LHC RF 2011 and beyond…

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LHC Performance workshop 2011, Evian

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Outline

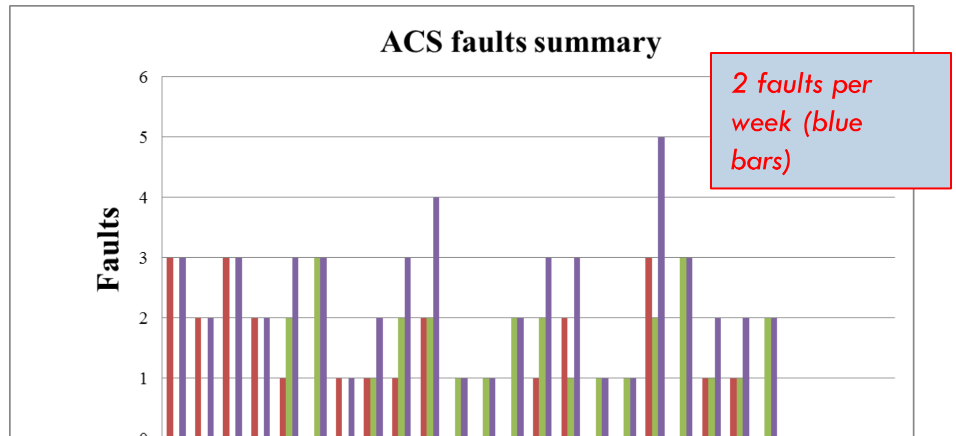
- RF performances 2011
  - Power and cavity
  - Debunching incidents
- New features 2011 vs. 2010
  - New RF features
  - Surviving a klystron trip
  - Longitudinal blow-up, beam spectrum and average bunch profile optimization
- The (near) future
  - 4 TeV
  - 25 ns
- Conclusions

Note: This version differs from the one shown in the workshop. The time domain bunch profile have been corrected on slides 15 and 17

RF performances 2011

Proton operation weeks 20 - 44

- 52 faults total, of which
  - 9 Arc Detector. None after modification of the hardware on week 25
  - 12 HOM. All on M1B2 (6 on 2B2, 6 on 4B2). This module has a problem (3B2 cannot be operated at more than 1.2 MV stable)
  - 7 Klystron Heater of which 4 on 2B1
- 11 of the 52 faults have triggered a crowbar (grounding of the HV to protect the klystrons)
- Zero fault on M2B2. A good one!



	20	21	22	23	24	25	26	28	29	30	31	32	33	34	36	37	38	39	40	41	42	44				
RF-Faults/wk	3	2	3	2	1	0	1	1	1	2	0	0	0	1	2	0	0	3	0	1	1	0	0	0	0	0
HV-Faults/wk	0	0	0	0	2	3	0	1	2	2	1	1	2	2	1	1	1	2	3	1	1	2	0	0	0	0
Tot-Faults/wk	3	2	3	2	3	3	1	2	3	4	1	1	2	3	3	1	1	5	3	2	2	2	0	0	0	0

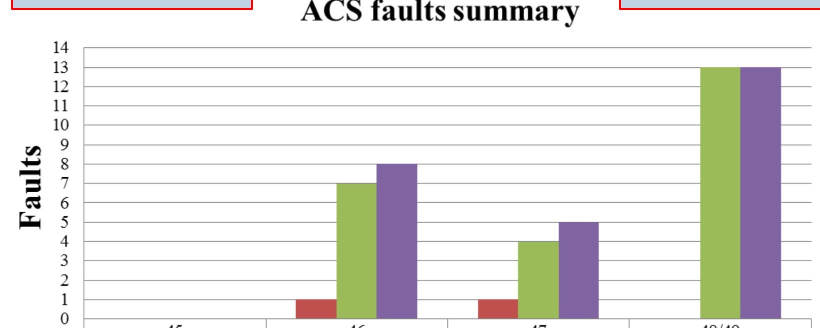
Analyzed by D. Glenat and D. Landre

Ions operation weeks 45 - 49

- 26 faults total, of which
  - 1 HOM on 4B2. Again M1B2
  - 11 Klystron Heater of which 8 on 7B1and 3 on 2B1. The equipment was recuperated from LEP. An upgrade is under study. Also the HV connectors (immerged in an oil bath) have shown traces of oil inside. Modifications are studied.
  - 4 PLC CPU faults (intlk system)
- 7 of the 26 faults have triggered a crowbar
- Again zero fault on M2B2

6.5 faults per week (blue bars)

