Wideband Feedback Systems

Full-Function Instability Control System

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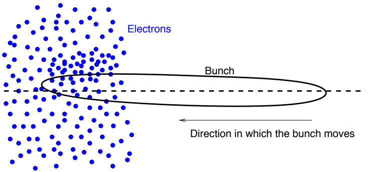
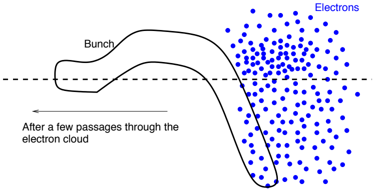
Review Charge and Why are we here?

- Wideband intra-bunch Feedback Systems for SPS (and LHC)
  - Address instabilities, increase bunch currents, increase LHC Intensity and Luminosity
- Charge to the Review Committee - Evaluate
  - Development of appropriate core competencies
  - The quality and significance of the LARP scientific and technical accomplishments, and the merit, feasibility and impact of its planned development program
  - Will these accomplishments lead to mature technical readiness?
  - What will be the demonstration of these goals?
- With respect to the most current LHC schedules and plans
  - What are the scientific and technical risks?
  - Are the available resources for LARP being optimally used?
- To Paraphrase the Talking Heads, "How Did We Get Here?"

CERN SPS Ecloud/TMCI Instability R&D Effort



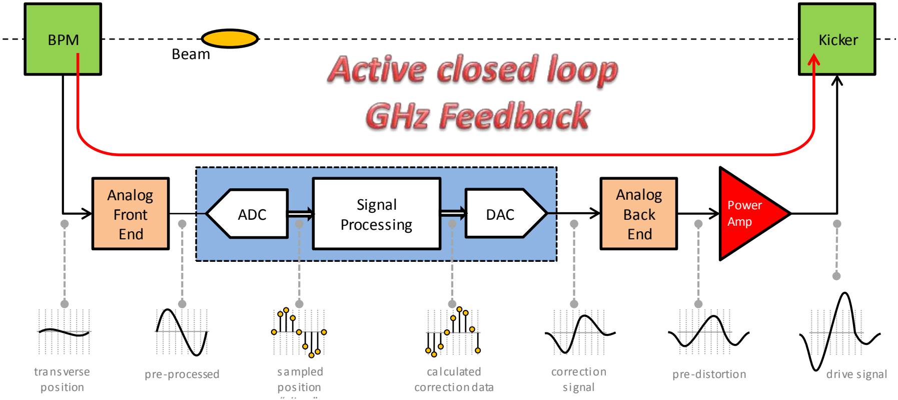


- Ongoing project SLAC/LBL/CERN via US LARP DOE program
- Proton Machines, Electron Cloud driven instability - impacts SPS as high-current LHC injector
  - Photoelectrons from synchrotron radiation - attracted to positive beam
  - Single bunch effect - head-tail (two stream) instability
- TMCI - Instability from degenerate transverse mode coupling - may impact high current SPS role as LHC injector
- Multi-lab effort - SLAC, CERN, LBL, INFN-LNF

SPS Ecloud/TMCI Instability R&D Effort

- Stabilize Ecloud and TMCI effects via GHz bandwidth feedback
  - Complementary to coatings, grooves, etc. for Ecloud control
  - Also addresses TMCI, allows operational flexibility
- MD efforts progressed from open-loop, driven studies to closed-loop studies with Demonstrator processing
- Analysis and simulation includes beam physics, feedback optimization, and methods to extract beam dynamics from MD studies and simulations
- LARP supported multi-lab effort - coordination on
  - Non-linear Simulation codes (CERN - SLAC)
  - Dynamics models/feedback models (SLAC - CERN)
  - Machine measurements- SPS MD (CERN - SLAC)
  - Kicker models and simulations (INFN-LNF, LBL, SLAC, CERN)
  - Hardware technology development (SLAC, KEK, CERN)
- LARP feedback program provides novel beam diagnostics in conjunction with technology development

Essential Features



Wideband Intra-Bunch Feedback - Considerations

The Feedback System has to stabilize the bunch due to E-cloud or TMCI, for all operating conditions of the machine.

