WIDEBAND VERTICAL INTRA-BUNCH FEEDBACK AT THE SPS – TECHNOLOGY DEVELOPMENT, RECENT ACCELERATOR MEASUREMENTS AND NEXT STEPS*

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Abstract

A wideband vertical intra-bunch feedback system is in development at the CERN SPS for use to control potential Ecloud and TMCI instabilities. The work is motivated by planned intensity increases from the LIU and HL-LHC upgrade programs. System technical features include pickups, upgraded kickers and related RF power amplifiers, 1 GHz bandwidth analog processing used in conjunction with a 4 GS/sec reconfigurable digital signal processing system. Recent results include driven beam experiments and beam simulation methods to verify the damping provided by the wideband system, and validate reduced MIMO models and model-based controllers. Noise effects and uncertainties in the model are evaluated via SPS measurements to predict the limits of control techniques applied to stabilize the intrabunch dynamics. We present data showing the excitation and damping of unstable modes. The plans for the next year, including experimental measurements, hardware upgrades and future control developments are described.

INTRODUCTION - CONTROL OF INTRA-BUNCH INSTABILITIES

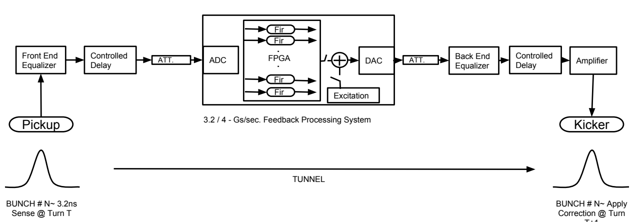

Figure 1: System diagram for the demonstration intra-bunch signal processing

Instability control via feedback at light sources and accelerators requires techniques to sense beam motion, compute correction signals and apply these corrections to the beam. This intra-bunch feedback system follows the same principles, but acts on modes of beam motion within a single bunch as well as coupled bunch modes between bunches. The basic formalism uses digital processing techniques to remove noise and DC orbit offsets from the bunch signals, apply gain at the oscillation frequency with a tailored phase shift to apply a net damping signal at a kicker structure. An intra-bunch feedback system using digital processing formalism has been demonstrated at JPARC [1, 2] for 150 ns long bunches and at the CERN PS for 60 ns bunches [3]. The challenge in our work directed at the CERN SPS is the necessary bandwidth, as the SPS bunch 4σ is roughly 1.7 ns, so our systems sample at 3.2 or 4 GS/sec (Fig. 2). The kicker and pickup elements then require roughly a GHz of bandwidth, and all the processing elements within the loop require careful attention to deviations from linear phase response to allow high closed loop gain without causing oscillations or instabilities.

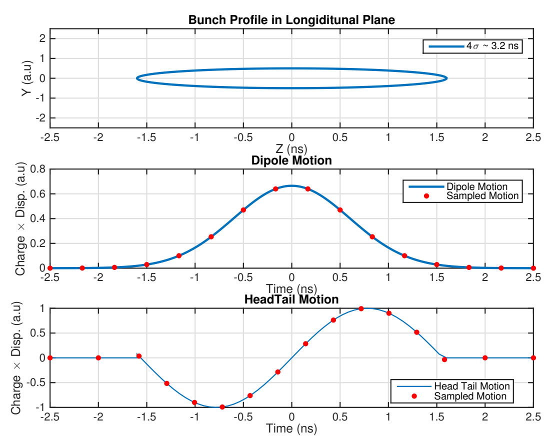

Figure 2: The intra-bunch system samples 16 vertical coodinates across each bunch, and computes correction signals in a processing filter to be applied on later turns.

