Feedback Control of SPS E-Cloud/TMCI Instabilities
Progress Report, Ideas for Discussion

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LARP Ecloud Contributors

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LHC/SPS Ecloud/TMCI driven instability R&D

Proton machines, Ecloud driven instability - impacts upgraded LHC (and SPS injector)

- Photoelectrons from synchrotron radiation - attracted to positive beam
- Coupled-dynamics, electrons act as lens to kick transversely (vertically)
- Single-bunch effect - head-tail (two-stream) instability

Research directions

- Simulations
- Machine measurements - understand required bandwidth, validate simulations
- What sort of feedback control is feasible? Development of 4 GS/sec. processing channel demonstrator

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)
- Hardware technology development (SLAC)
- Kicker Options - Design report (LBL/SLAC)

Organization and Lab Contributions

SLAC John Fox, Claudio Rivetta, Jeff Olsen

2 Stanford grad students

- Maximilian Swiatlowski (Analysis techniques)
- Ozhan Turgut (system identification, dynamics models)

Ecloud Simulation effort (LBL)

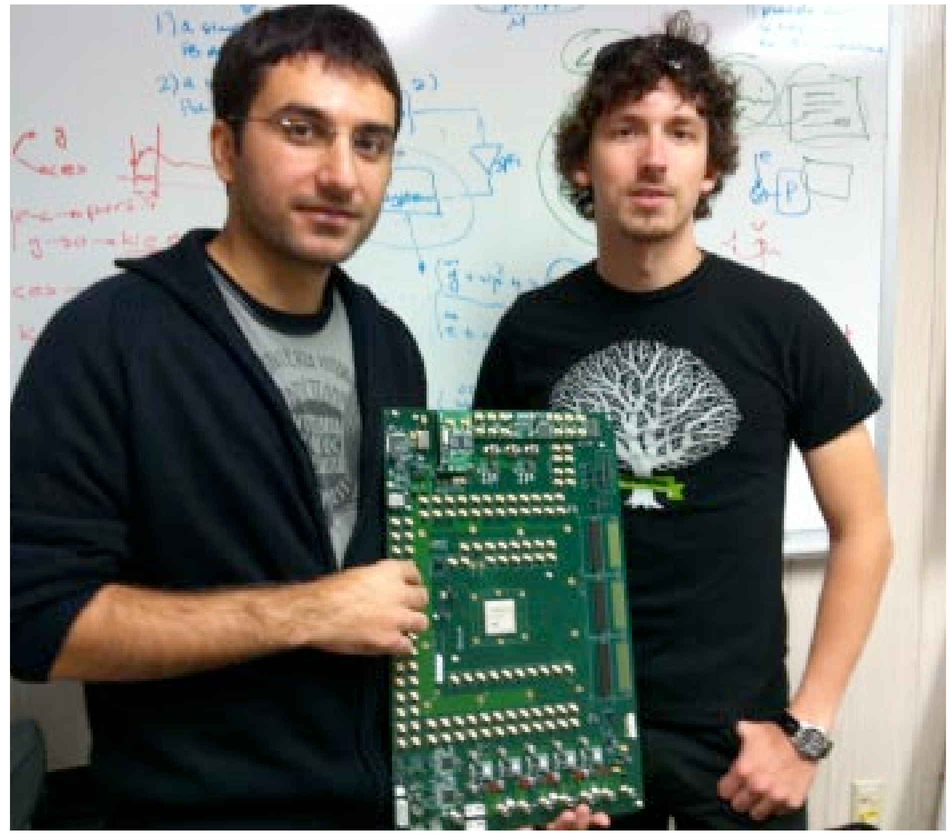
Jean-Luc Vay, Miguel Furman, R. Secondo

- simplified initial feedback model in WARP

Kicker Design study (SLAC/LBL)

CERN - Wolfgang Hofle, Benoit Savant

- SPS/LHC transverse feedback, TMCI models



Ecloud dynamics studies and Simulation effort (CERN)

Giovanni Rumolo, Gianluigi Arduini

Feedback Ecloud/TMCI mitigation is complementary to coatings, other dynamics approaches

SPS Instrumentation - setup

Pickups - wideband (exponential taper) striplines (T. Linnecar)

(history of directivity, past use in P-Pbar program)

Cable plant from SPS Tunnel to Faraday cage (instrument room)

Hybrid receiver (Anzac H9 Hybrids)

- Cable delays trimmed, matched, hybrids selected for matching
- Issues with 1700 MHz propagating modes - use of 800 MHz (1 GHz etc.) Bessel Filters

Data Acquisition (vertical plane) in Tektronix fast scope (2.5 GHz bandwidth, 10 or 40 PS/sample)

Offline data analysis in Matlab (and Python)

Equalization of stripline signal (thanks WH and RDM), removal of longitudinal motion

RMS techniques (with subtraction of DC transient)

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

FFT based sliding window techniques

- slice by slice (tune shifts within a bunch)
- within bunch (bandwidth or internal modes)

Quick Review of June 2009 and July 2010 SPS MD

- data recorded, pickup details, data acquisition (bandwidth of bessel filters, etc.)
- Beam conditions, machine state

Analysis techniques

- Equalization, suppression of longitudinal motion effects
- FFT based analysis - tune shifts of slices, FFT of modes within bunch
- RMS based analysis - amplitudes of motion vs. time, trajectories

Observations

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

Analysis of Ecloud simulations, Ecloud MD data, TMCI MD data

Time domain simulations, measurements - necessary to estimate feedback requirements

- 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 - important charge measurement (TMCI charge loss)
- frequencies within bunch - estimated bandwidth of instability signal, correction signal
- Growth rates of eigenmodes - initial fits and stability observations, gain requirements

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?

