RUNNING THE RF AT HIGHER BEAM ENERGY AND INTENSITY

Many thanks to T. Bohl, R. Calaga, W. Hofle, E. Shaposhnikova and J. Tuckmantel

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LHC workshop 2012, Chamonix

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Outline

- New features 2011 vs. 2010
  - New RF parameters
  - New hardware: One turn feedback
- The issue of bunch length
- Longitudinal blow-up, beam spectrum and average bunch profile
- Longitudinal damper in 2012
- 4 TeV and beyond
- The near future
  - Higher intensity
  - 25 ns operation
- Conclusions

RF performances 2011

See RF talk in Evian 2011

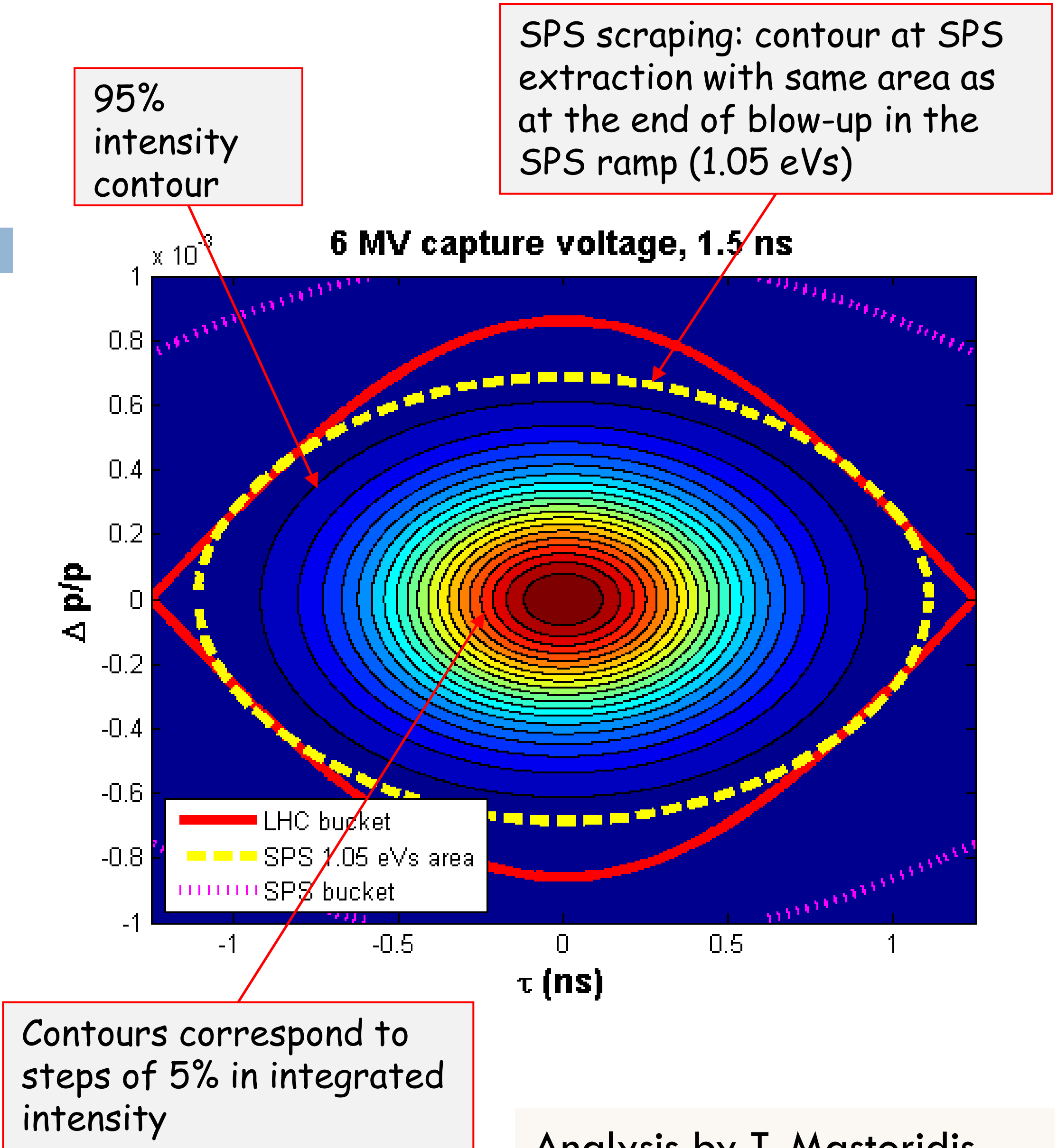
http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=155520

New features 2011 vs. 2010

Capture with 6 MV

- SPS bunch
  - 1.5 ns bunch length ($4\sigma_t$)
  - 4.5 10^{-4} momentum spread $\Delta p/p$ ($2\sigma_p$)
  - $4\pi\ \sigma_E\sigma_t$ emittance 0.48 eVs (~ 0.5 eVs as quoted by the SPS)
  - 95 % population within the $6\pi\ \sigma_E\sigma_t$ contour 0.72 eVs (Gaussian approximation)
- LHC bucket
  - 1.23 eVs bucket area
  - 8.6 10^{-4} bucket half height

Losses:
1.14 % if the bunch distribution is Gaussian with infinite tails
0.02 % if the distribution is a Gaussian truncated by the 1.05 eVs contour



Analysis by T. Mastoridis

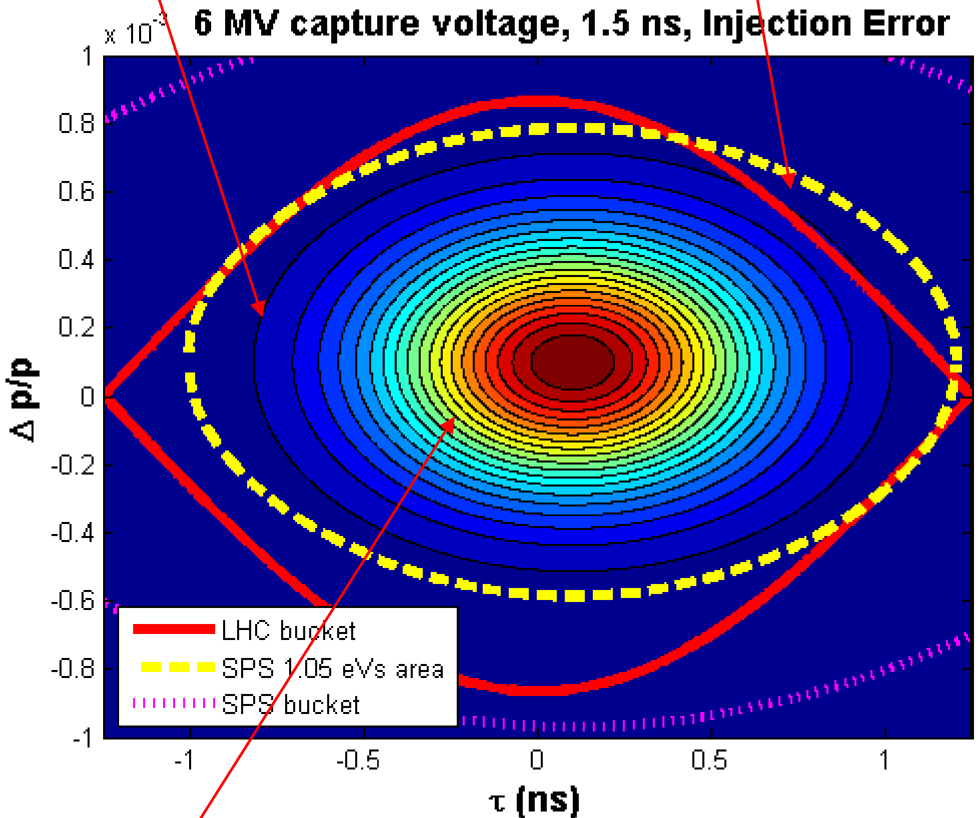
100 ps and 10^{-4} Δp/p injection errors

