Wideband Feedback Systems

Feedback Control of ECloud/TMCI Instabilities

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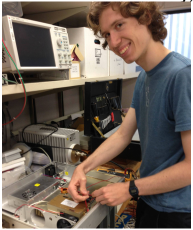
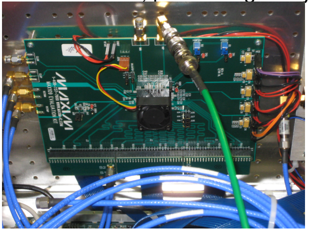
SPS Ecloud/TMCI Instability R&D Effort

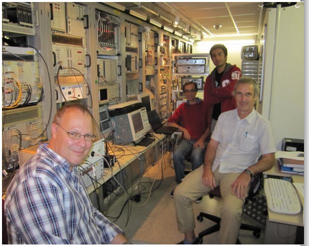
- Stabilize Ecloud and TMCI effects via GHz bandwidth feedback
- Proton Machines, Ecloud driven instability - impacts SPS as high-current LHC injector (applicable also to LHC,PS)
  - Photoelectrons from synchrotron radiation - attracted to positive beam
  - Single bunch effect - head-tail (two stream) 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)
  - Machine measurements- SPS MD (CERN - SLAC)
  - Kicker models and simulations (LNF-INFN,LBL, SLAC)
  - Hardware technology development (SLAC,KEK)
- 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 development

Organization and People - Some welcome new faces

- SLAC J. Fox (50%), C. Rivetta(50%), J. Olsen, J. Dusatko(30%)
- J. Cesaratto (Toohig Fellow)
- Ozhan Turgut, K. Pollock, S. Johnston (Stanford Graduate Students)
- CERN - W. Hoefle, G. Kotzian, B. Salvant, U. Wehrle
  - SPS/LHC Transverse Feedback
  - MD planning and MD measurements
  - TMCI simulations and measurements
- LBL Z. Paret, S. De Santis
  - Kicker study
- LNF-INFN F. Marcellini, S. Gallo, M. Zobov, A. Drago
  - Kicker study, Impedance estimates, processing study







Progress November 2012 - April 2013

- Project activity
  - Hardware efforts (4 GS/sec. demo system, Kicker design report)
  - MD results November 2012, January/February 2013 (Demo system commissioning, Instability Dynamics, closed-loop tests)
  - Dynamics analysis techniques to quantify nonlinear unstable oscillators
  - Ecloud/TMCI Modeling, dynamics estimation, feedback simulation efforts
- Research directions
  - Machine measurements - understand modal excitation, validate simulations
    - Commissioning of 1 bunch Demo processing channel
    - closed-loop tests and comparisons to simulation dynamics
  - Simulations - numeric nonlinear PIC, simplified linear models
    - Simplified feedback models - what sort of control is feasible? Robustness?
  - Kicker Structures
    - 3 lab Research effort to investigate useful 1 GHz Bandwidth Transverse Kicker

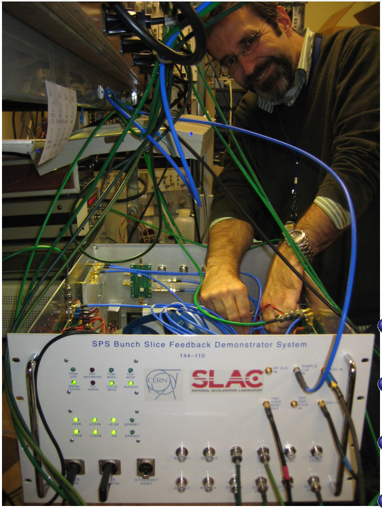
Technology Development for SPS tests

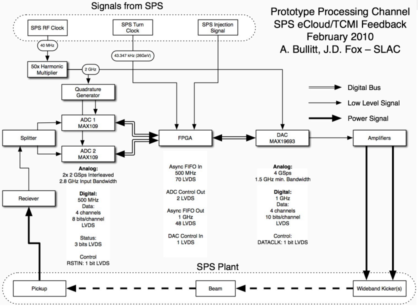


- Timing and synchronization master oscillator
- Beam Motion Receiver (delta/sigma system)
- 4(3.2) GS/sec. Beam excitation system (arbitrary waveform generator, 15K turns)
- 4(3.2) GS/sec. DSP Feedback Demo processor
- Tunnel amplifiers/control for beam excitation (4$\times$ 80W 1 GHz)

