

VACUUM TOLERANCE LIMITS FOR LSS7: BALANCING PERFORMANCE AND RADIATION EXPOSURE FOR HL-LHC

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Abstract

The High Luminosity LHC project requires a flexible approach to collimator vacuum conditioning that addresses both operational vacuum performance and the maintenance constraints associated with highly radioactive equipment. This work combines outgassing studies and LHC pressure profile analyses to optimize the vacuum conditioning procedure for collimators used for betatron cleaning installed in the Long Straight Section of Point 7 (LSS7) of the LHC. The proposed approach simplifies the bake-out procedure aligning with As Low As Reasonably Achievable (ALARA) principles [1], reducing intervention complexity and personnel radiation exposure without compromising vacuum quality. This study was supported by the HL-LHC project.

INTRODUCTION

Over the past three years, there have been an increasing number of critical failures of the edge-welded bellows of LHC collimators [2] which required interventions during operation for leak detection and inspection. Following identification of the main stress factors of the bellows, a detailed risk assessment of the existing collimators identified 6 critical units and 51 at high risk of failure. These failures are likely to cause leaks throughout the first Run of the high luminosity LHC era (foreseen to start in 2030) requiring machine interventions for the replacement of collimator units.

As nearly 40 % of the collimators are installed for betatron cleaning in the Long Straight Section of Point 7 (LSS7), a number of interventions are expected in this area. LSS7 is amongst the most radioactive regions of the LHC, with ionizing radiation levels above 2 mSv/h, measured 40 cm away from the beam path, which could further increase during HL-LHC operation. To minimize radiation exposure to personnel, the vacuum conditioning procedure for LSS7 sectors must be simplified by lowering the bakeout temperature and excluding selected components from the bakeout cycle.

Following the replacement of a collimator (TCSG) in the A6R7 sector of LSS7 (TCSG.A6R7.R), a systematic study was performed to assess the effects of the different vacuum conditioning procedures on the collimator and of a partial bakeout on the A6R7.R sector: a) A test was carried out during LHC operation by increasing the sector pressure to determine the maximum tolerable residual gas density with minimal operational impact, b) A series of outgassing studies were performed on a spare secondary collimator (TCS), along with pressure-profile simulations of the sector under different scenarios, c) A new procedure was applied for the reconditioning of the sector after the replacement of

Table 1: EoF Test Beam Parameters

Beam Intensity [p^+ / b]	Number of Bunches [b]	Beam Energy [TeV]
1.6×10^{11}	2400	6.8

the TCSG during the Year End Technical Stop (YETS) of 2025-2026.

END OF FILL TEST

During LHC proton operation, an End-of-Fill (EoF) test was performed to locally increase the A6R7.R sector pressure in LSS7 to assess the impact on machine operation. This determined the maximum acceptable pressure during operation. The LHC parameters used during this test are listed in Table 1.

For triggering a pressure increase, the 8 NEG cartridges (CapaciTorr Z 400) along the 70 m long vacuum sector were remotely heated for a few minutes, releasing mostly chemisorbed H_2 gas from the bulk of the NEG sinterized disks. As shown in Fig. 1, the nitrogen-equivalent maximum pressure reached 1×10^{-6} mbar, during which the beam lifetime reduced from 47 h to 45 h. This reduction remains acceptable as LHC proton fills last no more than 24 h. No impact was observed on any LHC detector backgrounds and no unusual beam losses were detected along the entire LHC ring.

ULTIMATE PRESSURE STUDIES

The positive EoF test results prompted a series of outgassing studies on a spare secondary (TCS) collimator.

Experimental Setup

The setup used is illustrated in Fig. 2; it consists of a real LHC collimator fitted with its upstream and downstream pumping modules, fully instrumented. The collimator jaws are made of C-C composites; an orifice with a known conductance of 9.6 l/s for N_2 separates the testbench domes. After bakeout at 250 °C for 48 h, the testbench ultimate pressure

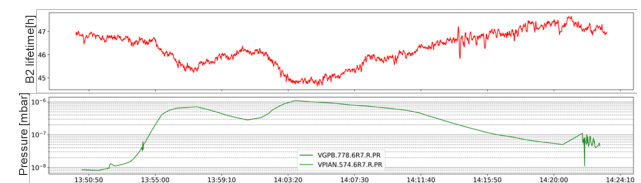


Figure 1: EoF test results, showing the beam lifetime (red) and nitrogen equivalent pressure (green)

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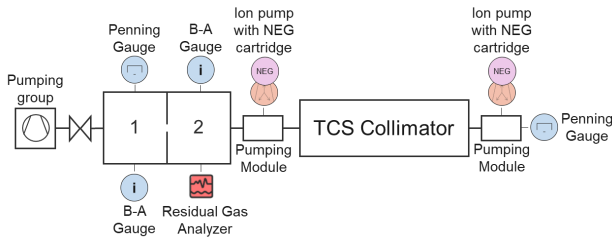


Figure 2: Schematic of the experimental setup for the collimator outgassing measurements.

