VACUUM SIMULATIONS FOR HL-LHC LONG STRAIGHT SECTIONS*

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Abstract

The High Luminosity Large Hadron Collider (HL-LHC) is entering its final development phase, requiring the optimisation of its vacuum layout to ensure reliable operation. The main upgrades with respect to the current LHC involve the Long Straight Sections next to the two large, general-purpose experiments (ATLAS and CMS), including new final focusing magnets and a full crab crossing implementation using superconducting crab cavities. Since residual gas critically affects collider performance, extensive vacuum simulations have been conducted to evaluate and minimise pressure levels. These include steady-state studies accounting for phenomena, like photon, electron and ion-induced desorption, to determine pressure. The simulations employ several complementary tools: Molflow+ for Monte Carlo particle tracking in ultra-high vacuum conditions, Synrad+ for synchrotron radiation effects, and MATLAB-based VASCO code for pressure stability analysis.

INTRODUCTION

The Large Hadron Collider (LHC) is the largest particle collider in the world [1]. With its roughly 27km of circumference, it hosts one of the largest vacuum systems. This includes ~55km of beam vacuum, which must ensure a low enough pressure to preserve beam lifetime and emittance.

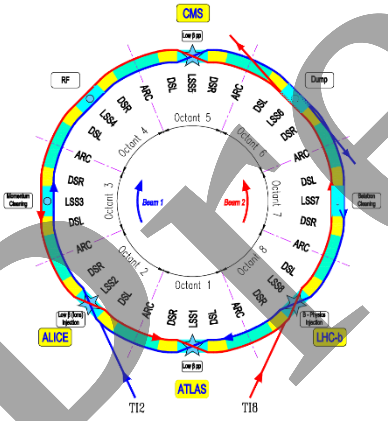

Figure 1: LHC schematic layout [1].

The beam vacuum system of the LHC, schematized in Fig.1, can be conceptually divided into two types:

- The 8 ARC vacuum sectors, each ~2.8 km long, in which the beam is bent by the cryogenic, superconducting LHC dipole magnets. Each beam travels in a separate pipe equipped with a beam screen to intercept the heat load and provide lower dynamic pressure and vacuum stability.
- The 8 Long Straight Sections (LSS), each roughly 500m in length, where the beam mostly travels in NEG coated warm beam pipes. Each LSS has a specific function (acceleration, injection, collimation, dump, collision) and is composed of multiple vacuum sectors. In the sectors closest to the four main LHC experiments the two beams share the same beampipe.

With the upcoming High Luminosity LHC upgrade [2], the whole of LSS1 and LSS5, hosting the ATLAS and CMS experiments respectively, will be completely renovated to improve the performance of the LHC machine. The goal of the High Luminosity LHC (HL-LHC) project is to increase the integrated luminosity by a factor of 10 compared to the LHC, to increase statistics on rare particle interactions.

The increase in luminosity is achieved through three major changes:

- Increase of the bunch intensity up to $2.3 \times 10^{11} p^{+}/bunch$
- New high-field, large-aperture, final-focusing triplet quadrupole magnets, to lower the β* at the interaction points to 0.15m.
- Implementation of a crab crossing scheme, to increase the effective interaction cross section.

The higher intensity, as well as the completely new layout, requires a careful study from the vacuum point of view to ensure good performance of the vacuum system. Multiple tools are used to simulate UHV conditions at CERN, providing a powerful method to predict the behavior of complex vacuum systems.

The following sections describe the specific use of the different tools employed to perform the simulations of the entire LSS of the HL-LHC.

MOLFLOW+ AND SYNRAD+, MONTE-CARLO SIMULATIONS OF VACUUM SYSTEMS AND SYNCHROTRON LIGHT

Molflow+ is a Test Particle Monte-Carlo (TPMC) simulator for vacuum simulations, developed at CERN [3]. The software can estimate the molecular flow of molecules in a vacuum system by tracking the trajectory of a subset of molecules and then scaling the results.

In the context of HL-LHC simulations, Molflow+ has been extensively used to estimate the conductance of non-cylindrical components and the effective pumping speed of vacuum pumps behind RF screens.

The Synrad+ code was also developed at CERN [3]. It shares the GUI and the TPMC algorithm with Molflow+ and allows calculation of the photon flux on surfaces due to synchrotron radiation (SR) emitted by particle beams.

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From magnetic field and beam parameters, the software computes the synchrotron radiation from particle tracking. This allows the reflection, scattering and absorption of the light to be reconstructed, and consequently the power deposition and gas load due to photon stimulated desorption to be understood.

The Synrad+ code has been used to calculate the linear photon flux on different components of the whole LSS. The entire geometry of the LSS was modelled in a simplified way, with the magnetic regions imported from the MADX representation of the machine optics for all dipoles and quadrupoles in the insertion region and the first half cells of the arc.

