LHC RF: 2012 PERFORMANCE AND PREPARATIONS FOR POST LS1 OPERATION

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Abstract

This paper presents the lessons learned through the RF system performance in 2012, the RF improvements in 2012, the RF plans for LS1, and the possible limitations on RF performance past LS1. An emphasis is placed on expected operation limits for operation with 25 ns bunch spacing, at 6.5 TeV, and/or with higher beam currents. Studies performed to improve understanding (single bunch and multi bunch intensity limits, beam spectrum and relation to heating) and to evaluate mitigation techniques for these limits are described. Development plans on new equipment are discussed. Of particular importance are the cavity set-point modulation technique, which significantly reduces the klystron forward power requirements, the longitudinal damper, batch-by-batch blow-up at injection, and the RF frequency cogging, essential for p-Pb operation.

2012 PERFORMANCE

The RF performed very well during 2012. The RF system did not limit the evolution of peak or integrated luminosity. The increased single bunch intensity (up to ≈ 1.65e11) did not introduce longitudinal instabilities or lead to klystron saturation. Klystrons were routinely operated with up to 165 kW per klystron at flat top (V_{RF} = 12 MV). Capture losses were negligible (below 0.5%) with the injection voltage at 6 MV (Figure 1). The abort gap and injection gap cleaning were on during injections.

The RF system was also readily available to varied modes of operation: manipulations of bunch length, RF gymnastics for p-Pb operation, and the 25 ns spacing run. A test was also conducted with lower RF voltage (6 MV) during the squeeze, with no noticeable improvement on transverse stability. RF phase modulation was also used to create longitudinally flatter bunches.

RF fault summary

The system reliability was improved over 2011. During the 2011 run there were 78 faults (2.08 per week in protons, 6.5 per week in ions). During the 2012 proton run there were just 43 faults (1.34 per week) as shown in Figure 2. Most of the faults were concentrated in short time periods, since they had a common cause. For example, the crowbar related issues in weeks 20 and 27-31, and the issues with the RF amplifier for station 4B1 in weeks 43-45. The related causes have been identified and cured. Outside these time periods, there were several weeks with no faults.

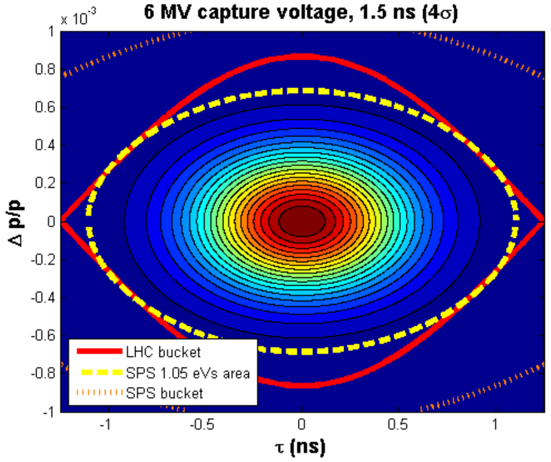

Figure 1: Comparison of SPS/LHC buckets and estimated bunch area at LHC injection (1.05 eVs). 4σ bunch length of 1.5 ns at injection.

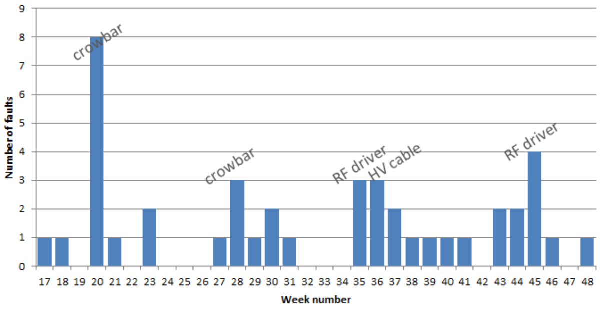

Figure 2: RF faults in 2012 (Courtesy D. Glenat).

In 2011 it was realized that cavity 3B2 cannot be operated reliably at 1.5 MV and above. Consequently, the cavity was operated with lower voltage in 2012, leading to a significant reduction in quenches, that contributed to the improved reliability.

There was also a rack recabling campaign in UX45 during the winter shutdown. All SMC cables were replaced by better quality cables. Since then, there were no more cabling related issues.

The RF system now employs about 800 interlocks. As a result there was only one serious debunching incident this year (5 in 2011).

