Modeling and Feedback Design Techniques for Controlling Intra-bunch Instabilities at CERN SPS Ring

C. H. Rivetta[1], J. D. Fox[1], O. Turgut[1], W. Hofle[2], K. Li[2].

[1]Accelerator Research Division, SLAC - USA

[2]CERN, Switzerland

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BROADBAND TRANSVERSE FEEDBACK SYSTEM - DOE LARP / CERN

- Motivation: Control electron-cloud (ECI) and Transverse Mode Coupled (TMCI) instabilities in SPS and LHC via broad-bandwidth feedback system.
  - Anticipated instabilities at operating currents
  - Complementary to electron-cloud coatings, grooves, etc.
  - Complementary to TMCI mitigation techniques
  - Intra-bunch Instability: Requires bandwidth sufficient to sense the vertical position and apply correction fields to multiple sections of a nanosecond-scale bunch.
- US LHC Accelerator Research Program (LARP) has supported a collaboration between US labs (SLAC, LBNL) and CERN
  - Develop a wide-band system to control the intra-bunch instabilities
  - Develop hardware and firmware technology to implement this system
  - Study via simulations the effects of the feedback system and validate via MD measurement
  - Design a model-based controller assuming the system is multi-input multi-output

Introduction

Lattices and main parameters for SPS ring

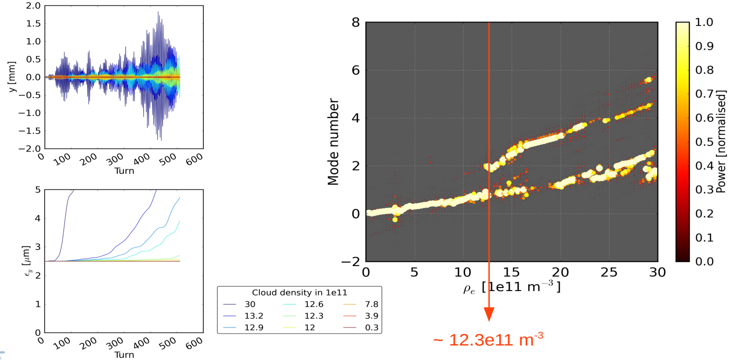
- - Q26 Optics (previous lattice)
  - Bunch length = 3.2ns (4 σ_Z at 26 GeV/c)
  - Tunes: $Q_X = 26.13, Q_Y = 26.185, Q_X = 0.0059$
  - Fractional tunes: Y - $\omega_\beta = 0.185$, Z - $\omega_s = 0.0059$
- - Q20 Optics (actual lattice)
  - Bunch length = 3 ns (4 σ_Z at 26 GeV/c)
  - Tunes: $Q_X = 20.13, Q_Y = 20.185, Q_X = 0.0170$
  - Fractional tunes: Y - $\omega_\beta = 0.185$, Z - $\omega_s = 0.0170$

General Considerations of Q20 optics

Electron Cloud Instabilities (ECI)

-SPS Q20 Lattice - No feedback, scan electron cloud densities
- Mode 0: $\omega_\beta = 0.185$, Mode 1: $\omega_\beta + \omega_s = 0.202$ at $\rho_e = 0\text{m}^{-3}$, 26 GeV/c.

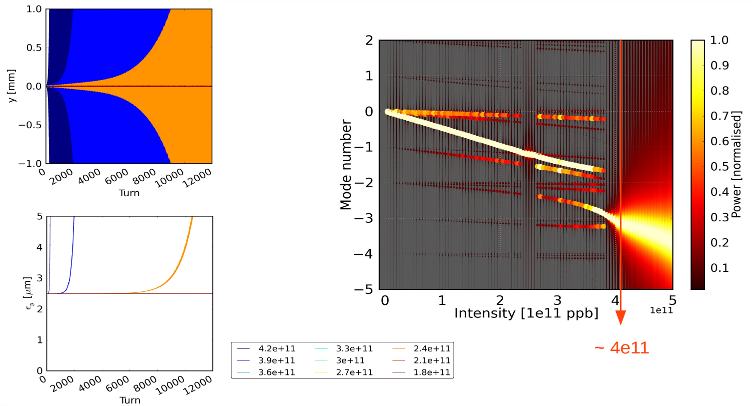
ρ_e = [1 – 30] x 1e11 m^{-3} (from red over green to blue)



General Considerations of Q20 optics

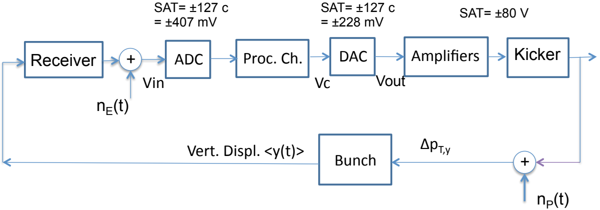
Transverse Mode Coupled Instabilities (TMCI)

-SPS Q20 Lattice - No feedback, scan for beam intensity
- Mode 0: $\omega_\beta = 0.185$, Mode -2 : $\omega_\beta - 2\omega_s = 0.151$ at $I_b = 0$mA, 26 GeV/c.



