Wideband Feedback Systems

Progress, near term Plans

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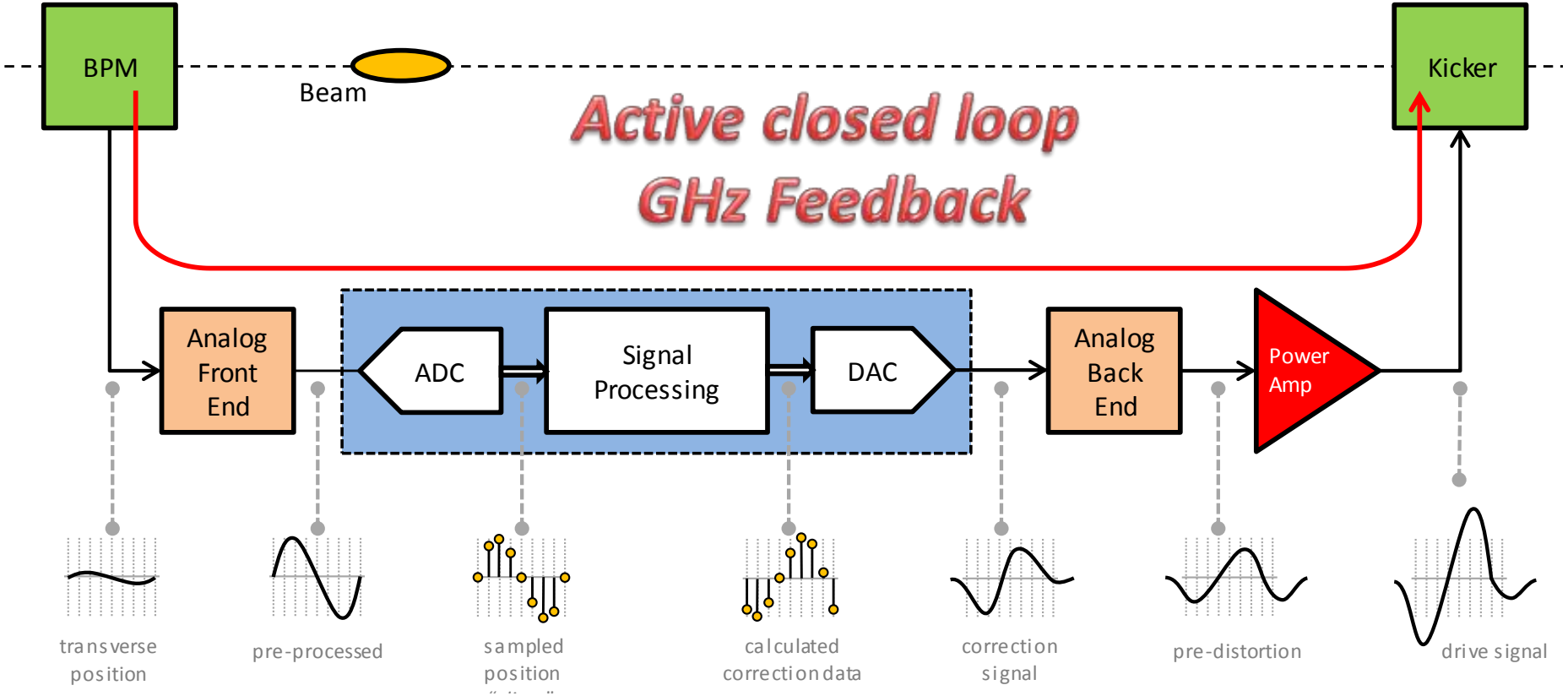
WBFS for intra-bunch Instability Control

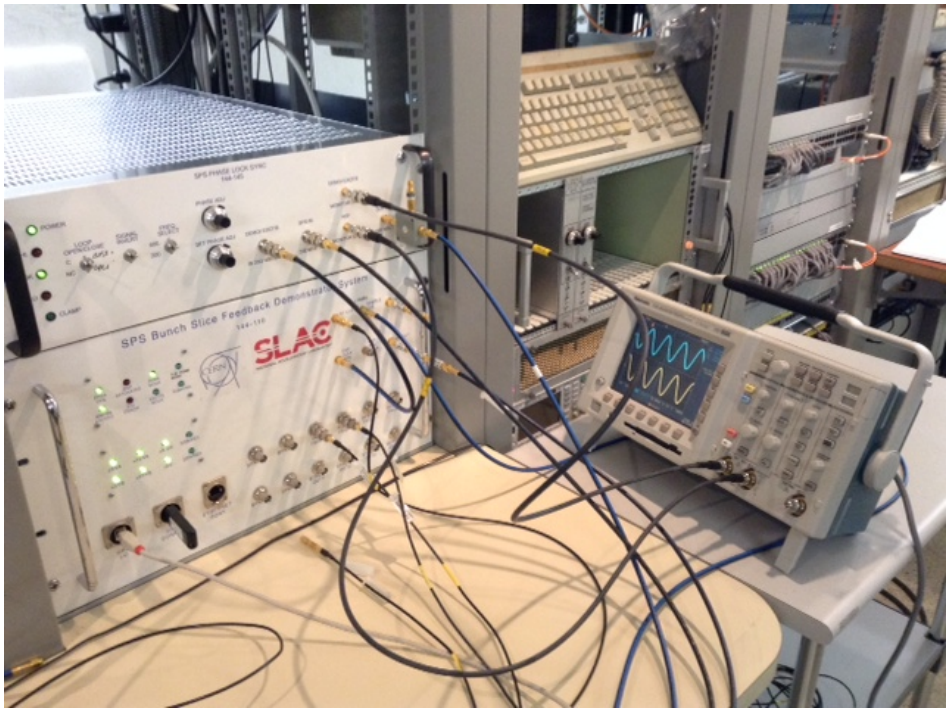


- Control of Ecloud and Impedance-driven transverse Intra-bunch instabilities - Demo system upgraded and expanded for 2015/2016 MD studies
- GHz Bandwidth Digital Signal Processing via reconfigurable architecture
- SPS Demonstrator system 1 - 64 bunches, modest kicker power with 1 GHz bandwidth
- Optimal Control Formalism - allows formal methods to quantify stability and margins
- Upcoming CERN September 2016 Review, Full-featured system recommendations

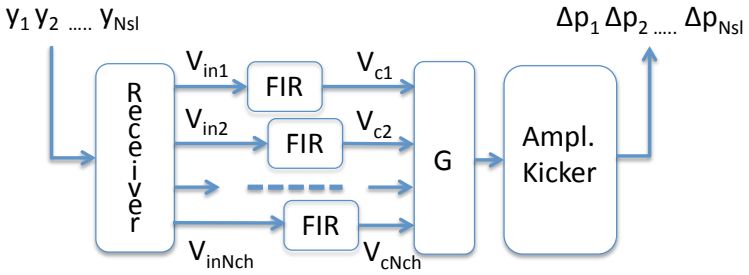
Progress since CM 24

- Demonstrator hardware system upgraded
  - Two bunch scrubbing fill controller (5 ns spacing), 64 bunch train controller
  - New back-end equalizer, Firmware tests, system testing in faraday cage
  - Power Amplifiers -two (new) amplifiers installed and ready for commissioning
  - Two stripline Kickers instrumented and powered (4 250W amps, 2 LARP, 2 CERN)
  - Tunnel infrastructure for 2 new amplifiers, monitoring and control - commissioned
  - Optimization of Slotline kicker design for CERN fabrication
  - CERN is investing in vacuum structures, cable plant, amplifiers and people
- Multiple MD studies at the SPS, coupling to CERN ABP groups
  - April, November, December 2015
  - Grow-damp studies with Q20 optics, Q26 optics
  - Low Chromaticity Studies with modal excitation
  - Q26 Lattice FIR control of unstable high intensity TMCI beam
  - Development of special beams (low intensity, linear lattice) for feedback tests
- Nonlinear simulation codes/feedback model studies, Model-based Control
  - New Matrix Control Methods for Q20 SPS Optics
  - Development of MD data analysis methods
  - Validate measurements against models
  - Reduced Model and Control design formalism (Ph.D. Thesis)

Upgrades to the Demo System at CERN

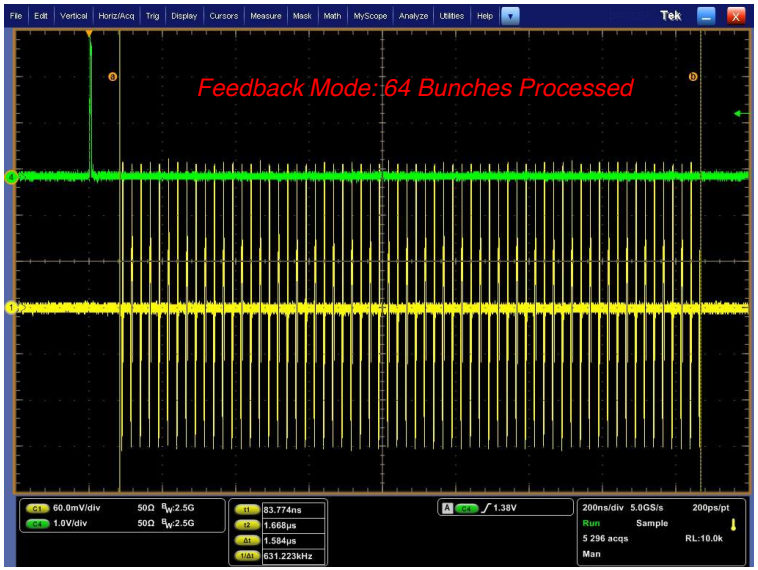


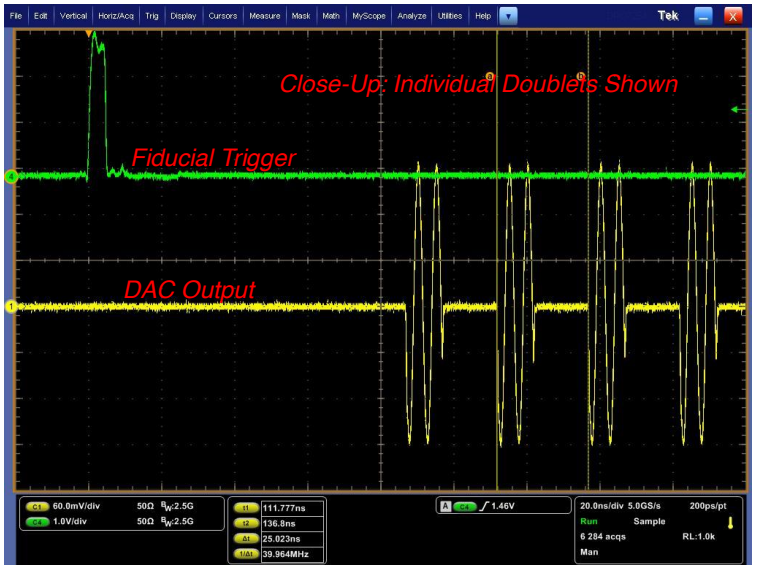
- Reconfigurable 4 GS/sec. processor
- Upgraded 2015/2016
  - 64 bunch train control, doublet scrubbing beam control
  - 16 slice FIR control, flexible slice gains
  - Feedback + Excitation mode
  - Robust Timing/Synchronization

