A 4 GS/s Feedback Processing System for Control of Intra-Bunch Instabilties

System overview and initial MD results at the SPS

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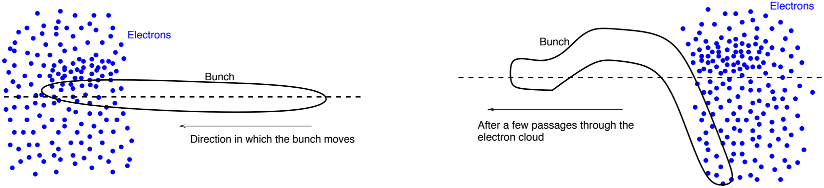
CERN SPS Ecloud/TMCI Instability R&D Effort



- 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
- Active feedback complementary to coatings, grooves, etc. and lattice modifications, allows operational flexibility
- LARP supported multi-lab effort - coordination on
  - Nonlinear simulation codes (LBL - CERN - SLAC)
  - Dynamics models/feedback models (SLAC - LBL-CERN)
  - Machine measurements- SPS MD (CERN - SLAC)
  - Kicker models and simulations (LNF-INFN,LBL, SLAC)
  - Hardware technology development (SLAC, KEK)

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Wideband Intra-Bunch Feedback - Challenges

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 (charge dependent tune shifts) - Impacts feedback filter bandwidth required for stability
- Acceleration - Energy Ramp has dynamics changes, synchronization issues (variation in β), injection/extraction transients
- Beam dynamics is nonlinear and time-varying (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
- Required bandwidth 1 GHz (sample 3.2 ns bunch at 4 GS/s rate)

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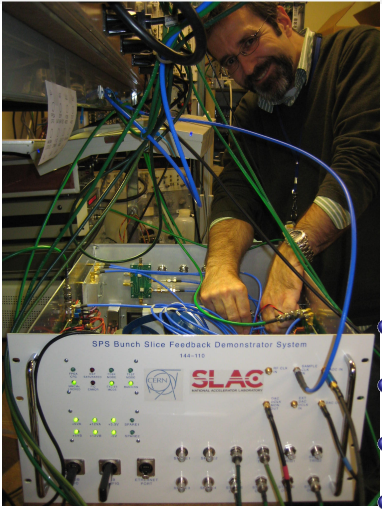
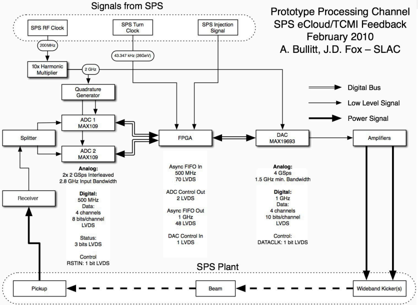
4 GS/s 1 bunch SPS Demonstrator channel MOPC28





- Proof-of-principle channel for 1 bunch closed loop tests in SPS - commissioned November 2012
- Reconfigurable processing - evaluate processing algorithms, allows two 2 GS/s input stream
- Technical formalism similar to 500 MS/sec feedback at PEP-II, KEKB, DAFNE
- Wideband control possible in SPS after LS1 after installation of wideband kicker

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Demonstration 1 bunch processor

- Synchronized DSP processing system, initial 1 bunch controller
- Implements 16 independent control filters for each of 16 bunch “slices"
- Sampling rate 4 GS/s (3.2 GS/s in SPS tests)
- Each control filter is 16 tap FIR (general purpose)
- A/D and D/A channels
- Two sets of FIR filter coefficients, switchable on the fly
- Control and measurement software to synchronize to injection, manipulate the control filters at selected turns
- Diagnostic memories to study bunch motion, excite beams with arbitrary signals
- Reconfigurable FPGA technology, expand the system for control of multiple bunches
- What’s missing? A true wideband kicker. Technology in development. These studies use a 200MHz stripline pickup as a kicker

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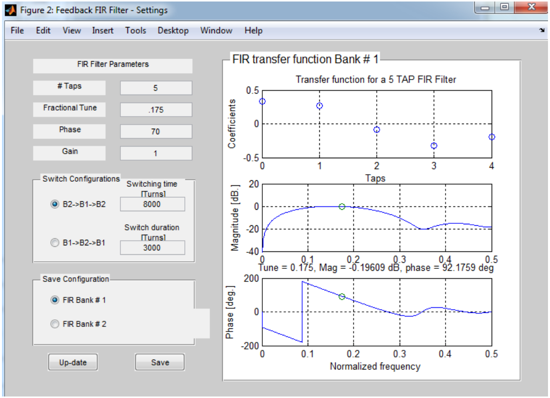
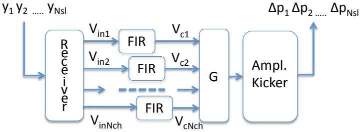
Feedback Filters - Frequency Domain Design

