Accelerator Dynamics, Control Implications and Simulation Efforts

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for the US-LARP CERN Wide Band Feedback System

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Accelerator Dynamics, Control Implications and Simulation Efforts

- Outline
  - Introduction
  - Accelerator Dynamics
    - Intrabunch instabilities
  - Control Implications
    - Control requirements & Design
  - Simulations
  - Research Plans
  - Conclusions

Introduction

- Control of strong head-tail and electron cloud instabilities
  – Limiting factor in LHC/Injectors to maximize intensities and luminosity – Necessity
- Control of Intrabunch instabilites
  – Wider scope, limiting factor in future accelerators
  – Unknown impact of feedback techniques in stabilizing intrabunch dynamics, technical limits/costs due to the implementations
  – LHC/Injectors need this solution and offer a landscape for applying this technique
    - Affordable, compatible with the state of the art

Introduction

- Electron Cloud Instabilities (ECI)
  - CERN is conducting an effort to coating critical parts of the accelerator with amorphous carbon
  - Wide band feedback is complementary
- Transverse Mode Coupled Instabilities (TMCI)
  - CERN redesigned the lattice for SPS (Q26 -> Q20) to increase the beam current threshold to TMCI.
- Scrubbing
    - Reduce the start-up time of the machines
- Instrumentation
    - Processing intrabunch signals is opening new options for instrumentation and bunch diagnostics.

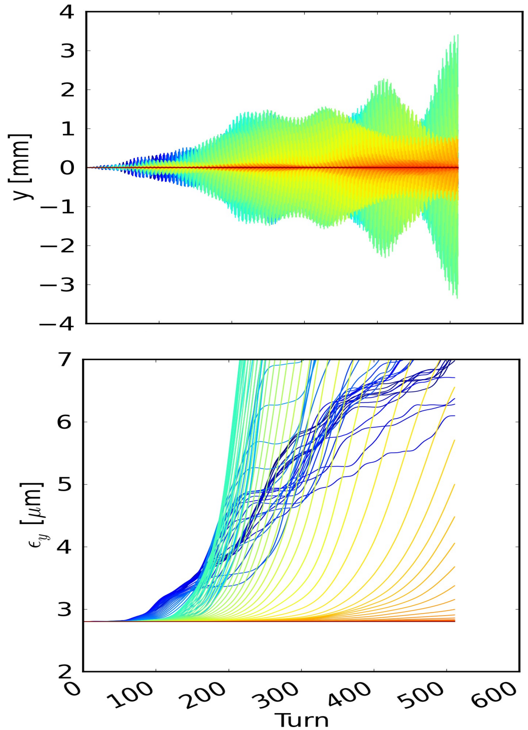
Accelerator Dynamics

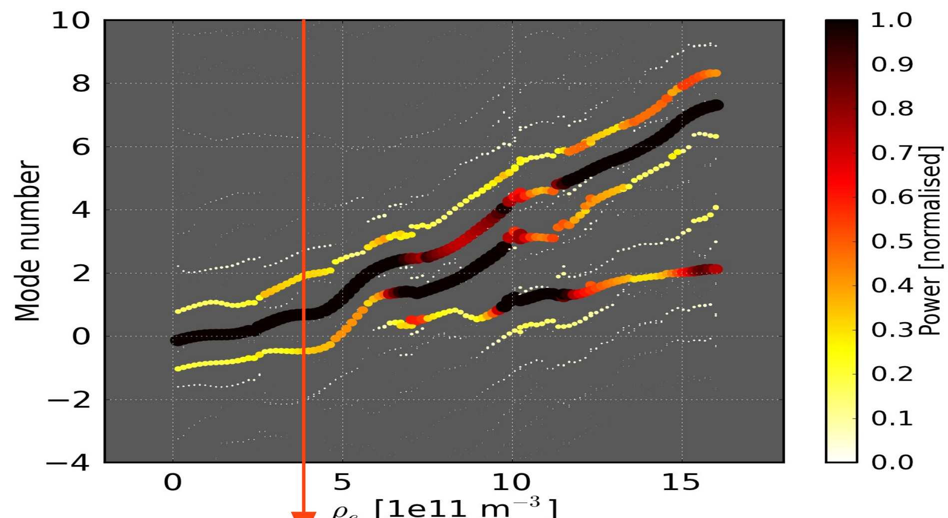
- Lattices and main parameters for SPS ring
  - Q26 Optics
    - Bunch length = 3.2n (4 σ_z at 26 GeV/c)
    - Tunes: Q_x = 26.13, Q_y = 26.185, Q_s = 0.0059
    - Fractional tunes: Y – ω_β = 0.185, Z - ω_s = 0.0059
  - Q20 Optics
    - Bunch length = 3 ns (4 σ_z at 26 GeV/c)
    - Tunes: Q_x = 20.13, Q_y = 20.185, Q_s = 0.0170
    - Fractional tunes: Y – ω_β = 0.185, Z - ω_s = 0.0170

Accelerator Dynamics

- Electron Cloud Instabilities (ECI)
  - SPS Q26 Lattice – No feedback, scan electron cloud densities
  - Mode 0: $\omega_\beta = 0.185$, Mode 1: $\omega_\beta + \omega_s = 0.191$ at $\rho_e = 0\ m^{-3}$, 26 GeV/c

$\rho_e = [1 – 16] \times 1e11\ m^{-3}$ (from red over green to blue)



