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Cavity Voltage Phase Modulation MD

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Summary

The LHC RF/LLRF system is currently setup for extremely stable RF voltage to minimize transient beam loading effects. The present scheme cannot be extended beyond nominal beam current since the demanded power would push the klystrons to saturation. For beam currents above nominal (and possibly earlier), the cavity phase modulation by the beam will be not be corrected (transient beam loading), but the strong RF feedback and One-Turn Delay feedback will still be active for loop and beam stability in physics. To achieve this, the voltage set point will be adapted for each bunch. The goal of this MD was to test an iterative algorithm that would adjust the voltage set point to achieve the optimal phase modulation for klystron forward power considerations.

1 Background

Beam loading effects in the LHC are really small due to the action of the strong RF feedback and One-Turn Delay feedback (OTFB). The resulting cavity voltage has an amplitude modulation within a few least-significant bits of our acquisition system, whereas the phase modulation is less than 1°, as shown in Figure 1 (data from 25 ns MD, 2100 bunches).

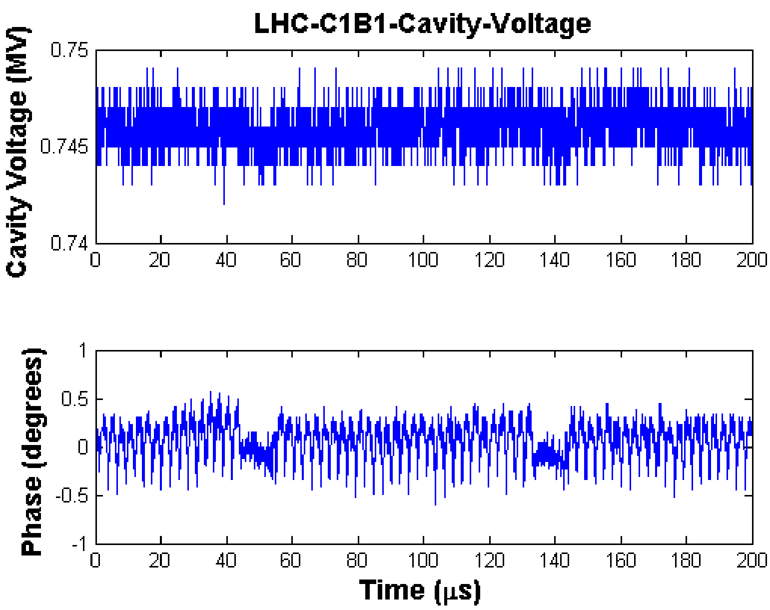

Figure 1: Cavity voltage with 2100 bunches, 25 ns spacing, 450 GeV.

This scheme though comes at the expense of klystron forward power. At least 200 kW of klystron forward power would be necessary at nominal intensity, the power at which the klystrons presently saturate. With different DC parameters it is possible to increase the saturation level to 300 kW, but this power will not be sufficient for ultimate beam intensity (1.7e11 protons/bunch). This scheme is described in more detail in [1]. Figure 2 shows the minimum necessary klystron forward power for different loaded Q values with the present scheme for nominal beam in physics and ultimate beam at injection and in physics.

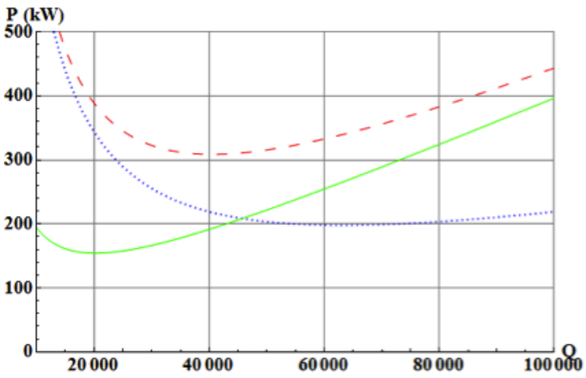

Figure 2: Klystron power vs. Q_L. Dotted blue trace: physics conditions, nominal beam current (0.56 A DC). Dashed red trace: physics conditions, ultimate beam current (0.86 A DC). Solid green trace: injection conditions, ultimate beam current.

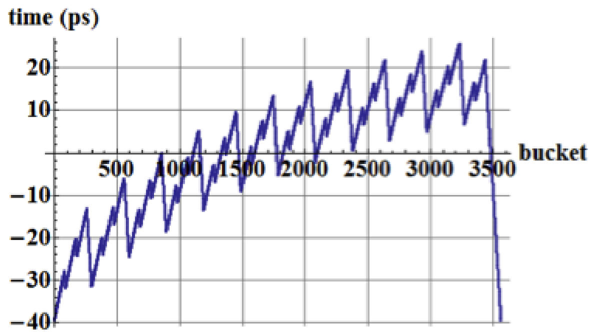

Figure 3: Estimated cavity phase modulation for design report beam parameters and pattern (7 TeV). Physics RF parameters. 2835 bunches, 1.7e11 p/bunch.