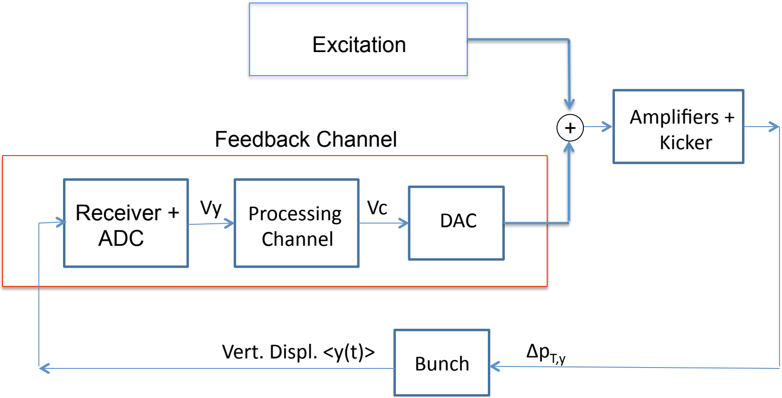


- FIR up to 16 taps
- Designed in Matlab
- Filter phase shift at tune must be adjusted to include overall loop phase shifts and cable delay



The processing system can be expanded to support more complex off-diagonal (modal) filters, IIR filters, etc as part of the research and technology development

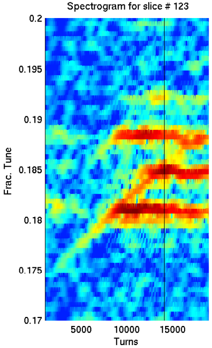
Measuring the dynamic system - open/closed loop

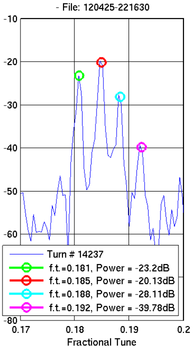


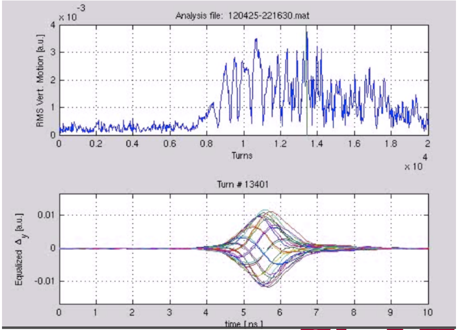
- We want to study stable or unstable beams and understand impact of feedback
- System isn't steady state, tune and dynamics vary
- We can vary the feedback gain vs. time, study variation in beam input, output
- We can drive the beam with an external signal, observe response to our drive
- Excite with chirps that can cross multiple frequencies of interest
- Unstable systems via grow-damp methods, but slow modes hard to measure

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!



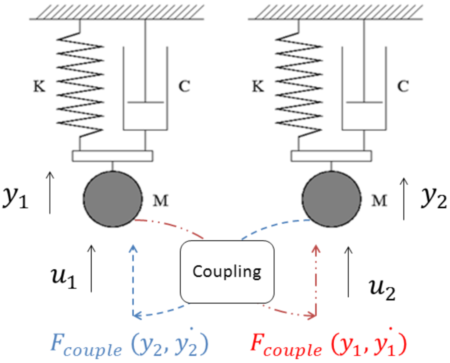




Excitation of multiple beam modes - time domain

Play

State Space two oscillator model - fit to measurements



$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \ddot{x}_1\\ \ddot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ k+k_{couple} & -k_{couple} & c+c_{couple} & -c_{couple}\\ -k_{couple} & k+k_{couple} & -c_{couple} & c+c_{couple}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ \dot{x}_1\\ \dot{x}_2\end{bmatrix} + \begin{bmatrix}0 & 0\\ 0 & 0\\ 1 & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}u_1\\ u_2\end{bmatrix}$$

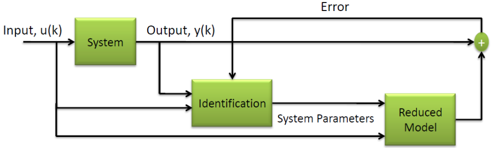
$$\begin{bmatrix}y_1\\ y_2\end{bmatrix} = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ \dot{x}_1\\ \dot{x}_2\end{bmatrix}$$

$$\begin{aligned}\dot{X} &= AX + BU\\ Y &= CX\end{aligned}$$

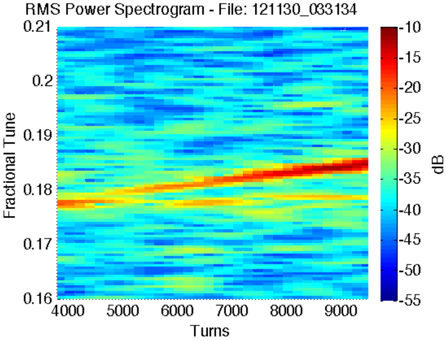
Eig (A) will give us the complex poles of the system, i.e damping and tune

