THE LHC RF OPERATION 2010 AND PLANS FOR 2011

7.12.2010

LHC workshop, Evian 2010

Reported by P. Baudrenghien CERN-BE-RF

The LHC RF team

LHC RF Project Leader: E. Ciapala

Longitudinal dynamics: E. Shaposhnikova, J. Tuckmantel

LLRF and RF Control team: M.E.Angoletta, L. Arnaudon, P. Baudrenghien, T. Bohl, A. Butterworth, F. Dubouchet, J. Ferreira-Bento, G. Hagmann, W. Hofle, M. Jaussi, S. Kouzue, D. Landre, J. Lollierou, J. Molendijk, J. Noirjean, A. Pashnin, J. Sanchez-Quesada, M. Shokker, D. Stellfeld, D. Valuch, U. Wehrle, F. Weierud

Klystron and ACS cavities team: O. Brunner, D. Glenat, P. Maesen, P. Martinez Yanez, C. Nicou, G. Pechaud, J. Pradier

« OP/RF » team: D. Jacquet, G. Papotti

US-LARP collaboration: J. Fox, C. Rivetta, D. Van Winkle, T. Mastoridis, SLAC

The way it was intended to work

RF challenge

- The LHC is a high-current collider (>0.5 A DC nominal)
  - The high-current is a challenge: The Cavity impedance must be reduced by order of magnitudes to keep the beam stable and control transient beam loading
  - The lifetime in collisions is another challenge: RF noise must be minimized
- Fortunately the design was good…
  - Low R/Q Superconducting Cavities are used for their low impedance for a given accelerating voltage
  - Cavities are single-cell, each with a private klystron. That gives much flexibility for improving performances using LLRF loops
  - Movable coupler allow for high bandwidth when needed (damping of injection transients) and high voltage during physics

Half detuning

- The LHC filling proceeds batch per batch in successive portions of the rings
- To avoid phase errors while filling, the RF phase must be kept rigorously constant in the beam portion and in the no-beam portion
- The strong RF feedback guarantees this voltage uniformity
- For a constant RF voltage, the klystron demanded power will be different in the beam-on segments and in the no-beam segment
- This power depends on the cavity tune. The “Half detuning” scheme makes the average power equal during beam and no-beam portions

$$x'_{opt} = \left[\frac{\Delta f}{f_0}\right]_{opt} = -\frac{1}{4} R/Q \frac{|I_b|}{|V_{acc}|}$$

- Once the half-detuning policy is enforced, klystron power is uniquely dependent on the RF voltage, beam current and cavity loaded Q

$$P(x) = \frac{1}{8}\frac{V_{acc}^2}{Q_L R/Q} + \frac{1}{2} Q_L R/Q \left[\frac{V_{acc}}{R/Q} x + \frac{I_b}{2}\right]^2$$

Movable Coupler

- For a given beam current we can now derive a coupler position that minimizes the klystron power

$$P(x) = \frac{1}{8}\frac{V_{acc}^{2}}{Q_L R/Q} + \frac{1}{2} Q_L R/Q \left[\frac{V_{acc}}{R/Q} x + \frac{I_b}{2} \right]^2$$

- At injection:
  - 8 MV at injection. Actually 4 MV are well sufficient to match the 0.7 eVs from the SPS. The designers probably wanted some margin if beam loading was too severe at injection?
  - Low Q_L favorable for fast damping of momentum/phase errors
  - For 0.5 A DC
    - Optimal Q_L ~ 30000 but intended 20000
    - Detuning -4.5 kHz
    - Klystron power 133 kW

- During physics:
  - Lifetime limited by intra-beam scattering. Emittance must be blown up to 2.5 eVs
  - 16 MV needed for the 2.5 eVs emittance
  - For 0.5 A DC
    - Optimal QL ~ 60000
    - Detuning -2.25 kHz
    - Klystron power 264 kW

Review of 2010

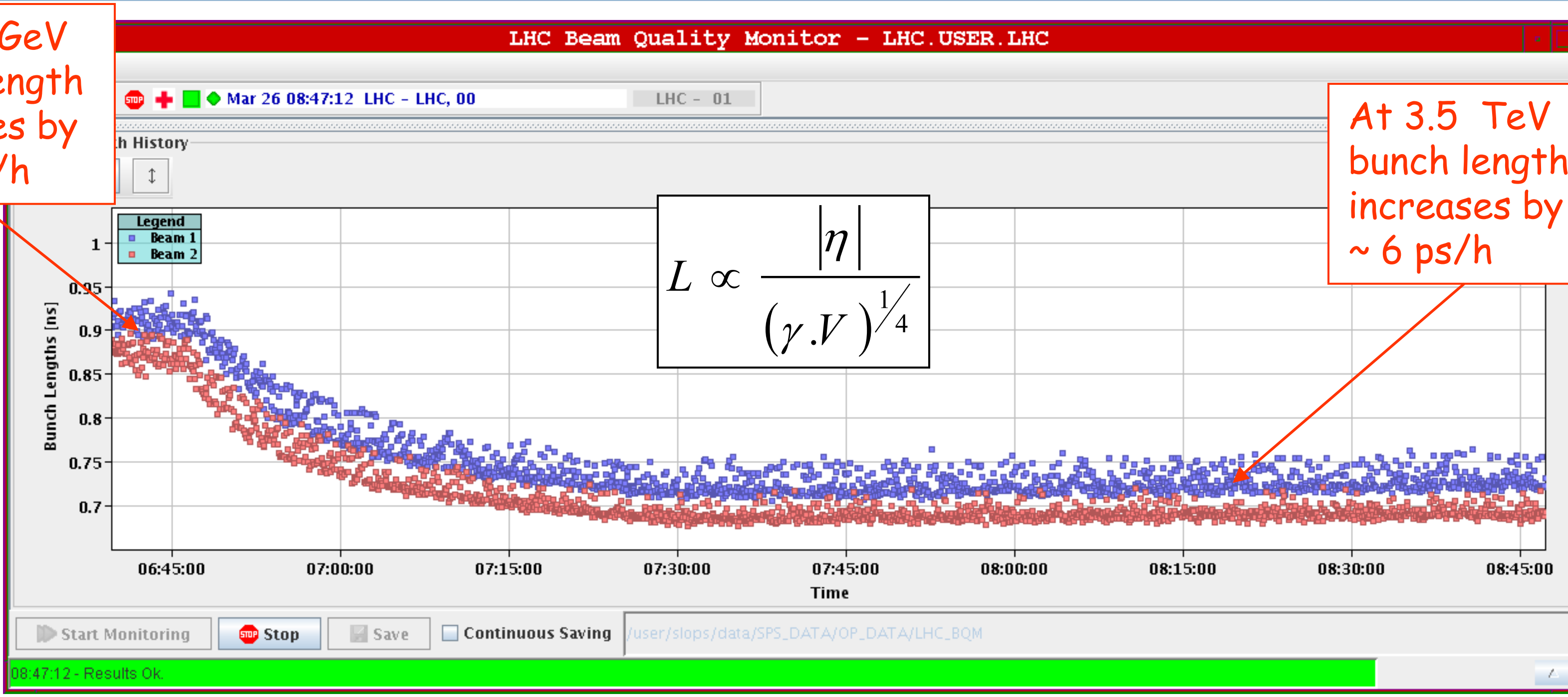
The way we ended-up operating it

Winter 2010. Single bunch towards nominal intensity

- We first captured with 8 MV (max at Q=20k). Change coupler to 60k before start ramp. Raise voltage to 12 MV. Ramp and physics with 12 MV
- Cogging worked very well: With bunch injected to collide in the IPs at 450 GeV, the collision point does not drift during ramping. No need for rephasing at 3.5 TeV
- The single-bunch cycle in the SPS produced low emittance: < 0.2 eVs for 5E9 p/bunch and < 0.4 eVs for 1.1E11 p/bunch (SPS RF voltage 7 MV @ 200 MHz at transfer)
- Lifetime was very good. Bunch lengthening was as expected from adiabatic evolution. Nothing dramatic when crossing the much feared 50 Hz synchrotron frequency. (f_{s0}=65.3 Hz at injection, 28.9 Hz in physics)

