PREPARATION OF THE 2026 LHC HIGH-INTENSITY TESTS IN VIEW OF HL-LHC

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Abstract

One of the main drivers of integrated luminosity production in the High-Luminosity LHC (HL-LHC) era is the bunch intensity, expected to reach 2.3×10^{11} protons per bunch at injection compared to the maximum 1.8×10^{11} protons per bunch achieved in Run 3 operation (2022–2026). Such high intensities bring significant challenges, in particular localized beam induced heating due to impedance and the associated risk of equipment damage. In that respect, any issue discovered only in Run 4 (2030-2033), the first run of the HL-LHC era, could lead to significant downtime or intensity limitations until appropriate mitigation measures are put in place. It is therefore essential to identify such potential limitations for elements that will not be upgraded as part of HL-LHC to achieve the target intensity before the end of the presently ongoing Run 3. This paper summarizes the preparation steps and strategy foreseen for dedicated high-intensity tests at the end of the 2026 LHC operation, as a last step before Long Shutdown 3 (LS3). The tests aim at reaching and sustaining HL-LHC beam parameters, in order to probe impedance-related limits and assess equipment non-conformities, as well as potential design issues and unknown limitations in view of reliable HL-LHC operation. Preparation for the high-intensity tests started with dedicated machine development studies in 2025, making significant progress towards HL-LHC beams and identifying critical devices. Key observations and plans for 2026 are presented.

INTRODUCTION

One of the key ingredients required to reach the challenging integrated luminosity targets of the High-Luminosity LHC (HL-LHC) is operation with significantly larger total beam intensity than what is achieved today in routine LHC operation. In the baseline HL-LHC scenario, this corresponds to about 30% higher bunch intensity and 10% more bunches compared to LHC operation in 2026 [1]. At the same time, LHC experience has shown that such an increase in beam intensity can reveal hardware limitations, equipment design weaknesses and previously unknown constraints related to beam impedance-induced heating that are not observed at lower intensities.

Recent examples include failures of warm vacuum modules in 2023 and 2025. In 2023, pressure spikes in sector A4L1 were followed by slow losses and beam dumps. The root cause was traced to beam-induced heating in an RF-finger of a warm vacuum module that damaged the tension spring [2–5]. Because the affected module was installed in a section shared by the two beams circulating in opposite direction, operation was interrupted to replace the faulty module. In 2025, a similar limitation was observed in sector 6L2 [6]. In that case, operation could continue in a degraded mode with asymmetric beam intensities [7]. Since the LHC will enter the Long Shutdown 3 (LS3) after the 2026 run, this is the last opportunity to probe HL-LHC beam conditions, while there is still time to identify and implement mitigations before Run 4. Because most of the installed hardware will remain unchanged after LS3, these tests can already provide meaningful information on HL-LHC readiness.

For this reason, two weeks at the end of the 2026 run will be dedicated to high-intensity tests [8, 9]. Their goal is to demonstrate hardware compatibility with HL-LHC beam conditions or, if that is not achieved, to identify the limiting devices and the corresponding mitigations. Because HL-LHC beam conditions cannot yet be fully achieved before LS3 in a single configuration, the strategy combines different beam types and beam energies. In addition to hardware validation, the campaign will also provide valuable operational experience with HL-type beams in areas such as electron-cloud, beam-beam effects and halo studies.

In this paper, we summarize the target conditions for the 2026 campaign, review the main machine constraints, the lessons learned from the 2025 Machine Development (MD) program and outline the proposed staged strategy to prepare and execute the high-intensity program before LS3.

HL-LHC TARGET CONDITIONS

The purpose of the 2026 high-intensity campaign is to reproduce the HL-LHC operating conditions as closely as possible. In the baseline HL-LHC scenario, the bunch intensity is 2.3×10^{11} ppb at injection and about 2.2×10^{11} ppb at the start of collisions, leaving some margin for losses at the start of the ramp and during the collapse of the separation bumps at top energy when the beams are brought into collision. The reference beam configuration is based on standard 4×72b trains with 2760 bunches, bunch lengths around 1.3 ns, corresponding to an RMS bunch length of 7.61 cm [10], and a collision duration of about 6–7 h [11, 12].

