P. Baudrenghien, J. Esteban Muller, E. Shaposhnikova, H. Timko

CERN BE-RF

Many thanks to

L. Arnaudon, T. Bohl, O. Brunner, A. Butterworth, W. Hofle, G. Kotzian, P. Maesen, D. Valuch

Chamonix 2016, Jan 25th ,2016

LESSONS LEARNT FROM 2015 RF AND ADT

2016 vs Run 1

- Change in Beam Parameters:
  - Increased energy: 6.5 TeV vs. 3.5-4 TeV
  - Reduced bunch intensity: 1.2E11 p vs 1.4E11p (end 2012)
  - Reduced bunch spacing: 25 ns vs. 50 ns -> increased total beam current (at constant bunch intensity)
- Change in RF System
  - No major change in hardware (except replacement of one module)
  - Change in RF parameters
    - Operational voltage set to 10 MV at 6.5 TeV (was 12 MV in 2012)
    - Small increase in target bunch length, to 1.35 ns for the blow-up (was 1.25 ns)
- Change in ADT System
  - Major change in hardware

Consequences: RF-longitudinal

- Reduced single-bunch instability threshold. At constant emittance, the threshold decreases with energy
- Reduced coupled-bunch instability threshold. At constant emittance, the threshold decreases with energy and total beam current
- Synchrotron radiation and its effects. Bunch shortening
- Beam loading compensation. Limited RF power
- Controlled longitudinal emittance blow-up during the ramp. Will it always work?

ADT renovated during LS1

- All new pickup cables
- Number of pickups doubled to 16
- Renovated power amplifiers
- New, more performant signal processing hardware
- Separation of the functionalities: main feedback, witness bunches, Injection and Abort gap cleaning and excitation
- Number of FGC functions doubled
- All new fesa3 classes
- All new graphical user interfaces

SINGLE-BUNCH LONGITUDINAL INSTABILITY THRESHOLD

Broadband impedance (single-bunch) limit (1)

$$\frac{\left|\mathrm{Im}\left(Z\right)\right|}{n} < \frac{|\eta| E}{e I_b \beta^2}\left(\frac{\Delta E}{E}\right)^2 \frac{\Delta\omega_s}{\omega_s} F \;\; f_0 \tau$$

- At a given energy, the RHS can be expressed as function of RF voltage, bunch current and bunch length

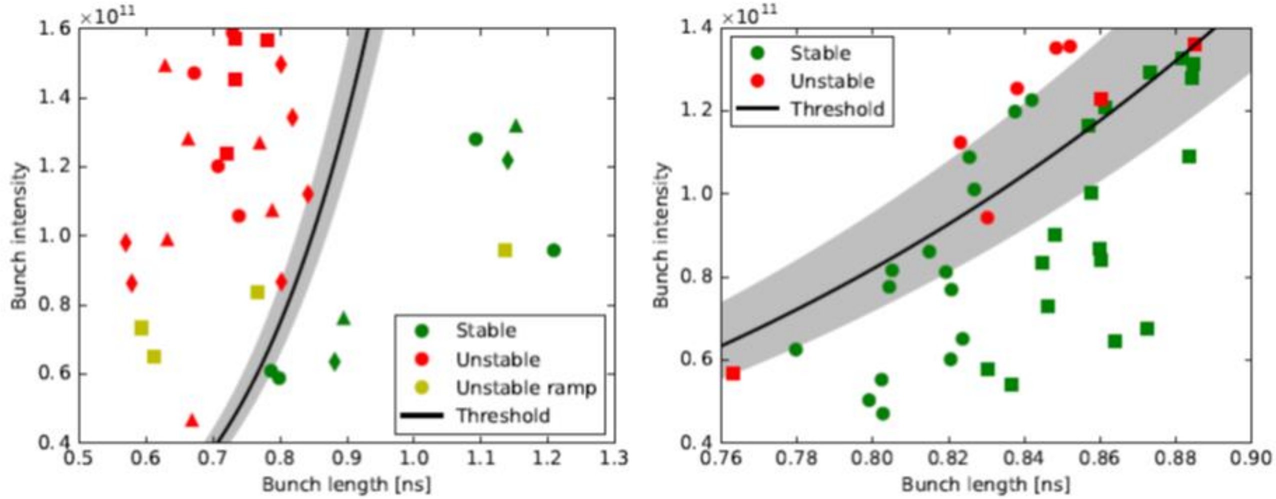
$$\frac{\left|\mathrm{Im}\left(Z\right)\right|}{n} < \frac{|\eta| E}{e I_b \beta^2}\left(\frac{\Delta E}{E}\right)^2 \frac{\Delta\omega_s}{\omega_s} F \;\; f_0 \tau \propto \frac{\tau^5 V}{I_b}$$

- The LHS depends on the machine impedance. It sets a limit on the RHS ratio for single-bunch stability (at a given voltage, bunch length and bunch “shape”)

See E. Shaposhnikova, Longitudinal beam parameters during acceleration in the LHC, LHC Project Note 242, Dec 2000

Broadband impedance (single-bunch) limit (2)

- The limit (loss of Landau damping) was measured during two MDs in 2015, and confirmed by parasitic measurements in physics (12 MV RF)



(a) MD 1 (b) MD 2

- At 6.5 TeV, the MD1+2 measurements led to the threshold (N_b in p per bunch)

$$\frac{\tau^5 V}{N_b} > (5.5 \pm 0.5)10^{-5} \quad ns^5 V$$

- Some dependence on longitudinal bunch profile
- Measurements in good agreement with Im(Z)/n = 0.08 ohm

See J.Esteban Muller, Longitudinal single bunch stability threshold, CERN-ACC-Note 2016-001

Broadband impedance (single-bunch) limit (3)

- From these measurements we can deduce the single bunch instability threshold (Loss of Landau damping) for various (V,τ) pairs at 6.5 TeV. Taking the conservative number and with understood *dependence on longitudinal distribution*, we *get*

N_b (p per bunch) in E11	10 MV	12 MV	14 MV	16 MV
0.9 ns	1.18	1.41	1.65	1.89
1 ns	2.00	2.40	2.80	3.20
1.1 ns	3.22	3.87	4.51	5.15
1.2 ns	4.98	5.97	6.97	7.96
1.3 ns	7.43	8.91	10.4	11.9

- Notice the strong (fifth power) dependence on bunch length and the gentle (linear) dependence on RF voltage

COUPLED-BUNCH LONGITUDINAL INSTABILITY THRESHOLD

Narrow-band impedance (coupled-bunch) limit (1)

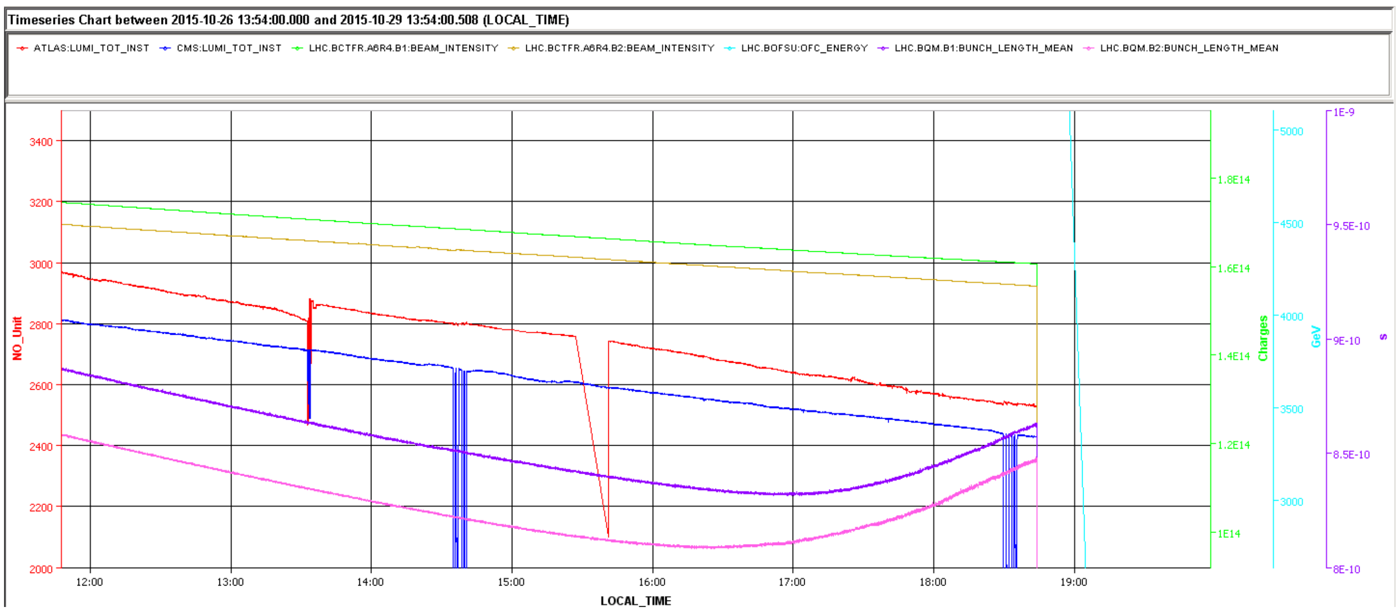
$$R_{sh} < \frac{|\eta| E}{e I_0 \beta^2} \left(\frac{\Delta E}{E} \right)^2 \frac{\Delta \omega_s}{\omega_s} \frac{F}{f_0 \tau} G(f_r \tau)$$