- unstable system- minimum gain required for stability
- E-cloud - Beam Dynamics changes with operating conditions of the machine, cycle (charge dependent tune shifts) - feedback filter bandwidth required for stability
- Acceleration - Energy Ramp has dynamics changes, synchronization issues (variation in β), injection/extraction transients
- Beam dynamics is nonlinear and time-varying (tunes, resonant frequencies, growth rates, modal patterns change dynamically in operation)
- Beam Signals - vertical information must be separated from longitudinal/horizontal signals, spurious beam signals and propagating modes in vacuum chamber
- Design must minimize noise injected by the feedback channel to the beam
- Receiver sensitivity vs. bandwidth? Horizontal/Vertical isolation?
- What sorts of Pickups and Kickers are appropriate? Scale of required amplifier power?
- Saturation effects? Impact of injection transients?
- Trade-offs in partitioning - overall design must optimize individual functions

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- Design must minimize noise injected by the feedback channel to the beam
- These questions can only be understood with both MD Studies and Simulation methods
- Receiver sensitivity vs. bandwidth? Horizontal/Vertical isolation?
- What sorts of Pickups and Kickers are appropriate? Scale of required amplifier power?
- Saturation effects? Impact of injection transients?
- Trade-offs in partitioning - overall design must optimize individual functions

Extensions from existing 500 MS/s architectures

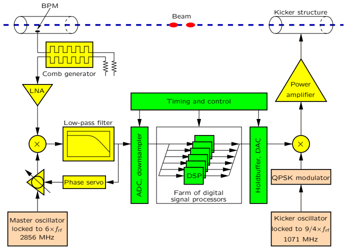
example/existing bunch-by-bunch feedback (PEP-II, KEKB, ALS, etc.)

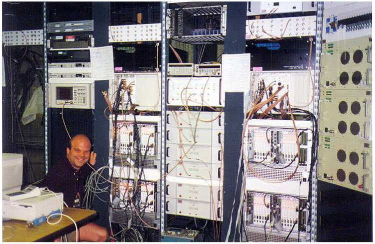
- Diagonal controller formalism
- Maximum loop gain from loop stability and group delay limits
- Maximum achievable instability damping from receiver noise floor limits

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

SPS and LHC needs may drive new processing schemes and architectures

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



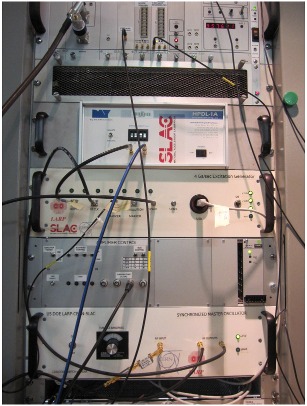


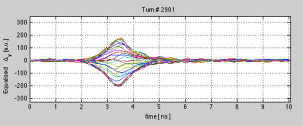
AY_008 HER and LER Electronics 10-4-97

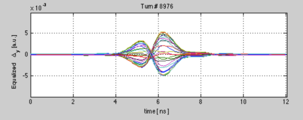
Progress since the 2012 DOE Review

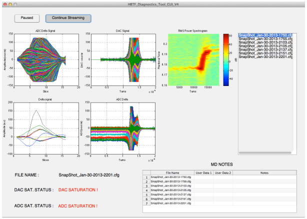
- Commissioning of Demonstrator hardware system, multiple MD studies prior to LS1
- Development of MD data analysis methods
  - Validate measurements against models
- Nonlinear simulation codes/feedback model studies
- Development of wideband kicker designs
  - Conceptual design report
  - Mechanical design
- LARP Internal Project Review - FNAL June 2013
  - Multi-year project proposal with resource plans
  - Proposal to develop full-featured system for post LS2 SPS use
- LIU-SPS High Bandwidth Damper Review - CERN July 2013
  - Decision to fabricate stripline and slotline style kickers for SPS installation
  - Stripline in fab for installation May 2014, slotline in final electromagnetic optimization
- FY14 prorities - expand Demonstration system for wideband operation, after LS1 explore controllers and wideband kicker with beam

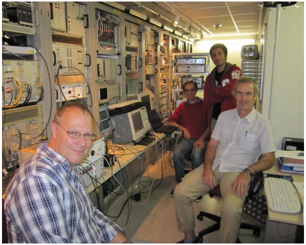
Beam Measurements, Simulation Models, Technology Development, Driven Beams and Demo System







