The LHC RF System

Is it working well enough?

LHC Performance Workshop, Chamonix 2011

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Special thanks to Elena Shaposhnikova, Joachim Tuckmantel, Thomas Bohl and Andy Butterworth for their corrections and suggestions
The LHC RF team

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BE-OP: D. Jacquet, G. Papotti

REVIEW OF PROTON RF OPERATION
2010

Very quick (3 slides)

For more details see write-up from Evian Dec 2010 RF paper @

http://indico.cern.ch/getFile.py/access?contribId=34&sessionId=0&resId=1&materialId=paper&confId=107310
• March 26\textsuperscript{th}, ramping single bunch pilot

Single bunch pilot in both rings, \( \sim 0.2 \text{ eVs} \). 8 MV at injection (\(fs0=65.3 \text{ Hz}\)), increased to 12 MV before ramp (\(fs0=80 \text{ Hz}\)), constant 12 MV during acceleration ramp (\(fs0=28.9 \text{ Hz} @ 3.5 \text{ TeV}\) ). BQM was not calibrated

• May 15\textsuperscript{th}, attempt to ramp nominal intensity single bunch

May 15\textsuperscript{th}. First attempt to ramp nominal intensity single bunch. Bunch length during ramp. The longitudinal emittance is too low (<0.4 eVs). The bunch shrinks below 550 ps and becomes unstable. Loss of Landau damping
May 28th: **Emittance blow-up in the SPS**
- SPS bunch 1.7 ns long bunch, 0.6-0.7 eVs
- 4 LHC cavities ON
- Capture with 3.5 MV
- Voltage increased to 5.5 MV in parabolic part of ramp
- 3.5 TeV: 0.8-0.9 ns long, 5.5 MV

**FastBCT and bunch length through the ramp. By increasing the SPS longitudinal emittance, the bunch was kept stable till flat top. Starting with 1.7 ns from the SPS we end-up with a stable 0.8-0.9 ns long bunch at 3.5 TeV**

June: **Emittance blow-up in the LHC.** Target bunch length 1.5 ns

Fall: 150 ns bunch spacing, increasing number of bunches
- SPS bunch length reduced to 1.5 ns
- All LHC cavities ON
- Capture with 3.5-4 MV
- Emittance blow-up to 1.2 ns in ramp
- Linear voltage rise to 8 MV during ramp
- 3.5 TeV: 1.2 ns long, 1.6 eVs, 8 MV

**End Oct: 368 nominal bunches with 150 ns spacing. 12% nominal!**
Bunch lengthening

- Oct 26th, fill 1444, 368? bunches, 150 ns 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
WORKING WELL ENOUGH?

Fighting the effects of RF noise...
LHC LLRF: Two-level hierarchy

**Beam control**
- one system per ring
- uses beam-based measurements (avg position and phase)
- updates once per turn (11 kHz)
- generates a **fixed amplitude RF reference sent to all 8 cavities**

**Cavity Controller**
- one system per cavity
- uses klystron and cavity field measurements
- updates at every bunch (40 MHz)
- generates the klystron drive (plus tuner control)
Phase noise without beam

SSB phase noise (in dBc/Hz) of the Vector Sum of the eight cavities B2 (green) compared to the RF reference (blue). No beam

- The Closed Loop bandwidth is ~ 300 kHz (single sided), limited by the 650 ns loop delay
- The Reference noise dominates at low frequencies (below 200 Hz)
- Imperfect compensation of the driver noise is responsible for the 200 Hz to 20 kHz range
- From 20 kHz to the 300 kHz closed-loop BW, the spectrum is flat, dominated by the measurement noise

In physics $f_{30} \sim 28$ Hz and dipole mode zero sits here...

VCXO $1/f^4$ law
Not understood

VCXO $1/f^2$ law
(resonator Q)

Imperfect TX and LLRF noise compensation

Demodulator noise

Closed Loop BW limit ~ 300 kHz
Phase noise with beam

- The **Main Phase Loop** reduces the noise on the dipole mode 0 synchrotron sidebands ($f_{s0} \sim 28$ Hz). Without it the Phase noise at $\pm f_{s0}$ lead to 300-400 ps/hour bunch lengthening [Mastorides1]
- Notice how the Phase Loop actually increases the noise PSD outside the synchrotron band, below 10 kHz. But the beam does not react
- The RF noise will also excite the beam on the higher dipole modes: @ $\pm n f_{\text{rev}} \pm f_s$
- What counts is the power that falls in the synchrotron bands only

