# Wideband Vertical Intra-Bunch Feedback At The SPS

## 2015 Results And Path Forward

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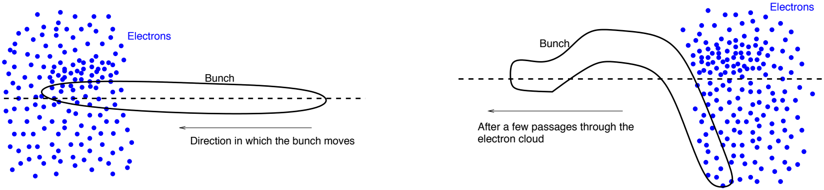
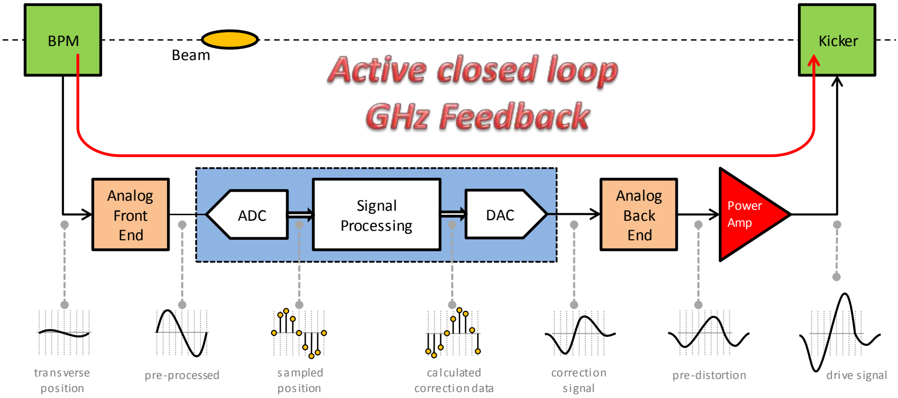
# CERN SPS Ecloud/TMCI Instability R&D Effort



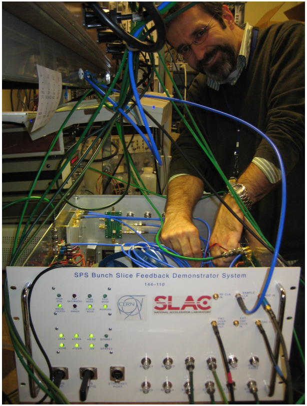

- Ongoing project SLAC/LBL/CERN via US LARP DOE program
- Proton Machines, Electron Cloud driven instability - impacts SPS as high-current HL-LHC injector
  - Photoelectrons from synchrotron radiation - attracted to positive beam
  - Single bunch effect - head-tail (two stream) instability
- TMCI - Instability from degenerate transverse mode coupling - may impact high current SPS role as HL-LHC injector
- Multi-lab effort - SLAC, CERN, LBL, INFN-LNF
- IPAC 2015 Posters MOPWI037 MOPWI041

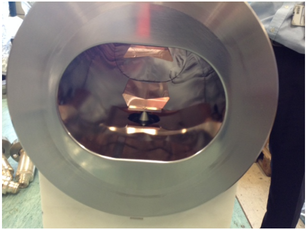
# Essential Features

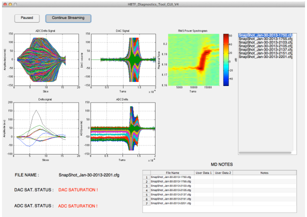


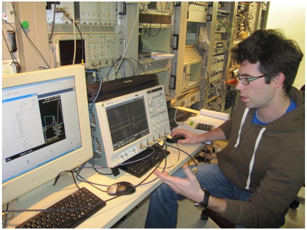

- Control of Non-linear Dynamics (Intra-bunch)
- GHz Bandwidth Digital Signal Processing - 4 GS/s ADC and DAC
- Optimal Control Formalism - allows formal methods to quantify stability and dynamics, margins
- Research phase uses numerical simulations (HeadTail), reduced models, technology development, 1 bunch Demonstrator, SPS Machine Measurements

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



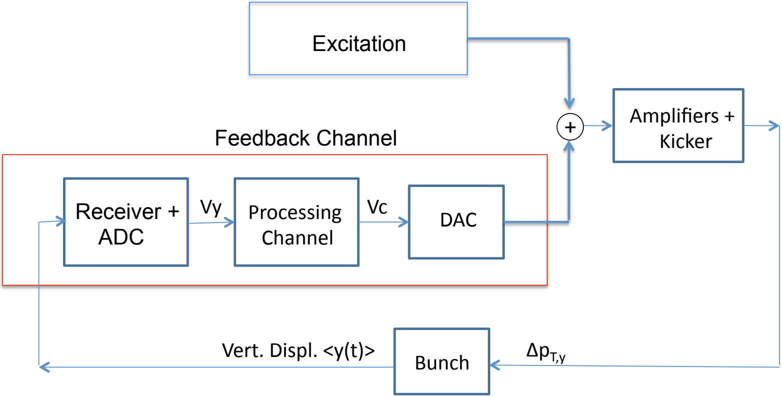


# How do you test and quantify Instability Control?

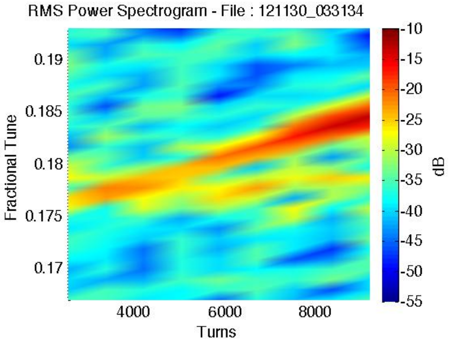
- "Do Feedback on Unstable Beams" - is not the first test!
- The main goal is to use this minimum hardware to quantify the impact of the feedback channel in the beam dynamics
- Validate operation of the system through measurements on single-bunch stable beams, then unstable beams
- We want to validate fundamental behavior of the feedback channel, compare to estimates using the reduced models / macro-particle simulators.
- Excite beam and do closed-loop tests. Measure changes in response due to feedback channel
  - Drive Mode 0, Mode 1, ... , and damp the bunch motion
  - Quantify and study the transients
  - Use switchable FIR coefficients for grow-damp and open-damp transient studies
- To conduct the measurements, excite and record via memory of DSP processing with MATLAB offline analysis.
- Technology of 4 GS/s processing and GHz bandwidth pickups, kickers challenging

