Cavity Voltage Phase Modulation MD blocks #3 and #4
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Summary

The LHC RF/LLRF system is currently setup for extremely stable RF voltage to minimize transient beam loading effects. The present scheme cannot be extended beyond nominal beam current since the demanded power would push the klystrons to saturation. For beam currents above nominal (and possibly earlier), the cavity phase modulation by the beam (transient beam loading) will not be corrected, but the strong RF feedback and One-Turn Delay feedback will still be active for RF loop and beam stability in physics. To achieve this, the voltage set point should be adapted for each bunch. The goal of these MDs was to test the firmware version of an iterative algorithm that adjusts the voltage set point to achieve the optimal phase modulation for klystron forward power considerations.

1 Introduction

An early version of the cavity phase modulation algorithm was tested during MD block #2 on June 22\textsuperscript{nd}-23\textsuperscript{rd} to evaluate the algorithm performance and feasibility. The justification for the algorithm, the development process, and the initial results from MD block #2 are described in [1]. The motivation behind the cavity modulation algorithm is described in more detail in [2].

In the first test during MD block #2, the algorithm was implemented in Matlab. This choice provided the necessary flexibility for adjustments and measurements. On the other hand, it increased the time between iterations (≈20 seconds), requiring a significantly higher gain. The gain used was at least three orders of magnitude higher than J. Tuckmantel’s simulations used for the algorithm development [3]. As a result, the stability margin was significantly reduced and the beam phase change was not adiabatic.

The successful results of the first MD and the associated data and information, motivated a simulation campaign to aid with the firmware development. The simulations were very helpful in identifying firmware flaws and stability issues, and evaluating parameters to optimize the algorithm performance. Initially these simulations included a version of the algorithm acting independently on the in-phase and quadrature components of the cavity voltage [4]. Later, the simulations and firmware were adapted to use the error signal phase (cavity voltage minus setpoint) as the feedback variable. The results of these simulations are briefly summarized in Section 2.

The proposed firmware and parameter set were extensively tested in simulations and the LHC LLRF test stand and were used during MD blocks #3 and #4 with very encouraging results. Implementing the algorithm in firmware reduces the time between iterations to 1-2 turns, a million times faster than the initial test.

2 Simulations

As described in [4], the adaptive algorithm simulations were developed in Simulink. For testing purposes, a simplified model of the LHC RF system was used. Models of the Beam, Cavity, Tuner Loop, LLRF feedback, and Adaptive setpoint were included.

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The adaptive algorithm was tested in two stages. First, an ideal Simulink scheme of the whole chain was developed for initial debugging and testing. This initial model also allowed us to tune the time constants of the LLRF feedback and tuner loop to replicate the real values, as well as the time constant of the adaptive setpoint to achieve the desired behavior.

In a second stage, the actual VHDL firmware was tested by a ModelSim simulation that was inserted into the Simulink scheme as a black box, replacing the earlier Simulink model of the adaptive setpoint.

The simulations were very helpful in identifying some important firmware flaws, for example errors in the gain, sign, and phase calculation of the error variable, as well as issues with overflows in the processing chain. These flaws were corrected accordingly.

Figure 1 shows the increasing peak-to-peak cavity voltage phase modulation and corresponding reduction of the phase modulation in the generator (klystron) current, leading to a reduction of the klystron forward power requirements. Figure 2 shows the resulting adjustment of the cavity detuning through the tuner loop. The One-Turn feedback system is occasionally switched off in the simulations to reduce computation time. A gain $\approx 500$ times higher than planned for operation was used in the simulation to compensate for the large ratio between simulation and real time. The target time constant for the physical system is $\approx 175k$ turns (15.5 seconds), about ten times slower than the tuning system (tuner time constant $\approx 1-2$ seconds).

3 MD block #3

3.1 Experimental Conditions

The MD was performed on October 12th with nominal LHC conditions at 450 GeV. After the initial 12 bunches, batches of 144 bunches were injected as close as possible (925 ns) using filling pattern “50ns_1374b_1368_0_1262_144bpi12inj”.

Two fills were used during the MD (3162, 3163), the first with 150 bunches and the second with 654 bunches.

