LHC ONE-TURN DELAY FEEDBACK COMMISSIONING

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Abstract

The LHC One-Turn delay FeedBack (OTFB) is an FPGA based feedback system part of the LHC cavity controller, which produces gain only around the revolution frequency (f_{rev} = 11.245 kHz) harmonics. As such, it helps reduce the transient beam loading and effective cavity impedance. Consequently, it increases the stability margin for Longitudinal Coupled Bunch Instabilities driven by the cavity impedance at the fundamental and allows reliable operation at higher beam currents. The OTFB was commissioned on all sixteen cavities in mid-October 2011 and has been used in operation since. The commissioning procedure and algorithms for setting-up are presented. The resulting improvements in transient beam loading, beam stability, and required klystron power are analyzed. The commissioning of the OTFB reduced the cavity voltage phase modulation from approximately six degrees peak-to-peak to below one degree at 400 MHz with nominal bunch intensity of 1.1e11 protons.

SYSTEM DESCRIPTION

Each LHC RF station consists of a single-cell superconducting cavity with a dedicated klystron and an LLRF system, including an OTFB system. The OTFB is a Cartesian Feedback using the baseband I/Q error signals: cavity antenna signal minus set point. It implements two identical filter chains in an FPGA, acting on the I and Q signals sampled at 40.08 MHz (bunch synchronous, $f_{RF}/10$) by 14 bit ADCs. Since the synchrotron frequency at the LHC is relatively low ($f_s \approx 55$ Hz at injection, 23 Hz in physics), the bandwidth of each f_{rev} comb is only about 100 Hz. The OTFB gain is approximately 20 dB. The bandwidth and gain are set to achieve the desired gain and phase margins. A detailed explanation of gain and bandwidth choices can be found in [1]. A complete report on the OTFB module has been published [2].

CONFIGURATION

To maximize the loop gain at the revolution harmonics without reducing loop stability margins, the OTFB system includes sufficient delay so that a full 360° phase shift is introduced between any two revolution harmonics [3]. It is thus appropriately named “One-Turn (delay) Feedback”. It is therefore critical to set the delay of the system correctly. The delay choice is complicated by the non-linear loop phase characteristics due to the limited bandwidth of the cavity-RF feedback-klystron system in closed loop. Therefore, an algorithm was devised to maximize the phase margin for *all* revolution harmonics within the band of the system [4].

To achieve this, the system is first characterized via a transfer function. Noise is injected right after the OTFB input switch and the resulting time domain signal is measured right before the switch, as shown in Figure 1, to determine the transfer function. This measurement is conducted with the cavity at nominal field, the main RF Feedback and Klystron Polar loops closed, and the OTFB open.

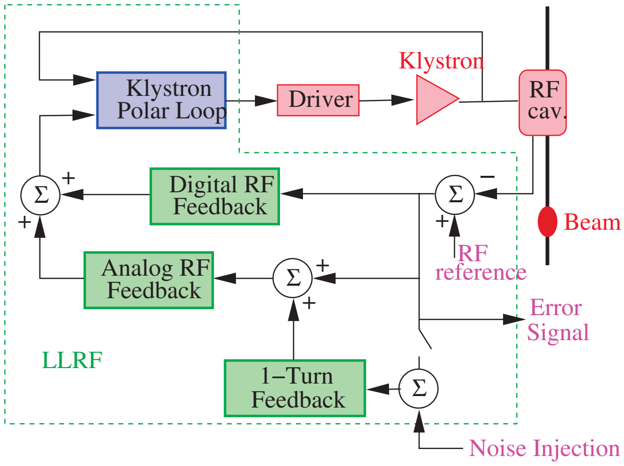

Figure 1: Simplified RF block diagram showing noise injection scheme.

The biggest challenge with this measurement is to identify ≈ 100 Hz wide peaks, spaced by 11 kHz, over a band more than 2 MHz wide. To provide a sense of the complexity, it should be noted that 2 million sample points would be necessary for a 2 Hz resolution over 2 MHz. The solution to this complex measurement was to modulate the injected narrowband noise signal to the revolution harmonic of interest and then demodulate the measured output [5]. With this novel scheme, a series of very narrowband measurements (≈3 kHz) with high resolution (1-2 Hz) are performed over a wide bandwidth. This technique is remotely accessible and configurable.

