LHC Cavity Voltage Phase Modulation

Full-detuning scheme for LHC

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Meeting 2: High Harmonic RF system Review,
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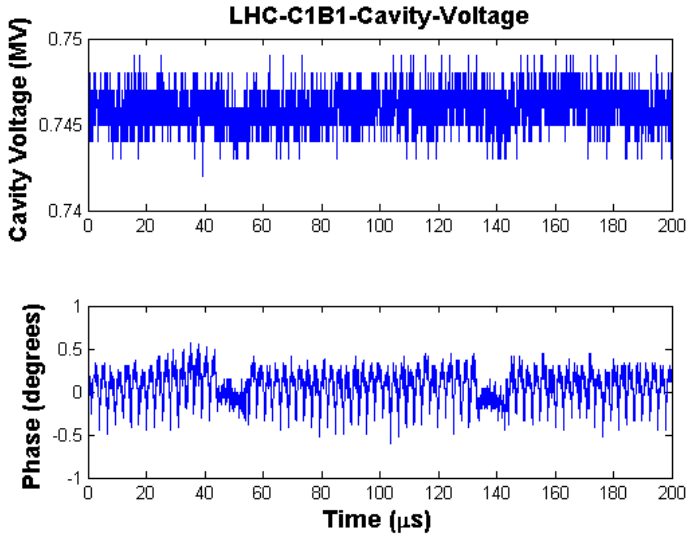
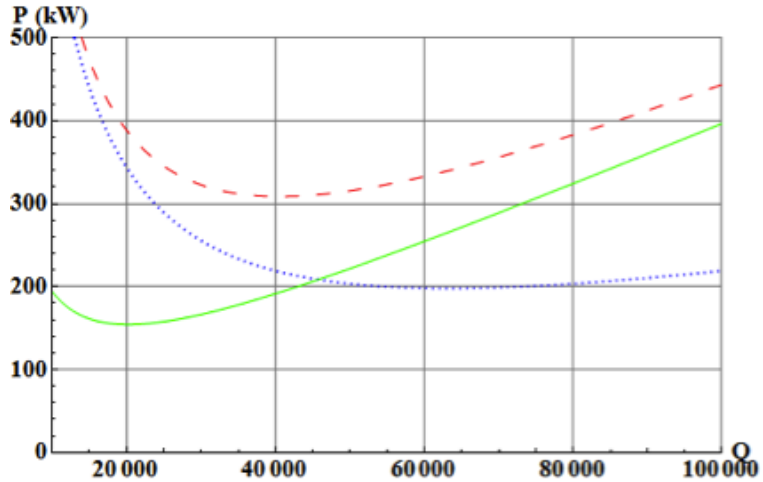
Background

- RF/LLRF currently setup for extremely stable RF voltage (minimize transient beam loading effects). Less than 1° RF phase modulation (7 ps)
- To continue this way, we would need at least 200 kW of klystron forward power at nominal beam current (0.58 A DC)
  - Klystrons saturate at 200 kW with present DC parameters (ultimately 300 kW). Sufficient margin necessary for reliable operation, additional RF manipulations etc.
  - The present scheme cannot be extended beyond nominal. Graphs for nominal (1.15e11 ppb, 25 ns, 7 TeV, 0.58 A DC), ultimate at 450 GeV (1.7e11 ppb, 25 ns, 0.86 A DC), ultimate at 7 TeV





