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18 kA VAPOUR COOLED CURRENT LEADS
TO TEST SUPERCONDUCTING MAGNET MODELS
FOR THE PROPOSED LARGE HADRON COLLIDER AT CERN

D. Hagedorn, F. Haug, L. Oberli

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18-kA VAPOUR COOLED CURRENT LEADS TO TEST SUPERCONDUCTING MAGNET MODELS FOR THE PROPOSED LARGE HADRON COLLIDER AT CERN

D. Hagedorn, F. Haug, L. Oberli
CERN, European Organization for Nuclear Research, 1211 Geneva 23, Switzerland
H. Benz, R.K. Maix, H. Sauter
ABB, Asea Brown Boveri AG, Zurich. Switzerland

In the framework of the Large Hadron Collider project at CERN the testing of superconducting magnet models requires low loss vapour cooled current leads rated up to 18 kA. One pair of such current leads has been designed and fabricated by ABB Zurich according to CERN specifications. The leads were successfully tested in the recently installed station at CERN, where superconducting magnets in the temperature range between 1.8 K and 4.2 K are being tested. A specific heat leakage of less than 1.2 W/kA at 18 kA has been measured under selfcooling conditions with a superconducting short at the bottom of the leads. The leads have also been used for the testing of a 9 T superconducting dipole magnet at superfluid helium.

INTRODUCTION

In collaboration with European industries CERN is developing superconducting magnet models for the proposed Large Hadron Collider (LHC). According to the present development status, several different magnet models will be tested at current levels between about 10 kA and 18 kA^[1]. Testing with such high currents requires low loss current leads spanning the temperature interval between room temperature and liquid helium temperature. At these current levels the current leads are the dominant source of heat leaking into the cryostat. Since the magnet models have to be tested inside an already existing double bath cryostat^[2] dimensional restrictions necessitated a special design for these leads. According to CERN specifications, ABB Zurich has designed a pair of 18 kA current leads applying the same design principles as for similar leads up to 5 kA for the OMEGA-Magnet at CERN^[3]. In particular stress was laid upon a highly effective heat exchanger with a large heat exchange area per unit length. The leads were successfully tested up to 18 kA in a first experiment with a superconducting short at the bottom of the leads. They were used in a second run for the testing of a 9 T superconducting magnet model. This paper describes the design and measured characteristics of the leads.

SPECIFIC REQUIREMENTS (SPECIFICATION)

The leads have to meet the selfcooling conditions and must be electrically and mechanically very reliable as they will be used for many runs to test various magnet models. In view of the limited space inside and outside the existing cryostat limitations for certain dimensions had to be respected (length, mounting flange diameter, etc.). The specified characteristics for the current leads are listed in table 1. The rated voltage in room temperature helium gas at atmospheric pressure is governed by the maximum voltage occurring during the rapid discharge of a magnet at maximum current (18 kA). The acceptable specific heat inleak of 1.2 W/kA is mainly governed by the maximum available liquifaction capacity. The zero flow stability is defined by the allowable operating time to deenergize safely the magnet from full current at cut-off coolant flow in case of a failure in the cryogenic system or in the mains supply.

DESIGN CONCEPT

The target of an optimum current lead design is to minimize the heat leak conducted down the lead from room temperature and the heat generated within the lead by ohmic losses. The design optimization is mainly concerned with the optimum shape of the heat exchanger part, the cooler. Theoretically it was already shown, that the losses can be reduced to near 1 W/kA by effective gas cooling through an appropriate geometry of the heat exchanger. Even then these losses represent a big share of the total system losses, amounting in the case of the CERN 1.8 K test facility to about 80 %.

The principle design for these leads was supported by a numerical calculation and later proved by tests on 5 kA prototype leads^[2]. A schematic arrangement of a current lead system for a bath-cooled superconducting object can be seen in Fig. 1. The residual heat flux $\dot{Q}_3$ is removed by the latent heat of the liquid helium. For autonomous operation of the current lead system the equation $\dot{W} \cdot I = \dot{Q}_3 = \dot{m} \lambda$ applies, the evaporated mass flow $\dot{m}$ being used for cooling. The current lead system is build-up by the warm connecting system (6-8), consisting of a heavy copper bar at ambient temperature, the cooler (5-6) with a high cooling surface and minimum volume; the cold connecting system (1-5), consisting of copper with low residual resistivity and equipped with contacts (1-2), (4-5) and (6-7) which have to be constructed in such a manner that their losses are as small as possible. The system can be described by a set of strongly non-linear differential equations, which can only be solved by numerical iterative methods. For a calculation the thermal and electrical properties of the cooler and the cooling medium helium from 4.2 K up to ambient temperature have to be taken into account as well as the cooler characteristics^[3].

The matrix cooler consists of a large number of undulated silver plated copper wires inside a stainless steel tube. Such a system represents a very effective cooler because of its large cooling surface and helium transparency. For this cooler type optimization diagrams were established as shown in Fig 2. It can clearly be seen that specific losses in the order of 1 W/kA can only be obtained with low current densities and long cooler lengths.