- Coupled-bunch instabilities are excited by wakefields that do not decay significantly between bunch passages
- In the frequency domain, this corresponds to longitudinal impedances with a bandwidth smaller than the inverse bunch spacing (40 MHz)
- Such are the RF cavities HOMs and fundamental resonance, plus other distributed narrow-band resonant structures
- All efforts were done during LHC design and LS1 to minimize these
- The threshold decreases with increasing energy AND with total beam current. So problems could be expected from 6.5 TeV operation combined with increased beam current (shorter bunch spacing)

See E. Shaposhnikova, Longitudinal beam parameters during acceleration in the LHC, LHC Project Note 242, Dec 2000

Narrow-band impedance (coupled-bunch) limit (2)

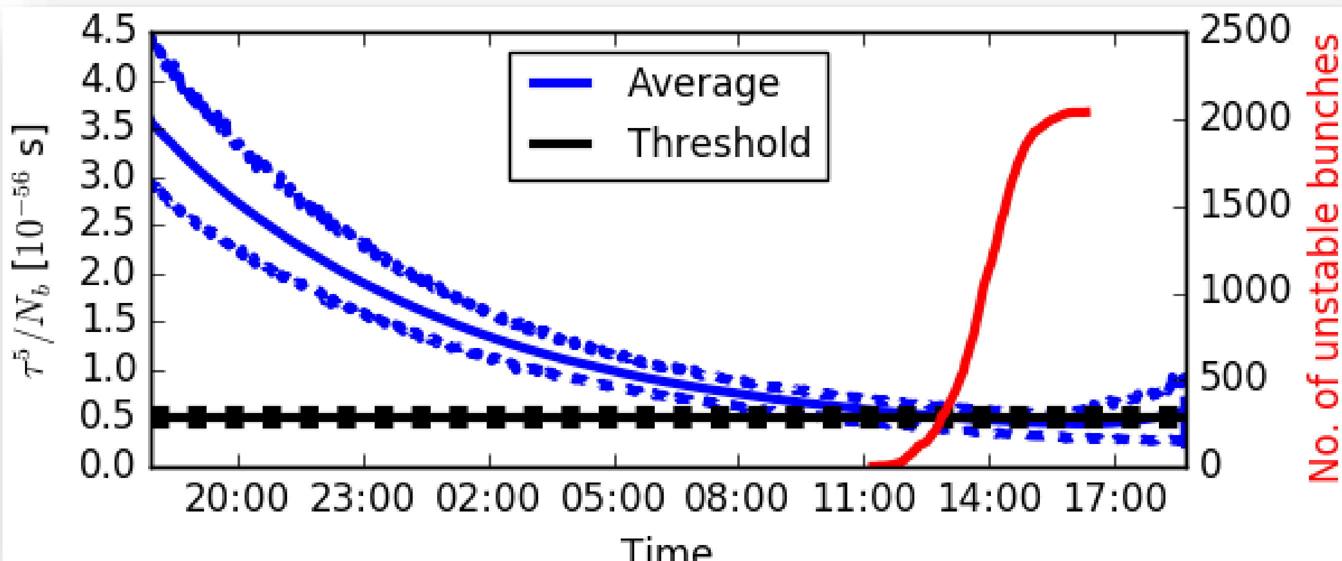
- But … that did not show up…
- With to-day's machine impedance, the longitudinal stability limit comes from single-bunch effect (broadband impedance)
- This is demonstrated by the longitudinal instabilities observed at the end of very long fills in 2015
- At the end of a long physics fills (4538), with 2200+ bunches, ~1.0E11 p/bunch, longitudinal instabilities were observed at 0.81 ns and 0.83 ns bunch length, that is the single-bunch instability limit



Top to bottom:
BCT B1 and B2
Atlas and CMS luminosities
Bunch length B1 and B2

Narrow-band impedance (coupled-bunch) limit (3)

- A finer analysis indicated that the longitudinal instabilities appeared at an intensity very close to the single-bunch instability threshold



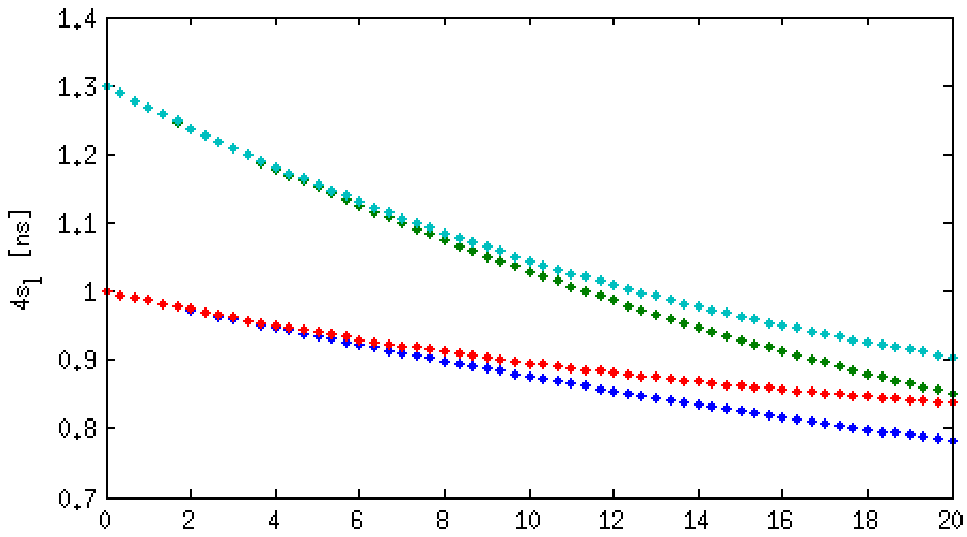
- Conclusion: in the longitudinal plane, the stability presently appears limited by single-bunch effects (broad-band impedance)

See H. Timko, Evian 2015 workshop

SYNCHROTRON RADIATION

Synchrotron radiation (1)

- The power radiated by a circulating particle scales as $1/\gamma^4$
- At 6.5 T
- With 28 … per beam
- This los … MW/beam)!
- Synchr… also provides longitud… ing time that scales as $1/\gamma^3$
- This eff… e longitudinal plane it moves … ch stability limit
- After 20 … duced from 1.25 ns down to 0.85 … stabilities were observed
- This behavi… ct against bunch shortening b… V.

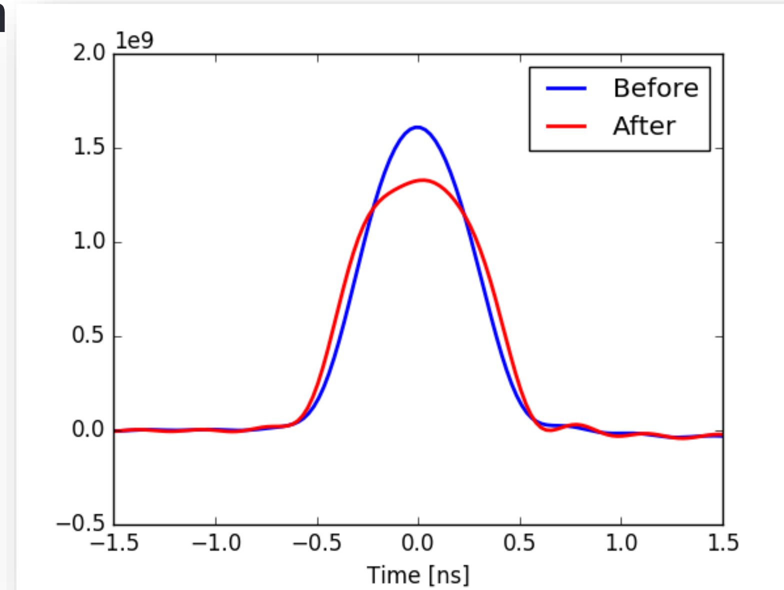


BL evolution at 6.5 TeV from model (which includes Synchrotron Radiation, Intra Beam Scattering and burn-off) and BL evolution using the observed transverse emittance evolution.
Courtesy F. Antoniou

