“What you get” – RF system

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Reporting for the RF group

1. The Past
2. The Future: anticipated limitations and actions taken
3. The Future: actions to be taken
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1 The Past
- RF performance in 2012
- 2012 Run RF Fault Summary
- New items 2012

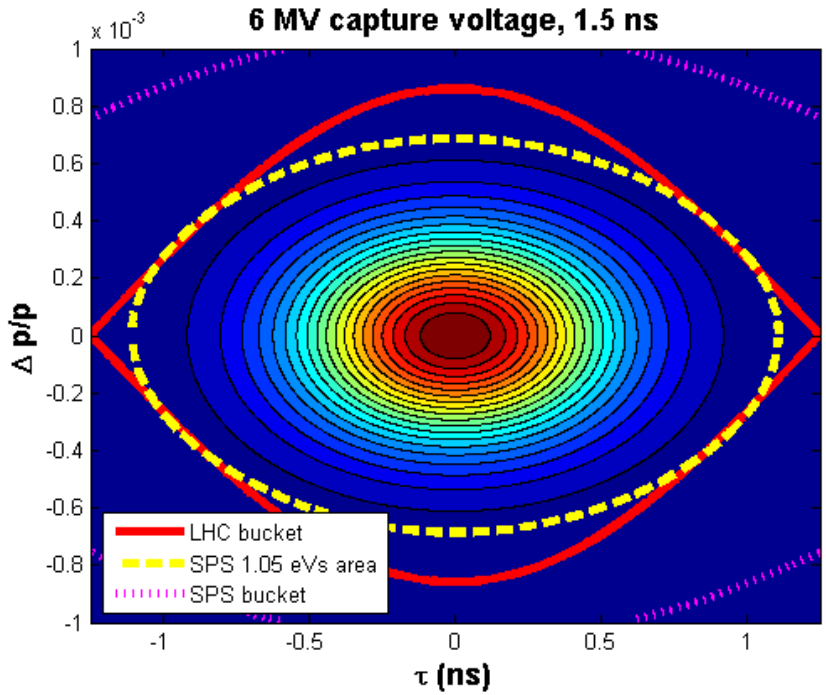
2 The Future: anticipated limitations and actions taken

3 The Future: actions to be taken

4 Conclusions, References

RF performance in 2012: no limits

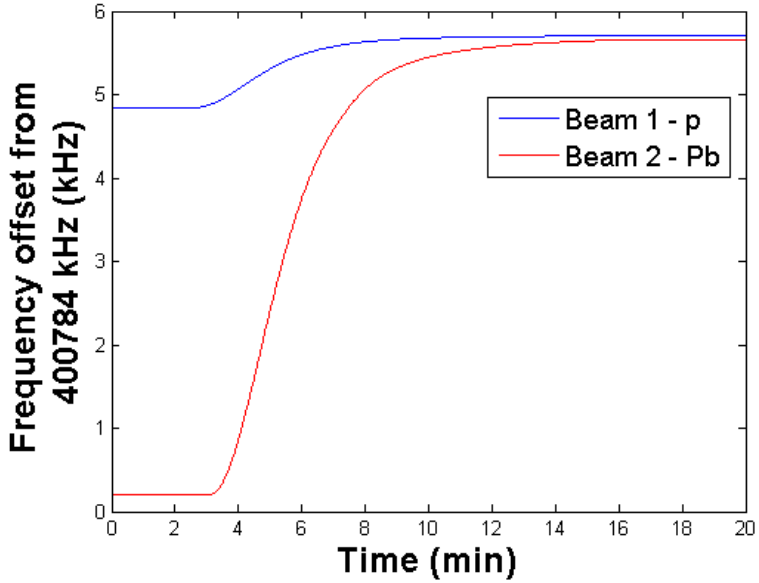
- The RF system did not limit peak or integrated luminosity in 2012
- Increased single bunch intensity (up to $\approx$ 1.65e11) did not introduce longitudinal instabilities or klystron saturation
  - After the RF voltage reduction at flat top (10 MV), we routinely operate with up to 165 kW per klystron
- Negligible capture losses (below 0.5%) with 6 MV injection voltage, AGC, and injection gap cleaning
- No problem with Q20 optics
- 25 ns run: fine adjust tuner, Q_L, decrease V_{RF} in ramp to deal with arcs in two different circulator loads in first two ramps
- Target bunch length often manipulated as needed for OP purposes or other studies



