LHC LLRF Models, Tools and Longitudinal Beam Dynamics Studies

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LARP LLRF Contributors:

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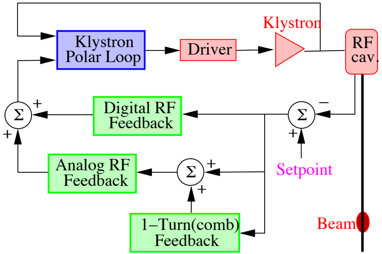
Motivation: LHC LLRF Optimization tools

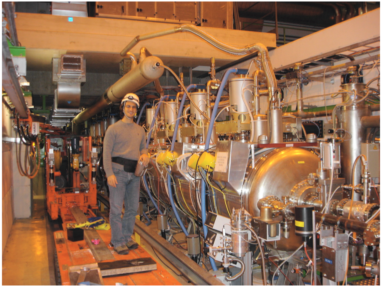
- Investigate the operational limits and impact on beam dynamics from the impedance-controlled RF systems. Look ahead to high current operations, possible upgrades and understand the role of the technical implementation.
  - Based on PEP-II experience, where limits of machine were understood, and overcome, via models and simulation studies of new control techniques
- As part of these studies, CERN requested model-based commissioning tools in 2009 - 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.



- Longitudinal coupled-bunch instabilities - Estimation of stability margins for different RF station configurations.

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.
- The motivation of this work is
  - To study and validate longitudinal beam diffusion models including the effect of RF station noise and feedback loops
  - To predict how the implementation of the system impacts the longitudinal emittance
  - To identify the sources of noise that are most damaging with the intent to selectively improve the responsible equipment
  - To set a noise threshold for acceptable performance



FY 2010 - 2011 Results

LLRF Optimization tools

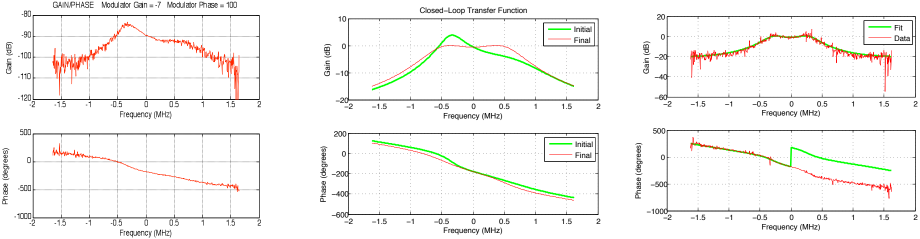
- The LLRF configuration tools have been used by the CERN BE-RF group to remotely commission the LLRF feedback loops of the RF stations during start up in November 09 / February 10 / February 11.
  - Tools reduced commissioning from 1.5 days/station to 1.5 hours/station.
  - Model based configuration adds consistency and reliability.
  - CERN BE-RF group have repeatedly expressed their support and enthusiasm for this collaboration.
  - Both groups (SLAC, CERN) are interested in expanding the capabilities and functions of these tools.

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 2010 - Nov 2010) which confirmed our theoretical formalism and models
- Multiple publications in peer-reviewed journals and conference proceedings.

Technical examples: LHC LLRF Optimization tools

- Tool measures the transfer function of the RF station - Estimates a mathematical model.
- Based on the model, the tool calculates the parameters of the LLRF controller for optimum stability margins.



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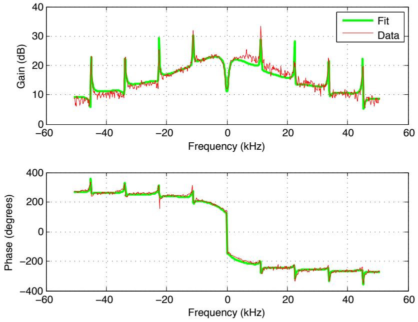
LLRF Controller commissioning tools - Future Steps

- Coupled-bunch instabilities are not an issue currently, but they do scale with beam current.
    - 1-turn feedback is critical at high currents
    - Work is in progress to test the 1-turn feedback functionalities of the commissioning tools. - Final commissioning starts June 2011.
- The biggest challenge is identifying the very narrow bandwidth peaks over a ± 300 kHz band



- With new firmware from J. Molendjik, we now have the ability to inject noise at any revolution harmonic, greatly improving the measurement resolution

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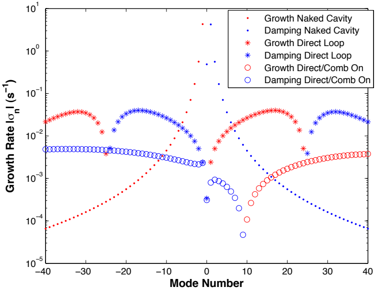
Estimates for high current operations

- Objective: Estimate instability growth rates due to the cavity fundamental. In particular, estimate the effect of the impedance reduction due to the cavity controller
  - The ultimate goal is to predict the maximum operating current as well as determine optimal configurations for best performance
- The effective cavity impedance is computed using a linearized model of the RF station and cavity controller around various operation points.



