THE LHC RF: OPERATION 2010 AND PLANS FOR 2011

Reported by P. Baudrenghien, CERN, Geneva, Switzerland
for the LHC RF Team*

Abstract

We will first briefly present the intended RF operation, as of the original Design Report. We will then review the 2010 operation: from the first collisions of single bunch pilot to the emittance blow-up required for nominal single-bunch intensity. RF noise will be briefly mentioned and results of bunch lengthening during physics will be presented. The difficulties to fill the machine given the intolerance of the Beam Loss Monitors to radiation created by capture loss will be reminded. Ions operation will not be covered. There will be a brief summary of klystron and cavity faults. The second part will address 2011 operation. The planned improvements will be presented (tools to ease energy matching, longitudinal damper, klystron DC settings). Finally the cavity impedance issue will be revisited with emphasis on the stability with RF feedback and the scenario of a klystron trip will be studied.

HOW IT WAS INTENDED TO WORK

The LHC is a high-current collider (more than 0.5 A DC nominal) and this brings two challenges for the RF: the Cavity impedance must be reduced by orders of magnitude to keep the beam stable and to control transient beam loading, and the RF noise must be minimized to achieve a luminosity lifetime in excess of 20 hours. The design was optimized for those [1]: low R/Q (45 Ω) Superconducting Cavities are used for their low impedance for a given accelerating voltage. These cavities are single-cell, each with a private klystron. This brings much flexibility for improving performance using a strong RF feedback [2]. Movable couplers allow for high bandwidth when needed (damping of injection transients) and high voltage during physics. The cavity loaded quality factor Q_L can be varied between 20k and more than 80k.

The LHC filling proceeds batch per batch in successive portions of the rings. To avoid phase errors while filling, the RF phase must be kept rigorously constant in the beam portion and in the no-beam portion, and this is achieved by the strong RF feedback. For a constant RF voltage, the transient beam loading will make the klystron demanded power different in the beam-on segment and in the no-beam segment, with the difference depending on the cavity tune. The "Half detuning" scheme was selected. It consists in detuning of cavity for half the beam current so that the power is identical during beam and no-beam portions, thereby minimizing the klystron peak power [3]

$$\frac{\Delta f}{f} = -\frac{1}{4}\,{}^{R}\!/\!{}_{Q}\,\frac{I_b}{V_{acc}} \tag{1}$$

where I_b is the RF component of the beam current and V_{acc} is the accelerating voltage per cavity. Once the half-detuning policy is enforced the klystron power is function of RF voltage, beam current and cavity loaded Q_L

$$P = \frac{1}{8}\frac{V_{acc}^{\;2}}{Q_L\,{}^{R}\!/\!{}_{Q}} + \frac{1}{2}Q_L\,{}^{R}\!/\!{}_{Q}\left[\frac{I_b}{4}\right]^2 \tag{2}$$

At injection a low Q_L is favourable for fast damping of momentum and phase errors. For 0.5 A DC (nominal current at the time), the original design proposed to use Q_L=20 k, 4.5 kHz detuning and 8 MV total (1 MV/cavity) at injection. The needed klystron power would be 167 kW. The 8 MV are well above matched capture voltage: in 2010 the SPS RF was set at 7.2 MV before transfer. The four-sigma bunch length was adjusted at 1.5 ns using longitudinal emittance blow-up. This results in 0.51 eVs. In the LHC the matched voltage would be 3.1 MV (0.51 eVs for a 1.5 ns bunch length). The Design Report was less optimistic on the SPS performances, specifying 0.7 eVs and 1.8 ns. This may indeed be the case with 25ns bunch spacing in the future. The margin in capture voltage may be needed with increasing intensity and emittance: there will be more bunch-to-bunch dispersion in the SPS bunch position (injection phase error) and length, and beam loading will be more severe. During physics the lifetime is limited by intra-beam scattering. The longitudinal emittance must be blown up to 2.5 eVs at 7 TeV. The intended RF settings for nominal intensity were 16 MV total with Q_L =60k and 2.25 kHz detuning at 7 TeV. The klystron power would have reached 270 kW for an RF saturation at 330 kW.

