Wideband intra-bunch feedback systems
opportunities, challenges and first results

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Multi-lab effort - SLAC, CERN, LBL, INFN-LNF through LARP and HL-LHC

Stabilize Ecloud and TMCI effects via GHz bandwidth feedback
  - Complementary to coatings, grooves, etc. for Ecloud control
  - Also addresses TMCI, allows operational flexibility

Intra-bunch and coupled bunch instabilities through same channel

LARP feedback program provides novel beam diagnostics in conjunction with technology development

DSP Intra-bunch feedback demonstrated at JPARC (150 ns bunch) and PS (60 ns bunch) - SPS is 2 ns
Technology Development, Beam Measurements, Simulation Models, and graduate education

Envelope Vertical motion of bunch centroid $-\tau = 338.7991$ turns

Vertical Displ. [mm]

Turns

J. D. Fox

John Adams Institute
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, Demonstrator System, SPS Machine Measurements

Demonstrator system 1 - 64 bunches, modest kicker power with 1 GHz bandwidth
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 $\beta$), 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
- 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
- These questions can only be understood with both MD Studies and Simulation methods
- Technical challenge in 4 GS/sec. sampling rates and 1 GHz control bandwidth
Extensions from existing 500 MS/sec. 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
How do you test and quantify Instability Control?

- "Do Feedback on Unstable Beams" - is not the first test!
- Main goal - 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
- Validate fundamental behavior of the feedback channel, compare to estimates using 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
Measuring the dynamic system - Modal Excitation

- **Mode zero excitation**

- **Mode 1 (head-tail) excitation**

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

Pickup requires equalization, Timing the front and back-ends is tricky
Chirp excitation in Frequency and time domain

- **same data, two complementary analysis methods**
  - Excitation methods (chirps, random, selected modes)
  - ability to clearly excite through mode 4
  - watch the movie, too!
Excitation of multiple beam modes - time domain

Play
Driven Motion Studies- closed loop feedback

- Driven chirp Pickup spectrogram (left)
- Driven Beam motion Spectral power (right)
- Chirp tune 0.19 - 0.17 turns 2K - 17K
- Study changes in dynamics with feedback as change in driven response
Driven Motion Studies - closed loop feedback

- Driven chirp Pickup spectrogram (left)
- Chirp tune 0.19 - 0.17 turns 2K - 17K
- Tune 0.183 (upper synchrotron sideband), Tune 0.175 Barycentric Mode
- Variation in Mode Zero Amplitude vs. loop gain (right)
- Study changes in dynamics with feedback as change in driven response
Identification of Internal Bunch Dynamics: Reduced Model

- characterize the bunch dynamics - same technique for simulations and SPS measurements
- critical to design the feedback algorithms
- Specify requirements for pickup, receiver, processing, power stages and kicker systems.
- Ordered by complexity, the reduced models could be
  - linear models with uncertainty bounds (family of models to include the GR/tune variations)
  - 'linear' with variable parameters (to include GR/tune variations-different op. cond.)
  - non-linear models
State Space coupled model - fit to measurements

- 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

\[ \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ k + k_{coup} & -k_{coup} & c + c_{coup} & -c_{coup} \\ -k_{coup} & k + k_{coup} & -c_{coup} & c + c_{coup} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \]

\[ \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \]

\[ \dot{X} = AX + BU \]
\[ Y = CX \]

\textbf{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 : \( K_{coup} \) and \( C_{coup} \)
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
- 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
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) - but nonlinear effects seen in machine data
- Study changes in dynamics with feedback as change in driven response of model
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.
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:** RMS Spectrogram of HEADTAIL Driven by 200 MHz Chirp Excitation

**Figure:** Vertical Motion of the Reduced Model.

**Figure:** RMS Spectrogram of Model Driven by 200 MHz Chirp Excitation
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 $f_\beta = 0.185$, $f_s = 0.017$
Simulation 4X4 model - advantage of MIMO formalism

- 4 Coupled-Oscillator model
- 4x4 modal (matrix controller)
- Much better control of all modes
- disadvantage - much more complex numeric processing (n^2 more)
- active research - what about sparse control with few off diagonal elements?
Model based Control - use optimal control methods

Figure 1: On the left we see the spectrogram of physical measurement showing chirp excitation where we excite mode 0, mode 1, and mode 2 excitation around turns 7000, 11500, and 17000 respectively. On the right, we see the same excitation and analysis applied to the reduced order model capturing linear dynamics.

