THE LHC RF: IS IT WORKING WELL ENOUGH?

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Abstract

We first briefly review the RF setting-up and operation in 2010. The issue of RF noise is developed in details, identifying the major noise sources and explaining why it did not lead to significant beam diffusion effects. A figure is given for its contribution to the bunch lengthening in physics, that is well below the effect of Intra-Beam Scattering. Capture losses were low in 2010 (below the 1% level) but still made filling troublesome due to the very large sensitivity of the Beam Loss monitors. The choice of voltage at injection is revisited and it is proposed to mismatch the capture in 2011 to reduce loss. We then present the longitudinal damper that will also reduce capture loss in multi-batch injection. The issue of surviving a klystron trip during physics is studied. Finally, the longitudinal 2011 parameters are presented.

PROTON RF OPERATION 2010

This section presents a very brief review of the proton RF operation. It is presented in much more details in [1].

The single bunch pilot (5 10^9 p) was ramped to 3.5 TeV on March 26th for the first time. The emittance at injection was 0.2 eVs. The bunch was captured with 8 MV (synchrotron frequency f_{s0}=65.3 Hz). The voltage was increased to 12 MV before the ramp (f_{s0}=80 Hz), then kept constant (f_{s0}=28.9 Hz @ 3.5 TeV). Bunch lengthening was as expected from adiabatic evolution in the ramp and nothing dramatic was observed when crossing the much feared 50 Hz synchrotron frequency.

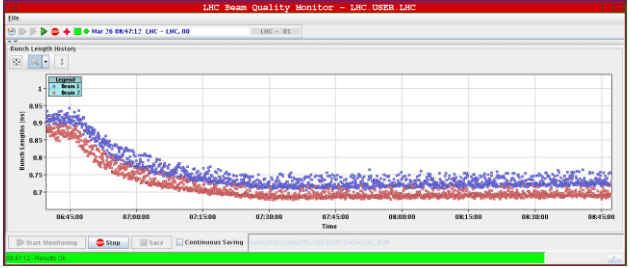

Figure 1: 4σ bunch length during the ramp. March 26th. Single bunch pilot in both rings, ~ 0.2 eVs.

Figure 1 shows the 4σ bunch length evolution. The measurement was not calibrated at the time. The bunch on the flat top is actually shorter than the indicated 700-750 ps. The lifetime was very good: with single bunch pilots, the bunch lengthening (4σ lenght) was around 30 ps/hour at the 450 GeV injection energy (8 MV) and 6 ps/hour at 3.5 TeV (12 MV).

Bunch intensity was increased in the coming months to reach the nominal 1.1 10^{11} p/bunch intensity. At injection, the nominal bunch was 1.2-1.3 ns long (4σ), with 0.3-0.4 eVs longitudinal emittance. The matched voltage is around 2.3-3 MV and we decided to capture with 5 MV. We then raised the voltage to 8 MV before the start of the ramp. Ramping was done with a constant 8 MV. The bunch was violently unstable. During the ramp it shrank down below 500 ps resulting in loss of Landau damping (figure 2).

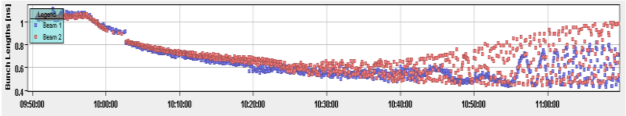

Figure 2: May 15th. First attempt to ramp nominal intensity single bunch. Bunch length during ramp. The longitudinal emittance is too low (< 0.4 eVs). The bunch becomes unstable when the length falls below 550 ps.

At the time longitudinal emittance blow-up was not available yet in the LHC but it was possible in the SPS [2]. So we decided to blow-up in the SPS to a 4σ length of 1.7 ns, maximum for injection in the LHC 400 MHz bucket. The longitudinal emittance became 0.6-0.7 eVs. We revised the voltage function in the LHC to better match the capture in order to preserve bunch length. After capture with 3.5 MV, the bunch would be 1.5-1.7 ns long. We raised the voltage linearly to 5.5 MV in the parabolic part of the momentum ramp, then kept it constant for the rest of the ramp and during physics. On May 28th a nominal intensity single bunch reached 3.5 TeV, with a length of 0.8-0.9 ns providing Landau damping sufficient to preserve stability (figure3).

Figure 3: Single bunch nominal intensity. Fast Beam Current Transformer (BCT) and 4σ bunch length through the ramp. The bunch shrinks from 1.5-1.7 ns on the flat bottom to 0.8-0.9 ns at 3.5 TeV.

