Design, Construction and Tests of 20 kA Current Leads for the CMS Solenoid

P. Fazilleau, P. Bredy, F. P. Juster, F. Kircher, Y. Pabot, L. Scola, and B. Curé

***Abstract*—The CMS experiment (Compact Muon Solenoid) is a general-purpose proton-proton detector designed to run at the highest luminosity at the LHC [1]. Distinctive features of the CMS detector include a high-magnetic-field solenoid (4 T) coupled with a multilayer muon system, a fully active scintillating-crystal electromagnetic calorimeter, a tile hadronic calorimeter, and a powerful inner tracking system.**

The two 20 kA current leads for the CMS electrical circuit have been designed, manufactured and tested by CEA Saclay.

Their design, with reliability as prime goal, is based on the use of a pure-copper braid, having an RRR of 130, placed inside a conduit and cooled by evaporating helium gas. Their length is of 3.3 m to cross the return yoke and their conductive cross-section has been fixed at 1800 mm^2, slightly above the optimal section.

An important specification is the behavior in case of lack of coolant: the current leads are able to hold the maximal current during 5 minutes followed by a fast discharge, time constant of 190 s, without any damage.

They are fully instrumented with sensors and diagnostics (temperature, voltage and helium flow) for safety and control. In case of discharge, they are submitted to a high voltage and then must ensure an insulation of 3 kV.

The tests will include insulation, mechanical and electrical tests (at nominal current, with and without coolant).

***Index Terms*—CMS, cryogenics, current leads, design.**

I. Introduction

A pair of cryogenic current leads for powering the CMS superconducting solenoid was designed, manufactured and tested by CEA Saclay. The solenoid produces a central field of 4 T; its magnetic energy is 2.7 GJ and its nominal current is 19.5 kA. The rated current of the leads has been chosen 10% higher than the nominal current of the solenoid, i.e., 21.5 kA.

Cryogenic current leads are the most vulnerable parts of the electrical circuit because they have to carry the magnet current from ambient temperature to liquid helium temperature while limiting the helium consumption. Moreover, the continuity of the lines between the magnet and the dump resistor is of prior importance; for that reason, the current leads must have as prime quality the robustness which includes particularly a long holding time without helium cooling. The current leads were designed so that they can carry the nominal current during 5 minutes followed by a fast discharge, time constant of 190 s, without coolant.

Manuscript received October 20, 2003.

P. Fazilleau, P. Bredy, F. P. Juster, F. Kircher, Y. Pabot, and L. Scola are with CEA/Saclay, DSM/DAPNIA/SACM, 91191 Gif-sur-Yvette Cedex, France (e-mail: p.fazilleau@cea.fr).

B. Curé is with CERN, CH-1211, Geneva 23, Switzerland.

Digital Object Identifier 10.1109/TASC.2004.831072

TABLE I
Electrical and Cryogenical Specifications

Electrics	
Nominal Current	19.5 kA
Rated Current	21.5 kA
Insulation Voltage	3 kV to ground
Head Heaters Power	3 kW per head
Cryogenics	
Helium Flow @ Rated	< 1.45 g/s
Helium Flow @ In	< 1.3 g/s
Helium Flow @ 0 A	# 0.8 g/s
Pressure Drop @ In	< 5 kPa

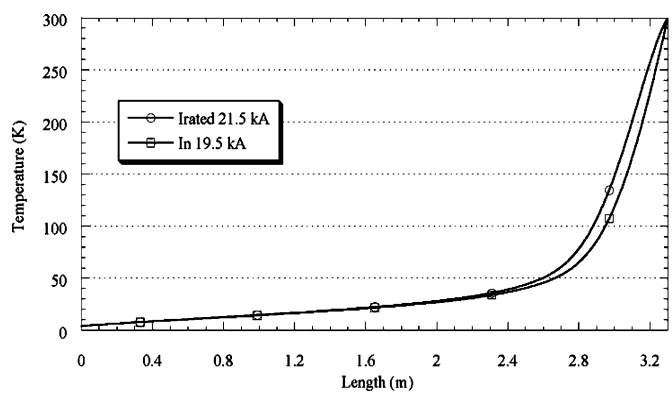

Fig. 1. Temperature along the copper braid (thermal exchanger).

Another important requirement is the exchanger length of the leads, minimum of 3.3 m because of the chimney height between the magnet and the electrical lines. This requirement and the specifications listed in Table I have led to the design presented in part II. Part III exposes the monitoring and instrumentation of the current leads. The tests performed at Saclay are detailed in the part IV.