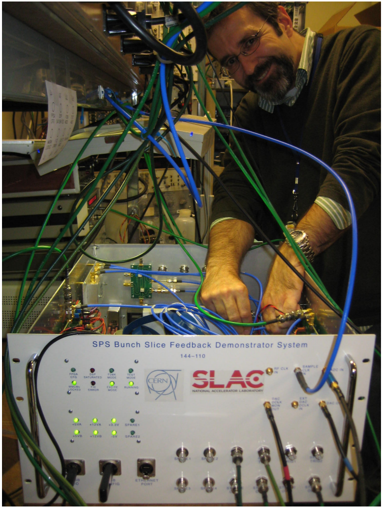


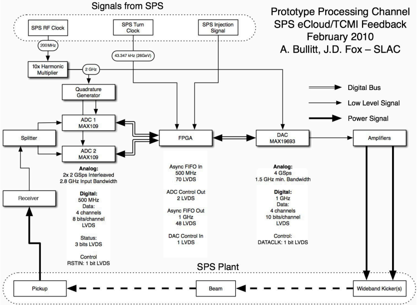


MD Results, technology and data analysis

- 2009 - 2012: MD studies of open-loop unstable motion, development of analysis methods, technology development of excitation system and in-tunnel amplifiers, limited bandwidth kicker, driven studies
- 2012 - 2013: MD trials (November, January, February) implement one-bunch feedback control (with 200 MHz bandwidth kicker)
  - 5 and 7 Tap FIR filters, gain variations of 30dB, Φ varied postive/negative
  - Studies of loop stability, maximum and minimum gain
- Driven studies (Chirped excitations)
  - variation in feedback gain, filter parameters
  - multiple studies allow estimation of loop gain vs frequency (look at excitation level of several modes)
  - interesting to look at internal beam modes
- Feedback studies of stable, marginally stable and unstable beams
- Analysis methods to validate feedback performance, validate models

4 GS/s 1 bunch SPS Demonstrator processing system



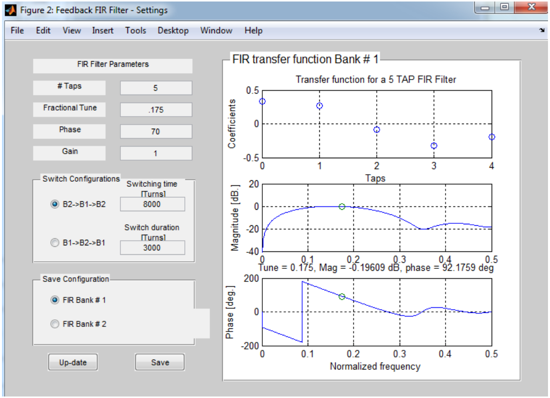


- Proof-of-principle channel for 1 bunch closed loop tests in SPS - commissioned November 2012
- Provides wideband control in SPS after LS1 (installation of wideband kicker)
- Reconfigurable processing - evaluate processing algorithms
- Technical formalism similar to 500 MS/s feedback at PEP-II, KEKB, DAFNE

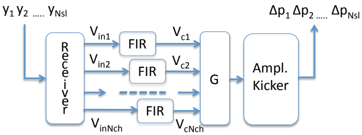
Demonstration 1 bunch processor

- Synchronized DSP processing system, initial 1 bunch controller
- Implements 16 independent control filters for each of 16 bunch “slices"
- Sampling rate 4 GS/s (3.2 GS/s in SPS tests)
- Each control filter is 16 tap FIR (general purpose)
- A/D and D/A channels
- Two sets of FIR filter coefficients, switchable on the fly
- Control and measurement software to synchronize to injection, manipulate the control filters at selected turns
- Diagnostic memories to study bunch motion, excite beams with arbitrary signals - Key feature for beam diagnostics and analysis
- Reconfigurable FPGA technology, expand the system for control of multiple bunches
- What’s missing? A true wideband kicker. Technology in development. These studies use a 200 MHz stripline pickup as a kicker

Feedback Filters - Frequency Domain Design



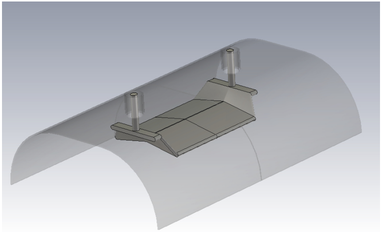
- FIR up to 16 taps
- Designed in Matlab
- Filter phase shift at tune must be adjusted to include overall loop phase shifts and cable delay

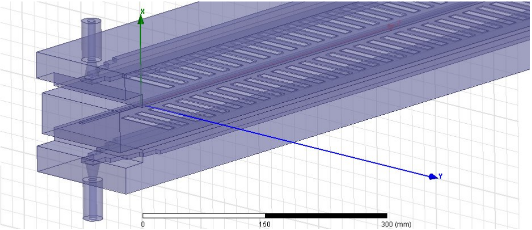


The processing system can be expanded to support more complex off-diagonal (modal) filters, IIR filters, etc as part of the research and technology development

