CM17 LLRF and Ecloud/TMCI Feedback

Progress and future directions

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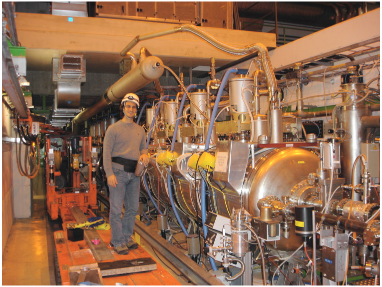
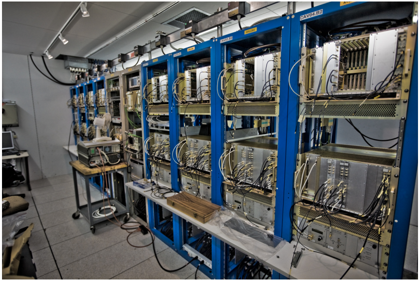
Motivation: LHC LLRF Models and Beam Studies

- Investigate the operational limits and impact on beam dynamics from the impedance-controlled RF systems. Look ahead to high current operations, possible upgrades and understand the role of the technical implementation.
  - Based on PEP-II experience, where limits of machine were understood, and overcome, via models and simulation studies of new control techniques

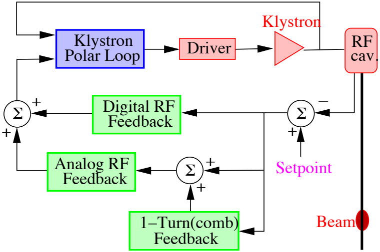




CM17 LLRF Progress and Plans - Optimization Tools

As part of these studies, CERN requested model-based commissioning tools - they are part of the beam/LLRF simulation.

- These tools operate remotely and allow identifying the RF station transfer function and designing the feedback loops using model-based techniques.
- Remote operation was crucial under the new stricter CERN polices preventing tunnel access when the magnets are energized.
- The LLRF configuration tools are routinely used by the CERN BE-RF group to remotely commission the RF stations. Tools reduce commissioning from 1.5 days/station to 1.5 hours/station.



- A new technique was implemented in the network analyzer to inject noise in particular frequency bands
- This allows increased Frequency resolution around the particular combs
- CERN colleagues modified the firmware in the one-turn delay filter board and commissioned the hardware in all the LHC stations
- Ongoing collaboration with the CERN BE-RF group on new features for future high-current operations. Operational commisioning of 1 turn feedback is still in progress

Motivation: RF Noise Effect on Beam Diffusion Studies

- The noise power spectrum of the RF accelerating voltage can strongly affect the longitudinal beam distribution and contribute to beam motion and diffusion.
  - Increased bunch length decreases luminosity and eventually leads to beam loss due to the finite size of the RF bucket.
- The choices of technical and operational configurations can have a significant effect on the noise sampled by the beam.

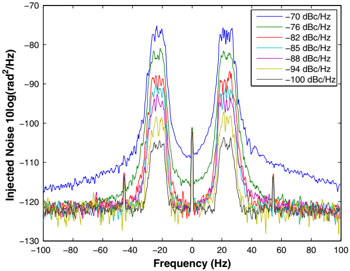


FIG. 9. Levels of injected noise around $f_{rev} \pm f_s$. Horizontal axis shifted by $f_{rf} + f_{rev}$.

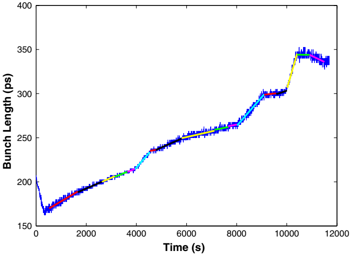


FIG. 10. Beam 1 bunch length growth. Data in blue. Linear segments correspond to different noise injection levels.

