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WIDEBAND FEEDBACK SYSTEM PROTOTYPE VALIDATION

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Abstract

A wideband feedback demonstrator system has been developed in collaboration with US-LARP under the joint leadership of CERN and SLAC. The system includes wideband kicker structures and amplifiers along with a fast digital reconfigurable system up to 4 GS/s for single bunch and multi bunch control. Most of the components have been installed in recent years and have been put into operation to test both intra-bunch damping and individual bunch control in a multi bunch train. In this note we report on the MD program, procedure and key findings that were made with this system in the past year.

INTRODUCTION – HISTORY, MOTIVATION AND OVERVIEW

A wideband feedback system has been proposed in the past and has been under study to be used in the SPS for instability mitigation. This was mainly motivated by the hard limit in the maximum reachable bunch intensity imposed by the transverse mode coupling instability (TMCI) threshold. Another limitation arises from electron cloud formation from multipacting which can also drive coherent instabilities and drastically limit the machine performance. These coherent instabilities would prevent reaching the beam parameters required by the LHC Injector Upgrade (LIU) in preparation for HL-LHC. In both cases, the instabilities feature coherently growing intra-bunch motion. Given the typical bunch length in the SPS which is in the range of 3 ns at injection energy, this renders signals in the 100 MHz up to the 1 GHz range. Conventional transverse feedback systems as used in the LHC or the SPS to-date operate with a roll off starting at already 1 MHz, thus, the frequencies exhibited by the aforementioned instabilities are way beyond the reach of these feedback systems.

Whereas a conventional transverse damper is ideally able to sample and act on the individual bunch centroid motion, a wideband feedback system is fast enough to sample individual time slices within a single bunch. This allows it to act distinctively on individual slices and thus to control coherent intra-bunch motion. The challenges with these systems, however, are multifold. For one, it is non-trivial to design kicker structures that can generate signals of up to 1 GHz with enough power to provide an adequate correction kick (or integrated deflecting voltage). The same holds true for the power amplifiers used to power the kicker structures which need to deliver high power in a very broad frequency range and with a correspondingly flat phase response. Moreover, the high sampling rate, noise filtering and the presence of synchrotron motion make the digital processing and finding suitable control algorithms very demanding.

Nevertheless, a system was devised and developed which features wideband kicker structures powered by wideband amplifiers with a frequency reach up to 700 MHz and 1 GHz, respectively. In conjunction with this, a fast digital signal processing unit which is fully reconfigurable and can run at a sampling rate of up to 4 GS/s allows the implementation of a variety of control techniques for sophisticated intra-bunch control.

It has been shown in simulations that a wideband feedback system can work to ameliorate both TMCI and e-cloud driven instabilities [1–4]. The simulations include a sophisticated model to mimic a realistic feedback system. This system was added on top of the basic chain of components to correctly simulate the beam dynamics of collective effects including important beam and machine parameters, impedances and electron cloud effects. Thus, the numerical proof of principle was at hand and to be complemented by an experimental realization. Fig. 1 displays an example of a simulation which shows an e-cloud instability being damped by a 500 MHz wideband feedback system. Beam centroid motion and transverse emittance are plotted as a function of the number of turns for different feedback gains. From a certain gain onward, the system mitigates the e-cloud driven intra-bunch coherent motion.

The project has been reviewed twice. Following the presentations during the last review, we will focus here on the key findings made during MDs. In the following two sections we will briefly describe the main components of the system and then discuss the MD program and results for single bunch and multi bunch studies.

SYSTEM INSTALLATION

The wideband feedback system installed in the SPS currently comprises of 2 stripline kickers with a bandwidth of up to 700 MHz which are each powered by two 250 W amplifiers with a bandwidth of 5 – 1000 MHz. A slotline kicker which can provide more kick strength in the range of 1 GHz is currently under construction [5, 6]. The digital signal processing unit has been developed and deployed and contains all the hardware, firmware and interfaces necessary to implement excitation signals or perform closed loop control for single as well as for multiple bunches in a 25 ns