J. Tuckmantel, Synchrotron Radiation Damping in LHC and Longitudinal Bunch Shape, LHC Project Report 819, June 2005
F. Antoniou, Luminosity modelling for the LHC, Evian workshop 2015

Synchrotron radiation (2)

- The ideal scenario would be to control bunch length in physics, as we do during the acceleration ramp
- The method used is the ramp is relatively violent as it must act against the rapid adiabatic bunch compression coming from the acceleration
- In static physics condition, we favour an alternative method, proposed at Fermilab: single-frequency sinusoidal RF phase modulation selectively exciting the core of the bunch
- Very encouraging tests in 2015 (end of fill MDs)
- Time needed to make it operational in stable beam in 2016



Measured on 28th October 2015 at the end of a physics fill

C. Tan, A. Burov, Phase modulation of the bucket stops bunch oscillations at the Fermilab Tevatron, PRST AB, 15, 044401 (2012)

BEAM LOADING COMPENSATION

Energy balance (today)

- In physics, 2 MW RF for < 3 kW passed to the beam
- (Almost) all power is dissipated in the circulator load
- What can we improve?
  - Voltage is required to provide for a bucket (V)
  - But.. there is no “fundamental” need for power, beside the small compensation of power lost by synchrotron radiation

Beam loading compensation

- Control of cavity voltage (including beam induced) is essential
  - We want to keep the voltage sensed by all bunches equal so that they have equal parameters (length, momentum spread)
  - We must compensate the beam-induced voltage at fundamental to avoid CBI caused by cavity impedance at fundamental
- We can derive a simple relation between I_g, V, I_b and the cavity detuning $\Delta\omega$

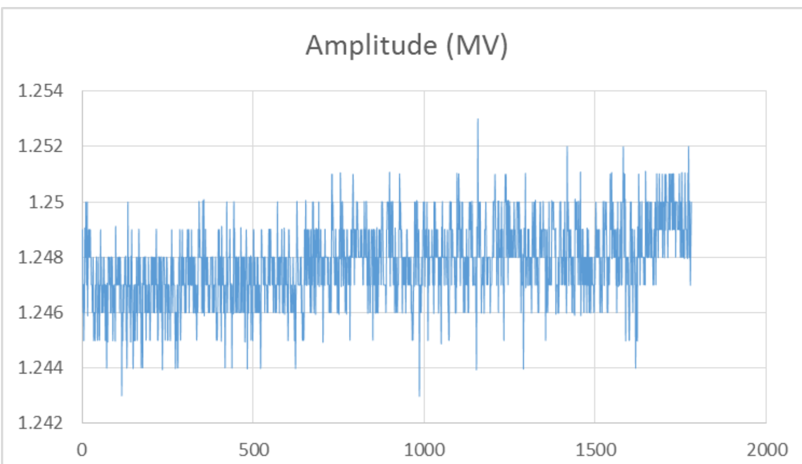
$$I_g(t) = \frac{V(t)}{2R/Q}\left[\frac{1}{Q_L} - 2j\frac{\Delta\omega}{\omega}\right] + \frac{dV(t)}{dt}\frac{1}{\omega R/Q} + \frac{I_b(t)}{2}$$

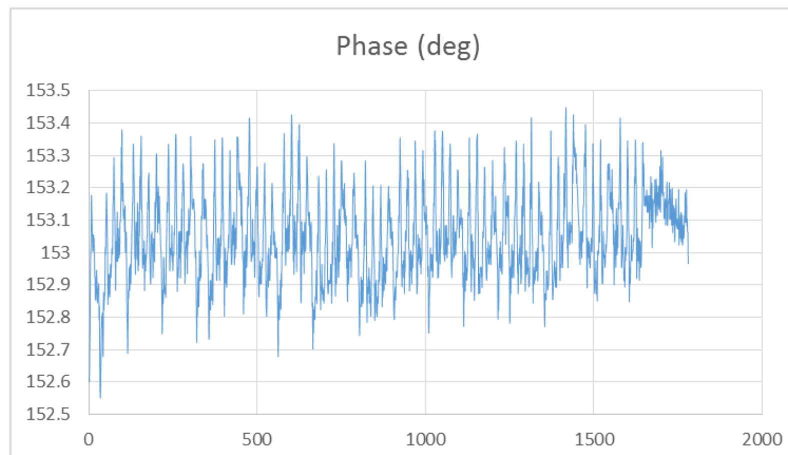
- The modulation in beam current $I_b(t)$ is imposed by the filling pattern: presence of small gaps for kicker rise time, plus a 3.2 μs minimum gap for the beam dump kicker

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

Beam loading compensation. To-day (1)

- So far we have operated the LHC RF for full compensation of the transient beam loading in the ACS cavities: $V(t) = V_0$
- The results are excellent: beam-loading invisible in amplitude, barely visible in phase (0.5 deg pk-pk)





Nov 2nd, 2015. Fill 4565. 2244 b. Cav4B1

Beam loading compensation. To-day (2)

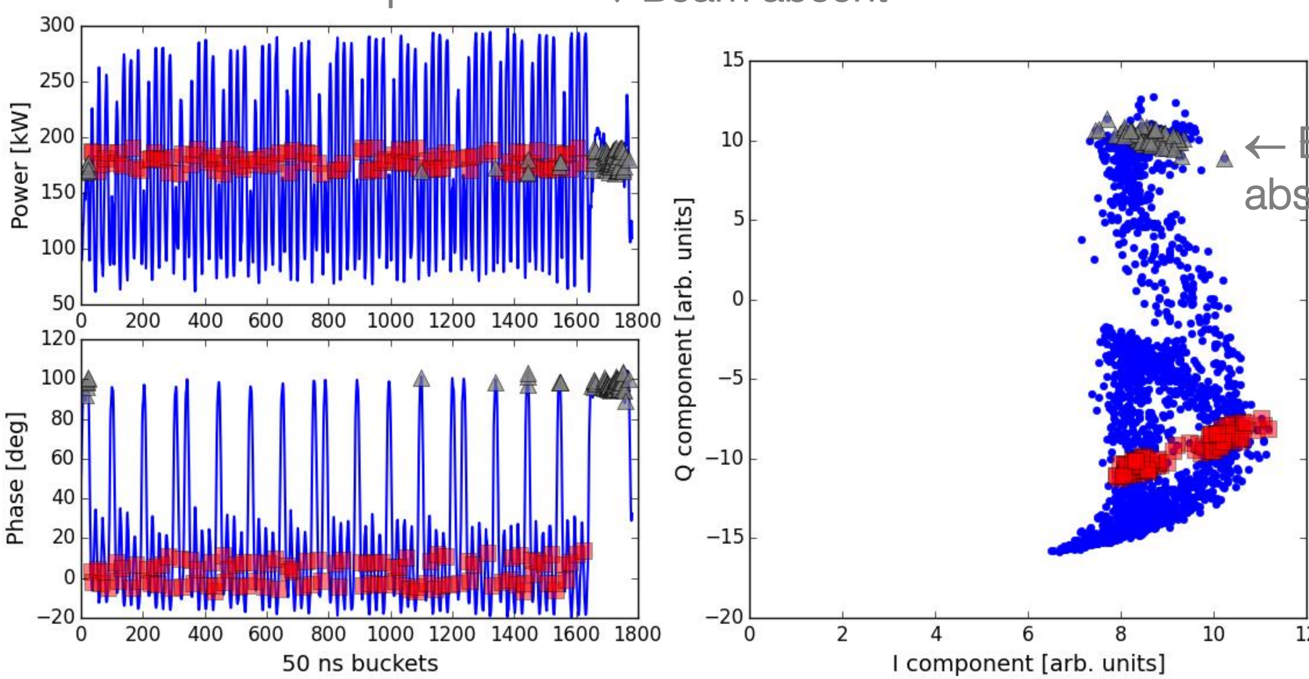
- The klystron current must “toggle” according to

$$I_g(t) = \frac{V}{2\,R/Q}\left[\frac{1}{Q_L} - 2j\frac{\Delta\omega}{\omega}\right] + \frac{I_b(t)}{2}$$

- After optimization of Q_L, and detuning, the required power is then simply proportional to voltage and peak RF component of beam current. Theory says 150 kW (10 MV, 1.2 A peak RF current), but we see large transients

