LHC LLRF UPGRADE:
CAVITY PHASE MODULATION TO REDUCE KLYSTRON POWER IN PHYSICS

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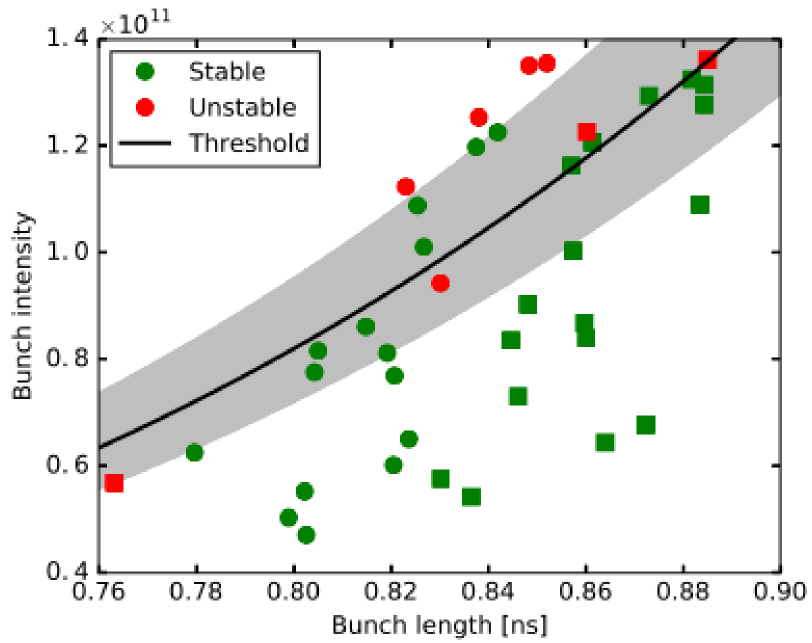
Outline

- Motivation
  - Why and what voltage in an Hadron collider?
  - Why do we have to compensate for beam loading?
- Beam loading compensation strategies
- Minimizing klystron power. Exact solution
- Mean power during fill
- RF performances
- Feedback from the LHC experiments
- Conclusions

Voltage in an Hadron collider. Why?

- In physics (constant energy), the power lost by synchrotron radiation is very small in hadron colliders. In the LHC it is 15 keV/turn at 7 TeV
- In high intensity machines, collective effects dominate: The required RF voltage is derived from the required longitudinal emittance (< bucket area) that will keep the beam stable
- In the LHC the longitudinal stability is governed by wide-band machine impedance (single bunch effect)
- The estimated Imaginary part of the wide-band impedance is 0.065 ohm [1]
- The HiLumi bunch intensity ($2.2\ 10^{11}$ p/bunch, τ=1 ns) will be unstable if V<12 MV.

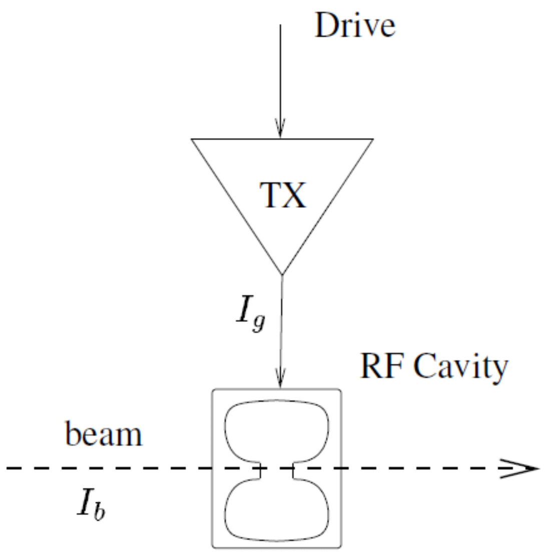


LHC single bunch instability threshold: 6.5 TeV, 12 MV. [2]

$$\frac{|\mathrm{Im}\, Z|}{n} < \frac{|\eta|\, f_{rev}}{eF\beta^2}\,\frac{1}{I_b}\,\frac{\Delta E^2}{E}\left[\frac{\Delta\Omega_s}{\Omega_s}\right]\tau$$

Beam loading

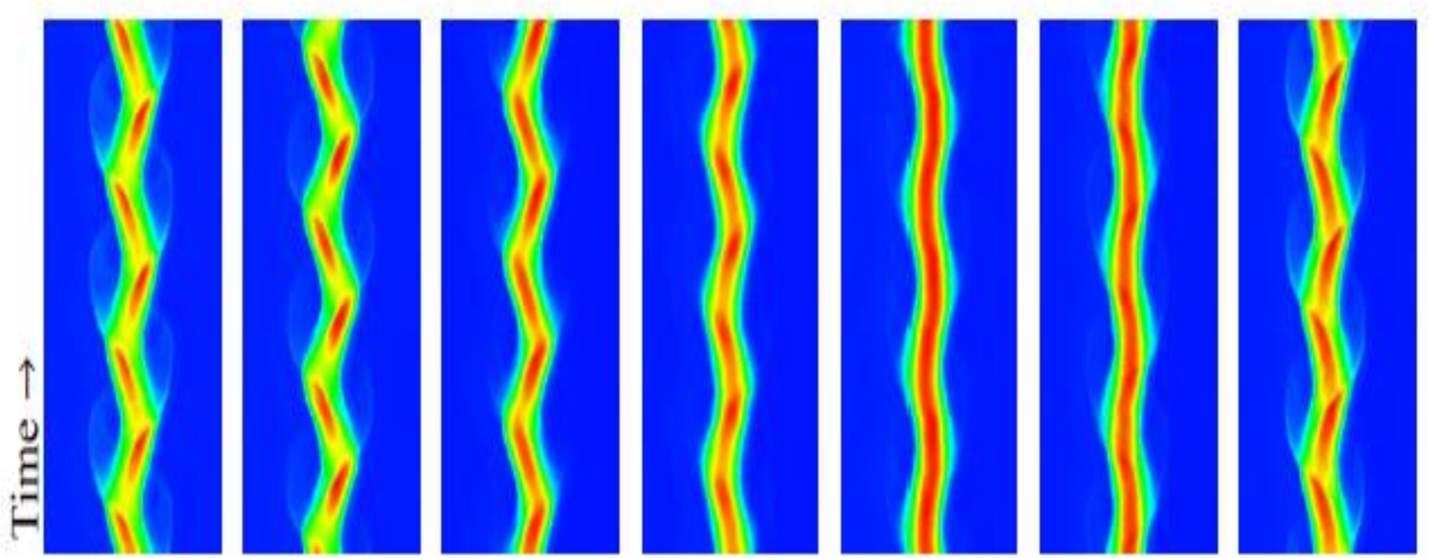
- Beam= charged particles in motion = current
- Cavity=resonant impedance
- Beam Crossing the cavity -> Beam induced electro-magnetic wave called wakefield
- The total voltage seen by the beam is the vector sum of the voltage due to the generator and the beam loading