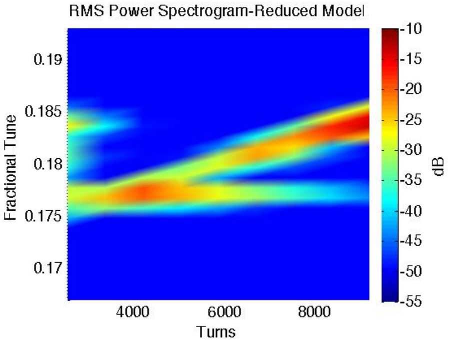
# Measuring the dynamic system - open/closed loop




- 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

# MD vs Model - open loop multiple mode excitations




- Driven chirp - SPS Measurement spectrogram (left), Reduced Model spectrogram (right)
- Chirp tune 0.175 - 0.195 turns 2K - 17K
- Tune 0.177 Barycentric mode, tune 0.183 (upper synchrotron sideband)
- Model and measurement agreement suggests dynamics can be closely estimated using fitted model
- Study changes in dynamics with feedback as change in driven response of model

# State Space coupled model - fit to measurements

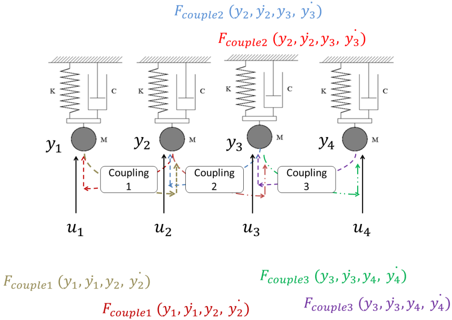



Figure 2 : Reduced model for intra-bunch dynamics.

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

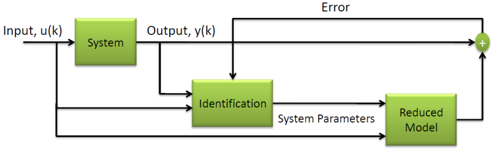
$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \dot{x}_1 \\ \dot{x}_2 \end{bmatrix}$$

$$\begin{aligned} \dot{X} &= AX + BU \\ Y &= CX \end{aligned}$$

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

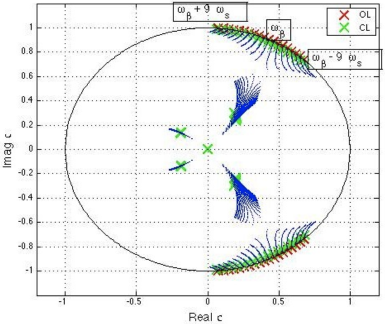
*$u_1$ & $u_2$ : external excitation*
*$y_1$ & $y_2$ : vertical motion*
*Coupling parameters : Kcouple and Ccouple*

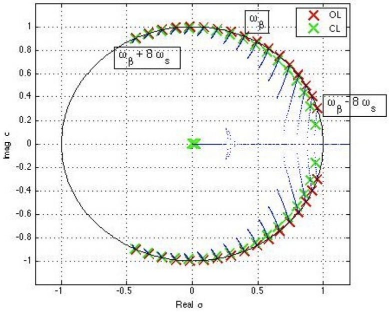
- Fit models to excitation, response data sets from chirps
- Characterize the bunch dynamics - same technique for simulations and SPS measurements
- Critical to evaluate the feedback algorithms



# Feedback design - Value of the reduced model

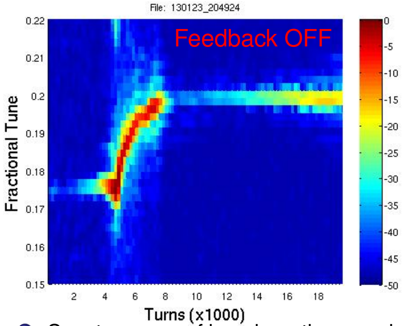
- Controller design requires a linear dynamics model
- The bunch stability is evaluated using root-locus and measurements of the fractional tune.
- Immediate estimates of closed-loop transfer functions, time-domain behavior
- Allows rapid estimation of impact of injected noise and equilibrium state
-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

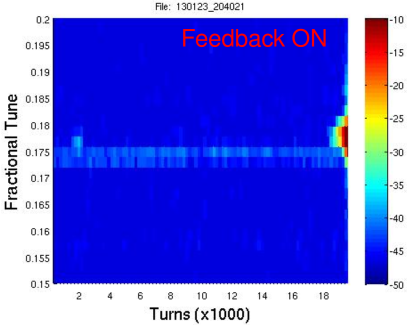


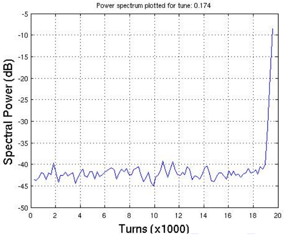

Left: FIR filter controller designed for Q26 at $f_\beta = 0.185$, $f_s = 0.006$
Right: IIR filter controller designed for Q20 at $f_\beta = 0.185$, $f_s = 0.017$

