LHC VACUUM SYSTEM: 2012 REVIEW AND 2014 OUTLOOK*

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Abstract

During 2012 only a few beam dumps were attributed to vacuum sector valve closures and the vacuum surface and coating group was involved in only two urgent interventions that kept the beam off for less than two days each. In this paper the pressure threshold policy adopted since the beginning of the LHC running is examined in terms of beam vacuum performances and beam dumps. The so-called "pressure spikes" detected during these years are treated and correlated with the cryogenic temperature, the beam pipe dimensions and non-conformities. A review of the standard and special interventions performed on the beam pipe during technical stops and shutdowns is given, with a list of the main characteristics and foreseen outcomes. Finally, the vacuum expectations during LHC nominal runs, that will follow the LHC consolidations during the Long Shutdown 1 (LS1), are discussed.

INTRODUCTION

The 50 ns scrubbing run and the five 25 ns (Machine Development) MDs performed in 2011 made the 2012 LHC dynamic vacuum negligible compared to the previous years. The reduction of the secondary electron yield well below the buildup threshold for 50 ns was observed all around the machine except where the sectors were opened to air during the winter technical stop. In 2012, 17 beam dumps were attributed to vacuum sector valve closures and this gave a total turnaround time (the time to get back to injection) of 52 hours. The 2012 LHC operation challenged the vacuum surface and coating group with two urgent interventions that made it necessary to stop the beam, however it was only for less than two days each time: the removal of the Longitudinal and Transverse Synchrotron Light Monitors (BSRT) and Wire Scanner Profile Monitor (BWS) in point 4.

In the context of the LHC operation request to reduce the beam downtime during urgent intervention and to minimize the number of technical stops that cause subsequent long recovery time, this paper focuses on the impact that the vacuum interlocks and interventions may have on the beam operation.

The strategy used by the vacuum, surface and coating group to protect the vacuum integrity of the LHC is described. A detailed description of the vacuum recovery after mechanical intervention and the procedure adopted during the years to minimize the beam downtime is given.

Based on the experience acquired during three years of LHC operation (2010-2012), this paper discusses the vacuum expectations and the major concerns for the 2015 LHC operation that will follow its consolidation during the Long Shutdown 1.

VACUUM INTEGRITY PROTECTION

The LHC beam vacuum system is divided into 230 sectors of varying length. The sectorisation strategy focused first on the arcs and standalone magnets, then the experimental areas and delicate equipment. The sector definition was a compromise between the safety and operational requirements, the costs and the ring complexity. The power limitation for bake-out and the reduction of potential intervention in high radiation area was taken into account in order to determine the sector valve position [1,2].

To protect the beam pipe from any possible sudden air venting, to minimize the propagation of the effect of a leak and finally to reduce the beam downtime, the 353 vacuum sector valves installed in the LHC are triggered to closure, by gauges and ion pumps, when the detected pressure rises above the interlock pressure limit.

The vacuum interlocks are set with different purpose for the warm and cold vacuum system.

On warm vacuum system, where the leak opening can saturate several NEG chambers, the vacuum interlocks are set to reduce the recovery time determined by the bake-out and NEG vacuum activation procedure.

On the cold vacuum system, the valve closure in case of pressure rises, minimizes the gas contamination of the beam screen and it avoids the need of a magnet warm-up.

The valve closing time varies from 0.5 to 1.1 s. This doesn't include the 300 ms integration time of a penning gauge due to its controller Pfeiffer TPG300 [3].

The pressure interlock threshold value, valid for most of the sector valves in the LHC is 4×10^{-7} mbar (N_2 equivalent).

This value is lower than the pressure value corresponding to 1.7×10^{17} He molec./m^3 that is the estimated gas density over 1m to induce a quench at 7TeV in the LHC superconducting magnet (7×10^8 protons/m/s lost in the cold mass).

The interlock threshold is obviously higher than 1×10^{15} H_2 molec/m^3 that is the maximum gas density allowed in the arcs to grant 100h beam lifetime.

Below this limit the vacuum beam lifetime remains always negligible compared to other beam lifetime factors. That is why the 100 hour limit was chosen.

