LEAK TIGHTNESS OF LHC COLD VACUUM SYSTEMS

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Abstract

The cold vacuum systems of the LHC machine have been in operation since 2008. While a number of acceptable helium leaks were known to exist prior to cool down and have not significantly evolved over the last years, several new leaks have occurred which required immediate repair activities or mitigating solutions to permit operation of the LHC. The LHC vacuum system is described together with a summary and timetable of known air and helium leaks and their impact on the functioning of the cryogenic and vacuum systems. Where leaks have been investigated and repaired, the cause and failure mechanism is described. We elaborate the mitigating solutions that have been implemented to avoid degradation of known leaks and minimize their impact on cryogenic operation and LHC availability, and finally a recall of the consolidation program to be implemented in the next LHC shutdown.

INTRODUCTION

Beam and insulation vacua of the 27 km circumference LHC are the largest of their type in the World, 22km being equipped with superconducting magnets. The integrated length of the cold helium circuits housed within the cryostats, and interfacing with the beam and insulation vacua, is over 500 km.

Adequate helium tightness is essential for both systems; for beam vacuum to ensure beam life time and avoid magnet quenches due to localised proton losses, and for insulation vacuum to minimise heat in-leaks by residual gas conduction.

The cold beam vacuum system was designed and constructed using the principle of no helium-to-beam vacuum joints of any kind (welds, brazes, clamping, etc). Many welds were exported to the insulation vacuum. The extensive QA programme included thermal cycling and combined leak testing of all beam vacuum components and subassemblies prior to their installation in the tunnel. The in-tunnel assembly works were hence restricted to beam vacuum-to-insulation vacuum joints, helium-to-insulation vacuum joints and atmosphere-to-insulation vacuum joints. This philosophy has been very effective, and with the exception of one helium-to-beam vacuum leak in a beam screen cooling capillary, found prior to the first cool down in December 2007, no other helium-to-beam vacuum leaks have been identified.

For the insulation vacuum, the number of in-tunnel welds was minimised, and all assemblies were fully leak tested prior to installation. However, thermal cycling of a 3 km arc was not possible as part of the QA programme. The LHC operates today with a number of tolerable helium leaks in the insulation vacuum, some of which were known prior to the first cool down and others which have developed.

INSULATION VACUUM OVERVIEW

The main characteristics of the insulation vacuum are shown in Table 1. The continuous cryostats of the arc magnets and helium distribution line (QRL) are sectorised with so-called vacuum barriers at 214m and 428 m intervals respectively. Additionally, each cryogenic connection between all superconducting magnets and the QRL, the so-called jumper, is also equipped with a vacuum barrier. The insulation vacuum of the LHC is hence sectorised into 234 subsectors. Each subsector is permanently equipped with total pressure gauges, turbomolecular pumping group, pressure relief valves, and valves to connect temporary equipment such as mobile pumping groups and leak detectors. The configuration of pumping groups and valves at the longitudinal vacuum barriers allows interconnection or isolation of subsectors.

Table 1: Characteristics of the LHC Insulation Vacuum

Characteristic	Quantity for LHC machine
Insulation vacuum system length	22,4 km
Welds	~ 250 000 (100 000 in-situ)
Weld length	~ 100 000 m
Elastomer joints	~ 18000
Elastomer joint length	~ 22 000 m
Multi-layer insulation	~ 450 000 m^2 or 200 m^2/m of cryostat
Vacuum subsectors	234
Vacuum subsector length	214 m (magnets) & 428 m (QRL)
Vacuum subsector volume	~ 80 m^3
Fixed turbo pumps	178
Nominal turbo pumping speed	0,25 l/s/m of cryostat
Fixed vacuum gauges	974
Mobile turbo pumping groups	36
Mobile primary pumping groups	36
Pumping ports for mobiles	484

TIGHTNESS CONSIDERATIONS

All gas species in the insulation vacuum have a very low vapour pressure below 4.2 K except for helium. Typical operational pressures in the LHC cryostats are < 1 E-6 mbar, measured by total pressure gauges mounted on the room temperature vacuum vessels. The pressure reading represents equilibrium between the thermal outgassing rate of the cryostat components, the very high pumping speed of the cryogenic surfaces, but the limited conductance to those surfaces via the multilayer insulation (MLI) blankets. During a typical cool down, following evacuation with primary and turbo pumps, the equilibrium pressure drops significantly at 200 K (H_2O) and 50 K (air components N_2, O_2, Ar).

Under nominal conditions, heat in-leaks to cryogenic surfaces are dominated by radiative effects. However, the heat in-leaks rise dramatically with a degraded vacuum. LHC cryoplant & cryostat design are based on a helium degraded vacuum up to 1 E-4 mbar.

