Performance of the Wideband Feedback Demonstrator System - Recent Results

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LARP Ecloud Contributors:

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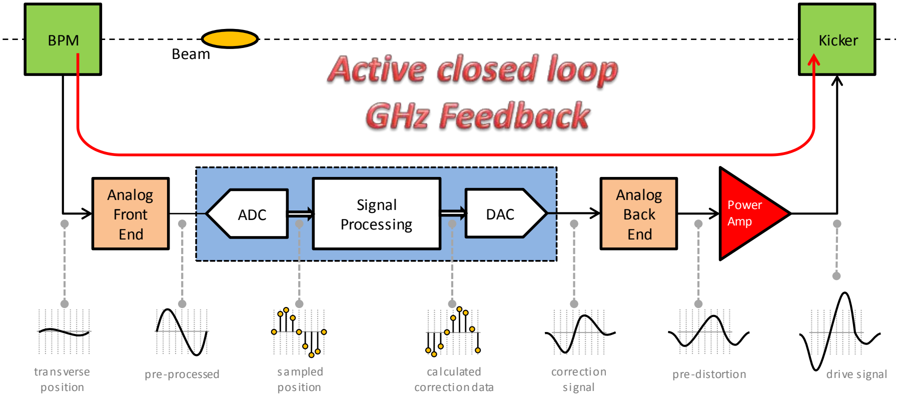
[5] KEK

WBFS - Functional requirements



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

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

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

Goals for Machine Development studies

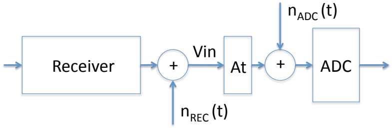
- Validation of firmware / hardware /software
  - Test hardware - firmware. Integrate processing with receiver, timing, SPS systems
  - Development of software tools to configure the feedback system and analysis of beam dynamics.
- Characterization of the Demonstrator prototype with beams
  - Limited kickers, kicker amplifier power necessitate well designed beam conditions
  - Validate the system performance and be able to extrapolate results to predict the feedback system behavior during real (unexplored) machine conditions.
  - Estimate the performance of a final full-feature system including wideband slotline kicker.
- Simulation and reduced model validation with machine measurements
  - Models allow design and analysis of different controllers as well as predict the behavior of the beam in different conditions
  - Allow estimation of system specifications, control dynamics for different machines

System and MD studies 2016

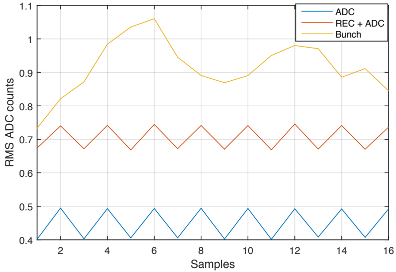
- System characterization, front end noise studies
- Stable single bunch Grow/Damp studies
  - validates installed kicker gain, models of beam and system
  - develops analysis tools
- Unstable single bunch studies
  - studies of head-tail and TMCI driven instability (open and closed loop), Q26 optics
  - very sensitive to beam conditions (limited dynamic control range from minimum kickers/amplifiers)
  - valuable for model validation, demonstration of unstable beam control
- Multi-bunch studies
  - use 64 bunch train control filter
  - Search for Ecloud driven motion, test control
  - Q20 optics, multiple 72 bunch batches

SNR and sensitivity of front-end receiver

Detail of Receiver - ADC



Front-end Noise and Bunch Motion



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

.

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

.

RMS damped Beam motion
Transverse
$\sigma_Y = 2.8\mu m$ rms
Contributions from synchrotron motion σ_Z,
sampling clock phase noise $\sigma_{\Delta T}$

$$\sqrt{\sigma_Z^2 + \sigma_{\Delta T}^2} = 6.25 ps \text{ rms}$$

Single Bunch - Head-Tail unstable, complex dynamics

Example - Detail at Injection

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

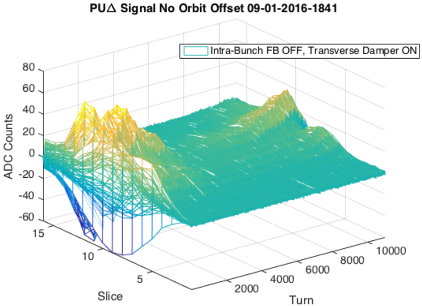


Figure: Vertical dipole motion. Charge is lost between injection and turn ∼ 1500 and then around turn ∼ 10000.

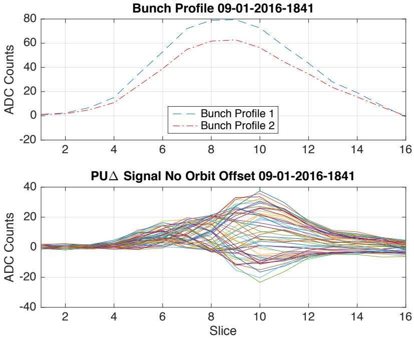


Figure: Vertical dipole motion across the bunch between turns 200 and 800.

