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RECENT RESULTS FROM THE WIDEBAND FEEDBACK SYSTEM TESTS AT THE SPS AND FUTURE PLANS

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Abstract

A high bandwidth transverse feedback demonstrator system has been devised within the LARP framework in collaboration with SLAC for the LHC Injectors Upgrade (LIU) Project. The initial system targeted the Super Proton Synchrotron (SPS) at CERN to combat TMCI and electron cloud instabilities induced for bunches with bunch lengths at the 100 MHz scale. It features a very fast digital signal processing system running at up to 4 GS/s and high bandwidth kickers with a frequency reach of ultimately beyond 1 GHz. In recent years, the system has gradually been extended and now includes two stripline kickers for a total power of 1 kW delivering correction signals at frequencies of currently more than 700 MHz. This talk will cover recent studies using this demonstrator system to overcome TMCI limitations in the SPS. We will conclude with future plans and also briefly mention potential applications and requirements for larger machines such as the LHC or the HL-LHC.

INTRODUCTION

The CERN Super Proton Synchrotron (SPS) will have to deliver high intensity beams up to 2.3×10^{11} ppb – twice the value of today – after the LHC Injectors Upgrade (LIU) in preparation for HL-LHC. Up to 288 bunches will have to be accelerated from 26 GeV to 450 GeV before extraction to the LHC. Transverse Mode Coupling Instability (TMCI) and electron cloud instabilities have been a concern in the past. One of the strategies for the mitigation of these types of instabilities was to use novel wideband feedback systems to combat the high frequency coherent motion.

A demonstrator system has been developed in a multi-laboratory effort under the LARP framework within LIU. The system features a very fast 4 GS/s digital signal processing unit which is fully reconfigurable and able to deal with up to 64 bunches independently [1]. A set of two stripline kickers with a frequency reach of 700 MHz are powered by four wideband power amplifiers for a total power of 1 kW. The system has been operated during the last two years to demonstrate control of intra-bunch motion as well as independent control of individual bunches in a train [2]. Recently, a slotline kicker has been added but has not yet been put into operation [3, 4]. Figure 1 shows the installations with their locations in the SPS ring all around BA3.

Today, the TMCI threshold is usually kept high by means of the Q20 optics which features a high synchrotron tune. However, the Q20 optics has high RF power requirements. During the last year, a new optics (Q22 optics) was tested in the SPS with relaxed RF power requirements during certain parts of the cycle [5]. On the other hand, the TMCI threshold for the Q22 optics is expected around 2.6×10^{11} ppb for nominal longitudinal parameters ($\varepsilon_z \approx 0.35$ eVs) which on the other hand is the required intensity for nominal beams at injection after LIU [6]. For this reason, during 2017, the wideband feedback demonstrator system was used to show that it is possible to overcome the fast TMCI by means of a transverse feedback system.

Section 2 discusses TMCI in the SPS. Section 3 shows measurements of the TMCI thresholds for the Q22 optics in the SPS. Section 4 shows results using the wideband feedback system to mitigate the observed TMCI in the SPS. Finally, Section 5 shows possible needs and requirements for similar feedback systems for LHC or HL-LHC.

TMCI IN THE SPS

In the SPS, the comparatively large bunch length leads to coupling of synchrotron sidebands at both low as well as higher orders. There is a regime of weak coupling between modes 0 and -1 where the TMCI growth rates are relatively low. These modes tend to decouple again at higher intensities. Then, there is the regime of strong coupling between modes -2 and -3 which generates a very fast and violent TMCI and leads to immediate loss of intensity down to just below the value of the threshold intensity. This fast TMCI establishes a hard limit on the maximum attainable intensity in the SPS. Figure 2 illustrates these different regimes of weak and strong coupling. The results were obtained from simulations using a slightly simplified representation of the SPS impedance model (a 1.3 GHz broadband resonator model). The figure also shows the corresponding signals observed in a wideband pickup revealing the different characteristics of the two regimes and also compares both simulated and measured signals which indeed show very good agreement [7].

