Operational and beam dynamics aspects of the RF system in 2016

P. Baudrenghien, J. Esteban Müller,
E. Shaposhnikova, H. Timko,
BE-RF

with the kind support of

B. Bielawski, T. Bohl, Y. Brischetto, A. Butterworth, R. Calaga, H. Damerau,
G. Hagmann, M. Jaussi, T. Levens, T. Mastoridis, J. Molendijk, A. Pashnin

Outline

Proton run

- Fault summary
- Klystron power limitation
- Full detuning
- Loss of Landau damping
- Bunch flattening
- Controlled emittance blow-up
- PS-SPS-LHC transfer studies

Ion run: cogging

Diagnostics & improvements

Forthcoming studies

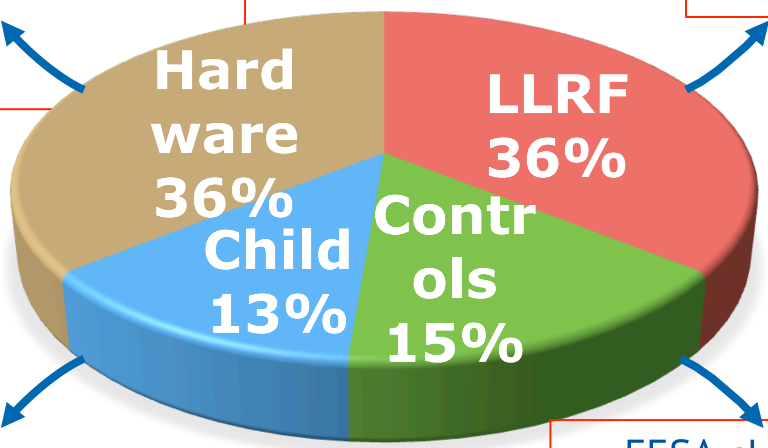
RF fault summary

The RF system performed very well:

- 39 faults (~31.5h downtime) and 10 beam dumps (physics, injection, MD)
- In total about 0.6% of LHC operation time!

- 24V power supplies, controls HW (50%)
- Crowbars (30%) – mostly after restart
- Tetrodes (end of life)
- Various

- Re-synchronization
- LLRF settings adjustments



- Electrical glitches
- Cryogenics

- FESA classes, Front-ends blocked
- PLC wrong measurements
- Communication problems (e.g. main coupler blocked)

LHC RF power

It was planned to recommission klystrons to 300 kW, but most klystrons saturate around 270 kW

- N.B. power calibrated with thermal heat load; error is about 20 %

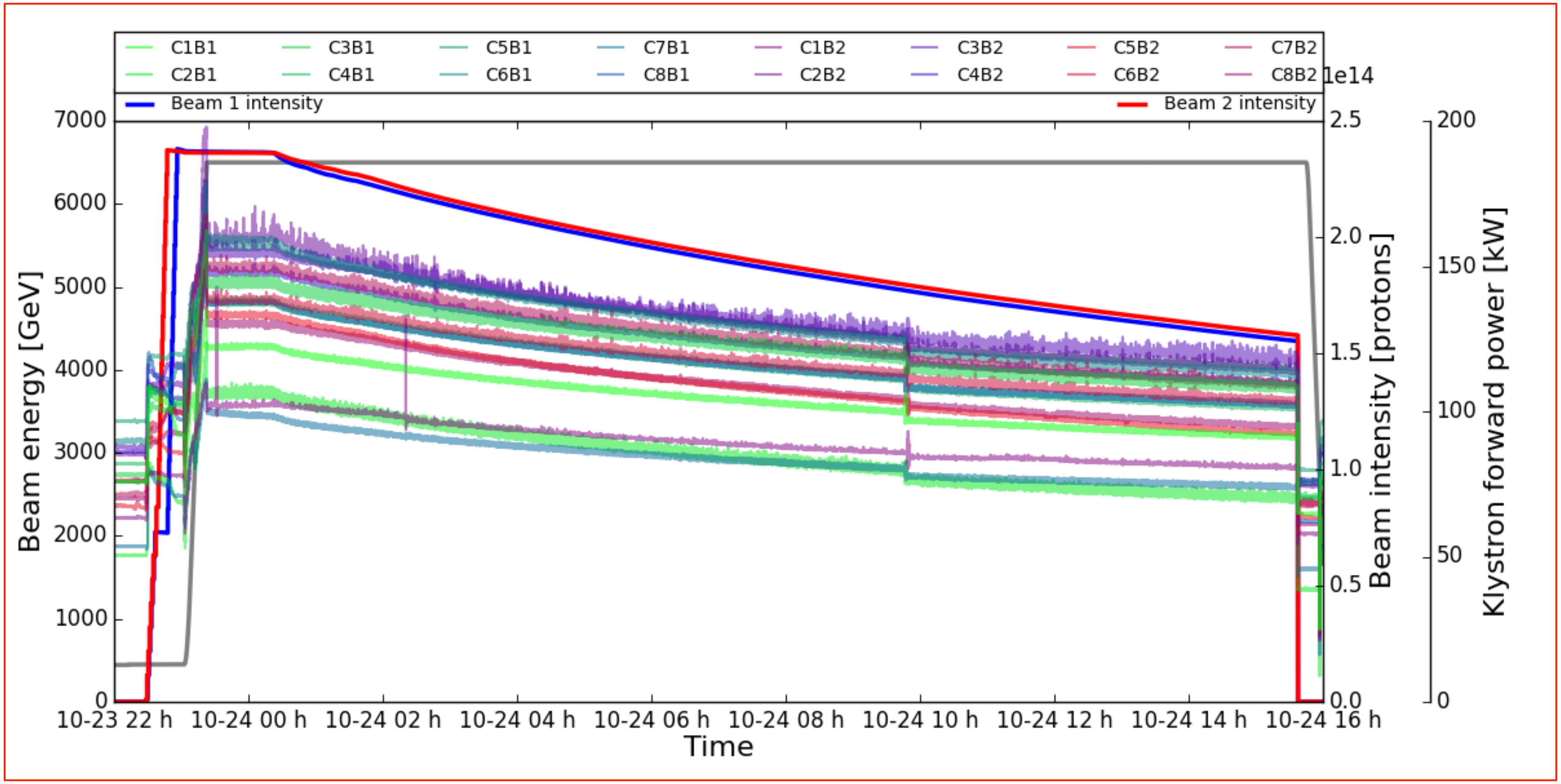
With the 48g48 batch pattern, the demanded power stayed limited this year