Estimates for high current operations

Conclusions

- In normal operation, the stability threshold (provided by Landau damping) is well above the estimated growth rates
- The growth rates are very sensitive to the settings of the cavity controller - 1-turn delay feedback makes the controlled sensitive to parameter variations (5^o error results in a 5-fold increases in growth rate)
- More significantly, operation with one parked cavity leads to diminished operational margins at both flat bottom and flat top
- These estimates do not include (yet) an important effect: as the beam current increases and the klystron will run closer to saturation, and the loop gain will decrease
  - Based on the available klystron power and the plans for klystron operation though, we do not anticipate a significant effect

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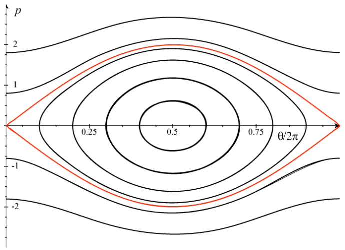
Longitudinal Emittance

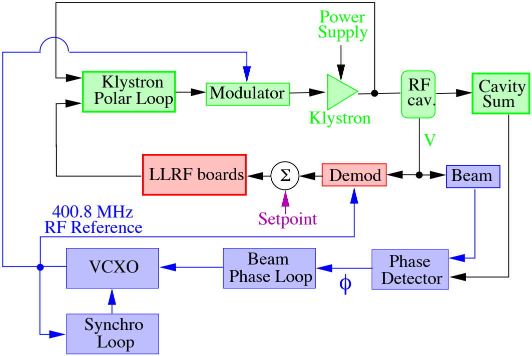
- The longitudinal emittance is a measure of the area in phase space occupied by the beam
  - Intrabeam scattering and RF noise lead to emittance increase
  - Energy lost to synchrotron radiation reduce the emittance
  - The synchrotron radiation for protons in the LHC is practically zero (damping time of tens of hours)



- As a result, the noise power spectrum of the RF accelerating voltage can strongly affect the longitudinal beam distribution - Decreases luminosity and eventually beam loss
- The bunch length growth rate is proportional to the phase noise spectral density
- Due to the beam periodicity, the noise spectrum is aliased to the band between DC and the revolution frequency f_{rev}
  - Equivalently, the beam is sensitive to the noise spectrum around $k \cdot f_{rev} \pm f_s$ (SSB).

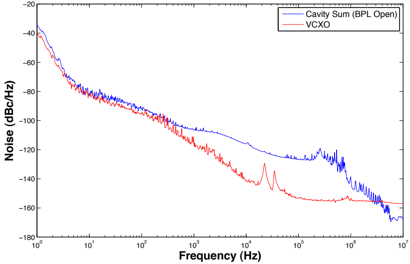
LHC RF system

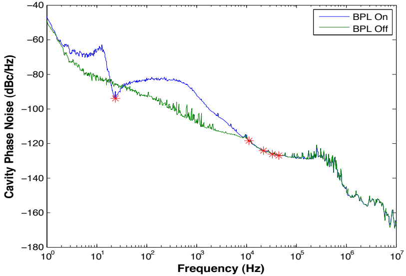
- Two major noise sources:
  - The RF reference noise introduced during the modulation/demodulation process in the Cavity Controller.
  - Intrinsic noise in baseband from the Cavity Controller feedback boards. Since the RF feedback impedance reduction is delay limited, the Cavity Controller includes very wide-band electronics (up to 100 MHz bandwidth components). The final RF feedback has a single sided bandwidth of $\approx$ 400 kHz, extending over 35 f_{rev} bands.



- The Beam Phase Loop (BPL) is a narrow bandwidth loop that modulates the RF reference to achieve damping of mode zero beam motion around the synchrotron frequency

Performance limiting components at LHC

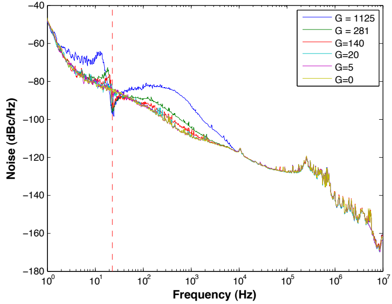




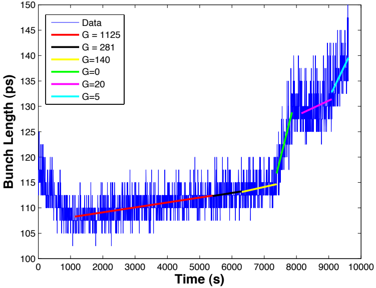
- Phase noise PSD of the RF sum (through an 8-way combiner) of the cavity voltage seen by the beam (no interfering electronics).
- The accelerating voltage phase noise is dominated by the 400 MHz reference up to 300 Hz, the Cavity Controller at higher frequencies
- The Beam Phase Loop (BPL) reduces the noise around the synchrotron frequency
  - The intensity lifetime would have been less than an hour otherwise

