Feedback Control of SPS E-Cloud/TMCI Instabilities

LARP CM14 Progress Report, Ideas for Discussion

April 27, 2010

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LARP Ecloud Contributors

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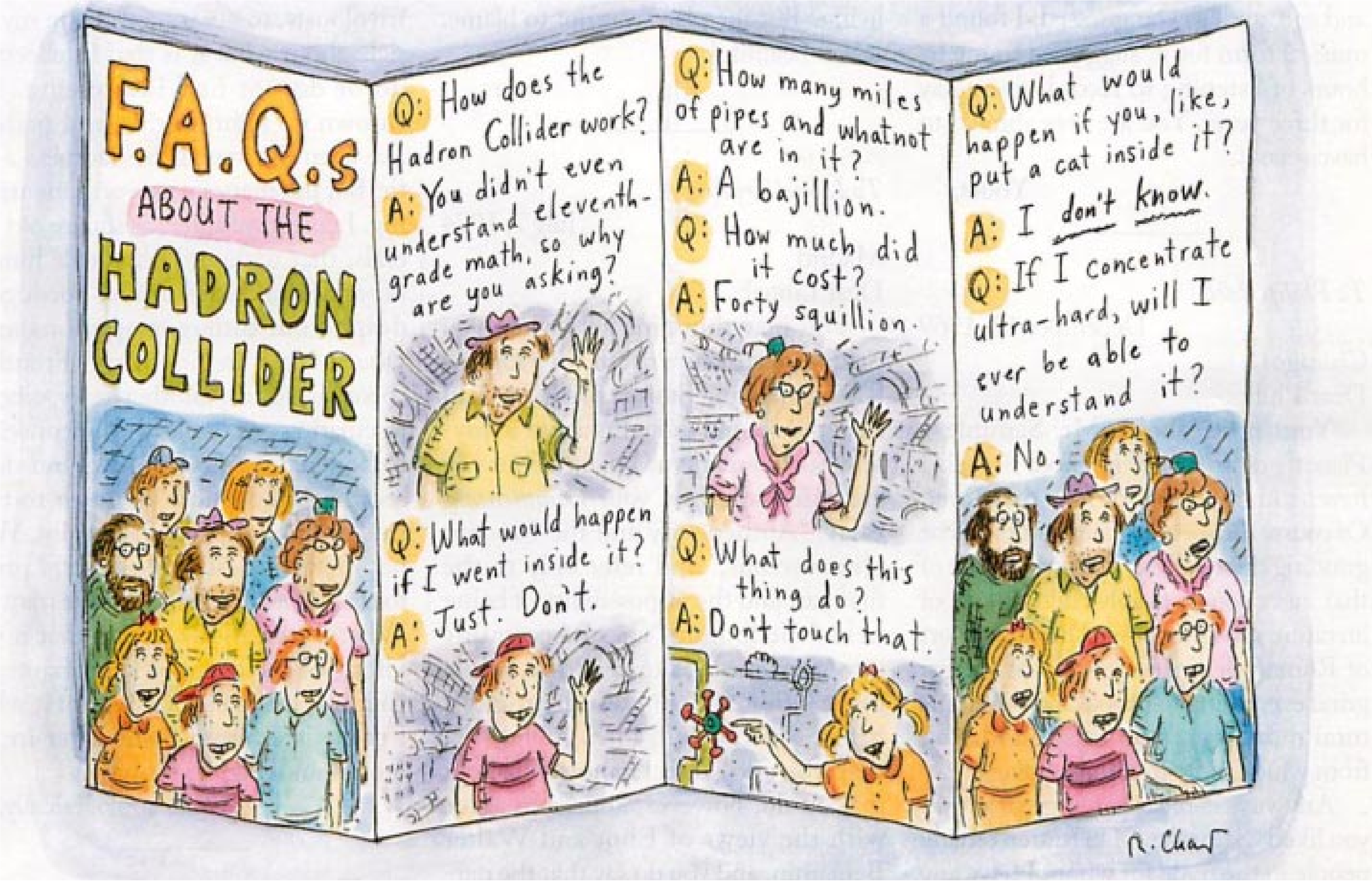
FAQ's on Feedback Control of SPS E-Cloud/TMCI Instabilities



Progress November 2009 - April 2010

- Organization and Staffing, coordination
- Ecloud/TMCI Modeling, dynamics estimation, feedback simulation efforts
- MD measurements, analysis techniques
- Recent MD results (pickup and kicker studies)
- Hardware efforts (4 GS/sec. synchronized excitation)
- near-term plans (MD, models, lab) - Chamonix emphasis on SPS intensities

Multi-lab effort - coordination on

- Non-linear Simulation codes (LBL - CERN - SLAC)
- Dynamics models/feedback models (SLAC - Stanford STAR lab)
- Machine measurements- SPS MD (CERN - SLAC - LBL)
- Hardware technology development (SLAC)

Recent WEB meeting with links

www.slac.stanford.edu/~jdfox/ecloudfeb10.pdf

Organization and Staffing

Biggest Change - step-up SLAC LARP Funding

Allows 2 Stanford grad students

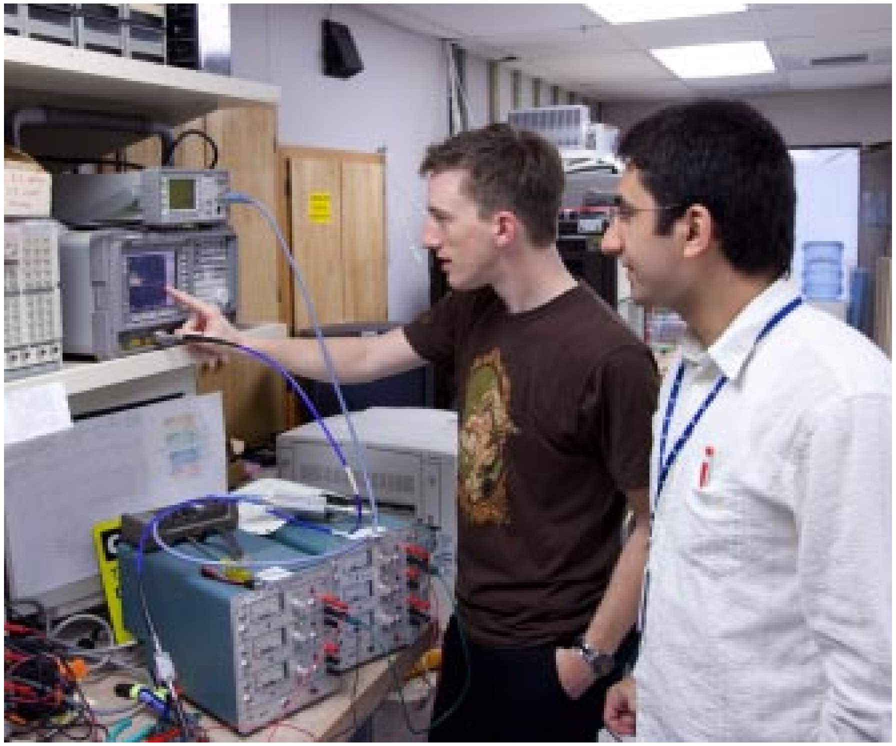
- Alex Bullitt (working on excitation system)
- Ozhan Turgut (system identification, dynamics models)

LARP support 25% for J. Fox, C. Rivetta

- Greater activity, increased progress winter 2010

Recent WEB meeting on Ecloud/TMCI feedback

www.slac.stanford.edu/~jdfox/ecloudwebfeb10.pdf



- coordinate efforts at SLAC, CERN, LBL,BNL
- efforts on Simulations (Ecloud and TMCI)
- Feedback modelling and dynamics estimations from simulations and MD measurements
- Validation of models
- Development of fast signal processing hardware, demonstration processing channels

Analysis of Ecloud simulations and Ecloud MD data

Time domain simulations, measurements

- What frequencies are present in the bunch structure?
- How do they evolve over the time sequence? Does the dynamics of the system change with time?
- Are there useful correlations between parts of the bunch, other bunches?
- How does the filling pattern, energy, machine parameters impact the unstable motion?

