E-Clouds / TMCI : Feedback Models, System Implications

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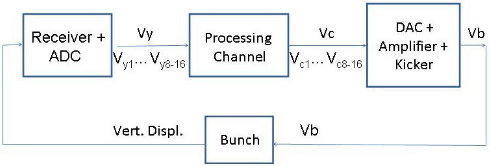
Electron Cloud / TMCI Project - DOE LARP / CERN

- Motivation: - Control E-cloud and TMCI effects in SPS and LHC via GHz bandwidth feedback
  - Complementary to E-cloud coatings, grooves, etc. Also TMCI
  - Anticipated instabilities at operating currents
  - Intrabunch 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
  - Large R & D effort coordinated on:
    - Non-linear Simulation codes (LBNL - CERN - SLAC)
    - Dynamics models/feedback models (SLAC - Stanford STAR lab)
    - Machine measurements- SPS MD (CERN - SLAC - LBNL)
    - Hardware technology development (SLAC)

Feedback Control System

Basics

- Feedback control is required when the original system is unstable or when performance cannot be achieved due to uncertainties in the the system characteristics
- Feedback control changes the dynamics of the original system - stabilize - improve performance

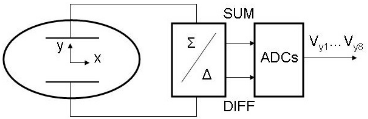


- Vy Multiple samples of the vertical position along the bunch
- Vc Control signal
- Vb Momentum Kick

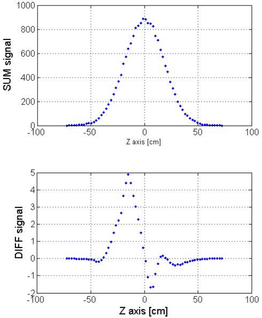
- Requirement for Feedback Control: Provide stability and satisfactory performance in the face of disturbances, system variations, and uncertainties.

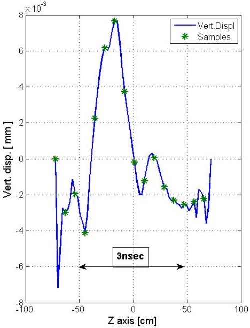
Feedback Control System

Basic Idea



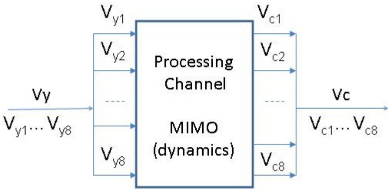
- RECEIVER Measures BPM signals, estimates the intrabunch Vertical Displacement

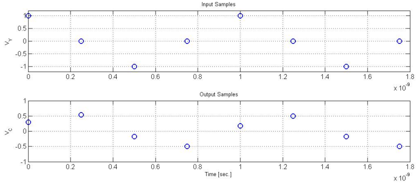




Feedback Control System

Basic Idea

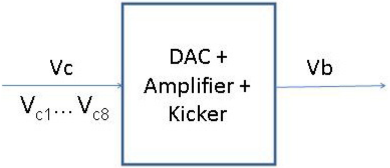


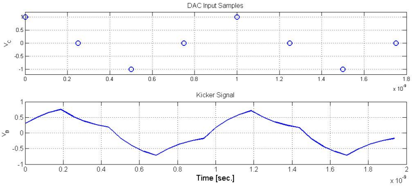


- PROCESSING CHANNEL Processes the multi-input signals and generates a multi-output control signal based on multiple input samples from previous turns.

Feedback Control System

Basic Idea



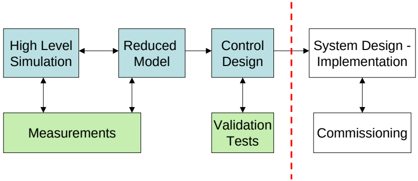


- DAC-Amplifier-Kicker Digital samples from the processing channel are converted to analog signal (DAC) , amplified and converter into an EM field by the kicker.

Goal - Plans

R & D lines

- Goal is to have a minimum prototype to fully understand the limitations of feedback techniques to mitigate E-cloud / TMCI effects in SPS.



