at the lead potential and it provides the leak tight separation between the 4.5 K helium circuit and the room temperature outside environment. All the wires of the lead instrumentation terminate in this connector with the exception of the temperature sensor TT811, located at the top of the resistive heat exchanger and accessible from outside. The wires of the TT811 temperature sensor are connected in a 4-pin connector incorporated in the top terminal of the lead.

The two instrumentation connectors have low voltage insulation between pins and their body is at the lead potential. The temperature sensors are electrically insulated (100 V) from the lead body.

During the high voltage insulation tests of the electrical circuits in the LHC tunnel, the lead instrumentation shall be left floating.

6.2.1 INSTRUMENTATION WIRES AND CONNECTORS

The 16-pin connector at the top of the resistive heat exchanger is a leak tight Fischer connector DEE 104 A086. The pin designation of the connector is indicated in Table 6.1. The four wires of each temperature sensor are twisted.

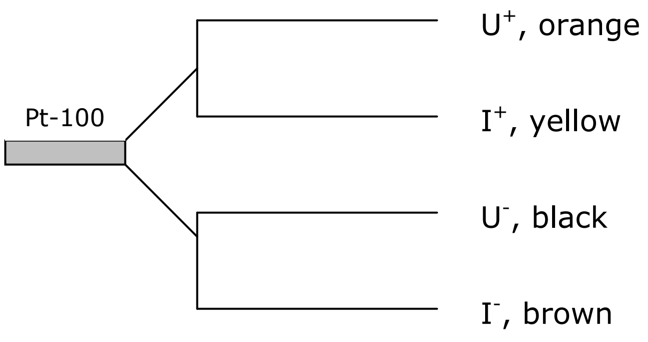

Fig.3: Schematic of Pt-100 probe and instrumentation wires in the lead

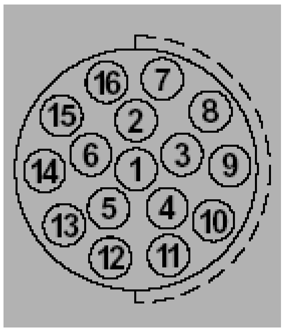

Fig.4: Schematic of DEE 104 A086 instrumentation connector (lead side)

Pin	Sensor	Signal
1	EE11	Voltage
2	EE12	Voltage
3	EE21	Voltage
4	EE22	Voltage
5	EE31	Voltage
6	EE32	Voltage
7	EE41	Voltage
8	EE42	Voltage
9	TT821	U^+
10	TT821	U^-
11	TT821	I^+
12	TT821	I^-
13	TT822	U^+
14	TT822	U^-
15	TT822	I^+
16	TT822	I^-

Table 6.1: Pin designation of the Fischer DEE104 A086 connector

The wires of the temperature sensor TT811 terminate in a 4-pin connector. The pin designation of this connector is summarized in Table 6.2

Pin	Sensor	Signal
1	TT811	U^+
2	TT811	U^-
3	TT811	I^+
4	TT811	I^-

Table 6.2: Pin designation of the connector relative to TT811

7. OPERATION

7.1 STAND-BY OPERATION

When there is no current in the lead, TT821 (and TT822) shall be set to 70 K.

7.2 OPERATION WITH CURRENT

Before powering the leads, TT821 (and TT822) shall be at the designated set-point temperature ($T_{HTS\ SET}$).

7.3 HELIUM MASS FLOW

During operation, the helium mass flow in the resistive part of the lead shall never exceed 120 % of the values listed in Table 5.1 both for stand-by conditions and operation with current. If those values of maximum control flow are exceeded, condensation and ice will build up at the top of the lead with consequent degradation of the lead electrical insulation properties.

7.4 POWER PERMIT SIGNALS

The powering of the leads requires:

1) TT821 ≤ $T_{HTS\ SET}$ and TT822 ≤ $T_{HTS\ SET}$,
2) the liquid helium shall be at its nominal operating value.

These signals shall be interlocked with the power converters.

The leads shall not be powered without the power permit from the QPS system.

7.5 PROTECTION

The resistive and HTS part of the lead shall be separately protected at 100 mV and 3 mV respectively (see section 4.2).

7.6 LIQUID HELIUM LEVEL

The nominal liquid helium level can vary over a length of 4 cm from the bottom end of the lead. To assure integrity of the HTS element, during operation the liquid He level shall never cover a length of more than 5 cm measured from the bottom end of the lead (see Fig.1).

8. RELIABILITY

The HTS current leads are designed as sturdy and reliable components able to guarantee continuous operation of the magnet systems during the LHC lifetime. However, if a failure occurs during operation, the design of the leads and the electrical feed boxes in which the leads will be incorporated should be such as to allow replacement of the current lead in the tunnel.

9. RADIATION RESISTANCE

The HTS leads will be subjected to ionising radiation.

The leads shall be able to withstand a maximum accumulated dose of 10^5 Gy without degradation of any of its properties.

10. SHIPPING, TRANSPORT AND INSTALLATION

The leads will be shipped in purpose-built crates, which assure damage-free delivery. Lifting will be done via lugs screwed in the lead flanges.

In any circumstances, the top (warm electrical connection) and bottom (free end of LTS wires) connections of the lead can withstand a maximum force (F_{MAX}) applied in any direction and a maximum torque (C_{MAX}) as specified in Table 10.1.

	TOP CONNECTION		BOTTOM CONNECTION
	F_{MAX} (N)	C_{MAX}(N·m)	F_{MAX} (N)
13000 A	800	80	200
6000 A	500	40	150
600 A	200	10	20

Table 10.1: Permissible forces and torques at the top and bottom connections

The cold end of the 13000 A lead includes a copper block which houses four bolts for the fixation of the copper stabilizing the LTS wires [1] (see Fig. 1). When connected to the lead, the copper stabilizer connection should apply a force of not more than 400 N and a torque of not more than 40 N·m.

The maximum horizontal and vertical acceleration that the leads are able to withstand in transport condition when supported vertically by fastening the lead insulating flange to the cryostat flange at the specified torque [1],[2],[3] - as after installation in the cryostat chimney – corresponds respectively to 0.5 g and 1.5 g.

REFERENCES

[1] Mechanical interfaces of 13000 A HTS current leads, LHC-DFLA-ES-0001, EDMS No.375283

[2] Mechanical interfaces of 6000 A HTS current leads, LHC-DFLC-ES-0001, EDMS No.375292

[3] Mechanical interfaces of 600 A HTS current leads, LHC-DFLB-ES-0001, EDMS No.375293

[4] Inner Triplet Feedboxes, DFBX, LHC Project Document No. LHC-DFBX-ES-0100

[5] Voltage withstand levels for electrical insulation tests on components and bus bar cross sections for the different LHC machine circuits, LHC-PM-ES-0001.00 rev. 1.0