Maximal blow-up in the SPS is not a lasting solution as it creates long bunches and results in capture loss at injection. Emittance blow-up in the LHC ramp is preferable. It is also needed for longitudinal stability at

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nominal intensity [3]. Longitudinal emittance blow-up became operational in the LHC on June 15th. We could then reduce the SPS bunch length to 1.5 ns (~ 0.5 eVs) at transfer to the LHC and capture the bunch with 3.5-4 MV. The voltage was increased linearly through the momentum ramp, to reach 8 MV on flat top. The LHC blow-up was active through the ramp, and adjusted to keep the bunch length at 1.5 ns [1]. This figure was reduced to 1.2 ns in September to prepare for bunch trains, resulting in a 1.6 eVs emittance on flat top. The LHC RF was operated with these longitudinal parameters (voltage and bunch length) for the rest of the year.

In the beginning of September we reconfigured the RF hardware for higher intensity (batch of bunches with 150 ns spacing) and faster ramp (15 minutes long): without active feedback a cavity presents a very large impedance to the beam and that can drive Coupled-Bunch instabilities. We therefore switched all klystrons on. The 150 ns bunch spacing did not cause any problem. The proton run came to an end in October with 368 nominal bunches at 150 ns spacing (12% nominal ring intensity). However, with the increased number of injections, the injection dump would fire on occasion, triggered by radiation measured by the Beam Loss Monitors (BLM) and found above threshold. The problem was traced to a small amount of beam, un-captured at each injection, and slowly drifting in the machine. See [1] for more details.

At 3.5 TeV the Synchrotron Radiation damping time is about two hundred hours. The target for longitudinal emittance blow-up growth time caused by RF noise was 13 hours minimum at 7 TeV (equal to the synchrotron radiation damping time at that energy). RF noise was a major concern during LHC design: klystrons convert HV ripples in phase modulation whose frequencies are harmonics of 50 Hz, extending to 600 Hz in the LHC. During acceleration the synchrotron frequency crosses the 50 Hz line and problems were expected. The LLRF was therefore designed to reduce noise sources and minimize their impact on the beam. Figure 4 shows the bunch length evolution during fill 1444. Observe the fast bunch lengthening during the first 60 minutes at 450 GeV (250 ps/hour), the reduction caused by the 15 minutes long acceleration ramp with controlled emittance blow-up, and the slow 15 ps/hour 4σ lengthening during physics.

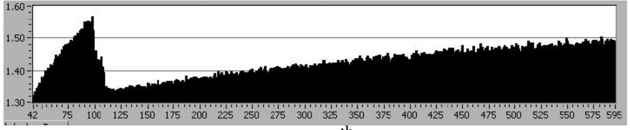


Figure 4: Fill 1444, Oct 26th, 150 ns spacing, 368 bunches. Horizontal axis in minutes. Vertical: 4σ bunch length in ns. The above data have not been corrected for the bandwidth of the measurement chain. The bunch length is over-estimated by 100-200 ps.

RF NOISE AND BEAM DIFFUSION

Beam diffusion caused by RF noise is a very important issue in hadron colliders. The observed intensity lifetime was very good in 2010. Still the RF team made a series of measurements and studies to better understand the sources of RF phase noise in the LHC and its effect on the beam. The LHC LLRF has a two-levels hierarchy [4],[5]:

- We have one **Beam Control** per ring, located on the surface. It uses beam-based measurements (phase averaged over all bunches), updates once per turn (11 kHz rate) and generates a fixed amplitude RF reference (VCXO) sent to all eight Cavity Controllers.
- Each cavity has its private **Cavity Controller**. It uses klystron and cavity field measurements, updates at the bunch frequency (40 MHz) and generates the klystron drive. It includes a Klystron loop to reduce klystron amplitude and phase ripples, and a strong RF feedback loop.

Figure 5 shows the Single Side-band (SSB) phase noise (in dBc/Hz) of the Vector Sum of the eight cavities B2 (green) compared to the RF reference generated by the Beam Control (blue), with no beam in the machine. The RF feedback closed loop bandwidth is 300 kHz (single sided). The noise in the Beam Control reference RF (VCXO) dominates at low frequencies (below 200 Hz). Imperfect compensation of the driver and klystron 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 (noise added by the cavity antenna demodulator).

