Feedback Control of SPS E-Cloud/TMCI Instabilities

C. H. Rivetta[1]
LARP Ecloud Contributors:
A. Bullitt[1], J. D. Fox[1], T. Mastorides[1], G. Ndabashimiye[1], M. Pivi[1], O. Turgut[1], W. Hofle[2], B. Savant[2], M. Furman[3], R. Secondo[3], J.-L. Vay[3]

[1]Accelerator Research Department, SLAC
[2]BE-RF Group CERN
[3]LBNL

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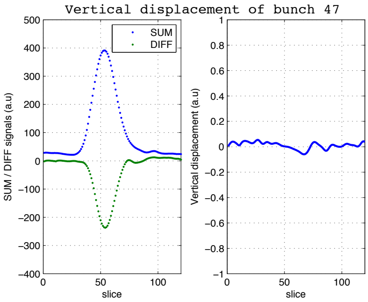
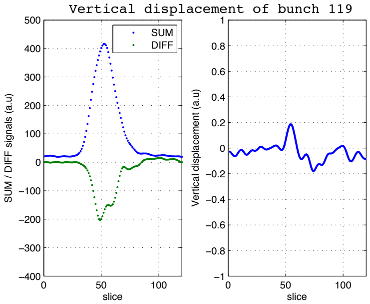
Electron Cloud / TMCI Project - DOE LARP / CERN

- 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)

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)





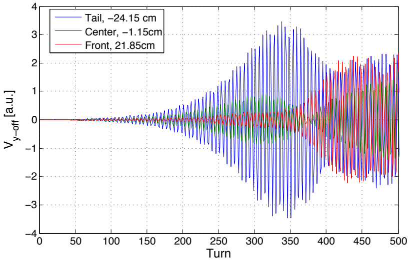
- Two batches: First 72 bunches stable, (e.g. bunch 47), second set of 72 bunches E-cloud instabilities, (e.g. bunch 119). Time span: 2.6 nsec.

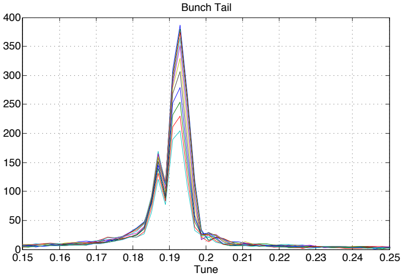
movie Vert. Displacement

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)



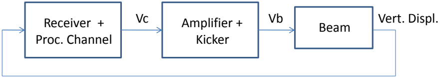


movie rms tune

Feedback 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



- Vert.Disp. 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 Systems

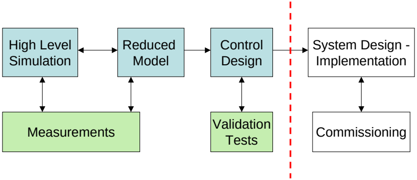
Requirements

- 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 $= T_{revolution}$

Plan - Progress

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.

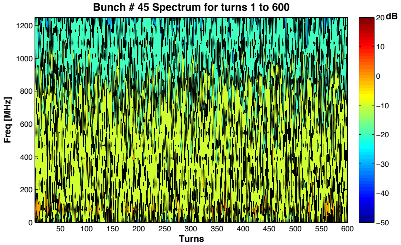


- R & D areas
  - Study and Development of Hardware Prototypes
  - Non-Linear Simulation Codes - Real Feedback Models - Multibunch behavior
  - Development and Identification of Mathematical Reduced Dynamics Models for the bunch - Control Algorithms
  - MD Coordination - Analysis of MD data - Data Correlation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

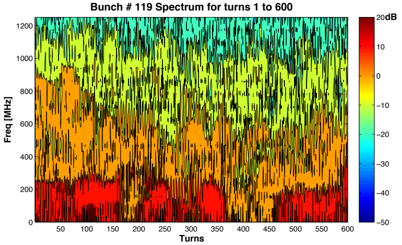
R & D areas

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

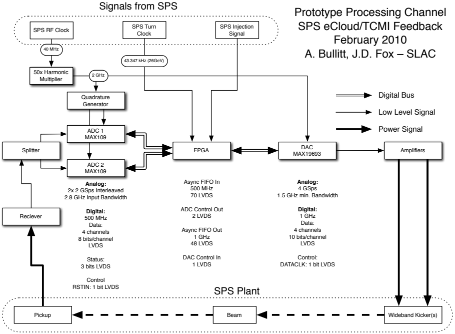
R & D areas

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: No major limitations - Propagation modes $\sim 1.7MHz$
  - Study receiver topology - noise / spurious perturbations floor

R & D areas

Hardware - Processing Channel - Excitation Prototype

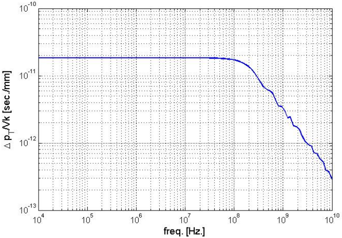


- Can we build a 'small prototype' style feedback channel? What fits in our limited LARP hardware budget? Develop for driving beam (identification) and closed-loop tests in SPS
- Idea - build 4 GS/sec. channel via evaluation boards and SLAC-developed Vertex 5 FPGA processor

R & D areas

Hardware - Kicker / Pick-up

- Amplifier - Kicker. Critical missing elements



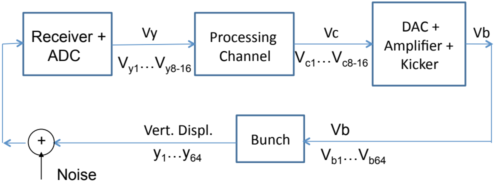
Test power amplifiers, set cable plant, loads for existent kicker.
Drive the bunch with the actual hardware.