On the other hand, there was a significant increase in crowbar inducing faults (from 11 to 20). Half of these faults took place in the first five weeks of the 2012 run

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and were attributed to one faulty solid state crowbar and one faulty thyratron. The rest are "real" crowbar events triggered by vacuum activity (arcing) in klystrons. There is some correlation of these events with klystrons being left at standby mode for extended periods of time. These events could be reduced after LS1 if the RF system is switched off when not in use.

The rest of the faults were separated into "unavoidable" faults and trips related to bad High Voltage contacts. The latter were either due to defective High Voltage connectors or to a damaged High Voltage cable (in September). The High Voltage cable has since been replaced and no more faults were observed. The High Voltage connectors have been upgraded, but due to the lengthy replacement process, they were only exchanged as needed. The upgrade campaign will be completed during LS1.

The good availability/reliability allowed us to make significant progress on our post-LS1 preparation during 2012.

NEW ITEMS FOR 2012

Batch-by-batch blowup

The batch-by-batch blowup was tested and commissioned during 2012 [1]. Its goal is to reduce the transverse emittance growth rates due to IBS by selectively blowing up the longitudinal emittance of the incoming batch at each injection. The technique worked well (Figure 3), but unfortunately, there was no measurable effect on luminosity. There are two explanations under investigation. First, it is possible that the IBS contributions to emittance growth are smaller than expected. Alternatively, it is suspected that smaller transverse emittances are achieved at flat top due to the action of the batch-by-batch blowup, but they are not preserved to physics. It was hard to test the latter explanation, since the BSRT was not available and there were no transverse emittance measurements. Operation with the Batch Compression, Bunch Merging and Splittings (BCMS) scheme beam and the corresponding higher brightness, or with higher single bunch intensities could show a more clear improvement.

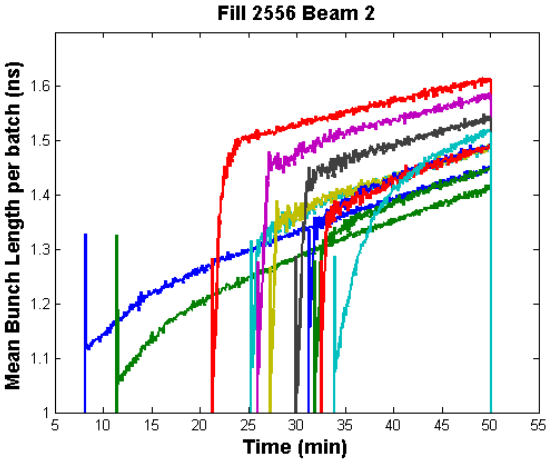

Figure 3: Mean bunch length per batch, fill 2556, Beam 2. First two batches are not blown up.

Cogging/Rephasing

Cogging/rephasing of the two rings at flat top is necessary for the p-Pb run. A technique was developed, tested, and used for a p-Pb physics fill and for MD purposes (two-beam impedance MD). The process starts by accelerating (decelerating) one beam to an off-centered orbit. After time t, the relative phase of the beam has drifted by $\Delta\phi = 2\pi\Delta f t$. If only one beam is moved, the crossing azimuth drifts by half that value. When the desired position is reached the beam is decelerated (accelerated) back to the centered orbit. Figure 4 shows the results during a p-Pb ramp. The difference of the two RF frequencies is evident during the ramp. The frequencies are kept apart until flat top, then the beams are rephased to make buckets 1 cross in IP1 and IP5 (as shown by the ATLAS BPTX signal). There is no evidence of an increase in the abort gap population during this process. Improvements were implemented to make the process more adiabatic for the 2013 p-Pb run.

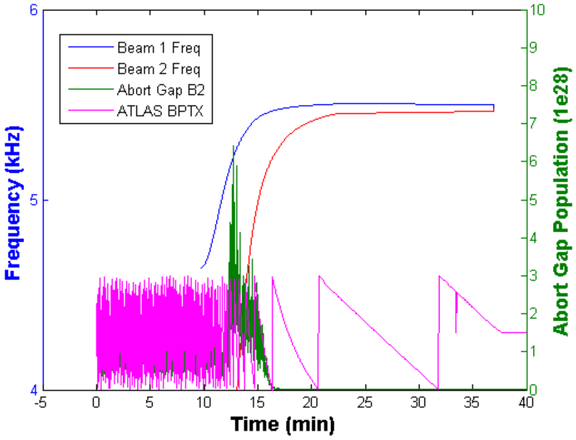

Figure 4: RF frequencies for the two rings during p-Pb ramp. ATLAS BPTX and abort gap population for Beam 2 also shown.