- Yet, main coupler heating was a recurrent issue (on C7B1)
- Peak power can be high (transients up to 250 kW)
- Power could be insufficient with batches of 288 bunches
- Back-up solution: full-detuning scheme for beam-loading compensation; also in preparation of higher intensities after LS2

Klystron forward power

Relatively low (average) power consumption in 2016

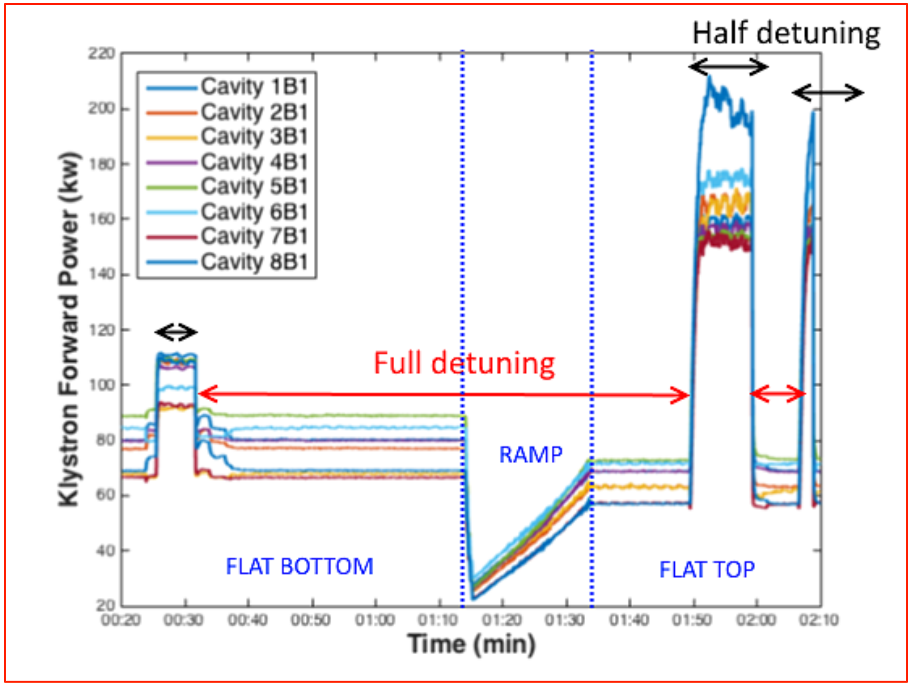
- 100-150 kW with full machine and batches of 48g48 bunches



Full detuning

Demonstrated in an MD and physics this year [1,2]

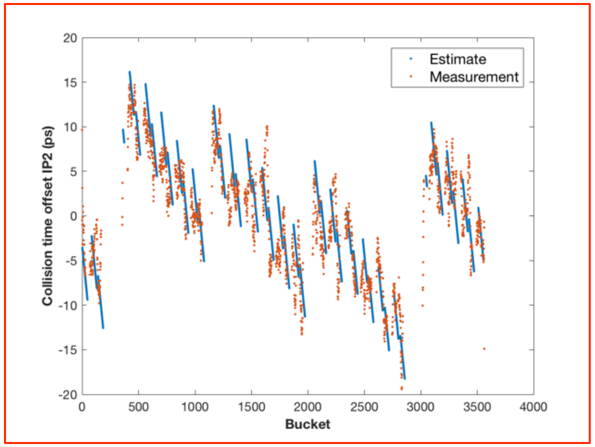
- Half detuning: voltage amplitude constant, phase modulus constant
- Full detuning: cavity voltage amplitude constant, phase modulated