The high-current operation of the SPS for HL-LHC injection will require mitigation of possible Ecloud and TMCI effects [4]. These intensity-limiting instabilities can be controlled through several measures, including special coatings of the vacuum chamber, tailored machine optics [5] or wideband feedback techniques [6]. A single-bunch wideband digital feedback system was initially tested at the CERN SPS in November 2012 [7, 8]. The project is part of a larger LHC injector upgrade [6]. In 2014, during the shutdown interval this system has been expanded with installation of wideband kickers and associated RF amplifiers [9]. While the original bandwidth-limited system achieved control of mode 0 and mode 1 unstable beams, we must explore the new wideband kicker performance, and understand necessary capabilities to control beams anticipated in the HL operating scenario.

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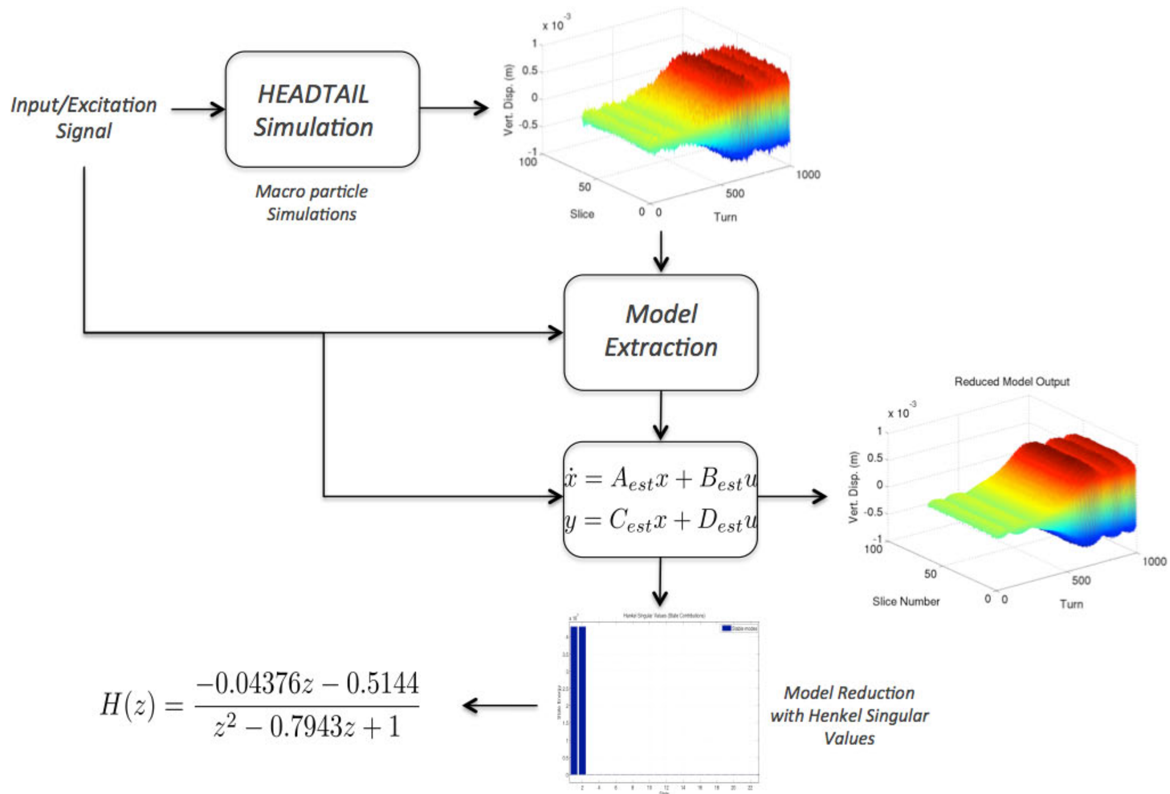

Figure 3: The reduced model parameters are generated by fitting the model response to physical data from machine measurements, or from numerical simulations such as Head-Tail or CMAD. The order or complexity of the reduced model is chosen to capture the most essential dynamics in the data set. This example shows open-loop motion of mode 0, excited by an external driving excitation

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 the 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. Our goal in testing the demonstration system is to validate the performance as achieved, and through simulation tools to predict the behavior for high-current and HL upgraded injector conditions. 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.