Losses:
1.69 % if the bunch distribution is Gaussian with infinite tails
0.4 % if the distribution is a Gaussian truncated by the 1.05 eVs contour

- In 2011 we have observed 0.5 % loss from injection to start ramp
- Abort gap and injection gap cleaning helped
- The situation should degrade with 25 ns: Transient beam loading and marginal stability in the SPS will lead to spread in b-to-b phase and length

95% intensity contour

SPS scraping: contour at SPS extraction with same area as at the end of blow-up in the SPS ramp (1.05 eVs)



Contours correspond to steps of 5% in integrated intensity

Analysis by T. Mastoridis

Note: Blow up during filling

- A consequence of the voltage mismatch (matched voltage is 2.5 MV) is the bunch length reduction after capture (from 1.5 ns to 1.1 ns)
- We could take advantage of the large available bucket to blow up the longitudinal emittance. With 1.5 ns and 6 MV, we get 0.83 eVs ($4\pi\ \sigma_E\sigma_t$) emittance
- We could increase it further if capturing with 8 MV as for Pb, leading to 0.97 eVs
- More on batch per batch blow up in following slides

Other changes

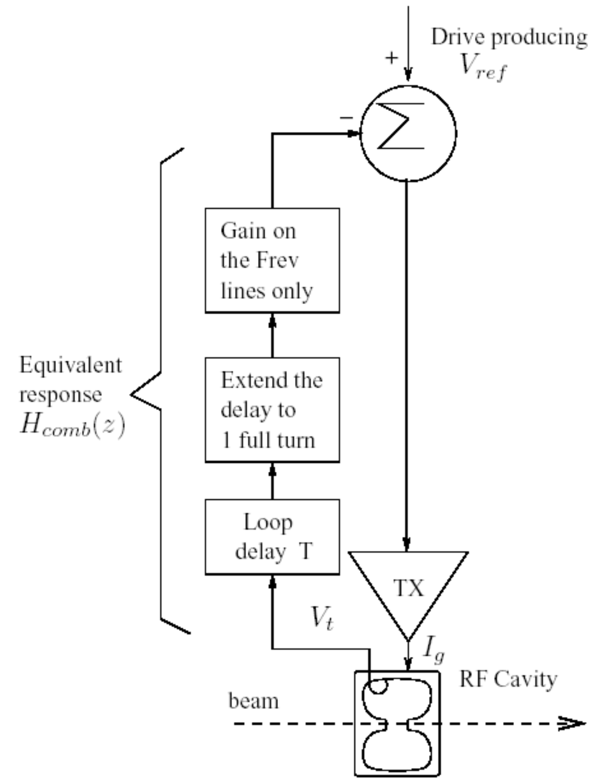
- The voltage in physics was increased from 8 MV to 12 MV to provide a larger longitudinal emittance, thereby reducing the transverse emittance growth due to IBS
- The longitudinal emittance blow-up was adjusted to keep the bunch length around 1.2 ns (later increased to 1.25 ns) during the 11 min long ramp
- At the beginning of the 3.5 TeV flat top we have 2 eVs longitudinal emittance in a 4.7 eVs bucket.

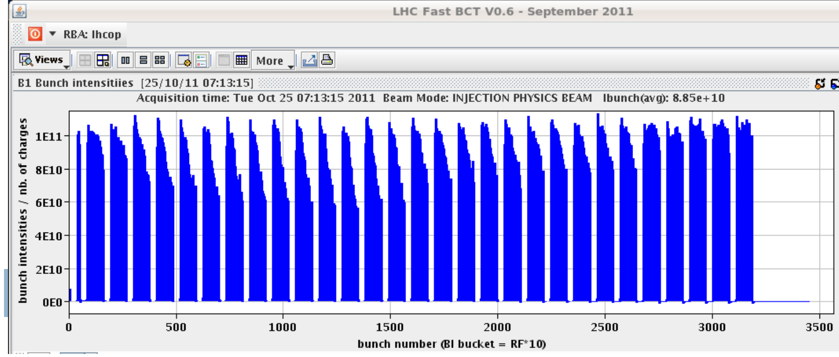
New hardware in 2011

The one-turn feedback (OTFB)

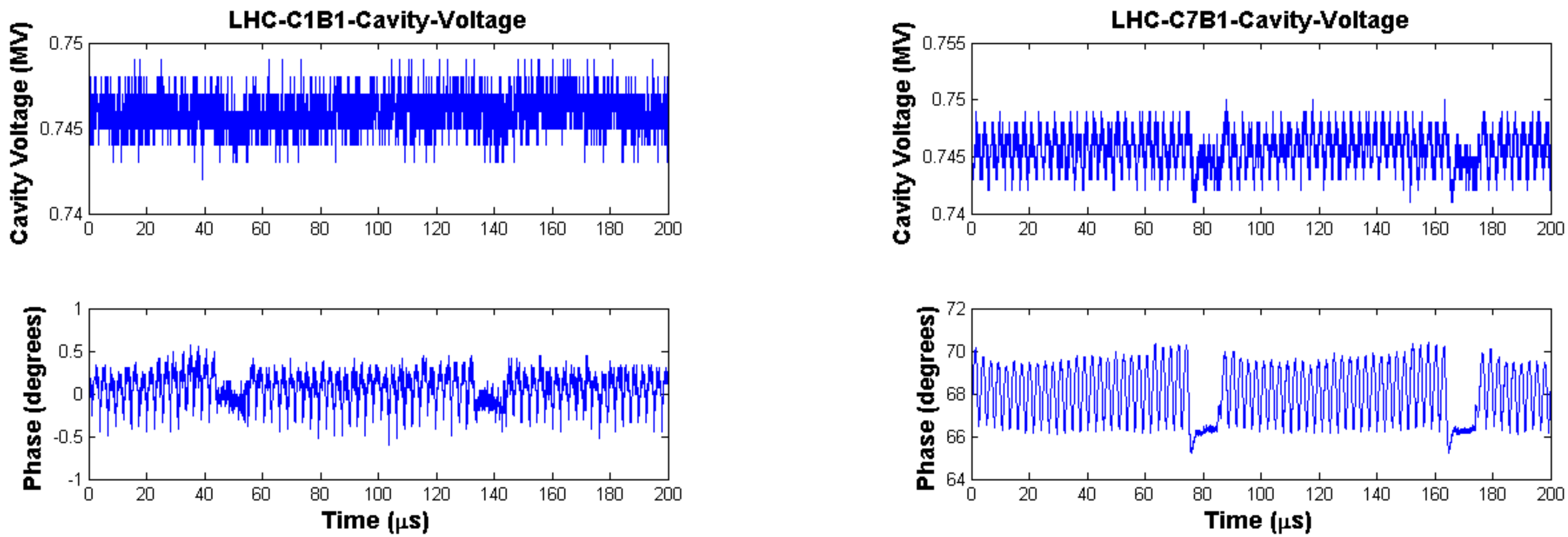
OTFB

- It compensates for the transient beam loading caused by the various gaps in the beam
- It reduces the effective cavity impedance on the revolution frequency sidebands of the fundamental RF, thereby improving stability (longitudinal coupled-bunch oscillations)
- It reduces the RF noise on the revolution frequency sidebands.



