

OVERCOMING RF POWER LIMITATIONS FOR THE HL-LHC ERA*

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Abstract

Limitations in RF power at the injection plateau of the Large Hadron Collider (LHC) have been a major concern for the High-Luminosity (HL) LHC era. The increased bunch charge requires more RF power to compensate beam loading. A higher RF voltage at the injection plateau is moreover vital for both the RF capture and to counteract particle leakage from the buckets. The projected RF power with HL-LHC parameters is beyond what the currently installed klystrons can provide. Consequently, an unacceptable amount of particles lost at the start of acceleration is expected. These limitations have now been overcome, thanks to a combination of several mitigations. More power from high-efficiency klystrons will be complemented by an evolved optimization of the RF system parameters in terms of tuning and quality factor. This contribution will give an overview on the operational improvements and mitigation measures that are currently being put in place to handle the HL-LHC beams. Essential studies in the framework of the LHC high-intensity tests in 2026 are outlined.

INTRODUCTION

The Large Hadron Collider (LHC) will undergo a high-luminosity (HL) upgrade for the next physics run starting in 2030 [1, 2]. A large portion of the luminosity increase will come from doubling the design bunch intensity from 1.15×10^{11} protons per bunch (p/b) to 2.3×10^{11} p/b at injection. The higher bunch intensity will significantly increase the power demand of the LHC RF system, due to stronger beam loading effects. In addition, increased RF voltage is required to maintain an acceptable amount of beam losses at the start of the acceleration ramp.

The start-of-ramp losses have two main sources. Uncaptured beam is generated at the bunch-to-bucket transfer when particles from the Super Proton Synchrotron (SPS) arrive outside the RF buckets in the LHC. The momentum spread of the HL-LHC bunches is expected to be larger, requiring a higher RF capture voltage to maintain the current amount of uncaptured particles. The other source is particles leaking from the RF buckets. Filling the two LHC rings with beam at the injection plateau takes on the order of 30 min to 60 min depending on the number of injections. During this time the circulating bunches slowly lengthen due to intra-beam scattering (IBS) and noise from the RF system [3]. Both these effects will cause particles to diffuse out of the RF buckets and circulate asynchronously with respect to

the RF system. In particular, IBS-driven bunch lengthening will become stronger with HL-LHC bunch intensities for which a higher RF voltage will be the main cure. Both the uncaptured beam and the particles diffusing out of the RF buckets will keep circulating outside the RF buckets until they are either removed by the abort-gap cleaning using the transverse damper [4] or are lost at the start of the ramp. By design, the start-of-ramp beam losses originating from the off-momentum particles will mainly be intercepted on the collimators in interaction region (IR) 3 [5, 6].

Beam loss monitors (BLMs) are placed all along the LHC ring to track particle losses over 12 running sums. Each running sum of each BLM has a threshold beyond which the BLM will trigger the beam to be sent to the beam dump [7]. Hence, if the capture voltage is insufficient, the amount of off-momentum particles will increase, leading to frequent beam dumps.

There are two ways to overcome these losses. One way is to accept more losses. This can be attained by, for instance, increasing the threshold of the BLM system in IR 3, provided that the equipment can accept more losses. Moreover, by removing additional off-momentum particles with the transverse damper prior to the ramp, a portion of the losses can be moved to the pre-ramp phase. However, the preferred way is to limit the generation of unbunched particles in the first place, which can be done by increasing the RF voltage. For HL-LHC, it is estimated that a total RF voltage of 7.9 MV is required to maintain the current amount of beam losses. This would require a peak RF power beyond the 300 kW available from the LHC klystrons by design [8]. The acceleration of beams during the HL-LHC era will therefore require a combination of both optimizing the RF system to maximize the RF voltage and accepting more start-of-ramp losses.