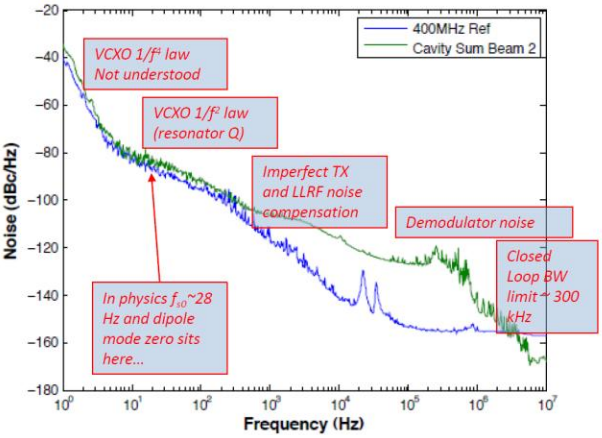


Figure 5: SSB phase noise *L(f)* (in dBc/Hz) of the Vector Sum of the eight cavities B2 (green) compared to the RF reference (blue). No beam.

If the beams were to sample the phase noise as represented in figure 5, the intensity lifetime would be less than one hour. The problem is the very low synchrotron frequency (28 Hz) that samples a large level of phase noise Power Spectral Density (PSD) caused by the $1/f^2$ phase noise characteristic of the VCXO. The LHC RF profited from the experience of SPS p-pbar RF operation. The Beam Control system was designed with a strong Beam Phase Loop (BPL) that compares the beam phase (averaged over all bunches of a given ring) with the cavity field Vector Sum and minimizes the error by acting on the VCXO input. Figure 6 shows the SSB phase noise of the Vector Sum with and without BPL.

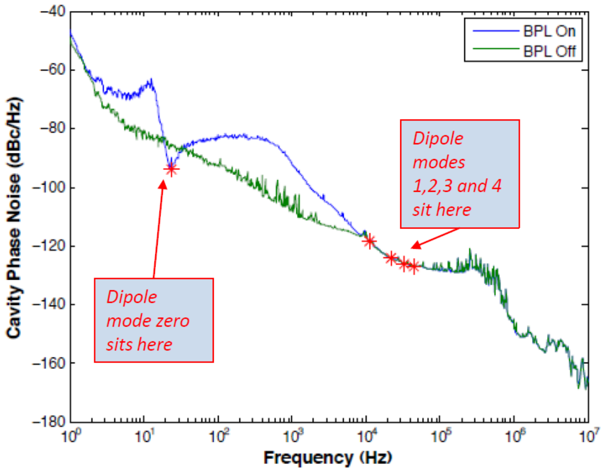


Figure 6: SSB Phase noise *L(f)* (in dBc/Hz) of the Vector Sum of the eight cavities B2 with Beam Phase Loop OFF (green) and ON (blue). Circulating beam at 3.5 TeV

The BPL reduces the noise on the dipole mode 0 synchrotron sidebands (f_{s0} ~ 28 Hz). Without it the phase noise at f_{s0} leads to 300-400 ps/hour bunch 4σ lengthening [6]. Notice how the Phase Loop actually increases the noise PSD outside the synchrotron band, below 10 kHz, but the beam does not react. As a bunch crosses the cavity at every turn, the revolution frequency sidebands are aliased into baseband and the RF noise in the bands $\pm n\, f_{rev} \pm f_{s0}$ will also excite the beam. As the BPL is clocked at the revolution frequency, it has no effect on the higher sidebands ($n \neq 0$).

By changing the BPL gain, we can modify the level of the phase noise PSD at the synchrotron frequency and observe the effect on beam diffusion. Figure 7 shows the 4σ bunch length of a bunch ($1\ 10^{10}$ p, 3.5 Tev, 8 MV RF) as the BPL gain is being varied. Without phase loop we get 400 ps/h for a SSB phase noise PSD of -85 dBc/Hz in a single synchrotron band. Bunch lengthening is proportional to the PSD sampled by the beam at the synchrotron frequency

$$\frac{d\sigma_\phi^2}{dt}=\frac{\Omega_s^2}{4}S_{\phi\phi}(f) \tag{1}$$

Where $S_{\phi\phi}(f)$ is the Phase Noise PSD in rad^2/Hz. Neglecting amplitude noise we have