SPS MD Studies

Ecloud studies June 2009, April 2010 July 2010. Vertical Instability develops after injection of second batch, within 100 turns. Time domain shows bunch charge, and transverse displacement 1E11 p/bunch (June2009). Roughly 25 slices (250 ps) between displacement maxima and minima

TMCI Studies July/August 2010. Single bunch injection at 1.3E11 (3E11). Vertical instability develops - time scales of 1000 turns

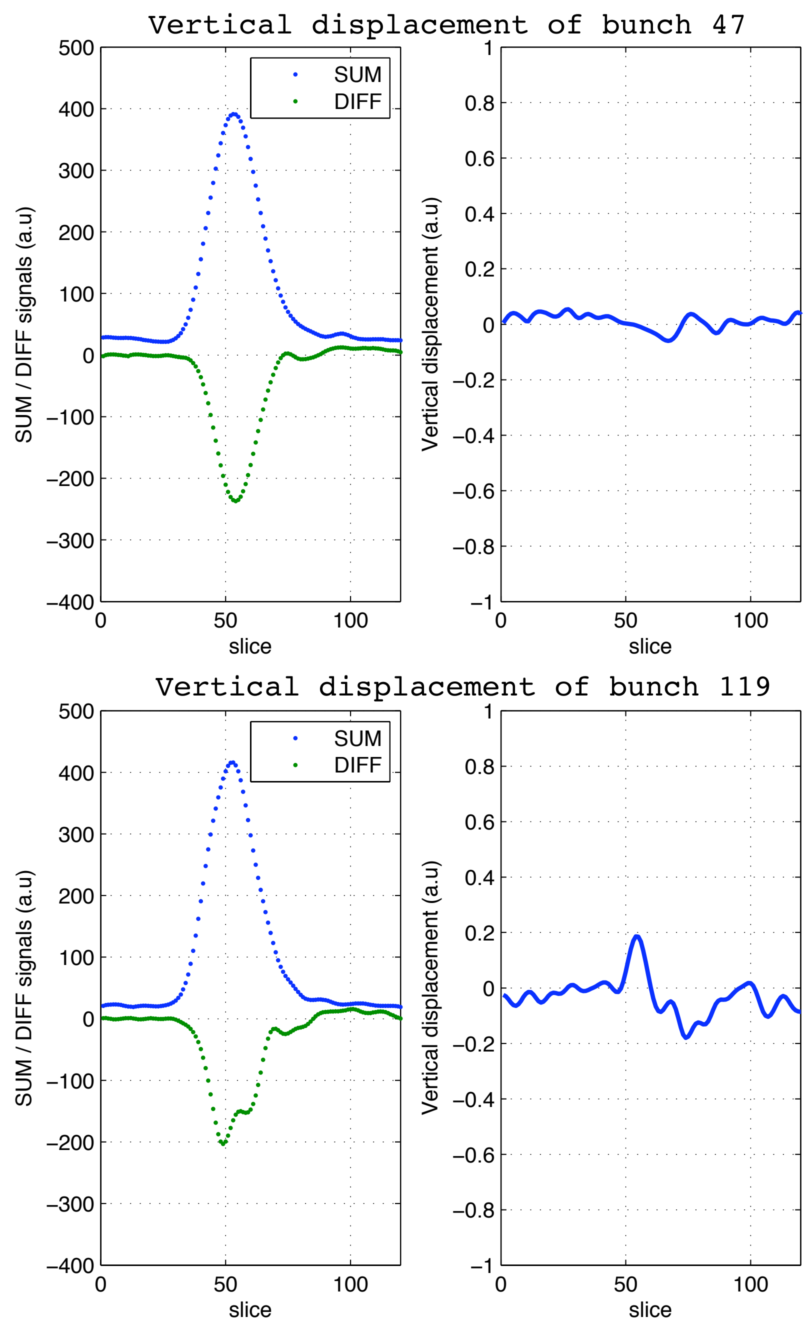
We need MD data to compare beam simulations and dynamics models, - extract beam dynamics necessary to design feedback.

April 2010 - characterize existing SPS pickups and drive tapered pickup as kicker

pickups -Noise, transverse resolution well-quantified

Kicker and Beam Excitation, mixed results

difficult to excite measurable response



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 initial 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

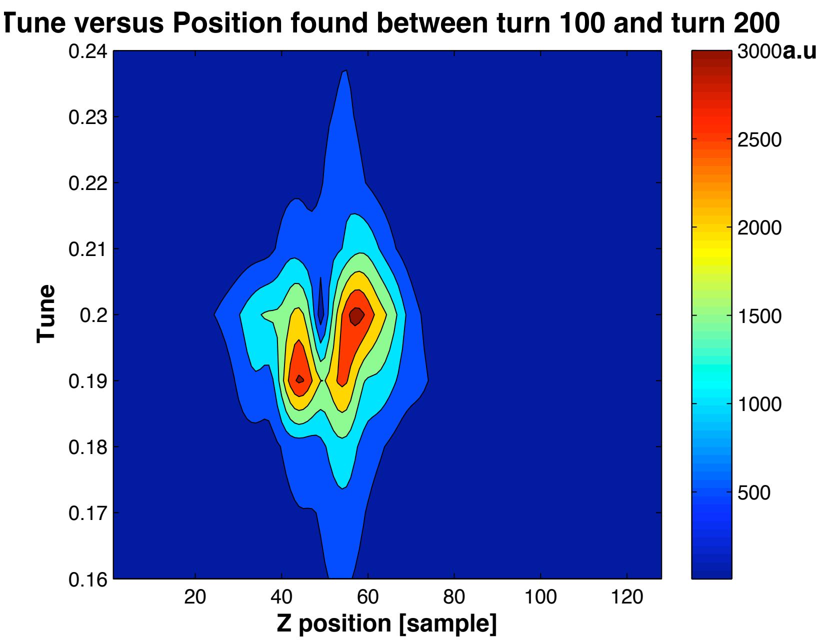
Analysis of Ecloud simulations and Ecloud MD data