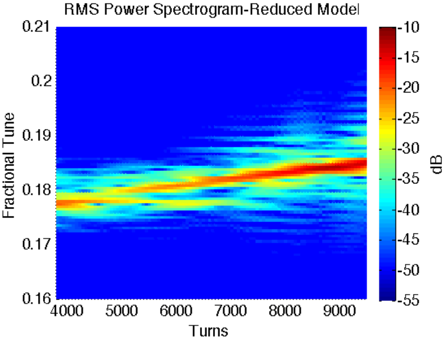
u_1 & u_2 : external excitation
y_1 & y_2 : vertical motion
Coupling parameters : Kcouple and Ccouple

- Fit models to excitation, response data sets from chirps
- Characterize the bunch dynamics - same technique for simulations and SPS measurements
- Critical to evaluate the feedback algorithms



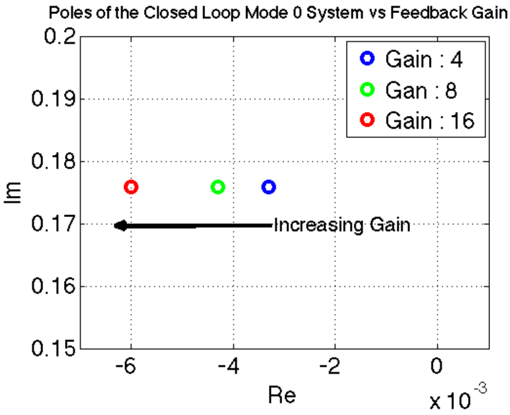
Driven Motion Studies- open loop mode 1 excitations





- Driven chirp- Measurement spectrogram (left) Model spectrogram (right)
- Chirp tune 0.17 - 0.185 turns 4K - 10K
- Tune 0.183 (upper synchrotron sideband), Tune 0.178 Barycentric Mode
- Model and measurement agreement suggests dynamics can be closely estimated using fitted model
- Study changes in dynamics with feedback as change in driven response of model

Driven Motion Studies- closed loop feedback mode 0- reduced model derived by fit to SPS MD data



$$\lambda = \zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2}$$

Gain	ω_n	$\zeta\omega_n$
4	0.176	0.0033
8	0.175	0.0043
16	0.176	0.0060

- Use closed loop beam data to fit to reduced linear harmonic oscillator model
- 3 Fitted reduced models, 3 feedback gains, 3 mode 0 pole locations
- Reduced model captures damping increase from feedback, center frequency of mode zero

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Example feedback control of unstable beam

- SPS cycle with chromaticity sweep to low (zero? slightly negative?) chromaticity after 1 sec into the cycle
- charge 1×10^{11}
- With no FB the bunch is mode zero unstable (loses charge, seen in SUM signal and tune shift)
- Feedback was applied to beam after 2k (46 ms) turns, for a duration of 16 k turns
- 5 tap FIR filter design, ϕ = 90°, G = 32.
- Stabilization of the dipole mode is clearly shown during the 16k turns when FB is ON
- The beam motion grows when the FB is switched off as shown at the end of the data recording, turns 18k – 20k.

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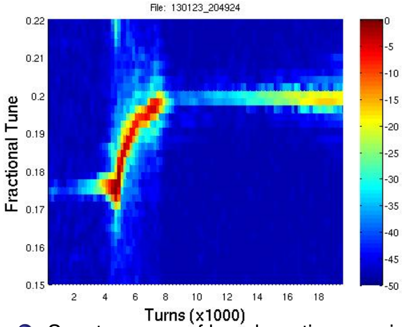
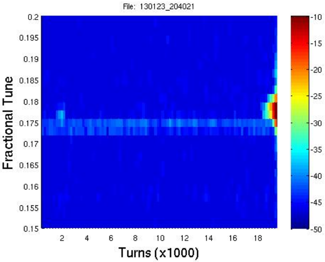
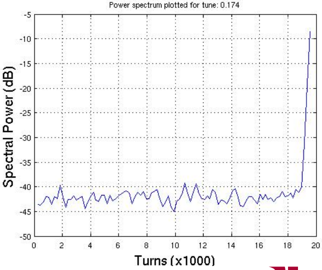
Feedback control of mode 0







- Spectrograms of bunch motion, nominal tune 0.175
- after chromaticity ramp at turn 4k, bunch begins to lose charge and gets tune shift.
- Feedback OFF -Bunch is unstable in mode zero (barycentric).
- Feedback ON - stability. Feedback is switched off at turn 18K, beam then is unstable