CM17 LLRF Progress and Plans -Beam Diffusion Studies and LLRF System noise Contributions

- Earlier measurements identified the RF reference (Local Oscillator distribution) as the dominating component affecting the beam diffusion. Studies are being conducted to identify alternative technical LO implementations to reduce this effect.
- Summer MD injected noise at specific frequencies and with varying amplitudes in a second round of measurements. Better quantify the relationship between the RF noise and longitudinal emittance blowup.
- Future work to develop a formalism to estimate more accurately the time evolution of the bunch length growth with the simulation and models.
- Multiple publications in the conference and refereed literature

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Radio frequency noise effects on the CERN Large Hadron Collider beam diffusion

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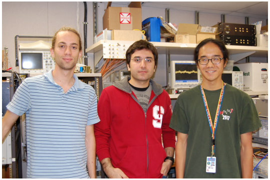
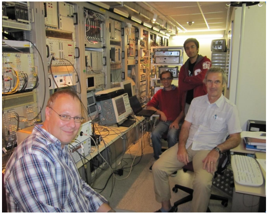
SPS Ecloud/TMCI Instability R&D Effort

- Motivation - control Ecloud and TMCI effects in SPS and LHC via GHz bandwidth feedback
- 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)

Organization and People

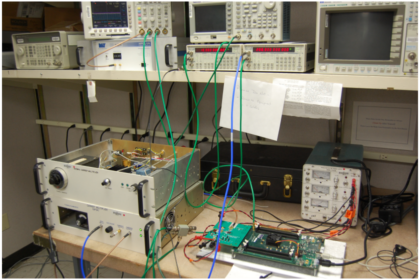
- SLAC J. Fox (50%), C. Rivetta(50%), J. Olsen, J. Dusatko(30%), M. Pivi(20%)
- J. Cesaratto (Toohig Fellow)
- Ozhan Turgut, Sho Uemura, I. Rivetta (Graduate Students and Summer Hire)
- CERN - W. Hoefle, B. Salvant, U. Wehrle
  - SPS/LHC Transverse Feedback
  - MD planning and MD measurements
  - TMCI simulations and measurements
- LBL J-L Vay, M. Furman, R. Secondo, S. De Santis
  - Kicker study, Ecloud Simulation effort (WARP), Pickup Equalizer

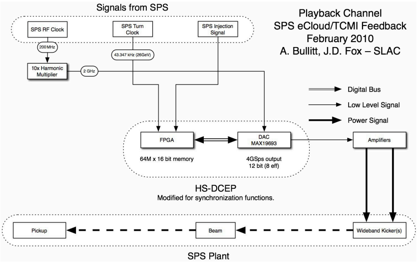




SPS Excitation MD July/August and November 2011

- 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

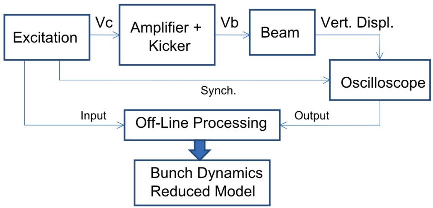




Driven Beam Motion Experiments

Goal: Drive individual sections of the bunch - Estimate Models

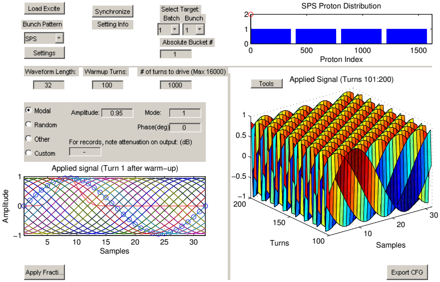
- Excitation - Power Stage - Vertical displacement measurement.
- Estimate bunch reduced dynamical model in open loop- Below e-cloud instability threshold. Increase currents and study dynamics change
- Compare MD results to macro-particle simulation codes



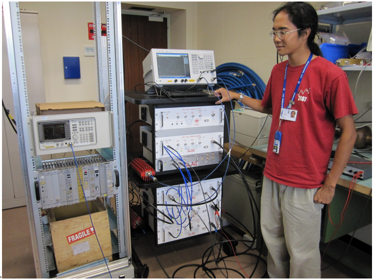
- Drive individually different areas of the bunch (Excitation - Amplifier - Kicker)
- Measure with scope the receiver signals $\Delta - \Sigma$. Estimate vertical displacement for different sections of the bunch.
- Based on Input-Output signals, estimate bunch reduced model.