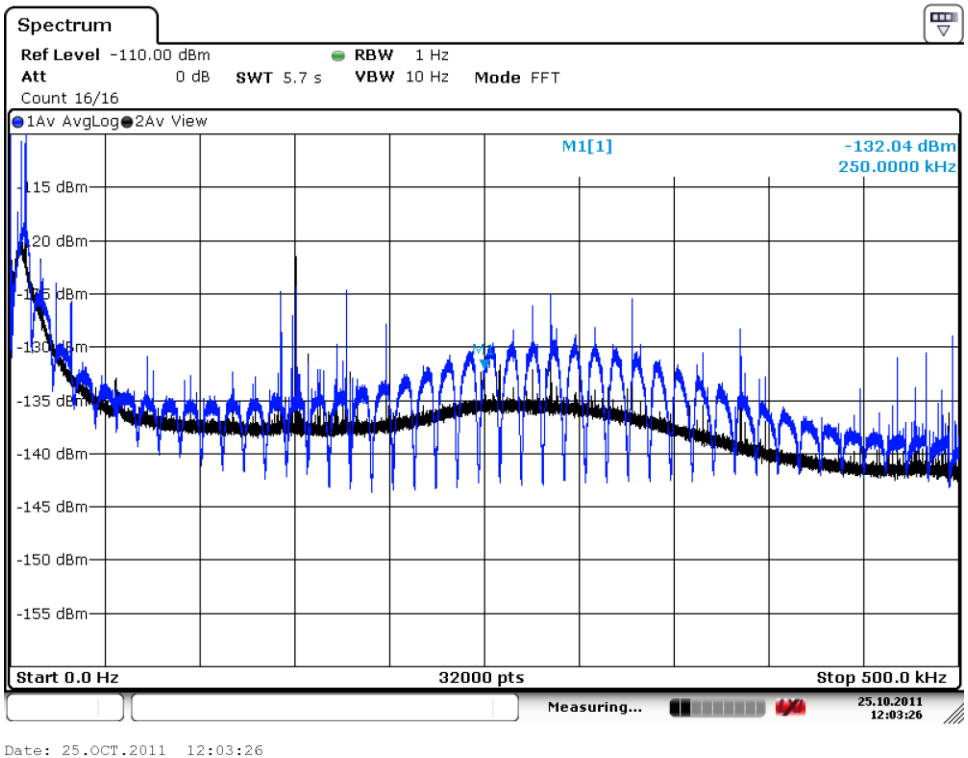


25 ns MD. 2100 bunches. ~2/3 rd nominal total intensity



Voltage amplitude and phase with OTFB on (Cav1B1, left) and off (Cav7B1, rigth). The OTFB gives at least a fivefold reduction of phase modulation, resulting **0.3% and 0.5 degree** field control. The required klystron transients do not increase. They are actually reduced.

OTFB: RF noise



Cavity 1B1 phase noise Power Spectral Density in physics conditions (1.5 MV, Q =60k), no beam. OTFB on (blue trace) , OTFB off (black trace). Up to 8 dB reduction of phase noise at the revolution harmonics

The issue of bunch length

Geometric Luminosity Factor

$$F = \frac{1}{\sqrt{1+\left(\frac{\theta\,\sigma_z}{2\sigma^*}\right)^2}}$$

- The bunch length affects luminosity via the geometric factor

Energy	3.5 TeV	4 TeV	7 TeV
β* [m]	1.0	0.7	0.55†
Emittance [μm]	2.5	2.5	2.5
σ_x [μm]	19.2	18	13.6
X-Angle [μrad]	260	290	250
Reduction (σ_z =7.5cm)	10.8%	14.4%	17.7%
Reduction (σ_z =9.5cm)	15.9%	20.6%	24.7%
1.35 ns, 10.125 cm σ_z		22.5 %	26.8 %

2011

Proposed 2012

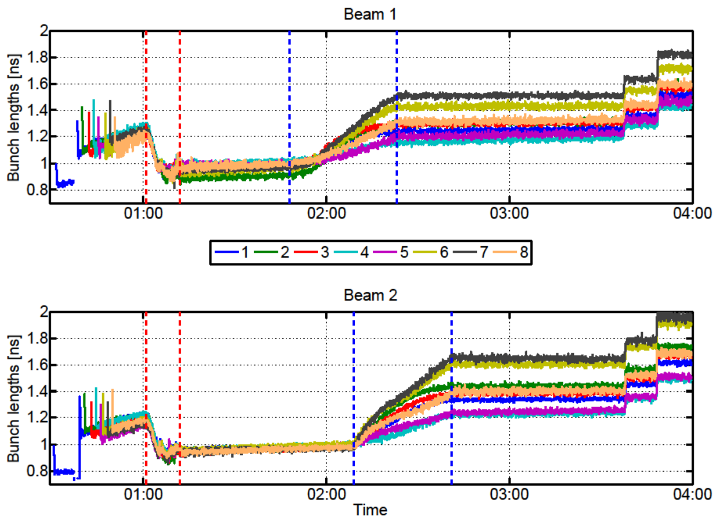
After LS1 ?

Analysis by R. Calaga

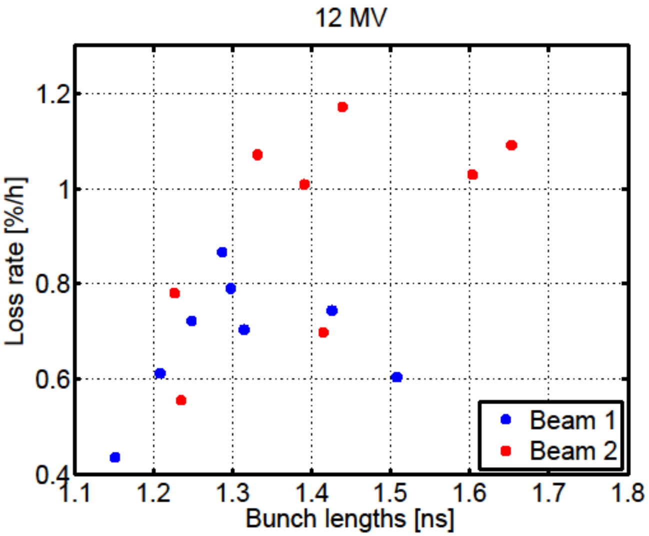
Lifetime vs. bunch length without collision

- An MD was performed in August to study the lifetime dependence on bunch length at 3.5 TeV, non colliding
  - Clear correlation of loss rate with bunch length

See Cern-ATS-Note2011-083-MD



Modulated bunch length blowup (between blue lines)

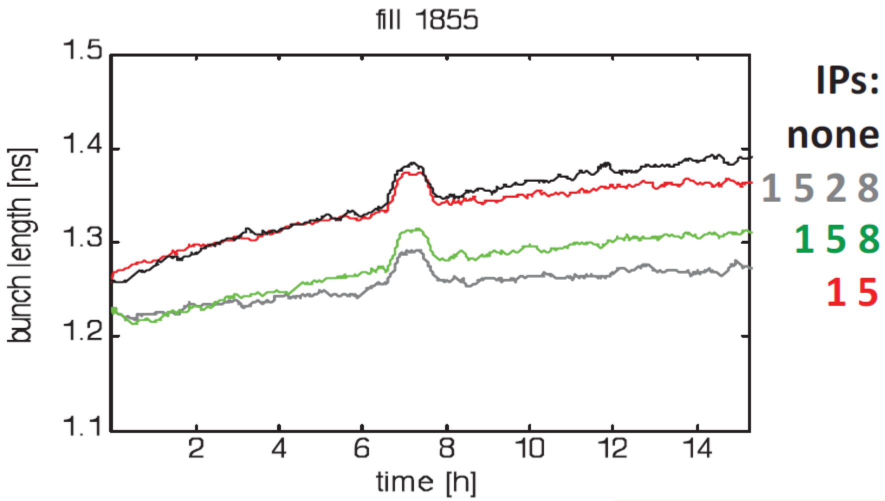


Loss rate dependence on bunch length

Without collision we can circulate 1.6 ns long bunches with losses at **1.2%/h** twice higher than 1.2 ns (0.5 %/h). **In collision** the observed **FBCT intensity loss is around 1.3 %/h** with 1.25 ns at end ramp

The effect of collision

- Fill with colliding and non-colliding bunches
- Observation of bunch lengthening vs. number of collisions



Presented at Evian 2011, G. Papotti

Analysis by G. Papotti, G. Trad

The number of IPs limits the maximum bunch length. Beyond 1.35-1.4 ns the length saturates and diffusion results in debunching. Collision seems to affect the momentum aperture.