The goal is to build general purpose testbed components to allow machine measurements, experiments of fundamental control ideas using the SPS

4 Gs/sec. 1 bunch SPS Demonstrator channel



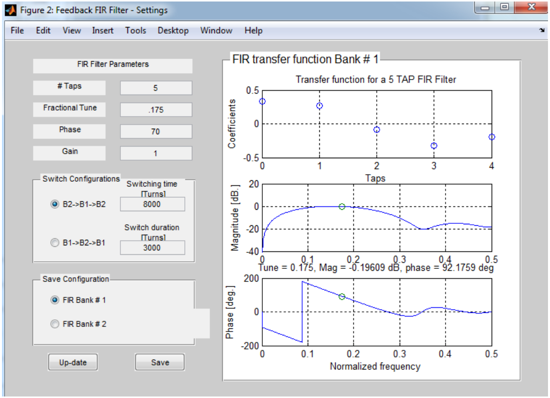


- Proof-of-principle channel for 1 bunch closed loop tests in SPS - commissioned November 2012
- Wideband control in SPS after LS1 (installation of wideband kicker)
- Reconfigurable processing - evaluate processing algorithms
- Technical formalism similar to 500 MS/sec feedback at PEP-II, KEKB, DAFNE

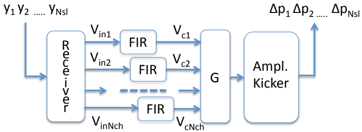
Demonstration 1 bunch processor

- Synchronized DSP processing system, initial 1 bunch controller
- Implements 16 independent control filters for each of 16 bunch “slices"
- Sampling rate 4 GS/sec. (3.2 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

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

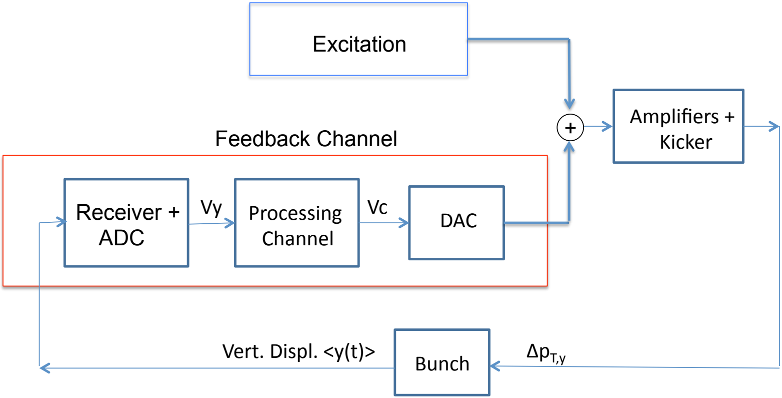


Recent MD Results

- 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 paramters
  - 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 naturally unstable beams

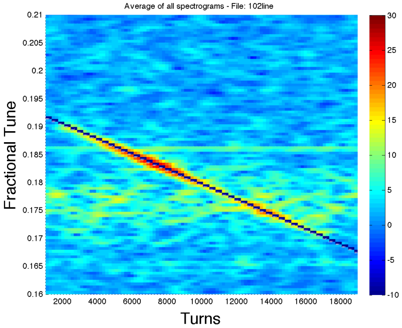
We are just starting to analyze data, a few examples to stimulate discussion

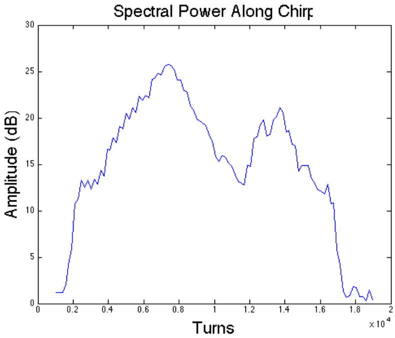
Measuring the closed loop system - methods



- We want to study stable or unstable beams and understand impact of feedback
- 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
- System isn't steady state, tune and dynamics vary
- Excite with chirps that can cross multiple frequencies of interest
- Unstable systems can be studied via Grow-Damp methods, but slow modes hard to measure

Driven Motion Studies- closed loop feedback

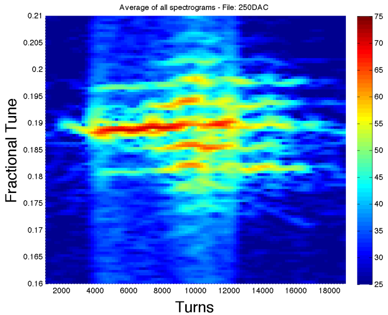




- Driven chirp Pickup spectrogram (left)
- Driven Beam motion Spectral power (right)
- Chirp tune 0.17 - 0.19 turns 2K - 17K
- Study changes in dynamics with feedback as change in driven response

Value of Driven measurements

- 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
- Measurements like this will help us quantify the frequency response of our feedback system.