OPERATIONAL OPTIMIZATION OF THE LHC RF SYSTEM

Studies were conducted on multiple fronts during the current run (2022-2026) to optimize the operation of the RF system in the LHC. One of the conclusions from the last run (2018) was the importance of frequent energy matching between the SPS and LHC [9]. Above a certain offset in energy between the two accelerators, the amount of uncaptured particles would increase significantly, adding to the beam losses at the start of the ramp. These offsets were as high as 200 ppm, corresponding to 90 MeV. After more regular corrections of the SPS-LHC energy matching during the current run, the standard deviation of the offsets for operational fills was reduced to 30 MeV [10].

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An optimization of the beam-loading compensation was performed to maximize the RF capture voltage for the injection plateau. To minimize the average power in steady state, the half-detuning beam loading compensation scheme is used at injection energy in the LHC. The cavity resonant frequency is detuned half-way between being resonant with and without beam [11]. The detuning set-point phase, related to the cavity detuning respective to the RF frequency, in the tuner controller must be optimized every time the beam current changes. Previously, this phase was optimized manually for all 16 cavities, while keeping the loaded quality factor constant. For HL-LHC, this phase will have to be adjusted more regularly, perhaps even during the injection process, to maximize the voltage. An iterative algorithm has therefore been developed and implemented to help automatically optimize the cavity frequency [12]. The plan for HL-LHC is to also create an optimizer for the adjustment of the cavity loaded quality factor, to further improve the beam-loading compensation and reduce the RF power required at a given voltage.

In the past, the injection of the very first long bunch train was considered to be the most limiting point of the LHC cycle in terms of RF power. The tuner controller, regulating the resonant frequency of the cavities, needs beam to bring the cavities into half-detuning, which takes on the order of 1 s [13, 14]. The cavities are initially tuned to the RF frequency when the first long bunch train is injected. This causes a large spike in beam-induced voltage, and consequently RF power, which limits the maximum RF voltage. To reduce the power transients right after injection of high-intensity bunch trains, the approach was to pre-detune the RF cavities to anticipate the beam loading of the first long train. The pre-detuning of the RF cavities at injection was optimized in simulations, showing good agreement with measurements, and is now used in operational physics fills [12, 15]. This has enabled the capture of high-intensity trains up to the HL-LHC bunch intensity with an RF voltage of 6 MV while minimizing the peak power as soon as the beam is present.

Figure 1 shows the reduction in peak RF power from simulation as a function of the pre-detuned cavity frequency $\Delta\omega$. The peak RF power is estimated from the first 500 turns after injecting the initial 288-bunch standard HL-LHC train with an RF voltage of 7.9 MV. As indicated in the figure, the peak power is reduced by a factor 2.5 from 943 kW without pre-detuning to 378 kW with pre-detuning [10, 12]. For comparison the peak power at injection in operation currently is on the order of 200 kW to 250 kW with a bunch intensity of 1.6×10^{11} p/b.

Applying the full-detuning scheme to further reduce the RF power demand at injection is currently being studied [10, 16, 17]. In this configuration, the RF cavity phase is modulated bucket by bucket to fully compensate beam loading. It is already applied during the acceleration ramp and at collision energy in the LHC [17]. However, it requires a modulated bunch-by-bunch phase of the injected beam. Figure 2 depicts the turn-by-turn transient in peak RF power

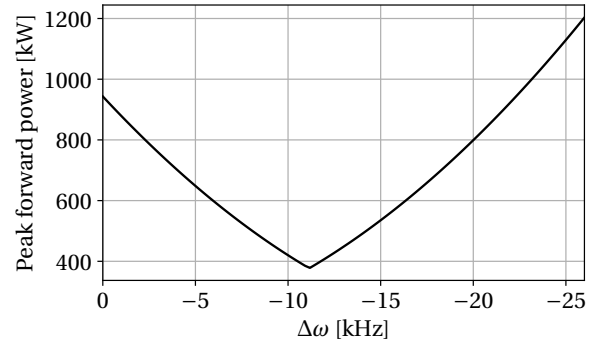


Figure 1: Peak power over the first 500 turns as a function of the pre-detuned frequency of the cavities from simulation with HL-LHC parameters [10].

at injection of the first 288-bunch HL-LHC standard train in simulation for four different capture voltages. The target voltage of 7.9 MV is within the capabilities of the current klystrons with full-detuning at injection.