- R & D areas
  - Non-Linear Simulation Codes - Real Feedback Models - Multibunch behavior
  - Development and Identification of Mathematical Reduced Dynamics Models for the bunch
  - Control Algorithms
  - MD Coordination - Analysis of MD data - Data Correlation between MD data / Multiparticle results
  - Study and Development of Hardware Prototypes

Multi-particle simulation codes

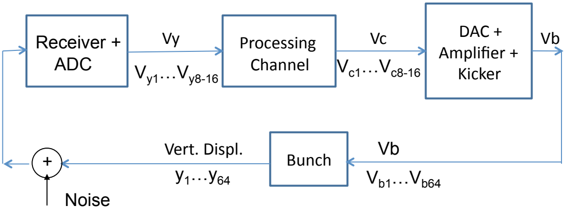
Reduced Model <–> Multiparticle Model <–> Real System (SPS ring)

- What is the difference between a Reduced Model and Multiparticle Model ?? Impact in the feedback system design??
  - Reduced Model: Gives a mathematically tractable tool to design the feedback control including system's performance specifications and system's external perturbations and uncertainties.(Model-Based Design)
  - Multi-particle Models: Gives a detailed behavior of the bunch dynamics. It is not a design tool but it is an excellent test-bench.
- Multi-particle simulation codes (WARP - HeadTail - CMAD) have been a very useful test-bench for designing MD analysis algorithms and tools.
- Important for the development of mathematical reduced dynamics models of the bunch.

Multi-particle simulation codes

Next step related to feedback control system:

- Add realistic models representing the receiver, processing channel, amplifier and kicker hardware. Test-bench to test feedback control system design.

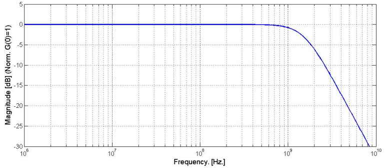


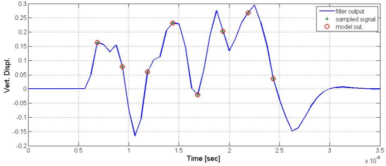
- Models include frequency response, signal limits and noise

Multi-particle simulation codes

Realistic models in the feedback channel

- Multi-particle codes interact with the feedback once per turn. Measure, Kick all samples representing the bunch at the same time.
- Feedback model has to follow that structure. Static matrix represents the transfer function of each block.
- Receiver: $V_y = M_R y, \qquad y = [y_1 \ldots y_{64}]^T, V_y = [V_{y1} \ldots V_{y8}]^T$





Feedback Control of Intra-Bunch Instabilities

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 $= T_{revolution}$
- GigaHz bandwidth to process intra-bunch signals.

Feedback Control of Intra-Bunch Instabilities

Mathematical Modeling and Feedback Design

- What is the best control strategy??
  - Unique robust control
  - Scheduled robust control
  - Adaptive controller
  - Non-Linear
  - Complexity: One control algorithm per sample (Diagonal) or Multi-input/Multi-output algorithms.
- The best answer...is given by the bunch dynamics, specifications, noise, signal perturbations,uncertainties, etc.
- A reduced model of the bunch dynamics is the first element to start designing a feedback control system.

Feedback Control of Intra-Bunch Instabilities

Mathematical Reduced Model on intra-bunch dynamics

- Linear Model (Set of coupled oscillators, Discrete, all the measurements at T_{rev} periodic)

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) + Du(k) \end{aligned}$$

  - It does not capture, tune shifts due to e-clouds and synchrotron motion of particles within the bunch

- Linear Model time-variant. Synchrotron motion effects can be included

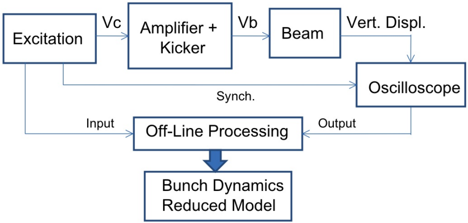
$$\begin{aligned} x(k+1) &= Ax(k) + B(kT_{rev})u(k) \\ y(k) &= C(kT_{rev})x(k) \end{aligned}$$

- All the parameters are identified based on measurements.
- Before we drive the bean in SPS, we use multiparticle simulators to mock-up the identification set-up.

Feedback Control of Intra-Bunch Instabilities

Identification of Internal Bunch Dynamics: Reduced Model

- Using a random sequence (V_C), drive a beam through the amplifier and Kicker.
- Measure the vertical displacement
- Based on Input- Output signals, estimate the bunch reduced model.



- We are measuring including Amplifier. Kicker, Receiver model
- Bunch has to be stable
- E-clouds/TMCI: need to stabilize the bunch and then run identification

Feedback Control of Intra-Bunch Instabilities

Next MD plan

- To validate multiparticle simulation codes, we are planing more MDs in SPS. It will help to have good test-bench multiparticle simulators to test feedback designs.
- In this MD we want to drive the bunch using the existent SPS kicker. Currents below E-cloud threshold (stable bunch).
  - Important to test the power level and kicker gain for prototyping new kicker.
  - Test of SLAC hardware - Back-end - Synchronization with SPS machine - Timing.
  - If it is possible to drive different sections of the bunch, test identification algorithms. - Calculate reduced dynamic model of bunch.
  - Perform bunch model identification at current levels near the instability threshold.
- Plan future MD to stabilize a few bunches or wait for a new kicker??