RF OPERATION 2010

Winter 2010. Single bunch towards nominal intensity

During the 2009-2010 shutdown, we had observed signs of overheating on the klystron collectors [4]. The supplier will modify the design but it will take several years before all sixteen klystrons are upgraded. Decision was taken to operate at reduced DC settings in 2010, thereby limiting the available RF power around 200 kW (instead of the nominal 330 kW). We first captured with 8 MV (Q_L =20k). At the end of the flat bottom the couplers were moved to Q_L =60k and the voltage raised to 12 MV before

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* **LHC RF Project Leader**: E. Ciapala; **Longitudinal beam dynamics:** E. Shaposhnikova, J. Tuckmantel; **LLRF and RF Control team:** M.E.Angoletta, L. Arnaudon, P. Baudrenghien, T. Bohl, A. Butterworth, F. Dubouchet, J. Ferreira-Bento, G. Hagmann, W. Hofle, M. Jaussi, S. Kouzue, D. Landre, J. Lollierou, J. Molendijk, J. Noirjean, A. Pashnin, J. Sanchez-Quesada, M. Shokker, D. Stellfeld, D. Valuch, U. Wehrle, F. Weierud; **Klystron and ACS cavities team:** O. Brunner, D. Glenat, P. Maesen, P. Martinez Yanez, C. Nicou, G. Pechaud, J. Pradier; **BE-OP :** D. Jacquet, G. Papotti; **US-LARP collaboration:** J. Fox, T. Mastoridis, C. Rivetta, D. Van Winkle, SLAC

starting the ramp. Ramp and physics with a constant 12 MV. Cogging worked very well: with the bunches injected to collide in the IPs at 450 GeV, the collision point does not drift during ramping. No need for rephasing at 3.5 TeV. The single-bunch cycle in the SPS produced low longitudinal emittances: around 0.25 eVs for the 5E9 p/bunch pilot and below 0.4 eVs for the 1.1E11 p/bunch nominal (SPS RF voltage 7.2 MV @ 200 MHz at transfer). The lifetime was very good. 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 shows the four-sigma bunch length evolution measured by the Beam Quality Monitor (BQM), during one of the early ramps. The BQM is the LHC version of the system developed for the SPS [5]. It was not calibrated at the time. The bunch on the flat top is actually shorter than the indicated 700-750 ps. With single bunch pilots, the bunch lengthening was around 30 ps/hour at the 450 GeV injection energy (8 MV) and 6 ps/hour at 3.5 TeV (12 MV).

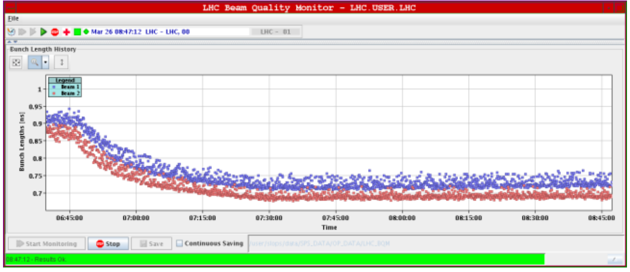

Figure 1: Four-sigma bunch length during the ramp. March 26. Single bunch pilot in both rings, ~ 0.2 eVs. 8 MV at injection (Ω_{s0} =65.3 Hz), increased to 12 MV before ramp (Ω_{s0} =80 Hz), constant 12 MV during acceleration ramp (Ω_{s0} =28.9 Hz @ 3.5 TeV).

Spring 2010. Ramping single bunch nominal intensity

At injection, the nominal intensity (1.1E11 p) single bunch was 1.2-1.3 ns long, 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).