The TMCI threshold of the SPS in its original design has been around 1.4×10^{11} ppb with an integer tune of 26 (Q26 optics). This would have been a serious limitation for the requirements of LIU. Today, this threshold is dealt with by means of a new optics (Q20 optics) which features a higher synchrotron tune [7] and therefore increases the threshold

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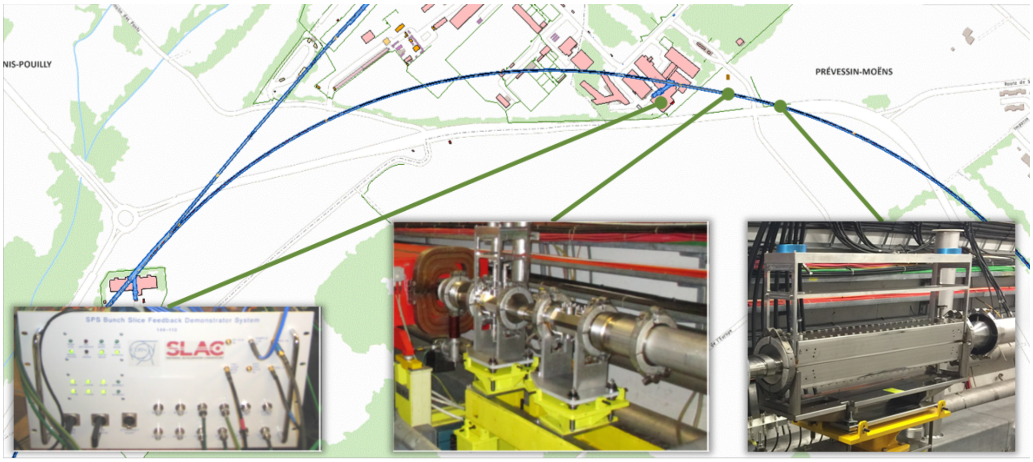

Figure 1: Installation of the wideband feedback system in the SPS. The fast digital signal processing unit is located on the surface in a Faraday cage. Two stripline kickers are installed in the SPS tunnel together with a set of power amplifiers. Recently, a slotline kicker has been installed slightly further downstream.

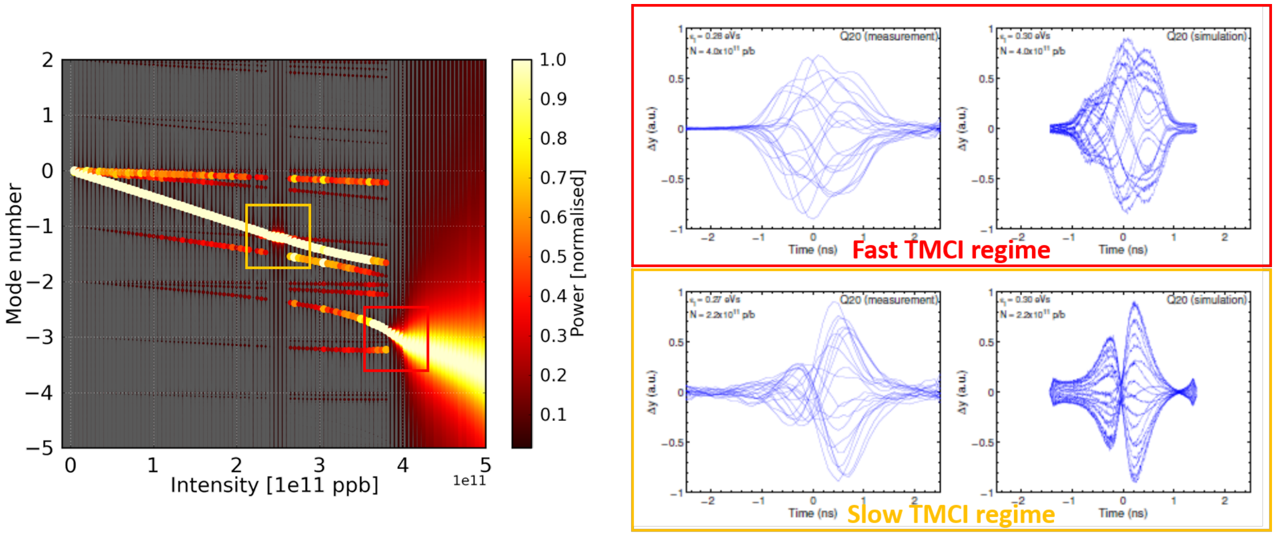

Figure 2: The tune shifts of the azimuthal modes with intensity are shown on the power spectrum plot on the left hand side. The two regimes of weak (yellow box) and of strong (red box) coupling are clearly visible. The right hand side shows the corresponding signals in a wideband pickup from measurements (left) and from simulations (right) [7].

