VACUUM CONDITIONS REQUIRED

V. Baglin, CERN, Geneva, Switzerland

Abstract

Several years will be required to reach the LHC nominal performances. During years 1 and 2, the LHC beam current will be limited, therefore the nominal performances of the vacuum system are not required. In this context, the vacuum performances for years 1 and 2 will be analysed. Particularly, the bake-out of the Long Straight Sections could be questioned. The implications of an unbaked vacuum system onto the resources, the installation schedule, the beam lifetime, the quench level, the dissipated power into the cold masses and the radiation dose onto the machine elements will be discussed.

INTRODUCTION

The Large Hadron Collider (LHC) beam vacuum system is composed with elements operating at room temperature or at cryogenic temperature. The full vacuum system is geographically divided in three areas: the arcs, the experimental region and the Long Straight Sections (LSS).

In the arcs, there are two vacuum systems: the beam vacuum and the insulation vacuum. These systems are fully integrated in the magnet cold bore and cryostat. So, they are required from day 1.

The vacuum system in the experimental areas is surrounded by the detectors. The final vacuum system is also entirely required from day 1.

The vacuum system of the LSS includes the standalone magnet (operating either at room temperature or cryogenic temperature) and the room temperature vacuum chambers. There are 265 vacuum valves which delimit vacuum sectors in the eight LSS. The LSS contains the accelerator equipments which are required for its operation (injection, extraction, diagnostics, collimation). Part of these equipments will not be required for the day 1 of operation. Therefore, it is worth looking at if all the vacuum system components and functionality is required for day 1.

This paper focuses on the vacuum conditions which are required in the LSS for day 1 of operation. The first section discusses the requirements and the minimum machine required for day 1, showing that the bake-out of the LSS could be questionable. The second section discusses the consequences of the absence of bake-out in the LSS. In the last section, a backup possibility to the bake-out of all the room temperature parts, as defined by the base line, is proposed in given circumstances.

REQUIREMENTS AND MINIMUM MACHINE

Before the installation of the vacuum components in the LHC LSS themselves, some other points shall be completed. The LHC layout shall be frozen, the layout database shall be filled and the integration of the vacuum system shall be finished [1]. The installation drawings shall be completed, approved and ready on time. All the components (vacuum chambers, instruments, controls …) shall be delivered and accepted on time.

Besides these fundamental requirements, a minimum of achievements are required for the operation of the machine at day 1. The supports of the vacuum chambers and the other devices shall be in place at the correct position. The vacuum chambers shall be connected and the vacuum system shall be leak tight. The pumping system shall be installed and operational. The controls and the interlocks to the LHC machine shall be installed and operational. All these aspects are part of the minimum machine for day 1 as far as they form an operational vacuum system.

However, the room temperature part of the LSS vacuum system shall be baked as it is defined by the base line. Considering the reduced machine performances required for the first years of operation, it can be questioned whether the vacuum system shall be operated with nominal performances. The next section discusses the consequence of the absence of bake-out in some of the room temperature vacuum sectors of the LSS.

ABSENCE OF BAKE-OUT IN THE LSS

The LHC will reach its nominal performances after several years of operation. During the first years, the machine performances will be limited [2]. In Table 1, the performances expected in stage 1 and stage 2 *i.e.* 2007 and 2008, are compared to the nominal performances of the machine.

At nominal, the vacuum pressure is dominated by the dynamic vacuum [3]. The pressure increase is stimulated by the photon, electron and ion desorption. However, in stage 1 and, in a less extend, in stage 2, these phenomena are greatly reduced or totally absent. In fact, only photon stimulated molecular desorption and ion stimulated molecular desorption could play a minor role in stage 2. It can be demonstrated that the corresponding pressure increase would be of a few 10^{-10} Torr. Finally, The bunch spacing will be such that no electron cloud and therefore no electron stimulated desorption will be present [2]. Therefore, the dynamic pressure in stage 1 and 2 is negligible compared to the thermal desorption of the unbaked LSS *i.e.* the vacuum is static.

In the following part of the paper, we will look at the performances of an unbaked vacuum system and look at the consequences of the beam particle scattering onto the residual gas.