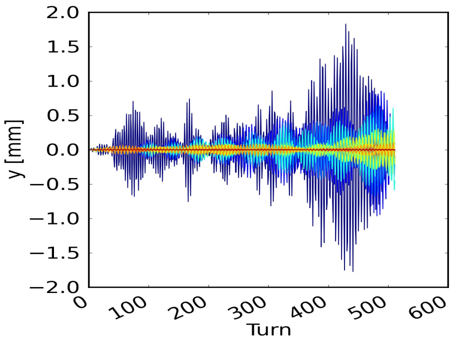


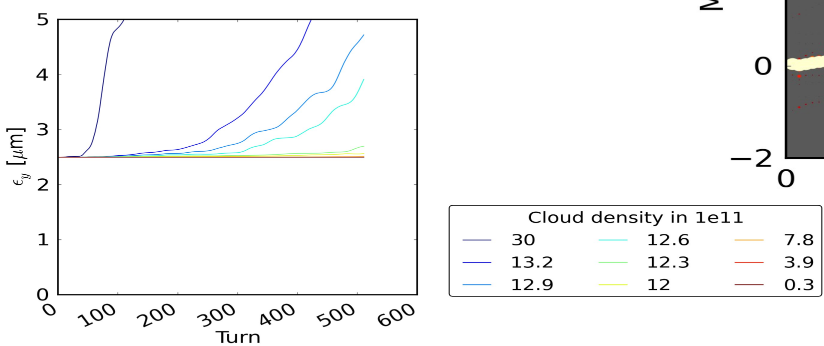
~ 4.2e11 m^{-3}

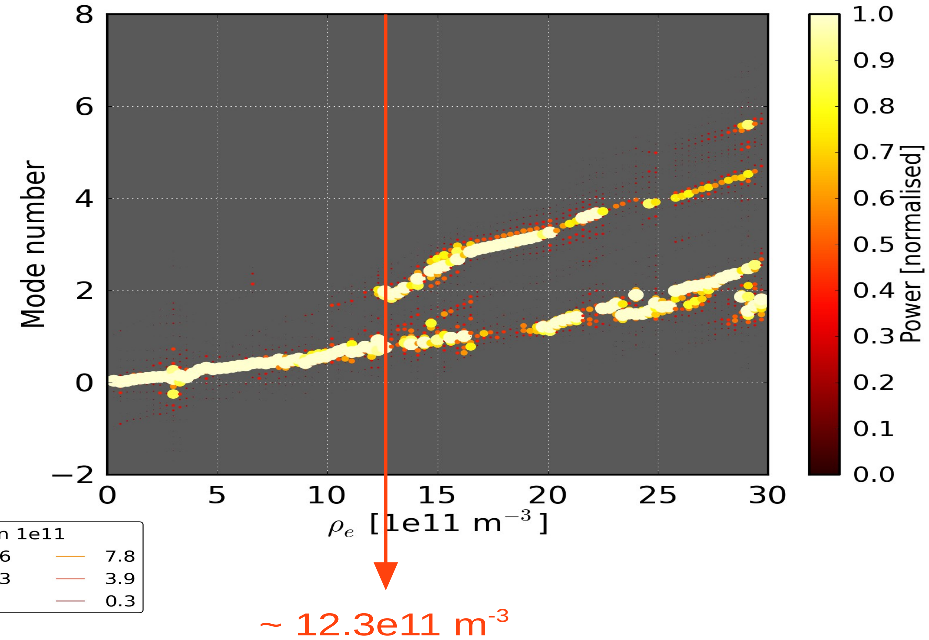
Accelerator Dynamics

- 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 $\rho_e = 0\ \mathrm{m}^{-3}$, 26 GeV/c

$\rho_e = [1 - 30] \times 1\mathrm{e}11\ \mathrm{m}^{-3}$ (from red over green to blue)

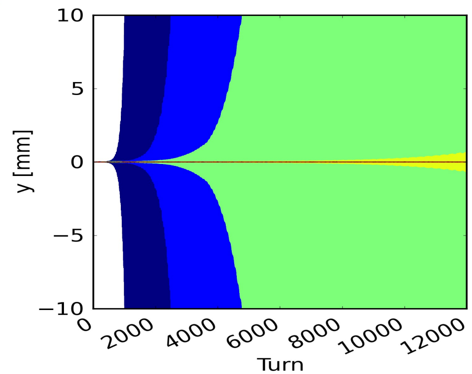


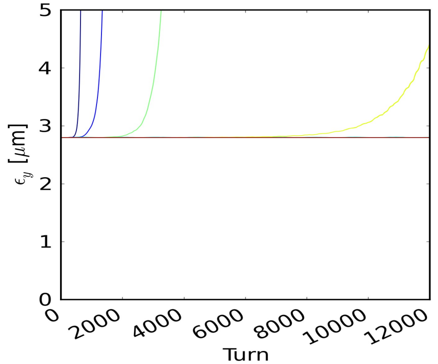


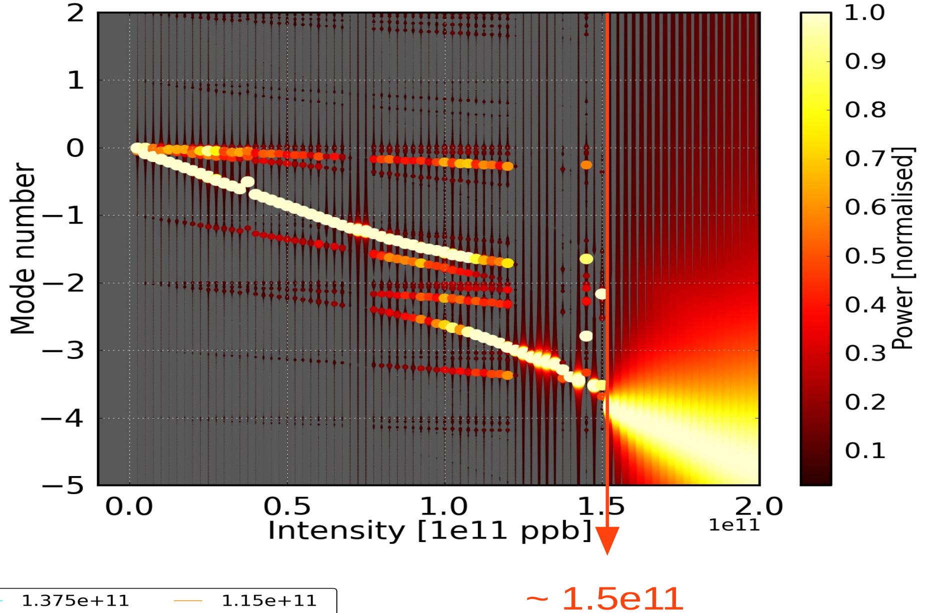


Accelerator Dynamics

- Transverse Mode Coupled Instabilities (TMCI)
  - SPS Q26 Lattice – No feedback, scan for beam intensity
  - Mode 0: $\omega_\beta = 0.185$, Mode -2: $\omega_\beta - 2\omega_s = 0.1732$ at $I_b \cong 0$ mA, 26 GeV/c