**SSB Phase noise (in dBc/Hz) of the Vector Sum of the eight cavities B2 with Main Phase Loop OFF (green) and ON (blue). With beam at 3.5 TeV**

[Mastorides1] T. Mastorides et.al., LHC Beam diffusion Dependence on RF noise: Models and Measurements, IPAC 2010
Scaling it all: From phase noise PSD (rad²/Hz) to Bunch Lengthening (ps/hour)

- May 7th, 2010: Single bunch p, 1E10 @ 3.5 Tev, 8 MV, observe bunch lengthening while varying BPL gain

![Graph showing bunch lengthening](image)

Notch at the synchrotron frequency

Left: Observe 4σ bunch length while varying Main Phase Loop gain
Right: SSB Phase Noise Power Spectral Density in dBc/Hz in one cavity. The synchrotron frequency is ~ 24 Hz

Without phase loop we get 400 ps/h for SSB phase noise PSD of -85 dBc/Hz in a single synchrotron band.
To achieve 10 ps/h, the SSB PSD must be below -101 dBc/Hz
The formula gives -98 dBc/Hz SSB phase noise PSD Cavity Sum for 10 ps/hour 4σ lengthening
Confirmed (within ~ 6 dB margin...) in an RF noise MD with ions Nov 23rd

<table>
<thead>
<tr>
<th>Phase Loop Gain (s⁻¹)</th>
<th>Lengthening (4σ length)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>400 ps/h</td>
</tr>
<tr>
<td>2</td>
<td>300 ps/h</td>
</tr>
<tr>
<td>10</td>
<td>70 ps/h</td>
</tr>
<tr>
<td>&gt;70</td>
<td>20 ps/h</td>
</tr>
</tbody>
</table>
The beam samples the RF field at the revolution frequency. It therefore reacts to the phase noise in all synchrotron sidebands (aliasing) -> we must sum noise contributions over all n freq +/- fs bands

- In the ~ 300 kHz BW of the effective cavity impedance we have ~ 60 such bands
- The noise floor PSD for 10 ps/h is therefore -101 dBc -10 log(60) = -119 dBc

SSB Phase noise (in dBc/Hz) of the Vector Sum of the eight cavities B2 with beam at 3.5 TeV.

Conclusion: We measure a noise level of ~ -125 dBc/Hz from 10 kHz to 500 kHz. Bunch lengthening caused by RF noise ~ 2.5 ps/h
For comparison the Tevatron RF phase noise is -106 dBc/Hz [Zhang]

WORKING WELL ENOUGH?

RF problems in 2010

- All LLRF electronics worked perfect. We have 50 VME crates with ~400 VME modules of 36 different makes, all custom-designed. Zero down-time
- Few problems with klystrons and modulators (see Olivier’s talk)
- Problem with Cav4B1 and Cav7B2
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 75 ns scrubbing run (Nov 18th-19th). Clear correlation between the injections and the cavity field ripples. No problem with the 150 ns spacing or with the injection of 24 bunches At 75 ns spacing

Nov 18th-19th. 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.

26.1.2011 Chamonix LHC workshop 2011
WORKING WELL ENOUGH IN 2011?

with increasing intensity....

Injection transient issues
Managing capture loss with higher intensity:
Longitudinal damper
SPS-LHC Capture

- SPS longitudinal parameters at transfer with 7.2 MV RF @ 200 MHz:
  - bucket: 3.0 eVs, +10.6E-4 Δp/p
  - bunch: 4σ bunch length 1.5 ns, 0.51 eVs, +4.5E-4 Δp/p

- Matched LHC capture voltage: 2.5-3.1 MV @ 400 MHz.

- LHC longitudinal parameters at transfer with 3.5 MV @ 400 MHz
  - Bucket: 0.94 eVs, +6E-4 Δp/p

- Loss are small (< 1 %) but cannot be zero because
  - 13.5 % of particles are outside the 2-D 4σ core
  - the SPS bucket is twice longer and 70% taller than the LHC bucket

Capture loss is unavoidable because the SPS bucket is so much larger than the LHC bucket (3.0 eVs compared to 0.94 eVs) and a significant part of the bunch falls outside the 4σ region.