- If the wakefield created by the passage of the bunch in the cavity has not decayed to zero by the next passage, it will act back on the bunch
- If the gain/phase shift of this natural beam/cavity feedback is unfavorable, instability will arise: The bunch starts oscillating in the bucket
- The situation gets worse if we have many bunches in the machine. The wakefield created by one bunch will act on the following one when it crosses the cavity, thereby creating coupling between the synchrotron oscillations of the individual bunches
- This effect, very important in high intensity synchrotrons, can lead to coupled-bunch longitudinal instability

Longitudinal Coupled-Bunch Instability

From H. Damerau [3]

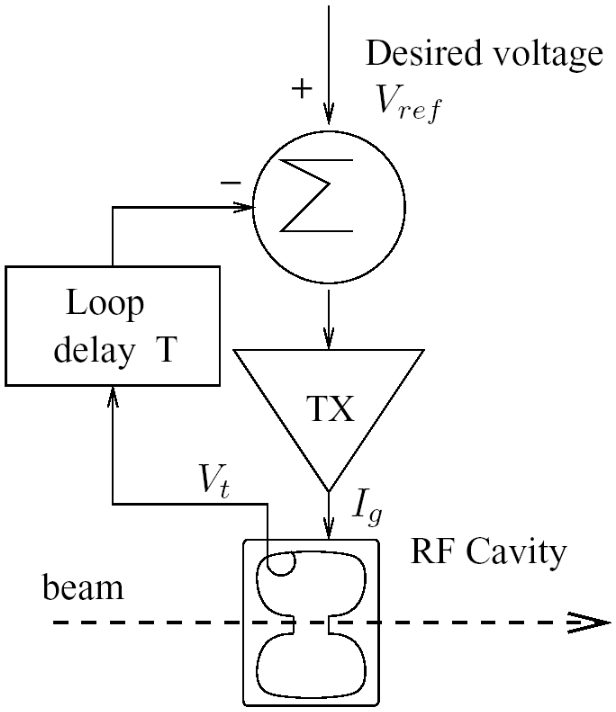


Conclusion:

- We need RF voltage in Hadron collider…
- ….and we need to compensate for beam loading.

Beam Loading Compensation

- CBI can come from all sorts of narrow-band impedances around the machine (discontinuities in vacuum pipe, or HOMs – from cavities or kickers)
- But when the cause is the cavity around fundamental, the LLRF can help much…and very economically
- The LLRF must "discipline" the total cavity voltage, thereby reducing the effective impedance, that is the ratio of $\Delta V/I_b$
- It must impose a field (Desired Voltage) and fight against the beam induced perturbation
- A classic method is the use of a feedback loop around TX-Cavity [4]



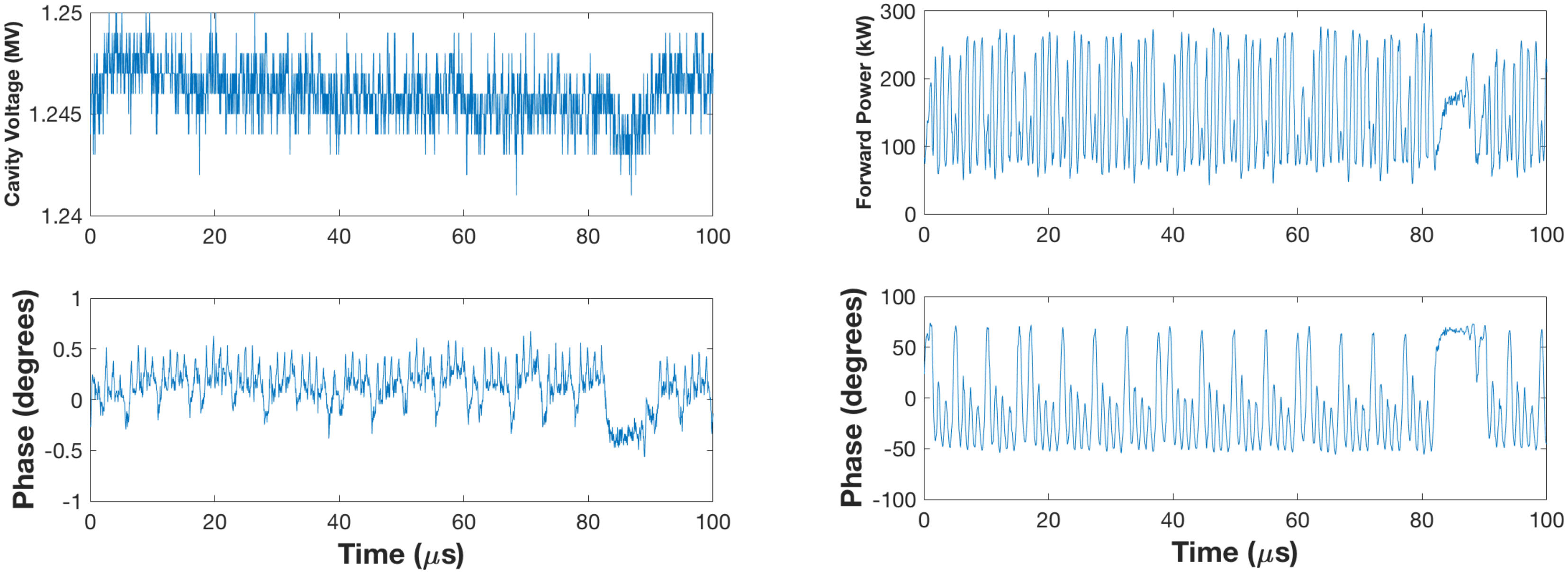
RF or Direct Feedback

Desired voltage. Two options

- Brute-force discipline
  - Keep voltage constant during one turn in both amplitude and phase
  - Good for beam parameters (all bunches identical)
  - Very demanding in RF power as the klystrons must compensate for the beam current transients
  - Power scales linearly with beam current
  - Used in most high intensity synchrotrons since late 80s [5]
- Psychology
  - *Manipulate* the beam by imposing a voltage that matches the beam-induced modulation [6]
  - Keep voltage amplitude constant during one turn (identical momentum spread, synchrotron frequency, IBS,..)
  - Enforce the exact phase modulation that the beam creates (modulation of bunch spacing)
  - Power is independent of beam current!
  - Very economical in RF power