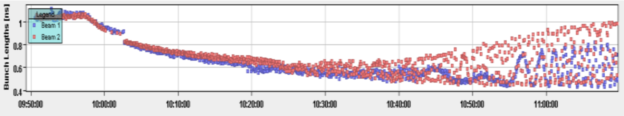

Figure 2: May 15th. First attempt to ramp nominal intensity single bunch. Bunch length during ramp. The longitudinal emittance is too low (< 0.4 eVs). The bunch becomes unstable when the length falls below 550 ps.

At the time longitudinal emittance blow-up was not available yet in the LHC but it was possible in the SPS [6]. So we decided to blow-up in the SPS to a 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 3.5TeV, with a length of 0.8-0.9 ns providing Landau damping sufficient to preserve stability (figure3).

Figure 3: Single bunch nominal intensity. Fast BCT and four-sigma 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.

Summer 2010. Longitudinal emittance blow-up in the LHC ramp

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 nominal intensity [7]. Blow-up in the LHC became operational on June 15th. The frequency of the synchrotron oscillation depends on the peak amplitude ϕ_{pk}

$$\Omega_s(\phi_{pk}) \approx \Omega_{s0}\left[1-\left(\frac{\phi_{pk}}{4}\right)^2\right] \tag{3}$$

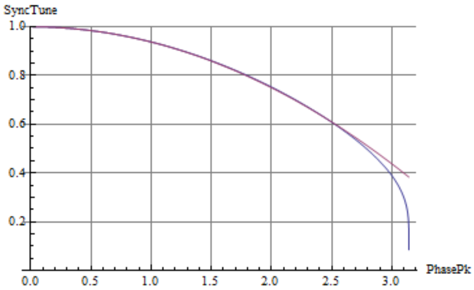

Figure 4: Ω_s/Ω_{s0} as a function of the maximum phase deviation in radian. Exact formula (bottom trace, blue) and approximation Equation (3). Non-accelerating bucket.

We modulate the RF with phase noise whose Power Spectral Density (PSD) covers only the synchrotron frequency band corresponding to the desired bunch length. For 1.2 ns four-sigma, we used

$$\frac{6}{7}\Omega_{s0} \le \Omega \le 1.1\Omega_{s0} \tag{4}$$

The upper frequency exceeds Ω_{s0} to be sure that we do not miss the core. Excitation is applied during the acceleration ramp. The spectrum of the phase noise tracks the changing Ω_{s0}. For a precise control of the bunch length we developed an algorithm that adjusts the amplitude of the excitation x_n from a measurement of the instantaneous bunch length (averaged over all bunches) L_n and comparison to the target L_0

$$\begin{aligned} & x_{n+1} = a.x_n + g.(L_0 - L_n) \\ & if \quad x_{n+1} \leq 0 \quad then \quad 0 \rightarrow x_{n+1} \\ & if \quad x_{n+1} \geq 1 \quad then \quad 1 \rightarrow x_{n+1} \end{aligned} \tag{5}$$

The diffusion is fast at the beginning of the blow-up and tends to slow down with time. The parameters *a* and *g* are functions during the ramp, optimized for a precise and smooth blow-up. The target bunch length L_0 was originally set at 1.5 ns with 5 MV, and later reduced to 1.2 ns with 8 MV. After blow-up to 1.2 ns we obtain an emittance around 1.6 eVs at 3.5 TeV, with 8 MV. We could then reduce the SPS bunch length to 1.5 ns (~ 0.5 eVs) at transfer to the LHC.

Figure 5: Sept 25th, fill 1372, 104 bunches/ring, 150 ns spacing. Bunch length and phase noise excitation level during ramping.

Another feature of the blow-up is the reduction of the dispersion in bunch length: at injection we would typically have ±200 ps variation between the various bunches. After blow-up in the LHC it would be reduced to ±40 ps. This favorable behavior, observed in the SPS also, is not very intuitive as the noise excitation is common to all the bunches of one ring.

