Effects of Cavity Pre-detuning on RF Power Transients at Injection Into the LHC

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Abstract

The RF cavities in the LHC experience strong beam-loading for bunch trains of lengths comparable to the cavity filling time. For High Luminosity (HL) LHC, the peak power demand is expected to go beyond the capability of the present RF system. Pre-detuning has been implemented to remove limitations from first-turn RF power transients. We show results from measurements and compare with expectations from simulation.

Introduction

- The cavity filling time corresponds to the length of a 36-bunch train
- The 400 MHz superconducting cavities are mechanically detuned by a stepper motor [1]
- The half-detuning beam-loading compensation scheme [2] is applied at injection
- The tuner needs several seconds to act and is not present for the first injection
- Detuning the cavities before injection reduces transients and increases the maximum bunch intensity possible to capture

Implementation

Normal operation:

- Tuner acts based on beam current → Very little detuning due to the initial 12-bunch train before the first long batch
- Steepest-descent algorithm with the cross-product between V_a and I_b

$$\left(\frac{\Delta\omega}{\omega_r}\right)_{n+1} = \left(\frac{\Delta\omega}{\omega_r}\right)_{n} - \frac{\mu}{2}\frac{x_{max} + x_{min}}{|V_a|^2}$$

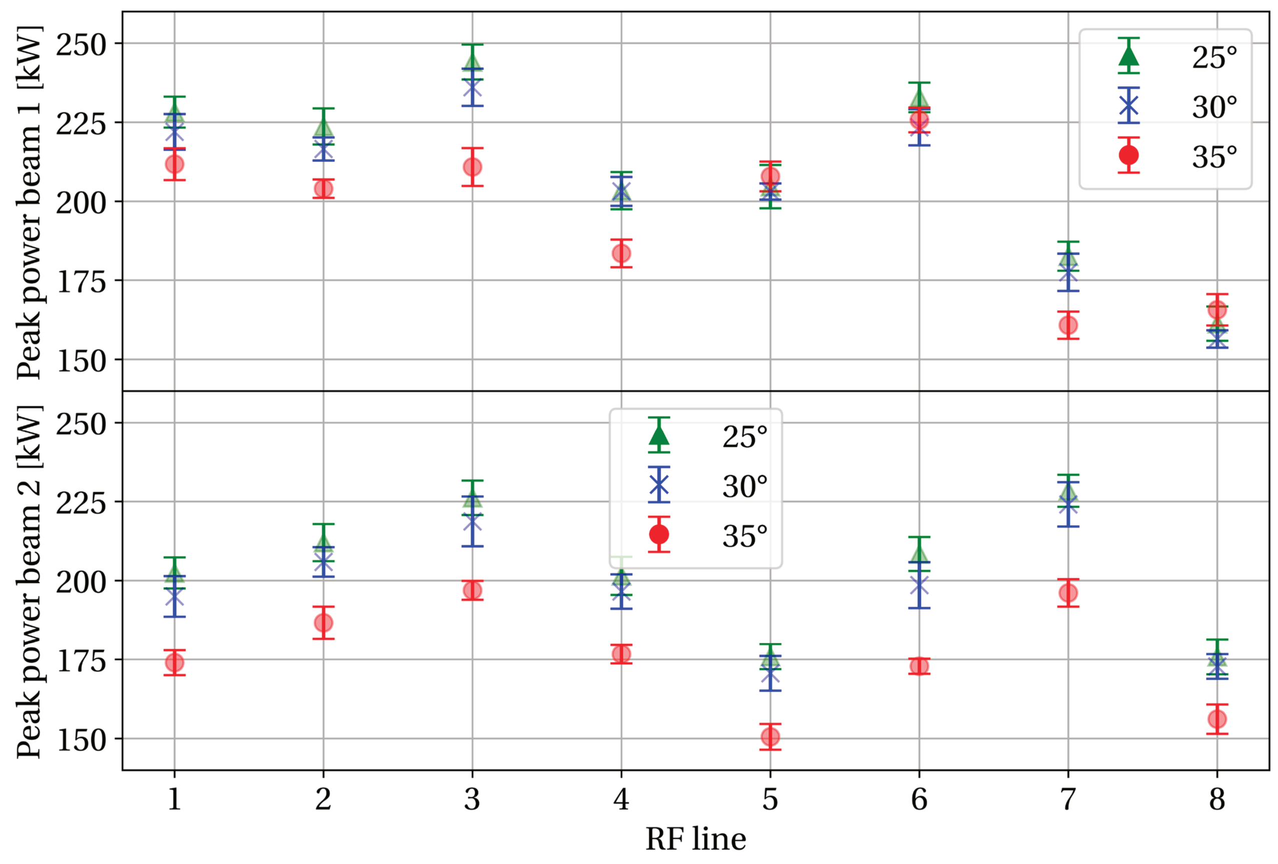
New addition:

- Add static phase offset to tuner module → detunes the cavity before the first injection of longer batches
- Phase is taken out after a certain intensity is reached

LHC Measurements

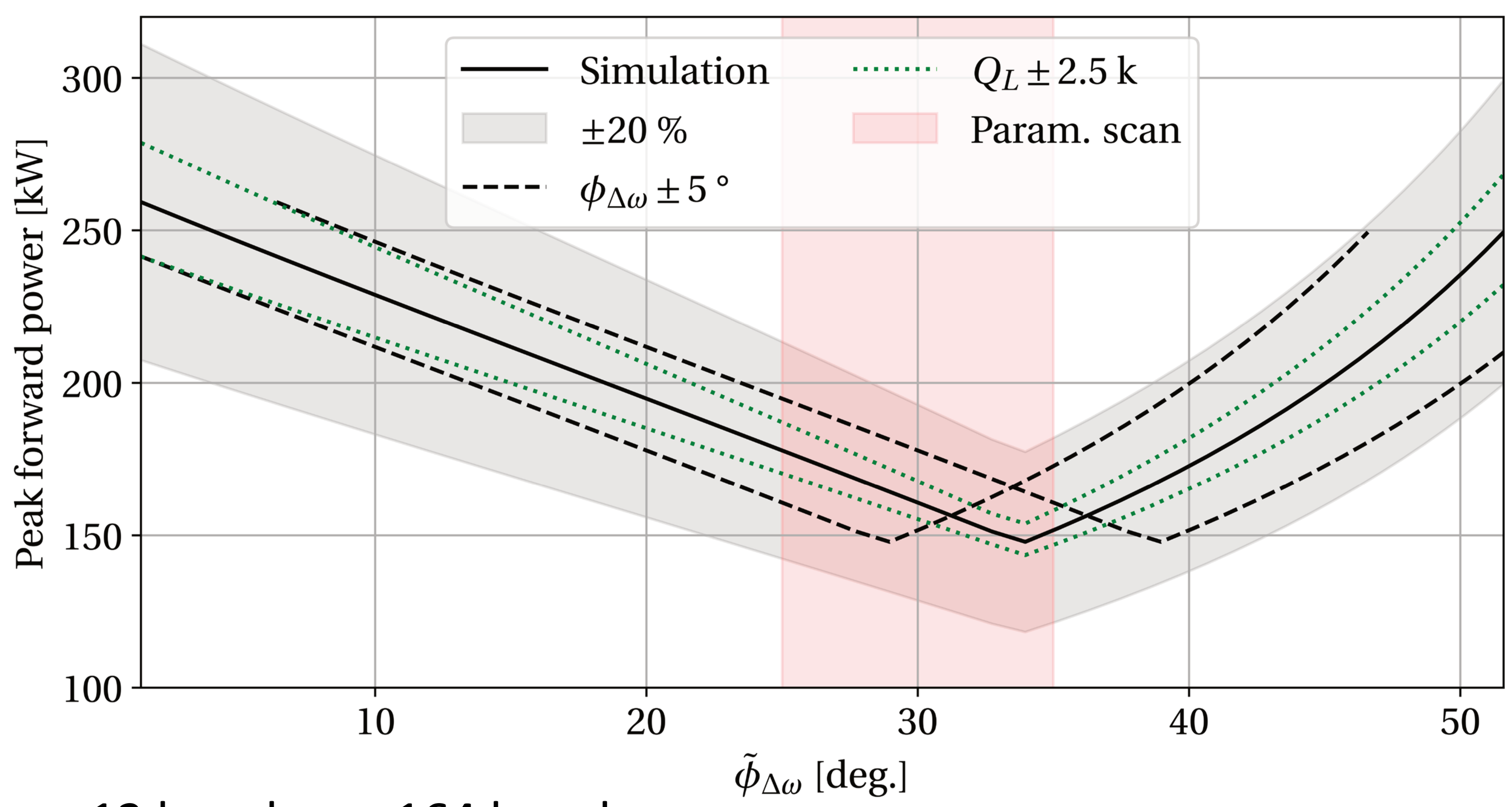
Detuning phase parameter scan during LHC operation (summer 2023)

- 164-bunch hybrid beam [3] with 1.58×10^{11} p/b
- Significant reduction in peak RF power
- Cavities 5, 6 and 8 for beam 1 see little-to-no reduction
- We expect to fine-adjust phase within 2.5°

