MODELLING AND STUDIES FOR A WIDEBAND FEEDBACK SYSTEM FOR MITIGATION OF TRANSVERSE SINGLE BUNCH INSTABILITIES

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Abstract

As part of the LHC Injector Upgrade (LIU) Project [1], a wideband feedback system is under study for mitigation of coherent single bunch instabilities. This type of system may provide a generic way of shifting the instability threshold to regions that are currently inaccessible, thus, boosting the brightness of future beams. To study the effectiveness of such systems, a numerical model has been developed that constitutes a realistic feedback system including real transfer functions for pickup and kicker, realistic N-tap FIR and IIR filters as well as noise and saturation effects. Simulations of SPS cases have been performed with HEADTAIL to evaluate the feedback effectiveness in the presence of transverse mode coupling and electron clouds. Some results are presented addressing bandwidth limitations and amplifier power requirements.

INTRODUCTION

Transverse mode coupling (TMCI) and electron cloud instabilities (ECI) pose fundamental limitations on the acceptable beam intensities in the SPS at CERN [2, 3]. With the ultimate goal to reliably provide the LHC with the beam required for High Luminosity LHC, different schemes are under investigation on how to deal with both TMCI and ECI. Among the different approaches, there is the option of a wideband feedback system for suppression of generic transverse single bunch instabilities. In the case of the SPS, single bunch instabilities from TMCI or ECI typically show unstable modes leading to intra-bunch motions at the scale of down to one third of the bunch length or less [2, 4]. With typical rms bunch lengths in the order of 1 ns, this requires feedback systems with bandwidths reaching up to 1 GHz in order to resolve the intra-bunch motion. At high power levels, the design of such systems becomes technically very challenging. Power limitations and noise issues need to be faced.

In an effort to study and to characterise the potential effectiveness of wideband feedback systems against TMCI or ECI, a numerical model of a realistic feedback system has been developed. It includes bandwidth limitations by providing realistic transfer functions for pickups and kickers. Furthermore, it includes FIR and IIR filters with variable phase adjustment to simulate intrinsic delay and noise filtering in the controllers. And finally, actual limitations such as saturation and noise levels in both the receiver and the amplifier channels can be taken into account. The feedback system has been implemented into HEADTAIL [5] and C-MAD [6]. Using this feedback model, the codes have been successfully benchmarked against each other.

We present studies performed with HEADTAIL to investigate bandwidth limitations when dealing with TMCI and ECI in the SPS using realistic parameters for a possible wideband feedback system. This work is to be understood as an extension of earlier studies initially started by Thompson [7]. The results presented are partly aimed to reproduce these previous findings and extend these to TMCI. Moreover, the new model allows to include further effects, stated above, which appear in realistic feedback systems and which can provide potential limitations in dealing with fast single bunch instabilities. These will be investigated in more detail in future studies.

FEEDBACK MODEL

The feedback system is modelled as a resistive feedback system with a phase separation between pickup and kicker of approximately 720 degrees, reflecting the setup during measurements recently taken at the SPS [8]. The pickup is assumed to be perfect for now. The kickers are bandwidth limited to 200 MHz, 500 MHz, 700 MHz or 1 GHz. The controller resembles a 5-tap FIR filter. A schematic of the feedback system is shown in Fig. 1. In contrast to [7], the gain remains constant along the bunch. The true vertical bunch slice position is passed to each channel of the feedback system.

Figure 2 shows the kicker transfer functions, with a 1-pole role-off of 45° of the phase at 3 dB. Figure 3 shows the frequency response of the 5-tap FIR filter, with the highest response at a phase of -90 degrees around the machine tune.

SIMULATIONS

The machine and beam parameters, corresponding to a nominal SPS beam at injection energy, are collected in Table 1. As a first approximation, a smooth lattice and linear synchrotron motion were assumed.

To explore the parameter spaces of the instabilities, scans were performed in beam intensity for TMCI and in central cloud density for ECI using nominal machine settings at injection energy and no feedback. The resulting instability thresholds can be extracted from Fig. 4. To investigate the effectiveness of the different feedback systems against TMCI or ECI, the beam intensity and the central

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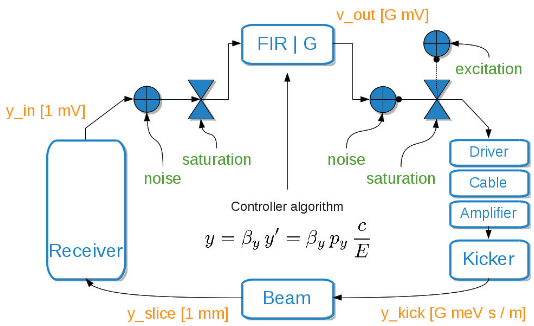


Figure 1: Schematic of the feedback system implementation along with indication of the output signals at selected components. The gain is simply a scale factor in this system.