RF performance in 2012: steps forward

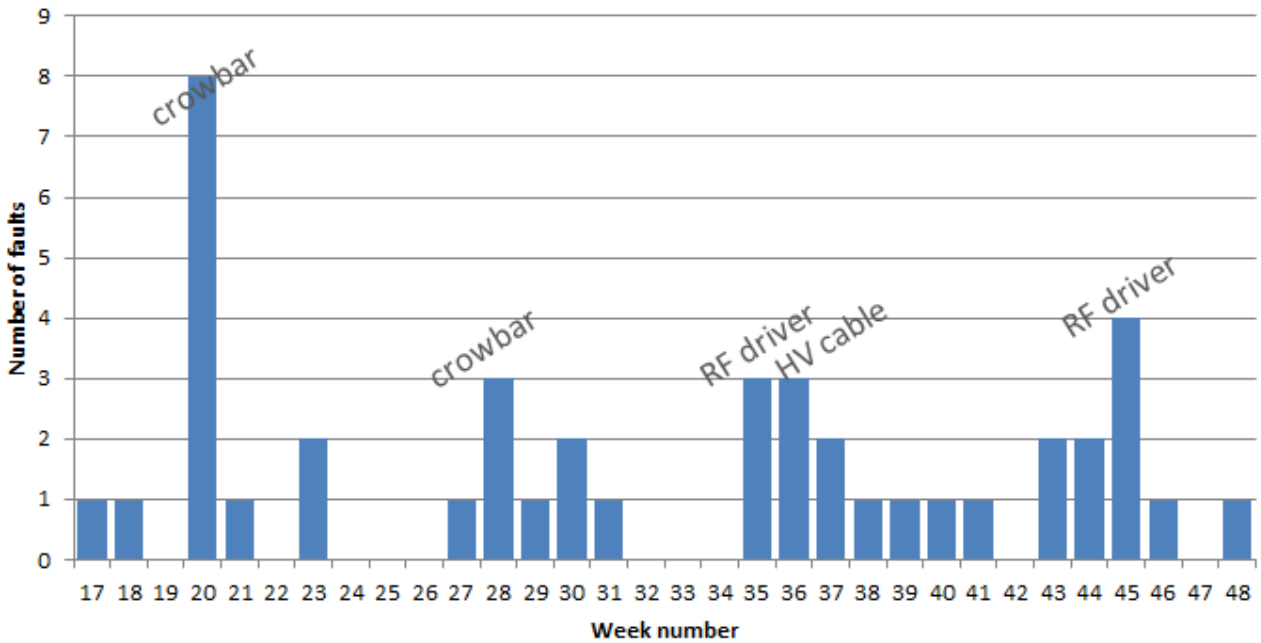
- Rack recabling campaign in UX45 during winter shutdown. All SMC cables replaced (better quality). No more cabling related issues
- About 800 interlocks currently set. As a result only one serious debunching incident this year (5 in 2011)

- Successful trial of RF gymnastics for p-Pb fill
- The good availability/reliability allowed us to make significant progress on our post-LS1 preparation during 2012



2012 Run RF Fault Summary

- Improved reliability over 2011
  - 2011 run: 78 faults (2.08 per week in protons, 6.5 per week in ions)
  - 2012 proton run: 43 faults (1.34 per week)
  - Several weeks when NO faults at all were recorded
- RF problems came in waves (wk 20, wk 35/36, both crowbar related, wk 43-45 4B1 RF Amplifier)
- The causes have been identified and cured