A very bad finish: 13 faults in wk 48/49



	45	46	47	48/49
RF-Faults/wk	0	1	1	0
HV-Faults/wk	0	7	4	13
Tot-Faults/wk	0	8	5	13

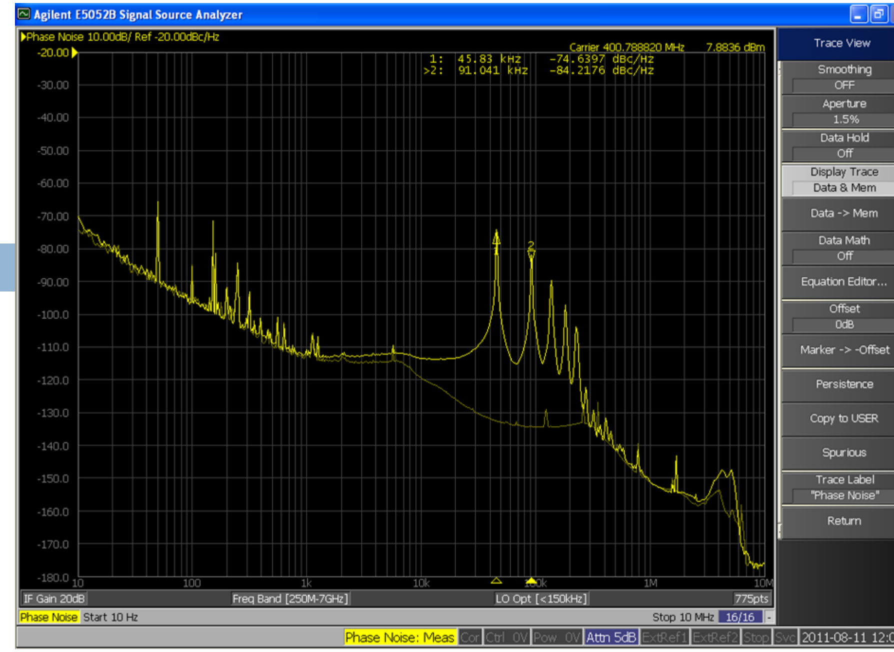
Analyzed by D. Glenat and D. Landre

Physics fills terminated by an RF fault

- From July 14th (RF intlk chain modified) till Dec 7th , the LHC had 142 Physics fills
- Of which 16 were dumped by the RF
  - 3 on *Klystron Filament Current* interlock
  - 2 on *Loss of Cryo Conditions*
  - 1 on *Klystron Power Supply* fault
  - 3 on *HOM Temperature too high*
  - 1 on *Controls Communication lost*
  - 1 on *Klystron Vacuum*
  - 1 on *Ion pump trip (vacuum)*
  - *4 not documented sufficiently* to be identified

Debunching incidents

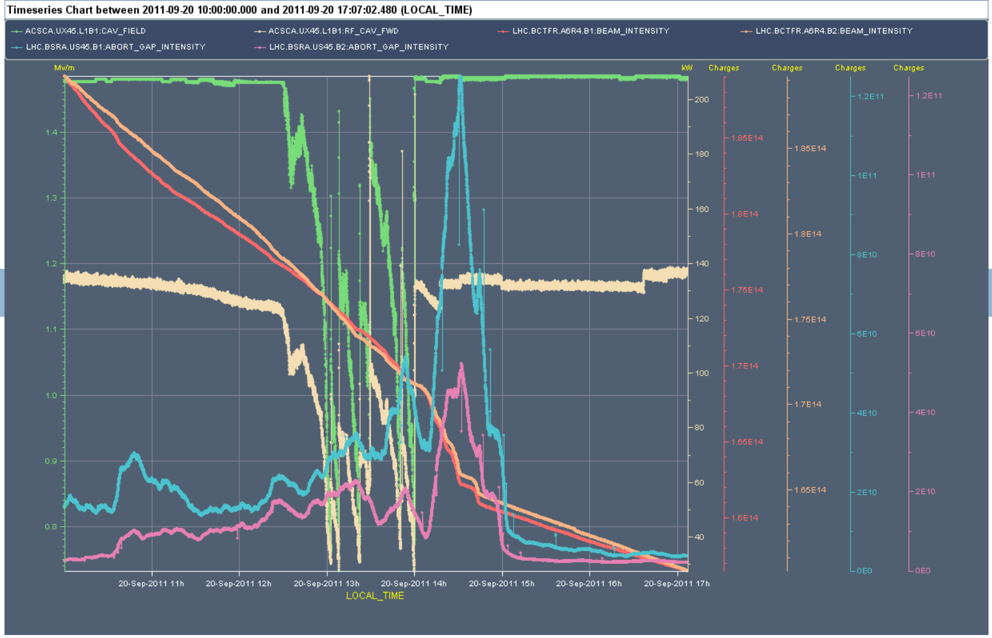
Aug 11th, Cav1B1, phase noise Power Spectral Density (PSD) showing spikes at 45 kHz and harmonics. These can go unnoticed by the beam if they are far from a revolution frequency harmonic



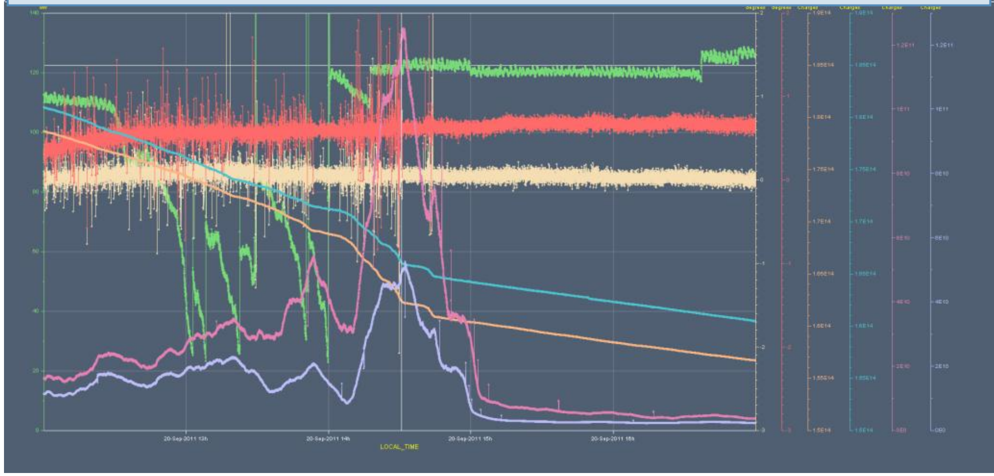
- Debunching during physics has been observed in a few occasions
  - Aug 11th. 4B1 and 4B2. The problem is traced to an overflow in the Cordic of the phase part of the klystron polar loop. Firmware corrected
  - Sept 20th. Large oscillation on Cav1B1voltage. Traced to a wrong phasing of the FPGA clocks following the replacement of the modulator card on Sept 19th (see next slide)
  - Oct 4th. Noise on Cav1B1, traced to a loose SMC connector on the modulator card
  - Nov 20th. Ions. 5E9 abort gap population in both rings. Traced to a wrong phasing of the FPGA clocks in the Synchro module, following the modification of the firmware
  - Nov 26th. Ions. An overnight attempt to work with only 6 out of eight klystrons in B1 drove the remaining klystrons in saturation (190 kW)

