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UPGRADE OF THE LHC MAIN RF SYSTEM FOR HL-LHC*

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Abstract

In the era of the High-Luminosity Large Hadron Collider (HL-LHC), the main RF system will be limited in voltage and power on the injection plateau due to strong beam loading. At the same time, significant start-of-ramp losses, originating from capture and flat bottom losses, are expected and can severely impact machine availability or even prevent the beam from reaching the collision energy. In this contribution, we present the recent experience with high-intensity beams during operation and dedicated measurements to give an update on the estimated RF voltage reach for HL-LHC beam parameters. Projections for beam losses at capture, along the flat bottom, and at the start of the ramp are calculated, taking into account also the effect of intra-beam scattering. We discuss in detail the mitigation measures put in place, such as high-efficiency klystrons, the revision of beam loss monitor thresholds at the start of the ramp, and automatic working point optimization.

INTRODUCTION

The main RF system of the Large Hadron Collider (LHC) consists of eight single-cell, superconducting RF cavities per beam, capable of maintaining a total voltage of up to 16 MV. Each cavity is equipped with a movable fundamental power coupler, through which the loaded quality factor Q_L can be adjusted approximately in the range of 10 k to 100 k, and a motor-driven tuner through which the resonant frequency of the cavity can be modified. Each cavity is separately driven by a 300 kW-rated klystron [1].

For the High-Luminosity (HL)-LHC era, the most challenging working point for the main RF system is the beam injection plateau. The required capture voltage is determined by the beam losses that can be accepted at the start of the ramp. Although this capture voltage is 'only' a projected 7.9 MV, the strong beam-loading conditions require the klystrons to work close to saturation. In the half-detuning beam-loading scheme, the RF voltage vector is maintained constant and the average RF power is minimized through detuning the cavities by half the beam-induced frequency shift, and optimizing as well the Q_L [3]. With the nominal HL-LHC beam, the peak RF beam current is 2.17 A for an emittance of 0.58 eVs after injection and filamentation, and the minimum average power is 270 kW, using a detuning of -9.9 kHz and a Q_L of 20.2 k. The corresponding steady-state power transients, determined by the RF- and one-turn-delay (OTFB) feedbacks, are expected to reach at least 320-330 kW, while from experience the present RF system can only supply ~270 kW with operational margin.

BEAM LOSSES AT INJECTION

The required RF power is determined by the capture voltage, which in turn is determined by beam loss constraints. To fill each ring in the LHC, typically 16-24 injections are necessary. At every injection, there are immediate capture losses when transferring the SPS bunches to the LHC, whose RF bucket is half the length. While new bunch trains are being injected, the circulating bunches are blown up due to background RF noise and intra-beam scattering (IBS), causing more particles to leak out of the RF buckets. In parallel, de-bunched beam drifting to the abort gap is being cleaned through noise excitation in the horizontal plane [2], injected in the transverse damper (ADT). The main bottleneck is the remaining de-bunched population at the start of the ramp. Beam loss monitors (BLM) around the interaction region (IR) 3 monitor the off-momentum losses and trigger the beam dump above a certain threshold to protect sensitive equipment from irradiation. To ramp the HL-LHC beams to flattop energy and bring them into collision, the RF capture voltage has to be large enough to keep the losses below the start-of-ramp BLM dump thresholds.

2024 Operational Experience

In 2024, two 25 ns-spaced beam types produced in the Proton Synchrotron (PS) – the so-called batch compression, merging, and splitting (BCMS) and the 'standard' beam – were used in LHC physics fills at an intensity of $1.6{\times}10^{11}$ p/b. Longitudinally, both beam types arrive with the same bunch length and momentum spread to the LHC. However, the BCMS beam has 20-25 % smaller horizontal and vertical emittances [4], and hence, larger IBS growth rates. To guarantee good machine availability, the capture voltage had to be increased from 5 MV to 5.5 MV when transitioning from the standard to the BCMS beam. Even with this 10 % increase in voltage, the start-of-ramp losses remained closer to the dump threshold with BCMS beams, see Fig. 1.

The 10 % voltage increase for BCMS beams can be taken as a worst-case estimate to make projections on RF power requirements for HL-LHC. First simulation studies [5], however, indicate that the difference in de-bunching rate should be smaller at $2.3{\times}10^{11}$ p/b than at $1.6{\times}10^{11}$ p/b.

For both beam types used in 2024, the LHC was filled with bunch trains of up to 3×36 b, with 24 injections in total. With this filling scheme, the injection took typically around one hour.