The sector valve opening is interlocked as well and a lower threshold has been set to 1×10^{-7} mbar. When the pressure goes below this value on both sides of the sector valve, it is possible to open it and connect the two sectors. The lower threshold is set to avoid mistakenly connecting a baked sector with an unbaked or open one and to let the pressure recover during operation after any possible sector valve closure due to pressure rise.

The sector valve interlock is triggered by a logic combination of signals and it applies a redundancy N=3 or 4 vacuum components: two gauges and one or two ion pumps. The redundancy N increases the reliability of the interlock system and eliminates the possibility of valves closure due to a single component failure.

The only condition while the beam is dumped due to vacuum is when N-1 of the N equipment reach the limit. In that case the signal for beam dump is sent to the sector valves for closure. The loss of the sector valves open status triggers the beam dump.

A general rule applied almost to the entire machine for sector valves closure is that once the interlock is triggered, the valve of the concerned sector and the valves of the two adjacent sectors close.

The experiment central beam pipes have a different rule regarding interlock valve closure: to protect the fragile beryllium central beam pipe from overpressure, the sector doesn't close in case of pressure rise. Instead, the Interaction Point (IP) sector valves stay open to keep the chambers connected with the two adjacent sectors. Those two sectors are the only warm sectors equipped with a rupture disk that opens at 500 mbar over the atmospheric pressure.

Finally there are pressure gauges and ion pump signals that are used by clients to monitor their vacuum status equipment. Those signals are used also as interlocks and each equipment owner decides the threshold and chooses how to use it. The table below summarizes the upper and lower vacuum interlock thresholds required and defined by the vacuum clients: Transverse Damper (ADT) by the clients.

Equipment	Lower threshold	Upper threshold
ADT	$5x10^{-7}$ mbar	$1x10^{-7}$ mbar
MKB	$2x10^{-5}$ mbar	$1x10^{-5}$ mbar
MKI	$2x10^{-8}$ mbar	$1x10^{-8}$ mbar
RF Cavities	$4x10^{-7}$ mbar	$1x10^{-7}$ mbar

Impact of the Pressure Threshold on Recovery Time

6 km of the LHC Long Straight Section are NEG coated. The NEG coating, after vacuum activation, enables a distributed pumping speed all along the beam pipes with a secondary electron yield close to unity and extremely low photon and ion induced desorption yield.

The NEG dissolves into the bulk, in the form of solid solutions, all main gases present in the air (Oxygen, Nitrogen, Carbon Dioxide, and Carbon Monoxide) except Argon [4]. After the NEG activation, an ultra-high vacuum pressure is granted in the warm straight section but, in case of leak, all the air is pumped by the NEG. This means the detection of a pressure increase in the gauge of the sector might not be as rapid as required.

The following example shows, seeing as each vacuum gauge indicates a local pressure value [5], how a pressure rise due to an air leak opening is masked by several meters of fully vacuum activated and NEG coated beam pipe.

In Figure 1 the pressure distribution time development in a simplified NEG coated system is described. The 114 m NEG coated sector is vacuum activated. At its extremities and every 28m there is a vacuum module with an ion pump. There is only one gauge positioned at 28m from the left end. In the unfortunate event that a leak opens at 7m from the gauge, the entire system would be affected by a distributed pressure increase.

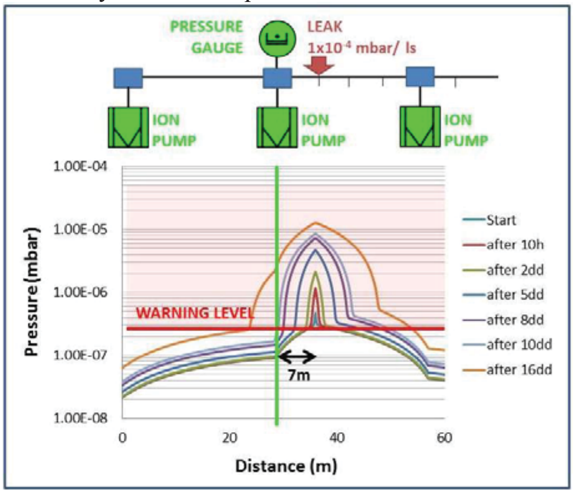

Figure 1: Pressure profile time evolution of a vacuum activated NEG vacuum sector when a leak of $1.4x10^{-4}$ mbar/ls opens at 7m far from the gauge. The pressure increase is proportional to the NEG saturated length.