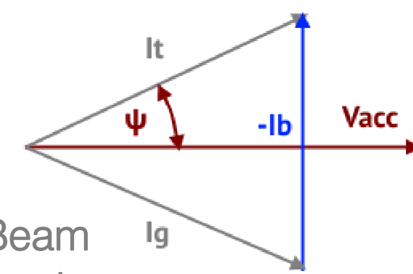
↓ Beam present ↓ Beam absent

$$P_g = \frac{V\ I_{b,pk}}{8}$$



← Beam absent

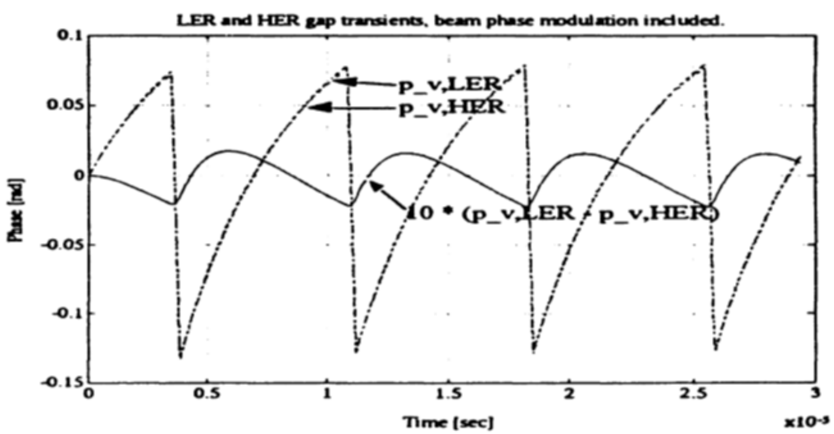
← Beam present



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

Beam loading compensation. A better scheme (1)

- Why do we care about voltage in turn segment where there is no beam?
- Alternative:
  - We keep the voltage *amplitude* constant over one turn
  - BUT we accept to modulate the voltage *phase* during the turn. This results in
    - A modulation of the distance between bunches. To be accepted by experiments
    - A required RF power INDEPENDENT of beam intensity
- The attractiveness of this scheme is evident: It was proposed for the LHC in 1991, was operational at PEP2 (1993-2008), used in an SPS test of the 400 MHz LHC cavity in 1995.

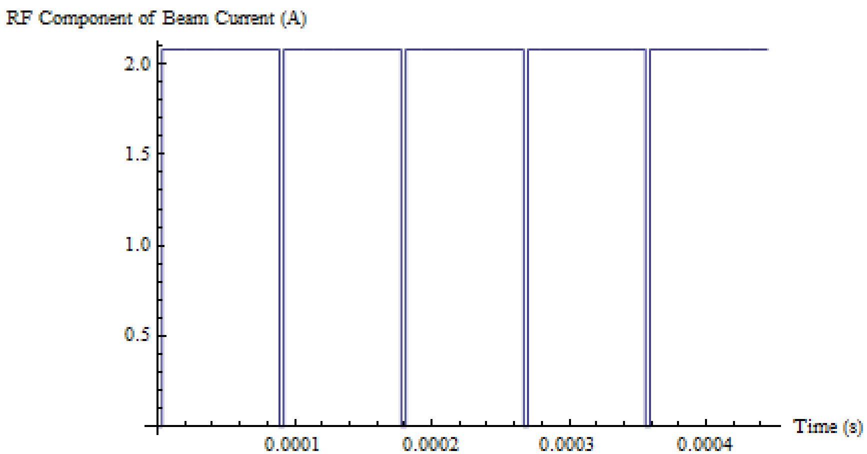


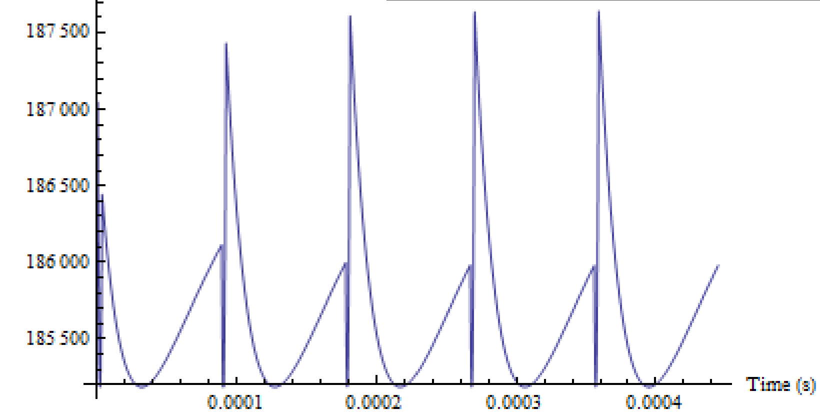
Phase slippage of the High and Low energy rings of PEPII, plus their difference. The pk-pk slippage was 70 ps.

F. Pedersen, RF Cavity Feedback, B factories conference, SLAC, April 1992
T. Bohl et al., A Superconducting RF Cavity for Bunch Compression of the High Intensity SPS Proton Beam at Transfer to LHC, IPAC95

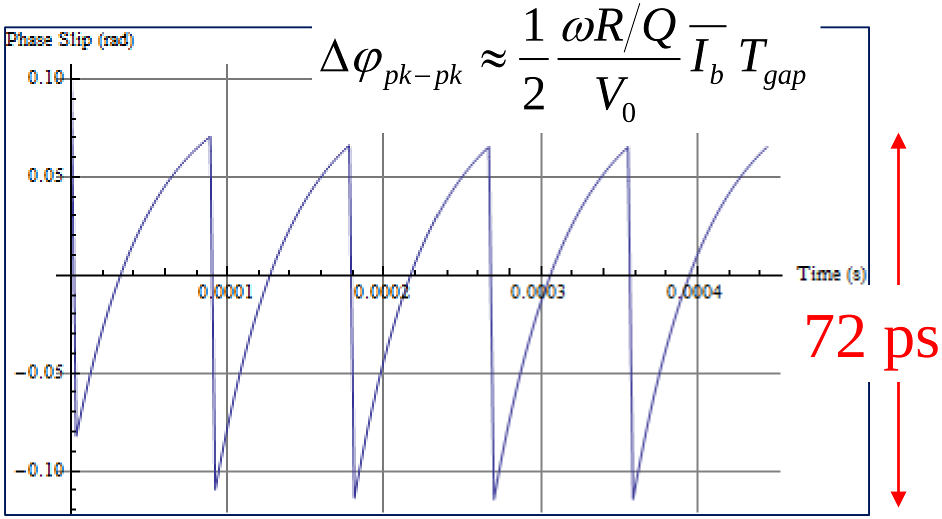
- The following figures consider the **HighLumi case**: 2808 bunches, 2.2E11 p/bunch, 1.11 A DC, cos^2 longitudinal bunch profile, 1 ns base length, bunching factor 0.9, 2 MV/cavity, Q_L=60000, R/Q =45 Ω. The cavity is at the optimum detuning (-9039 Hz). We consider the **3.2 μs long abort gap only**.

$$P_g(t) = \frac{V^2}{8R/Q}\frac{1}{Q_L}\frac{1}{(\cos\varphi(t))^2}$$





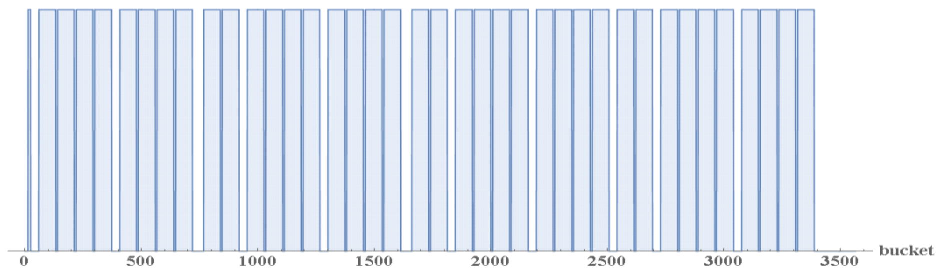
$$\Delta\varphi_{pk-pk} \approx \frac{1}{2}\frac{\omega R/Q}{V_0}\overline{I_b}\,T_{gap}$$

