Advances on LHC RF Power Limitation Studies at Injection

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ABSTRACT

RF power limitations are expected for the LHC main RF system in the HL-LHC era. The limitations are due to power transients at injection and high peak power demand in steady state with local control loops acting. The contribution revises the voltage and power estimates for HL-LHC based on 2022-23 experience.

INTRODUCTION

- High capture voltage → minimize beam losses seen at the start of the ramp
- Low capture voltage → lower power consumption in the presence of strong beam loading
- Superconducting cavities: eight per beam, $R/Q = 45\ \Omega$ [1]
- One klystron per cavity supplying 300 kW [2]
- Constant RF voltage vector
- Half-detuning beam-loading compensation scheme [3]
- The generator current I_{gen} can be related to the RF voltage $V(t)$ and the RF beam current $I_{b,rf}(t)$ through the circuit model in [4]:

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

Optimum detuning & loaded quality factor:

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

Min. aver. klystron forward power in steady state:

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

RF POWER LIMITATIONS

- Estimates for Run 3 based on 2018 operational experience [5]
- Lowest capture voltage for 1.4x10^{11} p/b in 2018 was 4 MV
- Limited by start-of-ramp losses
  - *When SPS-LHC energy mismatch was large (up to 90 MeV)*

Estimates based on Run 2 (2015-2018) operation for Run 3 (2021-2025) & Run 4 (HL-LHC)

When	N_b	δ_{SPS}	V_{LHC}	$P_{\mathrm{gen,opt}}$
Run 2	1.4×10^{11} p/b	3.74×10^{-4}	4 MV	84 kW
Run 3	1.8×10^{11} p/b	4.95×10^{-4}	7 MV	183 kW
Run 4	2.3×10^{11} p/b	5.32×10^{-4}	7.8 MV	265 kW

Scaling the capture voltage with the momentum spread of the injected bunches:

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

ADVANCES IN 2023

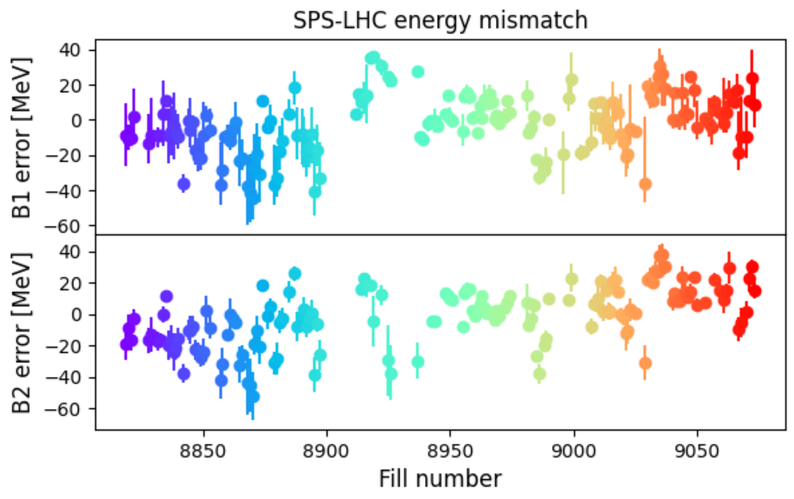
- Systematically good SPS-LHC energy matching
- Implemented pre-detuning of cavities before beam arrival [6]
  - *Focus: first-turn transients → peak power in steady state*
- Captured 2x10^{11} p/b with 4-7 MV in machine development (MD)

Improved SPS-LHC energy matching:

2018: -60..+90 MeV

2023: -60..+40 MeV

Data based on machine-learning phase space reconstruction [7]



UPDATED ESTIMATES

- Based on 2023 operational experience with 1.6x10^{11} p/b
  - *Wide range in peak powers*
- Max. 7 MV with 2.0x10^{11} p/b
- Confirms HL-LHC voltage/power estimates

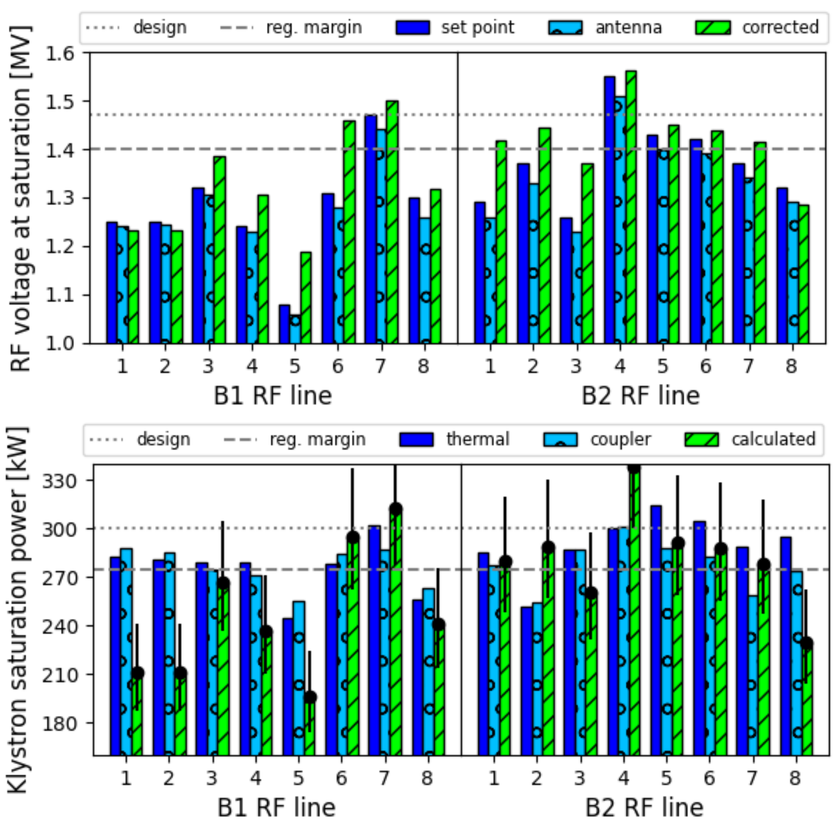
∴ High-efficiency 350 kW klystrons are a must

Scenario	Beam parameters N_b	ε	SPS parameters $V_{\mathrm{SPS,200}}$	$V_{\mathrm{SPS,800}}$	δ_{SPS}	LHC parameters V_{LHC}	τ_{LHC}	$P_{\mathrm{gen,opt}}$	$P_{\mathrm{gen,peak}}$
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

POWER AND VOLTAGE CALIBRATIONS

- Maximum voltage & power w/o beam, just before saturating
  - *Folding in beam-based voltage calibration*
- Power calculated using $Q_L = (20 \pm 2.5)$k
- Five out of 16 lines underperform
  - *Is it a lack of power or an error in Q_L?*

Voltage (top) and power (bottom) in calibration measurement without beam. Expecting 1.4 MV for 275 kW and 20 k.



CONCLUSIONS

- Pre-detuning implemented
- SPS-LHC energy matching improved
- Capturing 2.0x10^{11} p/b for the first time
- For HL-LHC, expect 267 kW average, resulting in 320 kW peak power in the best case

PLANS FOR 2024

- Calibrate Q_L to understand voltage shortcomings
- Attempt reducing the capture voltage further

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