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IMPACT OF A WIDEBAND FEEDBACK PROTOTYPE SYSTEM ON TMCI IN THE SPS

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Abstract

The transverse mode coupling instability (TMCI) in the SPS has been identified as one of the potential performance limitations for future high intensity LHC beams that will be required for the High Luminosity (HL)-LHC era and is being addressed by the LHC Injector Upgrade Project (LIU). A potential mitigation can be provided by wideband feedback systems with a frequency reach of about 1 GHz. For this reason, the development of a prototype system has been started in a CERN collaboration within the US-LARP framework in 2008. In this report, we present latest experimental results in 2017 where this prototype system was used in single and multi-bunch studies. In particular, the successful mitigation of TMCI at injection in an operationally interesting regime has been demonstrated for the first time.

INTRODUCTION

As part of the LHC Injector Upgrade Project (LIU) [1] the SPS is being prepared to deliver 2.3×10^{11} protons per bunch (ppb) to the LHC. It is foreseen to inject and accumulate four batches of 72 bunches with $\simeq 2.6 \times 10^{11}$ ppb at the injection plateau at 26 GeV/c to meet the target intensity for transfer to the LHC [2]. With the classical SPS optics at integer tunes of 26 ("Q26 optics"), this intensity is not reachable as it is far beyond the Transverse Mode Coupling Instability (TMCI) threshold. This is true for any longitudinal emittances that can be transfered between PS and SPS accelerator taking into account the upgraded RF systems [3].

The TMCI is characterized by strong internal transverse bunch oscillations that develop within fractions of a synchrotron period at injection into the SPS. The frequencies of this instability reach up to 1 GHz and beyond, and are well within reach of observation [4]. The scope of the original project for a vertical intra-bunch transverse feedback demonstrator system [5] to mitigate e-cloud driven instabilities was extended to cover as well the case of impedance driven TMCI. Simulations have shown that this instability can be cured in Q26 with this type of feedback employing multi-tap FIR filters in the feedback path for every slice of the bunch sampled [6].

VERTICAL INTRA-BUNCH FEEDBACK DEMONSTRATOR

The demonstrator system for the vertical plane developed and deployed is a multi-laboratory effort [7]. Today the system comprises an exponential coupler pick-up [4] to sense the beam vertical motion, a receiver and digital processing operating at a sampling frequency of 3.2 GS/s locked to the SPS 200 MHz RF [8]. Two new strip-line kickers with a total installed RF power of 1 kW were developed, built and commissioned. A slotted Faltin type kicker was developed [9,10], built and installed in the year-end technical stop 2017/2018 and is scheduled for commissioning with beam during the present 2018 SPS run. This additional kicker will extend the frequency reach of the feedback system beyond 1 GHz and complements the strip-lines that cover the sub-GHz frequency range.

FEEDBACK RESULTS WITH Q20 AND Q26 OPTICS

Injection into the SPS for the LHC type beams takes place above the transition energy. The instability threshold of the TMCI scales linearly with the slippage factor and can be raised by lowering the transition energy. Therefore an alternative optics called "Q20", was developed [3] with an integer tune of 20. It triples the instability threshold for the same longitudinal emittance by having injection further away from transition energy and has become the standard optics for LHC-type beam. It is likely to be used as well for the upgraded beams with higher intensity after the long shutdown (LS2).

Multi-Bunch Beam Results in Q20 Optics

Multi-bunch beams in the SPS suffer both coupled bunch and single bunch instability by impedance and by electron cloud effects for 25 ns bunch spacing. The electron cloud instability (ECI) is presently mitigated by running with high chromaticity and by conditioning the vacuum chamber to reduce the secondary emission yield for electrons. The thresh-

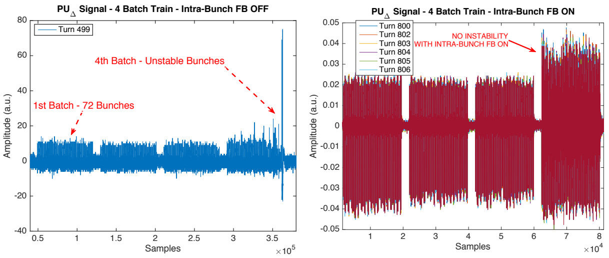

Figure 1: Multi-bunch beam with four batches of 72 bunches; vertical instability in the last batch (left) can be cured by the wideband feedback (right) [11].

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old of the ECI increases after running extended periods under these conditions. The regular transverse feedback system acting on a bunch-to-bunch basis and in principle capable of damping all coupled bunch rigid dipole modes up to half the bunch repetition frequency is essential under these conditions. Risetimes of the coupled bunch instability are faster than 1 ms (< 40 turns) for the highest intensities. The conventional transverse feedback was upgraded [5] in long shutdown 1 (LS1) in 2014 and now features modern digital processing with extensive diagnostics possibilities.

