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F. Clari*, O. Dunkel, M. Genet, Ch. Gregory, P. Sievers

Abstract

To allow the measurements of the superconducting LHC magnets up to their nominal field with well-proven, standard techniques, easy access into the apertures is required at ambient temperature and atmospheric pressure. A warm bore anti-cryostat is inserted into the cold bore vacuum pipe of the magnet, where the evacuated radial gap between these two parts serves as thermal insulation. To allow for maximum accessible cross-section during the measurements, the small radial gap of 3.5 mm has to accommodate superinsulation, support spacers and electrical heaters for the thermalization. Design aspects, related to the high magnetic fields, quenches, mechanical loads, vacuum, reliability and ease of handling have to be addressed. The design of the anti-cryostat and the cryogenic test of a prototype model are described. The heat load on the cold mass of the magnet by this prototype was below one watt per meter.

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Prototype Development of a Warm Bore Insert for the LHC Magnet Measurements

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Abstract -To allow the measurements of the superconducting LHC magnets up to their nominal field with well-proven, standard techniques, easy access into the apertures is required at ambient temperature and atmospheric pressure. A warm bore anti-cryostat is inserted into the cold bore vacuum pipe of the magnet, where the evacuated radial gap between these two parts serves as thermal insulation. To allow for maximum accessible cross-section during the measurements, the small radial gap of 3.5 mm has to accommodate superinsulation, support spacers and electrical heaters for the thermalization. Design aspects, related to the high magnetic fields, quenches, mechanical loads, vacuum, reliability and ease of handling have to be addressed. The design of the anti-cryostat and the cryogenic test of a prototype model are described. The heat load on the cold mass of the magnet by this prototype was below one watt per meter.

I. INTRODUCTION

For the magnetic measurements of the LHC dipoles, standard rotating coil techniques will be applied [1]. In order to avoid technical complications, caused by the very long and narrow magnet aperture and in particular by its vacuum chamber kept at liquid helium temperature, a thermally insulated tube is inserted into this cold bore, which allows to perform the magnetic measurements at ambient temperature and pressure along the warm bore of this anti-cryostat [2]. Similar approaches have been adopted previously at FERMILAB and DESY and recently also at SSCL [3].

II. OPERATIONAL CONDITIONS

The anti-cryostat must be designed for maximum free inner diameter, vital for high precision magnetic measurements, while still minimising the heat leak into the 1.8 K liquid helium bath of the magnet. Straightforward estimates indicate that heat leaks through radiation of well below 1.5 W/m should be achieved with the envisaged geometry.

In order not to interfere with high precision magnetic measurements inside the anti-cryostat non magnetic components and in particular low permeability stainless steels have to be used. Clean, inorganic components with low outgassing have to be applied in order to prevent contamination of the cold bore during the magnet test by absorbed gas which later during operation might be desorbed through the synchrotron radiation of the circulating proton beams.

At this moment of time it cannot be excluded that the heat input through the anti-cryostat raises slightly the average temperature of the superconducting coil, which would lead to lower quench levels than during normal operation of the magnet without anti-cryostat. Therefore provision must be made to evacuate temporarily the anti-cryostat, thus cutting all heat input into the magnet which allows quench studies under realistic conditions.

The force F per unit length L acting on the warm bore in its horizontal plane induced during a possible quench of the magnet by eddy currents is given by :

$$F/L = (2R^2 d\rho) \cdot B \cdot dB/dt$$

with R = Radius of the pipe, d = Wall thickness of the pipe, ρ = Specific electrical resistance, B = Magnetic field density, dB/dt = Decay of the magnetic field during the quench. With $R = 17.75$ mm, $d = 0.5$ mm, $\rho = 7 \times 10^{-7} \Omega \text{ m}$ and with a maximum $dB/dt = 70 \text{ T/s}$ at $B = 7 \text{ T}$ [4] a maximum lateral force of 220 N/m will occur. Tests with such force have shown a temporary ovalization of the cross section of the pipe of + 0.98 mm with no residual, plastic deformation thereafter.

III. LAYOUT AND DESIGN

A cross section and a side view of the anti-cryostat are shown in Fig.1 and Fig.2. The warm bore tube with an inner diameter of 35 mm and a wall thickness of 0.5 mm is placed inside the magnet cold bore with an inner diameter of 43 mm, thus leaving a radial insulating vacuum gap of only 3.5 mm. The warm bore consists of a seamless, drawn pipe of non magnetic stainless steel (AISI TYPE 316LN) with a total length of 13 m.

Fig. 1. Cross section of the anti-cryostat inside the cold bore vacuum pipe of the dipole (not to scale).

Fig. 2. Side view of the anti-cryostat.

To maintain the temperature of the warm bore at room temperature while the magnet is cold, three independent, mineral insulated, coaxial, electrical heating cables with an outside stainless steel jacket with a diameter of 0.3 mm are soft soldered onto the outside of this pipe each forming a loop over its total length. With a current of 0.4 A and a voltage of 13 V over each loop a power of 1.5 W/m is dissipated. The same power could, in the limit, be dissipated by only one of the three heaters which provides sufficient redundancy in case of failure of one of the three.