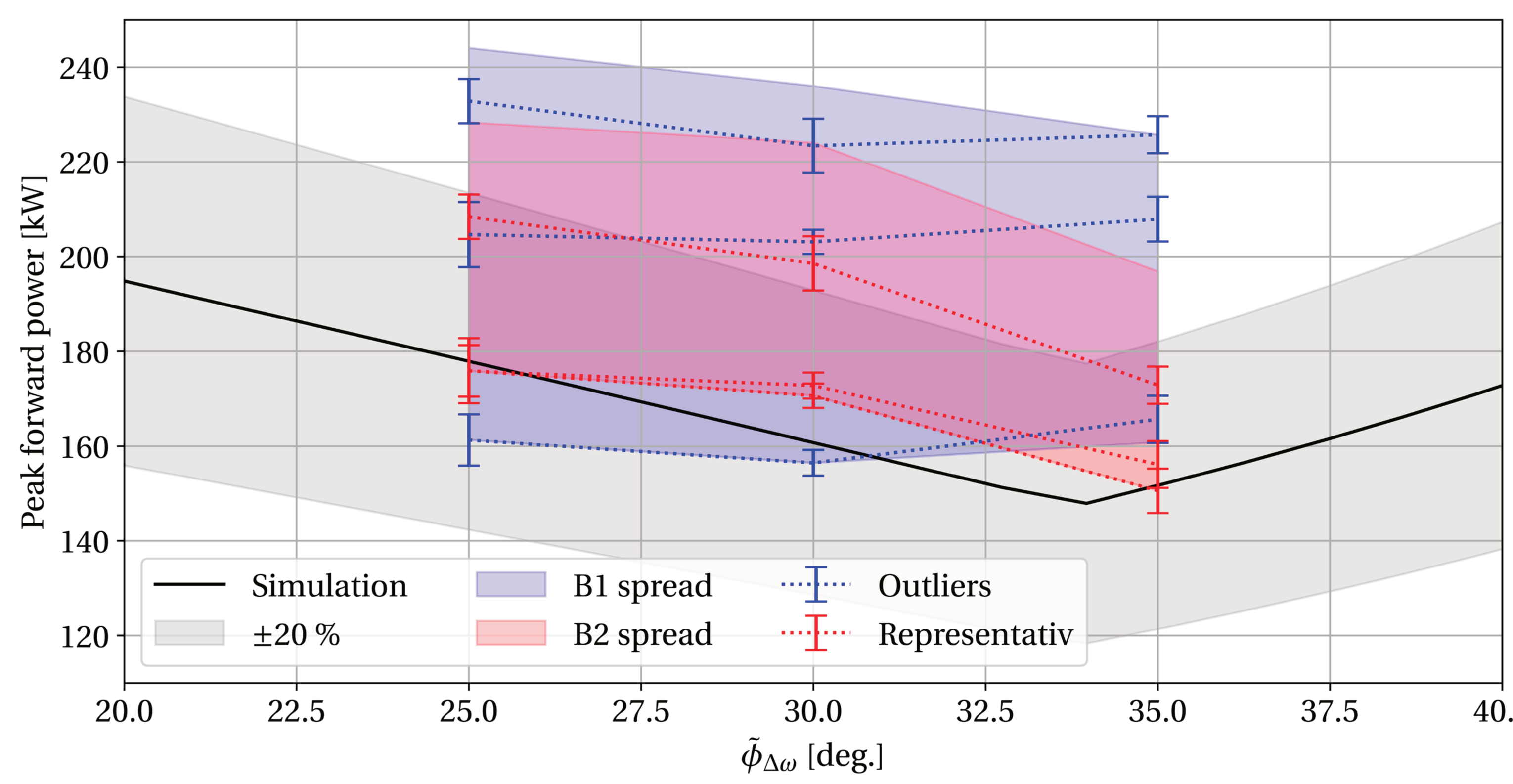


	25 to 30	30 to 35	Mean standard deviation
Beam 1	-1.06 kW/°	-3.37 kW/°	4.85 kW
Beam 2	-1.21 kW/°	-4.31 kW/°	5.03 kW

