FIRST RESULTS AND ANALYSIS OF THE PERFORMANCE OF A 4 GS/s INTRA-BUNCH VERTICAL FEEDBACK SYSTEM AT THE SPS*

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Abstract

We present experimental measurements taken from SPS machine development studies with an intra-bunch feedback channel. These studies use a 3.2 GS/s digital signal processing system to implement general-purpose control algorithms on multiple samples across a single SPS bunch. These initial studies concentrate on single-bunch motion, and study the vertical betatron motion as the feedback control is varied. The studies are focused on validating simulation models of the beam dynamics with feedback. Time and frequency domain results include excitation and damping of intra-bunch motion with positive and negative feedback. We present initial results showing the impact of wideband feedback to excite/damp internal modes of vertical motion as well as stabilize an unstable beam.

OVERVIEW

The high-current operation of the SPS for LHC injection requires mitigation of possible Ecloud and TMCI effects [1]. A single-bunch wideband digital feedback system has been developed to explore new technology and control techniques. Implemented with reconfigurable FPGA methods, this system includes synchronization functions to generate 3.2 or 4 GHz samping clocks locked to the SPS RF system, and diagnostic functions which manipulate feedback parameters and record bunch motion for 20,000 turns at selected intervals [2]. The demonstration system still requires the development and commissioning of a wideband kicker [3] and this first study uses an existing stripline pickup as a kicker with 200 MHz bandwidth. The project is part of a larger LHC injector upgrade which includes simulation studies [4][5] and a machine measurement (MD) program.

EXPERIMENTAL METHOD

Quantifying how a feedback system changes system dynamics requires the ability to excite and measure system responses. In this study, we use a wideband excitation system [6] to excite the beam and record the resulting beam motion within the feedback processing channel. Figure 1 shows how 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 time domain sequences of the excitation signal V_{ext} and the resulting bunch response V_{in} can be processed to reveal frequency or time domain behavior of the beam system, or the combined Beam-Feedback system [7].

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.

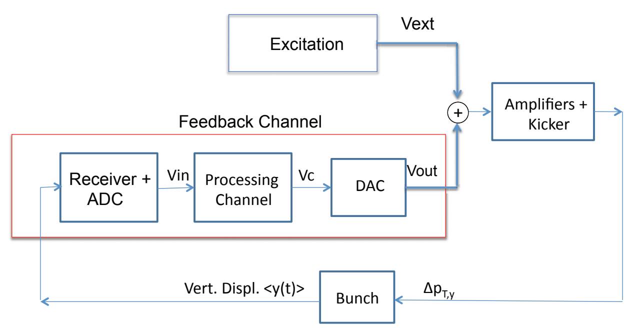

Figure 1: Loop topology for measuring beam dynamics changes due to feedback. An excitation signal V_{ext} drives the beam, while the closed loop feedback acts in response to the excitation. Time-domain samples of the excitation, and the beam response V_{in} are processed in both time and frequency domains.

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. The external excitation system is synchronized to the injection process, so that coordinated studies can be made of injected bunches. 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.

The proper synchronized timing of the pickup and kicker signals and external excitation signal with respect to the

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sampling clocks and circulating beam requires care to time align the samples. This is typically done via measurements of modal excitation as the time alignment is varied, and also through direct observation at a kicker termination load of driven and beam induced signals. An additional issue in analyzing the data is that each injection cycle is unique with variations in stored charge. Comparisons of behavior from multiple transients requires normalization in processing, as the feedback loop gain is proportional to charge/sample, and the vertical tune variation with current must be considered in frequency domain studies.