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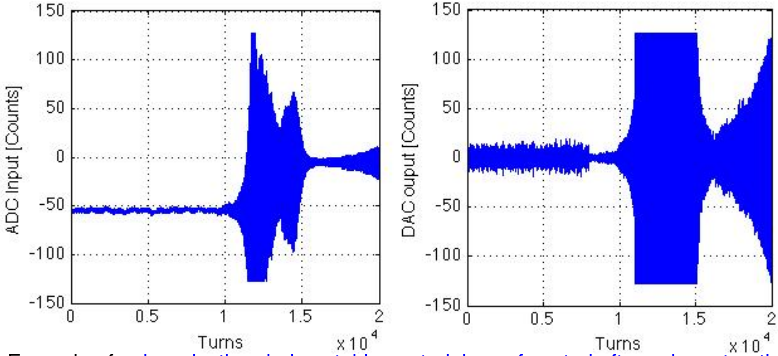
Recapture loss of control -input, output via snapshot



- Example of gain reduction during stable control, loss of control after gain restoration 3k turns later. Transient deserves more complete analysis.
- Mode zero unstable beam
- Gain modulated $\times 8$ -> $\times 2$ -> $\times 8$ during cycle
- For turns 0-8k, 8k-11k, 11k-end
- Input (left), DSP output (right). Note gain of filter, DC suppression and saturation

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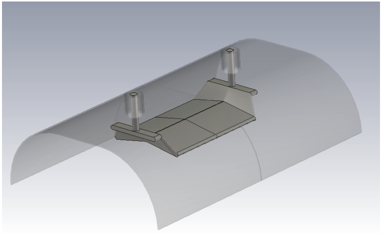
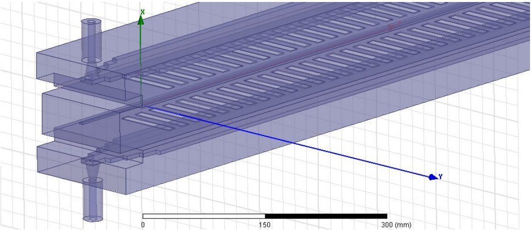
1 GHz wideband kicker development (J. Cesaratto)

- LNF-INFN,LBL and SLAC Collaboration. Design report SLAC-R-1037
- Evaluate stripline array, overdamped cavity trio and slotline options.
- Slotline and Stripline prototypes in fab based on HFSS simulations, shunt impedance, overall complexity, number of amplifiers and timing adjustments





Summary - Wideband Feedback program directions

- Plans for next two years
  - Beam-Feedback simulations (nonlinear and reduced model,fit to MD data)
  - Development of optimal control approaches, use of simulations, fit of models to MD data
  - Demo System Expansion (control 16 - 48 bunches, timing and synchronization methods, beam receiver and offset rejection techniques)
  - Fabrication of wideband Transverse Kicker proof of principle prototype (CERN)
- FY15 - FY16 Tests of expanded bunch demo with wideband kicker
- FY17 Design , FY19 commission full-function system for SPS ring at HL upgraded intensity
  - Beam line pickups/kickers
  - Beam motion receiver, processing electronics
  - 4 - 8 GS/s DSP for intra-bunch feedback
  - System timing, synchronization clocks/oscillators
  - GHz bandwidth Kicker(s), Power Amplifiers
  - Operator interfaces, control/monitoring software
  - Beam diagnostic software, configuration software
  - Accelerator dynamics models, stability tools

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Acknowledgements and Thanks

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- Thanks to CERN, SLAC, and LARP for support
- Many thanks to J. Dusatko and J. Olsen at SLAC for their online MD support!

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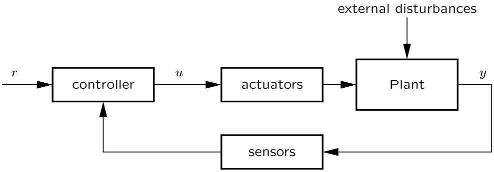
The Big Picture

Feedback basics

The objective is to make the output y of a dynamic system (plant) behave in a desired way by manipulating input or inputs of the plant.

Regulator problem - keep y small or constant

Servomechanism problem - make y follow a reference signal r



Feedback controller acts to reject the external disturbances.

The error between y and the desired value is the measure of feedback system performance. There are many ways to define the numerical performance metric

- RMS or maximum errors in steady-state operation
- Step response performance such as rise time, settling time, overshoot.

An additional measure of feedback performance is the average or peak actuator effort. Peak actuator effort is almost always important due to the finite actuator range.

Feedback system robustness - how does the performance change if the plant parameters or dynamics change? How do the changes in sensors and actuators affect the system?

