WIDEBAND VERTICAL INTRA-BUNCH FEEDBACK AT THE SPS - 2015 RESULTS AND PATH FORWARD*

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Abstract

We present experimental measurements taken from CERN SPS machine development studies with a wideband intra-bunch feedback channel prototype. The demonstration system is a digital processing system with recently installed wideband kicker and amplifier components. This new hardware extends the bandwidth up to 1 GHz and allows driving and controlling multiple vertical transverse modes in the bunch. The studies are focused on driving the bunch with spectrally controlled signals to identify a reduced model of the bunch dynamics and testing model-based feedback controllers to stabilize the bunch dynamics. The measurements are structured to validate reduced MIMO models and macro-particle simulation codes, including the dynamics and limits of the feedback channel. Noise effects and uncertainties in the model are evaluated via SPS measurements to quantify the limits of control techniques applied to stabilize the intrabunch dynamics.
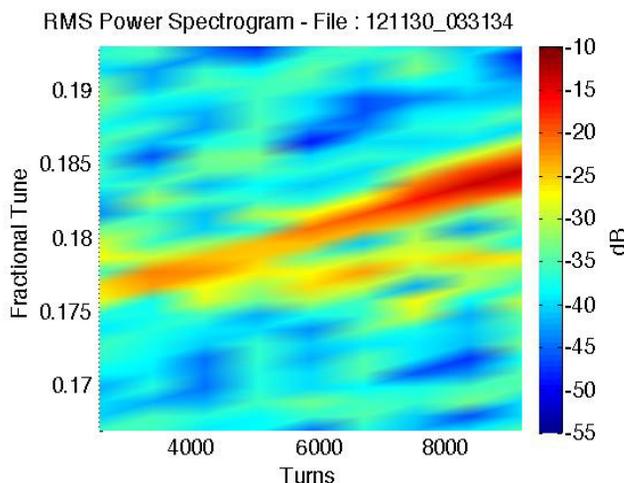
Figure 1: Open-loop vertical beam response chirp spectrogram measurement (no feedback). A 16 sample modulated excitation is driven by the kicker unto the SPS beam for 10,000 turns. The chirp excitation passes through the mode zero tune of 0.177 at turn 4000, and then the mode 1 upper synchrotron sideband at turn 8000 (Q20 lattice). The color code shows the amplitude of the motion for the detected signal.
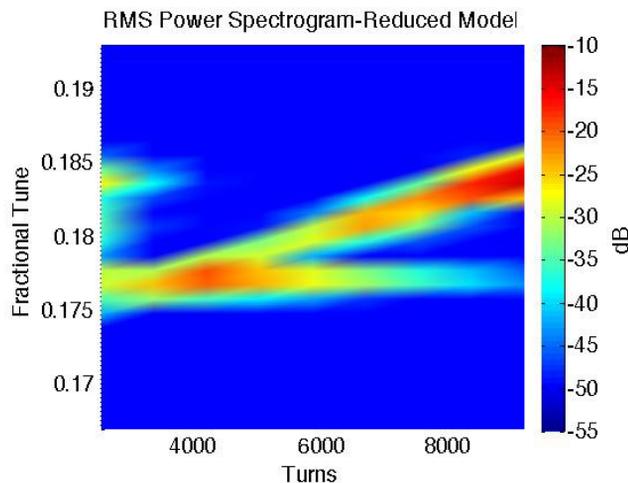
Figure 2: Beam motion spectogram response for the reduced beam model (same excitation as Figure 1). Comparing with the physical measurement we see very close agreement between the oscillation frequencies and the amplitudes of the excited motion.

EVALUATING THE UPGRADED SYSTEM PERFORMANCE

A single-bunch wideband digital feedback system was initially commissioned at the CERN SPS in November 2012[1]. The project is part of a larger LHC injector upgrade[2]. In 2014 during the shutdown interval this system has been expanded with installation of wideband kickers and associated RF amplifiers[3]. While the original bandwidth-limited system achieved control of mode zero and mode 1 unstable beams, we must explore the achieved performance of the wideband kickers, and understand necessary capabilities to control beam conditions anticipated in the HL operating scenario. Our goal in testing the demonstration system is to validate the performance as achieved, and using simulation tools predict behavior for high-current and HL upgraded injector conditions. We cannot expect the limited-function Demonstration System to have the capability of the final system, instead we want to confidently predict the behavior and margins of a more complex full-featured system. To do this, we need methods to simulate realistic future beam conditions interacting with possible feeback systems, and methods to compare the behavior of the Demonstration system and beam against simulations. In this near term we must study the system under a sub-set of HL beam conditions, and validate that our