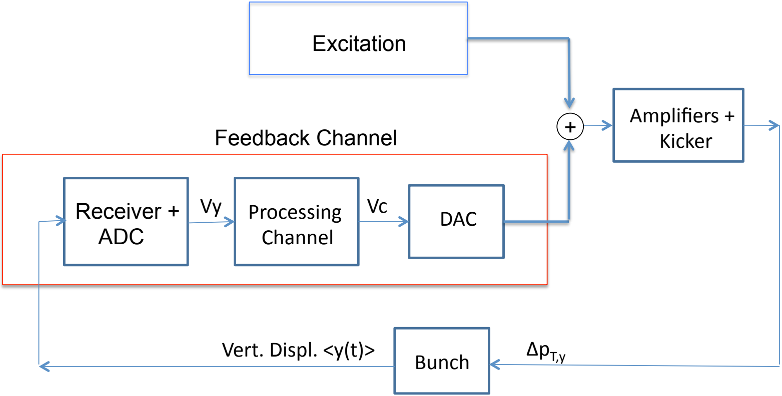
1 GHz wideband kicker development

- CERN, LNF-INFN, LBL and SLAC Collaboration. Design Report SLAC-R-1037
- Evaluate stripline array, overdamped cavity trio and slotline options.
- Reviewed July 2013 at the CERN LIU-SPS Review
- Decision - Slotline and Stripline prototypes in fab based on electromagnetic simulations, shunt impedance, overall complexity, number of amplifiers and timing adjustments
- Collaboration: J. Cesaratto (SLAC), S. De Santis (LBL), M. Zobov (INFN-LNF), S. Gallo (INFN-LNF), E. Montesino (CERN), et al





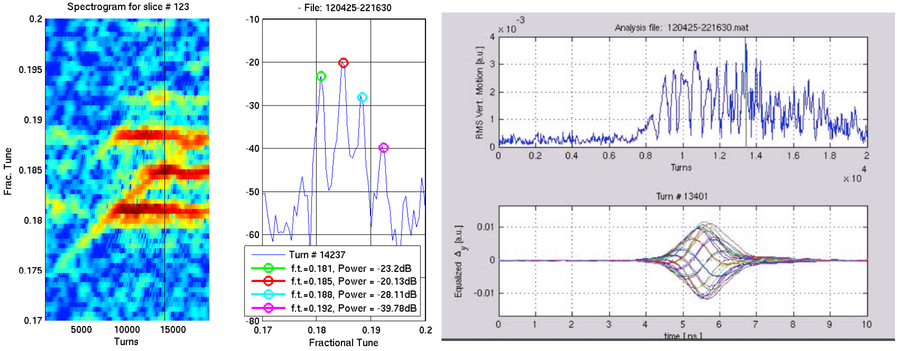
Measuring the dynamic system - open/closed loop



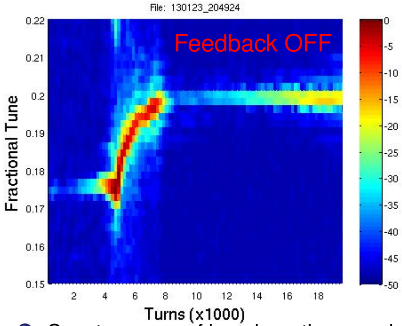
- We want to study stable or unstable beams and understand impact of feedback
- System isn't steady state, tune and dynamics vary
- We can vary the feedback gain vs. time, study variation in beam input, output
- We can drive the beam with an external signal, observe response to our drive
- Excite with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

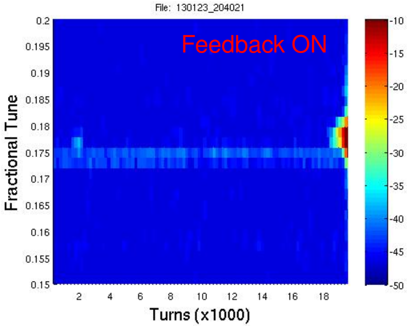
Chirp excitation in represented in frequency and time domain

- same data, two complementary analysis methods
  - Excitation methods (chirps, random, selected modes)
  - mode-specific shaped temporal excitations
  - ability to clearly excite through mode 4

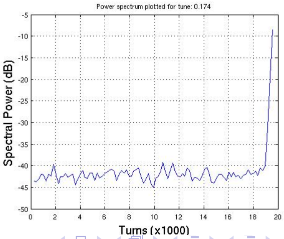


Feedback control of mode 0



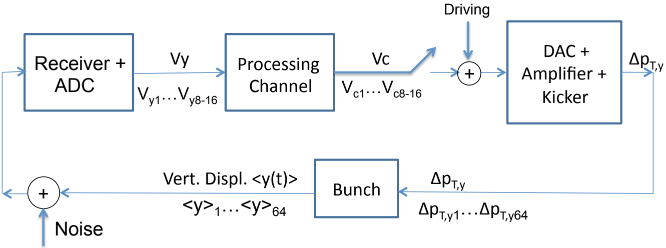


- Spectrograms of bunch motion, nominal tune 0.175
- After chromaticity ramp at turn 4k, bunch begins to lose charge $\rightarrow$ tune shift.
- Feedback OFF -Bunch is unstable in mode zero (barycentric).
- Feedback ON - stability. Feedback is switched off at turn 18K, beam then is unstable