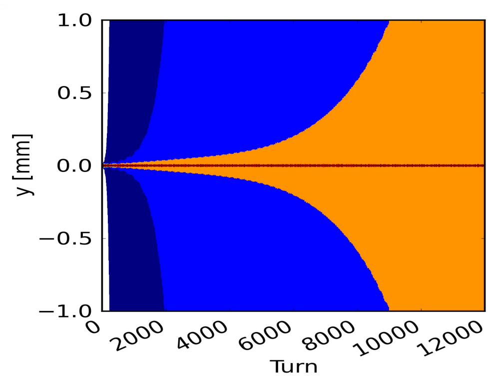


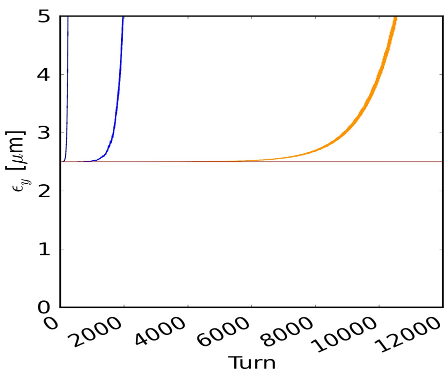


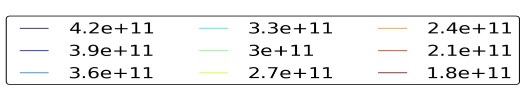


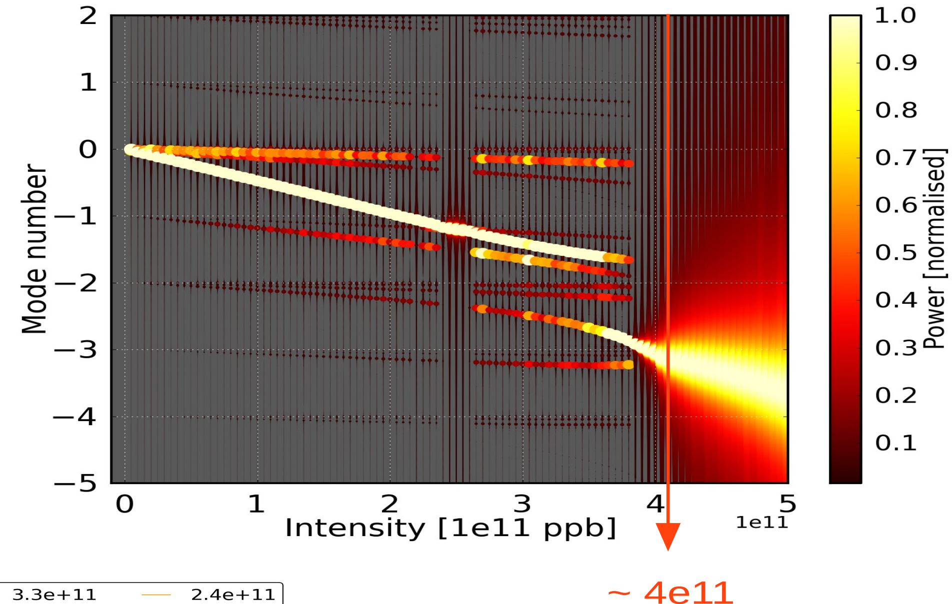
Accelerator Dynamics

- 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 $I_b \cong 0$ mA, 26 GeV/c







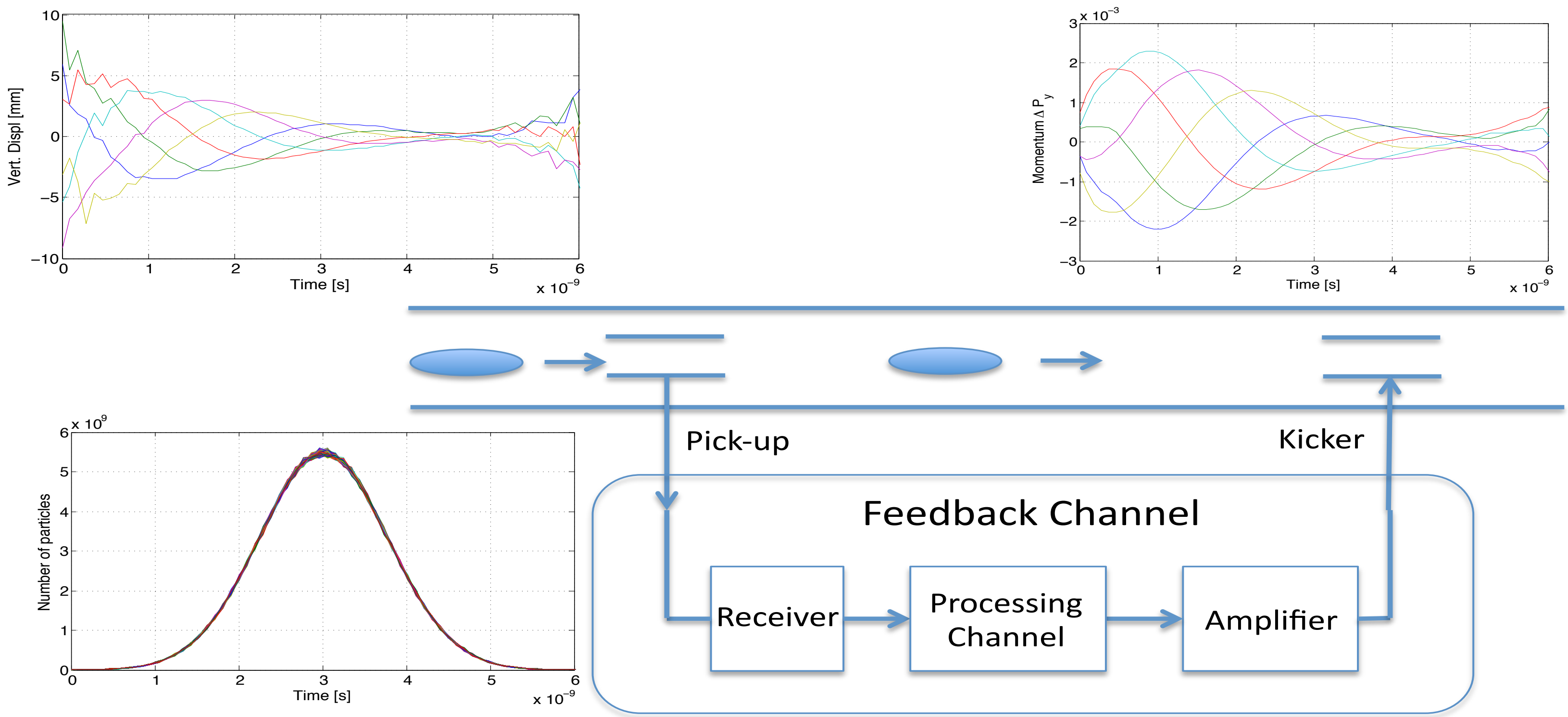


Accelerator Dynamics

- Requirements - Summary
  - ECI: Stabilize bunch at modal frequencies
    - Examples for SPS at E/c = 26GeV/c
    - Q26 Optics: needs to cover range (0.185, 0.2322)
    - Q20 Optics: needs to cover range (0.185, 0.2530)
  - TMCI: Stabilize bunch at modal frequencies
    - Examples for SPS at E/c = 26GeV/c
    - Q26 Optics: needs to cover range (0.185, 0.1614)
    - Q20 Optics: needs to cover range (0.185, 0.1340)
  - Design for different machines PS, SPS, LHC.
  - For a particular machine,
    - Stabilize individual bunches at different energies, during ramping, etc.
    - Operate at different beam intensities.
    - Reject injection transient perturbations.

