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FOR CRYOGENIC SERVICE

by

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INTRODUCTION

Delivering high currents efficiently and reliably from a source at ambient temperature to a cryogenic environment can still create problems, despite numerous developments in the field. Vapour-cooled current leads usually suffer from shortcomings inherent to design principles. Their efficiency depends critically on optimized conductor cross-section and good heat exchange with cooling vapour, a challenge to simple construction in a limited space. Moreover, optimized leads are susceptible both to thermal runaway should the cooling be insufficient, and to build-up of ice on terminations at reduced current. Finally, a sound construction of the terminations is essential to provide adequate mechanical support and ensure electrical insulation to ground combined with leaktightness of the helium circuit in all service conditions.

In order to overcome these difficulties, we have designed, built and tested vapour-cooled current leads based on the following concepts. A conductor with a large specific heat exchange area is made of standard copper braids. The warm and cold terminations are crimped in solid copper blocks. Besides suppressing all soldered joints, this makes it possible to have a flexible cold end taking assembly tolerances and thermal contractions. The top of the current lead has been designed in such a way as to integrate electrical insulation, connection to helium recovery and electrical cables, temperature sensor and a self-acting thermostatic valve, which controls the cooling vapour flow through the lead as a function of vapour outlet temperature.

Fig. 1. Completed 1600 A and 400 A Current Leads

Thanks to modular construction, it is possible to manufacture current leads optimized for any current up to 4000 A, with only three basic types of components and an adequate combination of standard size copper braids. The basic components, manufactured by industry within standard mechanical tolerances, are assembled into functional modules, eventually put together to form complete current lead units. Figure 1 shows two completed current leads with nominal current carrying capacities of 400 A and 1600 A.

DESIGN AND CONSTRUCTION

A cut-away view of the top of a current lead, showing the different modules and their components, appears in Fig. 2. A detailed description of construction features and manufacturing techniques is given in Ref. 1.

Conductor Module (a)

The conductor proper is constituted of standard electrolytic copper braids assembled coaxially. The resistivity ratio between ambient and liquid helium temperatures of the copper used is 94.7²; consequently, a design value of $2 \cdot 10^5 \text{ A cm}^{-1}$ has been chosen for the invariant LI/A^3 , thus defining optimal conductor cross-section A as a function of lead effective length L and nominal current I . Table 1 gives the design characteristics of the current leads shown in Fig. 1.

Fig. 2. Cut-Away View of the Top of a Current Lead.
 (a) Conductor Module, (b) Temperature
 Monitor, (c) Vapour Collector, (d) Lead
 Feedthrough, (e) Thermostatic Valve.

Table 1. Characteristics of Current Leads shown in Fig. 1.

Nominal current	[A]	400	1600
Effective length	[m]	0.95	0.95
Conductor cross-section	[cm ²]	0.19	0.76
Heat exchange area	[m ²]	0.5	1.9
Electrical resistance at 20°C	[μΩ]	930	233

The multi-braid conductor is crimped at both ends between tapered sleeves; the radial crimping pressure of about 1000 bar guarantees plastic deformation and hence good electrical contact.

Such a construction ensures a good heat exchange between conductor and cooling vapour and makes the lead terminations fully resistant to thermal excursions.

Temperature Monitor (b)

The vapour temperature is measured a few millimeters downstream of the "warm" termination by means of a platinum resistor temperature gauge, held in an insulating ring. This measurement, which gives a good estimate of the maximum temperature reached in the lead under normal conditions, is a useful operational parameter.

Vapour Collector (c)

The function of this module is to ensure electrical insulation between the current lead and the vapour recovery system, while providing a housing for the thermostatic valve. The collector body, made of high-molecular density polyethylene, can accommodate either an ISO NW 25 or a swaged pipe fitting. Leaktightness is achieved by clamping the polyethylene surfaces flat onto stainless steel flanges by means of tie-bolts exerting a pressure of about 100 bar on the sealing surfaces, maintained by sets of spring washers.

Lead Feedthrough (d)

Besides supporting the current leads on the insulating top flange of the cryostat, this module provides thermal insulation by reducing conduction to the termination (thin stainless steel tubing), convection along the lead passage and radiation to the cold conductor (multilayer aluminized mylar).

