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ADVANCES ON LHC RF POWER LIMITATION STUDIES AT INJECTION*

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Abstract

The average power consumption of the main RF system during beam injection in the High-Luminosity Large Hadron Collider is expected to be close to the maximum available klystron power. Power transients due to the mismatch of the beam and the action of control loops will exceed the available power. This paper presents the most recent estimations of the injection voltage and steady-state power needed for HL-LHC intensities, taking also beam stability into account. It summarises measurement and simulation efforts ongoing to better understand power transients and beam losses, and describes the operational margin to be taken into account for different equipment.

INTRODUCTION

The LHC is equipped with eight radio-frequency (RF) lines per beam. Each line consists of a high-power klystron, a single-cell superconducting cavity, and an independent cavity controller. The cavity controller comprises a one-turn-delay and a direct RF feedback, the latter having a low- and a high-pass branch.

For proton operation at the injection plateau, a dominant portion of the forward RF power is required to compensate beam loading. During the injection process, the RF voltage has to be kept constant over one turn, both in amplitude and phase, to efficiently capture SPS trains of bunches, which arrive with an equi-distant bunch spacing. With the voltage vector kept constant, the lowest power consumption is achieved using the half-detuning beam loading compensation scheme [1]. After the injection process, an adiabatic transition to the full-detuning beam-loading compensation scheme [2, 3] takes place, in which only the voltage amplitude is kept constant and the RF phase is modulated over the turn. This allows for a significant reduction in the RF power, providing the required voltage during the energy ramp and flattop, which would otherwise be beyond the reach of the present system.

For the LHC superconducting cavities, we apply the circuit model of the cavity-transmitter-beam interaction as derived in [4], where the generator current I_{gen} can be related to the cavity voltage V, the cavity detuning $\Delta\omega \equiv \omega_r - \omega_{\text{rf}}$ from the resonant ω_{r} to the RF angular frequency ω_{rf}, the loaded quality factor Q_L and the RF beam current $I_{\text{b,rf}}$ as follows:

$$I_{\text{gen}}(t) = \frac{V(t)}{2 R/Q} \left(\frac{1}{Q_L} - 2i \frac{\Delta\omega}{\omega_{\text{rf}}} \right) + \frac{dV(t)}{dt} \frac{1}{R/Q\, \omega_{\text{rf}}} + \frac{1}{2} I_{\text{b,rf}}(t)\,, \tag{1}$$

where $R/Q = 45\,\Omega$ [5]. The half-detuning scheme optimises the detuning and the loaded Q to

$$\Delta\omega_{\text{opt}} = \frac{R/Q\, I_{\text{b,rf}} \omega_{\text{rf}}}{4V} \quad \text{and} \quad Q_{L,\text{opt}} = \frac{2V}{R/Q\, I_{\text{b,rf}}}\,. \tag{2}$$

Under steady-state conditions, this results in the minimum average klystron forward power of

$$P_{\text{gen,opt}} = \frac{1}{8} \frac{V^2}{R/Q\, Q_L} + \frac{1}{32} R/Q\, Q_L I_{\text{b,rf}}^2 = \frac{V I_{\text{b,rf}}}{8}\,. \tag{3}$$

At high bunch intensities towards the HL-LHC target, RF power limitations are expected (i) during the injection process and (ii) along the flat bottom [6]. This is because the SPS RF bucket has twice the length of the LHC bucket, and the SPS extracted bunch length[1] τ is long compared to the LHC bucket; for HL-LHC intensities, the bunch length spread over one bunch train is expected to be (1.65 ± 0.15) ns compared to the 2.5 ns RF period. Both capture and flat bottom losses are highly undesired as they hit the accelerator aperture at the start of the ramp. They can trigger a beam dump if they exceed the machine protection limits, in which case a roughly two-hour magnetic cycle is needed before beam can be injected again. Thus, on one hand, a higher the capture voltage is desirable to lower the losses from the tails of the bunches. On the other hand, a lower injection voltage reduces the power consumption. At injection, the maximum power consumption occurs in turn-by-turn and bucket-by-bucket transients that are due to the mismatched bunch, energy and phase errors at injection, and the action of global and local control loops. In steady state, bucket-by-bucket transients remain due to the regulation of the LHC cavity control loop.

