Wide-band Feedback Systems to Diagnose and Suppress Intra-Bunch Motion in Accelerators

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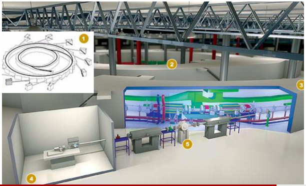
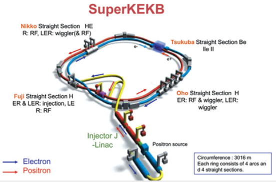
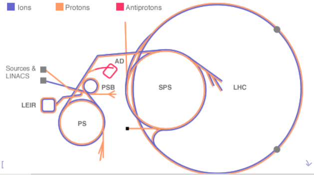
Impedances, Instabilities and Feedback Control

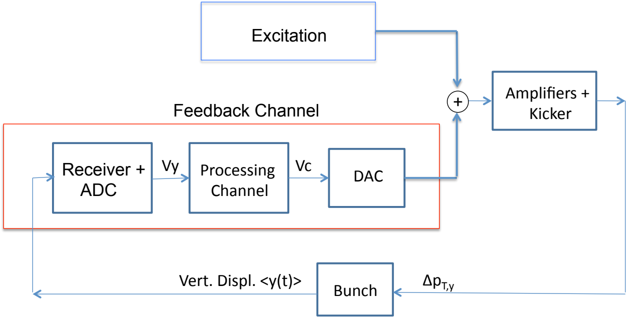
- Transverse and longitudinal instabilities -beam loss, emittance increase
  - Impedance-driven Instabilities - including TMCI
  - Ion or Electron-cloud disturbances
  - Rejection of disturbances from RF system or other sources
- Feedback
  - a kind of "programmable impedance"
  - a means to damp or excite beam motion
  - a powerful beam diagnostic
- Wideband - capability to address many (all?) beam modes
  - Coupled-bunch instabilities -bandwidth consistent with bunch spacing (500MHz)
  - Intra-bunch motion - bandwidth consistent with bunch length (1-2 GHz or ?)
- Intra-bunch wideband feedback - examples from JPARC and SPS
- Diagnostic Examples from light sources, particle colliders





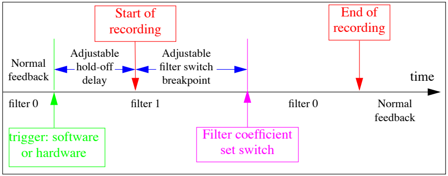


Diagnostics for a dynamic system - open/closed loop



- 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 motion vs time
- We can drive the beam with an external signal, observe response to our drive
  - Excite with chirps that can cross multiple frequencies of interest
- Use programmable features, and data memory, within the feedback system to excite and record beam motion
- excellent frequency resolution, measurement of modal amplitudes, structures from long sequences, high sampling rates (narrowband resolution from processing gain)

Grow/damp transient measurement

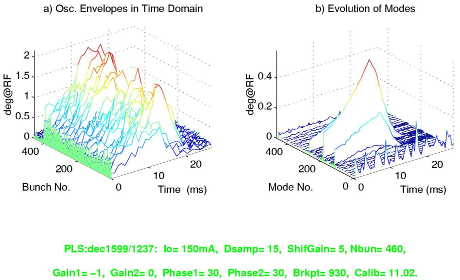


A transient diagnostic technique that generates

- 1.2MB record of the motion of all bunches
- Complete modal information

Transient measurement to characterize open-loop dynamics of an unstable system.

Linear time control is difficult when making an exponentially growing measurement.



- Transient Domain - requires time-varying feedback processing, and bunch motion recording during transient

Diagnostics - instabilities from insertion gap

TUPOR023 Proceedings of IPAC2016, Busan, Korea

INVESTIGATION OF TRAPPED RESONANT MODES IN INSERTION DEVICES AT THE AUSTRALIAN SYNCHROTRON

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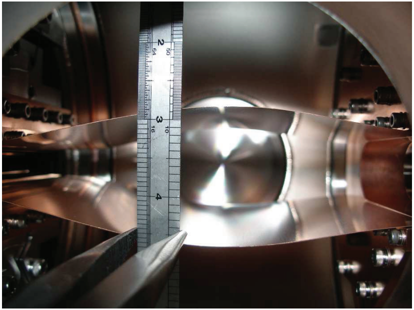
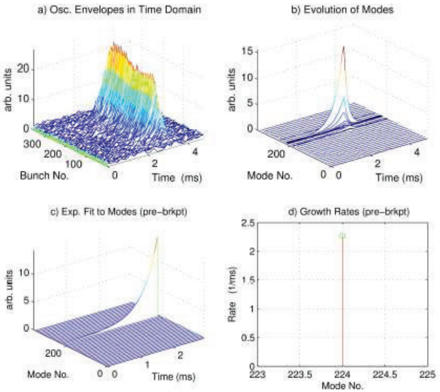


Figure 2: Transition taper view at 6mm gap on IVU5.



- Discovery of unexpected strong vertical instability with insertion device closure

AuLS- instabilities from insertion gap

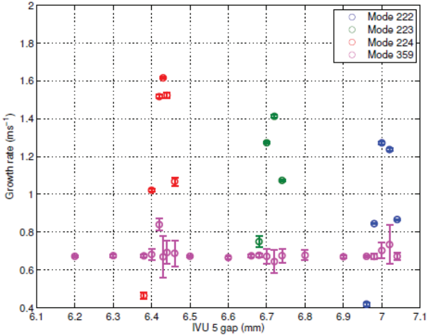


Figure 4: Instability mode growth rates for IVU05 vs gap.

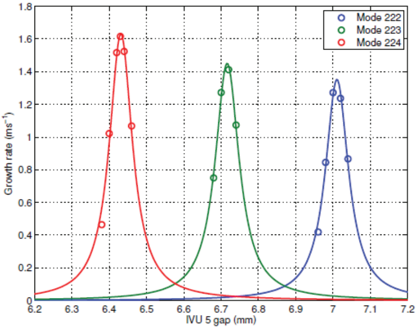


Figure 5: Second order resonance fits for modes 222 – 224.

- Data suggests 3 strong resonances, excited as the gap closes
- Can be modeled via HFSS, etc and resonator impedance,Q and center frequency quantified
- APS study of longitudinal HOMS in section Examples

Intra-Bunch Feedback at JPARC - horizontal plane

THO3AB01 Proceedings of HB2014, East-Lansing, MI, USA

PERFORMANCE OF TRANSVERSE INTRA-BUNCH FEEDBACK SYSTEM AT J-PARC MR

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K. Nakamura, Kyoto University, Kyoto, Japan
Y. Shobuda, JAEA, Ibaraki, Japan

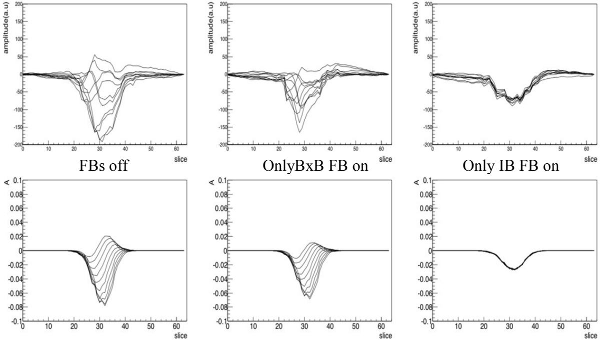
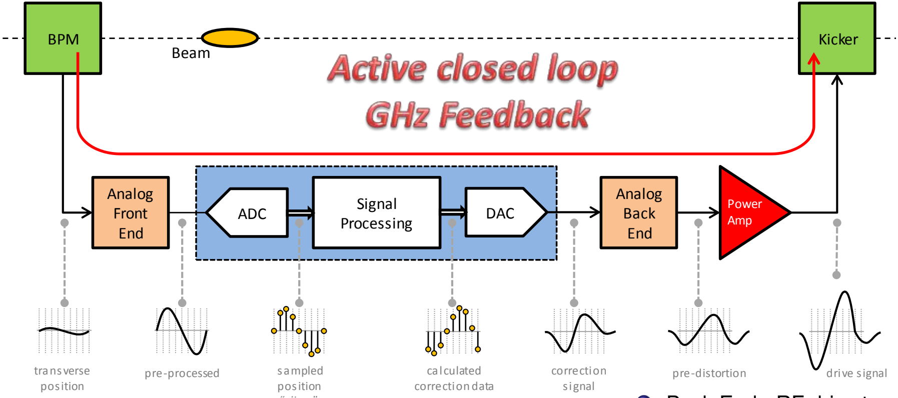


Figure 9: The delta signal motion around 250th turn after a perturbation kick. The top figures are for the experimental results (Left: all FBs off, Middle: only BxB FB on, Right: only intra-bunch FB on) and the bottom ones are for the simulations (Left: all FBs off, Middle: only BxB FB on, Right: only intra-bunch FB on).