Observations

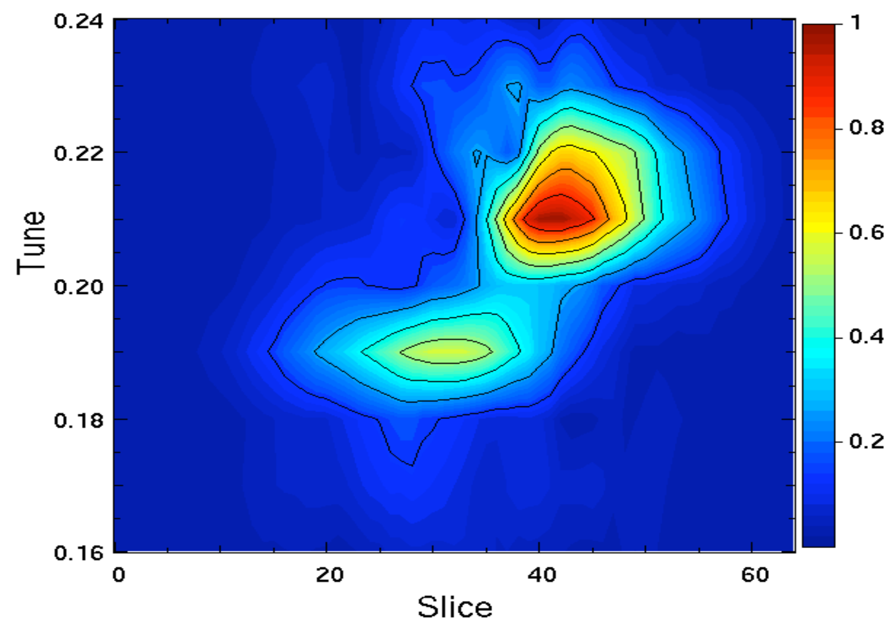
- tune shifts within bunch due to Ecloud, bursting, positions of unstable bunches in trains
- frequencies within bunch - estimated bandwidth of instability signal, correction signal
- Growth rates of eigenmodes - initial fits and stability observations

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?



MD Data - Bunch 119 June 2009

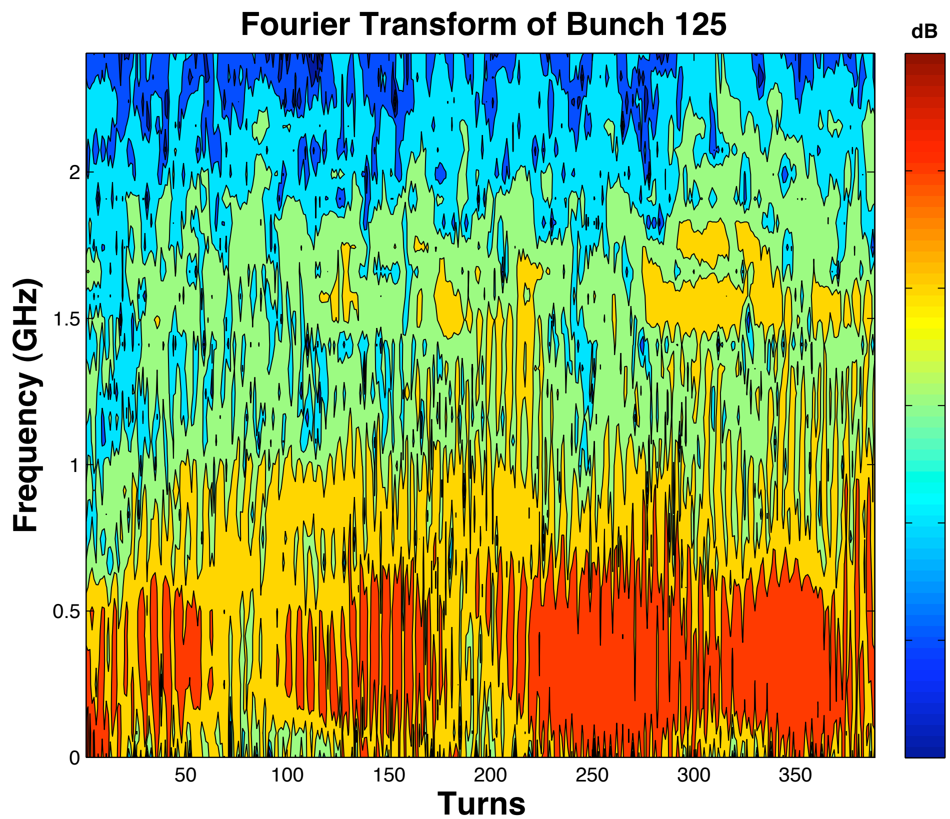


WARP - SEY adjusted, different Bunch

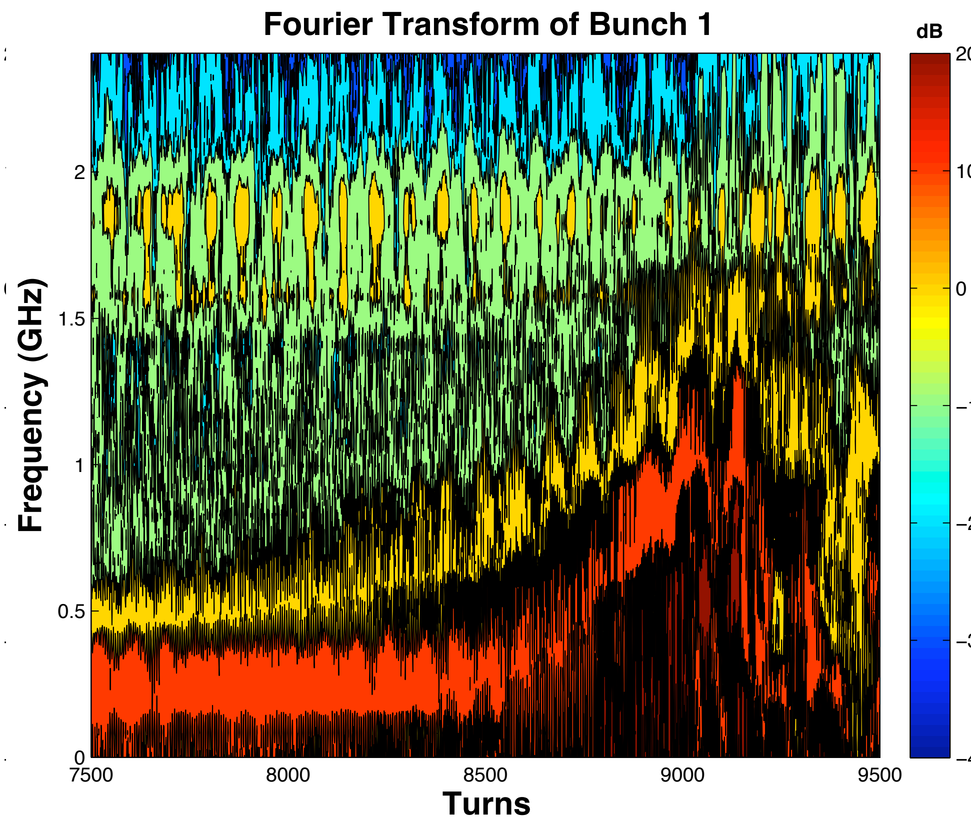
Ecloud MD and TMCI MD - observations from Bandwidth analysis