RF POWER LIMITATIONS

Based on the LHC 2018 (Run 2) operational experience and the expected future SPS beam parameters, detailed RF power and voltage estimates for Run 3 and HL-LHC were given and refined [7–9]; see Table 1. In 2018, the capture voltage in the LHC was reduced stepwise over a period of about one month. The minimum voltage operationally acceptable was found to be 4 MV, as start-of-ramp losses occasionally reached up to 60 % of the beam dump threshold [10]. At that time, SPS-LHC energy matching and energy errors varied between -60 MeV to +90 MeV (or -1.3×10^{-4} to $+2.0\times10^{-4}$ in relative momentum offset) [10]. The largest

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[1] The bunch length is defined as a scaled full-width-half-maximum (FWHM) bunch length $\tau \equiv 2/\sqrt{2\ln 2}\,$FWHM. For a Gaussian bunch, this results in a four-sigma bunch length.

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Table 1: Estimates of LHC capture voltage V_{LHC} and optimum, average klystron forward power in the half-detuning scheme $P_{\mathrm{gen,opt}}$, based on 2018 operation with bunch intensity N_b and momentum spread δ_{SPS} at SPS extraction.

When	N_b	δ_{SPS}	V_{LHC}	$P_{\mathrm{gen,opt}}$
2018	1.4×10^{11} p/b	3.74×10^{-4}	4 MV	84 kW
Run 3	1.8×10^{11} p/b	4.59×10^{-4}	6 MV	161 kW
Run 3	1.8×10^{11} p/b	4.95×10^{-4}	7 MV	183 kW
HL-LHC	2.3×10^{11} p/b	5.32×10^{-4}	7.8 MV	265 kW

losses occurred for a +90 MeV offset. The voltage estimates in Table 1 are then simply scaled from the 2018 momentum spread δ_{SPS} and capture voltage V_{LHC}:

$$V'_{\mathrm{LHC}} = \left(\frac{\delta'_{\mathrm{SPS}}}{\delta_{\mathrm{SPS}}}\right)^2 V_{\mathrm{LHC}} \, . \qquad (4)$$

The design klystron forward power is 300 kW [11]. According to the HL-LHC estimates, capturing proton beams would be difficult, as the power transients between beam- and no-beam segment would go beyond the available power.

ADVANCES IN 2023

In Run 3, a concerted effort was put to systematically ensure good SPS-LHC energy matching. Since 2023, also beam profiles are logged during the first 500 turns at injection. Figure 1 shows the energy error at injection, as detected by a new machine-learning (ML) phase-space reconstruction tool [12, 13], for a roughly two-month physics production period in 2023. For both beams, the energy error remains

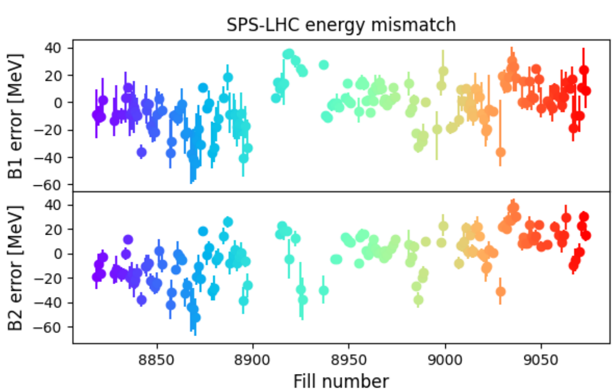

Figure 1: Fill-by-fill (color coded) energy error at injection, as determined by the machine-learning reconstruction based on acquired injection profiles (of the first bunch of each batch). The error bar shows the peak-to-peak variation from one batch to another. The plot includes all physics fills between 23rd May and 18th July 2023.

between -60 MeV to +40 MeV (or -1.3×10^{-4} to $+0.9\times10^{-4}$ in relative momentum offset). As shown in [10], the bunch length and the losses are only slightly affected in this energy mismatch region. Therefore, in 2024 the injection voltage in the LHC could be lowered further without producing significant start-of-the-ramp losses.

In a machine development (MD) session in 2022, high-intensity beams of 1.8×10^{11} p/b were captured for the first time. With a voltage of 4 MV, the power transients right at injection reached the klystron saturation levels [14]. However, in steady state, the peak power was about 10–30 % lower than the saturation value. It was estimated that capturing up to 2.0×10^{11} p/b should be possible assuming further optimisation on cavity and controls settings.