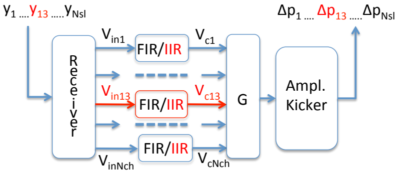
Feedback System

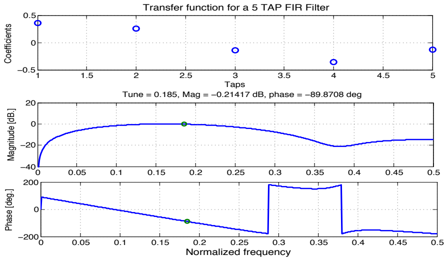
Block Diagram



4 GS/sec. digital channel. Flexible reconfigurable processing - 2 ADCs / 1 DAC
Analog equalization of pick-up and cable transfer functions.

Detail of processing channel and filter

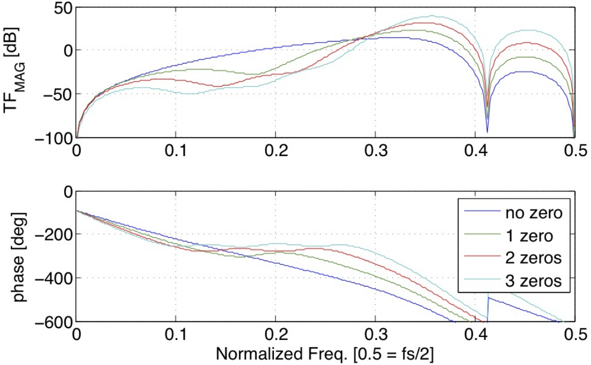




16 samples across 5ns bucket
Diagonal Controllers
16 tap FIR filters, IIR filters, ...

Feedback System

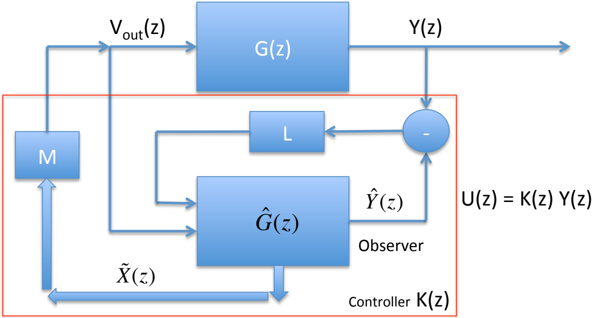
Controller based on an Infinite Impulse Response (IIR) filter bank



- Different filter characteristics were evaluated to understand the stability limits and the effect of the noise coupled from the receiver to the controller output.
- The design was focused on achieving a constant phase between input-output signals in order to introduce damping for the dominant unstable modes of the bunch. [paper IPAC 2014]

Feedback System

MIMO system - Model-based controller



- An observer is created based on the model of the bunch dynamics $V_{out}(z) \to Y(z) : \tilde{G}(z)$.
- The observer with gain L is used to estimate the internals states of the system $\tilde{X}(z)$.
- $\tilde{X}(z)$ is used to generate the feedback signal $U(z) = -M\tilde{X}(z)$.
- The controller $U(z) = K(z)Y(z)$ has two 'parameters' to adjust the Closed Loop response, the gain matrices L, M
- Different methods to design L, M

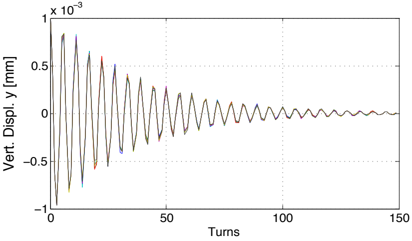
Feedback System

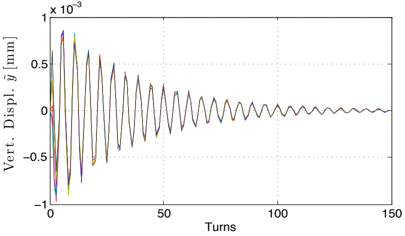
MIMO system - Model-based controller

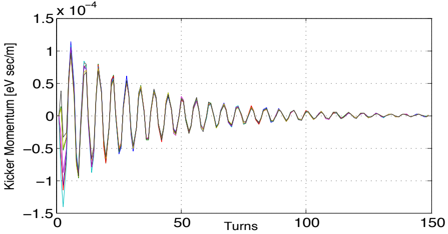
- A model of the bunch is defined including modes whose frequencies are $\omega_\beta + k\omega_s$ with $k = -6, ..., 0, ... + 6$
- We assume in the model that the damping for each mode is null (eigenvalues: $\lambda_k = \pm i\,(\omega_\beta + k\omega_s)$)
- The open loop system includes 1-turn delay to account the processing time since the signal is sensed until the correction signal is applied by the kicker
- Design criteria: Design M to set the dominant bunch dynamics and the L to have a fast observer
- To controllers are evaluated, (Design 1, Design 2), with different characteristics in the design of the observer.
- The final dominant eigenvalues of the system included the controller are: $\lambda_0 = \sigma \pm i\omega_\beta \simeq -0.027 \pm i\,2\pi\,0.185$
  $\lambda_k = \sigma \pm i(\omega_\beta + k\omega_s) \simeq -0.019 \pm i\,2\pi(0.185 + k0.017)$