SYSTEM DEVELOPMENT AND UPGRADES

The modular architecture and basic FPGA platform of the Demonstration Processor allows the expansion of new control filters and the additon of new control features. During the LS1 interval the analog signal processing of the system was carefully upgraded, with special attention to the input pickup processing and the behavior of the wideband equalizers and 3.2 GS/sec ADC stages. This improvement increased rejection of spurious signals and nonlinear behavior of the analog processing which had been visible in the original implementation data. With these improvements and development of a more robust grounding and shielding scheme, the analog front end systems now have a full 54 dB dynamic range and the noise floor is now flat over the operating frequencies. A new timing and synchronization system was incorporated which keeps the high-speed 3.2 or 4 GS/sec. output DAC stream phase aligned with the SPS RF system, so that timing consistency and operational robustness was improved. A new scrubbing fill feedback processing mode was added, so that two adjecent buckets with 5 ns separation can be indivually controlled, each with 16 samples of intra-bunch control. The single-bunch control filter has been extended to process and generate signals for a 64 bunch train. CERN completed the fabrication of two stripline kicker modules [10], which were installed on the SPS beam line with associated cabling and infrastructure to allow control and monitoring of new wideband RF amplifiers. The analog equalizer functions, needed to maintain linear phase response over the 1 GHz system bandwidth, were upgraded to include the responses of the new kicker cable plant [11]. An extensive evaluation of 11 commercial wideband RF amplifiers resulted in the development of a

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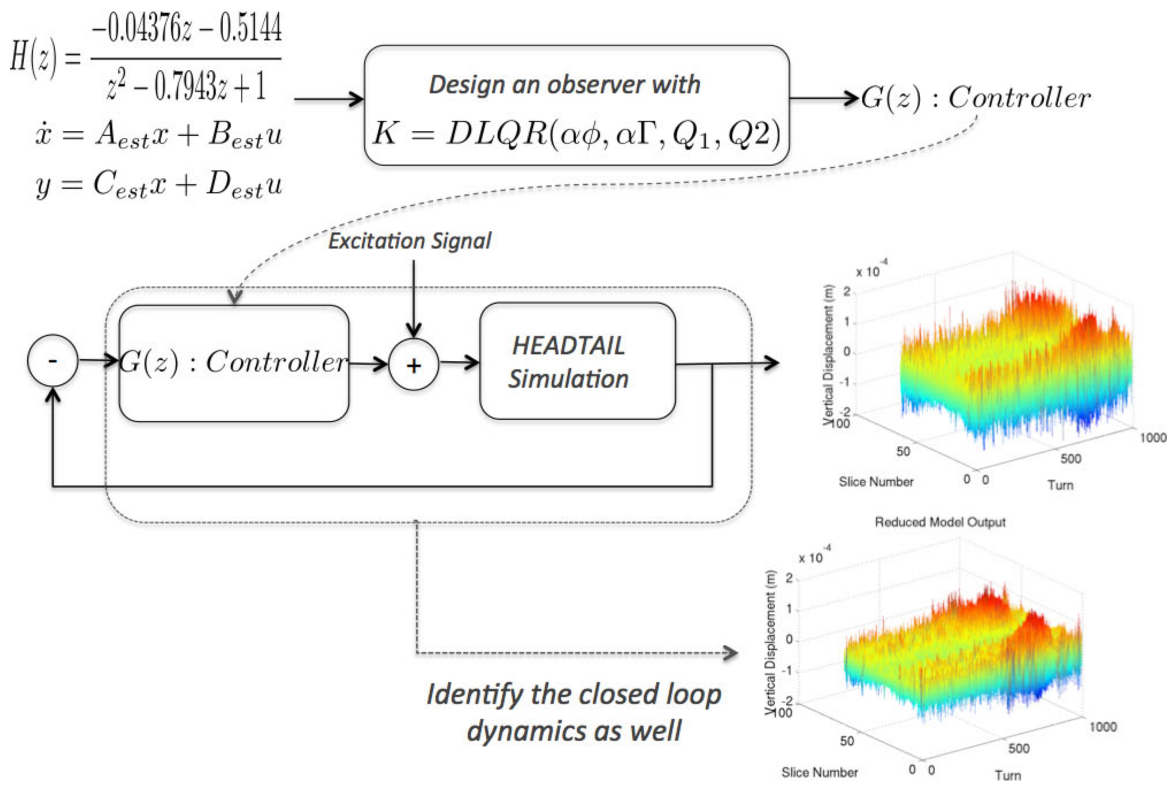