$$S_{\phi\phi}(f)=2.10^{\frac{L(f)}{10}} \tag{2}$$

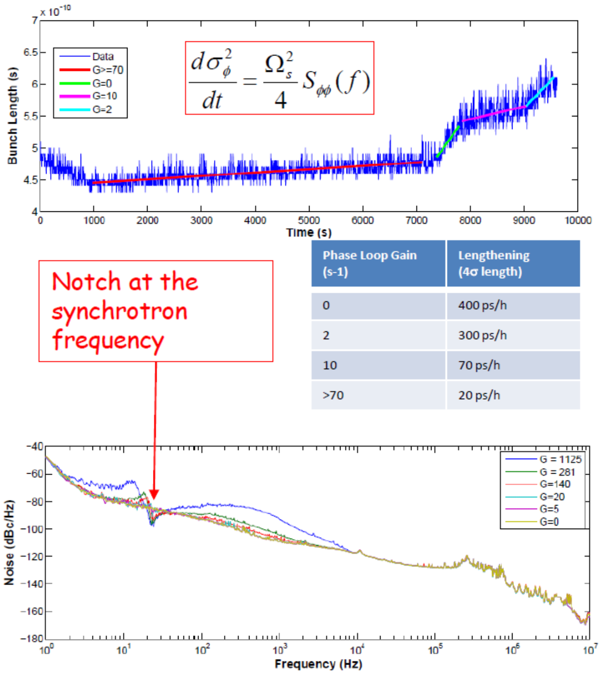
To achieve 10 ps/h 4σ–lengthening, the SSB PSD must therefore be below

$$-85-10\log[40]=-101\text{dBc/Hz} \tag{3}$$

In the 300 kHz of the noise BW we have 60 such bands (figures 5 and 6). The noise floor PSD for 10 ps/h is therefore

$$-101-10\log[60]=-119\text{dBc/Hz} \tag{4}$$

As we measure a noise level of ~ -125 dBc/Hz from 10 kHz to 300 kHz, the 4σ bunch lengthening caused by RF noise can be estimated around 2.5 ps/h. Please consult [6] for more details. More measurements on Beam Diffusion were done in Nov. 2010 while operating as Lead ion collider [7]. The results fit very well with the above figures.



Phase Loop Gain (s-1)	Lengthening (4σ length)
0	400 ps/h
2	300 ps/h
10	70 ps/h
>70	20 ps/h

Figure 7. Top: 4σ bunch length while varying BPL gain. Bottom: SSB Phase Noise *L(f)* in dBc/Hz in one cavity. The synchrotron frequency is ~ 28 Hz

CAPTURE REVISITED

With 7.2 MV RF at 200 MHz, the SPS bucket has a 3.0 eVs area and $\pm 10^{-3}$ Δp/p momentum half height. After longitudinal blow-up in the SPS ramp the bunch has a 1.5 ns 4σ-length and $\pm 4.5\ 10^{-4}$ Δp/p, resulting in 0.51 eVs emittance. The matched capture voltage in the LHC is between 2.5 MV and 3 MV at 400 MHz. In 2010 we have captured with 3.5 MV, resulting in a 0.94 eVs bucket area and $\pm 6\ 10^{-4}$ Δp/p bucket half height (figure 8).

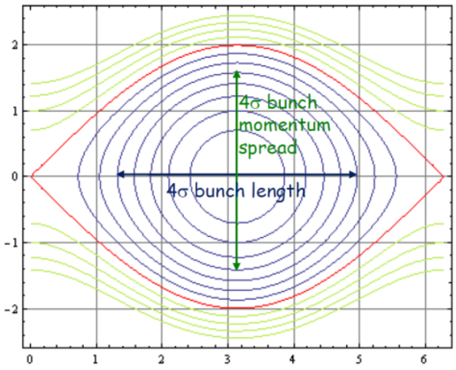


Figure 8: Trajectories in normalized phase space (ϕ, $1/\Omega_s\ d\phi/dt$) at capture in the LHC with 3.5 MV RF. The separatrix is marked in red. The 4σ length and momentum spread of the injected bunch are marked in blue and green respectively.

Losses are small (< 1 %) but cannot be zero because a significant portion of the bunch (13.5 % for a pure two-dimensional Gaussian distribution) is outside the marked 4σ boundary. The SPS bucket being much larger than the LHC bucket (twice longer, 70% taller and more than three times the area), part of the injected bunch falls outside the LHC bucket. Reducing the SPS bunch length is not a long-term solution as shorter bunches will not be stable in the SPS at nominal intensity (25 ns spacing). What we can do is to increase the LHC RF voltage at injection to capture more off-momentum particles. In 2011 we will experiment with a strongly mismatched voltage (5-6 MV) during filling. Calculations are being done, taking the exact SPS conditions, to predict the LHC capture loss for varying LHC injection voltages [11].

LONGITUDINAL DAMPER

The Beam Phase Loop minimizes the phase error averaged over all bunches. For the first injected batch it will efficiently damp any phase or energy error (if common over all bunches of the batch) via a proper modulation of the RF frequency. As more batches are injected, the injection error is given less and less importance in the average as it competes with the contributions from the quiet circulating bunches. That results in capture loss increasing with the number of injections.

