A 4 GS/s FEEDBACK PROCESSING SYSTEM FOR CONTROL OF INTRA-BUNCH INSTABILITIES*

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Abstract

We present the architecture and implementation overview of a digital signal processing system developed to study control of electron cloud and transverse mode coupling instabilities in the CERN SPS. The system is based on a reconfigurable processing architecture which samples vertical bunch motion and applies correction signals at a 4 GS/s rate, allowing 16 samples across a single 5 ns SPS RF bucket. The system requires wideband beam pickup(s) and vertical kicker structure(s) with GHz bandwidth. This demonstration system implements a general purpose 16 tap FIR control filter for each sample. We present results from SPS machine studies showing the impact of wideband feedback to excite/damp internal modes of vertical motion as well as stabilize an unstable beam. These results highlight the challenges of intra-bunch feedback and show proof of principle feasibility of the architecture.

OVERVIEW

The high-current operation of the SPS for LHC injection requires mitigation of possible Ecloud and TMCI effects [1]. The project is part of a larger LHC injector upgrade, which includes simulation studies[2][3][4] and a machine measurement (MD) program[5].

Figure 1 shows the testbed demonstration system which has been implemented using a mix of commercial evaluation boards and minimal custom PC electronic assemblies [6]. The critical digital functions are coded as FPGA gateware, allowing selections of an arbitrary SPS bucket to sample or drive, and the generation of correction signals using FIR or IIR filter structures. The system is synchronized to the SPS through an RF signal, a revolution fiducial and an injection synchronization signal.The RF is harmonically multiplied to generate a sampling clock of $n \times RF$, (in these studies $n = 8$ though the hardware can run at 4 GS/s or $n = 10$). A wideband pickup and beam vertical position receiver generates a 1 GHz bandwidth baseband beam position signal, which is sampled in a front-end A/D system. The selected bunch samples are processed in an FIR filter array, which implements 16 independent 16 tap FIR control filters on the selected bunch. The calculated correction signals are output through a single D/A converter, processed to generate a phase equalized differential kick

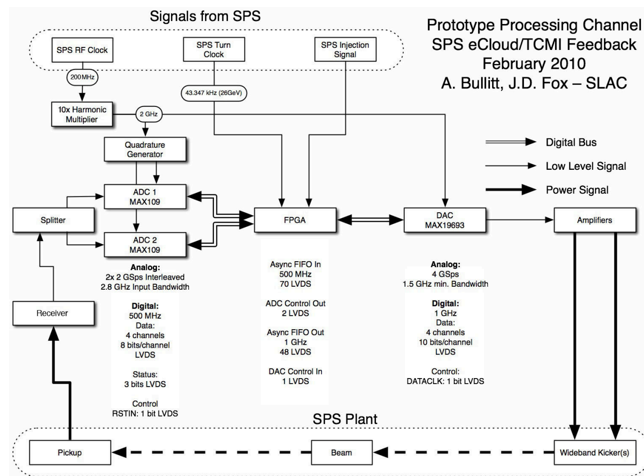

Figure 1: Block diagram of the demonstration system implemented at the SPS, showing the signal paths and the timing synchronization to the SPS. Not shown are the input phase equalization filters in the baseband path to correct for the pickup and cable transfer functions, and the back end equalizers used to correct the nonlinear phase response of the cable and kicker transfer functions [7].

signal, amplified via four 80 Watt 20 - 1000 MHz power amplifiers, and impressed onto the beam using a stripline kicker. The demonstration system still requires the development and commissioning of a wideband kicker [8] and this first study uses an existing exponential taper stripline pickup as a kicker with 200 MHz bandwidth.

The architecture is flexible and reconfigurable, allowing the testbed to reconfigure from a single 4 GS/s interleaved input to two parallel 2 GS/s channels, for example to sample Delta (orbit offset) and Sigma (charge sum) signals to normalize the orbit signal for charge, or to allow two independent pickups at arbitrary β offset to be implemented to make a quadrature input processing channel. It also can be upgraded to allow the use of an 8 GS/s back end D/A and four 2 GS/s A/D streams if greater system bandwidth is desired.