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Significant quantities of helium can be cryosorbed on cold surfaces at liquid helium (LHe) temperatures. Each 214 m insulation vacuum subsector can cryosorb ~ 100 mbar.l of He at the equilibrium pressure of 1 E-4 mbar. Considering 200 days of continuous LHC operation, without any turbo pumping on the vacuum subsector, 100 mbar.l is accumulated with a continuous cold helium leak rate of 5.0 E-6 mbar.l/s. This value was used to determine the acceptable room temperature leak rates of all LHC assemblies and subassemblies taking into account that leak fluxes may theoretically increase up to 10^3 between RT and LHe (density and viscosity effects without geometrical changes). The RT acceptance criterion for all cryogenic circuitry, prior to installation, was therefore < 1 E-9 mbar.l/s.

LEAK OBSERVATIONS

During the installation and subsequent RT testing of the LHC, many leaks were identified and eliminated. However, the LHC operates today with a number of known but tolerable helium leaks in the insulation vacuum.
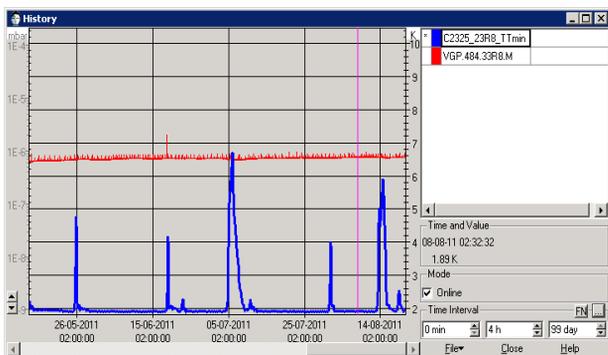

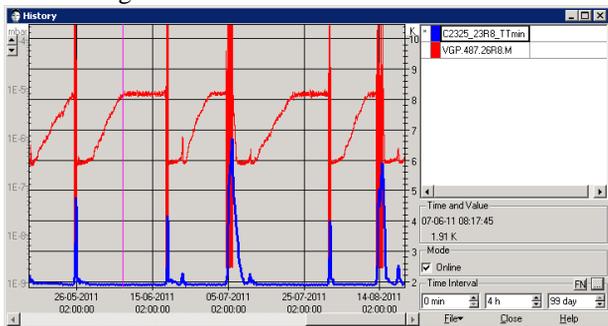Figure 1: Subsector with no helium leak

Figure 2: Subsector with a large helium leak.

The above figures illustrate different leaks in the insulation vacuum, and show total pressure and cold mass temperature fluctuations. Helium is cryosorbed on the 1.9 K surfaces and the pressure would continue to rise up to the saturated vapour pressure of 18 mbar. However, continuous operation of the turbo ensures a much lower equilibrium pressure. Small increases in cold mass temperature liberate the cryosorbed gas. With large leaks the insulation vacuum pressure rises several orders of magnitude during these temperature fluctuations. Turbo pumps remove the helium from the volume and the cold

surfaces are effectively regenerated. However, these large pressure rises produce big increases in heat in-leaks, and the cryogenics operation team have implemented procedures to minimize their impact on system recovery.

Large leaks are isolated at the subsector boundaries to stop propagation to neighbouring subsectors. The equilibrium pressure is used to monitor the evolution of large leaks.

In summary, there are fourteen helium leaks where equilibrium pressure is maintained with the turbomolecular pump and 8 which create significant pressure fluctuations at temperature transients. Two of the large leaks are in the E-2 mbar.l/s range, and the equilibrium pressure is at the 1 E-4 mbar limit for cryogenic operations. Four leak failures occurred on flexible hoses of arc electrical feed boxes (DFBA) and had to be repaired immediately by re-warming the subsectors.

In cases where helium leaks had been measured prior to cool down, the equilibrium pressure at saturation can be used to estimate the increase in leak magnitude under cold conditions. The limited data give values between 100 and 7000.

LEAK MITIGATION

Each insulation vacuum volume is equipped with a permanently installed turbomolecular pump. With conforming leak tightness, the turbomolecular pumps are redundant during steady state LHC operation. However, with large leaks that saturate the cold surfaces or smaller leaks that create a pressure rise due to a temperature fluctuation, pump operation is essential.

The initial reliability of the turbomolecular was very poor. Many bearing failures occurred prematurely due to long-term storage prior to use and subsequent maintenance errors. These issues are now understood and preventive maintenance is strictly followed at 2 or 4 year intervals depending on the pump model.

Figure 3: Additional turbo pump mounting on magnetically coupled flanges.