Identification and Control of Instabilities

Figure 2: Identification of the intra-bunch dynamics and model based controller based on the identified model. In this example, open loop simulation data from the nonlinear macro particle code HeadTail is used to get the model of the bunch for mode 0 dynamics. A controller is designed based on the model. The controller is tested using HeadTail simulation for mode 0 and mode 1 dynamics.

Figure 3: Comparison of the closed loop dynamics in between model based IIR is compared with FIR filter. Closed loop eigenvalues are close for both filters however more study is required to understand robustness, required control power and implementation complexity.

The dynamics from a head-tail simulation is used to design a controller
MD data can be used the same way
model-based controller formal method has better damping for mode 1 than FIR controller
Feedback control of mode 0

- Spectrograms of bunch motion, nominal tune 0.175
- After chromaticity ramp at turn 4k, bunch begins to lose charge → tune shift.
- Feedback OFF - Bunch is unstable in mode zero (barycentric).
- Feedback ON - stability. Feedback is switched off at turn 18K, beam then is unstable.
December 2014 Unstable beam - Open Loop

- Open Loop SPS Measurement - Vertical Centroid (left) Spectrogram (right)
- Intensity $2 \times 10^{11}$ with low chromaticity Q26 lattice (special beam)
- $\nu_y = 0.185, \nu_s = 0.006$
- Unstable modes 0 begin at injection, charge loss starts at turn 2000
- Significant intensity-dependent tune shifts at turn 4500 as charge is lost
- Chromatic effects seen as mode 1 and 2 sidebands with large mode 0 motion
- Data taken inside the feedback system via snapshot memory
"Unstable" beam - Stable with feedback control

- Closed Loop SPS Measurement - Vertical Centroid (left) | Spectrogram (right)
- Intensity $2 \times 10^{11}$ with low chromaticity Q26 lattice (special beam)
- $\nu_y = 0.185$, $\nu_s = 0.006$
- Small residual mode zero driven motion, reduced by the feedback gain.
- Mode 1 and 2 sidebands controlled to noise floor (3 $\mu$m rms)
April 2015 SPS MD - Grow/Damp measurements

- Grow/damp SPS Measurement - Damping Gain G=4 (left) G=16 (right)
- Intensity $1.1 \times 10^{11}$ with low chromaticity Q26 lattice (special beam)
- $\nu_y = 0.185 \ \nu_s = 0.006$
- Feedback gain is switched to promote instability, then damp it
- Quantifies damping from increased gain of system, compare to models
April 2015 SPS MD - Impact of FIR feedback gain

- damping rate SPS Measurement - Damping G=4 (left) G=16 (right)
- Intensity $1.1 \times 10^{11}$ with low chromaticity Q26 lattice (special beam)
- $\nu_y = 0.185 \; \nu_s = 0.006$
- Feedback phase held constant, impact of two gains on achieved damping
- Quantifies damping from configuration of FIR filter, compare to models
- $G=4 \; \tau = -342 \; \text{turns}, \; G=16 \; \tau = -93 \; \text{turns}$
- Is this the "best" one can do? what about more sophisticated control methods?
April 2015 SPS MD - Grow/Damp measurements

- Grow/damp SPS Measurement - Damping gain G=16 (left) Spectrogram(right)
- Intensity $1.1 \times 10^{11}$ with low chromaticity Q26 lattice (special beam)
- $\nu_y = 0.185$ $\nu_s = 0.006$
- Feedback gain is switched to promote instability, then damp it
- Quantifies damping from increased gain of system, compare to models
April 2015 SPS MD - Evolution of modes vs. turn #

Kick-Damp - Injection kick, no feedback turns 0-500, Feedback damp after turn 500

Shows evolution of excited and damped modes
4 GS/s 1 bunch SPS Demonstrator processing system

- Proof-of-principle channel for 1 bunch closed loop tests in SPS - initial tests 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 - timing/synchronization, noise floor of A/D, 64 bunch train controller, scrubbing doublet controller, slice gains
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, D. Aguilera
- 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 Slotline kicker development

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

![Kicker Geometry](image-url)
- **Shapal** spacers, 12 mm diameter
- **WR-430 waveguide**, 109.22 x 54.61 mm, 1000 mm long
- **Stripline electrode**, 68 x 5 mm, 1000 mm long
- **Beam pipe**, 132 x 52.3 mm,
- **Coaxial-to-stripline transition**, based on **Kyocera RF UHV feedthrough**
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.