Courtesy D. Glenat

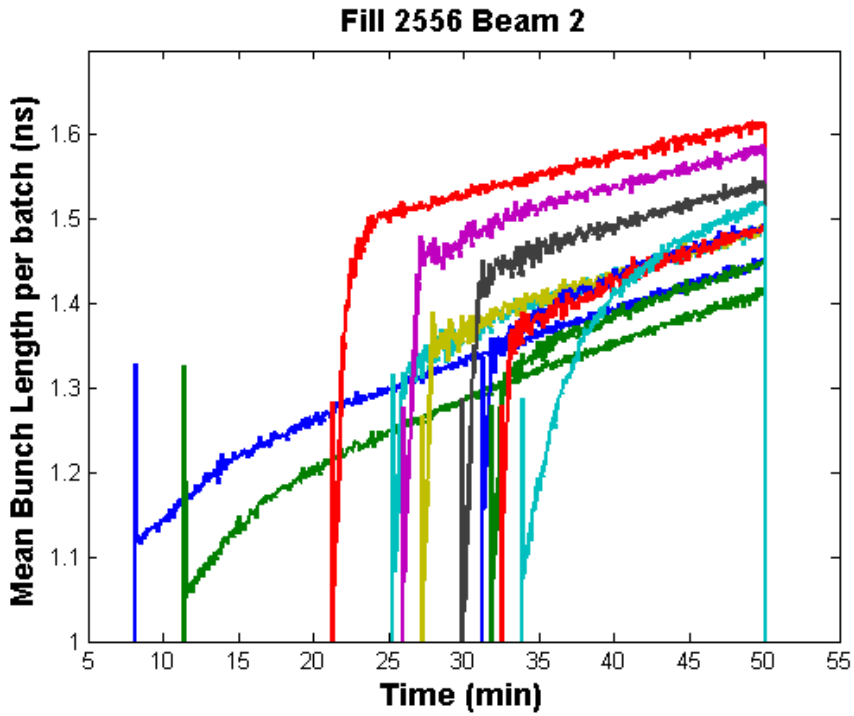
2012 Run RF Fault Summary

- Improvement mostly due to significant reduction of HOM and Arc faults (sick cavity 3B2 consistently operated at lower voltage)
- On the other hand, increase in crowbar inducing faults (from 11 to 20)
  - Half of them in first five weeks (1 faulty solid state switch, 1 faulty thyratron)
  - The others are “real” crowbar triggered by vacuum activity (arcing) in klystrons. Some correlation with klystrons left at standby mode for extended period of time $\rightarrow$ If possible, switch RF system OFF when not in use
- Remaining faults separated into
  - Trips related to bad HV contact. Most of them in September due to a damaged HV cable (replaced – no more faults). Other related to defective HV connectors (long process $\rightarrow$ only done where absolutely necessary, the upgrade campaign will be completed during LS1)
  - “Unavoidable” faults
- In summary, improvement in reliability, steps were taken for even better future performance

Batch-by-batch blowup

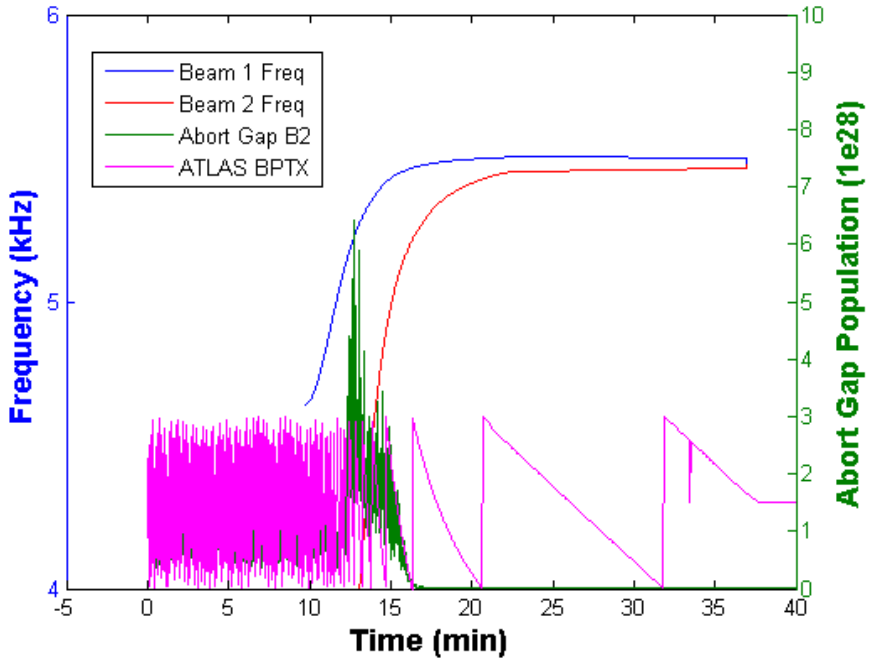
- Reduce the transverse emittance growth rates due to IBS by selectively blowing up the longitudinal emittance of the incoming batch at each injection
- Tested and commissioned during 2012 [9]. No obvious effect on luminosity
  - IBS has smaller contribution to emittance growth than expected?
  - Smaller transverse emittances achieved at flat top, but not preserved to physics?

- We were not able to measure emittances before squeeze (BSRT availability)
- We hope to see a bigger effect during the p-Pb run and with BCMS
- Improvement should become more evident as Q20 optics fully exploited (stronger IBS?)