Worst debunching event, Sept 20th

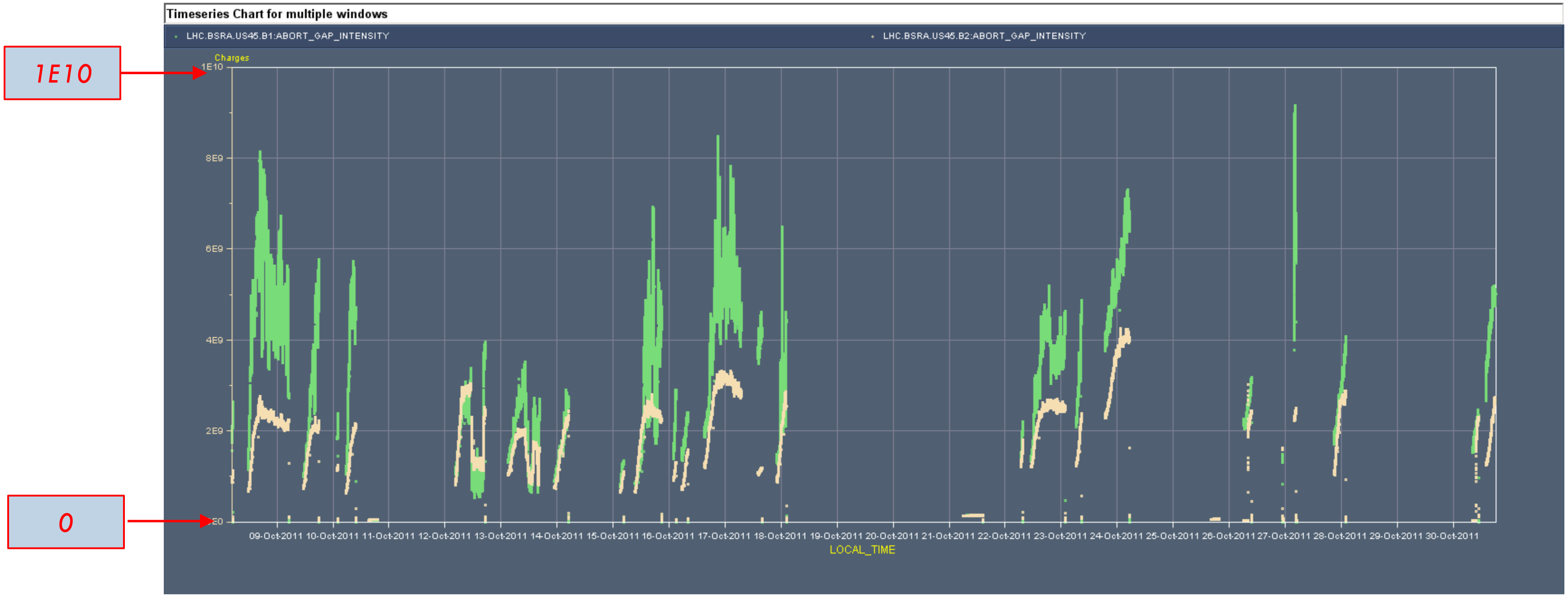
- Following the replacement of the RF modulator card on Cav1B1, Sept 19th, the phasing of the FPGA clocks was not re-calibrated
- On the next fill (Sept 20th) the klystron polar loop became unstable resulting in large effects on the cavity voltage (dropped from 1.5 MV to below 1 MV), activity on phase loop, detuning of the cavity, but barely any effect on the lifetime as the noise frequency was outside the Beam response
- When we tried to cure it around 14:00, we restored the cavity field/tune but moved the noise spectrum close to the beam response, resulting in large debunching ~1.2E11 p in abort gap corresponding to ~ 3.6E12 unbunched beam
- The losses were stopped after opening the offending LLRF loop
- Although there is no hardware coupling between the 2 rings, a similar effect was observed on B2



Top: Cav1B1 field (green), CavFwd (beige), BCT and abort gap population (both rings)
Bottom: The noise in Cav1B1 results in shaking both beams (PhaseError B1 in beige, B2 in red)



Normal debunching during physics



- All p physics fills (stable beams) from Oct 8th till Nov 1st
- Observe Abort Gap population during stable beam. B1 in green, B2 in beige.
- The maximum over the ~ four weeks period (30 stable beams)is 9E9 (B1) and 4E9 (B2)
- As the power radiated in synchrotron light scales as γ^4, expect improvement with increased energy (natural cleaning will be faster)

