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Supercritical Helium Cooling of the LHC Beam Screens

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Abstract

The cold mass of the LHC superconducting magnets, operating in pressurised superfluid helium at 1.9 K, must be shielded from the dynamic heat loads induced by the circulating particle beams, by means of beam screens maintained at higher temperature. The beam screens are cooled between 5 and 20 K by forced flow of weakly supercritical helium, a solution which avoids two-phase flow in the long, narrow cooling channels, but still presents a potential risk of thermohydraulic instabilities. This problem has been studied by theoretical modelling and experiments performed on a full-scale dedicated test loop.

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1 INTRODUCTION

The high-energy, high-intensity proton beams of the future Large Hadron Collider (LHC), a superconducting accelerator cooled by superfluid helium at 1.9 K, presently under construction at CERN [1], will induce heat loads into the cryogenic system through several mechanisms: synchrotron radiation from bending magnets, heating produced by image currents in the resistive wall and effective impedance due to changes in cross-section of the beam channels, loss of stray particles from the beam halo, inelastic scattering by residual gas molecules, acceleration of photoemitted electrons by the beam electrical field. In view of the large thermodynamic cost of refrigeration at 1.9 K, it is advisable to intercept the largest possible fraction of the beam-induced heat loads on a beam screen, cooled by forced flow of supercritical helium between 4.6 and 20 K. The beam screen also acts as an intermediate-temperature baffle for the efficient cryopump constituted by the 1.9 K surface of the magnet cold bore, thus preventing desorption of the trapped gas molecules and avoiding breakdown of the beam vacuum [2].

After recalling the operating constraints of the beam screen, in terms of heat loads and temperature range, we present the cooling scheme and hydraulic design retained. The use of weakly supercritical helium flowing in long, parallel narrow channels with an aspect ration of 10^4, creates a risk of flow instabilities, which were carefully studied by theoretical modelling and confirmed by experiments on a full-scale thermohydraulic test loop.

2 HEAT LOADS AND OPERATING TEMPERATURE

The heat loads deposited in the beam screens by synchrotron radiation, resistive heating and photoelectrons, depend strongly on the energy E and intensity Ib of the circulating beams. Thermodynamic considerations favour the operation of the beam screens at a temperature well above the 1.9 K of the magnets. However, in order to limit the resistive heating, as well as the residual conductive and radiative heat inleaks to the 1.9 K cold mass, the beam screens must operate at temperature below about 30 K. Moreover, the operating temperature must match the available interfaces at the existing cryogenic plants. Table 1 gives the heat loads in “nominal” (E = 7 TeV and Ib = 0.536 A) and “ultimate” (E = 7 TeV and Ib = 0.848 A) conditions and their dependence on beam parameters.

Table 1 Heat loads in “nominal” and “ultimate” operating conditions (per aperture)

	Dependence		Average per cell [W/m]		Peak value [W/m]	
	E	Ib	Nominal	Ultimate	Nominal	Ultimate
Synchrotron radiation	E^4	Ib	0.164	0.260	0.206	0.326
Resistive heating	-	Ib^2	0.200	0.502	0.200	0.502
Photoelectrons	-	Ib^3	0.094	0.371	0.500	1.98

3 COOLING SCHEME AND HYDRAULIC DESIGN

The heat loads are extracted by a non-isothermal cooling loop operating between 4.6 K and 20 K, which reduces by a factor 8 the entropic cost with respect to 1.9 K isothermal cooling. This cooling range has been imposed by the availability of interface conditions of existing cryoplants, which will be reused for the production and distribution of the refrigeration. Due to very little space in the magnet aperture, long narrow cooling channels in parallel [3] are required. Figure 1 shows the transverse cross-section of the beam screen. Weakly supercritical helium is used to avoid potential problems of two-phase cooling. A valve controls the outlet temperature of the beam screen circuits. Figure 2 shows the beam screen cooling scheme and the pressure vs. enthalpy diagram with the working line in “ultimate” conditions, which avoids crossing the two-phase dome, however not far above the critical point. Such a loop is subject to control difficulties and risks of instabilities, because of :

- several circuits in parallel controlled by a single valve,
- long cooling loop (53 m) giving a relativly long time response (about one minute),
- strongly varying properties of helium close to the critical point.