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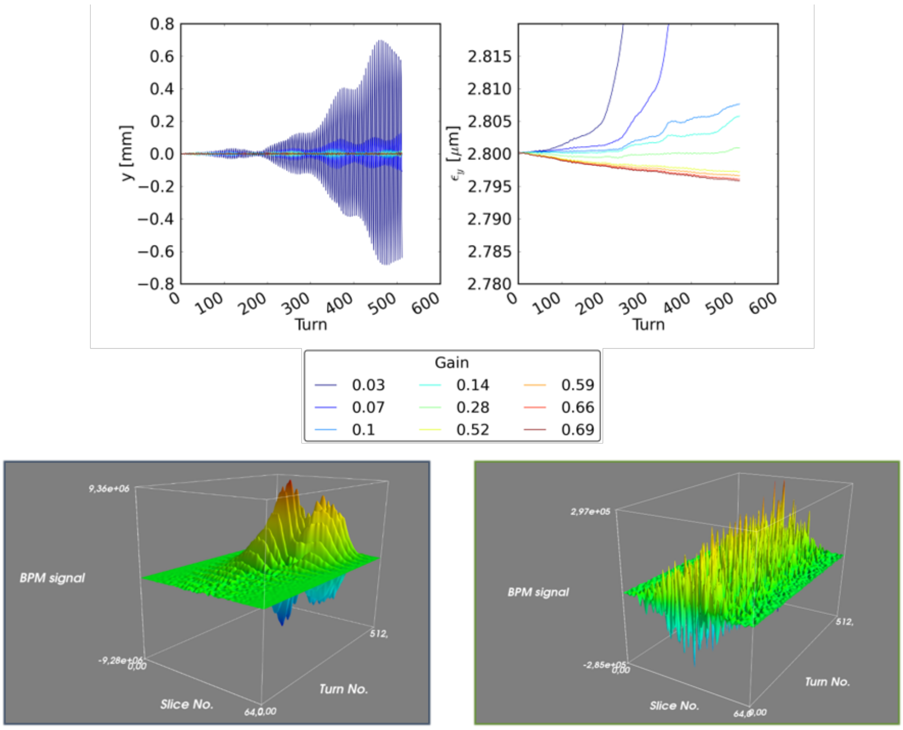

Figure 1: Simulation of an e-cloud driven instability. The top plot shows the beam centroid motion and transverse emittance plotted as a function of the number of turns for different feedback gains for a 500 MHz wideband feedback system. The bottom plots show the time evolution of the intra-bunch motion for a gain of 0 (left side) and a gain of 0.4 (right side).

bunch train. Different filters have been designed and implemented to cope with the different optics configurations, namely the classical Q26 as well as the Q20 optics which features by a factor 2.5 increased synchrotron frequency. Fig. 2 shows a schematic of the location of the installed components, all located around BA4 of the SPS. The system uses an exponential coupler as pickup [7, 8].

MD PROGRAM AND RESULTS

The aim of the wideband feedback demonstrator system is the experimental verification of damping of TMCI and e-cloud-like instabilities. Therefore, one of the main goal of the MDs was to show damping of intra-bunch motion for both single and multi-bunch instabilities in order to verify the frequency reach of the system. As explained above, this is the part which poses the most challenging requirements on the entire feedback chain.

Going for the most straightforward option of setting the machine to operate somewhere beyond the TMCI threshold and using the wideband feedback system to cure the instability is, unfortunately, not a viable strategy. For cost reasons, the system had to be built with reduced specifications and in particular with the power amplifiers being one of the main cost drivers, the output power of the system is very limited and not able to handle the fast rise times of a typical TMCI, in particular during transients at injection and with the presently achieved noise floor. Therefore, the strategy chosen instead was to identify a working point that would exhibit an intra-bunch motion while at the same time being slow enough such that it could be handled by the wideband feedback system with its reduced power. It is known from simulations as well as measurements that this working point, or rather region of working points, does exist in the SPS [9] and the task for the single bunch studies was to find this point in the machine, set up the wideband feedback system and then to close the loop on the instability to hopefully regain the beam stability.

The multi bunch studies involve the injection of up to 4 batches of 72 bunches into the SPS. For this reason these latter studies required dedicated MD time. Due to reduced machine availability, only about 50% of the dedicated MDs could be realized as planned.