- Long Bunch 150 - 200 ns
- 100 MHz sampling rate, 64 samples/bunch
- diagonal FIR processing, similar to bunch by bunch systems
- parallel with bunch by bunch feedback
- tune tracking during energy ramp (sequence of FIR filters)

SPS - Wideband IntraBunch Demonstration system

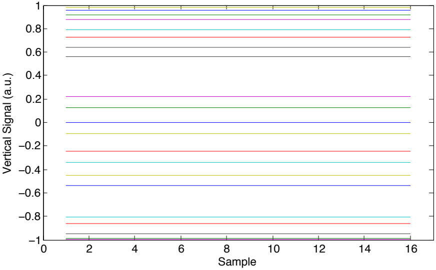


- Pickup - provides moment (charge*position)
- Analog Front End - Δ and Σ
- GHz Bandwidth, equalization

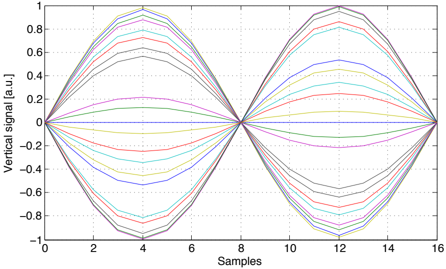
- 4 - 8 GS/s DSP
- Orbit rejection, processing gain
- Tailored gain vs. phase for damping

- Back End - RF drive to power stages, equalization
- Kickers - converts RF to transverse kick
- Timing, Synchronization, Diagnostics

Measuring the dynamic system - Modal Excitation



Mode zero excitation

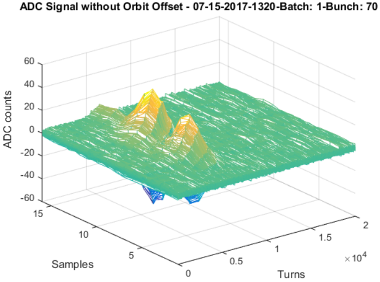


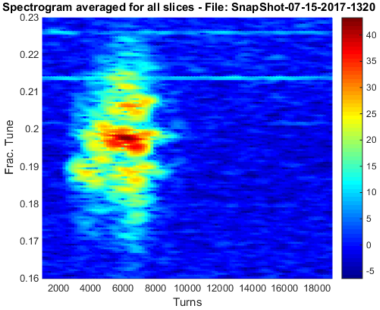
Mode 1 (head-tail) excitation

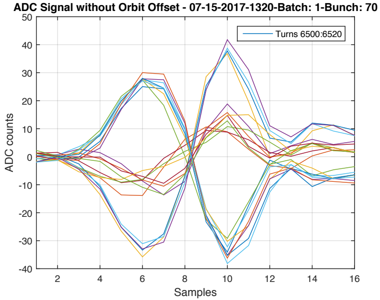
- Inside the DSP processing we can sum in an Excitation signal file
    - 16 unique samples/turn (4 ns duration)
    - 20,000 turn sequence, synchronized to injection
    - Spatially-shaped excites particular mode
    - Spatial Waveform is amplitude modulated at selected tune frequency
    - Chirps span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

Intra-Bunch SPS studies - Q26, Q20 and Q22 Optics

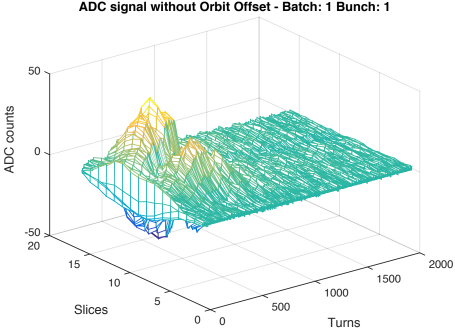
- Studies of stable, unstable beams
- Single-bunch and bunch train studies
- Driven and damped motion studies
- Study interaction with transverse dampers
- modes 0,1,2 (higher?) damping to noise floor
- use of 500 MHz striplines, 1 GHz bandwidth slotline kicker in fab

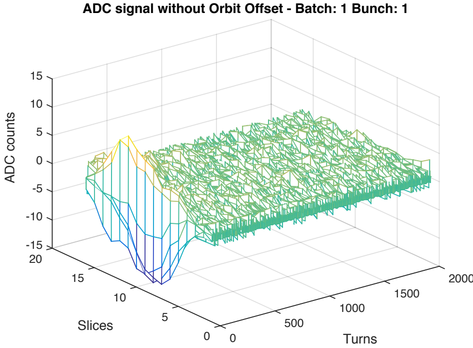






Feedback Stabilizes Single Bunch Instability





- Intensity $2x10^{11}$ with low chromaticity Q26 lattice (special beam)
- LEFT Instability seen immediately from injection - Wideband Feedback OFF
  - Instability leads to loss of charge without feedback, roughly 400 - 800 turns
- RIGHT Instability controlled from injection - Wideband Feedback ON
  - Head-Tail instability (intra-bunch)
- Important to understand injection transient and saturation impacts

Single Bunch - Stabilized by feedback

- Q26 Optics, Charge $\simeq 2.05 \times 10^{11}$ part.
- Transverse damper is ON. Wideband feedback is ON.
- TWC $= 1.4$MV, Chromaticity posiitve, tune $= 0.183$, $\epsilon_y = 1.7\mu m$.

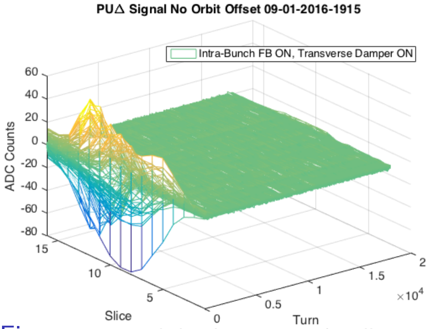


Figure: Vertical dipole motion. Small amount of charge is lost at injection.

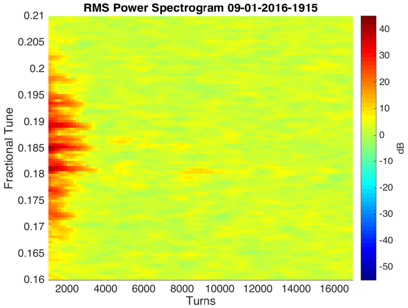


Figure: Spectrogram.

Single Bunch - Damp - Grow transient

- Q26 Optics, similar machine-beam conditions that above
- The wideband feedback in ON during injection up to turn 8000, then it is OFF
- The beam becomes unstable after opening the feedback loop

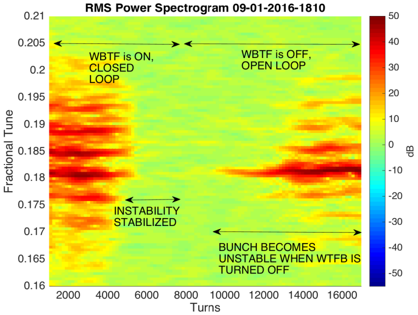


Figure: Spectrogram of a bunch.
The wideband feedback (WBFB) is ON until turn 8000. The bunch becomes unstable after WBFB is turned OFF.