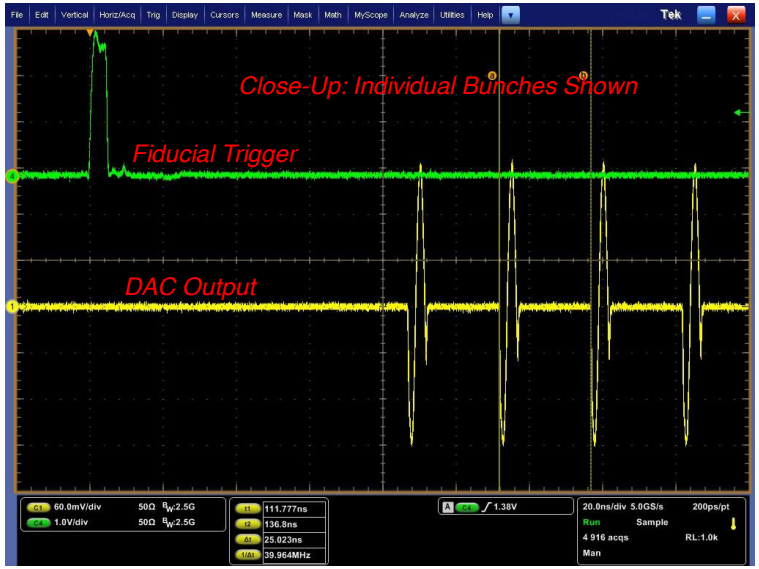


The processing system can be further expanded to support more complex off-diagonal (modal) filters, IIR filters, etc as part of the research and technology development

Expansion from Single Bunch - to 64 bunch train





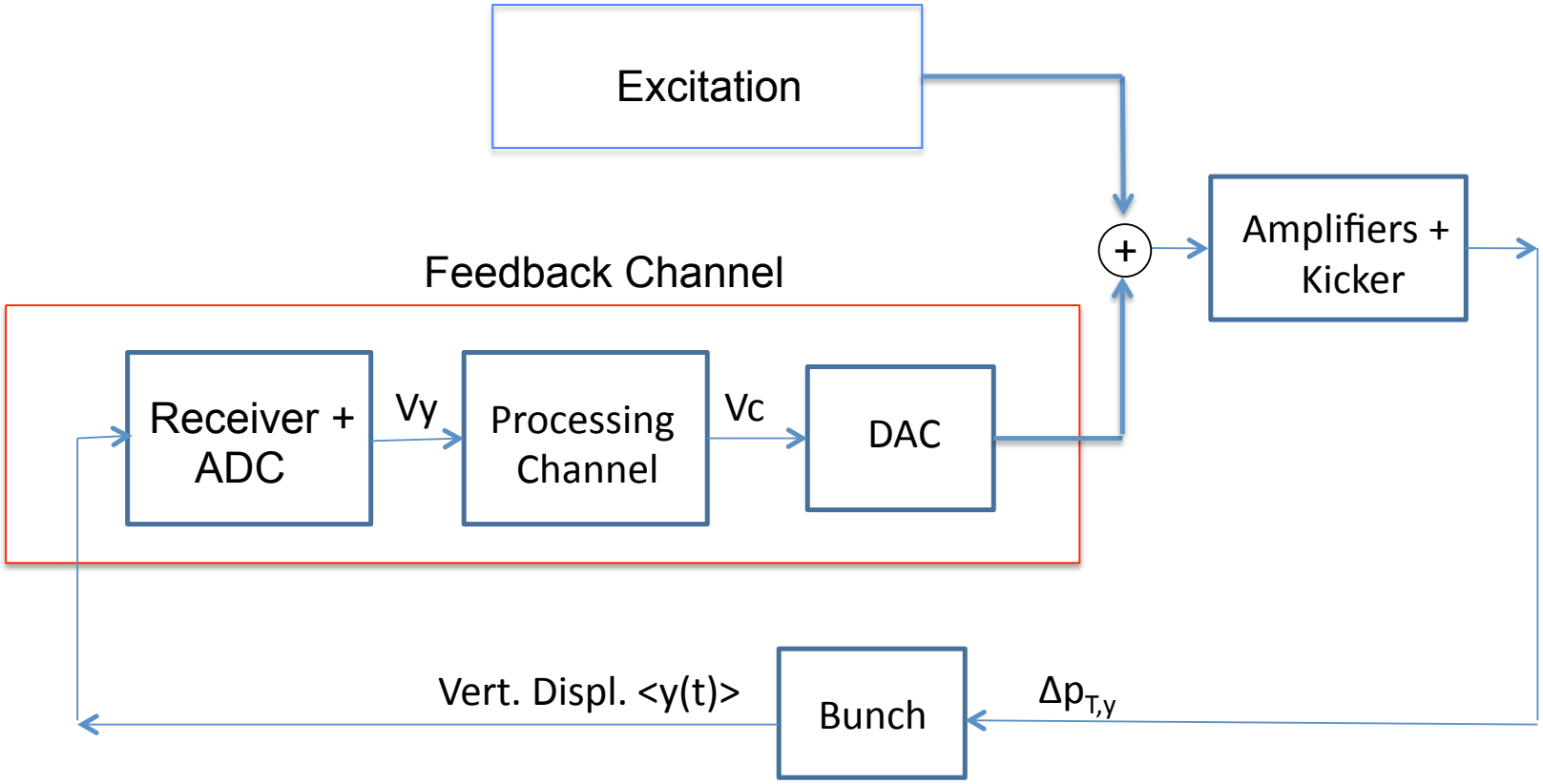


- Expansion to 64 bunch mode, with existing FIR diagonal filters
- Sampling for doublet (5 ns spacing) scrubbing fills, single or 32 doublets
- Flexibility of reconfigurable architecture allows expansion

Goals of the MD measurement series

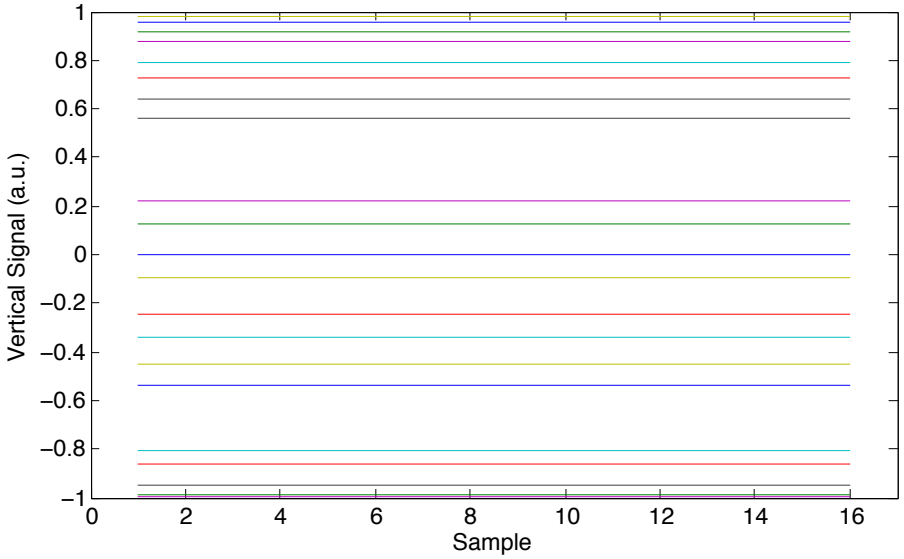
- Evaluate System Performance (Engineering)
  - Receiver, equalizer, pickup, Frequency/time response and noise floor
  - A/D, D/A and DSP system functionality
  - Control filters, functionality
  - User Interface and operational flexibility
  - Timing and Synchronization - functionality, flexibility
  - Power Amplifiers - frequency, time response, power output (2 LARP, 2 CERN)
  - Stripline Kicker Response
- Action of Feedback on Beam Dynamics (Beam Physics)
  - April, November, December 2015 (April 2016 delayed to June)
  - studies show mode zero, mode 1 control
  - Grow-damp studies with Q20 optics, Q26 optics
  - Low Chromaticity Studies with modal excitation
  - Q26 Lattice FIR control of unstable high intensity TMCI beam
  - Development of special beams (low intensity, linear lattice) for feedback tests
- Measure Beam/System responses, compare with Simulation models (Control Theory)
  - New Matrix Control (MIMO) Methods for Q20 SPS Optics
  - Development of MD data analysis methods
  - Validate measurements against models
  - Reduced Model and Control design formalism (Ph.D. Thesis)

Measuring the dynamic system - open/closed loop

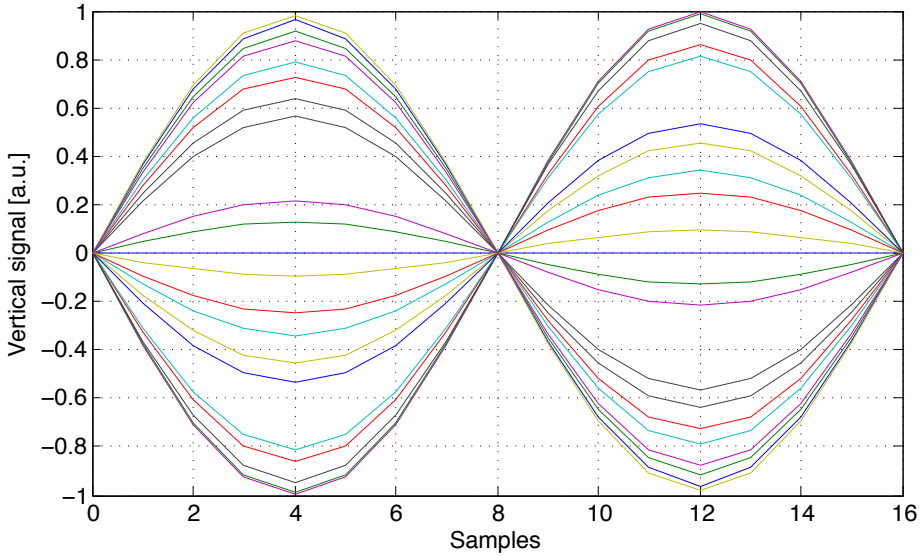


- We want to study stable or unstable beams and understand impact of feedback
- System isn't steady state, tune and dynamics vary
- We can vary the feedback gain vs. time, study variation in beam input, output
- We can drive the beam with an external signal, observe response to our drive
- Excite with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