During the conceptual design of the LHC cryostats, special valves & ports were developed with magnetically

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coupled low cost flanges. These additional DN100 ports, initially foreseen for leak detection, can be used to mount additional turbomolecular pumps in subsectors with large leaks, without breaking the insulation vacuum. These high conductance connections allow a 3 fold increase in helium pumping speed, and have avoided re-warming the LHC sectors 3-4 and 4-5. At these critical leak positions, the turbomolecular pumps are powered on diesel secured electrical power supplies. To avoid mechanical stress cycles at the leak location, temperature fluctuation above 80 K are avoided, and pressure cycles within the helium volumes are limited (early opening of cryogenic quench valves). The vacuum control system generates alarm messages (email and SMS) to system experts incase of turbo pump or insulation vacuum pressure anomalies. These known leaks will be localize and repaired in the next long shutdown

Access to the LHC tunnel is excluded during machine operation. There are many hundreds of turbomolecular pumping systems, and despite the preventive maintenance schedule, random failures can and do occur. The turbomolecular pumping systems include redundancy to avoid disturbance of LHC operation. Based upon operational experience, consolidation will be made in 2013 to complete missing redundancy at QRL extremities and in the 3 arcs which were not re-warmed following the incident of 2008.

LEAK CAUSES & EXAMPLES

Several RT leak failures due to liquid metal embrittlement (LME) were confirmed and repaired during LHC installation. Foreign metals were found to be present in the weld bath (Cu, Ag). Other welding weaknesses, for example inclusions, root porosity or poor penetration remain vulnerable to the induced stresses and strains during cool down and warm-up. The LHC operates with a large helium leak in a machine sub-sector of arc 3-4. The leak appeared during the second cool down of the zone.
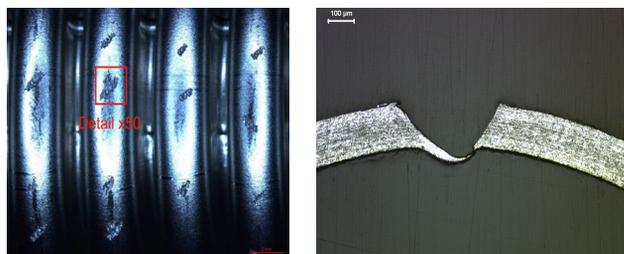

Figure 4: Metal hose with damage convolution summits.

Four large leaks have occurred at identical metal hoses which were exposed to helium flow conditions above their specification. Ultrasonic vibrations created local impacts and welding at multiple points between the undulation summits and braid. All four leaking hoses have been replaced. All the hoses exposed to high flow condition will be replaced in the next long shutdown, and cool down procedures have been adapted.
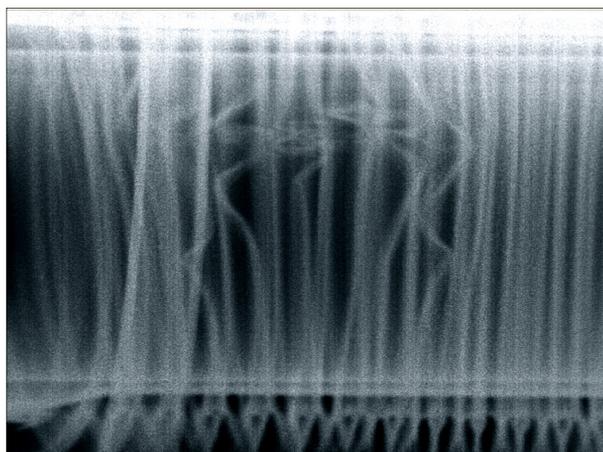

Figure 5: Damaged convolutions in a QRL bellows.

During the programmed LHC stoppage in December 2010, a large pressure rise was observed in a vacuum subsector of the QRL 4-5 due to a suspected air leak. Upon restart of cryogenic operations a large helium leak was also present. X-ray examination of an internal bellows shows abnormal deformation of several convolutions. It is suspected that solidified air blocked the undulation movement and damaged the bellows. The helium leak is now pumped with additional turbomolecular pumps.

During the same stoppage, the vacuum pressure in several other insulation vacuum subsectors rose sharply above 30 K, again due to suspected air leaks. These pressure rises in the mbar range were outside the operating range of the turbomolecular pumps and mobile primary pumps had to be employed. With the LHC in continuous cold operation their origin and elimination cannot yet be investigated.

CONCLUSION

The LHC cold vacuum systems are unparalleled in complexity. Adequate leak tightness has enabled full exploitation of the LHC. Decisions taken in the conceptual design, manufacturing, installation and testing of the cold beam and insulation vacua have led to today's excellent performance. A number of stable tolerable helium leaks are contained with reliable and redundant turbomolecular pumps. Several mitating solutions have been implemented to minimise leak impact and degradation. Operational experience has identified areas where pumping redundancy is missing. The next long shutdown will be the used to implement necessary improvements and eliminate existing leaks and weaknesses.

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