Feedback Control of SPS E-Cloud/TMCI Instabilities

LARP DOE Review May 2011

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SPS Ecloud/TMCI Instability R&D Effort

- Ongoing project SLAC/LBL/CERN via US LARP
- Proton Machines, Ecloud driven instability - impacts SPS as high-current LHC injector
  - Photoelectrons from synchrotron radiation - attracted to positive beam
  - Single bunch effect - head-tail (two stream) instability
- TMCI - Instability from degenerate transverse mode coupling - may impact high current SPS role as LHC injector
- Multi-lab effort - coordination on
  - Non-linear Simulation codes (LBL - CERN - SLAC)
  - Dynamics models/feedback models (SLAC - LBL-CERN-Stanford STAR lab)
  - Machine measurements- SPS MD (CERN - SLAC - LBL)
  - Hardware technology development (SLAC)

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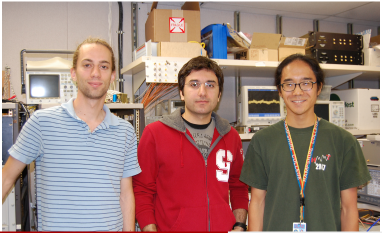
Progress July 2010 - June 2011

- Motivation - control Ecloud and TMCI effects in SPS and LHC via GHz bandwidth feedback
- Complementary to Ecloud coatings, grooves, etc. Also applicable to TMCI.
    - Technical formalism similar to 500 MS/sec feedback at PEP-II, KEKB, DAFNE
    - Ecloud/TMCI Modeling, dynamics estimation, feedback simulation efforts
    - Dynamics analysis techniques to quantify nonlinear unstable oscillators
    - MD results June 2009/April, July 2010 (Instability Dynamics, Pickup and kicker studies)
    - Hardware efforts (4 GS/sec. synchronized excitation, 1 GHz power amps)
    - Near-term plans (Summer 2011 MD, models, 4 GS/sec. excitation system) - Response to Chamonix emphasis, SPS 2013 shutdown
- Research directions
    - Simulations - numeric nonlinear PIC, simplified linear models
    - Machine measurements - understand required bandwidth, validate simulations
    - Simplified feedback models - what sort of control is feasible? Robustness?
    - Development of 4 GS/sec. processing channel technology
    - Kicker Structures
        - Research effort to investigate useful 1 - 2 GHz Bandwidth Transverse Kicker
        - Array of 1/4 λ Striplines? Periodic slotline? Overdamped Cavity?

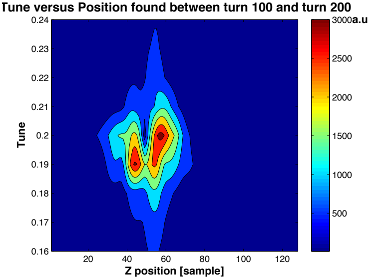
Organization and Staffing

- SLAC J. Fox (50%), C. Rivetta(35%), J. Olsen, J. Dusatko(30%)
- 2 Stanford grad students, I almost grad student
  - Ozhan Turgut (System Identification, Dynamics Models)
  - Sho Uemura (Amplifier Systems, MD instrumentation)
  - Ivo Rivetta (Excitation system and MATLAB tools)
- CERN - W. Hoefle, B. Salvant
  - SPS/LHC Transverse Feedback
  - MD planning and MD measurements
  - TMCI simulations and measurements
- LBL - Ecloud Simulation effort (WARP), Kicker study (S. De Santis)
  - J-L Vay, M. Furman, R. Secondo
  - Numeric nonlinear dynamics, Simplified initial feedback model in WARP

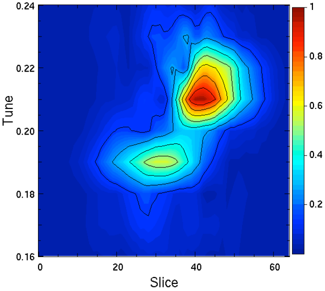


Analysis of Ecloud simulations and Ecloud MD data

- Observations
  - tune shifts within bunch due to Ecloud, bursting, positions of unstable bunches
  - information in SUM signal
  - frequencies within bunch - estimated bandwidth of instability signal, correction signal
  - Growth rates of eigenmodes - initial fits and stability observations
- Simulations - access to all the beam data. What effects are not included?
- Machine measurements - what can we measure? with what resolution? What beam conditions?