Measuring the dynamic system - Modal Excitation



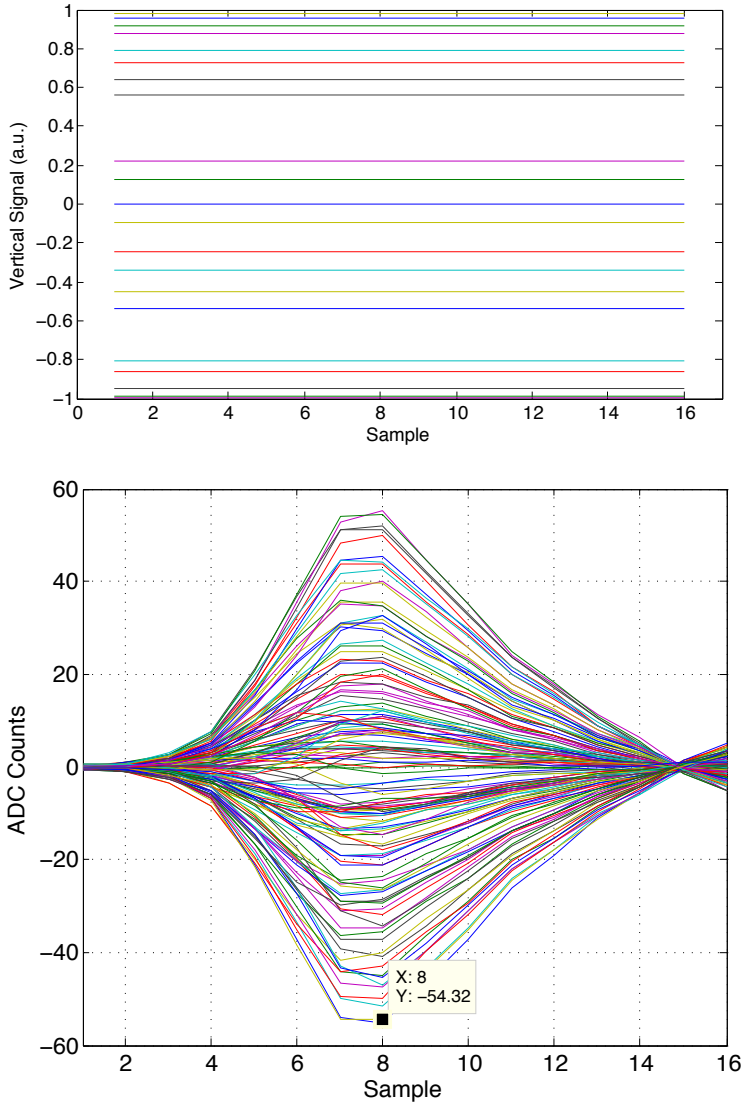
Mode zero excitation



Mode 1 (head-tail) excitation

- Inside the DSP processing we sum in an Excitation signal file
  - 16 unique samples/turn (4 ns duration)
  - 20,000 turn sequence, synchronized to injection
  - Spatially-shaped excites particular mode
  - Spatial Waveform is amplitude modulated at selected tune frequency
  - Chirps span range of tunes for selective excitation and spectrum analysis

Measuring the dynamic system - Beam response

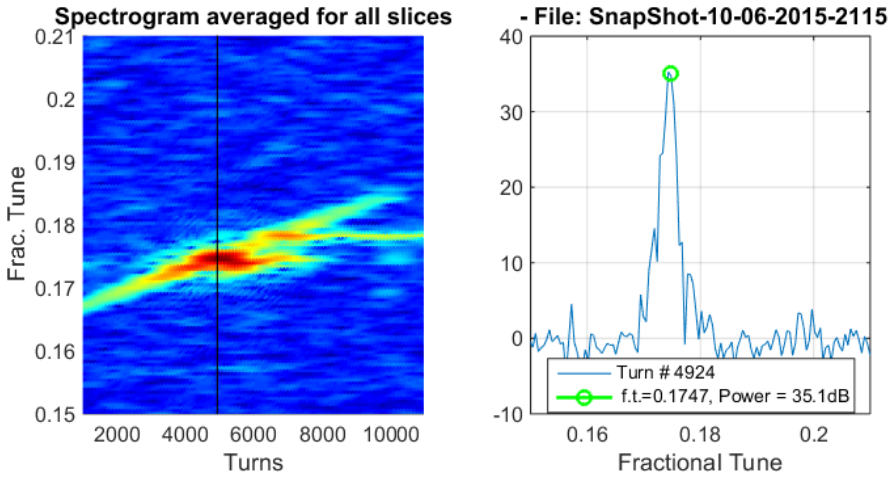


- Pickup,Kicker require equalization, Timing the front and back-ends is tricky
- Higher modes well-damped, difficult to excite

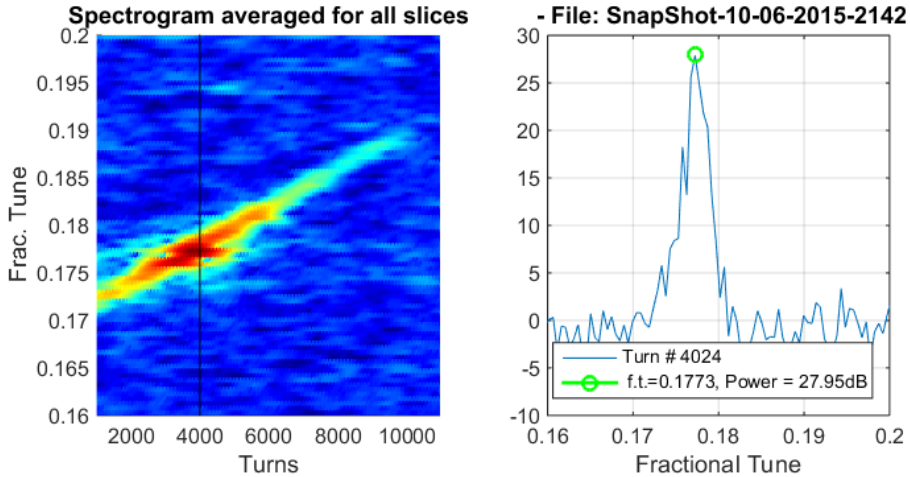
MDs September-October 2015

- Tests of the system with new wideband kicker and amplifiers
  1. open loop beam excitation, goal to test the kicker strength, induce high order mode intra-bunch motion
  2. Operate Demo system in closed loop to damp high order mode intra-bunch motion
- open loop test, several beam parameters and intensities
  - Preliminary results do not show complete agreement with simulation results using HeadTail or CMAD
- Closed loop - achieved beam damping with saturation gain limits
  - With limited power, very difficult to control the machine parameters such that signals induced by the beam motion do not saturate the feedback system
  - For MD June 2016, we have double the kicker-amplifier capability, increasing the dynamic range of feedback system. This should help.

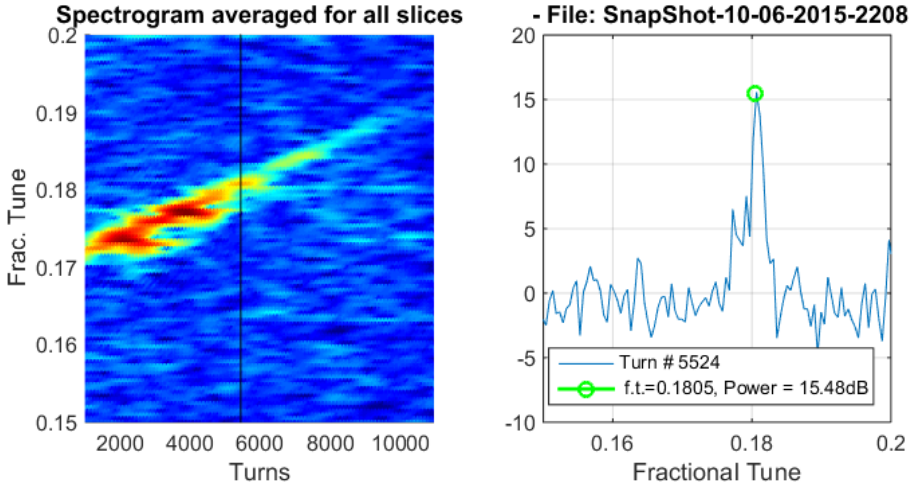
Open-Loop Studies September-October 2015



Beam Spectrogram driven by Mode 0 excitation

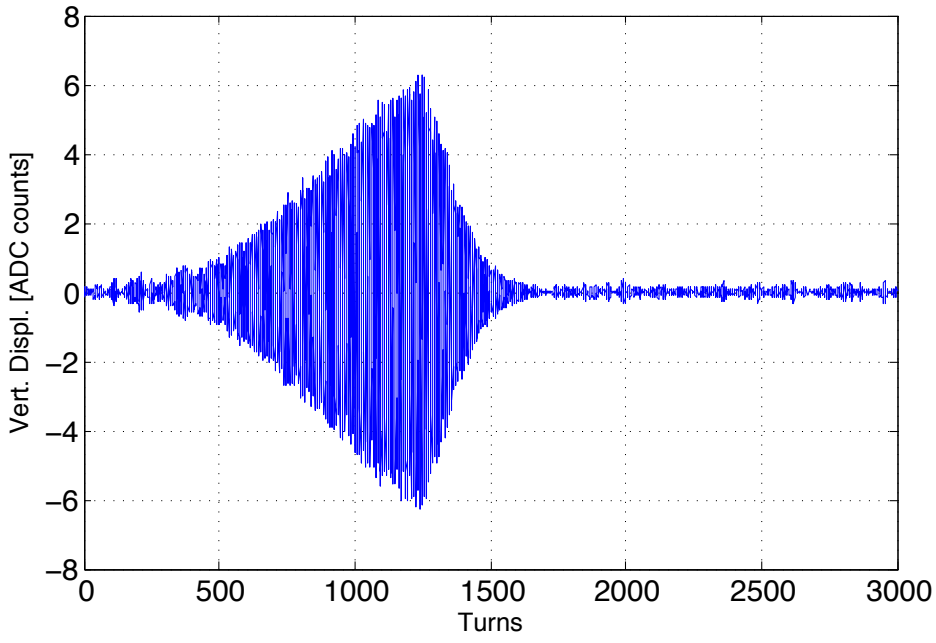


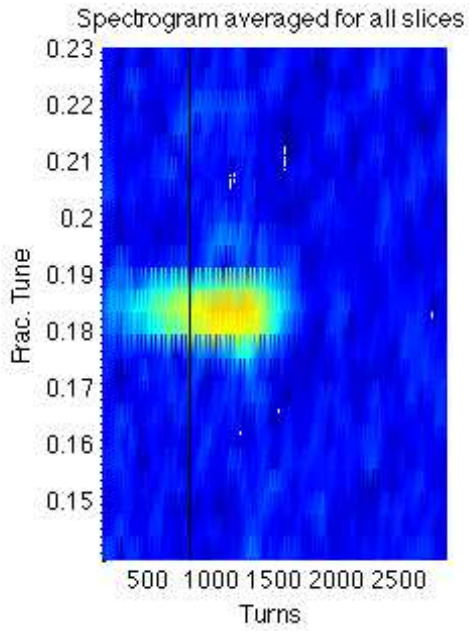
Beam Spectrogram driven by Mode 1 excitation