- An example spectrogram of excited beam from the Feb 2013 MD
- DAC output signal, Multiple modes are clearly visible.
- Positive feedback excitation from turns 4K-12K

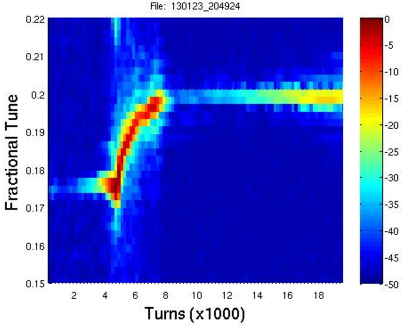
MD Feedback studies on unstable or marginally stable beams

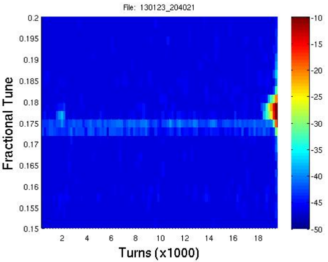
- Manipulate feedback parameters, study free beam responses
- Feedback control as time-varying parameter (on, off, variable gains, filters, Positive/Negative feedback etc.)
- Study changes in dynamics vs. feedback configuration (grow/damp studies)
- Manipulation of feedback filters allows growth of instability from stable controlled state, measurement in small-amplitude conditions
- Easily measures fastest modal growth rates - requires care to measure slow modes in presence of fast modes
- Disadvantage - requires feedback control to do most studies

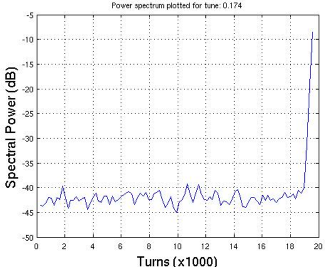
Example feedback control of unstable beam

- SPS Cycle with chromaticity sweep to low (zero?) chromaticity after 1 sec into the cycle
- charge 1×10^{11} with slightly negative chromaticity
- 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
- Similar 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.

Feedback control of beam



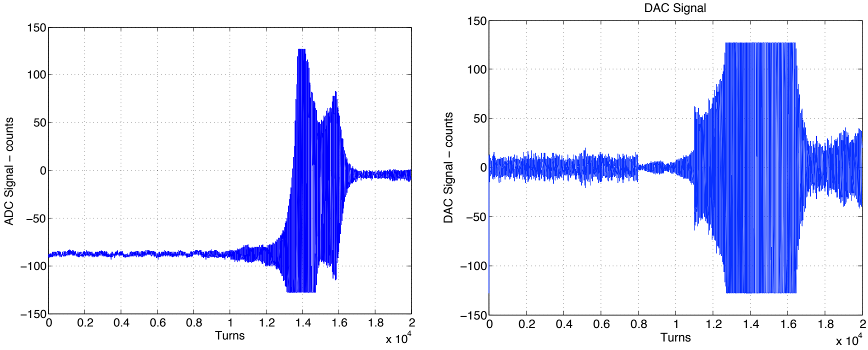




- Spectrograms of bunch motion, nominal tune 0.175
- after chromaticity ramp at turn 4k, bunch begins to lose charge and gets tune shift.
- Feedback OFF -Bunch is unstable in mode zero (barycentric).

