ATS-Note-2016-061 MD
2016-10-18
Themistoklis.Mastoridis@cern.ch

Cavity Voltage Phase Modulation MD

T. Mastoridis, P. Baudrenghien, J. Molendijk, H. Timko/ BE-RF
Keywords: Beam Dynamics, RF, LHC, Longitudinal, Cavity Phase, Power Requirements

Summary

The LHC RF/LLRF system is currently configured 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 exceed the peak klystron power and lead to saturation. A new scheme has therefore been proposed: for beam currents above nominal (and possibly earlier), the cavity phase modulation by the beam will 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 a new algorithm that would adjust the voltage set point to achieve the cavity phase modulation that would minimize klystron forward power.

1 Introduction

An early version of the cavity phase modulation algorithm was tested in 2012 to evaluate the algorithm performance and feasibility. The justification for the algorithm, the development process, and the initial results from those tests are described in [1], [2]. The motivation behind the cavity modulation algorithm is described in more detail in [3], [4].

The successful results of these first tests and the associated data and information motivated a redesign of the algorithm to increase performance and robustness. The redesigned algorithm was tested in simulations and later in the RF test stand. The goal of this MD was to confirm the performance improvement and reliability before operational commissioning.

2 Experimental Conditions

The MD (LHC MD number 249) was performed on October 3^{rd}-4^{th} with nominal LHC conditions at 450 GeV followed by a ramp to 6.5 TeV. After the initial 12 bunches, batches of 96 bunches were injected up to 1164 bunches for Beam 2. Due to transfer line issues, only two 96-bunch batches were injected in ring 1 for a total of 204 bunches.

The klystron transient behavior depends on the length of the beam/no-beam segments in the machine. Therefore, the two batch configuration (≈ 5 μs long) in the machine closely resembles the situation of a full machine with an abort gap (Beam 1). On the other hand, a half-full machine leads to the highest phase modulation along a turn, so the Beam 2 pattern provided very useful information too.

During the MD, the self-learning algorithm which adjusts the voltage set point adaptation over a turn was tested. The algorithm uses the klystron current and cavity voltage modulation due to beam loading to calculate an appropriate correction for the cavity phase set-point over a turn. It is a very slow feedback algorithm, with a time constant of a few seconds, that gently converges to the phase modulation that minimizes the klystron power. The bunches follow the phase modulation without being affected (synchrotron frequency around 55 Hz at 450 GeV, and 20 Hz at 6.5 TeV).

This is an internal CERN publication and does not necessarily reflect the views of the CERN management.

3 Observations

The primary metric for the algorithm's performance is the average and peak klystron power. It is also important to check that there are no unwanted effects due to the algorithm's action, such as bunch lengthening or beam loss. The phase modulation should be compared among all cavities to confirm that there is no energy exchange between cavities through the beam.

3.1 Average Klystron Power

The average klystron power was significantly reduced for both Beams, as expected. Figure 1 shows the average klystron power for all Beam 1 stations. The increase in power after the first injection of a long batch is clear at 00:26. Injections took place with fixed voltage and phase set-point along the ring. With this scheme (in operation since the LHC start-up), the power is minimized with the "half-detuning" strategy [3]. It should be noted that the required power does not further increase with subsequent injections since the half-detuning algorithm uses a 1 μs running average of the klystron power. The voltage phase modulation algorithm is switched on at 00:32 and the average klystron power returns to the pre-injection level. The algorithm's gain was increased at 00:34, with a further marginal improvement in klystron power. The spread

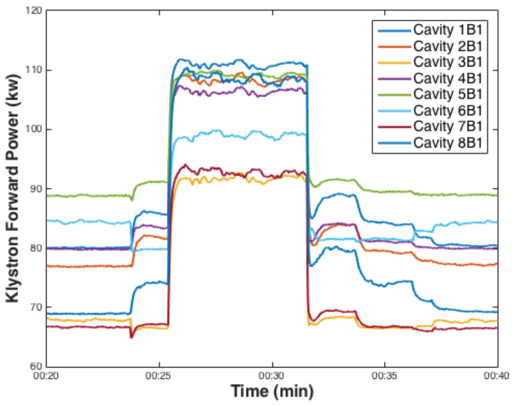

Figure 1: Average Klystron forward power. 204 bunches, Beam 1.