Figure 4: The reduced model behavior under the action of a feedback controller can be directly compared to the behavior of the nonlinear simulation with that controller, or against with machine studies of the beam under the action of that controller through the Demonstration system.

new variant of a commercial 5 - 1000 MHz amplifier with excellent time response to 100% AM modulated signals. Two of these 250W amplifiers, with associated remote control functions, have been installed and commissioned in the SPS tunnel. Two more are expected to be installed on the second stripline kicker in winter 2015/2016.

REDUCED MODEL DEVELOPMENT AND APPLICATION

This feedback task is challenging as the beam dynamics and instability physics is inherently nonlinear. Nonlinear particle tracking codes such as Head-Tail can simulate complex dynamics and can faithfully replicate physical beam dynamics if there is good knowledge of machine impedances, a high order model of the machine lattice, and realistic estimates of electron-cloud densities, etc. It is possible to include a simplified feedback processing model into this type of simulation [12]. But this simulation produces time-domain trajectories over finite time intervals, and produces no insight into stability magins and the impact of small changes in parameters on stability. This type of time-domain nonlinear tool also does not have a direct formal method to design feedback controllers. We need reduced system models to design our feedback controllers using modern control methods. This design approach gives us analytic methods to specify the control filter, directly estimate the stability margins of the closed loop system and identify the necessary system bandwidth and gain as a function of reduced model parameters.

The reduced model represents the dominant dynamics in the physical system with a discrete-time linear MIMO model of coupled harmonic oscillators [13, 14] and we design feedback controllers using these linear models [15, 16]. As seen in Figure 3, the model is fit to either machine measurement data or numeric simulation data. The reduced model is analytic and linear, and allows design of control filters using optimal and modern control techniques. After the optimization of a control filter with the linear model, as seen in Figure 4 we then study system performance using the head-tail simulation code with an incorporated feedback model [13, 17]. The use of any of these codes only has value if the results can be compared in a quantified way with actual physical measurements. One very important value of the reduced model is to validate the fidelity of numeric simulations against physical beam measurements. If the two reduced models, independently derived from simulations and machine studies have good agreement, then the numeric simulation parameters are faithfully reproducing the actual physics seen in the 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.

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EVALUATING THE UPGRADED SYSTEM PERFORMANCE

We use two core methods to evaluate the behavior of both simulation studies and physical beam measurements. Both methods utilize the feedback system processing to excite the beam from data files, and record the beam responses digitally within the feedback processing. One technique uses frequency-domain tests by applying swept excitations, a complementary method uses time domain studies where the feedback gain is varied in time while the beam motion is recorded (grow-damp studies).

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 quasi-steady state excitations originate from data samples stored within the feedback processing system (effectively arbitrary waveforms which can be applied to 16 samples across the bunch for thousands of turns) [18]. These excitations can be modulated in frequency, and in spatial pattern, to allow careful excitation of particular intra-bunch modes.