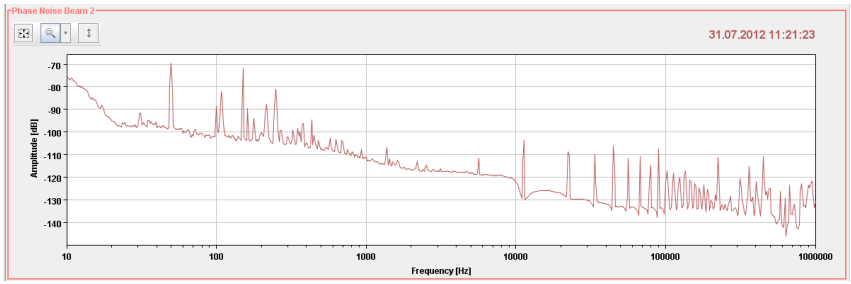
Cogging/Rephasing

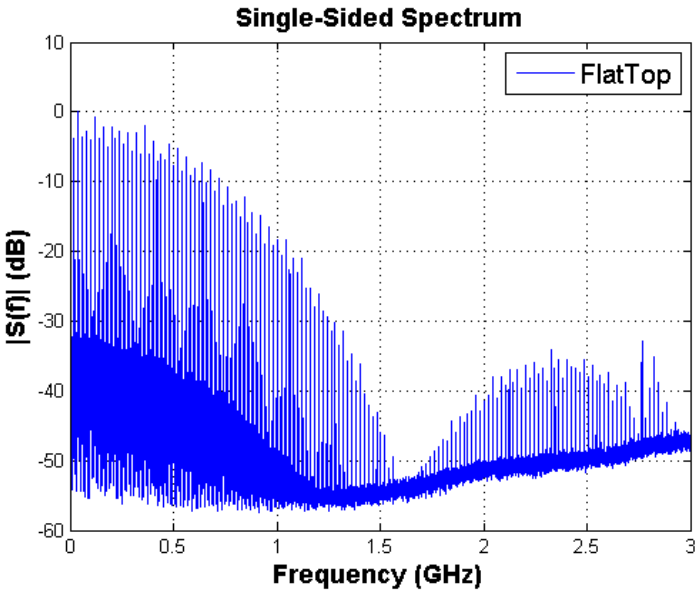
- Cogging/rephasing of the two rings at flat top is necessary for p-Pb run
- Technique developed, tested, and already used for p-Pb physics fill and for MD purposes (two-beam impedance MD). Possible to make process more adiabatic
  - We accelerate (decelerate) one beam to an off-centered orbit
  - After a time t, the phase has drifted by $\Delta\phi = 2\pi\Delta f\ t$
  - The crossing azimuth drifts by half that value (if we move one beam only)
  - When the desired position is reached we decelerate (accelerate) back to the centered orbit

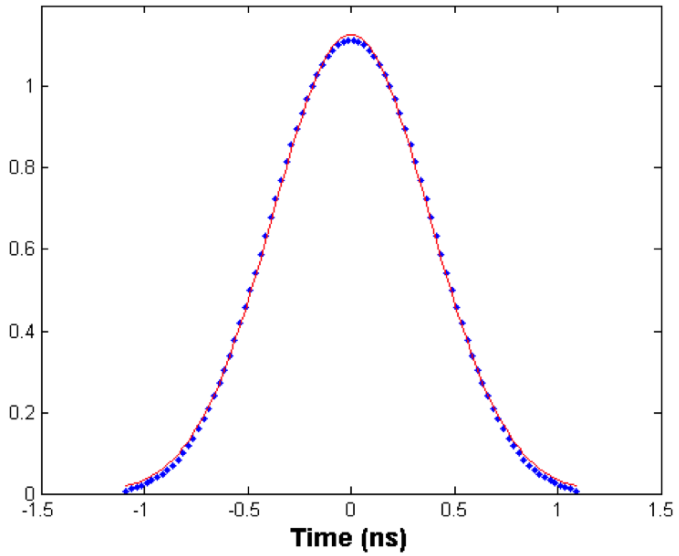


Other improvements/measurements

- A test was conducted with lower RF voltage (6 MV) during the squeeze
  - No improvement of transverse instabilities
- Beam Spectra, bunch profiles, cavity sum phase noise are now available and/or logged. Additional instrumentation installed
- Faster BQM (≈1 sample/second) tested at flat bottom last week, to be tested during the ramp, used during 2013 p-Pb run







1 The Past

2 The Future: anticipated limitations and actions taken
- Power Limits
- Longitudinal Broadband Impedance
- Longitudinal Single-bunch Stability
- Longitudinal Coupled-bunch Instabilities
- Bunch Length vs. Longitudinal Distribution

3 The Future: actions to be taken

4 Conclusions, References

25 ns, 6.5 TeV implications

Higher Energy

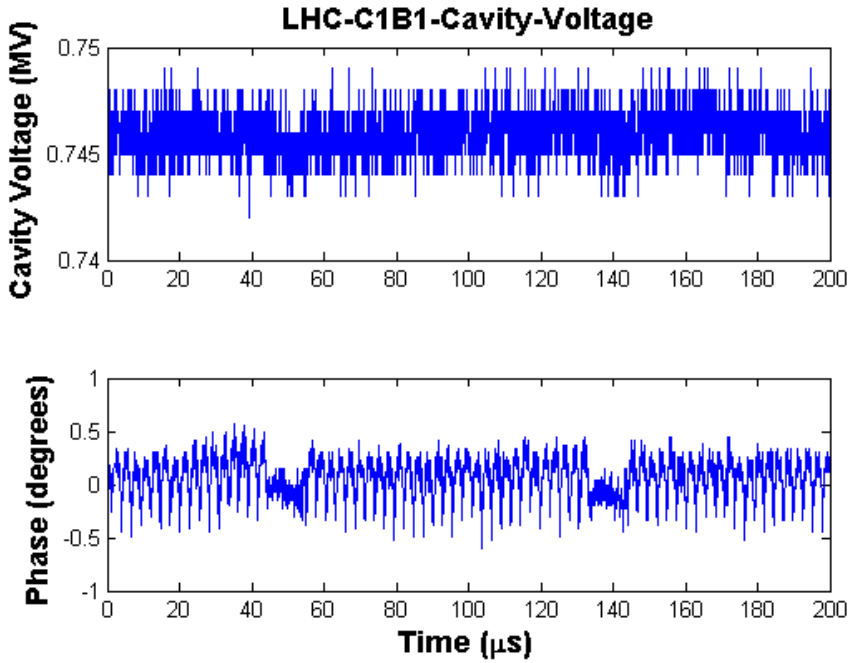
- Longitudinal single/multi-bunch stability thresholds reduced with higher energy [1, E. Shaposhnikova]
  - Longitudinal emittance blowup necessary
  - Constant bunch length during ramp maintains or slightly increases stability margins
- Synchrotron radiation damping time will be significantly reduced $\rightarrow$ possible bunch shrinking at flat top
  - For 7 TeV operation, 63 h IBS growth time and 12.9 h radiation damping time resulting in a 16.2 total emittance damping time [2, J. Tuckmantel]
  - Modified blowup algorithms could be used at flat top if this becomes an issue