Model-Based Controller

Results for controller: Design 1



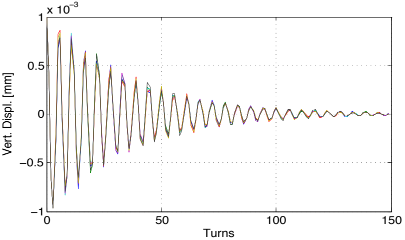


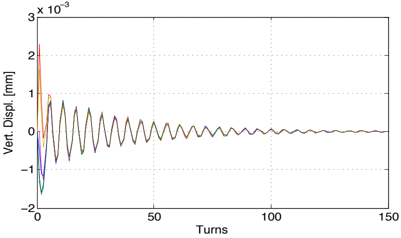


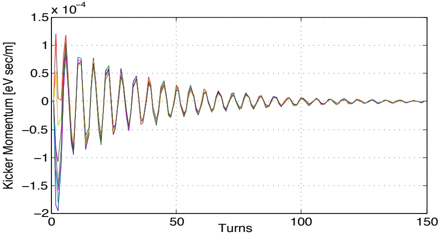
- Upper plot: Vertical motion (left: Bunch, right: Observer)
- Lower plot: Kicker Momentum
- Transient first turns due to the observer dynamics. (Initial conditions of the bunch / observer are different.

Model-Based Controller

Results for controller: Design 2







- Upper plot: Vertical motion (left: Bunch, right: Observer)
- Lower plot: Kicker Momentum
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Model-Based Controller

Robustness Analysis

- Both the betatron and synchrotron frequency and the growth rate per mode was changed to evaluate the stability limits of both designs
- Keeping the controller parameters constant and equal to the nominal design, the beam parameters were changed
- The stability robustness is very similar for both cases
- The bunch stability reach its limit when the betatron frequency is around 0.85 or 1.2 times its nominal value. The high order modes define this stability limit.
- Similarly, the stability reaches its limits when the synchrotron frequency is around 0.7 to 1.3 times its nominal value.
- Maximum growth rate that it is possible to damp 0.03 - 0.035 1/turns if all the bunch modes are equally unstable
- The maximum growth rate that is possible to stabilize for individual modes is: For modes $0, \pm 1, \pm 2, \sigma \simeq 0.05$ 1/turns, while for modes $\pm 3, \pm 4, \pm 5, \sigma \simeq 0.04$ 1/turns.

Model-Based Controller

Remarks about this pre-design

- The model-based design defines controller with an order equal to the system model. In general, it is a high order controller
- It links all the measured variables with the control variables. (Previous implementations in used a 'diagonal' scheme)
- It can limit the implementation and processing in the FPGA
- Because it is tailored to the model of the system allows to set better the performance around the nominal values but could be sensitive to parameter variations.
- It requires a model of the bunch dynamics. Identification techniques are under study to evaluate that model in real-time based on measurement [Ozhan Turgut, HB2014]
- It is necessary to evaluate reduced or simplified controllers and compare its stability and performance with respect to the full-order controller

Conclusions and Future Work

- A pre-design of a model-based controlled has been evaluated in simulation with good results.
- It allows to include the specifications in the design in a relatively simple way.
- Simulations included a multi-mode bunch dynamical model but excluded other effects as chromaticity, etc. It needs to be considered for final design
- To define the final controller for the SPS Q20 optics, it is necessary to evaluate the different controller options studied, taking into account the performance achieved and the implementation and system limitations.
- Based on a acceptable design, implement the controller in the FPGA and test in the CERN SPS with the new wide-band kickers

Thanks to the audience for your attention!!!, ...Questions?

Feedback Systems

General Requirements

- Original system unstable- Minimum gain for stability
- Delay in control action - Maximum gain limit
- Bunch Dynamics Nonlinear - tunes/growth rates change intrinsically
- Beam Dynamics change with the machine operation
- noise-perturbations rejected or minimized
- Vertical displacement signals has to separated from longitudinal/horizontal signals
- Control up-date time $= T_{revolution}$

Prototype in SPS ring

- Bunch length $\simeq 2.5 - 3.5$ ns
- Sampling frequency $\simeq 4$ G Samples/s