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ABSTRACT

A sudden loss of insulation vacuum in an accelerator cryomagnet system be it due to a helium leak from a cryogenic circuit or leak from atmosphere has consequences for the cold mass as well as for the vacuum enclosure. The vacuum enclosure for the LHC dipole cryostat is made of carbon steel to reduce costs and to provide magnetic shielding. In the case of a loss of insulation vacuum the vacuum enclosure will be cooled rapidly but must not reach temperatures low enough to cause embrittlement of the wall material.

Helium gas at room temperature was admitted into the insulation space of a modified prototype cryomagnet, the cold mass of which had been previously cooled to 80 K. The evolution of temperature with time of the cold mass and of the vacuum enclosure has been measured and the corresponding heat influx estimated from a simple model.

INTRODUCTION

The Large Hadron Collider (LHC) project, currently under design at CERN ¹ relies on extensive use of high field superconducting magnets operating below 1.9 K in a pressurized bath of helium II.

Superconducting magnet cold masses for accelerators are housed in horizontal cryostats ² which provide mechanical support and limit heat inleaks ³ to a level compatible with the LHC refrigeration capacity.

To limit convective heat transport, under normal operating conditions the outermost cryostat envelope or vacuum enclosure contains an insulation vacuum in the 10^{-4} Pa range. To reduce costs and to shield stray field the current LHC dipole vacuum enclosure design is based on a cylindrical shell 10 mm thick of diameter 1 m by 10 m long in ISO 430 carbon steel.

A sudden loss of insulation vacuum in a cold cryomagnet will cause a rapid increase in convective heat transfer and cooling of the vacuum enclosure wall towards a safety limit defined by the low temperature embrittlement of carbon steels. Loss of insulation vacuum may be due to an air leak from the ambient surroundings or to an internal dry helium leak from a cryogenic circuit. In the first instance rapid formation of an insulating ice layer on the vacuum enclosure and on all internal components will progressively reduce heat transfer to the cold mass. In the second case, only an external insulating frost layer will form. The significantly higher thermal conductivity of helium gas compared to that of air increases the internal heat transfer from the vacuum enclosure to the cold mass and leads to proportionately lower vacuum enclosure wall temperatures.

Following sudden degradation to atmospheric pressure of the insulation vacuum with dry helium gas at room temperature, the evolution of cold mass, helium vessel and vacuum enclosure temperatures with time has been measured on a representative full-scale 10 m-long dipole cryostat.

EQUIPMENT AND TEST PROCEDURES

The T.A.P. cryomagnet ⁴ (Fig. 1a), in common with derivatives currently proposed for LHC, operates under normal conditions at 4 distinct temperature levels: the cold mass at 1.9 K, the inner radiative insulation at 4.5 to 20 K, the thermal screen at 50 to 75 K and the vacuum enclosure at ambient temperature.

Tests were conducted using a simplified version of the T.A.P. cryomagnet reassembled as shown in Fig. 1b. The helium vessel, supported to the vacuum enclosure via its 3 composite support posts, was left uninsulated at each end but was wrapped circumferentially along its entire length with a 30-layer superinsulation blanket. No thermal shield was mounted.

An initial insulation vacuum of around 10^{-2} Pa was pumped which on cooling the cold mass from room temperature to 80 K improved into the 10^{-4} Pa range. Throughout the tests, ambient conditions in still air with a constant relative humidity of 45 % and temperature of 294 K were maintained. About 6 m³ of dry helium gas at room temperature were admitted into the insulation space at an average rate of 13 L.s⁻¹, up to a pressure of 0.115 MPa to compensate the effects of gas cooling. The average cold mass temperature was measured with one platinum resistance thermometer (PRT) placed internally. Six PRT attached to the vacuum enclosure outer wall measured its temperature at the locations indicated in Fig. 2. Additional temperature monitoring was performed with a contact thermometer. Following the admission of helium gas the evolution of cold mass and vacuum enclosure wall temperatures was recorded over a 24 hour period.

MATHEMATICAL MODEL

Basic Assumptions

The evolution with time of heat flux and temperature in the different cryostat components has been simulated with a one-dimensional radial model, shown schematically in Fig. 3. The vacuum enclosure at temperature T₁ receives heat Q₀₁ from the environment at temperature T₀ by natural convection in air and by radiation. The helium vessel at temperature T₂ receives heat Q₁₂ from the vacuum enclosure by convection in the helium gas at 0.1 MPa which was admitted to break the insulation vacuum, as well as by conduction in the helium trapped between superinsulation layers. The cold mass at

Figure 1a. Transverse cross-section of the T.A.P. cryomagnet.

Figure 1b. Transverse cross-section of the test cryomagnet.

1. Cold mass
2. Helium vessel
3. 30 layer superinsulation blanket
4. Vacuum enclosure
5. Support post

temperature T_3 receives heat Q_{23} from the helium vessel by conduction in the static helium gas which fills the helium vessel. No convection can occur in the restricted spaces between superinsulation layers and between the helium vessel and cold mass. This model takes no account of water condensation or ice formation on the outside surface of the vacuum enclosure.