models of the feedback and beam are faithfully duplicating the real-world measured performance. These tests are also very significant technical demonstrations of the functioning of the 4 GS/sec digital signal processing hardware and build confidence that the proposed full-function architecture can be developed and commissioned as planned.
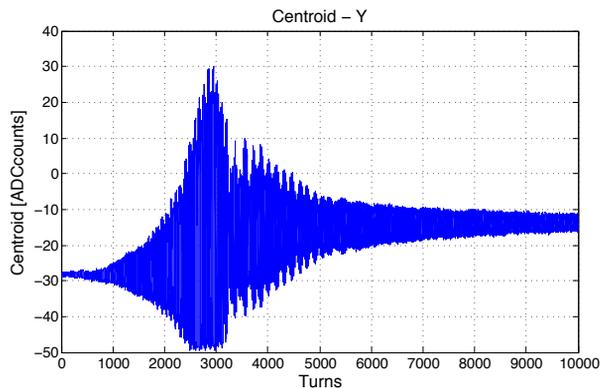
Figure 3: Open-Loop (no feedback) time-domain recording of bunch motion, Q26 lattice, vertical centroid via bunch samples. Unstable bunch motion grows from injection, with charge loss, then stability at roughly turn 3000.
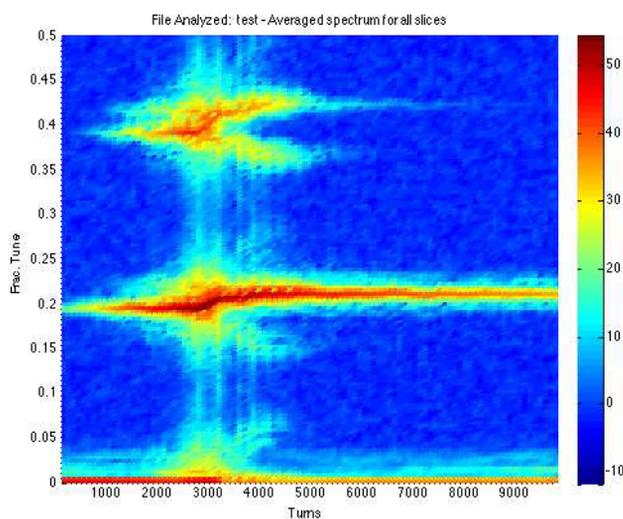
Figure 4: Open-Loop (no feedback) spectrogram of same transient as Figure 3. The beam is TMCI unstable in these conditions, $\nu_y = 0.185$ $\nu_s = 0.006$. Unstable modes 1 and 2 begin at turn 2000 and with charge loss end at turn 4500. Significant intensity-dependent tune shifts are seen as charge is lost in the transient.

We model system performance using the head-tail simulation code with an incorporated feedback model[4], also critical are linear reduced model codes especially important for the analytical design of control filters[5][6]. The use of any of these codes only has value if the results can be compared in a quantified way with actual physical measurements. With this understanding we can make confident predictions for the performance of yet-unbuilt expanded feedback capabilities, the behavior of systems under higher

intensity beam conditions or for new optics, etc. We use two core methods to evaluate the behavior of both simulation studies and physical beam measurements.

The frequency domain studies use swept excitation chirps driving the beam-feedback system across a frequency span that includes oscillation modes of interest, and measuring the beam response using a spectrogram technique. These excitation studies can be done without feedback, or with feedback in various forms. We can also drive either the nonlinear head-tail numeric simulation, or the reduced model linear simulation with the identical chirp, and study the simulation result using the same spectral techniques. An example of comparing physical measurements with measurements of a reduced feedback model is shown in Figures 1 and 2. The only real significant difference is the presence of external noise in the physical beam measurement, the reduced model has only numeric noise. But we see excellent agreement with the frequencies excited in the beam in both cases, and excellent respresentation of the mode zero and mode 1 amplitudes. This suggests that the reduced model can be used with good fidelity to predict the beam responses, and can be used in the design of feedback controllers with confidence that the analytic results faithfully replicate the physical system[7].

Time-domain studies are the second method we use to analyse the performance of the combined beam-feedback system. Figure 3 shows an open-loop (no feedback) time recording of the bunch motion where the beam is exhibiting transverse mode-coupling instability and is unstable in mode 2. The time domain shows the growth of beam motion, and then, as charge is lost from the bunch, stability of the system. Figure 4 shows the spectrogram representation of this transient, we see the prominent excitation of mode 2 as well as the clear tune shift as charge is lost at turn 3000. A similar beam condition, but with the feedback system active, is shown in Figures 5 (time domain) and 6 (spectrogram). Under the action of the feedback, the beam motion is controlled and the large charge loss does not occur.