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Along the HL-LHC cycle, the bunch intensity decreases due to burn-off in collisions, while the bunch length evolves under the combined effect of synchrotron radiation damping and controlled longitudinal emittance blow-up once the target bunch length is reached. The exact luminosity and burn-off conditions depend on the pile-up target, which is planned to increase gradually over the HL-LHC operational years from 132 to 180 for two high-luminosity experiments, ATLAS and CMS.

Overall, the HL-LHC performance scenario is built around a total, nominal integrated luminosity target of about 3000 fb^{-1} from Run 1 to the end of HL-LHC operation in 2041. Not reaching the target HL-LHC bunch intensity would have a substantial impact on integrated luminosity and could compromise the ability to meet these performance goals. For example, operating with 1.8×10^{11} ppb instead of 2.2×10^{11} ppb could cost about 30-50 fb^{-1} per year, rising to 50-75 fb^{-1} per year if combined with two weeks of downtime, compared to the presently assumed 200-250 fb^{-1} per year in Run 4 [12].

The HL-LHC scenarios include the following beam type options [13, 14]:

- **Standard 4×72b beams** as the nominal HL-LHC baseline, since they maximize the number of colliding bunches in all experiments and ensure fast filling of the machine to avoid beam quality degradation. At the same time, they are the most critical in terms of e-cloud induced heat load [15–17]. Mitigation measures for e-cloud are foreseen during LS3, such as the Beam Screen Treatment project (BST) [18].
- **BCMS 5×48b beams** as the main alternative scenario. They keep the same number of injections as the nominal baseline and provide similar luminosity potential in the two high-luminosity experiments, ATLAS and CMS, at the expense of a 10% lower luminosity in LHCb and ALICE. Due to the reduced number of consecutive, 25 ns spaced bunches (48b vs. 72b), BCMS beams reduce e-cloud head-load, result in smaller emittances at injection and offer a more favorable configuration for full-machine high-intensity studies in 2026.
- **8b4e beams** as a fallback option in case of severe and unforeseen e-cloud limitations with 25 ns beams (Standard and BCMS). They were successfully used in 2017 as a mitigation to losses and beam instabilities in sector 16L2 [19–21] or as part of hybrid beams in 2023, a combination of 25 ns and 8b4e beams as a trade-off between performance and e-cloud limitation. Since they are not part of routine operation, 8b4e beams may lead to increased vacuum activity and may require dedicated conditioning in both the injectors and the LHC.

MAIN CONSTRAINTS FOR 2026 TESTS

The main constraints for the 2026 tests arise either from systems that are scheduled to be upgraded in LS3 to ensure compatibility with HL-LHC beams, or from effects for which mitigation measures are planned during LS3. The most relevant constraints are the following:

- **Beam-intercepting devices:** The dump system (TDE) and the septum protection system (TCDS), protecting the device in the event of an asynchronous firing of the extraction kickers (MKD), are compatible with HL-LHC bunch intensities at 3 TeV, while 6.8 TeV operation with standard 25 ns beams exceeds the safe limit [22,23]. 8b4e beams with full HL-LHC bunch intensity remain within the TCDS-safe envelope.
- **Electron-cloud heat load:** The maximum number of bunches is limited by cryogenic constraints. It should be possible to reach the maximum number of bunches at 3 TeV with BCMS beams (2748 bunches), while standard beams are only possible with a reduced number of bunches, approximately 2400 bunches at 3 TeV and 1700 at 6.8 TeV [15].
- **Injection kickers:** Vacuum and temperature limitations arise for long, high-intensity back-to-back fills for Beam 1, where the injection kicker system has not yet been upgraded for HL-LHC, which can result in delays during injection for kicker cool-down [24].
- **Radiation-protection constraints:** Only limited collisions are possible with a maximum of 1 fb^{-1} integrated luminosity over the two weeks [25]. No high-luminosity collisions are allowed during the last three days of the tests to avoid delays in the early LS3 activities.
- **RF injection power limitations:** The absence of the high-efficiency klystrons foreseen for installation before HL-LHC operation is expected to lead to higher losses at the start of the ramp and several mitigation measures have been implemented for the test [26].