Phase space trajectories in normalized phase space (φ, \(1/\Omega_s d\phi/dt\)), 3.5 MV SPS bunch length (4σ) 3.8 radian @ 400 MHz (dark blue horiz. arrow) SPS bunch height +/- 1.5 in normalized \(1/\Omega_s d\phi/dt\) unit (dark green vert. arrow)
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, it considers the average only.
- Long Damper: Damp the injection phase/energy error batch per batch.
- In the LHC we use the 400 MHz cavities as damper. We can change the RF phase in the 1μs gap between circulating and incoming batch.

Oct 30, 50 ns spacing, 12 bunches per inj, injection transient 7th bunch 4th batch, 1 ms between traces, dipole oscillation (+- 100 ps, ~45 Hz frequency) lasting for 1 s with reduction by ~ 2 only.

Q=60K, 1 MV plus 100kV step in quadrature 2 μs per div
Longitudinal damper. How efficient?

- Each cavity can give a 50 kV step in the 1μs gap between circulating and incoming batch.
- With 8 cavities we can give momentum kick 0.4 MeV/c per turn (50 kV/cav).
- Given the 46 Hz synchrotron freq, that is 100 MeV/c per synchrotron period (bang-bang regime).
- At 450 GeV/c that is \( \Delta p/p = 2.2E-4 \)
- We can reduce energy error by 1/3 bucket half height in 1 synchrotron period. GOOD.
- Klystron peak power margin needed for damping. Will orient the choice of klystron DC settings. MD time needed…

The longitudinal damper acting by modulation of the RF field phase looks promising for damping batch-per-batch injection errors. (Was suggested 10 years ago…). It does not have sufficient BW to act on the bunch-per-bunch phase error in a batch. Sunglasses?
WORKING WELL ENOUGH IN 2011?

with increasing intensity...

Surviving a klystron trip
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 \( Z(\omega) \) 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 \( L \) the 4\( \sigma \) bunch length

\[
\Delta\omega_s = \omega_s \frac{\pi^2}{16} \left( \frac{h L}{2 \pi R} \right)^2
\]
3.5 TeV conditions

We consider 1.2 ns bunch length (4 sigma) and nominal beam current 0.58 A DC.

The synchrotron frequency is 31 Hz. $\Delta \omega / 4 = 7$ s$^{-1}$.

With RF feedback only, the maximum growth rate is 0.013 s$^{-1}$ (0.005 s$^{-1}$) per cavity and the max tune shift 0.07 Hz while the tune spread is 4.4 Hz. The corresponding mode number is $\sim -12$.

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 $\Delta \omega / 4 = 7$ s$^{-1}$. GOOD!

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$^{-1}$ (0.87 s$^{-1}$), with 1 Hz tune shift, still OK given $\Delta \omega / 4 = 7$ s$^{-1}$.

Conclusion: One cavity trip OK at nominal

<table>
<thead>
<tr>
<th>$V_{RF}$ (MV) tot</th>
<th>$Q_L$</th>
<th>$f_d$ (kHz)</th>
<th>$f_s$ (Hz)</th>
<th>$\sigma$ (s$^{-1}$)</th>
<th>$\Delta \omega / 2\pi$ (Hz)</th>
<th>$\sigma$ (s$^{-1}$)</th>
<th>$\Delta \omega_s / 4$ (s$^{-1}$)</th>
<th>$\Delta f_s$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cav with fdbk</td>
<td>14</td>
<td>6.00E+04</td>
<td>3</td>
<td>31</td>
<td>0.013</td>
<td>0.07</td>
<td>0.005</td>
<td>7</td>
</tr>
<tr>
<td>1 cav fdbk off</td>
<td>14</td>
<td>6.00E+04</td>
<td>3</td>
<td>31</td>
<td>1</td>
<td>1</td>
<td>0.87</td>
<td>7</td>
</tr>
<tr>
<td>8 cav with fdbk</td>
<td>14</td>
<td>6.00E+04</td>
<td>3</td>
<td>31</td>
<td>0.1</td>
<td>0.56</td>
<td>0.04</td>
<td>7</td>
</tr>
<tr>
<td>7 cav with fdbk</td>
<td>14</td>
<td>6.00E+04</td>
<td>3</td>
<td>31</td>
<td>1.1</td>
<td>1.49</td>
<td>0.91</td>
<td>7</td>
</tr>
<tr>
<td>+1 cav fdbk off</td>
<td>14</td>
<td>6.00E+04</td>
<td>3</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Growth rates for 1 cav at 3.5 TeV with nominal current and 14/8 MV