Feedback algorithm complexity and numeric scale

Frequency spectrograms suggest:

sampling rate of 2 - 4 GS/sec. (Nyquist limited sampling of the most unstable modes)

Scale of the numeric complexity in the DSP processing filter

- measured in Multiply/Accumulate operations (MACs)/sec.

SPS -5 GigaMacs/sec (6*72*16*16*43kHz)

- 16 samples/bunch per turn, 72 bunches/stack, 6 stacks/turn, 43 kHz revolution frequency
- 16 tap filter (each slice)

KEKB (existing iGp system) - 8 GigaMacs/sec.

- 1 sample/bunch per turn, 5120 bunches, 16 tap filters, 99 kHz revolution frequency .

The scale of an FIR based control filter using the single-slice diagonal controller model is not very different than that achieved to date with the coupled-bunch systems.

What is different is the required sampling rate and bandwidths of the pickup, kicker structures, plus the need to have very high instantaneous data rates, though the average data rates may be comparable.

Extensions from existing 500 MS/sec. architectures

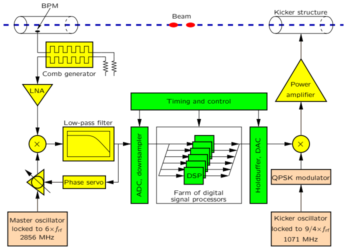
example/existing bunch-by-bunch feedback (PEP-II, KEKB, ALS, etc.)

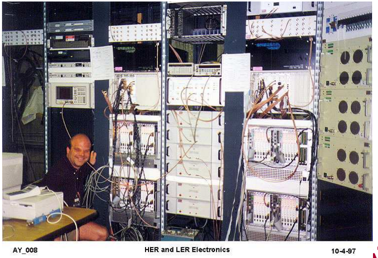
- Diagonal controller formalism
- Maximum loop gain from loop stability and group delay limits
- Maximum achievable instability damping from receiver noise floor limits

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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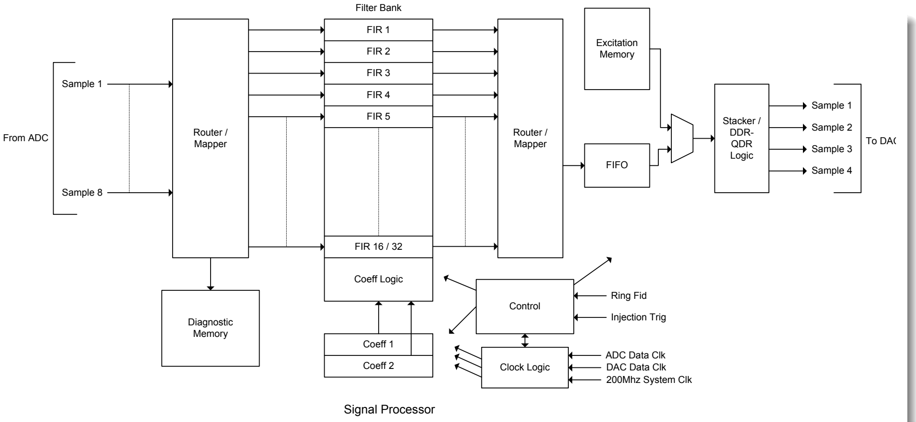
Data Flow in A/D, FPGA and D/A



Planning a Realistic Feedback Test MD

- How does one test this system with real accelerator beams?
- "Do Feedback on Unstable Beams" - is not the first test!
- The main goal is to use this minimum hardware to quantify the impact of the feedback channel in the beam dynamics
- Validate operation of the system through measurements on single-bunch stable beams, then study more complex cases
- Timing and synchronization
    - As for Excitation, setting up consistent timing of front-end, back-end is critical
    - Use excitation methods to time back-end data stream and beam
    - Matlab codes to time front-end data path to beam and define the overall phase of the closed loop system

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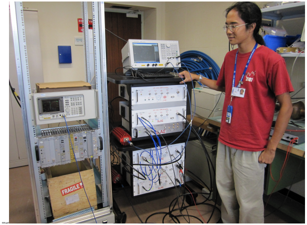
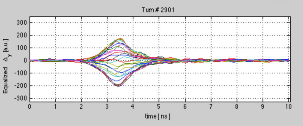
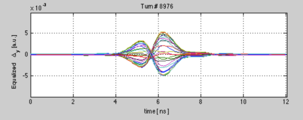
Planning a Realistic Feedback Test MD, II

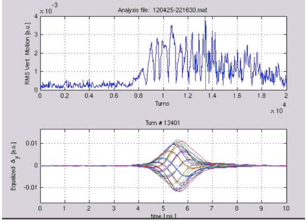
- We want to validate fundamental behavior of the feedback channel, compare to estimates using the reduced models / macro-particle simulators.
- Excite beam and do closed-loop tests. Measure changes in response due to feedback channel
    - Drive Mode 0, Mode 1, ..., and damp the bunch motion
    - Quantify and study the transients
    - Use switchable FIR coefficients for grow-damp and open-damp transient studies
- To conduct the measurements, ideally use snapshot memory of ADC data stream, read via PC interface, MATLAB offline analysis.
- To drive the beam, use either the excitation system or the intrinsic capability of the feedback prototype channel.