TEST PRIORITIES

Because of the present machine constraints, full HL-LHC beam conditions cannot be reached before LS3 in a single configuration. The 2026 high-intensity campaign is therefore planned around tests at two beam energies: first, a cycle at 3 TeV top-energy as the main test platform, followed by a second cycle at 6.8 TeV for further validation.

3 TeV Phase

The priority of the 3 TeV phase stems from the fact that it maximizes the information that can be gained on beam-impedance induced heating limitations while remaining within a safer operational envelope. In particular, impedance-driven heating is expected to be largely energy-independent provided that comparable bunch-length evolution can be achieved. At this energy, baseline HL-LHC beams remain within the safe limits for the TCDS, turnaround is faster and the available heat-load margin allows operation with a larger number of bunches. For these reasons, the first phase of the

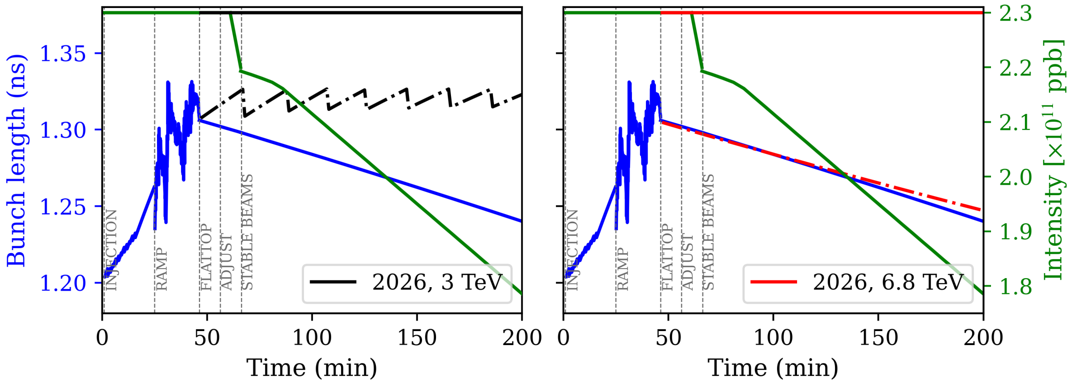

Figure 1: Simulated bunch length (blue) and bunch intensity (green) during collisions for an HL-LHC physics production fill. Left: conditions reproduced during the 3 TeV high-intensity tests; black lines show the simulated intensity (solid) and bunch length (dashed), the latter growing due to IBS and controlled via RF voltage manipulations. Right: bunch intensity (red solid) and bunch length (red dashed) during the 6.8 TeV high-intensity tests.

campaign is centered on tests at 3 TeV, where the objective is to reproduce HL-LHC-like heating conditions as closely as possible and maintain them for several hours.

The main drawback of the 3 TeV cycle is that synchrotron radiation damping is not yet sufficient to compensate the bunch length growth driven by IntraBeam Scattering (IBS) at this energy. Such compensation is expected only at higher energies, around 5–5.5 TeV, depending on the conditions in the transverse plane. As a result, the bunch length naturally increases with time, which would limit the duration over which HL-LHC-like conditions can be maintained.

Figure 1 compares the predicted evolution of bunch length (blue) and bunch intensity (green) during a nominal HL-LHC physics fill at 6.8 TeV, from injection to the first two hours of collisions, in the proposed test scenarios. In the nominal HL-LHC case, bunch intensity decreases because of burn-off, while bunch length decreases due to synchrotron radiation. By contrast, during the 3 TeV tests (left plot) the bunch intensity is expected to remain essentially constant in the absence of collisions (black solid line), while the bunch length would increase because of IBS (black dashed line). To maintain a short bunch length over longer periods, the RF voltage will be increased in steps as discussed in the next section.

At 3 TeV, in terms of beam types, BCMS beams are given highest priority, since they provide the best compromise between large number of bunches and reduced e-cloud heat-load and therefore offer the most favorable configuration to achieve the largest number of bunches [15]. Standard beams are the second priority, as they provide the most representative scenario for the nominal HL-LHC baseline, but with a lower number of bunches in these tests.

