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Potential of High-Temperature Super Conductor Current Leads for LHC Cryogenics

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Abstract

The reference design for the Large Hadron Collider (LHC) at the European laboratory for particle physics, CERN is based on the generalised use of High-Temperature Superconductor (HTS) current leads. This paper discusses the envisaged cooling methods for these HTS leads and lists the possible gains and drawbacks for the cryogenic system linked to these different solutions. The aspects considered for this comparison are the design of interfaces, the adaptability to load changes, the design of the heat exchangers for the lead cooling and the exergetic costs of refrigeration within the already well defined cryogenic infrastructure for the LHC machine.

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The reference design for the Large Hadron Collider (LHC) at the European laboratory for particle physics, CERN is based on the generalised use of High-Temperature Superconductor (HTS) current leads. This paper discusses the envisaged cooling methods for these HTS leads and lists the possible gains and drawbacks for the cryogenic system linked to these different solutions. The aspects considered for this comparison are the design of interfaces, the adaptability to load changes, the design of the heat exchangers for the lead cooling and the exergetic costs of refrigeration within the already well defined cryogenic infrastructure for the LHC machine.

INTRODUCTION

Approximately 3200 kA of DC current will have to enter the LHC machine through about 2650 leads. Cooling these leads in the conventional way would require a liquefaction rate of 290 g/s distributed over the eight cryogenic plants. The development of HTS leads within the recent years allows to envisage new solutions for current lead cooling [1]. The most important aspect is of course the significant decrease of the liquefaction load on the refrigerators. A second gain can be the suppression of warm control valves and piping if the leads are cooled by thermal contact at the cold end of the normal conducting part.

The choice of the cooling method for the leads depends on possibilities to implement them into the cryogenic system and the capabilities of the chosen HTS material.

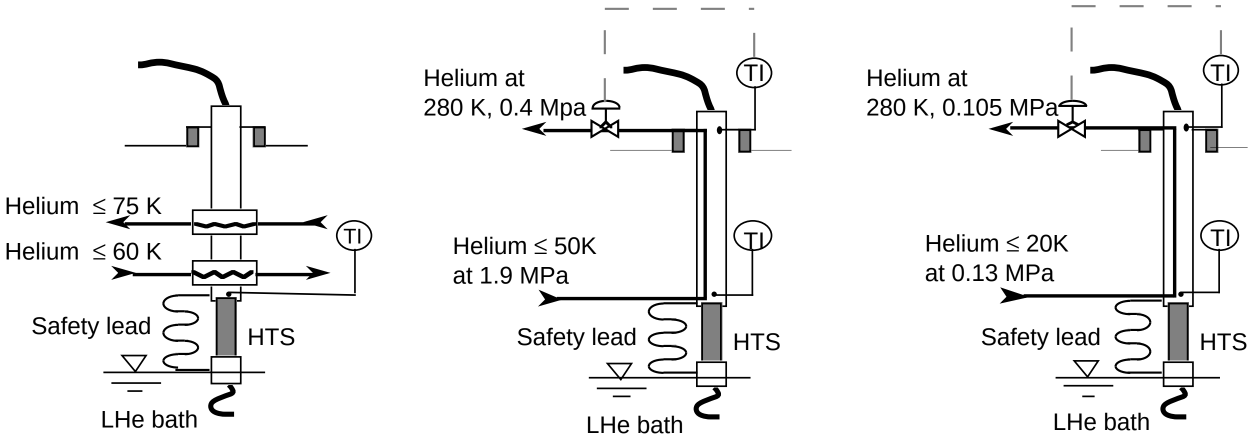
CRYOGENIC INFRASTRUCTURE FOR THE LHC

The LHC machines has eight access points numbered from one to eight. The total cryogenic infrastructure that influences the decision how to cool the HTS current leads can be characterised by the following constraints.