Proton Measurements

- By varying the BPL gain, we could change the noise level around the synchrotron frequency and look at the result on the longitudinal beam emittance.



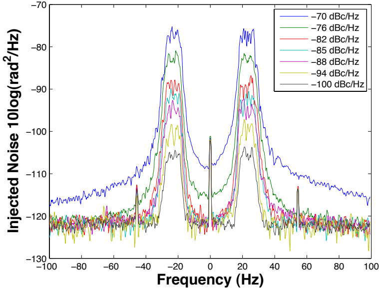
RF station 6B2 noise spectral density with BPL gain



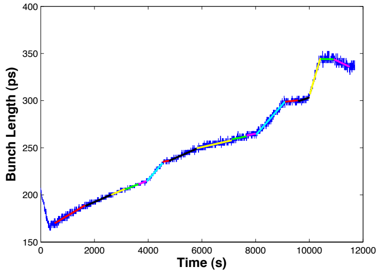
Beam 2 Bunch Length with time

Ion Measurements

- For a more quantitative and accurate study, a technique was developed to inject noise of controllable amplitude in a narrow band around the synchrotron sidebands of a set revolution harmonic ($k = 1$ for these measurements)



Levels of injected noise around $f_{rev} + f_s$. Horizontal axis shifted by $f_{rf} + f_{rev}$



Beam 1 bunch length growth

LHC RF Noise Threshold

- With these measurements and the relationship between bunch length growth rate and noise power spectral density it is possible to estimate the noise threshold for acceptable performance
  - Acceptable performance set to $\frac{d\sigma}{dt} = 2.5$ ps/hr (comparable to Intrabeam Scattering levels)
- The single-sideband noise power level *per cavity* is approximately -102 dBc/Hz for LHC (assuming *uncorrelated* noise sources)
- The goal is to estimate whether the RF noise can become excessive with the addition of the necessary loops for future high current operation
- If the noise threshold is crossed, these tools and measurements can be used to identify the sources of noise that are most damaging with the intent to selectively improve the responsible equipment

Future Direction (from: P. Baudrenghien, Deputy BE-RF, CERN)

Topics

- The following three topics are priority. The collaboration will imply travels to CERN
  - LLRF alignment tools
    - 1-Turn feedback
    - Alignment Optimization with circulating beams
  - Beam diffusion caused by RF noise
  - Stability margin for the cavity impedance at the fundamental
- Also: Participation to data analysis from SLAC is also foreseen for
  - Longitudinal damper commissioning
  - Optimization of the longitudinal parameters

FY2012 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. Extend RF station identification process to operation with beam in the machine.

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.

FY2012 Plans

- LLRF Tools, Models, Diffusion Studies and High-Current estimation ,
  - As the LHC increases beam current, we need to also increase the SLAC LLRF effort. In 2011, SLAC participation was reduced relative to 2009/2010.
  - We need to pace LHC RF system commissioning, validate 1-turn delay feedback model for setup tools at high beam currents.
  - Study and extend RF station identification tool for operation of the system with beam in the machine.
  - Continuation of noise studies, estimate longitudinal emittance growth, system limits
  - Requested staffing 0.5 FTE, plus 0.5 FTE new student (0.5 FTE student - SLAC match)
  - Travel budget $15K

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- T. Mastorides et. al., *LHC Beam Diffusion Dependence on RF Noise: Models and Measurements*, Submitted to Physical Review ST-AB.
- T. Mastorides et. al., *Studies of RF Noise Induced Bunch Lengthening at the LHC*, PAC 2011, New York, USA.
- T. Mastorides et. al., *RF system models for the LHC with Application to Longitudinal Dynamics*, Physical Review ST-AB, Oct 2010.
- T. Mastorides et. al., *LHC Beam Diffusion Dependence on RF Noise: Models and Measurements*, Proceedings IPAC 2010, 23-28 May 2010, Kyoto, Japan.
- D. Van Winkle et. al., *Commissioning of the LHC Low Level RF System Remote Configuration Tools*, Proceedings IPAC 2010, 23-28 May 2010, Kyoto, Japan.

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