Feedback Control of SPS E-Cloud/TMCI Instabilities

LARP DOE Review July 2012

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SPS Ecloud/TMCI Instability R&D Effort

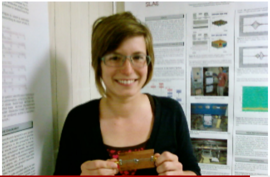
- Stabilize Ecloud and TMCI effects via GHz bandwidth feedback
- Proton Machines, Ecloud driven instability - impacts SPS as high-current LHC injector (applicable also to LHC,PS)
  - Photoelectrons from synchrotron radiation - attracted to positive beam
  - Single bunch effect - head-tail (two stream) 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)
  - Kicker models and simulations (LNF-INFN,LBL, SLAC)
  - Hardware technology development (SLAC,)
- Complementary to coatings, grooves, etc. for Ecloud control
- Also addresses TMCI , allows operational flexibility
- LARP feedback program provides novel beam diagnostics in conjunction with technology devleopment

Progress July 2011 - June 2012

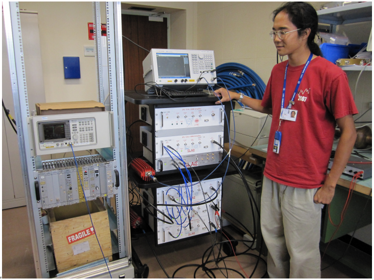
- Project activity
  - Ecloud/TMCI Modeling, dynamics estimation, feedback simulation efforts
  - Dynamics analysis techniques to quantify nonlinear unstable oscillators
  - MD results July/August 2011,November 2011, April 2012 (Instability Dynamics, Pickup and Kicker studies)
  - Hardware efforts (4 GS/sec. synchronized excitation, 1 GHz power amps to tunnel)
- 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?
  - Near-term plans (Summer 2012 MD, models, 4 GS/sec. demo system) - Response to Chamonix emphasis, SPS 2013 shutdown

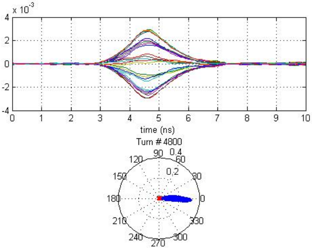
Organization and People - Some welcome new faces

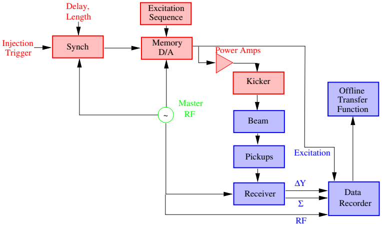
- SLAC J. Fox (50%), C. Rivetta(50%), J. Olsen, J. Dusatko(30%), M. Pivi(20%)
- J. Cesaratto (Toohig Fellow)
- K. Li (CERN Marie Curie Fellow)
- Ozhan Turgut, K. Pollock (Stanford Graduate Students)
- CERN - W. Hoefle, B. Salvant, U. Wehrle
    - SPS/LHC Transverse Feedback
    - MD planning and MD measurements
    - TMCI simulations and measurements
- LBL J-L Vay, M. Furman, Z. Paret, R. Secondo, S. De Santis
    - Kicker study, Ecloud Simulation effort (WARP), Pickup Equalizer
- LNF-INFN F. Marcellini, S. Gallo, M. Zobov, A. Drago
    - Kicker study, Impedance estimates

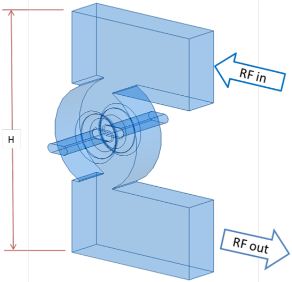


Recent efforts and Recent progress



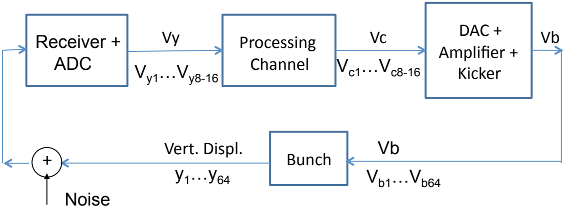






Macro - Particle Simulation Codes : Realistic Feedback

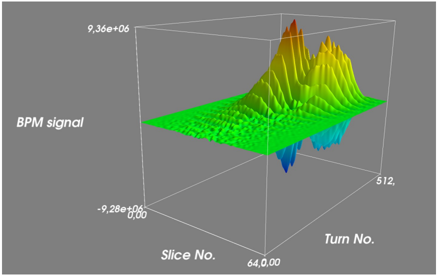
Add realistic blocks representing feedback system

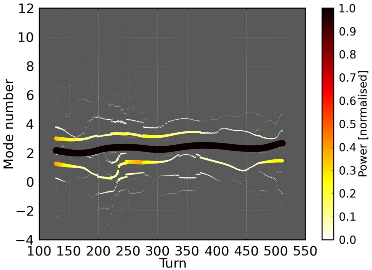


- Receiver, processing channel, amplifier, kicker include frequency response, signal limits and noise.
  - Each block is modeled in the code by a matrix representing the frequency response
  - $[V_{b_1} \dots V_{b_{64}}]^T = M_{PWR}\,[V_{c_1} \dots V_{c_{16}}]^T$ (DAC+Amp.+Kicker)
- Include the main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

