LHC LLRF Models, tools and Studies
Feedback Control of SPS E-Cloud/TMCI Instabilities

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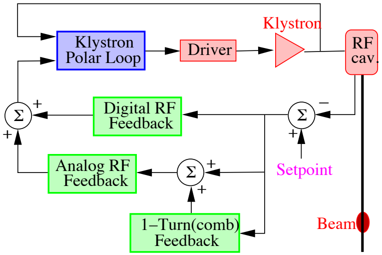
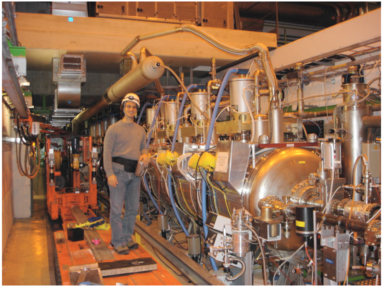
Motivation: LHC LLRF Optimization tools

- Investigate the operational limits and impact on beam dynamics from the impedance-controlled RF systems. Look ahead to high current operations, possible upgrades and understand the role of the technical implementation.
  - Based on PEP-II experience, where limits of machine were understood, and overcome, via models and simulation studies of new control techniques
- As part of these studies, CERN requested model-based commissioning tools - they are part of the beam/LLRF simulation.
  - These tools operate remotely and allow identifying the RF station transfer function and designing the feedback loops using model-based techniques.
  - Remote operation was crucial under the new stricter CERN polices preventing tunnel access when the magnets are energized.



Motivation: RF Noise Effect on Beam Diffusion Studies

- The noise power spectrum of the RF accelerating voltage can strongly affect the longitudinal beam distribution and contribute to beam motion and diffusion.
    - Increased bunch length decreases luminosity and eventually leads to beam loss due to the finite size of the RF bucket.
- The choices of technical and operational configurations can have a significant effect on the noise sampled by the beam.



FY 2010 Results

LLRF Optimization tools

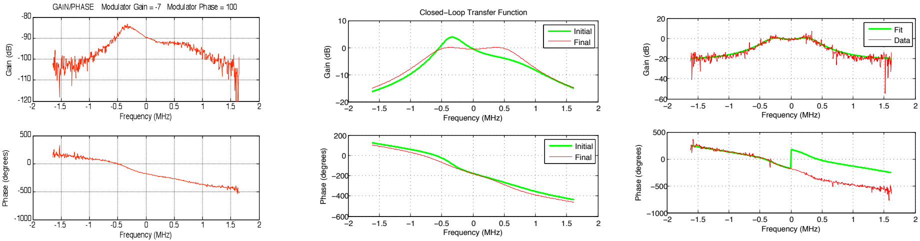
- The LLRF configuration tools have been used by the CERN BE-RF group to remotely commission the LLRF feedback loops of the RF stations during start up in both November 09 / February 10.
  - Tools reduced commissioning from 1.5 days/station to 1.5 hours/station.
  - Model based configuration adds consistency and reliability. CERN BE-RF group have repeatedly expressed their support and enthusiasm for this collaboration.

RF Noise Effect on Beam Diffusion Studies

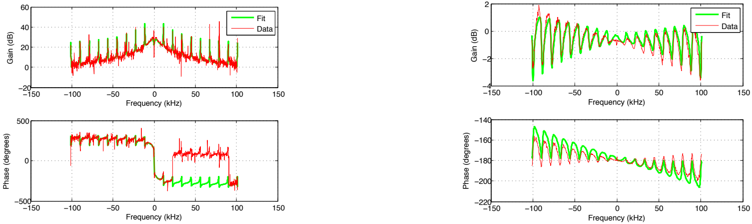
- To better understand the RF-beam interaction we developed a theoretical formalism relating the equilibrium bunch length with beam dynamics, accelerating voltage noise, and RF system configurations
- Conducted measurements at LHC (May) which confirmed our theoretical formalism and models
- T. Mastorides defended his Ph.D. thesis, with significant LARP funded LHC work
- Multiple publications in peer-reviewed journals and conference proceedings.

Technical examples: LHC LLRF Optimization tools

- Tool calculation and adjustment of RF station closed loop gain/phase.

