

# CONTROL OF INTRA-BUNCH VERTICAL MOTION IN THE SPS WITH GHz BANDWIDTH FEEDBACK\*

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## Abstract

A GHz bandwidth vertical beam feedback system has been in development at the CERN SPS for control of unstable vertical beam motion in single bunch and bunch train configurations. We present measurements and recent studies of stable and unstable motion for intensities up to  $2 \times 10^{11}$  p/bunch [1]. The system has been operated at 3.2 GS/s with 16 samples across a 5-ns RF bucket (4.2 ns  $3\sigma$  bunch at injection) and experimental results confirm damping of intra-bunch instabilities in Q20, Q22 and Q26 optics configurations. Instabilities with growth rates of 1/200 turns are well-controlled from injection, consistent with the achievable gains for the 2 installed stripline kickers with 1 kW broadband power.

Measurements from multiple studies in single-bunch and bunch train configurations show achieved damping rates, control of multiple intra-bunch modes, behavior of the system at injection (including interaction with the existing vertical damper) and final damped noise floor. The work is motivated by anticipated intensity increases from the LIU and HL-LHC upgrade programs [2], and has included the development of a new 1 GHz bandwidth slotline kicker structure and associated amplifier system.

## TRANSVERSE WIDEBAND INTRA-BUNCH FEEDBACK DEMONSTRATION SYSTEM

A single-bunch wideband digital feedback system was initially commissioned at the CERN SPS in November 2012 [3]. Over time the system has been extended to include control for trains of 64 bunches [4] and configured with two 500-MHz bandwidth stripline kickers, each powered with 500W of broadband RF power.

Over time the system has been used to study single bunch and multi-bunch beams at the SPS in Q26, Q20 and most recently Q22 optics. The essential goals in all these studies is to try to quantify the behavior of the feedback in terms of damping intra-bunch motion from impedance mechanisms, TMCI, or Ecloud mechanisms.

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ADC Signal without Orbit Offset - 07-15-2017-1252-Batch: 1-Bunch: 70

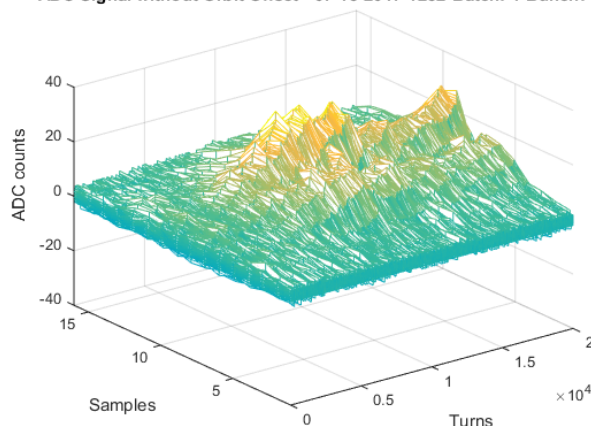


Figure 1: Vertical motion signal showing 16 samples across the bunch for 20,000 turns. Positive feedback is applied from turns 3500 - 6500, there is no feedback applied after turn 6500. The bunch motion is excited and continues without being damped.

## Q22 OPTICS STUDIES

In this conference paper we cannot show more than a small fraction of the studies, instead we show results from one type of study of the Q22 optics in development in July 2017. These studies are done immediately after injection into the SPS at 26 GeV energy, and before any acceleration ramp. The charge per bunch was  $1.2 \sim 1.5 \times 10^{11}$  P/bunch. For these machine conditions we implement a 5 tap FIR diagonal control filter configured for the nominal tune of 0.183. In these studies the existing 20 MHz bandwidth transverse damper is on.