HeadTail study - Ecloud driven instability of SPS

Ecloud instability, 10^{11} protons/bunch, $\rho_e \approx 6 \times 10^{11} e^- m^{-3}$

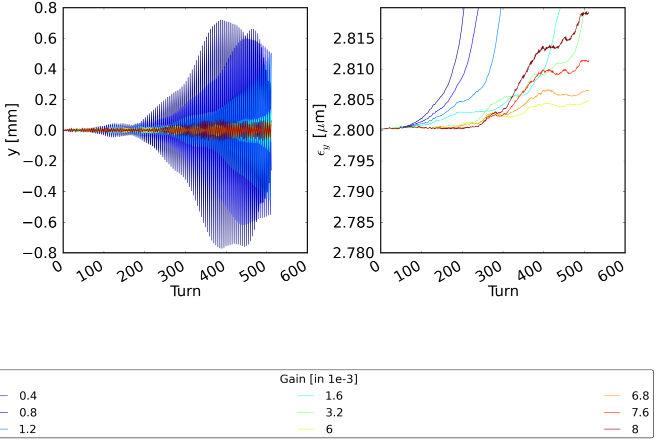




- Clear coherent motion above the instability threshold
- The mode evolution reveals the presence of predominantly modes {0, -1, -2} (shifted)

HeadTail - simplified feedback model, 200 MHz Kicker

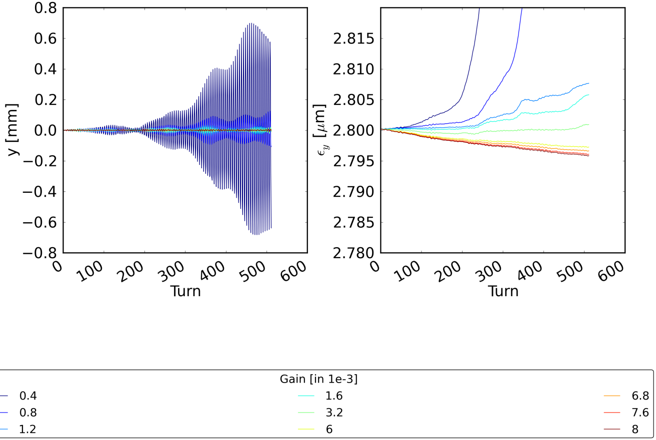
Ecloud instability, 10^{11} protons/bunch, $\rho_e \approx 6 \times 10^{11} e^- m^{-3}$



- Motion is unstable at all gain settings

HeadTail - simplified feedback model, 500 MHz Kicker

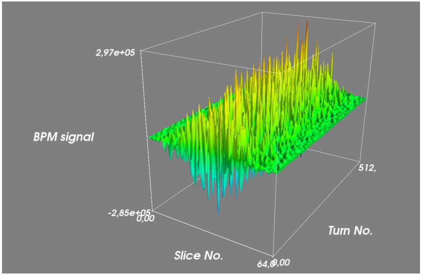
Ecloud instability, 10^{11} protons/bunch, $\rho_e \approx 6 \times 10^{11} e^- m^{-3}$

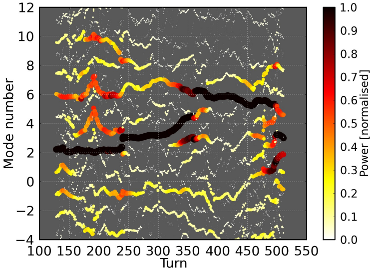


- Motion is stable for gain > threshold

HeadTail study - simplified feedback, 500 MHz Kicker

Ecloud instability, 10^{11} protons/bunch, $\rho_e \approx 6 \times 10^{11} e^- m^{-3}$





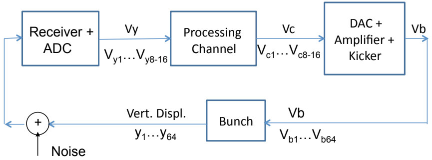
- Clear damping of the coherent motion
- Remaining power is distributed over modes {2,6}

- Nonlinear system, difficult to quantify margins

Progress in Simulation Models

- Significant efforts, including feedback to WARP, Head-Tail and CMAD
- Significant progress, especially in understanding numeric noise in models, impact on feedback noise model
- Still needs realistic channel noise study, sets power amp requirements
- Still needs more quantitative study of kicker bandwidth requirements
- Head-tail offers path to evaluate TMCI and feedback methods
- Critical to validate simulations against MD data
- Continued progress on linear system estimation methods

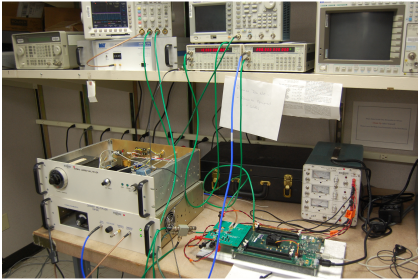
Add realistic components to the feedback channel - CMAD / HeadTail / Warp

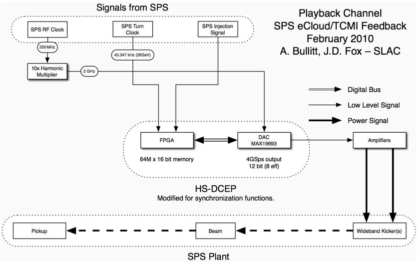


- Bunch is sampled in z using 64-80 samples (equal charge - equal distance)
- Receiver, processing channel, amplifier, kicker include frequency response, signal limits and noise.
- Processing channel can operate from 1 to 64 samples to model different sampling rates.