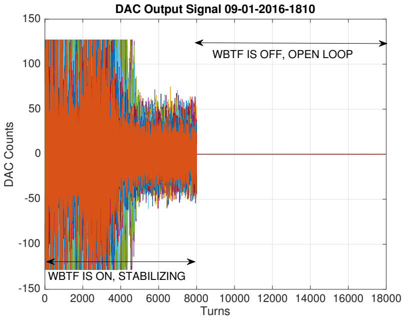
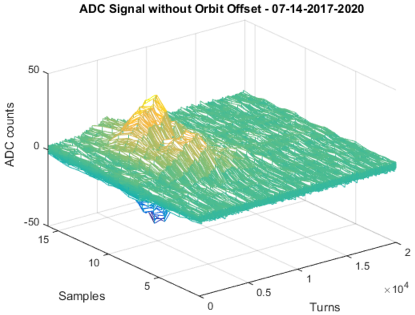
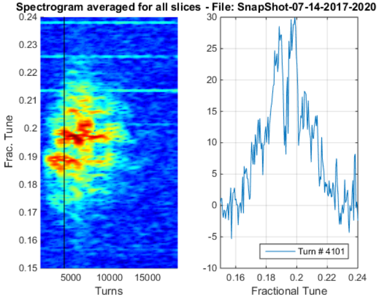


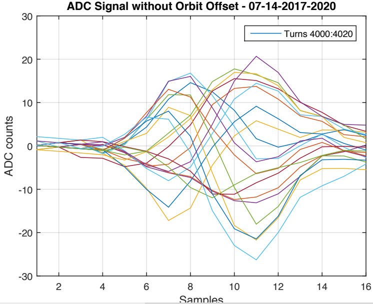
Figure: DAC signal (Amplifier, Kicker signals). Loop is opened at turn 8000

Stable Q22 study - pos FB excitation, free decay

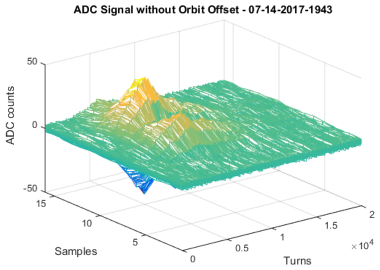


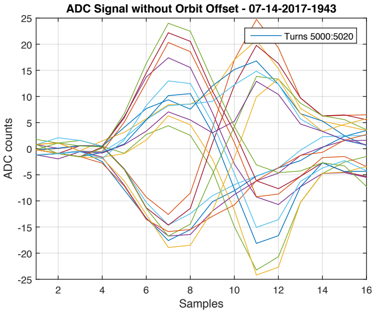
- Stable bunch is excited with positive feedback for 5000 turns -instability grows
- Pos FB SG 3 damp SG 15
- Transverse damper 2 ON 1 OFF
- unstable bunch develops mode 1 and mode 0
- Evidence of power converter noise and tune modulation

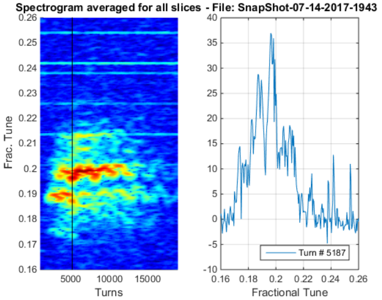


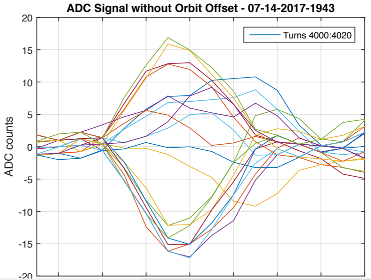


single bunch Q22 study - pos excite, open loop decay

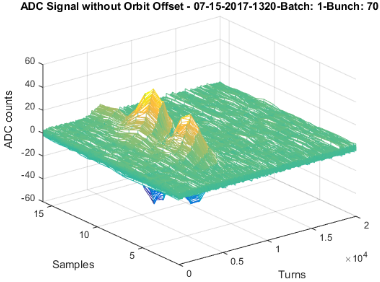


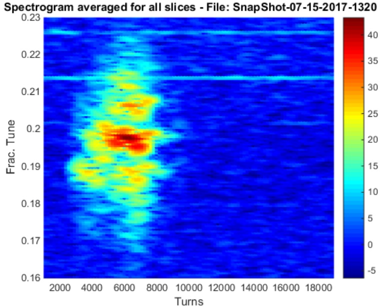


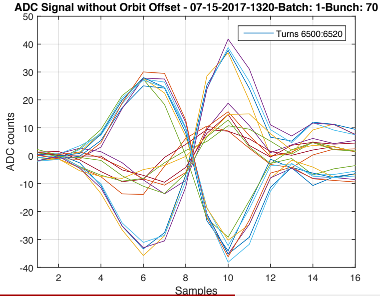




Q22 high gain damping 7-15 1320

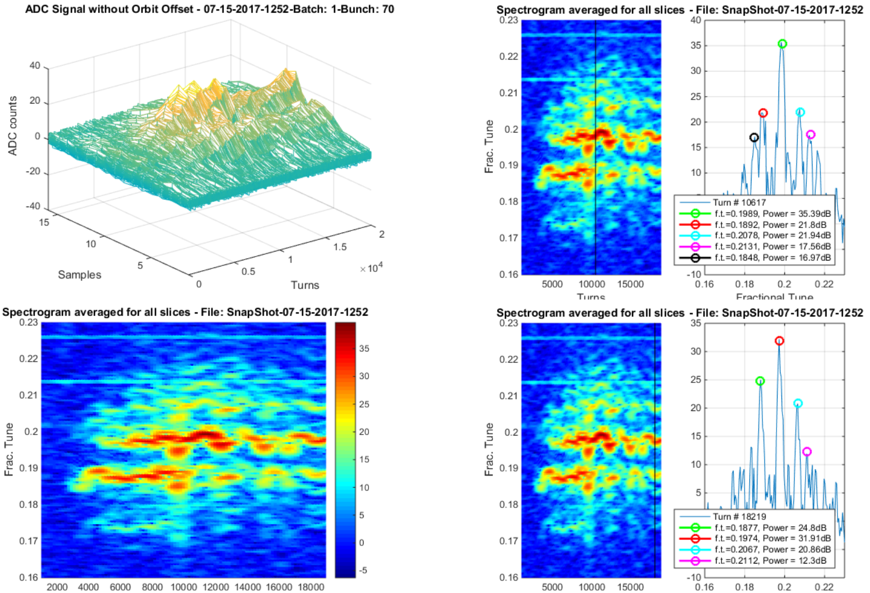




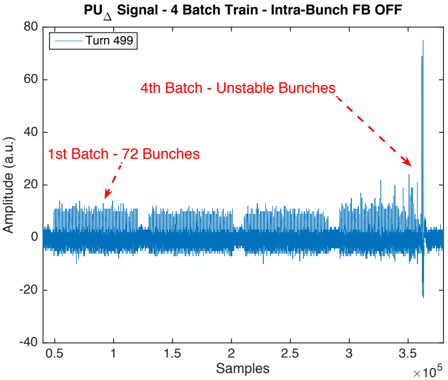


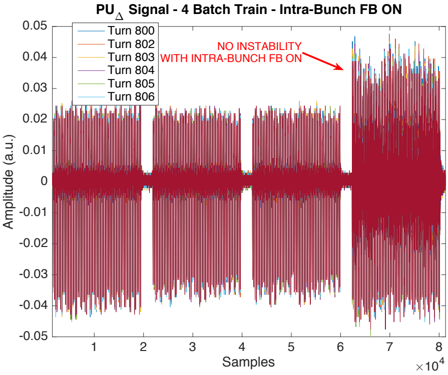
- Mostly mode 1 excited, some mode 2
- Evidence of power converter noise and tune modulation
- Mode 0 seems well-controlled by transverse dampers
- Complete mode 1 damping to noise floor
- Studies of damping rate vs feedback gain
- Instability threshold via pos FB gain study

