EC-TMCI Instability Control via Feedback Techniques

Progress and future directions

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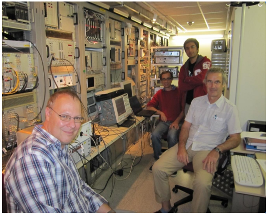
SPS Ecloud/TMCI Instability R&D Effort

- Motivation - control Ecloud and TMCI effects in SPS and LHC via GHz bandwidth feedback
- Ongoing project SLAC/LBL/CERN via US LARP
- 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

Organization and People - Some welcome new faces

- SLAC J. Fox (50%), K. Li, C. Rivetta(50%), J. Olsen, J. Dusatko(30%), M. Pivi(20%)
- J. Cesaratto (Toohig 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





Wideband Intra-Bunch Feedback - 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

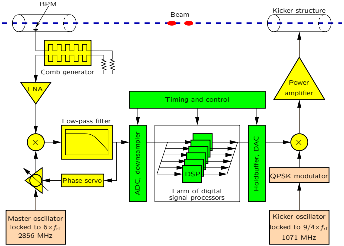
example/existing bunch-by-bunch feedback (PEP-II, KEKB, ALS, etc.)

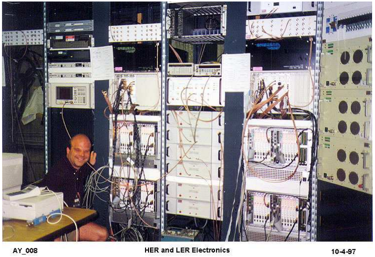
- Diagonal controller formalism
- Maximum loop gain from loop stability and group delay limits
- Maximum achievable instability damping from receiver noise floor limits

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

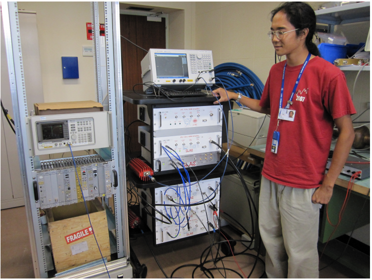
SPS and LHC needs may drive new processing schemes and architectures

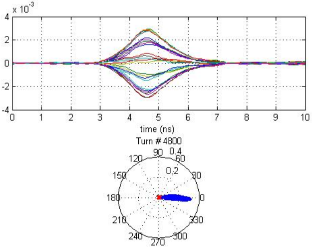
Existing Bunch-by-bunch (e/g diagonal controller) approaches may not be appropriate

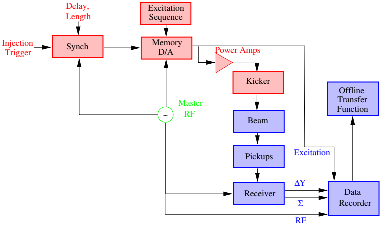




Recent efforts and Recent progress







Delay, Length

Excitation Sequence

Injection Trigger

Synch

Memory D/A

Power Amps

Kicker

Master RF

~

Beam

Offline Transfer Function

Pickups

Excitation

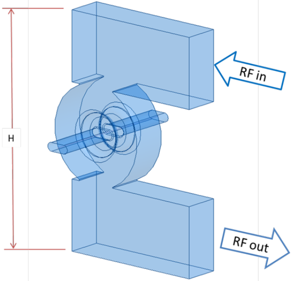
Receiver

ΔY

Σ

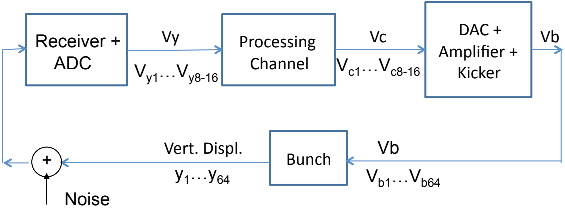
Data Recorder

RF



Macro - Particle Simulation Codes : Realistic Feedback

Add realistic blocks representing feedback system

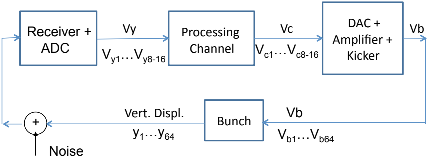


- Receiver, processing channel, amplifier, kicker include frequency response, signal limits and noise.
  - Each block is modeled in the code by a matrix representing the frequency response
  - $[V_{b_1} \ldots V_{b_{64}}]^T = M_{PWR}\,[V_{c_1} \ldots V_{c_{16}}]^T$ (DAC+Amp.+Kicker)
- Include the main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