The control filters are implemented in a "slice by slice" scheme much like the "bunch by bunch" sampling used in coupled-bunch feedback systems. The 16 samples are taken across a single 5 ns RF bucket and each independent filter channel calculates the corresponding correction signal to be applied on the next turn. Design of the control filters, and specification of the filter coefficients are done using

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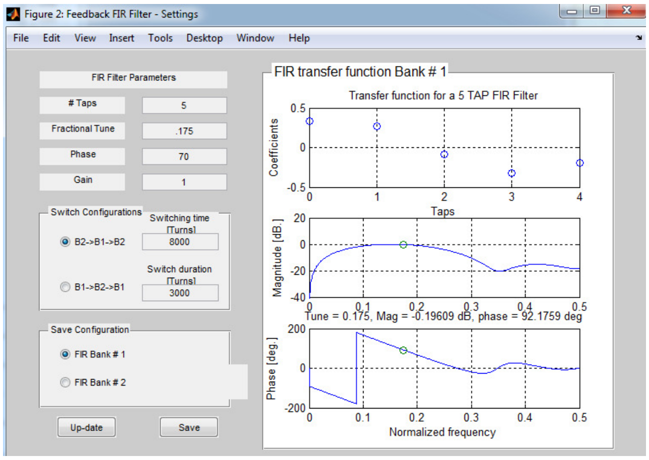

Figure 2: Typical control filter (bandpass filter at a nominal vertical tune of 0.175). The same filter coefficients are applied to each of the 16 control filters taken across the SPS bunch. With the use of the synchronizing signals it is possible to switch two independent filter sets "on the fly" to change feedback parameters during a machine cycle, allowing the system to track variations in tune, or to allow grow-damp or other time varying feedback studies

off-line MATLAB system models [5]. Figure 2 shows a typical 5 tap filter design optimized for a fractional vertical tune of 0.175. The panel also controls turn-synchronized functions which manipulate feedback parameters at specified turn counts in the sequence after injection.

EVALUATING THE FEEDBACK SYSTEM WITH BEAM

To test and evaluate the performance of this channel requires careful measurements of stable and unstable beams. "Doing Feedback" without quantitative knowledge of margins, stability limits due to tune variations, charge variations, changes in the machine lattice, impact of external noise signals, etc. is not useful. Quantifying how feedback changes system dynamics requires the ability to excite and measure system responses. With this approach we can use stable beams and study how the feedback system impacts the dynamics (and compare results with simulation models). We can study low currents, and predict how the system dynamics will change as intensities are increased in future upgraded conditions. We can then study more complicated cases of unstable beams with the confidence that our feedback channel is acting as designed.

In these studies we use a wideband excitation system [9] to excite the beam and record the resulting beam motion within the feedback processing channel. Figure 3 shows the combined beam-feedback system. The action of the feedback loop around the beam can change the system dynamics in response to an excitation applied through the kicker system. The external excitation system is synchronized to the injection process, so that coordinated studies can be made of injected bunches or at particular points during the

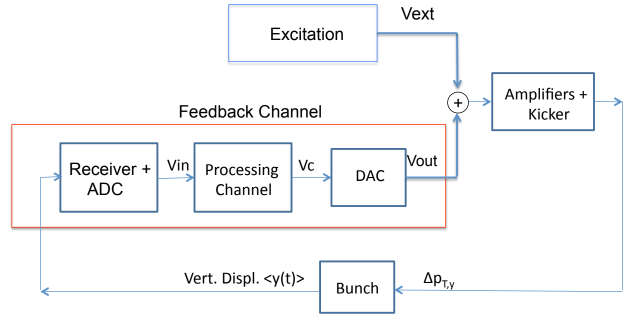

Figure 3: Loop topology for measuring beam dynamics changes due to feedback. An excitation signal $V_{\rm ext}$ drives the beam, while the closed loop feedback acts in response to the excitation. Time-domain samples of the excitation, and the beam response $V_{\rm in}$ are processed in both time and frequency domains.

energy ramp. The time-domain sequences of the excitation signal $V_{\rm ext}$ and the resulting bunch response $V_{\rm in}$ can be processed to reveal frequency or time-domain behavior of the beam system, or the combined beam-feedback system [10]. This driven response method can be used for physical experimental systems, or to evaluate the response of a nonlinear simulation code such as HeadTail or CMAD [2][3].

The feedback applied in this measurement can be time-varying (it can stabilize an unstable beam, turn the feedback off for a selected number of turns, then reapply control). Time varying feedback can also apply positive feedback for a short interval, excite internal motion of the bunch, and then restore damping feedback as a means to study marginally stable or stable beam modes. Comparisons of behavior from multiple transients requires normalization in processing as each injection cycle is unique with variations in stored charge and the feedback loop gain is proportional to charge/sample. An additional factor in analysis is the vertical tune variation with current which must be considered in frequency domain studies.

The SPS bunch used in these studies was of nominal intensity 1.1×10^{11} p/bunch, and studies were done at the 26 GeV injection energy before acceleration. The injected bunch has typical σ_z of 0.7ns, the 3.2 GS/s sampling captures the vertical displacement into 16 independent "slices" within the 5 ns RF bucket. The processing system uses 8 bit quantization with over 54 dB dynamic range per sample. If 1000's of turns are processed using FFT methods to compute a spectrogram, the effective dynamic range becomes 70 dB or more for measurements of beam motion. For these studies control filters were FIR 5 to 7 tap bandpass filters, and identical filters are applied to each of the 16 samples taken across the bunch.