II. Current Leads Design

A. Gas-Cooled Leads Theory

All the calculations presented in this paper (except the transient state without cooling solved with a FEM method in II-D.) use a one-dimensional model. The two well-known steady state equations of a gas cooled lead are:

$$\frac{d}{dz}\left(Ak(\theta)\frac{d\theta}{dz}\right) - h(T)p\cdot(\theta - T) + \frac{\rho(\theta)I^2}{A} = 0$$
$$C_p m\frac{dT}{dz} = h(T)p\cdot(\theta - T) \qquad (1)$$

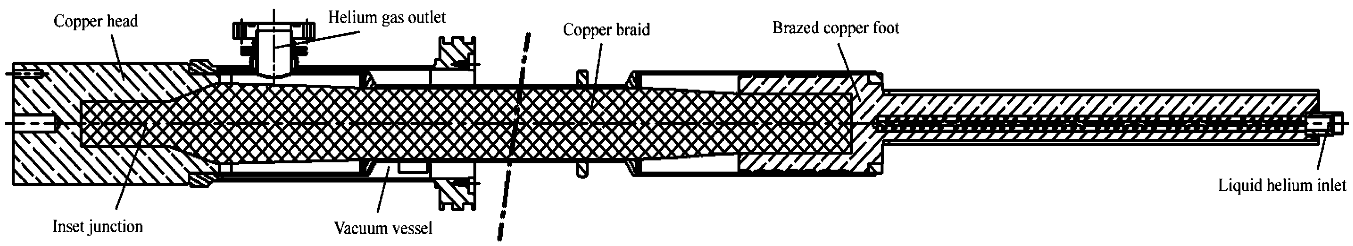

Fig. 2. 20 kA current lead for the CMS solenoid.

where z is the axial distance along the lead; θ and T are respectively the copper lead and helium gas temperatures; $k(\theta)$, $\rho(\theta)$, A and p are respectively the thermal conductivity, electrical resistivity, cross-section and wetted perimeter of copper. $Cp(T)$, m and $h(T)$ are respectively the helium specific heat, mass flow rate and heat transfer.

The boundary conditions at the foot and the head of the lead are $\mathrm{T}(0) = 4.5\,\mathrm{K}$ and $\mathrm{T}(\mathrm{l}) = 300\,\mathrm{K}$, l being the heat exchanger length. The mass flow rate is usually controlled by a valve but in order to calculate the optimal lead parameters, with a mass m (g/s) of liquid helium boiled off by the heat load from the lead, we used the following equation:

$$C_L m = Ak(\theta)\left.\frac{d\theta}{dz}\right|_{z=0}, \qquad (2)$$

where C_L is the liquid helium latent heat of vaporization.

The Wiedemann-Franz law was not used because high-pure copper does not follow it accurately [2]. The maximal Reynolds number was calculated equal to 220, over the whole range between 4.5 K and 300 K, far below 2300, prevailing a laminar gas flow. The Nusselt number was chosen between 2.6 (minimal value) and 5. From these values, the heat transfer was deduced using the helium thermal conduction $Kg(T)$ and the calculated hydraulic diameter (0.6 mm). The equation was solved numerically and Fig. 1 shows the temperature profile for a self boiled off lead at 19.5 and 21.5 kA, respectively nominal and rated currents.

B. Structure

The thermal exchanger is a pure copper braid, RRR of 130, made of 9167 wires of 0.5 mm diameter. This is a well-proven technology, already used on ALEPH [3]. The braid was manufactured by T.M.F. ($\mathrm{S^t}$ Chamond, France). No alternative was possible concerning the choice of the copper used for the current leads; their large length due to the height of the chimney would have conduct to a cross section 4 to 5 times bigger in the case of use of a low resistivity copper (ATLAS design [4]) and consequently to cumbersome leads.

The use of a braid as a thermal exchanger has two advantages:

- the wetted perimeter is large and so is the exchange surface between copper and helium,
- the braid, well compressed, is placed inside a stainless steel conduit and the helium gas is constrained to flow past the braid strands.