Winter 2010. Single bunch towards nominal intensity

At 450 GeV bunch length increases by ~ 30 ps/h



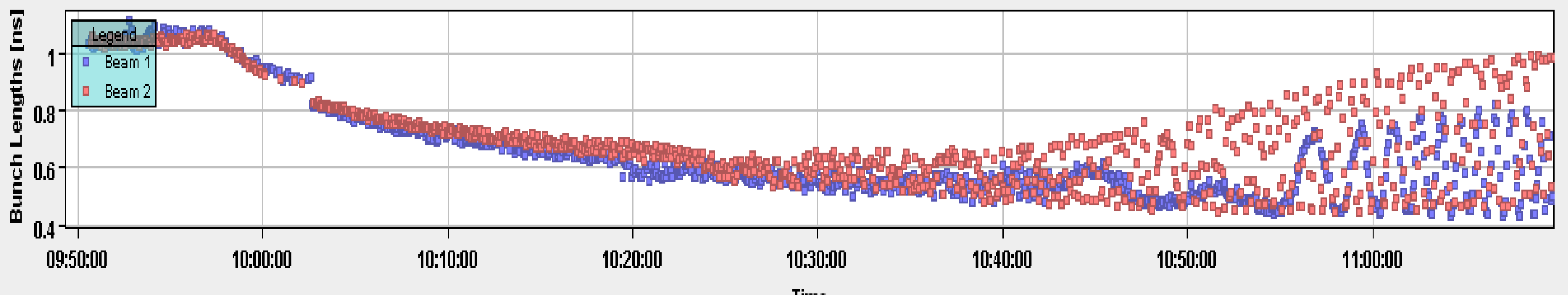
$$L \propto \frac{|\eta|}{(\gamma . V)^{1/4}}$$

At 3.5 TeV bunch length increases by ~ 6 ps/h

- March 26: Single bunch pilot in both rings, ~ 0.2 eVs. 8 MV at injection (f_{s0}=65.3 Hz), increased to 12 MV before ramp (f_{s0}=80 Hz), constant 12 MV during acceleration ramp (f_{s0}= 28.9 Hz @ 3.5 TeV) . BQM was not calibrated.
- Nothing dramatic when crossing 50 Hz
- Would it remain that good with multi-bunch?

Ramping nominal bunch intensity

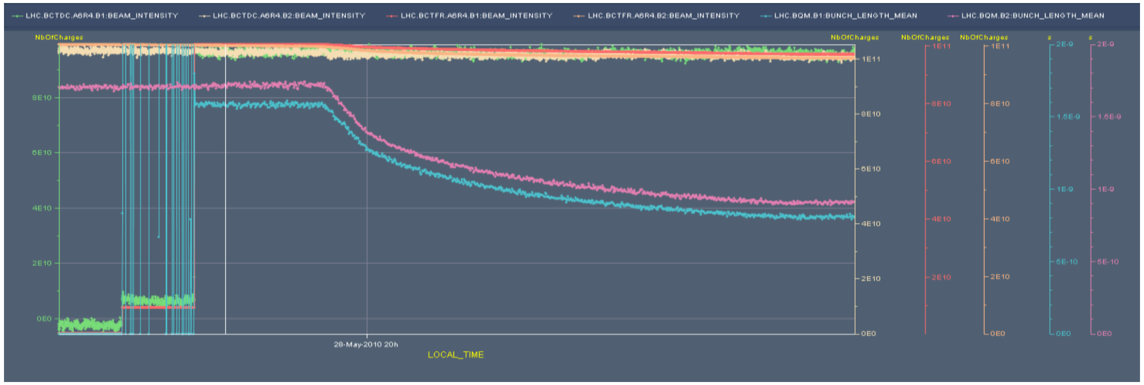
- Inject 1.1E11, 1.2-1.3 ns long, 0.3-0.4 eVs
- Capture with 5 MV (matched voltage ~ 3 MV)
- Raise voltage to 8 MV before start ramp. Ramp with constant 8 MV
- Very unstable. The bunch shrinks down to < 0.5 ns and we lose Landau damping



May 15th. First attempt to ramp nominal intensity single bunch. Bunch length during ramp. The longitudinal emittance is too low (<0.4 eVs). The bunch becomes unstable

Ramping nominal bunch intensity

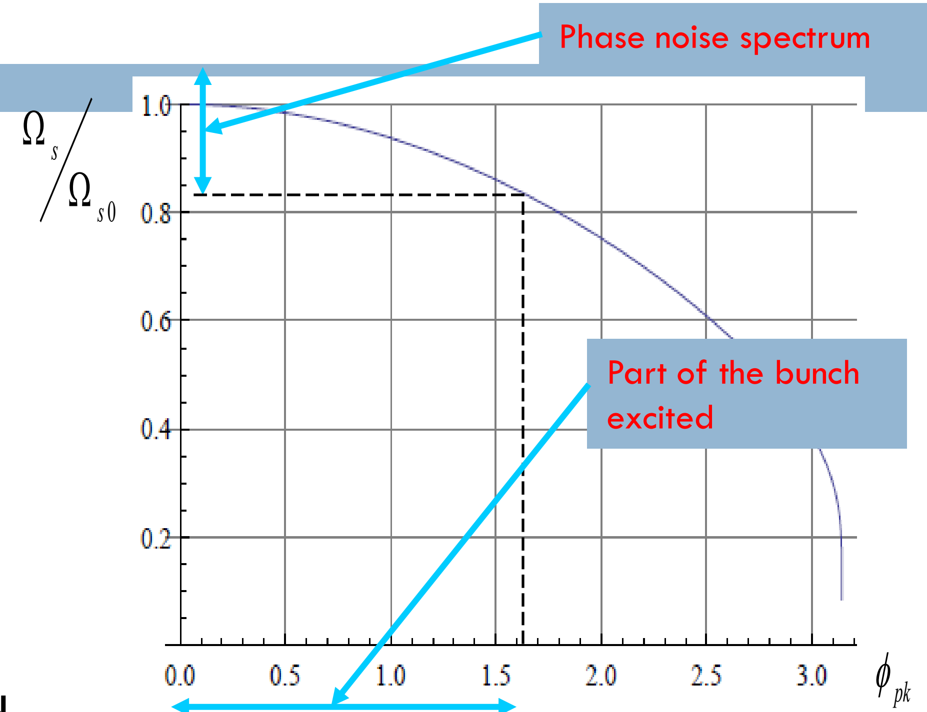
- Let us blow-up maximally in the SPS:1.7 ns long bunch, 0.6-0.7 eVs
- Revise voltage function in the LHC to preserve bunch length
  - Keep matched voltage in the LHC ~ 3.5 MV
  - Get 1.5-1.7 ns after capture
  - Ramp voltage to 5.5 MV in parabolic part of ramp
  - Keep constant 5.5 MV in rest of ramp and physics
- May 28th: Nominal at 3.5 TeV, 0.8-0.9 ns long



FastBCT and bunch length through the ramp. By increasing the SPS longitudinal emittance, the bunch was kept stable till flat top

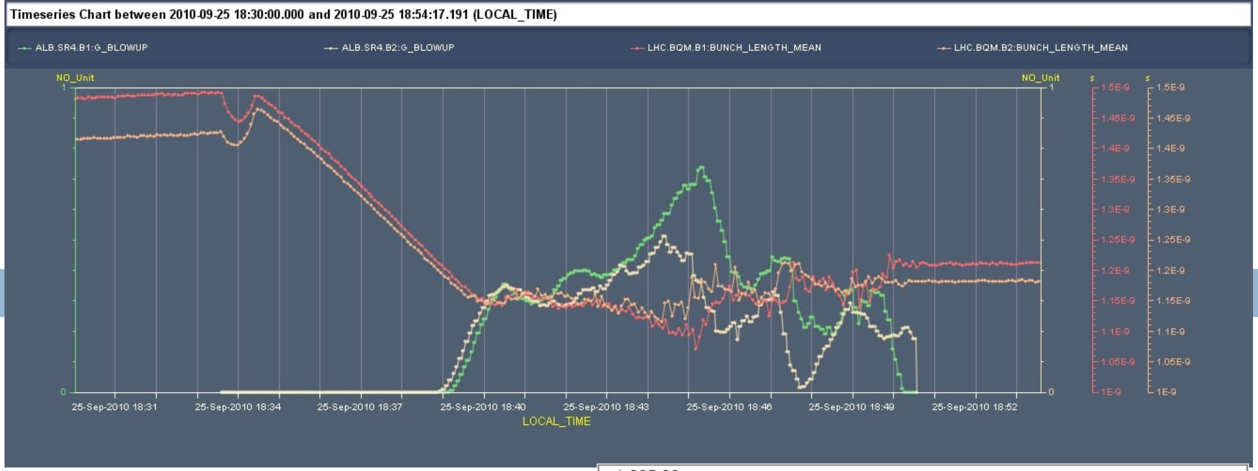
Longitudinal emittance blow up in the LHC