Single bunch instabilities

As mentioned above, the first step in using the wideband feedback system for single bunch studies was to find the right working point for exciting an intra-bunch instability at sufficiently low growth rates, such that the instability could still be handled within the limitations of the system. Fig. 3 shows simulations from [9] where the left plot shows the growth rates of an instability as a function of the longitudinal emittance and the bunch population. The sharp yellow boundary separates the regions of the classical fast TMCI in red from the more stable regions in blue. Within the stable regions, it is possible to make out a light blue island which features comparatively low growth rates. The plot on the right hand side shows the turn-by-turn signal along the bunch as it would be picked up by a wide band beam position

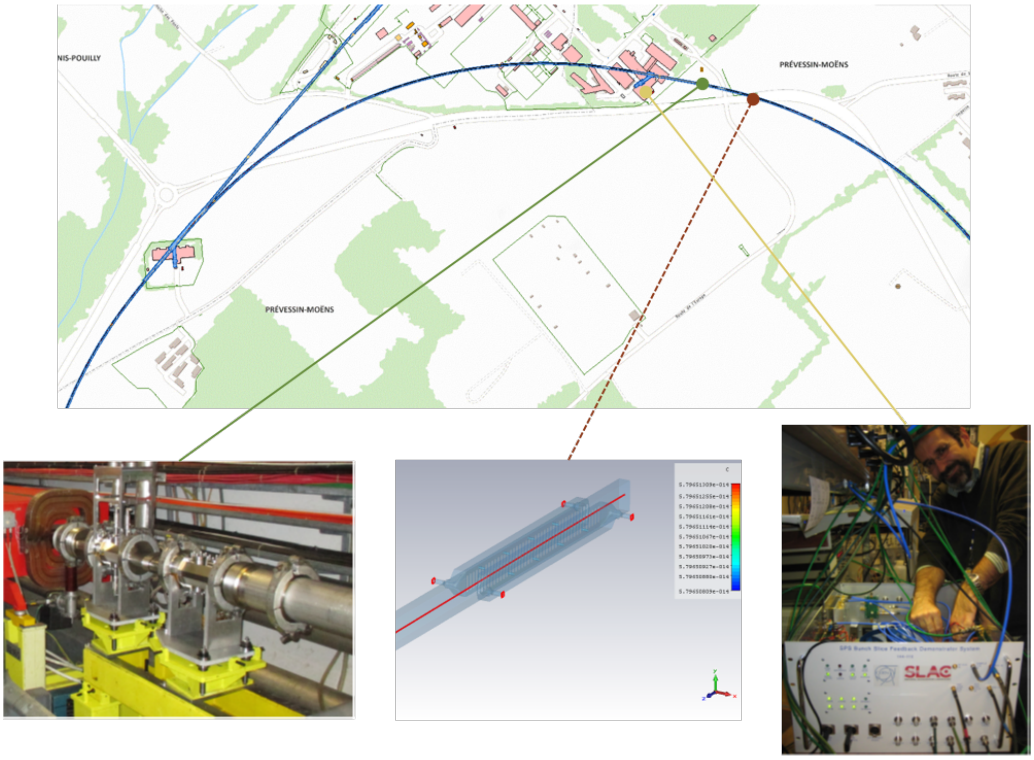

Figure 2: Location of the stripline kickers (green) and the feedback box (yellow). A slotline kicker is still under fabrication but is foreseen to be installed close to the stripline kickers.

monitor. The signal features a single node and an oscillation along the bunch with a phase shift of about 180 degrees from the tail to the head. The regime clearly shows coherent intra-bunch motion suitable for demonstrating the frequency reach of the wideband feedback system.

To obtain the same instability in practice, the machine had to be set up very carefully using a variety of parameters. To make the beam more susceptible to instabilities without the need of pushing the intensities too far, it was decided to conduct the studies using the Q26 optics. Therefore, the required machine parameters were not expected to exactly match the region of working points found in the simulation mentioned above. The longitudinal emittance was typically somewhat below 0.3 eVs. The transverse emittance was chosen to be rather large, above 3 μm in order to suppress space charge forces as much as possible as it is not entirely clear how exactly space charge would influence the pure TMCI. The intensity was tuned around 1.6×10^{11} ppb. The main diagnostics used was the FBCT to detect losses occurring due to instabilities as well as the fast losses application to distinguish slower headtail-like instabilities from TMCI. Finally, the headtail monitor, basically a scope with a high sampling rate connected to a large memory buffer for turn-by-turn acquisition along the bunch was used to detect coherent intra-bunch motion. This instrument could be used in addition to the internal ADC of the feedback box, the latter one which could be gated to read out on an individual bunch.