Higher Beam Current

- More concerned with higher beam current. Implications:
  - Increase in demanded klystron power
  - Reduced margin for coupled-bunch instabilities
  - Potential for heating issues
- Various actions have been taken, studies conducted, and new algorithms developed to be ready for higher beam current

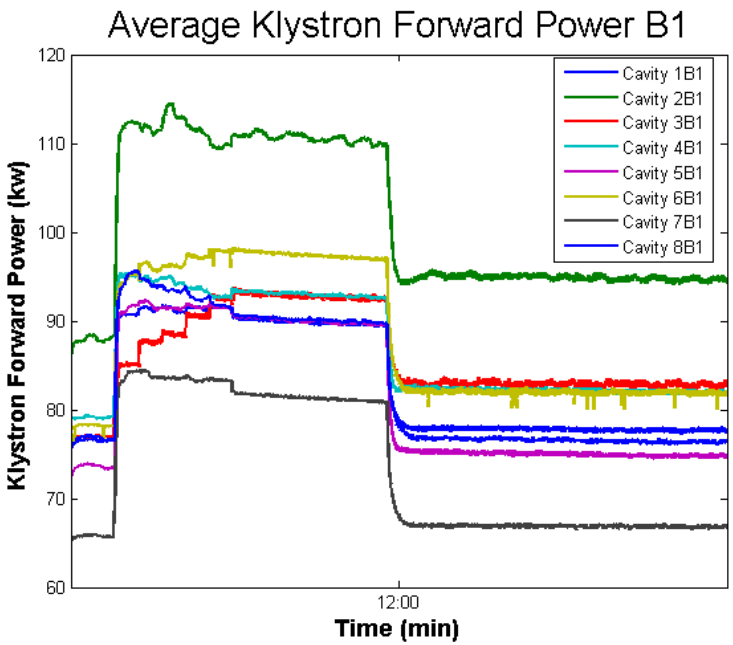
Cavity Voltage Setpoint Modulation

- RF/LLRF currently setup for extremely stable RF voltage (minimize transient beam loading effects). Less than 1° (7 ps) phase modulation (with ≈ 0.4 A DC)
- To continue this way, we need at least 200 kW of klystron forward power at nominal intensity. This scheme cannot be extended beyond nominal.
- 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 – by adapting the voltage set point for each bunch
- Up to 65 ps peak to peak displacement over a turn in physics (for ultimate beam, 25 ns spacing) compared to 1.25 ns bunch length
  [3, P. Baudrenghien]
  - Even smaller shift of collision point in IP1, IP5 due to symmetry

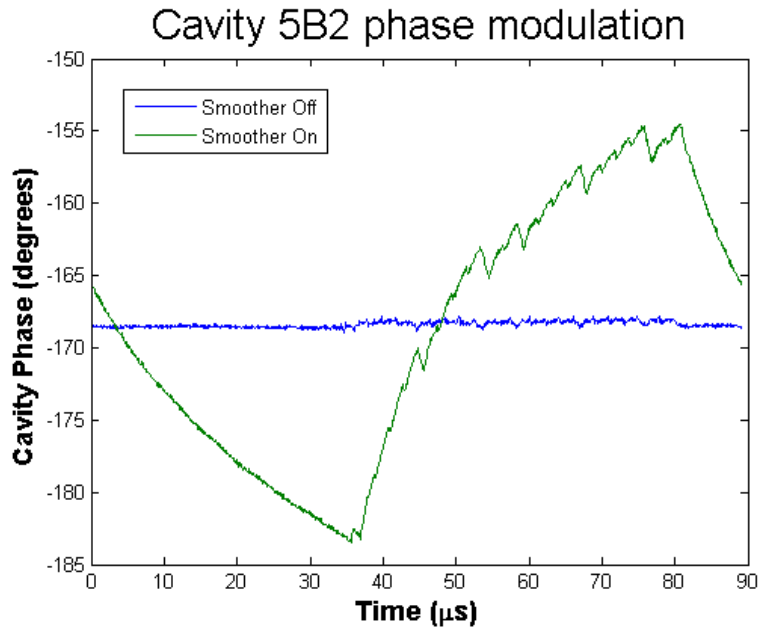


Cavity Voltage Setpoint Modulation - Results

- Significant reduction of klystron forward power achieved
- With this scheme klystron forward power requirements are independent of beam current, since the cavity is detuned further
  - Existing RF would be sufficient even for High-Lumi LHC (1.1 A DC)
- This technique also helps reduce reflected power and beam induced voltage in the case of a klystron trip [4], [5]



