CONTROL OF INTRA-BUNCH VERTICAL INSTABILITIES AT THE SPS-MEASUREMENTS AND TECHNOLOGY DEMONSTRATION*

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Abstract

We present recent measurements demonstrating control of unstable beam motion in single bunch and bunch train configurations at the SPS. The work is motivated by anticipated intensity increases from the LIU and HL-LHC upgrade programs [1], and has included the development of a GHz bandwidth reconfigurable 4 GS/S signal processor with wideband kickers and associated amplifiers. The system was operated at 3.2GS/s with 16 samples across a 5 ns RF bucket (4.2 ns 3σ bunch at injection). The experimental results confirm damping of intra-bunch instabilities in both Q20 and Q26 optics configurations for intensities of 2×10^{11} p/bunch. Instabilities with growth times of 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 and final damped noise floor.

TRANSVERSE WIDEBAND INTRA-BUNCH FEEDBACK DEMONSTRATION SYSTEM

A single-bunch wideband digital feedback system was initially commissioned at the CERN SPS in November 2012 [2]. The Demonstration hardware was implemented to evaluate intra-bunch instability control using a processing scheme of 16 samples of dipole motion taken across each 1.6 ns (1σ) bunch. Over time the system has expanded to include 2 500 MHz bandwidth stripline kickers, each powered with 500W of broadband RF power. The initial single-bunch processing capability has been extended to include control for trains of 64 bunches [3]. These tests are very significant technical evaluations of the 4 GS/s digital signal processing hardware and validate that the proposed full-function architecture and control techniques could be developed and successfully commissioned.

SINGLE BUNCH STUDIES

To explore control of possible TMCI motion, we configure the machine with a nominal vertical tune of 0.183 (synchrotron tune of 0.006), Q26 lattice and inject a single bunch of intensity 2.05×10^{11} particles. With careful adjustment of slightly positive chromaticity the machine exhibits unstable motion after injection. The wideband feedback system snapshots the beam motion, and as seen in Fig. 1 the initial injection transient damps but unstable motion develops with roughly 1000 turns growth time, ultimately charge is lost from the bunch near turns 1500 and 10,000. Fig. 2 shows the same injection transient as spectrogram in the frequency domain, where the injection transient is seen to broadly contain spectral content and where mode 0 and mode ±1 are seen to persist strongly and grow in intensity with time. The charge losses in the system are clearly seen in the sudden upward tune shifts (the loses are also seen in the intensity of the beam SUM signal in the processing chain). This unstable motion is present with the SPS vertical transverse damper ON, as the 20 MHz bandwidth system is insufficient to control this single bunch instability.

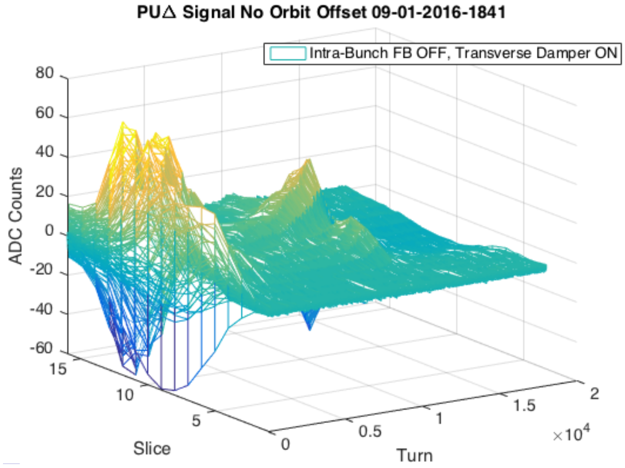

Figure 1: Open-Loop (no feedback) time-domain recording of vertical bunch motion, Q26 lattice, nominal 0.183 tune. Unstable bunch motion grows from injection, with charge losses seen at turns 1500 and 10,000.

For these machine conditions we implement a 5 tap FIR diagonal control filter configured for the nominal tune of 0.183. Fig. 3, 4 and 5 show the initial injection transient is damped to the channel noise floor with negligible charge loss. 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. Higher intensity injections with faster growth rates saturate