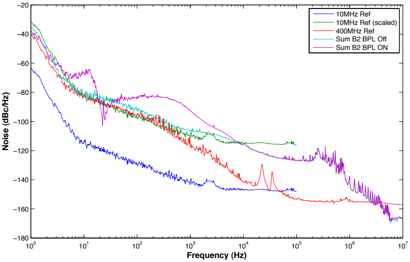


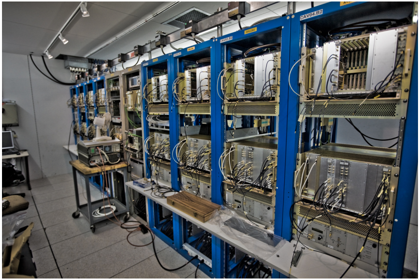
- 1-turn feedback models ready. Waiting for hardware commissioning.



RF Noise Effect on Beam Diffusion Studies

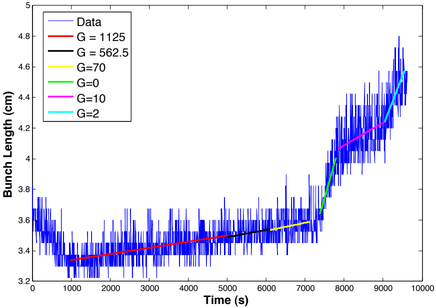
- Determined that the RF reference dominates beam diffusion related to RF noise
- Collaboration with BE-RF on technical means to improve noise spectrum





RF Noise Effect on Beam Diffusion Studies

- Anticipated a close relationship between RF station noise spectrum and beam diffusion rate.
- April 2010 measurements showed clear correlation between the bunch length **as estimated by our theoretical formalism** and the longitudinal emittance growth



FY2011 Research Plan

LLRF Optimization tools

- The 1-Turn Feedback routines of the optimization tools suite have been tested on the RF station prototype and on one real LHC station.
- LHC operations has not yet commissioned the 1-Turn Feedback. As currents increase, the 1-Turn feedback will be commissioned for all RF stations. The optimization tools will be validated and available for this commissioning.
- Final validation measurements of the complete suite will be conducted.
- Ongoing collaboration with the CERN BE-RF group on new features for future high-current operations.

RF Noise Effect on Beam Diffusion Studies

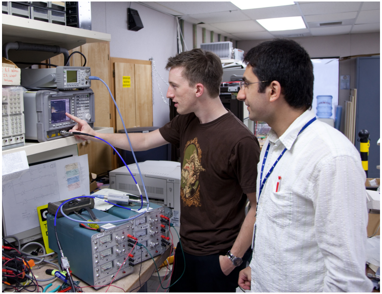
- Research plan: inject noise at specific frequencies and with varying amplitudes in a second round of measurements. Better quantify the relationship between the RF noise and longitudinal emittance blowup.
- Our earlier measurements identified the RF reference (Local Oscillator distribution) as the dominating component affecting the beam diffusion. Studies are being conducted to identify alternative technical LO implementations to reduce this effect.
- We would like to develop a formalism to estimate more accurately the time evolution of the bunch length growth with the simulation and models.

Ecloud Project Motivation and Progress July 2009 - July 2010

- Motivation - control Ecloud and TMCI effects in SPS and LHC via GHz bandwidth feedback
- Complementary to Ecloud coatings, grooves, etc. Also applicable to TMCI.
  - Technical formalism similar to 500 Ms/sec feedback implemented at PEP-II, KEKB, DAFNE
  - Ecloud/TMCI Modeling, dynamics estimation, feedback simulation efforts
  - Dynamics analysis techniques to quantify nonlinear unstable oscillators
  - MD results June 2009 (Instability Dynamics) April 2010 (pickup and kicker studies)
  - Hardware efforts (4 GS/sec. synchronized excitation)
  - near-term plans (MD, models, lab) - Response to Chamonix emphasis on SPS intensities
- Multi-lab effort - coordination on
  - Non-linear Simulation codes (LBL - CERN - SLAC)
  - Dynamics models/feedback models (SLAC - Stanford STAR lab)
  - Machine measurements- SPS MD (CERN - SLAC - LBL)
  - Hardware technology development (SLAC)
- FY2010 first year of LARP SLAC staff support

Organization and Staffing

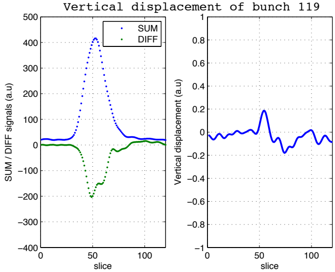
- Greater activity, increased progress winter 2010
- Program emphasis on coordinating models, machine measurements, and feedback estimation. Develop more realistic feedback model in WARP (R. Secondo)
- Multi-lab WEB meetings on Ecloud/TMCI feedback
  - www.slac.stanford.edu/∼jdfox/ecloudwebfeb10.pdf
- Biggest Change - step-up FY2010 SLAC Funding