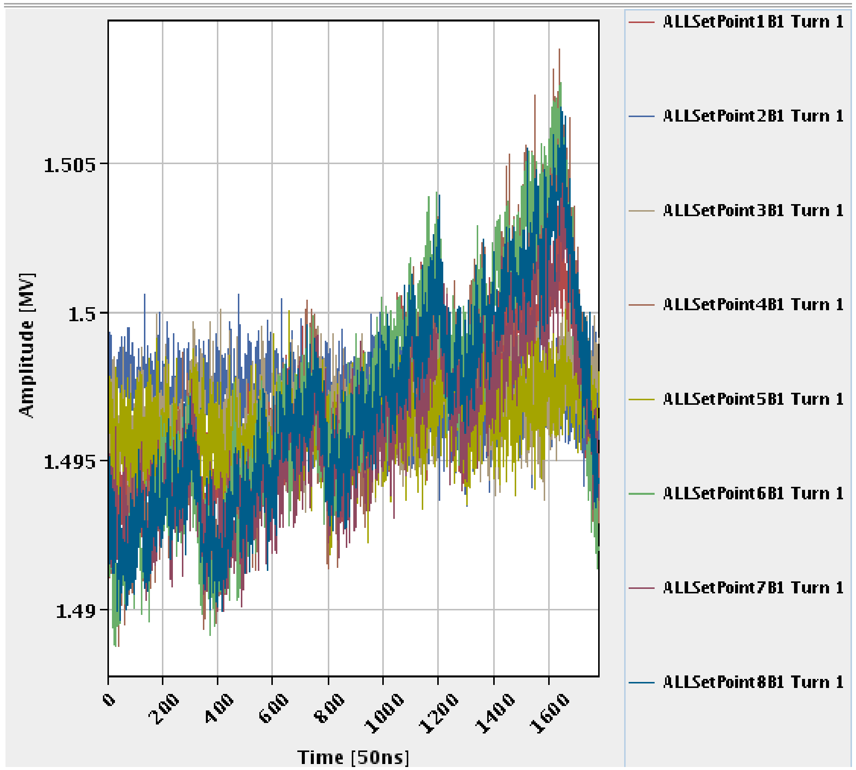
Brute-force discipline. 2016 situation

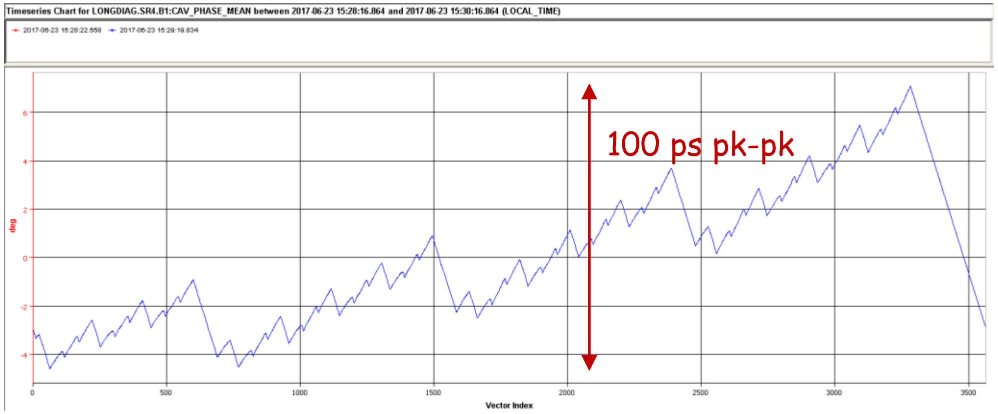
2244 bunches, 25 ns spacing, 1.2E11 p/bunch, 6.5 TeV



- The cavity voltage and phase are kept constant during one turn (0.4% in amplitude, 1 RF degree in phase). Left plots
- Very demanding in RF power as the klystrons must compensate for the beam current transients. Right plots
- Klystron power toggles between 80 kW and 250 kW
- Dynamic situation: Strong peaks during the beam to no-beam transients

Phase Modulation. 2017 situation

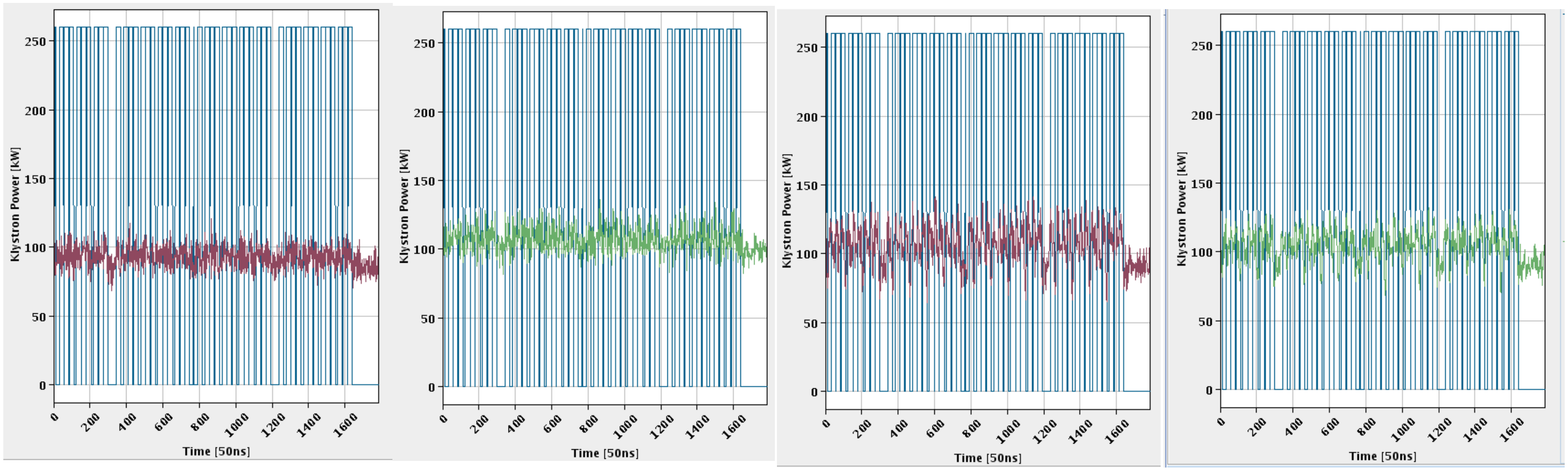




Fill 5864, 2371 bunches, 25 ns spacing, 1.1E11 p/bunch, 6.5 TeV

- The cavity voltage is kept (almost) constant in amplitude. Left: 10 kV pk-pk compared to 1.5 MV
- The cavity phase is modulated along the turn (right).