Observations

- tune shifts within bunch due to Ecloud, bursting, positions of unstable bunches in trains
- information in SUM signal
- frequencies within bunch - estimated bandwidth of instability signal, correction signal
- Growth rates of eigenmodes - initial fits and stability observations

Simulations - have access to all the beam data, but what effects are not included?

Machine measurements - what can we measure? with what resolution? What beam conditions?

Observations from June 09 SPS MD Studies

2 72 bunch trains, 1E11 P/bunch, 25 ns separation. Data sampled 10 ps/point

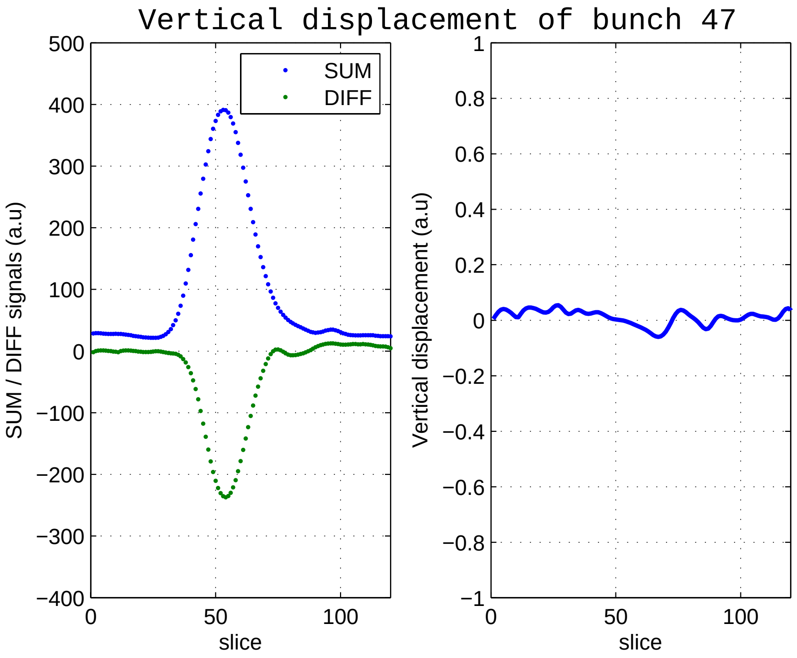
Vertical Instability develops after injection of second batch, within 100 turns. Modes within unstable bunch develop very rapidly at injection- first 100 turns

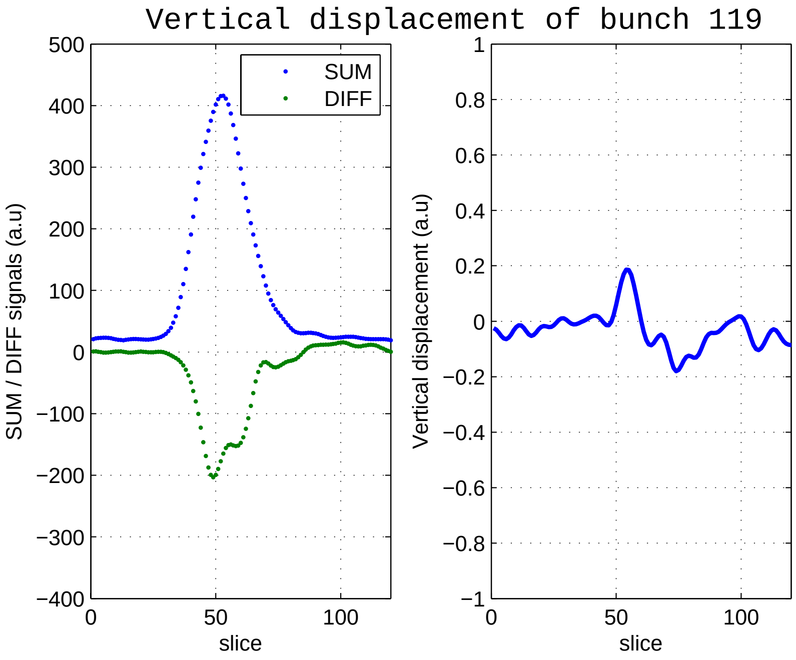
Time domain figures show bunch charge, and transverse displacement, second figure is vertical displacement after removal of DC transient. Data extracted to show bunch 47 and 119 on turn 80

Stable (bunch 47 and earlier) bunches do not show vertical motion

Bunch 119 - shows head and tail displacement

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


Vertical displacement of bunch 47


Vertical displacement of bunch 119

MD Progress November 2009 - April 2010

recent Machine Measurement (MD) results

two efforts to characterize existing SPS pickups and kickers

pickups - very successful

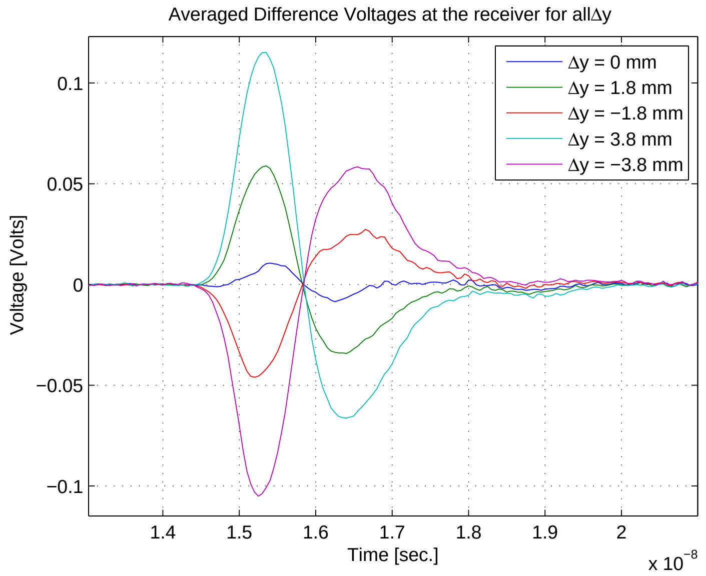
Noise, transverse resolution well-quantified

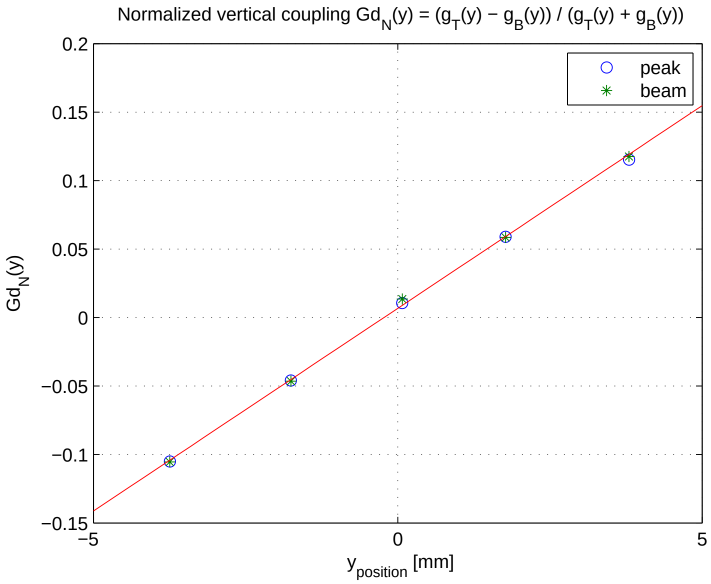
25 microns rms at 0.5E11 (vertical)

Kicker and Beam Excitation MD efforts

two efforts, mixed results

- difficult to excite measurable response
- focus on exponential kicker frequency response as kicker
- What power level is useful/necessary to do this measurement?
- Chamonix implication->fab 2012 kicker?





MD data -Interesting Issues to sort out

Horizontal injection transient feedthrough (movie)

Time scale of injection transient vs. Time scale of instability growth

- Injection transient - 50 turns damping
- Instability growth - less than 100 turns

Concern - will injection transients saturate the ecloud feedback?

- Gain partitioning in channel, noise floor in transverse receiver, power levels
- Needs study and straw man design

Tune 0.2 (5 turns/cycle), growth rate 50 turns - 10 cycles

- What gains are required? Stability? group delay limits?