The chromaticity was then carefully adapted to move it as close as possible to zero while still remaining positive. Typically the bunch was stable at intermediate chromaticity values and became unstable when the chromaticity was lowered. Unfortunately, the arising instabilities were exclusively of mode type zero and did not feature any intra-bunch coherent mode pattern. It became clear that by using just the chromaticity it was not possible to isolate an instability which would feature any coherent intra-bunch motion. Instead, the main RF voltage proved to be an important knob to adjust, and by lowering the RF voltage it was possible to induce instabilities that did contain a distinguishable amount of intra-bunch motion. Still, the signals were dominated by a strong coherent motion of the bunch centroid which would quickly saturate the wideband feedback system rendering it virtually ineffective upon closing the loop. To ameliorate this situation, we then added the conventional transverse damper [10] to control and remove the centroid component and prevent saturation of the wideband feedback system. Doing this, finally, it was possible to isolate a clean coherent intra-bunch instability in a reproducible manner. Fig. 4 shows a snapshot from a headtail monitor acquisition. The signal looks very similar to the once predicted in the simulations.

It is to be noted, that the conventional damper was active during this time during growth of the intra-bunch motion. The coherent intra-bunch instability ultimately leads to losses which could be seen on the BCT. It is in this configuration, that the wideband feedback loop was closed. Fig. 5

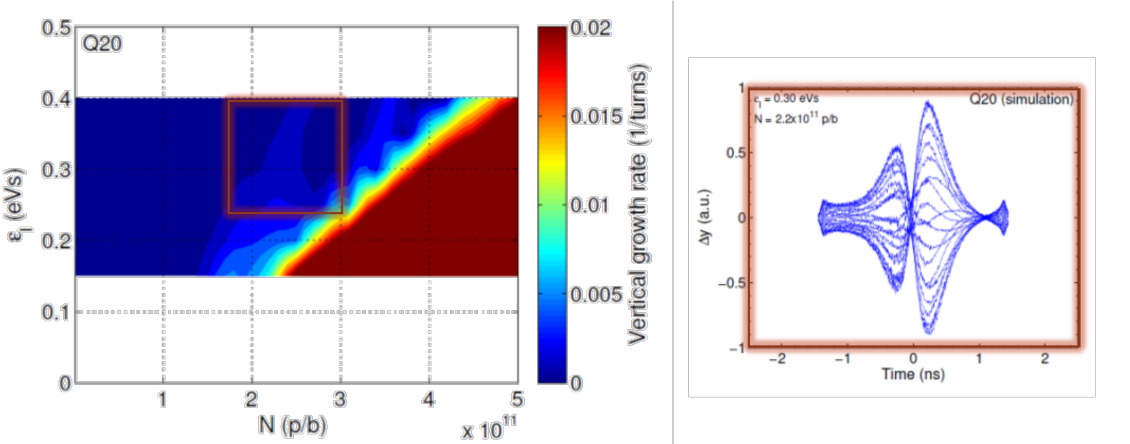

Figure 3: Simulations of the single bunch growth rate (colour-coded) as a function of the longitudinal emittance and the bunch intensity. The red frame indicates a good potential working area to test a wideband feedback system. The plot on the right hand side displays the BPM signal produced by instabilities arising from operation close to this working point and features a clearly visible coherent intra-bunch motion.