New Diagnostics

During 2012 new RF diagnostics were made available to the CCM (fixed displays for CCC) and/or TIMBER. These include the average beam spectra which are particularly useful to analyze the effect of bunch spectrum on heating (Figure 5), individual bunch profiles (Figure 6), and the cavity sum phase noise which can help identify the cause of debunching incidents (Figure 7). Finally, an implementation of the Beam Quality Monitor (BQM) with faster sampling rate (≈1 second between samples, down from 4 seconds/sample) was tested at flat bottom.

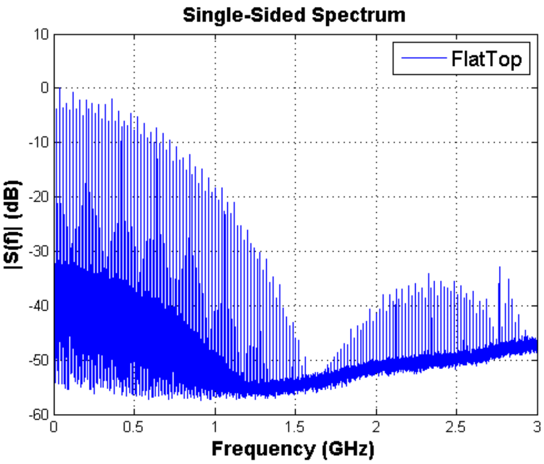

Figure 5: Average beam spectrum at flat top.

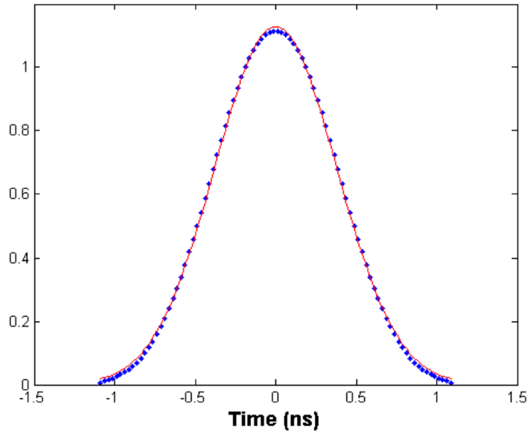

Figure 6: Single bunch profile with high sampling rate scope in UX45 (40 GSamples/second).

ANTICIPATED LIMITATIONS AFTER LS1 AND ACTIONS TAKEN

25 ns, 6.5 TeV implications

The higher beam energy implies lower thresholds for longitudinal single and multi bunch instabilities [2]. As a result, the longitudinal emittance blowup is absolutely necessary to guarantee stability. As long as the same operational scheme of a constant bunch length during the ramp is used, the stability margins will be maintained [3], [4].

The higher beam energy also implies a significantly reduced synchrotron radiation damping time, which might result in bunch shrinking at flat top. For 7 TeV operation, a 63-hour IBS growth time and a 12.9-hour radiation damping time have been estimated [5], resulting in a total emittance damping time of 16.2 hours. If this becomes an issue, it should be possible to modify the existing blowup algorithms for use at flat top.

The RF system is more affected by the possible increase in beam current due to 25 ns spacing. Such an increase implies higher demanded klystron power and reduced margin for coupled-bunch instabilities. If the higher beam current is reached through a single bunch intensity increase, thresholds for single-bunch longitudinal instabilities should be investigated.

During 2012, various actions have been taken, studies conducted, and new algorithms developed to either confirm sufficient margins of operation or adapt the RF system appropriately for higher beam current.