Klystron forward power in MD

Effect on experiments

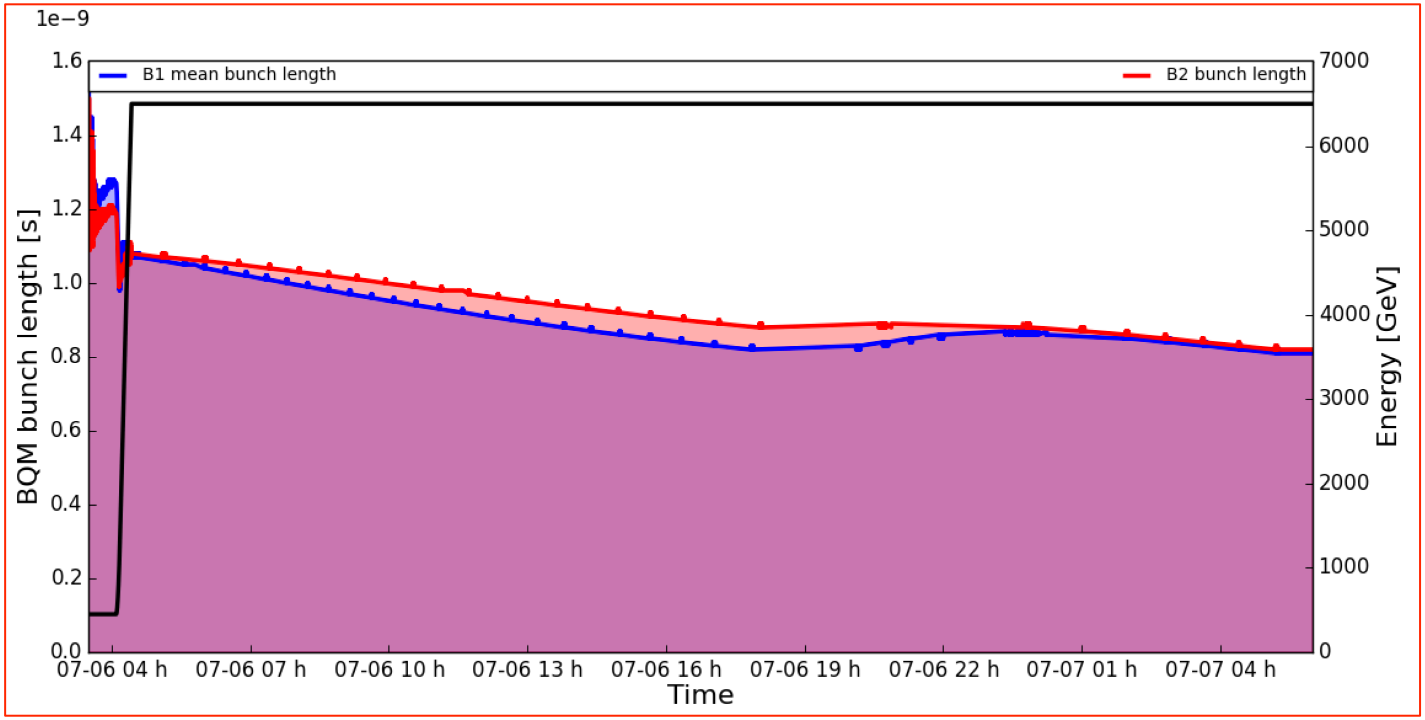
- Modulation of collision time w.r.t. bunch clock (all IPs)
- Modulation of z-vertex (IPs 2&8)



Modulation of collision time (ALICE, *courtesy of S. Paramesvaran, R. Shahoyan and S. Foertsch*)

Loss of Landau damping (1)

Single-bunch loss of Landau damping in long fills observed according to predicted threshold [3]. Coupled-bunch stability threshold for this beam is higher than the single-bunch one.

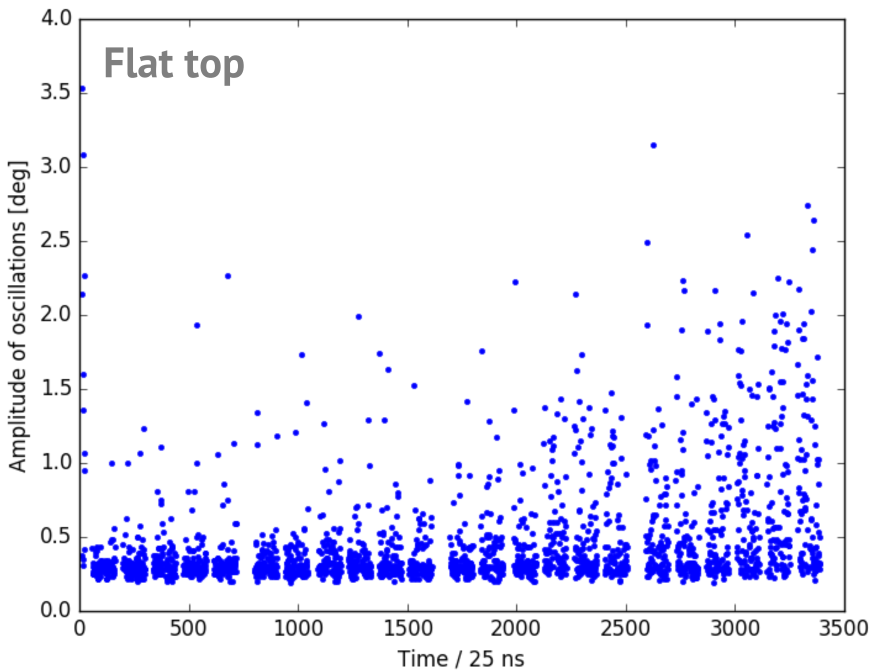


Bunch length oscillations in physics around 0.9 ns

Loss of Landau damping (2)

Undamped injection oscillations

- Bunch phase oscillations at arrival to flat top depending on time spent at flat bottom (and thus position along the ring) [4]