We use the capability of the system to change the filter coefficients during the store, and snapshot the beam motion. In these studies after injection and injection transient damping we excite the beam with positive feedback from turns 3000 - 6500, and then observe the beam motion for different gains of damping feedback applied from turns 6500 to 20,000. These studies are done in a single shift, with every attempt to keep the machine state constant. Because each injection transfers a unique charge, we sort the injected charge on each transient and try to compare transients at the same charge. This example series shows a single bunch (70) in a train of 72, bunches 9 - 72 excited by a positive feedback filter from turn 3500 to 6500. From turn 6500, we explore damping

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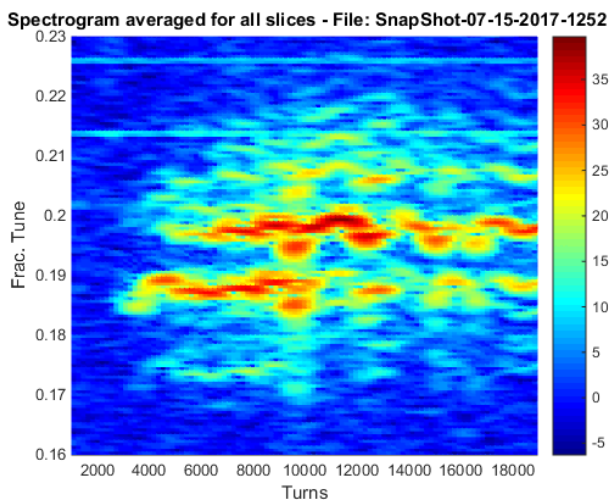


Figure 2: Spectrogram of the data from Fig. 1. the nominal vertical betatron tune is 0.185. Modes 0,1 and 2 are excited by the positive feedback. There is an interesting beating effect seen around turn 10,000.

ADC Signal without Orbit Offset - 07-15-2017-1320-Batch: 1-Bunch: 70

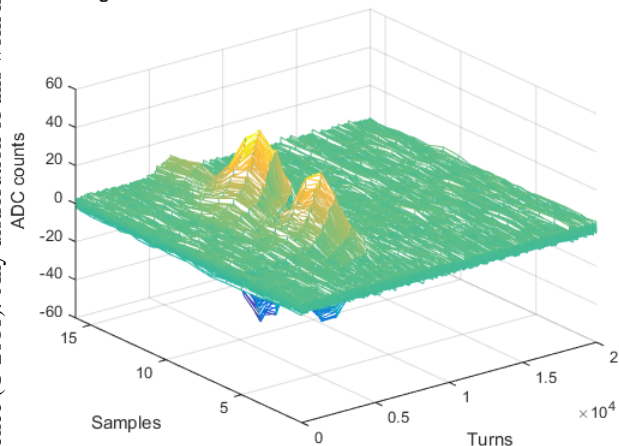


Figure 3: Same beam conditions as Fig. 1, with positive feedback excitation turns 3500–6500. Damping feedback is applied from turn 6000 to 20,000. The beam motion in damped down to the noise floor with damping rate roughly 1/500 turns.

filters with a gain of zero, a high gain case, and a gain 1/4 of the high gain case.

Figures 1 and 2 show the beam excitation, and subsequent motion for the case where post excitation there is no gain. The motion continues after the interval of excitation, many modes, predominantly modes 1, 2 and 3 are clearly visible in the spectrogram. At the end of the record, it looks like mode 1, with a clear head-tail pattern, is the dominant motion.

Figures 3–5 show a similar beam, but with the feedback configured at near maximum gain to damp during the interval after turn 6500. We see similar beam excitation, we can also see the clear head-tail structure of the beam motion at turn 6500 in Fig. 4. The spectrogram shows the motion is damped

ADC Signal without Orbit Offset - 07-15-2017-1320-Batch: 1-Bunch: 70

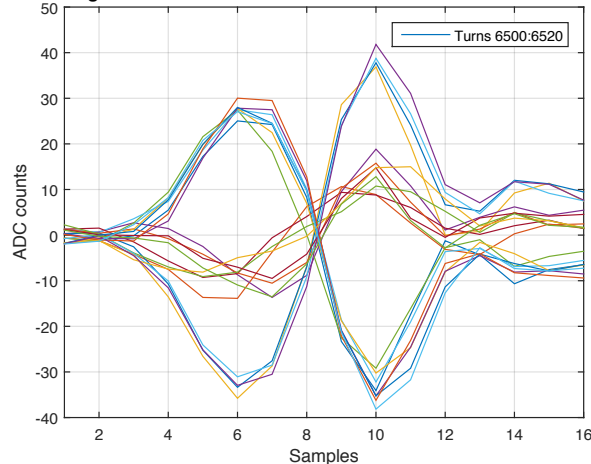


Figure 4: Vertical ADC signal across the bunch for turns 6500 - 6520. This excited beam is clearly showing head-tail mode 1 motion.