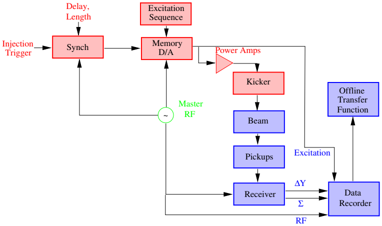
System Development for MD studies

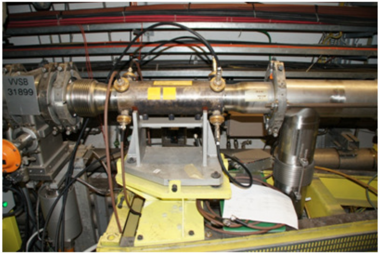
- 4 GS/sec bunch-synchronized random excitation system with GUI
- Broadband 80W 20 - 1000 MHz amplifiers
  - Longer Fabrication, more interaction with AR-Kalmus than planned
  - Modified outpout stage bias (more class A, less AB) to improve transient response
  - Not ideal, useful for MD studies
  - Chassis , couplers, remote control for tunnel hardware



Recent efforts

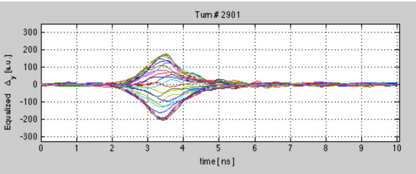




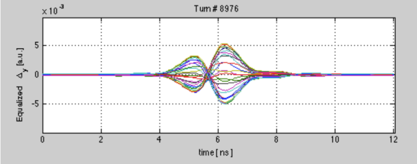


Results from Summer 2011 Excitation studies

- We excite the single bunch (stable) beam from our amplifier array
- Study motion via pickup array, receiver system, digitize at 40 GS/sec.
- Movies (time domain), and Spectrograms (frequency domain)
    - Driven from Synthesizer at betatron frequency
    - Driven from Excitation system at mode 0, mode 1, etc. frequencies