Normal debunching

Bunch length mean

FBCT. We loose 20% intensity in 15 hours, or **1.33%/hour**

After 5 hours in physics, the abort gap population has reached an **equilibrium between debunching** (4E9-8E9 p) **and momentum collimation**. This happens for a length **1.35-1.4 ns**

Notice the saturation of bunch length around 1.35-1.4 ns. **In collision** the bunch cannot grow any wider.

Oct 16-17, 2011. A long fill. More than 15 hours in collision

RF strategy:

We think that bunch length at end ramp cannot be increased much.

We suggest a series of fills with 1.25 ns (2011 settings), 1.3 ns and 1.35 ns, at the beginning of the run, for comparison

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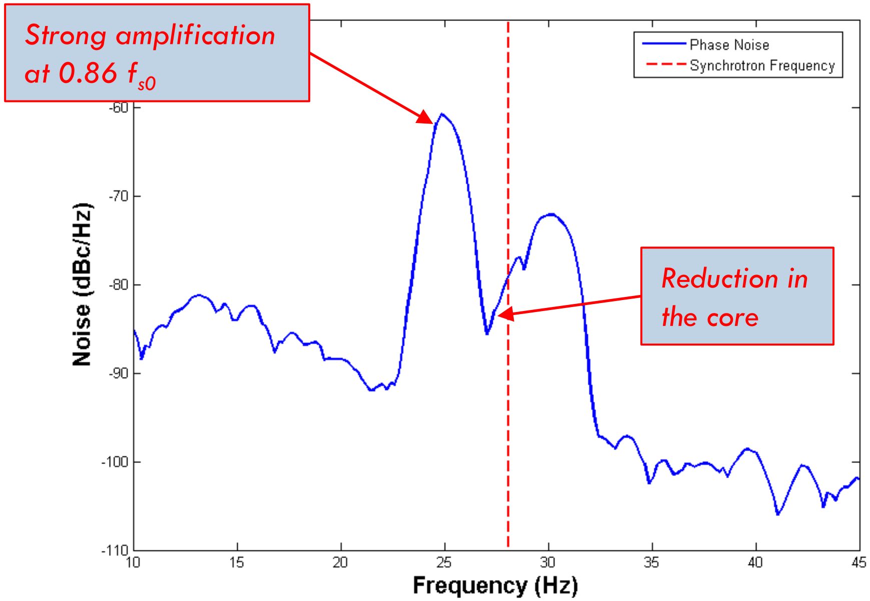
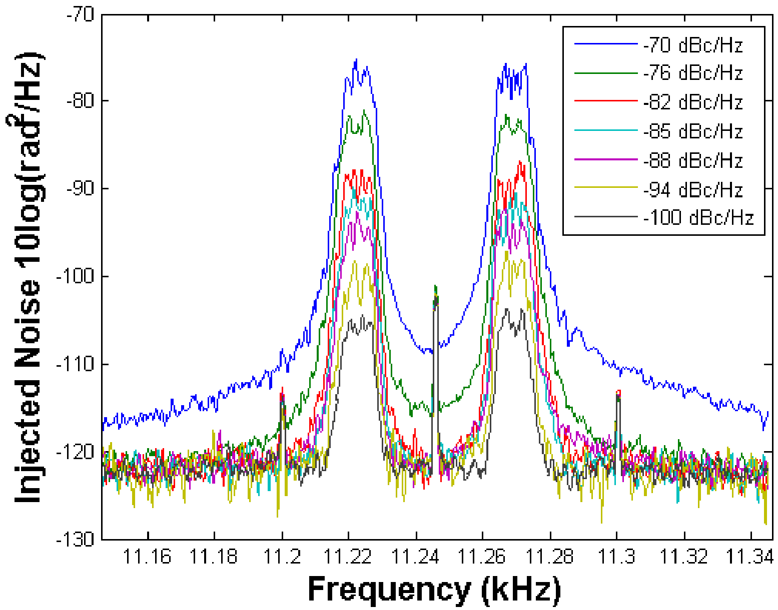
Longitudinal blow-up, beam spectrum and average bunch profile

Emittance blowup comparison

- We are trying to inject a flat noise spectrum 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 $f_{rev} \pm f_s$



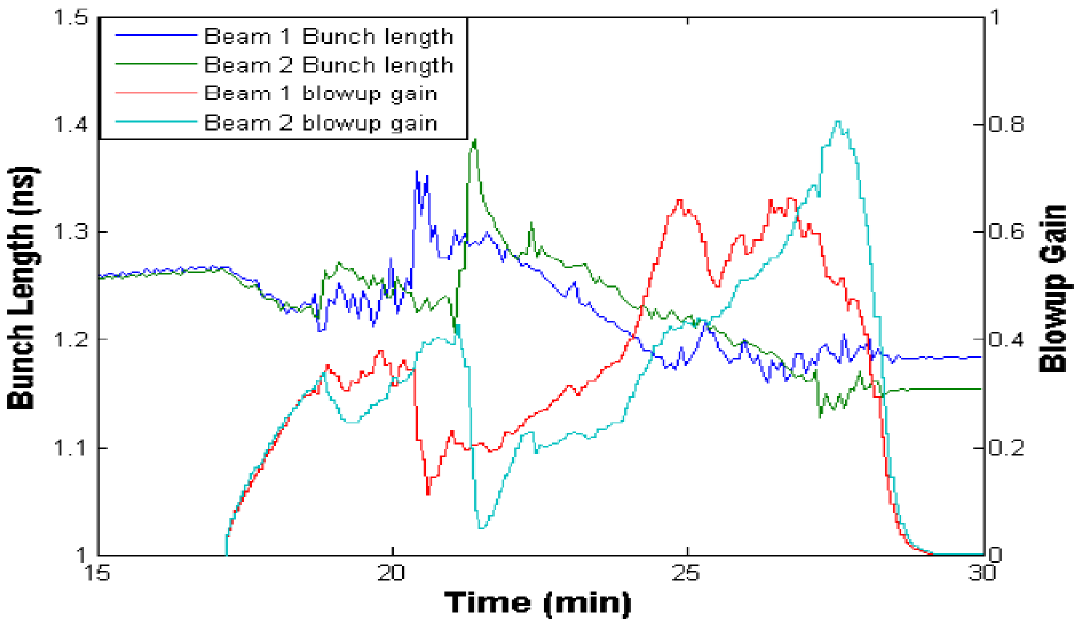


Phase noise PSD measured in the RF sum of the 8 cavities during blow-up. f_{s0}=28.5 Hz

Old blow up

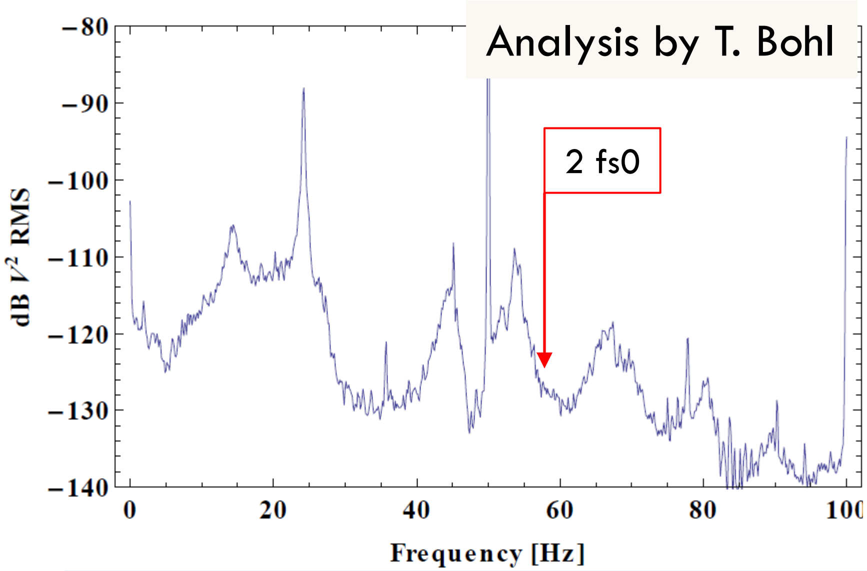
- The old blow-up caused unexplained "explosions" in bunch length. Precise results could only be achieved with feedback from bunch length

Bunch length and amplitude of blow up during the ramp. Notice the fast increase one third through the ramp. The feedback correctly reduced the excitation to keep the overall performances acceptable.
These "explosions" are now believed to be caused by the distortion of the phase noise spectrum by the phase loop.