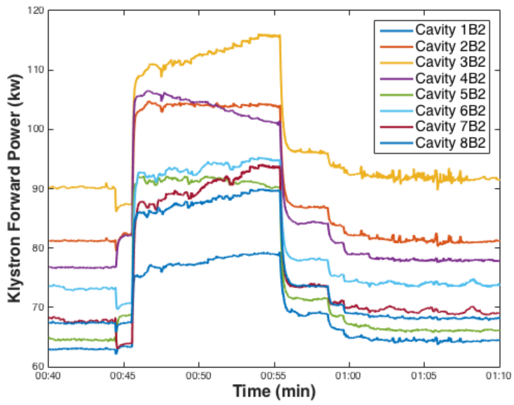

Figure 2: Average Klystron forward power. 1164 bunches, Beam 2.

in klystron power over all the stations is due to small differences in the Q_L value. The average power over all stations is 76.9 kW, compared to the theoretical vale of 77.2 kW for the desired $Q_L = 20,000$.

Similarly, Figure 2 shows the average klystron power for all Beam 2 stations. The first injection of a 96-bunch batch was at 00:46. Additional batches were injected up to 1164 bunches. The algorithm was switched on at 00:55 with a significant improvement in klystron power requirements. The algorithm's gain was increased at 00:58 and 00:59 with additional (but smaller) gains in performance. The average power over all stations is 74.0 kW, compared to the theoretical optimal vale of 77.2 kW.

Encouraged by the good performances at 450 GeV, it was decided to ramp the two beams with the voltage modulation. Several RF parameters change during the ramp: the cavity loaded Q_L is increased from 20,000 to 60,000 at the start of the ramp, the RF voltage increases from 0.750 kV to 1.25 MV (per cavity), the stable phase varies between 180° and 175°. The algorithm automatically adapts to these changes. Figures 3 and 4 show the same time interval as above, but further include the subsequent ramp. The average klystron power is reduced before the start of the ramp, when the Q_L value is increased threefold at 01:13. The power is then steadily

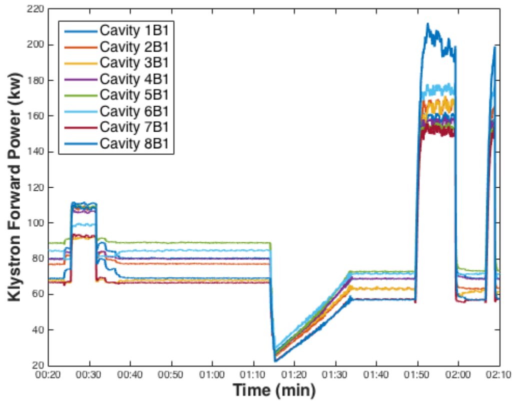

Figure 3: Average Klystron forward power. 204 bunches, Beam 1.

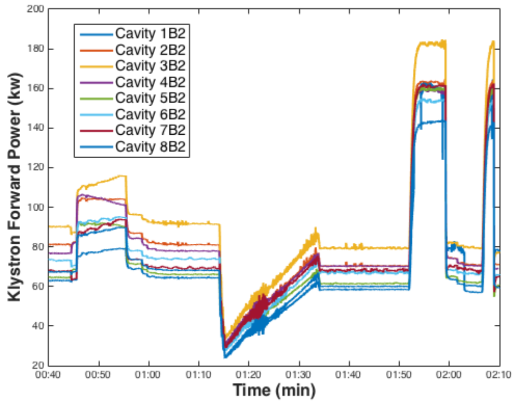

Figure 4: Average Klystron forward power. 1164 bunches, Beam 2.

increased during the ramp as the cavity voltage rises. The algorithm was on throughout this process and actively adjusted the optimal cavity phase modulation. The algorithm was switched off at 01:50 for Beam 1 and 01:52 for Beam 2. The required klystron power increased from an average of about 65 kW to more than 160 kW for Beam 1 and from about 68 kW to 160 kW for Beam 2. The algorithm was subsequently switched on again at 01:59 and the performance improvement was achieved again. The algorithm was switched off/on once again a few minutes later.

The average power over all stations was 65.2 kW for Beam 1 and 68.3 kW for Beam 2, whereas the theoretical optimal value is 72.3 kW for a $Q_L = 60,000$. The results are very positive, but they also seem to indicate that the actual Q_L is on average a bit off from the desired setting.

3.2 Klystron Power per Turn

It is also interesting to compare the klystron power per turn with and without the algorithm. With the fixed cavity phase method (half-detuning) used in operation since the LHC start-up, the cavity is detuned so that the average klystron power is equal during the beam and no-beam segments. This results in a high average power. The instantaneous power during the beam to no-beam transitions is also very high (orange traces, Figures 5, 6). With the new method (cavity voltage phase modulation and full-detuning), the average klystron power during the beam and no-beam segments is still the same, but is now significantly reduced (blue traces). In addition, the peak transients at each beam-no beam transition (and vice-versa) that were observed with the previous method, have now almost disappeared and are within the acquisition noise for Beam 2. The improvement for Beam 1 is significant, but there is still some residual additional power in the beam segment (Figure 5). After investigation, it was discovered that the source of this discrepancy is the phasing between the analog and digital loops in the LLRF feedback. The phase is correct for Beam 2, but there was a 10° offset in Beam 1.