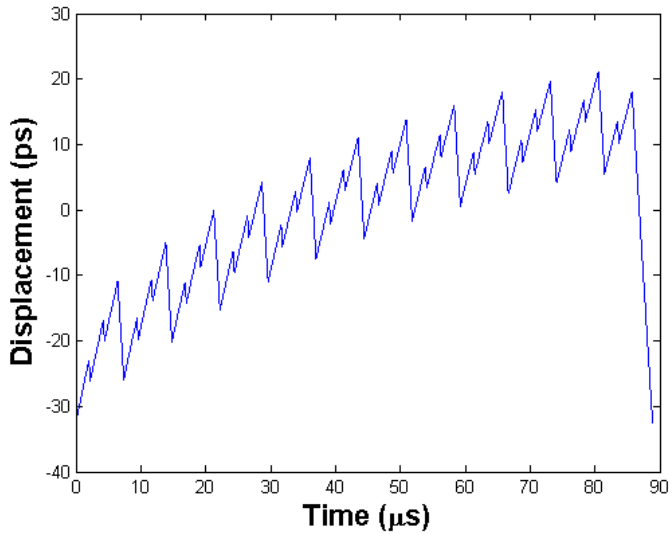
Solution

- For beam currents above nominal (and possibly earlier), we will accept the cavity phase modulation by the beam in physics (transient beam loading), but keep the strong RF/OTFB for loop and beam stability
- To achieve this, we have to adapt the voltage set point for each bunch
  - Method proposed by D. Boussard for the LHC in 1991 [1]:
    - *Assuming that the bunch distribution is known, it is possible to compute the resulting phase modulation in the RF cavities*
    - *If the voltage setpoint is modulated with the computed value, the variation of the klystron current goes to zero*
    - *The phase modulation is not reduced by the RF feedback, but at the same time, there is no extra RF power requested*
  - More details in IPAC '12 paper [2]
- The idea was taken one step further using an iterative algorithm to adjust the voltage phase modulation from observations of the klystron drive. This technique has the added advantages of self-adjusting to
  - Bunch intensity and filling pattern
  - Bunch length (resulting in changes to 400 MHz component of beam current)
  - RF voltage, cavity loaded Q, and cavity detuning

Pros and Cons

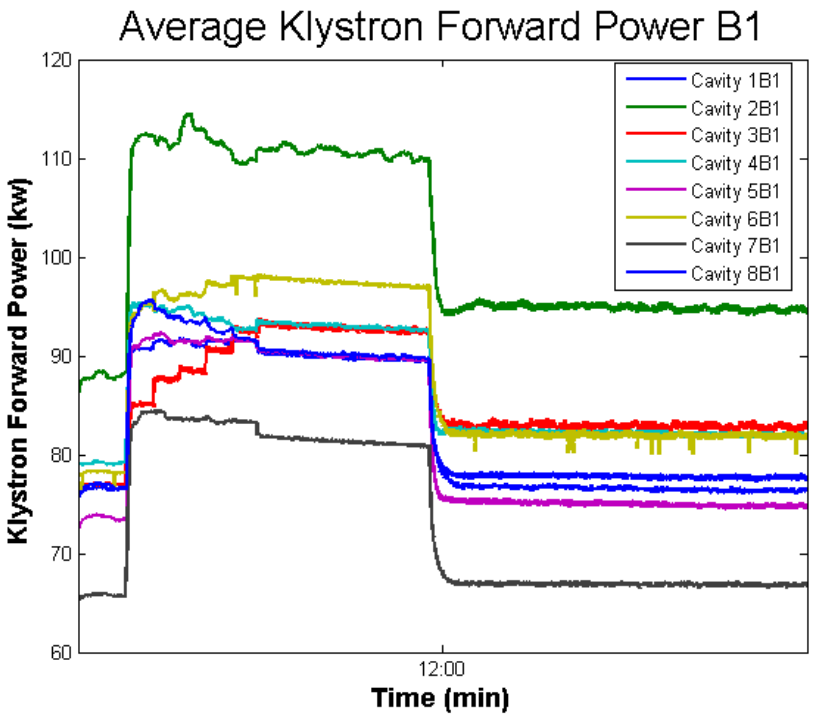
- Iterative, independent of beam current, cavity voltage and Q_L
- The algorithm keeps the bucket area constant (RF voltage amplitude unchanged), but allows for bunch phase modulation
- This technique also helps reduce reflected power and beam induced voltage in the case of a klystron trip [3], [4]
- Significant reduction of klystron forward power expected