Autumn 2010. Increasing the number of bunches, 150 ns and 50 ns spacing

Begin September we reconfigured the RF for higher intensity (batch of bunches with 150 ns spacing) and faster ramp: 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. So far we had observed no bunch lengthening in physics, beyond the 1.5 ns target bunch length. Suspicions came that some particles (the tails of the bunch) were lost out of the bucket. So it was decided to reduce the target bunch length to 1.2 ns and increase the voltage to 8 MV in order to keep 1.6 eVs emittance, sufficient to reduce the damaging effect of Intra-Beam Scattering. Capture voltage was set to 4 MV with a cavity Q_L=20k. To limit dissipation in the klystron collectors we set all cavities at 1 MV (~150 kW) and used ±60 degrees counter-phasing per pair. The counter-phasing was zeroed at the beginning of the ramp, then the voltage was increased linearly from 4 MV to 8 MV during the ramp. This resulted in a more gentle bunch length reduction than with the previous voltage rise in the parabolic part of the ramp only. The blow-up shown on figure 5 corresponds to these new RF settings.

The 150 ns bunch spacing did not cause any problem. 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. When the next bunch or batch is injected behind the previously injected one, the kicker deflects the un-bunched beam in the 8 μs long kicker window. This un-bunched beam then hits the TDI, causing radiation that propagates in the tunnel, hits the BLMs on the cold magnets downstream, and are wrongly considered as loss of circulating beam. The BLM system then triggers the dump. The situation worsens with the number of injections as the Beam Phase loop efficiency decreases. The sensitivity of the BLM towards capture loss was calibrated and we found the dump level to be at an un-bunched beam line density of 3.3E6 p/m or a maximum loss per injection of ~9E9 p (8 μs long kicker window). The above capture loss mechanism was studied in 2003 with the concern of un-bunched beam in the abort gap. The allowance was one hundred times larger than today's dump level [8]. The situation got even worse when trying 50 ns spacing in October: as bunches are placed closer together and with more intensity in the SPS, we have more dispersion in bunch position and length along the batch resulting in more un-captured beam [9].

Transfer from the SPS 200 MHz bucket into the LHC 400 MHz bucket cannot be done without loss. Unavoidable tails in the SPS 1.5 ns long bunch will fall outside the LHC bucket. The RF team hopes to keep capture loss below 1% per injected batch. With 4x72 nominal intensity bunches per batch, the 1% results in 3.2E11 p loss/inj, a factor 35 above the present dump level. To operate reasonably at nominal intensity, the sensitivity of the BLM dump system to injection loss must therefore be decreased by 2 orders of magnitude.

If the injection goes OK, the LHC can tolerate capture loss. On Oct 27th, with 368 bunches injected, 4.3E13 p total per beam, Cav4B1 started generating significant RF noise resulting in severe debunching. It was decided to start ramping anyway and 3.5 % of the total intensity got lost (1.6E12 p) on the momentum collimators (figure 6). The fill proceeded to physics smoothly.

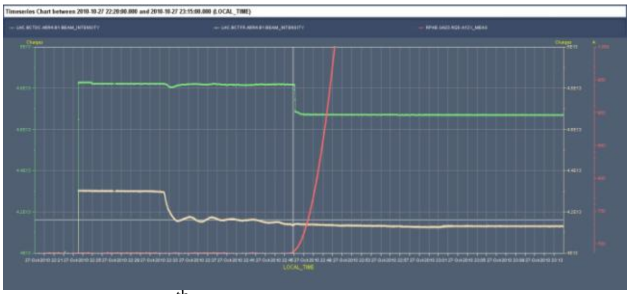

Figure 6: Oct 27th, fill 1450, 150 ns spacing, 368 bunches, 4.3E13 p total per beam. Beam 1 Fast BCT (beige), DC BCT (green) at beginning of ramp (red). The loss corresponds to 1.6E12 p.