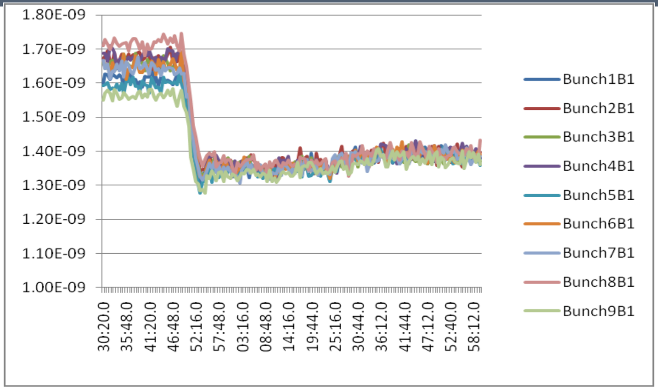
- From June 15th on, blow-up in the LHC
- Rectangular Phase Noise Power Spectral density that excites only the core
  - hit: $6/7\ f_s < f < 1.1\ f_s$
    corresponds to a 1.2 ns window in the core
  - and follow f_s along the ramp
    from Hz to Hz
- Algorithm to adjust the amplitude of the excitation x_n from a measurement of the instantaneous bunch length (mean) L_n and comparison to target L_0
- Target bunch length L_0 originally set at 1.5 ns (later reduced to 1.2 ns). We obtain > 1.5 eVs at 3.5 TeV
- We can now reduce the SPS bunch length to ~ 1.5 ns (0.5 eVs)

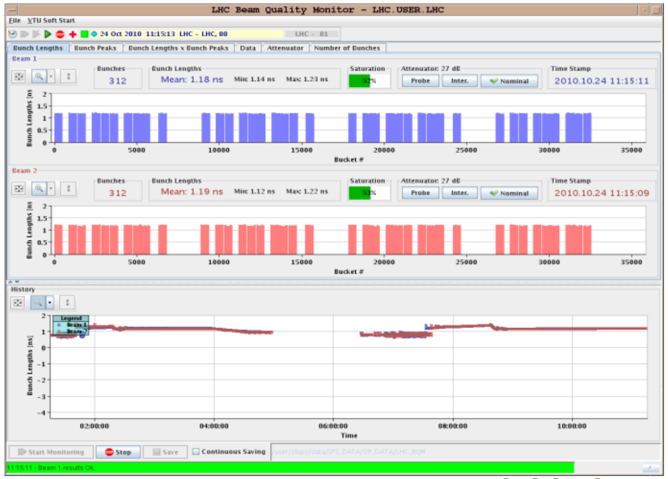


$$
\begin{aligned}
&x_{n+1} = a.x_n + g.(L_0 - L_n) \\
&if \quad x_{n+1} \leq 0 \quad then \quad 0 \rightarrow x_{n+1} \\
&if \quad x_{n+1} \geq 1 \quad then \quad 1 \rightarrow x_{n+1}
\end{aligned}
$$

Long. blow-up







- The LHC Longitudinal Blow-up has performed…perfectly
  - Top: Sept 25th, fill 1372 first time 104 bunches/ring, 150 microsec spacing. Observe bunch length and phase noise excitation level
  - Middle: July 12th, 9x single nominal. Convergence of bunch length during blow-up
  - Bottom: Oct 24, Fill 1438, 312 nominal bunches/ring, 150 microsec spacing, The target bunch length is set at 1.2 ns and all 312 bunches fit in a +- 40 ps window after the ramp, 8 MV

Pushing the intensity

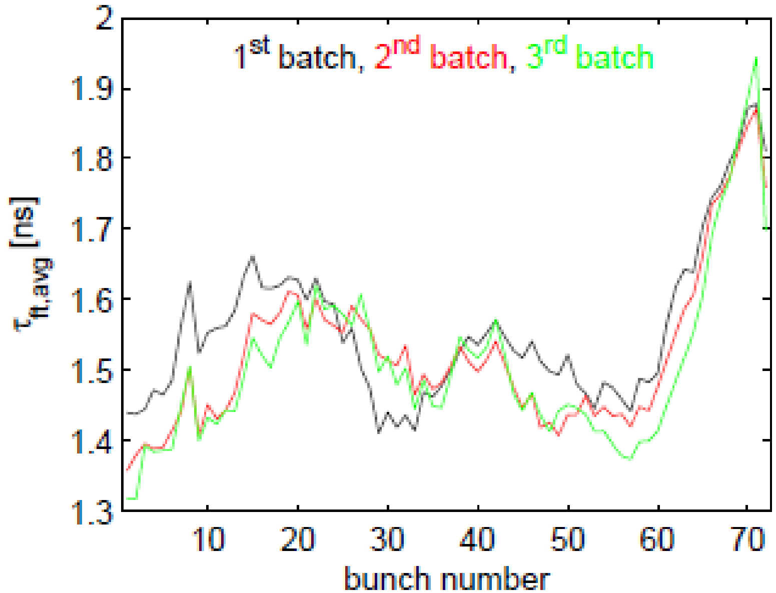
- Begin September we reconfigure the RF for higher intensity and faster ramp
  - No more idling cavity. All klystrons ON. Without active feedback a cavity presents a very large impedance to the beam and that can drive Coupled-Bunch instabilities (see further)
  - Lebedev's analysis: there is no observed bunch lengthening beyond the1.5 ns target bunch length because we loose out of the bucket
  - Lebedev's recommendation: increase RF voltage, reduce bunch length (keep emittance ~1.7 eVs for IBS)
- Target bunch length during emittance blow-up reduced from 1.5 ns to 1.2 ns
- Capture with 4 MV with QL=20k. To limit dissipation in klystron collector we set all cavities at 1 MV (~150 kW) and use +- 60 degrees counter-phasing per pair
- Null counterphasing at begin ramp, then linear voltage rise from 4 MV to 8 MV during the ramp. More gentle bunch length reduction then with the previous voltage rise in the parabolic part of the ramp.

Capture loss

- With the increased number of injections, the injection dump would fire, triggered by radiation measured by BLMs and above threshold
- It was traced to a small amount of un-captured beam at each injection, that slowly drifts. When the next bunch/batch is injected in front of the previously injected one, the kicker deviates the unbunched beam in the 8 microsec long kicker window. This unbunched beam then hits the TDI, causing radiation that propagates in the tunnel, hits the BLMs on the cold magnets downstream, and are wrongly considered as loss of circulating beam. The BLM system triggers the dump…
- The situation worsens with the number of injections as the Beam Phase loop efficiency decreases.

Capture loss

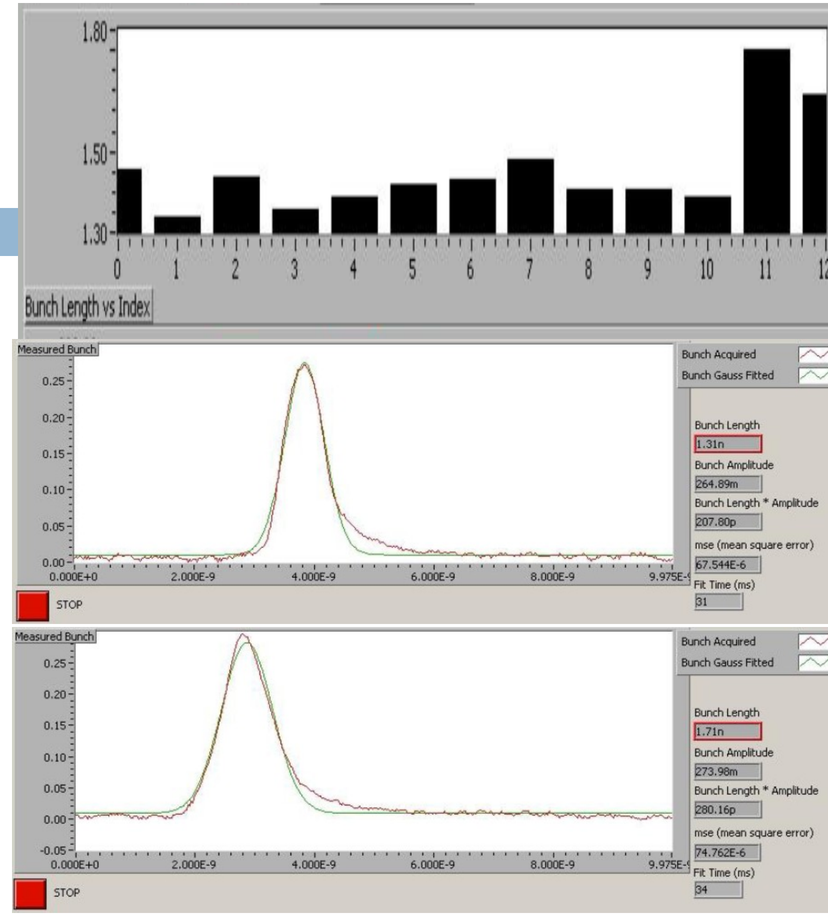
- Calibrating injection loss vs BLM radiation measurement, Sept 30th
  - Present Dump Level = 1E10 p lost per inj = 3.3E6 p/m uniform around the ring
- Begin Oct (150 microsec bunch spacing) we reach ~ 1/3 BLM dump level (3E9 p kicked out at injection) with 16 nominal bunches (1.6E12 injected intensity). That amounts to ~ 2 per mil lost at injection.
- With 216 bunches per injection we could extrapolate loss to 4E10 p/inj
- From MDs in the SPS we know that the situation will get worse when reducing bunch spacing…



Example of bunch length variations along the SPS batch at 450 GeV , batch of 72 bunches, 25 ns spacing, G.Papotti et al. , AB-MD Note-2008-032

Capture loss

- …indeed the situation got worse with 50 ns spacing: as the bunches are placed closer together and with more intensity in the SPS, we have more dispersion of bunch position/length along the batch -> more debunching
- Oct 30: 50 ns spacing. 12 bunches per inj. Observe 6th inj B1, first LHC turn
- The dispersion in bunch phase/length along the batch is caused by the imperfect compensation of the transient beam loading in the SPS 200 MHz and 800 MHz cavities.