	Stage 1	Stage 2	Nominal
Months of operation	4	7	7
Days of operation	100	175	175
Bunches	1/43/156	936/2808	2808
Protons/bunch	10^{10}-9 10^{10}	10^{10}-9 10^{10}	1.1 10^{10}
Protons	10^{10}-1.4 10^{13}	(3.7–9.8) 10^{13}	3.2 10^{14}
Current (mA)	0.02 - 25	70 - 80	582
Average current (mA)	8	140	582

Table 1 : Comparison of the estimated performances of stage 1 and 2 with the nominal LHC performances [2].

Unbaked vacuum system

The pressure in a static vacuum system is defined by the ratio of the thermal outgassing rate to the pumping speed.

When performing the bakeout of a vacuum system, the temperature of the vacuum chambers is increased in the range 200 – 300 ºC. In doing so, the chemically bound molecules are released from the oxide layer and are pumped away from the vacuum system. During the bake-out, the thermal desorption rate of the chemically bounded molecules is increased exponentially and, correspondingly, the amount of gases in the oxide layer's reservoir decreased. After cooling down to room temperature, the thermal desorption rate is strongly reduced and the residual gas is dominated by H_2. The bake-out is a well known recipe to reduce the pressure down to a few 10^{-10} Torr within a week. The price to pay is the compatibility to 200 – 300 ºC of the vacuum components and the installation and operation of (removable) insulation jackets, thermocouples and heating tapes.

In the case of an unbaked vacuum system, the residual gas is dominated by H_2O and the system requires several weeks of pump down. In the LSS, of course, the Non Evaporable Getter (NEG) will not be activated if there is no bake-out, and the pumping system will rely only on sputter ion pumps. To estimate the pump down, we assume a typical Cu chamber of 8 cm diameter with lumped ions pumps spaced by ~ 30 m at maximum. The pumping speed is 30 l/s and the specific conductance equals 80 l.m/s. The outgassing rate of water, as a function of time t, is measured to be 3 10^{-5} / t *i.e.* 10^{-10} Torr.l/(s.cm^2) after 100 h of pumping [4].

Figure 1 shows the evolution of the maximum and average pressure in the unbaked Cu vacuum chambers of the LSS. After 3 month of pump down, the pressure is 10^{-8} Torr. For the purpose of the discussions in this paper, we will assume that the pressure in the unbaked vacuum chambers of the LSS is given after 3 months and 12 months of pumping for stage 1 and stage 2 respectively. So, a pressure of 10^{-8} Torr and 5 10^{-9} Torr are expected in stage 1 and stage 2.

It shall be noted that, in the LSS, the distance between two successive ion pumps is not strictly 30 m. On average, it equals 20 m. Reducing the distance to 20 m between two pumps will reduce the pressure to 5 10^{-9} Torr and 10^{-9} Torr in stage 1 and stage 2.

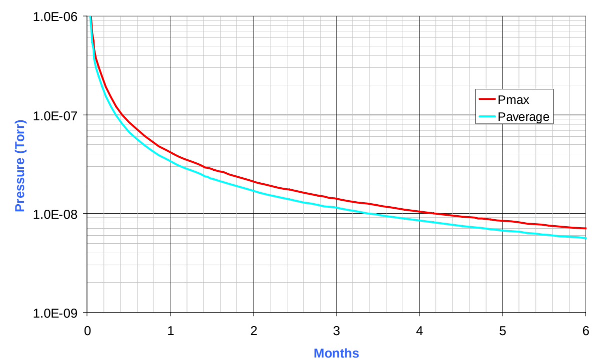

Figure 1 : Expected evolution, with time, of the maximum and average pressure in the unbaked vacuum chambers of the LSS. A distance of 30 m is assumed between two successive ion pumps

Vacuum lifetime

At nominal, for the proton beams, the vacuum lifetime, τ, equals 100 h. This lifetime guarantees a luminosity lifetime of 15 h [5]. With reduced current, taking into account the collisions, the intra beam scattering lifetime and the luminosity decay time, a vacuum lifetime of 35 h and 50 h shall be guaranteed for stage 1 and stage 2 respectively. So, the maximum pressure shall be limited to a given level. This maximum H_2O pressure is a function of the length, L, of the unbaked system. Due to the fact that the gas density in the arcs is negligible, the maximum pressure scales like (1), where σ_{H2O} is the proton scattering cross section onto the nucleus of the H_2O molecules.

$$\overline{P_{max}} \sim \frac{1}{L\,\tau\,\sigma_{H2O}} \qquad (1)$$

Figure 2 shows the maximum pressure as a function of the number of unbaked LSS. The length of one LSS is about 530 m. The figure shows that maximum pressure above 5 10^{-8} Torr in all the LSS still guarantee a vacuum lifetime of 100 h. So, leaving the LSS unbaked is not a limiting factor for the luminosity lifetime.