Power limits: Cavity Voltage Setpoint Modulation

The RF/LLRF systems are currently setup for extremely stable RF voltage (minimize transient beam loading effects). Less than 1° (7 ps) cavity phase variation along the turn is achieved as a result (Figure 8). If this scheme

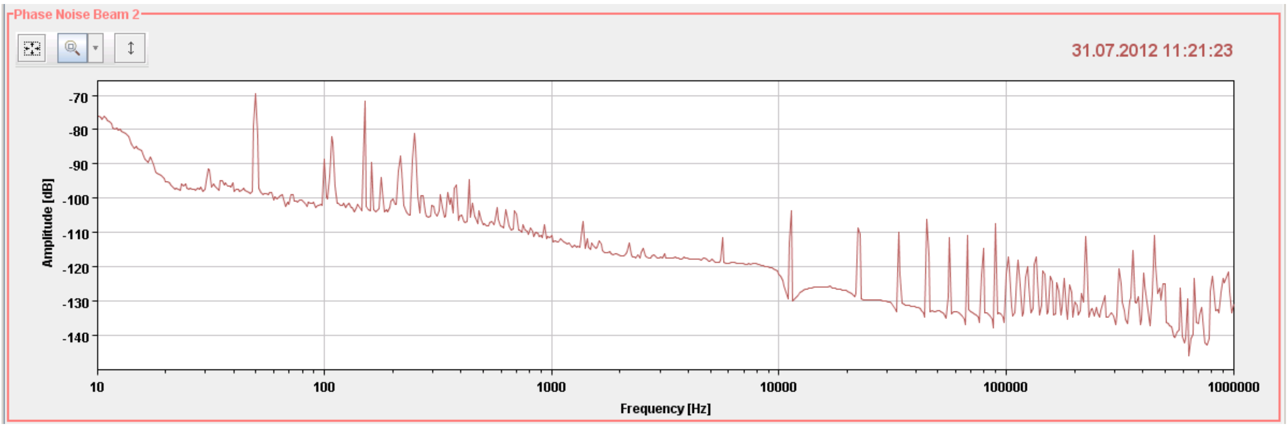

Figure 7: Cavity Sum Phase Noise in stable beams (Beam 2). The lines at the revolution frequency harmonics are a result of the small residual uncompensated beam loading. Also visible are the 50 Hz line and its harmonics, as well as the mechanical resonances of the cavity tuner.

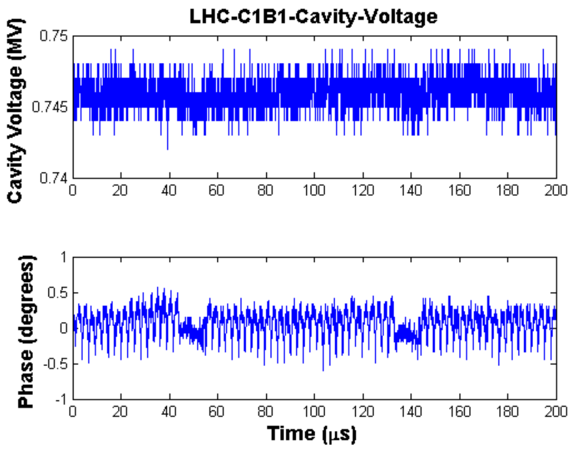

Figure 8: Cavity amplitude and phase with 2100 bunches, 25 ns spacing (≈ 0.4 A DC). The gaps between batches and the abort gap are visible in the phase plot.

is preserved, more than 200 kW of klystron forward power would be required for 25 ns operation with nominal bunch intensity (≈ 0.58 A DC). Even though the klystrons are rated to 300 kW, this scheme cannot be extended beyond nominal due to the reduced margin of operation, variations among the stations, and transient behavior between the beam and no-beam segments of the turn [6].

The reduced margins were evident during the short 25 ns run in 2012, when to cope with the first two ramps of 72 bunch trains at 25 ns spacing, the tuners and couplers had to be fine adjusted and the RF voltage at flat top reduced to deal with arcs in two different circulator loads during the first two ramps. It is also possible that this equipment is simply in need of conditioning at this higher power; either way, an alternative scheme for operation with beam current above nominal (and possibly earlier) would be helpful and absolutely necessary for the High Lumi LHC upgrade (2.2e11 protons/bunch, 1.1 A DC, 25 ns spacing).

With this new scheme, the beam induced cavity phase modulation in physics will be included in the cavity voltage setpoint for each bunch using an adaptive algorithm. As a result, the strong RF feedback and One-Turn feedback systems will not act on transient beam loading, but still continue regulating the cavity voltage, reducing the cavity effective impedance, and compensating for unwanted perturbations.