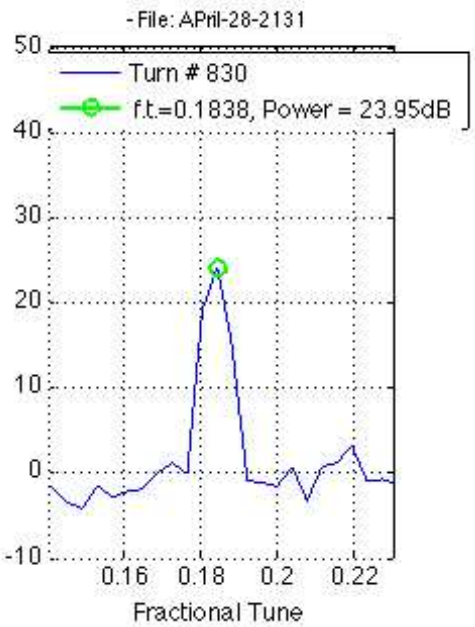


Beam Spectrogram driven by Mode 2 excitation

April 2015 SPS MD - Grow/Damp measurements

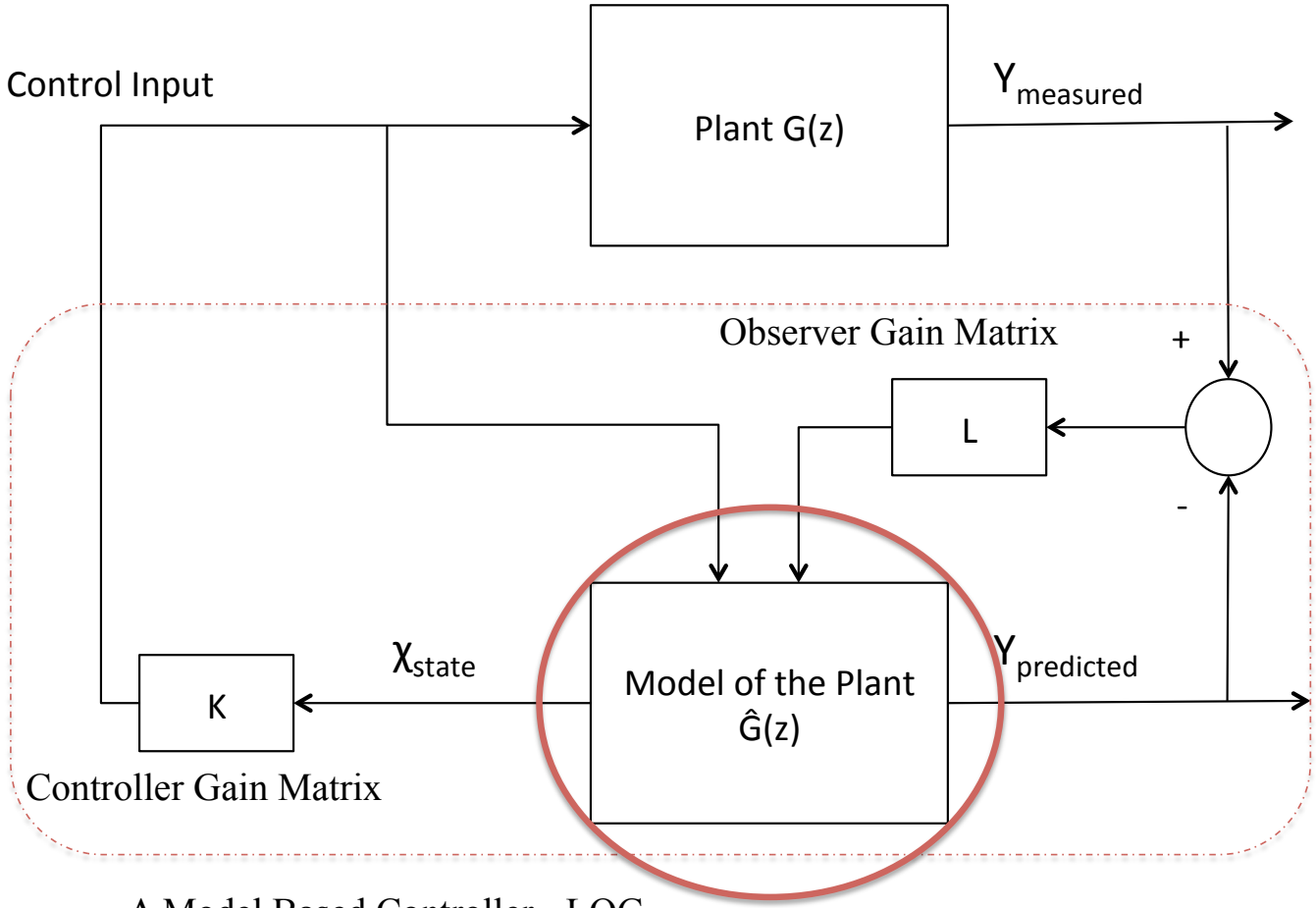






- Grow/damp SPS Measurement - Damping gain G=16 (left) Spectrogram(right)
- Intensity $1.1x10^{11}$ with low chromaticity Q26 lattice (special beam)
- $\nu_y = 0.185$ $\nu_s = 0.006$
- Feedback gain is switched to promote instability, then damp it
- Quantifies damping from increased gain of system, compare to models

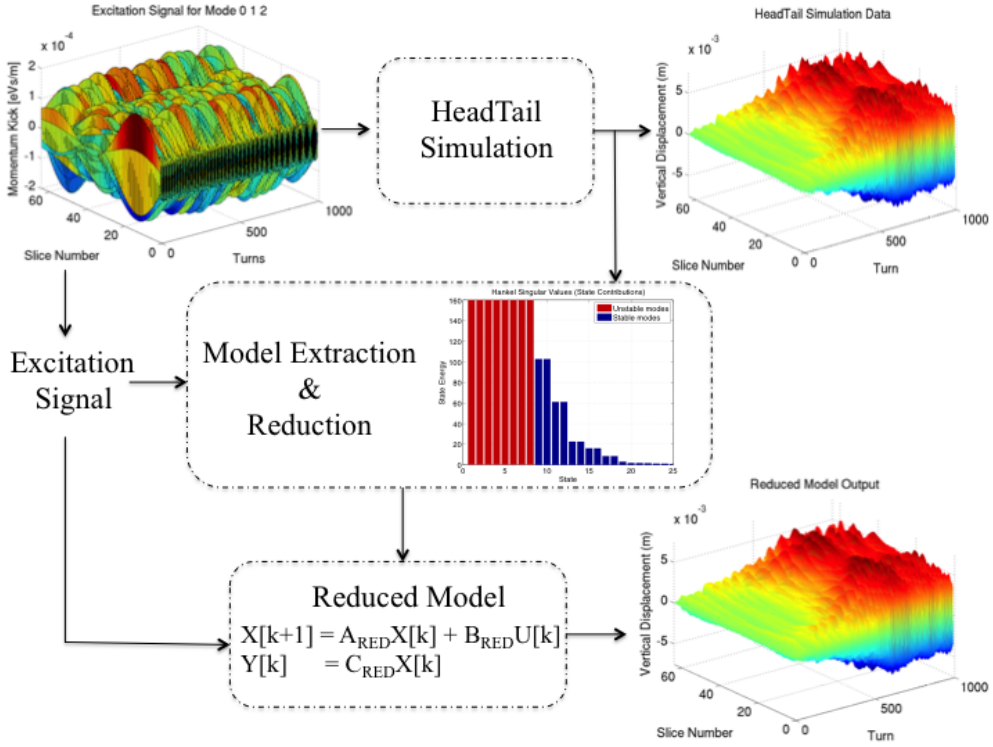
New Model-Based Control Studies



A Model Based Controller - LQG

- Control of Non-linear Dynamics (Intra-bunch) is challenging
- Tune variations, optics issues limit FIR gain
- Control Formalism - allows formal methods to quantify stability and dynamics, margins
- New directions, model based MIMO formalism

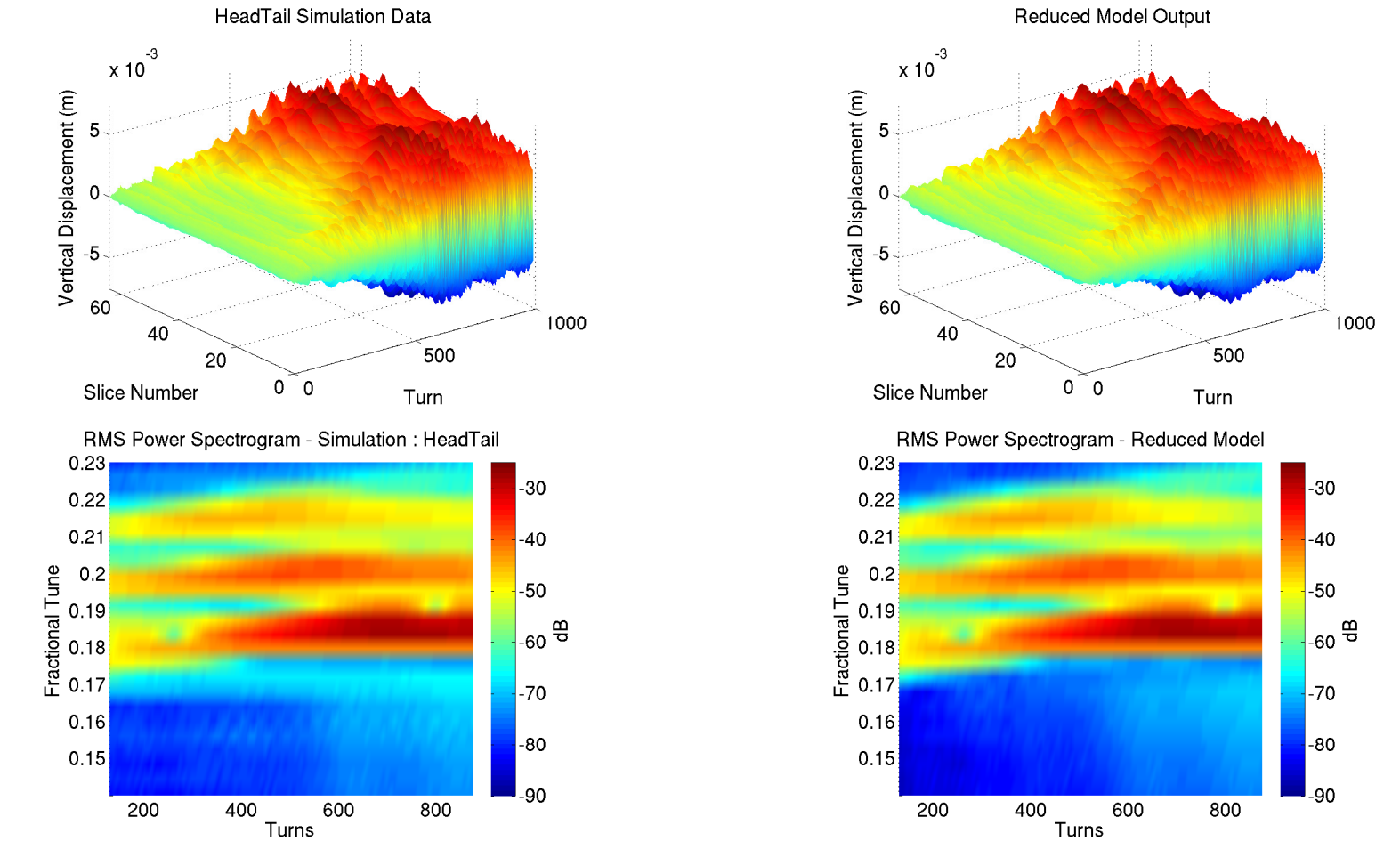
Model - is derived from Simulation or MD studies



- Parameters of the transfer function representing the modes 0, 1 and 2 dynamics are identified using open loop simulation data.
- We use the same excitation signal to drive the reduced order model and compare the time domain result with HeadTail simulation result for model verification.
- This model is used to design a model-based controller (Discrete-time linear quadratic optimal controller).