Single Bunch - Head-Tail unstable, is this TMCI?

Example - Detail at turns 8000 - 10000

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

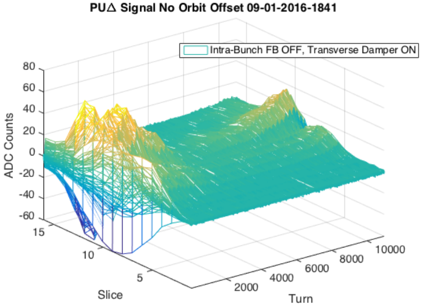


Figure: Vertical dipole motion. Charge is lost between injection and turn $\sim$ 1500 and then around turn $\sim$ 10000.

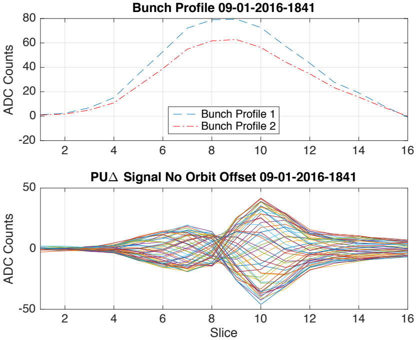


Figure: Vertical dipole motion across the bunch between turns 9000 and 9500.

Single Bunch - Head-Tail unstable, complex dynamics

Example - Spectrogram

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

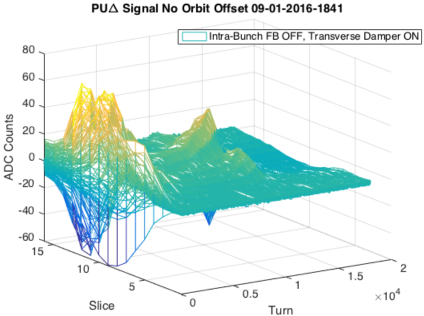


Figure: Vertical dipole motion. Charge is lost between injection and turn ∼ 1500 and then around turn ∼ 10000.

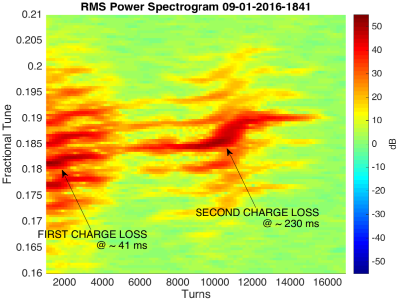
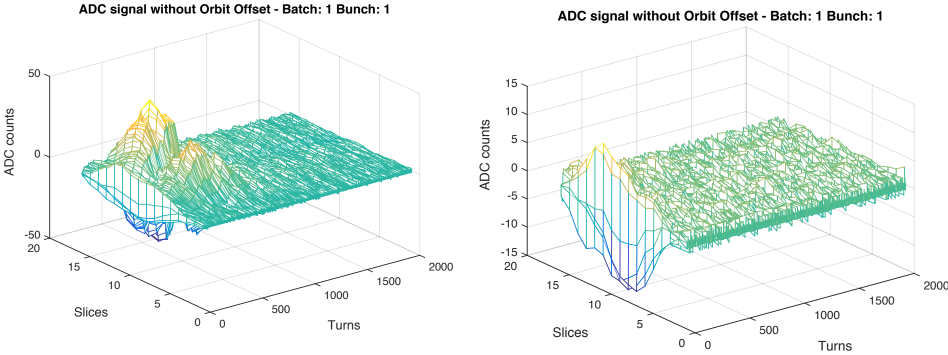


Figure: Spectrogram.

Intra-Bunch Instability Movie 09-01-2016-1841

- Q26 Optics, 2.05×10^{11}. Transverse damper is ON. Wideband feedback is OFF.
- TWC = 1.4MV, Chroma $\sim$ -0.03 (assumption $>$ -0.15, not low chromaticity), tune 0.183
- Observations: Traveling waves (?) between turns 230-290 and 480-570 . Turn 0 - injection.
- Difficult to interpret (is this TMCI? or are there multiple modes?)

Feedback Stabilizes Single Bunch



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

Single Bunch - Stabilized by feedback

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

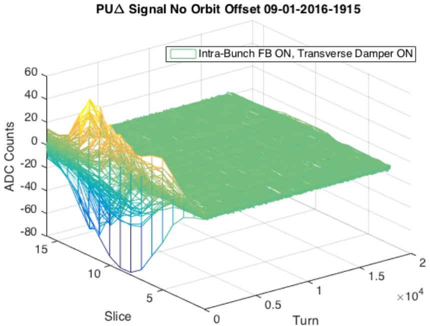


Figure: Vertical dipole motion. Small amount of charge is lost at injection.

