**A WARM BORE ANTICRYOSTAT FOR SERIES MAGNETIC MEASUREMENTS
OF LHC SUPERCONDUCTING DIPOLE AND
SHORT STRAIGHT SECTION MAGNETS**

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All LHC twin-aperture magnets will be tested under operating conditions to verify their performance. The field measurement equipment works at ambient temperature and pressure. Each magnet is therefore equipped with two warm bore anticryostats. As a consequence a total of nearly 80 anticryostats of different lengths have to be assembled, handled and serviced during the test period. Two main constraints determine the frame for the design of these anticryostats: inside a given beam pipe aperture of 50 mm kept at 1.9 K, a warm bore aperture of 40 mm must provide the highest possible mechanical stability and robustness for numerous mounting cycles as well as the lowest possible heat losses towards the cryogenic system. In addition, compatibility with high magnetic fields and an insulation vacuum of about 10^{-7} mbar have to be maintained. This paper describes how a satisfactory mechanical stability as well as heat losses in the order of 0.8 W/m are achieved with a design based on very careful space and material optimization. Other aspects like assembly, installation, thermal behavior and temperature control during the operation are described.

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A WARM BORE ANTICRYOSTAT FOR SERIES MAGNETIC MEASUREMENTS OF LHC SUPERCONDUCTING DIPOLE AND SHORT-STRAIGHT-SECTION MAGNETS.

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ABSTRACT

All LHC twin aperture magnets will be tested under operating conditions to verify their performance. The field measurement equipment works at ambient temperature and pressure. Each magnet is therefore equipped with two warm bore anticryostats. As a consequence a total of nearly 80 anticryostats of different lengths have to be assembled, handled and serviced during the test period. Two main constraints determine the frame for the design of these anticryostats: inside a given beam pipe aperture of 50 mm kept at 1.9 K, a warm bore aperture of 40 mm must provide the highest possible mechanical stability and robustness for numerous mounting cycles as well as the lowest possible heat losses towards the cryogenic system. In addition, compatibility with high magnetic fields and an insulation vacuum of about 10^{-7} mbar have to be maintained. This paper describes how a satisfactory mechanical stability as well as heat losses in the order of 0.8 W/m are achieved with a design based on very careful space and material optimization. Other aspects like assembly, installation, thermal behavior and temperature control during the operation are described.

INTRODUCTION

All superconducting LHC dipole and quadrupole magnets must be tested at cryogenic temperature while the test equipment for magnetic field measurements operates at ambient temperature and pressure. The necessary measurement conditions are provided by a warm bore anticryostat, which is a well insulated, single-walled tube, kept at ambient temperature by low-voltage coaxial heating wires. Each magnet aperture is equipped with an anticryostat so that it can be measured individually with various types of instruments. Following an earlier

R&D period [1] the series production of the anticryostats has now started and more than 30 units are presently operational.

Providing an appropriate environment for magnetic measurements of superconducting magnets, anticryostats are exposed to severe - and sometimes contradictory - operating conditions. They have to leave enough space for high resolution magnetic measurements needing the largest possible aperture, while the beam pipe apertures of the magnets are determined by the machine design.

These constraints leave only little space for an efficient thermal insulation towards the cold mass which is operating at 1.9 K. As the anticryostat must maintain its temperature around 300 K, an important temperature gradient towards the cold mass has to be taken into account for the design.

Another important boundary condition is the mechanical stability of the coaxial tube system of the anticryostat. A mass of up to 3.1 kg/m of the measurement instrumentation introduced in the warm bores must not damage the anticryostats and has to be maintained well centered in the magnet aperture. For this reason the support system of the coaxial tubes has to be as rigid as possible at the same time as it limits thermal losses by conduction.

As the anticryostats form part of the magnet cryostat the entire design must be absolutely leak tight in order to ensure a good insulation vacuum for the cryogenic system. Moreover all used material must be nonmagnetic with magnetic permeability not exceeding $\mu \leq 1.005$. Huge magnetic fields of up to 9 Tesla with sharply decreasing decays of more than 35 T/s [2], causing eddy currents and thus lateral forces (Figure 1) in the order of 150 N/m on the cross section must not damage the anticryostats. In addition, the magnetic field measurements must not be disturbed by the presence of the anticryostats.