SPS Excitation MD 2011 and 2012

- Past MD efforts look at unstable beam - very complex dynamics
  - 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
  - Develop time and frequency domain analysis tools

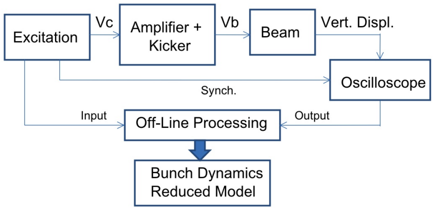




Driven Beam Motion MD Experiments July/August, November 2011 and April 2012

Goal: Drive individual sections of the bunch - Estimate Models

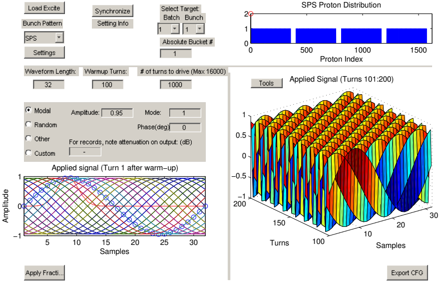
- Excitation - Power Stage - Vertical displacement measurement.
- Estimate bunch reduced dynamical model in open loop- Below e-cloud instability threshold. Increase currents and study dynamics change
- Compare MD results to macro-particle simulation codes



- 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.

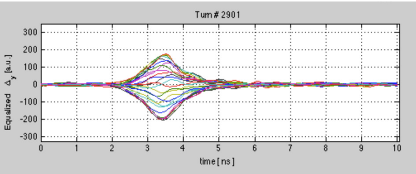
System Development for MD studies

- 4 GS/sec bunch-synchronized random excitation system with GUI
- Broadband 80W 20 - 1000 MHz amplifiers
  - Not ideal, useful for MD studies
  - Chassis , couplers, remote control for tunnel hardware
- Hardware equalizer for real-time front end

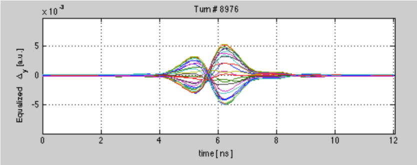


Example Results from 2011/2012 Excitation studies

- 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
  - Excitation files can be sines, band-limited random noise, chirps, etc. for 15,000 turns



Barycentric driven motion

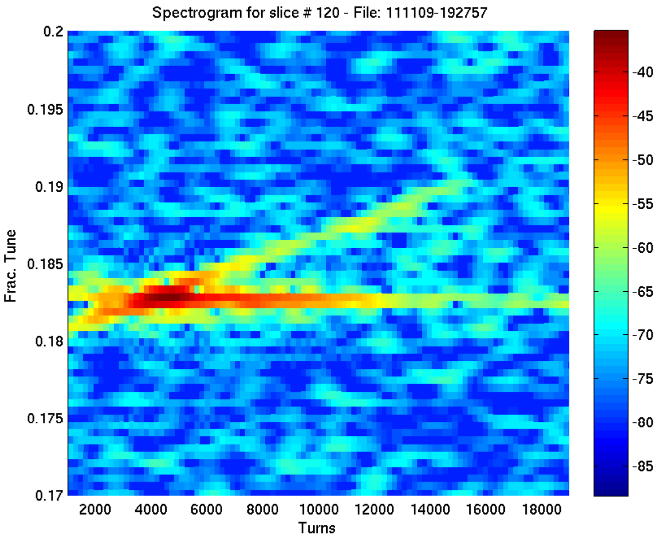


Head-tail driven motion

Movies, spectrograms from Excitation studies

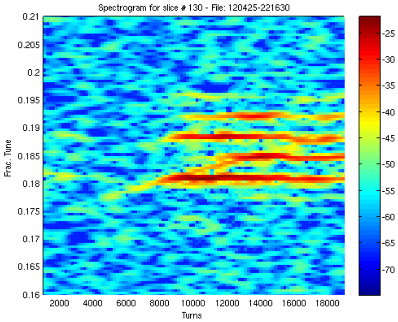
Play

Movies, spectrograms from Excitation studies



Excitation MD July/August, Nov 2011 and April 2012

- Excitation methods (chirps, random, selected modes)
- Chromaticity 0, on the verge of instability



- Spectrogram of beam motion for a slice in the tail of the beam
- In looking at particular turns, we can see the relative amplitudes of the excited modes
- In this example, we see the excitation of 4 modes, from ν_{β_y} to $\nu_{\beta_y} + 3\nu_s$