DRIVEN MOTION STUDIES AND MODEL FITTING

One type of study applicable to stable or controlled unstable beams drives the closed loop system with a chirp and

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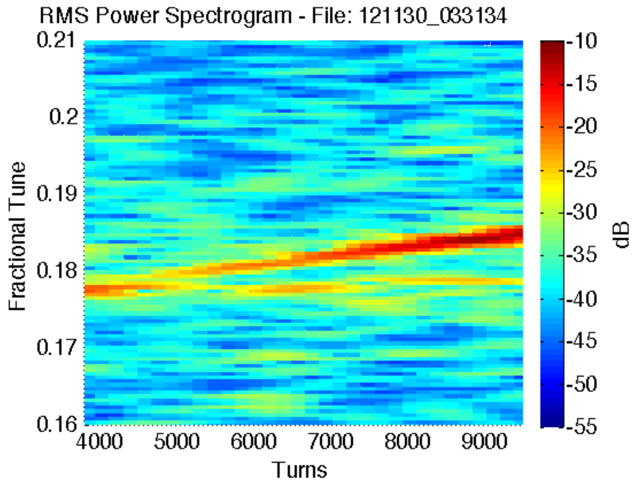

Figure 4: Measured RMS spectral power for a mode 1 excitation of the physical system. The barycentric mode 0 tune of 0.178 is weakly driven in this mode 1 excitation pattern. The chirp crosses the mode 1 tune (upper synchrotron sideband) of 0.183 near turn 8500. Noise floor below -55dB has been suppressed for clarity.

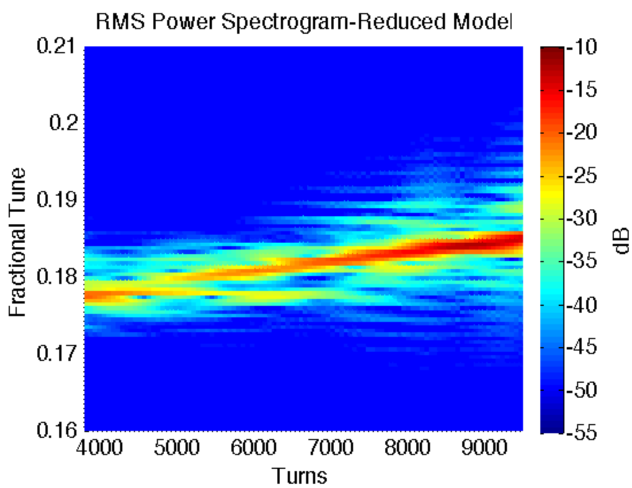

Figure 5: RMS spectral power for a mode 1 excitation of the reduced 2-oscillator model system as fit to the data in Figure 4.

measures an effective beam transfer function. A series of studies are made as feedback properties are varied, so that the free response (no feedback) can be compared to closed loop responses. Figure 4 shows an open loop study which drives the physical beam using an excitation chirp. The excitation can be phased across the bunch samples to couple to particular beam modes as the chirp frequency varies over the measurement range[9]. A simplified two coupled oscillator beam model can be fit to this response using a state space estimated transfer function [10]. Using the simplified model each beam mode can be studied analytically as feedback parameters are varied. Figure 4 shows the measured RMS power for a mode 1 excitation chirp driving the beam, while Figure 5 shows the response of the fitted simplified model to the same mode 1 excitation chirp frequencies. The agreement between the measured and model responses gives confidence that the behavior of the physical system to feedback parameter changes can be calculated using the reduced models. If the feedback gain is varied and the beam measured at various gains, we can fit reduced models for each feedback gain case. With the reduced models we can calculate the complex eigenvalues of the driven responses. Figure 6 shows a closed-loop driven study of mode 0, as the feedback gain is increased we see the reduction in Q_{eff} of the driven mode 0 motion. The oscillation frequencies do not shift, showing that the feedback filter phase is resistive and nearly optimal. Because the existing kicker bandwidth is limited, these first studies concentrate on modes 0 and 1, though the technique is generally applicable to any mode within the feedback bandwidth.

CONTROL OF AN UNSTABLE BEAM

Another analysis technique applicable to unstable systems uses a time-varying feedback filter, and records the beam motion in the time domain. In this example the machine chromaticity was ramped to near zero at 2000 turns after injection, which results in a mode zero unstable beam. As seen in Fig. 7, the beam rapidly goes unstable and loses charge over roughly 1000 turns (resulting in a tune shift) until the lower intensity beam is stable. For similar beam conditions Fig. 8 shows the feedback channel configured for negative feedback for 18,000 turns, then the feedback gain is set to zero. In this transient the beam motion at mode 0 is stabilized (damped to 2× the receiver noise floor of 11 μm RMS at this current). After the feedback is turned off similar instability and beam loss is observed as for the injection without feedback. Measurements of this type help show the instability growth rate and validate the feedback damping [5].