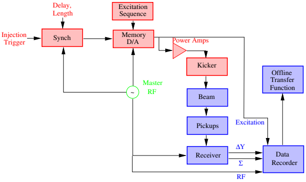
Beam Measurements, Simulation Models, Technology Development, Driven Beams and Demo System

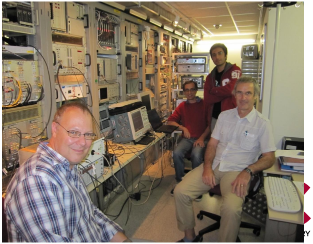












FY2013/2014 Development path - Research Areas

- During LS1 shutdown interval
- Expand Demo system
  - Low-noise transverse coordinate receivers,orbit offset and pickup techniques
  - Wideband Kicker Prototype for SPS Installation LS1 (CERN supported)
  - Expand Master Oscillator, Timing system to synchronize to the SPS RF system, Energy ramp control
  - Expand firmware, design multi-bunch control, explore orbit offset/dynamic range improvements
- Diagnostic and beam instrumentation techniques to optimize feedback parameters and understand system effectiveness
- Development of matlab tools for system timing/phasing alignment (repeatable operating point)
- Continued simulation and modeling effort, compare MD results with simulations, explore new controllers for Q20 optics

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FY2015/2016 Research plans, Technology development path

- MD measurements with wideband DEMO system (SPS beam time and analysis)
  - Diagnostic and beam instrumentation techniques to optimize feedback parameters and understand system effectiveness, interaction with existing feedback
  - Continued simulation and modeling effort, compare MD results with simulations, explore new controllers
  - Evaluate Kicker performance, options (wideband? dual band?) Estimate useful required power for full-function
- Technology Development and estimation for kicker systems
  - Wideband 20 - 1000 MHz RF power amplifiers, with acceptable phase response
  - RF monitoring, control for SPS tests
- High-speed DSP Platform consistent with 4 -8 GS/sec sampling rates for full SPS implementation
  - lab evaluation and firmware development
  - estimation of possible bandwidths, technology options for deliverable

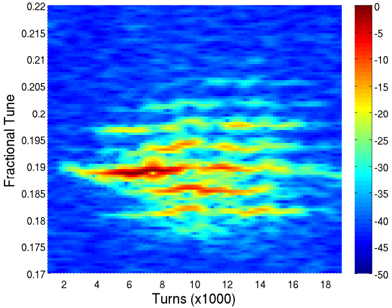
MD Results

- 2009/2010 MD studies of open-loop unstable motion, development of analysis methods
- 2011/2012 MD studies using excitation system and in-tunnel amplifiers, limited band kicker
- 2012/2013 MD trials (November, January, February) implement one-bunch feedback control
- 5 and 7 Tap FIR filters, gain variations of 30dB, Φ varied postive/negative
- Studies of loop stability, maximum and minimum gain
- Driven studies (Chirped excitations)
  - variation in feedback gain, filter parameters
  - multiple studies allow estimation of loop gain vs frequency (look at excitation level of several modes)
  - interesting to look at internal beam modes
- Feedback studies of stable, marginally stable and unstable beams

A few examples to stimulate discussion

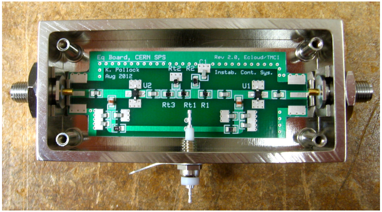
Positive Feedback Excitation of Internal Modes

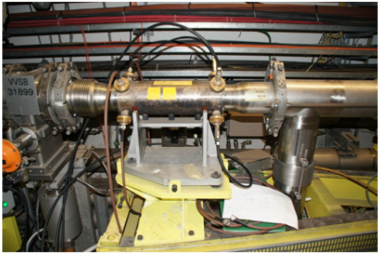
- We need to characterize the response of the combined beam-feedback system
- Drive the beam using excitation chirps
- Vary the feedback gain and phase.
- Beam response shows effect of feedback on beam dynamics



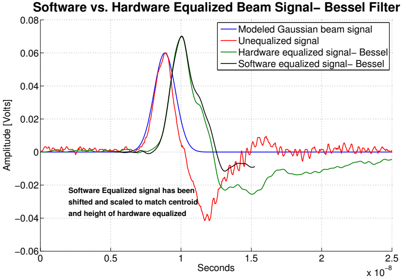
- An example spectrogram of unstable excited beam from the Feb 2013 MD
- ADC Input signal, positive feedback excitation turns 4000 to 12000 gain increased x4.
- turns 0 - 4k Negative FB, Positive turns 4K-12K, negative turns 12K - 20K