New features 2011 vs. 2010

New RF features

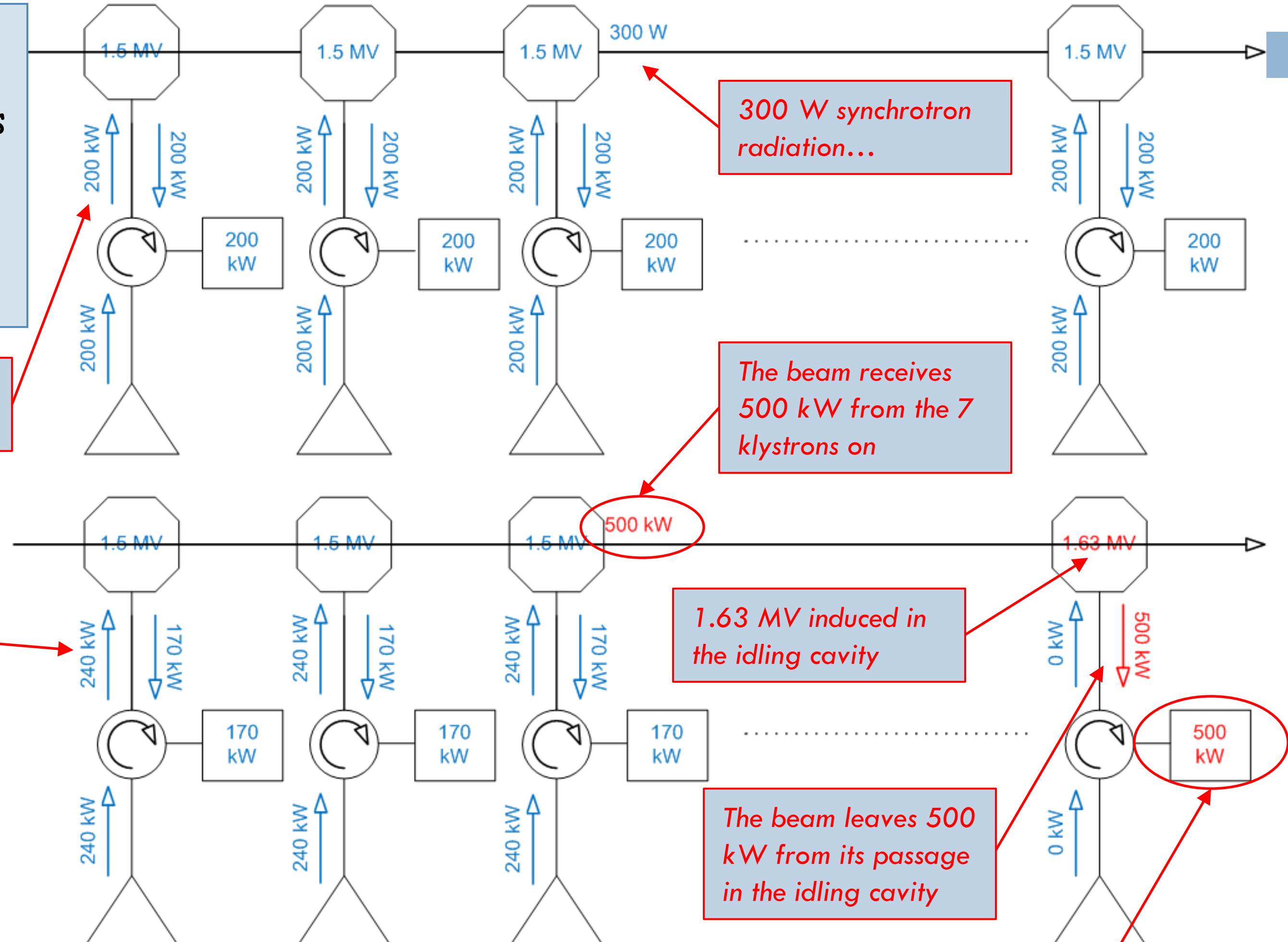
- The capture voltage was increased from 3.5 MV to 6 MV. Together with Injection Gap Cleaning, that reduced capture losses. (The 0.6 eVs bunch is now injected in a 1.2 eVs bucket, compared to 0.9 eVs in 2010). We measure 0.5 % loss from injection to 3.5 TeV
- The voltage in physics was increased from 8 MV to 12 MV to provide a larger longitudinal emittance (at constant bunch length), thereby reducing the transverse emittance growth due to IBS
- The longitudinal emittance blow-up was adjusted to keep the bunch length around 1.2 ns (later increased to 1.25 ns) during the 11 min long ramp
- At the beginning of the 3.5 TeV flat top we have 1.9 eVs longitudinal emittance in a 4.7 eVs bucket (1.5 eVs in 3.8 eVs bucket in 2010)
- The One Turn Feedback was commissioned on all cavities. It reduces the transient beam loading to less than 0.5 degree pk-pk @ 400 MHz with 2100 bunches, 1E11 p/bunch (Chamonix 2012)

Surviving a klystron trip

- When a klystron trips
  - The beam induced voltage in the idling cavity may lead to a quench (if it exceeds the 2 MV conditioning level)
  - The reverse power extracted from the beam, and dissipated in the load may exceed its rating (rated 300 kW CW)
- Some beam escapes from the bucket as it gets reduced by 1/8 in voltage (1/16th in bucket area). Not a concern.
- The maximum load power set the first limit: When we exceeded 1100 bunches, mid-June 2011, we linked the klystron surveillance to the beam dump system
- **From then on, the trip of a single klystron would dump both beams**

Klystron trip with nominal

2808 bunches, 1.1E11 p/bunch, 1.2 ns 4-sigma length, 3.5 TeV conditions (1.5 MV/cavity, Q=60k).
Top: All klystrons on
Bottom: one klystron off
Static conditions.



200 kW, fully reflected

300 W synchrotron radiation…

The beam receives 500 kW from the 7 klystrons on

240 kW, of which 70 kW are passed to the beam

1.63 MV induced in the idling cavity

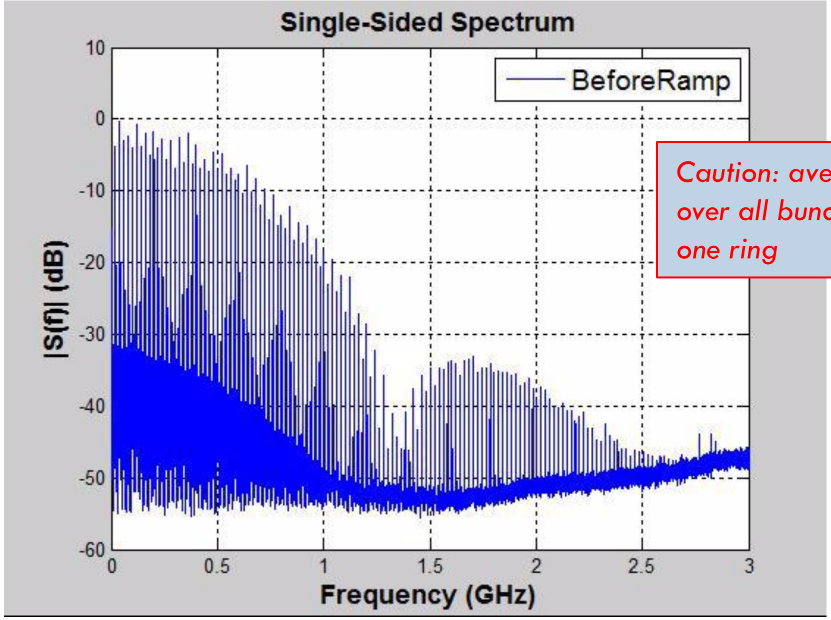
The beam leaves 500 kW from its passage in the idling cavity