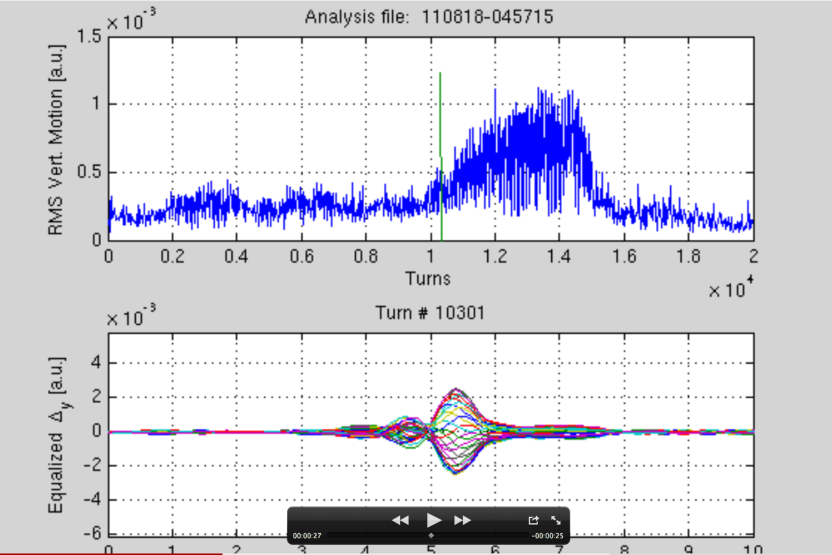


Barycentric driven motion

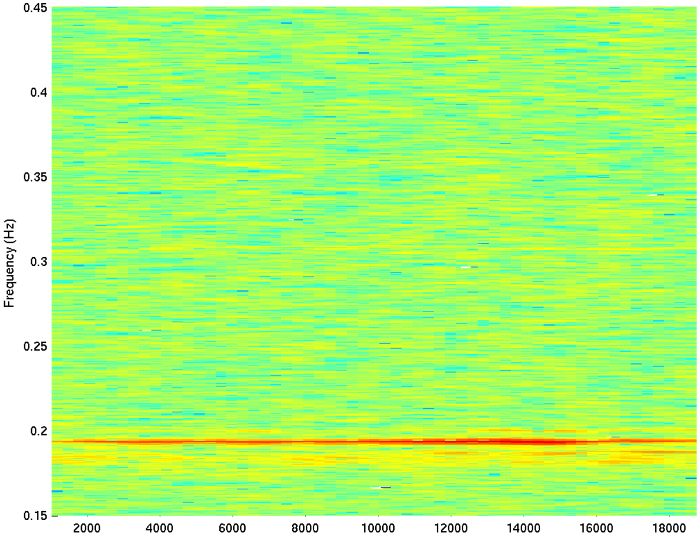


Head-tail driven motion

Movies, spectrograms from Summer 2011 Excitation studies

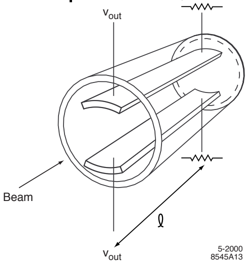


Movies, spectrograms from Summer 2011 Excitation studies

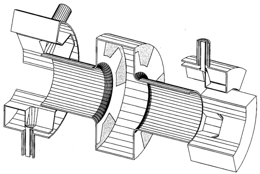


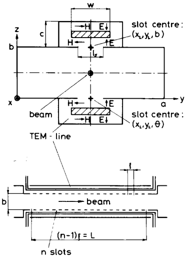
Kicker Options Design Study

- FY2011 S. De Santis, 2012 S. De Santis and J. Cesaratto
- 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

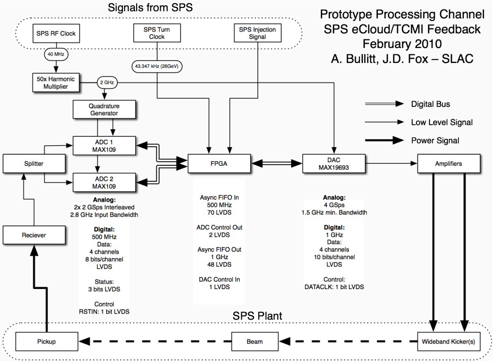


Longitudinal Kicker Exploded Cut-View





4 Gs/sec. 1 stack SPS feedback channel

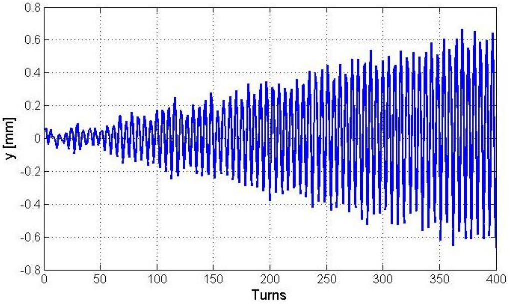


- Can we build a ’small prototype’ style feedback channel? What fits in our LARP budget? Ready for closed loop tests in SPS before the 2013 shutdown, using existing kicker and excitation system?
- Idea - build 4 GS/sec. channel via evaluation boards and SLAC-developed Vertex 6 FPGA processor

Modelling the driven bunch MD

Simulation Results - Estimation of Vertical Displacement.