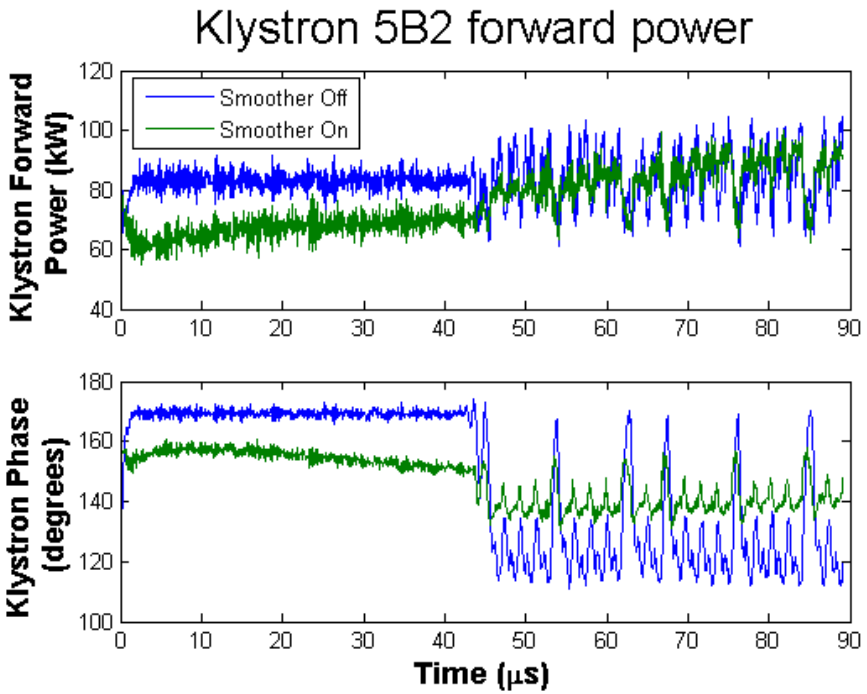
- Up to 55 ps peak to peak displacement over a turn in physics (for ultimate beam, 0.86 A DC) compared to 1.25 ns bunch length
  - Even smaller shift of collision point in IP1, IP5
- Phase modulation at injection would lead to increased capture loss due to unevenly spaced receiving buckets
  - Fill with half-detuning scheme, switch algorithm on during pre-ramp
  - Lower voltage at injection $\rightarrow$ more power for transient beam loading compensation



MD Results

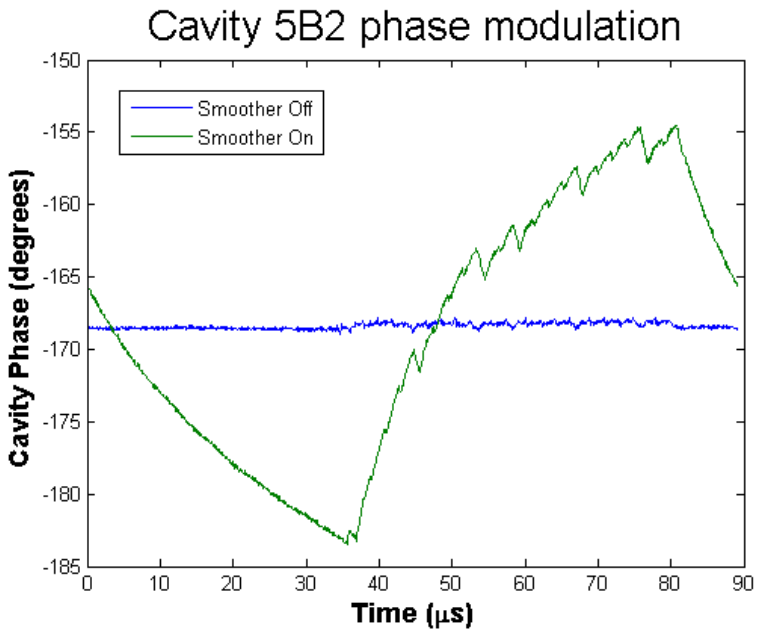
- The algorithm was tested using simulations and during 2012 MD periods
- A significant reduction in average klystron forward power was achieved
- With this scheme klystron forward power requirements are in theory very slightly dependent on beam current
  - Existing RF would be sufficient even for High-Lumi LHC (1.1 A DC)



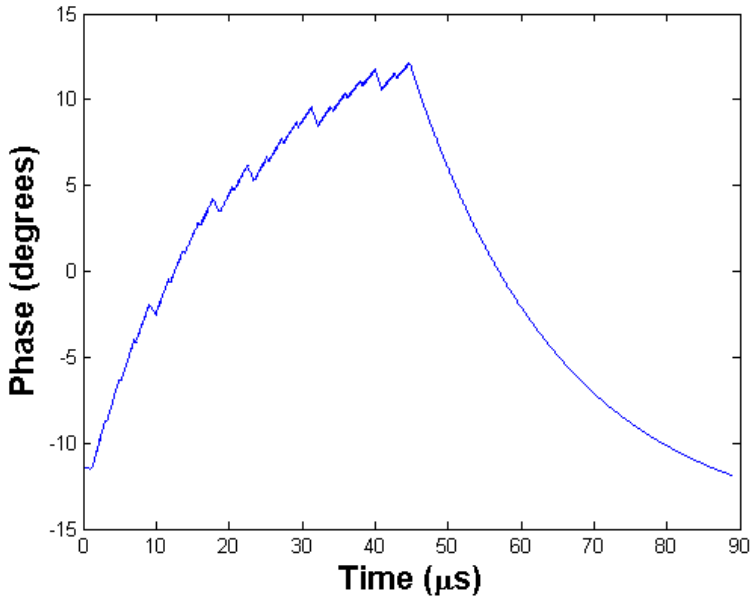


MD Results

- "Smoothing" algorithm worked very well with 1-Turn feedback OFF. Discrepancy with 1-Turn feedback was explained after the end of the run.