Progress in Simulation Models

- Significant efforts, including feedback to WARP, HeadTail 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
- HeadTail offers path to evaluate TMCI and feedback methods
- Critical to validate simulations against MD data
- Continued progress on linear system estimation methods

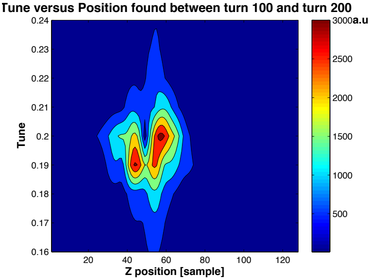
Add realistic components to the feedback channel - CMAD / HeadTail / Warp



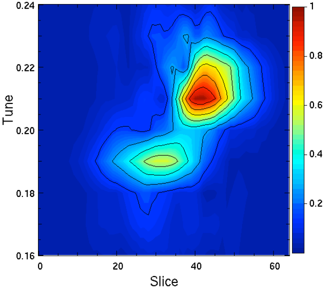
- Bunch is sampled in z using 64-80 samples (equal charge - equal distance)
- Receiver, processing channel, amplifier, kicker include frequency response, signal limits and noise.
- Processing channel can operate from 1 to 64 samples to model different sampling rates.

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



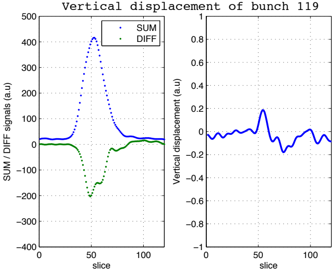
MD data June 2009

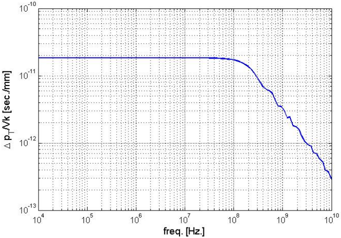


WARP simulation

SPS Studies 2009, 2010, 2011,2012

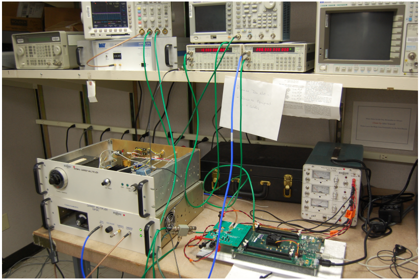
- Open-Loop unstable beam measurements
- Vertical Instability develops within 100 turns. Time domain ,frequency domain studies 1E11 p/bunch
- Use this technique to compare models, MD data - extract beam dynamics necessary to design feedback. Roughly 25 slices (250 ps) between displacement maxima and minima
- Spring/summer 2011 - 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

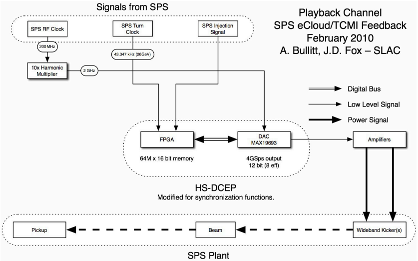




SPS Excitation MD 2011 and 2012

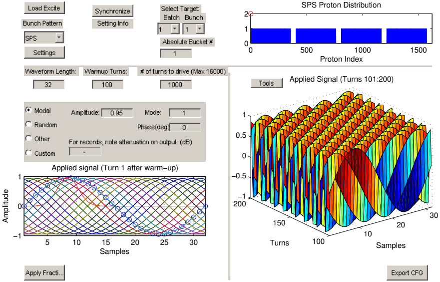
- Past MD efforts look at unstable beam - very complex dynamics
  - Plan - Drive beam below threshold - look at dynamics as currents increase
  - Drive selected bunch via existing pickup, observe response
  - Validate numeric codes against machine data
  - Important test bed for full-scale back end at 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





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


Bunch Pattern: SPS

Select Target: Batch 1, Bunch 1

Absolute Bucket #: 1

Waveform Length: 32

Warmup Turns: 100

# of turns to drive (Max 16000): 1000

● Modal
○ Random
○ Other
○ Custom

Amplitude: 0.95

Mode: 1

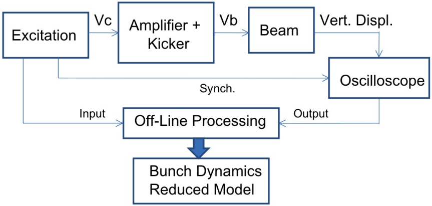
Phase(deg): 0

For records, note attenuation on output: (dB) -

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

Goal: Drive individual sections of the bunch - Estimate Models

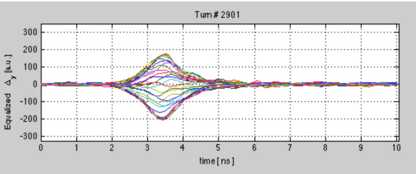
- Excitation - Power Stage - Vertical displacement measurement.
- Estimate bunch reduced dynamical model in open loop- Below e-cloud instability threshold. Increase currents and study dynamics change
- Compare MD results to macro-particle simulation codes