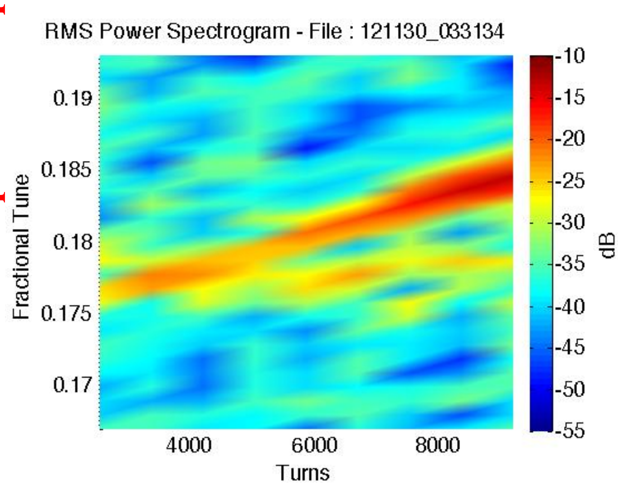

Figure 5: Open-loop vertical beam response chirp spectrogram measurement (no feedback). A 16 sample modulated excitation is driven by the kicker onto the SPS beam for 10,000 turns. The chirp excitation passes through the mode zero tune of 0.177 at turn 4000, and then the mode 1 upper synchrotron sideband at turn 8000 (Q20 lattice). The color code shows the amplitude of the motion for the detected signal.

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 5 and 6. 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 0 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 [13].

Time-domain studies are the second method we use to analyze the performance of the combined beam-feedback system. Figure 7 shows an open-loop (no feedback) time recording of the bunch motion where the beam is unstable in mode 0. The time domain shows the growth of beam motion, and then, as charge is lost from the bunch, stability of the system. Figure 8 shows the spectrogram representation of this transient, we see the prominent excitation of mode 0, plus modes 1,2 from chromatic effects, 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 9 (time domain) and 10 (spectrogram). Under the action of the feedback, the beam motion is controlled and the large charge loss does not occur.

To validate the damping rates achieved, studies such as shown in Figures 11 and 12 the polarity of the feedback is switched during the fill so that the beam is first excited, then damped by the feedback system. Damping rates are shown for two feedback gains. The measurements are taken from the SPS (low chromaticity Q26 lattice and bunch intensity of 1.1×10^{11}). The factor of 4 gain increase and the measurements of the damping rates are used to validate the expected damping rate based on knowledge of the system gain, kicker strength, and other system parameters.

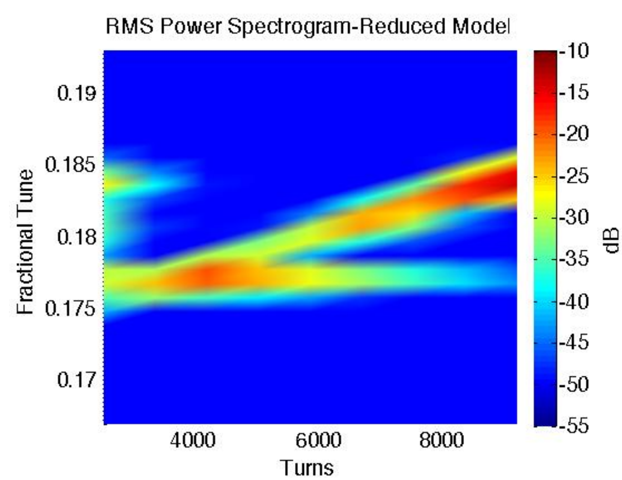

Figure 6: Beam motion spectogram response for the reduced beam model (same excitation as Figure 1). Comparing with the physical measurement we see very close agreement between the oscillation frequencies and the amplitudes of the excited motion.