The simulation was run until enough Monte Carlo statistics were collected. A script in MATLAB was then used to convert the flux from the model into a linear average to be used in simulations with the VASCO code. The estimated radiation flux is shown in Figure 2 for one beam only. The higher SR flux on the left-hand side of the plot identifies the sectors directly downstream of the ARC bending magnets for this beam. All the other peaks in the simulation represent aperture changes, where the SR fan is intercepted by the walls of the vacuum chamber.

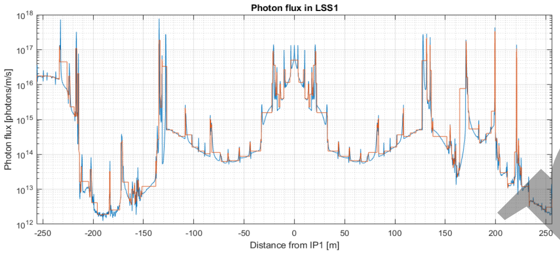

Figure 2: Synchrotron radiation flux distribution in LSS1 as calculated by Synrad+, and average value used as input for VASCO simulations.

VACUUM STABILITY CODE

The VAcuum Stability COde (VASCO) is a MATLAB simulation code developed at CERN [4]. The tool is specifically designed to simulate the pressure/density profile in a hadron accelerator. The geometry is simplified to a series of cylindrical segments in a fashion similar to finite element analysis. In each segment, the density profile is calculated according to the gas balance equation. In the calculation, several effects are taken into account: thermal desorption, lumped and distributed pumping, desorption stimulated by electrons (ESD), photons (PSD) and ions (ISD). To properly simulate the latter, the code simultaneously tracks multiple gas species, enabling the user to study cross-talk effects between the various gases. In fact, the aim of the code when it was first developed was to calculate the critical current for accelerators, i.e. the current at which a pressure runaway induced by ISD occurs [5].

The authors of this paper further continued the development of the tool. In particular, the calculation of the pressure profile has been optimized by using a specialized MATLAB solver for the differential equations instead of the inverse matrix calculation that was used in the original code. Furthermore, the input and output files of the code were improved, and a simple GUI has been developed to increase the usability of the tool. Documentation of this new version of the code is available in [6].

The VASCO code has several limitations. First of all, the simulation is 1D, meaning that complex geometries have to be modelled with only two parameters: an equivalent diameter and the length. To increase resolution a single component may be modelled by multiple segments. Moreover, with the equations that are implemented in VASCO, the gas beaming effect cannot be modelled, meaning that with particular geometries the pressure may be underestimated.

The choice of the many input parameters for the desorption yields represents most of the work around the simulation and directly influences the quality of the results. Since most of the parameters actually depend on the history of the surfaces, assumptions must be made to best represent the real system.

To simulate the vacuum system of the HL-LHC, several “simulation scenarios” have been identified:

- Machine startup: 50% of nominal current, ISD and ESD as main sources of gas. Scenario used for calculating the critical current.
- Intensity ramp-up: machine at full intensity, gas load dominated by ESD and PSD.
- Fully conditioned machine: machine at full intensity, PSD dominated gas desorption. Desorption yields conditioned with a dose equivalent to 1 year of continuous beam operation.

For each of the scenarios, the parameters for the simulations were chosen by review of the available literature and experimental data.

When the intrinsic limitations of this simulation approach are well understood the simplicity of the VASCO code makes it very powerful and versatile. Simulations of hundreds of meters of beamline can be run in just a few minutes.

The input file for the VASCO code is a spreadsheet table which contains the geometric and desorption parameters for each segment. For the HL-LHC simulations, each component of the beamline was modelled as one or multiple segments. For non-cylindrical components, an equivalent diameter was calculated to achieve the same conductance, estimated with TPMC simulations. Appropriate parameters for outgassing and desorption yields were chosen, assuming the different operational scenarios of the machine. The synchrotron radiation flux profile was calculated with Synrad+, with an average calculated for each segment. The simulations were run for the different operational scenarios identified for the machine. In Figure 3, the pressure profile output for a VASCO simulation is shown for the fully conditioned machine with ultimate parameters.

The pressure profiles calculated for each case comply with the density requirements dictated by the HL-LHC TDR for a minimum of 200h of beam lifetime. The average molecular densities calculated for LSS1 are shown in Table 1.

The VASCO code performs every calculation in terms of molecular density. Those values are then converted into N_2 equivalent pressures. While this can be useful to compare the simulation results to gauge readings and to quickly compare different layouts, the direct use of molecular densities is recommended when performing background or particle interaction simulations.