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

<table>
<thead>
<tr>
<th></th>
<th>$V_{RF}$ (MV) tot</th>
<th>$Q_L$</th>
<th>$f_d$ (kHz)</th>
<th>$f_s$ (Hz)</th>
<th>$\sigma$ (s$^{-1}$)</th>
<th>$\Delta \omega/2\pi$ (Hz)</th>
<th>$\Delta \omega/4$ (s$^{-1}$)</th>
<th>$\Delta f_s$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cav with fdbk 10 kHz</td>
<td>4.00E+04</td>
<td>10</td>
<td>46</td>
<td>0.2</td>
<td>0.3</td>
<td>0.19</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>1 cav with fdbk 5 kHz</td>
<td>4.00E+04</td>
<td>5</td>
<td>46</td>
<td>0.1</td>
<td>0.15</td>
<td>0.135</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>8 cav with fdbk 10 kHz</td>
<td>4.00E+04</td>
<td>10</td>
<td>46</td>
<td>1.6</td>
<td>2.4</td>
<td>1.53</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>8 cav with fdbk 5 kHz</td>
<td>4.00E+04</td>
<td>5</td>
<td>46</td>
<td>0.8</td>
<td>1.2</td>
<td>1.08</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>1 cav fdbk off 10 kHz</td>
<td>4.00E+04</td>
<td>10</td>
<td>46</td>
<td>15</td>
<td>2.4</td>
<td></td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>1 cav fdbk off 5 kHz</td>
<td>4.00E+04</td>
<td>5</td>
<td>46</td>
<td>8.5</td>
<td>3</td>
<td></td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>7 cav with fdbk + 1 cav fdbk off 5 kHz</td>
<td>4.00E+04</td>
<td>5</td>
<td>46</td>
<td>9.2</td>
<td>4.05</td>
<td>16</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>7 cav with fdbk + 1 cav fdbk off 10 kHz</td>
<td>4.00E+04</td>
<td>10</td>
<td>46</td>
<td>16.4</td>
<td>4.5</td>
<td>16</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>1 cav parked</td>
<td>4.00E+04</td>
<td>100</td>
<td>46</td>
<td>15-20</td>
<td></td>
<td></td>
<td>7.5</td>
<td>16</td>
</tr>
</tbody>
</table>

- **1.5 ns bunch length (4 sigma) and nominal beam current 0.58 A DC**
- **The synchrotron frequency is 46 Hz.** The Landau damping $Dw_s/4=16$ s$^{-1}$
- **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.

**Conclusion:**

Cavity trip towards the end of filling is fatal at nominal intensity (with half detuning). **OK at half nominal.**

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?

Refill with 1 line off not possible much above ½ nominal.
Higher order modes?

\[ \sigma_I < \sqrt{m \frac{\Delta \omega}{4}} \]

Sacherer's Form Factor for a resonator at \( f_{\text{res}} \) and bunch length \( \tau_L \) \[\text{[Sacherer1]}\]

\[ \Delta \phi = 2\pi f_{\text{res}} \tau_L \]

\[ \Delta \phi = 3.8 \text{ radian at injection and 3.0 radian at 3.5 TeV} \]

Higher modes have much weaker growth rates

Sensitivity to phase misalignment

- Small deviations in the RF feedback OL phase create large asymmetry in the effective impedance and changes growth rates much
- Top Left to right: Effective cav. Impedance with perfect adjustment and 5 degrees offset
- Bottom: Resulting growth rates @ 3.5 TeV. Increased by factor 4

For on-line optimization, we will measure Fdbk response, with beam by injecting noise with no Power Spectral Density in the synchrotron bands
Surviving a klystron trip

- Longitudinal stability OK at 3.5 TeV with one klystron tripping
- But, above half nominal, the beam induced voltage in the idling cavity will much exceed 2 MV and the RF power dissipated in the load will exceed 300 kW [Joachim1]. The RF will trigger the beam dump to protect cavity/load in case of a trip above half nominal
- Non-adiabatic voltage change -> debunching
  - The abort gap gets populated but is naturally cleaned in ~ 18 min (collimator at 3x bucket half height)
  - In 2010, a loss of 3 klystrons at ~12% nominal resulted in 0.5% loss and 7E6 p/m in the abort gap. Limit was specified at 3E6 p/m at 7 TeV [Elena1]

Calculations on-going to compute the % of unbunched beam for 1 klystron trip at 14 MV (T. Argyropoulos). In parallel we study the compensation via the remaining klystrons

Fast BCT (Orange), Abort Gap Population (Blue) and Cav1B1, Cav2B1 and Cav3B1 field. 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 debunched intensity was rather small ~2E11 (0.5%) equivalent to the “normal intensity loss” in ~ 30 min during this fill. The resulting unbunched beam line density is 7E6 p/m, or 7E9 p in the 3μs long abort gap (BI measures 1.1E10 p, blue trace above). 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).