The klystron transient behavior depends on the length of the beam/no-beam segments in the machine. Therefore, a single 144-bunch batch (7.2 $\mu$s long) in the machine closely resembles the situation of a full machine with a 3.2 $\mu$s abort gap, but saves valuable MD time by reducing the injections. On the other hand, a half-full machine leads to the highest phase modulation along a turn, so the fill with 654 bunches provided very useful information too.
The LLRF system was in normal operation settings for 450 GeV during this MD (One-Turn Feedback was on). Cavity 3B2 is routinely operated with lower voltage due to arcing issues. The gain and “forgetting factor” of the adaptive setpoint algorithm were set to $2^{-16}$ and $1 - 2^{-24}$ respectively to achieve a time constant of about 12 minutes, much slower than the intended 15 seconds for future operation, to allow for measurements and observations. The update rate though was still once a turn.

Unfortunately, due to issues with the beam dump system, only beam 2 was available for just an hour and a half, reducing the amount of available data.

### 3.2 Average klystron forward power and cavity tune

For the first fill (3162), the algorithm was first switched on only for cavity 1B2 at 19:28. After careful observation and positive convergence, the algorithm was switched on for all cavities at 19:55 for 4 minutes.

Figure 3 shows the average klystron forward power during Fill 3162. The klystron forward power increase at 19:16 corresponds to the 144-bunch batch injection. The reduction in klystron forward power for cavity 1B2 when the algorithm was switched on at 19:28 is evident. Similarly for all other cavities at 19:55. The reduction amounts to 10-15 kW. Figure 4 shows the corresponding motion of the cavity tuner in relative steps (not proportional to the cavity detuning). As the cavity phase modulation increases and the klystron modulation decreases, the detuning of the cavity moves closer to zero. The tuners moved by approximately 3 kHz from the "half-detuning for peak current" [5] setting (~3.8 kHz) to the "full-detuning for the average RF current" setting (~800 Hz).

It should be noted that the algorithm was not allowed to converge in this first trial. After some observations with the algorithm on hold, Beam 2 was dumped at 20:12. The slow klystron forward power reduction throughout this fill is due to the reduction of the 400 MHz component of the beam current as the bunch lengthens quickly at 450 GeV due to strong IBS effects.

Figures 5, 6 show the average klystron forward power and tuner steps during Fill 3163. Six bunches were injected at 20:18, followed by multiple batch injections up to 654 bunches from 20:20 to 20:23. The small reduction in klystron forward power during the injections is due to the non-optimal cavity tuning, resulting in lower power requirement for the turn segments when beam is present. Therefore, as more batches are injected, the integrated power over a turn is reduced. The adaptive algorithm was switched on at 20:30 and off at 20:43. A 10-15 kW reduction of the klystron forward power was achieved, with a time constant comparable
to the estimated value of 12 minutes. The cavity tuners moved less in this case, since the "half-detuning" setting is equivalent to the "full-detuning" setting for a half-full ring.

Cavity 6B2 diverged halfway through this test. Subsequent analysis showed an interaction of the iterative algorithm with the very low frequency response of the RF feedback (close to $f_{RF}$). As a result, a filter was added in the iterative algorithm to reduce this coupling. The updated system was tested during MD block #4.

### 3.3 Klystron forward power and cavity voltage over a turn

Figures 7, 8 show the klystron forward power and cavity phase over one turn with the adaptive algorithm on and off. The resulting cavity phase modulation is approximately 9 degrees peak-to-peak. The peak-to-peak klystron phase is reduced by a comparable amount. It should be noted that the algorithm has not converged at this point, so the full reduction of the klystron phase modulation has not been achieved. The theoretically estimated cavity phase modulation at steady state is approximately 20° peak-to-peak, as shown in Figure 9.
3.4 Final setpoint and Bunch phase over at turn

Figure 10 shows the cavity phase at the end of the MD. There are substantial differences between the cavities, since the algorithm has not converged yet. These differences are accentuated by small differences in the cavity loaded Q values and the cavity detuning. Furthermore, cavity 6B2 was diverging as mentioned earlier and cavity 3B2 is operated with a different voltage.