Phase Modulation. 2017 situation



2371 bunches, 25 ns spacing, 1.1E11 p/bunch, 6.5 TeV

- Klystron power modulation during one turn for B1 klystrons 1 to 4
- The transients between beam and no-beam segments are barely visible
- Small noticeable difference during the abort gap (no-beam)

Minimizing klystron power. Exact solution

- We keep cavity voltage amplitude V_0 constant, but accept a phase modulation
- We assume that the beam current $I_b(t)$ is in quadrature with cavity voltage (almost 180º stable phase in physics). Then the required klystron power can be written [7]

$$P(t)=\frac{1}{2}R/Q\,Q_L\left|I_g(t)\right|^2=\frac{V_0^2}{8\,R/Q\,Q_L}+\frac{1}{2}R/Q\,Q_L\left[-\frac{V_0}{R/Q}\frac{\Delta\omega}{\omega}+\frac{V_0\frac{d\varphi}{dt}}{\omega R/Q}-\frac{1}{2}i_b(t)\right]^2$$

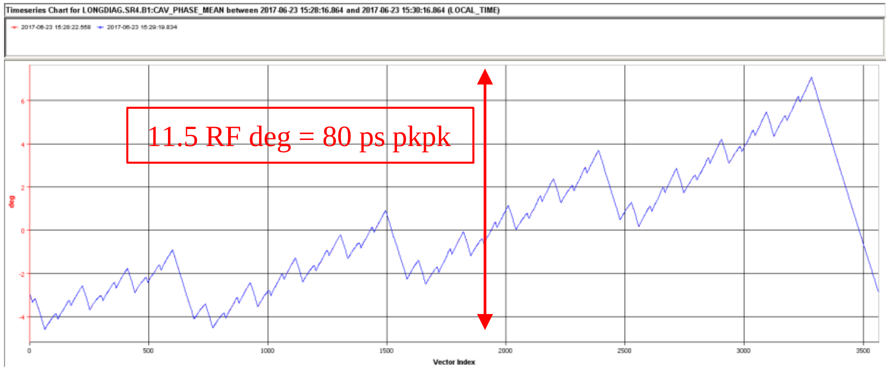
- The instantaneous demanded power will be minimal (and constant) if the derivative of the voltage phase modulation is proportional to the envelope of the beam current $i_b(t)$ [7]

$$\frac{d\varphi}{dt}=-\Delta\omega_{opt}\frac{i_b(t)-\overline{I_b}}{\overline{I_b}}$$

$$\Delta\omega_{opt}\approx-\frac{1}{2}\frac{R/Q\,\omega}{V_0}\frac{\int_u^{u+T_{rev}}i_b(t)\,du}{T_{rev}}=-\frac{1}{2}\frac{R/Q\,\omega}{V_0}\overline{I_b}$$

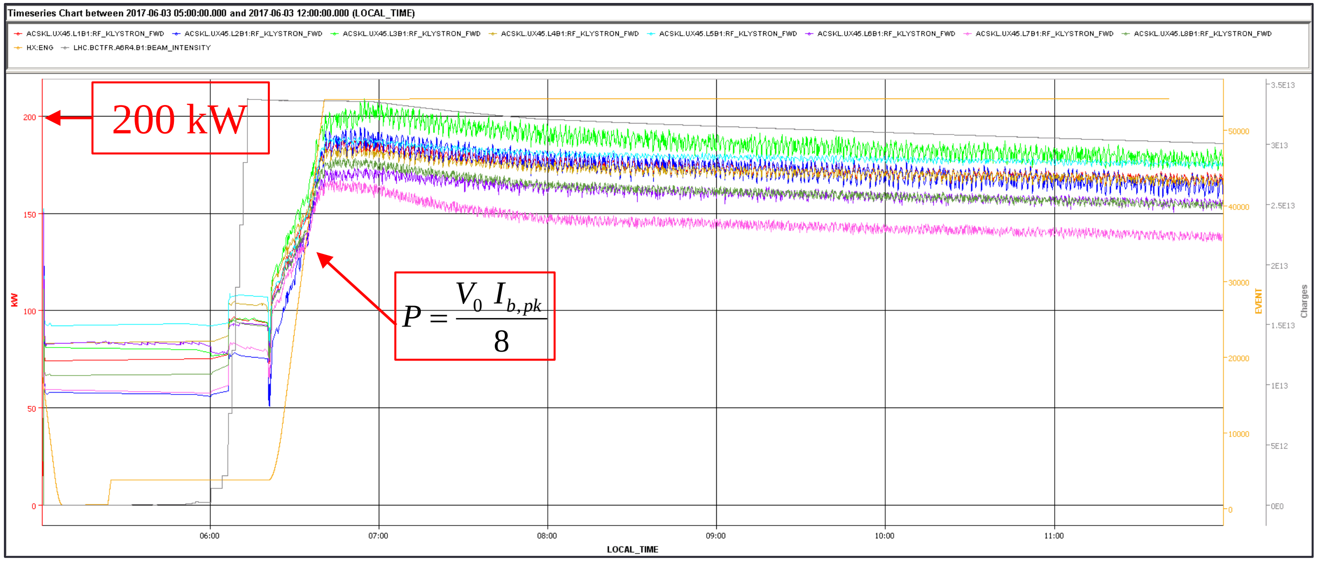
- Then the power is constant and **independent of beam current**…Great!

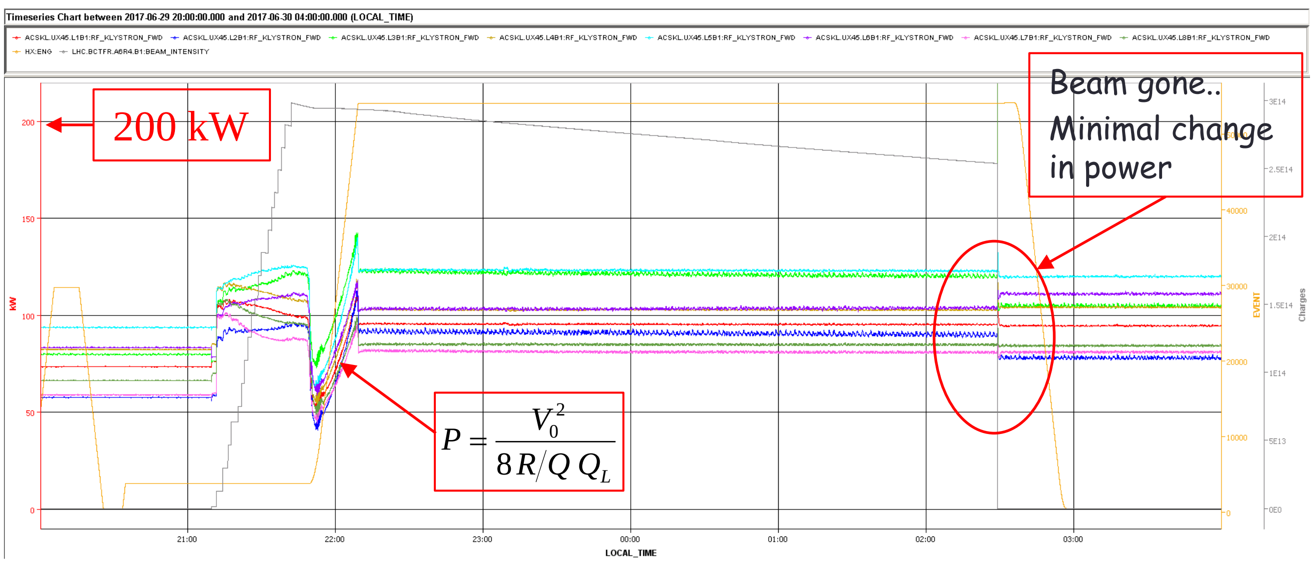
$$P(t)=\frac{V_0^2}{8\,R/Q\,Q_L}$$



Calculated cavity phase slippage for nominal beams in physics. Fill 5864

Mean power during fill





- Top: Fill 5737
  - Old scheme
  - Power increases during ramp
  - Noise ripples caused by the beam/no beam transients
  - Power scales as beam current -> **190 kW at 1.5 MV, 0.5 A DC**
- Bottom Fill 5887
  - New scheme
  - Power independent of beam current
  - Very small power change following beam dump
  - Power scales quadratically with beam voltage-> **104 kW at 1.5 MV, Q_L=60k**