MEASUREMENTS WITH HL-LHC BEAMS

Several tests with HL-LHC beams were performed in 2024 in the LHC on the injection plateau using the BCMS beam type, with bunch trains of 2×48 b. The beam had a

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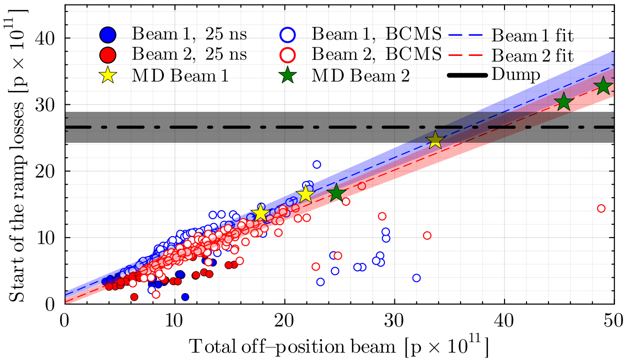

Figure 1: Start-of-ramp losses as a function of total off-position beam, which is outside the filled RF buckets, in operation for standard (full markers) and BCMS beam (empty markers), for Beam 1 (blue) and Beam 2 (red). The beam dump threshold is marked with a dashed black line. Results from measurements with HL-LHC beam on flat bottom are marked with yellow (Beam 1) and green (Beam 2) stars.

nominal intensity and spread of (2.3±0.3)×10^{11} p/b along with a slightly reduced bunch length and momentum spread with respect to the HL-LHC baseline, see Table 1. The latter was due to a reduced RF voltage being available in the main RF system of the LHC injector, the Super Proton Synchrotron (SPS), 8.4 MV instead of the nominal 10 MV.

Table 1: BCMS beam parameters at SPS extraction and LHC RF voltage in 2024 operation with 1.6×10^{11} p/b (top row) compared to 2024 high-intensity measurements (middle row) and HL-LHC baseline (bottom row), both with 2.3×10^{11} p/b.

When	**Bunch length**	**Momentum spread**	**Transverse emittance**	**LHC voltage**
2024 op.	1.54 ns	4.58×10^{-4}	1.15 µm	5.5 MV
2024	1.60 ns	4.81×10^{-4}	2.15 µm	6.5 MV
HL-LHC	1.65 ns	5.32×10^{-4}	1.65 µm	7.9 MV

In a simplistic model, the required LHC voltage V_{LHC} for HL-LHC can be assumed to scale based on capture losses only, with the square of the momentum spread of the incoming beam $V_{\mathrm{LHC}} \propto \delta^2_{\mathrm{SPS}}$. Although in reality, start-of-ramp losses are a mix of capture and flat-bottom losses, along with ADT cleaning, so far, this scaling has proven to work in operation. In the 2024 high-intensity tests, the ratio of $V_{\mathrm{LHC}}/\delta^2_{\mathrm{SPS}}$ was the same as for the baseline HL-LHC scenario, while for operation a 6 % lower voltage was used.

At injection, the total off-position beam can be measured and compared to the operational fills to estimate what the losses at the start of the ramp would have been [5,6], see star markers in Fig. 1. In one case, three bunch trains have even been accelerated from 450 GeV to 500 GeV to see the actual start of ramp losses, and with 348 b spending an average of 6 minutes on flat bottom, the start-of-ramp losses reached 48 % of the dump threshold. This showed that, contrary to the operational experience, in the high-intensity test the capture losses were dominating over the ones driven by IBS, possibly due to the short time spent on flat bottom. From this test, one can estimate that with the present RF system and BLM thresholds, the number of HL-LHC bunches that can be accelerated is limited to ~750 b, while a full machine can reach up to ~2800 b depending on the filling scheme.

Voltage Estimates for HL-LHC

In the 2024 high-intensity test, the maximum voltage was 6.5 MV, with most klystrons being driven to saturation, and the OTFB being disabled. Working at saturation is, however, undesirable as it increases the amount of RF trips and as the low-level RF module that protects the klystron from overdrive needs to operate in a linear gain region below saturation. With operational margin, it is estimated that only ~6 MV could be maintained in HL-LHC conditions. In addition, should the OTFB be indispensable at injection, which is presently still under study, additional power transients of ~35 kW reduce the maximum RF voltage to ~5.5 MV.

For the HL-LHC era, the present klystrons are to be replaced by high-efficiency klystrons (HEK) [11] with an efficiency of 70 % instead of 60 %. While the high-voltage supply will be unchanged and delivering 500 kW DC, this will increase the nominal power from 300 kW to 350 kW. The upgrade represents 17 % more power and 8 % more voltage becoming available after the upcoming Long Shutdown (LS 3). Even if we scaled the 6.5 MV achieved in saturation in 2024, this would only bring us to 7.0 MV, without operational margin, and still 11 % below the estimated required voltage. Taking into account an operational margin and the need for a OTFB, this figure rises even to 30 %. In other words, the implementation of HEK is essential and necessary, and at the same time, additional mitigation methods will be required to achieve the HL-LHC goals.

MITIGATION STRATEGY

Apart from the HEK upgrade, several mitigations have been worked on. The three main areas are detailed below.

Calibration Efforts

In parallel to beam measurements and beam loss studies, significant effort has been put in the past seven years into calibrating basic RF parameters – voltage V, power P, and cavity loaded quality factor Q_L as accurately as possible. Without beam, these quantities relate as follows:

$$P = \frac{V^2}{8 \, {}^{R}\!/_{Q} \, Q_L} , \qquad (1)$$

where $R/Q = 45\ \Omega$ for the LHC cavities.