# SPS Measurement - Feedback control of mode 0

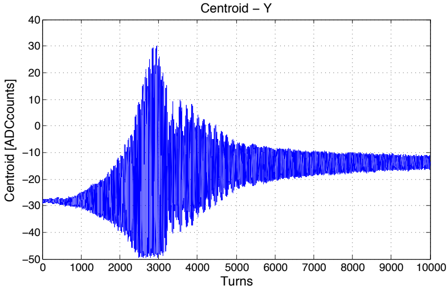


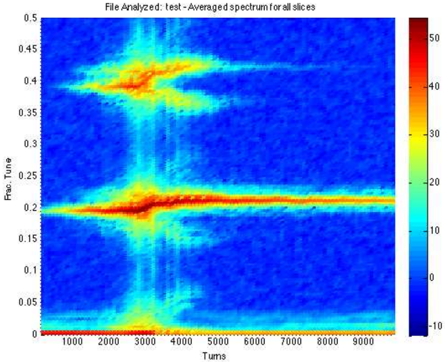




- Spectrograms of bunch motion, nominal tune 0.175
- After chromaticity ramp at turn 4k, bunch begins to lose charge $\rightarrow$ tune shift.
- Feedback OFF - Bunch is unstable in mode 0 (barycentric).
- Feedback ON - stability. Feedback is switched off at turn 18K, beam then is unstable



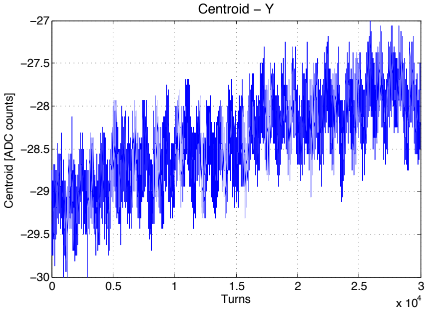
# SPS Measurement - TMCI Unstable beam

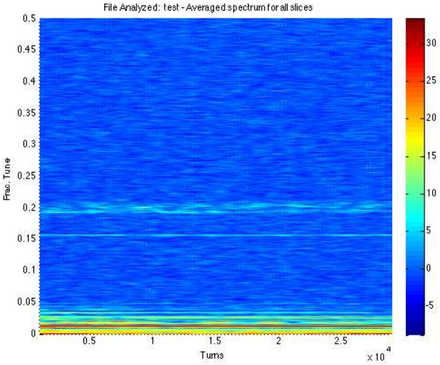



- Open Loop SPS Measurement - Vertical Centroid (left), Spectrogram (right)
- Intensity $\sim 2x10^{11}$ with low chromaticity Q26 lattice
- $\nu_y = 0.185$ $\nu_s = 0.006$
- Unstable modes 1 and 2 from the beginning and start to lose charge at turn 2000
- Significant intensity-dependent tune shifts as charge is lost at turn 4500

# SPS Measurement - TMCI Unstable - with feedback



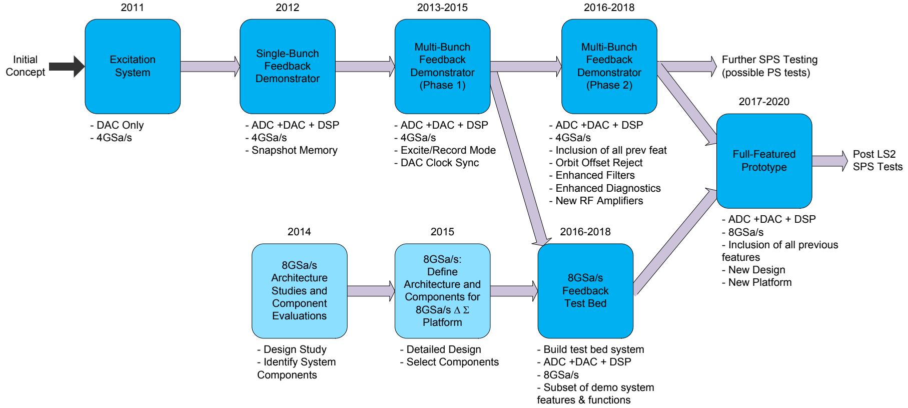




- Closed Loop SPS Measurement - Vertical Centroid (left), Spectrogram (right)
- Intensity $\sim 2x10^{11}$ with low chromaticity Q26 lattice
- $\nu_y = 0.185$ $\nu_s = 0.006$
- Mode 0, unstable mode 1 controlled to noise floor (2-3 $\mu$m), unstable mode 2 controlled
- Small mode 2 driven motion, reduced by the feedback gain

# Path Forward

- Research and development as part of LIU, HL-LHC and US LARP
- MD measurements with wideband DEMO system (SPS beam time and analysis)
  - Diagnostic and beam instrumentation techniques to optimize feedback parameters and understand system effectiveness
  - Continued simulation and modeling effort, compare MD results with simulations, explore new controllers
  - Evaluate new kickers (Stripline and Slotline) and upgraded tunnel high-power wideband RF amplifiers for SPS operation
- Technology development and system estimation for Full-Function system
  - Explore Q20 control methods (new filters, multiple pickups) - optimize system performance
  - Low-noise transverse coordinate receivers, orbit offset/dynamic range improvements, pickups
  - Expand master oscillator, timing system for energy ramp control
- High-speed DSP Platform consistent with 4-8 GS/s sampling rates for full SPS implementation
  - Lab evaluation and firmware development
- 2016 CERN Review, Recommendations on Full-Featured System