It is then possible to get the Nyquist plot of the system. The resonances at each revolution harmonic are measured, corresponding to a series of circles on the Nyquist plot. When the delay is adjusted, the circles’ orientation with respect to one another is changed. The delay is adjusted to maximize the phase margin, then the OTFB gain is set to achieve the desired gain margin, resulting in a well ad-

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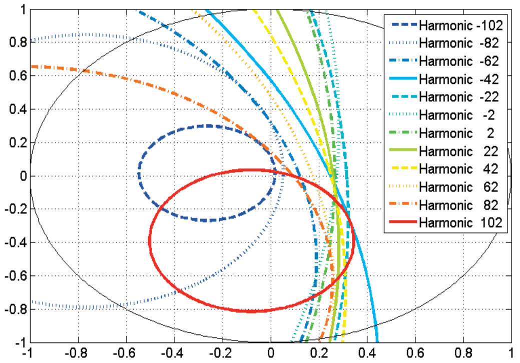

Figure 2: Nyquist plot of loop response with unit circle. Correct delay setting. Zoom around the origin.

justed system as seen in Figure 2. All 16 systems were set and tested using this algorithm without beam. A phase margin of about 60 degrees and a gain margin of about 10 dB was achieved. Once the delay and gain were correctly set, the loop was closed and the system remained stable.

OTFB COMMISSIONING AT 450 GEV

On October 24th, the OTFB was switched on and verified with beam on all but one cavity (7B1) in 20-30 minutes, after the extensive preparation and setting up without beam. Figure 3 compares the klystron power transients with the OTFB off/on and 120 bunches at 25 ns spacing (12+36+72 bunches, with gaps of 925 ns in-between batches). The maximum klystron forward power, as well as the overshoots in klystron power demanded by the RF feedback are reduced. The reduction in the transient klystron forward power is related to a “feedforward” correction in anticipation of the incoming batch from the OTFB action.

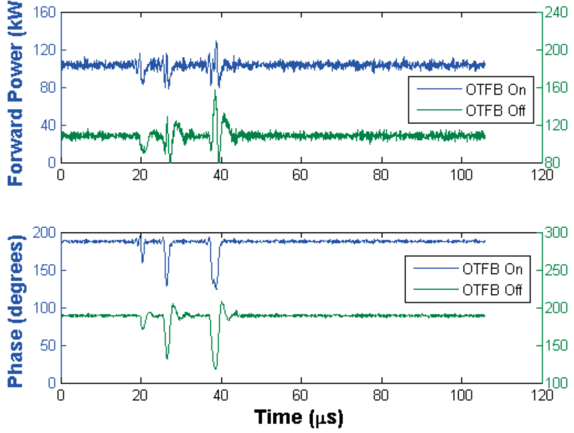

Figure 3: Klystron forward power and phase with OTFB on/off. Y axis are shifted for the two data sets, but have the same scale.

Figure 4 shows the corresponding cavity voltage with 2100 bunches (25 ns spacing) for cavities 1B1 (OTFB on) and 7B1 (OTFB off) with 0.75 MV per cavity. At least a five fold reduction of phase modulation is measured (from 5.5 degrees peak-to-peak and 1.27 degrees rms to 1.3 degrees peak-to-peak and 0.18 degrees rms). A small amplitude modulation reduction is also observed bringing the modulation below the measurement noise.

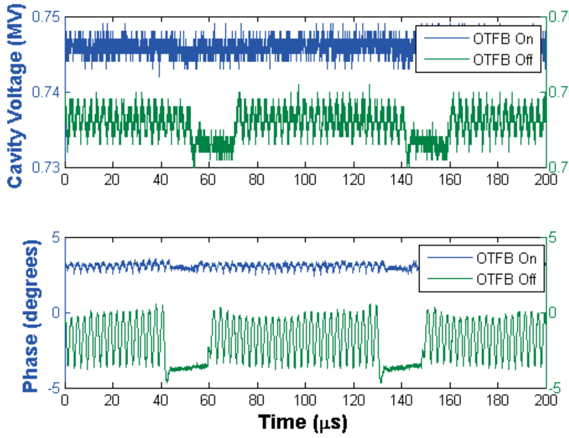

Figure 4: Cavity voltage with OTFB on (1B1) and OTFB off (7B1). Y axis are shifted for the two data sets, but have the same scale.

OBSERVATIONS AT FLAT TOP (3.5 TEV)

Measurements were conducted on October 26th with and without beam (50 ns spacing) to evaluate the OTFB performance at 3.5 TeV (1.5 MV per cavity). It should be noted that between the two sets of measurements at 450 GeV and 3.5 TeV the beam current (filling pattern and intensity) is different in addition to the cavity voltage, so it is not possible to directly compare the modulation level.