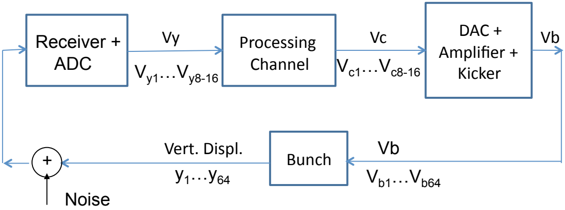
MD data June 2009



WARP simulation

Macro - Particle Simulation Codes : Realistic Feedback

Add realistic representing feedback system

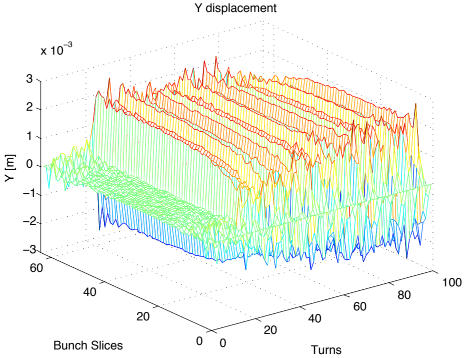


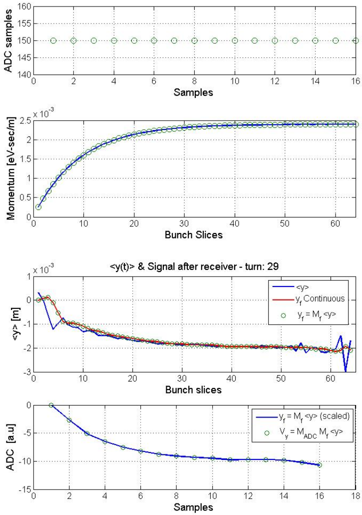
- Receiver, processing channel, amplifier, kicker include frequency response, signal limits and noise.
  - Each block is modeled in the code by a matrix representing the frequency response
  - $[V_{b_1} \ldots V_{b_{64}}]^T = M_{PWR}\, [V_{c_1} \ldots V_{c_{16}}]^T$ (DAC+Amp.+Kicker)
- Allows to include the main limitations in the feedback channel due to the hardware.

Macro-Particle Simulation Codes : Realistic Feedback

Results from C-MAD

Kick at turn 20, free vertical oscillation of the bunch. (out of scale)



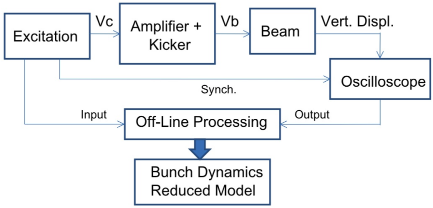


time span: 6.13 ns.

MD preparation

Goal: Drive individual sections of the bunch - Estimate Models

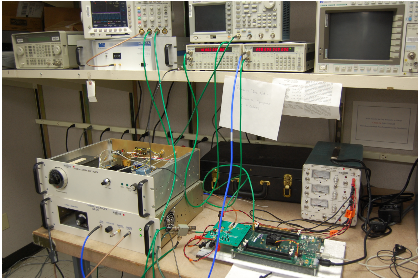
- Hardware development - Excitation - Power Stage - Vertical displacement measurement.
- Analyze and estimate using macro-particle simulation codes the signal levels and outcomes of MD measurements.
- Estimate bunch reduced dynamical model in open loop- Below e-cloud instability threshold.

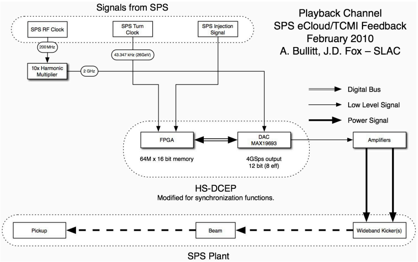


- Drive individually different areas of the bunch (Excitation - Amplifier - Kicker)
- Measure with scope the receiver signals $\Delta - \Sigma$. Estimate vertical displacement for different sections of the bunch.
- Based on Input-Output signals, estimate bunch reduced model.