FUTURE DIRECTIONS

Two styles of wideband kicker are in fabrication for installation at the restart of the SPS planned in November

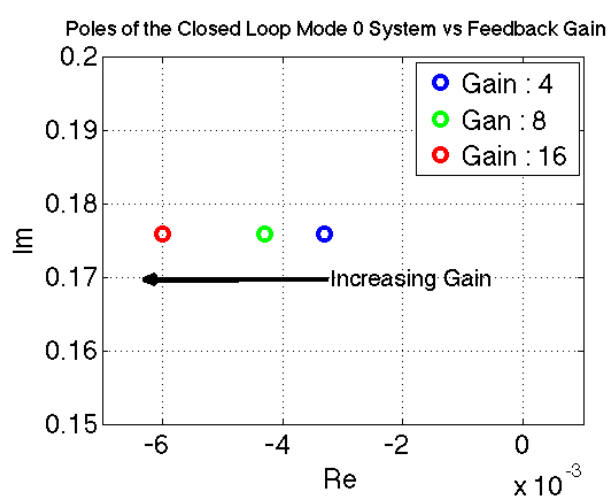

Figure 6: Pole locations of mode 0 under feedback control using three sets of physical measurements (three gains applied to the beam feedback). Using the three fitted simplified models, the increased damping of mode 0 created by increased gain is clearly quantified.

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2014[8]. A prototype element of a kicker array based on 10 cm long striplines will be available for initial tests, allowing full-bandwidth tests but with limited kick strength using the existing amplifiers. A slotline style kicker is also in fabrication for installation early in 2015. The slotline design is attractive in that a single structure with four feedthroughs can have the 1 GHz bandwidth and reasonable kick strength. These wideband elements will be critical for the system tests needed to validate the instability control methods. The demonstration system firmware is also being expanded to allow control of multiple bunches, implement an orbit-offset removal loop to improve the processing dynamic range, and to allow timing/phasing synchronization to the beam during an energy ramp.

SUMMARY

The demonstration system was commissioned November 2012 and used to study beam-feedback dynamics prior to the February 2013 SPS shutdown. Even with the limited bandwidth kicker, we are able to study control filters which stabilize unstable beam, and to quantify the achieved damping. These initial studies are very encouraging and provide vital physical measurements to compare against simulation models. This demonstration system development is a critical testbed to prove system functions and finalize system specifications for a full-capability multi-bunch feedback system for use after the 2019 SPS upgrade to deliver high-intensity LHC beams.

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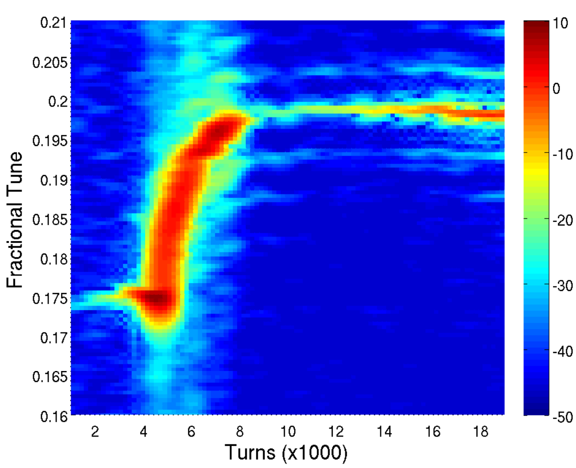

Figure 7: Frequency-domain spectrogram of unstable (no feedback) beam motion with charge loss. The machine chromaticity is ramped to zero at 2000 turns, resulting in mode 0 unstable beam. The dramatic tune shift is a sign of charge loss due to the unstable motion.

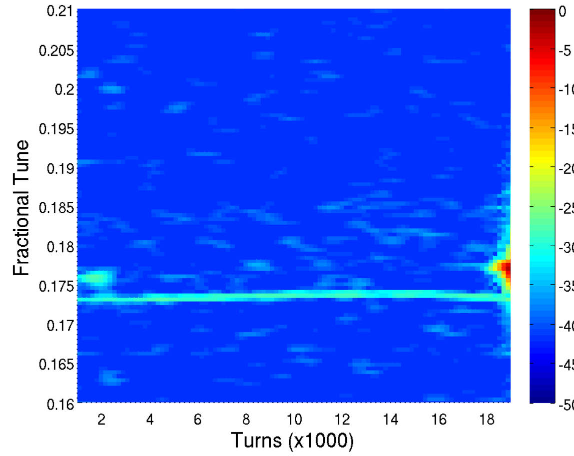

Figure 8: Identical injection case as Figure 7, but with feedback ON until turn 18,000. The stored beam is controlled vertically to 23 μm RMS (1.5 ADC counts), unstable beam motion occurs after feedback gain is set to 0.

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