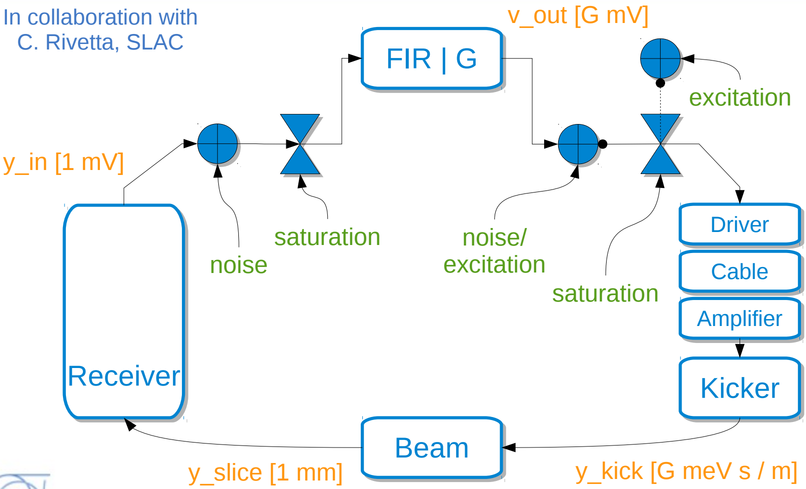
Progress in Simulation Models

- Critical to validate simulations against MD data
- Collaboration and progress from CERN and SLAC, but
  - Need to explore full energy range from injection through extraction
  - Explore impact of Injection transients, interactions with existing transverse damper
  - Still needs realistic channel noise study, sets power amp requirements
  - Still needs more quantitative study of kicker bandwidth requirements
  - Minimal development of control filters, optimal methods using nonlinear simulations
- Continued progress on linear system estimation methods
  - Reduced Models useful for formal control techniques, optimization of control for robustness
  - Model test bed for controller development



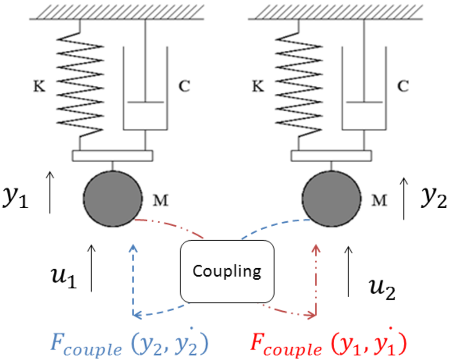
HeadTail Feedback Combined Model

In collaboration with
C. Rivetta, SLAC



- Nonlinear system, enormous parameter space, difficult to quantify margins
- Collaboration K. Li, O. Turgut, C. Rivetta

State Space coupled model - fit to measurements



$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \ddot{x}_1\\ \ddot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ k+k_{couple} & -k_{couple} & c+c_{couple} & -c_{couple}\\ -k_{couple} & k+k_{couple} & -c_{couple} & c+c_{couple}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ \dot{x}_1\\ \dot{x}_2\end{bmatrix} + \begin{bmatrix}0 & 0\\ 0 & 0\\ 1 & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}u_1\\ u_2\end{bmatrix}$$

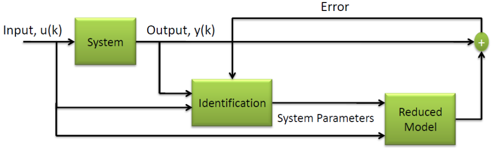
$$\begin{bmatrix}y_1\\ y_2\end{bmatrix} = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ \dot{x}_1\\ \dot{x}_2\end{bmatrix}$$

$$\dot{X} = AX + BU$$
$$Y = CX$$

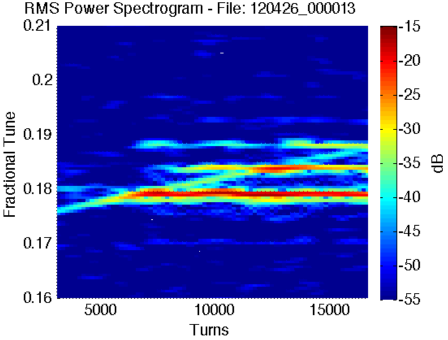
Eig (A) will give us the complex poles of the system, i.e damping and tune

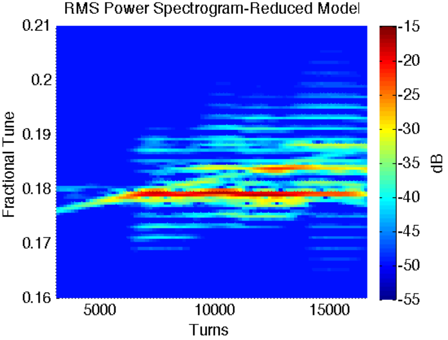
u_1 & u_2 : external excitation
y_1 & y_2 : vertical motion
Coupling parameters : Kcouple and Ccouple

- Fit models to excitation, response data sets from chirps
- Characterize the bunch dynamics - same technique for simulations and SPS measurements
- Critical to evaluate the feedback algorithms