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
- Optimzation technique - can be used for kicker. too



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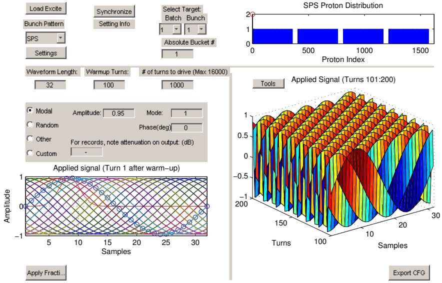
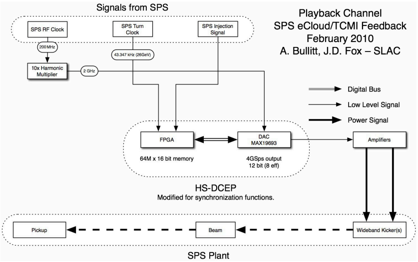
Excitation System Development for MD studies

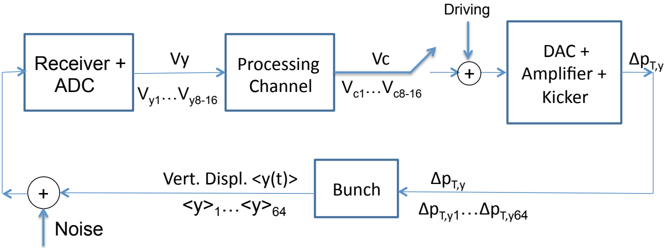
- 4 GS/sec bunch-synchronized random excitation system with GUI
- Broadband 80W 20 - 1000 MHz amplifiers
  - Not ideal, useful for MD studies
  - Chassis , couplers, remote control for tunnel hardware
- 16 samples/bunch with mode-specific modulation, 10,000 turns





Progress in Simulation Models

- Critical to validate simulations against MD data
- Progress from multiple labs, but
  - Need to explore full energy range from injection through extraction
  - Explore impact of Injection transients, interactions with existing transverse damper
  - Still needs realistic channel noise study, sets power amp requirements
  - Still needs more quantitative study of kicker bandwidth requirements
  - Minimal development of control filters, optimal methods using nonlinear simulations
- Continued progress on linear system estimation methods
  - Reduced Models useful for formal control techniques, optimization of control for robustness
  - Model test bed for controller development



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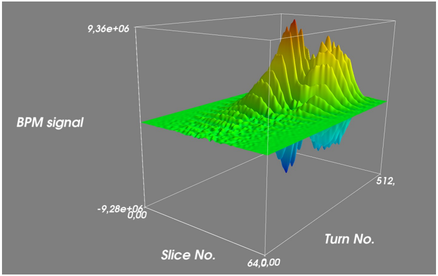
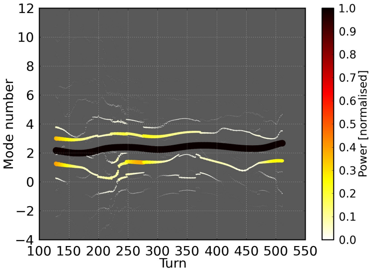
HeadTail study - Ecloud driven instability of SPS

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

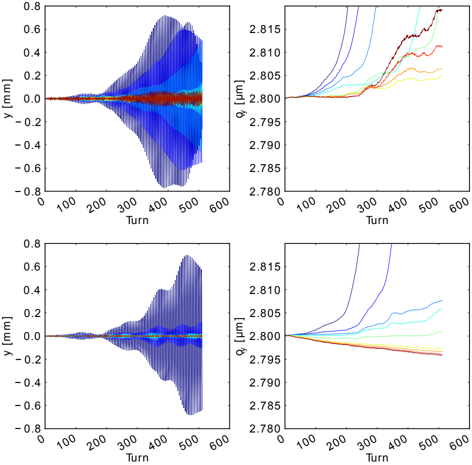




- Clear coherent motion above the instability threshold
- The mode evolution reveals the presence of predominantly modes {0, -1, -2} (shifted)

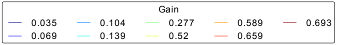
Macro-Particle Simulation Codes- HeadTail

- Electron cloud interaction with a bunch of 1.1×10^{11} protons.



Kicker $BW = 200$ MHz.