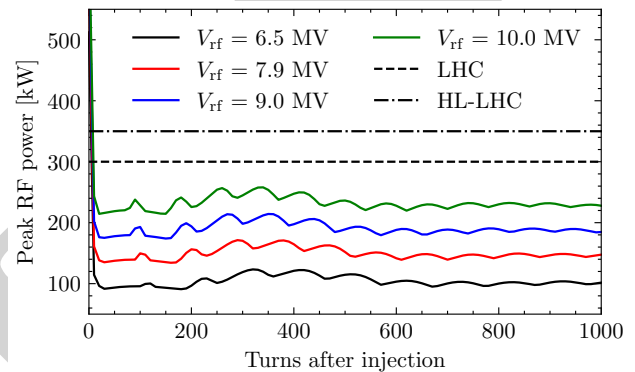


Figure 2: Simulated peak turn-by-turn RF power at injection in full-detuning at different RF voltages.

Tests are currently ongoing to produce these phase-modulated bunch trains from the SPS and a machine development (MD) session is planned to validate the injection process and the benefits in RF power at LHC injection. If successful, this could give additional operational power margin and possibly increase the RF voltage to further decrease start-of-ramp losses.

LOSSES AT THE START OF THE RAMP

The need to limit the beam losses at the start of the ramp constrains the RF voltage and hence the RF power at injection. A way to alleviate some of the power requirements of HL-LHC is therefore to accept more beam losses. Studies have been performed to probe the power deposition allowed in IR 3 [18]. In the past, the allowed power deposition was around 60 kW, but recent measurements indicate that up to 500 kW can be lost without damaging the equipment. The dump thresholds of the BLM system have been gradually increased since 2024 as a result. For the 2026 run, the applied BLM thresholds will allow up to 200 kW, an increase of a factor 3.3.

The off-position beam, related to the amount of off-momentum population, at the start of the ramp was estimated in the same way as in [19] during operation in 2024, 2025, and 2026. This was correlated with the maximum ratio to the dump threshold in IR 3 at the start of the ramp. The result of this analysis is summarized in Fig. 3. The maximum fraction to dump the beam is calculated by computing the proportion of the reading of each running sum of each BLM to its respective threshold, and then finding the maximum ratio overall in IR 3.