- SPS Kicker: Max. $V_\Delta = 200\,V$, 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 = 0.185)

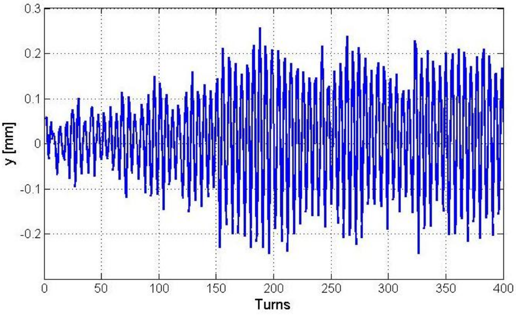


Kicker signal for all the slices: $V_b = 4.10^{-6} sin(2\pi 0.185 Turns)$ eV.s/m. C-MAD result: Vertical displacement of center of the bunch.

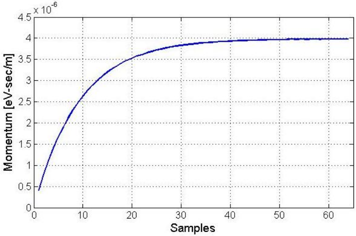
Modelling the driven bunch MD

Simulation Results - Excitation signal: Sweep around betatron frequency

- C-MAD simulation includes the frequency response of the kicker.
- The frequency of the excitation signal sweeps between $0.185 \pm 5\%$.



Momentum applied to the bunch at turn 50.

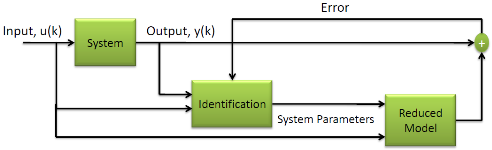


time span: 6.13 ns.

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

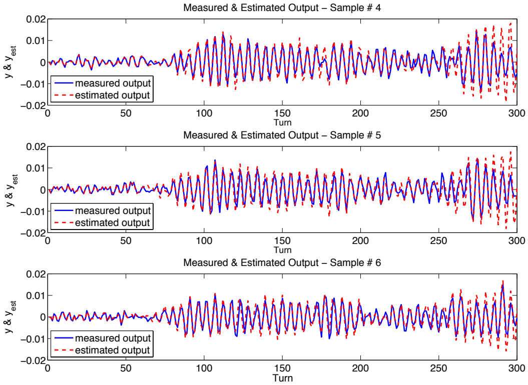
- linear models with uncertainty bounds (family of models to include the GR/tune variations)
- 'linear' with variable parameters (to include GR/tune variations-different op. cond.)
- non-linear models



Modeling and Identification

Bunch reduced dynamics model - Identification

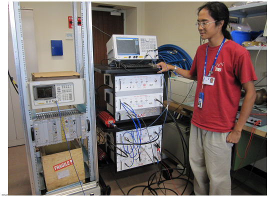
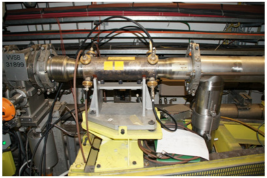
- Before we drive the beam in SPS, we use macro-particle simulation codes to mock-up the identification algorithms and set-up.



- 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.

CM17 Ecloud/TMCI Progress

- Lab effort -development/installation SPS 4 GS/sec. vertical excitation system
  - Modify existing system to synchronize with selected bunches - data for system ID tools. Installation of 4 100W 20-1000 MHz amplifier array, excitation system
- Understand Ecloud/TMCI dynamics via MD data, reduced models and numeric simulations
  - Participation in E-Cloud studies at the SPS July/August and November 2011
- Modelling, estimation of E-Cloud effects
  - 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


Research Goals 2012 and Beyond

- Technology R&D - specification of wideband feedback technical components
- Technical Analysis 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, develop 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