Spectrogram averaged for all slices - File: Snapshot-07-15-2017-1320

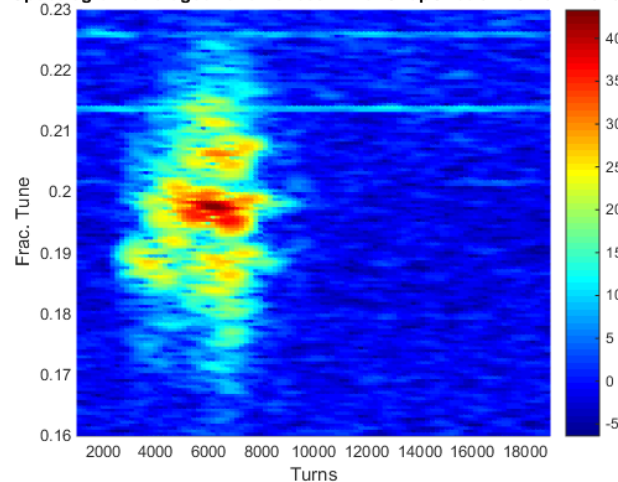


Figure 5: Spectrogram of the data of Fig. 3, showing the excitation of mode 0, strong mode 1, and mode 2 motion. The rapid damping to the noise floor is seen.

to the noise floor with roughly 1/500 turn damping rate. The control of this instability requires very careful match of the feedback gain and the machine current - the system with limited kicker power is running at high processing gain which uses roughly 1/3 of the output dynamic range.

Figures 6 and 7 show a case similar to the previous, but now the feedback damping gain is reduced to 1/4 the value seen in Figures 3–5. We can see that the motion is decaying more slowly than Figure 5, and unlike the no feedback case in Figure 1. It is possible to study a series of these transients and conclude the damping rate is scaling with the feedback gain during the portions of the damping transients when the processing system is free from saturation.

Higher intensity injections with faster growth rates saturate the control and lead to uncontrolled transients. These studies show ability to damp instabilities in modes 1,2,3

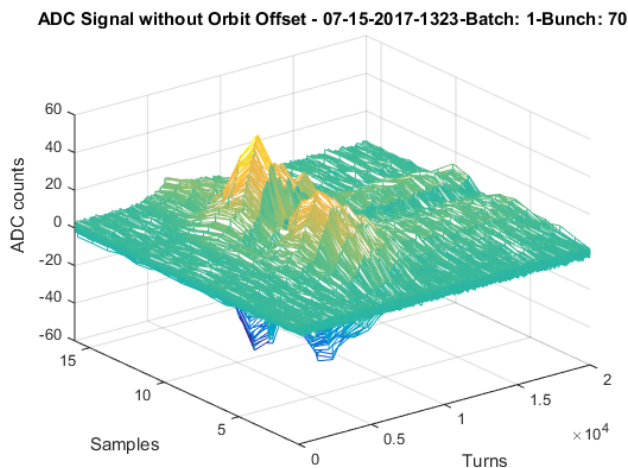


Figure 6: Similar study to Fig. 4, with the same positive feedback excitation from turns 300 - 6500. The damping gain in this study is 1/4 of the gain in Figs. 3–5. Similar excitation, but now the excited beam decays more slowly.

with 1/200 turn growth rates, and are vital to measure the achieved damping rates and noise floor and estimate the margins and capabilities of a fully-developed system with additional wideband kickers and amplifiers.