Around the outside of the warm bore and the heaters, shiny aluminium tape is wound which serves to reduce the emissivity of this surface and to distribute the heat supplied by the heating elements uniformly around its circumference. A small gap is left between the turns of the tape to help outgassing and pumping. On top of this Al-tape three layers of perforated aluminised mylar superinsulation are wrapped which thereafter are covered by an auxiliary thin walled stainless steel pipe, the screen. To facilitate assembly it consists of short segments with a length of 650 mm each which are progressively mounted together with the superinsulation. The inner and outer surfaces of each screen are mechanically polished to high brilliance and holes are drilled into it, again to improve outgassing and cryopumping towards the outside cold bore. The segments of the screens are joined together axially by special connecting units (see Fig.3) each fitted with six claws which are locked and secured into holes at each end of each screen.

Fig. 3. Cut through the connecting unit, equipped with the support feet and clamps fitted to the screens on either side.

Fig. 4. Assembly of the anti-cryostat with (from right to left) the screen, the connecting unit, the layers of the superinsulation and Al-tape wrapped around the warm bore.

Fig. 4 shows a photograph of the various layers between the warm bore and the screen with its connecting unit. The warm bore is centered radially within these junction pieces and thus within the screens by three support feet which are placed symmetrically around the circumference of the unit (see Fig.3). They are shaped like spring blades protruding towards the inside and made of low thermal conducting polyimide. Their geometry has to be optimised with respect to their mechanical rigidity and the capability to pick up tolerances in diameter of the warm bore as well as with respect to their thermal resistance.

An additional set of three support feet is mounted on this junction unit which are now oriented towards the outside, thus centering radially the total anti-cryostat within the cold bore. With a global radial spring constant of each support unit of 330 N/mm, a radial displacement of 0.06 mm is expected due to the weight of about 40 N of the magnetic field sensor passing along the warm bore. The total force to pull the anti-cryostat into the magnet is 160 N.

Fig.5. shows the layout of the anti-cryostat inside the magnet test stand. The anti-cryostat consists of one short part with a length of 2 m installed permanently inside the cryogenic supply box on the left side. The other 11 m long part is introduced from the right side through the cold bore of the magnet, which requires for the intermediate junction between the two parts of the warm bore a miniaturised flange. This has an outside diameter of 42 mm, fitted with a metallic gasket, which allows in the limit also the warm bore to cool down to cryogenic temperatures. The warm bore is axially fixed at the right side (see Fig.6) but can laterally, via a flexible bellows, be displaced to align it with respect to the magnet aperture. The opposite end is axially loaded by three springs with a total pulling force of 520 N and a spring constant of 2.5 N/mm to allow for differential thermal expansion between the magnet cryostat and the warm bore, in particular when cooled to cryogenic temperature. Fig.7 shows a photograph of the spring loaded end flange.

IV. MEASUREMENTS ON A PROTOTYPE

A prototype of the anti-cryostat with a reduced length of 6 m has been built and tested in an assembly simulating the geometry of the magnet cold bore, however, at 4.2 K boiling helium temperature. The heat input from the anti-cryostat into the helium bath could readily be measured via the power dissipated in the electrical heaters during the steady state of the warm bore. Fig.8 shows the power per unit length of the anti-cryostat versus the steady state temperature of the warm bore for two types of screens (gold plated:top, mechanically polished:bottom).

Fig. 5. Layout of the magnet test stand fitted with the anti-cryostat (not to scale).

Thus, values of at most 1 W/m can be expected in the final layout of the test stand. Fig.9 shows the temperature measured along the inside surface of the warm bore at a heat input of 1.04 W/m. Cryopumping of the small gaps between the warm and the cold bores along the anti-cryostat should lead to increased vacuum and thus to higher steady state temperatures at its axial center than at its ends, where thermal conduction through rest gas from the "warm" environment at these locations occurs.

The time constant dK/dt of the temperature of the warm bore when after reaching the steady state the heating power is cut, is also significant for the thermal quality of the anti-cryostat. A value of 8.5 K/h has been measured. This allows also in the case of failure of the heating system, sufficient time to intervene before condensation of humidity or formation of ice sets in inside the warm bore. The average temperature along the warm bore can readily be followed via the temperature dependence of the resistance of the copper heating wires. A temperature coefficient of the resistance of about $3.5 \times 10^{-3}/K$ was measured which should allow the monitoring and control of the temperature of the warm bore within a precision of ± 5 K.

V. CONCLUSION

The very tight geometrical constraints imposed on the anti-cryostat and especially on the evacuated thermal insulating gap of only 3.5 mm between the warm bore at 295 K and the cold bore at 1.8 K, required particular effort and high precision for the construction of the anti-cryostat prototype. The selected design proved to comply well with these constraints. Moreover, the heat inleak through this anti-cryostat into the helium bath was well within the expected value of below 1 W/m which still depended significantly on the relatively poor global insulating vacuum in the test set-up. Thus, even lower heat inleaks should be reached with improved vacuum, as expected in the final magnet test stands. The total heat load caused by two anti-cryostats on the cryogenic system of twin-aperture dipoles, 10 m long will thus amount to about 20 W. Clearly, when more radial space for the insulating gap around the anti-cryostat can be made available, as one may expect from the increase of the inner diameters of the superconducting coils from 50 mm to 56 mm, as presently foreseen, this heat load will be substantially reduced.

Fig. 6. Details of the fixed (right side) and axially spring loaded (left side) end flanges of the warm bore.

Fig. 7. Overall view of the axially spring loaded end flange of the warm bore.

Fig. 8. Average heat inleak through the anti-cryostat into the Helium bath versus the steady state temperature of the warm bore for two different types

Fig. 9. Steady state temperature along the warm bore of the anti-cryostat thermalized against the He bath with a power of 1.04 W/m.

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