Peak detected Schottky

- Peak Detected Schottky measurements also indicate a “hole” in the Beam Transfer Function, presumably from the enhanced excitation at the edge of the bunch
- This effect is present in the majority of fills, but not all
- It could not be correlated with the jumps in bunch length mean during the blow up
- But it is consistent with a depletion of the bunch frequency spectrum, caused by a selective excitation at the edge of the bunch



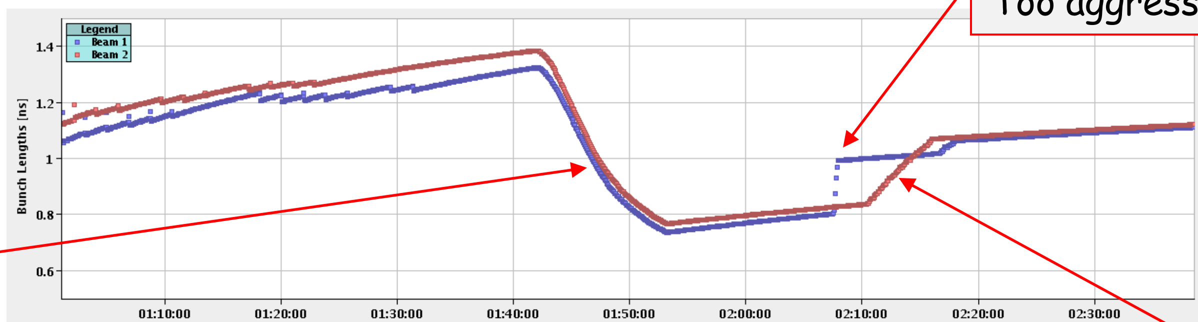
Schottky spectrum shortly after start physics. f_{s0} = 28.5 Hz. The qudrupole spectrum ranges from 57 Hz down to around 40 Hz. Notice the notch around 47 Hz

New blow up

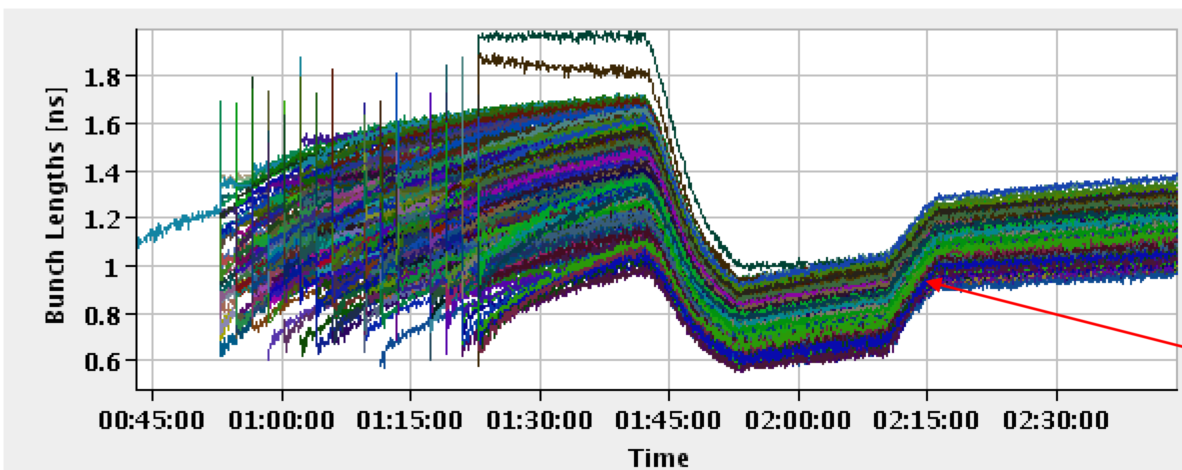
- The first trial of the new blow-up, with Ions at 3.5 z TeV was very conclusive: regular bunch lengthening, equal for all bunches

First trial with B1. Too aggressive!

Ramping without blow up



Reduced noise power tried with B2. Very smooth and linear effect without feedback from bunch length



Same effect on all 358 bunches

Bunch length mean (top) and b-by-b Beam 2 (bottom), 358 bunches

Batch per batch blow up

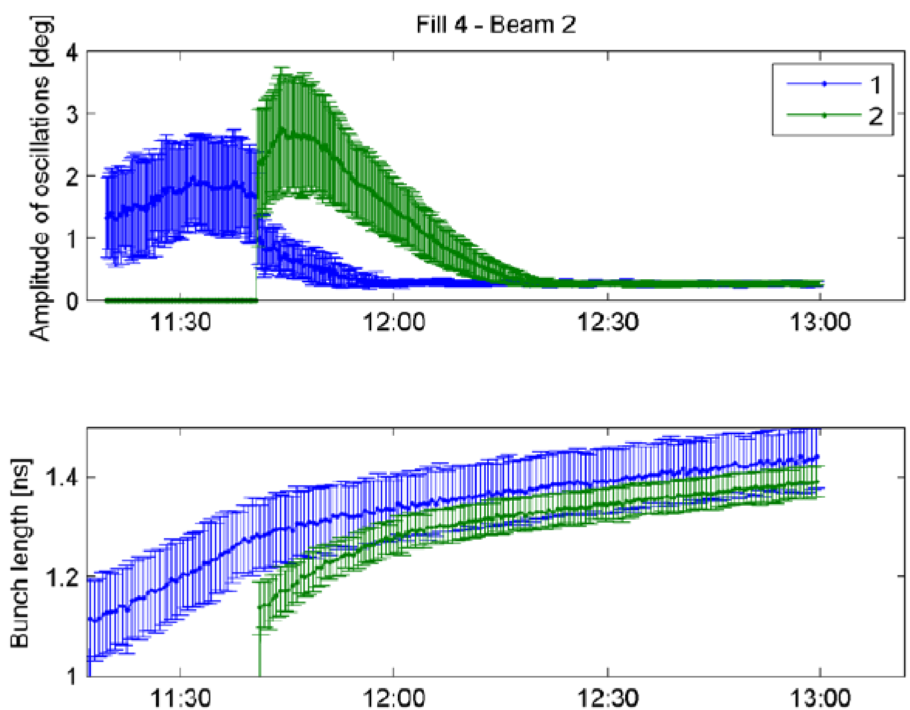
- The new blow up will be more "predictable" and opens the road to selective blow-up of the injected batch in 2012
- This will hopefully reduce transverse emittance growth on the flat bottom
- This may become essential with the SPS Q20 optics, leading to reduced longitudinal emittance at injection and increased effect of IBS

RF strategy:
We commission the new blow up (but acting on all bunches) at start up.
We test the "last injected batch blow up" as soon as possible.