- Linear model - allows analytic knowledge of limits
- better than FIR for closer ω_β and ω_s Tunes, optics issues limit
- Control Formalism - allows formal methods to quantify stability and dynamics, margins
- model based MIMO formalism uses information from pickup more completely

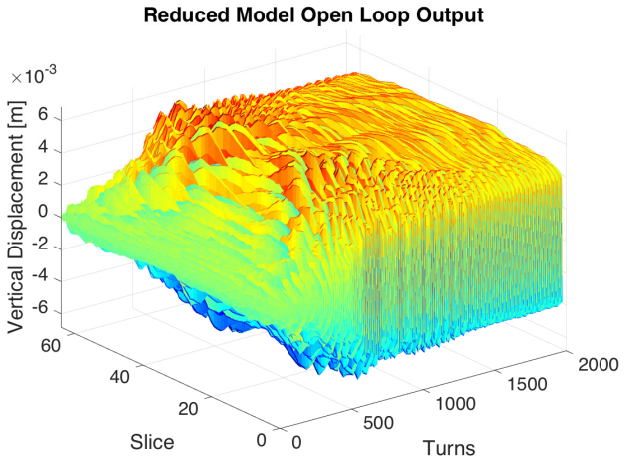
Head-Tail vs Reduced Model results



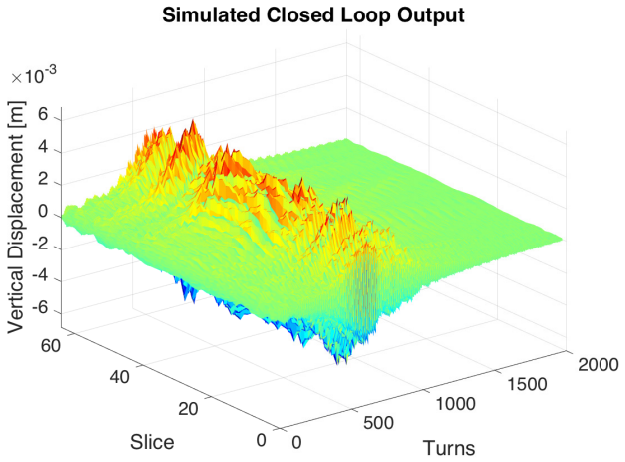
- Time Domain data is fit, Models in Time and Frequency Domain
- Model can be fit to simulation or physical machine data

MIMO Control - Closed Loop (Simulation)

- Controller is designed for the open loop reduced order MIMO model identified using open loop HeadTail simulation data.



: Open loop driven response time domain trajectory.



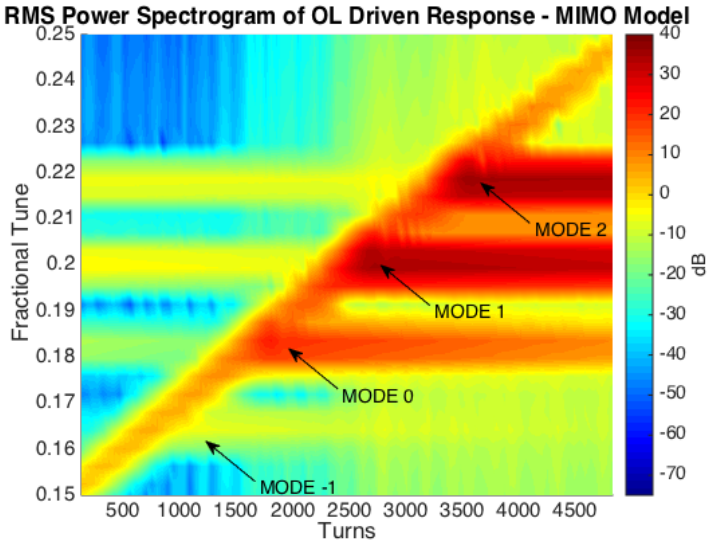
: MATLAB simulated closed loop driven response time domain trajectory.

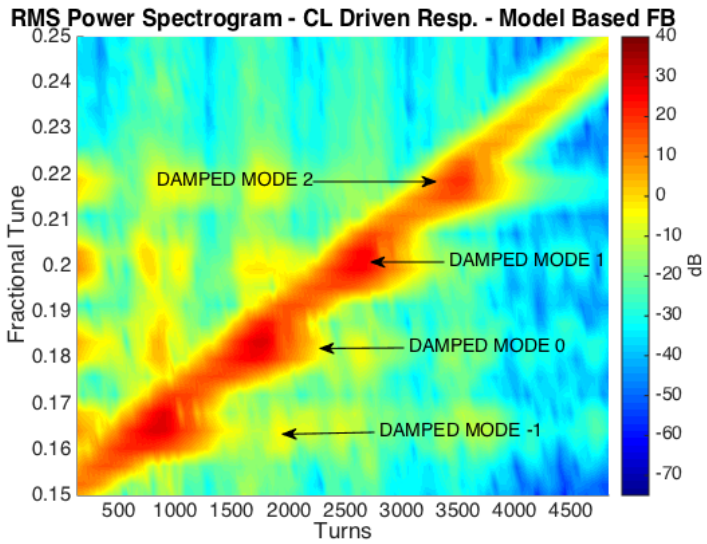
Intra-Bunch Dynamics

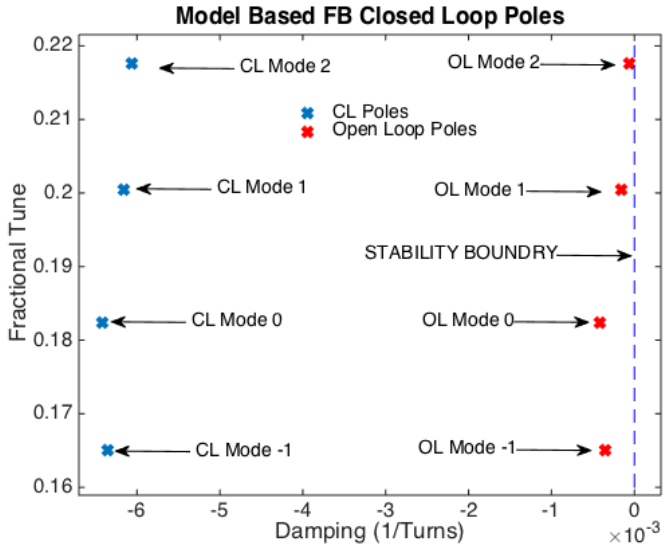
MODE	OL (Turns)	CL (Turns)
0	-0.000 ± 0.1850i (∞)	-0.0048 ± 0.1850i (208)
1	-0.0011 ± 0.2015i (909)	-0.0058 ± 0.2012i (169)
2	-0.0016 ± 0.2181i (625)	-0.0079 ± 0.2181i (126)

- Very Promising - Explore implementation in Demo System
- Achieves higher damping compared to FIR, better control for Q20 optics

MIMO Modal 4X4 controller - Beam Simulation







- 4 Coupled-Oscillator model
- 4x4 modal (matrix) controller
- Much better control of all modes compared to FIR
- disadvantage - much more complex numeric processing (n^2 more)
- active Ph.D. research - what about sparse control with few off diagonal elements?
- O. Turgut Contributed Oral at IPAC 2016

Next MD studies with wideband DEMO system

- Excitation of higher intra-bunch modes, damping studies
- Development of special beams for feedback tests with CERN ABP
  - With limited kicker power, to date difficulties exciting/driving modes 2 - 8
  - Our next path - work with lower intensity (less intensity tune shifts)
  - Investigate bandwidth of kicker, compare to models
  - Damp head-tail unstable motion, or excite then damp head-tail motion
  - Validate new Kickers (Stripline) and upgraded tunnel High-Power wideband RF amplifiers
- Development of Control Techniques
  - Single-bunch IIR, scrubbing doublet and FIR 64 bunch train control
  - Diagnostic and beam instrumentation techniques to optimize feedback parameters and understand system effectiveness
  - Use of reduced model as tool, use of both numeric simulations (Head-Tail) and physical MD data to understand system requirements for robust control with HL intensities and lattices
- MD and Beam studies workshop Saturday with joint SLAC/CERN Team

Goals Before the September 2016 Review

- Use MD studies summer 2016 to validate system models
- Estimate system requirements for robust instability control at SPS, LHC
- Proof of principle using limited Kicker power
- Validate damping as achieved consistent with engineering design
- System Conceptual Design Report
- FY16 priorities
  - Commission second kicker, wideband amplifiers
  - MD efforts - explore excitation, damping of internal beam modes
  - MD Data Analysis methods
  - Explore/validate Q20 control methods, compare models with physical measurements
  - Demonstrate 64 bunch train controller, doublet controller
- If possible, Slotline kicker design ready for CERN fabrication

Potential Applications at CERN (W. Hofle, K. Li, et al)

W. Hofle / K. Li Transverse Feedback in the HL-LHC Era 28.10.2015 5th Joint HighLumi LHC - LARP Meeting

Instabilities: Potential for New Feedbacks

PS:

- Instability for high intensity TOF beams

SPS:

- Single bunch vertical instability for high intensity 25 ns beam

LHC:

- Instabilities at injection for nominal 25 ns beam
- Instabilities at flat top for nominal 25 ns beam
- Control of the doublet beam for scrubbing

HL-LHC:

- Instabilities from crab cavity HOMs

	Required bandwidth	Rise time
PS (TOF)	~ 800 MHz	50 turns
SPS (h plane)	~ 20 MHz	750 turns
SPS (v plane)	→ 500 MHz	150 turns
LHC (injection)	→ 2 GHz	250 turns
LHC (squeeze)	> 20 MHz ?	10'000 turns
LHC (doublet)	> 100 MHz ?	50 turns
HL-LHC (crabs)	→ 1.75 GHz	10'000 turns

See K. Li, 15.10.2015, LIU-HighLumi Day, https://indico.cern.ch/event/437662/

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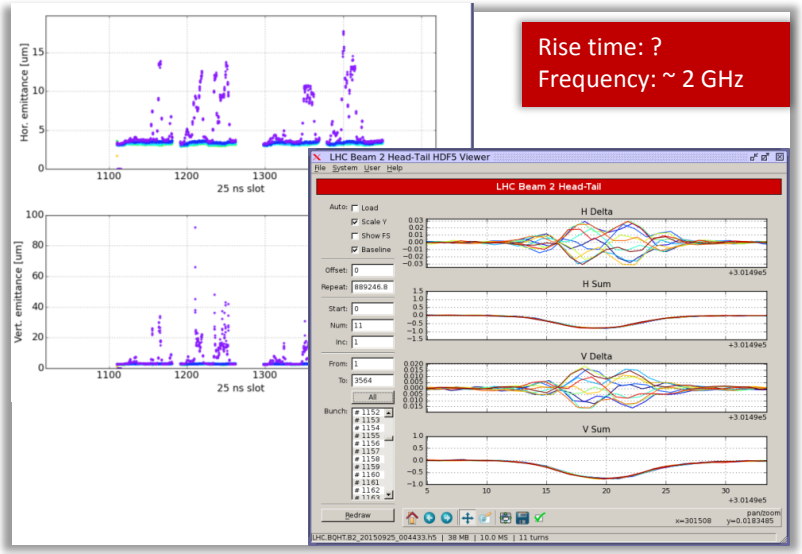
Looking at HL-LHC (W.Hofle, K. Li, et al)