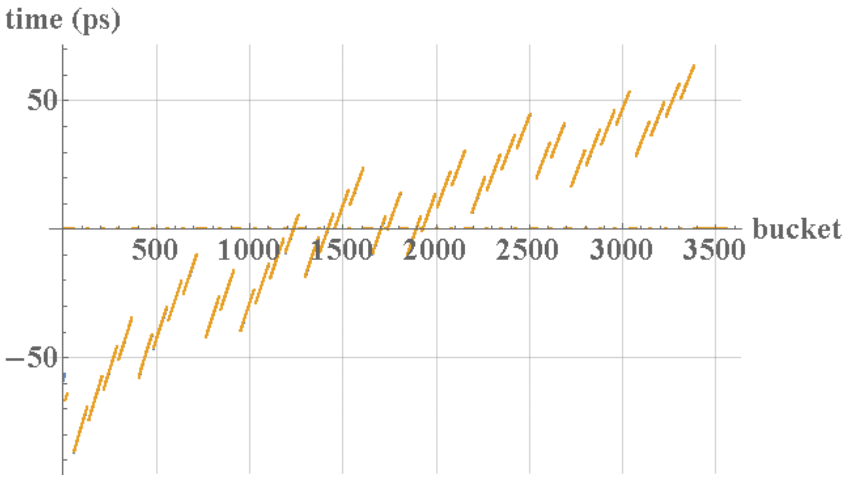


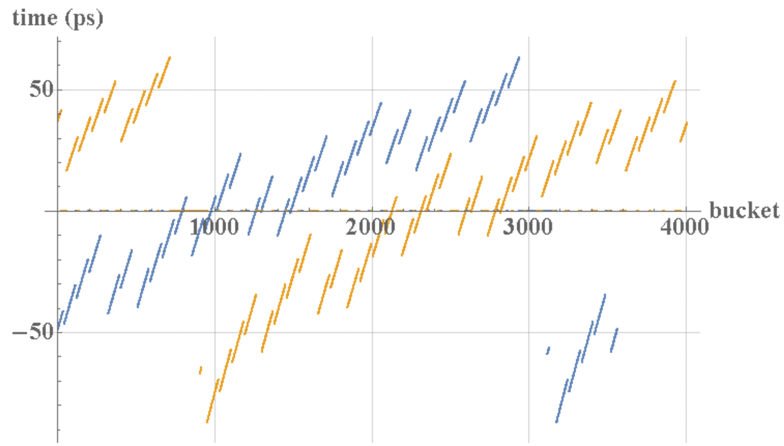
Top left: Component $i_b(t)$ of beam current at 400 MHz. 3.2 μs long abort gap.
Top right: Klystron power, almost independent of beam current
Bottom left: Phase modulation at 400 MHz. We get 0.180 rad pk-pk (10.3 degrees) at 400 MHz equal to 72 ps pk-pk.

Beam loading compensation. A better scheme (2)

$$\Delta\varphi_{pk-pk} \approx \frac{1}{2}\frac{\omega R/Q}{V_0}\overline{I_b}\, T_{gap}$$







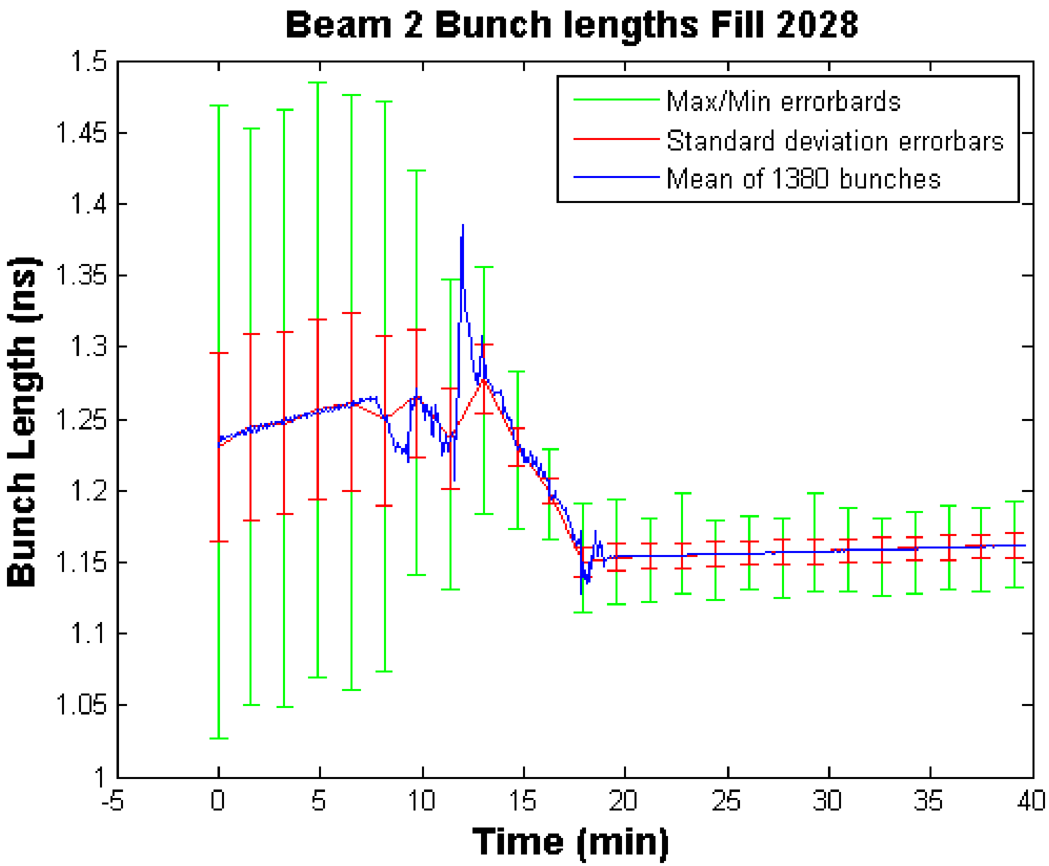
HiLumi conditions: 2,2E11 p/bunch, 12 MV, QL=60k
Top: Filling pattern. Note that the "abort" gap is 5 microsec long (including the 12b batch)
Bottom left: Phase modulation at IP1 and IP5
Bottom right: Phase modulation at IP8 and IP2

- Recall that the phase "swing" scales with gap length. Will be much larger for partial filling….

CONTROLLED LONGITUDINAL BLOW-UP DURING RAMP

Controlled emittance blow-up (1)

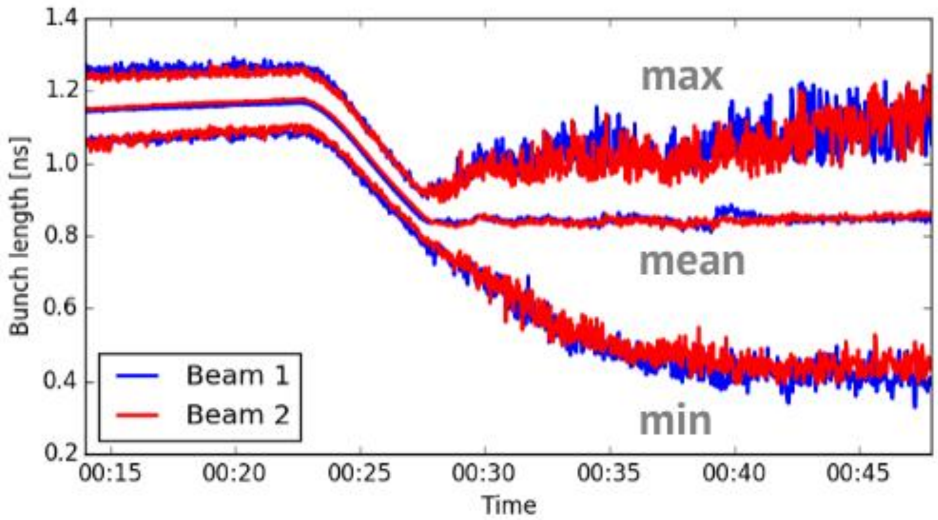
- Longitudinal blow-up (factor 5) is essential for acceleration of the nominal intensity LHC bunch
- It was commissioned in 2010 and worked reliably since, with operational beams



P. Baudrenghien et al., Longitudinal Emittance Blow-up in the LHC, IPAC 2011

Controlled emittance blow-up (2)