In Figure 1 the case of a $1.4x10^{-4}$ mbar/ls leak is used to describe the pressure evolution along the system. After 10 hours the gauge still registers a pressure of $8x10^{-8}$ mbar while at the position of the leak the pressure is $1x10^{-6}$ mbar. It takes between 8 and 10 days and about 12 m of saturated NEG chamber to reach the interlock level ($4x10^{-7}$ mbar) on the gauge.

The NEG saturation length is linear with the time the NEG is exposed to air. An increased interlock threshold level of one order of magnitude would require 10 times more time to be detected. Once the NEG coating in the sector is widely saturated, it takes a complete bake out and NEG activation intervention for the initial condition to be restored – the recovery time is consequently severely affected.

Dealing with pressure spikes

Pressure gauge controllers and ion pump power supplies have "no intrinsic intelligence". The interlock crate that receives the signal from the gauges and pumps is only "logic"-based *i.e.* there is no signal treatment.

With the actual system of vacuum interlocks, it is impossible to distinguish a pressure spike from a pressure rise due to a leak before the pressure starts decreasing again. Pressure spikes exceeding the high interlock limit will always trigger the sector valve fast closure, as requested after the incident in the arc 3-4.

Mainly during 2011, some non–conformities present at the level of the RF inserts in LHC sectors like the A4L2, A4R2, A4L8 and A4R8 [6] caused six beam dumps. The number of dumps due to RF finger non-conformities was reduced after the 2011-2012 winter technical stop where most of the critical non–conformities were exchanged (e.g. CMS and vacuum module VMTSA, in Figure 2). In some more severe cases the interlock level was increased up to $1x10^{-6}$ mbar to let the beam circulate without interruption. Protecting the machine is always the priority, so each case of interlock level increase was and has to be evaluated with the owners of the surrounding equipment and endorsed by the LHC operators.

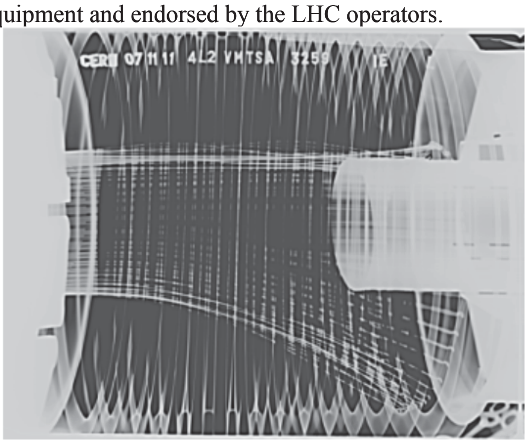

Figure 2: X-ray image of the non-conform RF fingers detected in a VMTSA vacuum module.

During periods like the scrubbing runs or the MDs, to allow for the conditioning of the machine, the interlock can be temporarily increased. In these cases a vacuum operator is always present in the control room to monitor the pressure rises around the ring. As the beam lifetime during scrubbing is shorter, a smaller vacuum beam lifetime remains negligible compared to the beam lifetime.

Beam dumps related to vacuum

During 2012, 17 beam dumps were attributed to vacuum sector valve closures (Figure 3) and this gave a total turnaround time (*i.e.* the time to get back to injection) of 52 hours.

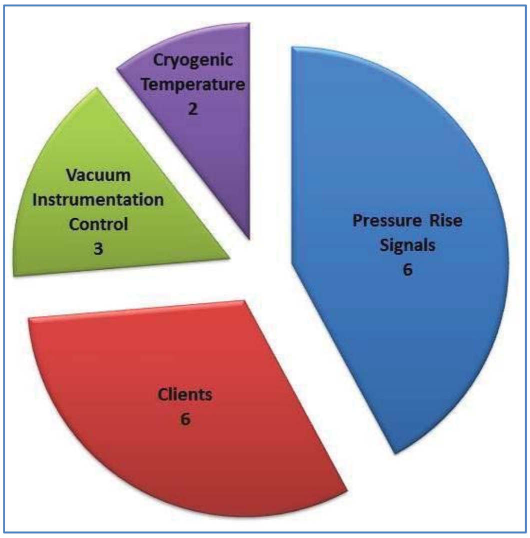

Figure 3: The type distribution of beam dumps attributed to vacuum sector valve closures during 2012.