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- C. Rivetta, et al, *Mathematical Models of Feedback Systems for Control of Intra-bunch Instabilities Driven by Eclouds and TMCI*, Proceedings PAC 2011, New York
- R. Secondo, et al, *Simulation Results of a Feedback Control System to Damp Electron Cloud Single-Bunch Transverse Instabilties in the CERN SPS*, Proceedings PAC 2011, New York
- J-L Vay, et al, *Direct Numerical Modeling of E-cloud Driven Instability of a Bunch Train in the CERN SPS*, Proceedings PAC 2011, New York
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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
- D. Van Winkle, et. al., *Commissioning of the LHC Low Level RF System Remote Configuration Tools* Presented at IPAC'10, Kyoto, Japan, 23-28 May 2010, pp TUPEA063
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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.
- J. R. Thompson et. al., *Initial Results of Simulation of a Damping System of Electron Cloud-Driven Instabilities in the CERN SPS*, Presented at Particle Accelerator Conference (PAC 09), Vancouver, BC, Canada, 4-8 May 2009.
- 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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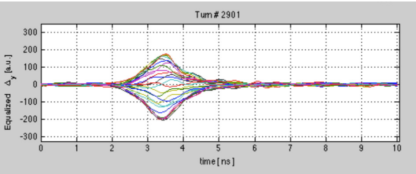
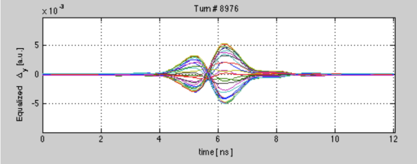
- G. Rumolo, *Experiments on SPS e-cloud instability*, CERN Electron Cloud Mitigation Workshop 08.
- M. Venturini, *Progress on WARP and code benchmarking*, CERN Electron Cloud Mitigation Workshop 08.

CM17 Results from Excitation studies

- We excite the single bunch (stable) beam from our amplifier array
- Driven from Excitation system at mode 0, mode 1, etc. frequencies
- Study motion via pickup array, receiver system, digitize at 40 GS/sec.
- Movies (time domain), and Spectrograms (frequency domain)
  - We can excite barycentric or head-tail, higher modes - study dynamics as currents are increased towards instability thresholds

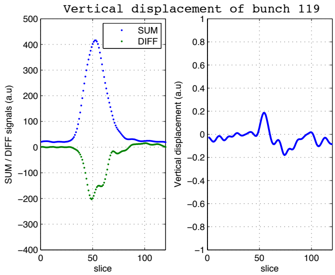


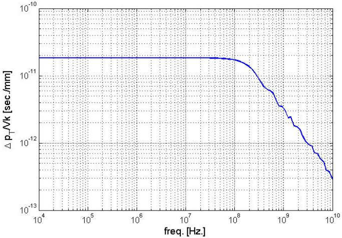


- 2012 Plan - develop 4 GS/sec. proof of principle feedback system
  - Identify critical technology options, evaluate difficulty of technical implementation
  - Explore 'small prototype' functional feedback channel for 2012 fab and MD use
  - Evaluate SPS Kicker options: develop wideband prototype, 2013 shutdown window

SPS Studies 2009, 2010, 2011

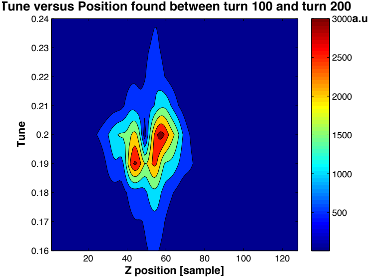
- Open-Loop unstable beam measurements
- Vertical Instability develops within 100 turns. Time domain ,frequency domain studies 1E11 p/bunch
- Use this technique to compare models, MD data - extract beam dynamics necessary to design feedback. Roughly 25 slices (250 ps) between displacement maxima and minima
- Spring/summer 2010 - develop 4 Gs/sec. excitation system, drive tapered pickup as kicker
  - pickups and receiver studies
  - Noise, transverse resolution
  - 25 microns rms at 0.5E11 (vertical)
- Beam Excitation studies, stable beam
  - Develop excitation system with synchronized oscillators
  - Use 20 - 1000 MHz amplifier array, with 200 MHz bandwidth kicker
  - Study internal modes, look for dynamics change as currents