The LHC does not have a dedicated longitudinal kicker. Unlike in the transverse plane, Landau damping is sufficient to keep the nominal intensity beam stable in the longitudinal plane. But some damping of the longitudinal errors would be highly desirable at each batch injection to minimize capture loss. With the strong RF feedback, we can precisely control the field in the RF cavities. In the LHC, small-signal field change is possible in ~1 μs [5], which is the time separation between the successive batches at injection. By quickly modulating the phase of the cavity field between the batches, we can give momentum kicks to the incoming batch only, while keeping the field quiet for the circulating bunches. PEPII used a similar system that they nicknamed the Sub-Woofer as it would take care of the lower frequency part of the damping bandwidth. (The high frequency part was sent to a real longitudinal wideband kicker).

The efficiency depends on the amplitude of the quadrature voltage step that the klystron can create in the cavity in 1 μs. We have measured 70 kV on a test stand [5]. As the klystron DC power has been since reduced from 300 kW to 200 kW, we will take the more conservative figure of 50 kV per cavity. With eight cavities the maximum momentum kick is therefore 0.4 MeV/c per turn, or 90 MeV/c per synchrotron period (f_{s0}~50 Hz). At injection the 2σ bunch energy spread is 202.5 MeV/c (±4.5 10^{-4} Δp/p). Our damper could reduce the energy error by 1σ bunch energy spread in a synchrotron period. That should be fast enough to avoid filamentation and to reduce capture loss significantly. It will be commissioned in 2011.

The longitudinal damper acting by modulation of the RF field phase looks promising for damping batch-per-batch injection errors but it does not have sufficient bandwidth to act on the bunch-per-bunch phase error in a given batch.

RF PROBLEMS IN 2010

The problems found with the RF power and the cavity conditioning are presented in a companion paper [8].

In operation we had problems with two cavities:

- RF noise on Cav4B1 was first observed towards the end of a physics fill on early morning Sept 26th. It was visible on the bunch length monitoring (the trace became a bit more noisy) but did not affect the luminosity. Later re-filling became impossible however as debunching was very fast at 450 GeV. The cavity was not operational for the rest of the run. We have replaced all modules in the LLRF and several suspicious cables and connectors. The cavity is in operation and being monitored closely.
- Cav7B2 became noisy at high current levels (48 bunches per batch) during the 75 ns scrubbing run (Nov 18th-19th). There was a clear correlation between the injections and the cavity field ripples. No problem was observed with the 150 ns spacing or with the injection of 24 bunches batches at 75 ns spacing.

All LLRF electronics worked perfect: we have more than 50 VME crates installed with ~400 VME modules of 36 different makes, all custom-designed. The only faults were caused by damaged cables and connectors: all SMC cables in the Cavity Controllers will be replaced with higher-quality during the 2011 technical stops.

SURVIVING A KLYSTRON TRIP

This section is concerned with the longitudinal Coupled-Bunch Instability caused by the impedance of the RF cavity at the fundamental. The growth rate and tune shift of coupled-bunch mode *l* (dipole only) can be computed from the cavity impedance. With I_0 the DC current and f_b the bunching factor (≤ 1).

$$\sigma_l + j\Delta\omega_l = -\frac{\eta\, q\, I_0 f_b}{2\beta^2\, \Omega_s\, E\, T_{rev}} \sum_{p=-\infty}^{\infty} \omega Z(\omega) \qquad (5)$$

With

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2} \qquad (6)$$

and

$$\omega = (p.h + l)\omega_{rev} + \Omega_s \qquad (7)$$

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 much by the LLRF feedback. The above equation can be used to analyze different configurations. The exercise was done independently by the author (using a simple linear model for the RF feedback loop and with a conservative bunching factor equal to one) and by the US-LARP collaboration (with a complex model including klystron non-linearity, finite bunch length and the exact configuration of the LLRF loops as recorded during the winter 2010 setting-up). Both results will be listed, with the one from the simple model first and the prediction from the more complex model between brackets. Stability is preserved if the growth rate is significantly smaller than the tune spread [9]

$$\sigma_l < \frac{\Delta\Omega_s}{4} \tag{8}$$

With tune spread function of the 4σ bunch length L

$$\Delta\Omega_s = \Omega_s \frac{\pi^2}{16}\left(\frac{hL}{2\pi R}\right)^2 \tag{9}$$

3.5 TeV conditions

We consider the following nominal cavity and longitudinal parameters: 14 MV total RF, cavities at half detuning (3 kHz), main coupler at position Q_L=60000, 1.2 ns bunch length (4σ) and nominal beam current 0.58 A DC. The synchrotron frequency is 31 Hz.