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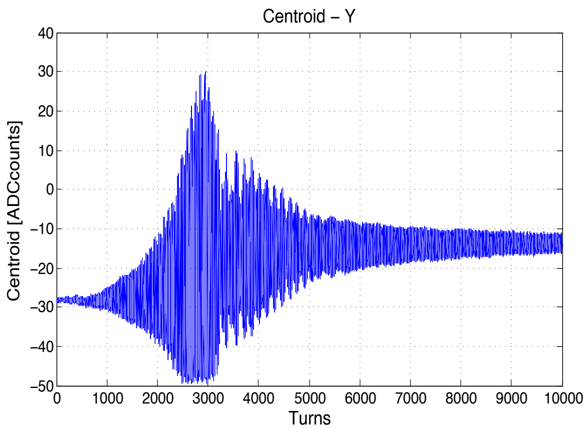

Figure 7: Open-Loop (no feedback) time-domain recording of bunch motion, Q26 lattice, vertical centroid via bunch samples. Unstable bunch motion grows from injection, with charge loss, then stability at roughly turn 3000.

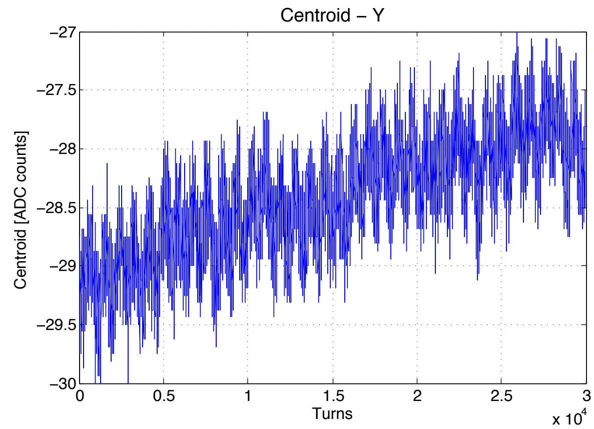

Figure 9: Closed-Loop (feedback on) time-domain recording of bunch motion, bunch samples averaged to show the vertical centroid. The same beam conditions as Figure 7 (mode 0 instability) but motion is controlled by the feedback system. Vertical sensitivity is roughly 14 µm/count.

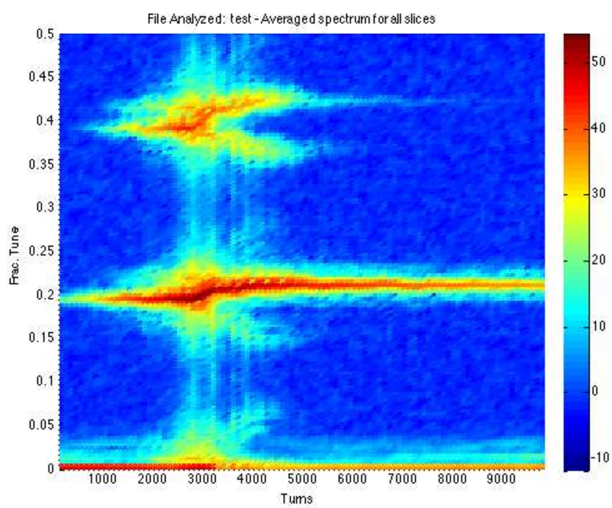

Figure 8: Open-Loop (no feedback) spectrogram of same transient as Figure 7. The beam is unstable in these conditions, $\nu_y = 0.185$ $\nu_s = 0.006$. At turn 2000 chromatic effects show sidebands of the mode zero motion, and with charge loss these end at turn 4500. Significant intensity-dependent tune shifts are seen as charge is lost in the transient.