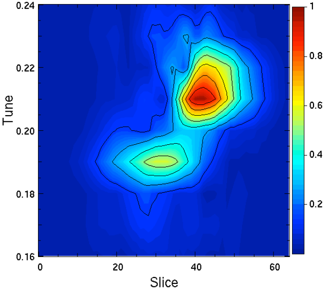


Analysis of Ecloud simulations and Ecloud MD data

- 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?

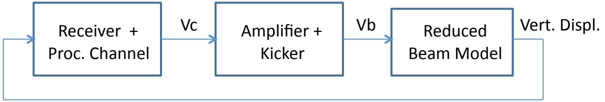


MD data June 2009

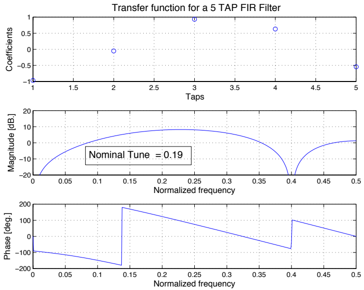


WARP simulation

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?



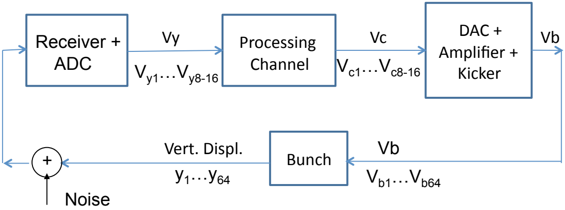
Moving towards Engineering - SPS Wideband Transverse Feedback System

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

- Critical missing and undeveloped element - useful high-power kicker and power amplifier components in SPS. CERN's interest - very high. (see W. Hofle CM-16 talk)
  - 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 2012 Accelerated research and design report on Kicker System, suggested implementation. Test low power lab models, RF simulation, detailed design
- FY2013 - fab of prototype kicker, vacuum components, installation in SPS with Amplifiers and Cable plant
- Dovetails with parallel system estimation and 2012 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, closed loop studies, operational experience

Macro - Particle Simulation Codes : Realistic Feedback

Add realistic blocks representing feedback system

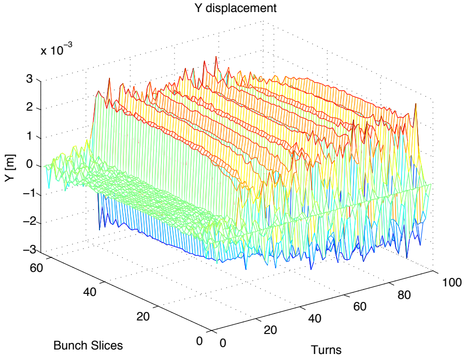


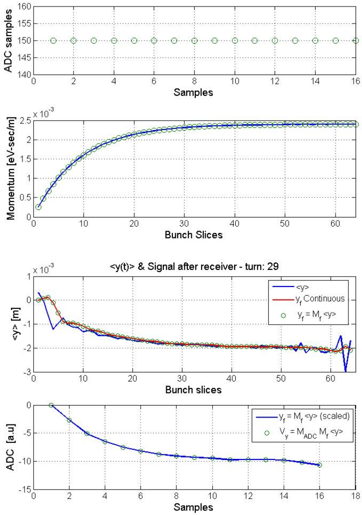
- Receiver, processing channel, amplifier, kicker include frequency response, signal limits and noise.
  - Each block is modeled in the code by a matrix representing the frequency response
  - $[V_{b_1} \dots V_{b_{64}}]^T = M_{PWR}\,[V_{c_1} \dots V_{c_{16}}]^T$ (DAC+Amp.+Kicker)
- Include the main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

Summary - 2011 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 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
- 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