Longitudinal damper in 2012

Dipole oscillations at injection

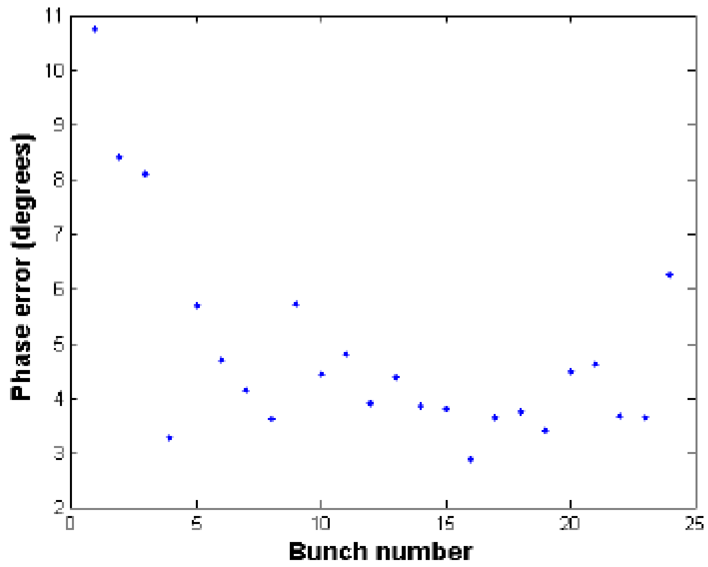
- Long lasting dipole oscillations have been observed in batch mode (50 ns): growing for 10 min after injection, then decaying with more than 30 min time constant.
- They do not depend on the number of bunches per batch, nor on the batch spacing
- With 25 ns spacing the oscillations do not grow. They are quickly reduced to 1-2 degrees, then damped in twenty minutes
- MD is needed to check the influence of longitudinal emittance on stability



Amplitude of the dipole (top) and quadrupole (bottom) oscillations with batch injction (12b followed by 36b).
ATS Note 2011/031/MD

Longitudinal damper

- We will use the accelerating cavities as longitudinal kicker, changing the RF in the 1 microsec. long gap between the circulating beam and the freshly injected batch
- The available kick strength (50 kV/cavity) is sufficient to damp the common mode, that is the average phase/energy error of the new batch, before filamentation takes place (see Chamonix 2011)
- Not much can be done for the modulation along the batch
- Firmware upgrade needed. Will be available in the Summer



Phase error at injection for the 24 bunches of a batch, 25 ns spacing. This pattern fits well with the measurements at SPS extraction.

4 TeV and beyond

4 TeV and beyond…

- 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

- higher bunch intensity
- 25 ns bunch spacing

Longitudinal stability

- Broadband stability criteria: We have circulated single-bunch of 2.5E11 p during MDs in 2011, at 450 GeV. As the stability improves with energy we do not anticipate problems
- 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). However we have no measurement of damping time for coupled bunch instabilities. We wish to check our calculations with experiments (MD requested in 2012)

    MD RFStabBatch_2012
  - We seem OK with the cavities HOM (according to J. Tuckmantel). We may discover an offending narrow-band impedance. MD time requested

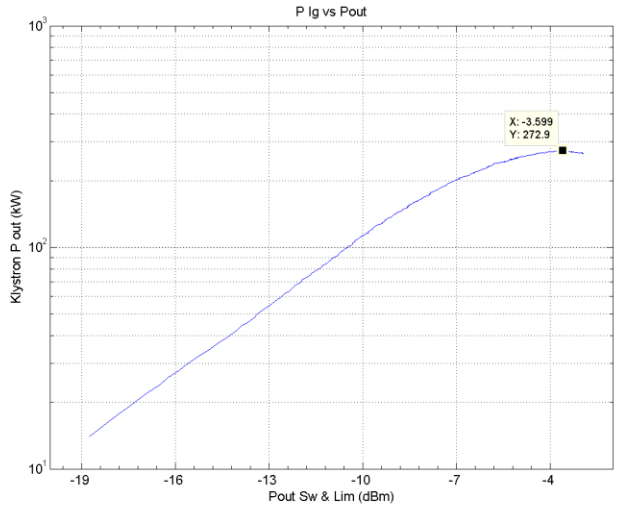
    MD LHC-MD-REQUEST-RF-2012-RFimp

25 ns in 2011

- With 25 ns spacing the dipole oscillations at injection do not grow. They are damped very slowly (10-20 min)
- The injection phase along the batch confirms the SPS data (slide 26). We have observed 70 ps spread in a 24 bunches batch
- At 450 GeV we have circulated 2100 bunches at 1E11 p/bunch. The uncompensated transient beam loading was below 0.5 degree at 400 MHz (slide 11), with a klystron power around 110 kW as expected
- We have ramped 3 batches (12b + 24b + 24b). These batches are however too short to cause full transient beam loading. We need to ramp a 288b batch.

Needed Klystron power for nominal

- We need 200 kW CW for operation with 25 ns, **nominal**, at 3.5 TeV (at injection 110 kW OK)
- With the present DC settings (50 kV, 8A), the klystrons saturates at 200 kW RF. As we need margin for regulation, this does not allow for 25 ns ramping but is sufficient at injection
- We would change the klystron DC settings to 57kV/8.7 A before starting the ramp. That raises saturated RF at 270 kW
- This was tested on Oct 6th, with 12b + 24b + 24b
- Do we have enough margin for the peak power needed to compensate for transient beam loading caused by the gaps? To be tested with 288b, 25 ns spacing ASAP



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

RF strategy:

We commission the klystron HV change at start ramp with the 25 ns MDs.

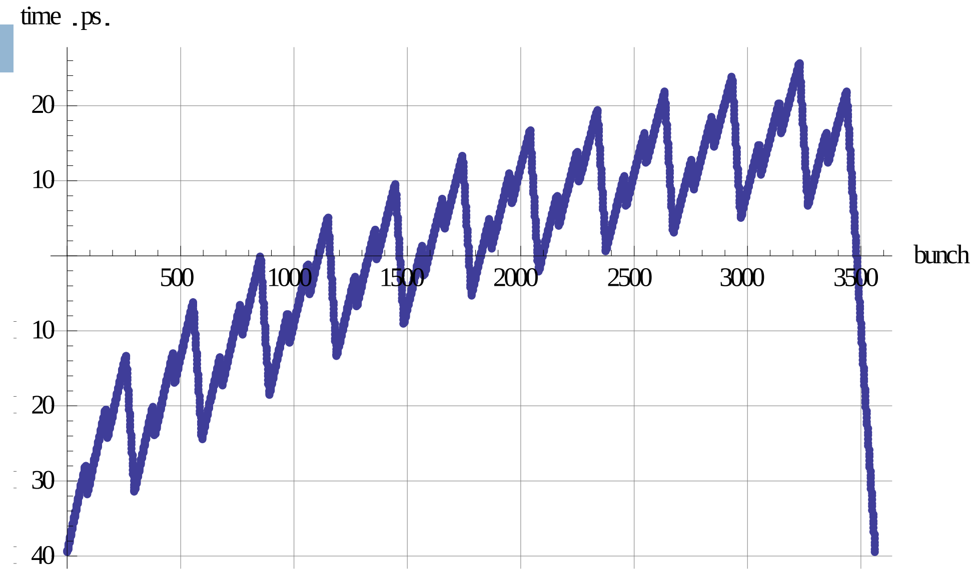
We want to ramp 288b batch (1 batch sufficient) to reach maximum beam loading.