- Motion is unstable at all gain settings

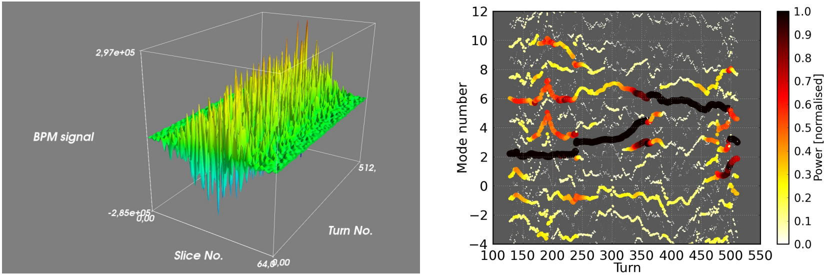


Kicker $BW = 500$ MHz.

- Evolution of the bunch centroid motion and the normalized emittance for different gains G.
- Motion is stable for gain > threshold
- Ecloud density $= 6 \times 10^{11}\, e/m^3$

HeadTail study - simplified feedback, 500 MHz Kicker

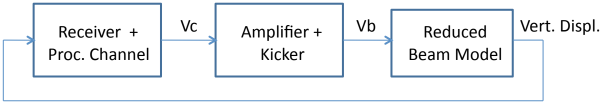
Ecloud instability, 10^{11} protons/bunch, $\rho_e \approx 6 \times 10^{11} e^- m^{-3}$



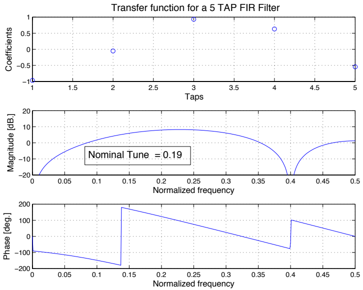
- Clear damping of the coherent motion
- Remaining power is distributed over modes {2,6}

- Nonlinear system, difficult to quantify margins

Closed-Loop feedback around the Reduced Model

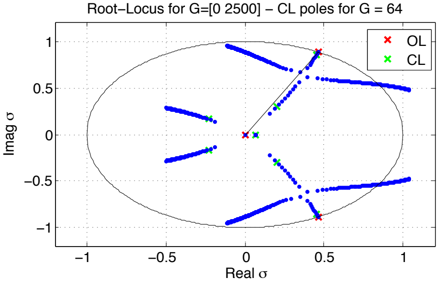


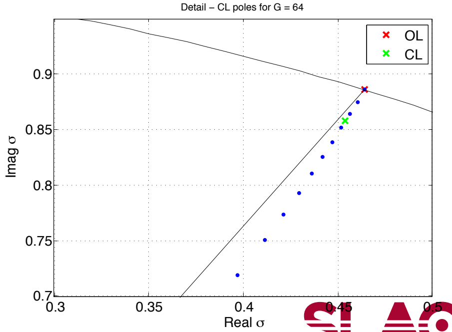
- Use the reduced model, with realistic feedback delays and design a simple FIR controller
- Each slice has an independent controller
  - This example 5 tap filter has broad bandwidth - little separation of horizontal and vertical tunes
  - But what would it do with the beam? How can we estimate performance?



Feedback design - Value of the reduced model

- Analytic estimates of loop stability vs. gain for SPS MD mode zero case
- Estimates of sensitivity to parameter variations (tune shifts, etc.)
- Immediate estimates of closed-loop transfer functions, time-domain behavior from transients
- Allows rapid estimation of impact of injected noise and equilibrium state
- Rapid computation, evaluation of ideas
- Uses control system formalism





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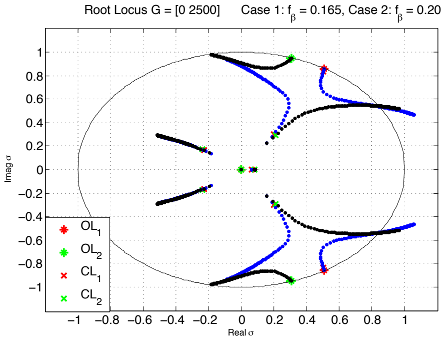
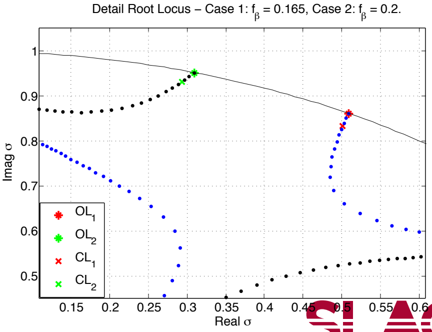
Feedback design - Value of the reduced model

- Analytic estimates of loop stability vs. gain for two tunes mode zero MD
- Estimates of sensitivity to parameter variations (tune shifts, etc.)
- Immediate estimates of closed-loop transfer functions, time-domain behavior from transients
- Allows rapid estimation of impact of injected noise and equilibrium state
- Rapid computation, evaluation of ideas
- Uses control system formalism





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