Feedback Control of Intra-Bunch Instabilities

Analysis kicker requirements

- Kicker is one of the blocks in this feedback channel that received less attention
- No simple device, GigaHz bandwidth, High power, ...
- Requirements (??), we start some studies using multi-particle simulators.

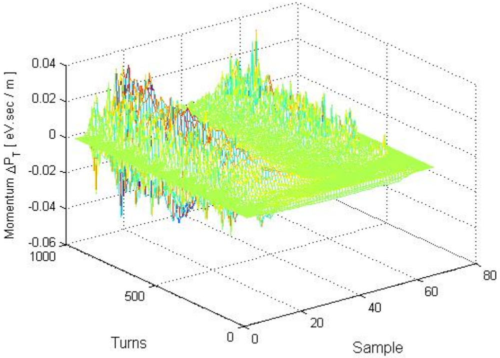
$$\frac{d^2y(t)}{dt^2} + \omega_{\beta F}^2 y(t) = K(e(t) - y(t)) + \Delta P_T(t)$$
$$\frac{d^2e(t)}{dt^2} + \omega_{EC}^2 e(t) = K(y(t) - e(t))$$

- Stabilizing feedback control: y(t) –> 0, then $\Delta P_T(t) \simeq Ke(t)$
- Open Loop; guess the signal kicker $_T(t)$ such y(t) = 0 very difficult
- Ideal Closed Loop: we can have an estimation of $\Delta P_T(t)$

Feedback Control of Intra-Bunch Instabilities

Analysis kicker requirements

- For relative large feedback gain, y(t) –> 0 in presence of e-cloud, we can have an estimation of the signal level generated by the kicker $\Delta P_T(t)$ to reject the electron cloud perturbation.



Conclusions

- Progress in this area: Reduced Models, Models of realistic feedback for multiparticle codes, development of Identification tools, and preliminary analysis of kicker specifications.
- Real Hardware models - Matlab tool to generate equivalent matrices, needs to include and test in multi-particle simulation codes.
- Reduced Models - Identification - We are working in the bunch dynamic model that captures the synchrotron motion of particles withing the bunch. (stable bunch, kicker effect)
- Kicker Analysis of kicker effects in closed loop operation, plan to study kicker design option

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

Feedback Systems

Basics

- For a single bunch, the observation of the vertical displacement of the centroid $y(t)$ after a "local momentum kick" $M_k(t)$, follows simplified dynamics given by

$$\frac{d^2y(t)}{dt^2} + D\frac{dy(t)}{dt} + \omega_{\beta F}^2 y(t) = M_k(t)$$

- A controller or damper defines a mapping $M_k(t) = C(y(t))$ (includes dynamics, e.g.: function of $\int y(t).dt, y(t), \frac{y(t)}{dt}...$), such that the overall vertical bunch dynamics is

$$\begin{aligned} \frac{d^2y(t)}{dt^2} + D\frac{dy(t)}{dt} + \omega_{\beta F}^2 y(t) &= G_d\frac{dy(t)}{dt} \\ \frac{d^2y(t)}{dt^2} + (D - G_d)\frac{dy(t)}{dt} + \omega_{\beta F}^2 y(t) &= 0 \end{aligned}$$

- Given D, the idea is to adjust G_d such that $\gamma = D - G_d > 0$ (stability) and the "oscillation have acceptable damping" (performance). The eigenvalues of the original equation

$\lambda_{1,2} = \frac{-D \pm \sqrt{D^2 - \omega_{\beta F}^2}}{2}$ are shifted to $\lambda_{1,2} = \frac{-\gamma \pm \sqrt{\gamma^2 - \omega_{\beta F}^2}}{2}$

Feedback Systems

Basics

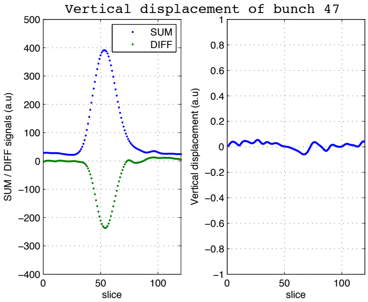
- For a multiple bunches in a ring (collective effects), we can extend the dynamic mode of the bunch centroids,