Iterative algorithm

- We have implemented an iterative method that adapts to slowly changing conditions (ramp, decreasing intensity in physics, change of bunch length -> Effect on RF component of beam current) [8].
- We use Steepest Descent algorithm, that is we apply small corrections proportional to the gradient of the power w.r.t. the derivatives of the phase modulation. Time index *n*, iteration index *k*

$$\dot{\varphi}_{k+1,n} = \dot{\varphi}_{k,n} + \alpha \frac{\partial P_{k,n}}{\partial \dot{\varphi}_{k,n}}$$

$$\dot{\varphi}_{k+1,n} = \dot{\varphi}_{k,n} + \alpha \frac{\omega R/Q}{V_0^2} \mathrm{Im}\left[I_{g,n} \mathrm{conj}\left[V_n \right] \right]_k$$

Phase modulation derivative. Iteration k+1

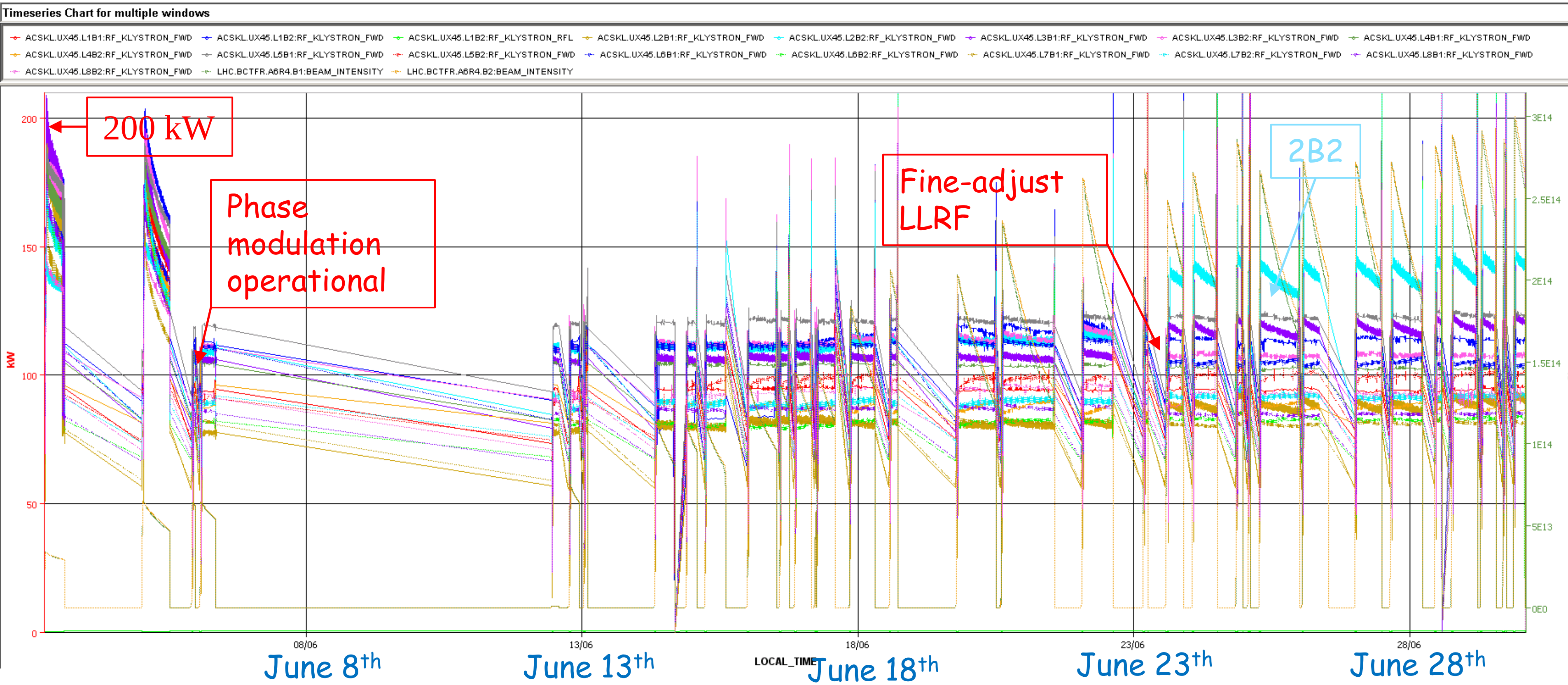
Phase modulation derivative. Iteration k

Klystron current (coupler in WG)

Cavity voltage (Antenna)

- The correction is proportional to the sine of the phase difference between klystron current and cavity voltage. We update the derivative of the phase modulation
- Then we integrate the derivative over 1 turn and remove the mean, that will be adjusted by the tuning.

RF Performances



- Voltage phase modulation switched ON June 4th, 2017
- Above plot shows the power of all klystrons, plus beam intensity for all fills that made it to physics (injphys, preramp, …, stable), from June 3rd till now
- All klystron power below 120 kW (except 2B2, @ 140 kW)

CMS feedback

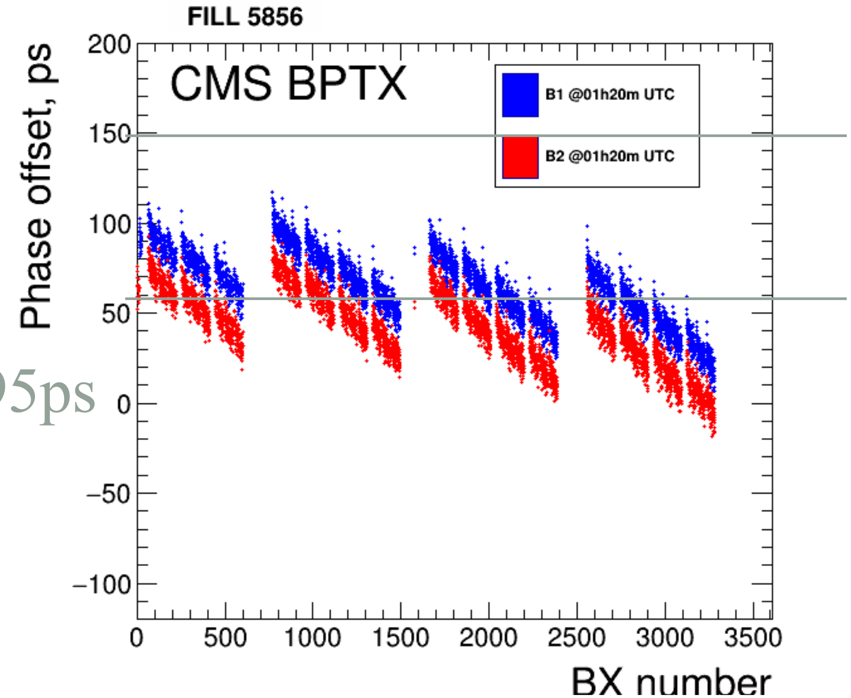
Courtesy of C. Schwick, J. Boyd, LHC Physics coordinators