Thermostatic Valve (e)

Compact enough to fit into the current lead unit, the valve must operate reliably and reproducibly without external power

Table 2. Characteristics of Thermostatic Valve Materials at 298 K (25°C)

Material		Cu Be 2	Silicone Oil
Mass density	[kg m ⁻³]	8260	970
Specific heat	[J kg ⁻¹ K ⁻¹]	420	1500
Thermal conductivity	[W m ⁻¹ K ⁻¹]	98.5	0.16
Thermal diffusivity	[m ² s ⁻¹]	2.8 x 10 ⁻⁵	1.1 x 10 ⁻⁷
Volume thermal expansion coefficient	[K ⁻¹]	5.7 x 10 ⁻⁵	9.45 x 10 ⁻⁴

source, while exhibiting sufficient gain to maintain the temperature of the outcoming vapour constant within a range of ± 10 K around the set point. To achieve this, the valve actuator makes use of the thermal expansion of a fluid contained in a metal bulb; the volume variation is translated into a linear displacement by a piston of appropriate cross-section which in turn actuates the valve.

A survey of possible fluids with high thermal expansion and being able to withstand temperatures well below ambient without freezing has led to select a silicone oil⁴, currently used for lubrication under vacuum. The bulb body is made of copper-beryllium alloy (Cu Be 2) exhibiting high strength and good thermal conductivity. Relevant physical properties of thermostatic valve materials appear in Table 2.

The resulting linear sensitivity of the device is 0.50 mm K⁻¹ in the working temperature range; the valve seat is designed so as to approximate a logarithmic variation of flow cross-section across the first 6 mm of its travel (Fig. 3). The working range has been set so that with no current flowing through the lead, the vapour outlet temperature is 10 K below the ambient. This draws a vapour flow which is sufficient to keep the residual conductive heat inleak along the lead to a fraction of its value at nominal current.

The mechanical tolerances required on piston and guide to ensure proper assembly and operation of the device are below 0.01 mm; this also guarantees reproducibility of the linear travel to within 0.5 %. Equally important to obtaining the required travel characteristic is the volume of working fluid in the bulb, which has to be precisely adjusted at a fixed temperature. As a result of this calibration procedure, the dispersion in valve characteristics measured on 20 units is within ± 1 K.

A look at the thermal diffusivities of the silicone oil and copper-beryllium alloy (Table 2) reveals that temperature variations propagate 250 times faster in the bulb body than in the working

Fig. 3. Characteristics of Thermostatic Valve.

fluid; the latter is, therefore, the prime source of time lag in the response of the thermostatic valve. Dynamic tests show time constants ranging from 50 to 60 seconds, in accordance with calculations made with the "thermometer time lag" model⁵. This is much shorter than the response time of the current lead at nominal current (typically 10 minutes), thus avoiding thermal run-away or annoying oscillations.

PERFORMANCE

Measurements at ambient temperature

The electrical and hydraulic resistances of the current leads have been measured at ambient temperature. The manufacturing process guarantees a reproducibility of electrical resistance within 1 %, and hydraulic resistance within 5 %.

The electrical insulation to ground has been checked by applying a d.c. voltage of 5 kV between current lead and cryostat; in all cases, the leakage current was less than 1 μ A.

Following thermal shock at liquid nitrogen temperature, pressure testing of the leads at 3 bar differential pressure revealed no leak in the helium circuit.

Fig. 4. Thermal Performance of 1600 A Current Leads.

Fig. 5. Temperature at Top of 1600 A Current Leads (a) without, (b) with Thermostatic Valve.

Cryogenic Operation

Lead pairs of each type have been tested up to 10 % above their design currents in the self-cooling mode, i.e. cooled by the flow of helium they vaporize from the bath. The variation of specific heat inleak with operating current (Fig. 4) shows a minimum of 1.7 W kA^{-1} for the design current of the lead, thus confirming the validity of the sizing approach. The installation of thermostatic valves drastically reduces the working temperature range of the "warm" terminations of the leads between nominal and zero currents (Fig. 5) so that icing can easily be avoided.

Reliability tests have been performed on thermostatic valves using a dedicated test set-up simulating accelerated cycles of current lead operation. All thermostatic valves have undergone reproducibly 750 thermal cycles over a period of one month without failure.

In view of the good results obtained, the sixteen 1600 A current leads equipping the eight superconducting quadrupole magnets⁶ of the ISR high-luminosity insertion⁷ were retrofitted with such thermostatic valves. Besides stabilizing lead top temperatures during operation, the valves distribute more efficiently the cold

helium flow during magnet cooldown, thus reducing by six hours the total cooldown time. In the case of a magnet quench, the valves close within a few seconds and prevent ice build-up.

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