FIGURE 1. Forces on the anticryostat cross section due to eddy currents.

DESIGN

Layout

Figure 2 shows a general layout of a test stand fitted with anticryostats. It can be seen that the twin aperture with a length of 19.6 m (10.6 m for Short Straight Sections (SSS)) are fitted with two anticryostats, a 2.8 m long upstream tube which remains fixed in the cryogenic feed box (CFB) and a 16.8 m long (7.8 m for SSS) downstream part which comes with the magnet and which has to be installed in each magnet to be cold tested.

FIGURE 2. Layout of a cold test bench for dipole magnets equipped with anticryostats.

Different types of magnetic measurement equipment need a good straightness and an excellent quality of the inner surface of the warm bore tube. Perfectly smoothed junctions and welds are required and no sharp edges, burrs or bumps must occur inside the tube. Alignment issues are also an important subject in particular for the bent cryodipoles. The centerline of a horizontally well aligned anticryostat on a test bench can be seen in Figure 3. One can clearly recognize the magnet curvature as well as the straight parts formed by the upstream anticryostat and the downstream part sticking out the cryostat end cap. Supports which are fixed in a distance of 700 mm on the anticryostats keep the warm bore centered to the curvature and avoid a direct contact with the magnet cold bore.

In order to form a continuous tube, a smooth and leak tight junction is required which supports a vacuum of 10^{-7} mbar and cryogenic temperatures in case of a vacuum break. It is realized with a spring loaded metallic gasket and a special centering ring kept together with the end flange of the upstream anticryostat, two half flanges and eight bolts.

Components

The anticryostat is built as a coaxial tube system (Figure 4), consisting of a seamless, cold drawn pipe of stainless steel (AISI Type 316L) with an inner diameter of 40 mm and a wall thickness of 0.7 mm. The tube is equipped with four mineral-insulated coaxial heater cables with an outside stainless-steel jacket of 0.5 mm diameter and an inside conductor of 0.09 mm diameter. Each of them forms over its total length a loop which is soft soldered in the form of a helix around the outside surface of the warm bore. The incoming and the outgoing cable part of each loop must be soldered together as close as possible to avoid formation of

FIGURE 3. Horizontal alignment of a pair of dipole anticryostats on a test bench.

parasitic magnetic fields by the heater loops. Supplied with a maximum current of 1 A and a maximum voltage of 30 V, each heater can either warm up the anticryostat from cryogenic temperatures up to ambient temperature or – the common case during measurement operation – maintain the warm bore at

FIGURE 4. Cross section of an anticryostat with inner and outer spacers

ambient temperature. Each heater can dissipate a maximum of about 2 W/m heater length while the average dissipation during normal operation is around 0.8 W/m for all four heaters in one aperture.

An aluminum ribbon is wrapped around the warm bore and the heaters in order to reduce the emissivity of this surface. Small gaps are left between the turns which help out-gassing during vacuum pumping of the magnet cryostat.

On top of the aluminum ribbon two blankets of multilayer superinsulation (MLI - each has 4 layers separated with net-type sheets) are installed in a way that any gap of the inner layer is covered by the outer one. This guarantees a minimum of heat losses by thermal radiation.

Mainly for reasons of mechanical protection the MLI is then covered by a thin-walled stainless steel tube, the screen. In order to facilitate the assembly, this tube is cut in 700 mm long segments and mounted step by step together with the MLI. The segments are connected end to end in a way that they form a continuous tube over the whole length of the anticryostat. A pin with a diameter of 6 mm is fixed on every eighth tube segment and is kept in place by a U-shaped stopper which is soft soldered previously on the warm bore. This is to avoid a movement of the screen tubes relative to the warm bore due to differential thermal expansion and during the installation in a magnet. A 10 μm silver layer on the inside and outside surface of the tubes reduces their emissivity and improves the thermal behavior of the anticryostat towards the cryogenic installation of the test benches (see “Thermal Behavior” below).