The solution to this limitation is based on a method proposed by D. Boussard for the LHC in 1991 [2]. The cavity set point is modulated in anticipation of the beam, so that the RF loop – and thus the klystron – does not try to reduce the beam loading effects in the cavity. This method maintains the strong RF feedback and OTFB though, with the corresponding positive effects for longitudinal stability.

The trade-off with this method is the introduction of a phase modulation over the turn. As an example, Figure 3 shows the estimated cavity phase modulation for the design report beam parameters and filling pattern (at 7 TeV). The peak-to-peak variation is only 60 ps though for an ≈ 1.2 ns long bunch. Furthermore, since this modulation would be almost symmetric for the two rings, the collision point would barely shift in IP 1 and 5.

2 Experimental Conditions

The MD was performed on June 22^{nd}-23^{rd} with nominal LHC conditions at 450 GeV. After the initial 12 bunches, batches of 144 bunches were injected as close as possible (925 ns) using filling pattern "50ns_1380b_1380_0_1274_144bpi12inj". Six fills were used during the MD (2763-2768), all with 12+144 bunches, with the exception of fill 2767 when 12+720 bunches were injected.

The klystron transient behavior depends on the length of the beam/no-beam segments in the machine. Therefore, a single 144-bunch batch (7.2 μs long) in the machine closely resembles the situation of a full machine with a 3.2 μs abort gap, but saves valuable MD time by reducing the injections. On the other hand, a half-full machine leads to the highest phase modulation along a turn, so the 12+720 fill provided very useful information too.

The OTFB was kept off during all but the last fill, to increase the beam loading effects and thus the observed signals.

During the MD, the self-learning algorithm which adjusts the voltage set point adaptation over a turn was tested ("feedforward" algorithm). An initial step applies a phase modulation based on an estimate of the beam loading from a simplified cavity model and the beam pattern. Then, an iterative algorithm converges to the optimal phase modulation.

For MD purposes, Matlab was used to apply the algorithm, which allowed more flexibility for adjustments, but significantly increased the time between iterations (≈20 seconds). As a result, a much higher gain had to be used – 3 orders of magnitude higher than J. Tuckmantel's simulations on the "feedforward" algorithm [3]. In the final implementation, the algorithm will be included in the LLRF firmware, allowing iterations every 1-2 turns (1e5 times faster than during the MD), and much reduced adjustments between iterations. The nominal tuner loop is active.

3 Observations

For the first fill (2763), we only applied the estimated initial correction, approximately 15 minutes after the last injection. A reduction of klystron forward power was observed, as seen in Figure 4 (Cavity 3B2 is operated with lower voltage and is not presented in this note).

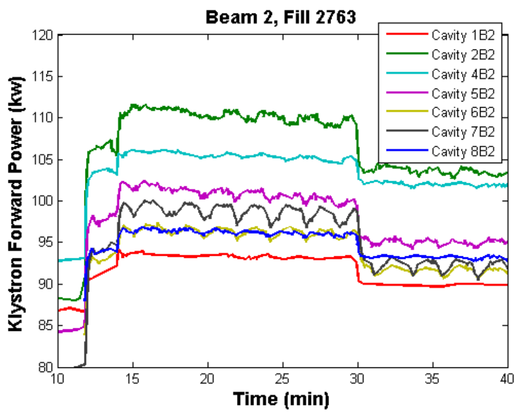

Figure 4: Average Klystron forward power. 12+144 bunches, Beam 2, Fill 2763. Initial correction applied at minute 30, approximately 15 minutes after the last injection.

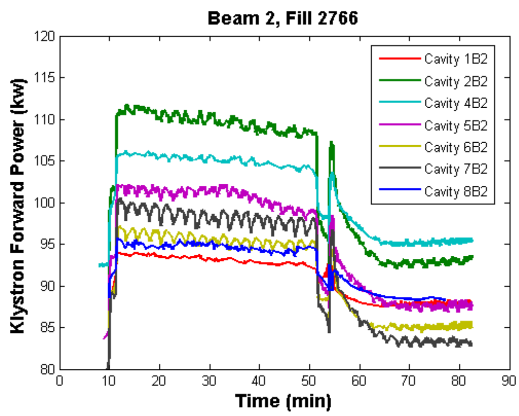

Figure 5: Average Klystron forward power. 12+144 bunches, Beam 2, Fill 2766. Initial correction applied at minute 50. Adaptive algorithm switched on a couple of minutes later.