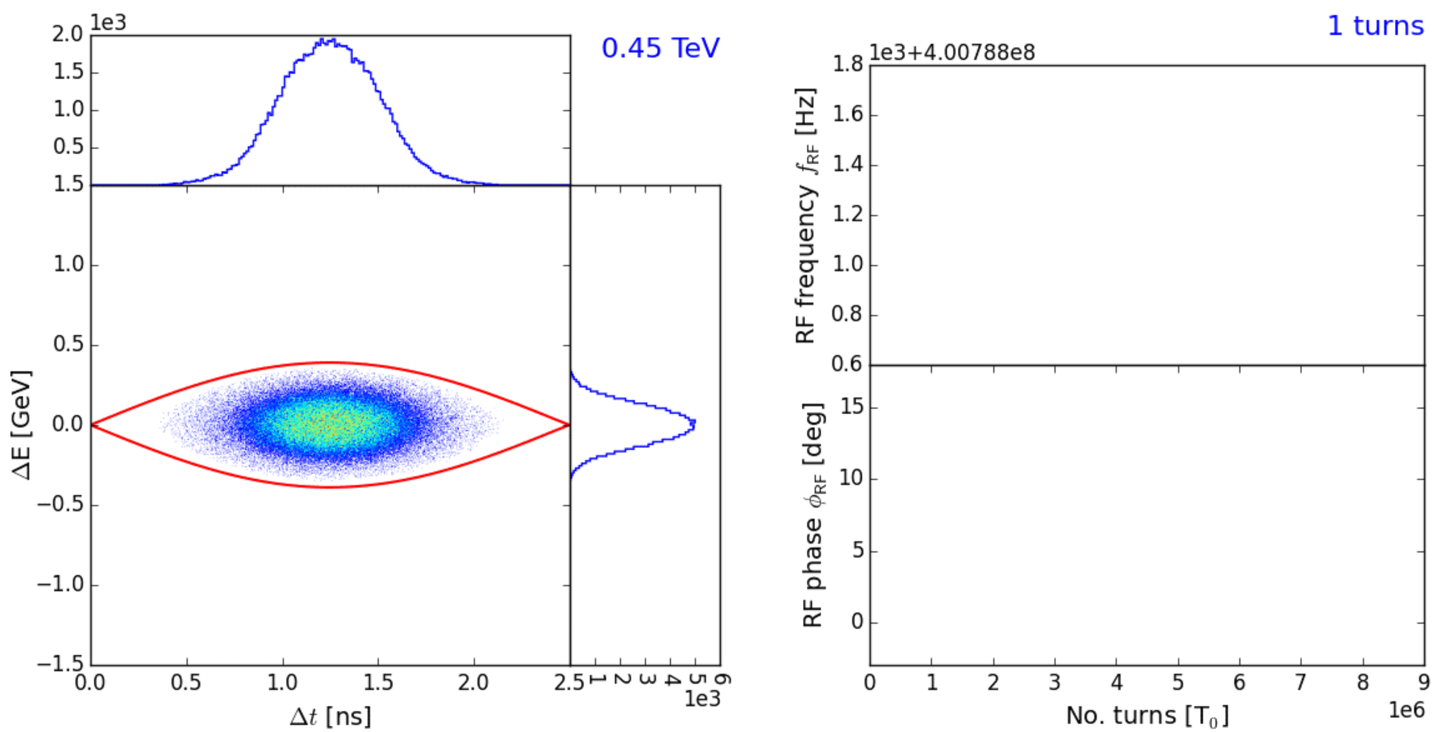
- BUT…bifurcation of bunch lengths were observed on several occasions, during MDs, with larger initial spread in bunch length & intensity



- With increased bunch/beam intensity, we anticipate that the beam coming from the SPS will have more spread in bunch intensity-length

Controlled emittance blow-up (3)

- A particle simulations code (BLonD) was designed to investigate



- Optimization of the code is needed for multi-bunch simulation of the LHC in an acceptable time

See ref on BLonD code

ADT

Transverse Feedback System

The transverse damper is a feedback system: it measures the bunch-by-bunch oscillations and damps them by fast electrostatic kickers.

Closed Loop Feedback → modified Target Response $T(s)$:

$T(s)$

Too high gain will make the loop unstable

$OL(s) = GH_SH_CH$

Key Parameters:

K……. Feedb

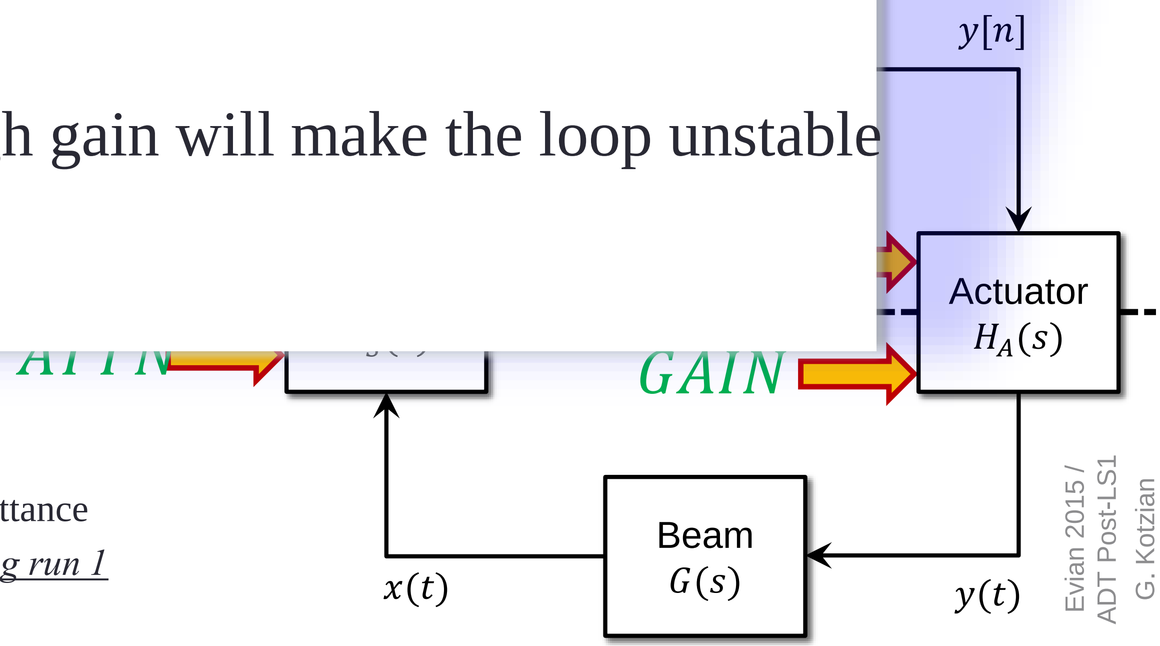
ϕ_{PK} … Feedb

T……..Total l

Primarily designed for:

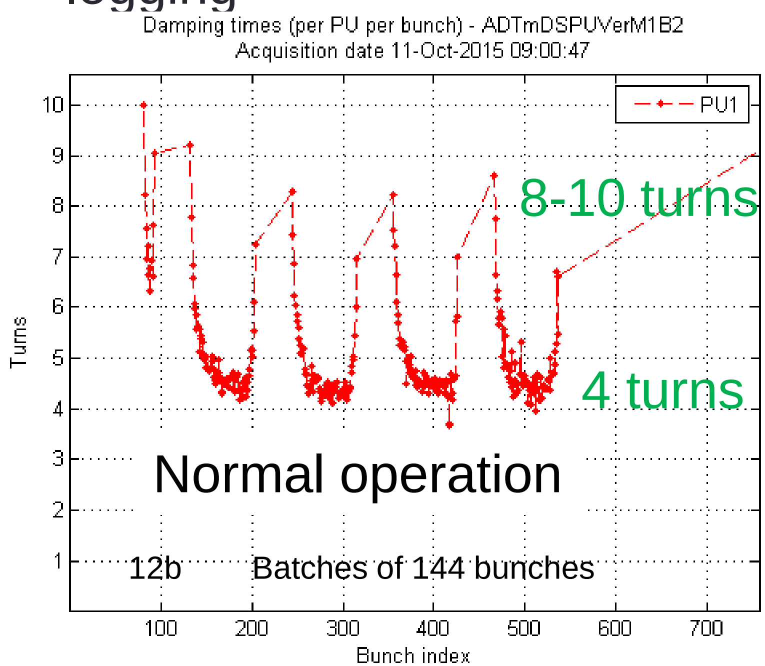
- Damping of injection oscillations
- Counteract coupled bunch instability
- Preservation of the transverse beam emittance

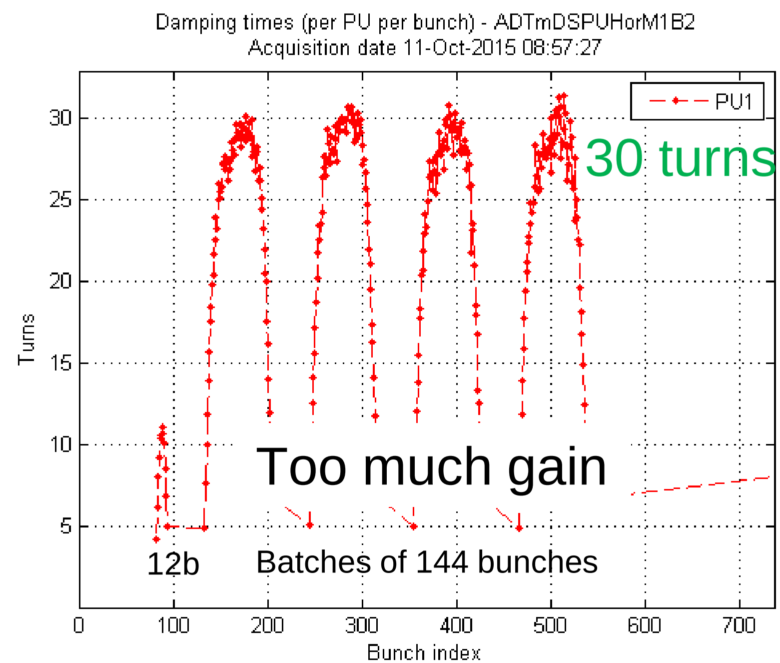
… plus more and more features added during run 1



Lessons learned: Is the damper working?