Observations -

- Ecloud signal bandwidth - roughly 300 - 1000 MHz (but bandlimited in acquisition)
- TMCI signal bandwidth - initially 300 MHz, grows to above 1.5 GHz as full amplitude develops



Ecloud



TMCI

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)

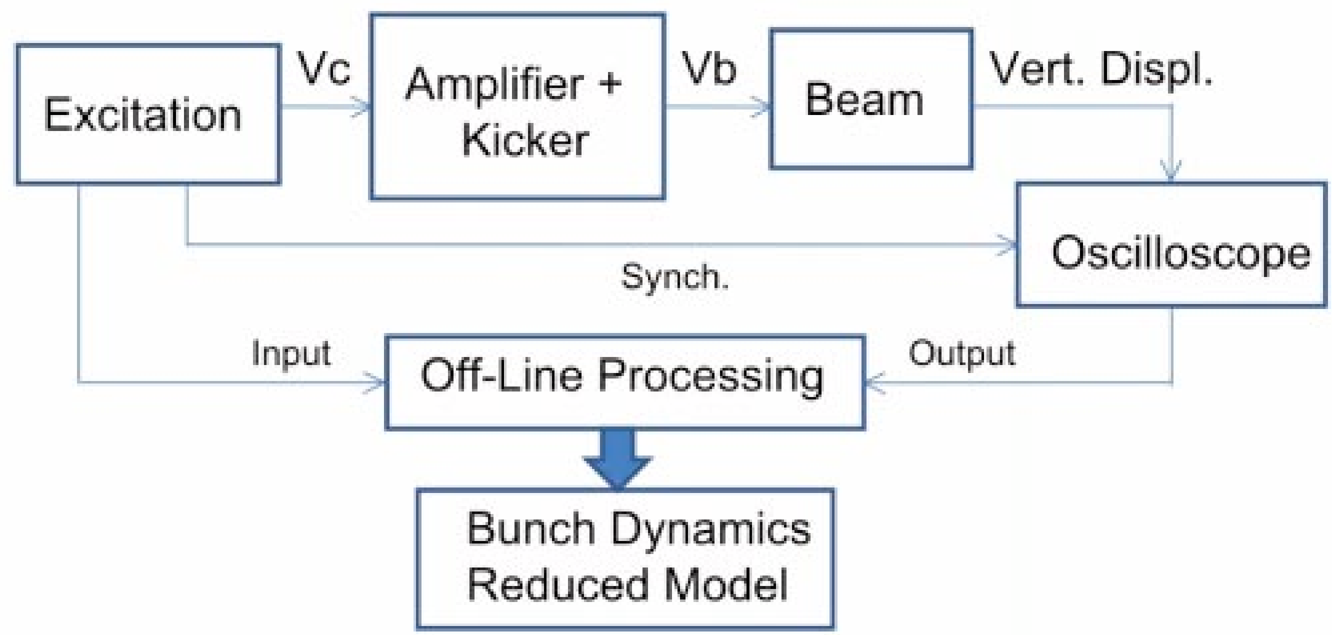
RMS techniques - on SUM and Delta (estimation of motion of the beam, time evolution, charge loss)

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

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

Identification of Internal Bunch Dynamics: Reduced Model

- characterize the bunch dynamics, critical to design the feedback algorithms
- .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

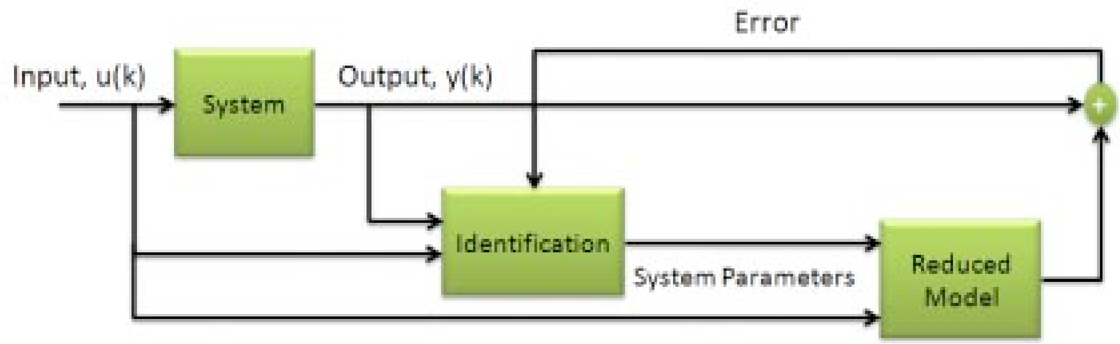
Recent effort - Ozhan Turgut

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.

System Identification



$$x(k+1) = A(kT)x(k) + B(kT)u(k)$$

$$y(k) = C(kT)x(k) + D(kT)u(k)$$

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?