With the final cavity phase adaptation, it is straightforward to compute the cavity sum phase and compare that to the beam phase. Figure 11 shows the resulting picture. It is not surprising that the beam is following the cavity sum phase.

3.5 Cavity sum phase noise

Figure 12 shows the cavity sum phase noise when the adaptive setpoint algorithm is on. As expected, noise is introduced at the revolution harmonics. This noise has a very narrow bandwidth though (a few Hz) and as a result it does not overlap with the synchrotron sidebands. Consequently, no negative effects on beam lifetime and diffusion were observed. During fills 3162, 3163, the bunch length growth was dominated by IBS and was unchanged when the adaptive setpoint algorithm was switched on.
4 MD block #4

4.1 Experimental Conditions

The MD was performed on November 27th with nominal LHC conditions at 450 GeV. After the initial 12 bunches, batches of 144 bunches were injected as close as possible (925 ns) using filling pattern “50ns_1374b_1368_0_1262_144bpi12inj”.

Two fills were used during the MD (3326, 3327). During fill 3326, an initial test was conducted with the gain and “forgetting factor” of the adaptive setpoint algorithm set to $2^{-18}$ and $1 - 2^{-26}$ respectively to achieve a time constant of about 4 minutes and allow for measurements and observations. After a successful quick first test, the values were set to the nominal $2^{-14}$ and $1 - 2^{-22}$ respectively (time constant of 30 seconds) for the rest of the MD. Similarly, the algorithm was tested with a single 144-bunch batch in the machine during the beginning of fill 3326 and after a successful result, additional batches were injected up to 654 bunches (half-full machine). The same scheme with 654 bunches was used for fill 3327.

The LLRF system was initially in normal operation settings for 450 GeV during this MD, but the One-Turn Feedback was switched off at points as necessary. It was realized that with the One-Turn Feedback off the algorithm converged with no problem to the theoretically estimated value for the cavity phase. With the One-Turn Feedback on, a couple of cavities showed signs of oscillation and the final cavity phase was less than the estimated value. This discrepancy is being studied.

4.2 Klystron forward power

Figure 13 shows the average klystron forward power during Fill 3327. A 6-bunch batch is injected at 11:40, a 144-bunch batch at 11:43, and then the batches are injected to reach 654 bunches. After the first 144-bunch batch injection, the average klystron forward power does not further increase due to the half-detuning setting. The adaptive algorithm is switched on at 12:00 and the klystron forward power is reduced in a matter of tens of seconds. As expected, the klystron forward power is now independent of beam current and comparable with the klystron power with no beam in the machine.

Figure 14 shows the klystron forward power over a turn with and without the adaptive algorithm. The amplitude of the klystron power are reduced, but the effect of the adaptive algorithm is more pronounced on the significant reduction of the klystron phase transients.
4.3 Cavity voltage over a turn

Figure 15, 16 shows the resulting cavity phase modulation of about 30° peak-to-peak. This phase modulation is very similar to the theoretically estimated value of about 35° peak-to-peak.

5 Conclusions

The new adaptive “feedforward” algorithm for adjusting the cavity set point in anticipation of the beam was tested during MD blocks #3 and #4 with 150 and 654 bunches. Due to beam dump system problems the MD was limited to beam 2 and a total time of 1.5 hours during MD block #3. The results were very encouraging. Significant klystron power reduction was observed (peak and average) and the final cavity set point phase modulation approached the theoretically estimated value. The peak-to-peak beam modulation reached 210 ps for the worse case scenario of a half-full ring (much smaller for a full ring). Even this value though is small compared to the approximately 1.2 ns long bunch. Since this modulation would be almost symmetric for the
two rings, it should not affect the LHC experiments. The algorithm and supporting software is in almost operational state. A negative interaction with the One-Turn Feedback has to be investigated. The algorithm stops short of the optimal value with the One-Turn Feedback on and is more susceptible to oscillations. Studies are conducted to determine the cause of this issue, as well as to improve the algorithm compensation of the transients between the beam and no-beam segments.

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References