The design of the lead is shown on Fig. 2. The braid is brazed inside the OFHC copper foot with tin-silver solder and is inset into the copper head with a press at 500 tons. The latter junction was tested mechanically up to 1 ton; it was also tested electrically and the resistance was below 1 $\mu\Omega$. The junction of the braid to the heads made under pressure, which is the technique commonly used for the electrical cables, guaranties mechanical solidness, reliability against overwarming (far upper soft solder melting point), along with good electrical conductance. That technique cannot be used for the foot because such junctions have too high electrical resistances due to the impurities on the braid strand surfaces. They could not operate at liquid helium temperature, the produced Joule heat should cause the foot superconducting lines to return to the resistive state.

Fig. 3. A current lead with the mechanical support, insulation tubes and flanges.

The NbTi superconducting lines coming from the solenoid windings are soldered onto the current lead feet with tin-lead. Parallel Nb_3Sn shunts are soldered between the feet and the NbTi lines. They remain superconducting at temperatures above the NbTi critical temperature and are able to conduct the full current in case of a sudden temperature rise (up to 14 K). The leads were equipped with auxiliary parts and introduced inside a mechanical structure to support the electromagnetic forces (cryogenic parts manufactured by SDMS, $\mathrm{S^t}$ Marcellin, France).

To prevent frost and to protect seals at the lead heads, heaters have been mounted onto the connections between the electrical lines and the heads: 2 kW as heating fingers to warm the copper head and 1 kW as grid heaters in order to warm the helium gas. A vacuum tube surrounds the heat exchanger at the outer part of the lead as shown in Fig. 3.

C. Helium Consumption

The use of a pure copper requires to not work at overloaded conditions because of the cross section, less large than a lead made of lower RRR copper. To enhance the safety margin, it was

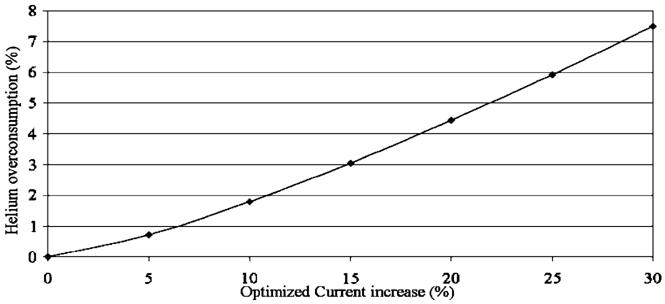

Fig. 4. Helium over-consumption vs optimized current increase. Consider a first current lead with a optimized current I_{opt1}, equal to its operating current, and a second lead with an optimized current I_{opt2}, also operating at the current I_{opt1} (the lengths of both leads are identical). The helium self consumption of the latter is compared to the former.

then decided to over-optimize the lead, meaning the optimum current and consequently the cross-section is taken 10% larger. This oversizing results in an over-self-consumption of only 2% of helium as presented in Fig. 4.

D. Transient State in Case of Lack of Coolant

An important specification is the behavior in case of lack of coolant: the current leads must hold the nominal current during 5 minutes (time given to the operator) followed by a exponential resistive fast discharge, time constant of 190 s, without suffering any damage, in particular the electric insulation must keep its integrity and its quality. The maximal temperature of the insulation in that case must not exceed 450.

Calculations made with the CAST3M code [5], based on a FEM method, have been performed, taking into account the fact that the heads of the current leads are connected to the outer electrical lines (large thermal inertia) and that their foot temperatures are floating. Figs. 5 and 6 describe the evolution of the voltage drop of the leads and the temperature of the hottest point of the heat exchanger, located 30 cm below the lead head. Both evolutions rise rapidly with time and the voltage is a good gauge of the exchanger temperature profile The use of a lower RRR would have led to lower temperatures and as mentioned before, it would have been feasible only if the length had been shorter. Nevertheless, the use of a long lead has an interesting characteristic; it was shown [6] that the thermal time constant varies with l^2. The 3.3 m long lead has then a 10 times greater time constant that a 1 m long lead (at same RRR). A longer optimum lead is safer than a shorter optimum one in the case of cooling helium stoppage.

III. Instrumentation and Safety

Because the current lead burnout should irreversibly damage the superconducting magnet, safety measures are redundant. Three kinds of signal are monitored for safety as shown in Fig. 7:

- Helium flow shortage; a threshold of 0.8 g/s initiates a slow discharge with the power supply (5 hours duration).
- Voltage drop of each lead; it is the more sensitive parameter to any variation of the temperature profile. A low threshold of 90 mV initiates a slow discharge with the power supply. A high threshold of 110 mV triggers a fast discharge.
- Temperature at the hot point of the lead; its exact situation was given by the calculations without helium cooling (cf. II-D.). A threshold of 300 K triggers a fast discharge.