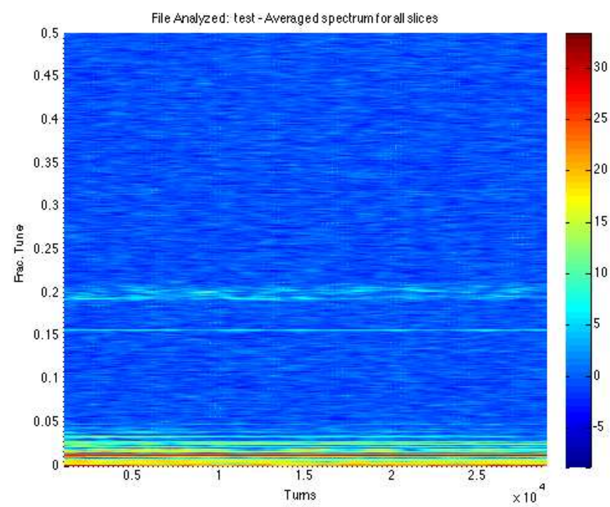

Figure 10: Closed-Loop (feedback on) spectrogram of Figure 7 transient. The beam is unstable in these conditions, Q26 lattice, $\nu_y = 0.185$ $\nu_s = 0.006$. A small amount of motion at mode zero is seen, this driven motion is reduced by the feedback gain. The feedback control keeps the mode 1 and 2 sidebands at the noise floor of the feedback receiver, or roughly 6 microns.

ESTIMATING THE IMPACTS OF SYSTEM NOISE AND LIMITATIONS

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 9) as the fluctuating centroid controlled to less than 1 count of ADC resolution (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.

SUMMARY AND PLANS FOR NEXT MD STUDIES

The immediate tasks at hand are the validation of the kicker and amplifer performance. Another important task is exploration of control methods for several candidate ma-

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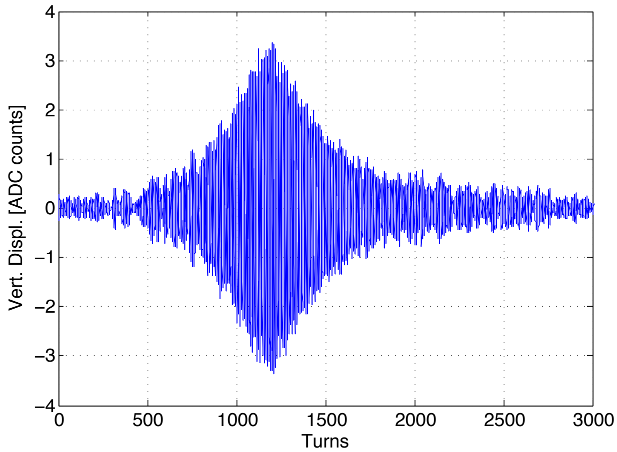

Figure 11: Time domain grow-damp study, SPS beam with excitation of mode 0, followed by damping through the feedback system with gain x4

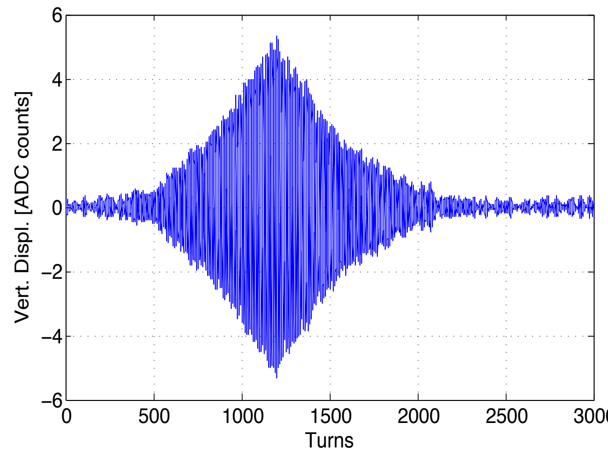

Figure 12: Time domain grow damp study, same beam conditions as Figure 11 but with damping gain x16

chine 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 [15, 16].

The goal of developing a full-function instability control system for the SPS is envisaged to span two generations of hardware. The Slotline wideband kicker design is still in mechanical design and we anticipate this new kicker will be fabricated and installed in 2016 [10], with commissioning in 2017. During this interval before LS2 we want to explore a second hardware platform as shown in Figure 13, based on a higher sampling rate A/D and D/A processing system, with associated higher-capacity FPGA processing functions [9]. This increased processing capacity may be needed to support architectures with multiple pickups, or possible two-channel processing streams which use both the Δ signal (beam motion) and the Σ signal (bunch charge) as part of the computation of a correction signal. These studies and technology development will be used to propose in 2017 the full-function system design for use in the SPS as the HL LHC injector.