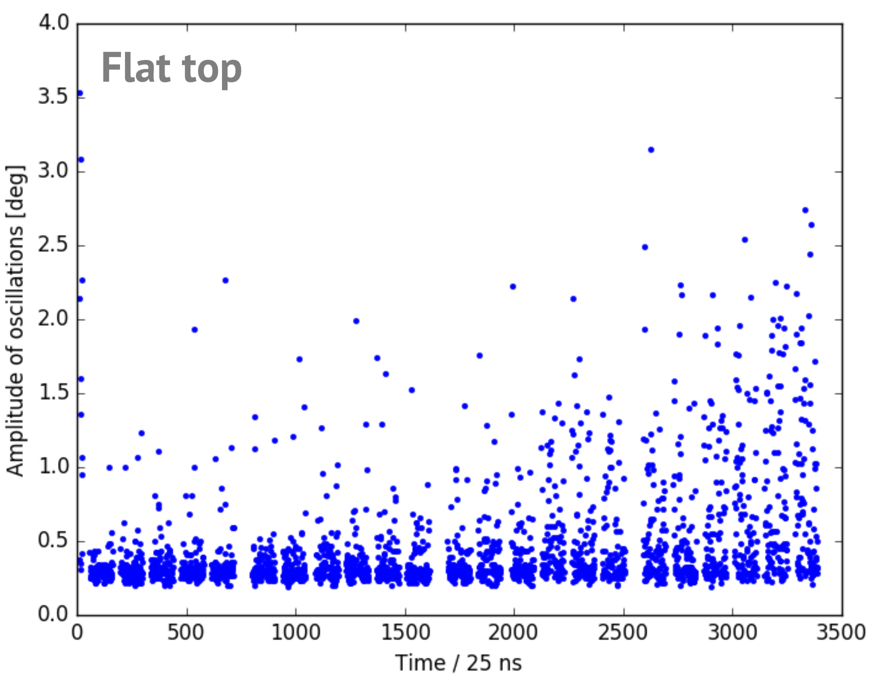


The damping time is of the order of an hour! How do oscillations survive the ramp?

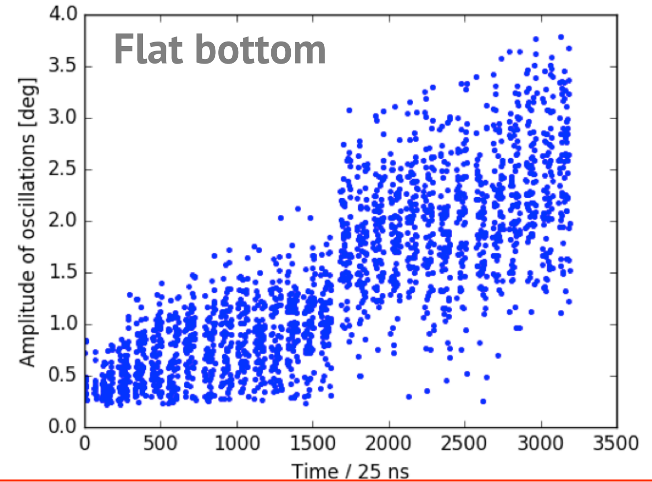
Loss of Landau damping (2)

Undamped injection oscillations

- Bunch phase oscillations at arrival to flat top depending on time spent at flat bottom (and thus position along the ring) [4]



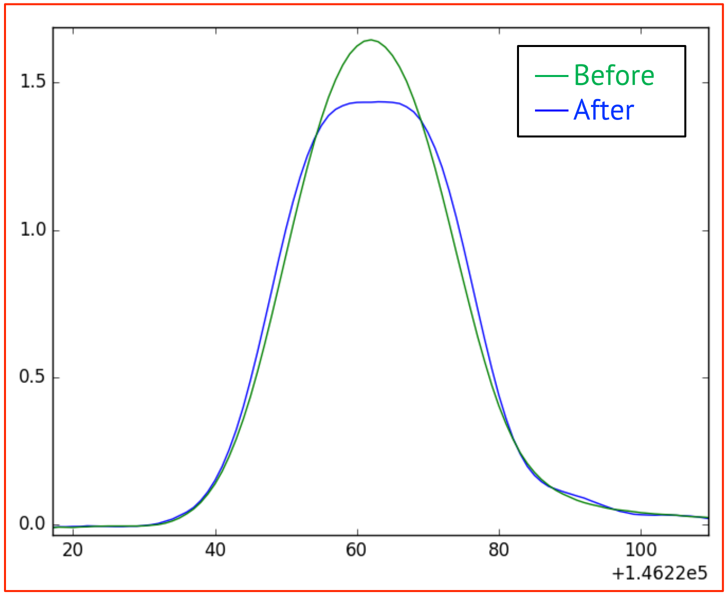
The damping time is of the order of an hour! How do oscillations survive the ramp?