- Cryogenic installations are only located in the four equidistant even numbered points around the 27 km long LHC ring called the even points.
- Due to safety reasons the use of LN2 is prohibited in the LHC ring tunnel.
- The superconducting magnets are supplied from a cryogenic transfer line running in parallel to the magnet cryostats connecting the refrigerators installations at the even point with all consumers in the 3 km long sector and in the odd numbered points called odd points.
- The refrigerators will supply helium at 2.2 K/0.13 MPa, 4.6 K/0.3 MPa, and 50 K/1.9 MPa. The return gas to the refrigerators is designed to be at 20 K/0.13 MPa and 75 K/1.7 MPa.
- The pipe diameters in the separate transfer line are designed for the maximum flow during cool down and no increase of any of these lines is envisaged due to requirements for the HTS cooling.
- The pressure levels for the suction and discharge of the cycle compressors are given at 0.13 MPa, 0.25 to 0.45 MPa and 2.0 MPa.
- The main amount of cooling capacity is required by the leads grouped in feed boxes at the extreme (odd and even) end of each sector.

POSSIBLE COOLING METHODS FOR THE HTS CURRENT LEADS

Three cooling methods for the HTS current leads as shown in the sketch in Figure 1 were envisaged as principle possibilities [2].



Method 1 Method 2 Method 3

Figure 1 Envisaged cooling methods for the HTS current leads in the LHC machine

These cooling methods within the fixed frame of the cryogenic system have certain advantages and drawbacks which are considered under the aspects of:

- Line and interface design
- Pressure drop in the lines for the supply and return of the thermal shield cooling of the LHC sectors
- Dependency on the operation mode of the cryogenic installation and the LHC machine
- Suitability for the cooling at both the odd and the even points
- Design of the heat exchanger to cool the warm part of the lead
- Exergetic costs of cooling

Finally the HTS current lead will have to be compared to conventional current leads used in the same frame of cryogenic boundary conditions to evaluate their advantages.

Method 1: Contact cooling of the lead at the warm end of the HTS conductor with heat intercept at higher temperature level

The leads are cooled by the use of two heat exchangers connected to the normal conducting copper part of the lead. The main heat leak into the lead is intercepted at a rather high temperature below 75 K which is the maximum specified return temperature to the refrigerators. The maximum temperature of the HTS is fixed by the lower heat exchanger using the coldest gas of the thermal shield circuit available at the location of the lead.

No warm return lines, no flow control valves and no temperature control at the warm end is needed for the individual lead. The piping that is connected to the leads heat exchangers has to be electrically insulated.

The cooling flow is taken from the thermal shield supply of the magnet cryostats and fed back to the thermal shield return in the separate cryoline. The increased flow in the thermal shield lines results in an additional pressure drop of the whole system which has to be added to the exergetic losses of the lead cooling.

Active control of the lead temperature can be realised for a set of leads which are cooled in series by controlling the mass flow through all leads depending on the warm return temperature. The supply temperature must not increase to guarantee the operation of the HTS material. During partload operation the tendency of a cryoplant will always be to operate at higher temperature level therefore a special control has to be foreseen to guarantee a thermal shield supply temperature of 50 K.

The suitability for the cooling at both the odd and the even points depends on the maximum operation temperature of the HTS leads. As the total load of the thermal shield for the magnet cryostats has to be absorbed by the supply helium before it can cool the current leads at the odd points, the lowest temperature to supply the leads ranges up to 67 K. As a result HTS leads cooled with method 1 have to be designed for operating temperatures up to 72 K at currents up to 12.5 kA.

The heat exchanger arrangement to cool the warm part of the lead has still to be developed. Depending on the total current in the current feed box the lead is situated in, its flow may vary between 16 and 205 g/s. The pressure drop per heat exchanger should not exceed 0.5 kPa to keep the total pressure drop within sensible values.

Method 2: Gas flow cooling in direct contact with the lead between 50 K and 280 K

The leads are cooled by forced flow of helium at about 50K and 1.9 MPa through their normal conducting upper part. This helium is warmed up to about 280 K and fed back to the suction of the medium pressure compressors at 0.45 MPa.

Warm return lines, flow control valves and temperature control at the warm end is needed for each individual lead. The cold piping that is connected to the lead heat exchangers has to be electrically insulated.

The cooling flow is taken from the thermal shield supply of the magnet cryostats. this requires a flow increase of 3% to 12 % in the thermal shield lines depending on the individual sector and results in an additional pressure drop of 5% to 25% which adds up to the exergetic losses of the lead cooling.