Q22 train of 72 - bunch 70 M 1 doesn’t damp w/o FB



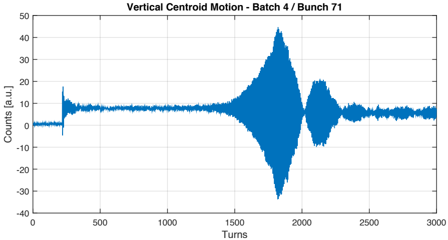
SPS - High Current Multi-Bunch Control

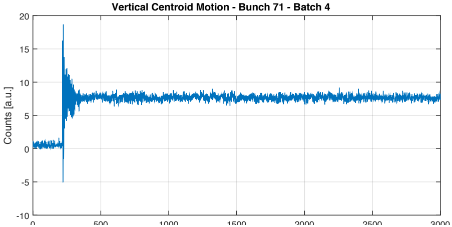


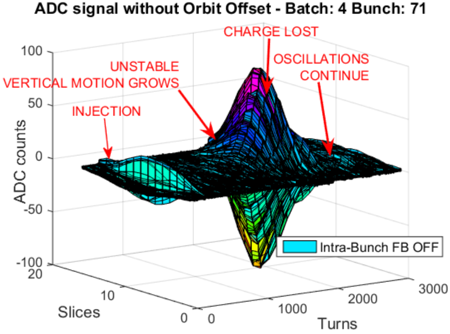


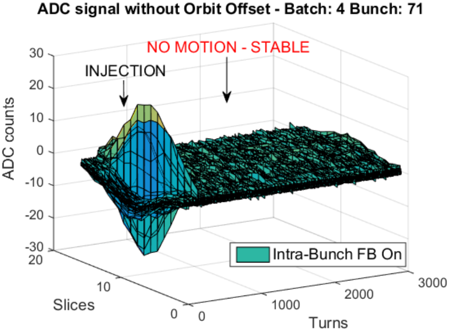
- High Current Train SPS Measurement - 4 stacks of 72 bunches
- Intensity $1.8x10^{11}$ with low chromaticity Q20 lattice (special beam)
- Instability seen at end of 4th stack - Wideband Feedback OFF
- Instability controlled on 4th stack - Wideband Feedback ON
- Instability leads to loss of charge from end of Stack 4
- in both cases existing SPS Transverse damper is ON

Data Snapshot - High Current Multi-Bunch Control







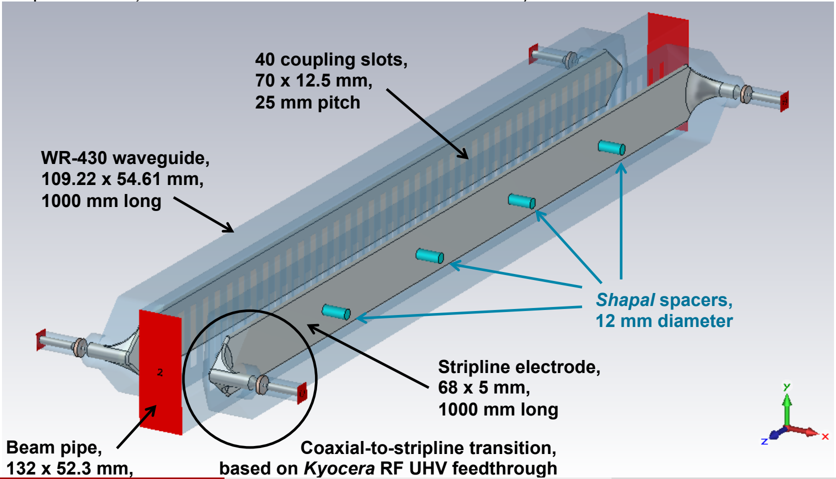


SPS MD studies - Q26, Q20 and Q22 Optics

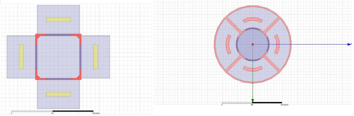
- System Technology
  - demonstrated intra-bunch control of unstable beams
  - Achieved damping rates 1/200 turns (limited kicker)
  - Noise floors in system, damped beam noise floors
  - Development/evaluation of control filters for Q20 vs other optics (impact of Q_s)
  - Analysis tools and comparisons to simulation methods
- Single Bunch Studies (in progress)
  - Control Head-Tail type intrabunch instability
  - Damping of intrabunch unstable motions with growth time > 200 turns
  - Explore interaction of Wideband and traditional mode 0 transverse damper
  - Generation/study/control of a clear "TMCI" instability in progress
- Multi-Bunch Control (in progress)
  - WBFB controls collective effect and intra-bunch instabilities in multi bunch trains
  - control of unstable bunch motion, study of damping of bunch vs. position
  - MD Goal - induce intra bunch instabilities via electron clouds in the last batch, but to date unstable bunches at end of train present only Mode 0 motion.
  - Further MD studies can explore control of a clear "Ecloud" driven instability (higher intensity?)
- In progress -optimal controllers to stabilize motion with faster growth rates. Installation of slot line kicker/amplifiers will provide significant gain increase

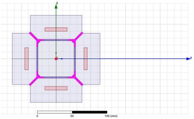
1 GHz Wideband Slotline kicker development

- 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, in fabrication for 2019 CERN installation)

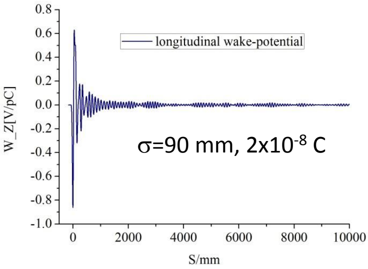


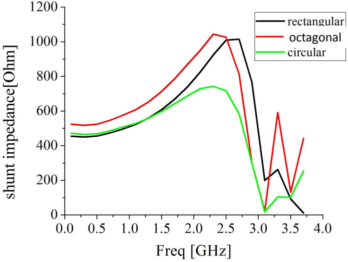
Wideband Kicker - initial study for LHC and FCC - broadband Z_l? (G. Zhu)



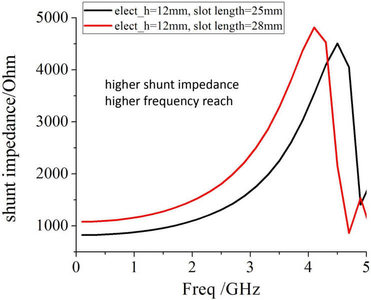


aperture
frequency reach
size of “good field” region
shunt-impedance
beam coupling impedance
manufacturing



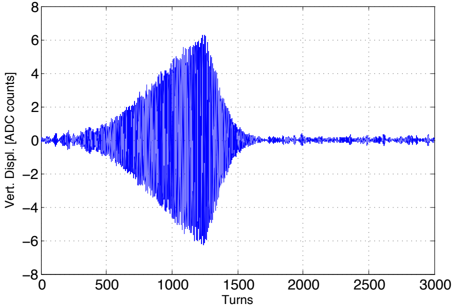


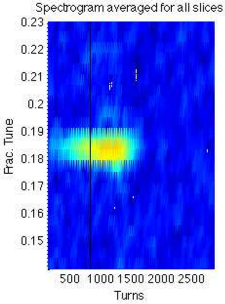
52 mm aperture

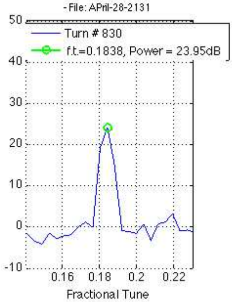


Intrabunch Feedback - Beam Diagnostic Value

- Feedback and Beam dynamics sensitive measure of impedance and other dynamic effects
- Complementary to existing beam diagnostic techniques
- Novel time and frequency domain diagnostics
  - reconfigurable platform, 4 - 8 GS/s data rates
  - snapshot memories, excitation memories
  - stable and unstable systems can be studied with various methods







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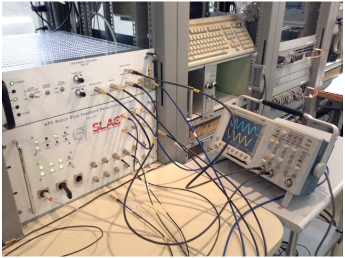
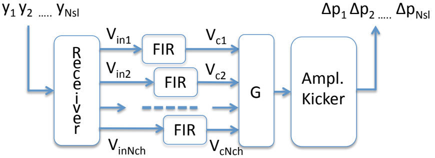
- Thanks to D. Teytelman, M. Boland, G. Rehm and M. Tobiyama for contributions for this talk. We acknowledge S. Uemura, A. Bullitt, J. Cesaratto, J. Goldfield, J. Platt, K. Pollock, N. Redmon, S. Verdu, S. De Santis, G. Kotzian, D. Valuch, M. Wendt, D. Alessini, A. Drago, S. Gallo, F. Marcellini, M. Zobov and D. Teytelman for SPS System contributions and years of collaboration.
- We acknowledge our many friends and collaborators at US, European and Japanese labs, with whom we have learned so much.
- We are grateful for the collaboration and generous help with the SPS studies from everyone in the control room and operations groups.