Bunch flattening in long fills

Vertex reconstruction is not accurate enough for LHCb for bunch lengths < 0.9 ns (for one polarity)

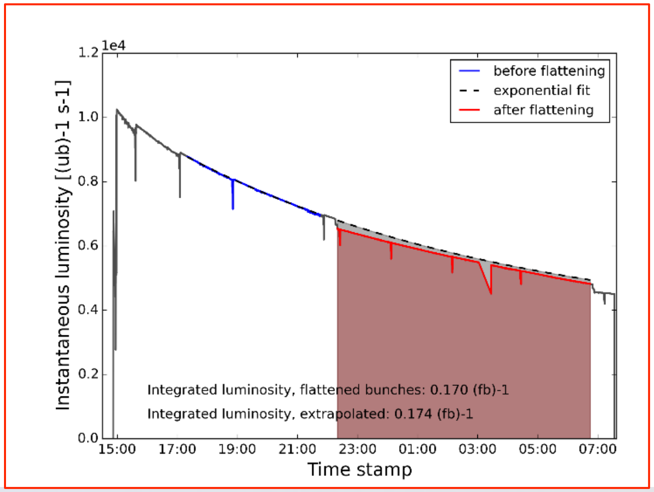
- Bunch flattening used operationally to regulate the bunch length [5]



Bunch flattening in Stable beams
17th June 2016 (B2)

- Increases bunch length by 150-200 ps
- Reduces heat load (~5 %)
- Luminosity loss ~2.5-4.5 % in IPs 1&5
- Loss-free mechanism

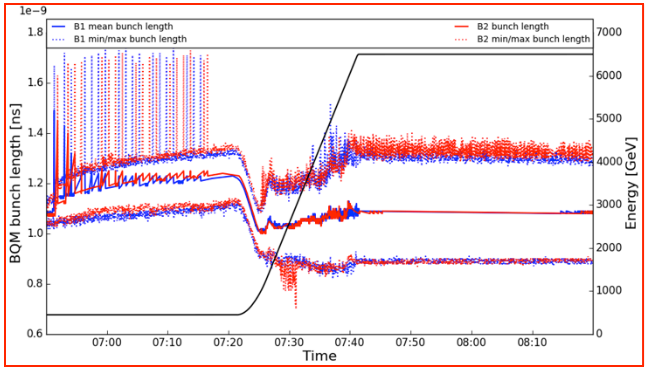
ATLAS Luminosity, 6th August 2016



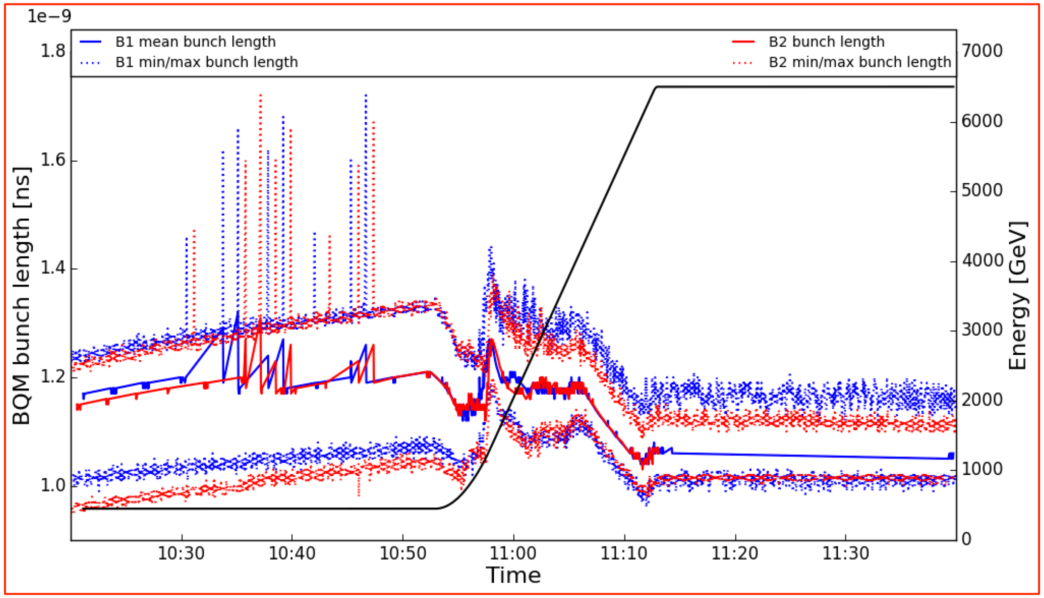
Controlled emittance blow-up (1)

In 2016, blow-up was close to the limit of stability as the target bunch length was decreased from 1.25 ns to 1.1 ns [6]

- Modified initial target bunch length for better convergence
- Blow-up simulations show resonant excitation and island creation in phase space; studies to be continued