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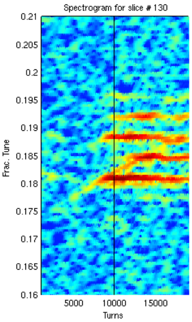

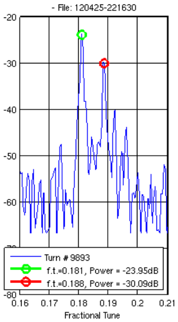

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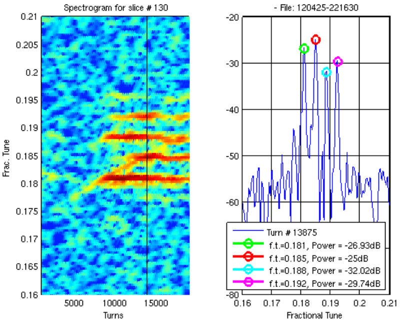

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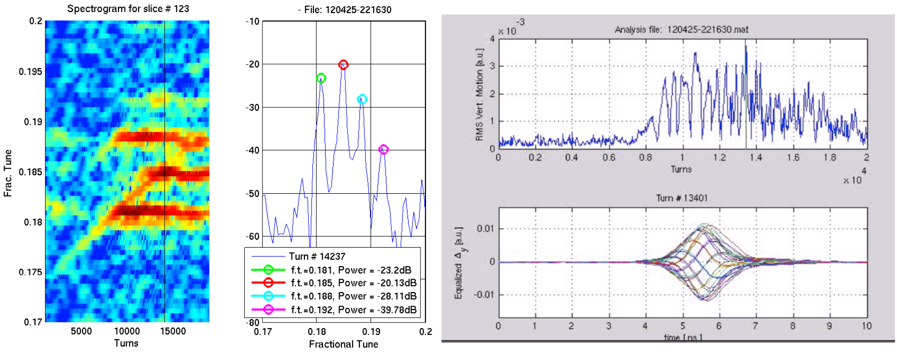
Chirp excitation in Frequency and time domain

- same data, two complementary analysis methods
  - Excitation methods (chirps, random, selected modes)
  - ability to clearly excite through mode 4
  - watch the movie, too!

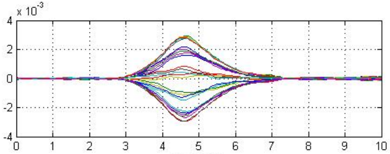


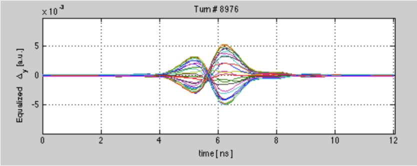
Excitation of multiple beam modes - time domain

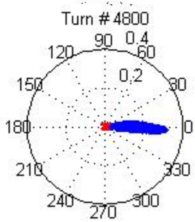
Excitation of multiple beam modes - frequency domain

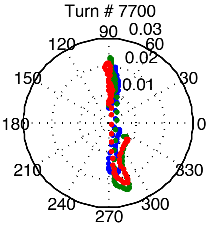
Vector (Modal) Analysis of Beam Motion J. Cesaratto

- We excite the beam from our amplifier array
- Study motion via pickup array, receiver system, digitize at 40 GS/sec.
- Plot slice phase at modal frequency





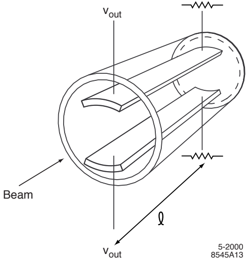


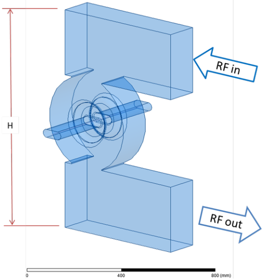


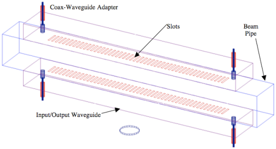
Barycentric mode 0 motion

Kicker Options Design Study

- LNF-INFN,LBL and SLAC Collaboration. Excellent progress 2012
- 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