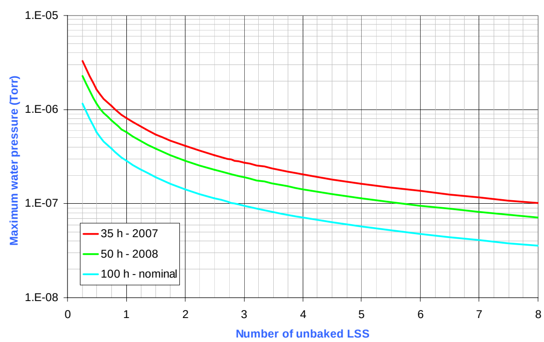

Figure 2 : Maximum pressure as a function of the number of unbaked LSS which guarantee a vacuum lifetime of 35h, 50 h and 100 h.

Similar estimations can be performed for the ion beam case. When operating with ions, with the exception of the uncontrolled ions losses, the LHC vacuum is dominated by the thermal gas load [6]. At nominal, the luminosity lifetime, which is dominated by the beam-beam lifetime, equals 6 h [5]. However, in the early ion scheme, the circulating current is reduced, so, to maintain the luminosity lifetime to its nominal value, the beam gas lifetime can be reduced from 100 h to 25 h. Thus, it can also be demonstrated that a pressure below 10^{-8} Torr in all the LSS will ensure that the luminosity lifetime stays at 6 h.

Magnet quench level

The proton scattering onto the nucleus of the residual gas split into inelastic interactions (60% of the cross-section) and elastic ones (40%). In the latter case the scattered protons survives until it reaches the collimator system. In the former case most of the secondary particles impact onto the cold masses along the fist 12 m downstream of the interaction point [7]. A proton loss rate of $7\ 10^8$ p/(m.s) leads to a magnet quench [8]. The proton loss rate dN/dx is a function of the average beam current, I, and the maximum pressure. It scales like (2).

$$\frac{dN}{dx} \sim \frac{I}{e} \overline{P_{max}} \sigma_{H2O} \qquad (2)$$

With nominal current, a H_2O pressure above 10^{-6} Torr leads to a magnet quench. Therefore, since the expected pressure in the unbaked Cu vacuum chamber is below 10^{-8} Torr, there is no risk of a magnet quench in the LSS due to an unbaked vacuum chamber in its vicinity.

Dissipated power into the cold masses

Athough there is no risk of magnet quench in unbaked areas with stage 1 and stage 2 beams, a significant pressure could dissipate a significant power in the cold masses. Therefore the power dissipated into the cold masses shall be estimated. The loss of protons with energy, E, dissipates a power, dW/dx, given by (3). At nominal, a proton loss rate of $3.4\ 10^4$ p/(m.s) leads to a power of 75 mW/m which is dissipated in the cold masses.

$$\frac{dW}{dx} \sim \frac{dN}{dx} e\, E \qquad (2)$$

We assume that the pressure bump (due to the unbaked system) located at room temperature in the vicinity of the cold masses can produce heat load in the cold masses. Table 2 shows the expected proton loss rate and dissipated power into the cold mass for the years 2007 and 2008. In the case of an unbaked vacuum system, the dissipated power in the cold mass is much less than the design value.

	Stage 1	Stage 2
I [mA]	8	140
P [Torr]	10^{-8}	$5\ 10^{-9}$
dN/dx [p/(m.s)]	$8.7\ 10^2$	$7.6\ 10^3$
dW/dx [mW/m]	2	17

Table 2 : Proton loss rate and dissipated power into the cold masses in the case of an unbaked vacuum system in the vicinity of the cold masses.

Radiation dose

The collision of the protons with the residual gas is a source of radiation dose. The dose depends on the gas pressure, the energy and intensity of the circulating beam.

At nominal, in the arcs, along the dipole magnets, the radiation dose is estimated to be 5 Gy/year [9].