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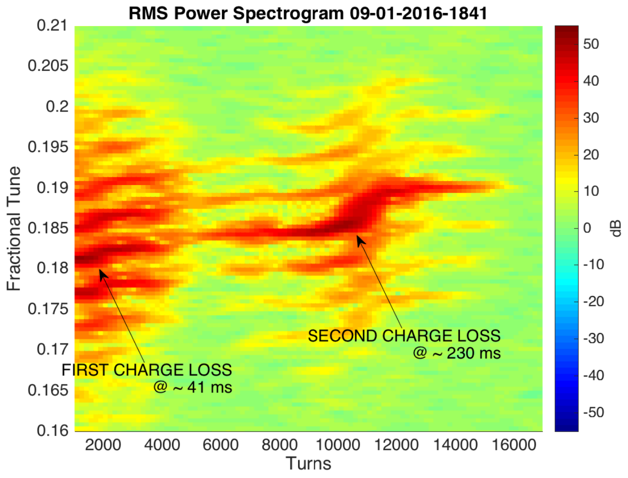

Figure 2: Beam motion spectrogram response for the transient in Fig 1. The initial transient shows roughly 7 modes (possibly nonlinear effects in instrumentation), with mode 0 and ±1 growing over time. The charge losses are seen in the sudden tune shifts.

the control and lead to uncontrolled transients, injections of slightly less charge are marginally stable or stable, and do not exhibit the unstable beam growth for the feedback system to control. These studies show ability to damp instabilities with 200 turn growth times, 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.

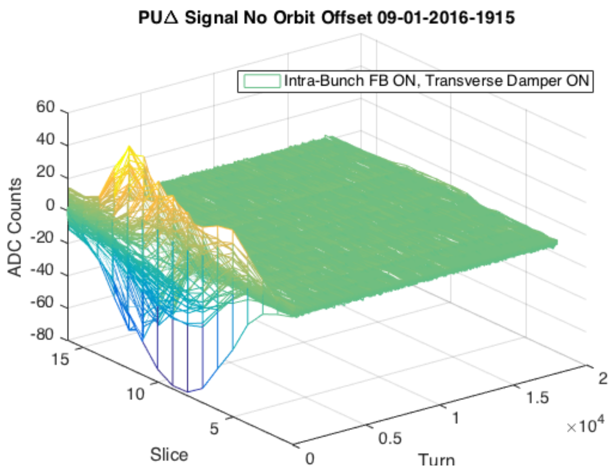

Figure 3: Closed-Loop (feedback ON) time-domain recording of vertical bunch motion, Q26 lattice, nominal 0.183 tune, same machine configuration as Fig. 1 and 2. The injection transient is damped to the processing noise floor in 2000 turns.

BUNCH TRAIN STUDIES

In 2016 the Demonstration system processing was expanded to allow the control of 2 64 bunch trains, each bunch having the 16 tap diagonal filter structure. This expanded configuration was developed to explore control of Ecloud induced motion. Studies were made in the SPS using the Q20 optics, with the lattice chromaticity set very close to zero and intensities of 1.8×10^{11} p/bunch. In these conditions successive stacks of 72 bunches were injected into the SPS. In these studies the 4th stack of bunches would exhibit unstable motion after a few hundred turns for several tail bunches of the 4th stack (Fig. 6). This behavior is seen even with the existing SPS transverse damper ON, and leads over time to charge loss from the tail of the stack at roughly turn 1000. The same beam conditions, but with the wideband feedback ON, is Fig. 7. In this configuration the feedback is controlling the last 64 bunches of 72 in stacks 3 and 4

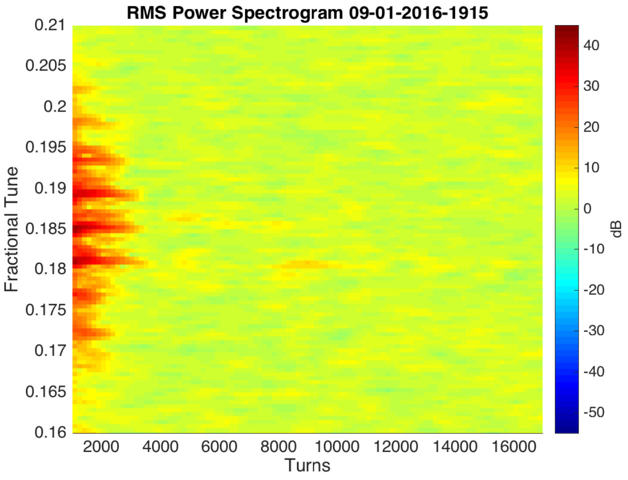

Figure 4: Closed-loop Feedback-ON spectrogram of Fig. 3 data. The injection transient is damped and unstable motion is controlled to the channel noise floor.