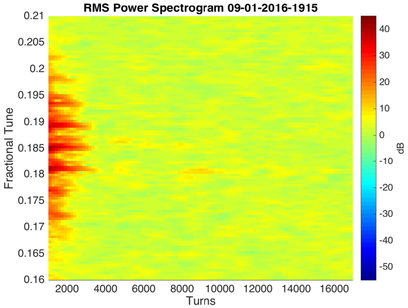


Figure: Spectrogram.

Single Bunch - Damp - Grow transient

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

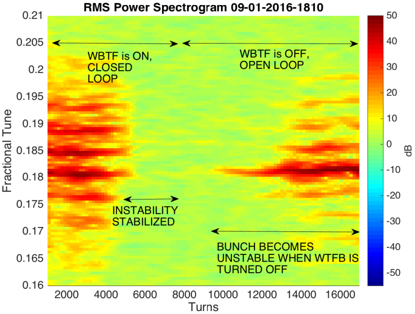


Figure: Spectrogram of a bunch.
The wideband feedback (WBFB) is ON until turn 8000. The bunch becomes unstable after WBFB is turned OFF.

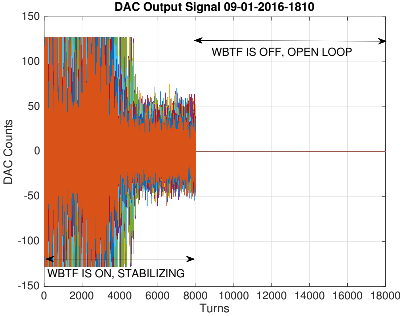
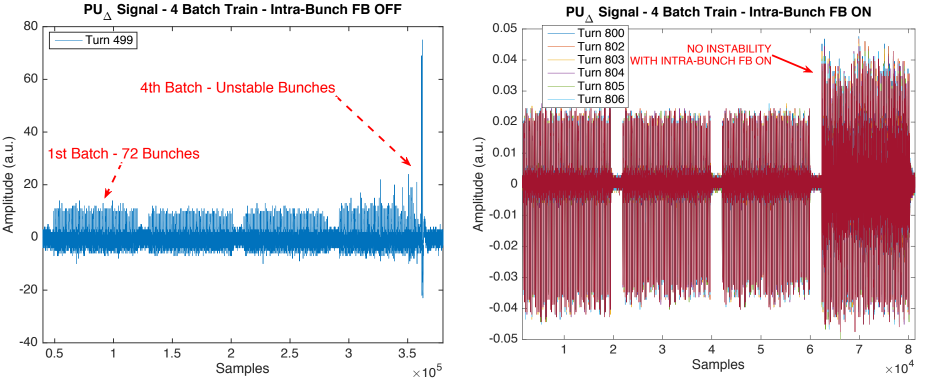


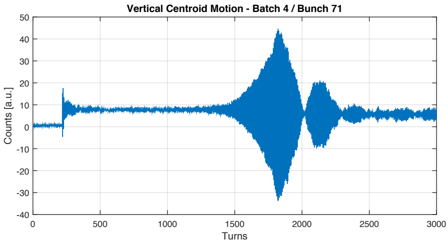
Figure: DAC signal (Amplifier, Kicker signals). Loop is opened at turn 8000

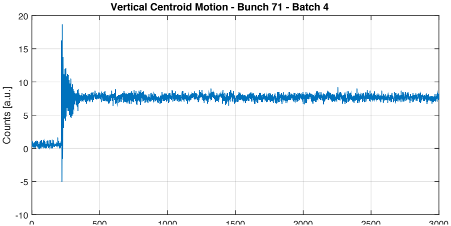
June 2016 SPS MD - High current Multi-Bunch Control

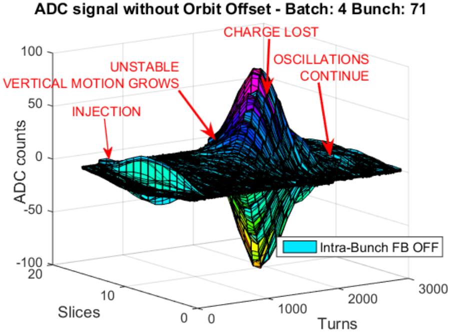


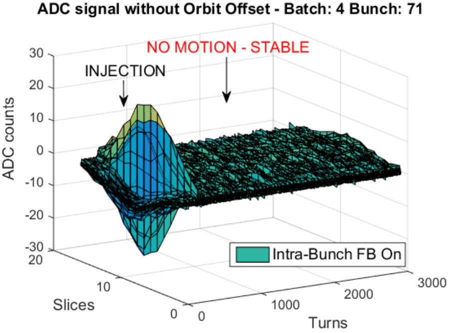
- High Current Train SPS Measurement - 4 stacks of 72 bunches
- Intensity 1.8$x10^{11}$ with low chromaticity Q20 lattice (special beam)
- Instability seen at end of 4th stack - Wideband Feedback OFF
- Instability controlled on 4th stack - Wideband Feedback ON
- Instability leads to loss of charge from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