6.8 TeV Phase

The 6.8 TeV phase is intended as a complementary validation step for effects that cannot be fully addressed at 3 TeV. The beam conditions targeted during these tests are shown in the right plot of Fig. 1, with bunch intensity represented by a solid line and bunch length by a dashed lines. During this phase, the conditions are closer to the nominal HL-LHC cycle, including top energy optics, collimation settings, synchrotron radiation levels and e-cloud conditions. Its main limitation comes from e-cloud heat load, which restricts the maximum number of bunches to 1700 bunches [15]. In addition, testing 25 ns beams at 6.8 TeV requires accepting a limited risk for the TCDS for a short period of time.

Despite these limitations, the 6.8 TeV phase remains important. Measurements with HL-LHC beam types provide indeed direct information on e-cloud heat-load projections for cells that will not be coated in LS3 and could help steer the selection of half-cells for the BST project. More generally, it also provides valuable operational experience with HL beams from injection to top energy and allows the best possible validation of the beam and machine parameters for the baseline operational scenario. Beyond e-cloud studies, the 6.8 TeV phase could also provide the first opportunity to collide with HL-LHC beams and study beam-beam effects, lifetime, dynamic aperture, halo behaviour and the evolution of transverse tails, including possible e-cloud-related contributions. Halo measurements are in particular important following the project decision to remove from the baseline the hollow electron lenses for active halo control [27]. These studies would provide important input for the baseline operational scenario and complement the measurements at 3 TeV focused on impedance beam-induced heating.

At 6.8 TeV, standard beams are given first priority, since they provide the most direct validation of the nominal HL-LHC operational scenario. Current projections indicate that, because of e-cloud heat-load constraints, only about 1900 bunches may be reachable instead of the nominal 2760. If time allows, 8b4e beams would then be tested as a complementary option. 8b4e beams remain within the TCDS-safe envelope even at full HL-LHC bunch intensity, they provide a valuable way to identify limitations specific to the filling pattern and allow gaining operational experience in case 8b4e or hybrid beams, that combine standard and 8b4e filling patterns, in case they become necessary in the HL-LHC era. Taken together, these studies would probe the two extreme cases within the range of possible HL-LHC filling schemes.

MACHINE DEVELOPMENT STUDIES

A major objective of the 2025 MD studies was to prepare the 3 TeV cycle. As explained in the previous sections, the main limitation is the short time during which the bunch length stays close to HL-LHC conditions. The goal was therefore to control the bunch length evolution and to keep HL-LHC-like conditions for a duration representative of an HL-LHC fill, taking into account that, during the tests, the intensity remains constant due to the absence of collisions. The expected bunch-length evolution was calculated with analytical models of IBS and synchrotron radiation and these models were benchmarked against dedicated measurements.

Simulations indicate that, for an initial transverse emittance of about 2.1 μm, a bunch intensity of 2.3×10^{11} ppb, an initial RF voltage of 7.6 MV and RF voltage steps of 0.5 MV up to 16 MV, it is possible to keep the bunch length at around 1.3 ns for about 20 minutes of each voltage step. This would extend the duration of the 3 TeV plateau to a maximum of about 5-6 h. Since the optimal HL-LHC fill length is about 6 h, including the intensity decay due to collisions, this duration provides an adequate time to probe HL-LHC conditions. The studies also showed that increasing the transverse emittance to about 4 μm, in combination with the RF-voltage steps, could further extend this time scale if needed by about a factor 2.5 through the reduction of the IBS growth rates.

These projections were validated experimentally with dedicated measurements. Six HL-LHC individual bunches were brought to 3 TeV to measure their bunch-length evolution. They were divided into two groups with different transverse emittances: one close to the nominal value of about 2 μm and one around 4 μm. Two methods were successfully tested to obtain the larger transverse emittance: either directly from the injectors or by controlled emittance blow-up with the transverse damper in the LHC at injection.

Figure 2 shows the bunch length evolution of all bunches, comparing the measurements (scatter points) with the model predictions (solid lines). The RF voltage steps applied during the test are also shown in green. Two distinct evolutions are clearly observed, corresponding to the two transverse emittance groups: bunches with lower transverse emittance show a faster bunch length growth, while bunches with larger transverse emittance evolve more slowly.