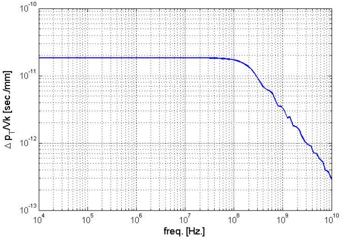


- Allows 2 Stanford grad students
  - Alex Bullitt (working on excitation system)
  - Ozhan Turgut (system identification, dynamics models)
- LARP support 25 % for J. Fox, C. Rivetta

SPS Studies

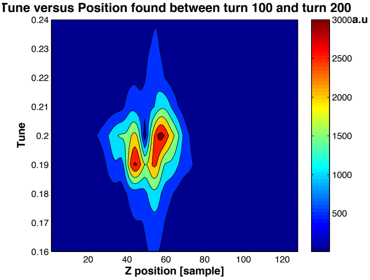
- Vertical Instability develops after injection of second batch, within 100 turns. Time domain shows bunch charge, and transverse displacement 1E11 p/bunch (June 2009)
- Use this technique to compare models, MD data - extract beam dynamics necessary to design feedback. Roughly 25 slices (250 ps) between displacement maxima and minima
- April 2010 - characterize existing SPS pickups and drive tapered pickup as kicker
  - pickups - very successful
  - Noise, transverse resolution well-quantified
  - 25 microns rms at 0.5E11 (vertical)
- Kicker and Beam Excitation, mixed results
  - difficult to excite measurable response
  - 1/f Kicker response, limited power
  - Chamonix Implications-> kicker fab?



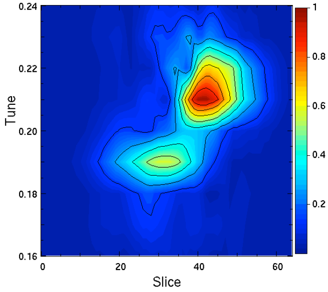


Analysis of Ecloud simulations and Ecloud MD data

- Observations
  - tune shifts within bunch due to Ecloud, bursting, positions of unstable bunches
  - information in SUM signal
  - frequencies within bunch - estimated bandwidth of instability signal, correction signal
  - Growth rates of eigenmodes - initial fits and stability observations
- Simulations - access to all the beam data. What effects are not included?
- Machine measurements - what can we measure? with what resolution? What beam conditions?



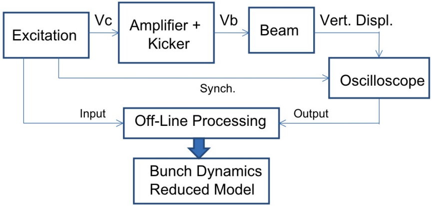
MD data June 2009



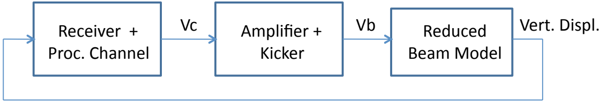
WARP simulation

Identification of Internal Bunch Dynamics: Reduced Model

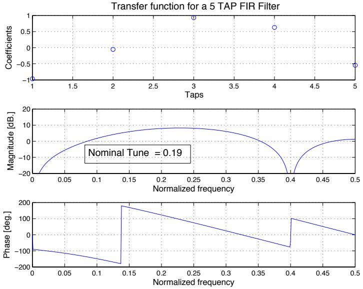
- characterize the bunch dynamics - same technique for simulations and SPS measurements
- critical to design the feedback algorithms
- Specify requirements for pickup, receiver, processing, power stages and kicker systems.
- Ordered by complexity, the reduced models could be
  - linear models with uncertainty 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



Closed-Loop feedback around the Reduced Model

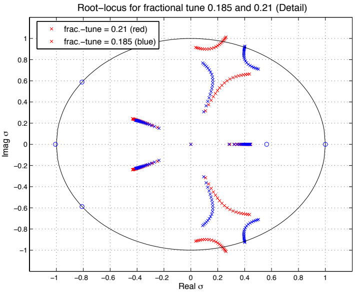


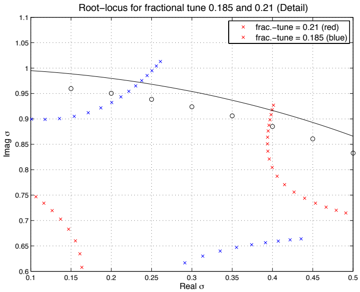
- Use the reduced model, with realistic feedback delays and design a simple FIR controller
- Each slice has an independent controller
  - This example 5 tap filter has broad bandwidth - little separation of horizontal and vertical tunes
  - But what would it do with the beam? How can we estimate performance?