Fig. 1 shows a case with injection of the nominal LHC beam with four batches of 72 bunches into the SPS with 25 ns spacing [11]. The conventional feedback system is always required for these types of beams to stabilize against coupled bunch instabilities. With low chromaticity, at the end of the fourth batch a vertical instability can be provoked on a few bunches which is not cured by the conventional coupled bunch feedback. On the other hand, in conjunction with the wideband feedback system the instabilities on the fourth batch can be cured and losses at injection are reduced [11,12]. With the demonstrator system, a maximum number of 64 bunches can be damped, limited by the FPGA resources and implementation of the phase adjustment using multi-tap FIR filters requiring large amounts of memory and signal processing resources [8].

Occasions to conduct multi-bunch machine studies (MDs) in the SPS are limited as dedicated machine time is needed to inject several batches into the SPS. Moreover, the experience with the feedback and signal processing has shown that it is particularly challenging to address these transverse instabilities for the Q20 optics with feedback since the synchrotron frequency is very high. Alternative signal processing schemes were developed but have not yet been applied in practice to the Q20 optics. These schemes use shorter tap FIR filters [13] or a decomposition of the motion in modes that can be treated separately [14].

Single Bunch Beam Results in Q26 Optics

Single bunch MDs initially focused on studies using the Q26 optics where the TMCI threshold around nominal longitudinal emittances is reached already at low intensities of $\simeq 1.5 \times 10^{11}$ ppb. Using a wideband feedback system for these types of beams is expected to extend the operational range to lower values of chromaticity with a potential beneficial effect on beam lifetime. Fig. 2 shows the injection of a single bunch in the so-called slow TMCI regime, giving rise to an instability featuring a distinct intra-bunch pattern. Bunch charge is lost after a short time in this case (left graph) and the signal vanishes after 1500 turns. The right hand graph shows how the oscillation is damped with no intra-bunch motion developing with wideband feedback on. For these studies the conventional transverse feedback was routinely used to suppress any coherent dipolar motion. The wideband feedback system was necessary to successfully control the intra-bunch motion which at the same time demonstrated the frequency reach of this system.

FEEDBACK RESULTS FOR Q22

In 2017 an optics requiring less RF voltage, with integer tune of 22, "Q22", has been studied [15]. It was shown that without any transverse feedback system the single bunch intensity is limited in this optics to below 2.5×10^{11} ppb at 0.32 eVs longitudinal emittance, see Figure 3. This is short of the target intensity that the SPS must accept at 26 GeV/c for the LHC injector upgrade in order to deliver 2.3×10^{11} ppb at transfer to LHC [2].

In the late part of the 2017 run the SPS was limited to bunch intensities of 2.5×10^{11} ppb for other reasons and therefore the last studies in 2017 with the wideband feedback were carried at lower RF voltage with beams having a smaller longitudinal emittance, leading to a lower TMCI threshold. To mitigate the instability at injection, the conventional coupled bunch feedback with 20 MHz bandwidth was tried on its own, or in combination with the wideband feedback. The conventional feedback damps well the dipolar oscillations at injection and maintains the bunch center of mass at the closed orbit. The developing headtail oscillation contents can then be efficiently damped by the wideband feedback system, operating at lower gain and power than the conventional damper.

The results are summarized in Fig. 4, showing the evolution of losses at injection for the three cases: without any feedback the beam is quickly lost at injection and only an intensity of 1.6×10^{11} ppb is maintained; using the conven-

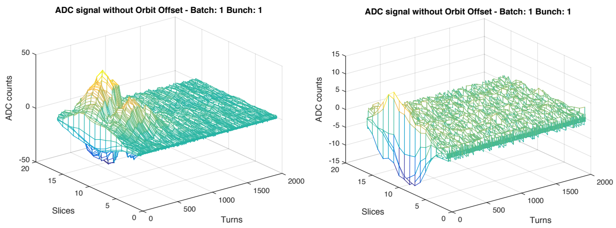

Figure 2: Single bunch headtail instability at injection into the SPS with the conventional feedback operating and wideband feedback system off (left) and on (right); the beam is lost after 1500 turns with wideband feedback off [11].

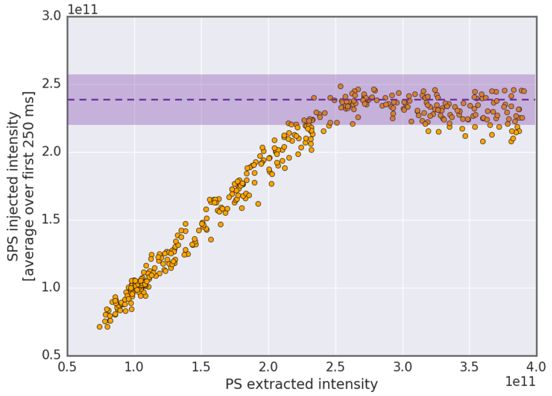

Figure 3: Q22: Instability threshold for 0.32 eVs [15].