### OBSERVATIONS

One difficulty with these studies is the unique injection charge on each transient, so that comparing cases from different transients requires many cases and sorting them by injected charge. This variation in charge allows a study of the impact of the wideband feedback on the injected beam. Since the instability growth rates scale with bunch charge, by taking many transients with the feedback in a constant state, but allowing the beam current to vary, it is possible to find a threshold current below which the feedback damps instability, and above which the motion cannot be controlled. Figure 9 shows such a study which compares injections without any wideband feedback (just the nominal 20 MHz transverse injection damper) and injections with the wideband feedback operating. This study shows the wideband feedback can increase the allowed injected current, and maintain stability, for currents roughly 27% higher than without wideband feedback.

### SUMMARY AND PLANS FOR NEXT MD STUDIES

In January 2018 the slotline kicker [5] [6] with 1 GHz bandwidth was installed on the SPS beamline, and these studies can be continued looking at the excitation and control of higher intra-bunch modes. During 2018 (before the LS2 shutdown) we want to explore the behavior of the 1-GHz bandwidth intra-bunch feedback, and quantify the system specifications required for control of Ecloud and TMCI instabilities in the SPS running the HL intensity beams for the HL-LHC.

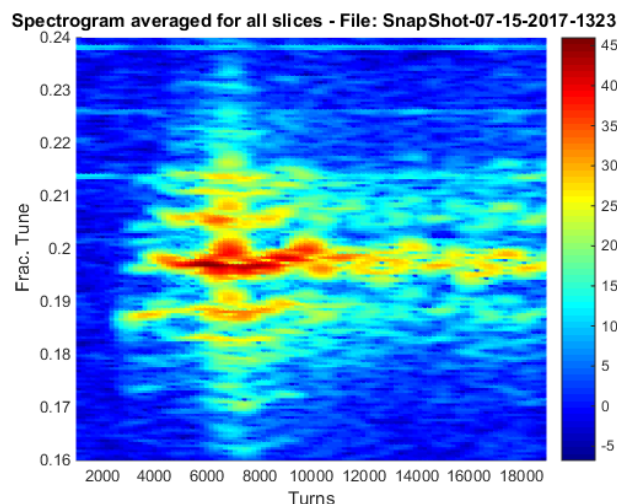


Figure 7: Spectrogram of the data from Fig. 6. Comparing to figure 3, the excitation is similar, but the motion is now decaying weakly, consistent with the reduced feedback gain of 1/4. The motion is damped but not yet at the noise floor at turn 20,000.

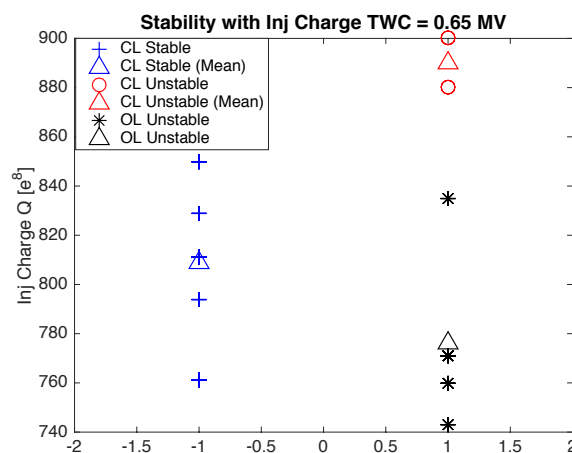


Figure 8: Study of multiple injections, each with unique bunch charge. The data on the right of the figure are all unstable beam cases, with no feedback, or high charge with feedback. The Data on the left shows stable beam cases under the impact of feedback. In these studies, at 0.65 MV total RF voltage, the open loop instability threshold is  $\approx 0.7 \times 10^{11}$  ppb. WBFS pushes the instability threshold up to  $\approx .89 \times 10^{11}$  ppb or a 27% increase.

We are investigating modal (matrix) controllers which are advantageous for the control of many unstable modes, or for targeting the available kicker power to selected modes (for example, not trying to control the barycentric injection transient but using the kicker power on specific intra-bunch modes) [7]. It is vital we to study and validate the performance of various control filters in the physical machine, particularly with regard to the dynamic range required in the processing and possible sensitivity to out of band noise signals [8].

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