Before: spread 410-450 ps

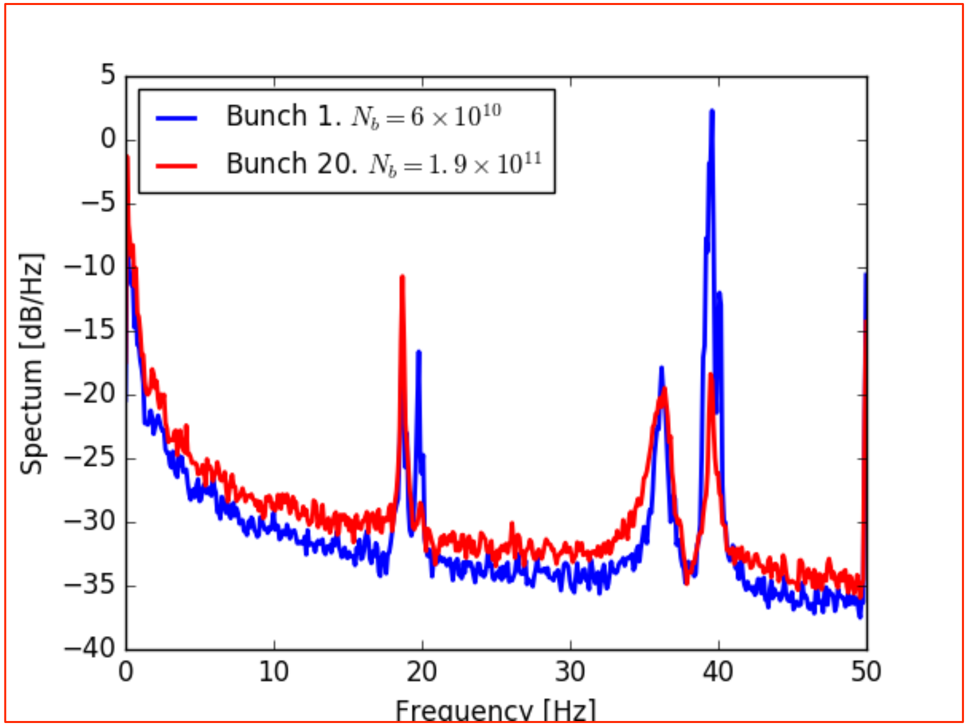


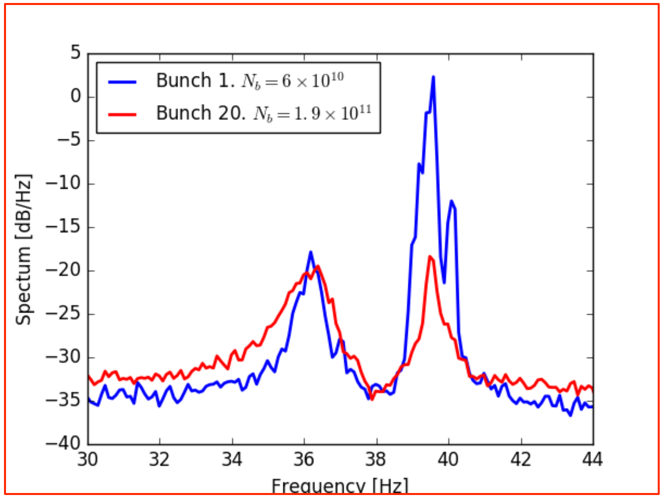
After: spread 120-160 ps

Controlled emittance blow-up (2)

Powerful diagnostics for synchrotron frequency distribution: peak-detected Schottky spectrum

- After blow-up: depleted region close to the centre of the bunch





Zoom on quadrupolar line

Dipolar and quadrupolar lines of Schottky spectrum

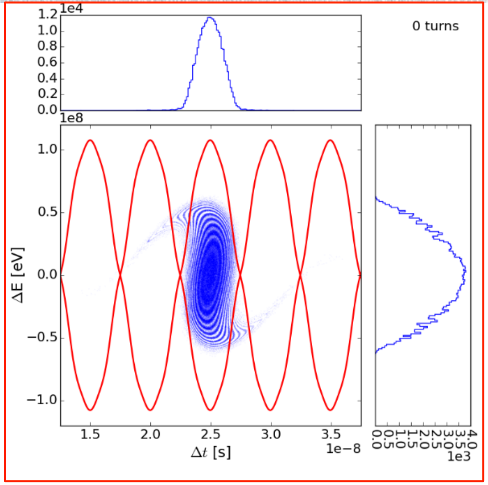
PS-SPS-LHC bunch-to-bucket transfer

Repeated **satellite investigations** in SPS/LHC: injection losses are close to dump threshold

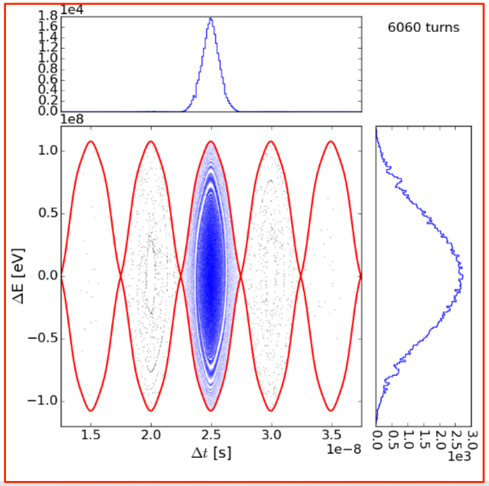
- SPS-LHC transfer losses are on the per mille level; hard to do better

Main **origin of LHC satellites**: S-shape bunches injected into SPS after PS rotation

- Switching on second 40 MHz PS cavity w/ optimised settings proposed in 2012 [7]
- Reduced the PS-SPS transfer losses as predicted from 5 % to 2.5 %
- Reduced the satellite population by a factor 5-10 in the LHC