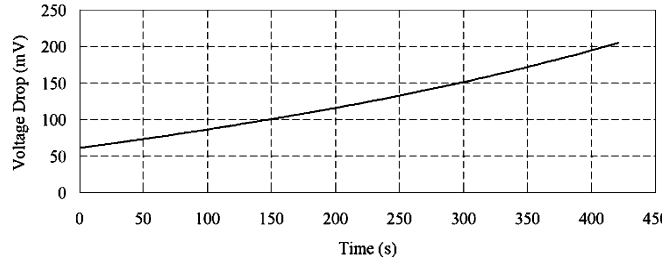

Fig. 5. Voltage drop at the terminals of the lead ($U_{exchanger}$) without cooling.

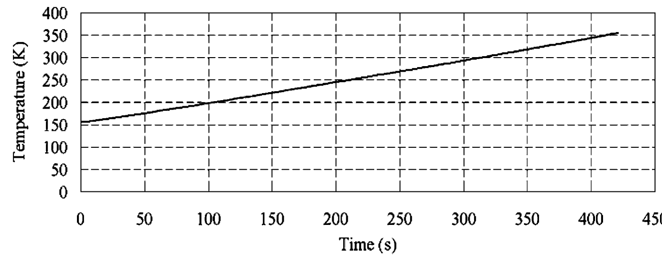

Fig. 6. Temperature of the hot point without cooling.

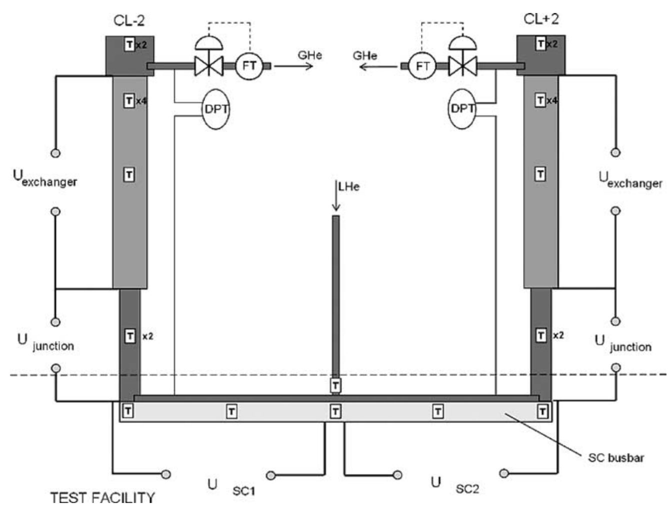

Fig. 7. Instrumentation monitoring. The scheme presents the instrumentation of the leads and the instrumentation used on the test facility (below part).

Others parameters are measured and activate alarms: temperature of the heads, voltage and temperature of the foot junctions.

IV. Tests Procedure and Analysis

A. Operating Conditions

The pair of current leads was installed in a 8 m deep test cryostat, with their feet short-circuited by a superconducting line. The short was instrumented with voltage taps and temperature sensors as shown on Fig. 7. The minimal mass flow rate, corresponding to the limit of instability, has been determined for several current values. The test results are presented on Fig. 8.

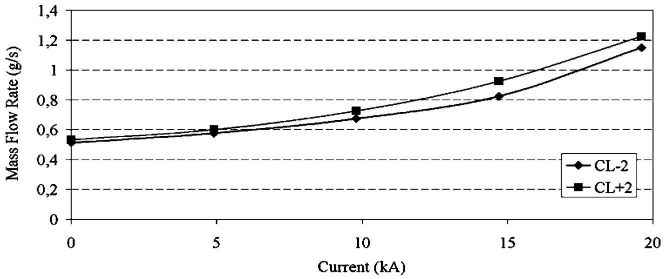

Fig. 8. Mass flow rate versus current.

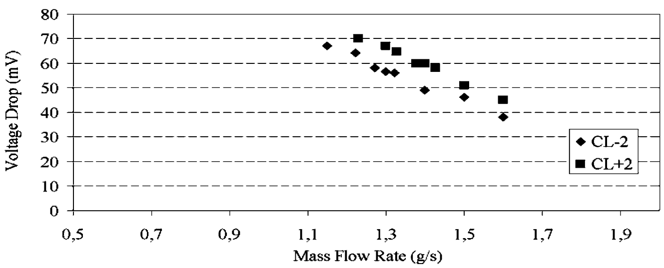

Fig. 9. Voltage drop ($\mathrm{U_{exchanger}}$) versus mass flow rate.