Another interesting observation is the natural cleaning of the abort gap at 3.5 TeV. Later in fill 1450, the HV Power Supply feeding the first four klystrons of beam 1 tripped twice. Cav4B1 had been switched off-line following the noise problem mentioned above and the 8 MV re-distributed over the remaining seven cavities. When the power supply tripped, the voltage therefore dropped from 8 MV to 4.57 MV, resulting in small debunching and increase of bunch length (from 1.23 ns to 1.43 ns). The abort gap got populated at each trip. But the operation crew restarted the Power Supply and put the three cavities back on with barely any loss (figure 7).

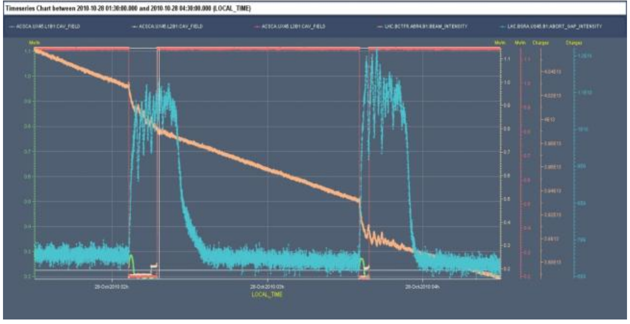

Figure 7: Fast BCT (orange) on a much enlarged scale, Abort Gap Population (blue) and Cav1B1, Cav2B1 and Cav3B1 field.

Notice that the cleaning of the abort gap does not depend on the time when the cavities are switched back on but takes place ~15 min after the cavities where switched off. That is the time for the debunched beam to move to the momentum collimator. The particles lost from the buckets loose energy through synchrotron radiation. The ones that were below the acceptance energy drift radially inwards till they hit the momentum collimator. The ones that had excess energy first surf on the buckets in phase space until they cross between buckets and move to the lower energy side. They then drift and hit the collimator.

The Cavity Controllers have a sequencer to handle this recovery after a trip. When a klystron or RF power converter trips, the LLRF loop settings (tuner position, klystron polar loop gain and phase) are frozen. When the veto condition is removed and OP sends the RF ON command, the voltage set-point gently returns to the demanded value and the loops are active again. Only the loss of cryogenic conditions on a module would make the RF fire the beam dump.

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 8 shows the bunch length evolution during fill 1444. Observe the fast bunch lengthening during the first 60 min at 450 GeV (250 ps/hour), the reduction caused by the 15 minutes long accelerating ramp with controlled emittance blow-up, and the slow 15 ps/hour lengthening during physics.

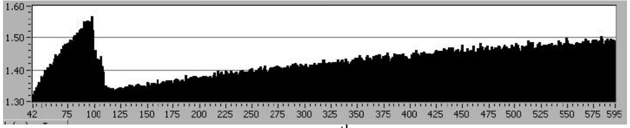

Figure 8: Fill 1444, Oct 26th, 150 ns spacing, 368 bunches. Horizontal axis in minutes. Vertical: bunch length in ns. The above data have not been corrected for the bandwidth of the measurement chain. The bunch length is over-estimated by 100-200 ps.

Figure 9 corresponds to the same fill. Shown are the profiles of bunch 1, beam 1 at various moments in the fill. RF noise was finally not a problem in 2010.

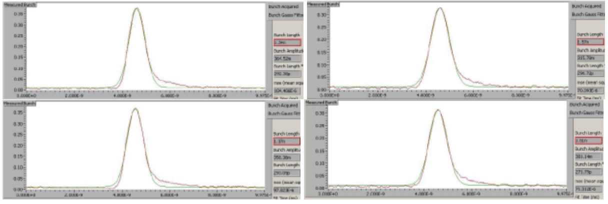

Figure 9: Fill 1444 as above. Longitudinal bunch profiles at different times, 3 GHz BW. Top left: injection, 1.34 ns long. Top right: start ramp, 1.57 ns long. Bottom left: end ramp, 1.37 ns long. Bottom right: end physics, 1.51 ns. The bunch length is over-estimated by 100-200 ps.