Configuration	**Detuning (kHz)**	**Growth rate simple model σ (s^{-1})**	**Growth rate exact model σ (s^{-1})**	**Tune shift Δω/2π (Hz)**	**Tune spread Δf_s (Hz)**	**$\Delta\Omega_s/4$ (s^{-1})**
1 cav with fdbk	3	0.013	0.005	0.07	4.4	7
1 cav fdbk off	3	1	0.87	1	4.4	7
8 cav with fdbk	3	0.1	0.04	0.56	4.4	7
7 cav with fdbk + 1 cav fdbk off	3	**1.1**	**0.91**	**1.49**	**4.4**	**7**

Figure 9: 3.5 TeV conditions with nominal beam and RF. Maximal growth rate for various configurations.

With RF feedback only, the maximum growth rate is $0.013s^{-1}$ per cavity ($0.005s^{-1}$ predicted with the more complex LLRF model) and the max tune shift 0.07 Hz/cavity while the tune spread is 4.4 Hz. The corresponding most unstable mode number is $l \approx -12$ (figure 10).

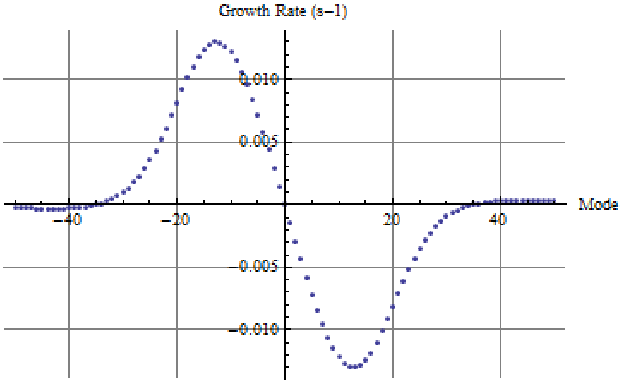


Figure 10: 3.5 TeV conditions with nominal beam and 14 MV total RF. Growth rates as a function of mode index l (dipole mode). Computed with the simple linear model.

So the 8 cavities will give a total growth rate of $0.1s^{-1}$ ($0.04s^{-1}$), that is two orders of magnitude below the $7s^{-1}$ Landau damping.

If a cavity trips during physics, it sits, without impedance reduction, at the 3 kHz detuning. Its contribution to the growth rate jumps to $1s^{-1}$ ($0.87s^{-1}$), with 1 Hz tune shift, still OK given the $7s^{-1}$ damping. From the stability point of view we can survive several klystrons tripping during physics. But the numbers are so good that further analysis is required: with Q_L=60000, the cavity single-sided -3 dB BW is 3.5 kHz. The 3 kHz detuning (very small for a high intensity machine) combined with the effective impedance flattened by the strong RF feedback over a 600 kHz two-sided BW explain the very low growth rates: the terms p=-1 and p=1 cancel out in equation (5). But a small asymmetry in the feedback response will have a big effect on the growth rates. Figure 11 compares the effective cavity impedance with near-perfect adjustment of the RF feedback and with a five degrees alignment error. Figure 12 shows the respective growth rates. The largest rate is increased from 0.013 s^{-1} to 0.06 s^{-1}. Phase drifts are likely to happen in operation, caused by either aging or uncompensated klystron saturation effects. In the coming years we will study the feasibility of on-line optimization: we will measure feedback response, with circulating beam, by injecting noise with no Power Spectral Density in the synchrotron bands.

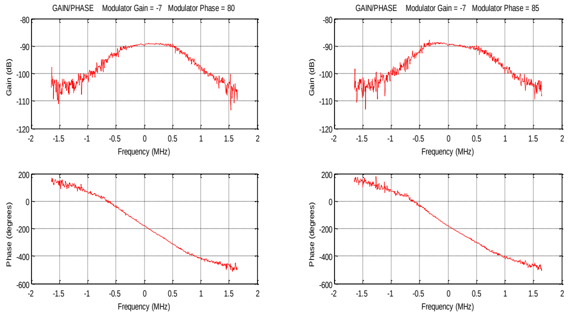


Figure 11: Effective cavity Impedance with near-perfect RF feedback adjustment (left) and 5 degrees offset (right). Simple linear model.