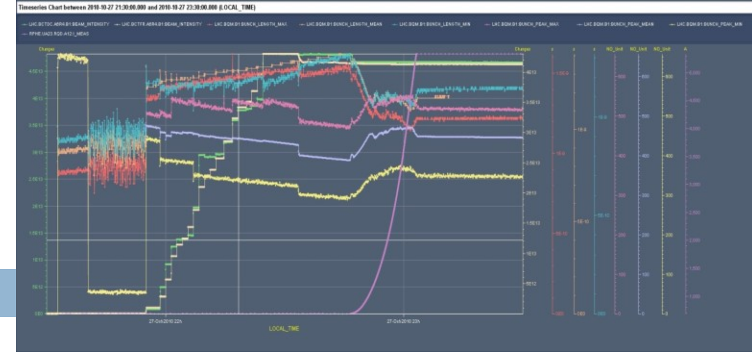
Top: Length of the individual bunches in the twelve bunches batches at injection. From 1.31 ns (bunch 1) to 1.71 ns (bunch 11)
Middle: Bunch 1 profile. Gaussian, 1.31 ns long
Bottom: Bunch 11 profile, triangular, 1.71 ns long

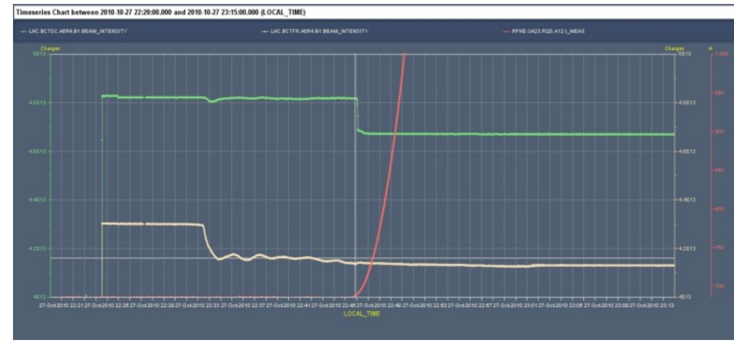
Capture loss

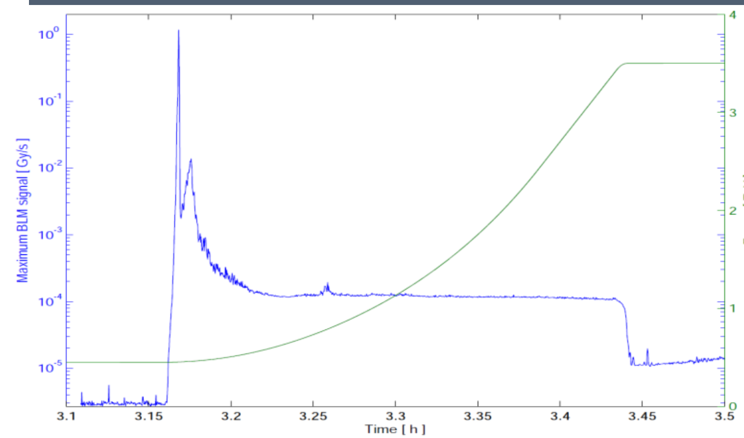
- Capture loss cannot be negligible. We transfer from an SPS 200 MHz bucket to an LHC 400 MHz bucket. The SPS bunch will always have some tails that fall outside the LHC bucket, resulting in capture loss
- In 2003, the issue of unbunched beam line density was studied. At the time the issue was the maximum beam intensity in the abort gap
- The allowance for unbunched beam line density was ~ 2.6E8 p/m at injection energy, ~100 times larger than allowed to-day (3.3E6 p/m) [Shaposhnikova]
- Expected RF performances
  - One can hope to have ~ 1% capture loss
  - 1% nominal 216 bunches batch = 2.4E11 p loss/inj
  - That is 24 times larger than present BLM dump level
- **Conclusion:** To operate smoothly with nominal, the sensitivity of the BLM dump system to injection loss must be increased by 2 orders of magnitude (x100)

[Shaposhnikova] Abort Gap Cleaning and the RF System, Chamonix 2003

Capture loss





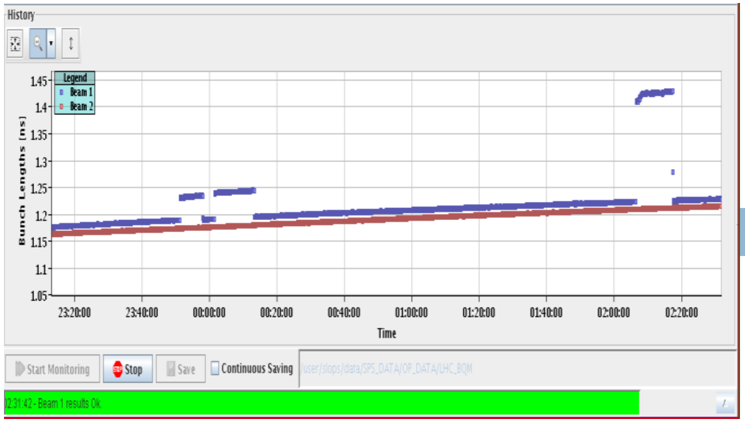


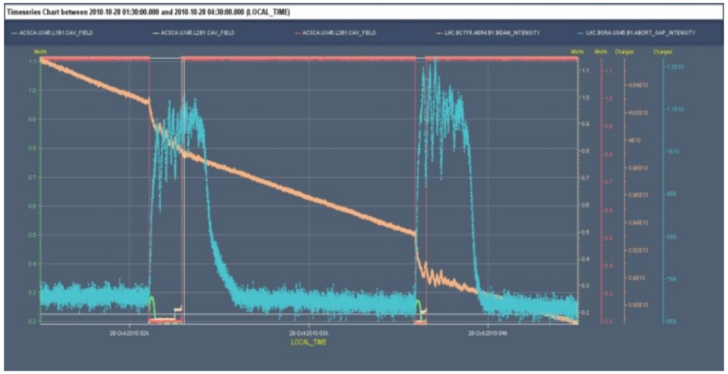
- If the injection goes OK, the LHC can tolerate capture loss
- Oct 27th, fill 1450, 150 ns spacing, 368 bunches, 4.7E13 p total per beam
  - Just after last injection, Cav4B1 starts injecting noise resulting in severe debunching
  - Decide to ramp anyway
  - Unbunched beam (due to the RF noise) gets lost at the start of the ramp ~ 1.6E12 p (~ 3.5% total B1)
  - The momentum collimators do their job OK
  - The fill proceeds smoothly to physics…

If we consider the intensity lost from the fast BCT, we had lost out of the buckets about ~1.6e12p (B1 only). They were then lost within the first ~25 s of the ramp. No BLM losses were seen when the particles left the buckets. The peak loss rate at the TCP in IP3 was ~ 1 Gy/s and we had losses in all the sectors. See attached the loss map and the zoom in IP3. The hierarchy was respected. In the plot "BLM_and_Energy", we see the maximum loss amplitude as a function of time during the ramp. Momentum losses were high throughout the ramp. Reproduced from OP logbook, Oct 27, 2010, night, entry 50, S. Radaelli, D. Jacquet

Natural Abort Gap cleaning

- Oct 28th, fill 1450, M1B1 trips twice with 4E13 p, resulting in severe debunching (voltage drops from 8 MV to 4.5 MV (4B1 was off, only 7 cavities used)
- The abort gap gets populated at each trip
- OP restarts the 3 cavities with barely any loss
- We observe natural cleaning of the abort gap. Particles lost from the buckets loose energy through synchrotron radiation. The ones that were below the acceptance energy drift radially inwards till they hit the momentum collimator. The ones that had excess energy first surf on the separatrix until they cross the bucket and move to the lower energy side.
- All in all, a very good lumi fill