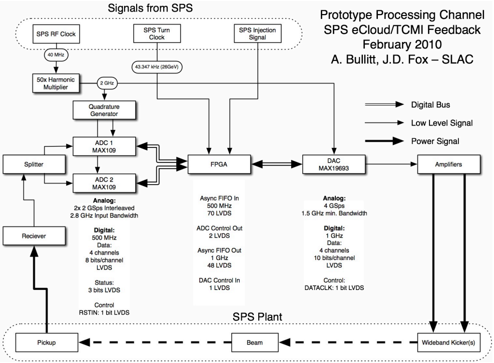
Root Locus Study - Tune shifted from 0.185 to 0.21

- We study the stability for a range of tunes
- This filter can control both systems- Maximum damping is similar in both cases
- Is this realistic case to design? We need more data from simulations and MD
- We need models for dynamics vs. beam energy, interaction with ramp





Design study - 4 Gs/sec. 1 stack SPS feedback channel



- Can we build a 'small prototype' style feedback channel? What fits in our limited LARP hardware budget? what to do in 2010/ 2011? Develop for closed loop tests in SPS
- Idea - build 4 GS/sec. channel via evaluation boards and SLAC-developed Vertex 5 FPGA processor

Summary - 2010 LARP Ecloud/TMCI effort

- Understand Ecloud dynamics via simulations and machine measurements
  - Participation in E-Cloud studies at the SPS (next opportunity July 2010)
  - Analysis of SPS and LHC beam dynamics studies, comparisons with Ecloud models
- Modelling, estimation of E-Cloud effects
  - Validation of Warp and Head-Tail models, comparisons to MD results
  - comparisons with machine physics data (driven and free motion), Critical role of Ecloud simulations in estimating future conditions, dynamics
  - extraction of system dynamics, development of reduced (linear) coupled-oscillator model for feedback design estimation
- Lab effort -development 4 GS/sec. excitation system for SPS
  - Modify existing system to synchronize with selected bunches - data for system ID tools
  - Identify critical technology options, evaluate difficulty of technical implementation
  - Explore 4 Gs/sec. 'small prototype' functional feedback channel for 2011 fab and MD use
  - Evaluate SPS Kicker options re: CERN request, 2012 shutdown window

Request for SPS Feedback System

What can we do for the SPS shutdown?

- CERN’s interest - very high. Critical missing element - useful high-power kicker and power amplifier components in SPS
  - Identify the Kicker technology as an accelerated research item, design prototype kicker and vacuum components for SPS fabrication and installation
  - Kicker design/fab requires joint CERN/US plans, they are ready to collaborate
  - Specify power amplifiers, cable plant, loads, diagnostics, all vacuum components
- FY 2011 Accelerated research and design report on Kicker System
  - design report, suggested implementation, test low power lab models, RF simulation
- FY2012 - detailed design and fab of prototype kicker, vacuum components
- FY2013 - installation in SPS with Amplifiers and Cable plant
  - Vacuum components essential for shutdown
- Dovetails with parallel system estimation and development of ’quick prototype processor’
  - Model closed-loop dynamics, estimate feedback system specifications
  - Evaluate possible control architectures, implementations, via technology demonstrations
  - SPS Machine Physics studies, development of ’small prototype’, closed loop studies

FY2011 Plans

- LLRF Tools, Models and High-Current estimation
  - We need to pace LHC RF system commissioning, validate comb model for setup tools
  - Continuation of noise studies, estimate longitudinal emittance growth, system limits
  - Staffing 0.25 FTE, plus 0.5 FTE new student
  - Travel budget $11.5K
- Ecloud/TMCI Feedback
  - Consistent with plans, continue MD effort, simulations, model feedback options
  - Lab effort to build 'quick prototype' 4 GS/sec processing model
  - Staffing LBL 0.4 FTE, SLAC 1.75 FTE staff, 2 FTE Students
  - M&S $75K
  - Travel $26K (SLAC and LBL)
- Extra effort on Kicker for SPS 2013 upgrade installation
  - FY 2011 0.5 - 0.75 FTE staff to develop Kicker design options report, $25K M&S , $6K travel
  - FY 2012 1 - 1.5 FTE staff, $250K M&S for kicker and cables, $50K for amplifiers, $6K travel

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