Getting Ready - SPS Excitation MD summer 2011

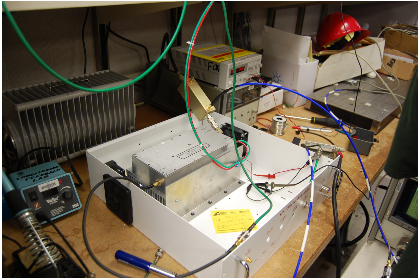
- Past MD efforts look at unstable beam - very complex dynamics (see CM-15 movies)
  - Plan - Drive beam below threshold - look at dynamics as currents increase
  - Drive selected bunch via existing pickup, observe response
  - Validate numeric codes against machine data
  - Important test bed for full-scale back end at 4 GS/sec.
  - Lots of detailed hardware and software to develop and get ready to do the measurements

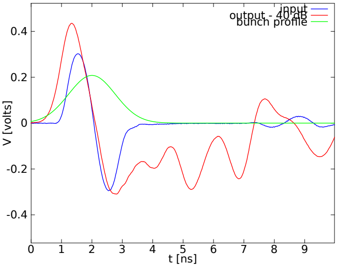




Amplifier Development for MD studies

- Broadband 80W 20 - 1000 MHz amplifiers
  - Longer Fabrication, more interaction with AR-Kalmus than planned
  - modified outpout stage bias (more class A, less AB) to improve transient response
  - Not ideal, useful for MD studies, Chassis , couplers, control in fab, tunnel cart ready to load

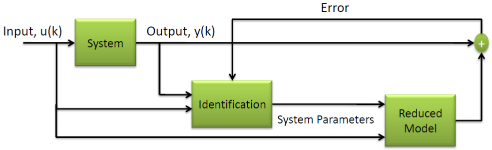




Identification of Internal Bunch Dynamics: Reduced Model

- characterize the bunch dynamics - same technique for simulations and SPS measurements
- critical to design the feedback algorithms
- Specify requirements for pickup, receiver, processing, power stages and kicker systems.
- Ordered by complexity, the reduced models could be

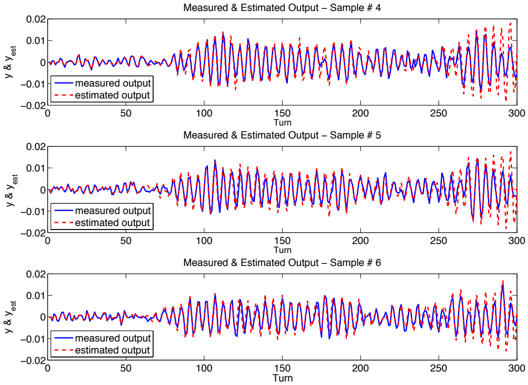
- linear models with uncertainty bounds (family of models to include the GR/tune variations)
- 'linear' with variable parameters (to include GR/tune variations-different op. cond.)
- non-linear models



Modeling and Identification

Bunch reduced dynamics model - Identification

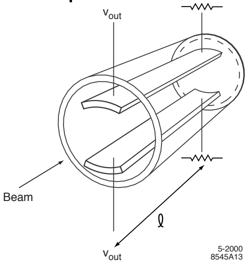
- Before we drive the beam in SPS, we use macro-particle simulation codes to mock-up the identification algorithms and set-up.



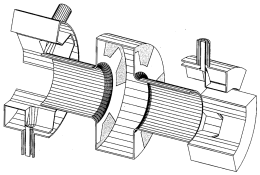
- Bunch driven by white noise using C-MAD code. $y(t)$: C-MAD vertical displacement for slices 4-5-6, $y_{est}(t)$: Estimated vert. displ. using lineal time-variant reduced model.