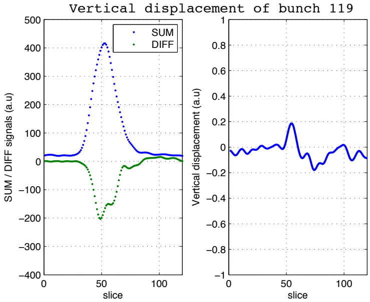
$$\begin{aligned}
\frac{d^2 y_1(t)}{dt^2} + D\frac{dy_1(t)}{dt} + \omega_{\beta F}^2 y_1(t) &= W_1(y_1(t), ..., y_n(t)) + M_{k1}(t) \\
..... &= .... \\
\frac{d^2 y_n(t)}{dt^2} + D\frac{dy_n(t)}{dt} + \omega_{\beta F}^2 y_n(t) &= W_n(y_1(t), ..., y_n(t)) + M_{kn}(t)
\end{aligned}$$

- Now due to $W_i(y_1(t), ..., y_n(t))$ there is coupled motion between n bunches. The system has $2n$ eigenvalues, stables or inestables.
- We need to measure $y_1(t), ..., y_n(t)$ and drive the beam with $M_{k1}(t), ..., M_{kn}(t)$ on turn-by-turn basis. Those signals are finite duration (samples) and arranged in a unique measurement and driving "series channel'. receiver - amplifier - kicker
- A controller or damper defines a mapping $M_k(t) = C(y(t))$, where $M_k(t) = [M_{k1}(t)...M_{kn}(t)]^T$ and $y(t) = [(y_1(t)...y_n(t)]^T$ are vectors. processing channel

Simple Observations from SPS Studies

- SPS MDs: 2 in 2008, 1 in 2009, recently in 2010
- June 2009, SPS injection 26GeV, Charge: 1E11p/bunch, separation 25 nsec.,
- Time domain Vertical pick-up signals: SUM and DIFF - Extracted Vertical displacement (Data sampled 20 ps/point)





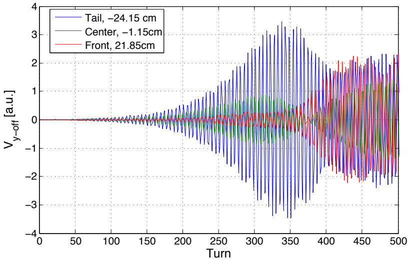
- Two batches: First 72 bunches stable, (e.g. bunch 47), second set of 72 bunches E-cloud instabilities, (e.g. bunch 119). Time span: 2.6 nsec.

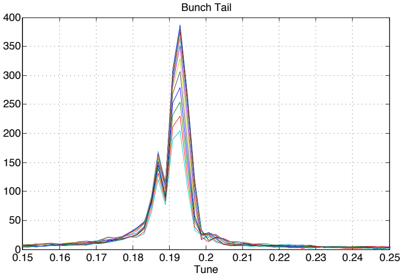
movie Vert. Displacement

Simple Observations from SPS Studies

Tune shift

- Different time evolution of the vertical displacement for different sections of the bunch.
- Tune shifts within the bunch due to E-cloud, (Tune = 0.185)



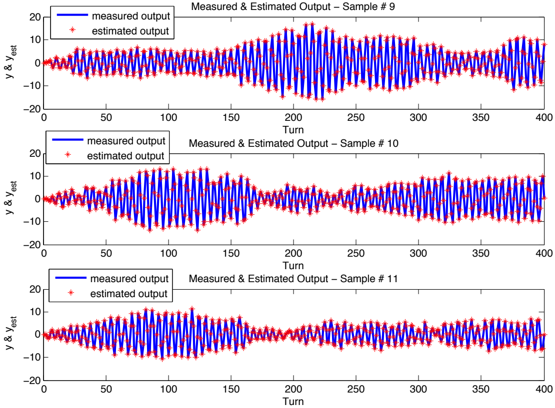


movie rms tune

Plan - Progress

Identification of Internal Bunch Dynamics: Reduced Model

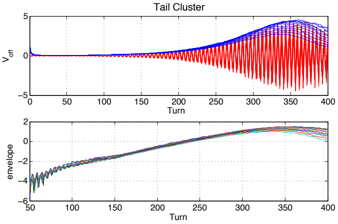
- Comparing the input random sequence to the vertical displacement slide per slide we can calculate the reduced model

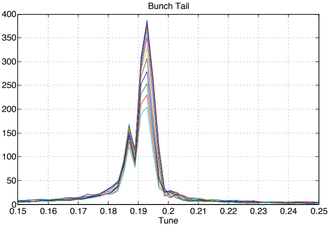


Plan - Progress

Identification of Internal Bunch Dynamics

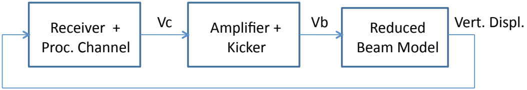
- Based on the natural response of the bunch when interacting with e-clouds we can measure the worse case dynamics model