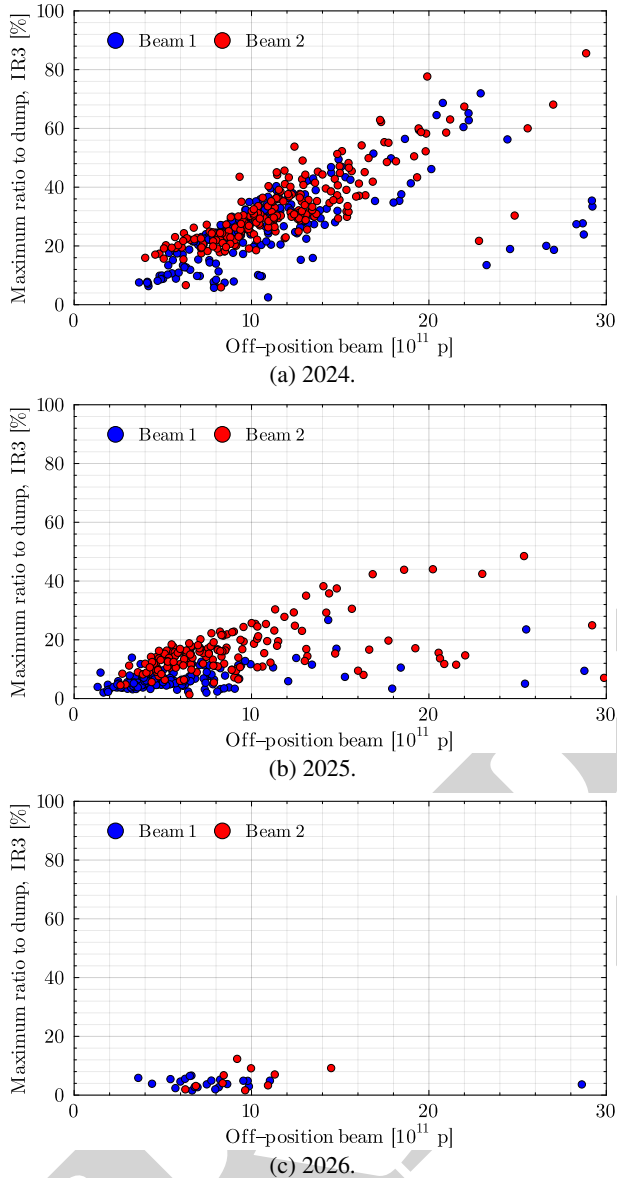


Figure 3: Maximum ratio of dump threshold in IR 3 as a function of estimated off-position beam at the start of the ramp. Each point corresponds to a fill.

The ratio to dump for a given amount of off-position beam, on average, has decreased over the past three years due to the threshold increase. This can be observed from 2024 to 2025 and is reflected by the decrease in the slope between Fig. 3a and Fig. 3b, which is caused by the thresholds of the most limiting BLM in IR 3 being increased. There was also an RF

voltage increase from 5.5 MV to 6.5 MV during this period, which explains the lower amount of off-position beam overall in Fig. 3b and 3c. At the time of writing, there have not yet been many physics fills during the 2026 run. So far in 2026, all physics fills have had a ratio to dump below 20%, with a comparable amount of off-position beam compared to 2025.

THE 2026 HIGH-INTENSITY TEST

A high-intensity (HI) beam test is scheduled for the end of the 2026 run, where the LHC will run with beams of HL-LHC intensity for two weeks to probe the HL-LHC operational scenario. Among the potential limitations for HL-LHC, this test will give insight into the operation of the RF system during this era.

The installation of high-efficiency (HE) klystrons is foreseen for HL-LHC and will increase the available RF power for each cavity from 300 kW to 350 kW [20]. Calibration studies of the LHC RF system have shown that with the current klystrons the capture voltage is limited to 6.5 MV while the HE ones could give an additional 1 MV [21]. As the HE klystrons will not be available during the HI test, the start-of-ramp losses will be higher than in the HL-LHC era. The temporary solution for the HI test will instead be to increase the BLM system's dump thresholds in IR 3. Around 6 MV is expected to be sufficient to avoid frequent beam dumps with the threshold increase. This will come at the cost of losing a significant amount of the beam during the injection process. Simulations show that the combined bunch intensity loss from uncaptured particles and IBS-driven debunching can be as much as 1.5% to 2.3% without the extra power from the HE klystrons [10]. For reference, the design specifications for HL-LHC give a 4.3% total loss in intensity from SPS extraction to collisions. The amount of losses during the HI test will likely not be acceptable during HL-LHC as there are other parts of the cycle where significant losses are expected as well.

CONCLUSIONS

A number of studies have been performed during the current LHC run to address the RF power limitations during the injection plateau for the HL-LHC era. In particular, the optimization of beam-loading compensation through the half-detuning algorithm and pre-detuning at injection were essential. This has already enabled the capture of bunch trains with 2.3×10^{11} p/b while using an RF voltage of 6 MV and without saturating the klystrons for a significant amount of time.

Moreover, the increase in BLM thresholds in IR 3 will be an important ingredient for the HL-LHC operational scenario for the RF system as well. The updated thresholds will be particularly essential to accelerate beams during the 2026 HI beam test as the HE klystrons will not be available. The HE klystrons and potentially applying full-detuning at injection will further improve operational margins by increasing the available RF voltage.

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