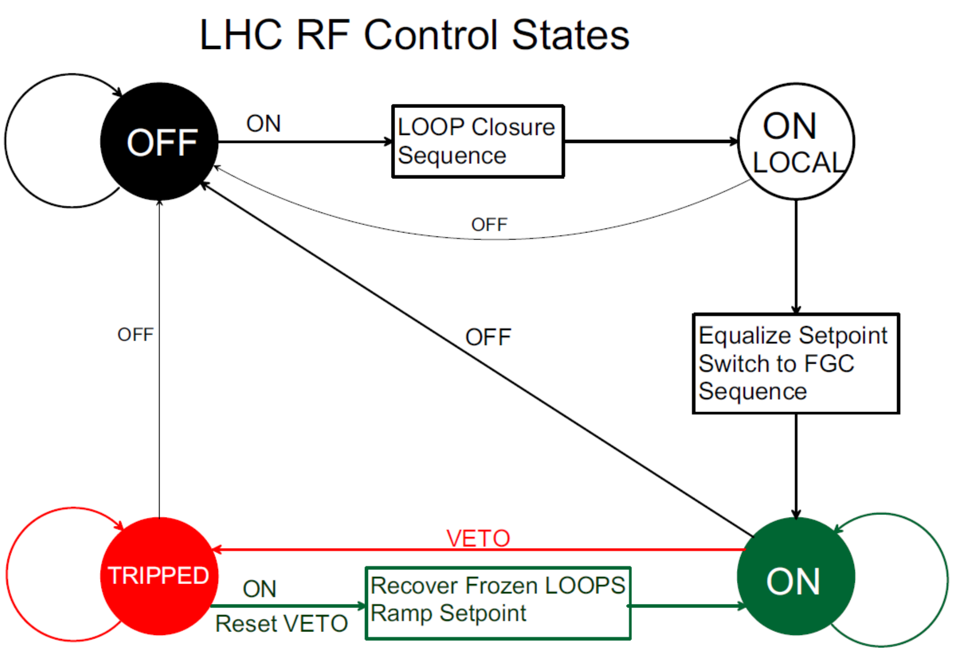




Top: BQM bunch length showing switching off of Cav4B1, followed by trip of a companion cavity, then later, the full M1B1 module tripping. The bunch length jumps from 1.23 ns to 1.43 ns
Bottom: Fast BCT, Abort Gap Population and Cav1B1, Cav2B1 and Cav3B1 field. Notice that the cleaning of the abort gap does not depend on the time when the cavities are switched back on but takes place ~15 min after the cavities where switched off (time for the debunched beam to move to the momentum collimator). Notice also that the cavity voltage does not go to zero when the klystron trips, but to ~ 200 kV, that is the voltage induced by the ~12% nominal beam

RF recover from Klystron or PC Trip

- When a klystron or RF power converter trips, the Cavity Controller goes from state ON to TRIPPED. All loop settings (tuner position, klystron polar loop gain/phase) are frozen
- When the VETO condition is removed and OP sends the RF ON command, the voltage set-point gently returns to the FGC demanded value and the loops are active again
- Only the loss of cryo conditions on a module would make the RF fire the beam dump.

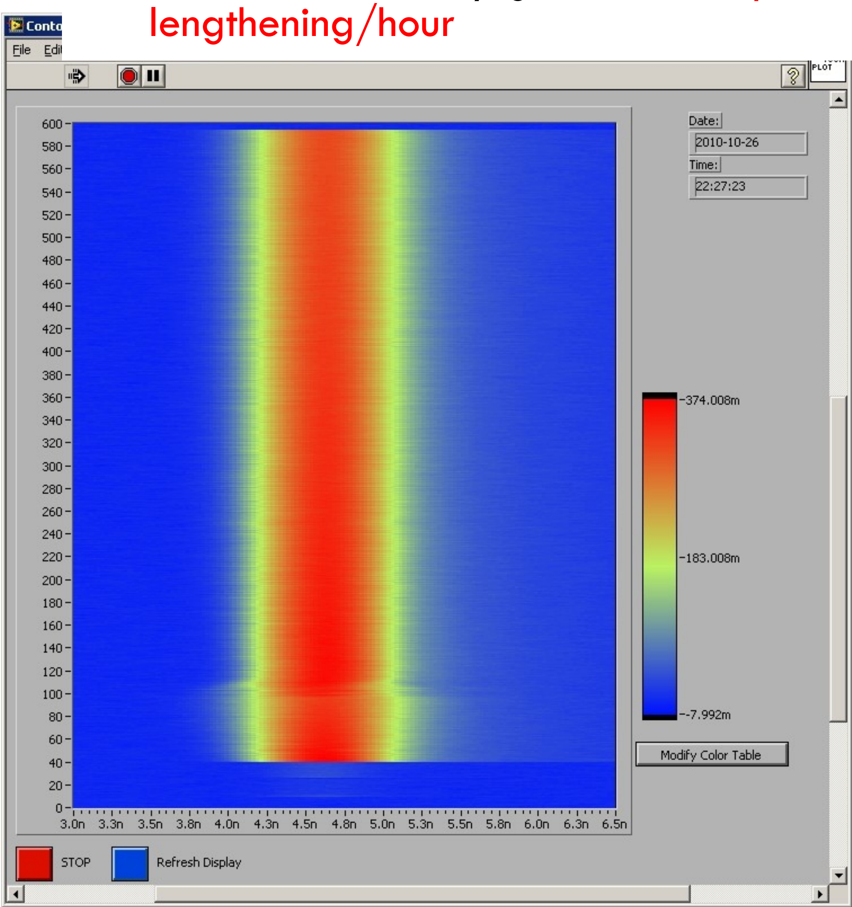


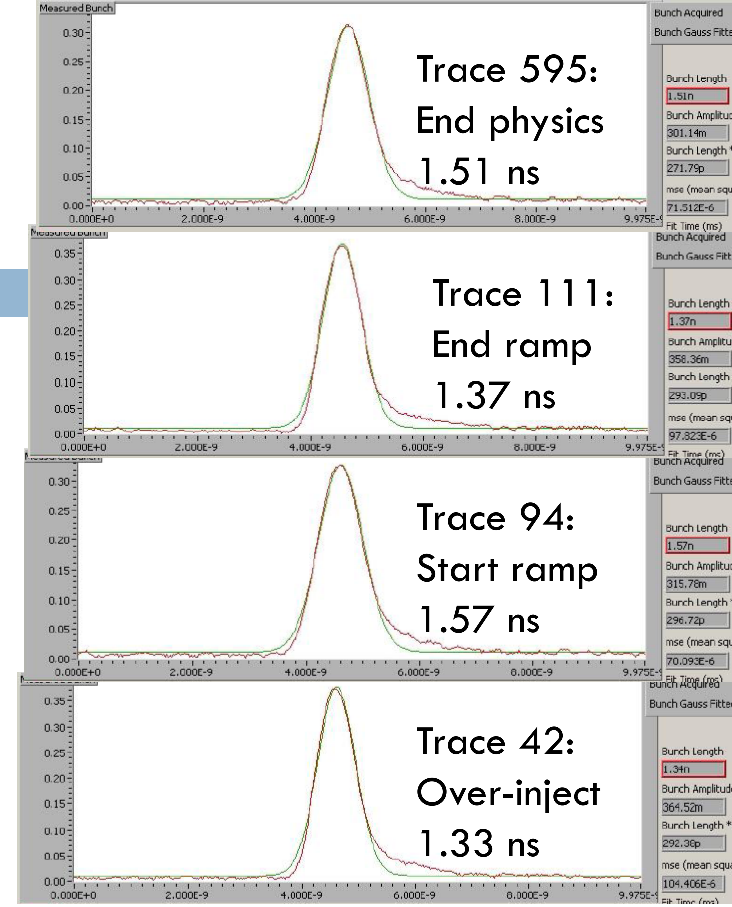
RF noise

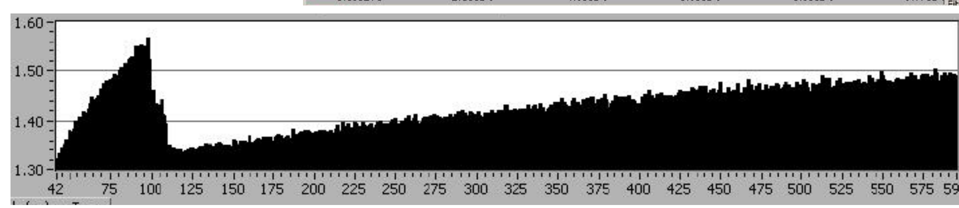
- At 3.5 TeV the Synchrotron Radiation damping time is ~ 200 hours
- The target for Longitudinal Emittance blow-up caused by RF noise was 13 hours minimum at 7 TeV (equal to the Synchrotron Radiation damping at that energy)
- The RF design was optimized to reduce the RF noise. For a collider phase noise is the most damaging
- Klystrons produce significant RF noise by converting HV ripples in phase modulation. The frequencies are harmonics of 50 Hz, extending to 600 Hz. During acceleration the synchrotron frequency crosses the 50 Hz line
- RF noise turned out to be a “no-problem” in 2010
- More on the topic in Chamonix.