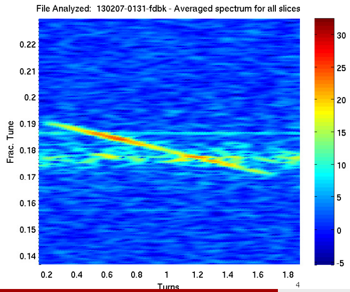
# Upgrades to the SPS Demonstrator - Roadmap

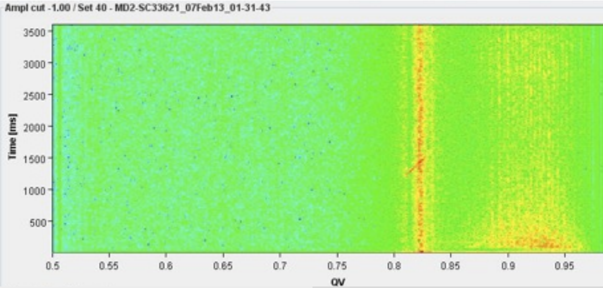



- The Demo system is a platform to evaluate control techniques
- MD experience will guide necessary system specifications and capabilities
- The path towards a full-featured system is flexible, can support multiple pickups and/or multiple kickers
- We will benefit from the combination of simulation methods,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

# 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



# Acknowledgements and Thanks


- We especially acknowledge the skillful fabrication, test and installation of the stripline kicker in time for startup this fall (Thanks E. Montesinos and team!)
- We are grateful to 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, 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

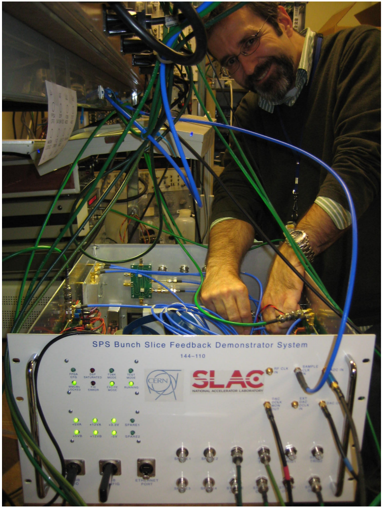
Work supported by DOE contract DE-AC02-76SF00515 and US LARP program

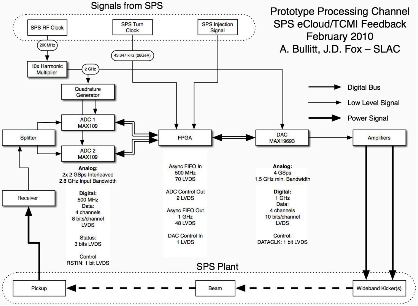
# Wideband Intra-Bunch Feedack - Considerations

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 $\beta$), 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
- 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

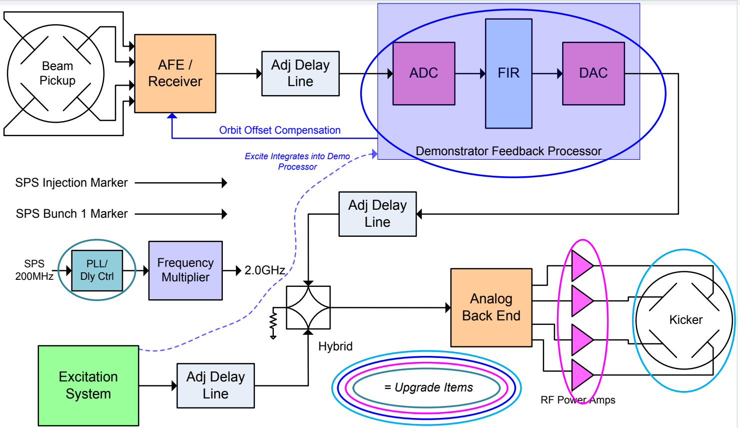
# 4 GS/s 1 bunch SPS Demonstrator processing system




- Proof-of-principle channel for 1 bunch closed loop tests in SPS - Commissioned November 2012
- Provides wideband control in SPS with installation of wideband kicker and amplifiers
- Reconfigurable processing - Platform to evaluate control methods, algorithms and architectures
- Features upgraded during LS1 - timing/synchronization, noise floor of A/D, scrubbing fill controller.

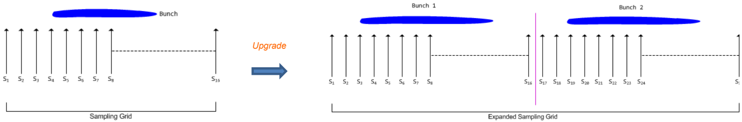
# LS1 Upgrades to the SPS Demonstrator System




- Fall 2014 - Robust Timing re-synch, improved digitizer noise floor, integrated excitation
- Summer 2014 - New wideband striplines for beamline
- Summer 2014- Evaluate power amplifier options, Winter 2015 commissioning
- FY14 -FY15 Expand DSP capabilities to Scrubbing fill, synched excitation, multi-bunch

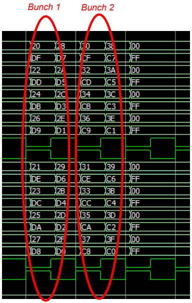
# Scrubbing Fill Controller - implemented for December 2014 MD tests

*Existing Processing* *New 32-sample Processing*




**Processing of Single Scrubbing bunch Doublet**

- Enables Demo Unit to process a Single scrubbing pattern doublet (two adjacent bunches) / Feedback, Excitation, FEC, Snap Record
- Idea Proposed by J. Fox
- This will become a special operating mode (scrubbing mode) to the "regular" demo unit operation (single-bunch)
  - Has capability of recording snapshot data (32-sample)
  - Retains Feedback+Excitation Mode as well
  - Mode selection in SW or separate configuration (different FPGA cfg file)
- Status
  - FPGA code complete (for main function, snapshot code expansion in the works)
  - Undergoing simulation verification →
  - Tried test FPGA compile: routed to speed w/o resource issues
  - Will deploy onto HW and test next week
  - Plan is to implement prior to shipping box back to CERN
- What about multi-bunch mode?
  - Not forgotten!
  - Work will start on this as soon as single-bunch scrubbing mode is completed
  - Some of the concepts developed here lend to multibunch mode
  - Completed Winter/Spring 2015