Dynamics change with energy ramp

- bunch length change, synchronous phase change etc. slow compared to instability growth rates
- Analysis suppresses longitudinal motion - implications for actual channel

Exponential Stripline as Kicker

Frequency response falls as 1/f - is this useful for MD studies?

Feedback System: General Considerations

The feedback system has to stabilize the bunch due to the e-cloud induced or TMCI instability for all the operation conditions of the machine (SPS or LHC).

Requirements for the feedback design

- unstable system - minimum gain required for stability
- delay in the control action (limits gain & bandwidth achievable)
- Ecloud - Beam Dynamics is nonlinear. (tunes or resonant frequency, growth rates change intrinsically)
- e-cloud - Beam Dynamics change due to the operation conditions of the machine.
- Beam signals -Vertical information must be separated from longitudinal/horizontal signals, spurious beam signals and external propagating modes in vacuum chamber
- design has to minimize noise injected by the feedback channel to the beam.

Design has trade-offs in partitioning - overall design must optimize individual functions

Receiver sensitivity vs. bandwidth? Horizontal/Vertical isolation

What sorts of Pickups and Kickers are useful? Scale of required amplifier power?

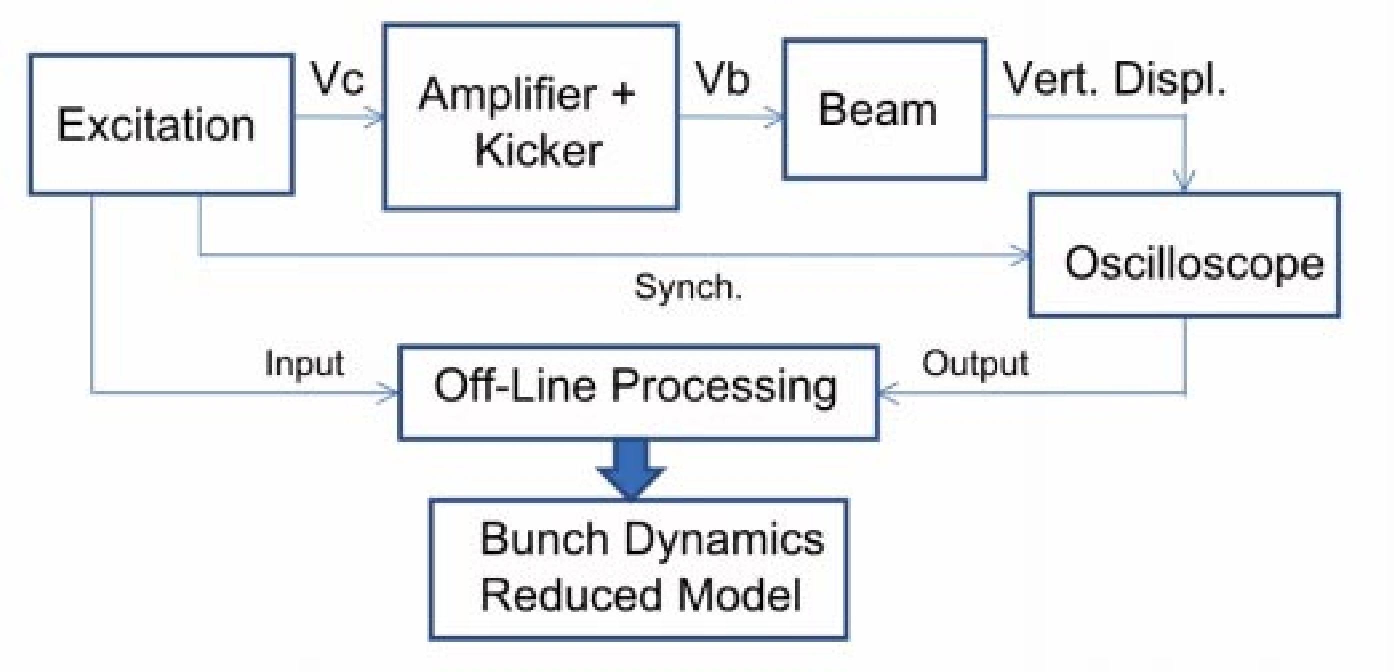
New Wideband Kicker array? Design/development timescale?

Identification of Internal Bunch Dynamics: Reduced Model

- characterize the bunch dynamics
- 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



System Identification via excitation response

Recent effort - Ozhan Turgut

Use a reduced coupled oscillator model (finite # of “slices” of order 8 - 16 corresponding to 4 Gs/sec. sampling)

Excite model (or real machine, or non-linear simulation) with shaped noise

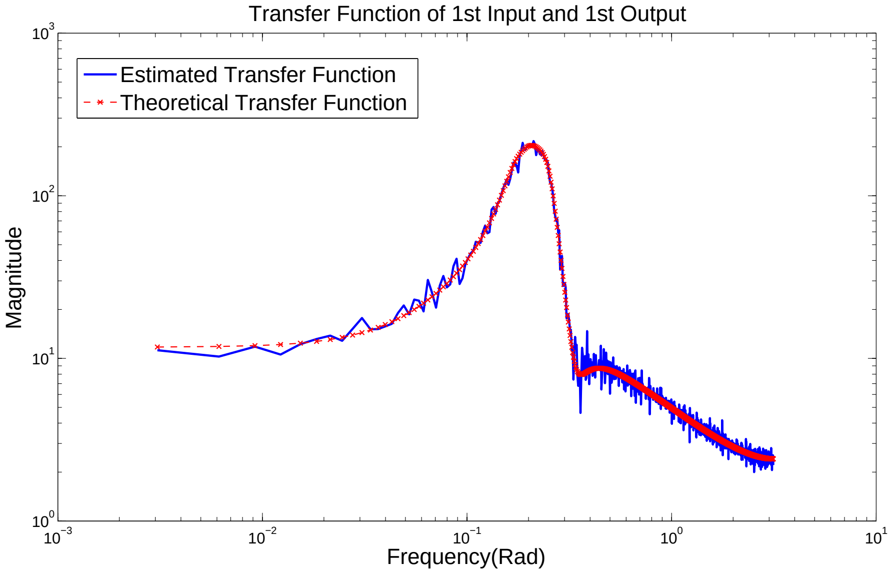
fit model parameters to response, use reduced model for feedback design.

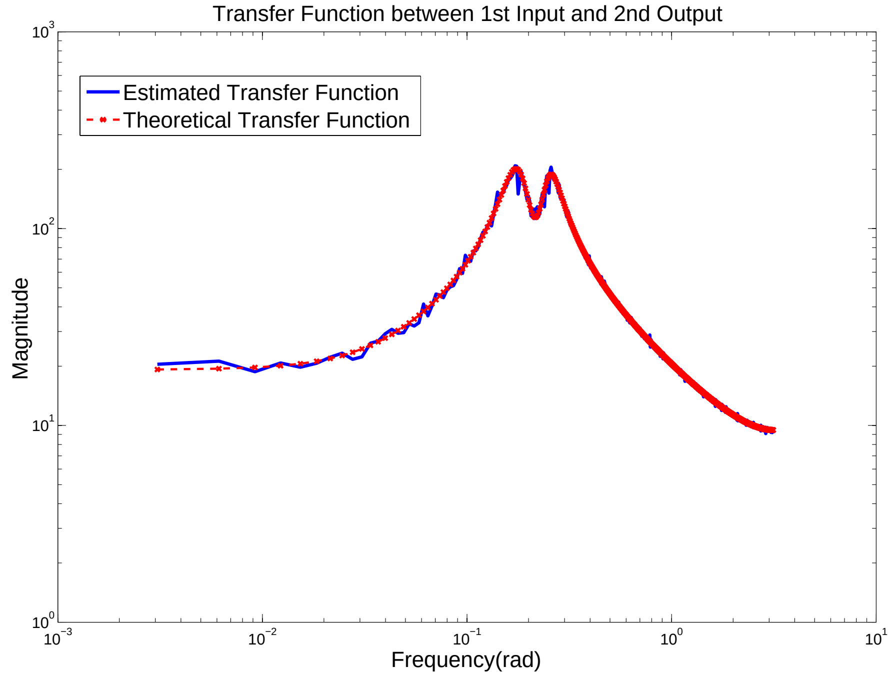
This model fits “all” parameters from inputs to outputs (e.g. oscillator center frequency, Q, complex coupling constant), and it is a time-invariant system. Doesn’t know physics of Ecloud or TMCI

Our problem is time-varying - approach?