Control Implementation

- General feedback control scheme



- The receiver has to measure the vertical motion of individuals parts along the bunch
- Feedback channel processes the different samples to generate the control signal
- Amplifier + Kicker: boost the control signal to drive different parts along the bunch

Control Implementation

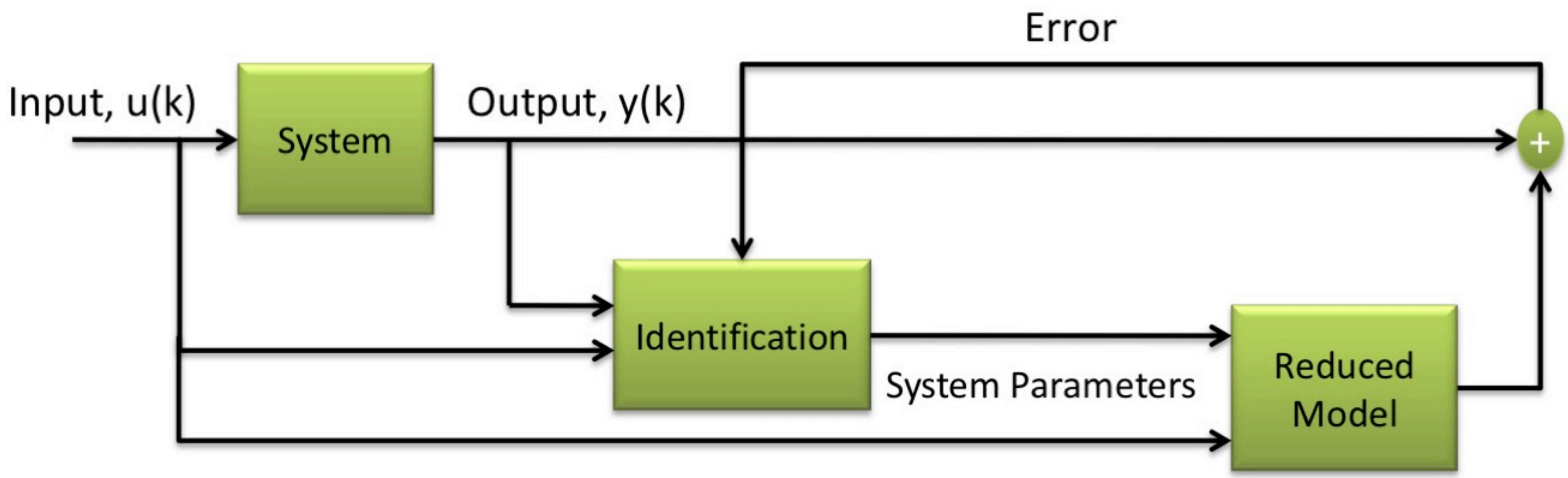
- Control Requirements
  - Stabilize the intra-bunch dynamics
    - Unstable modes for ECI-TMCI
    - Robust to parameter changes in the beam dynamics, to different operation conditions (steady-state) of the machine
  - Maximum dynamic range to keep stability-performance for a maximum set of transient conditions
  - Feasible controller
    - Unstable dynamics set the minimum gain in the controller
    - Intrinsic delay sets the maximum gain in the controller
  - Reject noise and perturbations
    - Isolate vertical displacement signal from longitudinal/horizontal signals.

Control Implementation

- Model-based Control
  – To design the controller, it is necessary to characterize the bunch dynamics
    - Develop mathematically tractable modelsthat allows to design the controller
    - Develop measurements and identification techniques to extract the parameters for the model based on measurements in the machine.
  – Based on the bunch dynamics model, design a controller and test it using macro-particle simulation codes and conducting machine developments (MDs) in the SPS ring

Control Implementation

- Identification Techniques

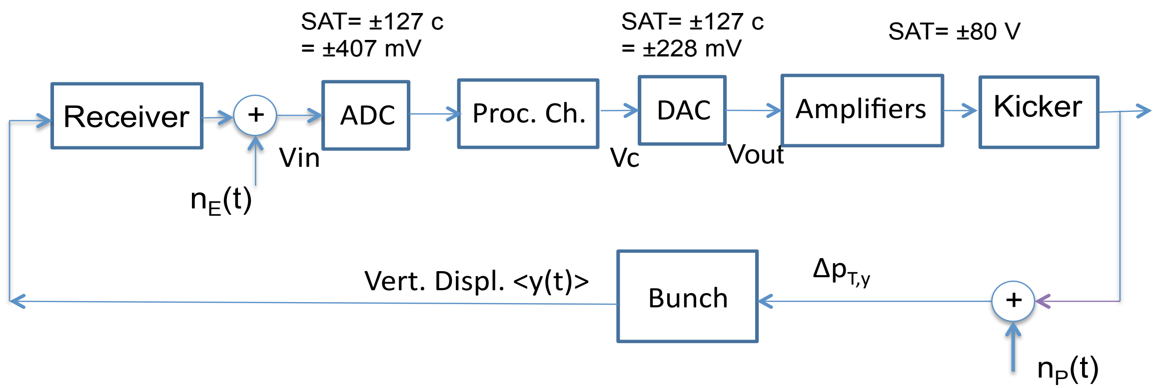


  - Based on a reduced model of the bunch dynamics, system identification techniques allow estimating the model parameters based on machine measurements when the bunch is driven by particular signals (persistent exciting signals).