500 kW dissipated in the load. ***Destruction…***

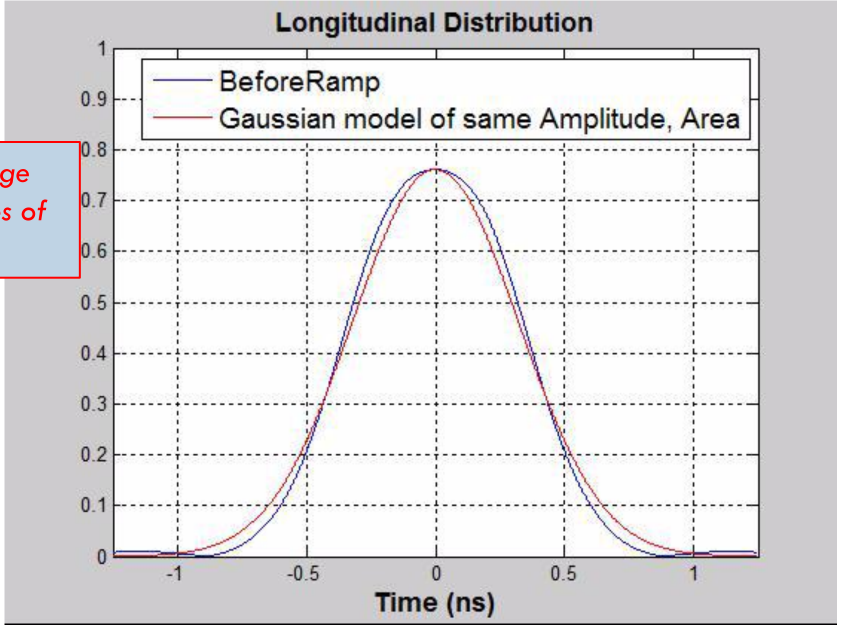
Longitudinal blow-up, beam spectrum and average bunch profile

Longitudinal beam distribution (protons)

- Beam Spectra were measured during the ramp
  - High frequency components from injection (SPS blowup?) get amplified during ramp (longitudinal emittance blowup)
  - In the time domain we see the "distortion" due to the blowup at ±600 ns, where the blowup is strongest.

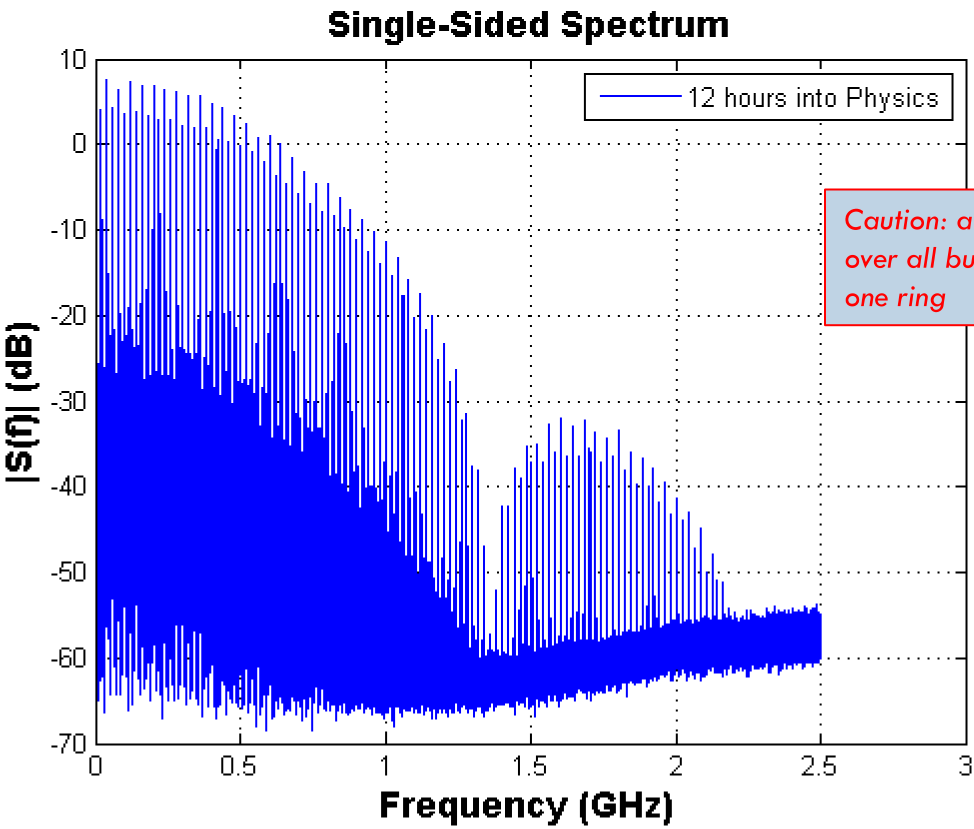


Caution: average over all bunches of one ring



Longitudinal beam distribution (protons)

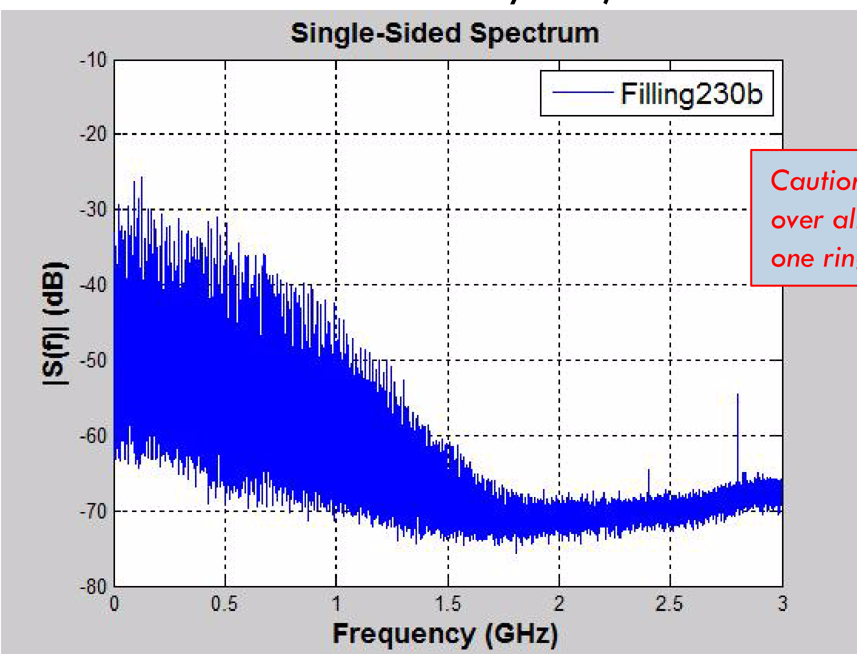
- The beam spectrum is almost unchanged even 12 hours into physics