In the LSS, the radiation dose is estimated from FLUKA simulation taking into account the beam optics and the vacuum envelope [10]. The simulation shows that a pressure bump of 10^{16} H_2/m^3 produces 2.8 Gy/h at the level of the vacuum chamber. At nominal, in the LSS Cu chamber, the residual gas is dominated by CH_4 after the NEG activation. The equivalent H_2O pressure equals $6\ 10^{-12}$ Torr (equivalent to $2\ 10^{11}$ CH_4/m^3 or 10^{12} H_2/m^3) [11]. Therefore, at nominal, the annual radiation dose at the level of the NEG Cu vacuum chambers equals 1.5 Gy/year.

In the case of an unbaked vacuum chamber in the LSS, the radiation dose will increase proportionally to the pressure. Table 3 shows the expected radiation dose at the level of an unbaked vacuum chamber during the first year of LHC operation. Significant radiation dose could be delivered. This requires a close monitoring during the first year of operation. However, this level of radiation dose is small compared to other sources. The dose to components due to the losses on the collimators are much higher (MGy/year). But, this level is still significant in the LSS 4 where the beam instrumentations needs to be carefully shielded. When operating with 1/3 of nominal current with 10^{-9} Torr H_2O equivalent the calculated radiation dose at the level of the equipment equals 10 Gy/year [12, 13].

	Stage 1	Stage 2
I [mA]	8	140
P [Torr]	10^{-8}	$5\ 10^{-9}$
Dose [Gy/year]	15	280

Table 3 : Radiation dose expected at the level of the unbaked vacuum chambers during the first years of LHC operation.

IMPLICATIONS

The previous section has shown that some of the room temperature sectors of the LSS could remain unbaked for the first years of the LHC operation.

The installation of the vacuum system in the LSS is a 1.5 years long project. Based on previous experience, the installation has been studied in details and is divided in several parts [14].

- Installation of the sectorisation modules (vacuum valves with instrumentation) upstream and downstream to the standalone magnets. Connection to the beam vacuum of these magnets.
- Installation of the insertion elements (Roman pots, beam instruments…) and installation of the vacuum components (vacuum chambers, instrumented bellows…) of the room temperature parts.
- Installation and test of the bake-out system.
- Installation of the control system in parallel with the mechanical installation and the bake-out installation.
- Reception of the vacuum sectors of commissioning of the controls.
- Bake-out and NEG activation.

Due to space constraints, a maximum of 2 teams can work in parallel per half LSS. The mechanical and bake-out installation of “simple” vacuum sectors will be done by 4 teams of the subcontractor and the installation of the complex vacuum sectors (kickers, RF cavities….) will be done by 1 AT/VAC team. The bake-out and the NEG activation will be done by 2-3 AT/VAC-TS/MME teams. In addition, there is one AT/VAC backup team and another one available either for backup or exploitation of the PS and SPS complex.

From the information above, a schedule and a resource planning is built [15]. About 45 weeks and 53 weeks are required to perform the full installation of the bake-out system and the full activation of the NEG in the LSS. The resource planning shows that, for some periods of a few weeks long, the available manpower for the bake-out and the NEG activation is about two times lower than required.

Since, skipping the bake-out is the last resort to allow a closure of the vacuum system in time, an alternative to the “full” bake-out scenario to stay within the schedule can be acceptable when :

- The vacuum installation is facing too many problems (leak, non conformities, layout errors…).
- Part of the components within the same vacuum sectors are delayed, *i.e.* the vacuum sector cannot be closed.

In these cases, the deployment of the AT/VAC and TS/MME bake-out and activation teams as rescue teams (Vacuum SAMU) is required.

The decision to skip the bake-out of a vacuum sector shall be made, at least, in collaboration with the equipment owners, TS/IC, the experience interface if applicable and the management.

The base line remains the “full” bake-out and NEG activation of the vacuum system. In a minimal scenario, at least, the 4 experimental zones will be baked and NEG activated, all the permanent bake-out system will be installed and as much as possible vacuum sectors will be baked and NEG activated. The remaining unbaked vacuum sectors will be baked and NEG activated before stage 2 (2008).

It should be noted that when the vacuum sector valves are open, the thermally desorbed H_2O from the unbaked surfaces will be pumped in the standalone magnet. Given the large pumping speed of the cryosurfaces with respect to the ion pumps, most of the H_2O will be condensed over ~ 0.5 m at each extremity of the standalone. After 6 months of operation, ~ 50 monolayers of H_2O will be adsorbed at each standalone extremity. Before operating above the electron cloud threshold, the H_2O shall be removed from the standalone magnet by a warm up above 190 K to avoid vacuum transients and significant heat loads [16, 17]

CONCLUSIONS

The LHC will reach its nominal performances after several years of operation. Therefore, the vacuum system might not have to be operated to its nominal performances from day 1. So, the minimum vacuum system does not require a “full” bake-out of the LSS. From the LHC operation point of view, it is shown that the radiation dose in the unbaked vacuum sector is the limiting factor. In fact, due to the background limitation in the experiments and the radiation dose onto the equipment, only some vacuum sectors of the LSS 3, 6 and 7 might remain unbaked.