Satellite formation: rotated bunches from PS at and after injection to SPS



Ion run

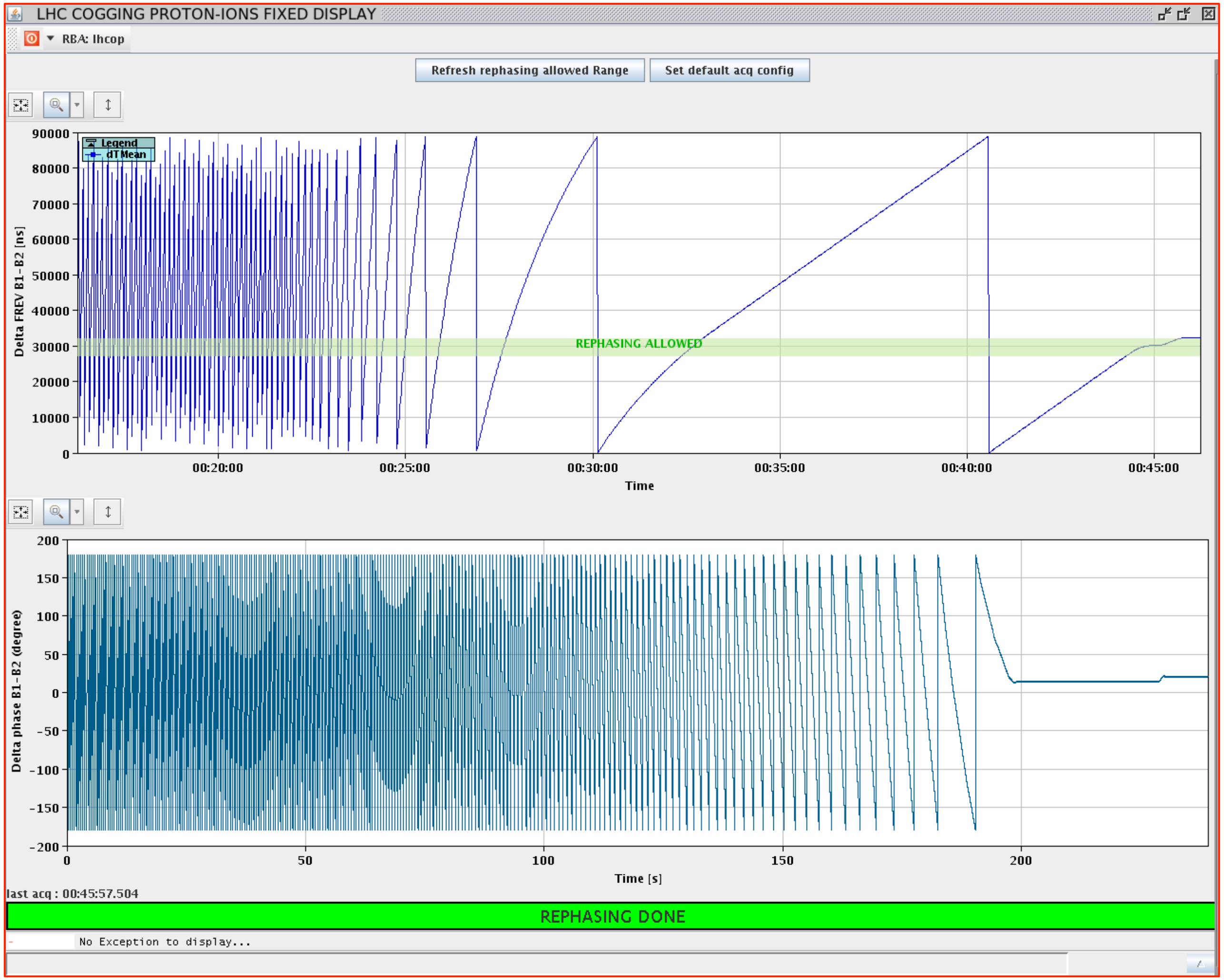
Set-up of RF system for ions went smoothly

- Preparation of RF parameters at 4 TeV & 6.5 TeV
- Commissioning of p-Pb, Pb-p injection & cogging
- At 6.5 TeV, increase the difference in frequencies to make the cogging faster (15 min instead of an hour)