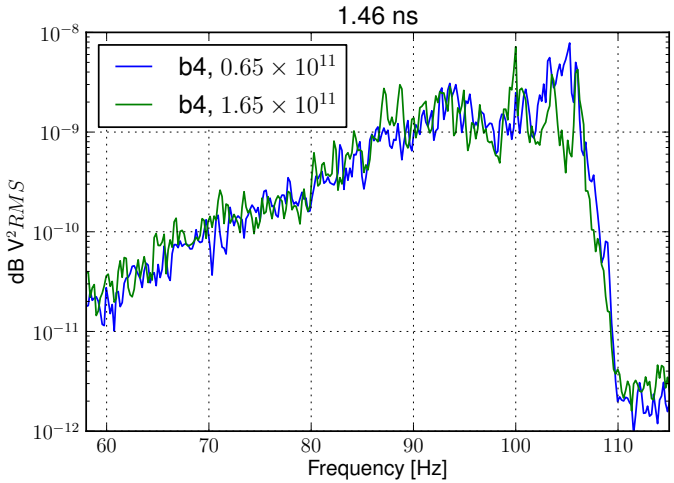
Klystron Forward Power, 144 bunches



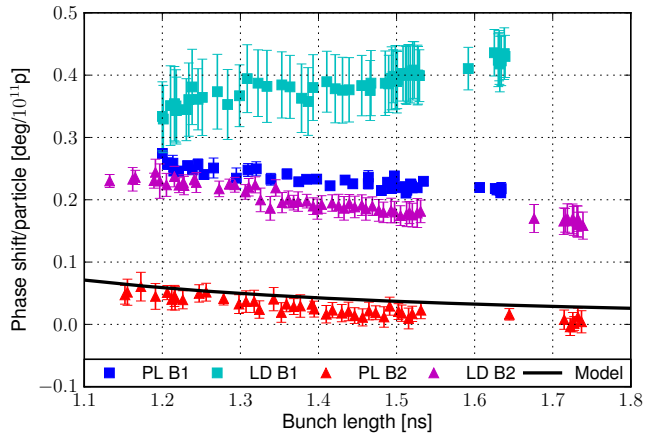
Cavity phase over a turn, 654 bunches

Longitudinal Broadband Impedance

- **Peak-detected Schottky** (reactive): Quadrupole tune shift very small, especially for long bunches: 0.2 Hz/1e11 at f_s for 1.4 ns. Very difficult to see in Schottky spectra and to decouple from longitudinal distribution effects
- **Stable phase shift** measurements (resistive): measured higher broadband impedance than expected, but systematic measurement errors comparable/higher than actual phase shift contribution from impedance (0.05 degrees/1e11 for 1.4 ns). Post processing of the data might lead to a gain in resolution
- **"Flat bunches" MD** (reactive): Shift of phase modulation gave an estimation of $\approx$ 0.2 Hz/1e11
- Reactive impedance seems comparable with and definitely not larger than the estimated and budgeted values ($\approx$ 0.06 Ω in Design Report). Hard to tell on resistive part
- The most sensitive measurement seems to be the loss of Landau damping during the ramp with beam phase loop off [6, E. Shaposhnikova]. Simulations/estimations of instability threshold during the ramp necessary for conclusion



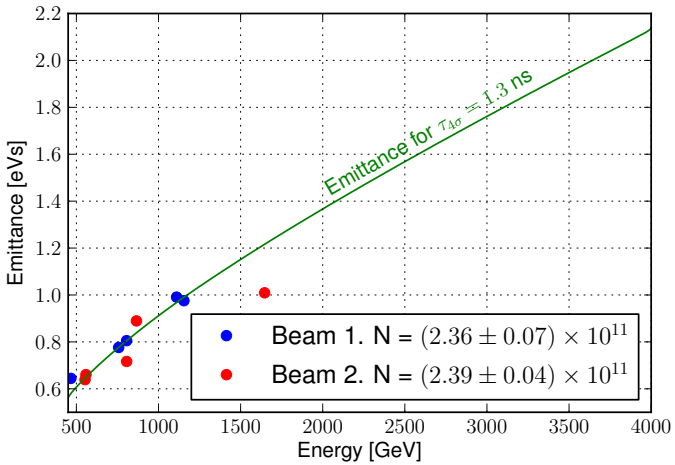
Courtesy J. Esteban Muller



Courtesy J. Esteban Muller

Longitudinal Single-bunch Stability

- Assuming emittance blowup during the ramp, stability is similar at flat bottom and flat top [1, E. Shaposhnikova]
- Dedicated MDs and observations during High-pile MD to estimate threshold
  - Two bunches per ring with intensities up to 3e11 and emittance of $\approx$ 0.6 eVs are stable throughout the cycle (beam phase loop on)
  - Bunches of 2.4e11and 0.6 eVs stable at 450 GeV. Instabilities develop during the ramp with the beam phase loop off [7, E. Shaposhnikova], [8, J. Esteban Muller]
  - Bunches with residual oscillations from injections closer to instability during the ramp
  - Longitudinal damper could help