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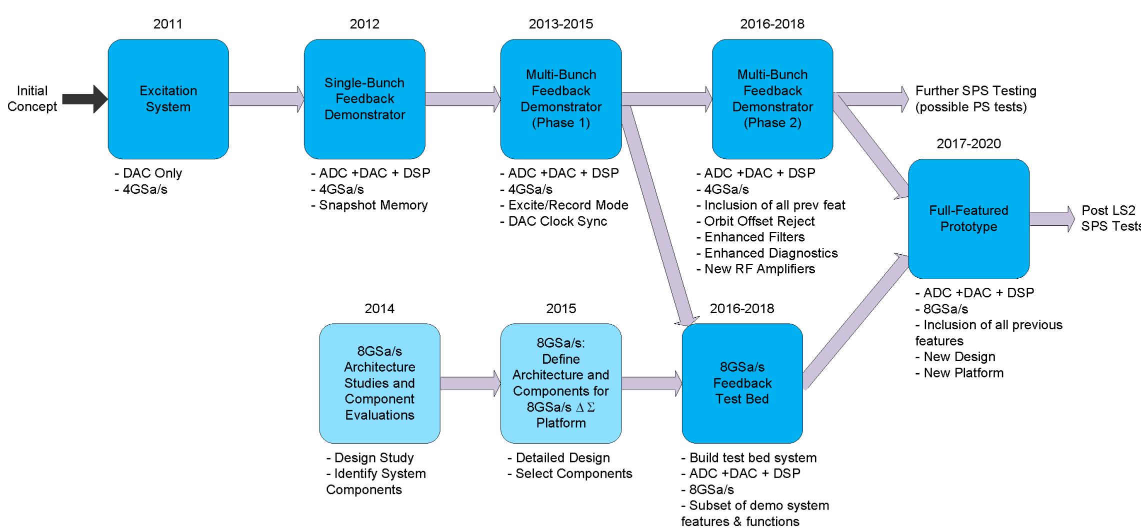

Figure 13: The development plan for the LARP Wideband Feedback effort, showing a possible path of expansion of the Demonstration system, and a parallel technology path with a higher sampling rate. We anticipate that the operational experience from the demonstrator system will guide the features to be implemented in the full-featured system.

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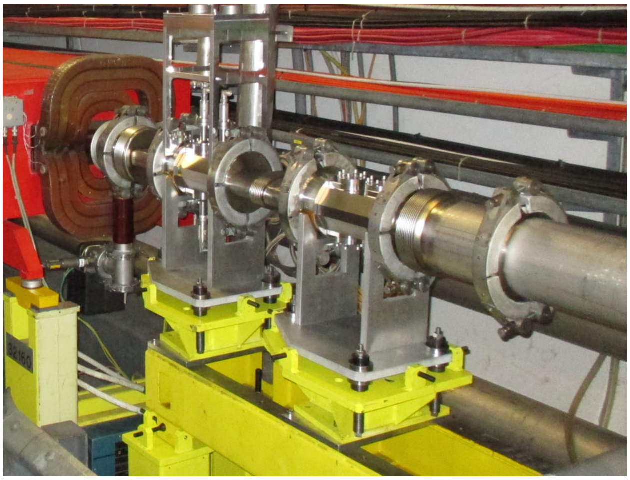

Figure 14: Two stripline vertical kickers on the SPS beamline, developed for the 1 GHz bandwidth wideband intra-bunch feedback.

Figure 15: Two wideband 5 - 1000 MHz amplifiers installed in the SPS tunnel as part of the upgrade to use 1 GHz bandwidth vertical kicker striplines. Two more additonal amplifiers will be installed in 2016 to power the second stripline.

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