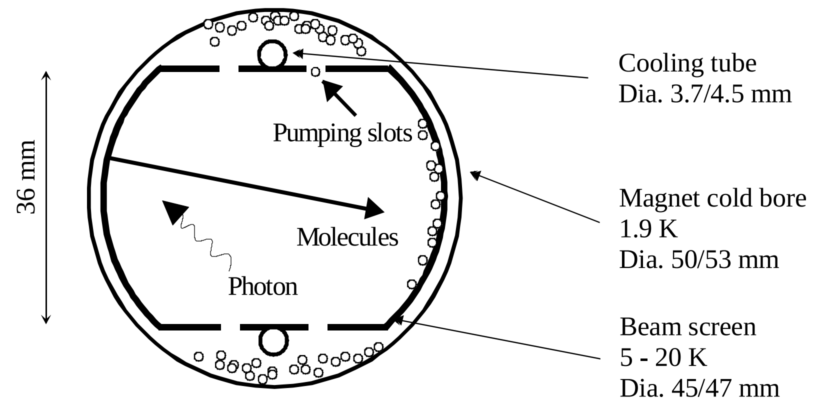
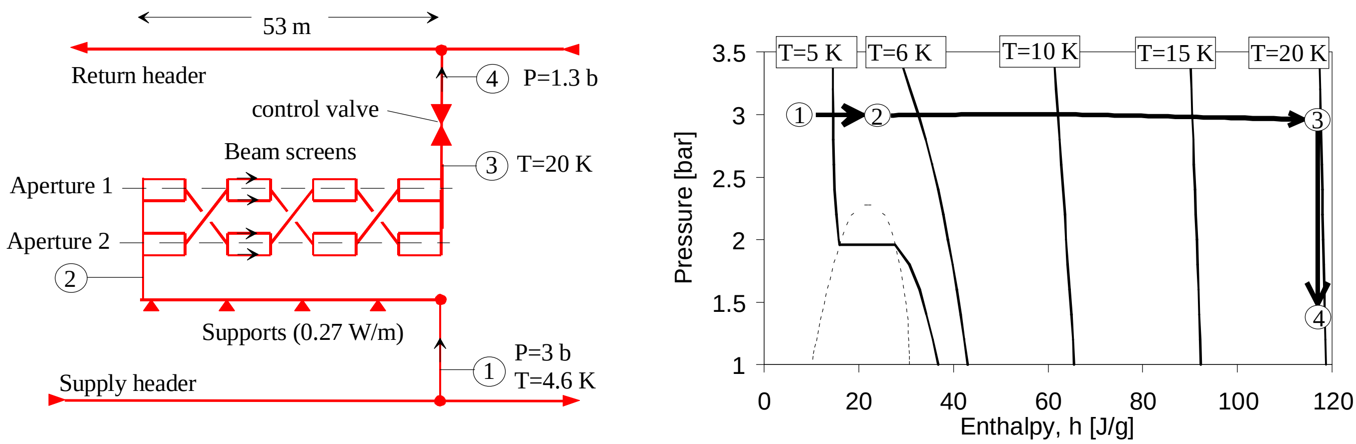


Figure 1 Transverse cross-section of beam screen



a) Cooling scheme

b) Working line on P-h diagram

Figure 2 Beam screen cooling

4 RISK OF THERMOHYDRAULIC INSTABILITIES

The properties of supercritical helium are quantitatively similar, within the pressure and temperature range of interest, to those of ordinary fluids in the neighbourhood of their respective critical points. Specific heat, compressibility and ratio of specific heats increase as the critical point is approached, while sound velocity and thermal diffusivity vanish [4]. However, as the state of the fluid gets some distance away from the critical point, it behaves much like a pure liquid or an ideal gas. Therefore, the equation of state can be approximated by two straight lines on a volume vs. enthalpy diagram as shown in Figure 3.

Model

This work examines the unidirectional propagation of a thermal pulse along the channel under a uniform heat flux. The dynamic state of the fluid in the test section can be described as follows.

Mass conservation $$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}=0$$

Energy conservation $$\frac{\partial h}{\partial t}+u\frac{\partial h}{\partial x}=\frac{\dot{Q}}{\rho}$$

Momentum conservation $$-\frac{\partial P}{\partial x}=\underbrace{\rho\frac{\partial u}{\partial t}+\rho u\frac{\partial u}{\partial x}}_{acceleration}+\underbrace{\frac{f}{2D}\rho u^2}_{friction}$$

Equation of state $$v=f(h,P)$$

Where D is the diameter, f the friction factor, x the length, $\dot{Q}$ the total heat load, u the velocity, ρ the density and v the specific volume.