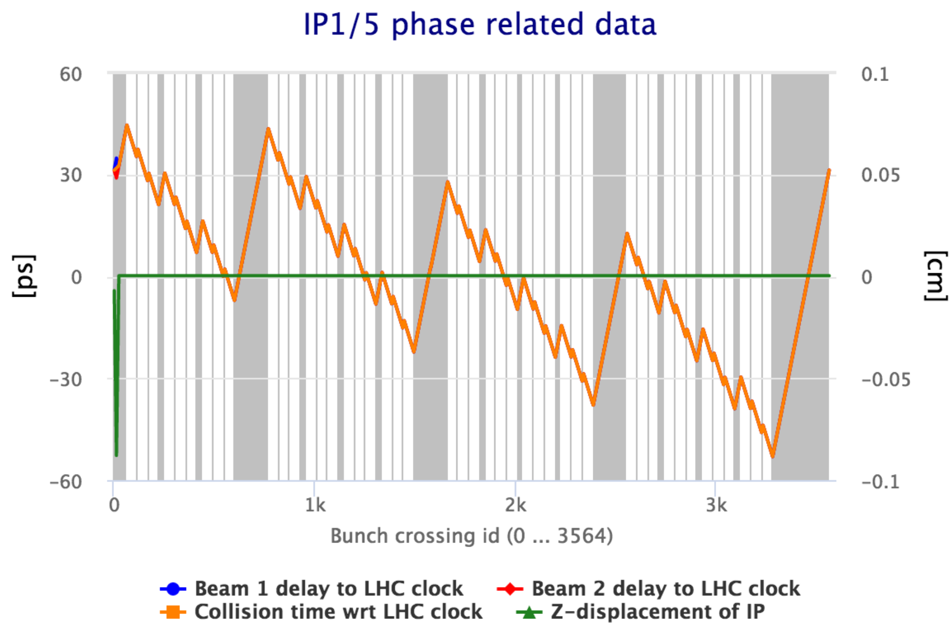
Fill 5856

(25ns_2173b_2161_1872_1962_144bpi_17inj)

- Time of collision modulation
  measurement: Δ ≈ 95ps
  prediction: Δ = 97ps

Δ≈95ps



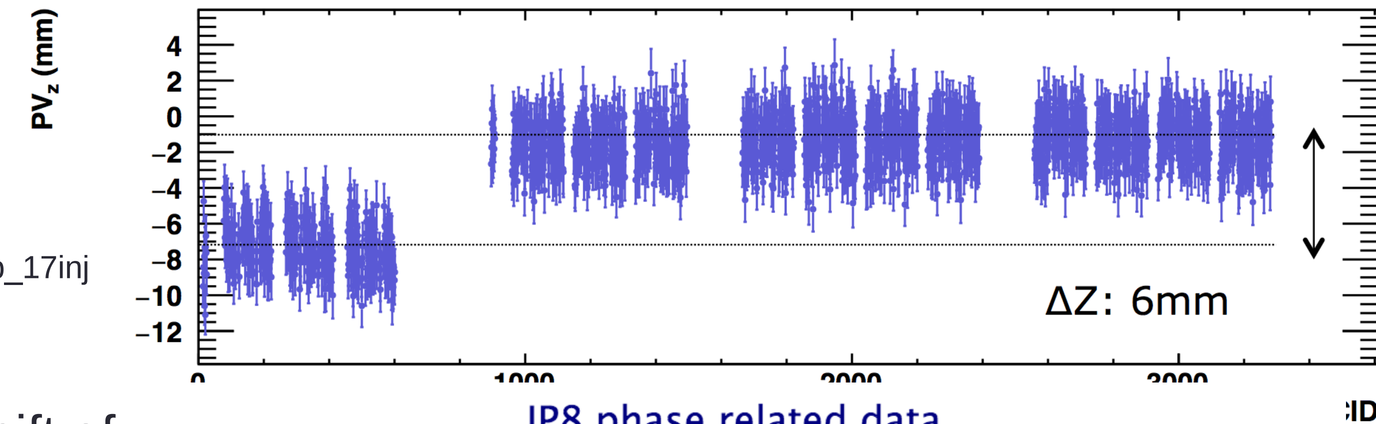


Feedback: LHCb

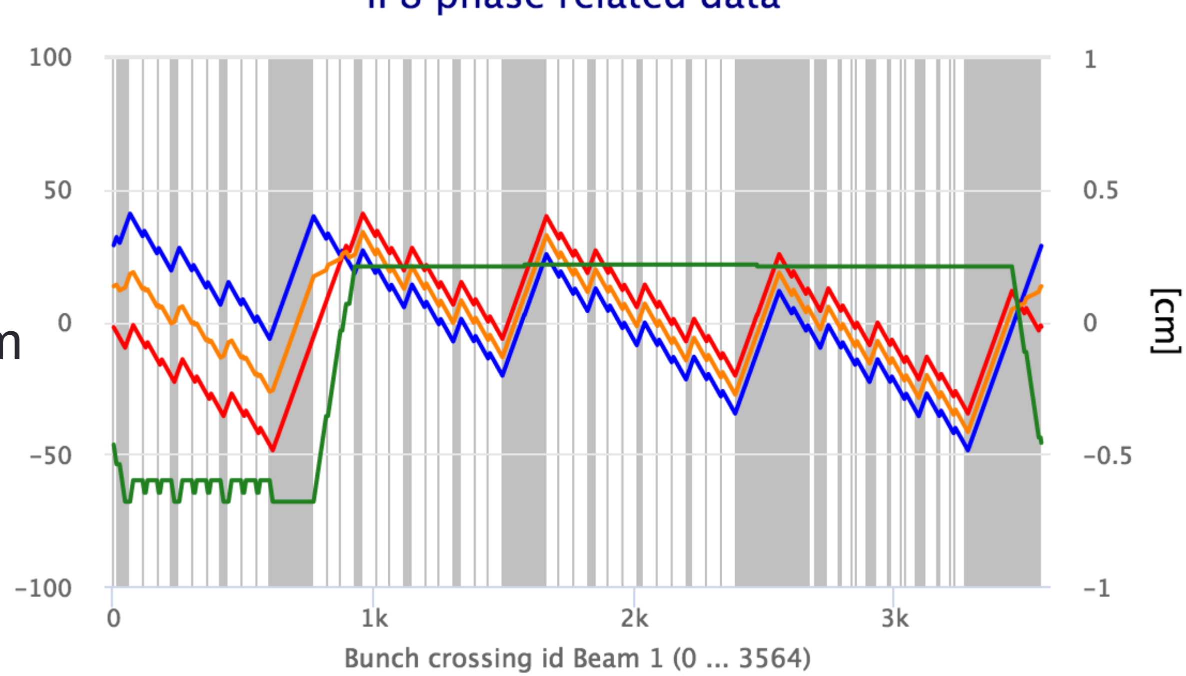
Courtesy of C. Schwick, J. Boyd, LHC Physics coordinators