Figure 5 shows the cavity voltage with 1380 bunches (50 ns spacing) at flat top and without beam. Both sets of measurements refer to cavity 1B1 with OTFB on. The cavity voltage modulations are very comparable in the two situations (although the abort gap is only barely visible in the cavity phase), showing the significant beam loading reduction achieved. In the cavity voltage case the modulation is so low that the discretization due to the least significant bit of the data acquisition is visible. These are in loop measurements and since the reference is faithfully followed, out of loop measurements might be necessary to fully quantify the performance.

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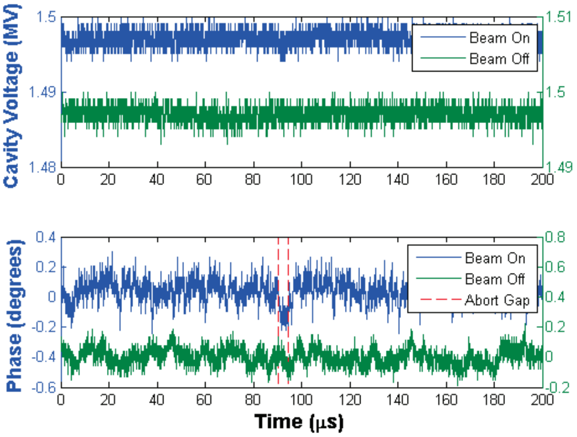

Figure 5: Cavity voltage without beam and with 1380 bunches, 50 ns spacing, and OTFB on (Cavity 1B1). Y axis are shifted for the two data sets, but have the same scale.

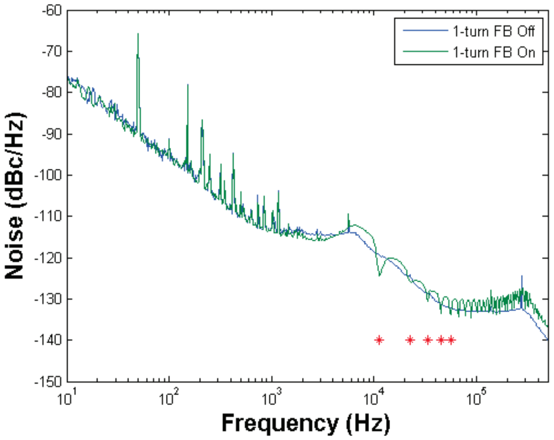

Figure 6: Cavity 2B1 phase noise with OTFB on/off. The locations of the first five revolution harmonics are indicated by asterisks.

PHASE NOISE MEASUREMENTS

The noise in the RF loop can be referred to two sources: measurement noise in the input of the RF feedback (mostly in the demodulation of the cavity voltage) and noise from the feedback electronics at the RF feedback output [6]. As the OTFB increases the open loop gain by about 20 dB on the f_{rev} harmonics, there were concerns that it would increase the feedback electronics contribution to RF noise. As it also increases the loop gain though, the net effect depends on the relative amplitude of measurement and feedback electronics noise. In the LHC, the feedback electronics noise dominates with the loop parameters set for normal operation. As a result, the OTFB gain improves the overall cavity phase noise at the f_{rev} harmonics. Outside the f_{rev} band the OTFB adds noise. Since the beam is most sensitive to the noise at the synchrotron sidebands of all the revolution harmonics ($nf_{rev} \pm f_s$), the net effect is a reduction of the RF noise experienced by the beam and thus a reduction of the RF noise contributions to beam diffusion [6], [7].

The cavity phase noise (cavity 2B1) was measured with OTFB on/off (no beam) at physics conditions (1.5 MV, Q=60k). The blue trace in Figure 6 corresponds to the situation with OTFB off, whereas the green shows the phase noise spectrum with the OTFB on. An up to 8 dB reduction of phase noise at the revolution harmonics is observed. It should be noted that this is an out of loop measurement, derived from a separate cavity antenna with no intervening electronics.

CONCLUSIONS

The LHC OTFB was tested and commissioned during the 2011 run. The algorithms for the setting-up procedure and commissioning were presented. Significant improvements in transient beam loading were observed. As a result, the longitudinal beam position modulation along the ring was reduced. Longitudinal stability improvements are also anticipated (to be measured during a 2012 Machine Development period). The cavity voltage modulation was reduced from approximately six degrees peak-to-peak to below one degree at 400 MHz with nominal bunch intensity of 1.1e11 protons. A small reduction in klystron forward power transient was also observed. The RF phase noise was also reduced in the frequency bands where the beam reacts. After the successful commissioning, the OTFB has been used since October 2011 for the LHC luminosity production runs.

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