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He leaks in the CERN LHC beam vacuum chambers operating at cryogenic temperatures

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Abstract

The 27 km long large hadron collider (LHC), currently under construction at CERN, will collide protons beam at 14 TeV in the centre of mass. In the 8 arcs, the superconducting dipoles and quadrupoles of the FODO cells operate with superfluid He at 1.9 K. In the 8 long straight sections, the cold bores of the superconducting magnets are held at 1.9 or 4.5 K. Thus, in the LHC, ~75% of the beam tube vacuum chamber is cooled with He.

In many areas of the machine, He leaks could appear in the beam tube. At cryogenic temperature, the gas condenses onto the cold bores or beam screens, and interacts with the circulating beam. He leaks creates a He front propagating along the vacuum chambers, which might cause magnet quench.

We discuss the consequences of He leaks, the possible means of detections, the strategies to localise them and the methods to measure their size.

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1. Introduction

The LHC-beam vacuum system is built with vacuum chambers operating at room temperature or cryogenic temperature. Despite all the precautions taken during the design and the construction of the vacuum system, some leaks could appear before or during beam operation.

Most of the room temperature vacuum chambers will be coated by a TiZrV getter layer. These vacuum chambers are located in the long straight sections around the interaction regions. The air-leak detection will be performed by well-mastered techniques.

The remaining part of the LHC, i.e. the arcs and some elements in the long straight section operate at 1.9 or 4.5 K. The occurrence of He leaks in a cryosorbing environment implies a potential condensation of gas, in the vicinity of the leak, before any possible detection. During operation, the leaks could create local pressure bumps associated with background to the experiments or activation of the machine elements or could even quench a superconducting magnet.

A quench occurs when too many protons are locally lost in a cold mass. In the presence of a leak, the nuclear scattering of the proton beam (60% of the total cross section) on the He molecules leads to a significant amount of proton loss in the cold mass [1]. These protons are lost into the cold mass by inelastic scattering within 10 m. At 450 GeV, a total number of 7×10^8 protons/m/s lost in the cold mass is sufficient to provoke a quench. This number reduces to 8×10^6 protons/m/s at 7 TeV [2]. For comparison with the design beam life time, the proton loss rate around the ring due to the nuclear scattering on the residual gas is 3×10^4 protons/m/s. A quench is triggered when the dissipated energy in the cold mass is 51 and 9 W/m at 450 GeV and 7 TeV, respectively. The difference comes from a wider particle shower required to trigger a magnet quench at 450 GeV than at 7 TeV.

Taking into account the total nuclear scattering cross-section, an average He density over 1 m below

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1.7×10^{17} He/m^3 will avoid the magnet quench at 7 TeV. This gas density is equivalent to 5.6×10^{-5} Pa when measured at room temperature.

At injection energy, the total nuclear scattering cross-section decreases. The average He density increases to 1.8×10^{19} He/m^3. At injection, the performance limitation will come from the cold masses cooling capacity.

In this paper, all the pressure at cryogenic temperature are given as if they were measured at room temperature, i.e. the thermal transpiration correction from cryogenic to room temperature is included.

2. He leaks

During the beam screen design phase, special attention was paid to avoid full penetrating welds between the He vessel and the beam vacuum. All the beam screens will be tested for leaks, at cryogenic temperature before insertion into the cold bores. Nevertheless, He leaks could appear along the beam screen cooling capillaries or at defect welds of the cold bore.

In the case of an He leak, an He wave develops with time along the beam vacuum chamber [3]. The He condenses onto the 1.9 K surface up to a monolayer. For larger surface coverage, the He pressure increases to the saturated vapour pressure (2261 Pa). With time, the He accumulates and the He wave can span over several tens of metres before being detected.

A model of the He propagation wave has been developed for the design of the relativistic heavy ions collider (RHIC) and is used here [3]. This model was validated in a dedicated experiment performed with an LHC-type cold bore held at 1.9 K [4]. This model is used to compute the average He density 1 m around a leak.