Fill 5856

25ns_2173b_2161_1872_1962_144b_17inj



- LHCb measures a shift of the vertex position in z
- Agreement within 15%
  measurement: Δ ≈ 6mm
  prediction: Δ = 7.1mm



Conclusions

- With the old scheme, the LHC klystrons are close to saturation with 0.5 A DC and will not cope with the HiLumi intensity
- The Voltage Phase Modulation scheme is a very attractive alternative to the Fixed Voltage (also called Half Detuning) scheme used from LHC start-up till June 4th, 2017
- It provides the same performance in terms of Beam Stability caused by cavity impedance at fundamental
- It gives the same uniform bunch parameters: RF limit on momentum aperture, synchrotron frequency, bucket area (longitudinal stability)
- But it introduces a small modulation of bunch spacing, in the order of 70 ps pk-pk over one turn for a *full* machine-> some effects on Time of collision and z-vertex, observed by the experiments [8]
- Full Detuning is in operation since Fill 5742 (June 4th)
- The algorithm automatically adjusts to filling pattern, bunch intensity, bunch length
- The required klystron power is close to the theoretical no-beam value. Very encouraging for HiLumi

$$P = \frac{V_0^2}{8 R/Q \, Q_L}$$

References

[1] E. Shaposhnikova et al., Loss of Landau damping in the LHC, IPAC 2011

[2] J.F. Esteban-Muller et al., LHC Longitudinal single bunch Stability threshold, CERN-ACC-NOTE-2016-0001

[3] H. Damerau et al., Longitudinal Coupled-Bunch instabilities in the CERN PS,PAC 2007

[4] D. Boussard, Control of Cavities with High Beam Loading, IEEE Transactions on Nuclear Science, Vol NS-32, No5, Oct 1985

[5] D. Boussard, RF Power Requirements for a High Intensity Proton Collider, PAC 1991

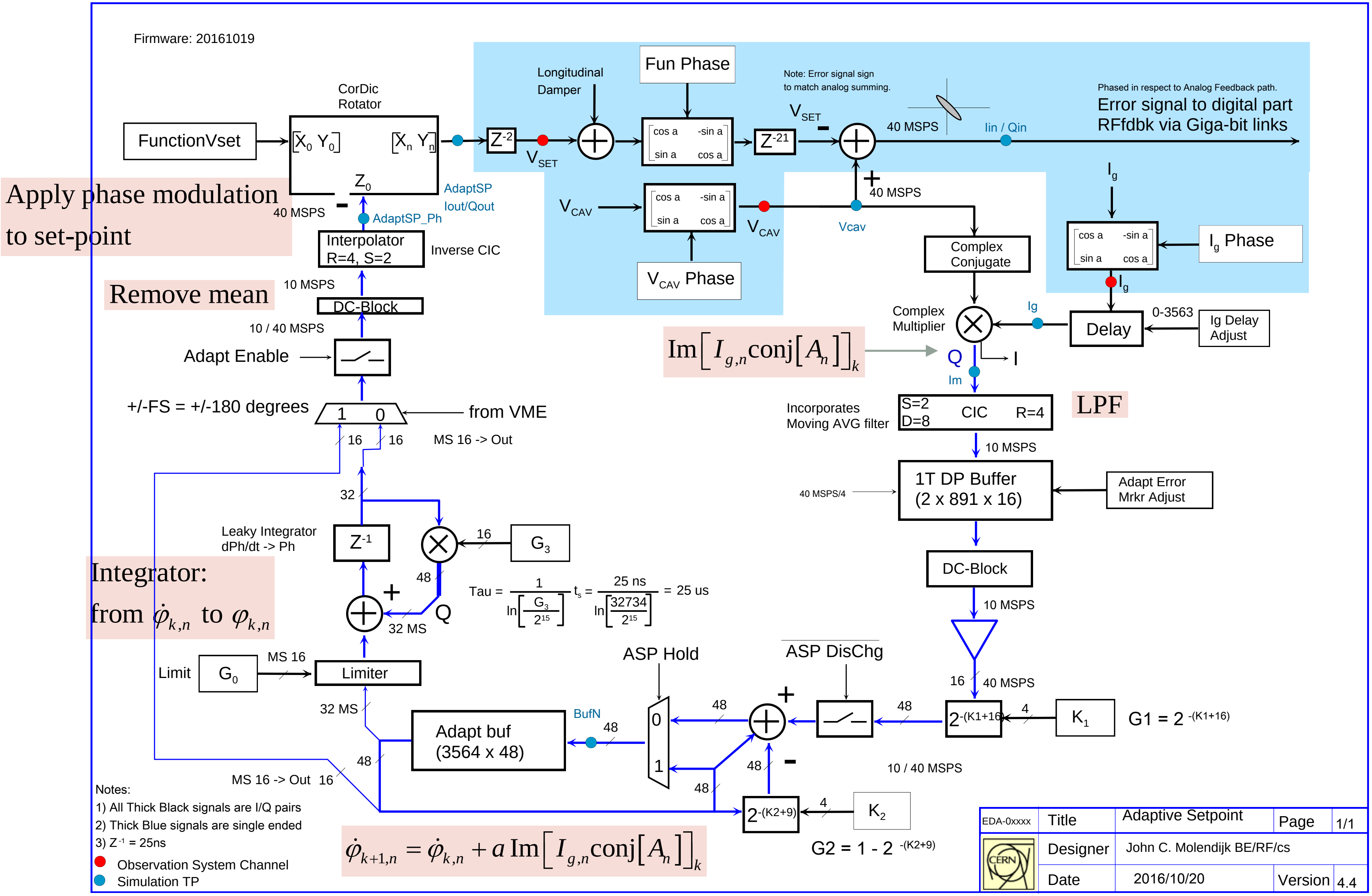
[6] T. Mastoridis, P. Baudrenghien, J. Molendijk, A Cavity Voltage Phase Modulation to Reduce the HL-LHC RF Power Requirements, submitted to PRAB

[7] J. Tuckmantel, Cavity-Beam-Transmitter Interaction Formula Collection with Derivation, CERN-ATS-Note-2011-002 TECH