*Digital Simulator result – showing two 16-sample bunches being output to DAC*

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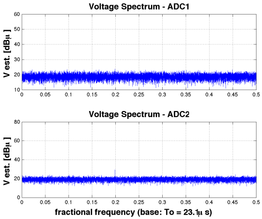
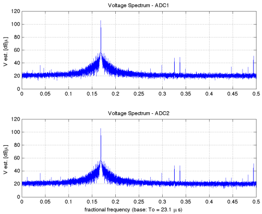
- wideband system allows control with 5 ns bunch spacing

# Quantifying Performance of the DEMO A/D System

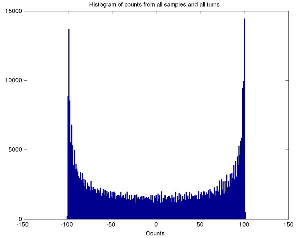
- The dynamic range, linearity and nonlinear behavior of the DEMO system was carefully quantified during LS1- important to estimate impact behavior in beam studies
- Noise pick-up seen in commissioning was addressed with new physical layout of A/D cards, copper ground plate, double-shielded cables
- Full 54dB dynamic range achieved, spurious narrowband interfering signals eliminated
- Performance in the SPS Faraday cage - the next tests




Spectrum of 50 ohm terminated input

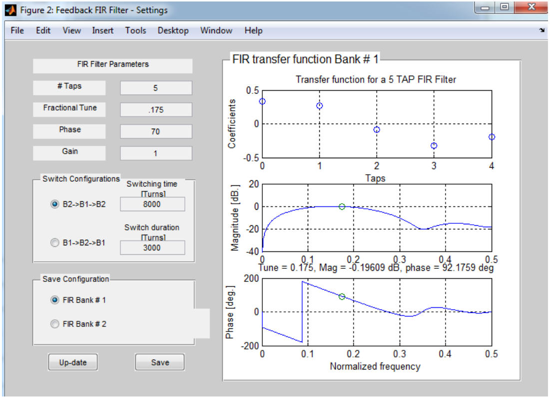



Spectrum of near full scale 200 MHz Input

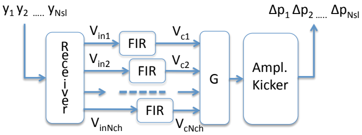



Histogram of near full scale 200 MHz input

# Feedback Filters - Frequency Domain Design

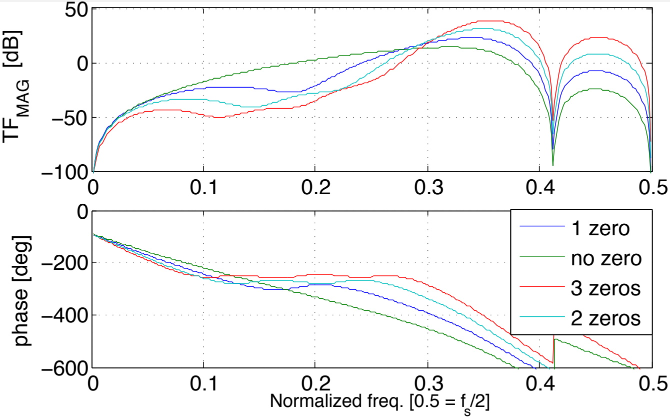



- FIR up to 16 taps
- Designed in Matlab
- Filter phase shift at tune must be adjusted to include overall loop phase shifts and cable delay



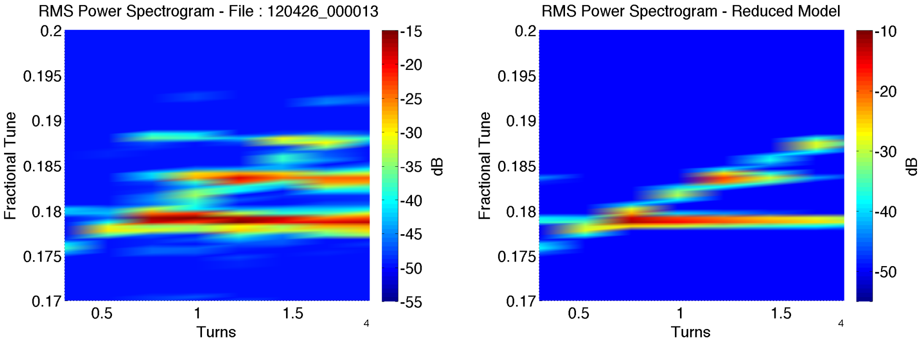

The processing system can be expanded to support more complex off-diagonal (modal) filters, IIR filters, etc as part of the research and technology development