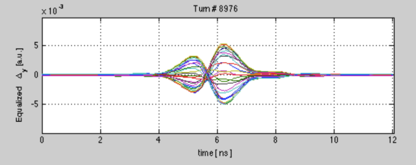
- Drive individually different areas of the bunch (Excitation - Amplifier - Kicker)
- Measure with scope the receiver signals $\Delta - \Sigma$. Estimate vertical displacement for different sections of the bunch.
- Based on Input-Output signals, estimate bunch reduced model.

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

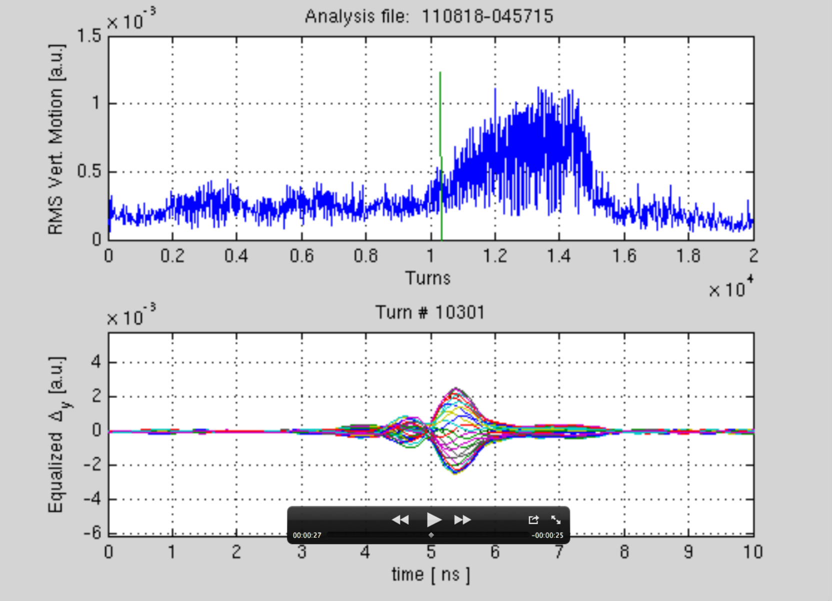


Barycentric driven motion

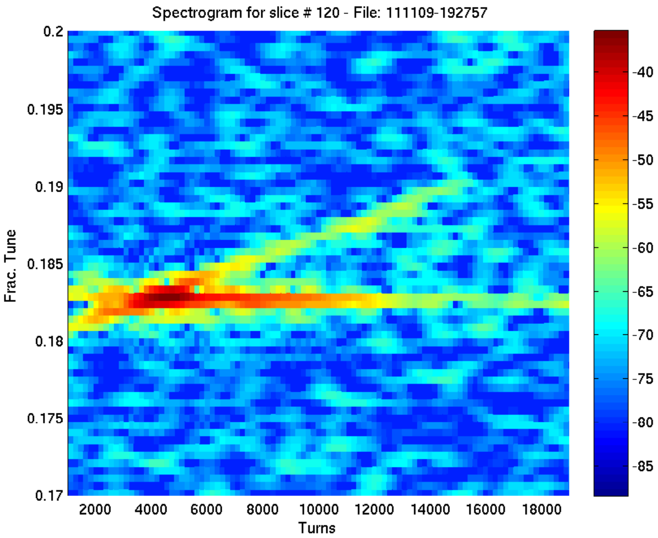


Head-tail driven motion

Movies, spectrograms from Excitation studies

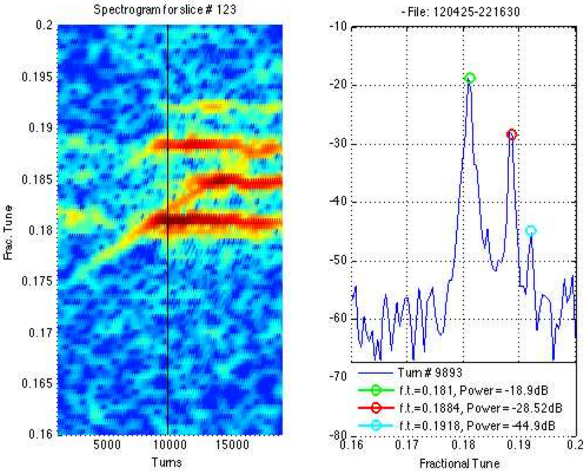


Movies, spectrograms from Excitation studies



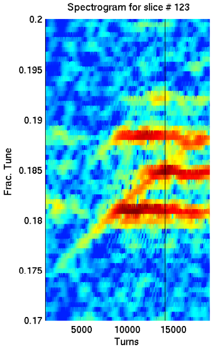
Excitation MD July/August, Nov 2011 and April 2012

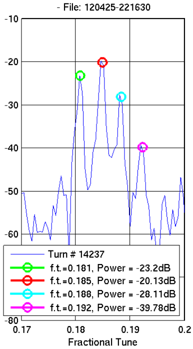
- Significant developments and sophisticated analysis
  - Excitation methods (chirps, random, selected modes)
  - ability to clearly excite through mode 4

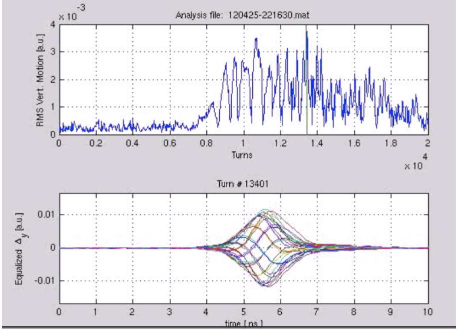


Chirp excitation in Frequency and time domain