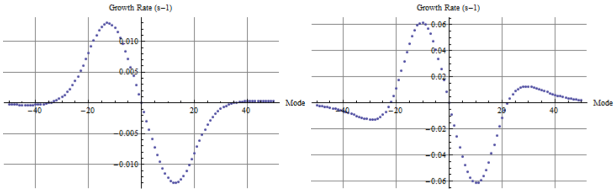


Figure 12: Growth rates corresponding to the situations of figure 11. Notice the different vertical scales.

When a klystron trips at nominal intensity, the beam induced voltage in the idling cavity will much exceed the safe 2 MV cavity voltage and the RF power dissipated in the load will exceed 300 kW [10]. Above half nominal, the RF will trigger the beam dump when one klystron trips to protect the idling cavity and its circulator load.

Another concern is the population of the abort gap with debunched beam following the abrupt voltage reduction caused by a klystron trip. In 2010 we have survived a trip of 3 out of 7 cavities during physics at 12% nominal current. This resulted in only 0.5 % debunched beam. The abort gap got populated but it cleaned naturally after ~18 minutes as the unbunched beam lost energy through synchrotron radiation and finally ended up on the momentum collimators [1]. Calculations are being done to compute the amount of unbunched beam expected to populate the abort gap following a klystron trip [11]. The 2010 precedent is very reassuring but the figure strongly depends on the actual bunch distribution. Both calculations and Machine Developments sessions (intentional klystron trip) are needed in 2011 to define the beam intensity at which a klystron trip is considered as safe. On the longer term, the solution is a compensation for a klystron trip by quickly increasing the voltage demanded from the remaining 7 cavities. This scheme is being studied.

450 GeV conditions

We now consider the situation during filling: 4 MV total RF, cavities at half detuning (10 kHz), main coupler at position Q_L=20000, 1.5 ns bunch length (4σ) and nominal beam current 0.58 A DC. The synchrotron frequency is 46 Hz. The Landau damping $\Delta\Omega_s/4=16s^{-1}$.

Configuration	**Detuning (kHz)**	**Growth rate simple model σ (s^{-1})**	**Growth rate exact model σ (s^{-1})**	**Tune shift Δω/2π (Hz)**	**Tune spread Δf_s (Hz)**	**$\Delta\Omega_s/4$ (s^{-1})**
1 cav with fdbk	10	0.2	0.19	0.3	10	16
1 cav with fdbk	5	0.1	0.135	0.15	10	16
1 cav fdbk off	10	15		2.4	10	16
1 cav fdbk off	5	8.5		3	10	16
1 cav parked	100	15-20	7.5		10	16

Figure 13: 450 GeV conditions with nominal beam and 4 MV total RF. Maximal growth rate for various configurations. Contribution per cavity.

With RF feedback only, the maximum growth rate is $0.2s^{-1}$ ($0.19s^{-1}$) per cavity and the tune shift 0.3 Hz/cavity, to be compared to a 10 Hz tune spread. The corresponding mode number is $l \approx -12$. The large growth rate (compared to the 3.5 TeV situation) is due to the large detuning that is not strictly needed with only 4 MV. Deviating from a strict half-detuning policy, and with 5 kHz detuning only, the growth rate drops to $0.1s^{-1}$ ($0.135s^{-1}$) per cavity.

So the 8 cavities will give a total growth rate of $1.6s^{-1}$ ($1.53s^{-1}$) or $0.8s^{-1}$ ($1.08s^{-1}$) for 10 kHz and 5 kHz detuning respectively. That is still comfortably below the $16s^{-1}$ Landau damping. Notice however that the margin is reduced compared to the 3.5 TeV case. The 1-T feedback would help at injection.

If a cavity trips towards the end of the filling, its contribution to the growth rate and tune shift jumps to $15s^{-1}$ and 2.4 Hz (10 kHz detuning) or $8.5s^{-1}$ and 3 Hz (5 kHz detuning). With the larger detuning we probably loose the beam on mode l=-1, while it should remain stable with the smaller detuning.

We conclude that a cavity trip towards the end of filling will make the beam unstable at nominal intensity with half detuning. It could be survived at half nominal.

Filling with one klystron off

If one klystron or cavity is off, we would “park” the cavity, that is detune it maximally (100 kHz detuning) and enter the coupler to reduce its Q_L to 20000. In the conditions considered above (4 MV total from the remaining seven cavities and nominal beam current 0.58 A DC) the growth rate caused by the un-damped cavity would be $20s^{-1}$ if its tune happens to be on a revolution frequency line and $15s^{-1}$ ($7.45s^{-1}$) if its tune is just in between two revolution frequency lines. Recalling the $16s^{-1}$ Landau damping at injection, we conclude that re-fill with one line off will not be possible much above half nominal.