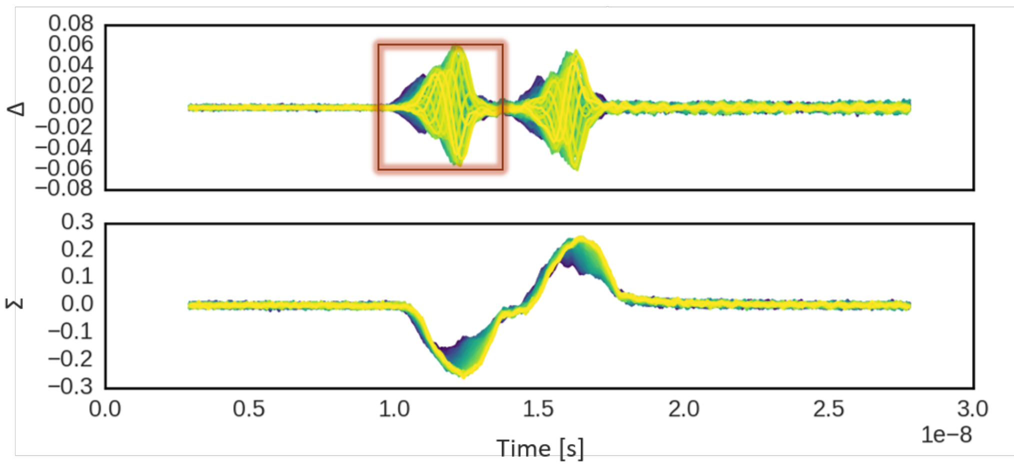

Figure 4: A snapshot of the instability produced in the SPS acquired with the headtail monitor. The top plot shows the Δ-signal and features the single node very similar to what has been computed in simulations as show in Fig. 3 (red frame). The second signal is an artifact from the reflected signal in the headtail monitor as becomes clear also from the bottom plot which shows the Σ-signal.

shows the typical signature of this instability with the top plots showing the beam intensity lost over a few 100 μs and the bottom plots showing the signal acquired up by the internal ADC of the feedback box. The bottom plot shows the delta signal which clearly features the single node and the 180 degrees face shift from head to tail which is characteristic for the coherent intra-bunch motion. The observed signal corresponds to what is seen by the headtail monitor – note that here the ordering of the channels is inverted in time.

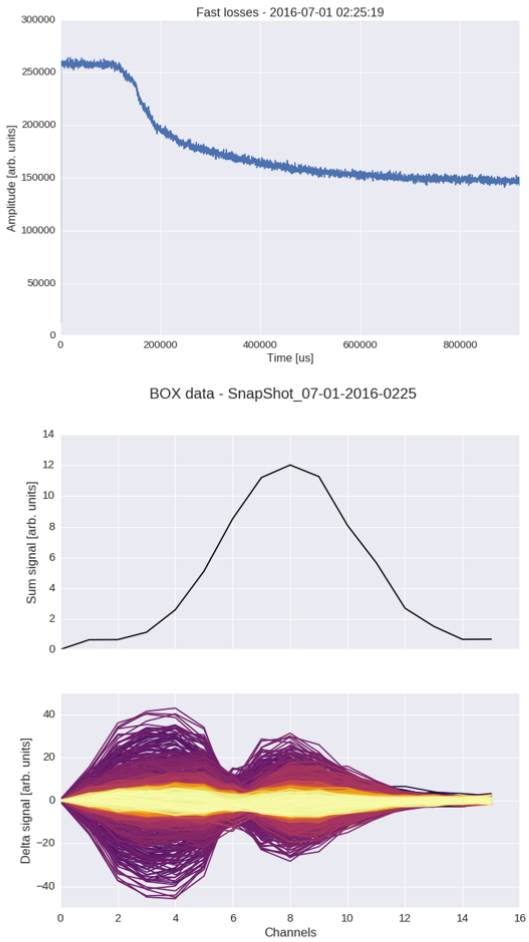

Figure 5: Open loop signature and acquisition of the internal ADC. Fast losses are visible accompanied by a distinct coherent intra-bunch oscillation shown in the bottom plot which displays the turn-by-turn delta signal across the bunch.

After recording the instability above, the loop was closed for the following supercycle. The signature of the instability with the loop closed is shown in Fig. 6. The beam does no longer exhibit any signs of instabilities. The intensity is similar, but no losses are visible. The ADC shows initial coherent motion corresponding to the injection oscillations. These are damped rapidly by the transverse damper after which the growth of the coherent intra-bunch motion featured in Figs. 4 and 5 is entirely suppressed. The loop was opened and closed randomly several times during the following 30 minutes and the picture remained absolutely consistent in that the intra-bunch motion rose each time the loop was opened and was damped when the loop was closed.

With this, the experimental verification of intra-bunch damping at high frequencies was achieved, however, keeping in mind that the machine had to be carefully tuned in order to be compatible with the reduced specifications of the wideband feedback system. As the system was built to also help mitigation of e-cloud instabilities, the next step was to show multi-bunch control in a batch of several bunches.