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

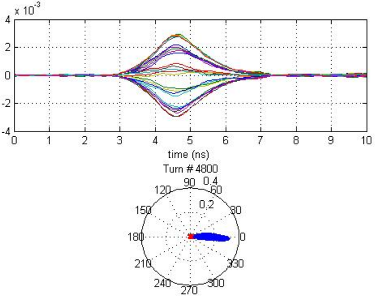


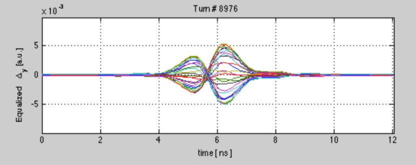


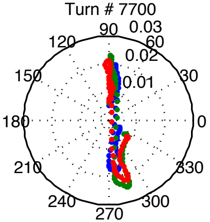


Vector (Modal) Analysis of Beam Motion J. Cesaratto

- 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



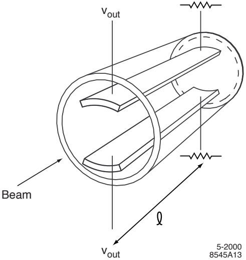


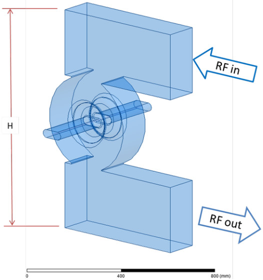


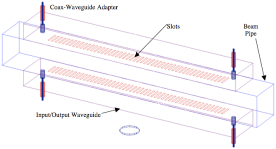
Barycentric mode 0 motion

Kicker Options Design Study

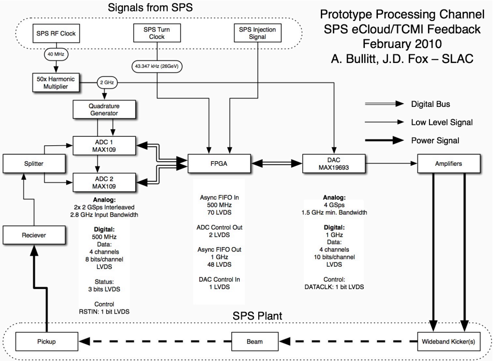
- LNF-INFN,LBL and SLAC Collaboration. Excellent progress 2012
- Goals - evaluate 3 possible options
    - Stripline (Arrays? Tapered? Staggered in Frequency?)
    - Overdamped Cavity (transverse mode)
    - Slot and meander line (similar to stochastic coooling kickers)
- Based on requirements from feedback simulations, shunt impedance, overall complexity - select path for fab







4 Gs/sec. 1 stack SPS feedback channel



Signals from SPS

Prototype Processing Channel
SPS eCloud/TMCI Feedback
February 2010
A. Bullitt, J.D. Fox – SLAC