[Joachim1] J. Tuckmantel, Consequences of an RF Power Trip in the LHC, AB-Note-2004-008 RF, Jan 2004
[Elena1] E. Shaposhnikova, Abort gap cleaning and the RF system, Chamonix 2003
RF DIAGNOSTICS 2011

Observing the expected... and monitoring the unexpected...
RF measurements (1)

• BQM upgrade
  – Presently one turn analyzed every 4 seconds
  – Upgrade to make several acquisitions over successive turns
    • Improve the quality of the estimates (less noise)
    • 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
  – Make the application more user-friendly

• Wide-Band PU Peak detected signal
  – Monitor voltage matching
  – Detect quadrupole oscillations
RF measurements (2)

- Precise **bunch profile** measurements using Synchrotron Light monitors (tails of the bunch) to confirm observation with the our Wideband PU (see below)

![Graph showing measured bunch profile with Gaussian fit comparison.](image)

Fill 1444, Bunch 1 Beam 1 at the end of the ramp. The measured profile seems to have smaller tails than the Gaussian fit. Real or measurement artifact? Horiz. Axis in ns
RF measurements (3)

• Logging/analysis of bunch by bunch phase
  – Measurement available bunch per bunch, turn per turn in the Beam Phase Module
  – FFT and estimation of growth rates
  – Fixed display in CCC for monitoring
  – 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

• Precise measurement of stable phase to measure the heat load due to the e- flux (e- clouds). Popular demand (Elena, Gianluigi)

Help from OP needed for the GUI applications
KLYSTRON OPERATION 2011

Adjusting klystron DC power to the RF needs
Klystron operation in 2011

- **During physics**
  - 1.75 MV/cav and QL=60k
  - We need 142 kW per klystron with zero beam intensity and 155 kW at 1/3 nominal (0.193 A DC)
  - Using 50kV/8A for DC settings we get ~200 kW saturated RF power and 250 kW dissipated in the collector

- **During filling**
  - 0.5 MV.cav and QL=20k
  - We need 35 kW with zero beam current and 39 kW with 1/3 nominal
  - Using 50kW/8A DC settings we would get 365 kW dissipated in the collector. Too much!
  - We will use 46kV/7.6A DC (350 kW DC) or somewhat below to have 300 kW max in the collector
  - Ideal settings will depend on the needs of the longitudinal damper
LONGITUDINAL PARAMETERS 2011
Longitudinal parameters 2011

- SPS beam (same as in 2010)
  - 1.5 ns, 4σ length

- Capture
  - 3.5-4 MV
    - To be tried: Higher capture voltage. Consequence on capture loss? MD time needed

- Ramping
  - Linear voltage rise to 14 MV through the ramp
  - Emittance blow-up to 1.2 ns
    - To be tried: blow-up to 1 ns (bunch length 250 ps σₜ as in design report)

- Physics: Fixed 14 MV @ 3.5 TeV
  - In 2010 with 1.2 ns, 8 MV we had 1.6 eVs bunch emittance in a 3.7 eVs bucket
  - In 2011 with 1 ns, 14 MV, we have 1.5 eVs bunch emittance in a 4.9 eVs bucket
CONCLUSIONS

Is it working well enough?
Conclusions

• The overall RF reliability has been excellent
• The klystrons do trip on occasion. Improvements are on-going (Olivier’s talk)
• So far we could survive a klystron trip. From the RF protection point of view that will be the case till half nominal. The beam will remain stable either during filling (half nominal) or in physics (nominal). Calculations are being done to estimate abort gap population following a klystron trip
• With a klystron out-of-order and its cavity in parked position, we can refill at half nominal but probably not at nominal
• The design has succeeded in reducing the RF noise at a level corresponding to 2.5 ps/hour bunch lengthening
• The longitudinal damper will be installed. The goal is to keep capture loss at the 1% level
• Higher voltage at injection must be tested at start-up
THANK YOU FOR YOUR ATTENTION...