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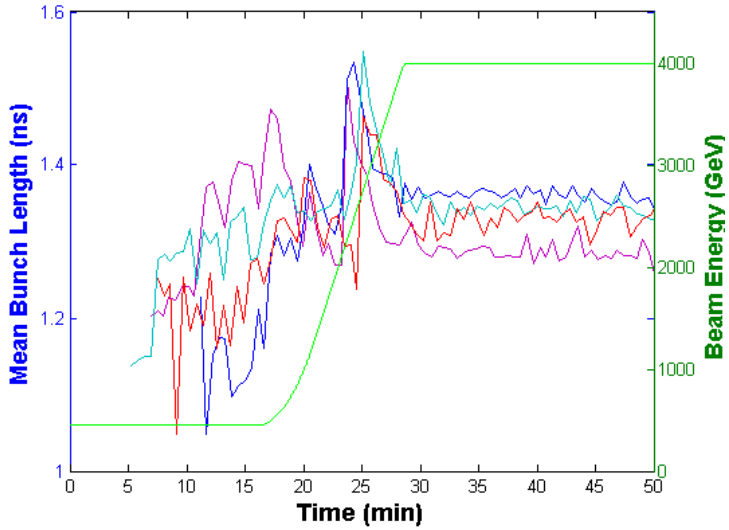
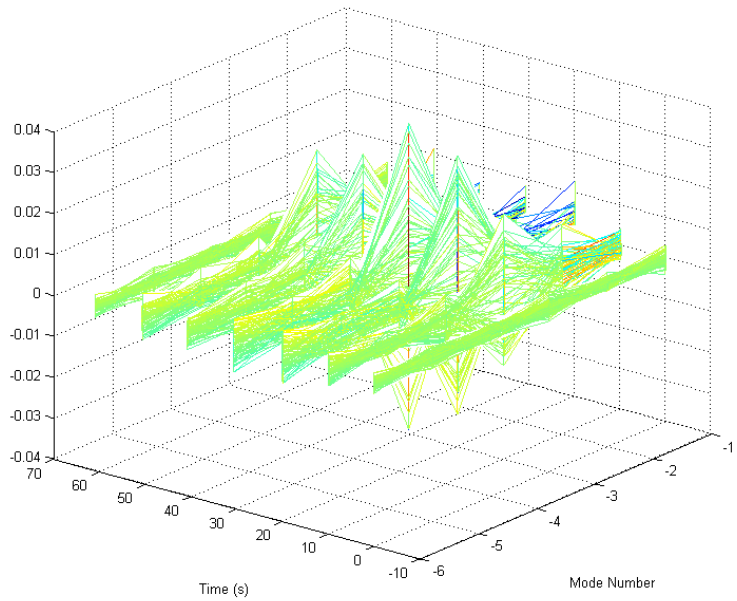


Longitudinal Coupled-bunch Instabilities (CBI)

- A factor of four stability margin on CBI due to the fundamental impedance of the 400 MHz cavities has been estimated, even with ultimate LHC beam (1.7e11) [3, P. Baudrenghien]
- An MD was conducted to validate these estimates and prove that longitudinal CBIs due to fundamental impedance are not an issue for higher beam currents
- Reduced RF feedback gain and excited most unstable coupled-bunch mode n (dipole) by injecting narrow band phase noise in the cavity, centered at $nf_{rev} \pm f_s$

- Even after an 18 dB RF gain reduction and turning the 1-turn feedback off (comparable to a situation with more than 10 times higher beam current), the beam was stable. Full analysis pending
- Similar results with LLRF fault on December 1st (cavity in open loop)
- Plot: Fourier decomposition of bunch-by-bunch phase acquisition over 73 turns, repeated every 10 seconds. Mode ± 3 excited for 30 seconds. Excitation and subsequent damping observed



Bunch Length vs. Longitudinal Distribution

- Tests were conducted to check the feasibility of operation with shorter/longer bunch lengths
- No show-stopper from RF
- No limitations either in terms of heating, *assuming* the beam spectrum does not deviate much from the one during the test. More details by B. Salvant tomorrow
- One important lesson from 2012 is that the bunch length is a very useful/important, but sometimes limited metric
  - We have observed variations in the longitudinal distribution from fill to fill and from flat bottom to flat top (mostly due to the emittance blowup)
  - These variations are often important: for example during heating exercises and longitudinal stability MDs
  - We should be careful when making conclusions on the heating of structures with narrowband impedances
- “Flat Bunches” were also tested
  - Effects on heating were recorded (B. Salvant *et. al.*)