Radial Stability

A good radial stability of the anticryostat relative to the magnet is necessary, in particular for the magnetic axis measurements of the LHC quadrupoles. The spacers on one hand have to center and to stabilize the screen relative to the warm bore and the magnet cold bore during operation and on the other hand to limit the thermal losses due to conduction to a minimum.

An acceptable compromise has been found in using four different shapes of spacers, machined from unfilled polyimide (SintimidTM). The mass of 3.1 kg/m of the measuring shafts as well as 1.4 kg/m (0.7 kg/m for the warm bore, 0.6 kg/m for the screen tubes, rest MLI and heaters) mass of the anticryostat is supported by two inner and two outer “feet” with a spring constant of 50 N/mm each. The small wall thickness of the screen tube (0.5 mm) leads to a deformation of the tube under load and makes the total support weaker. Laboratory tests showed an average spring constant of 35 N/mm on the “feet” fitted onto the screen tube. The resulting weight of the measuring shaft and the anticryostat distributed over the inner and outer “feet” lowers the warm bore by approximately 0.8 mm. For this reason the spacers are designed in a way that they position the warm bore by 0.8 mm above the center of the beam pipe.

The “spring” shaped spacers located on the upper side of the tubes cope with tolerances and additional thickness at welds seams and are not affected by the vertical load. Nevertheless their pushing force towards the beam pipe defines the necessary mounting forces during the

FIGURE 5. Spacers

installation of the anticryostat together with the friction coefficient of the spacers on the beam pipe. A maximum force of about 250 N is applied in the final phase of the introduction in the magnet or at the beginning of the removal phase.

Thermal Retraction

Due to accidental or intentional cooldown of the anticryostats to cryogenic temperatures the warm bore may retract axially by more than 50 mm. For a good control of these movements the warm bore is axially fixed to the cryostat on the downstream side. A flexible bellows allows lateral adjustment of ± 4 mm for a final radial alignment relative to the measuring shafts. The upstream end of the anticryostat forms the “floating” end of the installation and can recover the thermal retraction. Three axially loaded springs with a total applied force of 450 N keep the warm bore under tension at any time and avoid buckling during thermal cycles of the magnet which causes axial movement between the cold bore and the warm bore.

Another axial movement is caused by the thermal retraction of the screen tubes. They adopt an intermediate temperature between the magnet and the anticryostat warm bore which is estimated to be 150 – 180 K. In order to minimize this movement, screens are fixed together in sets of eight and fitted at one end to a stopper on the warm bore. The retraction movement can therefore be limited to a maximum of 15 mm so that the inner spacers cannot damage either the heaters or the MLI.

THERMAL BEHAVIOR

Heat Losses

In addition to the mechanical stability the thermal behavior of the anticryostats is of crucial importance. The heat dissipation towards the cryogenic installation must be reduced to a minimum and no cold spots must appear inside the measuring aperture. Any heat transfer via convection, conduction or radiation therefore needs to be minimized.

As the anticryostat operates in the insulation vacuum of the magnet cryostat, which is of the order of 10^{-7} mbar, the heat transfer via convection can be considered as negligible. The heat losses via conduction are due to the spacers and the way they are mounted on the screen tube. A small contact surface to the warm and cold bore, a poor thermal contact between spacer and tube (spacer is only loosely clipped) and a thermal conductivity of only 0.22 W/m-K of unfilled polyimide reduce to a minimum the losses via conduction. In addition, inner and outer spacers are mounted in a longitudinal distance of 350 mm to each other in order to maximize the conduction length. Laboratory tests [1] show that about 36% of the total heat dissipation at operation temperature are due to conduction via the spacers.

More than 60% of the total losses are due to thermal radiation so that a particular effort has been made on this issue. Apart from a shiny aluminum ribbon (see the Components section above) and the MLI which fills the remaining gap between warm bore and screen, special attention has been given to the outer surface of the screen tube which directly radiates to the magnet cold bore. No MLI could be wrapped around here as the frequent handling and installation would regularly damage it and the only way to improve the heat losses seemed to

be a surface treatment. A series of radiative heat loss measurements have been carried out at the CERN Cryolab [3-7]. These determined that a 10 μm thick silver layer deposited on the outer and inner surfaces of the screen tube reduces the total heat losses of the anticryostat by about 20% at the operation temperature relative to that for non treated tubes.