June 2016 SPS MD - High current Multi-Bunch Control


Vertical Centroid Motion - Batch 4 / Bunch 71


Vertical Centroid Motion - Bunch 71 - Batch 4


ADC signal without Orbit Offset - Batch: 4 Bunch: 71

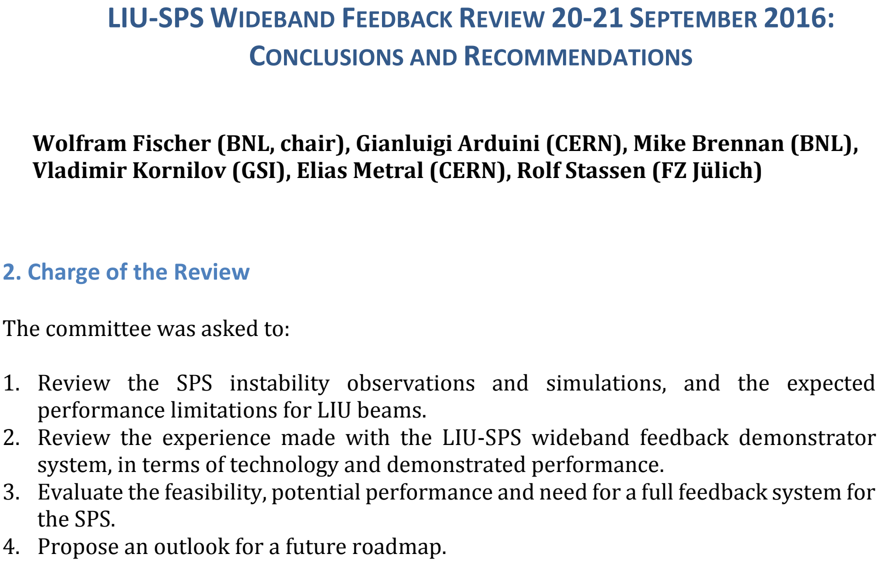

ADC signal without Orbit Offset - Batch: 4 Bunch: 71

Summary of MD studies

- Single Bunch Studies
  - Control Head-Tail type intrabunch instability
  - Damping of intrabunch unstable motions with growth rate > 200 turns
  - Recent results due to the combination of both improved hardware (2 set of wide-band kickers / amplifiers) and a careful setting of SPS beam parameters.
  - Generation/study/control of a clear "TMCI" instability in progress
- Multi-Bunch Control
  - Demo WBFB able to control collective effect instabilities in a multi bunch trains
  - The goal of this test was to induce intra bunch instabilities via electron clouds in the last batch, but beam presented only Mode 0 motion.
  - During the Aug-Sept MD we observed instabilities in isolated bunches in the second batch. Some preliminary data was recorded to study the bunch motion characteristics. There was no time to close the feedback and study in detail the effect of the WBFB.
  - Further MD studies can explore control of a clear "Ecloud" driven instability
- Further studies are possible to optimally configure controllers to stabilize motion with faster growth rates. Installation of the slot line kicker and associated amplifiers will provide significant gain increase

Lessons Learned from MD studies

- Critical experience with GHz bandwidth system, 4 GS/s DSP
  - Techniques to time Pickups, Kickers with 100 ps resolution
  - Techniques to drive intra-bunch motion, study kicker performance
  - synchronization to SPS RF, low phase noise Master Oscillator
  - Two pickups ? (increased sampling rate, reduced noise)
  - Value of 8 GS/sec architecture (bandwidth, or charge normalization)
- Beam and Feedback Dynamics
  - driven studies on stable beam, dynamics, feedback
  - growth/damping rate studies. comparisons to models
  - FIR diagonal control for single-bunch and trains
  - Value of more sophisticated filter R&D
- CERN participation in Beam and Accelerator configuration
  - Special beams critical in studying intra-bunch dynamics
  - Value of shared MD planning, execution and analysis
- Just starting most useful MD phase
  - Continued quantitative analysis of MD data is necessary to fully characterize the feedback system stabilizing intrabunch motion and the damping limits due to modest installed power on amplifiers and kickers.
  - Simulations of model-based control techniques are very promising in terms of better use of installed power and allowable dynamic range of control



LIU-SPS WIDEBAND FEEDBACK REVIEW 20-21 SEPTEMBER 2016: CONCLUSIONS AND RECOMMENDATIONS

Wolfram Fischer (BNL, chair), Gianluigi Arduini (CERN), Mike Brennan (BNL), Vladimir Kornilov (GSI), Elias Metral (CERN), Rolf Stassen (FZ Jülich)

2. Charge of the Review

The committee was asked to:

1. Review the SPS instability observations and simulations, and the expected performance limitations for LIU beams.
2. Review the experience made with the LIU-SPS wideband feedback demonstrator system, in terms of technology and demonstrated performance.
3. Evaluate the feasibility, potential performance and need for a full feedback system for the SPS.
4. Propose an outlook for a future roadmap.