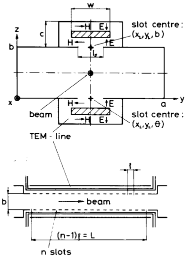
Kicker Options Design Study

- FY2011 Effort 0.3 FTE
- Goals - evaluate 3 possible options
  - Stripline (Arrays? Tapered? Staggered in Frequency?)
  - Overdamped Cavity (transverse mode)
  - Slot and meander line (similar to stochastic coooling kickers)
- Based on requirements from feedback simulations, shunt impedance, overall complexity - select path for fab

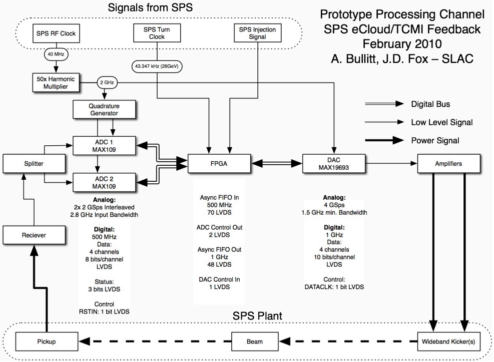


Longitudinal Kicker Exploded Cut-View





4 Gs/sec. 1 stack SPS feedback channel



- Can we build a 'small prototype' style feedback channel? What fits in our limited LARP hardware budget? what to do in 2011/ 2012? Develop for closed loop tests in SPS
- Idea - build 4 GS/sec. channel via evaluation boards and SLAC-developed Vertex 5 FPGA processor

SPS Wideband Transverse Feedback System

What can we do before the SPS Shutdown? During? Post 2013??

- CERN's interest - very high. (see W. Hofle CM-16 talk) Critical missing and undeveloped 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, CERN has tunnel space allocation in plan
  - Specify power amplifiers, cable plant, loads, diagnostics, all vacuum components
- FY 2011 Accelerated research and design report on Kicker System, suggested implementation
- FY2012 - test low power lab models, RF simulation, detailed design
- FY2013 - fab of prototype kicker, vacuum components, installation in SPS with Amplifiers and Cable plant
  - Vacuum components essential for 2013 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

Summary - 2011 LARP Ecloud/TMCI effort

- Understand Ecloud/TMCI dynamics via simulations and MD
  - Participation in E-Cloud studies at the SPS (July 2010, and summer 2011)
  - Analysis of SPS and LHC beam dynamics studies, comparisons with Ecloud models
- Modelling, estimation of E-Cloud effects
  - Validation of Warp and Head-Tail models, comparisons to MD results
  - comparisons with machine physics data (driven and free motion), Critical role of Ecloud simulations in estimating future conditions, dynamics
  - Extraction of system dynamics, development of reduced (linear) coupled-oscillator model for feedback design estimation
  - Inclusion of feedback models in WARP, CMAD and Head-Tail codes
- Lab effort -development 4 GS/sec. excitation system for SPS
  - Modify existing system to synchronize with selected bunches - data for system ID tools
  - Identify critical technology options, evaluate difficulty of technical implementation
  - Explore 4 Gs/sec. 'small prototype' functional feedback channel for 2012 fab and MD use
  - Evaluate SPS Kicker options: develop wideband prototype, 2013 shutdown window

System Development Goals 2012 and Beyond

- Technology R&D - specification of wideband feedback technical components
- Technical Anal;ysis of options, specification of control requirements
  - Single bunch control (wideband, vertical plane) - Required bandwidth?
  - Control Algorithm - complexity? Flexibility? Machine diagnostic techniques?
  - Fundamental R&D in kickers, pickups - technology demonstration in SPS
  - Wideband RF instrumentation, high-speed digital signal processing
- Develop proof of principle processing system, evaluate with machine requirements
- System Design proposal and technical implementation/construction plan
- Plans 2012-2013
  - Develop a technology small-scale prototype, prototype wideband kicker
  - Functionality to test feedback techniques on a subset of bunches, evaluate options
  - Excellent Ph.D. material (accelerator physics, nonlinear control), can support several students

FY2012 SPS Wideband Ecloud and TMCI Effort

- Resouces and direction
  - Consistent with plans, continue MD effort, simulations, model feedback options
  - Lab effort to build 'quick prototype' 4 GS/sec processing model
  - Existing Staffing LBL 0.4 FTE, SLAC 1.1 FTE staff, 2 FTE Students , 0.5 allmost student
  - Project could use additional 0.75 - 1 FTE staff resources for expanded prototyping
  - M&S $75K
  - Travel $30K (SLAC and LBL)
- Extra effort on Kicker for SPS 2013 upgrade installation
  - FY 2011 0.5 FTE staff to develop Kicker design options report, $6K travel
  - FY 2012 1 - 1.5 FTE staff, $25K M&S , $6K travel
  - FY2013 1 FTE Staff, $250K M&S for kicker and cables, $50K for amplifiers,
- SLAC effort lost 50% matching SLAC resources for staff in FY2011