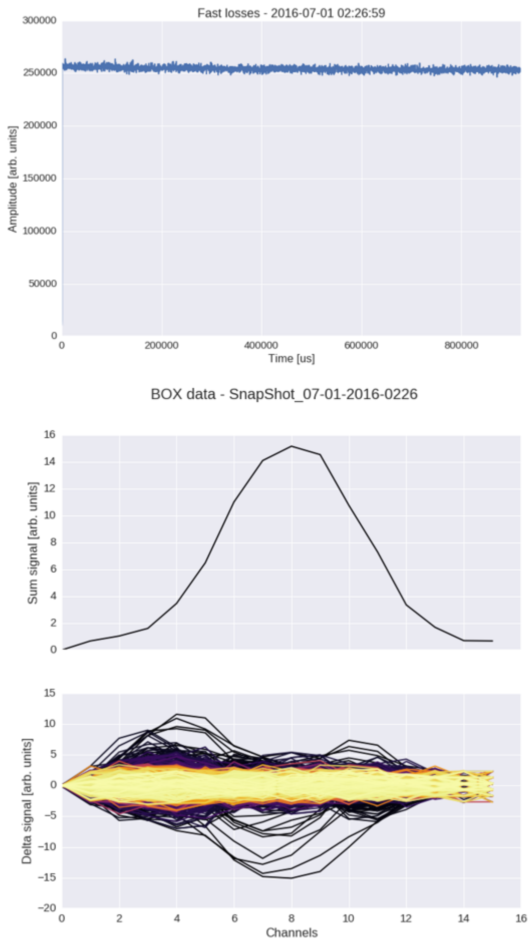

Figure 6: Closing the loop fully restores beam stability. Losses are fully mitigated and the coherent intra-bunch oscillations are no longer seen in the ADC.

Multi bunch instabilities

Multi bunch instabilities occur at certain conditions in the SPS when several trains of 72 bunches at high intensity are injected (approaching 2×10^{11} ppb for Q20 optics). Normally, the transverse damper should take care of coupled bunch instabilities of any order in the SPS. If the instability is not of coupled bunch type and contains intra-bunch motion then the transverse damper will be ineffective against these instabilities, however. During the SPS scrubbing runs in 2014 and 2015, multi-bunch instabilities were routinely observed despite having the transverse damper set up and active. It is assumed, that these instabilities are generated by e-cloud. During the scrubbing runs, chromaticity and even octupoles had to be employed in order to stabilize the beam. These, however have undesirable side effects as the large tune spread can substantially decrease the beam lifetime.

With e-cloud being the likely origin of the observed instabilities, finding a good working point to test the wideband feedback demonstrator system with limited power becomes very hard. As conditioning and de-conditioning of the inner vacuum surfaces takes place continuously and dependent on the composition of the supercycle or the operational program, e-cloud effects are intrinsically not reproducible.

The strategy here was to prepare a high intensity scrubbing beam at close to 2×10^{11} ppb and inject batches of 72 bunches into the SPS with the Q20 optics and high chromaticity. Having the transverse damper active is mandatory here to suppress coupled bunch instabilities. Slowly lowering the chromaticity at a certain point leads to losses. Looking at the headtail monitor or at the LHC BPMs one can observe the last bunches of the later batches starting to oscillate.

One can use the headtail monitor to also look into the intra-bunch motion of individual bunches in the batch. Figs. 7 shows a zoom into the last bunches of an unstable batch. One can see the last bunches going unstable. A zoom into an individual bunch reveals that the type of instability corresponds rather to a mode 0-like instability, meaning rather a pure centroid motion and less of a coherent intra-bunch pattern. In principle, this kind of pattern can be damped by the conventional damper, however, with several adjacent bunches oscillating at random phases this can be difficult for the transverse damper to handle.

Given the fact that unstable bunches are preferably located towards the end of batches and that the instability grows despite the presence of the transverse damper suggests that the instability is likely to be a result of e-cloud effects. With the high bandwidth and the advanced control algorithms of the wideband feedback system, this device is ideally suited to control individual bunches within a batch entirely separated from each other. As shown in the previous experiment with single bunches it could even damp intra-bunch motion. The observed types of instabilities in the multi-bunch configuration did not show this feature however.

Nevertheless, the instability provided a good test for the multi-bunch controller of the wideband feedback system. For this test, we set up the machine to exhibit a multi-bunch instability as described above keeping the wideband feedback loop open. Once a reproducible condition was reached for the instability, the loop was closed.