Feedback is switched off at turn 18K, beam then is unstable

Unstable beam -Input, Output signals 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

Future Directions - beam studies

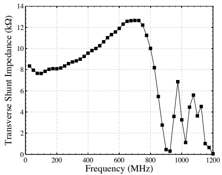
- The Demo platform is a reconfigurable testbed for control techniques
- Provides unique beam diagnostics and opportunities for new measurement methods
- Studies of unstable systems are difficult, control and time varying gain is a useful method (grow-damp techniques)
- To date, unstable beams available have had mode zero instabilities, we want to study higher internal modes
- Complementary methods with driven responses
- We are eager to collaborate on novel beam diagnostics and measurement techniques, analysis methods
- Analysis of recent MD transients will require some time, future talks and discussions

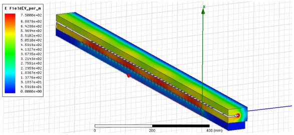
FY2013/2014 Technology development path

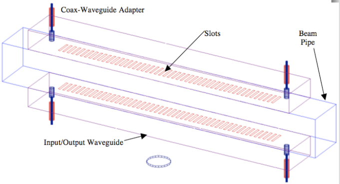
- Low-noise transverse coordinate receivers and pickup techniques,
  - (Noise floor sets limits on damped beam motion and influences equilibrium emittance)
- Wideband Kicker Prototype for SPS Installation LS1
- High-speed DSP architectures consistent with 4 GS/sec sampling rates for full SPS implementation
- Wideband 20 - 1000 MHz RF power amplifiers, with acceptable phase response
- Master Oscillator, Timing system to synchronize to the SPS RF system, control sampling
- Diagnostic and beam instrumentation techniques to optimize feedback parameters and understand system effectiveness

Kicker Options Design Study (J. Cesaratto)

- LNF-INFN,LBL and SLAC Collaboration. Excellent progress 2012-2013
- Goals - evaluate 3 possible options. Design Report Spring 2013
- Based on requirements from feedback simulations, shunt impedance, overall complexity - Provide CERN with a recommendation of which kicker technologies to fabricate.

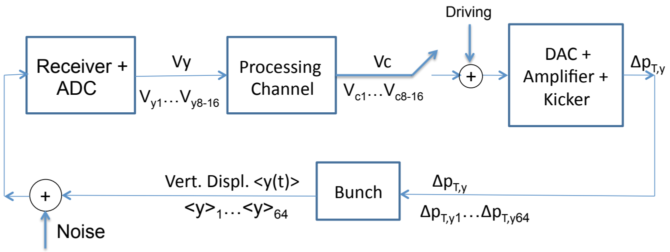






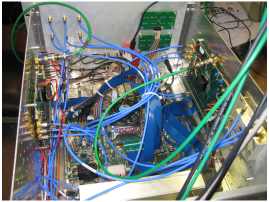
Progress in Simulation Models

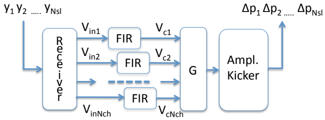
- Critical to validate simulations against MD data
- Still needs realistic channel noise study, sets power amp requirements
- Still needs more quantitative study of kicker bandwidth requirements
- Head-tail offers path to evaluate TMCI and feedback methods
- Continued progress on linear system estimation methods
- Model test bed for controller development

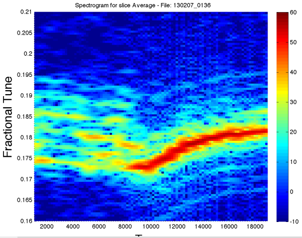


Ecloud/TMCI Progress

- 4 GS/sec processing demonstration prototype
  - FPGA platform, testbed for control techniques
  - Builds on existing timing and amplifier system for proof of principle tests
  - Wideband control in SPS after LS1 (installation of wideband kicker)
- SPS MD studies with Demo system, analysis methods
- Kicker design/estimation effort
  - Significant progress, welcome contributions from LBL, LNF-INFN and SLAC.
  - Important Milestone - recommendation of geometry for CERN fab, SPS installation
- Simulation methods - combination of feedback model with HeadTail, study MD cases







Ecloud/TMCI Wideband Feedback "Full-Function Prototype"

- System capability to control full SPS ring at HL upgraded intensity
  - Beam line pickups/kickers
  - Beam motion receiver, processing electroniucs
  - 4 - 8 Gs/sec DSP for intra-bunch feedback
  - System Timing, Synchronization Clocks/Oscillators
  - GHz bandwidth Kicker Power Amplifiers
  - Operator interfaces, control/monitoring software
  - Beam diagnostic software, configuration software
  - Accelerator Dynamics models, Stability tools
- Full-Function protoype completed in FY18 for commissioning in FY19
  - "Full-Function" - capability to control full ring at high intensity
  - "Full-Function" - synchronization during energy ramping
  - Integration of system control/beam diagnostics for operation
- Areas of SLAC/CERN contributions
  - SLAC - Feedback signal processing and control software, diagnostic software
  - CERN - tunnel based vacuum Components (kickers) and cable plant
  - Opportunity for collaborative engineering team , shared operational expertise