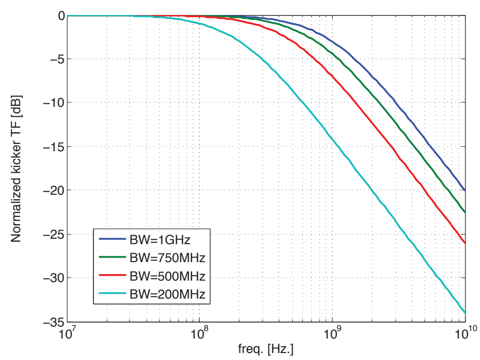


Figure 2: Kicker transfer functions for kicker bandwidths of 200 MHz, 500 MHz, 700 MHz and 1 GHz.

cloud density were set to $I = 1.4 \times 10^{11}$ ppb and to $\rho_e = 6 \times 10^{11}$ m $^{-3}$ well above the respective instability thresholds. A scan was then performed in the feedback gain to see whether beam stability could be restored.

For TMCI from Fig. 5 it becomes clear, that a feedback system with a bandwidth of 200 MHz at a gain of about 0.4 is indeed able to damp the TMCI occurring at $I = 1.4 \times 10^{11}$ ppb.

For the ECI on the other hand, Fig. 6 shows that the beam

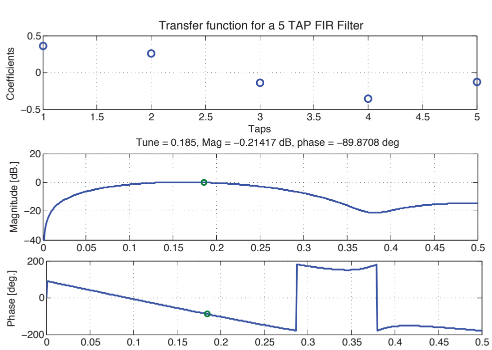
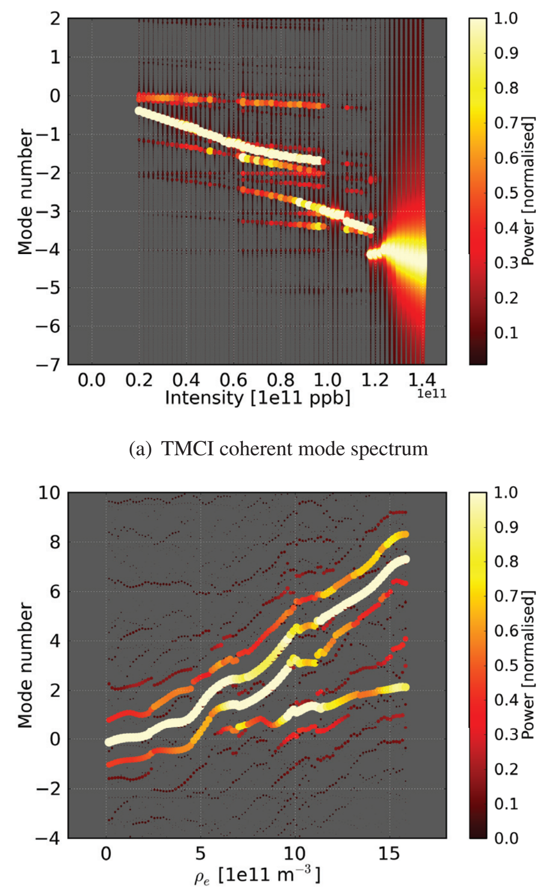


Figure 3: Magnitude and phase behaviour of the FIR filter vs. fractional tunes.

Table 1: SPS Machine Settings at Injection Energy

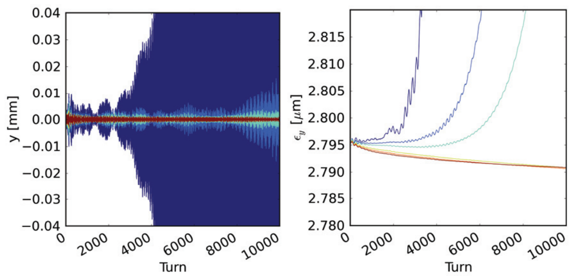
Intensity	1.1×10^{11} ppb
Energy	26 GeV
Emittances $[\varepsilon_x^n, \varepsilon_y^n]$	2.8, 2.8 µm
Bunch length rms	0.23975 m
Beta functions $[\langle\beta_x\rangle, \langle\beta_y\rangle]$	42, 42 m
Tunes $[Q_x, Q_y, Q_s]$	26.13, 26.185, 0.0059
Chromaticities $[Q'_x, Q'_y]$	0, 0
Impedance	Broadband resonator
Shunt Impedance	15 MΩ / m
Resonance frequency	1.3 GHz
E-cloud regions	Bending magnets