RF noise

- Oct 26th, fill 1444, > 300 bunches, 150 microsec spacing
- Observe Bunch 1 B1 from injection
- 1 min between traces
  - Flat Bottom: traces 40 to 93
  - Ramp: traces 94 to 111
  - Physics: traces 112 to 595
- All in all…it is very good…~ 15 ps bunch lengthening/hour



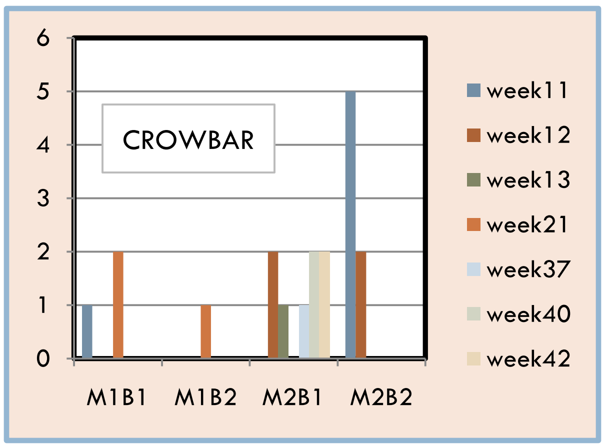


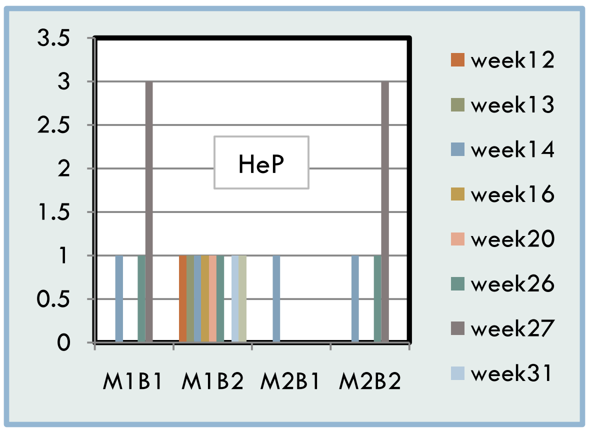


Bunch length evolution during fill 1444 (~ 10 hours). The above data have not been corrected for the bandwidth of the measurement chain -> over-estimate the bunch length by ~ 100-200 ps

Statistics on RF problems

- Waveguide arcing close to main coupler: Much problems when increasing beam current. False alarms. Solved by ORing the detectors by pair
- Klystron Vacuum: Mainly K2B2. Klystron will be replaced during shutdown
- Main Coupler Blowers: false alarms from the air pressure detectors. Solved by ORing with measured temperature of in/out air flow
- Others: K2B1 oscillation in the filament heater circuitry, problem with the Cathode current tetrode. Replaced
- He Pressure: real quenches. Mainly M1B2. ~ one quench every two weeks
- Crowbar:
  - Real problem on thyratron M2B1. Replaced on wk 42. No problem since
  - False triggers for the other events?

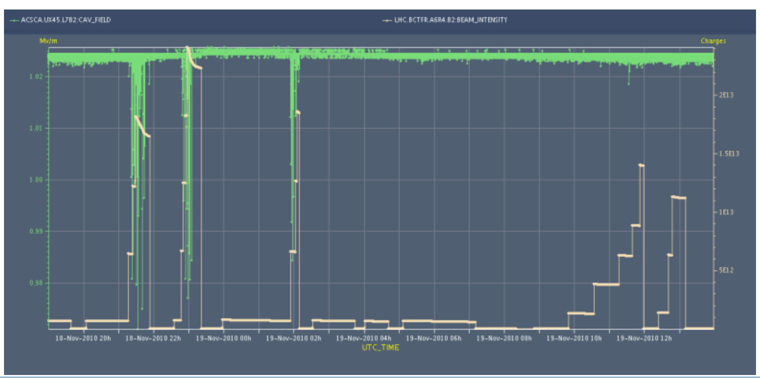




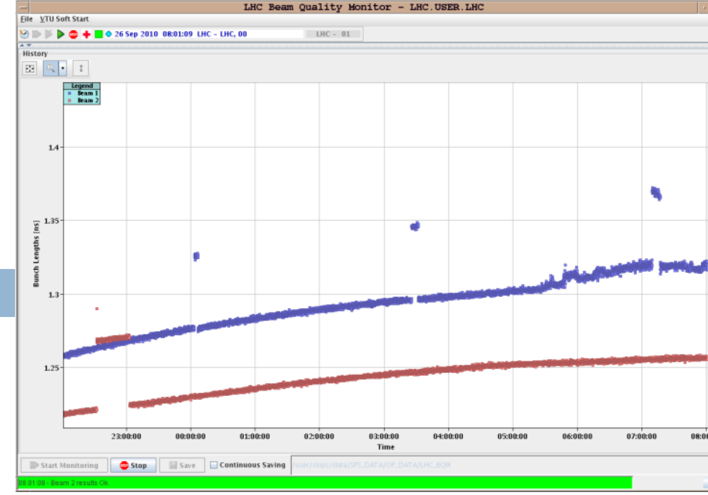
Units	Arc	Kly Vac	Mc Blower	other
1B1	2	0	0	0
2B1	4	1	1	16
3B1	4	0	0	2
4B1	0	0	0	0
5B1	4	0	0	0
6B1	2	0	0	3
7B1	5	0	0	1
8B1	2	0	0	0
1B2	4	0	0	1
2B2	1	12	0	0
3B2	2	0	0	4
4B2	2	0	0	0
5B2	0	0	0	0
6B2	0	0	1	0
7B2	1	0	0	0
8B2	1	0	4	0
Total	34	13	6	27

Cav4B1 and Cav7B2

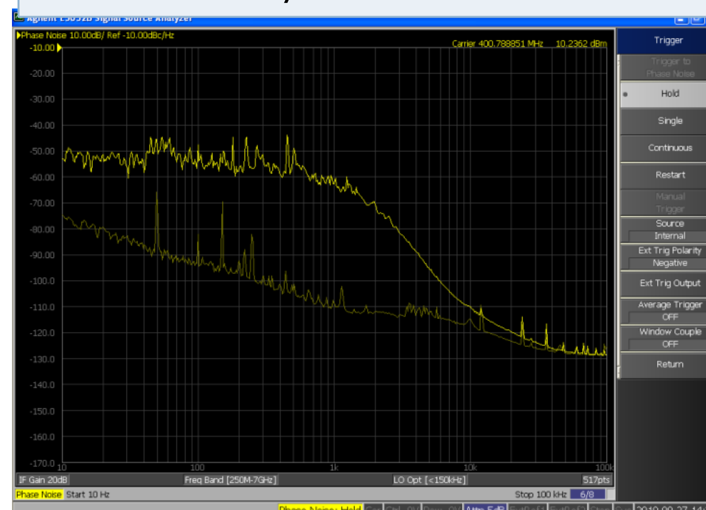
- Cav4B1 started injecting noise towards the end of a physics fill on Sept 26th morning. Noise could be reproduced without beam but never lasted long. It died out as soon as voltage or frequency changed. We have replaced all modules in LLRF. Did not cure the problem. Cav4B1 has not been operational since
- Cav7B2 became noisy at high current levels during the 50 ns run (Nov 18th). No problem at lower current
- These problems are worrying. To be investigated during hardware re-start. We do not know what it is…



Nov 18th. Pushing the current on the flat bottom, 50 ns spacing. Observe Cav7B2 voltage and FastBCT current. Clear correlation between injections and Cavity Field noise



Sept 26th. During physics fill Cav4B1 starts injecting RF noise. Visible on the BQM. No effect on luminosity. But significant effect when we later try to fill…



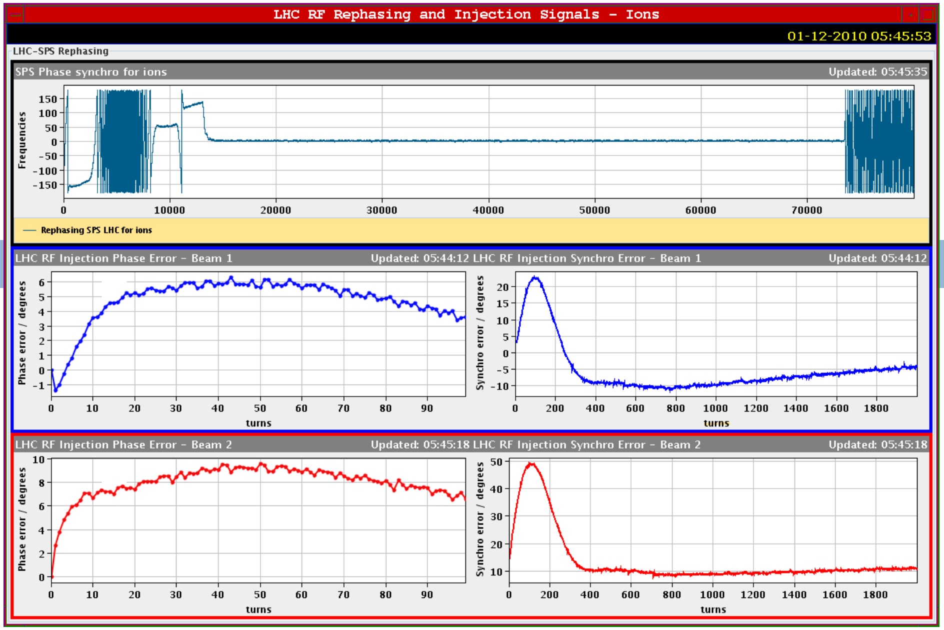
Sept 27th. Investigation of Cav4B1 noise without beam. Up to 40 dB increase in Phase Noise Power Spectral Density around 1 kHz. The noise is intermittent.