Summary - Ecloud/TMCI Feedback program directions

- LARP
  - LARP program is transitioning, wideband feedback is proposed as a US deliverable for HL upgrade
  - R&D program continues on path to full-function prototype
  - Plan incorporates training of Grad students, role of Fellow/postdoctoral contributions
- Plans for next two years
  - Use recent MD data to better simulate beam instablities and feedback system properties
  - Wideband kicker (in conjunction with SLAC/LBL/LNF-INFN) - install at end of LS1
  - Expand Demo prototype to control 16 - 48 bunches, useful for Ecloud/TMCI studies
- Areas of SLAC/CERN LARP activity
  - Beam-Feedback simulations (nonlinear and reduced model)
  - Development of optimal control approaches, use of simulations, fit of models to MD data
  - Hardware development (timing and synchronization methods, beam receiver and offset rejection techniques)

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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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Research Goals 2013 and Beyond

- simulation techniques, feedback models for Ecloud and TMCI
  - Single bunch control (wideband, vertical plane) - Required bandwidth?
  - Control Algorithm - complexity? Flexibility? Machine diagnostic techniques?
  - vital effort, continue K. Li's path
  - evaluate system limits, tradeoffs, feasibility of various control methods
  - Extraction of system dynamics, development of reduced (linear) coupled-oscillator model for feedback design estimation
- proof of principle processing system
  - Expand 1 bunch 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
  - Technology R&D - wideband feedback technical components
  - Fundamental R&D in kickers, pickups - technology demonstration in SPS
- We will learn from the expanded "demo" at the SPS after LS1
- Can then confidently design a full-function system for SPS, and if desired, LHC and PS

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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

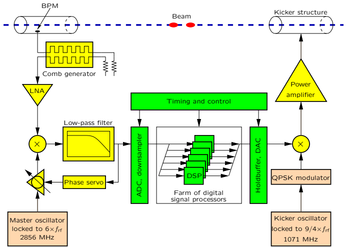
example/existing bunch-by-bunch feedback (PEP-II, KEKB, ALS, etc.)

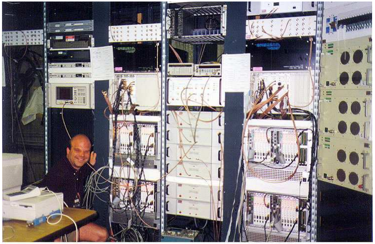
- Diagonal controller formalism
- Maximum loop gain from loop stability and group delay limits
- Maximum achievable instability damping from receiver noise floor limits

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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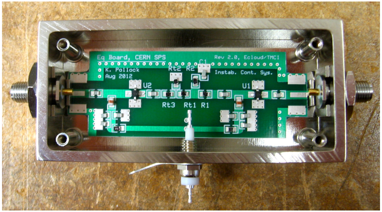
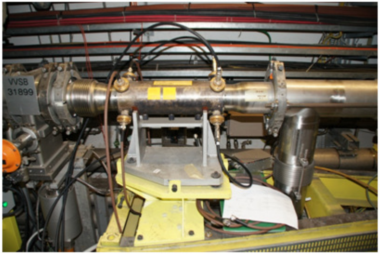
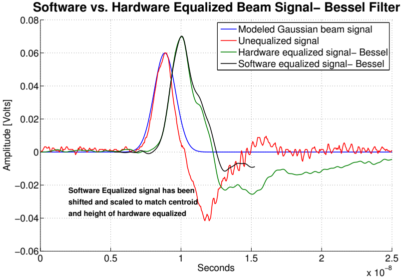
Hardware Equalizer





- 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
- Optimzation technique - can be used for kicker. too



Future Directions - beam studies

- The Demo platform is a reconfigurable testbed for control techniques
- Provides unique beam diagnostics and opportunities for new measurement methods
- Studies of unstable systems are difficult, control and time varying gain is a useful method (grow-damp techniques)
- To date, unstable beams available have had mode zero instabilities, we want to study higher internal modes
- Complementary methods with driven responses
- We are eager to collaborate on novel beam diagnostics and measurement techniques, analysis methods
- Analysis of recent MD transients will require some time, future talks and discussions