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

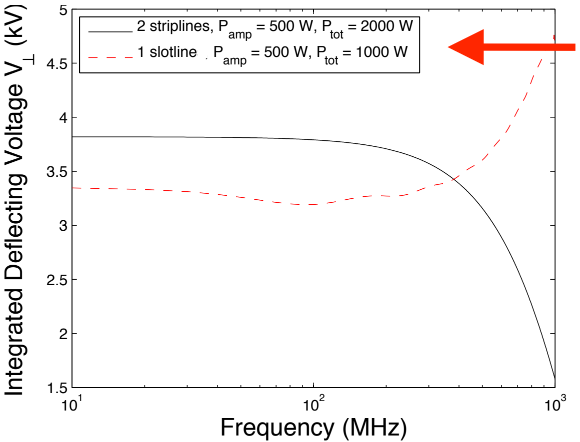
SPS Demonstrator System DSP Features



- Reconfigurable 4 GS/sec. DSP platform
- 1 GHz system bandwidth
- GUI for operations/Control
- Processing Upgraded LS1 and 2015/2016
  - 64 bunch train control, scrubbing beam control
  - 16 slice FIR control, flexible slice gains
  - On the fly filter coefficient swap
  - Feedback + Excitation mode
  - Robust Timing/Synchronization
  - Digital Output RF upconvert
- 2 wideband Stripline Kickers designed, cabled and commissioned - Slotline designed, in fab
- 4 1 GHz 250W RF power amps in tunnel



Complementary Striplines and Slotline

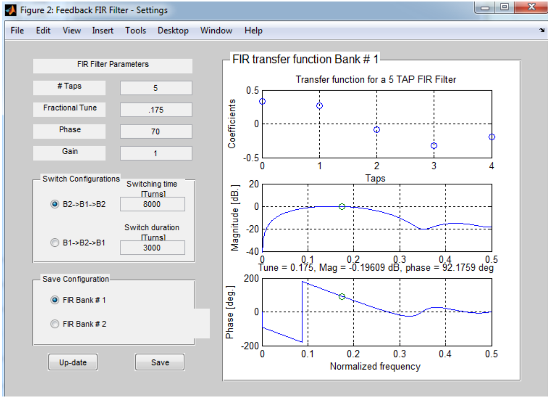


CERN plans to install:

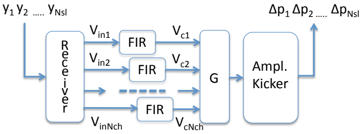
- 2 Striplines
- 1 Slotline

- 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 Filters - Frequency Domain Design

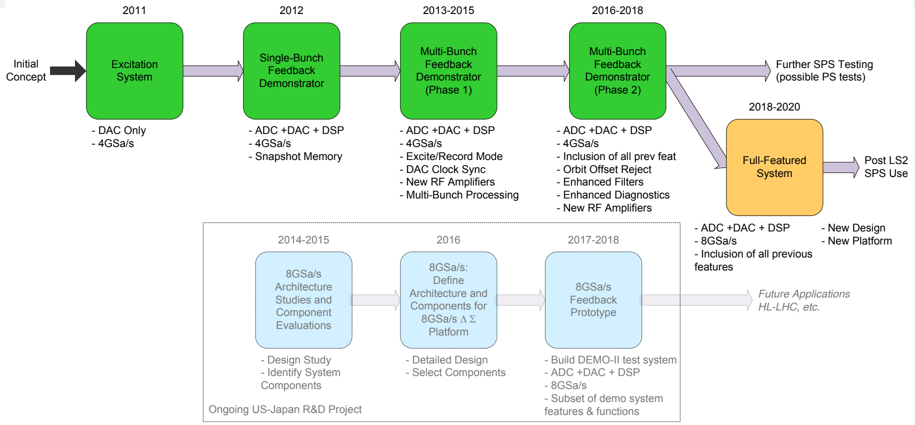


- FIR up to 16 taps
- Designed in Matlab
- Filter phase shift at tune must be adjusted to include overall loop phase shifts and cable delay
- Based on methods used in coupled-bunch systems



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

Upgrades to the SPS Demonstrator - Roadmap



- The Demo system is a reconfigurable platform to evaluate control techniques
- MD experience has guided necessary system specifications and capabilities
- The path towards a full-featured system is flexible, can support multiple pickups and/or multiple kickers
- US-Japan testbed in progress to validate 8 GS/s processing technology

Wideband Feedback - Implementation in LHC

- Architecture being developed is reconfigurable!
- Processing unit implementation in LHC similar to SPS:

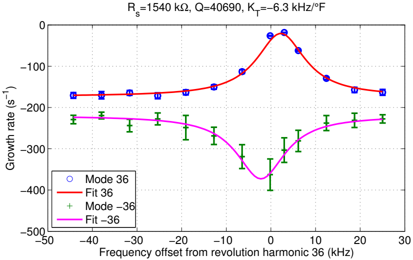
	SPS	LHC
RF frequency (MHz)	200	400
f_{rev} (kHz)	43.4	11.1
# bunches/beam	288	2808
# samples/bunch	16	16
# filter taps/sample	16	16
Multi-Accum (GMac/s)	3.2	8

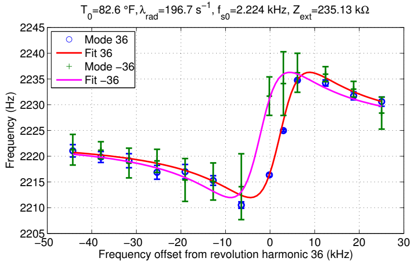
- LHC needs more multiply-accumulation operation resources because of # of bunches, but reduced f_{rev} allows longer computation time (assuming diagonal control).
    - LHC signal processing is roughly x2 more FPGA resources
    - Similar architecture can accommodate needs of both SPS and LHC.
- Still need kicker of appropriate bandwidth with acceptable impedance for LHC. Learn from SPS Slotline, simulation study of 4 GHz slotline in process at CERN.

Next Technology Development Opportunity

- Upgraded High-speed DSP Platform consistent with 4 -8 GS/sec sampling rates for MD studies
  - Parallel 4 GS/sec ADC paths, for multiple pickups or improved noise floor
  - Explore value of $\Delta\Sigma$ front end, with charge normalization
  - Low-noise transverse coordinate receivers, orbit offset/dynamic range improvements, pickups
  - Expand Master Oscillator, Timing system for Energy ramp control
  - Allow multiple kickers, $\pi/4$ separation, higher gain
- Upgraded Demo platform - Funding?
  - Greater FPGA resources, allows more complex modal filters, higher sampling rate filters
  - Two 4 GS/sec input ADC streams, allowing single 8 GS/sec data path, or two pickups with 4 GS/s data paths
  - Reconfigurable FPGA processing allows re-targeting to LHC, other facilities
- Lab evaluation and firmware development
- Validate key features for robust control for Q20, Q22, Q26, other possible dynamics

Recent study of APS Longitudinal HOMs





Invited Paper at IBIC 2017

CHARACTERIZING THE COUPLED BUNCH DRIVING TERMS IN A STORAGE RING *

Katherine C. Harkay†, Tim Berenc, Louis Emery, Ulrich Wienands, ANL, Argonne, IL, USA
Dmitry Teytelman, Dimtel, Inc., San Jose, CA, USA
John Byrd, LBNL, Berkeley, CA, USA
Rohan Dowd, Australian Synchrotron, Clayton, Australia

- Study of all Longitudinal HOM's
- Systematic grow-damp studies
- Systematic drive-damp studies
- quantifies actual as built machine

Limitations on system gain

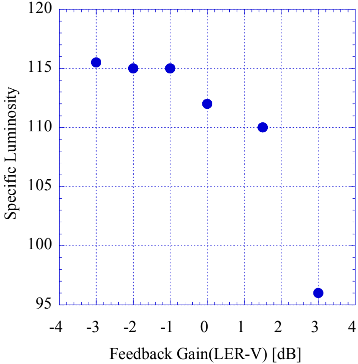
- For any causal feedback technique, the system gain and bandwidth are limited
- Gain is partitioned between pickup, receiver, DSP, RF amplifiers and kickers
- for FIR or bandpass filter, 2 gain limit mechanisms
  - Group delay/bandwidth gain limit - phase/gain margins lost as gain is increased, drive instabilities
  - Noise saturation limit - input noise$*$gain saturates kicker
- Impacts of injection transients, driven signals within the system filter bandwidth
- Do we see these limits in operating systems?