Divide time interval into sections?

Full non-linear or parametric approach?


Transfer Function of 1st Input and 1st Output


Transfer Function between 1st Input and 2nd Output

Driven Beam Experiments

Develop excitation technique using existing exponential striplines (requires power amps, hybrids, etc.)

Can be frequency domain or time domain study

Estimate dynamics below instability threshold (pre-chaotic motion, see tune shifts below threshold)

Idea - use 4 GS/sec. DAC hardware to drive noise sequences onto selected bunch(es)

measure excitation, response with two channel fast scope

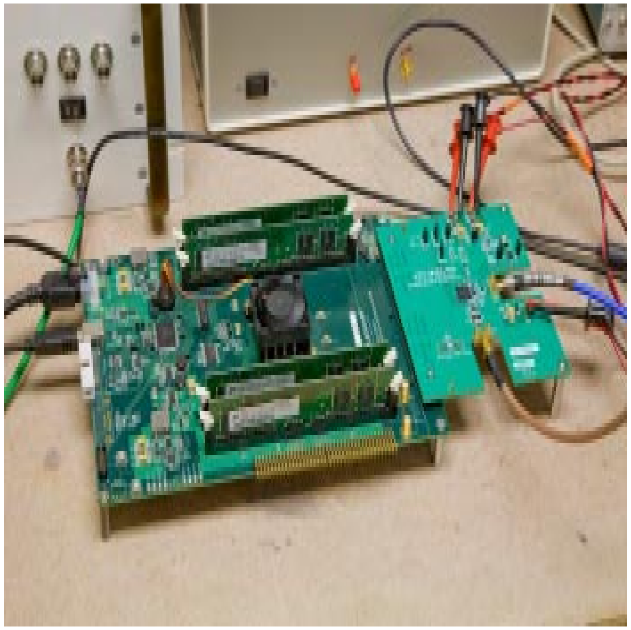
(avoids synchronization complexity)

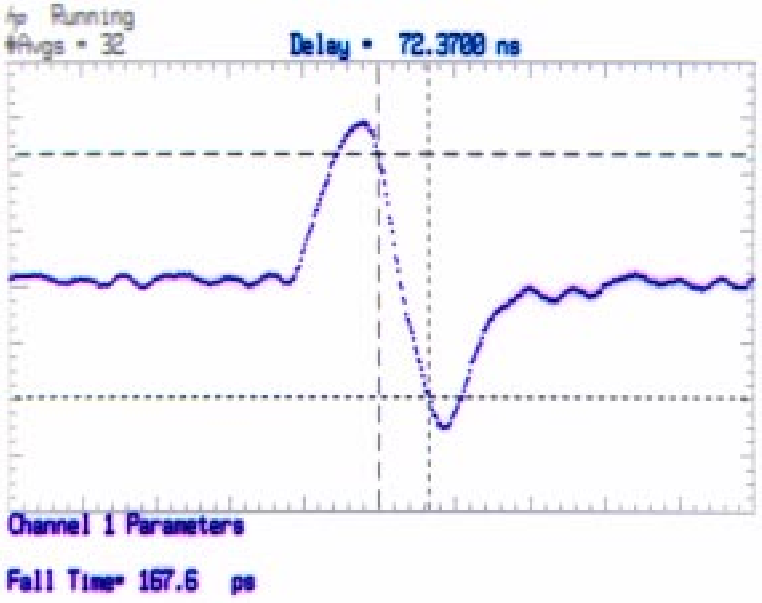
Time domain sequences - transform, average (transfer function estimator)

Frequency response of internal structure and modes

Can be done as excitation in simulation, too.

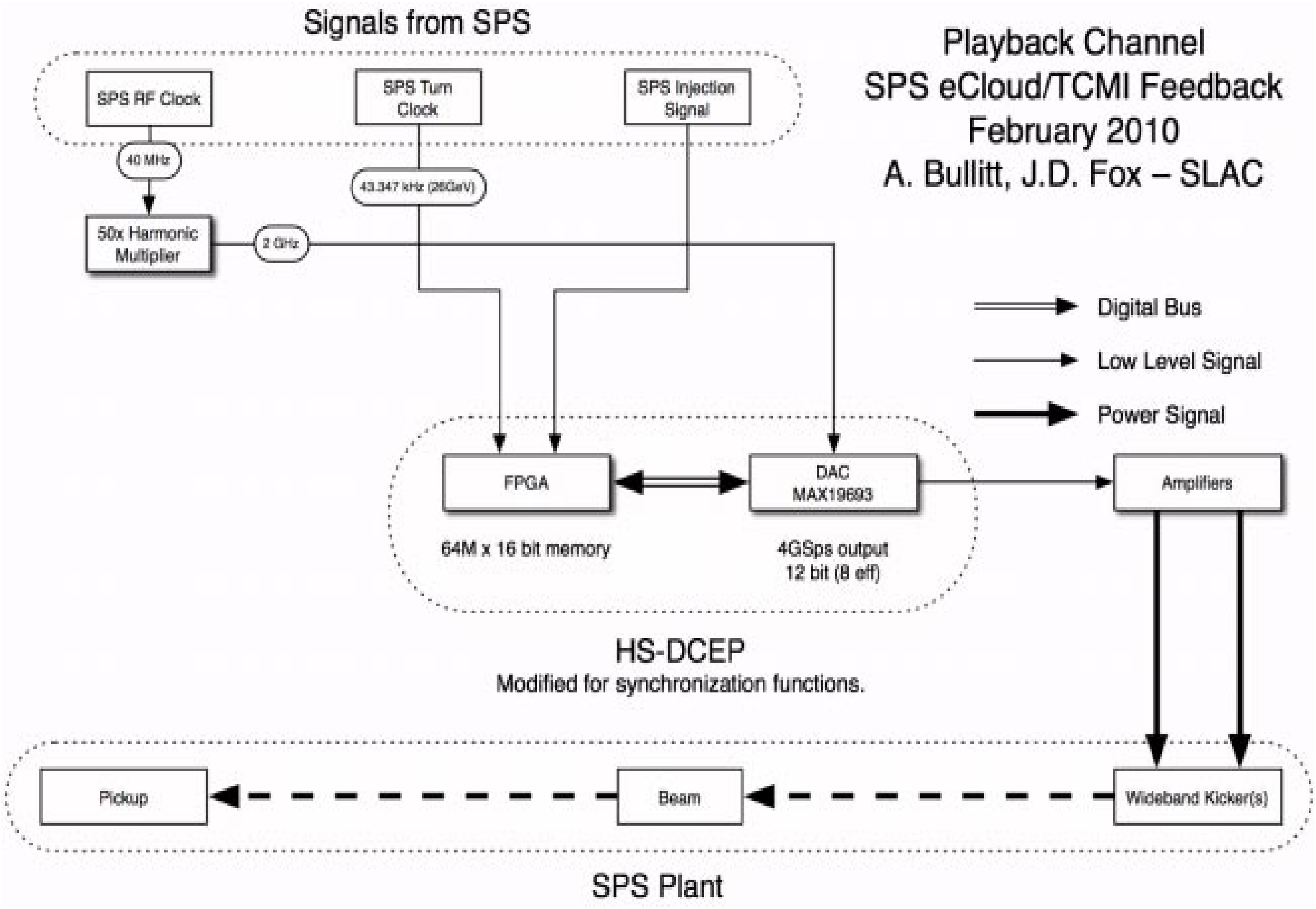
Valuable step in development of any possible feedback controller (Back End)