CERN plans to install:
- 2 Striplines
- 1 Slotline
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
Wideband 5 - 1000 MHz amplifier

- R&K Company developed a new design to meet our wideband requirements
- Extended low-frequency response, improved transient behavior
- Design also includes necessary remote control and monitor
- 4 R&K 5 - 1000 MHz 250W amplifiers installed in SPS tunnel

R&K's impulse response measurements
Before
After

LARP/HiLumi Collaboration Meeting, CM22 5/7/14

4 R&K 5 - 1000 MHz 250W amplifiers installed in SPS tunnel
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)
Next MD studies with wideband DEMO system

- Excitation of higher internal modes
  - With limited kicker power, difficulties exciting/driving modes 2 - 8
  - Our next path - work with lower intensity (less intensity tune shifts)
  - Special linear lattices, less chromaticity, we should see intra-bunch modes
  - Continued simulation and modeling effort, compare MD results with simulations
  - Validate new Kickers (Stripline and Slotline) and upgraded tunnel High-Power wideband RF amplifiers

- Development of Control Techniques
  - Single-bunch IIR, scrubbing doublet and FIR multi-bunch control
  - Diagnostic and beam instrumentation techniques to optimize feedback parameters and understand system effectiveness
  - Use of reduced model as tool, use of both numeric simulations (Head-Tail) and physical MD data to understand system requirements for robust control with HL intensities and lattices

- Path from single-bunch to train studies
- With slotline kicker commissioned, path to higher intensity studies
Next Technology Development

- High-speed DSP Platform consistent with 4-8 GS/sec sampling rates for full SPS implementation
  - Explore value of multiple pickups, improved noise floor
  - Explore value of multiple kickers, \( \pi/4 \) separation, higher gain
  - 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
- Lab evaluation and firmware development
Upgrades to the SPS Demonstrator - Roadmap

- DAC Only - 4GSa/s
- 4GSa/s
- ADC + DAC + DSP - 4GSa/s
- SNAP SHOT MEMORY
- Build test bed system
- ADC + DAC + DSP - 8GSa/s
- Subset of demo system features & functions

**The Demo system is a platform to evaluate control techniques**

- MD experience will guide necessary system specifications and capabilities
- The path towards a full-featured system is flexible, can support multiple pickups and/or multiple kickers
- We will benefit from the combination of simulation methods, machine measurements, and technology development
Wideband Feedback - Beam Diagnostic Value

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

- Detailed slice by slice information, very complete data with GHz bandwidth over 20,000 turns
System development and near term plans

- **Intensive MD program Spring/Summer 2016**
  - Development of special beams for feedback tests
  - What can we validate with this limited system?
  - 64 bunch train controller, 32 bunch scrubbing fill controller (doublet 5 ns spacing)
  - Power Amplifiers - 4 250W 5-1000 MHz amplifiers, 2 stripline kickers

- **Development of wideband kicker designs**
  - Commissioning of 2nd Stripline with beam, new amps
  - Optimization of Slotline design for Fab
  - Tunnel infrastructure for new amplifiers, monitoring and control

- **Simulation codes/feedback model studies, Model-based Control**

- **Near-term priorities**
  - Expand Demonstration system for multi-bunch operation, commission 2nd kicker, wideband amplifiers
  - MD efforts - explore controllers and wideband kicker with beam.
  - MD Data Analysis methods, Explore/validate Q20 control methods, MIMO controller FPGA complexity

- **Estimates of operational system capabilities/specifications and LIU Design Report Fall 2016**

- **Applicable to SPS/ HL-LHC? PS? FCC?**
Acknowledgements and Thanks


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- We are grateful to Sei Mizue and the R&K company (Japan) for their rapid prototype amplifier development, and their interest in meeting our unusual time-domain specifications

- We cannot adequately acknowledge the critical help from everyone who made the winter 2012 and 2014, 2015 feedback Demo MDs possible. We are grateful for the collaboration and generous help.