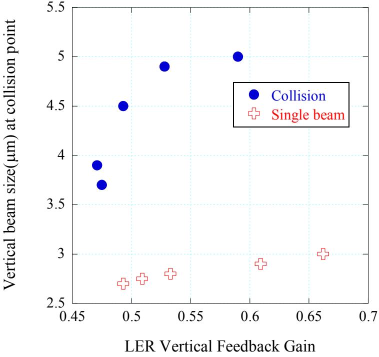
Impacts of feedback noise in beam collision

MOPD73 Proceedings of DIPAC2011, Hamburg, Germany

STUDY OF BEAM SIZE BLOWUP DUE TO TRANSVERSE BUNCH FEEDBACK NOISE ON $e^+ e^-$ COLLIDER*

Makoto Tobiyama# and Kazuhito Ohmi,
KEK Accelerator Laboratory, 1-1 Oho, Tsukuba 305-0801, Japan.





- Discovery of luminosity decrease in KEKB collider, function of vertical feedback gain

KEKB collider Impacts of feedback noise

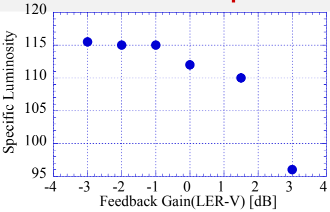


Figure 1: Luminosity reduction with the KEKB-LER vertical feedback gain.

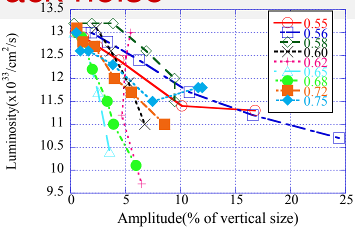
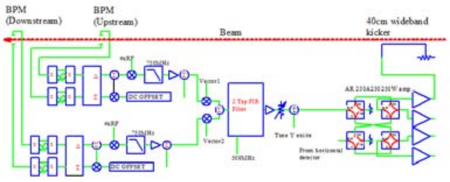


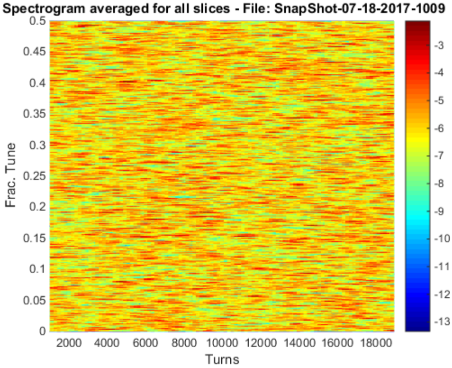
Figure 5: Luminosity degradation due to oscillation applied externally in the feedback system.

KEKB transverse bunch feedback system

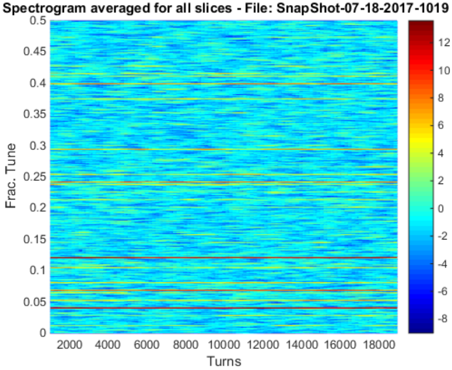


- Beam-Beam effect in collision amplifies noise in feedback system
- Understood via simulations and verified with noise injection into system
- Original KEKB vertical system used 2-tap filter, no processing gain. All noise folded into processing channel. SuperKEKB systems expanded with feedback filters

Noise Floor - Operational Demo SPS system



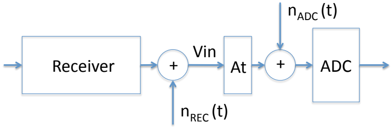
- ADC Terminated in 50 Ohms
  - very quiet, near theoretical quantizing noise
  - Spectrogram shows very flat spectrum, no clock pickup
  - System maximum gain is determined by receiver noise floor



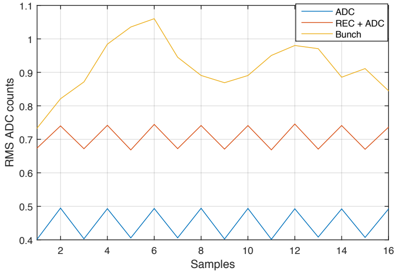
- Receiver with pickups (no beam condition, RF and magnets on)
  - Receiver broadband noise slightly higher than ADC quantizing noise (2dB? 3dB?)
  - narrowband lines seen - from ?

SNR and sensitivity of front-end receiver

Detail of Receiver - ADC



Front-end Noise and Bunch Motion



$ADC : +127c \,/ -128c = \pm 250$ mV ;
$\Delta V = 1.952$ mV/c.
Attn. $= 1/1.65$:
Vin $= \pm 407$ mV ; $\Delta V_{in} = 3.22$ mV/c

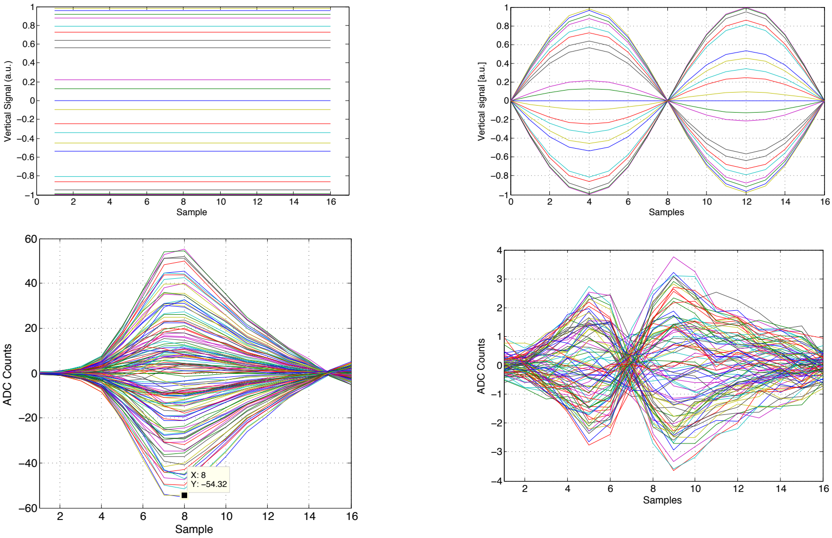
.

Front-end performance - Optimized existing configuration
$\sigma_{nADC} \simeq 0.45$ counts
$\sigma_{REC.Attn} \simeq 0.54$ counts
$\sigma_{Front-end} \simeq 0.7$ counts $\simeq 12\mu$m RMS per sample
$\sigma_{y-Centroid} \simeq 3\mu$m RMS

.

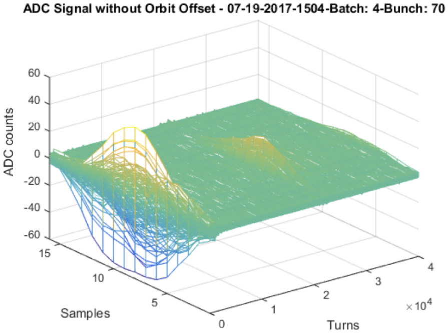
RMS damped Beam motion
Transverse
$\sigma_Y = 2.8\mu m$ rms
Contributions from synchrotron motion σ_Z, sampling clock phase noise $\sigma_{\Delta T}$
$\sqrt{\sigma_Z^2 + \sigma_{\Delta T}^2} = 6.25 ps$ rms

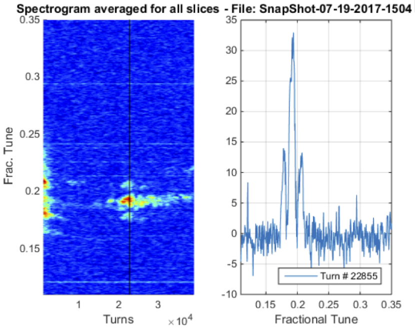
Measuring the dynamic system - Beam response

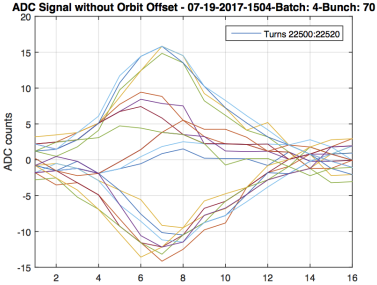


- Pickup,Kicker require equalization, Timing the front and back-ends is tricky
- Higher modes well-damped, difficult to excite