Instabilities hardly manageable

LHC:

- The pure current impedance model is expected to give rise to instabilities that can be handled by current means of stabilization (octupoles, perfect damper) for single as well as coupled bunch.
- When other sources of instability are folded in, the requirements on the means of stabilization drastically increase.
- Mid/end squeeze – not cured by present damper. Likely due to e-cloud – limitations to be re-assessed after more conditioning.
- Injection – instabilities and blow-up
- High Lumi LHC will see 25 ns stability issues combined with high intensity bunch currents → be prepared



- E-cloud instabilities force operation at chroma ~15, octupoles ~20A, damper gain ~0.25 (~ 10 turns) – highly sensitive to damper settings and coupling
- Change of WP required – Qh: 0.275, Qv: 0.295
- Still sporadically blow-up observed

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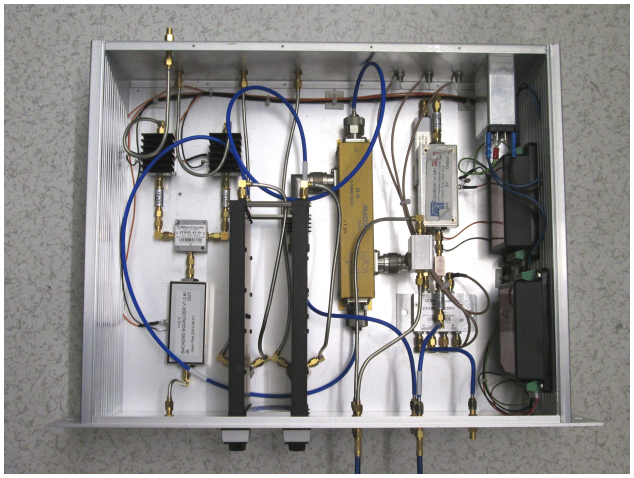
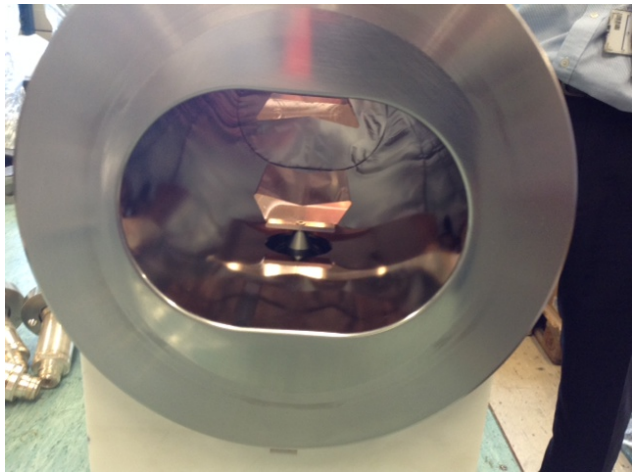
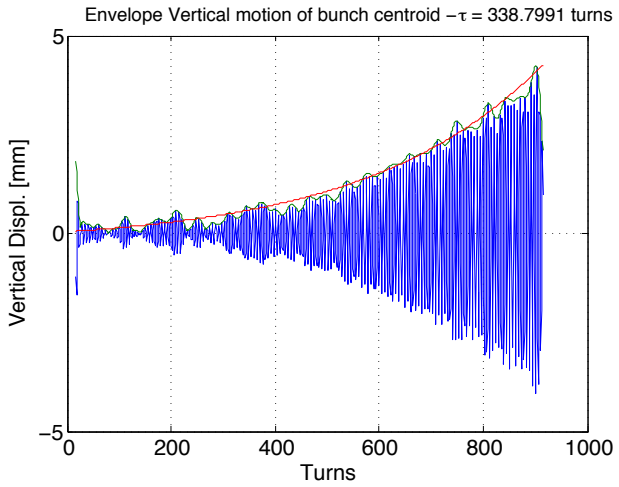
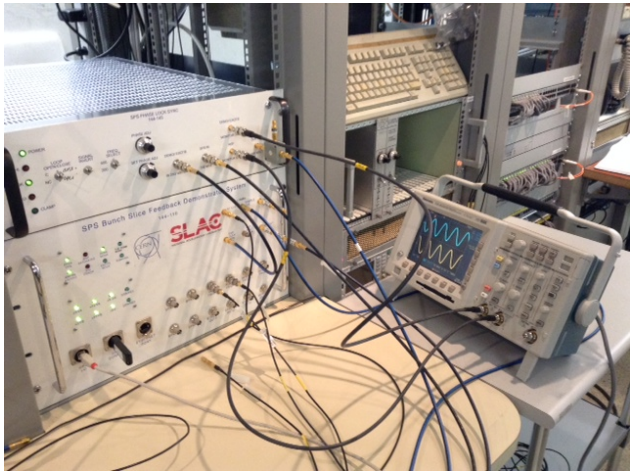
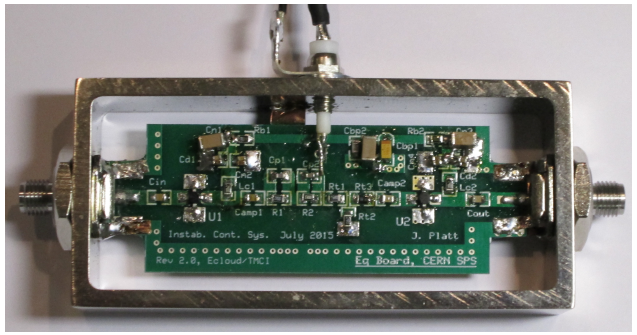
Technology Development, Beam Measurements, Simulation Models, and Graduate Education











Summary

- Summer MD Focus - Measure intra-bunch beam dynamics
- Head-Tail, Reduced Model studies, estimate limits of FIR control methods, value of IIR or MIMO methods.
- Quantify the engineering performance of the Demo system (Noise Floors, equalization, timing/synchronization)
- Stripline kicker bandwidth, performance of 1kW installed broadband RF power
- Estimate the value of a two pickup, two kicker system for variations of machine optics or rapid instability growth rates
- September Review - show the value of these techniques for the HI-LHC complex

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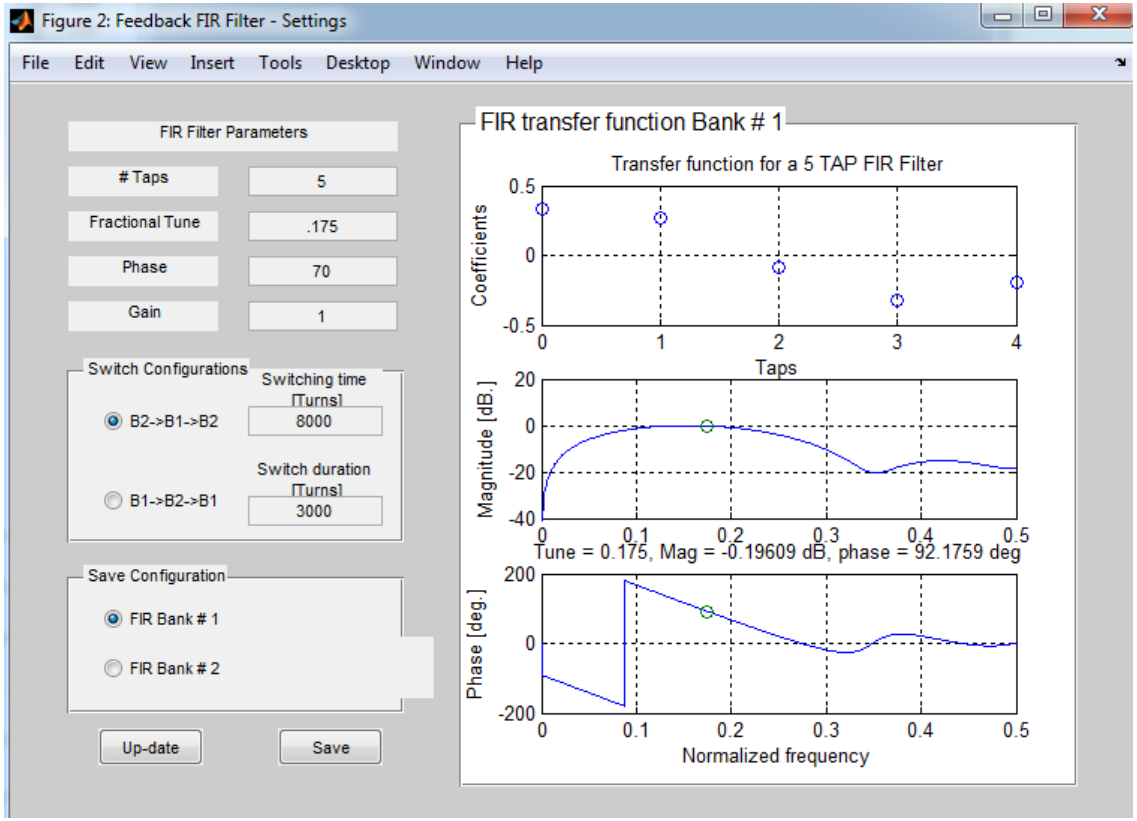
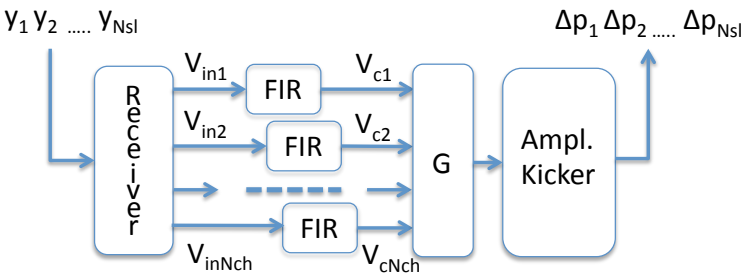
- We especially acknowledge the skillful fabrication, test and installation of the stripline kicker in time for startup fall 2015 by D. Aguilera and E. Montesinos, the help from CERN Vacuum, Survey, Surface Treatment and Main Workshop groups.
- We are grateful to Sei Mizue and the R&K company (Japan) for their rapid prototype amplifier development, and their interest in meeting our unusual time-domain specifications
- We cannot adequately acknowledge the critical help from everyone who made the winter 2012 and 2014, 2015 feedback Demo MDs possible. We are grateful for the collaboration and generous help.
- Thanks to CERN, SLAC, KEK and LARP for support
- We thank our Reviewers from the June 2013 Internal Review, the CERN LIU-SPS July 2013 Review, and the DOE LARP February 2014 Review for their thoughtful comments and ideas