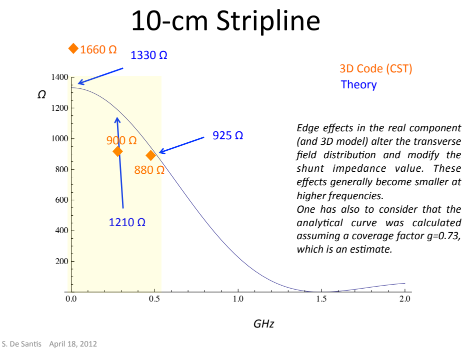


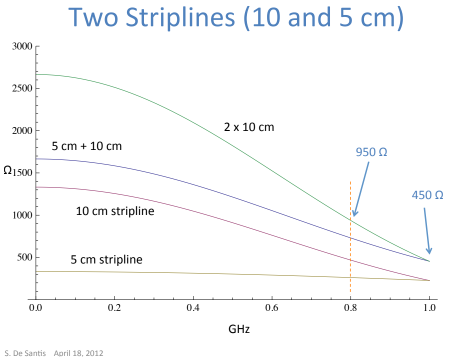
Goals of the SPS kicker study

- Establish a baseline for implementation of a vertical kicker system in the super proton synchrotron (SPS)
- Application to control electron cloud (ecloud) and transverse mode coupling instability (TMCI)
- Review and determine the capabilities of several possible implementations with the criteria:
  - Shunt impedance
  - Beam broadband impedance
  - Bandwidth
  - Heating issues
  - Fabrication complexity & complications
  - Vacuum chamber compatibility
  - Ease of coupling to external amplifiers
- Provide CERN with an evaluation and recommendation of which kicker technologies to use for fabrication.

Kicker Options - Ideas from S. De Santis and Z. Paret

- Study of multiple striplines for bandwidth and overall shunt impedance
- RF models and estimates

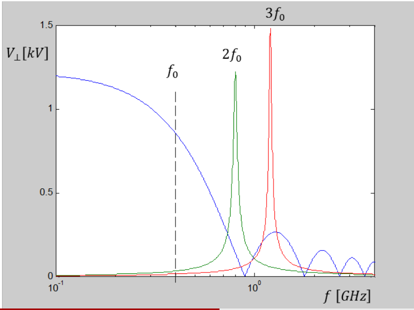




Kicker Options - Idea from S. Gallo

- Use 25 ns interval between bunches, have kicker with 20 ns fill time
- High shunt impedance, requires more complex off-diagonal processing, input and output data at different rates

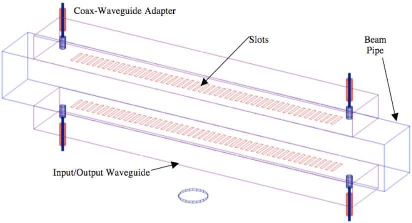
	Kicker #1	Kicker #2	Kicker #3
Type	Stripline	Cavity, TM110 defl. mode	Cavity, TM110 defl. mode
3-dB bandwidth	DC – 400 MHz	800 ± 16 MHz	1200 ± 16 MHz
Length	17 cm	15 cm	10 cm
Filling time	0.6 ns	10 ns	10 ns
Q_l	---	25	38
Shunt Impedance	≈ 1.5 kΩ (@ DC)	≈ 1.5 kΩ (@ 800 MHz)	≈ 2.2 kΩ (@ 1200 MHz)

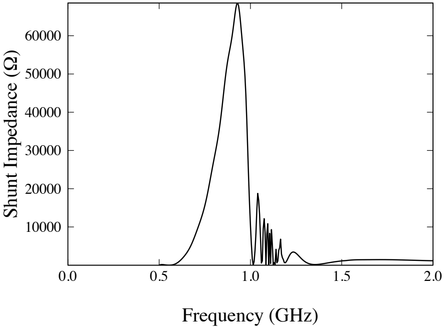


Assuming that each kicker is powered by a 1 kW source covering the entire device bandwidth, the resulting transverse voltage transferred to the beam as a function of the frequency is shown in the following plot.

Kicker Options - Idea from J. Cesaratto

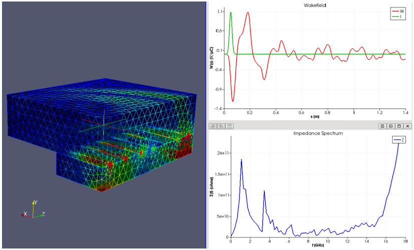
- similar to stochastic cooling kickers
- wideband - (longitudinal Impedance estimate in progress by M. Zobov)





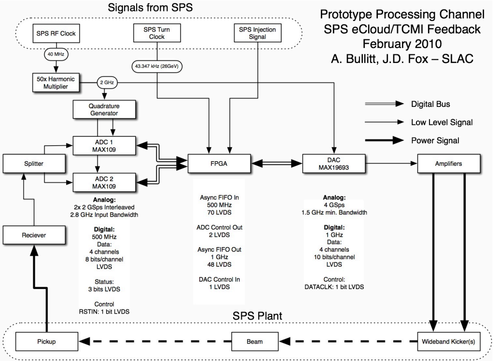
Model of slotted-type kicker for the SPS

- Evaluation of a new high bandwidth kicker using a slotted structure as modeled in ACE3P
- Broadband impedance calculations are important for these structures
- Plan to expand into a full scale model, to determine feasibility as a wide band kicker



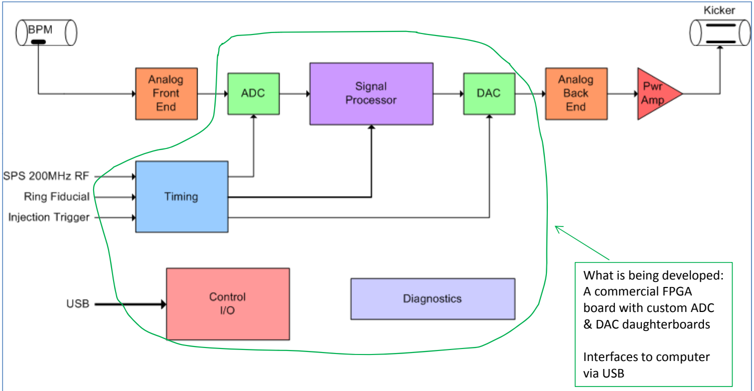
- simplified slotline 1/4 scale model
- On left are fields excited by the beam
- Plotted to the right are the wakefields and impedance