- 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

Non-Linear Simulations

- Multiparticle simulation codes 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.
- 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.



- J-L Vay - R.Secondo talks

Plan - Progress

Mathematical Modeling and Feedback Design

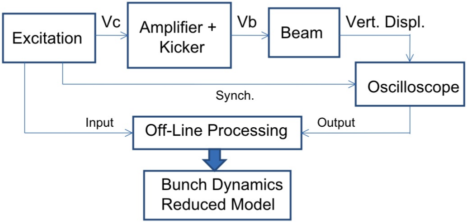
- From previous analysis : Bunch Dynamics is unstable, non-linear. Delay in the control action. Noise and spurious perturbations. Limited Power. Parameters change.
- What is the best control strategy??
  - Unique robust control
  - Scheduled robust control
  - Adaptive controller
  - Complexity: One control algorithm per sample or Multi-input/Multi-output algorithms.
- Control Design using Model-Based Design
  - Mathematical reduced dynamics models of the bunch.
  - Requires identification of the bunch dynamics (Measurement of the response to a given excitation)

Plan - Progress

Identification of Internal Bunch Dynamics: Reduced Model

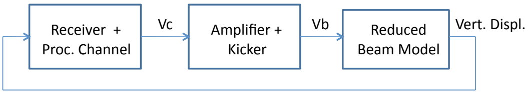
- Characterize the bunch dynamics - same technique for simulations and SPS measurements
- Critical to design the feedback algorithms
- Ordered by complexity, the reduced models could be

- Linear models with uncertainty bounds (family of models to include the GR/tune variations)
- 'Linear' with variable parameters (to include GR / tune variations - Synchrotron osc. - Different op. cond.)
- Non-linear models

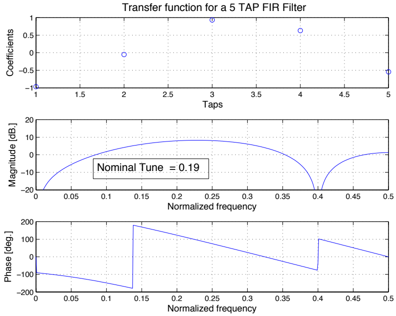


Plan - Progress

Closed-Loop feedback around the Reduced Model



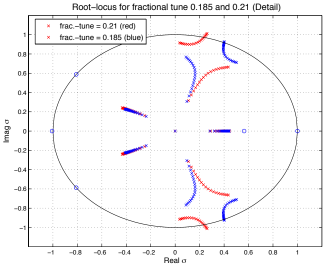
- Use the reduced model, with realistic feedback delays and design a simple FIR controller
  - Each slice has an independent controller
  - This example 5 tap filter has broad bandwidth - little separation of horizontal and vertical tunes
  - But what would it do with the beam? How can we estimate performance?

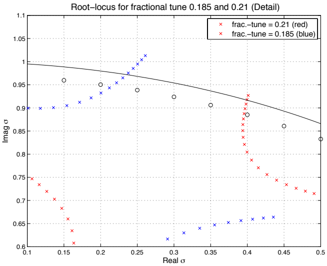


Plan - Progress

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





Plan - Progress

MD plans

- 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 next MD to stabilize a few bunches

Conclusions

Summary - 2010 LARP Ecloud/TMCI effort

- Lab effort -development 4 GS/sec. excitation system for SPS
  - Modify existing system to synchronize with selected bunches - data for system identification tools
  - Identify critical technology options, evaluate difficulty of technical implementation
  - Explore 4 Gs/sec. 'small prototype' feedback channel for 2011 fab. and MD use
  - Evaluate SPS Kicker options: CERN request, 2012 shutdown window
- Understand E-cloud dynamics via simulations and machine measurements
  - Participation in E-Cloud studies at the SPS (July 2010) - Data under Analysis
  - Analysis of SPS and LHC beam dynamics studies, comparisons with E-cloud models
- Modeling, estimation of E-Cloud effects
  - Validation of Warp, Head-Tail and CMAD models, comparisons to MD results
  - Integrate realistic models of feedback system hardware in Warp, Head-Tail and CMAD simulators.
  - Comparisons with machine physics data (driven and free motion), Critical role of E-cloud simulations in estimating future conditions, dynamics
  - Extraction of system dynamics, development of reduced coupled-oscillator model for feedback design estimation

Conclusion

Request for SPS Feedback System

- What can we do for the 2012 SPS shutdown? CERN's interest - very high.
  - Critical missing element - useful high-power kicker and power amplifier components in SPS
  - Identify the Kicker technology as an accelerated research item, design prototype kicker and vacuum components for SPS fabrication and installation
  - Kicker design/fab requires joint CERN/US plans.
- FY 2011 - Accelerated research and design report on Kicker System
  - Design report, suggested implementation, test low power lab models, RF simulation.
- FY2012 - Detailed design and fab of prototype kicker, vacuum components
- FY2013 - Installation in SPS with Amplifiers and Cable plant
  - Vacuum components essential for shutdown
- Dovetails with parallel system estimation and development of 'quick prototype processor'
  - Model closed-loop dynamics, estimate feedback system specifications
  - Evaluate possible control architectures, implementations, via technology demonstrations
  - SPS Machine Physics studies, development of 'small prototype', closed loop studies stabilizing a few bunches.

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