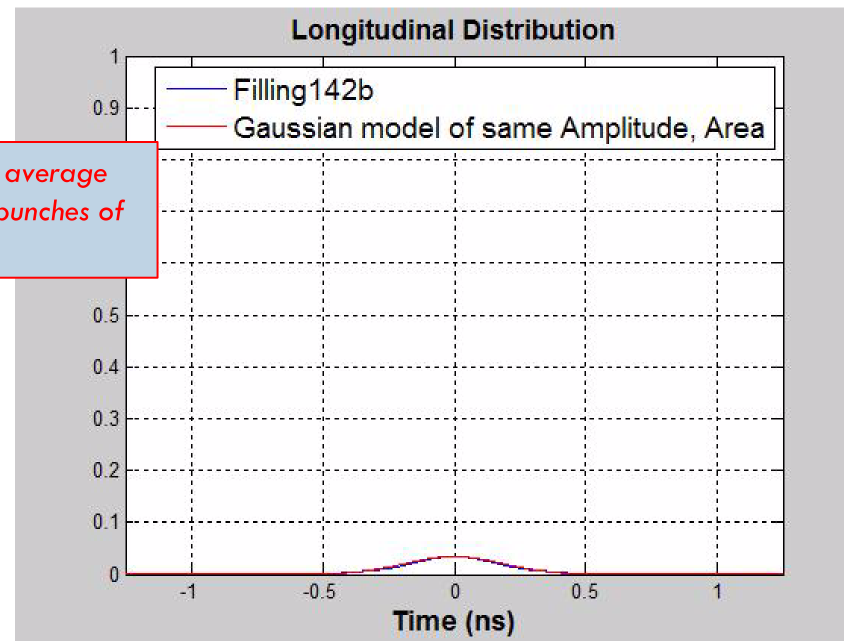
Caution: average over all bunches of one ring

Longitudinal beam distribution (ions)

- Beam Spectra were measured during a fill
  - No High frequency components at injection (blowup in the SPS but strong IBS plus RF noise responsible for the shape?), but they appear during the blow-up in the ramp
  - The beam spectrum is almost gaussian after 2-3 hours at flat top (strong diffusion caused by IBS)



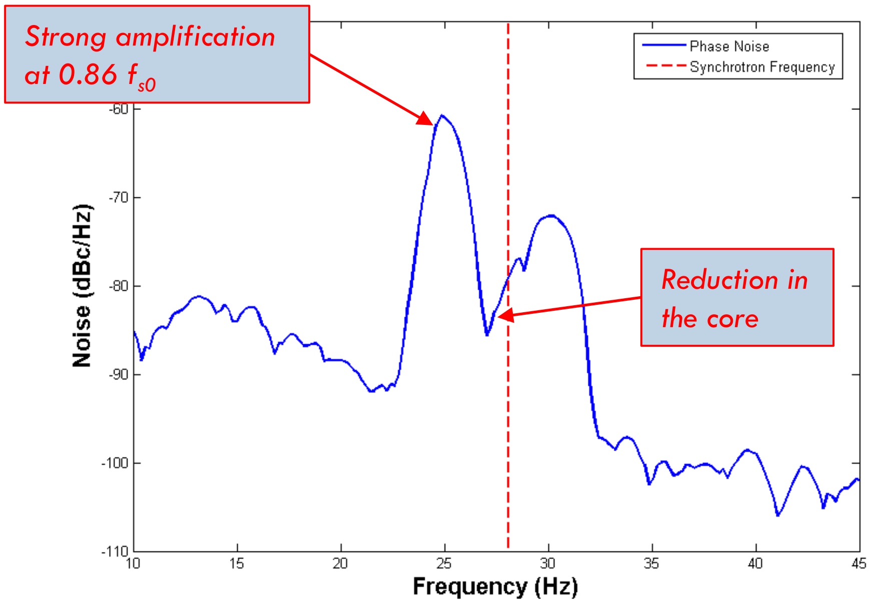
Caution: average over all bunches of one ring

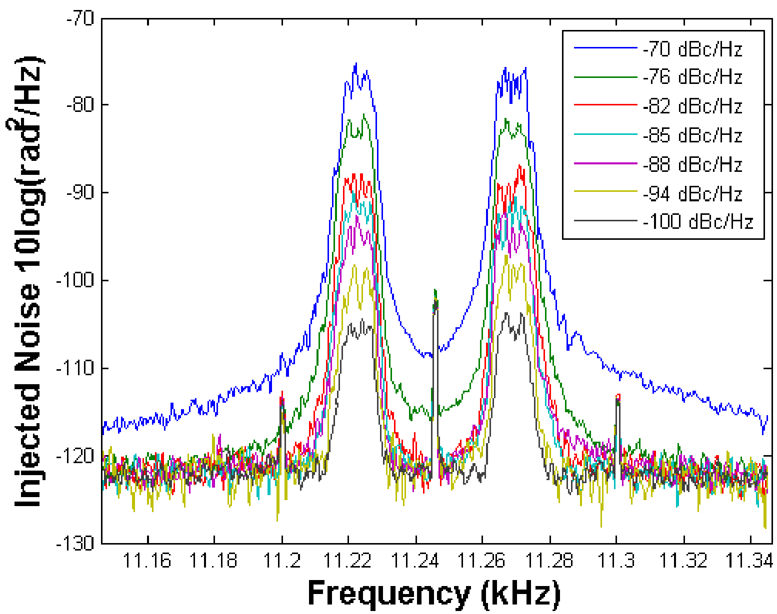


New Emittance Blowup

Emittance blowup comparison

- We are trying to inject a flat noise spectrum around ranging from 0.86 f_{s0} to 1.1 f_{s0}
  - Left: Old blowup through beam phase loop. Noise is shaped by the loop action
  - Right: New blowup through the setpoint on first harmonic. Achieve flat spectrum at $f_{rev} \pm f_s$