Table 1: Average Densities in LSS1

Gas	H_2 [m^{-3}]	CH_4 [m^{-3}]	CO [m^{-3}]	CO_2 [m^{-3}]
Simulated avg.	$9.3 \times 10^{11} \div 3.5 \times 10^{12}$	$2.4 \times 10^{11} \div 1.2 \times 10^{12}$	$1.6 \times 10^{11} \div 1.1 \times 10^{12}$	$1.6 \times 10^{11} \div 2.0 \times 10^{12}$
HL-LHC 200h [2]	6.4×10^{14}	9.6×10^{13}	6.4×10^{13}	4.2×10^{13}

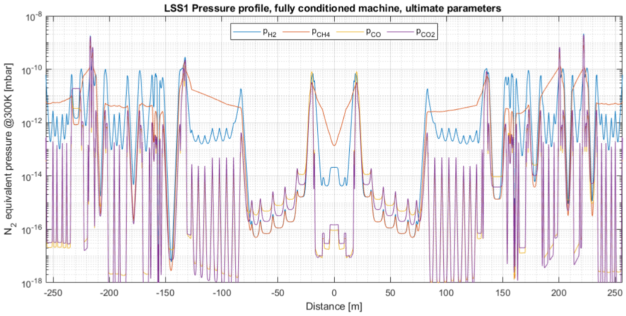

Figure 3: Pressure profile for LSS1, simulated assuming a fully conditioned machine and ultimate parameters.

The code also allows the calculation of the critical current at machine startup, i.e., when the ISD yields are higher. Using the same model as for the pressure profile calculation, the critical current is computed by finding the beam current at which the solution of the VASCO model diverges. The critical current for the HL-LHC machine with its startup parameters was estimated at 5.4A, guaranteeing a safety margin of about 5 on the ultimate intensity. Through continued beam operation, and thus particle bombardment of the surface, the ISD yields are expected to decrease, leading to an increase of the critical current.

The runaway location corresponds to the peak of the pressure profile evaluated at a current just below the critical threshold, while the gas most prone to trigger the runaway is the one that first shows divergence.

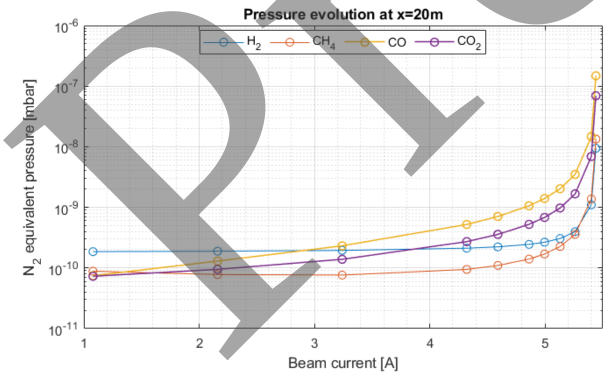

Figure 4: Pressure at the runaway location calculated for increasing beam currents. The critical current value is indicated by the graph asymptote.

In the new LSS1 and LSS5 of the HL-LHC, the runaway point is situated at ~20m from the interaction point, inside the TAXS absorber chamber, and is most likely caused by CO buildup. The pressure evolution at the runaway location is shown in Figure 4, plotted against the beam current.

With this information, and further simulation studies, a layout optimization in the region has been possible by replacing two ion pumps by non-evaporable getter modules, simplifying installation and operational aspects.

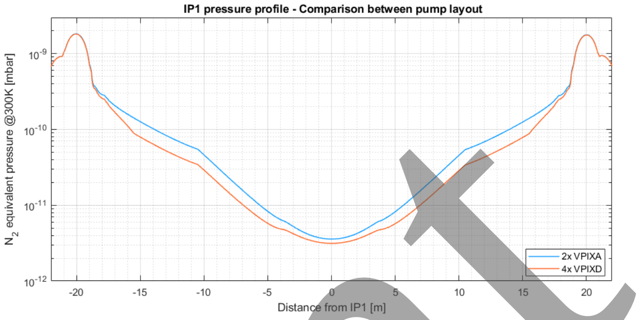

Figure 5: Pressure profile comparison of the ATLAS experimental beampipe with different pumping layouts.

This simulation approach is very suitable for quickly studying the impact of layout changes. As a further example, a model was created for the ATLAS experimental beam vacuum system, and simulations have been run to support the replacement of the custom-made annular ion pump present in the vacuum sector with two 20 L/s commercial ion pumps, as shown in Figure 5.

CONCLUSION

This paper presents a general overview of the workflow adopted for the vacuum simulations in the HL-LHC Long Straight Sections, along with a brief description of the various tools employed.

Detailed simulations of the machine's long straight sections have been carried out to evaluate pressure profiles and critical currents under different scenarios, ensuring compliance with the TDR specifications. The results have played a key role in guiding design decisions, such as the definition of the optimal vacuum pumps in the vicinity of the interaction regions.

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