RF problems

The following problems were observed

- Waveguide arcing: the problem arose when increasing the beam current in fall. Arcing would happen close to the main coupler and was thought to be caused by radiation. It was solved by ANDing the detector signals by pair.
- Klystron vacuum: the fault affected K2B1 (klystron 2, beam 1) mainly. It was switched off-line for the remaining of the run and will be replaced during the shutdown.
- Main Coupler Blowers: false alarm from the air pressure detectors. The problem was solved by using

the air flow in/out temperature as redundant measurements for validating the fault.

- Oscillation in the filament heater circuitry in K2B1. There was a real problem with the Cathode Current tetrode. It has been replaced.
- Quenches: observed on all four modules but more frequent on M1B2 (module 1, beam 2). We have recorded one quench every two weeks on the average. These result in a beam dump triggered by the RF.
- Crowbar on the HV supply: there was a real problem with the thyratron for M2B1. It was replaced on week 42.
- Spurious in the klystron drive: we have observed three spurious lines at 340 kHz, 490 kHz and 670 kHz in the drive of all klystrons. It has no effect on the beam and is present without beam. It however requests a significant power from the klystrons. We will investigate it during re-commissioning.
- RF noise on Cav4B1: 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 problem could be reproduced without beam but never lasted long. It died out as soon as voltage or frequency was changed. We have replaced all modules in the LLRF and tried to put the cavity back in service on Oct 27th. After ten hours of quiet operation, the problem came back (figure 6). Cav4B1 has not been operational since. The problem must be understood.
- 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.

PLANS FOR 2011

The following new features will be developed and deployed through the year.

SPS-LHC Phase-Energy matching

Figure 10 shows the display used by the operation to monitor the SPS-LHC longitudinal injection transients in 2010.

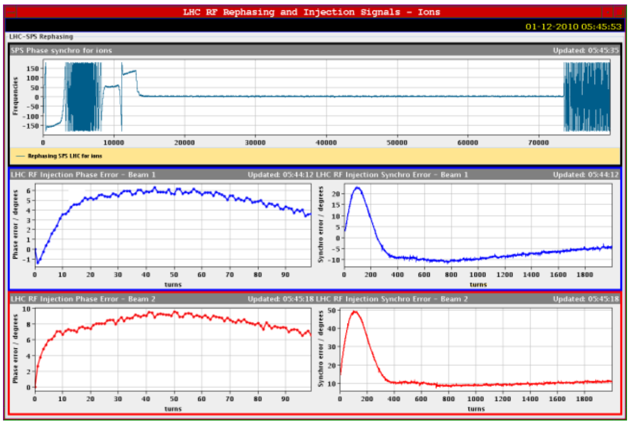

Figure 10: The top trace shows the LHC-SPS phase beat. It monitors the rephasing. The horizontal axis is labeled in SPS turn (23 µs/turn). The other four traces show: Phase Loop (left) and Synchro Loop (right) injection transients. Beam 1 (blue) and 2 (red). Horizontal axis in LHC turns (89 µs revolution period).

The OP crew would correct the injection phase error for each beam, estimate the energy (frequency) error from the Synchro Loop transients and trim the injection frequency to reach a best compromise between the two rings, while keeping the radial position of the circulating (captured) beam close to centre. An application will be developed to help the OP with these adjustments in 2011 (estimation of the errors and proposed corrections).

Longitudinal damper for injection errors

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 [2], 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 kicker).

In the absence of a real kicker, the LHC longitudinal damper will allow for the correction of the average phase and energy error at each batch injection. The bandwidth is not sufficient to correct for the bunch to bunch variations within a batch. The LLRF feedback loop can change the cavity field in 1 µs in the small-signal regime but, in order to give an effective momentum kick to the beam, we need klystron power to get the injection errors damped within a few synchrotron periods. Otherwise filamentation and loss will take place before sufficient damping effect. These considerations will be important for the optimization of the klystron DC settings in 2011 (see below). Dedicated Machine Development time will be needed.