The trade-off of this scheme is that it results in a modulation of the bunch phase over a turn. This modulation though will only be ≈ 65 ps over a turn in physics, for ultimate beam (1.7e11 protons/bunch, 0.86 A DC, 25 ns spacing), compared to a 1.25 ns long bunch. Furthermore, the collision point shift will be much smaller in IP1 and IP5 due to the symmetrical phase modulation in the two rings.

The phase modulation would be more significant at 450 GeV. To avoid injection complications, the current scheme will be used during injection and then the adaptive algorithm will be switched on during pre-ramp. Since the RF voltage setting at injection is much lower, there is sufficient power available for transient beam loading compensation at 450 GeV.

The algorithm was tested during MD sessions in 2012 with very encouraging results [7], [8]. Figure 9 shows the significant reduction in klystron forward power achieved during the test. The power increases at injection with the old scheme (single 144 bunch batch). A few minutes later the algorithm is switched on and the power returns close to the pre-injection levels. Figure 10 shows the resulting cavity phase modulation during a similar test with a half-full machine (654 bunches). This filling scheme actually results to the highest possible phase modulation (≈ 30° or 210 ps).

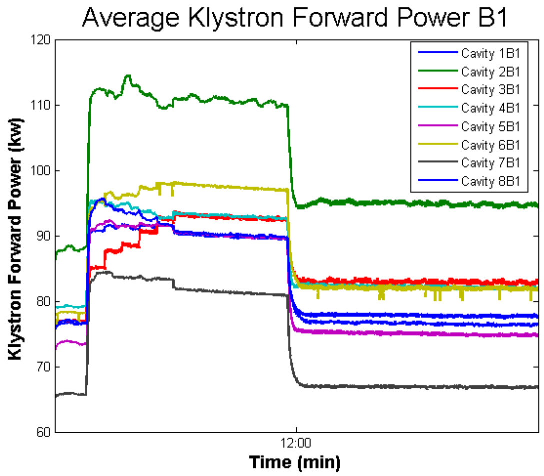

Figure 9: Average klystron forward power during cavity phase modulation MD. 144 bunches.

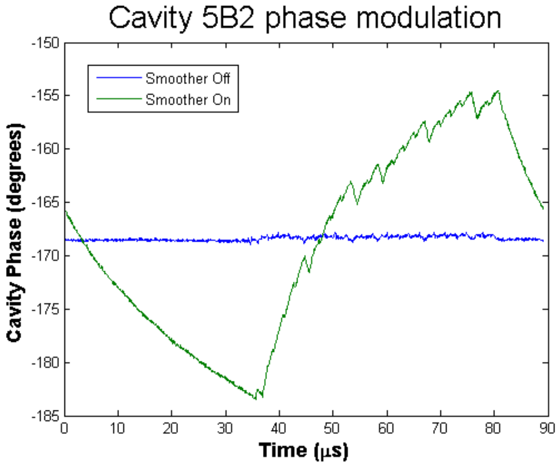

Figure 10: Cavity phase over a turn during cavity phase modulation MD. 654 bunches.

It is important to note that with this scheme the klystron forward power requirements are independent of beam current. As a result, the existing RF system will be sufficient even for High-Lumi LHC. A further positive side effect of the new scheme and higher cavity detuning is the reduced reflected power and beam induced voltage in the case of a klystron trip [6].

Longitudinal Single-bunch Stability

As mentioned above, as long as the bunch length is kept constant during the ramp through the emittance blowup action, the stability margin is similar at flat bottom and flat top [2]. Dedicated MDs and observations during the High-pile MD were used to estimate the single-bunch stability threshold. In the latter case, two bunches per ring with intensities up to 3e11 and emittance from $\approx$ 0.6 eVs at flat bottom to 2.6-2.9 eVs at flat top (bunch dependent) were stable throughout the cycle, as shown in Figure 11 [9]. The beam phase loop was on for this test. Even though the action of the beam phase loop is limited to mode zero motion, some coupling to other modes is possible with a small number of bunches. Consequently, this result is encouraging, but not necessarily reproducible with longer bunch trains.