DRIVEN MOTION STUDIES WITH CLOSED LOOP FEEDBACK

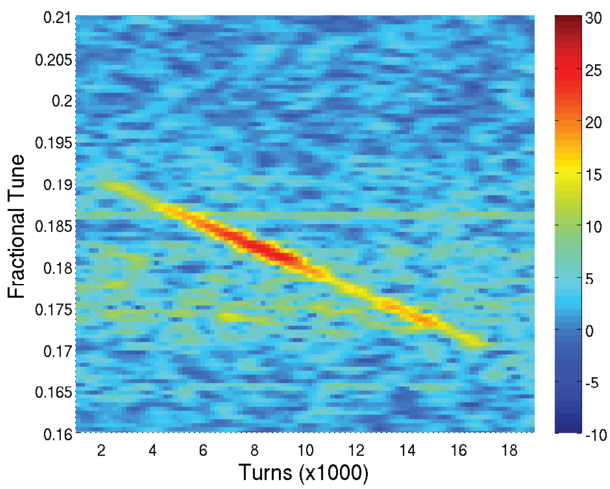

Figure 2: Spectrogram of combined feedback -single bunch system response (16 slices averaged). The excitation chirp starts at tune 0.19 and decreases over 15,000 turns (highlighted line). The intensity of the beam response is seen in two bands at tune 0.183 (upper synchrotron sideband) and tune 0.175 (barycentric mode zero).

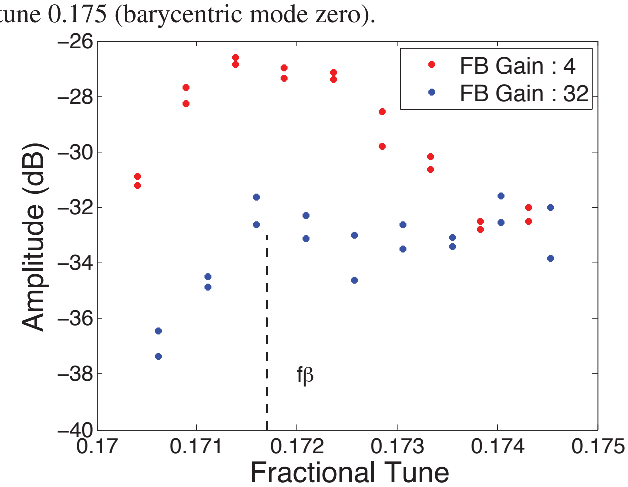

Figure 3: Comparison of amplitude of mode zero motion along a chirp for two feedback system gains. The increased loop gain reduces the driven motion.

One type of study applicable to stable or unstable beams drives the closed loop system with a chirp and 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 choices in feedback filter gain and phase. Using a frequency domain estimated transfer function [7], each beam mode can be studied. Figure 2 shows a closed loop study which spans mode 1 (upper synchrotron sideband) and mode zero (barycentric). Figure 3 shows the response magnitude along the chirp frequencies, and as the gain of the feedback is varied we see the variation in Q_{eff} of the resonant motion. The variation of response vs. feedback filter is helpful to understand the optimal filter phase and maximum system gain, as well as validate simulation models. Because the existing kicker bandwidth is limited, these first studies concentrate on mode zero, though the technique is generally applicable to any mode within the feedback bandwidth. The synchronized excitation signal can select particular modes to study, rather than just the fastest growing modes.

CONTROL OF AN UNSTABLE BEAM

Another analysis technique applicable to unstable systems uses a time-varying feedback filter, and records the beam motion. In these examples the machine chromaticity was ramped to near zero at 2000 turns after injection, which results in a mode zero unstable beam. As seen in Figure 4, 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 Figure 5 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 zero is stabilized (damped to 2× the receiver noise floor of 11 microns 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 can help show the instability growth rate and validate the damp-

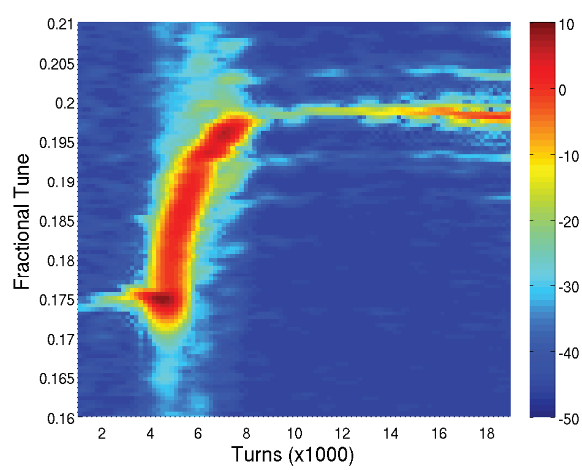

Figure 4: Frequency-domain spectrogram of unstable (no feedback) beam motion with charge loss. The machine chromaticity is ramped to zero at 2000 turns, resulting in mode zero unstable beam. The dramatic tune shift is a sign of charge loss due to the unstable motion.