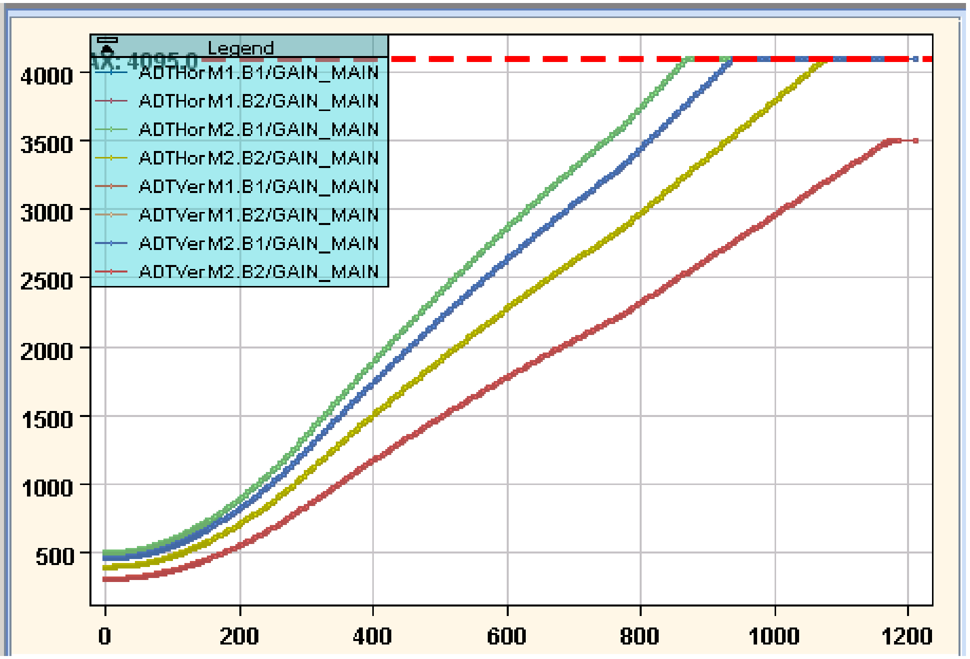
- Tools are being developed to monitor the ADT performance
  - Basic hardware functionality check will be part of the IQC
  - Advanced monitoring will come with a dedicated application and logging

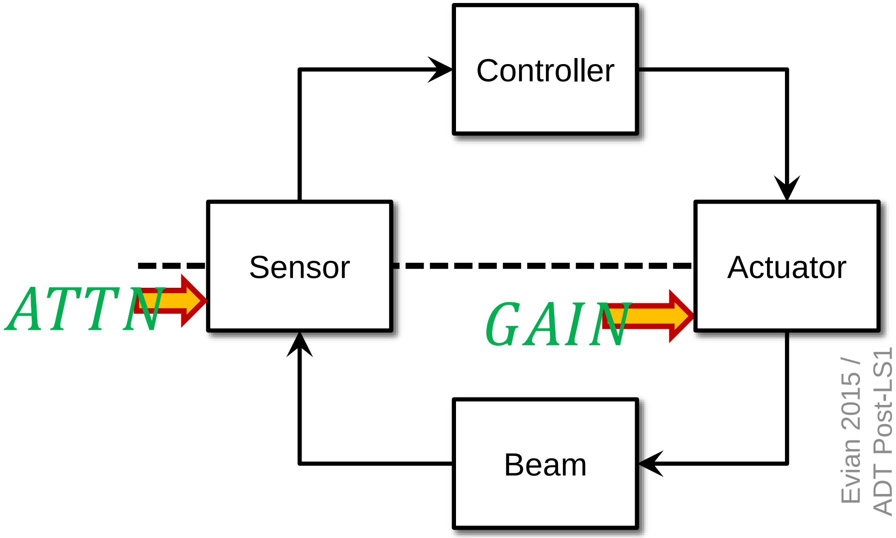




ADT lessons learned (since restart in 2015)

- Comfortable damper gain margin at injection
  - Running only with 1 active module → still correct damping
- Loop gain scales with energy, saturation effects during ramp
  - Different saturation times per beam per plane → depends on frontend gain
  - Mitigation measures foreseen → gain equalizer, rescaling, re-distribute loop gain





CONCLUSIONS

Longitudinal

Thank you, Questions?

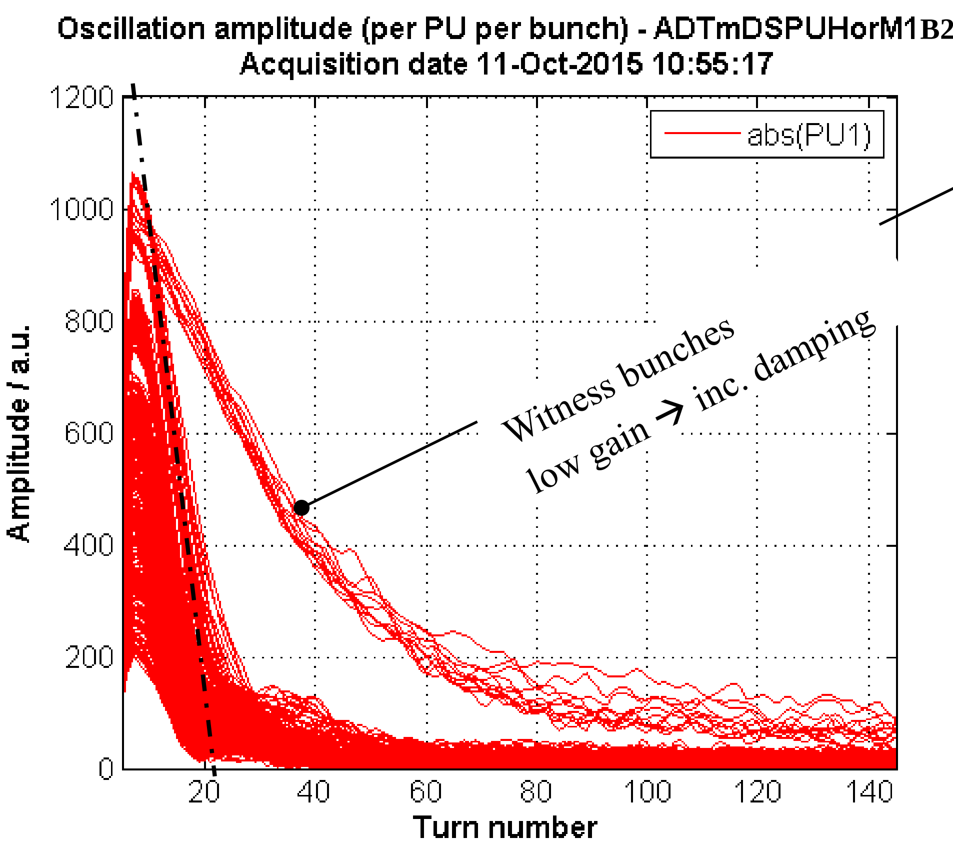
- The **single-bunch threshold** has been measured: nominal bunch intensity (1.1E11 p) will be unstable below 0.85 ns with 10 MV RF
- We have observed **no longitudinal coupled-bunch instability** (with 2200 b)
- We near **klystron saturation** with the “half-detuning” scheme. Test of full detuning must take place in 2016. Klystrons will be conditioned at 2016 restart to provide the specified 300 kW
- We have a method to recover bunch length at 6.5 TeV. It must be made **compatible with stable beam**
- Controlled longitudinal blow-up works fine with operational beams. With increased bunch intensity we expect more spread in parameters (from injectors) -> **studies needed**.