Work supported by DOE contract DE-AC02-76SF00515, the US LARP program, the FP7 High Luminosity LHC project and the US-Japan Cooperative Program in High Energy Physics

Feedback Filters - Frequency Domain Design



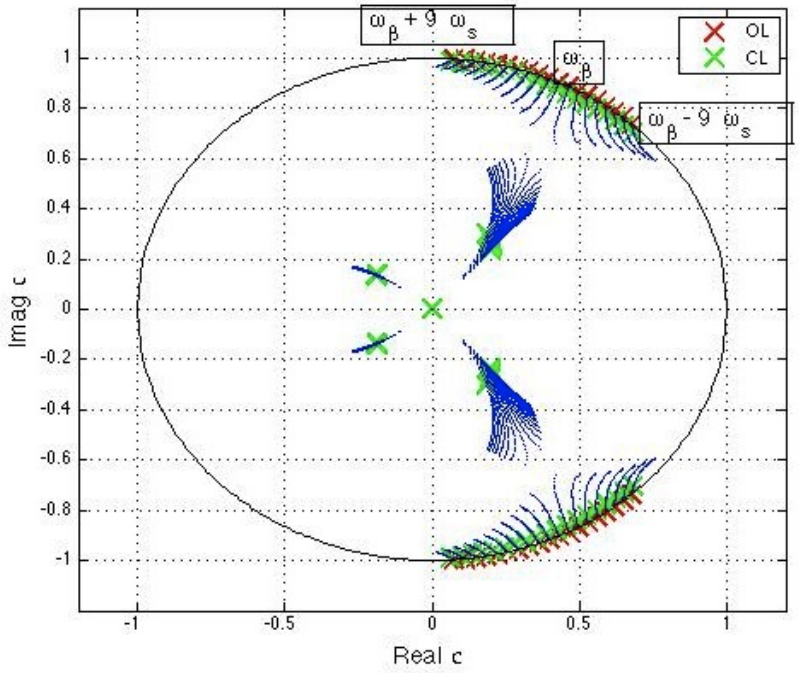
- FIR up to 16 taps
- Designed in Matlab
- Filter phase shift at tune must be adjusted to include overall loop phase shifts and cable delay
- Based on methods used in coupled-bunch systems

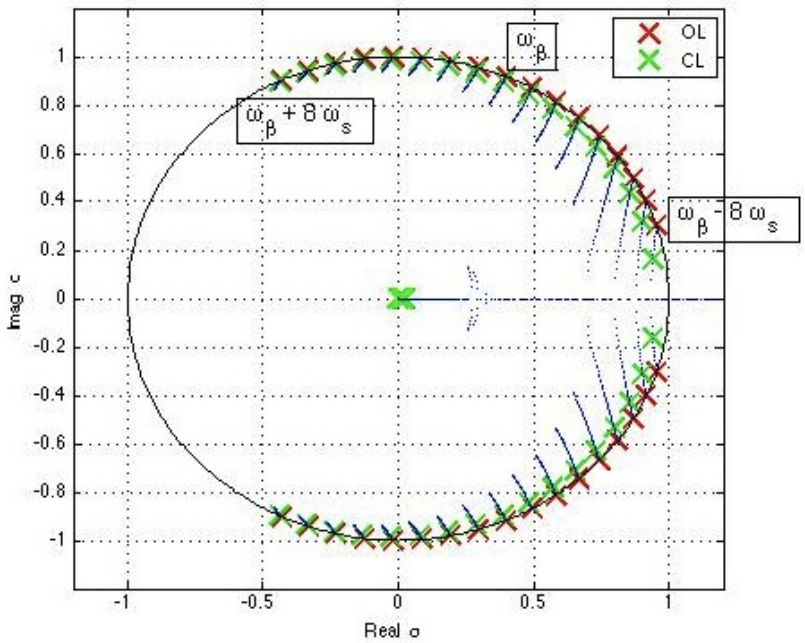


The processing system can be expanded to support more complex off-diagonal (modal) filters, IIR filters, etc as part of the research and technology development

Feedback design - Value of the reduced model

- Controller design requires a linear dynamics model
- The bunch stability is evaluated using root-locus and measurements of the fractional tune.
- Immediate estimates of closed-loop transfer functions, time-domain behavior
- Allows rapid estimation of impact of injected noise and equilibrium state
- Rapid computation, evaluation of ideas
- Q20 IIR controller is very sensitive to high-frequency noise - would higher sampling rate (two pickups) be helpful?

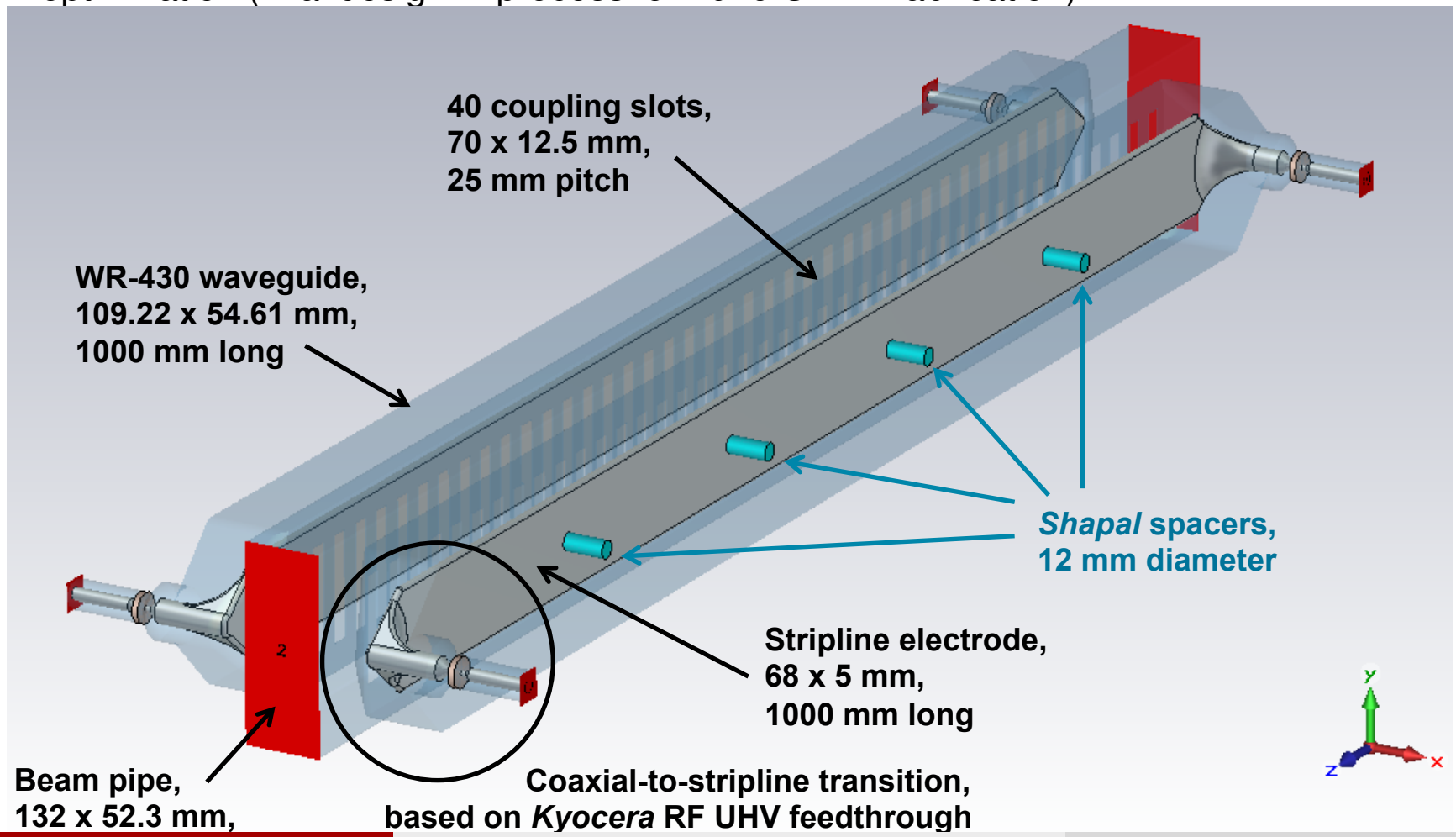




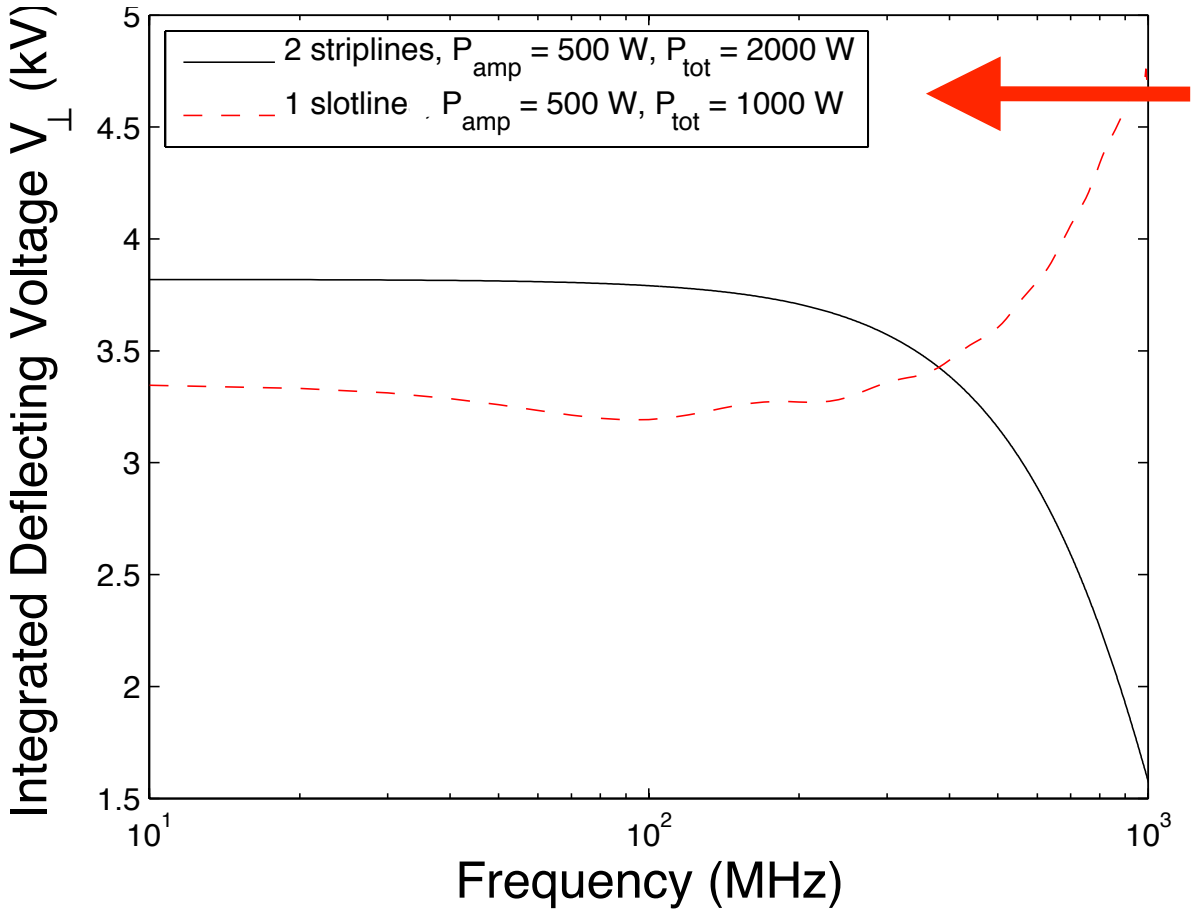
Left: FIR filter controller designed for Q26 at $f_\beta = 0.185$, $f_s = 0.006$
Right: IIR filter controller designed for Q20 at $f_\beta = 0.185$, $f_s = 0.017$