Concerning changing temperatures due to the operation mode of the cryogenic installation the remarks made for the cooling method 1 also apply here. The control is however more flexible in this case as each lead has its independent control loop.

Depending on the actual load for each individual sector the available temperature at the odd points ranges up to 66 K. As a result HTS leads cooled with this method have to be designed for operating temperatures up to 70 K at currents up to 12.5 kA.

The heat exchanger to cool the warm part of the lead will look like a conventional lead; no development for this part is therefore needed.

Method 3: Gas flow cooling in direct contact with the lead between 20 K and 280 K at low pressure

The leads are cooled by forced flow of helium gas at 20K and 0.13 MPa from the return lines of the beam screen cooling in the LHC magnets through the normal conducting upper part of the lead. This helium is warmed up to about 280 K and fed to the suction of the low pressure compressors at 0.101 MPa.

The line and interface design for these current leads is the same as for method 2. The lines for the supply and return of the thermal shield cooling of the LHC sectors are not influenced.

Changing temperatures of the cryoplant at off-design operation does not influence this cooling method as helium at ≤ 20K and 0.13 MPa will always be present in the return line from the beam screen cooling. As a consequence cooling method 3 is perfectly suitable to cool the HTS leads both at the odd and even points. The heat exchanger to cool the warm part of the lead will look like a conventional lead, no development for this part is therefore needed.

COMPARISON WITH A CONVENTIONAL CURRENT LEAD

Concerning the line and interface design only method 1 has an advantage against the conventional lead as no warm piping, no flow control valves and no temperature control at the warm end is needed. Concerning all other aspects mentioned, except the cooling capacity requirements, the HTS leads have no advantage or even a disadvantage if compared with conventional leads.

The most important aspect when using HTS leads is certainly the potential in liquefaction savings. As shown above this strongly depends on the implementation of the lead cooling into the total cryogenic system. A comparison of the exergetic cooling power for the different cooling methods mentioned, with the one for an optimised conventional current leads is given in Table 1. The 16% power saving potential for the HTS leads cooled by method 3 represent an equivalent of about 190 g/s of liquefaction at 4.5K. It should be noticed that the power saving figures from Table 1 are theoretical values and only valid for cryoplants which are well adapted to cover the resulting load within the given temperature range. For the four new plants to be installed in the LHC it is possible to adapt the process to the cooling needs. For the four already existing plants process calculations show that the electrical input power for each of the discussed methods to cool the HTS leads, is at about the same level.

Table 1 Comparison of the necessary cooling capacity of different HTS lead cooling methods for the LHC machine

		Conventional lead	HTS method 1	HTS method 2	HTS method 3
spec. exergy loss by evaporation of liquid He.	[W/kA]	79	8	8	8
spec. exergy loss from sensible gas heating	[W/kA]	341	182	123	137
spec. exergy loss from pressure loss in the lead	[W/kA]	10	9	74	8
spec. exergy loss from secondary pressure losses in the system (thermal shield lines)	[W/kA]	0.0	28.0	4	0.0
total specific exergy loss of the lead	[W/kA]	430	227	209	153
total specific exergy loss in percent of conventional lead	[%]	100	53	48	35
total exergetic power for all LHC leads	[kW]	1367	720	660	485
power saving potential for total LHC cryogenics	[%]	0.0	12	13	16

CONCLUSION

HTS leads have certainly an important potential for power saving on the cryogenic system for the LHC machine. Given the cryogenic system for the LHC the necessary cooling power for the current leads will be between 44 % and 30 % of that for conventional leads. Besides the aspect of power saving other aspects like the possible suppression of warm piping and warm control and the maximum operation temperature of the HTS material carrying a current of 12.5kA may play an important role for the decision of the final solution selected for the cooling of HTS leads. Depending on the development of the HTS leads and the cryogenic system envisaged in the coming year, either cooling method 1 due to its simple control and interface design, or the method 3 due to its larger power saving potential and independence from temperature fluctuations in the refrigerators, will be selected.

As a general conclusion, the decision to use HTS material for current leads should be taken as early as possible within a project phase as the design of the cryogenic system as a whole strongly influences the possible gains.

REFERENCES

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