Equations

The heat Q_{01} coming from the environment is the sum of natural convection and radiation where h is the natural convection heat transfer coefficient⁵ and σ is the Stefan-Boltzmann constant.

$$Q_{01} = h \cdot A_1 \cdot (T_0 - T_1) + \sigma \cdot A_1 \cdot (T_0^4 - T_1^4)$$

$$h = 1.3 \cdot \left(\frac{T_0}{D_1} \right)^{0.25}$$

Figure 2. Location of vacuum enclosure temperature measurements.

Figure 3: Heat transfer model scheme.

The heat Q_{12} between the vacuum enclosure and the helium vessel is given by convection in closed volume⁵ and by conduction in helium. The convection in closed volume is determined by the thermal conductivity k , and the convection factor f depending on the Prandtl Pr and Grashof Gr numbers which are functions of the isobaric thermal expansion α , the density ρ and the viscosity η .

$$Q_{12} = \frac{2 \cdot \pi \cdot L \cdot k \left(\frac{T_1 + T_2}{2} \right)}{\left[\frac{1}{f} \cdot \ln \left(\frac{D_1}{D_2 + 2 \cdot e} \right) + \ln \left(\frac{D_2 + 2 \cdot e}{D_2} \right) \right]} \cdot (T_1 - T_2)$$

$$f = 0.18 \cdot [Pr \cdot Gr]^{0.25}$$

The heat Q_{23} between the helium vessel and the cold-mass is given by conduction in helium.

$$Q_{23} = \frac{2 \cdot \pi \cdot L \cdot k \left(\frac{T_2 + T_3}{2} \right)}{\ln \left(\frac{D_2}{D_3} \right)} \cdot (T_2 - T_3)$$

The differential equation system which links the temperatures T_1 , T_2 and T_3 is:

$$\begin{cases} M_1 \cdot C(T_1) \cdot \frac{dT_1}{dt} = Q_{01}(T_1) - Q_{12}(T_1, T_2) \\ M_2 \cdot C(T_2) \cdot \frac{dT_2}{dt} = Q_{12}(T_1, T_2) - Q_{23}(T_2, T_3) \\ M_2 \cdot C(T_3) \cdot \frac{dT_3}{dt} = Q_{23}(T_2, T_3) \end{cases}$$

Results

This system is numerically solved using the Runge-Kutta algorithm. Fig. 4 shows the computed evolution of the different temperatures. For comparison, the measured values are plotted on the same graph (No measurement of the helium vessel temperature T2 is available). Concerning the cold mass temperature T3 the calculated values are in accordance with experiment. Because the model is one-dimensional, it takes no account of the asymmetric heat exchange between the top and the bottom parts of the vacuum enclosure but the calculated values of T1 predict very closely an average of the six temperatures measured. Fig. 5 shows the corresponding calculated heat exchange between the different components. The maximum heat received by the vacuum enclosure is around 8 kW and occurs 3 hours after the insulation vacuum is broken. The maximum heat flux received by the cold mass is around 8.3 kW and occurs after 1 hour. The heat flux received by the helium vessel has its maximum of 15 kW at the beginning.

VISUAL OBSERVATIONS

From the time of helium admission, condensation first appeared on the underside of the vacuum enclosure after about 20 minutes and frost formation followed after about 35 minutes. Frost formation continued spreading upwards around the vacuum enclosure from the underside to cover a maximum 70 % of the circumference after 6 hours and from this point a gradual melting from the top down began. Frost growth up to a maximum thickness of about 3 mm after about 3 hours was measured at the location of the lowest vacuum enclosure temperatures and the thickness then remained approximately stable until the onset of melting.

Figure 4: Calculated and measured temperature evolution.

Figure 5: Calculated heat exchange between environment, vacuum enclosure, helium vessel and cold-mass.

CONCLUSIONS

The effects of an abrupt loss of vacuum on a full-scale accelerator cryomagnet initially at 80 K with only one 30-layer superinsulation blanket directly wrapped onto the helium vessel have been studied. A simple mathematical model adequately predicts an average of the temperature evolution with time of the vacuum enclosure. Unaccounted for in this model, the external formation of an ice layer in the quantities described does not significantly affect the rate of heat transfer across the vacuum enclosure wall.

A simple model of this kind can be used to predict the behaviour of the LHC machine cryostats after a sudden loss of insulation vacuum.

It can be concluded that the minimum temperature of 260 K attained by the vacuum enclosure wall is well above the limit generally accepted for carbon steel embrittlement. Its temperature evolution, initially of about 35 K.h^{-1} , is not considered catastrophic and leaves sufficient time to render equipment safe within the scope of normal accelerator operations. Moreover, the heating power received by the cold mass is small as compared to that dissipated after a magnet resistive transition, and its consequences can therefore be easily handled by quench discharge devices.

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