For the next fill (2764), the adaptive part of the algorithm was switched on. It was soon obvious that some stations showed improvement, whereas others diverged. The cause of the problem was identified as a misalignment of the adaptive signal with bucket 1 and a rotation between the cavity voltage and the adaptive signal. Fills 2764-2765 were used to calibrate these signals, as well as to implement an appropriate phase rotation. Finally, Fill 2766 provided very encouraging results, with a significant average and peak klystron forward power reduction as shown in Figures 5, 6. An initial reduction due to the implementation of the estimated correction can be seen, followed by a transient before the further reduction due to the iterative algorithm. The transient is probably related to the high gain employed in the Matlab implementation. The corresponding phase modulation over a turn in the cavity is shown in Figure 7.

The same procedure was repeated with 12+720 bunches in Fill 2767 with very positive results. The reduction in klystron average power is shown in Figure 8, whereas Figure 9 shows the final cavity set point modulation. The phase modulation over a turn in the cavity is shown in

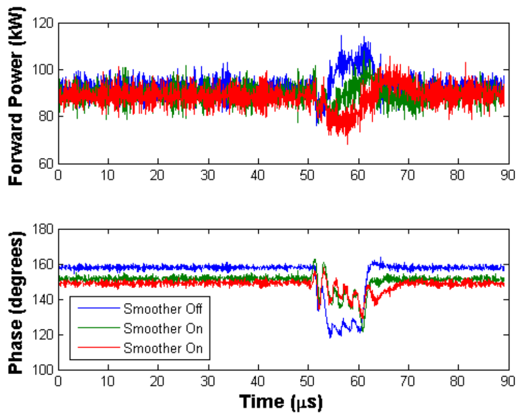

Figure 6: Klystron forward power over a turn. 12+144 bunches, cavity 1B2, Fill 2766.

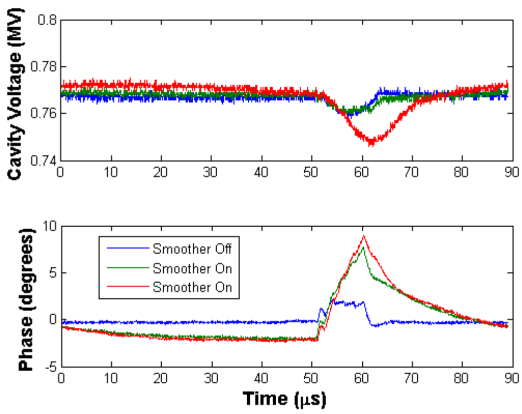

Figure 7: Cavity Voltage over a turn. 12+144 bunches, cavity 1B2, Fill 2766.

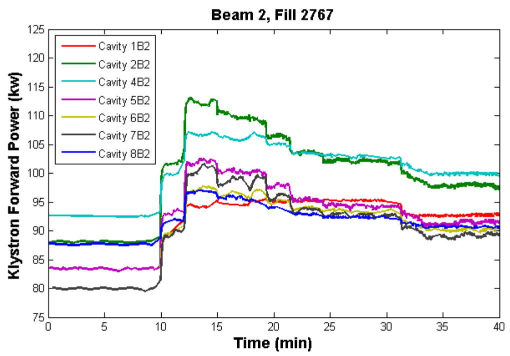

Figure 8: Average Klystron forward power. 12+720 bunches, Beam 2, Fill 2767.

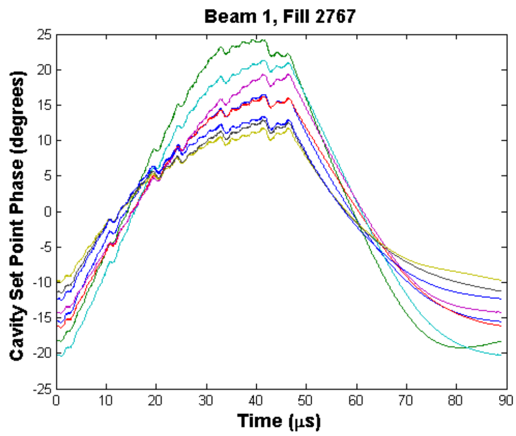

Figure 9: Final cavity set point phase modulation. 12+720 bunches, Beam 1, Fill 2767.

Figure 10, whereas Figure 11 shows the beam phase from an independent measurement through the Beam Phase Loop.