SPS RF Clock
SPS Turn Clock
SPS Injection Signal
40 MHz
43.347 kHz (26GeV)
50x Harmonic Multiplier
2 GHz
Quadrature Generator
ADC 1 MAX109
ADC 2 MAX109
Splitter
Reciever
FPGA
DAC MAX19693
Amplifiers

Digital Bus
Low Level Signal
Power Signal

Analog:
2x 2 GSps Interleaved
2.8 GHz Input Bandwidth

Digital:
500 MHz
Data:
4 channels
8 bits/channel
LVDS

Status:
3 bits LVDS

Control
RSTIN: 1 bit LVDS

Async FIFO In
500 MHz
70 LVDS

ADC Control Out
2 LVDS

Async FIFO Out
1 GHz
48 LVDS

DAC Control In
1 LVDS

Analog:
4 GSps
1.5 GHz min. Bandwidth

Digital:
1 GHz
Data:
4 channels
10 bits/channel
LVDS

Control:
DATACLK: 1 bit LVDS

SPS Plant
Pickup
Beam
Wideband Kicker(s)

- We are building a proof-of-principle channel for closed loop tests in SPS before the 2013 shutdown, using existing kicker and excitation system
- Flexible reconfigurable processing - evaluate multiple processing algorithms

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)

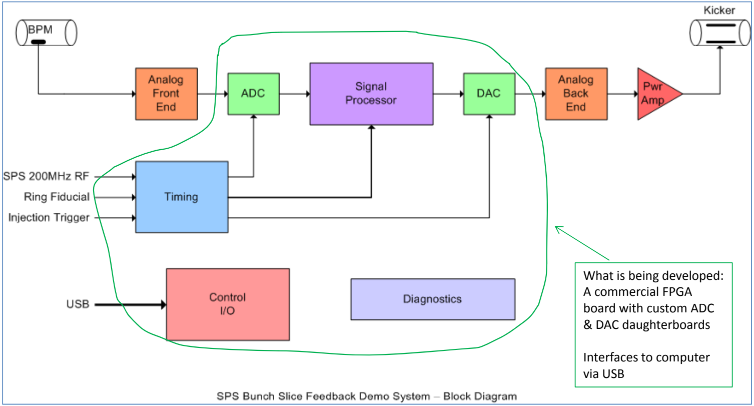
KEKB (existing iGp system) - 8 GigaMacs/sec.

- 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.

Proof of Principle processing



What is being developed:
A commercial FPGA board with custom ADC & DAC daughterboards

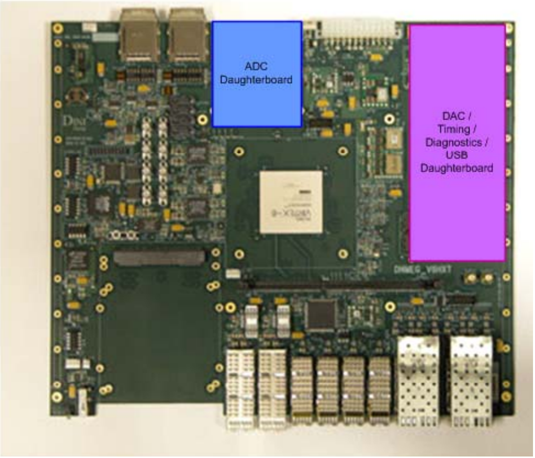
Interfaces to computer via USB

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

Recent LARP 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
- 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
- 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

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- WEBEX Ecloud Feedback mini-workshop February 2010 (joint with SLAC, Stanford, CERN, and LBL).
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- Performance of Exponential Coupler in the SPS with LHC Type Beam for Transverse Broadband Instability Analysis 1 R. de Maria BNL, Upton, Long Island, New York, J. D. Fox

SLAC, Menlo Park, California, W. Hofle, G. Kotzian, G. Rumolo, B. Salvant, U. Wehrle CERN, Geneva Presented at DIPAC 09 May 2009

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- W. Hofle, *E-cloud feedback activities for the SPS and LHC*, CERN Electron Cloud Mitigation Workshop 08.
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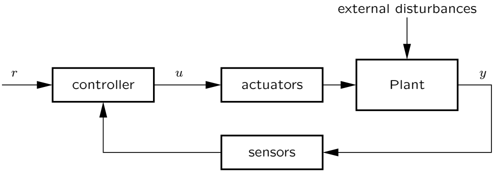
The Big Picture

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.

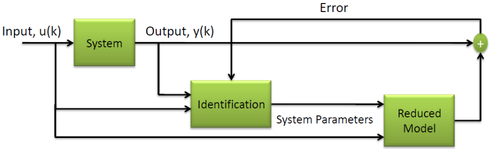
An additional measure of feedback performance is the average or peak actuator effort. Peak actuator effort is almost always important due to the finite actuator range.