Driven Beam Experiments

Develop excitation technique using existing exponential striplines

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)

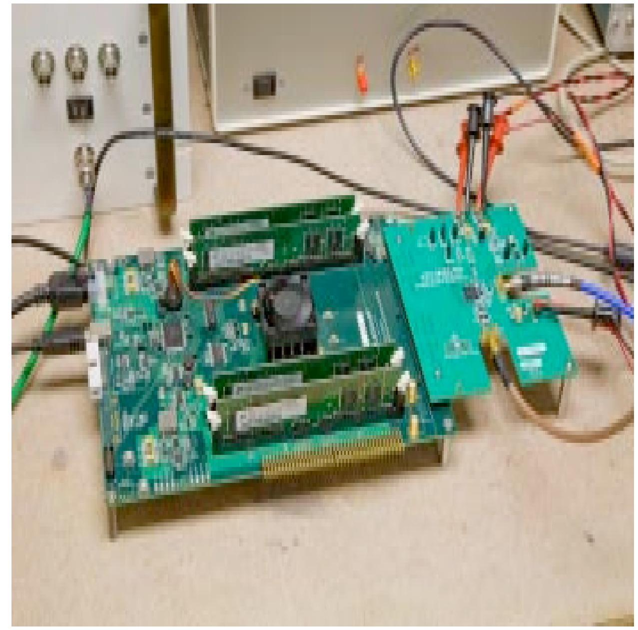
Time domain sequences - transform, average (transfer function estimator)

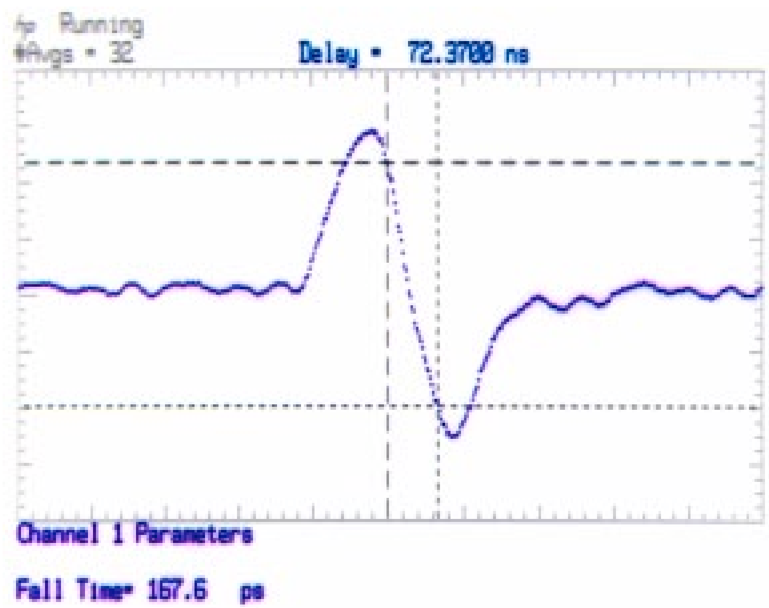
Frequency response of internal structure and modes Can be done as excitation in simulation, too.

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

Progress - Synchronized excitation code

400W (4 100W) 20 - 1000 MHZ amplifiers. Tunnel "cart" in progress for 2011 SPS MD





Doublet Response 4 GS/sec. D/A

Driven Beam Experiments

Progress - Synchronized excitation code - synch to SPS RF and turn

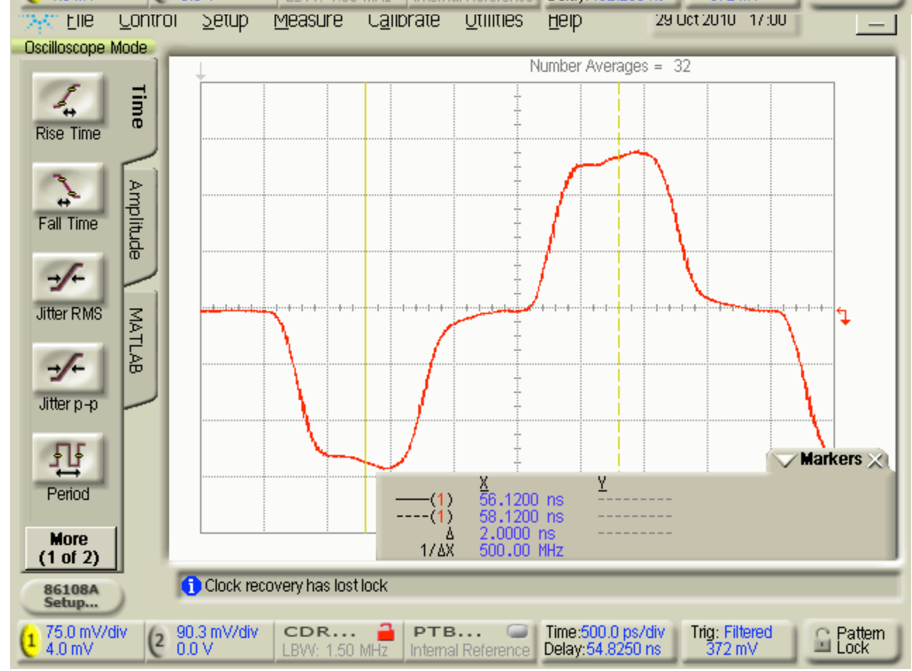
System can drive selected bunches in trains, 32 samples/bunch (250 ps/sample)