The procedure adopted is to superimpose on a steady inlet velocity, a time-dependent velocity variation and then linearise the equation of flow [5]. The stability of the pertubated system is analysed by studying the variations of its transfer function. The mechanism of the density-wave oscillations is as follows : inlet flow fluctuations create enthalpy perturbations in the “quasi-liquid” region. When these reach the “change-of-density” boundary they are transformed into void-fraction perturbations that travel with the flow along the channel, creating a dynamic oscillation in the “quasi-gas” region. With correct timing, the perturbation can acquire appropriate phase and become self-sustained.
A list of factors influencing stability, developed from the parametric analysis, is given in Table 2.

Table 2 Factors influencing stability

Stabilising	Destabilising
Increase of tube diameter	Subcooling of inlet temperature
Increase of pressure level	Restriction at tube outlet
Increase of mass flow	Increase of tube length

Experiment

We fabricated a 53-m test section which reproduces one of the cooling tubes. The operating range in this experiment is P between 2 and 4 bar, T between 4.5 and 25 K with a flow-rate ranging from 0.1 to 1.5 g/s. Pressure and temperature were measured at the inlet and the outlet positions of the test section with pressure transmitters at ambient temperature and Cernox™ resistance thermometers, respectively. Compressed helium gas is precooled by two heat exchangers, and its temperature stabilised near 5 K by a liquid bath heat exchanger. Heat is deposited in the stainless-steel tube by direct Joule heating. Proportional-integral-differential (PID) controllers are installed in order to adjust the inlet and outlet temperatures. The inlet pressure is adjusted by a mechanical pressure regulator.

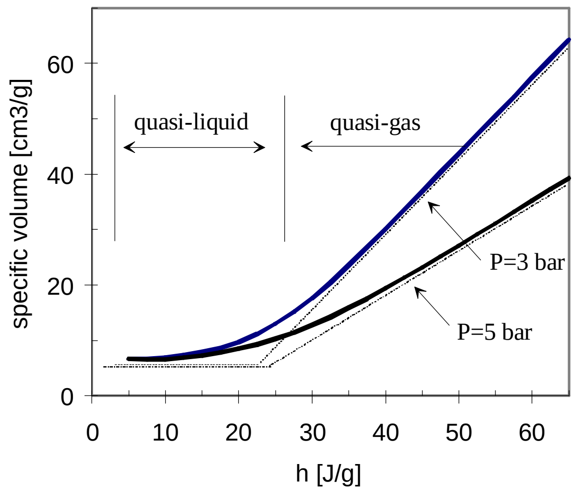


Figure 3 Volume vs. enthalpy of supercritical helium

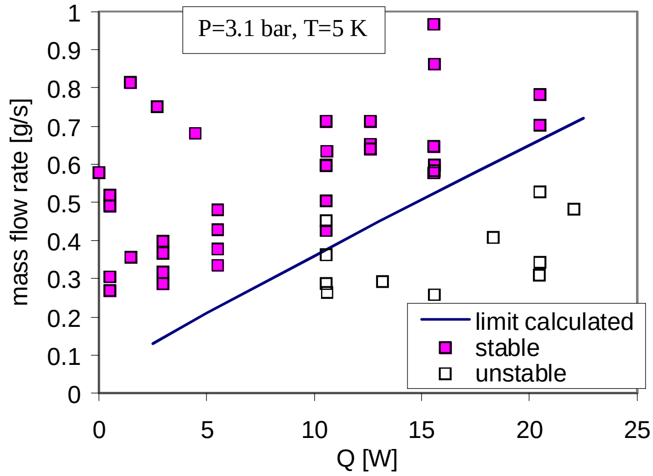


Figure 4 Stability domain and experimental points

Results

Data from several experimental runs are plotted on Figure 4. It appears that the predictive power of the model for the stability domain is correct. The unstable points correspond to oscillations with a period between 1 and 5 minutes. The experimental data also shows that increasing the inlet temperature increases the domain of stability.

5 CONCLUSIONS AND FURTHER WORK

The supercritical helium cooling scheme of the LHC beam screens has been validated - in steady state operation - on a full-scale geometry. Both theory and experiment have revealed the risk of flow instability by density wave oscillations, depending upon circuit geometry, applied heat load, and fluid inlet conditions, and the possible cures to the problem. First attempts have been made at controlling the beam screen temperature under application of strongly varying heat loads. This will be the subject of ongoing studies and further experimental work.

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