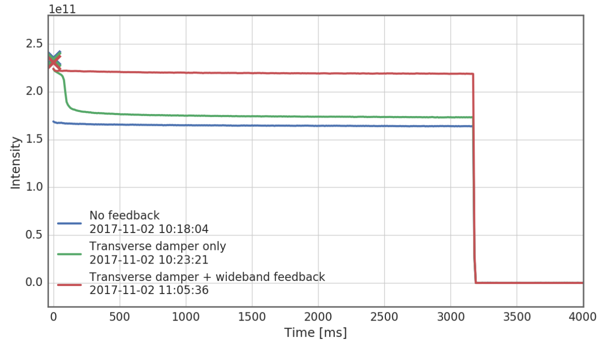

Figure 4: Intensity in Q22 without feedback and with the feedbacks operating.

tional coupled bunch feedback alone can contain the beam loss for some 100 ms when eventually the instability takes over and beam is lost rapidly to almost the same levels as without any feedback; in the case with wideband and conventional feedback system on, the injected intensity can be almost completely maintained without losses and the transmission reaches 95 %. Fig. 5 shows how the transmission increases from 80 % to 95 % when the wideband feedback is switched on in addition to the conventional transverse feedback in a reproducible way. Fig. 6 shows a plot of the intensity averaged during the first 250 ms in the SPS as a function of the injected intensity. Up to the injected intensity of 2.4 $\times 10^{11}$ ppb the good transmission could be maintained using both feedbacks in combination [16].

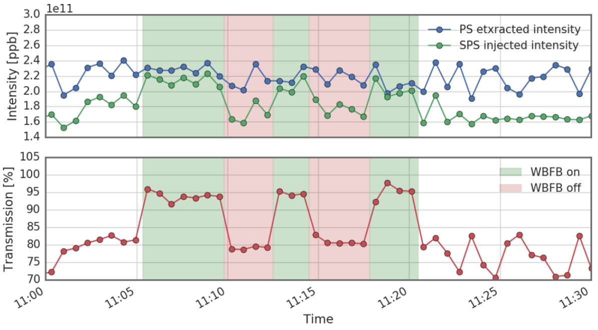

Figure 5: Transmission with wideband feedback on and off in Q22.

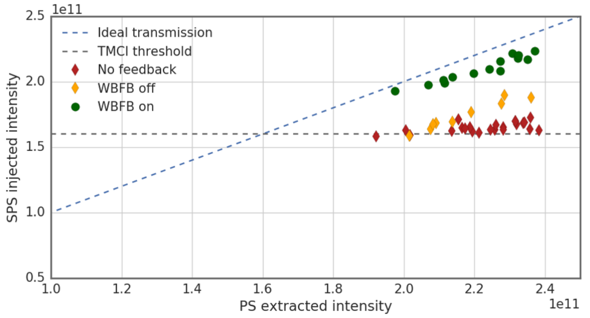

Figure 6: Intensity in SPS averaged over first 250 ms as function of PS extracted intensity without feedback and with feedbacks operating in Q22 optics.

In 2018 these experiments will be repeated using nominal LIU beam parameters with higher intensity and higher longitudinal emittance. The present results are very promising and demonstrate that the wideband feedback system has a potential to increase the intensity reach of the beams in the Q22 optics.

FUTURE RESEARCH

For the wideband feedback system, the objective for 2018 is to fully commission the slotted Faltin type kicker [9, 10] and to demonstrate its maximum operating frequency beyond 1 GHz. This will be beneficial for the single bunch studies as higher frequencies can be addressed. Using the full potential of the new kicker requires a set of dedicated power amplifiers with frequency reach beyond 1 GHz. The slotted kicker can also be used as a pick-up and beam induced signals will be verified as part of the commissioning plan. Studies with beam will concentrate on mitigation of the single bunch TMCI in the Q22 optics exploring high bunch intensities with nominal longitudinal emittance.

Future possible research directions include higher sampling rate feedback [17] and fixed frequency sampling as proposed for the SPS longitudinal feedback systems [18]. Further research on kicker structures for multi GHz reach is proposed in order to apply the principle of the wideband feedback to higher energy colliders such as LHC and FCC [19].

CONCLUSION

The transverse vertical plane wideband feedback demonstrator system has been successfully used in conjunction with the conventional transverse damper to mitigate intra bunch motion and to overcome the TMCI threshold at injection into the SPS at 26 GeV/c. Studies in 2017 also confirmed the beneficial effect on the multi-bunch beams in the Q20 optics with a demonstrated potential to damp single bunch instabilities. Further studies in 2018 will target higher single bunch intensities with LIU beam parameters in Q22 as well as the commissioning of the new slotted kicker with beam.

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