MD vs Model - open loop multiple mode excitations

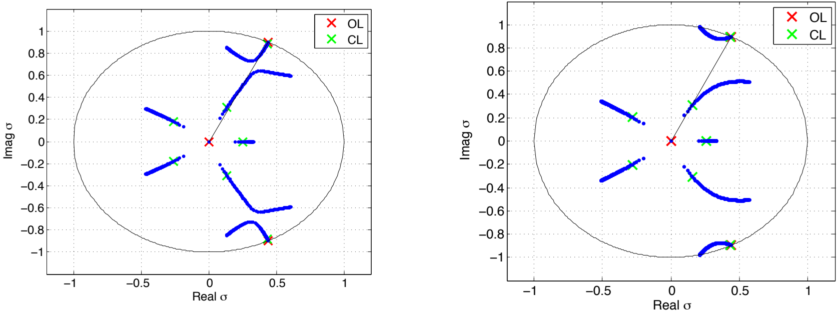




- Driven chirp- SPS Measurement spectrogram (left) Reduced Model spectrogram (right)
- Chirp tune 0.172 - 0.188 turns 2K - 17K
- 0.179 Barycentric Mode,Tune 0.184 (upper synchrotron sideband), 0.189 (2nd sideband)
- Model and measurement agreement suggests dynamics can be closely estimated using fitted model (4 oscillator model)
- Study changes in dynamics with feedback as change in driven response of model

Feedback design - Value of the reduced model

- Controller parameters are Gain, phase. Parametric sweep of 4<G<64
- 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



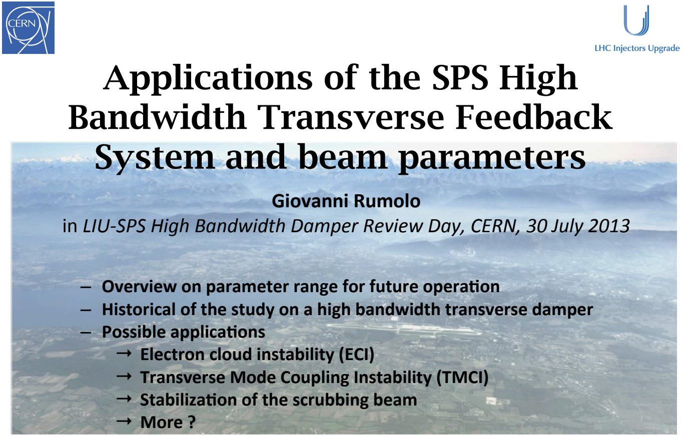
Left: Phase of FIR filter set such that the controller phase is $\phi = 70^o$ at $f_\beta = 0.176$
Right: Phase of FIR filter set such that the controller phase is $\phi = 30^o$ at $f_\beta = 0.176$

2012 DOE LARP Review - response

- July 2012 Presentation - emphasized 3 goals for FY2013
  - Develop 1 bunch Demo system for tests prior to late 2012 SPS shutdown
  - Design studies, report for wideband kicker options
  - Expanded simulation studies to estimate necessary feedback system performance
- Reviewer's report - 1 Comment, 1 Finding
- "Follow-up development on a wideband kicker technology and its implementation and test in SPS is encouraged."
  - Response - Design report and CERN Review July 2013. Approval for CERN fabrication of Stripline and Slotline prototypes. Designs in fab for tests post LS1
- "Develop a realistic plan with timeline to build a full-prototype wideband feedback system for installation in SPS in 2013"
  - 4 GS/s Demo system commissioned at SPS November 2012.
  - Machine Studies, demonstration of control with bandlimited temporary kicker
  - Significant Technical accomplishment, vital to get CERN approval at July 2013 LIU Review for CERN investments

Wideband Feedback - Benefits for HL LHC

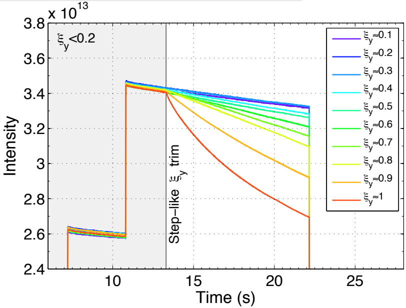
- CERN LIU-SPS High Bandwidth Transverse Damper Review
- Multiple talks, on impacts of Ecloud, TMCI, Q20 vs. Q26 optics, Scrubbing fill, etc.
  - Particular attention to talk from G. Rumolo



SPS wideband Feedback - helps with Ecloud instability control, applicable for possible TMCI

- Feedback is complementary to coatings, grooves, other methods
- Reduces need for chromaticity as cure for instability, low chromaticity beneficial for beam quality
- Provides a measure of flexibility in choice of operating parameters, lattice options
- Emittance growth from any coherent fast motion can be suppressed