Plans for 2011

New features will be developed and deployed through the year…

Do not expect it all in March

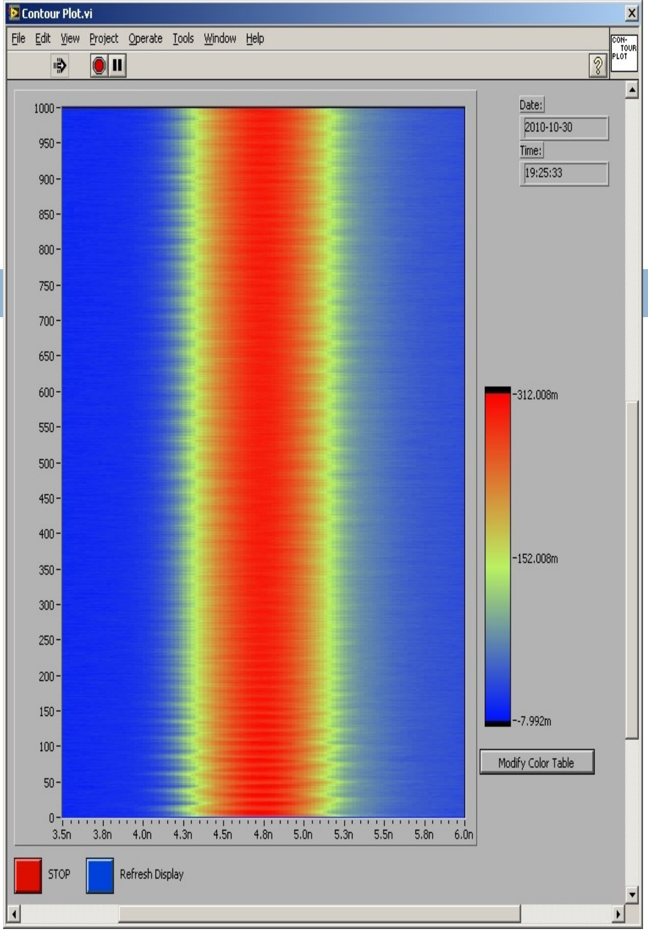
SPS-LHC Phase-Energy matching



- An application will be developed that
  - Acquires the injection transients
  - Fits the measured data to a model of the Beam Control/Beam system (using LSA settings for loop gains/time constants)
  - Derives Injection phase and energy errors (plus stable phase and VCXO errors) and propose trims
  - Interfaces with the IQC
- Reminder: The RF frequency must be kept constant during filling. Centering the circulating (captured beam) and making the frequency error minimum at injection (energy matching) are not equivalent. Often the OP crew does not trim the RF frequency for perfect energy matching because that would displace the closed orbit too much

Longitudinal damper

- The Main Beam Phase loop considers the average over all bunches. For the first injected batch, it will damp any phase or energy error via a proper modulation of the RF frequency
- As more batches are injected, their injection offsets come in competition with the captured beam that tell the Phase Loop to do…nothing…And injection transients are corrected less and less as filling proceeds
- Solution: Damp the injection phase/energy error batch per batch
- This will improve the capture of the later batches but it will only correct for the average injection phase/energy error in each batch. The BW is not sufficient for bunch by bunch damping.



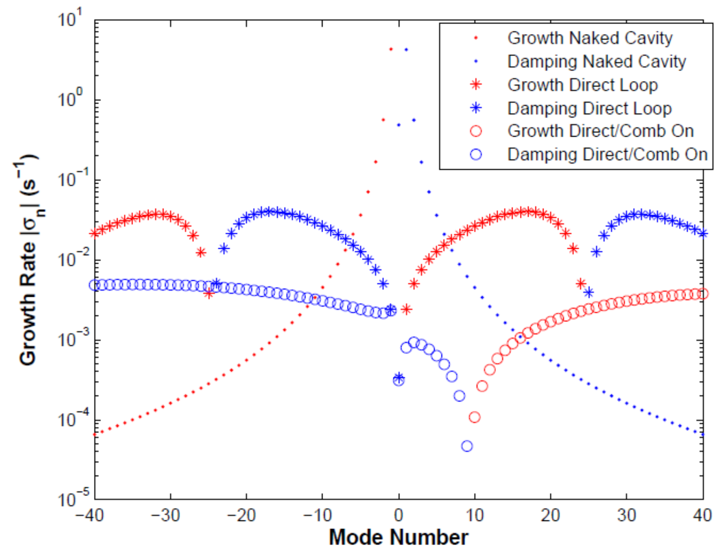
Oct 30, 50 ns spacing, 12 bunches per inj, injection transient 7^{th} bunch 4^{th} batch, 1 ms between traces, dipole oscillation (+- 100 ps, ~45 Hz frequency) lasting for 1 s without noticeable damping

Coupled-bunch instabilities

- The growth rate and tune shift of coupled-bunch mode *l* (dipole only) can be computed from the cavity impedance

$$\sigma_l + j\Delta\omega_l = \frac{\eta\, q\, I_0}{2\,\beta^2\,\omega_s\,E\,T_{rev}} \sum_{p=-\infty}^{\infty} \omega\, Z(\omega)$$

- With $\omega=(p\,h+l)\;\omega_{rev}+\omega_s$. For a cavity at the fundamental, only two terms in the above infinite sum are not negligible: p=1 and p=-1
- The impedance Z(ω) is modified by the LLRF loops. The above equation can be used to analyze different configurations
- Stability is preserved if the growth rate is significantly smaller than the tune spread: $\sigma_l < \frac{\Delta\omega_s}{4}$
- With $$\Delta\omega_s = \omega_s \frac{\pi^2}{16}\left(\frac{h\,L}{2\,\pi\,R}\right)^2$$



3.5 TeV conditions, nominal current. Growth rate of the dipole mode (sum 8 cavities) with RF feedback and 1-T feedback, compared to the cavity without feedback. Simulation using detailed LLRF model, including all loops, klystron non linearity, bunching factor, etc…
US-LARP collaboration. T. Mastoridis, SLAC

3.5 TeV conditions

WARNING: the results below much be compared to a previous analysis (E. Chapochnikova, LHC Project Note 242). Will be done before Chamonix

- We consider 14 MV, half detuning: 3 kHz, 1.2 ns bunch length (4 sigma) and nominal beam current 0.58 A DC
- The synchrotron frequency is 31 Hz. $\Delta\omega_s/4=7\ s^{-1}$
- With RF feedback only, the maximum growth rate is $0.012\ s^{-1}$ ($0.005\ s^{-1}$) per cavity and the max tune shift 0.06 Hz while the tune spread is 4.4 Hz. The corresponding mode number is ~ 15.
- So the 8 cavities will give a total growth rate of $0.1\ s^{-1}$ ($0.04\ s^{-1}$) , that is a good order of magnitude below $\Delta\omega_s/4=7\ s^{-1}$. GOOD!
- However the growth rate is very sensitive to the correct adjustment of the RF feedback Open-Loop phase. If that phase drifts by 10 degrees, the growth rate is multiplied by 10. See next slides.
- If a cavity trips during physics, it sits, without impedance reduction, at the 3 kHz detuning. Its contribution to the growth rate jumps to $1\ s^{-1}$ ($0.675\ s^{-1}$), with 1 Hz tune shift, still OK given $\Delta\omega_s/4=7\ s^{-1}$
- In 2010 we survived a trip of 3 out of 7 cavities during physics at ~ 12% nominal
- **Conclusion:** OK at 3.5 TeV. However when a klystron trips at nominal, the beam induced voltage in the idling cavity will exceed 2 MV -> dump to protect cavity

In blue, estimates from the more detailed model.US-LARP collaboration. T. Mastoridis, SLAC

450 GeV conditions

WARNING: the results below much be compared to a previous analysis (E. Chapochnikova, LHC Project Note 242). Will be done before Chamonix