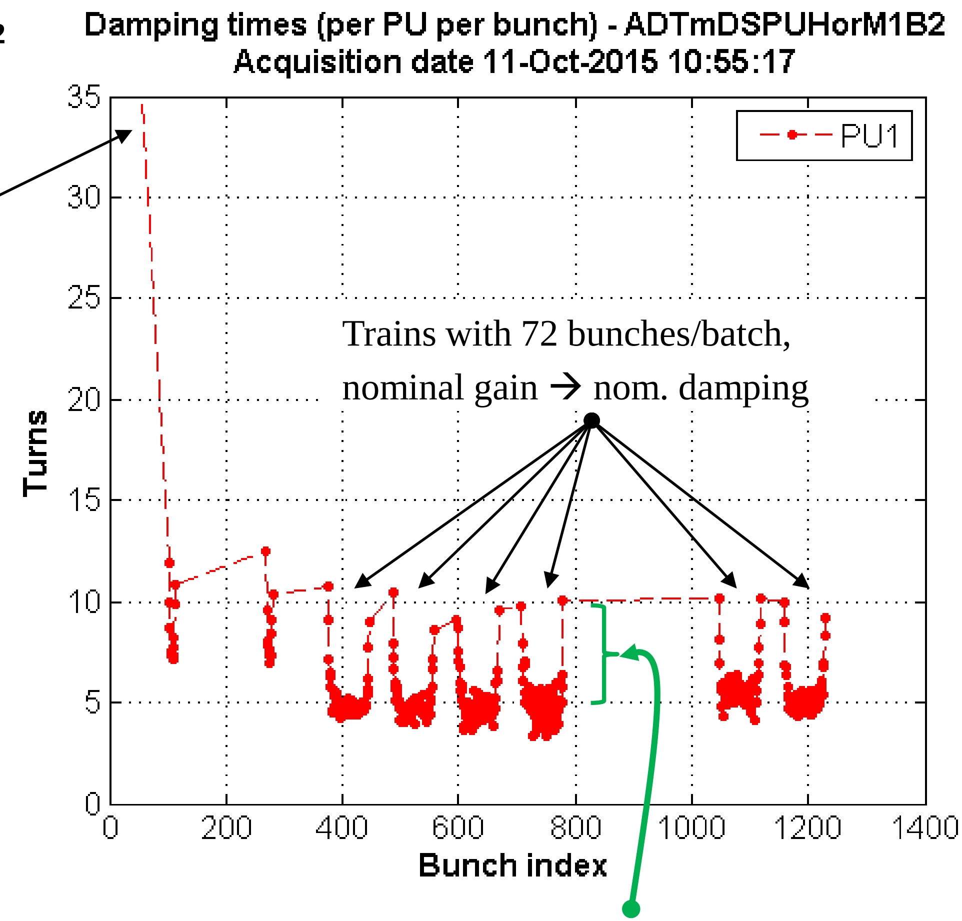
ADT

- New tools are being prepared for restart, which will **monitor functioning** of the ADT hardware
- Gain re-distribution should eliminate the **gain saturation** through the ramp
- The **separation of the functionalities**: main damper, cleaning, excitation will be completed for start-up
- **New pickups** and **new beam position modules** will be gradually commissioned during the run. It should be transparent to operation.
- Installation of additional **bunch per bunch observations** and commissioning of the **instability trigger network** is foreseen for the 2016 run. More in Andy’s talk to-morrow…

SPARE SLIDES

Damping Times per bunch





All bunches excited coherently during one turn.

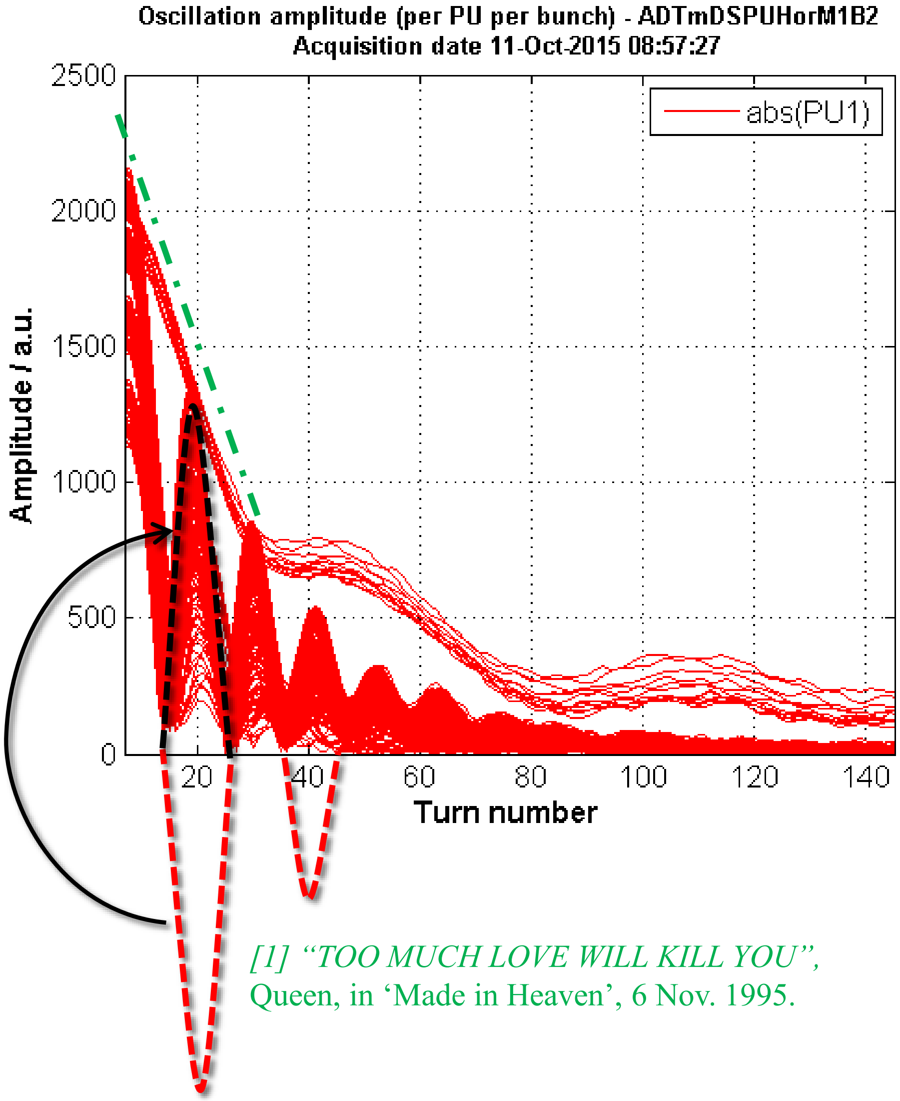
Transverse deflection by ADT << 1 mm.

➔ expected blow-up less than 1 %.

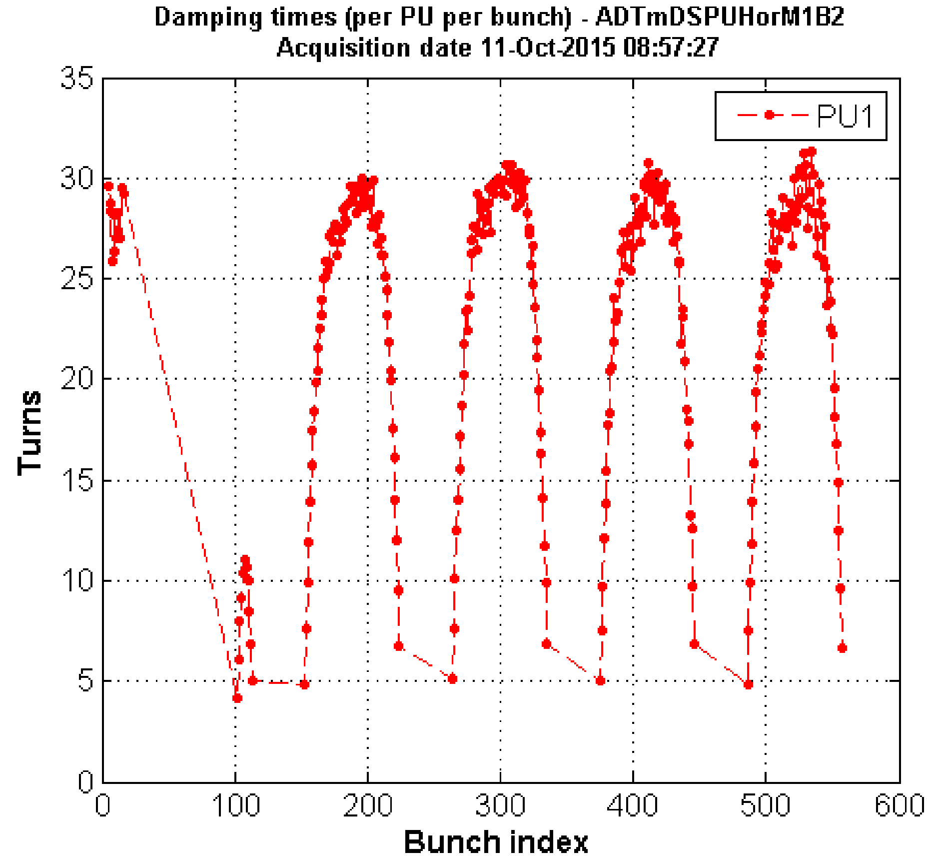
Factor 2 between bunches in the centre an the edge of trains > 12 bunches

Damper was originally designed to counteract maximum injection errors of 3.3sigma corresponding to 4 mm at beta=185m, with an estimated emittance blow-up better than 2% [1]

Pathological Case: Over-Damping



[1] *"TOO MUCH LOVE WILL KILL YOU"*,
Queen, in 'Made in Heaven', 6 Nov. 1995.



See also: *"MARGINS TO INCREASE ADT GAIN AT INJECTION"*, W. Hofle, LBOC 49, 6 Oct. 2015

https://indico.cern.ch/event/451051/