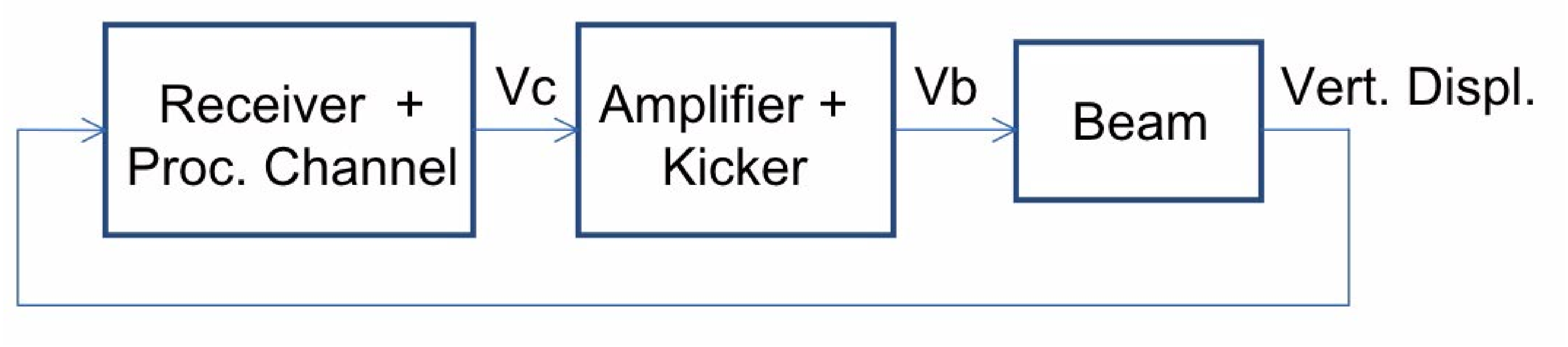


Doublet Response 4 GS/sec. D/A

Excitation system for SPS bunch MD



Closed-Loop feedback around the Model

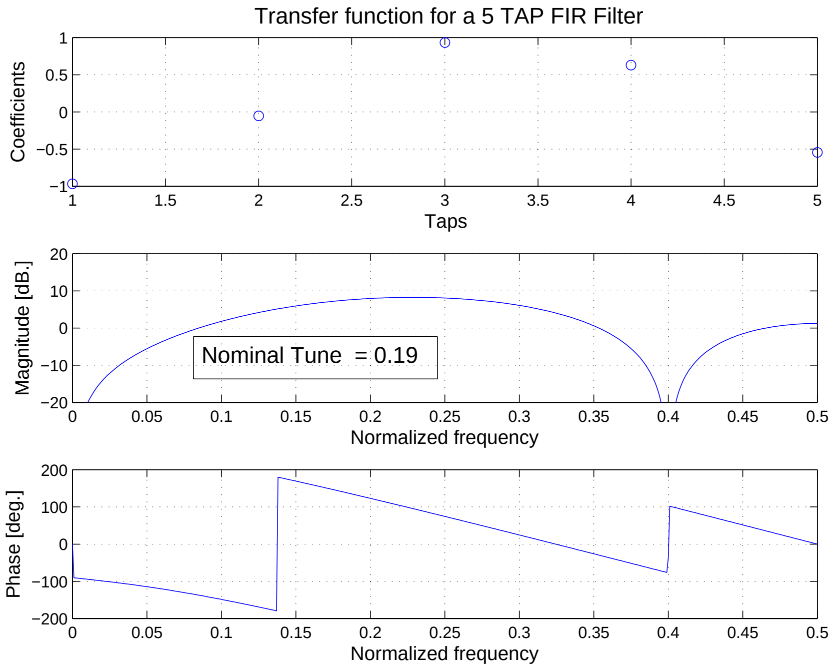


Use the reduced model, with realistic feedback delays and design a simple FIR controller

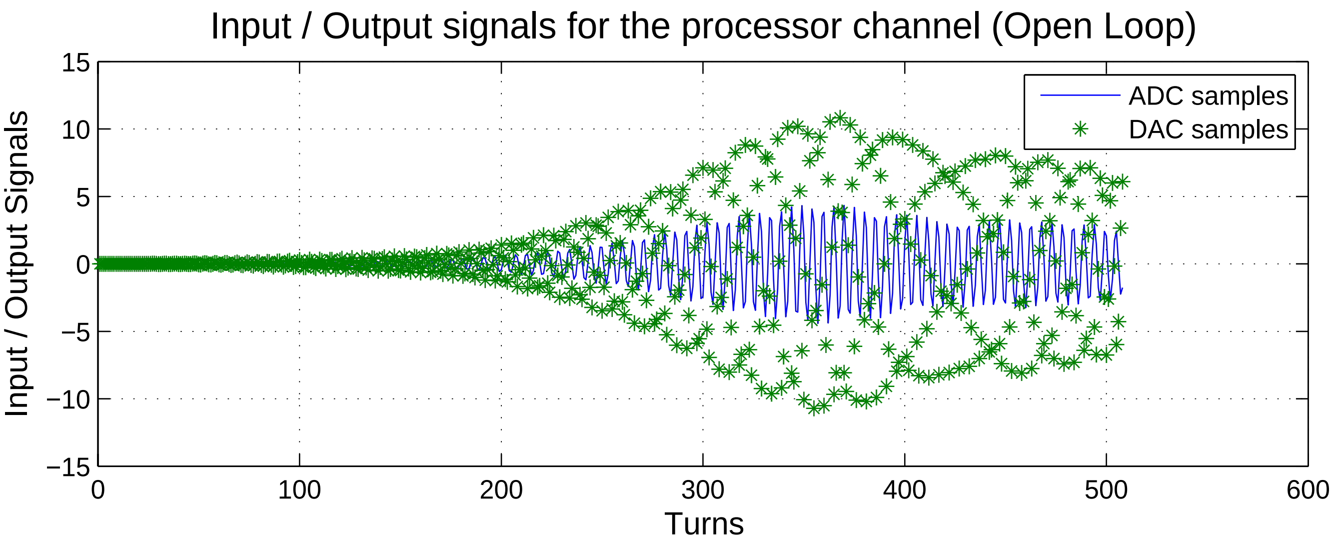
Each ‘slice” is an independent controller

This example 5 tap filter has broad bandwidth - little separation of horizontal and vertical tunes.

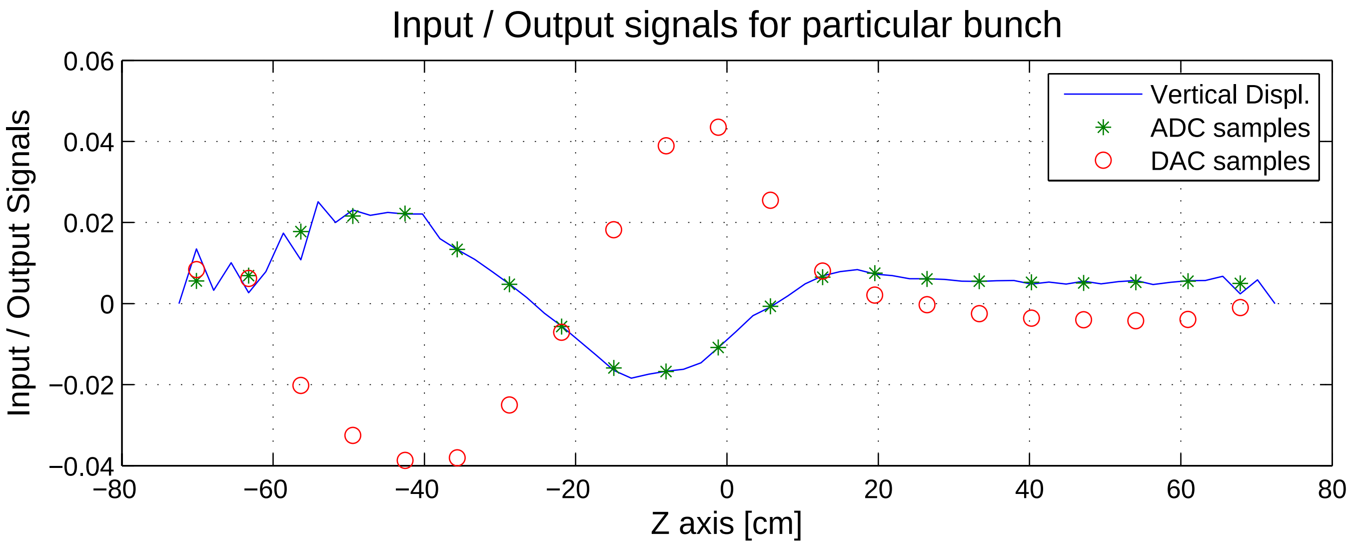
But what would it do with the beam? How can we estimate performance?