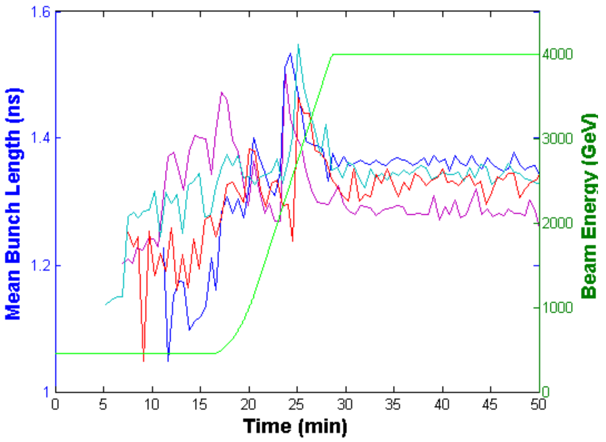

Figure 11: Bunch lengths during the ramp to 4 TeV. 4 bunches. High-pileup MD.

During dedicated MDs, bunches of up to 2.4e11 and $\approx$ 0.6 eVs were stable at 450 GeV. Longitudinal instabilities developed during the ramp with the beam phase loop off [10], [11]. Bunches with residual oscillations from injections were more unstable during the ramp. The longitudinal damper acting on the injection oscillations should help. Figure 12 shows the emittance and energy of the bunches when the instabilities appear. Not surprisingly, they approximately follow the emittance curve for a bunch of constant bunch length.

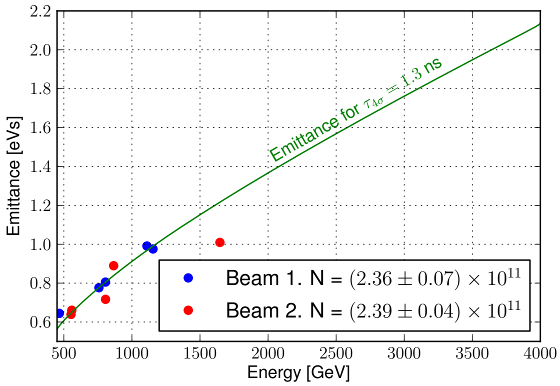

Figure 12: Loss of Landau damping as a function of emittance during the ramp. Courtesy J. Esteban Muller [11].

Longitudinal Coupled-bunch Instabilities

A factor of four stability margin on longitudinal coupled-bunch instabilities (CBI) due to the fundamental impedance of the 400 MHz cavities has been estimated, even with ultimate LHC beam (1.7e11 protons/bunch, 0.86 A DC, 25 ns spacing) [6]. An MD at 450 GeV was conducted to validate these estimates and prove that longitudinal CBIs due to the cavity fundamental impedance are not an issue for higher beam currents. To achieve this, the RF feedback gain was reduced and the most unstable coupled-bunch mode n was excited by injecting narrow band phase noise in the cavity, centered at $nf_{rev} \pm f_s$ (dipole mode). Even after an 18 dB RF gain reduction (1/8 linear) and turning the 1-turn feedback off (comparable to a situation with more than 10 times higher beam current), the beam was stable. Figure 13 shows the Fourier decomposition of bunch-by-bunch phase acquisitions over 73 turns, repeated every 10 seconds. During the beginning of these acquisitions, mode $n = \pm 3$ was excited for 30 seconds. Based on previous estimates, this is the most unstable mode for the given reduced RF feedback settings used for this measurement. The excitation and subsequent damping are evident.

During normal operation, the beam was also stable when due to a LLRF fault, a cavity was in open loop (December 1^{st} 2012), in agreement with the above observations.

It should be noted that these estimates and measurements only consider the effect of the cavity fundamental impedance on coupled-bunch instabilities. Other structures could contribute to the narrowband longitudinal impedance.

Bunch Length vs. Longitudinal Distribution

In 2012, tests were conducted to check the feasibility of operation with shorter/longer bunch lengths. No show-stopper was discovered from the RF system. There were also no limitations in terms of heating, *assuming* the beam spectrum does not deviate much from the one during the

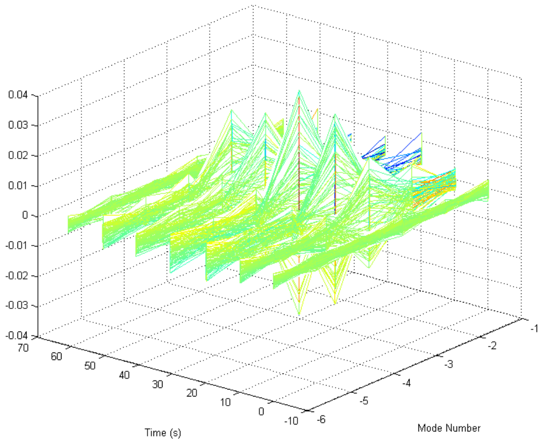

Figure 13: Modal decomposition of bunch phases. Growth and damping of mode -3 is evident.