4 Gs/sec. 1 stack SPS feedback channel



- Proof-of-principle channel for closed loop tests in SPS before the 2013 shutdown, using existing kicker and excitation system
- Reconfigurable processing - evaluate processing algorithms
- Technical formalism similar to 500 MS/sec feedback at PEP-II, KEKB, DAFNE

Proof of Principle processing

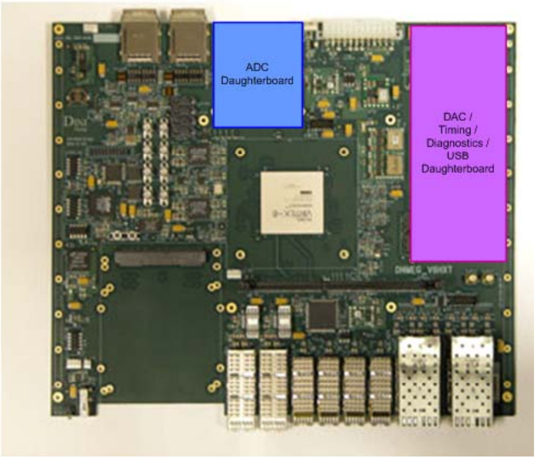


SPS Bunch Slice Feedback Demo System – Block Diagram

Prototype using FPGA evaluation board

Implementation Details:

- Developing Two Daughterboards: DAC Board & ADC Board
- DAC board also contains circuitry for Timing, Diagnostics and USB interface
- This flavor of FPGA is optimized for high-speed serial I/O, but still contains enough DSP resources (864 slices) for our requirements
- Has up to 16GB of DDR3 memory
- Has two high-speed I/O connectors for fitting daughterboards onto



Ongoing Technical Areas via LARP Feedback Program

- Low-noise transverse coordinate receivers and pickup techniques
  - (Noise floor sets limits on damped beam motion and influences equilibrium emittance)
- High speed A/D and D/A subsystems for 4 - 8 GS/sec sampling rates
- High-speed DSP architectures consistent with 4 GS/sec sampling rates for full SPS implementation
- Wideband 20 - 1000 MHz RF power amplifiers, with acceptable phase response
- Master Oscillator, Timing system to synchronise to the SPS RF system, control sampling
- Diagnostic and beam instrumentation techniques to optimize feedback parameters and understand system effectiveness

Ecloud/TMCI Progress

- Kicker design/estimation effort
  - Significant progress, welcome contributions from LBL, LNF-INFN and SLAC.
  - Important Milestone - recommendation of geometry for CERN fab, SPS installation
- Continued development SPS 4 GS/sec. vertical excitation system
  - System with 4 85W 20-1000 MHz amplifier array, excitation system
  - Used for MD measurements Summer 2011, Nov 2011, April 2012
  - Increasingly sophisticated analysis codes
  - Results show ability to excite through mode 4, value of beam diagnostic tool
- Understand Ecloud/TMCI dynamics via MD data, reduced models and numeric simulations
  - 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
- Design progress - 4 GS/sec processing demonstration prototype
  - FPGA platform, with D/A and A/D daughtercards in fab
  - Builds on existing timing and amplifier system for proof of principle tests

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
- 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
- We will learn from a limited "quick prototype" at the SPS
- Can then confidently design a true operational system for SPS,

- J. Cesaratto, et al *Excitation of Intra-bunch Vertical Motion in the SPS - Implications for Feedback Control of Ecloud and TMCI Instabilities* Proceedings IPAC12
- S. De Santis, et al *Study of a Wideband Feedback Kicker for the SPS* Proceedings IPAC12
- M. Venturini, et al *Analysis of Numerical Noise in Particle-In-Cell Simulations of Single-Bunch Transverse Instabilities and Feedback in the CERN SPS* Proceedings IPAC12
- C. Rivetta, et al*Feedback System Design Techniques for Control of Intra-bunch Instabilities at the SPS* Proceedings IPAC12
- C. Rivetta, et al *Reduced Mathematical Model of Transverse Intra-bunch Dynamics* Proceedings IPAC12
- J. Fox et al *A 4 GS/s Synchronized Vertical Excitation System for SPS Studies - Steps Toward Wideband Feedback* Proceedings IPAC12
- M. Pivi, et al *Simulation Code Implementation to Include Models of a Novel Single-bunch Instability Feedback System and Intra-beam Scattering* Proceedings IPAC12
- T. Mastorides, et al, *Radio frequency noise effects on the CERN Large Hadron Collider beam diffusion*, PRST-AB 14,092802 (2011)
- T. Mastorides, et al, *Studies of RF Induced Bunch Lengthening at the LHC*, Proceedings PAC 11, NY
- T. Mastorides, et al, *RF system models for the CERN Large Hadron Collider with application to longitudinal dynamics*, PRST-AB 13:102801,2010

- 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
- O. Turgut, et al, *Estimation of Ecloud and TMCI Driven Vertical Instability Dynamics from SPS MD Measurements - Implications for Feedback Control*, Proceedings PAC 2011, New York
- 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

- 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.
- 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.