Figs. 8 shows one of the unstable bunches in an unstable batch in terms of the signal acquired by the internal ADC of the feedback box, once with the feedback loop open on the left hand side, and then with the feedback loop closed on the right hand side. The growth of the bunch centroid motion and the mode 0-like pattern can be seen on the left plot and corresponds to what has been observed on the same instability with the headtail monitor. Upon closing the loop, the instability is perfectly damped. This was the case for all bunches within the batch meaning that the multi-bunch instability was perfectly mitigated by the wideband feedback system. Several measurements were taken, again randomly opening and closing the loop and the instability appeared and was suppressed in a reproducible manner.

SUMMARY AND NEXT STEPS

The experiments above show that the wideband feedback system in principle is able to damp intra-bunch instabilities as well as to independently control individual bunches in a multi-bunch batch. This implies that it is also possible to damp very high frequency multi-bunch or coupled bunch intra-bunch motion.

The multi-bunch studies were very difficult to reproduce from one dedicated MD to the next mainly because both the scrubbing beam and the machine could not be set up in a very reproducible manner. This is not surprising since the scrubbing beam was rarely deployed and usually needs dedicated preparation and setup throughout the injector chain starting from the PS Booster up to the SPS. One of the goals for the future will be to utilize the wideband feedback system to stabilize an actual scrubbing beam such that it can be run at low chromaticity and without making use of octupoles. For this, more tests should be done on multi-bunch batches to gain experience and confidence with the multi-bunch firmware and the configuration of the feedback box. A single batch could be enough for this. These types of MDs could potentially be run as parallel MDs with 72 bunches. Once the box is well set up it can be deployed during high intensity runs in the SPS.

For the single bunch studies it will be of high interest to see how the system can perform with modified optics and, in particular, with the Q22 optics which is foreseen to be tested in 2017. For this, new filters will have to be designed, implemented and tested. The Q22 optics has the potential to ameliorate certain limitations for the RF but at the same time it comes with a lower TMCI threshold close to the nominal intensity for LIU beams. This could ultimately prohibit the use of these optics. A wideband feedback system could be used to mitigate the TMCI, thus removing this limitation and opening up the parameter space for a successful deployment of these optics.

Both the single bunch as well as the multi-bunch operation modes still suffer from a lack of output power and it is not clear whether the kick strength is sufficient for the feedback system to work for operational beams. This will need to be tested. In addition, a slotline kicker structure is in fabrication and is planned to be installed during the 2017 YETS to complement the 2 stripline kickers probably with the same set of power amplifiers aimed to double the available kick strength.

One of the points not mentioned so far are the diagnostic possibilities of the system. With the signal acquisition and digital processing system at hand there are a variety of diag-