Open-Loop Feedback Signals



Top - ADC samples of input (1 slice) and generated output from 5 tap filter



Bottom - Input/ output for all slices of 1 single bunch (note head-tail differential motion)

Root Locus (closed loop), nominal tunes

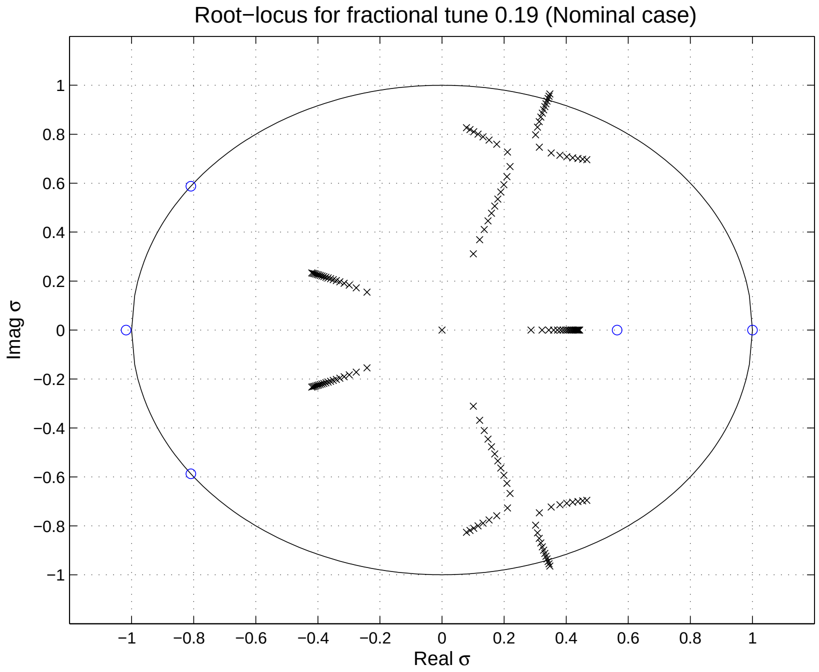
Root Locus - closed loop eigenvalues (vs. overall loop gain)

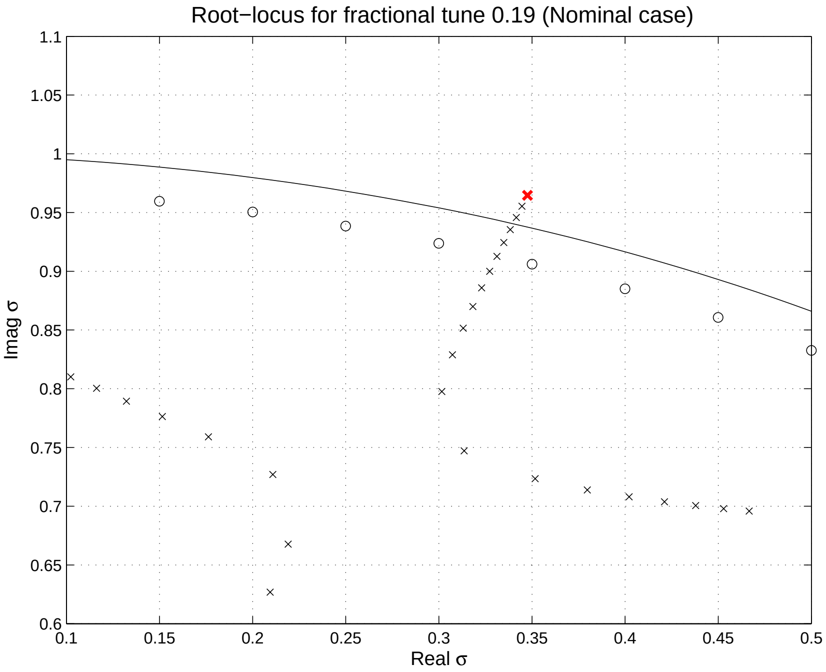
Analytic study of stability - what gain is needed for damping?

When will the loop go unstable with too much gain?

How does the feedback change the natural frequencies of the closed-loop system

Example - we start unstable, with gain bring to damping=growth rate, then extra gain shifts frequency, heads towards instability





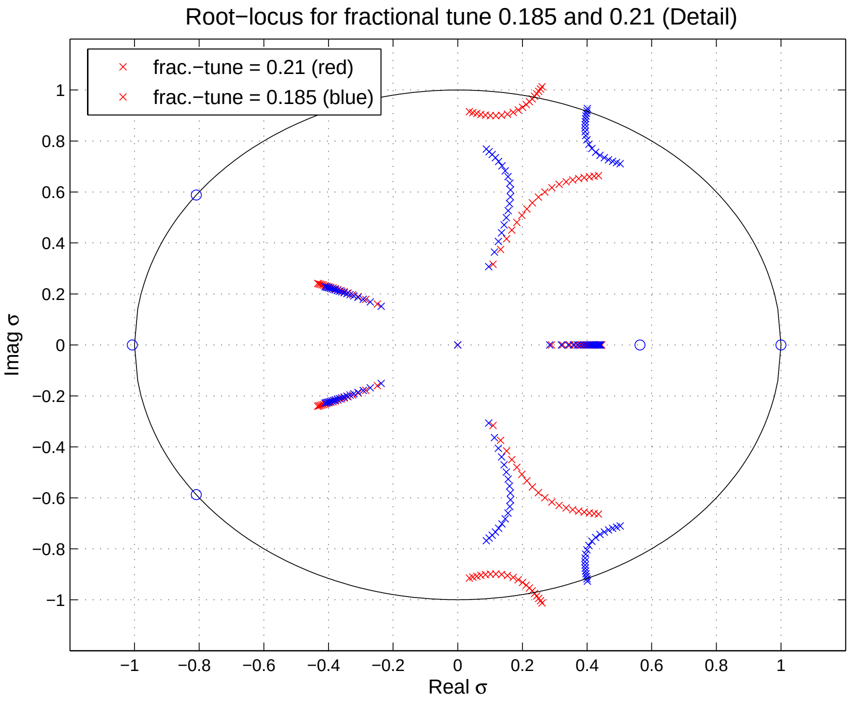
Tune shifted from 0.185 to 0.21

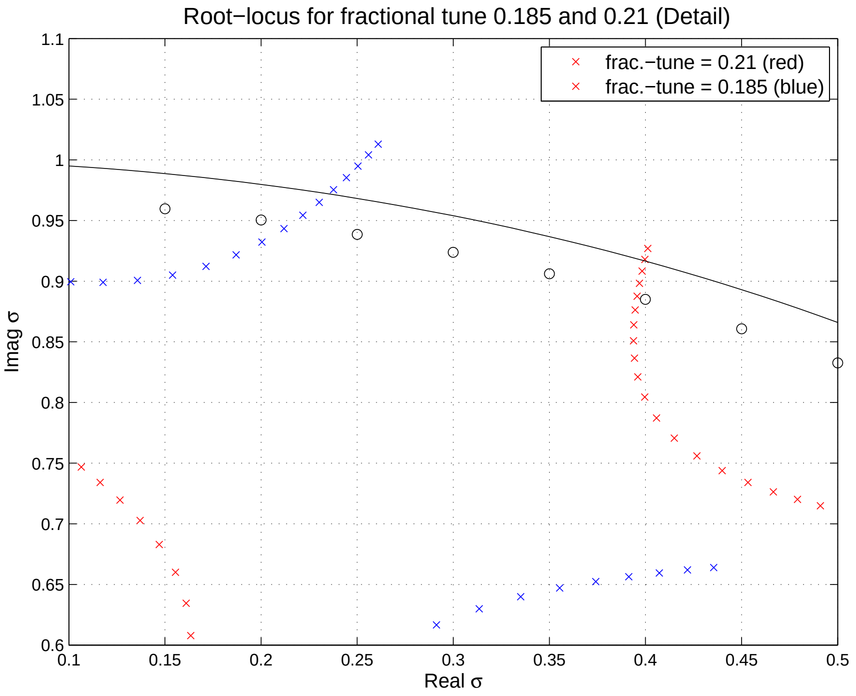
We study the stability for a range of tunes

This filter can control both systems

Maximum damping is similar in both cases

Is this realistic case to design? We need more data from simulations and MD





Feedback Channel - Complexity? 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.