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?

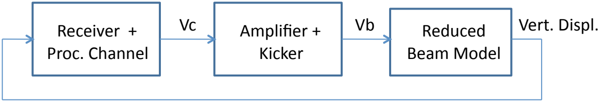
Identification of Internal Bunch Dynamics: Reduced Model

- 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



Closed-Loop feedback around the Reduced Model



Receiver + Proc. Channel

Vc

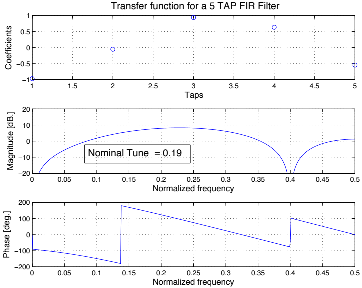
Amplifier + Kicker

Vb

Reduced Beam Model

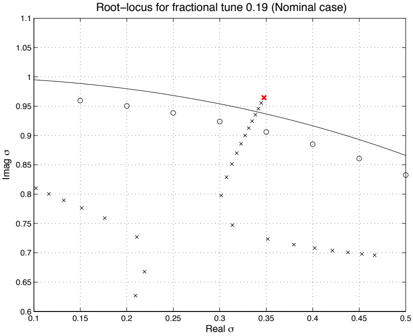
Vert. Displ.

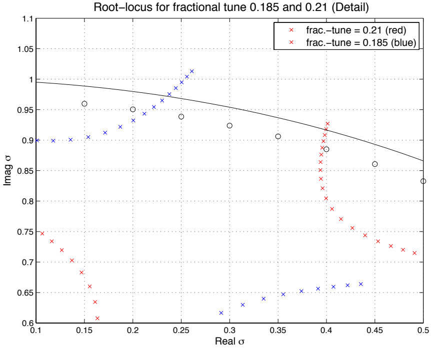
- Use the reduced model, with realistic feedback delays and design a simple FIR controller
- Each slice has an independent controller
  - This example 5 tap filter has broad bandwidth - little separation of horizontal and vertical tunes
  - But what would it do with the beam? How can we estimate performance?



Feedback design - Value of the reduced model

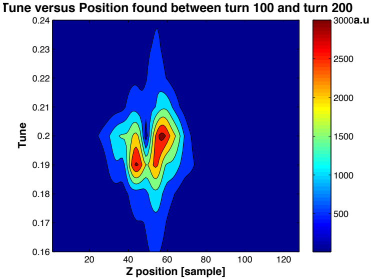
- Analytic estimates of loop stability vs. gain
- Estimates of sensistivity to parameter variations (tune shifts, etc.)
- Immediate estimates of closed-loop transfer functions, time-domain behavior from transients
- Allows rapid estimation of impact of injected noise and equilibrium state
- Rapid computation,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


Root−locus for fractional tune 0.19 (Nominal case)

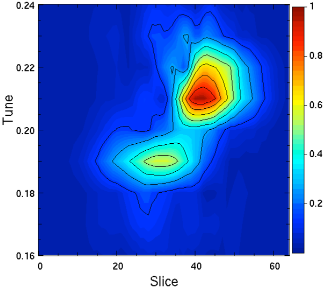

Root−locus for fractional tune 0.185 and 0.21 (Detail)

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?

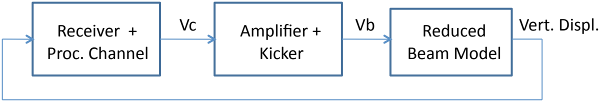


MD data June 2009



WARP simulation

Closed-Loop feedback around the Reduced Model



Receiver + Proc. Channel

Vc

Amplifier + Kicker

Vb

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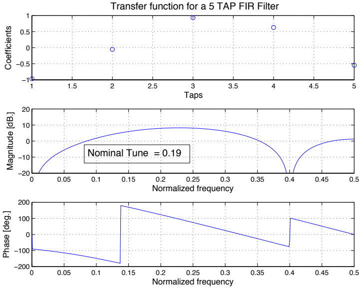
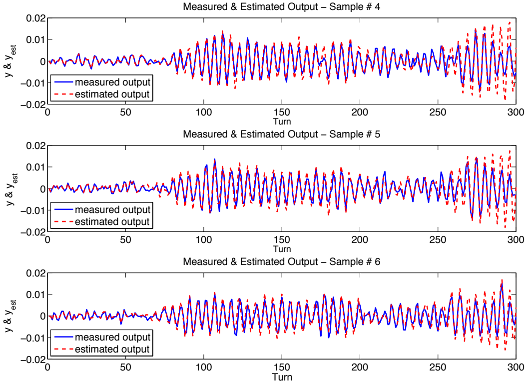


Modeling and Identification

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.