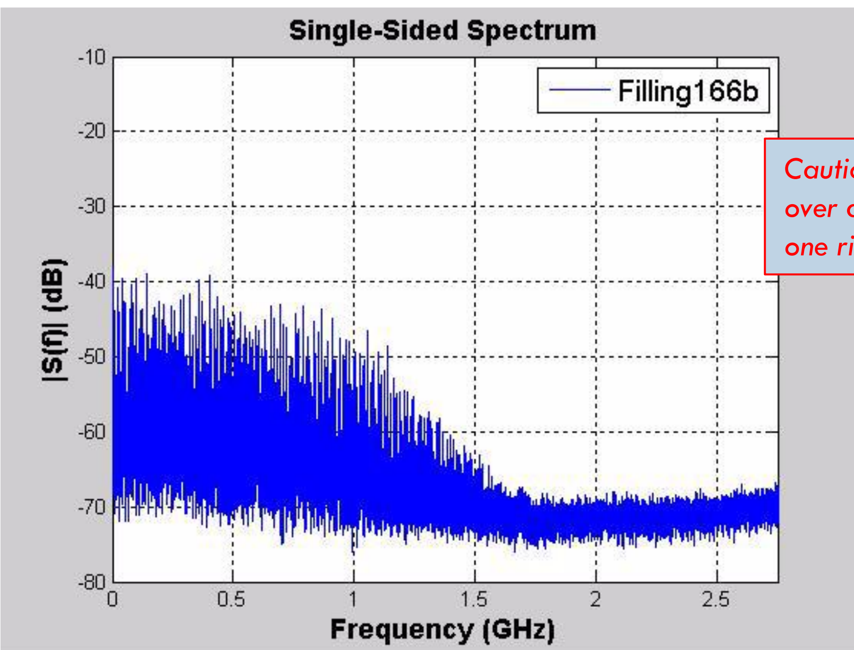




Phase noise PSD measured in the RF sum of the 8 cavities during blow-up. f_{s0}=28.5 Hz

New blowup results

- After some technical difficulties, we managed to blowup the (ion) bunches at flat top with the new blowup.
  - Much smoother. Small components at high frequencies. No visual deviation from gaussian.



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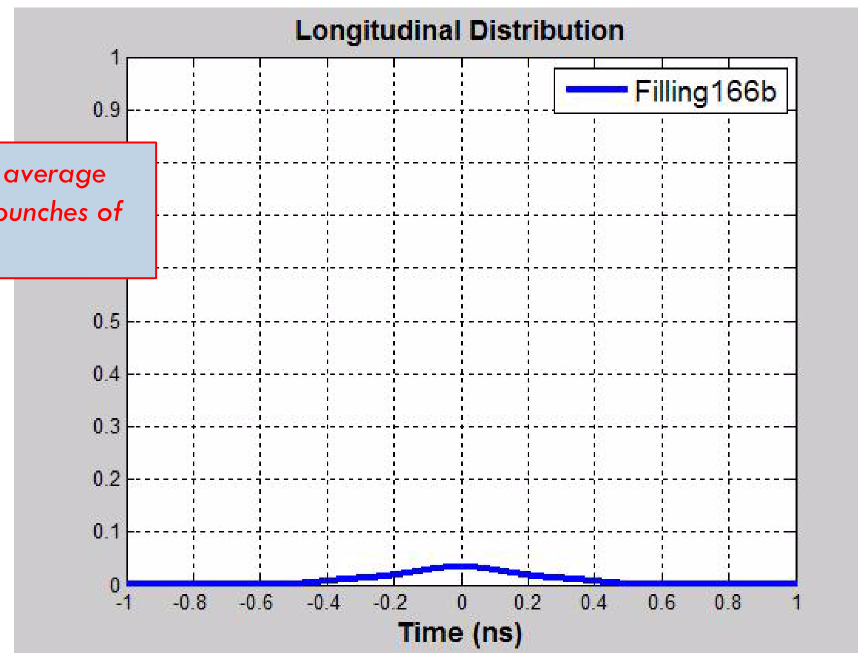


The near future

4 TeV and higher energy

Presented by R. Alemany in Session 8, Dec 14th, Implications of higher energy

Longitudinal stability

Presented by R. Alemany in Session 8, Dec 14th, Implications of higher energy

- Broadband stability criteria

$$\frac{|\mathrm{Im} Z|}{n} < \frac{|\eta| E}{e I_b \beta^2} \left(\frac{\Delta E}{E} \right)^2 \frac{\Delta \Omega_s}{\Omega_s} f_0 \tau \propto \frac{\varepsilon^{5/2}}{E^{5/4} V^{1/4} I_b} \propto \frac{\tau^5 V}{I_b}$$

- Narrow-band stability criteria

$$R < \frac{|\eta| E}{e I_{DC} \beta^2} \left(\frac{\Delta E}{E} \right)^2 \frac{\Delta \Omega_s}{\Omega_s} \frac{F}{f_0 \tau} G[f_r \tau] \propto \frac{\varepsilon^{3/2} V^{1/4}}{E^{3/4} I_{DC}} \propto \frac{\tau^3 V}{I_{DC}}$$

- Without blow-up the threshold quickly decreases during the acceleration ramp
- With a blow-up that keeps bunch length constant, the threshold increases linearly with the RF voltage

See: E. Shaposhnikova, Longitudinal Beam Parameters during acceleration in the LHC, LHC Project Note 242, Dec 2000

4 TeV and beyond…

Presented by R. Alemany in Session 8, Dec 14th, Implications of higher energy

- Thanks to the longitudinal blow-up, the stability is actually improved during the acceleration ramp as the voltage rises
- At constant bunch length and voltage, it is independent of energy

The near future

25 ns and higher intensity

Longitudinal stability

- Broadband stability criteria: We have circulated single-bunch of 2.5E11 p during MDs in 2011, at 450 GeV. At constant bunch length, stability is independent of energy and improves with increasing voltage . So we do not anticipate problems