- Thanks to CERN, SLAC, KEK and LARP for support

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Technology Development, Wideband Kickers, Beam Measurements, Simulation Models, and graduate education
Future (Potential) Collaborators:
1) BNL, USA
2) KEK, Japan

EXPERIMENTAL

MD STUDIES
1) Real dynamics.
2) Real design constraints
   Noise, Dynamic Range,
   Gain Limitations, Delays,
   Phases
3) Varying machine configs.

TEST/VALIDATION/IMPLEMENTATION

FEEDBACK CONTROLLERS

PHYSICS VALIDATION

NON-LINEAR MACRO PARTICLE SIMULATIONS
1) Numeric methods to study
   beam dynamics without beam
time.
2) Has control over noise,
   impurities, disturbances, etc...
3) Idealized system.

DATA FOR PARAMETER FITTING

REduced ORDER MODELS
1) Required for designing
   controllers.
2) Analytical calculations of
   stability, gain and phase
   margins are possible.
3) Can be used as diagnostics
   tools.

ANALYTICAL

CERN, SLAC, LBNL

CERN, SLAC

DEsign Step

TEST/VALIDATION

COMPUTATIONAL
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 GigaMac/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 GigaMac/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.
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
- Optimization technique - can be used for kicker, too

Software vs. Hardware Equalized Beam Signal – Bessel Filter

Modeled Gaussian beam signal
Unequalized signal
Hardware equalized signal – Bessel
Software equalized signal – Bessel

Software Equalized signal has been shifted and scaled to match centroid and height of hardware equalized
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
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 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
- Conceptual design by John Cesaratto, details by Silvia Verdu, M. Wendt
- Plan for mechanical design, fabrication by E. Montesino for 2016 CERN fabrication

**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.**
Scrubbing Fill Controller - implemented for December 2014 MD tests

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

- wideband system allows control with 5 ns bunch spacing
Progress - Techniques to time a selected bunch and position (O. Turgut)

- We excite the beam from our amplifier array
- To control the modes excited, we must have precision in excitation timing
- An off-time Mode 0 excitation will excite mode -1, 1
- Methods to repeatably position the kick, time the system
- Methods to maximize the effective kick applied to the beam

Goal is to synchronize kicker with any bunch in the bunch train so that we can kick any place within any bunch.

Barycentric driven motion
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
    - 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
April 2015 SPS MD - Impact of FIR feedback phase

- Damping rate SPS Measurement - FIR phase 90 (left) phase 157 (right)
- Intensity $1.1 \times 10^{11}$ with low chromaticity Q26 lattice (special beam)
- $\nu_y = 0.185, \ \nu_s = 0.006$
- Feedback FIR gain held constant, impact of two filter phases on achieved damping
- Quantifies damping from filter phase vs frequency of system, compare to models
- Phase $= 90 \ \tau = -339$, phase $= 157 \ \tau = -93$
- Is this the "best" one can do? what about more sophisticated control methods?

J. D. Fox
John Adams Institute
Applications of the SPS High Bandwidth Transverse Feedback System and beam parameters

Giovanni Rumolo
in LIU-SPS High Bandwidth Damper Review Day, CERN, 30 July 2013

- Overview on parameter range for future operation
- Historical of the study on a high bandwidth transverse damper
- Possible applications
  → Electron cloud instability (ECI)
  → Transverse Mode Coupling Instability (TMCI)
  → Stabilization of the scrubbing beam
  → More?
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)**

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

One train of 72 doublets in the SPS

Splitting in the first few ms (not visible)

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:

<table>
<thead>
<tr>
<th></th>
<th>SPS</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF frequency (MHz)</td>
<td>200</td>
<td>400</td>
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<tr>
<td>$f_{rev}$ (kHz)</td>
<td>43.4</td>
<td>11.1</td>
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<td># bunches/beam</td>
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<td>2808</td>
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<tr>
<td># samples/bunch</td>
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<td>16</td>
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<td># filter taps/sample</td>
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<td>16</td>
</tr>
<tr>
<td>Multi-Accum (GMac/s)</td>
<td>3.2</td>
<td>8</td>
</tr>
</tbody>
</table>

- 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 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.