Tunnel “cart” in progress for 2011 SPS MD

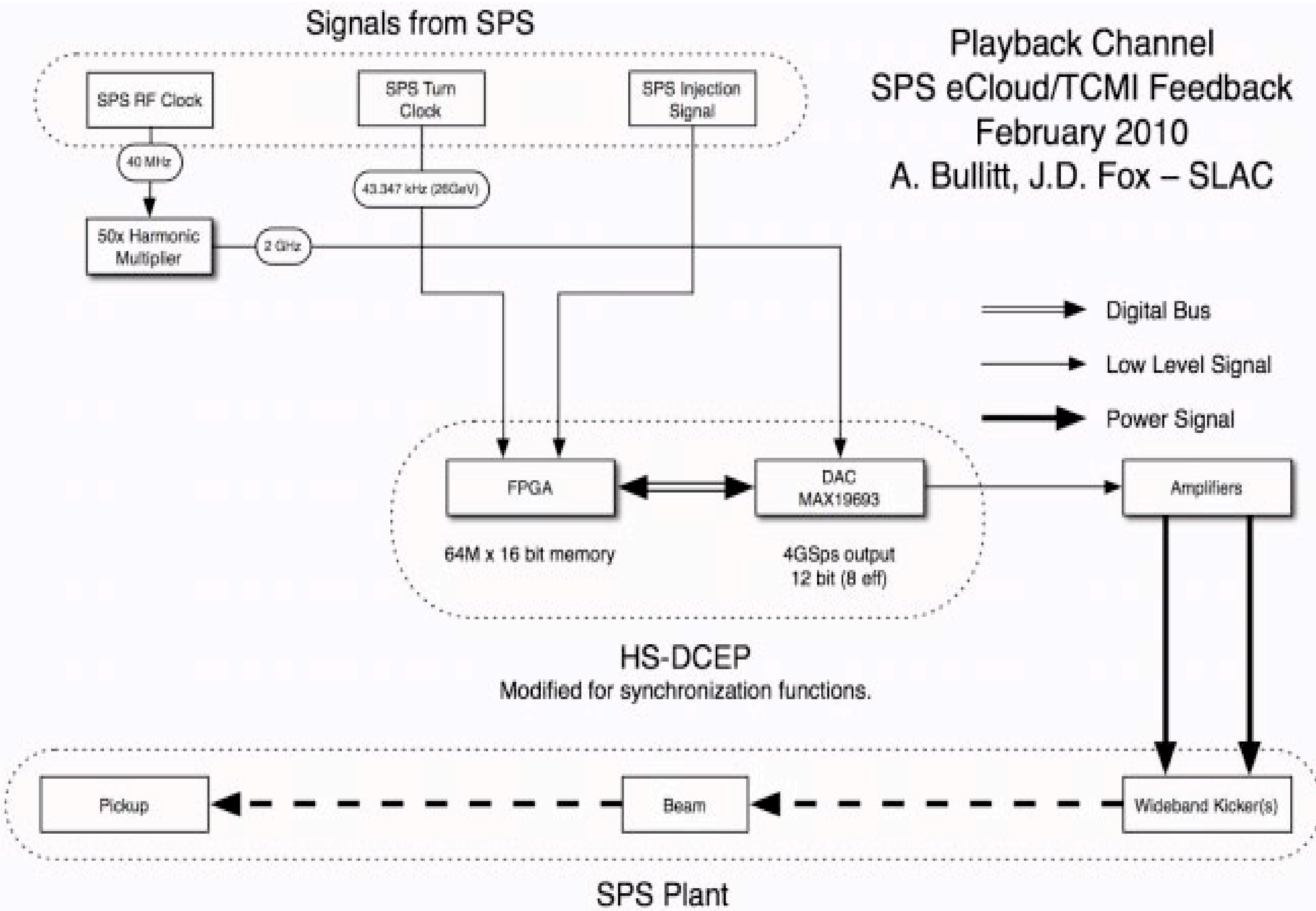
- 400W (4 100W) 20 - 1000 MHZ amplifiers ordered- delivery December 2010
- Tunnel high-power loads
- Simple on/off remote control

Design in progress

- How much instrumentation is worth it?
- directional couplers on loads?
- Diode Detectors on reverse power and interlock?
- add equalizer to compensate for cable and kicker response?



Excitation system for SPS bunch MD



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.

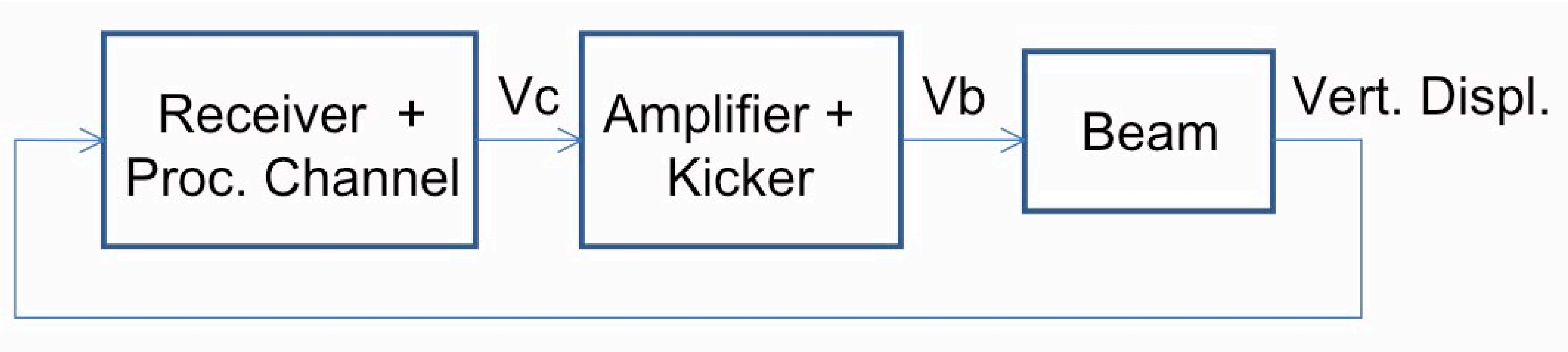
Design has trade-offs in partitioning - overall design must optimize individual functions

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?

Closed-Loop feedback around the Model

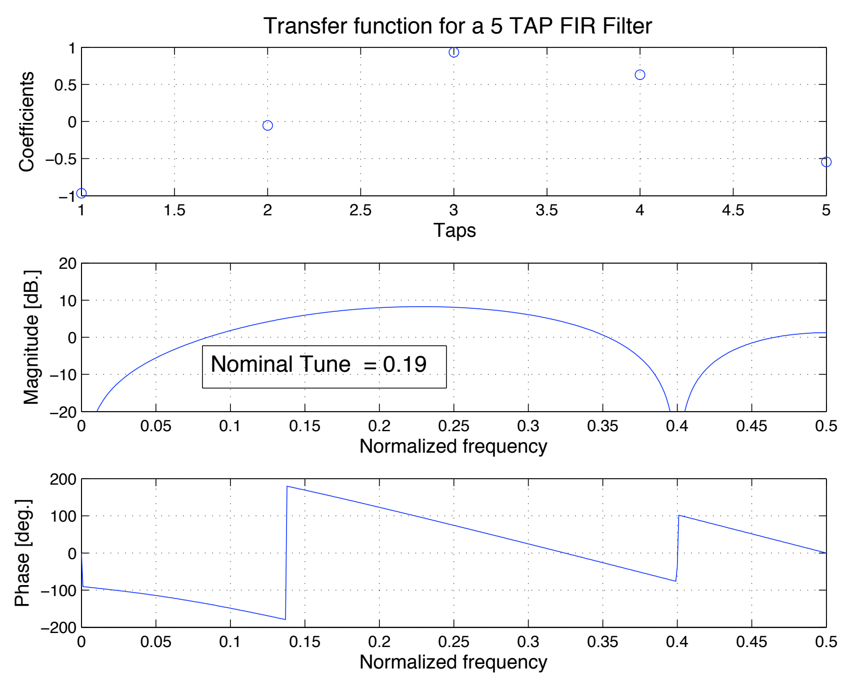


Use the reduced model, with realistic feedback delays and design a simple FIR controller

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?