# Example Q20 IIR control Filters



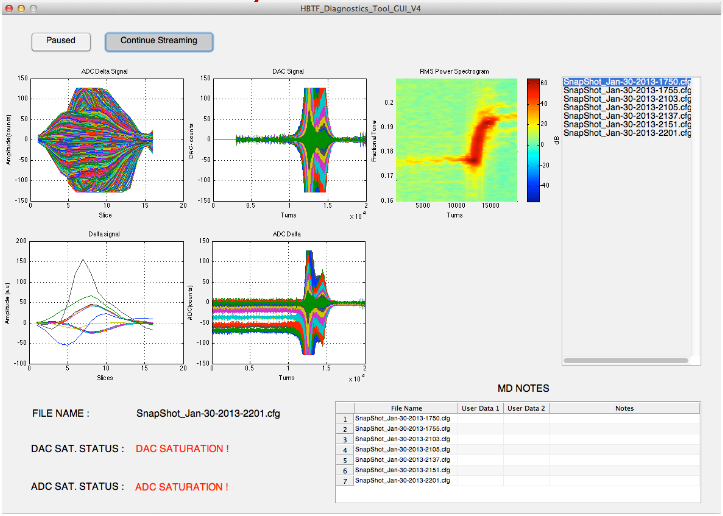

- Q20 optics has much higher synchrotron tune ( 0.017)
- Impact - much wider control bandwidth
- filters with flat phase response have high gain above the beam motion frequencies - add noise
- Technical direction - Explore multi-pickup sampling ( higher effective Nyquist limit, better rejection of noise)

# 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 ($2^{nd}$ sideband)
- Model and measurement agreement suggests dynamics can be closely estimated using fitted model (4 oscillator model) - but nonlinear effects seen in machine data
- Study changes in dynamics with feedback as change in driven response of model

# Online MD data analysis tool



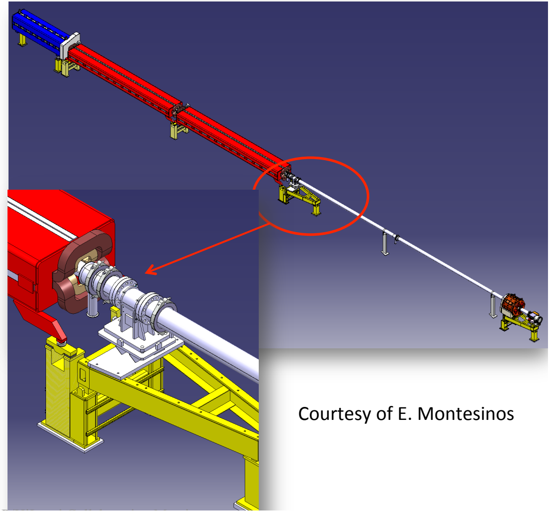

- Intended to run in faraday cage, check as each data set is recorded
- Does quick analysis, shows beam motion, system parameters
- Helps make the MD process more efficient, still have extensive off-line tools and codes

# 1 GHz wideband Stripline kicker development

- CERN, LNF-INFN, LBL and SLAC Collaboration. Design Report SLAC-R-1037
- Electrical and Mechanical design completed, fabricated by E. Montesinos et al
- Installed with 3 kicker support system fall 2014
- Collaboration: J. Cesaratto (SLAC), S. De Santis (LBL), M. Zobov (INFN-LNF), S. Gallo (INFN-LNF), E. Montesinos (CERN), et al

# 1 GHz Wideband Stripline Kicker array on beamline

- SPS Sextant 3, LSS3
- Housed in the second half of the 321 period of the SPS.
- Approximately 8 m of usable space following the dipole magnet
- 8 new 7/8” cables pulled to kicker location during LS1
- Power amplifiers still needed
  - Essential for operation of new kickers!
  - Critical items for post LS1 operation

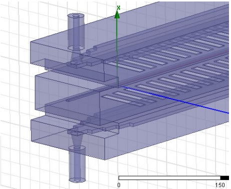


Courtesy of E. Montesinos

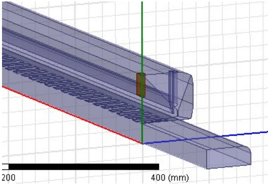
# 1 GHz Wideband Slotline kicker development

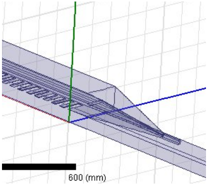
- CERN, LNF-INFN, LBL and SLAC Collaboration. Design Report SLAC-R-1037
- Reviewed July 2013 at the CERN LIU-SPS Review
- Slotline prototype in electrical design and HFSS optimization
- Silvia Verdu to continue effort started by John Cesaratto
- Plan for mechanical design, fabrication by E. Montesino for Fall 2015 SPS installation

- Down selection needed on port design
  - CERN mechanical engineering department to weigh in on complexity and feasibility
  - 3 port layouts
    - Tapered, lateral provide best matching
  - Currently, waiting for ME resources, following stripline development

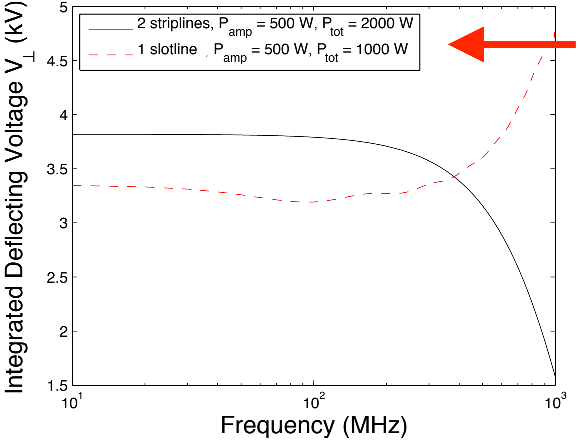



- Once choice is made on the port layout, another round of EM optimization needed, then mechanical design can begin.



# Complementary Striplines and Slotline



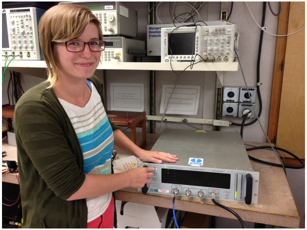

CERN plans to install:

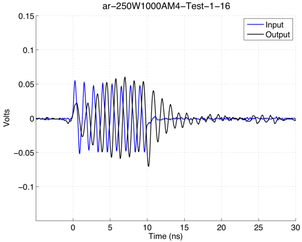
- 2 Striplines
- 1 Slotline

- 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.