The following paragraph summarizes the five reasons that caused the sector valve closure and induced the beam dumps in 2012.

Three vacuum beam dumps were related to vacuum instrumentation control: vacuum gauges, ion pumps or PLC which switched off or went to undefined status. During the LS1 the vacuum surface and coating group will implement all the Radiation to Equipment (R2E) recommendation to reduce the number of possible electronic fault.

Two pressure rise and beam dumps were connected to cryogenic temperature oscillations. One example is presented in Figure 4: after 10 hours of continuous neon injection in the LHCb beam pipe (SMOG – System for Measuring the Overlap with Gas injection) a beam dump was registered on the inner triplets on the right of IP 8 during beam injection. The beam screen equilibrium surface coverage depends on parameters such as the beam parameter and the beam screen temperature and is perturbed by gas load coming from the beam screen (BS) warm-up or quench or, like in this case, unusual high gas density in the beam pipe due to neon accumulation.

If the surface coverage exceeds its equilibrium value, pressure excursion or transient could appear during the beam injection due to cryogenics temperature oscillation [7,8].

Another type of vacuum beam dump was a pressure rise signal observed in the vicinity of the collimators. Unfortunately in this area it is tricky to distinguish the real pressure signal, when the gas desorption is induced by proton hitting the beam pipe walls from the "false" signals produced by a possible ionization of the cables (phenomena already observed in ISRs).

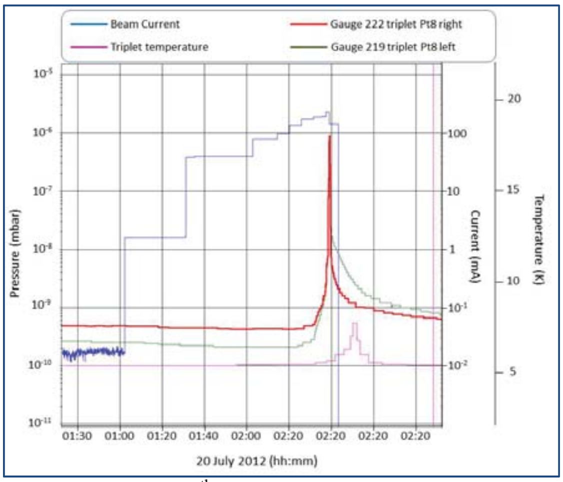

Figure 4: on the 20th of July 2012 a beam dump on the inner triplets on the right of IP 8 was registered during beam injection.

The final causes for beam dump were the mechanical non–conformities [6] of the vacuum beam pipes. At the moment all non-conformities have been detected and their reparation is foreseen during the LS1.

Finally the machine equipment like MKI, RF cavities, MKB and ADT that use vacuum gauges or pumps to monitor their equipment vacuum status, have directly or indirectly hardware-connected their vacuum alarm to the beam dump. The absence of any redundancy was the cause of four beam dumps during 2012.

VACUUM INTERVENTIONS

The standard vacuum intervention on the beam pipe restores the previous pressure in the concerned sector. This intervention has no impact on the LHC operation, beam lifetime and on the background of the experiments.

The vacuum intervention baseline is the bake out of each component of the beam pipe and the vacuum activation of the NEG coated components.

The intervention time schedule for venting and bake out for a typical LHC vacuum sector is two weeks. This time can vary, depending on the sector and the mechanical intervention complexity. This intervention includes the activities listed in Table 1. For each activity the average timescale is also given.

Table 1: Average timescale of the standard bake out and NEG vacuum activation intervention

Activity	Time (h)
Preparation and sector venting	0.5
Mechanical intervention	-
Pumping	1
Bakeout installation	24
Bakeout and NEG activation	120
Bakeout removal	12

The interventions performed with nitrogen venting, bake out and activation in 2012 are: the Zero Degree Calorimeter (ZDC) upgrade in point 2 left and right, the VMTSA reparation in point 8 left and right, the warm transition of the Q5 left of IP1 RF insert exchange, the Ionization Profile Monitor (BGI) opening in point 4 on the left and the BSRT removal in point 4 on the left.