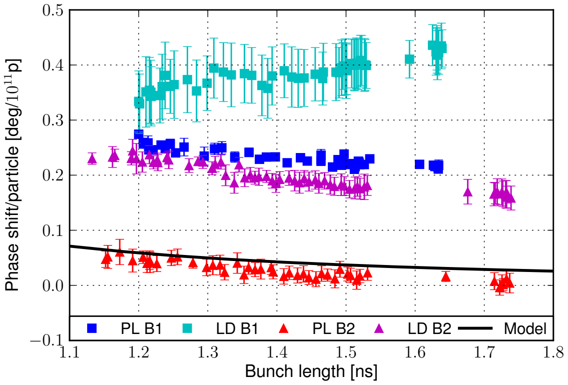

Figure 14: Stable phase shift for estimate of resistive broadband longitudinal impedance. Courtesy J. Esteban Muller [11].

test [12]. It should be noted though that the bunch length target has been slowly increased during 2011-2012 from the nominal 1 ns value to 1.25 ns. Reference [12] also reports on the tested “flat bunches” effect on heating.

An important lesson from 2012 operation was that the bunch length is a very useful and important, but sometimes limited metric: significant variations in the longitudinal distribution have been observed from fill to fill and from flat bottom to flat top (mostly due to the emittance blowup). These variations are often important; for example during heating exercises and longitudinal stability MDs. These variations should be taken into consideration before drawing conclusions on the heating of structures with narrow-band impedances.

Longitudinal Broadband Impedance Estimation

An effort was made to estimate the longitudinal broadband impedance through peak-detected Schottky [13] and stable phase shift measurements [14], as well as observations during the “flat bunches” test and the single-bunch stability MDs.

The stable phase shift measurements (resistive part of impedance) measured higher broadband impedance than expected. It is suspected though that systematic measurement errors are comparable or even higher than the actual phase shift contribution from the impedance (estimated to 0.05° per 1e11 protons for a bunch length of 1.4 ns). It might be possible to increase the resolution of these measurements through post processing the data. Figure 14 shows the stable phase shift with bunch length through two different acquisition modules for each ring, as well as the predicted behavior from the impedance model. Systematic errors seem to be present and to be different among modules.

During the “Flat bunches” MD, it was possible to estimate the reactive part of the broadband impedance to ≈ 0.2 Hz per 1e11 protons, through the varied reaction of different bunches on the very narrow and slowly changed phase modulation.

The Peak-detected Schottky measurements – useful for reactive broadband impedance estimates – were limited by the very small resulting quadrupole tune shift, especially for long bunches: 0.2 Hz per 1e11 protons at f_s for a bunch length of 1.4 ns. As a result, it is very difficult to distinguish such a shift in the Schottky spectra and to decouple it from longitudinal distribution effects. Figure 15 shows the peak-detected Schottky measurements for two bunches of comparable bunch length, but significantly different bunch intensities.

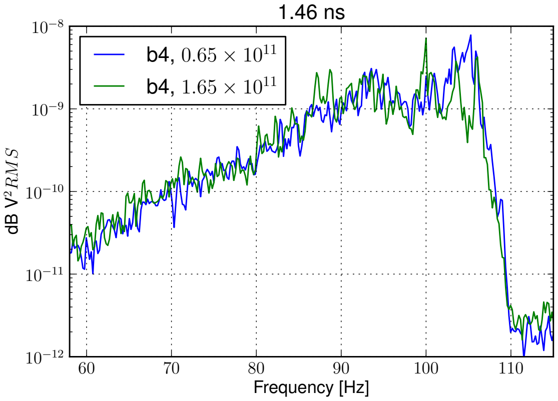

Figure 15: Peak-detected Schottky measurement, 1.4 ns bunch lengths, bunch intensities of 0.65e11 and 1.65e11 respectively. Courtesy J. Esteban Muller.

Through these estimates, it seems that the reactive impedance is comparable with and definitely not larger than the estimated and budgeted values ($\approx 0.06\ \Omega$ in Design Report, $\approx 0.09\ \Omega$ with later collimator design). It is harder to reach a conclusion on the resistive part.