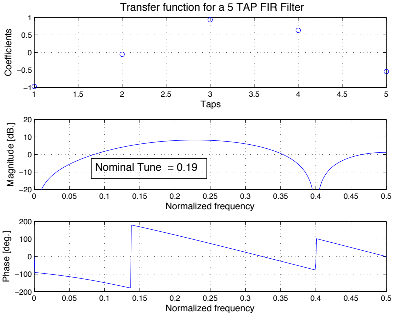


Plan - Progress

Closed-Loop feedback around the Reduced Model



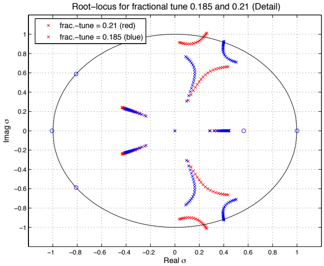
- Use the reduced model, with realistic feedback delays and design a simple FIR controller
  - Each slice has an independent controller
  - This example 5 tap filter has broad bandwidth - little separation of horizontal and vertical tunes
  - But what would it do with the beam? How can we estimate performance?

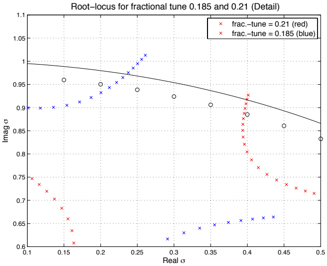


Plan - Progress

Root Locus Study - Tune shifted from 0.185 to 0.21

- We study the stability for a range of tunes
- This filter can control both systems- Maximum damping is similar in both cases
- Is this realistic case to design? We need more data from simulations and MD
- We need models for dynamics vs. beam energy, interaction with ramp

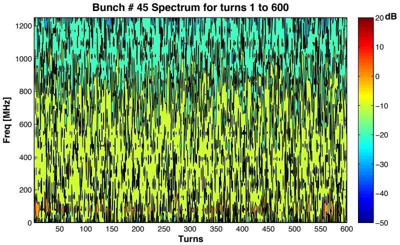




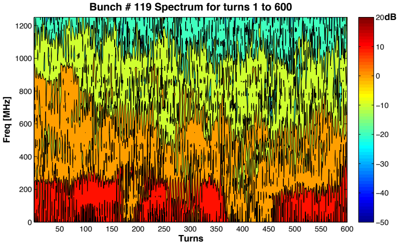
R & D areas

Hardware - Complexity? Scale?

Bunch Spectrum



stack 1-bunch 47



stack 2 - bunch 47 (bunch 119)

- Frequency spectrogram of bunch oscillations suggests for this case that a 4 Gsamples/sec (Nyquist limit) could be enough to measure the most unstable modes

R & D areas

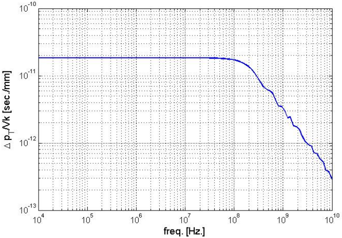
Hardware - Complexity? Scale?

- Assuming 16 samples/bunch/Turn, 72x6 bunches/Turn, 16 Multiplications/Accumulate (MACs) operations per sample (Proc. Ch. 16 taps FIR).
  - SPS = 6*72*6*16*43Khz = 5 GigaMACs/sec
  - KEKB iGp system = 8 GigaMACs/sec, (existent)
  - Dynamic bandwidth to process 4 Gs/sec
- Amplifier - Kicker: bandwidth limit about 1-2GHz, Power-Gain ??
  - Installed Kicker: Limited in bandwidth and power
  - Study option for kicker
- Receiver - Pick-up
  - Installed Pick-up: Propagation modes $\sim 1.7GHz$
  - Design new pick-up - CERN interest - Install 2012-2013
  - Study receiver topology - noise / spurious perturbations floor

R & D areas

Hardware - Kicker / Pick-up

- Amplifier - Kicker. Critical missing elements



Test power amplifiers, set cable plant, loads for existent kicker.
Drive the bunch with the actual hardware.

- Identify the Kicker technology as an accelerated research item, Study best kicker topology for prototype.
- Kicker design/fab requires joint CERN/US plans.
- Design kicker and vacuum components for SPS fabrication and installation

Plan - Progress

MD plans

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