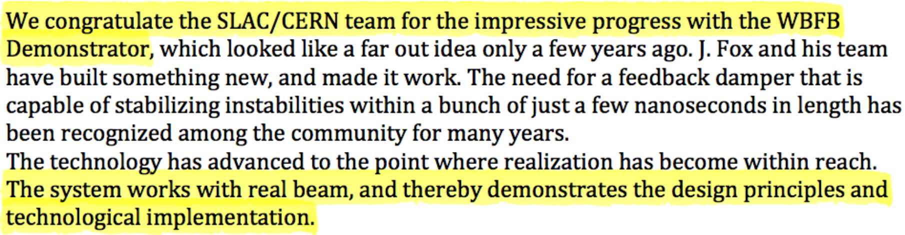
6. Experience with the WBFB Demonstrator

Findings

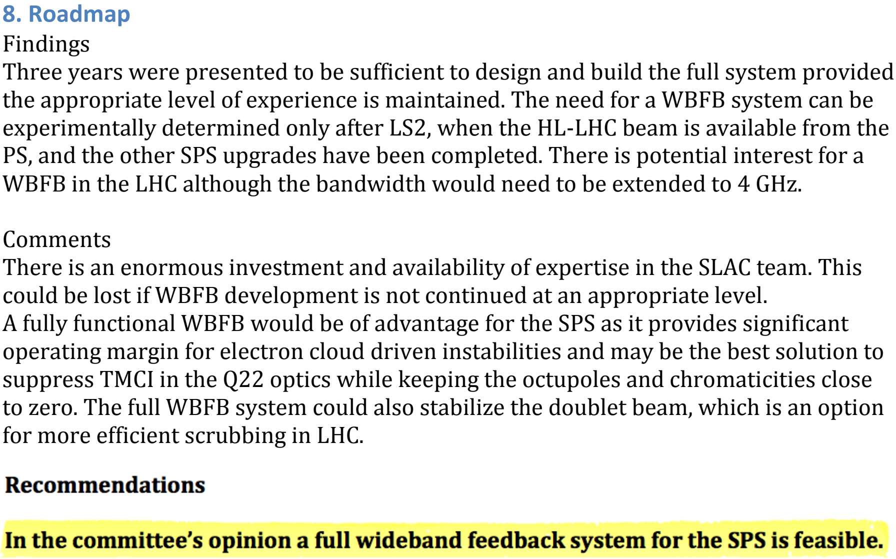
The WBFB Demonstrator consists of 2 wide band stripline kickers (BW < 1 GHz) with a total power of 1 kW (4x250 W with BW 5 MHz - 1 GHz). The WBFB Demonstrator is acting only in the vertical plane. It has damped:

- Single bunch intra bunch instabilities with growth times > 200 turns (slow head-tail instability), limited by the installed power
- Multi-bunch instabilities (up to 64 bunches in dipole rigid mode)

Comments



We congratulate the SLAC/CERN team for the impressive progress with the WBFB Demonstrator, which looked like a far out idea only a few years ago. J. Fox and his team have built something new, and made it work. The need for a feedback damper that is capable of stabilizing instabilities within a bunch of just a few nanoseconds in length has been recognized among the community for many years.
The technology has advanced to the point where realization has become within reach. The system works with real beam, and thereby demonstrates the design principles and technological implementation.



8. Roadmap

Findings

Three years were presented to be sufficient to design and build the full system provided the appropriate level of experience is maintained. The need for a WBFB system can be experimentally determined only after LS2, when the HL-LHC beam is available from the PS, and the other SPS upgrades have been completed. There is potential interest for a WBFB in the LHC although the bandwidth would need to be extended to 4 GHz.

Comments

There is an enormous investment and availability of expertise in the SLAC team. This could be lost if WBFB development is not continued at an appropriate level.
A fully functional WBFB would be of advantage for the SPS as it provides significant operating margin for electron cloud driven instabilities and may be the best solution to suppress TMCI in the Q22 optics while keeping the octupoles and chromaticities close to zero. The full WBFB system could also stabilize the doublet beam, which is an option for more efficient scrubbing in LHC.

Recommendations

In the committee's opinion a full wideband feedback system for the SPS is feasible.