Technology development

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

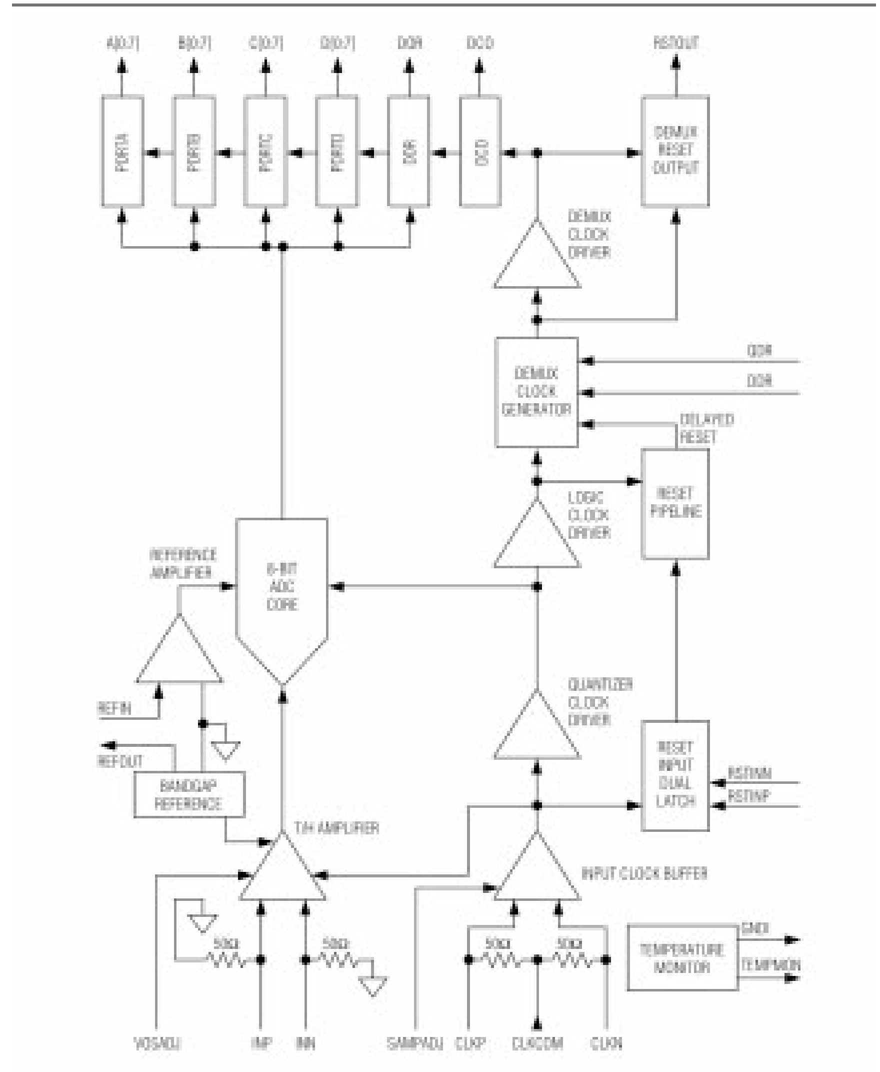
RF harmonic multiplier -> sampling from SPS RF

Tunnel “cart” power amps, loads, diagnostics, etc.)

We have the A/D, D/A Evaluation boards, plus Virtex6 Evaluation board and tools.