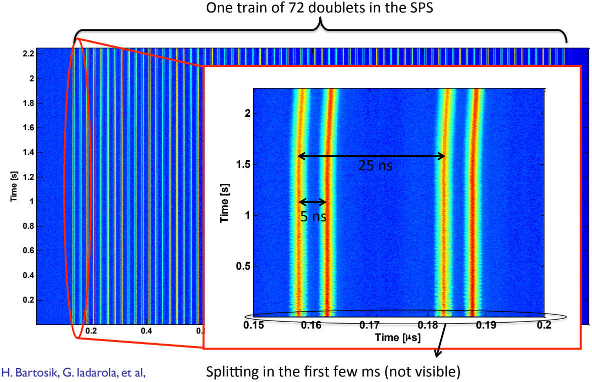
Effect of chromaticity on the lifetime of the 25ns beam in the SPS (2012)



H. Bartosik, G. Iadarola, et al, CERN-ATS-Note-2013-019

SPS wideband Feedback - value for Scrubbing Fill

- Comments from G. Rumolo
- Scrubbing Fill - 5 ns bunch separation
- Exceeds bandwidth of existing transverse damper
- Fill suffers from transverse instabilities and enhanced Ecloud
- Wideband feedback enhances scrubbing, potential use of this fill in LHC



H. Bartosik, G. Iadarola, et al,
Thanks to J. Esteban-Müller et al.

Wideband Feedback - Applications to the PS

- PS might benefit from wideband transverse feedback
- Reconfigurable, programmable architecture can target PS
- Comments from G. Rumolo

  - The **PS** transverse damper (23 MHz at 800 W CW)
    - Has enough bandwidth as to damp the headtail instabilities of the LHC beams at the injection plateau.
    - Has been proved to delay the coupled bunch ECI at 26 GeV/c already in the present functioning mode
    - Cannot damp the instability at transition of the high intensity single LHC-type bunches → larger bandwidth needed as the instability has a spectrum extending to more than 100 MHz.

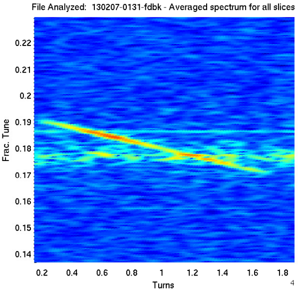
A. Blas, K. Li, N. Mounet, G. Sterbini, et al.

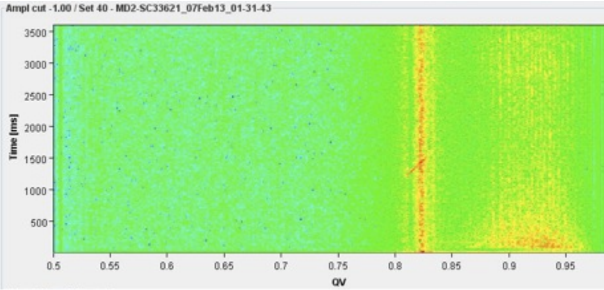
Wideband Feedback - Applications to the LHC (G. Rumolo)

- Reconfigurable, programmable architecture, technology applicable to LHC
  - **LHC** would benefit of a high bandwidth transverse feedback system in the future to produce 25ns beams with the desired high quality
    - Presently, 25ns beams in the LHC still suffer from detrimental electron cloud effects
      - Instabilities observed at the injection of long trains
      - Emittance blow up along the trains
    - The scrubbing process by only using nominal 25ns beams does not seem to quickly converge to an electron cloud free situation in the LHC
      - The electron cloud still survives in quadrupoles and is at the buildup limit in the dipoles (awakens on the ramp)
      - There seems to be also a fast deconditioning-reconditioning cycle even between fills separated by only few “idle” hours
  - Developing a high bandwidth feedback system in the SPS first ....
    - could allow stabilization of the scrubbing beam in view of its use for the LHC
    - would be an invaluable experience to assess its potential against electron cloud effects and extend its use to LHC, too.

Wideband Feedback - Beam Diagnostic Value

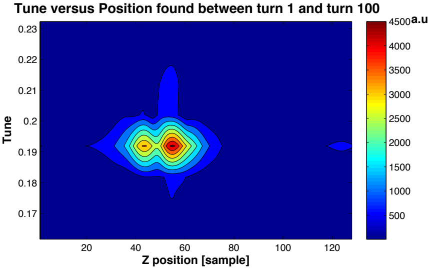
- processing system architecture/technology
  - reconfigurable platform, 4 - 8 GS/s data rates
  - snapshot memories, excitation memories
  - applicable to novel time and frequency domain diagnostics
  - Feedback and Beam dynamics sensitive measure of impedance and other dynamic effects
- Complementary to existing beam diagnostic techniques