4 batch Q20 study - bunch 70 batch 4 open loop





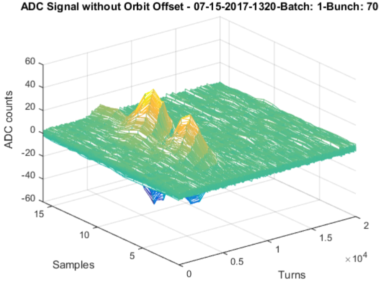


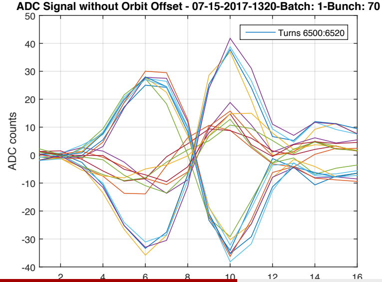
- Study unstable bunch at end of last train
- Attempt to excite Ecloud instability
- unstable bunch in batch is mode zero motion
- study can also focus on tune shifts vs bunch position

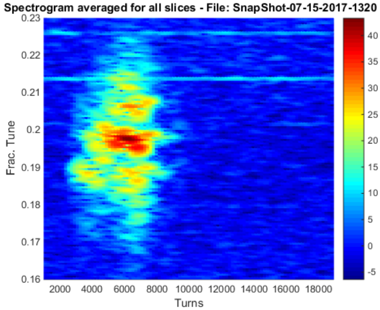
Damping studies

- Studies of excited beam, followed by damping at various damping gains
    - bunch 70 of multi-bunch Q22 fill
    - Both transverse dampers ON
    - Studies from July 15 , 8 minute interval
    - attemp to have similar currents, excitation, only vary damping gain
    - Excitation is postive feedback SG=3 for turns 3000 - 6500
    - Damping is from turn 6500
- damping SG varied by x8 from 3 (highest),4,5,6 (lowest)
- we have roughly 5 transients at each configuration (200 total)
- these examples selected as roughly equal currents
- need to quantify damping rates vs gain

Damping SG= 3 (highest gain)7-15 1320

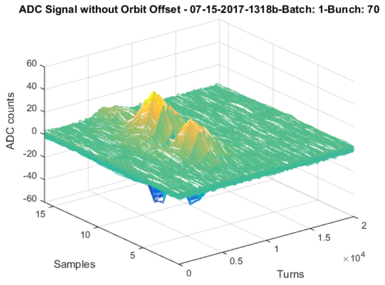


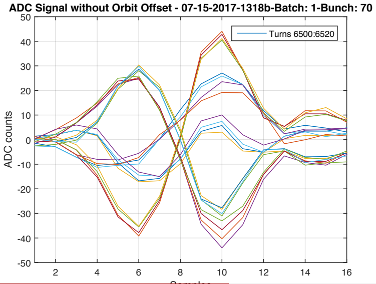


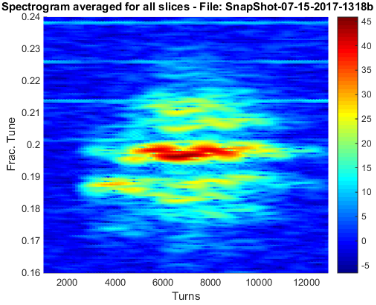


- Mostly mode 1 excited, some mode 2
- Mode 0 seems well-controlled by transverse dampers
- Complete mode 1 damping in roughly 1000 turns
- damping to noise floor

Damping SG= 4 (1/2 highest gain)7-15 1318b

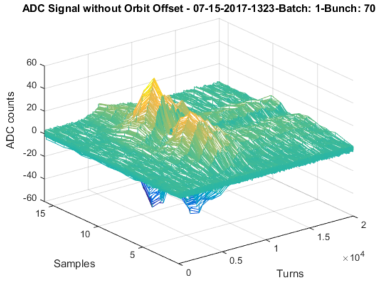


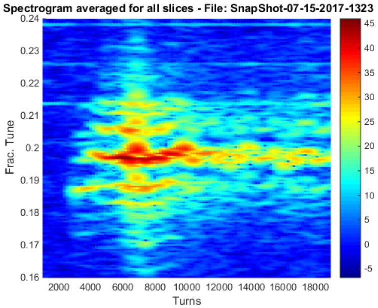


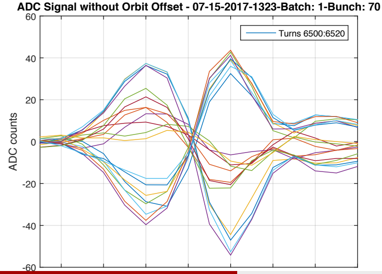


- Mostly mode 1 excited, some mode 2 -same case
- Mode 0 seems well-controlled by transverse dampers
- Complete mode 1 damping in roughly 3500 turns
- damping to noise floor

Damping SG= 5 (1/4 highest gain)7-15 1323

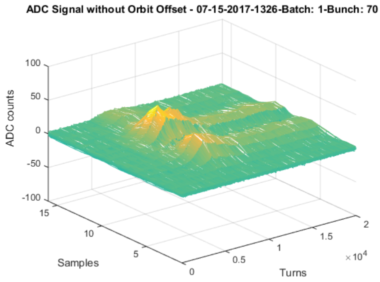


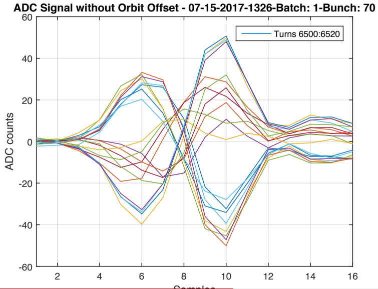


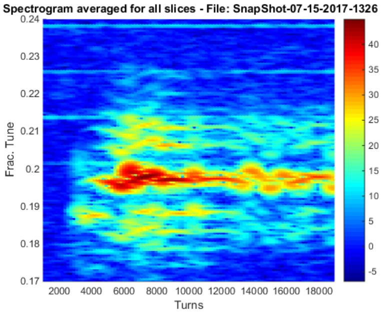


- Mostly mode 1 excited, some mode 2 -same case
- residual motion at mode 0 and 1,2 seen to be decaying
- Complete mode 1 damping in roughly 10000 turns
- Final damped state not recorded, post length

Damping SG= 6 (1/8 highest gain)7-15 1326

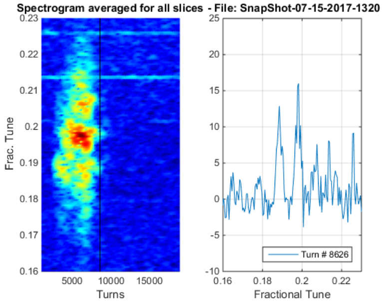


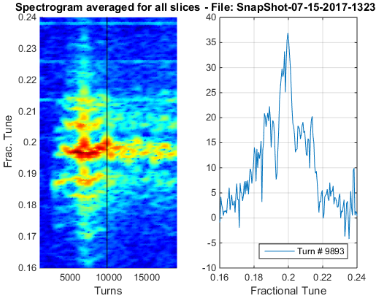


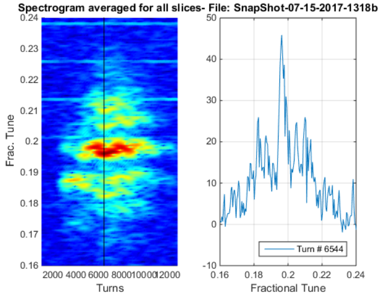


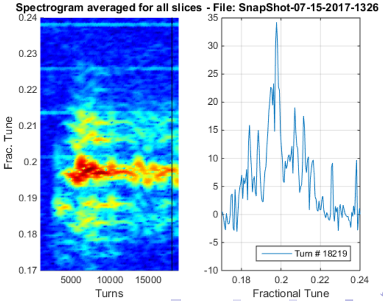
- Mostly mode 1, mode 2 -same case
- residual motion at mode 0 and 1,2 seen to be decaying
- Gain seems marginal, but is sufficient to damp
- Final damped state >10000 turns, post length