This type of steady state controlled beam study does not help quantify the gain margin, or stability margins of the system (this requires multiple studies at fixed gains, or the grow-damp method with time-varying gain). However, the steady state recording does have important information about the noise floor in the feedback detector and the processing filter. We see small motion of the beam at mode zero, which is a combination of driven motion, attenuated by the feedback action, plus the noise in the feedback receiver path. However, we see almost no detected signal at mode 2, which shows that the unstable motion is damped to the effective noise floor. This is seen in the time domain signal (Figure 5) as the fluctuating centroid controlled to less than 1 count of ADC resolution, or roughly 6 microns rms vertical motion. These studies are very helpful in understanding the impact of noise within the feedback channel, and choosing an optimal gain for the range of operating conditions.
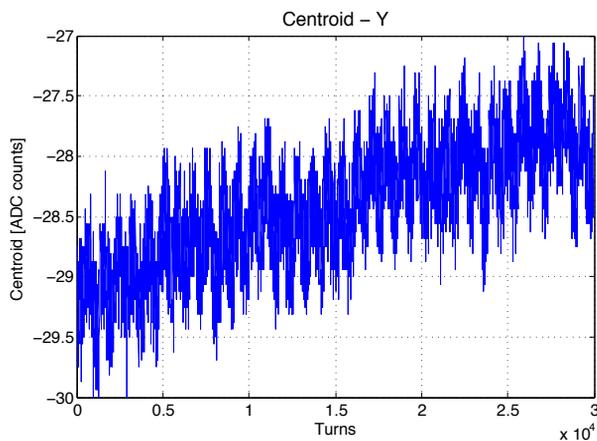
Figure 5: Closed-Loop (feedback on) time-domain recording of bunch motion, bunch samples averaged to show the vertical centroid. The same beam conditions as Figure 3 (TMCI unstable) but motion is controlled by the feedback system. Vertical sensitivity is roughly 14 μm/count
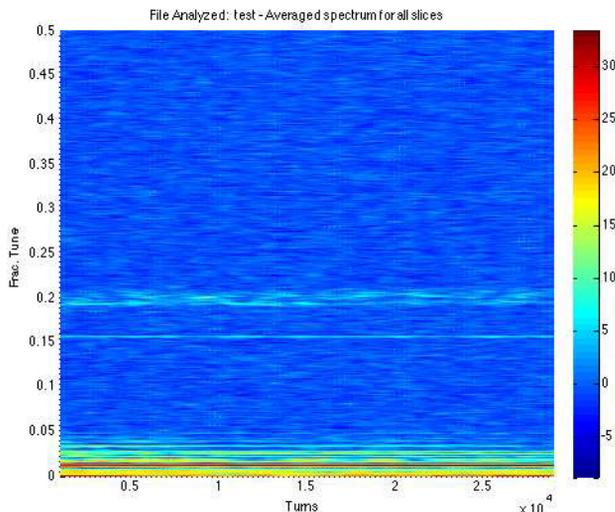
Figure 6: Closed-Loop (feedback on) spectrogram of Figure 5 transient. The beam is TMCI unstable in these conditions, Q26 lattice, $\nu_y = 0.185$ $\nu_s = 0.006$. The feedback control keeps the mode 1 and 2 unstable motion at the noise floor of the feedback receiver, or roughly 3 microns. A small amount of motion at mode zero is seen, this driven motion is reduced by the feedback gain.

SUMMARY AND PLANS FOR NEXT MD STUDIES

The immediate tasks at hand are the validation of the kicker and amplifer performance. We are developing expanded control modes via upgraded FPGA software to allow control of a 16 bunch train, with anticipated June 2015 commissioning. Another important task is exploration of control methods for several candidate machine optics. While we have shown good control with FIR based filters for the Q26 optics, control of the machine with Q20 or other proposed optics needs more study. An early IIR

filter design for the Q20 optics has been studied in simulations, we must study and validate the performance in the physical machine, particularly with regard to the dynamic range required in the processing and possible sensitivity to out of band noise signals[5][6].

The Slotline wideband kicker design is still in mechanical design and we anticipate this new kicker will be fabricated and available for installation and commissioning in late 2015[8], with installation early 2016. The goal of developing a full-function instability control system for the SPS is envisaged to span two generations of prototype hardware. During this interval before LS2 we want to explore a second hardware platform, based on a higher sampling rate A/D and D/A processing system, with associated higher-capacity FPGA processing functions[3]. These studies and technology development will be used in 2016 to propose the full-function system for use in the SPS as the HL LHC injector.

ACKNOWLEDGEMENTS

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