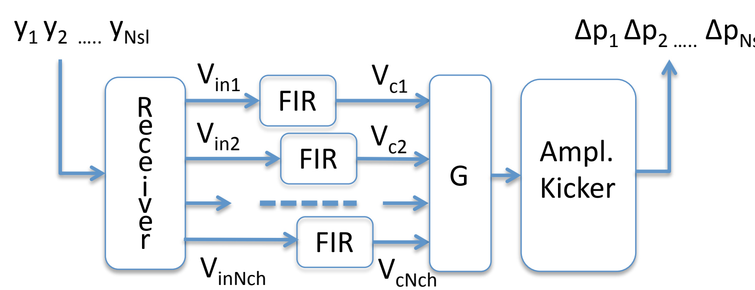
Control Implementation

- Control Configuration – Processing Channel

Block Diagram

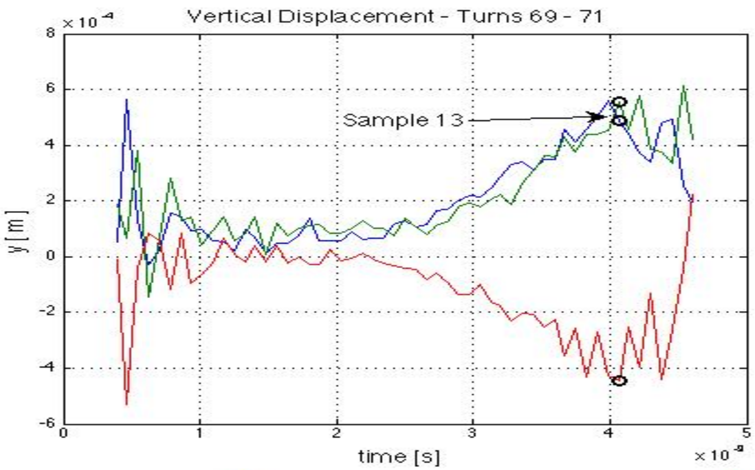


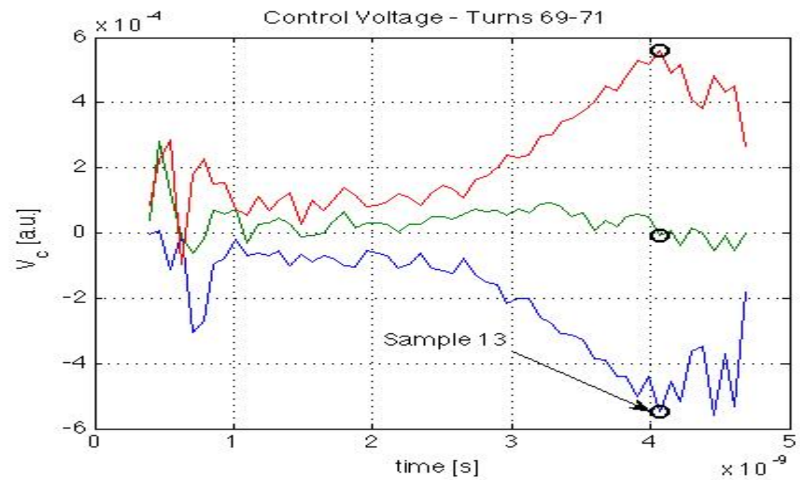
- 4 GSa/s digital channel. Flexible, reconfigurable processing
  - Analog equalization of pick-up and cable transfer functions
  - 2 ADCs / 1 DAC
- Detail of processing channel
  - 16 samples across 5 ns bucket
  - Finite impulse response (FIR) filter
  - Infinite impulse response (IIR) filter
  - Individual processing per sample
    - Diagonal controller
  - Processing multiple samples

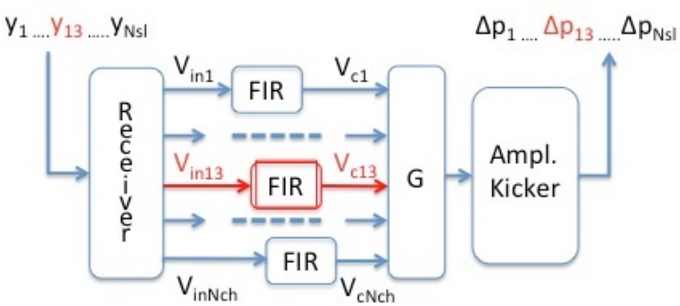


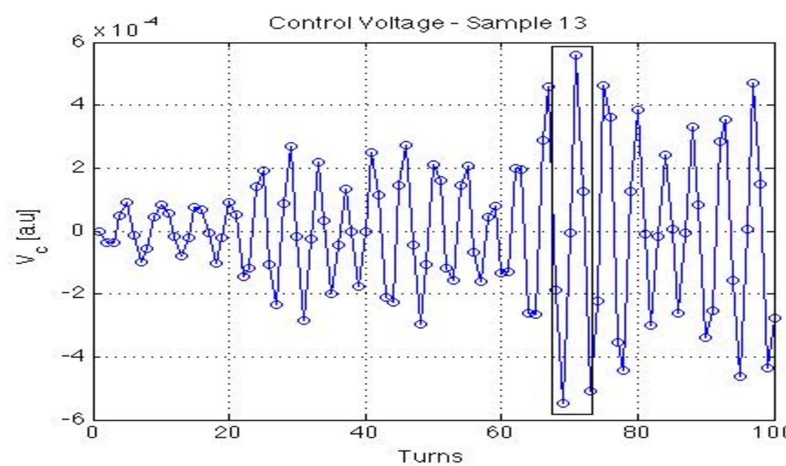
Control Implementation

- Control Configuration – Processing Channel







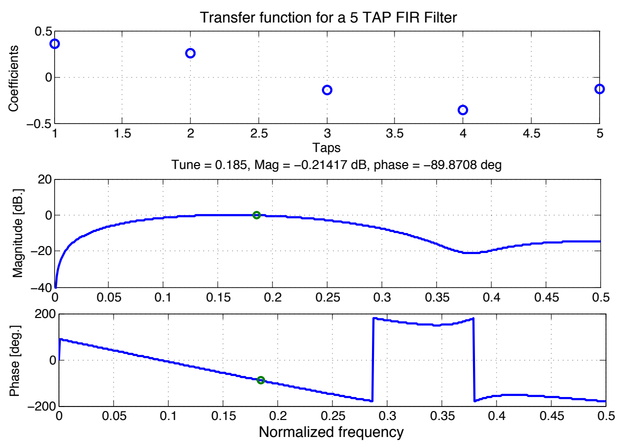


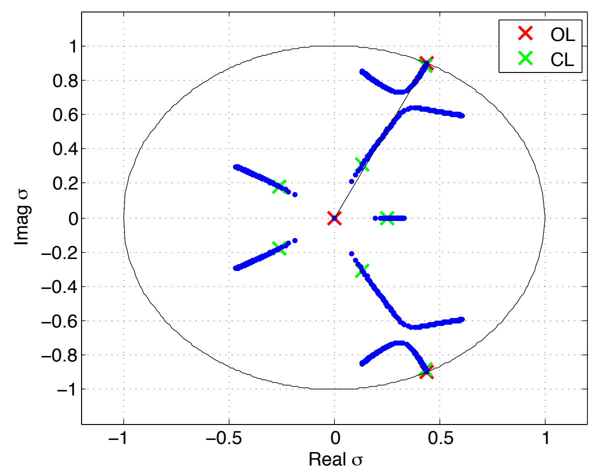
Receiver, Amplifier, Kicker need large bandwidth to processes the signals within the bunch

Accelerator Dynamics

- Model-Based Control Design
  - Assess system stability and performance
    - Design stabilizing controller for the unstable bunch
    - Guarantee robust system stability under different machine conditions and parameters. Quantify robustness
    - Guarantee performance system specification based on the perturbing signals and noise.
- Example of FIR filter