Compare 4 damping gains x8, x4, x2 and x1

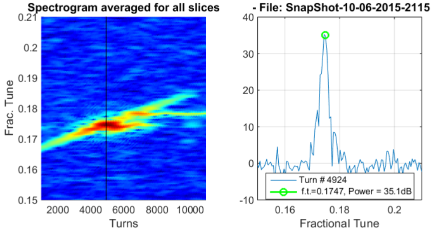




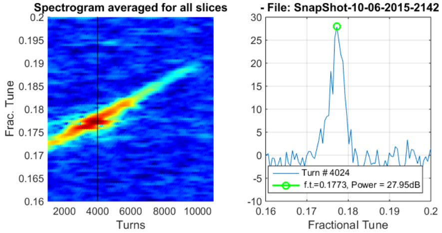




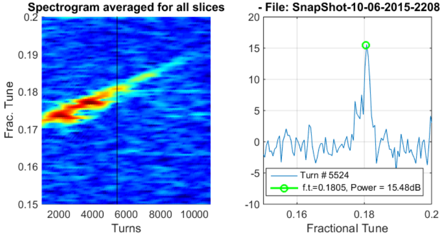
Open-Loop Studies September-October 2015



Beam Spectrogram driven by Mode 0 excitation

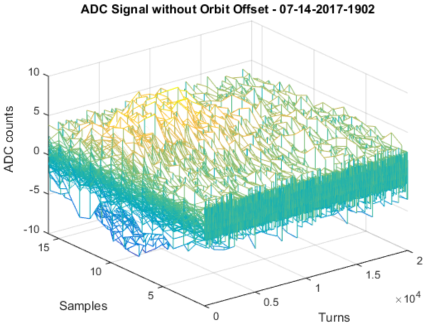


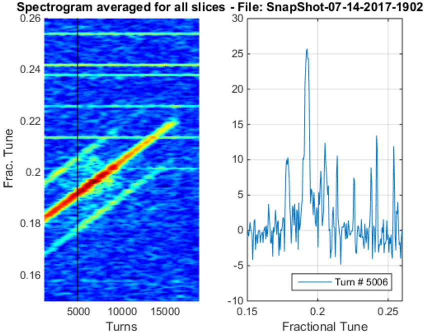
Beam Spectrogram driven by Mode 1 excitation



Beam Spectrogram driven by Mode 2 excitation

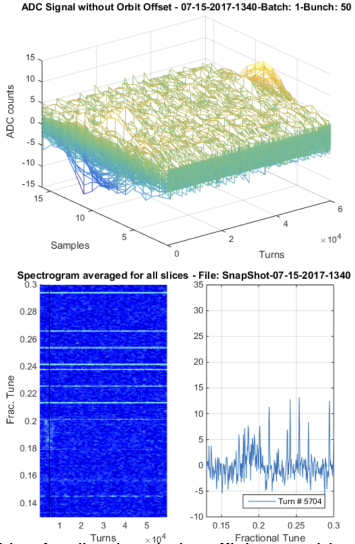
single bunch Q22 study - Driven chirp mode zero excitation open loop



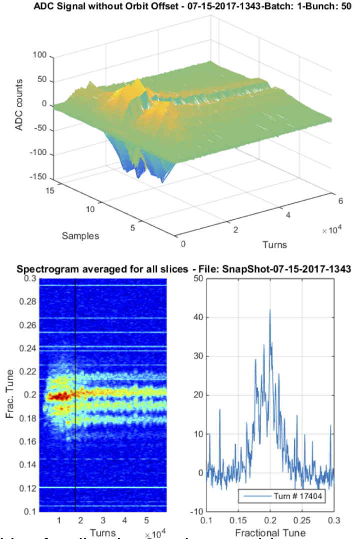


- Mode Zero temporal shape
- Chirp from 0.18 to 0.22
- Note Processing Gain (sensitivity) of spectrogram

Excite bunch 50- excite feedback SG4 vs SG3

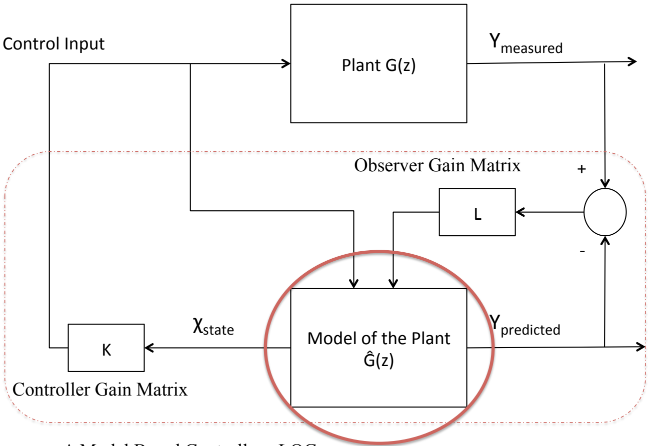


positive feedback gain insufficient to drive unstable growth



positive feedback x2 gain now drives unstable growth

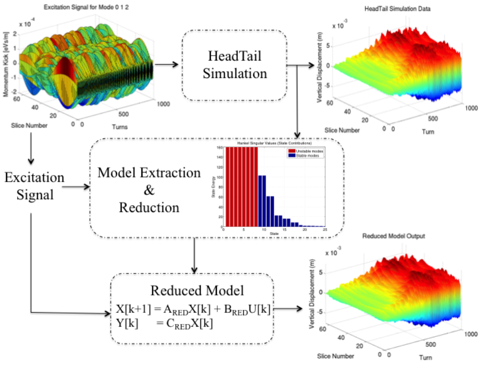
Advantages of Model-Based Control



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
- Ph.D. Thesis for O. Turgut - New directions, model based MIMO formalism

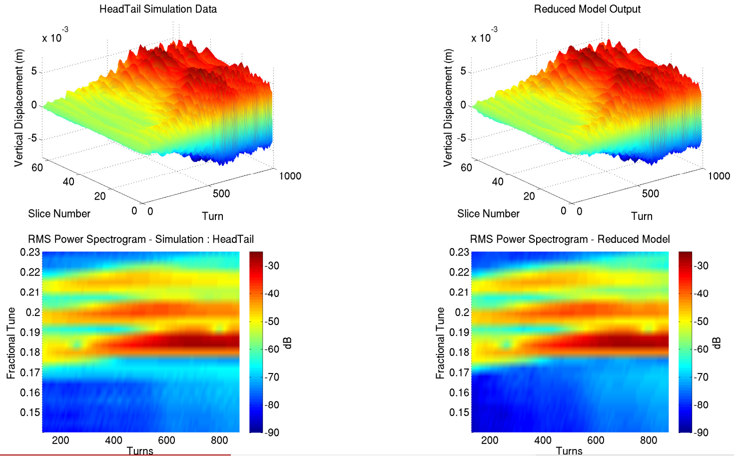
Model - is derived from Simulation or MD studies



- 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).

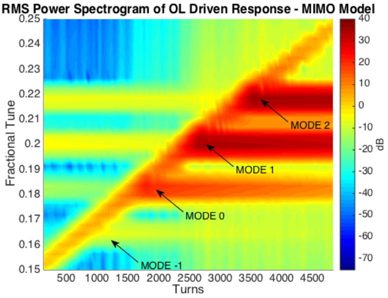
- Linear model - allows analytic knowledge of limits
- better than FIR for closer ω_β and ω_s Tunes, optics issues limit
- Control Formalism - allows formal methods to quantify stability and dynamics, margins
- model based MIMO formalism uses information from pickup more completely

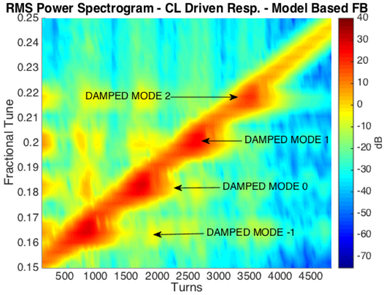
Head-Tail vs Reduced Model results

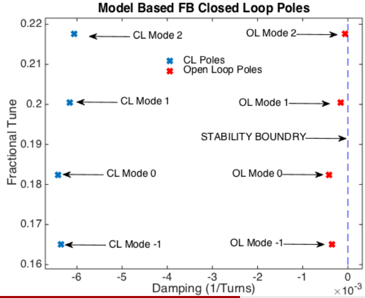


- Time Domain data is fit, Models in Time and Frequency Domain
- Model can be fit to simulation or physical machine data
- comparing simulation, experimental reduced models excellent way to validate nonlinear simulations

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)
- What about sparse control with few off diagonal elements?
- O. Turgut Stanford Ph.D. Defense October 6

Beam Measurements, Simulation Models, Technology Development, Wideband Kickers and Demo System