  MD LHC-MD-REQUEST-RF-2012-RFimp

- Narrow-band stability criteria: We have circulated 2100 bunches, 25 ns spacing, 1E11 p/bunch, at 450 GeV.
  - The impedance of the cavities at the fundamental should not be a problem up to ultimate (2808 b, 1.7E11 p/bunch). We however wish to check our calculations with experiments

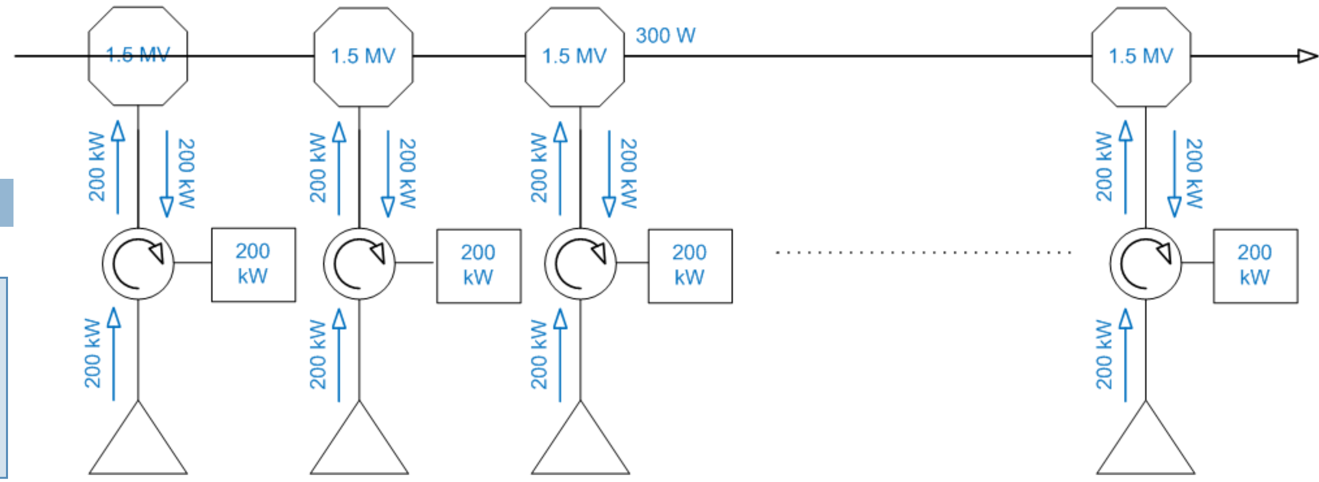
    MD RFStabBatch_2012

  - We may discover an offending narrow-band impedance. MD time requested

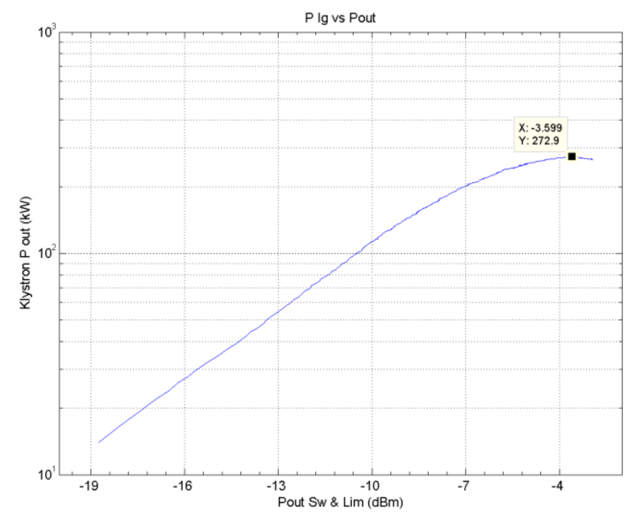
    MD LHC-MD-REQUEST-RF-2012-RFimp

Klystron power

2808 bunches, 1.1E11 p/bunch, 1.2 ns 4-sigma length, 3.5 TeV conditions (1.5 MV/cavity, Q=60k).



- We need 200 kW CW for operation with 25 ns, nominal, at 3.5 TeV (at injection 110 kW OK)
- We would change the klystron DC settings before starting the ramp
- This was tested on Oct 6th, with 12b + 24b + 24b
- Do we have enough margin for the transients? To be tested with 144b, 25 ns spacing ASAP



Saturation curve of Kly8B1 with 57.3 kV/8.7A. Saturation at 270 kW

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Conclusions

2011 and beyond (1/2)

- Except for the last two weeks, the RF has performed very reliably in 2011.
  - We have a problem with Cav3B2. Field emission in this cavity is believed to cause the HOM problems in the adjacent 2B2 and 4B2. Module 1B2 will be replaced during LS1
  - We have no problem with the rest of the critical RF equipment (cavities, klystrons, main couplers, tuners, cryo modules, etc…)
  - We have an identified problem with the klystron heaters. An upgrade is under study
- The debunching during physics is moderate. The abort gap population is equivalent to a fat pilot. It will be reduced with increased energy. The few incidents are understood.
- With the increased capture voltage, the Injection Gap Cleaning, and the shieldings, filling has been much easier in 2011. Injection losses will come back with 25 ns operation as the SPS parameters are less stable through the batch. We will commission the longitudinal damper in 2012

2011 and beyond (2/2)

- The longitudinal blow-up is a tool essential to the LHC operation. With it, stability actually improves with energy. We are investigating more gentle technics that would reduce the HF part of the beam spectrum and make it even more versatile, allowing its use at constant energy (batch per batch blow-up at injection for example to reduce IBS effects during filling - smaller longitudinal emittance is expected from the SPS with low γ_t optic)
- For 25 ns operation, the present RF system can (likely) do with nominal intensity. Going beyond will require work on the LLRF (modulation of the phase set point, review of the tuning algorithm), and careful studies of the effects of a trip on the major RF components (induced cavity voltage, main coupler power, arcing in circulator and waveguide, maximal field in the load,…). We must survive 3 turns before the beam is actually dumped… It is important to start before LS. (more in Chamonix 2012)
- MD time is needed to fulfill all the above promises….

thank you very much for your attention!