To recuperate this margin, the short peak power demand at injection has to be ideally lowered to the same level as the transients in steady state. This can be achieved by pre-detuning the RF cavities close to the optimum half-detuning value (Eq. (2)), before the arrival of the first long batch that is comparable to the cavity filling time. In 2023, pre-detuning has been successfully put into operation [15]. It was demonstrated that injection power transients are not limiting anymore, and we can consider bucket-by-bucket transients in steady state as the ultimate limit.

During a subsequent MD session in 2023, 72-bunch trains of 2.0×10^{11} p/b were indeed successfully captured, with injection voltages as low as 4 MV and up to 7 MV, with 7 MV being close to the saturation limit of most klystrons. Capturing these intensities with 7 MV required to adjust the frequency and loaded quality factor of each individual cavity, leaving very little operational margin for errors in any of these parameters. Start-of-ramp losses could not be measured, so the minimum acceptable capture voltage for operation at these intensities is yet to be established. Studies are ongoing to correlate the operational start-of-ramp losses with the abort gap population at injection, which could help identifying the minimum capture voltage required for bunch trains at 2.0×10^{11} p/b.

OPERATIONAL EXPERIENCE IN 2023

During the 2023 proton run, a bunch intensity of 1.6×10^{11} p/b with hybrid[2] batch structure has been used. A capture voltage of only 5 MV was sufficient to operate at this intensity without any significant start-of-ramp losses.

Based on this recent operational experience, the estimates for HL-LHC can therefore be updated; see Table 2. With 1.6×10^{11} p/b, the average bunch length at the end of the LHC flat bottom was 1.23 ns in both beams, as measured by the LHC Beam Quality Monitor. Assuming no significant emittance blow-up on the LHC flat bottom, this corresponds to a longitudinal emittance ε of 0.45 eVs at SPS extraction. On the other hand, the bunch length measured at LHC injection by the ML tomography (same data set as in Fig. 1) is (1.25 ± 0.09) ns and (1.25 ± 0.12) ns in Beam 1 (B1) and Beam 2 (B2), respectively, corresponding to an emittance of 0.358 eVs. This points to significant emittance blow-up

[2] Hybrid batches consist of a 56 bunch ‘8b4e’ train (8 filled buckets followed by 4 empty ones) and 3-5 batches of 36-bunch standard 25 ns spaced beam; in all cases, every 10th bucket can be filled in the LHC resulting in bunch slots every 25 ns.

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Table 2: Beam and RF parameters for 2023 operation with hybrid beam, 2023 machine development data with standard beam, and expectations for HL-LHC standard beam operation.

Scenario	Beam parameters		SPS parameters			LHC parameters			
	N_b	ε	$V_{\text{SPS,200}}$	$V_{\text{SPS,800}}$	δ_{SPS}	V_{LHC}	τ_{LHC}	$P_{\text{gen,opt}}$	$P_{\text{gen,peak}}$
2023 (op)	1.6×10^{11} p/b	0.36-0.45 eVs	9.4 MV	1.7 MV	$(4.24\text{-}4.68)\times10^{-4}$	5 MV	1.08-1.23 ns	119-127 kW	160-230 kW
2023 (MD)	2.0×10^{11} p/b	0.55 eVs	9.4 MV	1.7 MV	4.95×10^{-4}	7 MV	1.25 ns	206 kW	230-310 kW
HL-LHC	2.3×10^{11} p/b	0.58 eVs	10 MV	2 MV	5.32×10^{-4}	6.5-7.9 MV	1.25-1.32 ns	212-267 kW	320 ± 15 kW

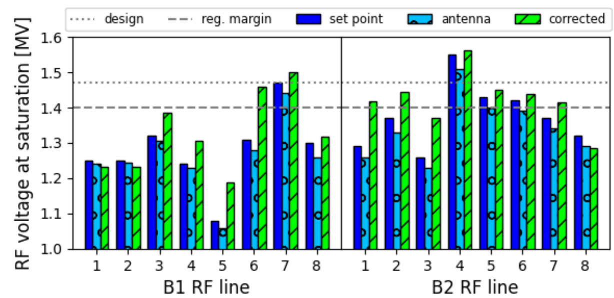
between injection and flat bottom (first row of Table 2). Scaling then to HL-LHC intensities based on Eq. (4) leads to 267 kW at injection (last row of Table 2), assuming that the SPS would operate at the maximum available voltage in both of its RF systems and at the largest affordable emittance [16]. It is worth noting that achieving the optimum power requires a continuous adaptive change of the Q_L from 20300 to 17300.