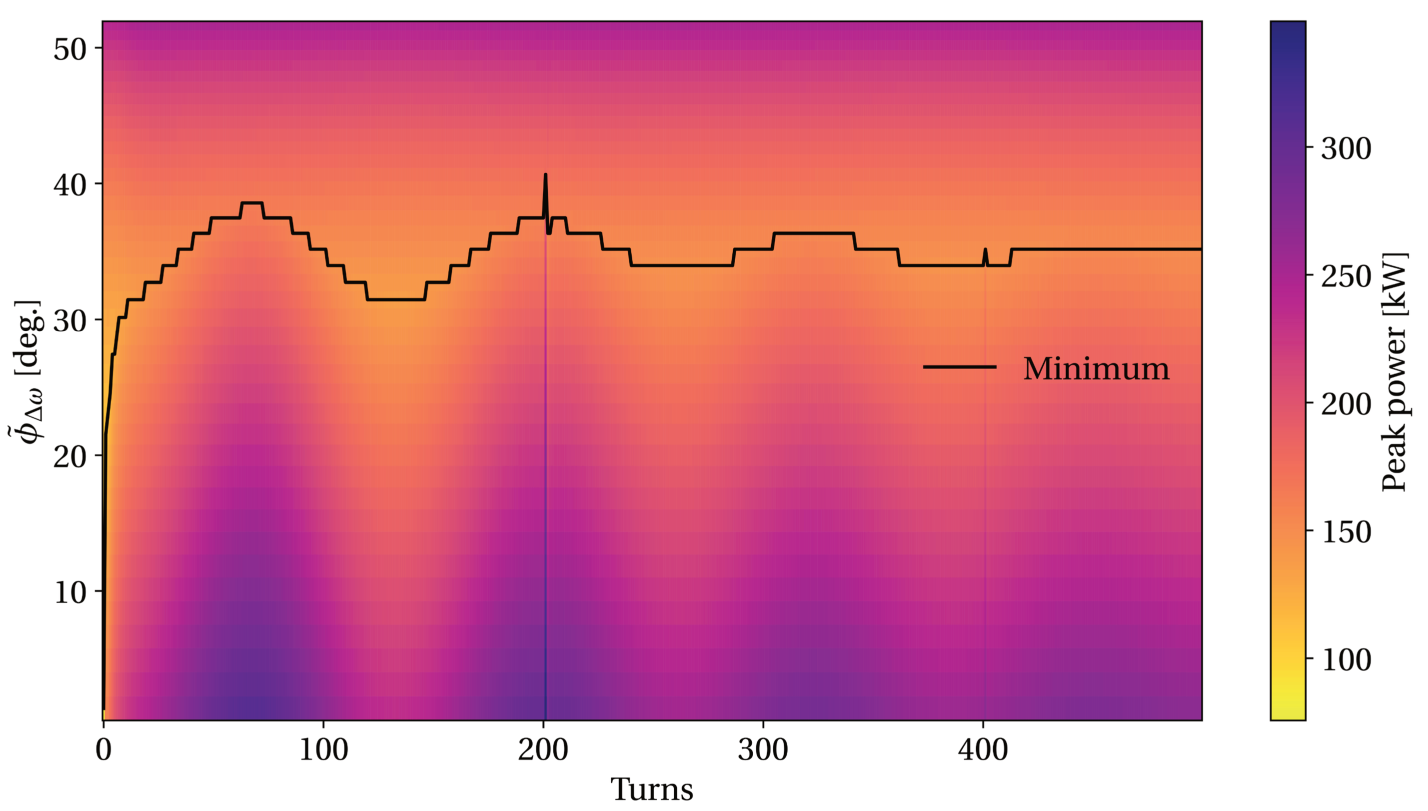
Simulations



- 12 bunches + 164 bunches
- Uncertainty from power measurement (±20%), reference phase in tuner (±5°) and loaded quality factor (±2500)



- Cavities follow reduction trend from simulation
- Systematic error in power due to difference in set point voltage and antenna voltage [4]
- Optimum phase should be in the range 28° to 38°



- Optimum phase (minimum in peak power) oscillates turn-by-turn due to oscillations in the beam

Conclusion

- Pre-detuning is now used in operation and shows a significant reduction in peak RF power at injection
- Measurement scan in detuning exhibits clear improvements in margin in available power and matches expectations from simulation
- The fill-by-fill variation should allow for a fine-tuning of the phase within 2.5°
- Simulation shows that the operational setting should be in the range 28° to 38°
- For accurate optimization at least 100 turns should be acquired

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[1] P. Baudrenghien, "The Tuner Algorithm of the LHC 400 MHz Superconducting Cavities", Tech. Rep. CERN-AB-Note-2007-011, CERN, Geneva, Switzerland, 2007.
[2] D. Boussard, "rf power requirements for a high intensity proton collider ; parts 1 (I, II, III) and 2 (IV, V, VI)", Tech. Rep. CERN-SL-91-16-RFS, CERN, Geneva, 1991.
[3] S. Albright et al., "Overview of the Beams from the Injectors", in Proc. "8th Evian Workshop on LHC operation", Evians Les Bains, France 2017.
[4] B. E. Karlsen-Baeck et al., "LHC MD 6944: Voltage Calibration", Tech. Rep. to be published.

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