Summary - Progress on 3 coupled research areas

- Technology of Feedback System (Engineering)
  - Receiver, equalizer, pickup, Frequency/time response and noise floor
  - A/D, D/A and DSP system functionality
  - Control filters, diagnostics
  - User Interface and operational flexibility
  - Timing and Synchronization - functionality, flexibility, synchronization with energy ramp
  - Power Amplifiers - frequency, time response, power output
  - Beam Kickers, bandwidth, shunt impedance, added broadband impedance
- Studies of Feedback on Beam Dynamics (Beam Physics)
  - Active machine measurement program
  - Development of special beams (low intensity, linear lattice) for feedback tests
  - Development of techniques to measure performance
  - Demonstration of Intra-bunch instability control, multi-bunch control
- Measure Beam/System responses, compare with Simulation models (Control Theory)
  - FIR and Maxtrix Control (MIMO) Methods for Q26, Q20 SPS Optics
  - Development of MD/simulation data analysis methods
  - Validate measurements against models
  - Reduced Model and Control design formalism (Ph.D. Thesis)
  - Evaluate architecture limits(two pickup/two kicker system advantages?)

Acknowledgements

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- We especially acknowledge the skillful fabrication, test and installation of the stripline kicker in time for startup fall 2015 by D. Aguilera and E. Montesinos, the help from CERN Vacuum, Survey, Surface Treatment and Main Workshop groups.
- We are grateful to Sei Mizue and the R&K company (Japan) for their rapid prototype amplifier development, and their interest in meeting our unusual time-domain specifications
- We cannot adequately acknowledge the critical help from everyone who made the 2012, 2014, 2015 and 2016 feedback Demo MDs possible. We are grateful for the collaboration and generous help.
- Thanks to CERN, SLAC, KEK and LARP for support
- We thank our Reviewers from the DOE LARP July 2016 Review, the SLAC September 2016 Internal Review, and the CERN LIU-SPS September 2016 Review, and the for their thoughtful comments and ideas

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

Where Are we today? What have we learned?

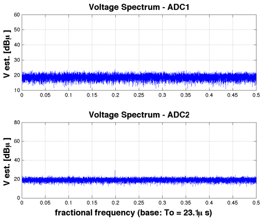
- Demonstrator hardware system, upgraded post LS1
    - intra-bunch control demonstrated
    - 64 bunch train control demonstrated
    - Two stripline kickers in place, 4x250W 1 Ghz amplifiers
    - FIR based single, doublet, train controllers
    - Many control concepts simulated, studied via head-tail, reduced models
    - Ready for continued intensive MD program with strong coupling to CERN ABP group
- What's not there?
    - No energy ramp synchronization -deferred due to lack of resources
    - Slotline kicker - delayed due to resources
    - Data to understand limits of FIR control for Q20 and Q20-like optics -just starting
    - Simulations/studies of growth rates vs. energy in ramp
    - Orbit Offset, partial removal in receiver (DSP dynamic range improvement)
- What Have we learned?
    - FIR control formalism works for mode 0 and intra-bunch modes (limits?)
    - Control models allow estimation of limits for various machine configurations
    - Synchronization and timing is critical, diagnostics to check timing critical
    - MD studies for intra-bunch measurements require careful beams and coordination with machine configurations

Limitations on system gain

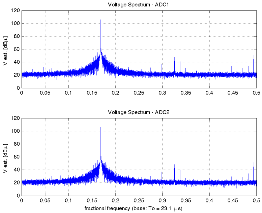
- Demonstrator System, useful for Train and single bunch studies
- For any causal feedback technique, the system gain and bandwidth are limited
- Gain is partitioned between pickup, receiver, DSP, RF amplifiers and kickers
- for our FIR bandpass filter, 2 gain limit mechanisms
  - Group delay/bandwidth gain limit - phase/gain margins lost as gain is increased, drive instabilities
  - Noise saturation limit - input noise$*$gain saturates kicker
- Impacts of injection transients, interactions with the SPS transverse damper
- What do our simulations and MD studies show?

Quantifying Performance of the DEMO A/D System

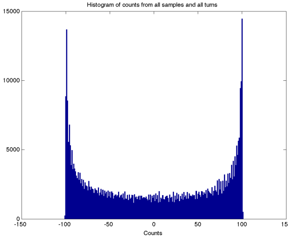
- The dynamic range, linearity and nonlinear behavior of the DEMO system was carefully quantified during LS1- important to estimate impact behavior in beam studies
- Noise pick-up seen in commissioning was addressed with new physical layout of A/D cards, copper ground plate, double-shielded cables
-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