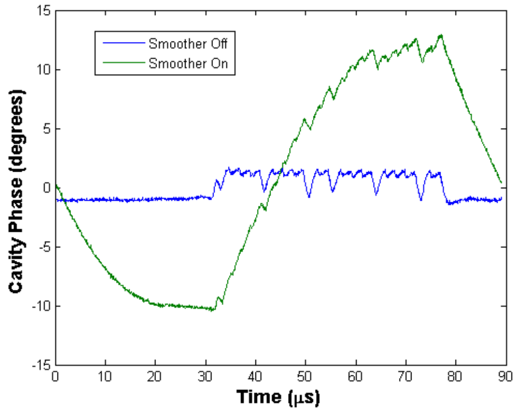

Figure 10: Cavity phase modulation over a turn. 12+720 bunches, Beam 2, Fill 2767.

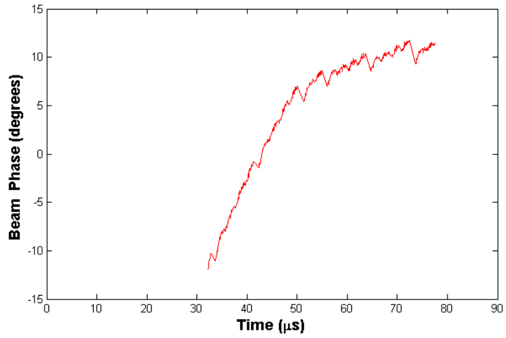

Figure 11: Beam phase modulation over a turn. 12+720 bunches, Beam 2, Fill 2767.

Finally, the test was repeated with 12+144 bunches and the OTFB on in Fill 2768, to confirm that the algorithm works even with the very small beam loading signals when the OTFB is on. The algorithm worked well once again, as shown in Figure 12.

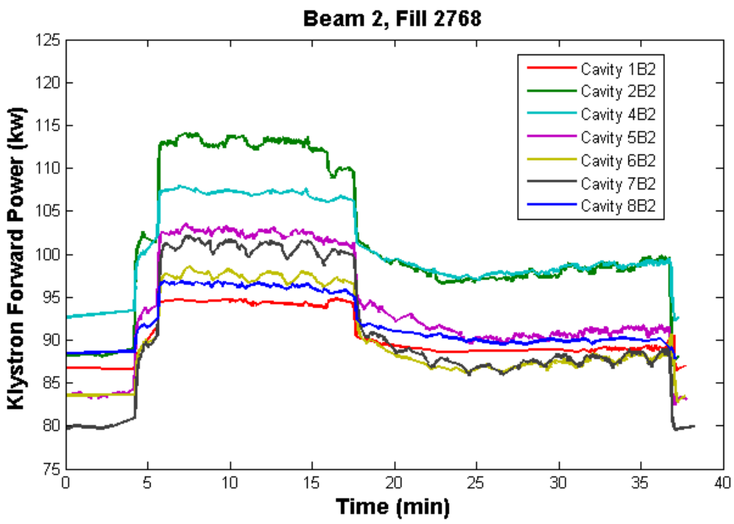

Figure 12: Average Klystron forward power. 12+144 bunches, Beam 2, Fill 2768.

4 Conclusions

The new "feedforward" algorithm for adjusting the cavity set point in anticipation of the beam was tested during this MD with 12+144 and 12+720 bunches. The results were very encouraging. Significant klystron power reduction was observed (peak and average) and the final cavity set point phase modulation approached the theoretically estimated value. The peak-to-peak beam modulation reached 120 ps for the worse case scenario of a half-full ring. Even this value though is small compared to the approximately 1.2 ns long bunch. Since this modulation would be almost symmetric for the two rings, it should not affect the LHC experiments. On the other hand, an addition of a harmonic cavity in the LHC would require a reevaluation of this scheme.

The algorithm was executed through Matlab during the MD, thus greatly increasing the iteration time and forcing a much higher gain. With the knowledge from the MD, firmware is being developed that would apply the correction every 1-2 turns with a much smaller gain. As a result, this process will truly be adiabatic for the beam and the convergence of the algorithm will be much quicker and smoother. This firmware based algorithm should be tested during the next MD block.

5 Acknowledgments

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References

[1] P. Baudrenghien, T. Mastoridis, "Proposal for an RF Roadmap Towards Ultimate Intensity in the LHC", Proceedings of Third International Particle Accelerator Conference 2012, New Orleans, Louisiana, USA, 20 - 25 May 2012.

[2] D. Boussard, "RF Power Requirements for a High Intensity Proton Collider", Proceedings of 14^{th} IEEE Particle Accelerator Conference, San Francisco, CA, USA, 6 - 9 May 1991.

[3] J. Tuckmantel, "Adaptive RF Transient reduction for High Intensity Beams with Gaps", EPAC 2006.