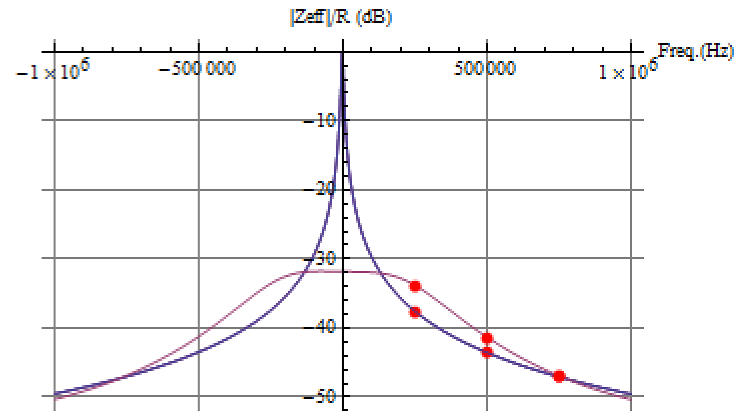
- We consider 4 MV, half detuning: 10 kHz, 1.5 ns bunch length (4 sigma) and nominal beam current 0.58 A DC
- The synchrotron frequency is 46 Hz. The Landau damping $\Delta\omega_s/4=16\ s^{-1}$
- With RF feedback only, the maximum growth rate is $0.2\ s^{-1}$ ($0.19\ s^{-1}$) per cavity and the tune shift 0.3 Hz for a 10 Hz tune spread. The corresponding mode number is ~ 15.
- The large growth rate is due to the large detuning that is not strictly needed with only 4 MV. With 5 kHz detuning, the growth rate drops to $0.1\ s^{-1}$ ($0.135\ s^{-1}$) per cavity
- So the 8 cavities will give a total growth rate of $1.6\ s^{-1}$ ($1.53\ s^{-1}$) or $0.8\ s^{-1}$ ($1.08\ s^{-1}$) (10 kHz or 5 kHz detuning), that is still comfortably below the $16\ s^{-1}$ Landau damping. Notice however that the margin is reduced compared to 3.5 TeV. The 1-T feedback would help at injection. Fine adjustment of OL phase will also help (see later).
- If a cavity trips towards the end of the filling, its contribution to the growth rate jumps to $15\ s^{-1}$ with 2.4 Hz tune shift and we probably loose the beam on mode 1
- **Conclusion:**
  - Cavity trip towards the end of filling is fatal at nominal intensity
  - To keep Landau damping do not reduce SPS bunch length below present 1.5 ns
  - Should we modify the Tuning system (Half-Detuning algorithm) during filling?

Filling with one klystron OFF

- If one klystron or cavity is off, we would detune it maximally (assume 100 kHz detuning) and enter the coupler maximally (Ql=20k)
- In the conditions of the previous slide (4 MV total from the remaining 7 cavities and nominal beam current 0.58 A DC) the growth rate caused by the un-damped cavity would be
  - 20 s^{-1} if its tune happens to be on a revolution frequency side-band
  - 15 s^{-1} (6 s^{-1}) its tune is just in between two revolution frequency side-bands
- **Conclusion:**
  - Recalling that the Landau damping $\Delta\omega_s/4=16$ s^{-1} at injection, operation with one line off will not be possible above ~ half nominal. In agreement with previous studies.
  - To keep Landau damping do not reduce SPS bunch length below 1.5 ns
- Note: In 2010 we have operated comfortably with one line OFF at ~15% nominal

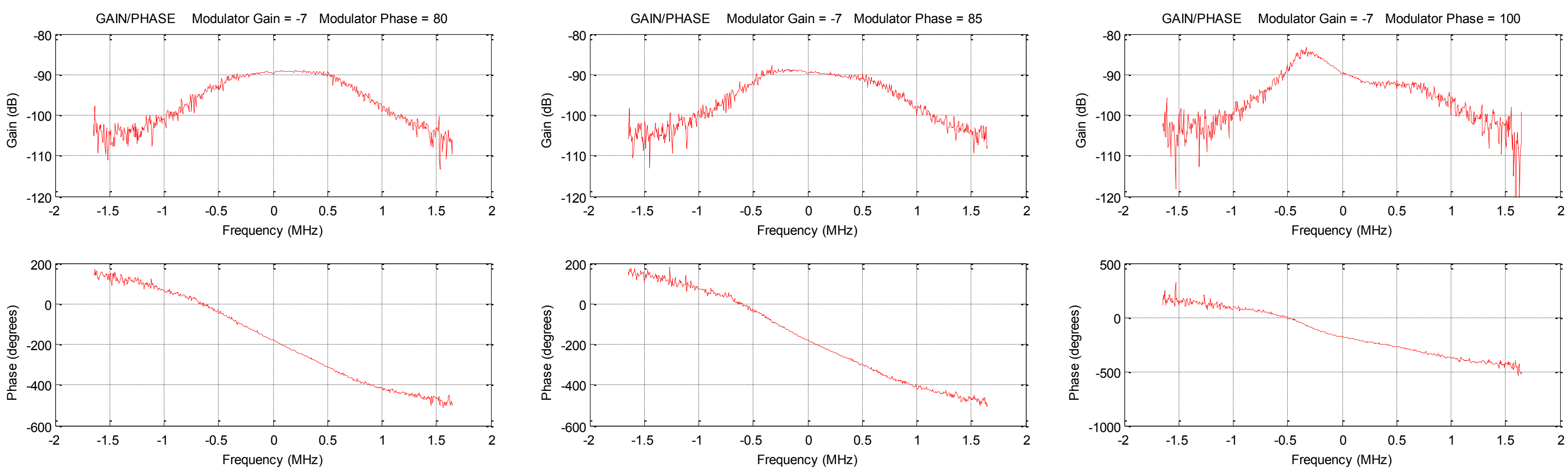
RF feedback

- RF feedback very efficiently reduces the coupled-bunch instability growth rate because
  - It reduces the peak cavity impedance
  - And…it makes the effective impedance symmetric around the cavity centre frequency
- So, there is cancellation between the unstable positive modes and the stabilizing negative modes.
- But…this works only if the feedback OL phase is precisely adjusted. Else the effective impedance becomes asymmetric



Sensitivity to phase misalignment

- Small deviations in the RF feedback OL phase create large asymmetry in the effective impedance. Below Left to right: perfect adjustment, 5 degrees offset, 20 degrees offset
- Such offsets can come from klystron saturation or detuning
- Ideas:
  - work with moderate detuning
  - and align RF feedback continuously with beam (see later)



LLRF alignment with beam

- Idea: periodically inject noise into the cavity, measure closed-loop response and optimize LLRF parameters accordingly
- Used in PEPII during physics
- Originally not foreseen for the LHC as hadrons were reputed very sensitive to RF noise…
- …however, measurements on Beam diffusion caused by RF noise have shown that the LHC beam is very tolerant to noise outside the synchrotron frequency sidebands
- The intent is to measured Closed-Loop response, in physics, with a noise spectrum having notches on the revolution frequency sidebands of the RF
- To be investigated further… more in Chamonix

RF measurements

- BQM upgrade
  - 8 Gs/s, all bunches, but only one turn analyzed every 4 seconds
  - Upgrade to make several acquisitions over successive turns. This will
    - Improve the quality of the estimates (less noise). That would also help the longitudinal blow-up that uses the BQM length measurements as input
    - Make stability analysis possible: measure dipole oscillations (variation of the centre of charge position) and quadrupole oscillations (variations of the bunch length). Important to diagnose longitudinal Coupled-Bunch instabilities
- Mountain Range
  - Present application is not really user-friendly
  - Adjustments of gains and triggers should be set from the machine intensity/bucket number
- Wide-Band PU Peak detected signal

RF measurements

- Logging/analysis of bunch by bunch phase
  - Measurement available bunch per bunch, turn per turn in the Beam Phase Module but the on-board memory can store only 15 turns
  - Fast serial transmission to a CPU
  - FFT and estimation of growth rates
  - Fixed display in CCC for monitoring. Help from OP welcome for the GUI application
  - Will diagnose dipole modes only
- Monitoring of the cavity noise
  - Acquisition of the second antenna signal from all cavities, demodulation with a system completely independent from the LLRF, extract amplitude/phase for each cavity, compute FFT
  - Fixed display in CCC for monitoring. Help from OP welcome for the GUI application.

Klystron operation in 2011

- DC parameters have been reduced to 50 kV/8A to protect the collectors. The saturated RF power is ~ 200 kW
- We want to operate between 100 kW and 150 kW because
  - Below 100 kW RF, we dissipate more than 300 kW in the collector. Not good for hardware lifetime
  - Above 150 kW RF the klystron gain drops as we get closer to saturation. That makes the LLRF loops less efficient
- During physics, with 1.75 MV/cavity (14 MV total), Q=60k, we need 140 kW. OK
- At injection, with 0.5 MV/cavity (4 MV total), Q=20k, we need only 35 kW. NOT OK
- Plan 2011
  - Work with reduced DC parameters 46 kV/7.6A or somewhat below during filling. Actual needed power will depend on the longitudinal damper's needs
  - Change to 50 kV/8A before ramp
  - Ramp/physics with 50 kV/8 A
  - The variation of DC parameters with circulating beam has been tested on Oct 27th

Thank you for your attention…