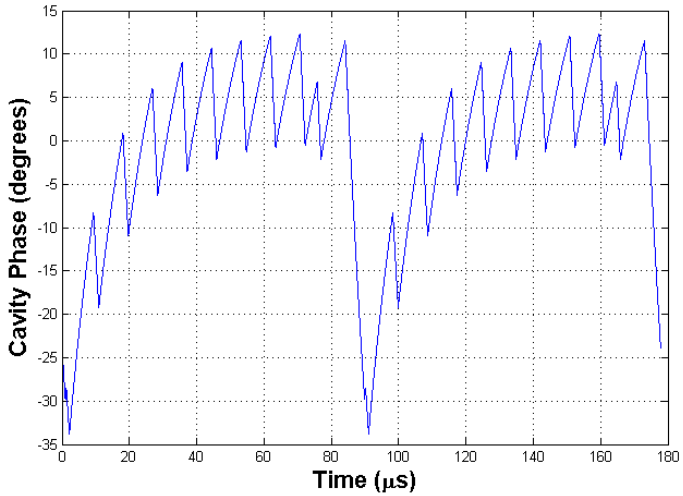
Cavity phase over a turn, 720 bunches



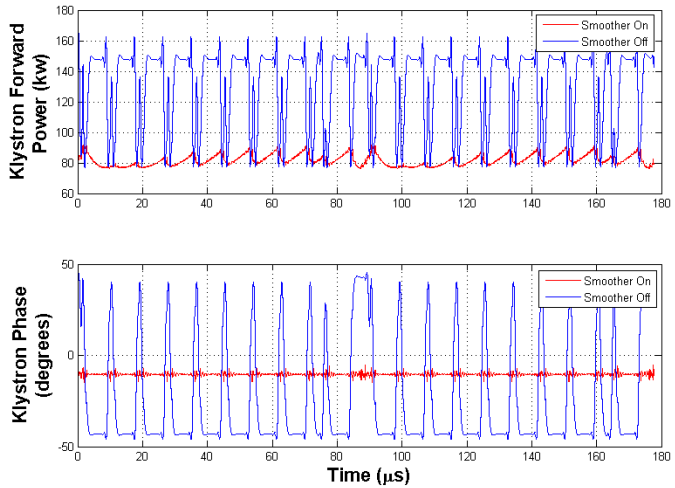
Estimated cavity phase modulation for 720 bunches.

Simulation Results

- The development continued after the end of the run to understand the interaction with the OTFB and converge on the final implementation
- Tests have now been conducted with the latest firmware in simulations (including two cavity RF system) and on the LLRF test stand
- The algorithm is ready to be commissioned in the beginning of the next LHC run



Cavity phase at 450 GeV with High-Lumi Beam Current.



Klystron Forward Power at 450 GeV with High-Lumi Beam Current.

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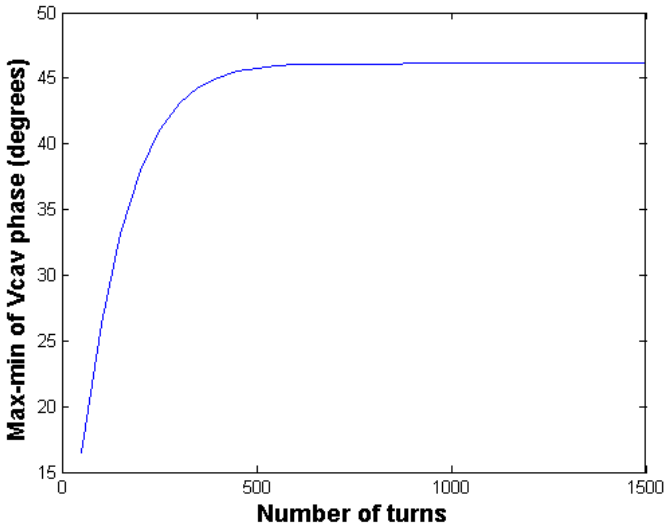
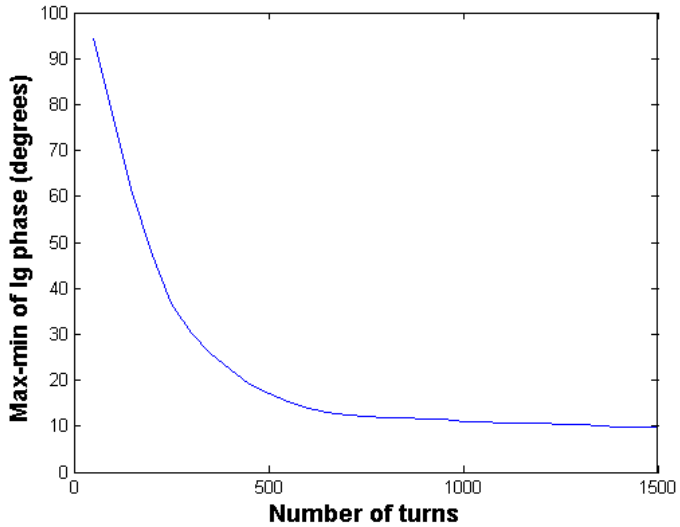