well beyond the operational intensities. As already mentioned above, the Q20 optics is very demanding in terms of required RF power and voltage. The intermediate Q22 optics can give some margin on the RF power during certain parts of the cycle. This comes at the price of a lower synchrotron tune, however [8]. As a consequence, the TMCI threshold decreases down to around 2.6×10^{11} ppb. In this configuration the Q22 optics is hardly suited for LIU. On the other hand, it provides the ideal testing platform for the wideband feedback system to demonstrate its capability to mitigate TMCI, in particular also, in the regime of strong coupling. If successful, the Q22 optics can become a viable option for LIU.

MEASUREMENTS OF THE TMCI THRESHOLD FOR Q22 OPTICS

In 2017 the new Q22 optics was prepared in the SPS and a high intensity beam was set up. The beam was used to explore the TMCI threshold for this optics configuration. As already mentioned, from simulations done in the past using the SPS impedance model, the threshold was predicted to be around 2.6×10^{11} ppb.

During the measurements, single bunches were injected into the SPS at different intensities. The bunch intensity was measured just before extraction in the pre-injector of the SPS, the Proton Synchrotron (PS), and a couple of hundreds of milliseconds after injection into the SPS. Figure 3 shows this intensity scan where the PS extracted intensity is plot-

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ted against the measured intensity in the SPS. It is clearly visible how an intensity of roughly 2.4×10^{11} ppb cannot be exceeded despite injecting higher intensities from the PS.

Once injecting intensities above this threshold value into the SPS one can observe a strong coherent activity associated with high losses. Looking at the headtail monitor one can see clear signatures of TMCI exhibiting a strong coherent oscillation along the bunch which is pronounced towards the tail of the bunch as shown in Figure 4. The top plot shows the turn-by-turn vertical delta signal along the bunch. On the bottom, the corresponding sum signal is shown. Later turns are colored in light colors and one can clearly observe the fast losses leading to a decrease of the sum signal.

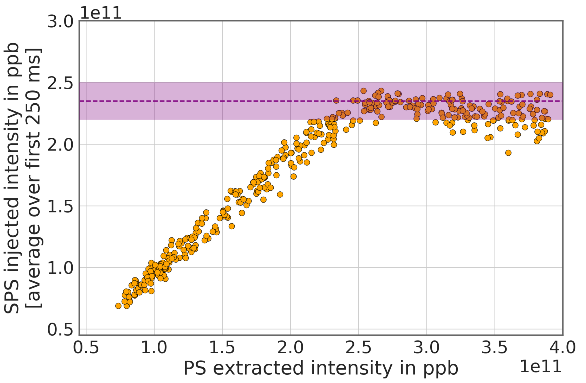

Figure 3: The intensity scan done to evaluate the TMCI threshold in the SPS. The plot shows the extracted intensity from the PS on the horizontal and the measured intensity in the SPS on the vertical axis. It is clearly visible how the maximum measured intensity after injection is limited to around 2.4×10^{11} ppb.

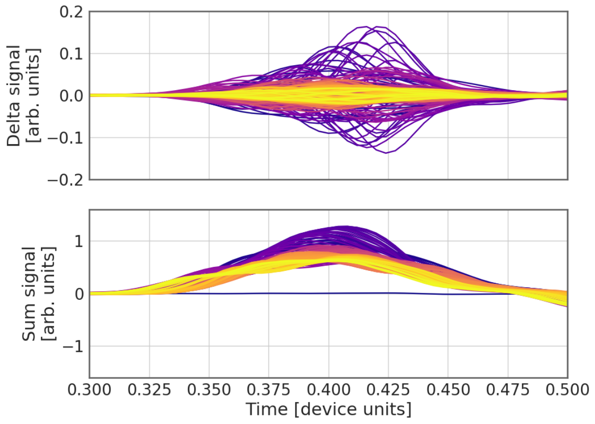

Figure 4: A typical signature of a fast TMCI instability as observed via an oscilloscope. Left is the head of the bunch, right is towards the tail of the bunch. The top figure shows the vertical delta signal, the bottom plot shows the sum signal. Early turns are in dark, later turns are in light colors.