1 GHz Wideband Slotline kicker development

- CERN, LNF-INFN, LBL and SLAC Collaboration. Design Report SLAC-R-1037
- similar in concept to stochastic cooling pickups, run as kicker
- Advantage - length allows Shunt Impedance AND Bandwidth
- J. Cesaratto, S. Verdu, M.Wendt, D. Aguilera electrical/mechanical design and HFSS optimization (final design in process for 2016 CERN fabrication)



Complementary Striplines and Slotline

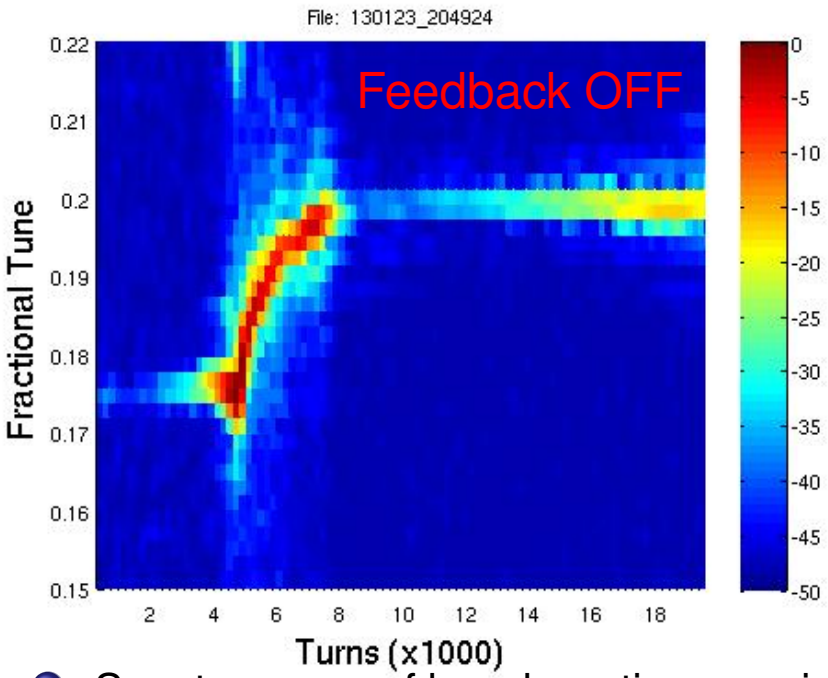


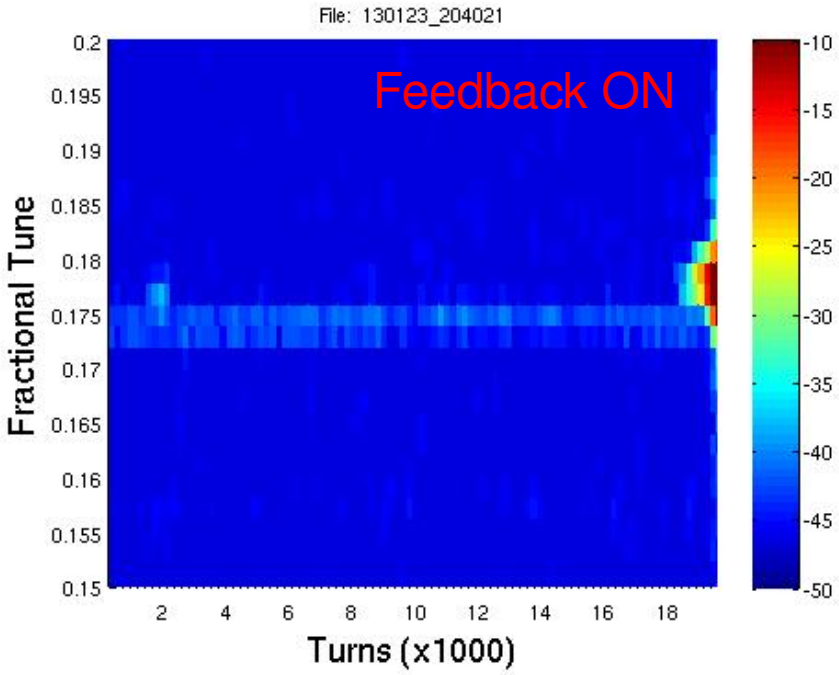
CERN plans to install:

- 2 Striplines
- 1 Slotline

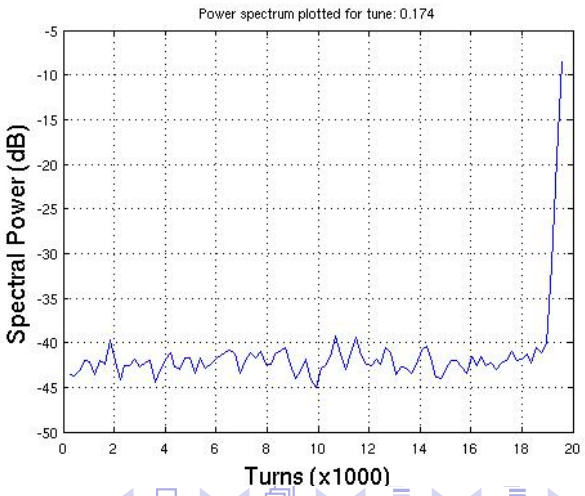
- At low frequencies, the striplines have slightly higher kick strength.
- However, the slotline can effectively cover the bandwidth up to 1 GHz.
- MDs with the new kicker prototypes are ABSOLUTELY ESSENTIAL to validate and confirm the technologies, bandwidth and kick strength needed.

Feedback control of mode 0

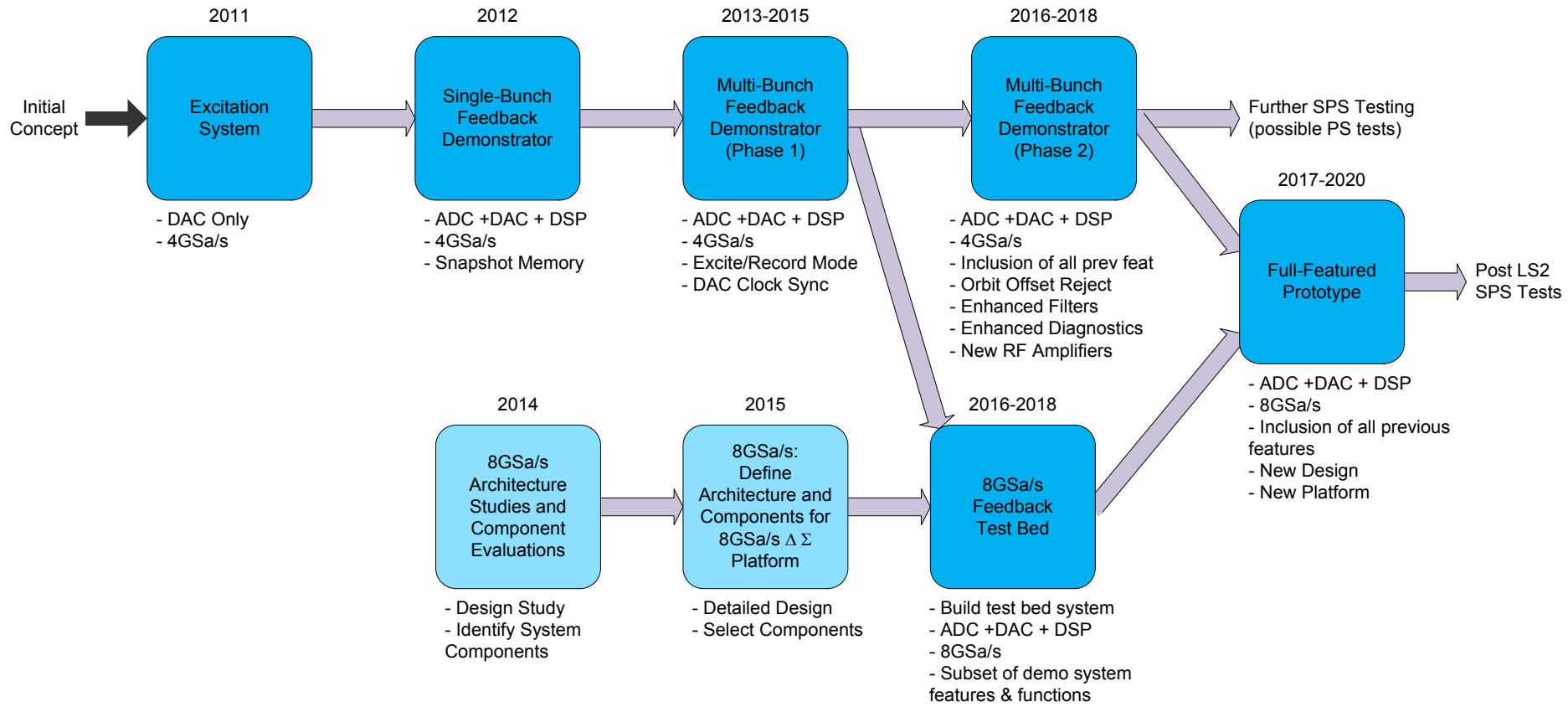




- Spectrograms of bunch motion, nominal tune 0.175
- After chromaticity ramp at turn 4k, bunch begins to lose charge → tune shift.
- Feedback OFF -Bunch is unstable in mode zero (barycentric).
- Feedback ON - stability. Feedback is switched off at turn 18K, beam then is unstable



Upgrades to the SPS Demonstrator - Roadmap



- The Demo system is a platform to evaluate control techniques
- MD experience will guide necessary system specifications and capabilities
- The path towards a full-featured system is flexible, can support multiple pickups and/or multiple kickers
- We will benefit from the combination of simulation methods, machine measurements, and technology development

Wideband Feedback - Beam Diagnostic Value

- processing system architecture/technology
  - reconfigurable platform, 4 - 8 GS/s data rates
  - snapshot memories, excitation memories
  - applicable to novel time and frequency domain diagnostics
  - Feedback and Beam dynamics sensitive measure of impedance and other dynamic effects
  - Complementary to existing beam diagnostic techniques- use kicker excitation integrated with feedback processing
- Detailed slice by slice information, very complete data with GHz bandwidth over 20,000 turns