1 The Past

2 The Future: anticipated limitations and actions taken

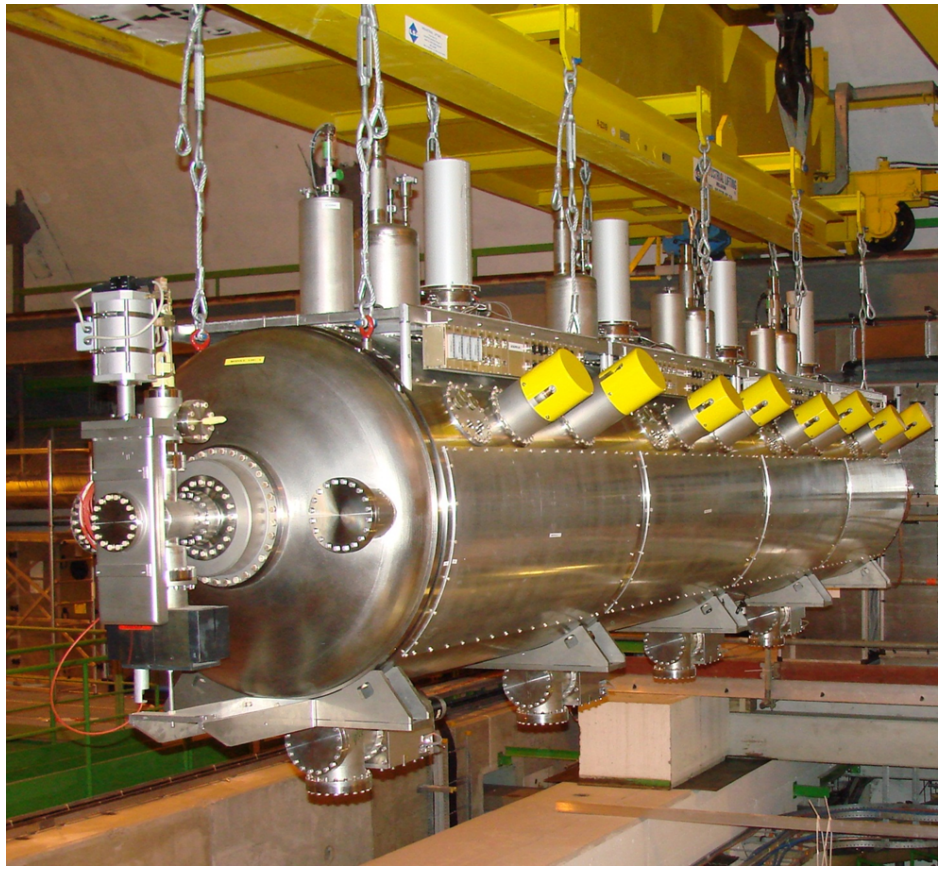
3 The Future: actions to be taken
- Module Replacement
- Further Diagnostics, New Systems

4 Conclusions, References

Module Replacement

- RF cryomodule 1B2 will be replaced during LS1
- Cavity 3B2 has been operating with lower voltage for more than a year

- Testing of spare module ("Europa") completed in August. No quench below 2.6 MV
- Emissions an order of magnitude less than the module to be replaced. Promising
- Still, some risk due to transportation, mounting etc.
- To mitigate, the replaced module will be repaired (no time estimate). To be safe, dismantling won't start before the new module is restarted and fully validated in the machine and new LHC spare cavities are procured



Further Diagnostics, New Systems

- Injection oscillations with slow damping times observed in the LHC since 2011 (not intensity driven). Further studies necessary to explain them
- Longitudinal Damper under development
  - Tested in the lab and for the first time with beam on Sunday. Analysis in progress
  - We hope to use it for normal operation in 2013
  - Reduce injection oscillations
  - Could also be of help if we ever have coupled-bunch instabilities of low order modes in the High-Lumi era
- “Fast diagnostics” for amplitude and phase observations/logging for each cavity are under development
  - Will immediately point to the “noisy” cavity in case of problem (such as saturation due to non-moving coupler, an issue that happened a few times in 2012)
- Continue faster BQM tests
- Bunch-by-bunch phase fixed display. Data available, software work necessary
- All RF VME front-ends will be moved to LINUX
  - Software drivers will need to be rewritten/recompiled

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Conclusions

- A very successful year for the RF (we think)
- Improved performance
- Flexibility for new modes of operation, MD requirements, p-Pb run
- Preparation for post-LS1 operation well under way
- During LS1 emphasis on module replacement

Acknowledgments

- Many thanks to the RF group

References

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[2] J. Tuckmantel], “Synchrotron Radiation Damping in LHC and Longitudinal Bunch Shape”, LHC Project Report 819, June 2005.

[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.

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