3.3 Abort Gap and Bunch Length

The abort gap population and bunch length were monitored during the MD. There were no signs of additional bunch lengthening or of an increase in the abort gap population when the algorithm was on, as shown in Figures 7 and 8. In addition, no debunching was observed when the algorithm was switched on-off and off-on at 6.5 TeV.

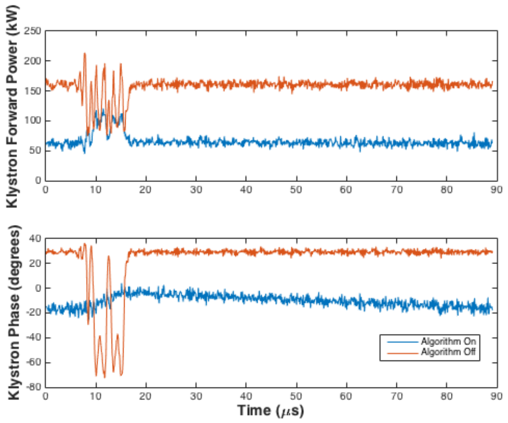

Figure 5: Klystron forward power per turn. 204 bunches, Beam 1.

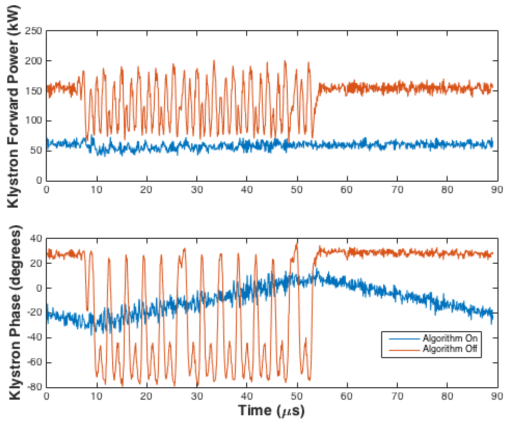

Figure 6: Klystron forward power per turn. 1164 bunches, Beam 2.

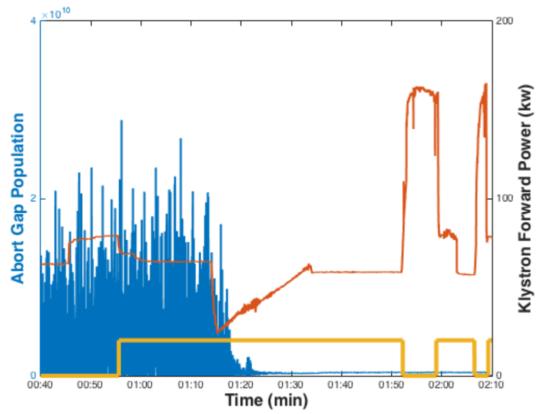

Figure 7: Beam 2 abort gap population and klystron 1B2 forward power. The yellow line indicates when the algorithm is on/off.

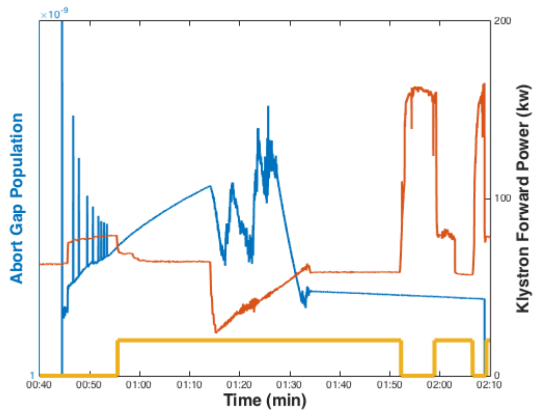

Figure 8: Beam 2 bunch length and klystron 1B2 forward power. The yellow line indicates when the algorithm is on/off.

3.4 Phase Modulation for all Cavities

Figure 9 shows the phase modulation for each cavity at 6.5 TeV. The phase modulation is almost identical for all stations. The black dashed line shows the theoretically estimated optimal phase modulation, which shows very good agreement with the acquired data. The small differences are due to slightly different LLRF settings for each station (mostly cavity Q_L). Figure 10 shows a similar picture for Beam 2. The phase modulation is very similar across all

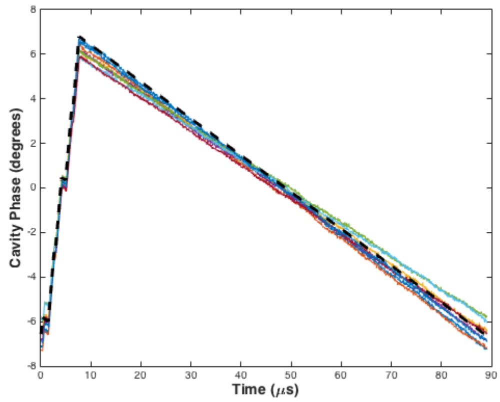

Figure 9: Phase modulation for all cavities. 204 bunches, Beam 1.