(a) TMCI coherent mode spectrum

(b) ECI coherent mode spectrum

Figure 4: The mode spectrum for different beam intensities (a) and central cloud densities (b). The spectrum is normalised for each value. Bright spots indicate modes containing high power, darker spots are modes with less power.



(a) 200 MHz feedback system

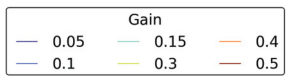
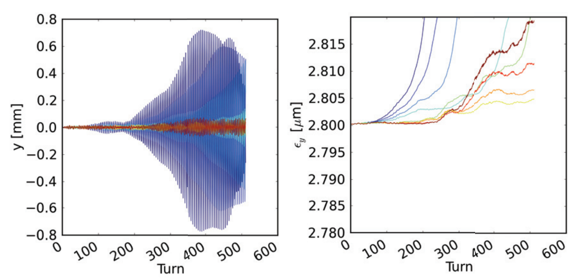


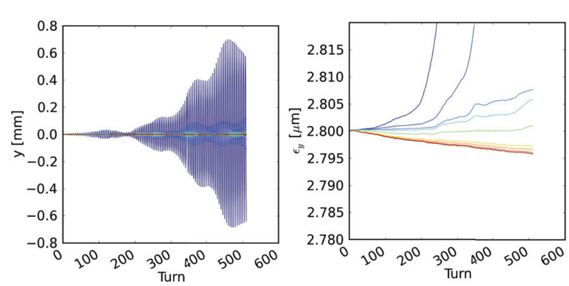
Figure 5: The evolution of the bunch centroid motion and the normalised emittance for different gains for the 200 MHz feedback system for the case of TMCI.

cannot be stabilised using a 200 MHz feedback system. Increasing the gain does reduce the instability rise time, however, before the instability can be fully damped, the gain acceptance of the system is exceeded and the feedback system itself drives the beam unstable again.

Instead, the 500 MHz system has a higher gain acceptance and the gains can be increased so that the beam can actually be stabilised as shown in Fig. 6. From there, a gain of 0.5 is required to fully mitigate the ECI.



(a) 200 MHz feedback system



(b) 500 MHz feedback system

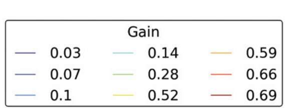


Figure 6: The evolution of the bunch centroid motion and the normalised emittance for different gains for the 200 MHz and the 500 MHz feedback systems for the case of ECI.

CONCLUSIONS AND OUTLOOK

In the framework of the LIU project, a high bandwidth feedback system is under investigation for mitigation of TMCI and ECI. Using HEADTAIL together with a recently implemented model for a realistic wideband feedback system, different scenarios were explored to study the impact of potential feedback systems at bandwidths 200 MHz and 500 MHz on the beam dynamics.

Two reference cases were run for a nominal SPS beam at injection energy. For the study of TMCI, the beam was tracked through the ring under the influence of a broadband impedance. For the study of ECI, the beam was subject to electron clouds distributed along the ring.

Adding the wideband feedback it could be shown that while a 200 MHz system is indeed able to damp instabilities arising from TMCI, it is insufficient to stabilise the beam against ECI. On the other hand, a 500 MHz system effectively provides mitigation of ECI.

A first estimate of the power requirements to damp the ECI resulted in kick strengths around 1×10^{-4} eV s/m. This value, however, depends strongly on the noise floors in the receiver and the amplifier and more studies are needed to give reliable estimates. Moreover, a pickup-receiver system that measures a charge $\times$ displacement product so that the effective gain of the feedback channel is reduced at the head and tail of the bunch, must be studied to understand how the residual motion of the controlled electron cloud system impacts the closed loop stability and modal content of the damped system. Another critical parameter to estimate is the behaviour of the system with realistic injection transients, and nominal synchrotron motion from energy errors at injection. These transients may be significant with regard to saturation effects in the processing and power stages.

Finally, as detailed engineering specifications for possible pickups and kickers are developed, their characteristics must be included into the feedback model of this simulation, so that the impact of realistic frequency and phase responses of all system elements can be better understood.

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