Estimates based on the loss of Landau damping during the ramp with beam phase loop off seem to provide the highest resolution [4]. Simulations and estimations of the instability threshold during the ramp are necessary before a conclusion could be drawn though.

THE FUTURE: ACTIONS TO BE TAKEN

Module Replacement

The most significant intervention to the RF system during LS1, will be the replacement of the RF cryomodule M1B2. Since cavity 3B2 has been operating with a lower voltage since the start-up and to improve future reliability and availability, it was decided to replace the faulty cryomodule with the spare (Figure 16). Testing of the spare module was completed in August 2012. No quench was observed below 2.6 MV and the x-ray emissions around the module were an order of magnitude lower than for the faulty module. There is still some risk of degradation during transportation and mounting. To mitigate the risk of affecting machine operation, the replaced module will not be dismantled for repair before the new module is restarted and fully validated in the machine. New LHC spare cavities are being produced.

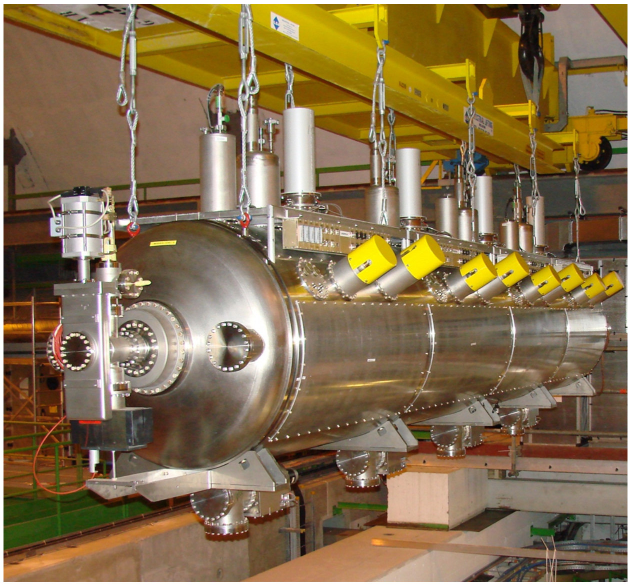

Figure 16: RF cryomodule (four cavities).

Further Diagnostics, New Systems

Injection oscillations with very slow damping times ($\approx$15 minutes) have been observed in the LHC since 2011 with 1.2e11 protons/bunch [15]. The situation has not degraded with the intensity increase to 1.6e11. Further studies are necessary to explain them. The Longitudinal Damper (under development) should help reduce the injection oscillations though. The new system has been tested in the lab and once with beam in the last day of 2012 operations. Analysis is in progress and further tests and commissioning are planned for the short 2013 operation. If emittance blowup is not sufficient to achieve longitudinal stability in the High-Lumi era, the Longitudinal Damper could also be of help with low order mode coupled-bunch instabilities, whereas a higher harmonic RF system could be used for other modes.

Tests of a faster BQM system are also planned for 2013.

During LS1, "Fast diagnostics" for amplitude and phase observations/logging for each cavity will be deployed. These modules will immediately point to the "noisy" cavity in case of a problem (such as saturation due to non-moving coupler, an issue that happened a few times in 2012) and help with RF debugging. A bunch-by-bunch phase fixed display should be developed during that time too. The data are already available, but some software work will be necessary. Finally, all RF VME front-ends will be moved to LINUX. This change will require rewriting and recompiling of software drivers.

Luminosity Leveling

In the later part of 2012, the RF voltage target for the end of the ramp was reduced from 12 to 10 MV. A few hours into the physics coast, the RF voltage was increased to 12 MV in one step, with a small ($\approx$2%) increase in luminosity.

Following this scheme, the longitudinal stability margin could be exploited for luminosity leveling. The RF voltage at the end of the ramp could be further reduced – as long as some stability margin is maintained – and then slowly increased during the physics coast, providing some amount of luminosity leveling.

CONCLUSIONS, ACKNOWLEDGMENTS

In conclusion, 2012 was a very successful year for the RF system, with improved performance and increased flexibility for new modes of operation, MD requirements, and the p-Pb run.

RF preparations for post-LS1 operation are well under way. During LS1, the RF emphasis will be on the cryomodule replacement.

Many people have contributed with material for this paper. The reported work though would not have been possible without the dedication and hard work of all RF group members.

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