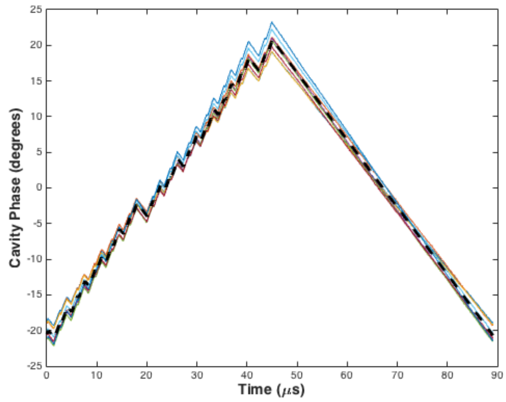

Figure 10: Phase modulation for all cavities. 1164 bunches, Beam 2.

cavities. With the beam intensity found during the MD, the theoretical phase modulation is 13.5° and 41.9° for Beams 1 and 2 respectively, to be compared to the observed 12.1-14.1° and 38.6-45.5° over all cavities. Notice the sawtooth ripple along the beam part: the larger drops are due to the gaps between the 96-bunch SPS batches (900 ns), the smaller drops correspond to the gaps between the 48-bunch PS batches (225 ns). There are also two 2.1μs long gaps.

3.5 Cavity Sum and Beam

Finally, Figures 11 and 12 show the beam phase and the cavity vectorial sum phase for both beams. As expected, the beam tracks the cavity sum within the acquisition precision.

4 Conclusions and Next Steps

The new cavity phase modulation algorithm for adjusting the cavity set point in anticipation of the beam was tested during this MD with 204 (Beam 1) and 1164 (Beam 2) 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 algorithm should be tested next with collisions to see any effect on the LHC experiments.

This Note is a short presentation of the MD results and the details of the algorithm have intentionally be left out. They will be presented in a future paper.

5 Acknowledgments

We would like to thank the operators (M. Pojer, D. Jacquet, M. Solfaroli Camillocci, and G. Rossano) for their help during the MD, the MD coordination team for the allocated time, and

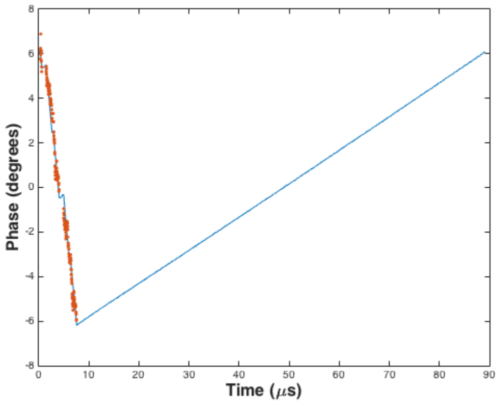

Figure 11: Beam phase and vectorial sum phase. Beam 1.

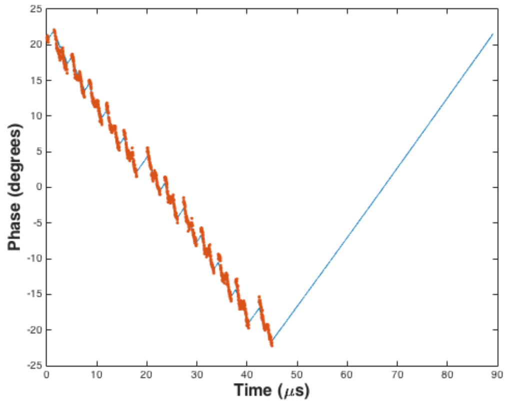

Figure 12: Beam phase and vectorial sum phase. Beam 2.

M. Jaussi for his assistance.

References

[1] T. Mastoridis, P. Baudrenghien, A. Butterworth, J. Molendijk, J. Tuckmantel, "Cavity Phase Modulation MD", ATS-Note-2012-075 MD, 27 September 2012.

[2] T. Mastoridis, P. Baudrenghien, A. Butterworth, J. Molendijk, J. Tuckmantel, "Cavity Voltage Phase Modulation MD blocks 3 and 4", ATS-Note-2013-013 MD, 8 March 2013.

[3] 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.

[4] 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.