  Frequency change: -20 Hz for Pb, +20 Hz for p, to displace the orbits

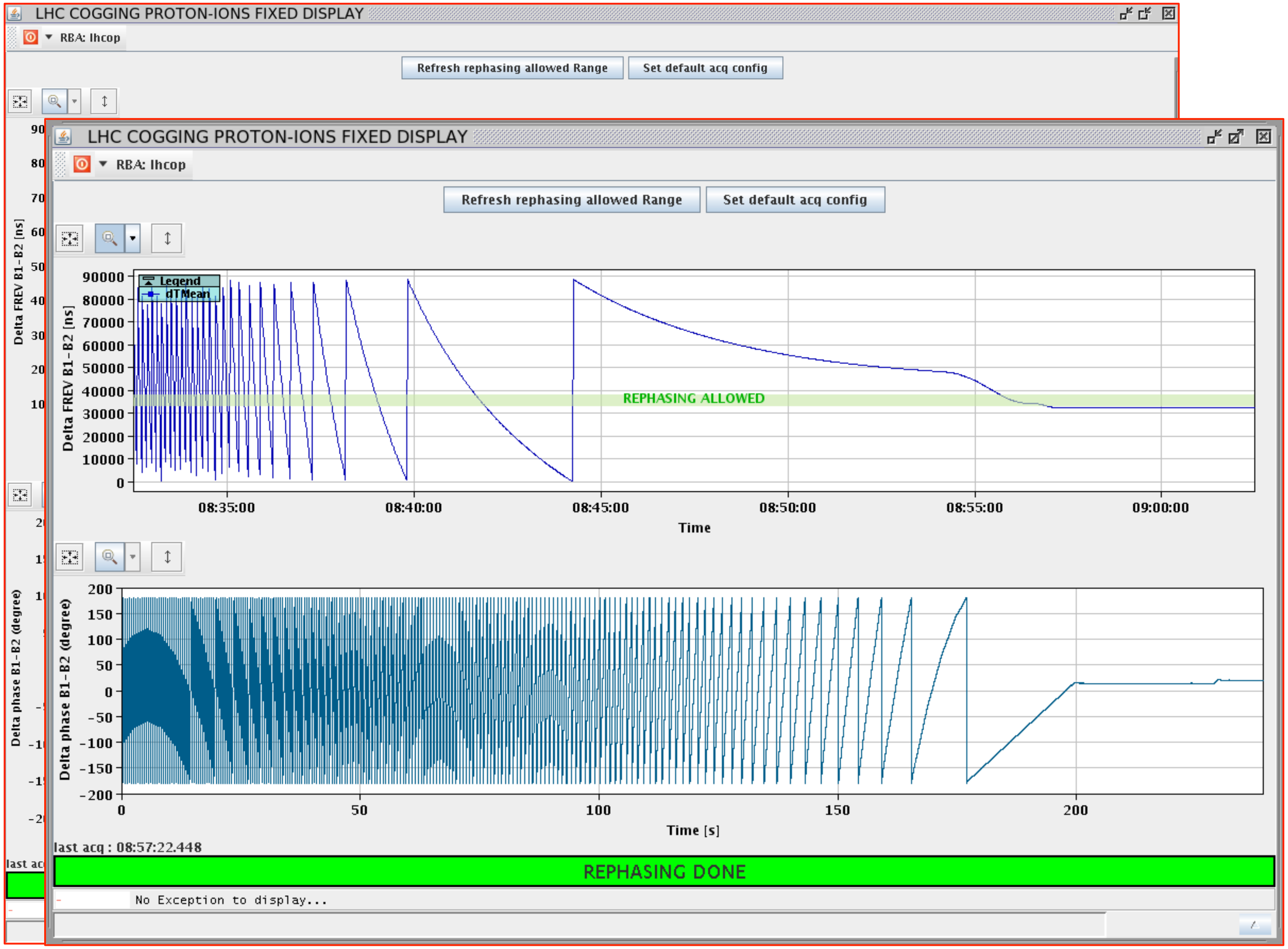
  Procedure was then to move to the mean frequency orbit (at 6.5 TeV: 400.789711 MHz). The mean orbit offset is only -0.1 mm (Pb) and +0.1 mm (p) at 6.5 TeV and three times larger at 4 TeV

Cogging during the ion run



pPb: approaching rephasing range from below

Cogging during the ion run



Pbp: approaching rephasing range from above

Diagnostics & improvements

Improved this year

- Power monitoring fixed display for power transients: new features, memory leak fixed
- New FESA classes for ObsBox to log stable phase oscillations and high-resolution profiles will be available for start-up 2017
- RF phase noise in B1 reduced (exchange of VCXO)

On the list for next year

- Fixed display for high-resolution profiles
- FESA3 migration
- Migration of commissioning tools (technical student)
- Peak-detected Schottky: documentation to be done
- Beam spectrum logging: communication issues with instrument under investigation
- LLRF recovery after power cut or power cycle: test in laboratory

Need: CO support for pyjapc (currently BI) & java library (currently CTF3)!

Forthcoming/continued studies

- Full detuning (if not becoming operational in 2017)
- Controlled emittance blow-up (limitations & optimisation of the excitation)
- Coupled-bunch instability: continue the studies of 2016, also for nominal LHC beam
- Bunch flattening and counteracting synchrotron radiation damping in a continuous way using band-limited RF noise (alternative to resonant excitation)
- Studies on longevity of injection oscillations
- 400 MHz cavity HOM measurements

Summary

Smooth operation of the RF system in 2016

Many studies & highlights

- Full detuning successfully tested to lower klystron forward power
- Loss of Landau damping observed in long physics fills
- Bunch flattening to control bunch length in physics
- Hitting the limit of the present controlled emittance blow-up
- Satellite reduction by PS bunch rotation as optimised in 2012

Unproblematic ion run

Diagnostics improvements continued

Still, many open questions remain… looking forward to an exciting new year 2017!

References

[1] T. Mastoridis et al., *Cavity Voltage Phase Modulation MD*, CERN-ACC-NOTE-2016-0061, (2016).

[2] P. Baudrenghien, *LHC Full Detuning*, at the LMC, 7th December 2016.

[3] J. Esteban Müller et al., *LHC Longitudinal Single-Bunch Stability Threshold*, CERN-ACC-NOTE-2016-0001, (2016).

[4] J. Esteban Müller et al., *LHC MD 652: Coupled-Bunch Instability with Smaller Emittance (all HOMs)*, MD Note to be published, (2016).

[5] H. Timko et al., *LHC MD 1279: Bunch Flattening in Physics*, MD Note to be published, (2016).

[6] J. Esteban Müller et al., *LHC MD 232: Longitudinal Impedance Evaluation*, MD Note to be published, (2016).

[7] H. Timko et al., *Longitudinal Transfer of Rotated Bunches in the CERN Injectors*, PRSTAB **16**, 051004, (2013)