From that, one can choose a nominal mass flow rate for any current, above the limit value. During all the tests, the lead heads were maintained at 300 K with the heaters described herein before.

At the nominal current of 19.5 kA, the voltage drop at the terminals of each lead is shown on Fig. 9 for several mass flow rates and compared to the value of 80 mV, voltage drop of an optimal lead (no heat enters or goes out at the top by conduction). It is obviously safer to work at a smaller voltage, i.e., at large mass flow rate, because the temperature profile is then far from the instability zone. But there is a balance to achieve because working at these mass flow rates generates a larger helium loss and a longer working time for the heaters.

The pressure drop along each lead was measured and never exceeds 2.5 kPa, less than the specified 5 kPa.

The operating condition results show a small discrepancy between both leads. As they were manufactured with the same copper braid, the difference should be explained by a slight compaction difference of the copper braids inside their stainless tubes, causing difference of the heat transfers between helium gas and braids.

B. Lack of Coolant

The superconducting line has been removed and a massive OFHC-copper short circuit was mechanically mounted with indium foils. Both leads were operating at their nominal current with helium flow, their temperature profile being stabilized. The controlled valves, located at the gas outlet, were suddenly closed in order to stop the helium cooling.

The temperatures, measured on the conduit and displayed on Fig. 10, do not exceed 360 K after ten minutes and consequently,

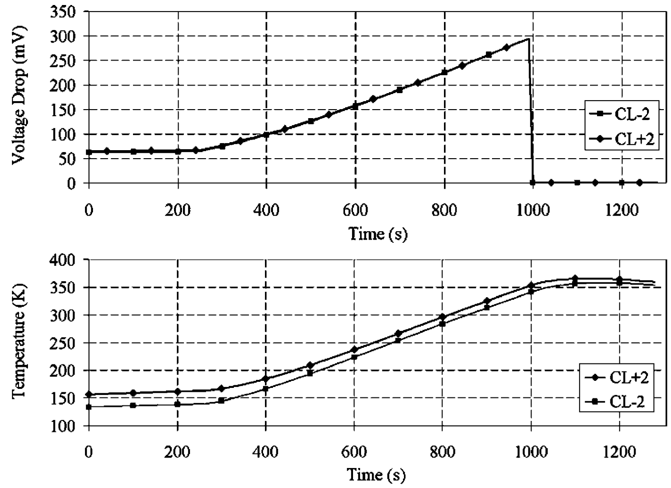

Fig. 10. Voltage drops ($\mathrm{U_{exchanger}}$) and hot point temperature evolutions without helium.

there is no damage on the electrical insulation. The temperature on the braid reached a higher temperature but this is less significant because the copper can withstand it. The voltage drop evolutions are very similar for both leads which underline the fact that the difference obtained during the operating conditions are due to the heat transfers to helium gas.

Pressure tests have been performed with alcohol at 3.3 MPa; furthermore, at the end of the electrical tests, the helium circuit has been tested up to 2.1 MPa.

V. Conclusion

Two cryogenic current leads for the CMS superconducting solenoid have been designed, manufactured and tested by CEA Saclay. A small discrepancy has been shown between both leads during the operating conditions, due to a slight difference of compaction in their stainless conduits. Nevertheless, they wholly fulfill the specifications, especially without coolant.

Acknowledgment

The authors would like to thank C. Lesmond for his strong interest and assistance during each step of the project, as well as the SACM and SIS teams involved in the assembly and the tests of the current leads.

References

[1] A. Hervé *et al.*, Status of the Construction of the CMS Superconducting Magnet at LHC, this conference.
[2] J. M. Lock, "Optimization of current leads into a cryostat," *Cryogenics*, vol. 9, pp. 438–442, 1969.
[3] C. Lesmond, J. C. Lottin, and J. P. Lottin, "Current leads for the ALEPH saolenoid," in *Proc. 12th Int. Cryo. Eng. Conf.*, 1988, pp. 247–250.
[4] A. Dudarev *et al.*, "20.5 kA current leads for ATLAS barrel toroid superconducting magnets," *IEEE Trans. Appl. Supercond*, vol. 12, no. 2, pp. 1289–1292, March 2002.
[5] Cast3m. [Online] http://www-cast3m.cea.fr/
[6] Y. Iwasa, *Case Studies in Superconducting Magnets: Design and Operational Issues*: Plenum Press, 1994.