The average steady-state power request at injection is thus still in line with the estimates in Table 1, and the reason for the reduced injection voltage in 2023 is the lower emittance arriving from the SPS. A large operational margin needs to be kept, as the peak power $P_{\text{gen,peak}}$ for 212 kW in steady state is estimated to be 250-260 kW in the best case; for 267 kW in steady state, the peak power would be around 320 kW. Based on the 2023 MD experience, the RF system at present is limited to an average power of about 206 kW (second row of Table 2), with a wide spread in peak powers ranging from 230 kW to 310 kW.

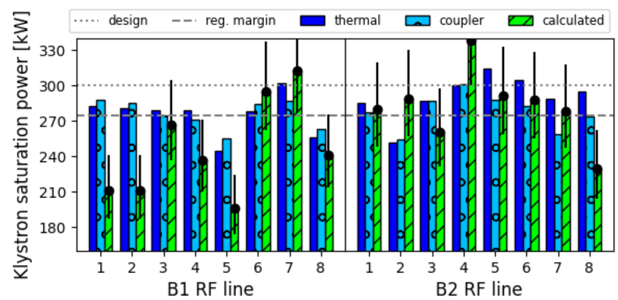
POWER AND VOLTAGE CALIBRATIONS

In 2022, the RF voltage was calibrated with beam, based on synchrotron frequency measurements performed cavity by cavity and with all cavities switched on for different operational voltages [17]. In a second calibration measurement in 2023, performed without beam with $Q_L = 20000$, the maximum available voltage just below the klystron saturation limit was measured cavity by cavity. The right bars in Fig. 2a show that, even with the corrections from the beam-based voltage calibration, only two out of eight B1 cavities and six out of eight B2 cavities reach the theoretically predicted 1.4 MV corresponding to 275 kW (assuming a regulation margin w.r.t. the design 300 kW).

The corresponding RF power is shown in Fig. 2b, from thermal and directional coupler measurements (estimated error ±20 %). As the RF voltage was calibrated with beam, we can also calculate the power by setting $I_{b,\text{rf}} = 0$ in Eq. (3), resulting in the right bar for each line in Fig. 2b. The largest uncertainty on this value comes from the knowledge of the actual loaded quality factor in the cavity. In the LHC, the Q_L can be adjusted from ~15000-80000, and is calibrated each year as a function of the main coupler position (controlled by a stepper motor). The loaded quality factor is then derived from a least-square fit to the open loop response of the cavity with the RF feedback. A rough estimate of the error of this fit is ±2500 at $Q_L = 20000$. Taking into account the corresponding error bars in Fig. 2b, four out of eight B1



(a) Set point, acquired, and calibrated voltages



(b) RF power from thermal and directional coupler measurements, as well as calculated from voltage

Figure 2: Maximum voltage achievable without beam. The theoretical values correspond to 300 kW (dotted) and 275 kW (dashed), the latter corresponding to the regulation margin.

cavities and seven out of eight B2 cavities reach 275 kW. The discrepancies on the other lines remain to be investigated.

CONCLUSIONS AND OUTLOOK

Power limitations at HL-LHC injection were studied since 2018. In 2023, cavity pre-detuning was implemented, relieving limitations from injection transients, and shifting the main focus to the peak power consumption in steady state. Also SPS-LHC energy matching was improved systematically in operation. For the first time, bunch trains with 2.0×10^{11} p/b were successfully captured. However, the maximum voltage maintainable with and without beam indicate lower power margins than expected. Extrapolating the experience with bunch trains of 1.6×10^{11} p/b results in power requirements that are out of reach with the present system at HL-LHC intensities. Calibration and beam loss studies will continue to carefully optimise the minimum capture voltage beyond 2.0×10^{11} p/b and to predict the additional RF power required to inject the HL-LHC proton beam.

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