It should be noted that the bunch length target during this MD was set below the specification of the 2026 tests and will need to be refined. Nevertheless, the study should be regarded as a proof of principle. The comparison between the two groups showed that the measured bunch length evolution is in excellent agreement with the IBS and synchrotron radiation model. These results provide strong confidence in the analytical IBS models for the LHC.

In 2025, a series of MDs focused on HL-LHC beams were also performed. Among the key MDs was the injection of 1152 bunches with the 4×72 HL-LHC beams, focusing on studies of injection losses, RF tuning, debunching due to IBS at injection and its correlation with losses at the start of the ramp [26,28]. These studies enabled the identification of the main limitations and the definition and implementation of mitigations for most of the issues expected during injection and ramping of HL-LHC beams.

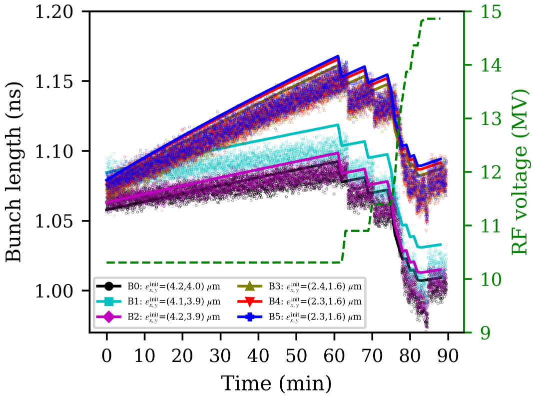

Figure 2: Bunch length evolution at 3 TeV from measurements (markers) and simulated from IBS and synchrotron radiation models (solid lines) for bunches with different transverse emittances. RF voltage steps shown in green.

A dedicated MD was carried out with 8b4e trains at HL-LHC bunch intensity in order to study beam-beam effects at high pile-up and to provide the first collisions with HL-LHC-type beams [29]. In this case, 8b4e beams were chosen to avoid the TCDS risk associated with 25 ns beams at top energy. During the test, the number of bunches was limited to 560 in trains of 2×56 bunches.

During this MD a large vacuum spike in sector 11R2, at the location of the Target Collimator Long Dispersion suppressor (TCLD), resulted in a beam dump. The TCLDs on each side of Point 2, in particular 11R2 for Beam 1 and 11L2 for Beam 2, are important during Pb-Pb operation to intercept particles originating from bound-free pair production. They are not used during proton operation and thus are set at large gaps [30]. Pressure activity above 10^{-6} mbar had already been observed in this region since the installation of the collimator and the start of Run 3 operation in 2022. This pressure rise appeared to be highly unpredictable, with no clear correlation to beam parameters [31], but did not impact beam operation with the nominal 25 ns bunch scheme. During this MD, however, the activity in 11R2 eventually led, after about one hour in collisions with 8b4e, to the first beam dump ever triggered by TCLD vacuum activity that reached the interlock value of 2×10^{-6} mbar.

Although vacuum activity had already been observed around this collimator with other beam configurations, including lower-intensity and hybrid beams, this event suggests a particular sensitivity of the TCLD to 8b4e beams. Impedance simulations have identified possible mitigations, such as operation with smaller gaps [32]. Since 8b4e beams are not used routinely in operation, some degree of conditioning over time is likely to occur. Dedicated studies with

8b4e beams can therefore help determine whether this limitation can be conditioned, while high-intensity tests with nominal 25 ns beams would allow to assess whether similar effects may also arise with HL-LHC beams.

TENTATIVE TIMELINE FOR THE 2026 HIGH-INTENSITY TESTS

The tentative proposal for the 2026 high-intensity test is based on a two-week campaign at the end of June 2026, after the ion run and before the start of LS3. The overall idea is to move gradually beyond present operational levels in terms of beam intensity and beam-induced heating, while keeping the strategy sufficiently staged to identify possible limitations early and adapt the program if needed. The first week is centered around the 3 TeV cycle, while the second week is devoted to 6.8 TeV.