# Evaluating Wideband RF Power Amplifiers

- 11 potential RF amplifiers were evaluated from US, Japanese and European vendors
- Bandwidths of 5 - 1000 MHz ( 80 - 1000 MHz), with 200 - 250W output power levels
- Use excitation system for wideband time domain excitations
- Study frequency domain and time domain responses. Concerns with phase linearity and time response
- Commercial amplifiers not specified for 100% AM modulation, wideband pulse responses
- Nonlinear effects, thermal tail effects also important



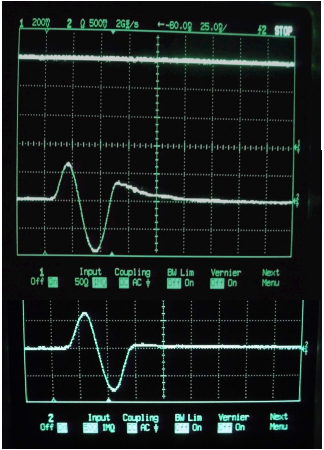



# R & K 5 - 1000 MHz amplifier

- R& K Company was interested in developing a new design to meet our wideband requirements
- After initial tests, worked with us to extend low-frequency response, improve transient behavior
- New amplifier design also includes necessary remote control and monitor features for operation in SPS tunnel
- Selection Fall 2014 - purchase of 2 R&K 5 - 1000 MHz 250W amplifiers for December 2014 delivery

Before

After



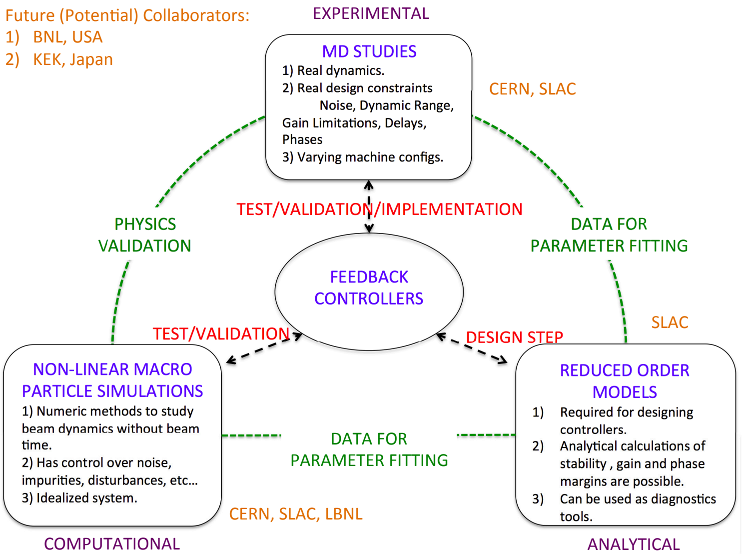

R&K's impulse response measurements

# From Demonstration system - to full-featured system

- The Demo system is being used for MD studies, and technology development through the end of 2016
  - Validate multi-bunch control
  - Explore scrubbing fill control
  - Evaluate Q20 control techniques, validate simulation models
  - Explore value of multiple pickups and kickers in system architecture
  - Diagnostic and beam instrumentation techniques to optimize feedback parameters and understand system effectiveness
  - Evaluate Stripline and Slotline wideband kickers and RF Amplifiers with beam
  - Design Report for full-featured system
- Action from LIU Review July 2013
  - End of 2016 - Wideband Feedback System review -Decision to proceed with full-featured system development for SPS installation
- WBFS has been estimated and budgeted within the LARP system for future production decision

# Multi-Lab Collaboration

Future (Potential) Collaborators:
1) BNL, USA
2) KEK, Japan



# DEMO Upgrade to 8 GS/s system

→ The current 4GSa/s architecture allows us to take 16 samples across an SPS bunch

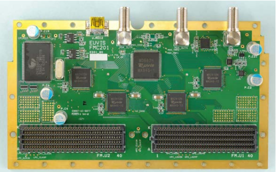
- Increasing the sampling rate to 8GSa/s allows us even greater flexibility:
  - Increased sampling resolution (32 samples across a single bunch / 125ps sample spacing)
  - Increased Flexibility:
    - Single ultra-fast 8GSa/s feedback channel

      -or-
    - Dual 4 GSa/s channels for *two* sets of pickups and kickers
  - Enables delta-sigma/delta-delta/sigma-sigma topologies (modelling studies suggest that these may be necessary for stability control)
  - Enhanced diagnostics

- To accomplish this, we need faster ADCs and DACs and are investigating new components:

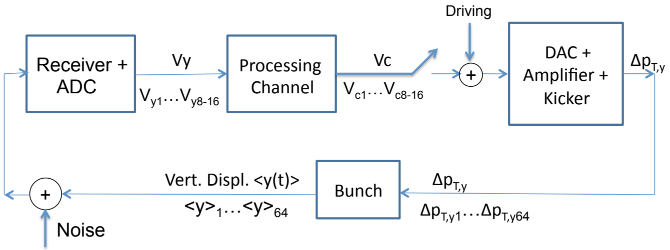
**DAC**: Have identified a high speed DAC (Euvis, Inc. MD662H DAC device: 8GSa/s, 12-bits) / Have purchased demo board and will begin evaluating

**ADC**: TI / National Semi has recently released a new 12-bit, 4GSa/s ADC. The AD12J4000 (we can use two in interleaved mode to reach 8GSa/s) / Will purchase a demo board soon and evaluate