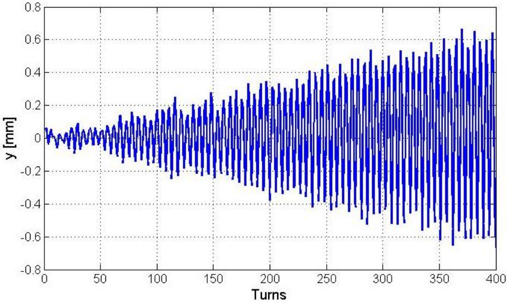


- Bunch driven by white noise using C-MAD code. $y(t)$: C-MAD vertical displacement for slices 4-5-6, $y_{est}(t)$: Estimated vert. displ. using lineal time-variant reduced model.

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)

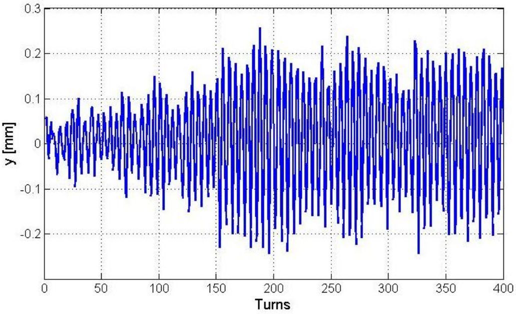


Kicker signal for all the slices: $V_b = 4.10^{-6} sin(2\pi 0.185\, Turns)$ eV.s/m. C-MAD result: Vertical displacement of center of the bunch.

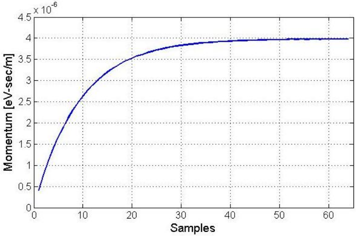
Modelling the driven bunch MD

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 $0.185 \pm 5\%$.



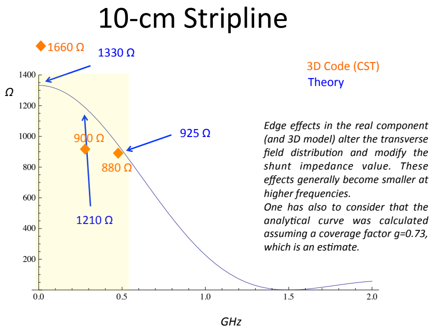
Momentum applied to the bunch at turn 50.



time span: 6.13 ns.

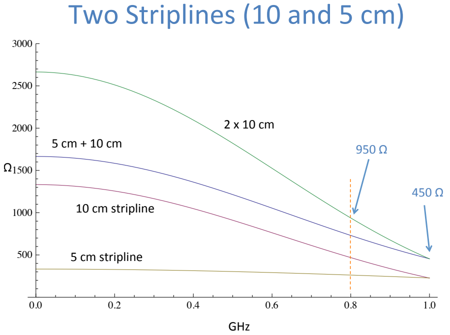
Kicker Options - Ideas from S. De Santis and Z. Paret

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


10-cm Stripline

Edge effects in the real component (and 3D model) alter the transverse field distribution and modify the shunt impedance value. These effects generally become smaller at higher frequencies.
One has also to consider that the analytical curve was calculated assuming a coverage factor g=0.73, which is an estimate.

S. De Santis April 18, 2012

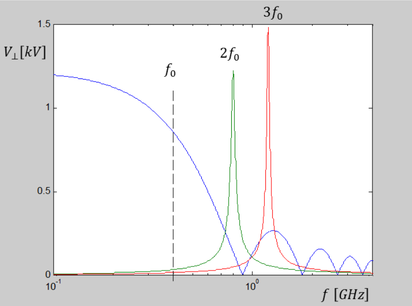

Two Striplines (10 and 5 cm)