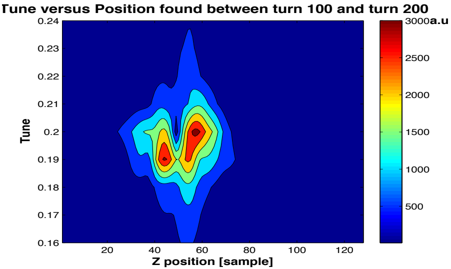




Wideband Feedback - Bunch and Slice specific information, control

- Reconfigurable processing system architecture/technology
  - Unique capability of bunch-specific and slice-specific control
  - Snapshot memories, excitation memories
  - Tune vs bunch position, time
  - Reactive feedback can add tune shifts to selected bunches
- Opportunity to develop novel control and diagnostic techniques





Review Structure

- Overview, Review Responses, Technology and Recent Progress
- We are here - next talks
- Control Techniques, Machine simulations, MD analysis and Options for next steps
- Plans, schedules, budgets and HL Impacts
- Discussion with Reviewers
- (Optional) Kicker Development - Progress and plans
- (Optional) Technology development and Demo/Proto roadmap
- Continued Discussion with Reviewers

Acknowledgements and Thanks

- We cannot adequately acknowledge the critical help fromeveryone who made the winter 2012 feedback Demo MDs possible. We are grateful for the collaboration and generous help.
- Thanks to CERN, SLAC, and LARP for support

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Research and Technology Timeline

2013 - 2014

Demo Prototype
Kicker Report/Fab
Expand Prototype
Beam – Feedback
Simulations

- Demo Commissioned
- MDs Jan.-Feb. 2013
- Kicker Design, Fabrication and Installation
- Data Analysis, Models and Simulation Tools
- Expand Hardware Capability
- MDs with new Hardware

2015 - 2016

Demo Prototype
Studies
Full-Function
Studies/Develop.
Beam – Feedback
Simulations

- MDs with new hardware
- Multi-bunch operation
- Data analysis, models and simulation tools
- System specifications and capabilities
- Full-function Wideband Feedback Technology Development.

2017 - 2018 - 2019

Full-Function
Wideband Feedback
Design-Fabrication
Beam – Feedback
Simulations

- Full-Function Wideband Feedback Design-Fabrication
- Continue MD studies
- Validate Energy Ramp
- Analysis, models and simulation tools

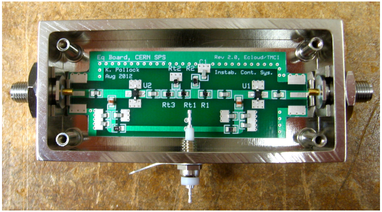
2020

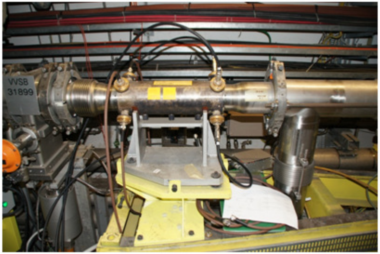
System Tests

- System Integration
- Full interface with CERN Control Room
- Estimation of System Limits and Performance
- LHC? PS? SPS?

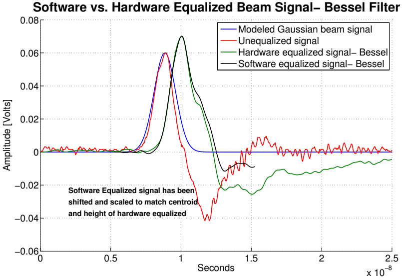
- Essential goal - be ready at end of LS2 with full-function system ready to commission
- SPS upgrade after LS2 (new injector, higher currents, new operational modes)
- We must use the demo system, MD time post LS1 to validate control ideas, validate kicker and technical approach. Full Function is only 1 design iteration away from Demo System

Hardware Equalizer





- Pickup response distorts beam signals
- Long cables also have nonlinear phase response
- Existing software equalizer used in matlab data processing
- we need a real-time (hardware) equalizer for processing channel
- Optimzation technique - can be used for kicker. too



Feedback algorithm complexity and numeric scale

Frequency spectrograms suggest:

sampling rate of 2 - 4 GS/sec. (Nyquist limited sampling of the most unstable modes)

Scale of the numeric complexity in the DSP processing filter

- measured in Multiply/Accumulate operations (MACs)/sec.

SPS -5 GigaMacs/sec (6*72*16*16*43kHz)

- 16 samples/bunch per turn, 72 bunches/stack, 6 stacks/turn, 43 kHz revolution frequency
- 16 tap filter (each slice)

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

- 1 sample/bunch per turn, 5120 bunches, 16 tap filters, 99 kHz revolution frequency .

The scale of an FIR based control filter using the single-slice diagonal controller model is not very different than that achieved to date with the coupled-bunch systems.

What is different is the required sampling rate and bandwidths of the pickup, kicker structures, plus the need to have very high instantaneous data rates, though the average data rates may be comparable.