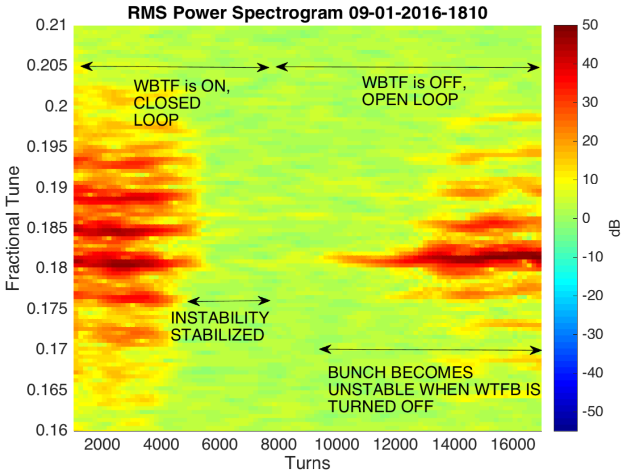

Figure 5: A Damp-Grow study of the same machine conditions. The feedback system gain is changed to zero at turn 8000, after which the unstable motion grows from the noise floor. Mode zero appears first, then multiple unstable modes appear.

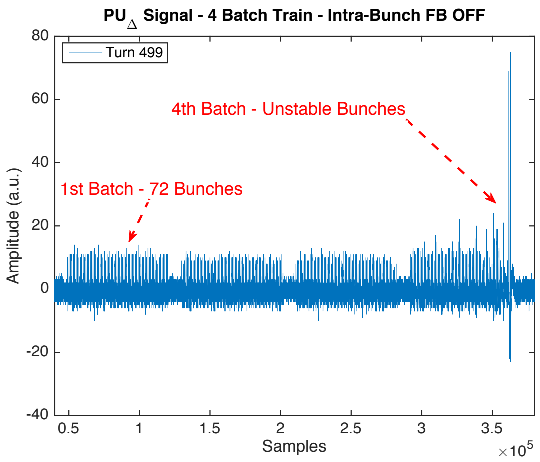

Figure 6: Open-Loop (feedback off) time-domain recording of bunch motion, intra-bunch samples averaged to show the vertical centroid. At turn 499 the data show the last bunches in stack 4 with vertical motion.

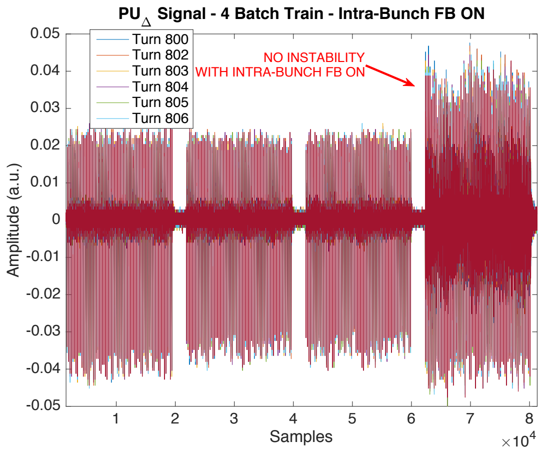

Figure 7: Closed-Loop (feedback on) transient recording superposing dipole motion on turns 800-806. The same beam conditions as Fig. 5 but with extra charge injected into the 4th stack. Even with this increased intensity the feedback stabilizes the bunch train without charge loss.

(stacks 1,2 and the first 8 bunches in stacks 3 and 4 are left uncontrolled). As seen, the feedback allows the injection of extra current into stack 4 without the unstable tail bunches. These initial studies require further study to quantify the unstable mode and growth rates, achieved damping rates, but are very promising. Quantitative analysis of the snapshot data of beam motion seen at the tail of stack 4 without wideband feedback suggest the motion is barycentric motion, with all samples across the bunch moving in phase (even with the SPS transverse damper ON).

SUMMARY AND PLANS FOR NEXT MD STUDIES

These encouraging initial results will be continued with studies in 2017 and 2018. Another important task is exploration of control methods for several candidate machine optics. We have shown good control with FIR based filters for the Q26 optics, and control of unstable Q20 optics with several unstable modes, control of the machine with Q20 and Q22 optics needs more study. The proposed Q22 optics in the SPS will have a lower intensity TMCI threshold. The HL Q22 configuration requires the design and evaluation of possible feedback controllers in addition to beam tests. 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) [4]. While simulation methods are needed to select likely control filters, 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].

The Slotline wideband kicker fabrication is underway and this new 1 GHz bandwidth kicker will be available for commissioning in early 2018 [6] [7]. During 2018 (before LS2) 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.

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