Table 2: Ultimate Pressure Measurement Results

Conditioning Scenarios	Ultimate Pressure [mbar]
Fully baked	$\approx 3 \times 10^{-10}$
Air vented unbaked	$\approx 3 \times 10^{-8}$
N ₂ vented unbaked	$\approx 1 \times 10^{-8}$

was 1×10^{-10} mbar, with background outgassing estimated at 3×10^{-9} mbar/s, expressed in N₂ equivalent.

Bake-out Scenarios and Results

Three conditioning scenarios were studied:

Scenario 1: Full bakeout of the collimator, modules, and testbench at 250 °C for 48 h, followed by instrumentation degassing, NEG cartridge activation, and ion pump startup. The duration of the test lasted 8 days in total, including the initial pump-down to a pressure of 1×10^{-6} mbar measured at the collimator extremity.

Scenario 2: Air-vented collimator for 72 h, then left unbaked along with the modules; testbench baked at 180 °C for 72 h to condition instrumentation, then instrumentation degassing, NEG activation and ion pumps turned on. The total duration of the test was 5 days.

Scenario 3: N₂-vented collimator for 24 h with identical conditioning to Scenario 2.

Prior to each unbaked test, the testbench and entire collimator assembly underwent a 250 °C/48 h bakeout to ensure standardized initial conditions. The 5-day total duration was selected for the unbaked tests to illustrate the worst-case scenario of an intervention during operation for collimator exchange and sector reconditioning.

Table 2 presents the N₂-equivalent ultimate pressure reached at the collimator extremity. The unbaked test results were obtained after 5 days of total pumpdown.

The measurement error bars are ~20 % due to instrumentation margins. As expected, the fully baked collimator exhibited the lowest pressure. The N₂-vented unbaked collimator showed a factor 3 x lower pressure than the air-vented unbaked collimator.

PRESSURE PROFILE SIMULATIONS

Figure 3 depicts the schematic of the A6R7.R sector. The sector is 69.5 m long, out of which 53.6 m are NEG coated chambers. The location of the NEG cartridges that were activated for the EoF test are shown, as well as the positions of



Figure 3: Schematics of the A6R7.R sector.

the primary collimators (TCP) and the secondary collimator (TCSG) which was to be replaced following an edge-welded bellows failure.

The pressure profile simulations were performed using the Vacuum Stability Code (VASCO) [3] incorporating data from the outgassing studies and EoF test. Three different scenarios are plotted together in Fig. 4.

The **Yellow** curve depicts the standard bake scenario of the whole sector using baked TCS outgassing data, multiplied by a factor of 3 for each TCP, as a conservative estimate due to their known higher outgassing rate.

The **Green** curve depicts the EoF test pressure profile, establishing a maximum pressure of $\sim 1 \times 10^{-6}$ mbar N₂ equivalent with minimal LHC operational impact.

The **Purple** curve depicts the partial bakeout of the sector excluding the TCS and the three TCP collimators from the bakeout cycle. Air-vented unbaked TCS data was used to account for atmospheric exposure pre-installation of the new TCS to be installed; N₂-vented unbaked data was multiplied by a factor of 3 for each TCP as a conservative approach. The TCPs retain part of their vacuum conditioning following the N₂ venting of the sector, since they are located 40 m away from the exchanged TCSG.

It is worth noting that the pressure increase during the EoF test was not uniformly 1×10^{-6} mbar, but mostly localized around the NEG cartridges. The partial bakeout scenario shows a factor 600 lower maximum N₂-equivalent pressure compared to the vacuum performance limits set by the EoF test.

Table 3 presents the average molecular gas densities in molecules per m³ expressed in H₂ equivalent molecular gas density. The first column presents the case of the HL-LHC vacuum performance criteria, showing the maximum acceptable single residual gas density, across the LHC ring, for 200 h of beam life time [4]. The second column presents the average residual gas density extracted from VASCO for the partial bakeout scenario of the A6R7.R sector, converted to H₂ equivalent using the nuclear scattering cross section ratios [5]. The average gas density across the 70 m long sector is one order of magnitude below the HL-LHC limits. For reference, the last column presents the average gas density obtained during the EoF test, simulated with VASCO, which exceeds the HL-LHC limits by more than one order of magnitude while showing minimal impact on machine operation. Therefore, no impact to the LHC operation should

Table 3: Average Molecular Gas Densities

	HL-LHC Criteria [mol/m ³]	Partial Bakeout [mol/m ³]	EoF Test [mol/m ³]
H ₂ eq. gas density	6×10^{14}	4×10^{13}	8×10^{15}