Finally three different methods have been applied to measure the total heat losses of an anticryostat and to verify the efficiency of the silver coated screen tubes: laboratory measurements of the electrical input power on a mock-up, in situ measurements of the electrical input power as well as cryogenic losses on the test bench. A comparison of the different measurements can be seen in Table 1.

TABLE 1. Comparison Between Different Heat Loss Measurements on a Dipole Anticryostat.

	Laboratory Tests	Electrical Power In-Situ	Cryogenic Losses
Non coated tubes, W/m	0.96	0.91	1.11
Coated tubes, W/m	0.78	0.73	0.83
Difference, W/m	0.18	0.18	0.28
Gain with coating, %	19	20	25

Temperature Controls

The electrical heating system is equipped with a DC power supply which feeds three of the four heaters with a current of up to 1 A; the fourth is used as a temperature gauge. Current and voltage of the gauge are read out by a PLC so that a regulation loop can then maintain or adapt the requested average temperature with respect to a reference. The average temperature of the anticryostat is extracted from the temperature dependent resistance of the Cu-heater of this loop. Temperature and power dissipated in the three heaters are transferred to a supervision system in the control room of the test station.

FIGURE 6. Cold spot in warm bore caused by an inner spacer.

One of the main difficulties of the temperature control is the length of the heaters, in particular those of the anticryostats for dipoles (39 m).

Due to an irregular temperature profile along the warm bore (Figure 7), the electrical resistance is not uniform along the heater

although the power supply sees a “uniform” resistance (and therefore temperature).

In the case of a local cool down of the heater due to a cold spot, the electrical resistance decreases locally.

As the regulation system maintains an average temperature, the resistance then increases in another sector of the heater. Figure 6 shows a small cold spot created by an inner spacer; larger cold spots may appear, i.e., with a broken spacer, when the screen tube would directly touch the magnet cold bore. This dynamic effect may have a negative effect on the magnetic measurement equipment when strong temperature differences or variations appear along the anticryostat during long term measurements. It is therefore of critical importance to limit cold spots to a minimum.

A typical temperature scan along a cryostat aperture on a test bench can be seen in Figure 7. Two different methods have been applied. The first consists in a scan with a PT100 gauge which has been pulled step by step along the warm bore. For the second one the electrical resistance of the magnetic measurement shaft has been used. The shaft is assembled from 13 coil segments, each equipped with three copper windings. After calibration at ambient temperature, these segments can be used as temperature gauges along the anticryostat once it is thermally stabilized. Variations may reach more than 10 degrees. The temperature difference of the two graphs comes from the fact that both measurements were carried out successively. Once the shaft is removed, the PT100 scan was made where the temperature profile of the warm bore had already changed.

It can also be seen that the synchronization of the temperature of the upstream and the downstream ends of the anticryostat may cause difficulties and a careful calibration of the control system is necessary.

FIGURE 7. Typical temperature profile in a warm bore of a dipole

CONCLUSION

A total of nearly 80 anticryostats with lengths between 3 m and 17 m will be necessary in order to be ready for the series tests for the LHC-magnets. In the frame of an industrial contract these anticryostats have to be manufactured, assembled, stored, installed, maintained and operated following the rhythm of the preset measurement program on the test benches.

In spite of the choice of delicate components and tight geometrical and thermal constraints, the selected design proved its performance during the cold tests of the pre-series of the LHC cyodipoles recently achieved. With a frequency of up to two magnets a week and

about 30 anticryostats presently in full operation, a first experience has been developed relative to the handling and installation process as well as the operation on the test benches. This industrially organized activity has identified only few minor problems due to procedures currently under approval rather than to conceptual errors. Some efforts still have to be undertaken to reach a smooth operation sequence without any disturbance to the magnet cold tests.

From an operation point of view the design has shown sufficient mechanical stability. Total heat dissipation from two 16.5 m long dipole and two 2.8 m long CFB type anticryostats of about 25 W represent a satisfactory thermal performance. Careful handling and good maintenance, in particular of the spacers, will help to maintain these results throughout the magnet cold test period.

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