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.

Wideband Intra-Bunch Feedack - General Considerations

The Feedback System has to stabilize the bunch due to E-cloud or TMCI, for all operating conditions of the machine.

- unstable system- minimum gain required for stability
- E-cloud - Beam Dynamics changes with operating conditions of the machine, cycle - feedback filter bandwidth required for stability
- Beam dynamics is nonlinear (tunes, resonant frequencies, growth rates, modal patterns change dynamically in operation)
- Beam Signals - vertical information must be separated from longitudinal/horizontal signals, spurious beam signals and propagating modes in vacuum chamber
- Design must minimize noise injected by the feedback channel to the beam
- Receiver sensitivity vs. bandwidth? Horizontal/Vertical isolation?
- What sorts of Pickups and Kickers are appropriate? Scale of required amplifier power?
- Saturation effects? Impact of injection transients?
- Trade-offs in partitioning - overall design must optimize individual functions

Extensions from existing 500 MS/sec. architectures

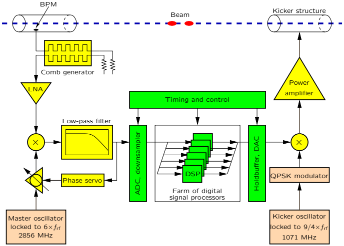
example/existing bunch-by-bunch feedback (PEP-II, KEKB, ALS, etc.)

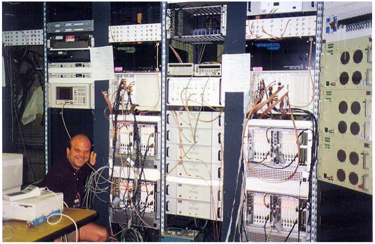
- Diagonal controller formalism
- Maximum loop gain from loop stability and group delay limits
- Maximum achievable instability damping from receiver noise floor limits

Electron-cloud effects act within a bunch (effectively a single-bunch instability) and also along a bunch train (coupling near neighbor bunches)

SPS and LHC needs may drive new processing schemes and architectures

Existing Bunch-by-bunch (e/g diagonal controller) approaches may not be appropriate





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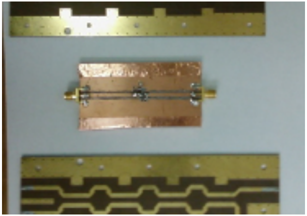
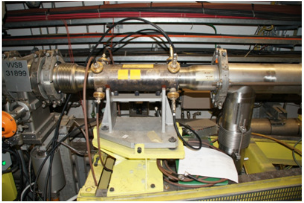
Hardware Equalizer





- Pickup response distorts beam signals
- Long cables also have nonlinear phase response
- Existing software equalizer used in matlab data processing
- we need a real-time (hardware) equalizer for processing channel
- Started by R. Secondo, now K. Pollock

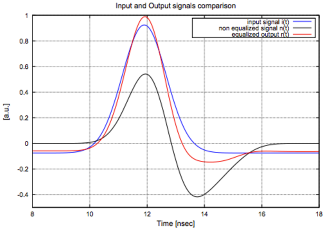
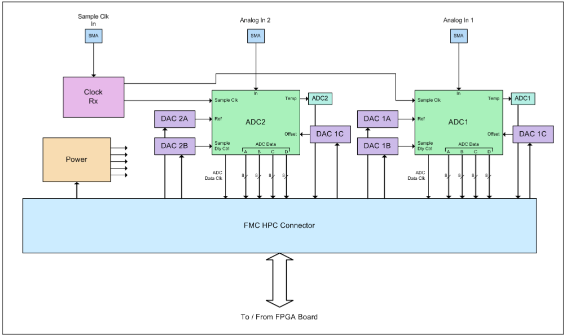


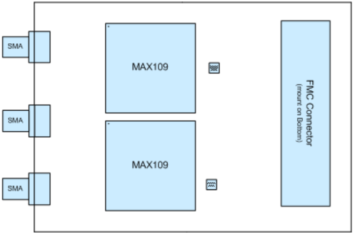
Figure 8: The input signal $i(t)$, non-equalized signal $n(t)$ and equalized output $r(t)$ using in the model a polynomial $P(s)$ with the values reported in Table 1.