MITIGATION OF TMCI USING THE WIDEBAND FEEDBACK SYSTEM

Having measured the TMCI threshold as a hard limit on the reachable intensity in the SPS for Q22 optics the question arises whether the wideband feedback system could be used to mitigate the instability and push the reachable intensity beyond the LIU limits. At the same time, this would serve as demonstration that such a system is indeed capable of mitigating also violent instabilities which exhibit a strong intra-bunch motion posing hard limits for many machines. Whereas in the past, the system had been used in the slow TMCI regime showing control of intra-bunch motion, it had never been used in the fast TMCI regime to actually extend the intensity reach beyond the TMCI threshold.

During these tests of the wideband feedback system, the TMCI threshold was artificially lowered using a decreased RF voltage due to temporary operational limitations, rendering a TMCI threshold around 1.6×10^{11} ppb. The TMCI mechanism itself does not change due to this, however. Figure 5 shows the intensities measured along the cycle, once in absence of any transverse feedback, then using only the SPS transverse damper, which has a frequency reach of up to 20 MHz, and finally, using the SPS transverse damper in combination with the wideband feedback system. It is clear, that only with the wideband feedback system active, the TMCI threshold could be exceeded.

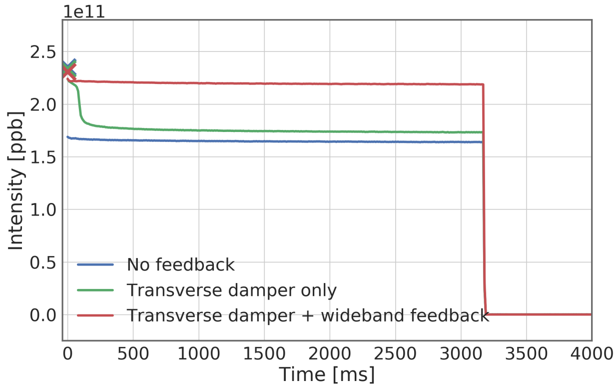

Figure 5: The DC BCT signals showing the intensity evolution on the flat bottom in the SPS for different combinations of active feedback systems. The crosses indicate the intensity measured at the extraction of the PS. The full extracted intensity can be maintained only with the combined operation of both the transverse damper and the wideband feedback system (red curve).

The crosses on the plot indicate the injected intensities as received from the PS. Without any feedback, looking at the DC beam current transformer (BCT) signal, already at the first sampling point after 5 ms, the bunch has lost all of its intensity down to below the TMCI threshold. In fact, these losses are so fast, that without knowledge of the intensity coming from the transfer line, they would go unnoticed from the pure BCT signal. The losses can be slowed down when using the transverse damper. However, the transverse damper alone does not have the necessary bandwidth to deal with the very fast intra-bunch motion excited during the TMCI and for this reason it can ultimately not stop the instability and the associated losses which reduce the bunch intensity below the threshold. Finally, the wideband feedback system was added to the active transverse damper and in this configuration, the instability could be kept under control and the bunch intensity constant beyond the TMCI threshold.

It is noteworthy that the wideband feedback system alone was also not able to stabilize the beam. The strong dipole components during the injection transient in combination with the fast TMCI tend to quickly drive the wideband system into saturation, rendering it ineffective. Despite the bandwidth limitations, the transverse damper has a lot more power to deal with the coherent dipole motion. Hence, the transverse damper is required to first remove the strong dipole component of the beam motion, after which the wideband feedback can be used effectively, to take care of the remaining high frequency components in the beam motion.