One exceptional intervention performed during the technical stop 4 on the LHC was the MKI exchange. This intervention was characterized by three peculiarities:

- 5 days of Technical Stop: continuous day and night shifts.
- Additional manpower
- 3 weeks of preparation of the kicker on the surface where the kicker was pumped and baked and kept under vacuum between its two sector valves until its installation in the machine.
- a complete week was dedicated to scrubbing the new component after its installation.

An exceptional, alternative solution is the intervention under neon flux [10]. This choice has to be made by the vacuum surface and coating group experts together with the LHC committee in order to evaluate possible consequences. This modus operandi reduces the intervention, avoids a major NEG saturation but a local saturation close to the exchanged piece is inevitable. The intervention consists of overpressurizing (100-300 mbar over the atmospheric pressure) the beam pipe with neon, exchanging or removing the damaged piece, closing the sector and pumping it down.

For the neon gas option and the neon intervention modus operandi cf. reference [9]. The concerned sector and its equipment must be able to stand the overpressurisation. A careful a priori preparation of the activities is important to minimize the mechanical intervention time.

The Neon venting without bake out is a five-day intervention that includes:

- compulsory bakeout of the neon trolley,
- neon venting and overpressurization of the vacuum sector,
- mechanical intervention and sector closure,
- neon pump down with a baked pumping group,
- neon pump down with the vacuum sector ion pumps.

Depending on the available time, the sector may just be pumped down or a partial bakeout of the saturated area may be added to the procedure.

The new uncoated installed piece or chamber would require beam conditioning, and temporary local pressure rises in its vicinity are expected during the restart of the LHC operation.

Three examples of neon intervention effectuated in 2012 are: the RF insert exchange in CMS, the BSRT and the BWS removal in point 4 right and left respectively.

2014 OUTLOOK

The LS1 vacuum consolidation includes:

- the reparation of all non-conformities,

• all the actions on the electronics to fulfill the R2E recommendations,

• the NEG coating of the 150 inter-modules in the experimental zone for e-cloud mitigation purpose,

• The insertion of NEG coated liners inside the 800 mm vacuum chambers to reduce the background in ALICE,

• the NEG coating of 150 module in the LSS for e-cloud mitigation purpose,

• the optimization of the pumping layout all around the machine where it was considered a potential limitation for the machine nominal operation: MKI, collimators and TDI where having a built-in operational contingency would grant more pumping speed.

More than 90% of the beam pipe will be opened to air during the LS1 and, as a consequence, the secondary electron yield and the electron stimulated gas desorption will be reset for almost the entire machine. Since previously scrubbed and air exposed surface scrubs about ten times faster than an "as-received" surface, the conditioning of "old" chambers and components will be faster [10]. Moreover the new components installed during the LS1 will need a complete conditioning.

The two major concerns, related to the vacuum activity after the LS1 are:

- the proton stimulated gas desorption at 6.5 TeV from collimators will be larger than what we had at 4TeV,

- the possible pressure excursion related to beam screen temperature regulation following operation with 25 ns beams.

Finally, after the LS1, the beam energy will approach its nominal value, leading to an increase of the synchrotron radiation critical energy, that is proportional to the photon stimulated desorption yield, and the augmentation of the photon flux. The expected desorption due to synchrotron radiation is one order of magnitude higher than the one experienced in 2012. This source of gas will decrease with the beam pipe conditioning. [11]

SUMMARY

The vacuum interlock system was designed to protect the integrity of the vacuum system from sudden pressure rise. The interlock limit is $4x10^{-7}$ mbar; it has been relaxed during scrubbing runs and MDs and in special cases where the presence of non-conformity in the beam pipe was detected.

The standard vacuum intervention includes the bakeout and NEG activation of the beam pipe that may take from 5 days with shifts, additional manpower and increased control of safety aspects, to 2/3 weeks depending on the sector complexity. The neon venting interventions may be carried out in special cases and require at least 5 complete days.

The operation experience from the 2012 run confirmed that the scrubbing and beam pipe conditioning approach is a valid option for the future beam operation.

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