4 GS/sec ADC sampling

ADC Daughterboard:

- Uses two Maxim MAX109 2.2GSa/s 8-bit ADCs in interleaved mode to get 4GSa/s sampling
- Receives external sample clock
- Delay for interleaved samples is generated externally
- Has fine delay vernier control for sample aperture (32ps max)
- Adjustable reference level
- Adjustable input offset compensation

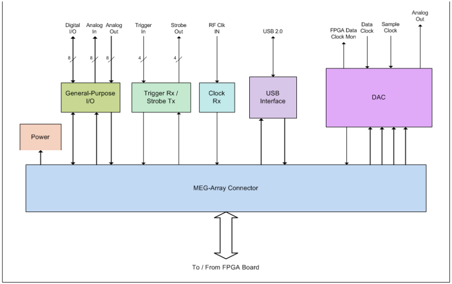


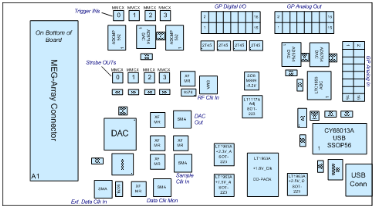


4 GS/sec D/A daughtercard with synchronization and timing functions

DAC Daughterboard:

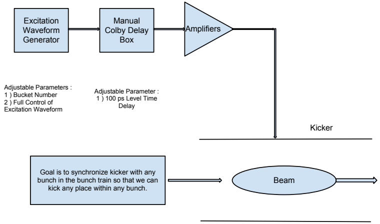
- Uses Maxim MAX19693 12-bit 4 GSa/s DAC
- Rx's External 2GHz sample clock
- Also Rx's RF clock and External Data Clocks
- Has output monitor for FPGA data clock
- DAC board also contains circuitry for Timing, Diagnostics and USB interface:
  - USB 2.0 Interface
  - (4) High-Speed Trigger Inputs
  - (4) High Speed Strobe Outputs
  - (8) General-Purpose Digital I/O
  - (4) Slow ADC Channels
  - (4) Slow DAC Channels

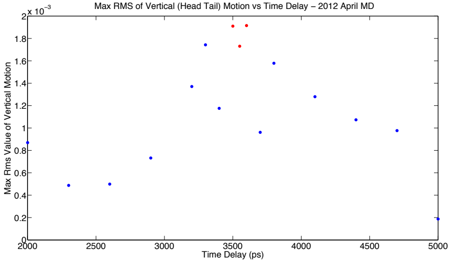




Progress - Techniques to time a selected bunch and position (O. Turgut)

- We excite the beam from our amplifier array
- To control the modes excited, we must have precision in excitation timing
- an off-time Mode 0 excitation will excite mode -1, 1
  - methods to repeatably position the kick, time the system
  - methods to maximize the effective kick applied to the beam

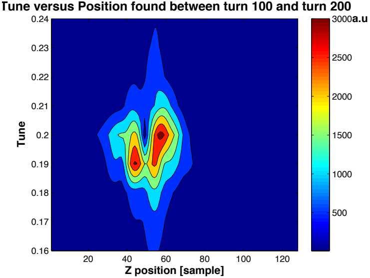




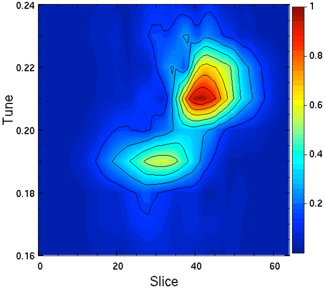
Barycentric driven motion

Feedback design and Estimation - value of models

- Value of nonlinear time-domain simulation models (HeadTail, WARP, CMAD)
  - Incorporate ecloud physics, impedance models
  - Well-developed and understood in accelerator community
  - Difficult to estimate limits of feedback methods - requires many simulations
  - Does not offer transfer function or frequency-domain closed loop response
  - Difficult to understand impact of feedback noise, due to numeric noise in simulation



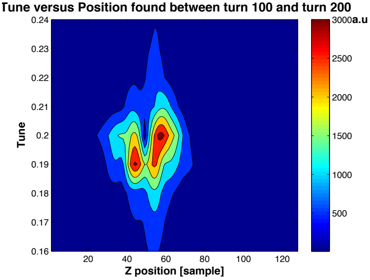
MD data June 2009



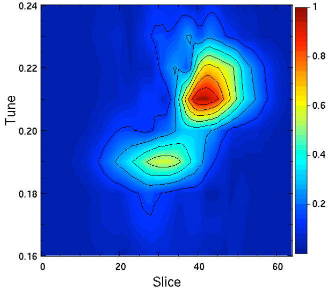
WARP simulation

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?



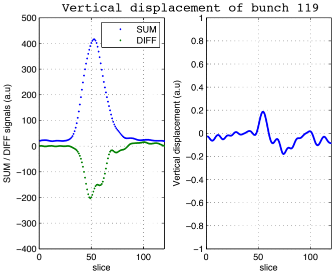
MD data June 2009

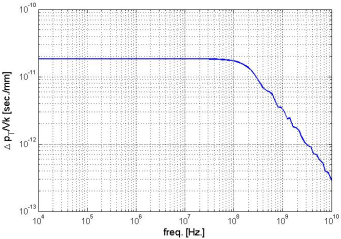


WARP simulation

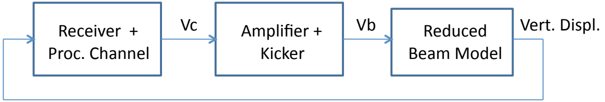
SPS Studies 2009, 2010, 2011, 2012

- 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





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?