2011 Use existing exponential striplines for kicker

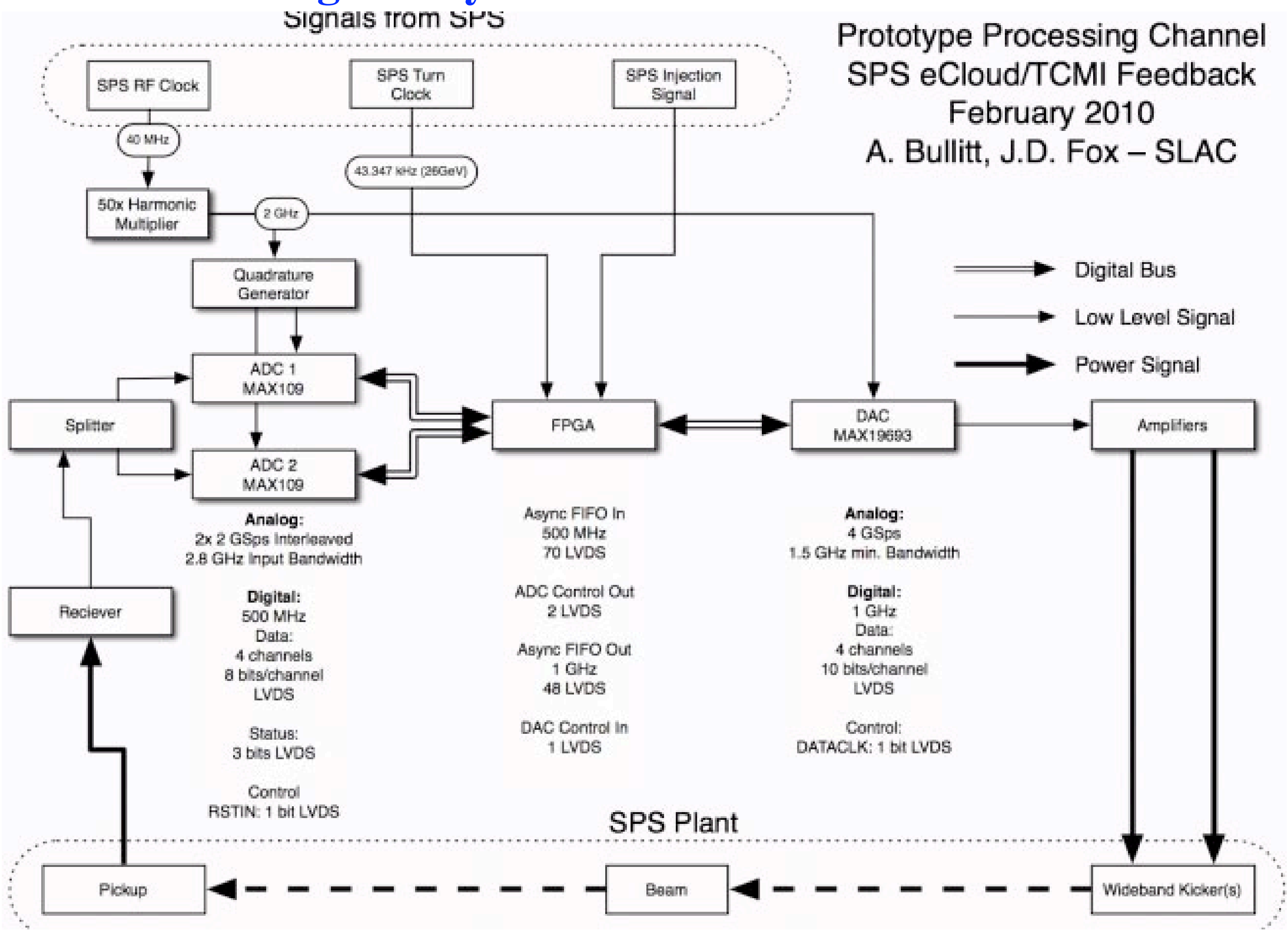
Critical Issue - Design of Full-bandwidth Kicker



ctional Diagram of the MAX109

MAXIM 109 2.2 GS/sec. A/D

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



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.

SPS Prototype Feedback Systems - options and direction

CERN's interest - very high

Critical missing element - useful high-power kicker and power amplifier components in SPS

- power amplifiers and cable plant in process (- amp cart rolled into tunnel)

Identify the Kicker technology as an accelerated research item, design prototype kicker and vacuum components for SPS fabrication and installation

FY 2011 LARP funded research and design report on Kicker system - 0.3 FTE

- design report, suggested implementation, test of low power lab models - LBL/SLAC

FY2012 - detailed design and fab of prototype kicker, vacuum components

FY2013 - installation in SPS with Amplifiers and Cable plant

- The Vacuum components are essential for shutdown, processing electronics is outside the tunnel

Dovetails with parallel system estimation and development of "quick prototype processor"

- 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

Progress FY2010 LARP Ecloud/TMCI

understand Ecloud dynamics via simulations and machine measurements, include TMCI

- Participation in studies at the SPS
- Analysis of SPS and LHC beam dynamics studies, comparisons with Ecloud models
- 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. 3 ECLOUD 2010 Talks

Are We On Track? How is the work Progressing?

Original research plan - Decision Point - late 2010

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

Our Conclusion - Yes, feasible, but

We don't have experience driving the beam, or a useful kicker design

- 2011 Kicker Design report should suggest a path

4 - 8 GS/sec. channel is technically possible

- but we don't know what bandwidth is really required

We don't have good dynamics knowledge, can't say what type of controller is best

- Progress with system estimation, feedback closed loop modelling, use simulations to estimate

Research Goals 2010 - 2012

- Modelling of closed-loop system dynamics, estimation of feedback system specifications
- Evaluation of possible control architectures, possible implementations, technology demonstrations
- Kicker design report, plan for fab of prototype for SPS shutdown installation
- SPS Machine Physics studies, development of "small prototype" and closed loop studies

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

Plans 2012 - 2013

Develop a technology demonstrator prototype and prototype wideband kicker

- functionality to test feedback techniques on a subset of bunches, evaluate options

We will learn from a limited "quick" prototype at the SPS

Can then confidently design a true operational system for SPS and LHC

Recent Publications and Talks from the LARP Ecloud Effort

Control of Transverse Intra-Bunch Instabilities using GHz Bandwidth Feedback Techniques. - Claudio Rivetta (SLAC National Accelerator Laboratory) Presented at the Ecloud 2010 ICFA workshop, Ithaca NY Oct 2010

Numerical Modeling of E-Cloud Driven Instability and its Mitigation using a Simulated Feedback System in the CERN SPS - Jean-Luc Vay (LBNL) Presented at the Ecloud 2010 ICFA workshop, Ithaca NY Oct 2010

Simulated Performance of an FIR-Based Feedback System to Control the Electron Cloud Single-Bunch Transverse Instabilities in the CERN SPS - RAFFAELLO SECONDO (LBNL) Presented at the Ecloud 2010 ICFA workshop, Ithaca NY Oct 2010

Simulation of E-Cloud Driven Instability and its Attenuation using a Feedback System in the CERN SPS J.-L. Vay, J.M. Byrd, M.A. Furman, G. Penn, R. Secondo, M. Venturini LBNL, Berkeley, California J.D. Fox, C.H. Rivetta SLAC, Menlo Park, California Presented at International Particle Accelerator Conference (IPAC 10), Kyoto Japan May 2010

SPS Ecloud Instabilities - Analysis of Machine Studies and Implications for Ecloud Feedback J.D. Fox, A. Bullitt, T. Mastorides, G. Ndabashimiye, C.H. Rivetta, O. Turgut, D. Van Winkle SLAC, Menlo Park, California J.M. Byrd, M.A. Furman, J.-L. Vay LBNL, Berkeley, California R. De Maria BNL, Upton, Long Island, New York W. Höfle, G. Rumolo CERN, Geneva Presented at International Particle Accelerator Conference (IPAC 10), Kyoto Japan May 2010

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