Cavity phase modulation evolution with algorithm. 450 GeV with High-Lumi Beam Current.



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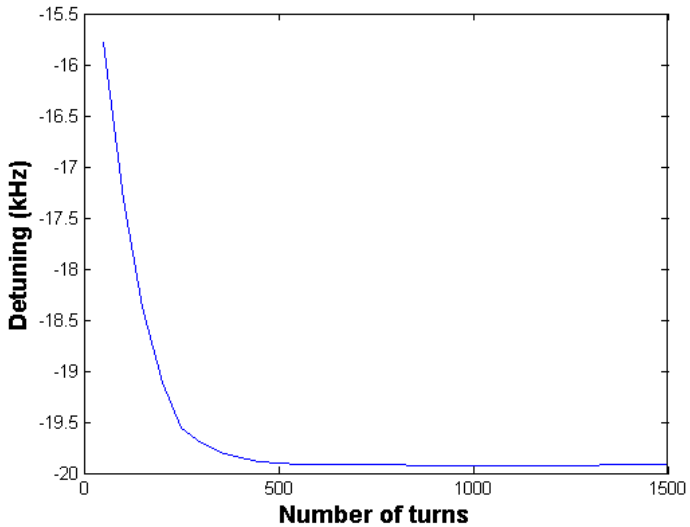
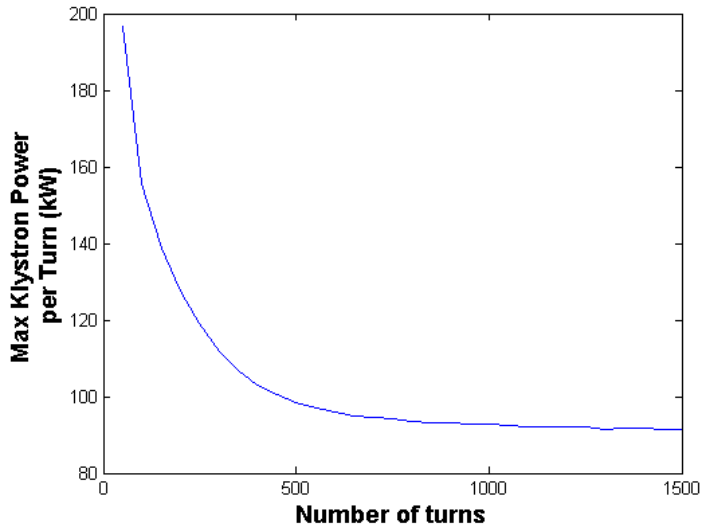


Detuning evolution with algorithm. 450 GeV with High-Lumi Beam Current.



Klystron Power evolution with algorithm. 450 GeV with High-Lumi Beam Current.

Consequences for Harmonic Cavities

- This new scheme is extremely beneficial in terms of fundamental RF power requirements for the LHC
- The phase modulation would be mirrored in the Harmonic Cavity setpoint
  - It slightly complicates the controls for the Harmonic Cavities
  - It has implications on the required power for the Harmonic Cavities (see next talk)
- We have tools to both estimate and simulate the expected behavior with Harmonic Cavities

References


[1] D. Boussard, “RF Power Requirements for a High Intensity Proton Collider", CERN-SL-91-16-RFS, 1991


[2] 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.


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


[4] T. Mastoridis, P. Baudrenghien, A. Butterworth, J. Molendijk, J. Tuckmantel, “Cavity Phase Modulation MD Blocks 3 and 4”, ATS-Note-2013-013 MD, 6 March 2013.