Spectrum of 50 ohm terminated input

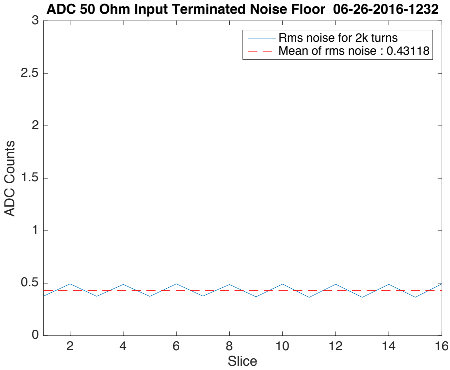


Spectrum of near full scale 200 MHz Input

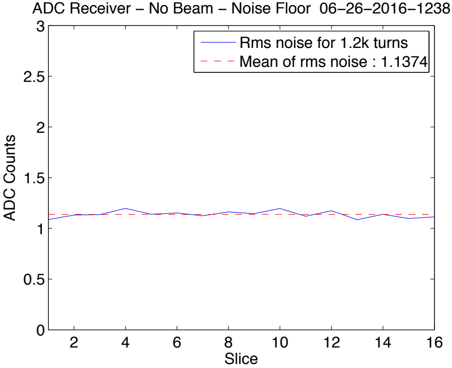


Histogram of near full scale 200 MHz input

Noise studies, receiver and ADC system



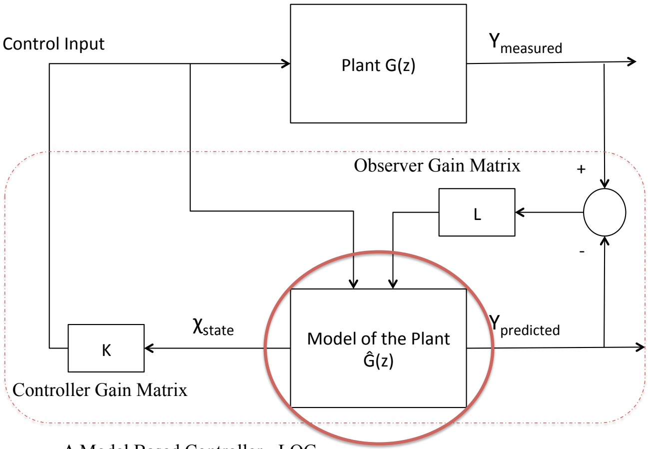
RMS Noise per slice, 50 Ohm terminated ADC



RMS Noise per slice, Receiver with pickup, no beam

- We can see the two ADC systems have slight differences
- Conclusion - receiver is setting noise floor
- ADC has full specified ENOB, sensitivity to master oscillator phase noise
- A perfect quantizer noise floor is $\frac{1}{\sqrt{(12)}} = 0.2887$ counts.
- We can benefit from increased kicker strength and amplifier power