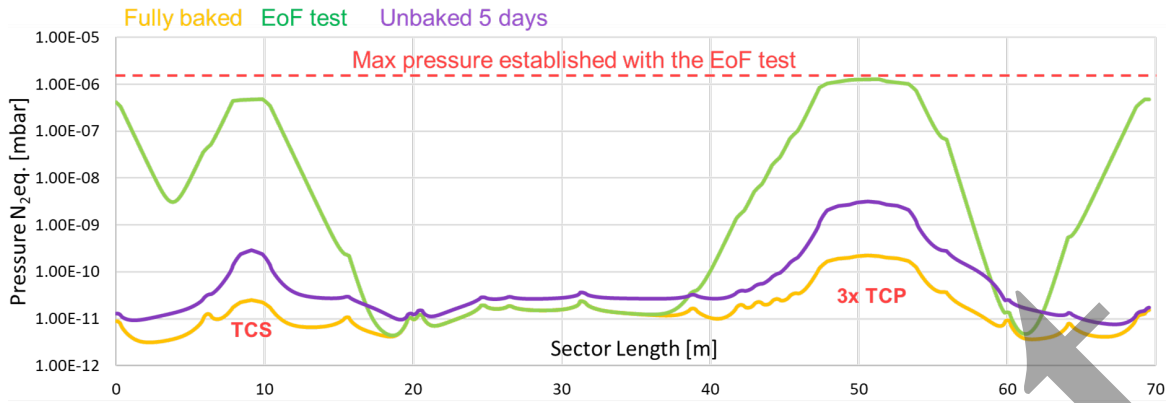


Figure 4: Pressure profile simulations for the A6R7.R sector.

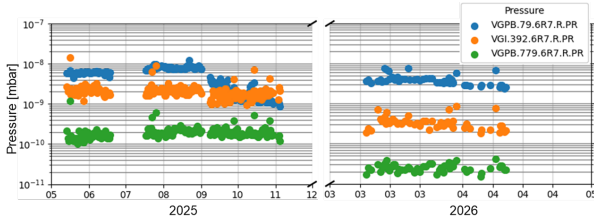


Figure 5: Static pressure comparison for the A6R7.R sector.

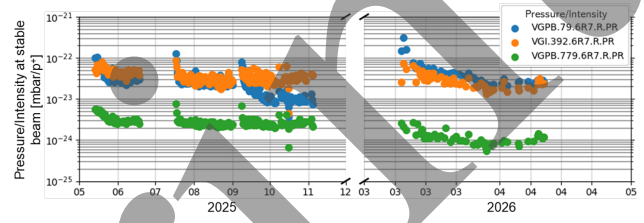


Figure 6: Comparison of pressure normalized to the intensity during stable beam for the A6R7.R sector.

be expected after the implementation of the partial bakeout on the sector.

IMPLEMENTATION IN THE LHC

During the YETS 2025-26, following the exchange of the TCSG collimator in A6R7.R, a partial bakeout procedure was implemented to condition the vacuum of the sector. For this procedure, only the NEG-coated chambers were conditioned, excluding from the bakeout cycle four collimators, two sector valves, and all warm modules across the sector. The process utilized just 25 % of the sector's total heating elements, considerably shortening connection and programming efforts from the personnel.

On the fifth day of pumpdown/conditioning, the Bayard-Alpert gauge at the center of the sector read N_2 -equivalent pressures in the 10^{-10} mbar range, before operation restart. Figure 5 compares the static pressures, without proton beam circulation, of three vacuum gauges from the vacuum sector, measured in 2025 and 2026 under similar conditions. The static pressure after the partial bakeout was lower than the previous year, likely due to the sector's NEG coating not being reactivated since 2014 and becoming slightly saturated over 12 years of high-intensity operation.

Figure 6 shows the pressure normalized to beam intensity ($\sim 4 \times 10^{14}$ p+, at 6.8 TeV) during LHC operation with stable beams for physics, for comparable 2025 and 2026 fills. After the initial scrubbing and conditioning over three fills, no deterioration of the vacuum performance, as compared to 2025, was observed following the partial bakeout of the sector.

CONCLUSIONS

With the possible increase expected in the number of collimators that will require replacement during HL-LHC operation, and the higher radiation levels expected in the betatron cleaning collimator region (LSS7), this work demonstrated the viability of implementing a partial bakeout for the reconditioning of any LSS7 sector, in the event of an intervention for collimator replacement during operation. Following implementation of this partial bakeout on the A6R7.R sector, the following points were achieved:

- Benchmarked new vacuum performance limits for LSS7 sectors with an end-of-fill beam test, with negligible machine impact observed at $\sim 1 \times 10^{-6}$ mbar.
- A final static pressure of 1×10^{-10} mbar after the reconditioning of the sector with no vacuum performance deterioration observed during 2026 LHC proton operation for physics.
- Reduction of the intervention time to 5 days, while significantly simplifying procedures leading to an expected radiation dose reduction to personnel of at least 50 %.

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