S. De Santis April 18, 2012

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

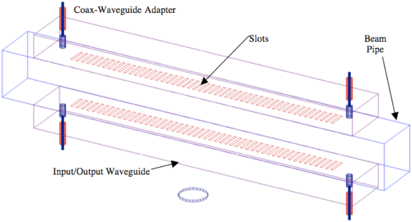
	Kicker #1	**Kicker #2**	**Kicker #3**
Type	Stripline	Cavity, TM110 defl. mode	Cavity, TM110 defl. mode
3-dB bandwidth	DC – 400 MHz	800 ± 16 MHz	1200 ± 16 MHz
Length	17 cm	15 cm	10 cm
Filling time	0.6 ns	10 ns	10 ns
Q_l	---	25	38
Shunt Impedance	≈ 1.5 kΩ (@ DC)	≈ 1.5 kΩ (@ 800 MHz)	≈ 2.2 kΩ (@ 1200 MHz)

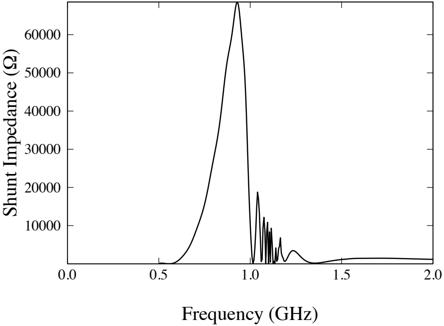


Assuming that each kicker is powered by a 1 kW source covering the entire device bandwidth, the resulting transverse voltage transferred to the beam as a function of the frequency is shown in the following plot.

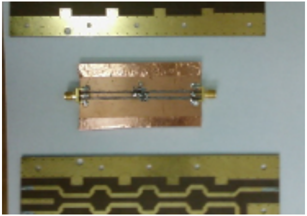
Kicker Options - Idea from J. Cesaratto

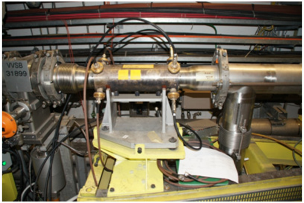
- similar to stochastic cooling kickers
- wideband - (longitudinal Impedance estimate in progress by M. Zobov)





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

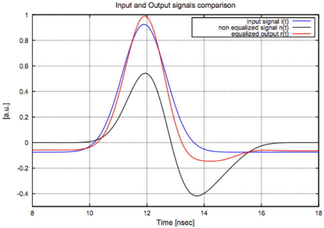
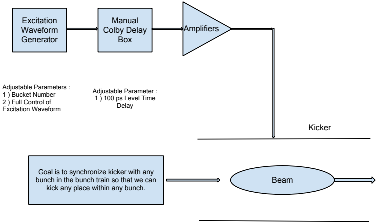


Figure 8: The input signal $i(t)$, non-equalized signal $n(t)$ and equalized output $r(t)$ using in the model a polynomial $P(s)$ with the values reported in Table 1.

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

- We excite the beam from our amplifier array
- To control the modes excited, maximise coupling, we must have precision in excitation timing
- We are developing excitation techniques for kicker timing
    - methods to repeatably position the kick, time the system
    - methods to maximize the effective kick applied to the beam



Excitation Waveform Generator

Manual Colby Delay Box

Amplifiers

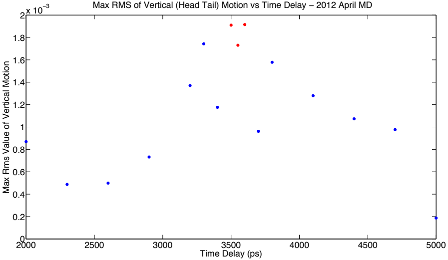
Adjustable Parameters :
1) Bucket Number
2) Full Control of Excitation Waveform

Adjustable Parameter :
1) 100 ps Level Time Delay

Kicker

Goal is to synchronize kicker with any bunch in the bunch train so that we can kick any place within any bunch.

Beam

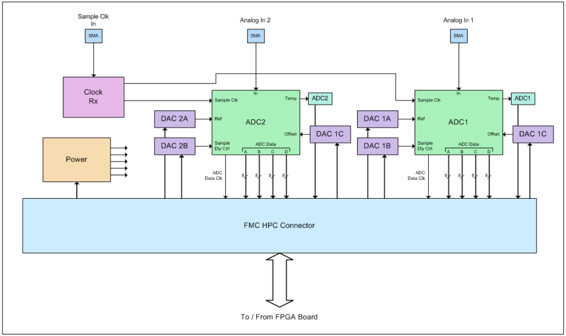


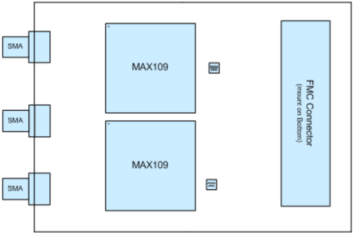
Barycentric driven motion

4 GS/sec ADC daughtercard

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