Modulation of the voltage

- With **ultimate** conditions (2808b, 25 ns spacing, 1.7E11 p/bunch) the present scheme requires more than 300 kW in physics (12 MV), that are not available from the klystron
- We would then accept the modulation of the cavity phase by the beam current (transient beam loading) and adapt the set point for each bunch accordingly
- Stability is preserved and we need 105 kW only, independent on beam current

Modulation of bunch phase

- The modulation of the cavity phase changes the bunch spacing and therefore the collision point. However the 65 ps displacement is small compared to the 1.2 ns 4-sigma bunch length
- As the filling pattern of the two rings is very similar, the phase modulations will cancel out in IP1 and IP5 and the resulting displacement of the collision vertex will be much smaller than the above 65 ps



Modulation of the cavity phase by the transient beam loading in physics. 2835 bunches, 1.7E11 p/bunch, 1.5 MV/cavity, Q_L=60k. The abort gap spans 127 empty buckets (25 ns spacing) or 3.2 microsec. Filling as in the original LHC design report

RF strategy:
We want to test the idea before LS1. MD time needed

Conclusions

Higher beam energy and intensity (1/2)

- In 2012 we intend the following upgrades
  - Further reduction of capture losses with the longitudinal damper
  - Modification of the blow-up method
  - Batch per batch blow-up at injection
- Data indicate that, with collisions, the momentum aperture is smaller than the bucket. With 1.4 ns, the *effective* bucket is full. If (and only if) really needed for other equipment, we propose to test physics with slightly longer bunches, early in the re-start
- Thanks to the longitudinal blow-up, the stability is independent on the energy. Operation at 4 TeV should not cause problems
- We have not approached single bunch intensity limit. We have circulated 3E11 p/bunch

Higher beam energy and intensity (2/2)

- There was no surprise from the first 25 ns tests
- The RF can deal with nominal total intensity (2808b, 25 ns, 1.1E11/bunch)
  - On the stability side, calculations show large margin from HOMs and cavity impedance at fundamental. However we would like to measure damping time of coupled-bunch mode for confirmation. MD time needed
  - On the klystron power side, we can deal with nominal if we increase the klystron DC settings (HV) before the ramp (to be tested during 25 ns MDs)
- For ultimate intensity (2808b, 25 ns, 1.7E11/bunch), the RF must allow for the modulation of the cavity phase by the transient beam loading. First tests should take place before LS1

thank you very much for your attention!

Longitudinal stability

- Broadband stability criteria

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

- Narrow-band stability criteria

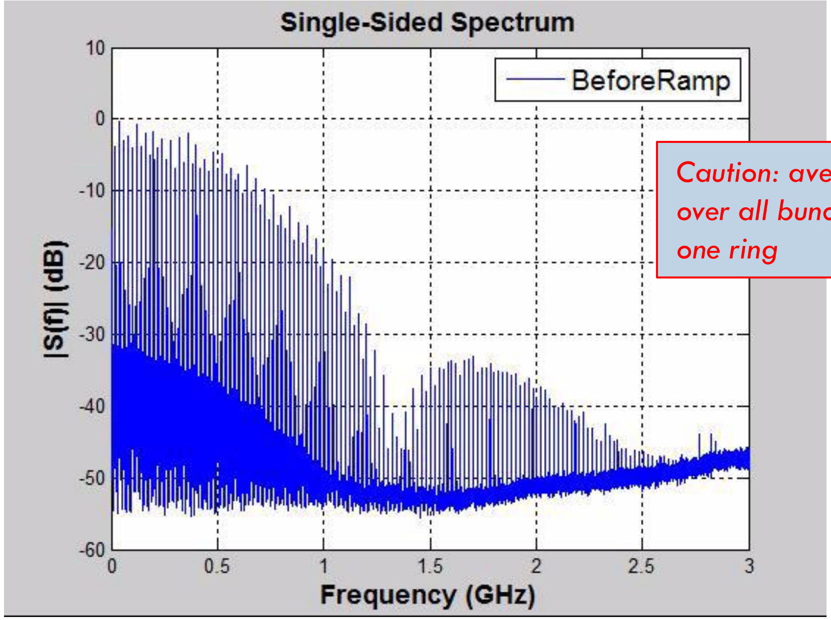
$$R < \frac{|\eta|E}{eI_{DC}\beta^2}\left(\frac{\Delta E}{E}\right)^2 \frac{\Delta\Omega_s}{\Omega_s}\frac{F}{f_0\tau}G[f_r\tau] \propto \frac{\varepsilon^{3/2}V^{1/4}}{E^{3/4}I_{DC}} \propto \frac{\tau^3 V}{I_{DC}}$$

- 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

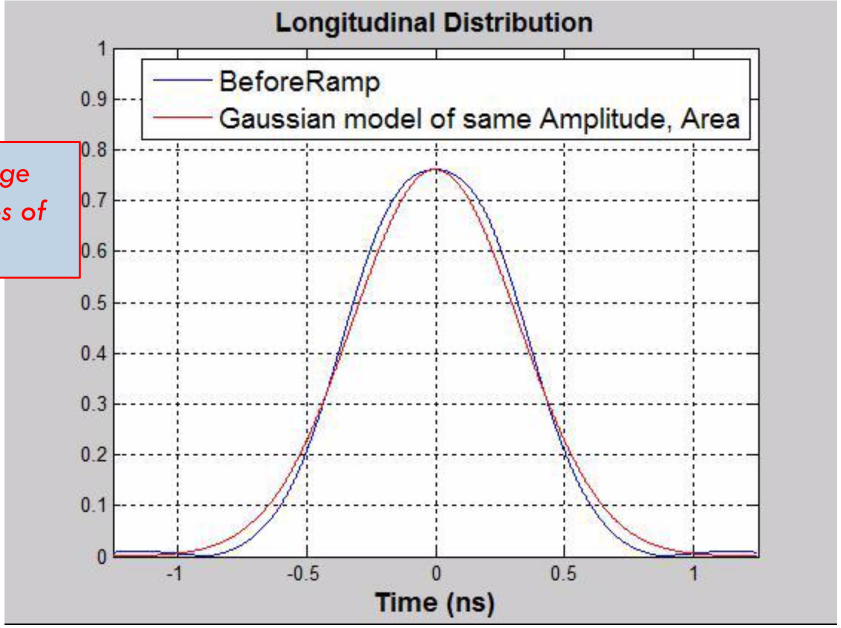
See: E. Shaposhnikova, Longitudinal Beam Parameters during acceleration in the LHC, LHC Project Note 242, Dec 2000

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.



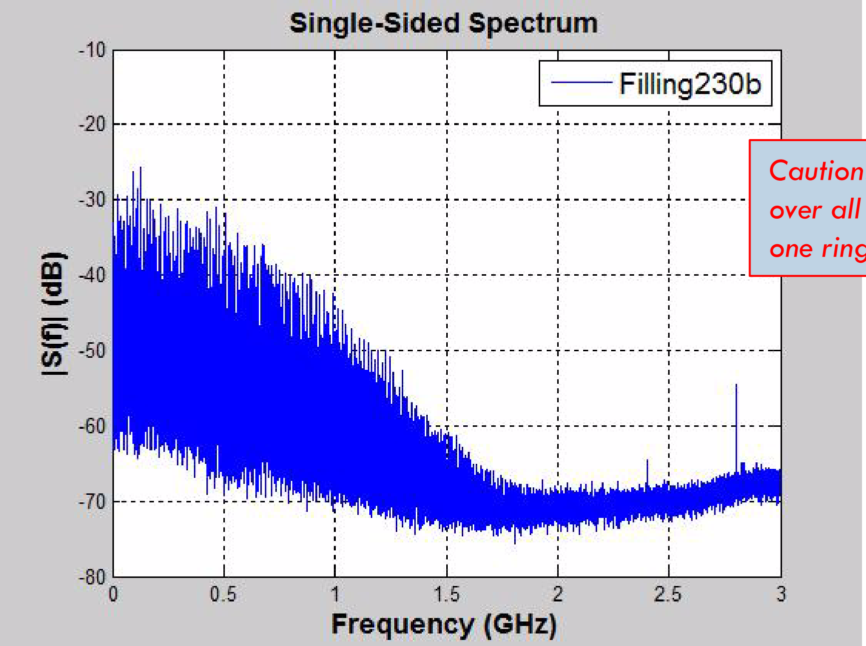
Caution: average over all bunches of one ring