It should be stressed that the base line is a “full” bake-out and NEG activation of the LSS. However, in the case of difficulties *e.g.* delay in the delivery of complex components, postponing the bake-out of some vacuum sectors may be the only possibility to guarantee that the vacuum system will be operational in due time. The few vacuum sectors which might remain unbaked at stage 1 will be baked before stage 2.

ACKNOWLEDGEMENTS

The author would like to gratefully acknowledge A. Rossi, P. Cruikshank, D. Forkel-Wirth, J-M. Jimenez, N. Hilleret, S. Roesler, P. Strubin and H. Vincke for their help to collect the required inputs and for the fruitful discussions.

REFERENCES

[1] Compressed Schedule - The Layout point of View. S. Chemli. Proceedings of the LHC Project Workshop – Chamonix XIV, CERN, January 2005. CERN-AB-2005-014, CERN, Geneva, 2005.
[2] R. Bailey. These proceedings.
[3] Overview of the LHC Vacuum System. O. Gröbner. Vacuum 60 (2001) 25-34.
[4] Le dégazage des matériaux. J-P. Bojon. CERN Vacuum Technical Note 02-03, Mars 2003.
[5] LHC Design Report, vol 1, the LHC Main ring. Edited by O. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock. CERN-2004-003, CERN, Geneva, 2004.
[6] Residual Gas Pressure during LHC Ion Operations. A. Rossi. I-LHC/LEIR meetings, 14 December 2004. http://project-i-lhc.web.cern.ch/project-i-lhc/ILHCandLEIR/Meeting_04_12_14/DynPressure LHC_04_12_14.pdf
[7] Momentum losses and momentum collimation in LHC : a first approach. J.B. Jeanneret. CERN SL/92-44 (EA), LHC note 211, CERN, Geneva, 1992.
[8] Quench Levels and Transient Beam Losses in LHC Magnets. J.B. Jeanneret, D. Leroy, L. Oberli, T. Trenkler. LHC Project Report 44, July 1996, CERN, Geneva, 1996.
[9] Radiation Dose for Equipment in the LHC Arcs. K. Wittenburg, R. Schmidt, T. Spickermann. Proceedings of EPAC' 98, Stockholm, Sweeden. CERN LHC Project Report 274, February 1999, CERN, Geneva, 1999.
[10] Radiation Monitors as a Vacuum Diagnostic for the Room Temperature Parts of the LSS. V. Baglin, V. Talanov, T. Wijnands. CERN LHC Project Note 378, January 2006, CERN, Geneva, 2006.
[11] Residual Gas density Estimations in the LHC Experimental Interaction Regions. A. Rossi, N. Hilleret. CERN LHC Project Report 674, CERN, Geneva, 2003.
[12] S. Roesler, private communication 20/01/2006.
[13] Simulation of the radiation levels and shielding studies at the BDI positions in IR4. A. Tsoulou, V. Vlachoudis, A. Ferrari. CERN LHC Project Note 367, May 2005, CERN, Geneva, 2005.
[14] Installation et mise en service du système à vide des sections droites longues (LSS) du LHC. M. Jimenez. CERN EDMS nº 593852, May 2005, CERN, Geneva, 2005.
[15] Installation Schedule for the Vacuum Activities in the Long Straight Section of the Machine : Standalone, Mechanical, NEG Activation. K. Foraz. CERN EDMS nº 673368, October 2005, CERN, Geneva, 2005.
[16] Vacuum Transients during LHC Operation. V. Baglin, Proceedings of the LHC Project Workshop – Chamonix XII, CERN, January 2004. CERN-AB-2004-014, CERN, Geneva, 2004.
[17] Gas Condensates onto a LHC Type Cryogenic Vacuum System Subjected to Electron Cloud. V. Baglin, B. Jenninger. Proceedings of EPAC' 04, Luzern, Switzerland. CERN LHC Project Report 742, August 2004, CERN, Geneva, 2004.