As a result of beam-based voltage calibration with small-intensity and small longitudinal emittance bunches, the voltage error has been lowered in previous years from 10 % to 3 % for each cavity [7]. Despite knowing the voltage experienced by the beam very well, if the observed klystron saturation is not at 300 kW, and/or the Q_L working point is inaccurate, the maximum voltage will be reduced.

Table 2: Deviation of the actual Q_L close to saturation from the 20 k working point determined at low power. Measured for the 16 RF lines of the LHC main RF system.

1B1	2B1	3B1	4B1	5B1	6B1	7B1	8B1
-5950	-4430	-1250	-4960	-6520	920	980	-5900
1B2	**2B2**	**3B2**	**4B2**	**5B2**	**6B2**	**7B2**	**8B2**
-300	720	-60	1990	-40	-930	-270	-5930

During 2025 hardware commissioning, the Q_L calibration method was significantly improved. Firstly, by measuring the voltage decay in the cavity when the RF is switched off in a step-like manner, as opposed to open-loop feedback response measurements used in previous years. Secondly, by comparing the Q_L at high- and low power. This demonstrated that the measured Q_L near saturation can differ significantly from its value at low power, see Table 2. This is attributed to the change in matching (impedance) between the circulator and the fundamental power coupler of the cavity as the power increases, see Fig. 2. An improved circulator adjustment for HL-LHC injection is to be studied during LS 3.

As for the power, all klystrons used to be adjusted to work at the same cathode voltage and current settings. However, the cathode current reading has its own uncertainty. In 2025, the RF measurement lines including the directional couplers of the klystron forward power acquisition were re-calibrated. With these new calibration factors, the power measurement is estimated to be known within 10 % precision [8]. Appropriate cathode currents were applied to each line to achieve 280–290 kW on most of them.

Combining these updated calibrations, the measured and calculated powers now agree, for all lines, within the known uncertainties. This more accurate working point should also provide us with a slightly increased voltage at flat bottom, which will be probed in 2025 with high-intensity beams.

Minimizing Beam Losses

The requirements on the capture voltage, and thus the RF power, can be relaxed if the start-of-ramp losses decrease with respect to the dump threshold. This can be achieved in three principal ways. Firstly, the start-of-ramp losses can be minimized by shortening the time spent on flat bottom. Therefore, injection schemes with less injections are favourable, which could shorten the injection time to almost one half, by injecting e.g. bunch trains of 4×72 b according to the baseline HL-LHC scheme. Also dedicated LHC filling could potentially help to lower time between injections.

Secondly, more efficient cleaning of the de-bunched beam on flat bottom would also decrease the start-of-ramp losses. Tests of inter-bunch-train ADT cleaning and RF noise cleaning are foreseen in 2025 for the first time.

Thirdly, the BLM thresholds themselves are being revised and irradiation studies on the sensitive equipment are being performed. Based on the scaling between off-position beam and start-of-ramp losses observed in the past years, it is estimated that a factor two increase in BLM thresholds could reduce the required voltage by 18 % at 1.6×10^{11} p/b.

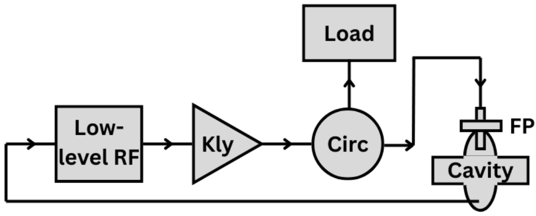

Figure 2: Sketch of the LHC RF line for one cavity, containing a klystron (kly), circulator (circ), load, fundamental power coupler (FPC), cavity, and low-level RF.

Minimizing Power Transients

The third pillar of the mitigation strategy is minimizing the required average klystron forward power, and reducing power transients along the ring.

In the half-detuning scheme, the power consumption is minimized in operation by finding the optimum Q_L and cavity tune experimentally, during beam commissioning. An automated procedure is currently being implemented to operate in the background at each injection, adjusting to variations in beam intensity and bunch length. In addition, to avoid power transients at the injection of the first bunch train, the cavities are pre-detuned before the arrival of the beam. The pre-detuning phase is optimized experimentally as well, see [9].

Furthermore, the option of using the full-detuning beam-loading compensation scheme [10] at injection is being studied, promising a 60-70 kW peak power reduction. In the full-detuning scheme, both average and peak power are reduced by allowing the RF phase to slip bunch by bunch. For this scheme to work at injection, without inducing more beam losses, the same bunch-by-bunch phase shift that is required in the LHC will also have to be obtained at SPS extraction.

CONCLUSIONS

In the HL-LHC era, RF voltage and power limitations are expected due to the tight beam loss constraints at start of ramp. In 2024, advances have been made in understanding beam-type dependent beam losses, where IBS-driven debunching plays a key role. Measurements with high-intensity beams confirm the required 7.9 MV capture voltage needed for HL-LHC. High-efficiency klystrons will provide 8 % more voltage margin. At the same time, at least 11 % in voltage is still missing. Several mitigation measures to reduce beam losses, power transients, and operational margins, are being studied and put in place for the post-LS 3 era.

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