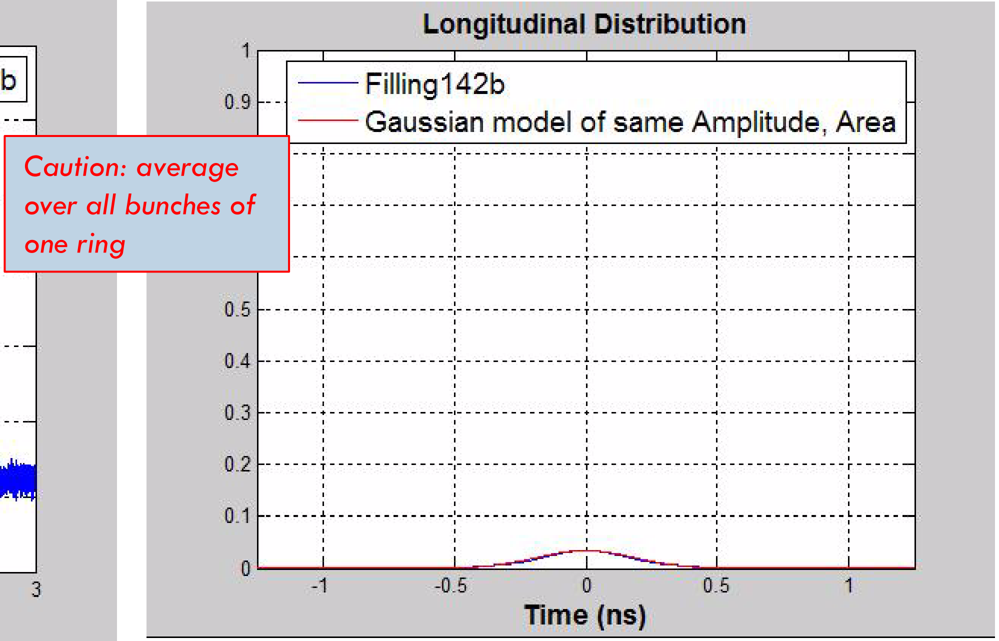


Analysis by T. Mastoridis

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)

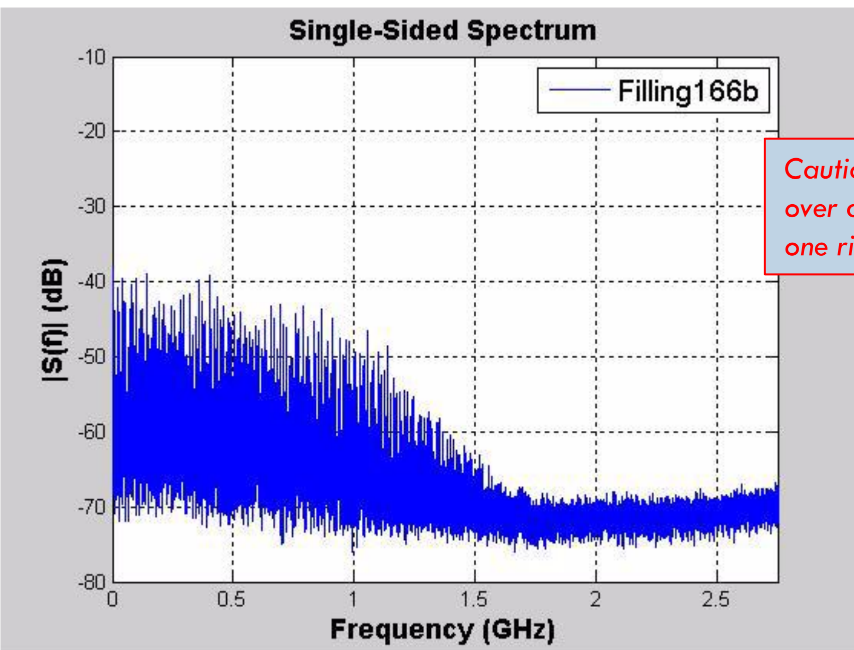




Analysis by T. Mastoridis

Spectrum and bunch profile with new blow up

- 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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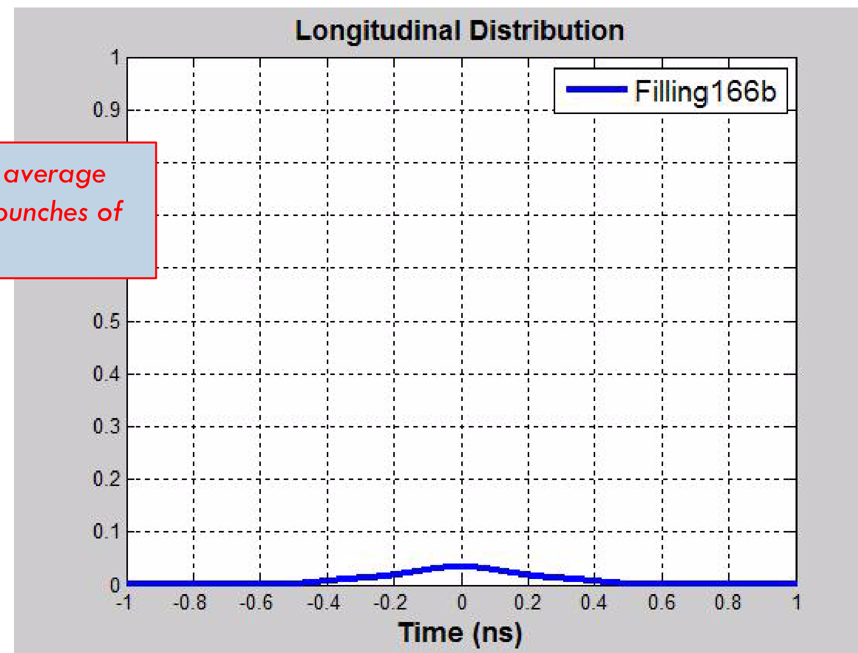
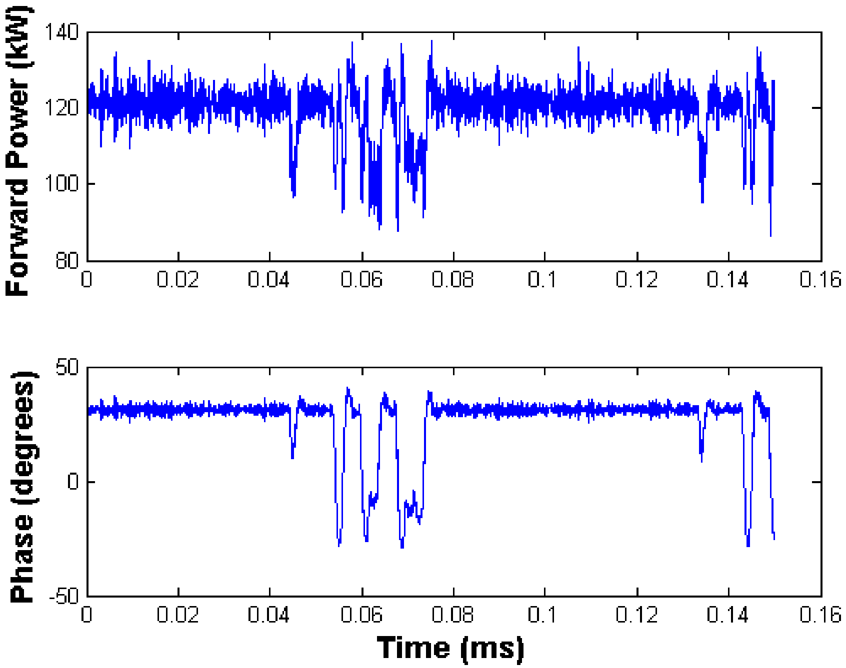


Constant RF field and half detuning

- So far we have kept the RF field constant during the turn, with full compensation of the transient beam loading
- The detuning is chosen to minimize the peak klystron power: The power remains constant over one turn, while the klystron phase flips between beam and no beam segments



Forward power and phase of klystron 5B2 with the 444 bunches (12+72+144+216), 25 ns spacing, 1.05 p/bunch at 450 GeV. The klystron power changes by 15 kW only between beam and gaps, but the phase of the klystron flips by 60 degrees.