The first days are devoted to preparation, cycle validation and an initial intensity ramp-up with both beams in the machine up to a level equivalent, in terms of beam-impedance-induced heating, to present operational conditions as required for machine protection. In this first week, the bunch intensity is kept constant at 2.3×10^{11} ppb, while the number of bunches is gradually increased fill by fill. This avoids the need to retune the bunch intensity from the injectors at every fill resulting in faster filling.

The proposed program then moves to single-beam operation, alternating between Beam 1 and Beam 2. This is motivated first, by the need to provide some cooling time for the Beam 1 injection kicker that has not yet been upgraded for HL-LHC beams and second, to reduce exposure to known vulnerabilities in warm vacuum modules located in common regions around ATLAS and CMS [4]. These vacuum modules will in any case be replaced during LS3. Indeed, the objective is not to be limited by equipment that is already scheduled for replacement, but rather to identify limitations that are relevant for HL-LHC operation. Once the maximum number of bunches has been reached, the proposed program proceeds to tests with both beams in the machine, increasing the number of bunches from about 1500 to the maximum in several steps.

The second week is devoted to 6.8 TeV and the proposal follows a different strategy. In this case, the starting point is 2460 bunches at a bunch intensity of 1.8×10^{11} ppb. The bunch intensity is then increased gradually towards 2.3×10^{11} ppb, while the number of bunches is reduced due to e-cloud heat-load limits. This approach provides the possibility to obtain e-cloud heat-load measurements at different bunch intensity steps and to refine the corresponding projections for HL-LHC operation. At 6.8 TeV, the main priority is the study of e-cloud with single-beam and both-beam configurations. At the end of e-cloud measurements, the beams can be brought into collisions thus obtaining for the first time measurements of beam lifetime, transverse tails and halo population with HL-LHC beams at the start of collisions, which is a critical phase in the cycle. However, these studies require accepting a limited but non-zero risk for the TCDS. Finally, if the program advances sufficiently far, 8b4e beams can be tested as a complementary option.

ADVANCING SELECTED TESTS

Two days of the high-intensity test program have been advanced to May 2026. As a result, the overall strategy is split into two parts: an early validation phase and the main dedicated high-intensity campaign at the end of June. The purpose of this early phase is to start probing the machine beyond present operational levels, gain first operational experience under these conditions and reduce the risk of encountering early showstoppers during the first days of the final campaign.

During these advanced tests, the plan is to perform single-beam studies at 3 TeV, gradually pushing the beam-induced-heating conditions beyond the present operational envelope. The strategy starts by increasing the number of bunches in small steps from fill to fill, first reaching conditions of about 25% above present operational levels and, if no issues are encountered, progressing towards 40% above the current envelope. At this stage, the goal is not yet to reproduce the full high-intensity test program, but rather to identify possible hard limitations early, validate procedures and gain experience beyond routine operation. At the same time, the level of risk must remain limited, since nominal physics production will continue after the tests.

CONCLUSIONS

The 2026 high-intensity tests are a critical step in the preparation for the HL-LHC era. Their main motivation is either to demonstrate successful operation with HL-LHC beams or to identify limiting devices and implement mitigations during LS3, rather than discovering such constraints only in Run 4. This remains essential, since the HL-LHC operational scenario has very limited tolerance to intensity limitations or hardware-related downtime in order to achieve its challenging integrated luminosity goals. At the same time, the scope of the program has grown well beyond hardware compatibility alone. The tests are also expected to provide operational experience with HL-LHC beams, guide LS3 actions and studies, strengthen confidence in the future operational scenario and overall improve readiness for HL-LHC.

To overcome present machine constraints and cover the widest possible range of cases, the proposed program combines two beam energies and tests with several beam types, from the nominal HL-LHC baseline to alternative scenarios. The 2025 MDs have already provided crucial input both for the 2026 campaign and for HL-LHC. They enabled first experience with HL-LHC beams, validated key elements of the 3 TeV cycle strategy, strengthened confidence in the analytical models and identified important points to be followed in 2026. The two days of the high-intensity tests that have been brought forward earlier in 2026, will provide further input and help maximize the chances of success of the final campaign. Taken together, these studies are expected to provide critical input for the preparation of the Run 4 operation.

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