OTHER POTENTIAL APPLICATIONS FOR WIDEBAND FEEDBACK SYSTEMS

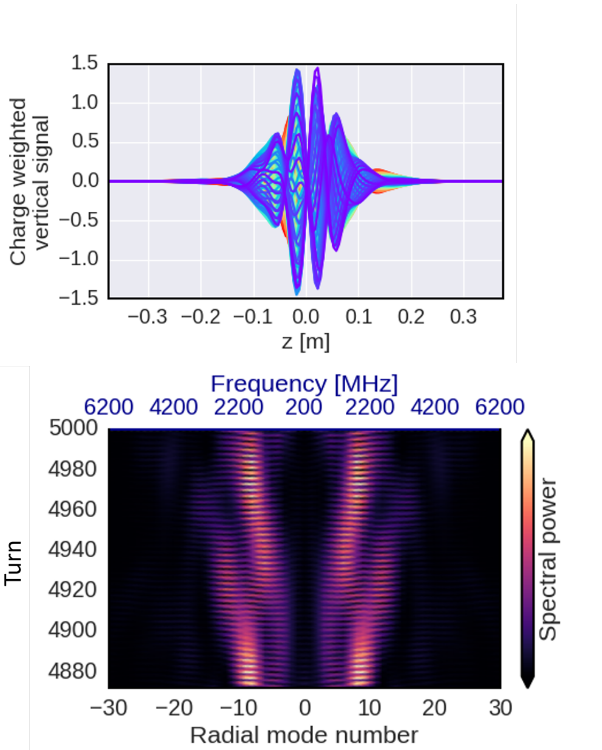

Figure 6: Signature of an electron cloud instability as simulated in the LHC at top energy. Fast intra-bunch oscillations are visible. A frequency analysis reveals frequencies up to 4 GHz. A gigahertz feedback system is likely required to reliably mitigate these types of instabilities.

With the successful demonstration of control of intra-bunch motion for nanosecond scale bunches as well as the mitigation of TMCI, the wideband feedback system technology has gained a level of maturity where other fields of application can be considered. One potential application is the use for instability mitigation in the LHC or the HL-LHC.

Impedance-driven instabilities in the LHC, to date, are dealt with by means of the LHC transverse damper for coupled-bunch instabilities and Landau octupoles to keep under control single-bunch instabilities [9]. The dominating sources of instabilities in the LHC are due to electron clouds which are generated in the LHC straight sections, dipole, quadrupole as well as higher multipole magnets [10]. Especially at flat top, simulations show that these instabilities contain very high frequency components (see fig. 6) as discussed in [11]. Most of the time, these instabilities can be kept under control by operating the LHC at very high chromaticities and strong Landau octupoles. This, however, limits the dynamic aperture and significantly reduces the operational parameter space.

A wideband feedback system could be used to handle these instabilities without introducing any non-linearities or generating large tune spreads, thus, keeping the dynamic aperture large and improving the beam lifetime.

CONCLUSIONS

In the present paper we have shown measurements of the TMCI threshold for the Q22 optics in the SPS. The maximum attainable intensity is limited by the strong coupling of modes -2 and -3 and, for nominal beam parameters, is at 2.6×10^{11} ppb. We have used a wideband feedback system in an attempt to overcome this intensity limit.

It turned out that the successful configuration to mitigate the TMCI is using the combined capabilities of both the standard transverse damper which has limited bandwidth, but high power output, together with the high bandwidth feedback system within its power limitations. The transverse damper is designed for fast damping of injection oscillations and mitigation of coupled-bunch instabilities which for LHC beams reach up to 20 MHz. As such it is well suited to efficiently remove any coherent dipole oscillations of the bunch centroid motion. The remaining high frequency signals are then within the dynamic range of the wideband feedback system and can successfully be processed and removed in order to stabilize the bunch against the TMCI. This has now been experimentally demonstrated in the SPS and the results have been presented.

In the near future the plan is to commission the newly installed slotline kicker which will have a yet extended bandwidth for increased power at 1 GHz and beyond. Initial tests will focus on measuring the response of the slotline structure. The current plan is then to move one of the existing sets of power amplifiers, currently used for the stripline kickers, to the slotline kicker to test the device with power and its performance to actively mitigate coherent intra-bunch motion.

Further use cases in the LHC or the HL-LHC were shown as well, where instability signatures at flat top triggered by electron clouds, feature coherent frequencies in the GHz range. To date, these types of instabilities can only be dealt with by means of high chromaticity and strongly powered Landau octupoles which can have a negative impact on the beam lifetime. A wideband feedback system could be used to mitigate these instabilities without at the same time compromising on the available operational parameter space or beam lifetime. Research and development is required, in particular, for kicker structures [12] and to extend the fast digital signal processing to higher sampling rates [13], including the evaluation of modern state of the art platforms such as uTCA and a fixed frequency sampling clock.

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