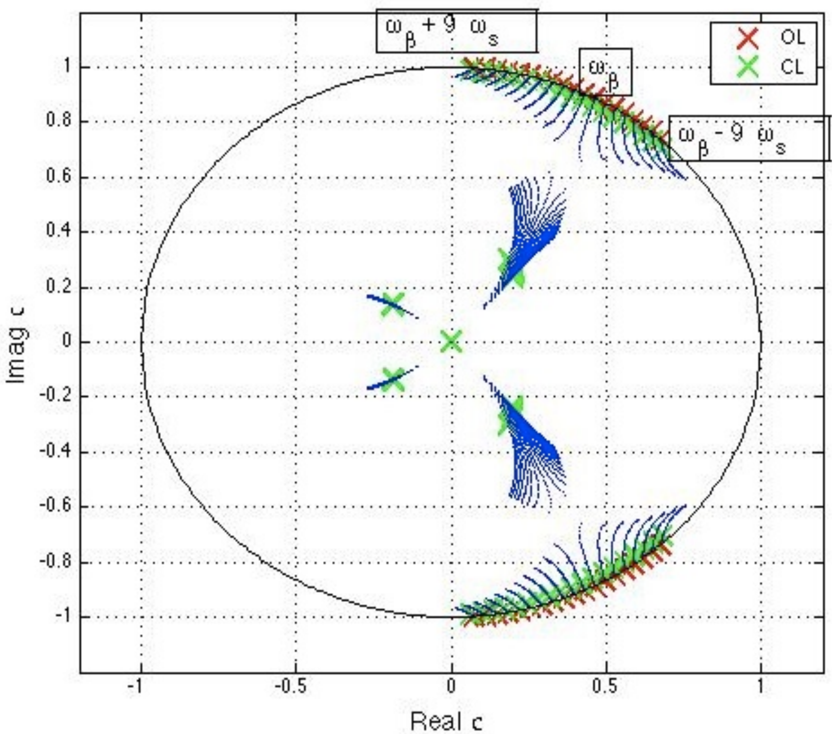
Root locus: Location of system eigenvalues for different controller gains

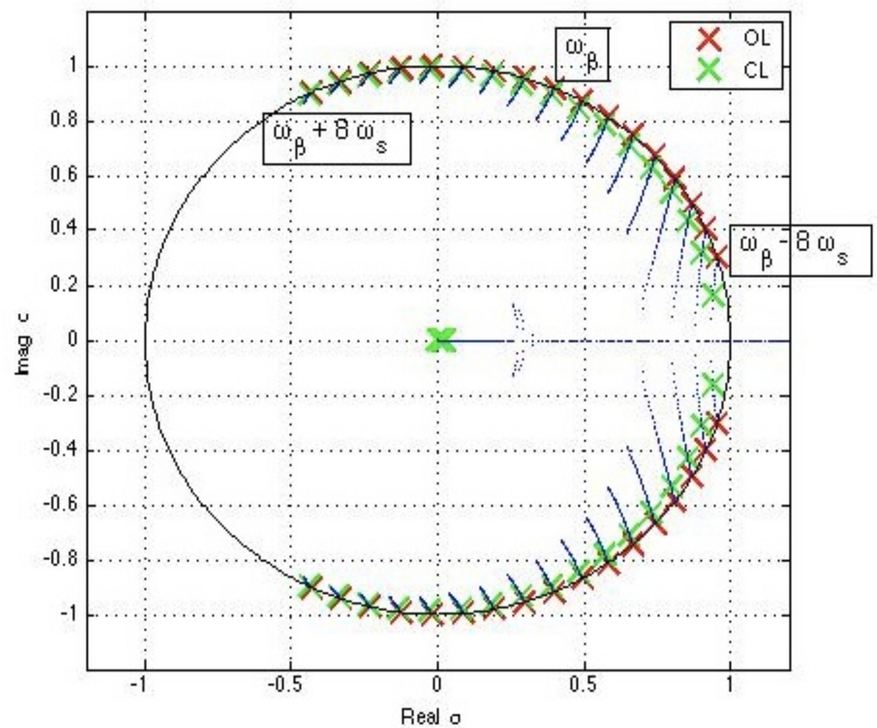




Control Implementation

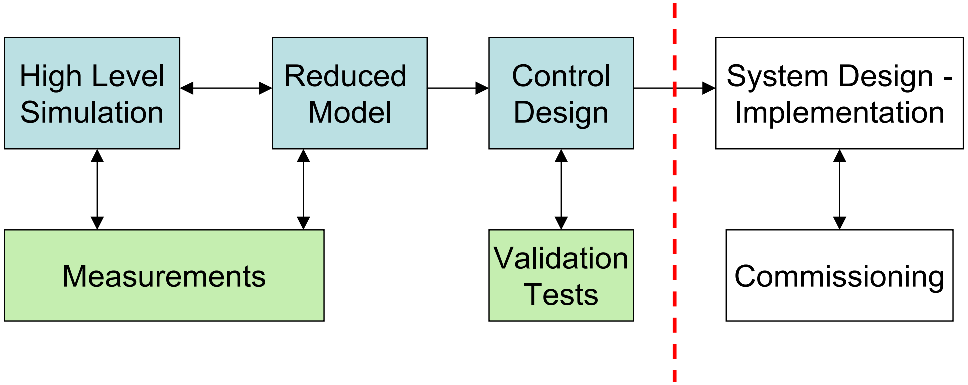
- Processing Channel – Filters
  - Root locus: System eigenvalues for different control gains. (Stable inside circle)
    - Q26 Optics — Q20 Optics
    - Finite Impulse Response Filter (FIR) — Infinite Impulse Response Filter (IIR)





Simulation Efforts

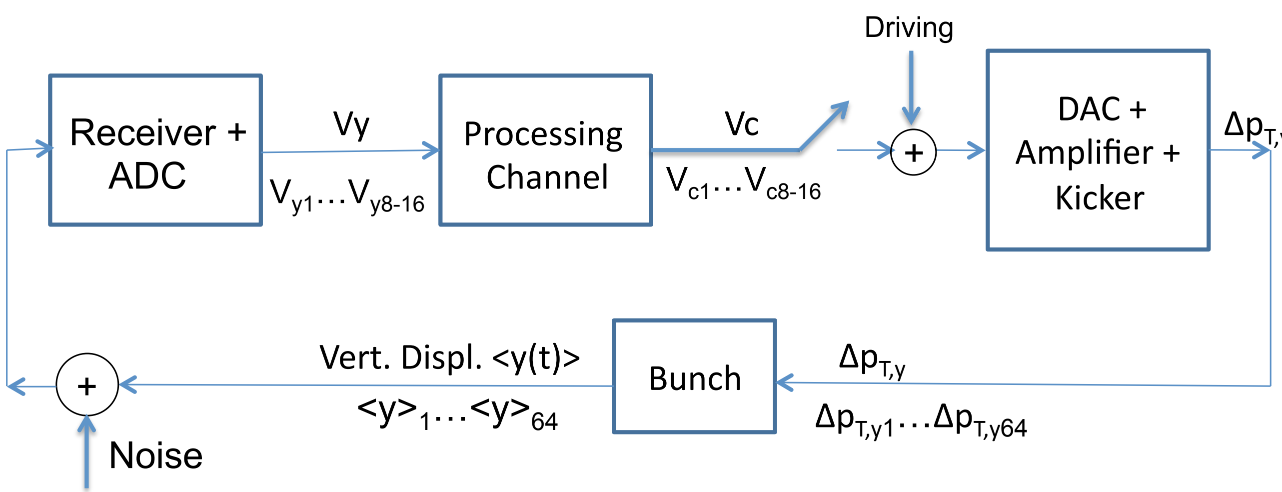
- Models – Simulations – MDs
  - Reduced model: Mathematical model of the bunch dynamics to design the controller
  - Macro-particles simulation codes: Provides a test-bed to explore control algorithms and measurement techniques
  - Machine Developments (MDs): Test and measurement periods using feedback system at the machine