Changing klystron DC settings between filling and ramping

In 2010 the klystron DC settings have been reduced to 50kV/8A to protect the collectors [4] resulting in a 400 kW DC power and a saturated RF power around 200 kW. We would like to operate with a used RF power between 100 kW and 150 kW because

- Below 100 kW RF, we dissipate more than 300 kW in the collector and that could lead to damage
- Above 150 kW RF the klystron gain drops as we get close to saturation. That makes the LLRF loops less efficient.

During physics in 2011, we plan to further increase the longitudinal emittance by raising the total voltage to 14 MV (1.75 MV/cavity). This is very close to the original design (16 MV). With Q_L=60k and 1.75 MV/cavity we need 142 kW per klystron with zero beam intensity and 155 kW at 1/3 nominal (0.193 A DC). These RF power levels are perfectly compatible with the present DC settings (50kV/8A). For the ions run in November we have operated reliably with 1.75 MV/cavity.

At injection, we will keep the voltage almost matched to the SPS emittance (4 MV total) and work with the lowest loaded Q (Q_L=20k). With 0.5 MV/cavity the needed RF power will be 35 kW with zero beam current and 39 kW with 1/3 nominal. That is not compatible with 400 kW DC power. It would result in too large a power dissipated in the collector (>360 kW). In 2010 we set all cavities at 1 MV and used ±60 degrees counter-phasing per pair to reduce the total voltage to 4 MV. But counter-phasing is not a solution with high beam intensity: the beam requires excess power from the klystron feeding the accelerating cavity and reduces the requested power in the decelerating cavity klystron. The solution is to operate with reduced klystron DC settings during filling. It will also increase klystron lifetime. As mentioned in the previous section, the actual needed peak power will depend on the longitudinal damper's needs. The scenario is

- Filling with 46kV/7.6A DC (350 kW DC) settings or somewhat below
- Change to 50kV/8A (400 kW DC) before ramp
- Ramp/physics with 50kV/8A

The variation of DC parameters with circulating beam and all LLRF loops operational has been tested on Oct 27th. The RF team needs time to commission it towards the end of the shutdown and with beam.

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 analysis is much simplified: we use formulas applicable to bunches short compared to the bucket width and consider dipole mode only. A more complete analysis will be presented at the Chamonix workshop. The growth rate and tune shift of coupled-bunch mode *l* (dipole only) can be computed from the cavity impedance

$$\sigma_l + j\Delta\omega_l = -\frac{\eta q I_0}{2\beta^2 \Omega_s E T_{rev}} \sum_{p=-\infty}^{\infty} \omega Z(\omega) \tag{6}$$

With

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2} \tag{7}$$

and

$$\omega = (p.h + l)\omega_{rev} + \Omega_s \tag{8}$$

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 by the US-LARP collaboration (with a complex model including klystron non-linearity, finite bunch length and fine optimization of the LLRF loops). 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 [10]

$$\sigma_l < \frac{\Delta\Omega_s}{4} \tag{9}$$

With tune spread function of the 4-sigma bunch length *L*

$$\Delta\Omega_s = \Omega_s \frac{\pi^2}{16}\left(\frac{hL}{2\pi R}\right)^2 \tag{10}$$

3.5 TeV conditions

We consider the following longitudinal parameters: 14 MV, cavities at half detuning (3 kHz), 1.2 ns bunch length (4-sigma) and nominal beam current 0.58 A DC. The synchrotron frequency is 31 Hz. $\Delta\Omega_s/4 = 7\mathrm{s}^{-1}$.

With RF feedback only, the maximum growth rate is $0.013\mathrm{s}^{-1}$ per cavity ($0.005\mathrm{s}^{-1}$ 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 mode number is $l \approx -12$.

So the 8 cavities will give a total growth rate of $0.1\mathrm{s}^{-1}$ ($0.04\mathrm{s}^{-1}$), that is a good order of magnitude below the $7\mathrm{s}^{-1}$ Landau damping. The growth rate is however very sensitive to the correct adjustment of the RF feedback Open-Loop phase. If that phase drifts by 10 degrees, the growth rate is multiplied by 10.