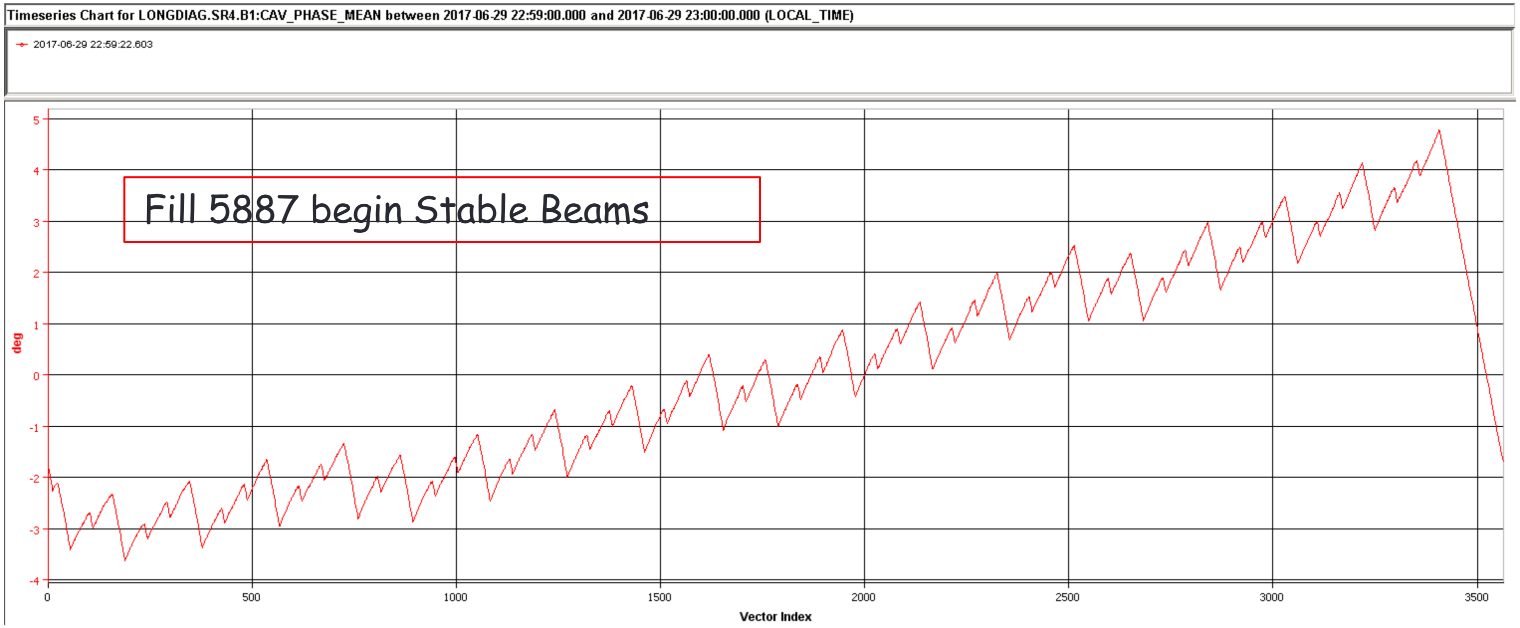
[8] T. Mastoridis, P. Baudrenghien, J. Molendijk, Cavity Voltage phase modulation to reduce the high-luminosity LHC rf power requirements, PRAB 20, 101003 (2017)

Additional material

Implementation



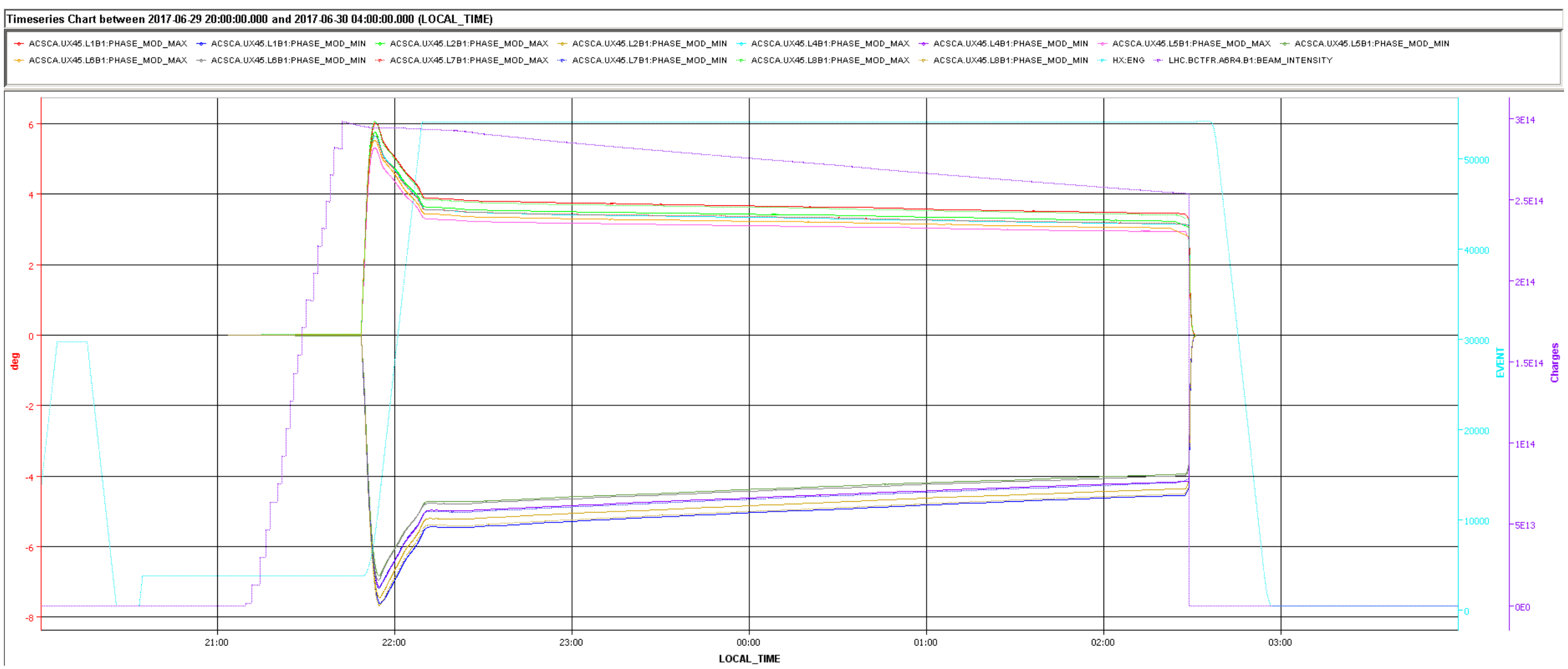
RF phase modulation



- CavityPhaseMeanB1, B2
  - Phase of the vectorial sum of the 8 cavities of each beam, in RF degrees at 400.8 MHz

In operation

- Filling is done with phase modulation OFF (sequencer driven)
- Phase modulation is switched ON before start ramp (sequencer driven)
- It then tracks the acceleration ramp (change of voltage), with very slow adaptation (time constant > 30 seconds, *adiabatic* to the beam, and slower than tuner reaction ~1s)
- It stays ON till dump, adapting to the variation of bunch intensity (and length).



Phase modulation Min-Max for the 8 cavities Beam 1. Fill 5887