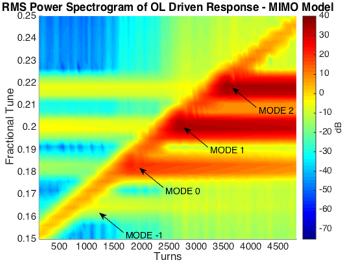
New Model-Based Control Studies

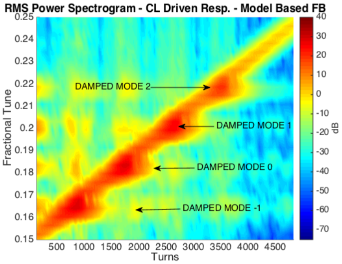


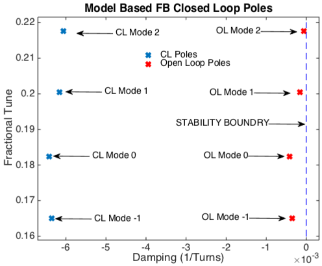
A Model Based Controller - LQG

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

MIMO Modal 4X4 controller - Beam Simulation

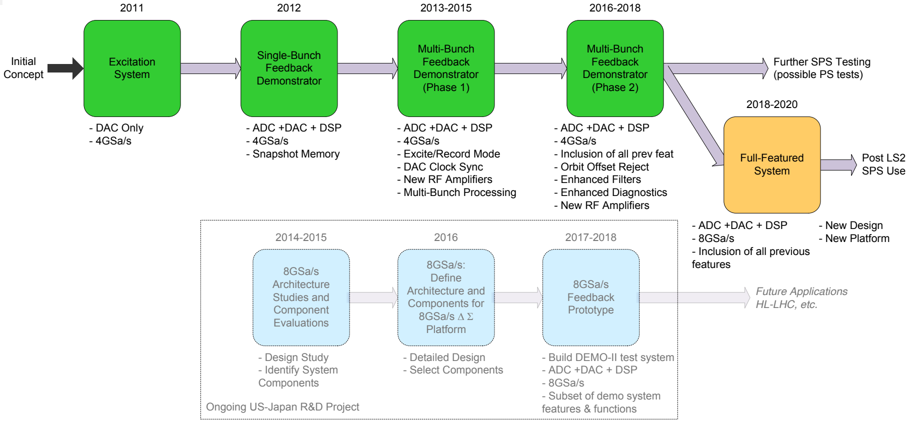

RMS Power Spectrogram of OL Driven Response - MIMO Model


RMS Power Spectrogram - CL Driven Resp. - Model Based FB


Model Based FB Closed Loop Poles

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

Upgrades to the SPS Demonstrator - Roadmap



Initial Concept

2011
Excitation System
- DAC Only
- 4GSa/s

2012
Single-Bunch Feedback Demonstrator
- ADC +DAC + DSP
- 4GSa/s
- Snapshot Memory

2013-2015
Multi-Bunch Feedback Demonstrator (Phase 1)
- ADC +DAC + DSP
- 4GSa/s
- Excite/Record Mode
- DAC Clock Sync
- New RF Amplifiers
- Multi-Bunch Processing

2016-2018
Multi-Bunch Feedback Demonstrator (Phase 2)
- ADC +DAC + DSP
- 4GSa/s
- Inclusion of all prev feat
- Orbit Offset Reject
- Enhanced Filters
- Enhanced Diagnostics
- New RF Amplifiers

Further SPS Testing (possible PS tests)

2018-2020
Full-Featured System
- ADC +DAC + DSP
- 8GSa/s
- Inclusion of all previous features
- New Design
- New Platform

Post LS2 SPS Use

2014-2015
8GSa/s Architecture Studies and Component Evaluations
- Design Study
- Identify System Components

2016
8GSa/s: Define Architecture and Components for 8GSa/s Δ Σ Platform
- Detailed Design
- Select Components

2017-2018
8GSa/s Feedback Prototype
- Build DEMO-II test system
- ADC +DAC + DSP
- 8GSa/s
- Subset of demo system features & functions

Future Applications HL-LHC, etc.

Ongoing US-Japan R&D Project

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

Summary - Lessons Learned

- Value of the DEMO program
  - Core processing functions can be implemented at 4 GS/sec, or 8GS/s
  - FIR diagonal control has limits, may be useful for practical intensities
  - Analog/RF functions demonstrated with 1 GHz bandwidth
  - Wideband RF amplifiers available
  - Promising new control methods could be implemented on a reconfigurable architecture, allows increased damping performance if required
  - Reconfigurable FPGA processing allows re-targeting to LHC, other facilities
- Development timescale of full-featured system
  - The design of a full-function system could be confidently started, resources would determine how long to commission a full-featured system
  - The core processing FPGA hardware could be designed with extra capacity
  - Flexible input paths would allow two pickups if desired
  - Future upgrades could implement new control filters and operating modes
- Value of continued Demo expansion - 2017/2018
  - Slotline validation
  - MD studies and extrapolation to HL needs
  - expansion of Demo capabilities, 8GS/s processing
  - Builds on existing chassis , allows upgrade at small cost
  - Starts path to full-featured system
  - Funding for this path not in LARP planning

Wideband Feedback - Implementation in LHC

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

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

- LHC needs more multiply-accumulation operation resources because of # of bunches, but reduced f_{rev} allows longer computation time (assuming diagonal control).
  - LHC signal processing is roughly x2 more FPGA resources
  - Similar architecture can accommodate needs of both SPS and LHC.
- Still need kicker of appropriate bandwidth with acceptable impedance for LHC. Learn from SPS experience.
- 8 GS/s system feasible for system bandwidth to 3 - 4 GHz

System Developments and MD Studies

- Demonstrator hardware system upgraded (Engineering)
  - Two bunch scrubbing fill controller (5 ns spacing), 64 bunch train controller
  - New back-end equalizer, Firmware tests, system testing in faraday cage
  - Power Amplifiers -evaluations, selection process via measurements
  - Two stripline Kickers instrumented and powered (4 250W amps, 2 LARP, 2 CERN)
  - Tunnel infrastructure for 4 new amplifiers, monitoring and control - commissioned
  - Optimization of Slotline kicker design for CERN fabrication
- Multiple MD studies at the SPS, coupling to CERN ABP groups
  - April, November, December 2015, June, July, August, November 2016
  - Grow-damp studies with Q20 optics, Q26 optics
  - Low Chromaticity Studies with modal excitation
  - Q26 Lattice - FIR control of unstable high intensity single bunch
  - Q20 4 stack high intensity train control
  - Development of special beams (low intensity, linear lattice) for feedback tests
- Reviews
  - LARP DOE Review (July 2016)
  - SLAC Wideband Feedback review (September 2016)
  - CERN LIU-SPS Wideband Feedback Review (September 2016)