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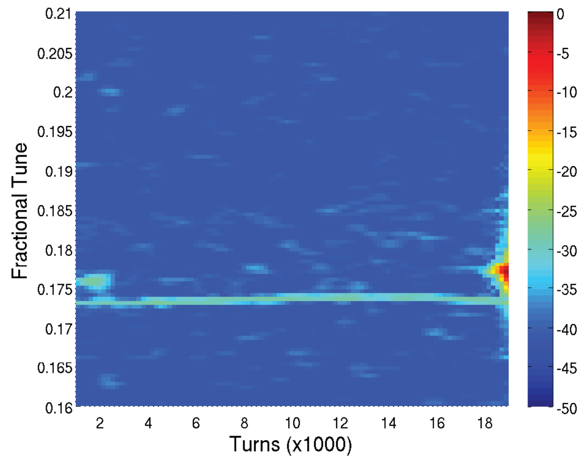

Figure 5: Identical injection case as Figure 4, but with feedback ON until turn 18,000. The stored beam is controlled vertically to 23 μm rms (1.5 ADC counts), unstable beam motion occurs after feedback gain is set to 0.

ing provided by the feedback channel.

TIME VARYING FEEDBACK WITH AN UNSTABLE BEAM

Another type of time-varying feedback study uses the feedback to stabilize a beam, then modifies the feedback gain for a short interval, followed by restoration of the original feedback. This type of grow-damp study can be used to understand growth and damping rates, and can also use positive feedback intervals to drive a naturally stable beam in order to observe the damping rates of internal modes. Figure 6 shows a case for unstable mode zero beam with an external chirp excitation, and in this transient the positive feedback interval shows internal modes up through mode 3 are strongly excited by the external chirp.

SUMMARY

A demonstration system was installed in the SPS in November 2012, and has been used to study the feedback performance prior to the February 2013 SPS shutdown. Even with the limited bandwidth kicker, we are able to study the impact of control filters to stabilize unstable beam, and to study the dynamics of the first 4 internal modes. These initial studies are very encouraging and provide vital physical measurements to compare against simulation models. With the installation of the true wideband kicker expected in 2014, we plan to develop effective wideband feedback control filters and control techniques for Ecloud and TMCI effects. This demonstration system development is a vital testbed to prove system functions for a future full-capability multi-bunch feedback system.

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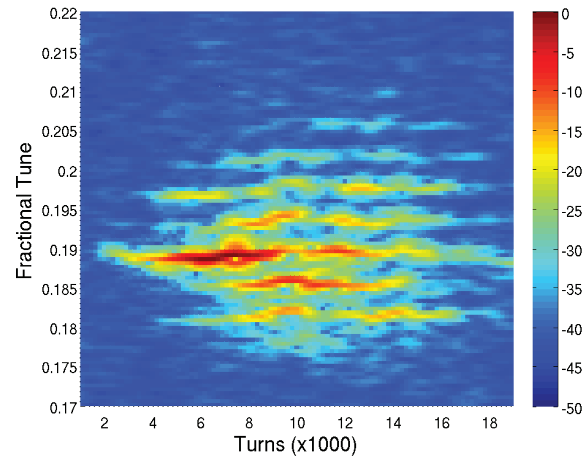

Figure 6: ADC input spectrogram averaged over 16 slices. Unstable beam transient with external chirp excitation, feedback stabilizes the beam as in Figure 5, feedback gain polarity is inverted and gain increased $\times 4$ turns 4000 to 12000, then restored. As the chirp excitation crosses through the barycentric mode at turn 4100 the beam is strongly excited, with motion seen at the fundamental plus upper and lower second sidebands. At turn 8000 the excitation crosses the first synchrotron sideband, both upper and lower sidebands are strongly excited. At turn 10000 simlar excitation of the third sidebands is seen. At turn 12000 original gain is restored, and the excited modes damped.

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