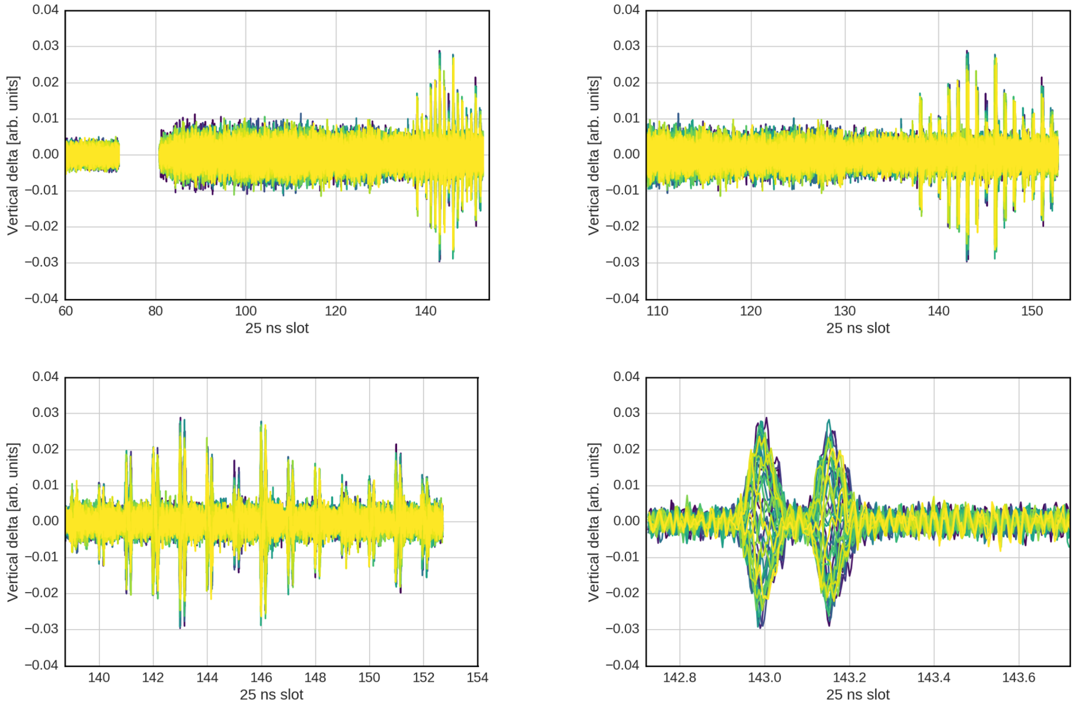

Figure 7: The plots above show a step-wise zoom into the final bunches of an unstable batch from the top-left to the bottom-right. Top left shows the headtail monitor acquisition of the entire batch with the last couple of bunches going unstable. The bottom right plot is a final zoom into an individual unstable bunch. For this bunch, the coherent centroid motion is well visible as well as the absence of any coherent intra-bunch structure. This is true also for all other unstable bunches in the batch.

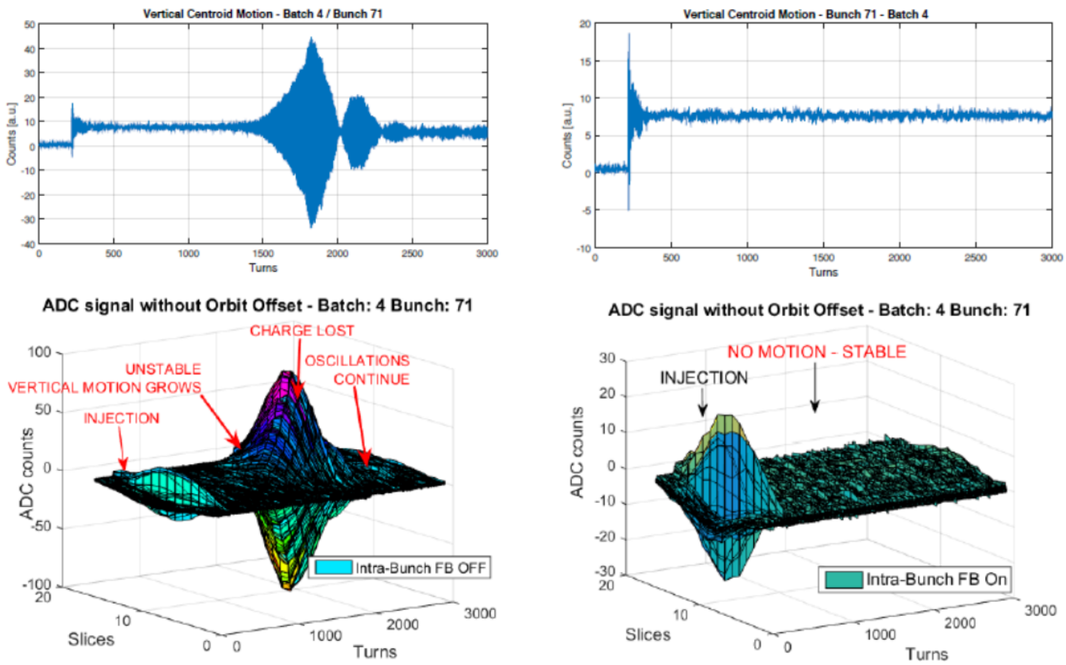

Figure 8: The bunch signal acquired by the internal ADC of the feedback box gated on bunch 71 in an unstable batch of 72 bunches. The left plot shows the growth of the centroid motion and the coherent mode 0-like bunch pattern when the feedback loop is open. The right plot shows the suppression of the same instability upon closing the feedback loop (note the different vertical scales).

nostic tools that one could think of designing. In particular, in combination with the kickers, the system can expand the present diagnostic capabilities for impedance and instability measurements to new regimes. The feedback system can be thought of as a programmable impedance and could be used to drive the beam at various modes to then check the beam response and thus probe impedances or also machine non-linearities.

In conclusion, at this point, important experimental proofs-of-principle for the wideband feedback system were made such as demonstrating the damping of intra-bunch motion as well as individual bunch control in a multi-bunch batch. The system holds lots of promise for the future applications but further R&D is required for a full understanding of its limitations and how to best overcome them such that it can be used for operational beams.

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