- MD data is used to validate the macro-particle simulation codes and reduced order model of the bunch
- With validated models it is possible to predict in simulations the behavior of new hardware and firmware,
  - e.g. Kicker bandwidth, RF power, control filters, etc.

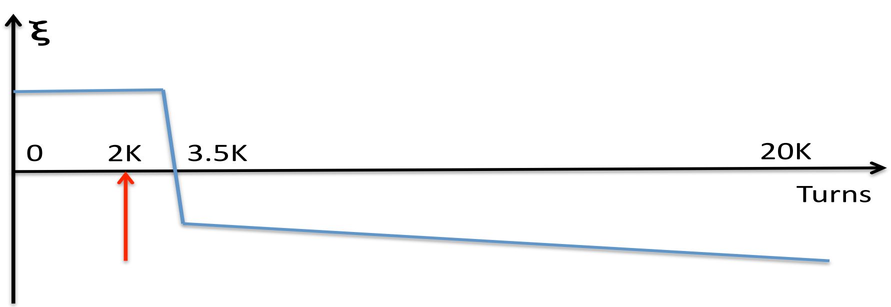
Simulation Efforts

- Realistic feedback channel models in macro-particles simulation codes (HT, CMAD)
  - Macro-particle simulation codes have been a very useful test-bench for designing MD analysis and tools.
  - Feedback channel model includes realistic representation of receiver, proc. channel, amplifier and kicker hardware.



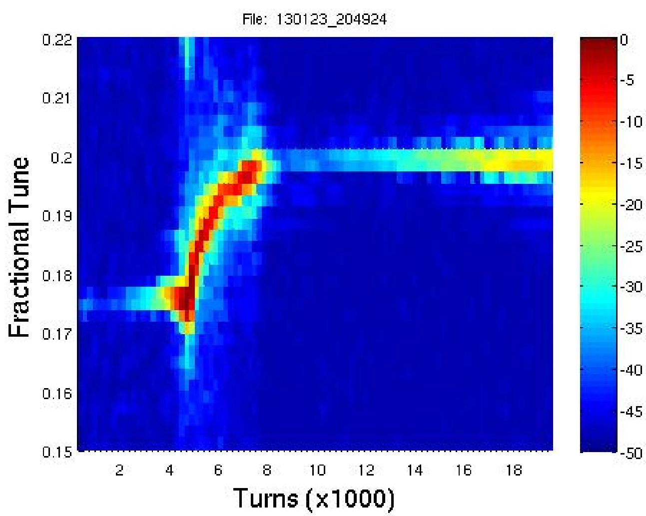
Simulation Efforts

- Models – Simulations – MDs
  - MD results
    - Control of Mode 0 instability with feedback
      - To generate an unstable bunch, the chromaticity is changed from positive to negative after injection
      - The beam is unstable in vertical plane: Mode 0 (barycentric motion)
      - The feedback loop is closed at turn 2000. Depending upon the gain G, it stabilizes the bunch
      - Around turn 4000, the vertical motion grows with a time constant $\tau \cong 350$ turns. At turn 20K, the growth time constant is $\tau \cong 200$ turns.



Simulation Efforts

- Models – Simulations – MDs
  - MD Results
    - Control of Mode 0 instability with feedback
      - Spectrogram of the vertical beam motion



Open Loop, bunch unstable around turn 3000

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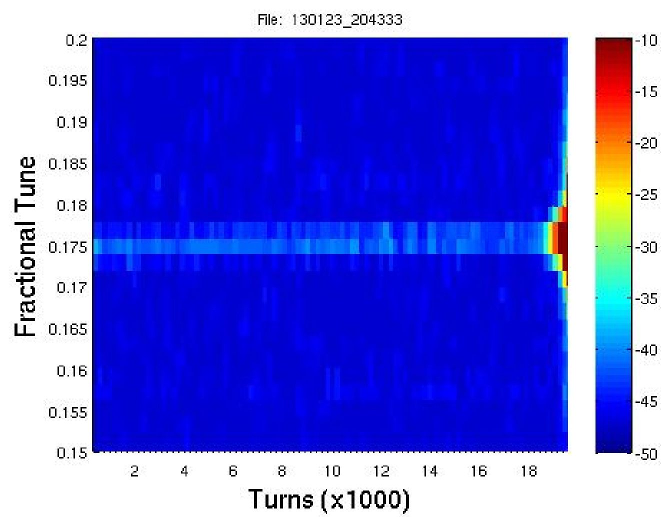
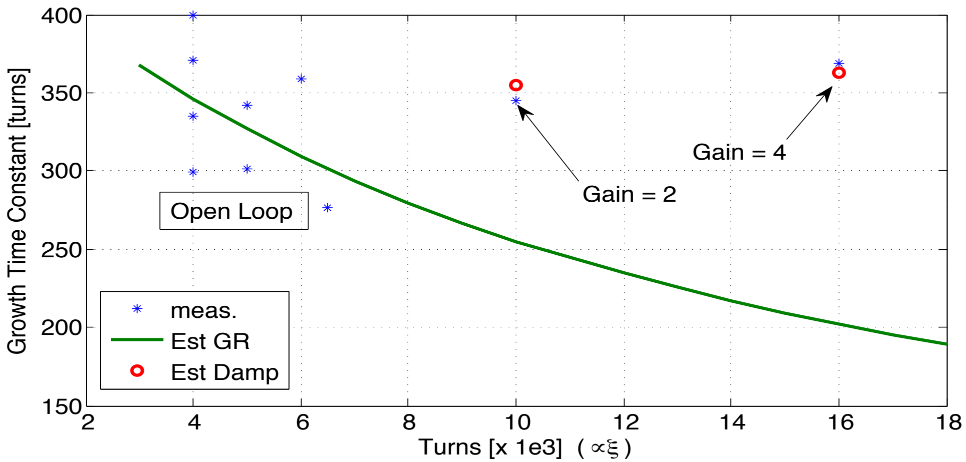


Closed Loop from turns 2K-18K, stabilizes the bunch up to turn 18K

Simulation Efforts

- Models – Simulations – MDs
  - Analysis of MD results
    - Unstable beam in Open Loop and Closed Loop for gains: G = 2, 4.
    - For gains: G = 8, 16, … the feedback stabilizes the bunch.
      - Assuming a simple damping model for the feedback, $\sigma_D = G.\ \sigma_1$, the final damping in the system is $\sigma_f(\xi) = \frac{1}{\tau_f(\xi)} = \frac{1}{\tau_{OL}(\xi)} - \sigma_D$
      - From the data: $\sigma_1 = 5.48 \times 10^{-4}$ turns^{-1}.