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- C. Rivetta, et al, *Control of Transverse Intra-bunch Instabilities using GHz Bandwidth Feedback Techniques*, Presented at the Ecloud 2010 ICFA Workshop, Ithaca, NY
- J-L Vay, et al, *Numerical modeling of E-cloud Driven Instability and its Mitigation using a simulated Feedback system in the cERN SPS*, Presented at the Ecloud 2010 ICFA Workshop, Ithaca, NY
- R. Secondo, et al, *Simulated Performance of an FIR-based Feedback System to Control Electron Cloud Single-Bunch Transverse Instabilities in the CERN SPS*, Presented at the Ecloud 2010 ICFA Workshop, Ithaca, NY
- J. D. Fox et. al., *SPS Ecloud Instabilities - Analysis of Machine Studies and Implications for Ecloud Feedback*, Proceedings IPAC 2010, 23-28 May 2010, Kyoto, Japan.

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- J.-L. Vay et. al., *Simulation of E-cloud Driven Instability and its Attenuation Using a Feedback System in the CERN SPS*, Proceedings IPAC 2010, 23-28 May 2010, Kyoto, Japan.
- WEBEX Ecloud Feedback mini-workshop February 2010 (joint with SLAC, Stanford, CERN, and LBL).
- J.D. Fox, et. al., *Feedback Techniques and Ecloud Instabilities - Design Estimates*, SLAC-PUB-13634, May 18, 2009. 4pp. Presented at Particle Accelerator Conference (PAC 09), Vancouver, BC, Canada, 4-8 May 2009.
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- Performance of Exponential Coupler in the SPS with LHC Type Beam for Transverse Broadband Instability Analysis 1 R. de Maria BNL, Upton, Long Island, New York, J. D. Fox SLAC, Menlo Park, California, W. Hofle, G. Kotzian, G. Rumolo, B. Salvant, U. Wehrle CERN, Geneva Presented at DIPAC 09 May 2009
- WEBEX Ecloud Feedback mini-workshop August 2009 (joint with SLAC, CERN, BNL, LBL and Cornell).
- J.D. Fox et. al., *Feedback Control of Ecloud Instabilities*, CERN Electron Cloud Mitigation Workshop 08.
- W. Hofle, *E-cloud feedback activities for the SPS and LHC*, CERN Electron Cloud Mitigation Workshop 08.

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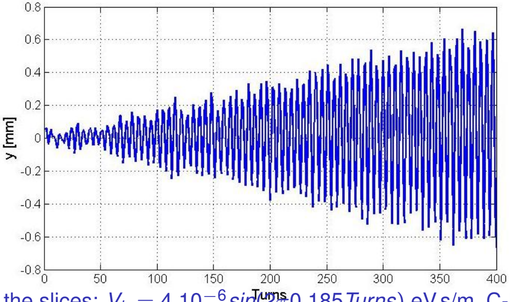
- R. De Maria, *Observations of SPS e-cloud instability with exponential pickup*, CERN Electron Cloud Mitigation Workshop 08.
- G. Rumolo, *Experiments on SPS e-cloud instability*, CERN Electron Cloud Mitigation Workshop 08.
- M. Venturini, *Progress on WARP and code benchmarking*, CERN Electron Cloud Mitigation Workshop 08.

MD preparation

Simulation Results - Estimation of Vertical Displacement.

- SPS Kicker: Max. $V_\Delta = 200V$, Max. Momentum $= 4.10^{-6}$ eV.s/m,
  Kick in single turn $\rightarrow y_{max} = 3.27\mu m$ at 26 GeV
- It is necessary to kick the beam using a periodic excitation near the betatron frequency (frac. tune = 0



Kicker signal for all the slices: $V_b = 4.10^{-6} sin(2\pi 0.185 Turns)$ eV.s/m. C-MAD result: Vertical displacement of center of the bunch.