Technology development

Can we build a “small” prototype” style feedback channel? What fits in our limited LARP hardware budget? what to do in 2010? 2011?

Idea - build 4 GS/sec. channel around

2 Maxim MAX109EVkit A/D evaluation boards

- 4/8 wide multiplexing, so 500 MHz sample rates?

SLAC-developed Vertex 5 FPGA parallel-processing

- digital I/O, 8 way raw parallelism

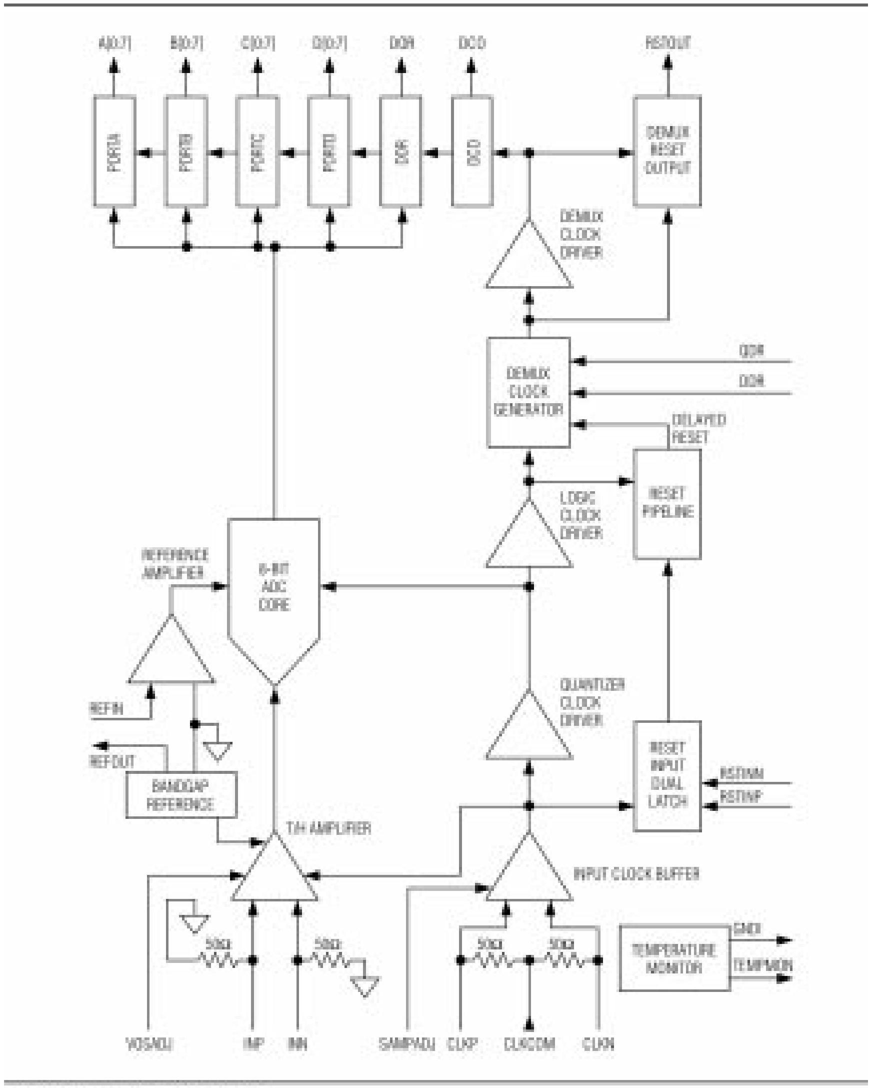
1Maxim 19693 D/A evaluation board

RF harmonic multiplier -> sampling from SPS RF

Use existing exponential striplines for pick and kicker

(requires power amps, power loads, hybrids, etc.)

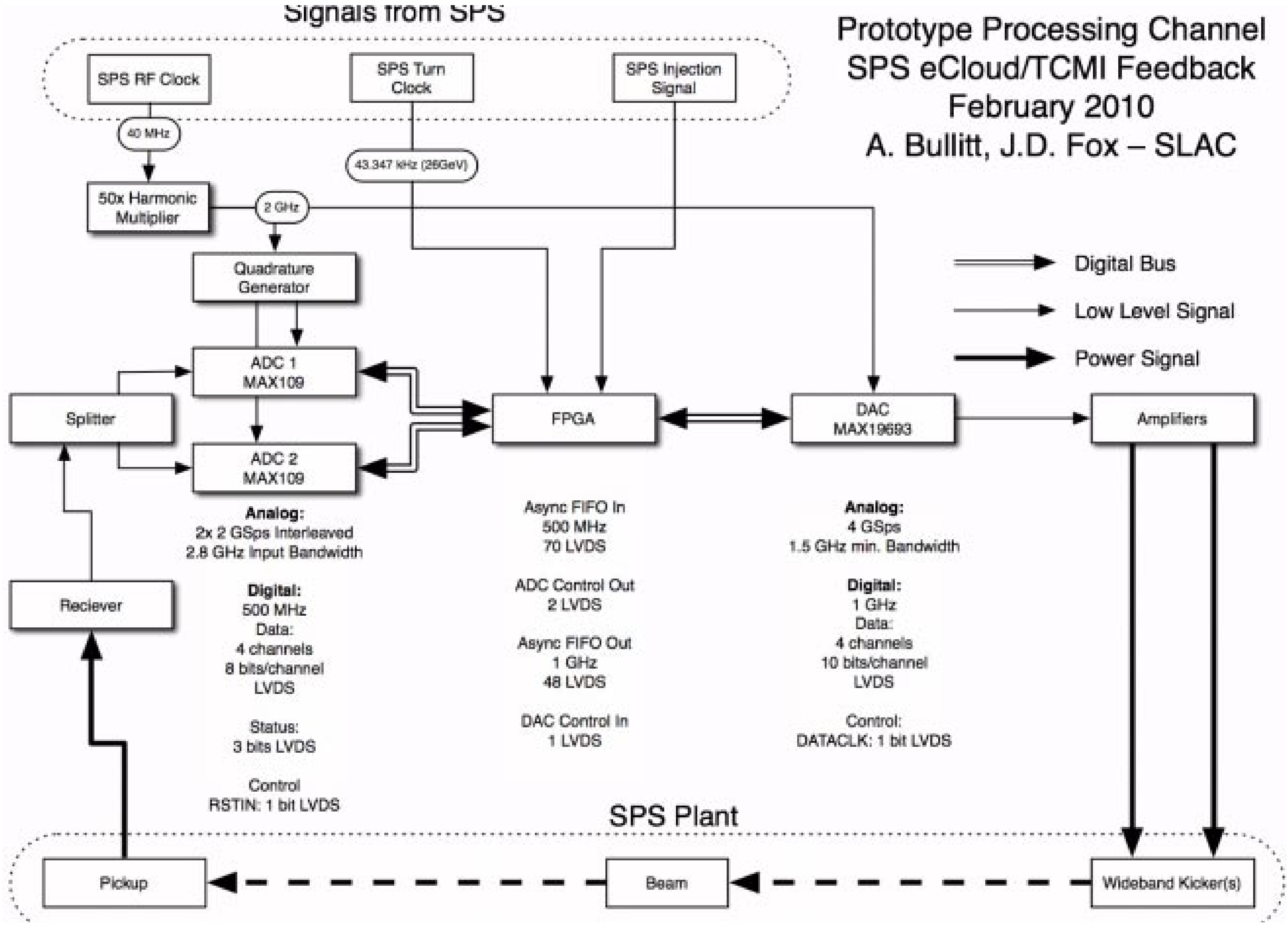
Maxtek 6 Gs/sec. A/D and D/A option with Synopsys FPGA development board is too expensive for our present budget, though is interesting for a more complete prototype implementation



ctional Diagram of the MAX109

MAXIM 109 2.2 GS/sec. A/D

Design study - 4 Gs/sec. 1 stack SPS feedback channel



Progress FY2009/2010 LARP Ecloud/TMCI

understand Ecloud dynamics via simulations and machine measurements, include TMCI