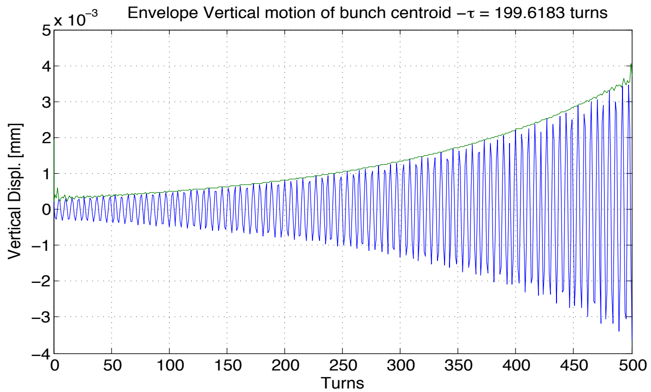


Simulation Efforts

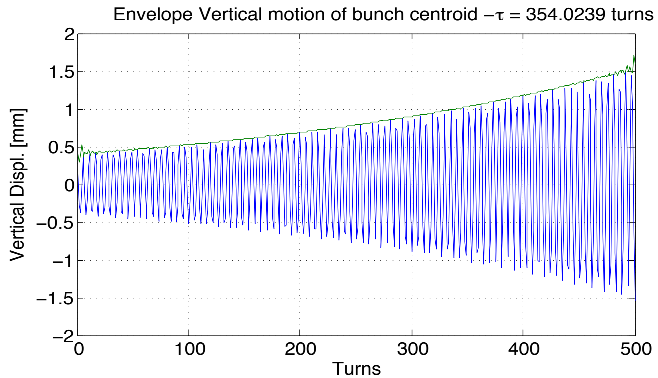
- Models – Simulations – MDs
  - Validation of Reduced model bunch dynamics

Mode 0 (barycentric vertical motion)

- The dipole motion of the bunch in the data analyzed is mainly barycentric (Mode 0).
- The parameters of the model are calculated based on the feedback system in place at SPS ring
- Simulation results show the case for gain $G = 4$.
- $\tau_{OL} = 200$ turns, $\tau_f = 360$ turns, for $G = 4$.



Open Loop



Closed Loop, $G = 4$

The feedback models in macro-particle simulation codes CMAD - HeadTail were validated using similar approach

Simulation Efforts

- Models – Simulations – MDs
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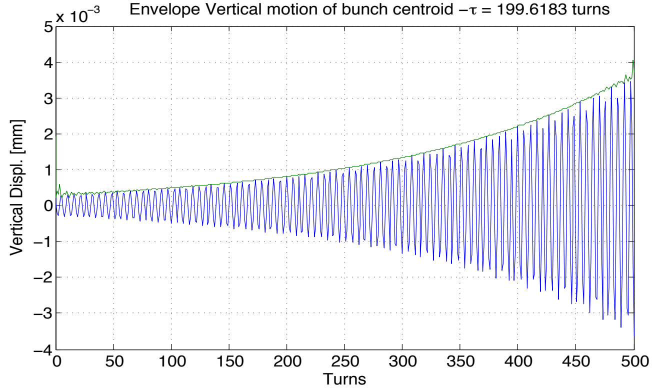
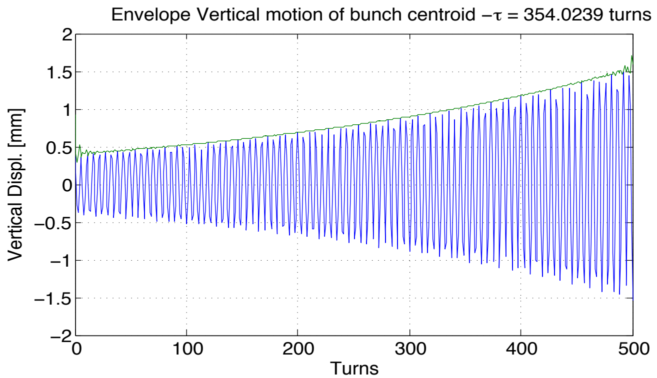


Open Loop



Closed Loop, $G = 4$

The feedback models in macro-particle simulation codes CMAD - HeadTail were validated using similar approach

Research Plans

- System Identification – Plan 2014
  - Based on the developed tool to identify and parameterize a reduced order model of the bunch dynamics
    - Test identification tool using macro-particle codes HT/CMAD
      - Quantify estimation errors
    - Test identification tool with real data
    - Analyze drive signals for identification
    - Prepare MD identification tools for new MDs (Sept 2014) .

Research Plans

- Models – Design Controllers – Plan 2014
  - Design controllers for SPS Q20 optics
    - Test using reduced models and multi-particle simulation codes (HT, CMAD)
    - Define filter implementation in FPGA firmware
    - Specify MD scenarios to test filters. (Nov 2014)
  - Design generic controllers
    - Test using reduced models and multi-particle simulation codes (HT, CMAD)
    - Define filter implementation in FPGA firmware

LARP

High Luminosity LHC

Research Plans

- Simulations – Plan 2014
  - Improve model of processing channel to include generic filters.
  - Analyze cases with new amplifiers – kickers
  - Test MD scenarios for Sep-Dec 2014
- MD analysis – Plan 2014
  - Impact of control variables in feedback stability and performance
  - Conclude Analysis for Mode 0 / Mode 1 data
  - Suggest MDs for Nov-Dec 2014

Conclusions

- We had a successful MDs during Jan-Feb 2013
  - Large amount of data have been taken and its analysis is giving information for models and simulations
  - Results have been useful to understand hardware limitations and project new MDs to take advantage of the new hardware under installation.
- We are in the process of finishing the data analysis and planning new MDs
  - Understand limits in the new hardware
  - Explore new control algorithms
  - Conduct MDs setting multibunches and different bunch energies in the machine
  - Evaluate open questions .....