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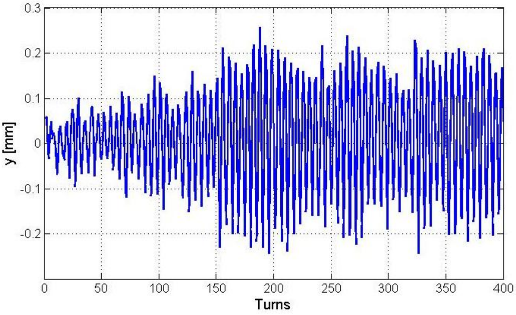
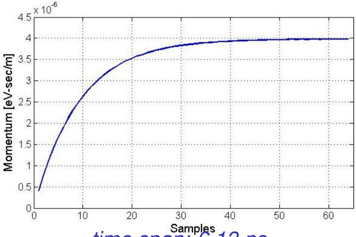
MD preparation

Simulation Results - Excitation signal: Sweep around betatron frequency

- C-MAD simulation includes the frequency response of the kicker.
- ... ween 0.185 $\pm$ 5%.



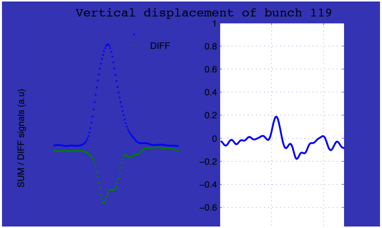
Momentum applied to the bunch at turn 50.

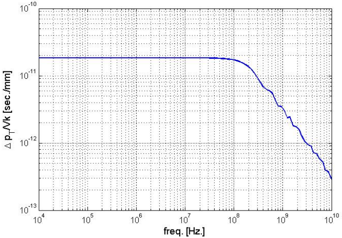


time span: 6.13 ns.

SPS Studies

- Vertical Instability develops after injection of second batch, within 100 turns. Time domain shows bunch charge, and transverse displacement 1E11 p/bunch (June 2009)
- Use this technique to compare models, MD data - extract beam dynamics necessary to design feedback. Roughly 25 slices (250 ps) between displacement maxima and minima
- April 2010 - characterize existing SPS pickups and drive tapered pickup as kicker
  - pickups - very successful
  - Noise, transverse resolution well-quantified
  - 25 microns rms at 0.5E11 (vertical)
- Kicker and Beam Excitation, mixed results
  - difficult to excite measurable response
  - 1/f Kicker response, limited power
  - Chamonix Implications-> kicker fab?





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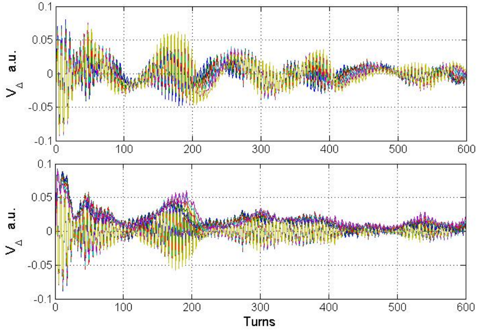
Analysis of Data - Further analysis of previous MDs

- SPS MD 2009 1^{st} stack: stable - 2^{nd} stack: e-cloud instabilities.
  SPS MD 2010 $1^{st} - 2^{nd}$ stack: stable -3^{rd} stack: e-cloud instabilities. How e-clouds affect different bunches??
- SPS MD 2009 Detailed measurement of the tune for different sections of the bunch - For all bunches of the 2^{nd} stack
- Analysis of the behavior in time domain of the different areas of the bunch. Effect of



Measurement of V_Δ (Equalized) for different slices in the tail of the bunch:
V_Δ perturbed by longitudinal dynamics due to injection mis-matching.
top: Raw data,
bottom: Subtract additive long. perturbation.
Tune: 0.195

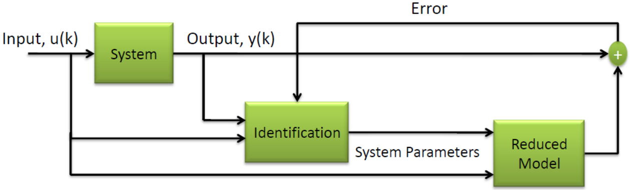
Modeling and Identification

Bunch reduced dynamics model - Identification

- Linear Time-Variant Model.- Synchrotron motion effects have to be included

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

- All par



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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?