Higher order Coupled-Bunch modes

In the above analysis we have considered dipole modes only. Following Sacherer’s formalism [9] we can compute a Form Factor F_m for each mode. With a 4σ bunch length in the 1-1.5 ns range and a resonator at 400 MHz, the dipole mode is excited much more than the higher order modes, validating the restriction of the above analysis to the dipole mode only.

LONGITUDINAL PARAMETERS FOR 2011

In 2011 it is intended to start physics with 75 ns bunch spacing, increasing the number of bunches to ~ 300. This would be followed by a short scrubbing run with 50 ns bunch spacing, then physics, reverting to 75 ns spacing, and further intensity increase to ~900 bunches (about one third nominal).

We keep the SPS longitudinal parameters unchanged: 7.2 MV RF @ 200 MHz and longitudinal blow-up to 1.5 ns (4σ) at transfer (0.51 eVs). While we have used 3.5-4 MV RF @ 400 MHz for capture in the LHC, we will experiment with higher voltages this year (5-6 MV). The voltage will be raised linearly during the momentum ramp to reach 12-14 MV at 3.5 TeV (we have used 8 MV in 2010), then kept at this level during physics. In 2010 the longitudinal blow-up during the ramp set the bunch length at 1.2 ns. We will experiment with settings in the 1ns range in 2011, resulting in a 1.5 eVs longitudinal emittance in a 5 eVs bucket (14 MV, 3.5 TeV).

CONCLUSIONS

In 2010 the LHC has made physics with 12% nominal intensity: 368 bunches with 150 ns spacing. The bunch lengthening (4σ-length) observed in physics was 15 ps/hour, probably mainly caused by IBS. There has been no visible effect of the RF noise. Neither did we find any problem related to the intensity increase until e-cloud effects put a stop to the raise.

RF reliability has been very good in 2010. The beam stability considerations presented above indicate that we can survive a klystron trip and operate with one klystron off, up to half nominal intensity. The RF should not be responsible for much down time in 2011 either. We do not expect big problems from the reduced bunch spacing (75 ns vs. 150 ns). The only clouds in this very bright picture are the problems observed with Cav4B1 (intermittent RF noise observed with and without beam) and Cav7B2 (RF noise observed with the injection of 48 bunches at 75 ns spacing). These two cavities are being monitored closely at start-up.

The longitudinal parameters will be optimized in 2011: the higher (mismatched) voltage at injection should reduce the capture loss. The higher voltage in physics allows for a smaller bunch length, and therefore better intensity lifetime, while keeping the longitudinal emittance about constant. Of course the overall effect on the luminosity must be evaluated.

A series of hardware upgrades will be commissioned through the year: the longitudinal damper is meant to reduce capture loss in multi-batch injection. The 1-Turn feedback will reduce transient beam loading. Depending on the optimal voltage for filling, we may implement operation of klystrons with varying DC parameters through the machine cycle [1].

We will continue the studies to identify the sources of RF noise and evaluate their effect on the beam. We will start investigating the longitudinal impedance of the machine.

REFERENCES

[1] P. Baudrenghien, The LHC RF: Operation 2010 and plans for 2011, Proceedings of the LHC Beam Operation Workshop, Evian, 7-9 Dec 2010

[2] T. Bohl *et al*, Controlled Longitudinal Emittance Blow-up in the SPS as injector and LHC Test-Bed, CERN-AB-Note-2003-084-MD, Dec 2003

[3] E. Shaposhnikova, Longitudinal beam parameters during acceleration in the LHC, LHC Project Note 242, Dec 2000

[4] The LHC Design Report, CERN-2004-003, June 2004

[5] P. Baudrenghien *et al,* The LHC Low Level RF, EPAC 2006, Edinburgh, UK

[6] T. Mastoridis *et al,* LHC Beam diffusion Dependence on RF noise: Models and Measurements, IPAC 2010

[7] T. Mastoridis *et al,* RF Noise Effects on Large Hadron Collider Beam Diffusion, to be submitted to the Phys. Rev. ST Accel. Beams

[8] O. Brunner, The LHC RF System: plans for the next long shutdown, these proceedings

[9] F.J. Sacherer, A Longitudinal stability criterion for bunched beams, IEEE Trans. Nucl. Sci., vol. 20, 1973

[10] J. Tuckmantel, Consequences of an RF Power Trip in the LHC, AB-Note-2004-008 RF, Jan 2004

[11] T. Argyropoulos, E. Shaposhnikova, Longitudinal parameters for a stationary bucket, to be published