Fig. 1 shows, in case of a leak, a typical evolution with time of the He pressure along the cold bore axis. The He leak is located at $x = 0$. At $t = 0$, the pressure at the leak, P_{XF}, is simply defined by the ratio of the leak rate, Q, to the cold bore's aperture pumping speed. As time goes, the cold bore saturates with He and the effective pumping speed at the level of the leak is decreased. As a result, the pressure at the leak is increasing. At the front of the leak, the pressure equals P_{XF}. The pressure profile along the cold bore is linear. At $t1$, the pressure at the level of the leak equals $P_{0,t1}$ and the pressure at the level of the front ($x = X_{\mathrm{F}}(t1)$) is P_{XF}. At larger time, $t2$, the pressure at the level of the leak has increased, and the He wave is arrived at $X_{\mathrm{F}}(t2)$.

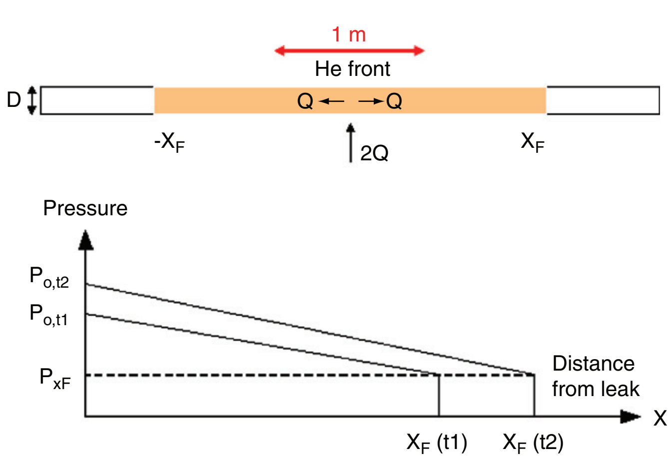

Fig. 1. Evolution of the He pressure with time along the cold bore axis.

3. Consequences

The main consequence of an He leak is the magnet quench. In the 2.5 km long arcs, the cold bores operate at 1.9 K. Fig. 2 shows the required time in the presence of a leak to provoke a magnet quench at 7 TeV as a function of the leak rate for 1/10 of nominal beam current (1st year of operation), 1/3 of nominal beam current (operation without electron cloud) and nominal beam current. The He leak rate is given at 300 K. This is twice the leak rate one would measure at room temperature with a leak detector located at a pumping port in the presence of the pressure front. A year of operation is defined as 150 days and we assume that the He could be evacuated at each shutdown. Low leak rates require, every year, a pumping of the beam tube with the cold bore held at more than 4 K. Large leak rates provoke a magnet quench. For instance, a magnet quench is provoked within 12 h for a He leak rate of 10^{-3} Pa l/s at nominal beam current, or for 4×10^{-3} Pa l/s at 1/10 of nominal beam current.

In the long straight section, some elements operate with a cold bore at 4.5 K. Since the equilibrium pressure is much higher at 4.5 K than that at 1.9 K, the He front speed is larger at 4.5 K. Therefore the tolerable leak rate is reduced, i.e. the curves of Fig. 2 are shifted towards lower leak rates. However, to trigger a quench, the length of the He pressure front shall be much longer than the length of the 4.5 K cold bores (40 m maximum).

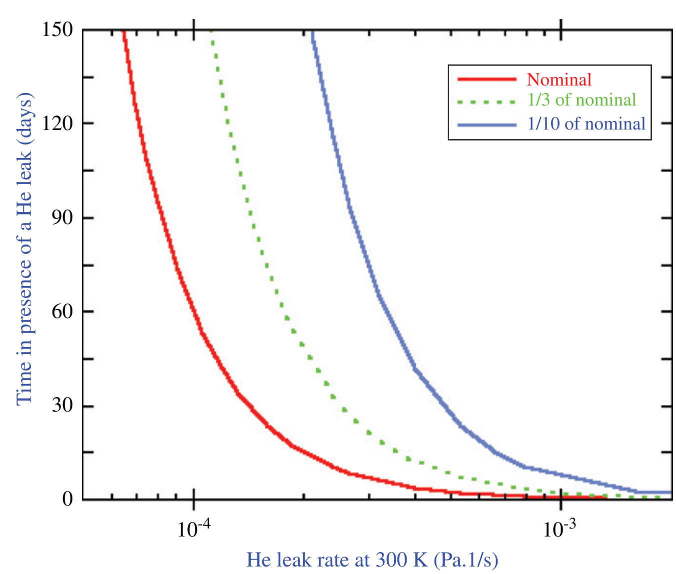

Fig. 2. Required time in the presence of a leak to provoke a quench at 7 TeV, as a function of the He leak rate.