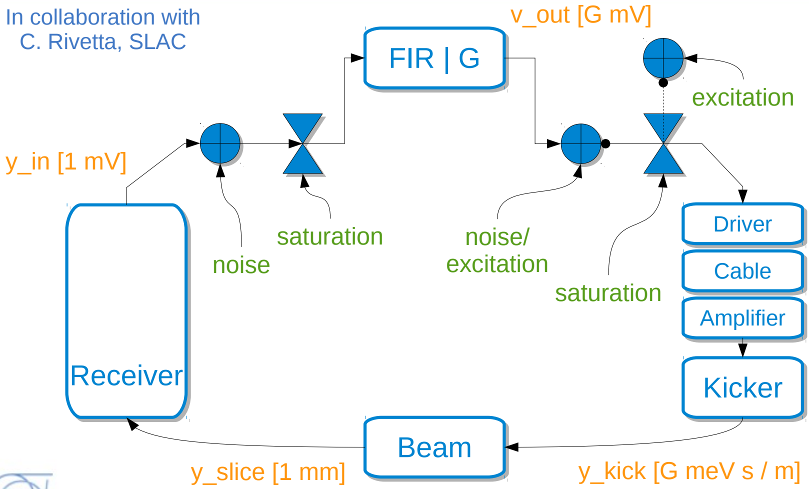
# Progress in Simulation Models

- 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

# Comparison of HEADTAIL with Reduced Model

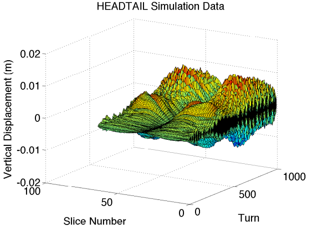



Figure : HeadTail Vert. Motion, Driven by 200 MHz, 0.144 - 0.22 Chirp, 1000 Turns.

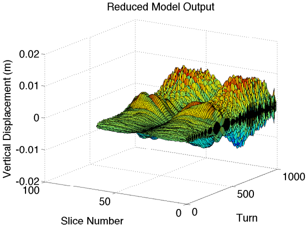



Figure : Vertical Motion of the Reduced Model.

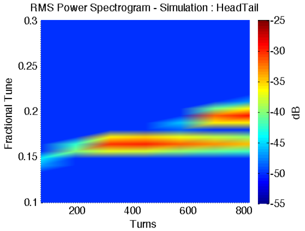



Figure : RMS Spectrogram of HEADTAIL Driven by 200 MHz Chirp Excitation

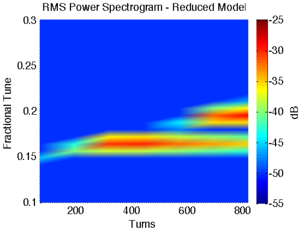
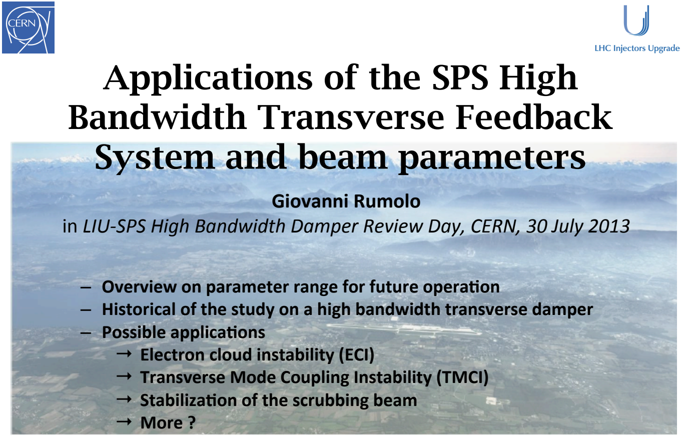



Figure : RMS Spectrogram of Model Driven by 200 MHz Chirp Excitation

# Wideband Feedback - Benefits for HL LHC

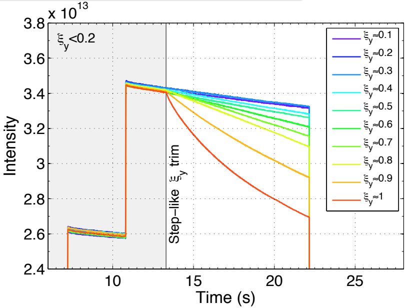
- CERN LIU-SPS High Bandwidth Transverse Damper Review
- Multiple talks, on impacts of Ecloud, TMCI, Q20 vs. Q26 optics, Scrubbing fill, etc.
  - Particular attention to talk from G. Rumolo



# 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

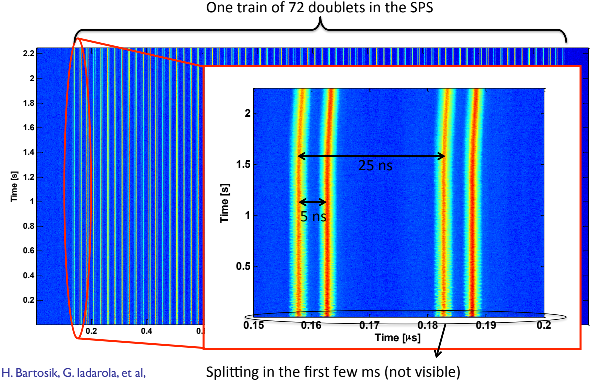
**Effect of chromaticity on the lifetime of the 25ns beam in the SPS (2012)**




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 - Implementation in LHC

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

| | SPS | LHC |
|---|---|---|
| RF frequency (MHz) | 200 | 400 |
| $f_{\mathrm{rev}}$ (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 $f_{\mathrm{rev}}$ allows longer computation time (assuming diagonal control).
  - LHC signal processing can be expanded from SPS architecture with 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 experience.