- Participation in studies at the SPS (next opportunity summer 2010)
- Analysis of SPS and LHC beam dynamics studies, comparisons with Ecloud models
- Initial coordination with B. Salvant on TMCI models - expand dynamics effort

Modelling, estimation of feedback options and feedback simulation

- extraction of system dynamics, development of reduced (linear) coupled-oscillator model for feedback design estimation
- develop analysis tools to quantify and compare system dynamics
- Initial study of feedforward/feedback techniques to control unstable beam motion, change dynamics. Estimate limits of techniques, applicability to SPS and LHC needs

Lab effort -develop 4 GS/sec. excitation system for SPS

- modify existing system to synchronize with selected bunches - data for system ID tools
- Identify critical technology options, evaluate difficulty of technical implementation
- explore 4 Gs/sec. “small prototype” functional feedback channel for 2011 fab and MD use

Two IPAC papers on Simulation effort, MD data and analysis

Goals -FY2009/2010 LARP Ecloud effort

understand Ecloud dynamics via simulations and machine measurements

- Participation in E-Cloud studies at the SPS (next opportunity spring 2010)
- Analysis of SPS and LHC beam dynamics studies, comparisons with Ecloud models
- Adaptation of SLAC’s transient analysis codes to Ecloud simulation data structures

Modelling, estimation of E-Cloud effects

- Validation of Warp and Head-Tail models, comparisons to MD results
- comparisons with machine physics data (driven and free motion), validation of models, estimates of dynamics. Critical role of Ecloud simulations in estimating future conditions, dynamics
- extraction of system dynamics, development of reduced (linear) coupled-oscillator model for feedback design estimation
- develop analysis tools, hardware systems to quantify and compare system dynamics
- evaluate feasibility of feedforward/feedback techniques to control unstable beam motion, change dynamics. Estimate limits of techniques, applicability to SPS and LHC needs
- Identify critical technology options, evaluate difficulty of technical implementation
- Evaluate SPS Kicker options re: Chamonix planning, 2012 shutdown window

Decision Point - late 2010

Is the Ecloud dynamics feasible for feedback control? What techniques are applicable?

Research Goals - 2009 - 2011

- Modelling of closed-loop system dynamics, estimation of feedback system specifications
- Evaluation of possible control architectures, possible implementations, technology demonstrations
- SPS Machine Physics studies, development of “small prototype” and closed loop studies

Decision point 2011 - Proof of principle design studies, estimates of performance

System development Goals 2012 and beyond

Technology R&D - Specification of wideband feedback system technical components

Technical analysis of options, specification of control system requirements

- Single bunch control (wideband, within bunch Vertical plane)- Required bandwidth?
- Control algorithm - complexity? flexibility? Machine diagnostic techniques?
- Fundamental technology R&D in support of requirements - Kickers and pickups?
- wideband RF instrumentation, high-speed digital signal processing

Develop proof of principle processing system, evaluate with machine measurements

System Design Proposal and technical implementation/construction project plan

Recent Publications and Talks from the LARP Ecloud Effort

Feedback Techniques and Ecloud Instabilities - Design Estimates. J.D. Fox, T. Mastorides, G. Ndabashimiye, C. Rivetta, D.Van Winkle (SLAC), J. Byrd, J-L Vay (LBL, Berkeley), W. Hofle, G. Rumolo (CERN), R.De Maria (Brookhaven). SLAC-PUB-13634, May 18, 2009. 4pp. Presented at Particle Accelerator Conference (PAC 09), Vancouver, BC, Canada, 4-8 May 2009.

Simulation of a Feedback System for the Attenuation of E-Cloud Driven Instability Jean-Luc Vay, John Byrd, Miguel Furman, Marco Venturini (LBNL, Berkeley, California), John Fox (SLAC, Menlo Park, California) Presented at Particle Accelerator Conference (PAC 09), Vancouver, BC, Canada, 4-8 May 2009

INITIAL RESULTS OF SIMULATION OF A DAMPING SYSTEM FOR ELECTRON CLOUD-DRIVEN INSTABILITIES IN THE CERN SPS J. R. Thompson?, Cornell University, Ithaca, USA, J. M. Byrd, LBNL, Berkeley, USA W. Hofle, G. Rumolo, CERN, Geneva, Switzerland 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)

Feedback Control of Ecloud Instabilities, J. Fox et al CERN Electron Cloud Mitigation Workshop 08

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

Observations of SPS e-cloud instability with exponential pickup, R. De Maria, CERN Electron Cloud Mitigation Workshop 08

Experiments on SPS e-cloud instability Giovanni Rumolo, CERN Electron Cloud Mitigation Workshop 08

Progress on WARP and code benchmarking Marco Venturini, CERN Electron Cloud Mitigation Workshop 08

Ecloud and Feedback - Progress and Ideas, J. Fox Et al LARP CM12 Collaboration meeting Napa CA, CM13 meeting Port Jefferson L

Movies of June 16, 2009 SPS MD

MD data at 1E11 P/bunch, with three chromaticity values (.1,.2 and -.1), 2 RF voltages

Pre-processing includes equalization (cable response), suppression of longitudinal motion

(www.slac.stanford.edu/~rivetta/e-clouds/movies_Aug09 and

also in http://www.slac.stanford.edu/~dandvan/e-clouds/aug_09/)

1E11 P/bunch, 25 ns separation, 72 bunches/batch (June 2009 MD data)

Injection of batch 1 (stable) followed by 2nd batch (which goes unstable)

Movie 1- Vdspl_bunch_47.avi Vdisplacement for bunch 47 1st batch (stable)

Movie 2 - Vdspl_bunch_119.avi Vdisplacement for bunch 47 2nd batch (#119 e-clouds)

Movie 3 - tune_s.avi Sliding Window spectrogram of Bunch 117 vertical signal by slice

Movie 4 - centroid.avi Centroid tune shift along 620 turns

Movie 5 - rms.avi RMS of slice motion with respect to the bunch centroid

These animations help show the complexity and non-linear behavior of the system

We need to extract simpler model dynamics to use to design/estimate feedback control

Movies, Continued

Video1: Tune evolution and RMS of the vertical displacement (motion of slices respect to the centroid) of bunch 47 of the 2nd batch for run 51. The bunch is unstable. The RMS value is high, intense oscillations, and significant tune shift. Notice the bunch wide oscillation around the peak of the RMS value. (behavior similar to the RMS.avi movie)

Video2: Comparison of tune evolutions of bunch 45 and 47 of the 2nd batch for run 51. Notice the similarities of both evolutions. Similar Ecloud density and intial conditions?

Video3: (The data was taken at unknown time after the injection). Tune evolution and RMS of the vertical displacement of bunch 47 of the 2nd batch for run 48. The bunch is unstable. The RMS value is high, intense oscillations, and significant tune shift. Notice a different evolution pattern of this bunch from those with digitalization which began at injection (such as Video1).

Video4: Tune evolution and vertical RMS of bunch 5 of the 2nd batch for run 51. The bunch is stable. The RMS value is low, small oscillations, no tune shift.

Video5: Tune evolution and RMS of the vertical displacement of bunch 47 of the 1st batch for run 51. The bunch is stable. The RMS value is low, little oscillations, and no tune shift

More movies in directory, look at Brief description of videos.pdf

Critical data to estimate - required sampling rate (bandwidth), growth rates, tune shifts, internal modes

Feedback Estimation- requires quantitative knowledge of ecloud/beam dynamics

Goal - develop quantitative analysis methods, normal-mode, other formalisms

- Equalization, suppression of longitudinal motion effects
- Modes within the bunch (e.g. bandwidth of feedback required)
- growth rates of modes (e.g. gain of feedback channel)
- tune shifts, nonlinear effects (e.g. Stability, robustness of feedback process)

sliding window FFT techniques - check tunes, tune shifts

- slice FFTs (tune per slice)
- vs. time (modes within a bunch)

RMS techniques - on SUM and Delta (estimation of motion of the beam, time evolution, charge loss)

Estimate impacts - injection transients, external excitations, imperfections/noise in receivers, power stages.

Recent Emphasis - System Identification methods to fit coupled-oscillator models to data