If a cavity trips during physics, it sits, without impedance reduction, at the 3 kHz detuning. Its contribution to the growth rate jumps to $1\mathrm{s}^{-1}$ ($0.87\mathrm{s}^{-1}$), with 1 Hz tune shift, still OK given the $7\mathrm{s}^{-1}$ damping.

In 2010 we have survived a trip of 3 out of 7 cavities during physics at 12% nominal current (figure 7).

Conclusions for 3.5 TeV

- From the stability point of view we can survive a klystron trip during physics
- However when a klystron trips at 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 [11]. Figure 7 shows a 200 kV beam induced voltage with 3.9E13 p and Q_L=30 k. Scaling it to nominal beam and Q_L=60 k, we get 3.3 MV that exceeds the maximum field at which the cavities are conditioned. **Above half nominal, the RF will trigger the beam dump when one klystron trips to protect the idling cavity and its circulator load**

450GeV conditions

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

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.

Conclusions for 450 GeV

- **Cavity trip towards the end of filling is fatal at nominal intensity with half detuning. It could be survived at half nominal**
- To keep Landau damping at injection we should not reduce the SPS bunch length below the present 1.5 ns
- When approaching nominal intensity we should re-consider the detuning during filling.

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 20k. 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
- 15s^{-1} (7.45s^{-1}) if its tune is just in between two revolution frequency lines

Conclusions

- Recalling the 16s^{-1} Landau damping at injection, **re-fill with one line off will not be possible much above half nominal**
- In 2010 we have operated comfortably with one line off at ~12% nominal

CONCLUSIONS

In 2010 the LHC has made physics with 12% nominal intensity: 368 bunches with 150 ns spacing. From the beginning of the intensity increase in September (batch injection with 150 ns spacing), the following longitudinal parameters have been used

- Filling: 1.5 ns long, 0.51 eVs bunches from the SPS (7.2 MV @ 200 MHz) captured with 4 MV RF (for a matched voltage between 2.3 and 3 MV)
- Ramping: linear voltage ramp from 4 MV to 8 MV. Longitudinal emittance blow-up to 1.2 ns length: as soon as the bunch length is reduced to 1.2 ns by the ramping, it is kept at this target value for the rest of the ramp
- Physics: 8 MV.

The bunch lengthening 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.

The main difficulty in 2010 has been the very high sensitivity of the BLMs to capture loss. A series of improvements are being made in the BI and CO groups (shielding, injection gap cleaning, sunglasses at injection). The longitudinal damper will also help. Machine Development time will be needed for its commissioning.

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 will start 2011 with the same longitudinal parameters as 2010, except for the RF voltage at 3.5 TeV that will be increased to 14 MV. We have used 1.7 MV/cavity during the ions run in November without problem.

On the RF hardware side the main operational difference with respect to 2010 will be the variation of the klystron DC settings (HV and Cathode current) between filling and start ramp. Time is required towards the end of the shutdown for measurement of the klystron characteristics at varying DC settings, plus some MD time for optimization with beam.

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 will be conditioned first as soon as the HV power supplies can be switched back on and we will concentrate on them in the last weeks of the shutdown.

REFERENCES

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

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

[3] D. Boussard, RF Power Requirements for a High Intensity Proton Collider, CERN SL/91-16 (RFS)

[4] A. Butterworth *et a*l, RF Performance and Operational Issues, LHC beam commissioning workshop, Evian 19-20 Jan 2010

[5] G. Papotti, A Beam Quality Monitor for LHC Beams in the SPS, EPAC 2008, Genoa, Italy

[6] 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

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

[8] E. Shaposhnikova, Abort Gap Cleaning and the RF System, Chamonix XII, 2003

[9] T. Bohl *et al.*, Longitudinal beam parameters and quality checks of the LHC beam in the SPS: further results and comparisons, CERN-AB-Note-2008-03, July 2008

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

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