CONSTRUCTION DETAILS

Based on these considerations the 18 kA current leads for the 1.8 K test facility at CERN were designed and constructed with a matrix cooler consisting of 96'000 undulated silverplated copper wires (0.1 mm $\emptyset$) which were enclosed in a stainless steel tube of 78 mm $\emptyset$. The connections to the warm and cold terminal are formed by a concentric grouping of 12 sub-bundles around the terminal core inside machined grooves. The sub-bundles are compressed and crimped into the these grooves and firmly fixed to the copper terminals by a hydraulic press. To provide electrical and thermal insulation the steel tube is surrounded by a Vetresite (G 10) tube. Fig. 3 shows an assembly drawing of the leads. The estimated temperature profiles along the cooler is indicated in the inserted diagram. For the optimum current the temperature gradient dT/dx is zero at the warm end. For lower currents an over-cooling occurs and at higher currents a temperature peak is built up in the so-called burn-through region between 80 % and 90 % of the cooler length. Fig. 4 shows the two 18 kA current leads during assembly. It is evident, that great care had to be taken not to damage the bundle of "silver hairs" while introducing them into the steel tube. The main design parameters of the current leads are summarized in Table 2.

TEST PROCEDURE

To avoid any unnecessary perturbation inside the delicate cooler structure the mounting of several thermometers inside the cooler for monitoring the total temperature profile along the cooler part was abandoned. Only two Pt-100 thermometers were mounted inside the cooler close to the burn-through region at about 80 % of the cooler length on each of the leads. In addition, thermometers were attached to the warm and cold terminals. The hair-like structure of the cooler did not permit

to mount voltage taps inside the cooler without affecting the cooler structure and performance. The leads were mounted inside the HeI-bath of the double bath cryostat described in detail elsewhere[2]. The warm terminals were connected to watercooled cables arriving from a 15 V, 20 kA thyristor controlled power supply. The cold terminals were electrically shortened by a superconducting cable which was later replaced by the superconducting magnet. The following parameters were continuously recorded for each of the leads during tests :

- coolant flow rate measured at 300 K
- voltage drop
- pressure drop
- temperatures of the warm and cold terminals
- temperature of the burn-through region.

The cryostat loss flow rate, the cryostat pressure, and the liquid He-level were kept constant. Watercooled cables and heating blowers were used to keep the warm terminals at ambient temperature at currents below 15 kA, whereas at higher currents the temperature of the warm terminals reached room-temperature without using the heating blowers. The measurements were carried out during a time interval long enough to reach steady state for the temperature and the voltage drop in the leads.

TEST RESULTS

The electric insulation between the current carrying parts and the mounting flange (ground) was tested by applying 2 kV DC during 1 minute the cryostat being filled with helium gas at room-temperature and atmospheric pressure. Table 3 shows the test results for the current leads at the nominal current of 18 kA for two different flow rates. Once the flow was adjusted to obtain ambient temperature at the warm terminals and once for minimum losses whereby the temperature of the warm terminal mounted to about 67°C. The applied forced flow air cooling was not sufficient and watercooling would have been required to keep the warm terminals at ambient temperature. Fig. 5 shows the losses per lead as a function of current level. Since only one point (in the burn-through region) of the total temperature profile could be measured, it was difficult to determine the optimum operating conditions especially at lower currents. At each current level the flow rate was stabilized at different levels to find the optimum in view of losses.

The zero flow stability test was started at nominal current with a flow rate of about 1.1 g/s and the temperature at the burn-through point of about 100 K. After stopping the flow for 2 minutes the temperature at the burn-through point reached a maximum of about 280 K showing a largely sufficient high reserve for the thermal inertia.

CONCLUSIONS

It has been shown that current lead systems also for very high currents with minimized specific losses can be designed reliably and that they can be operated with sufficient safety for steady state conditions. Even when cutting off the cooling gas flow they behave slowly enough to allow to deenergize a magnet system without danger of deterioration.

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Figure 1 : Schematic arrangement of vapour cooled current leads.

Figure 2 : Optimization diagram for current leads with a matrix cooler consisting of a large number of ondulated silver plated copper wires (0.1 mm Ø).

Figure 3 - Assembly drawing of the 18kA current leads and the estimated temperature profiles for different operating conditions

Table 1 - Specification for 18 kA-Current leads

Nominal current	18	kA
Insulation Voltage	≥ 2	kV
Specific heat leak per lead at 18 kA	≤ 1.2	W/kA
Helium mass flow rate per lead	1.03	g/s
Warm end Temperature at 18kA	300	K
Pressure drop at 18 kA and 1.03 g/s	≤ 5	kPa
Length (mounting flange-cold end)	900	mm
Zero flow stability at 18kA	≥ 2	min

Table 2 - Main design parameters for 18 kA leads

Current density (in copper)	24	A/mm ²
Cooler (heat exchanger) length	800	mm
Calculated specific losses	1.08	W/kA
Void fraction	80	%
Cooling surface per unit length	0.43	m ² /cm

Figure 4 - A 18 kA current leads during assembly

Table 3 - Measured characteristics at 18 kA

Coolant flow rate	1.007 g/s	1.105 g/s
Specific heat leakage	1.145 W/kA	1.25 W/kA
Voltage drop	122 mV	68 mV
Temperature of the He-gas at the burn-through point	220 K	100 K
Temperature at the warm end	67 °C	25 °C
Pressure drop	2.9 kPa	1.8 kPa
Zero flow stability	≥ 2 min.	≥ 2 min.

Figure 5 - Measured losses of the 18 kA current leads versus current level