RF System Models and Longitudinal Beam Dynamics

T. Mastoridis[1], P. Baudrenghien[1], J. Molendijk[1],
C. Rivetta[2], J.D. Fox[2]

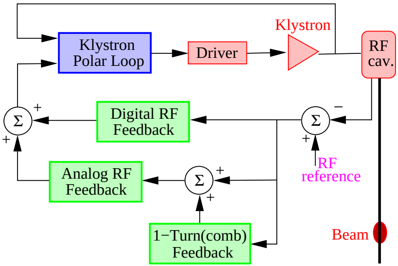
[1]BE-RF Group, CERN

[2]AARD-Feedback and Dynamics Group, SLAC

RF System models: Motivation

- The RF station-beam interaction defines many important beam dynamics.
  - As a result, determining the optimal settings for the RF/LLRF system to achieve both station and beam stability can be rather complex
- The theoretical study of the beam-RF interaction is difficult due to the complexity of the multiple feedback loops, the non-linear nature of the system, and the complicated multi-dimensional parameters space.
- A solely experimental approach would not only require a lot of machine time and suggest risks for system components, but also would not allow for an arbitrary variation of system parameters.
- Models and simulations [1] can help estimate the effect of RF configurations on beam dynamics, predict the beam behavior, determine optimal settings, and study alternative hardware designs.
  - The ability to adapt to completely different machines (hadron, lepton) and beam dynamics of interest is also an important aspect.

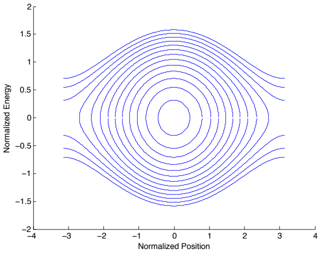
RF Station/Beam Dynamics Interaction Model



- RF system models were initially developed at PEP-II (J. Fox, T. Mastoridis, D. Teytelman, C. Rivetta [2], [3]) to help push the current to higher levels and better understand/utilize the trade-off between RF station and beam stability
  - Limit from coupled-bunch instabilities
- These models were updated for the LHC architecture and expanded for the beam dynamics of interest:
  - Multi-bunch: coupled-bunch instabilities driven by the cavity fundamental
  - Single-bunch diffusion due to RF noise, essential for a hadron collider with 10-20 hour long coasts
  - Single-bunch stability driven by broadband impedance

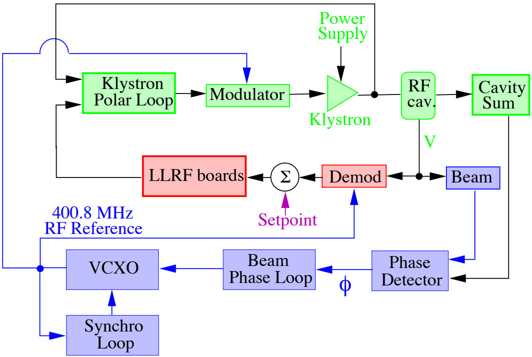
Longitudinal Emittance

- 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



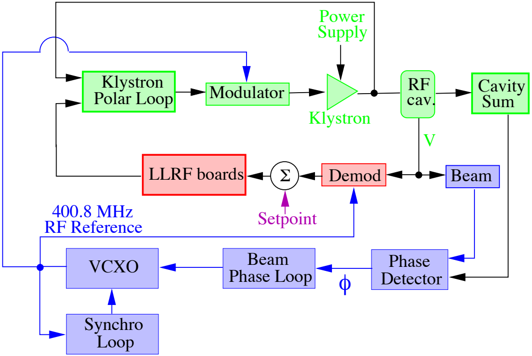
- The synchrotron radiation for protons in the LHC is practically zero (damping time of about a hundred hours at 3.5 TeV)
- As a result, the noise power spectrum of the RF accelerating voltage can strongly affect the longitudinal beam distribution
  - Increased bunch length decreases luminosity and eventually leads to beam loss due to the finite size of the RF bucket

LHC RF system



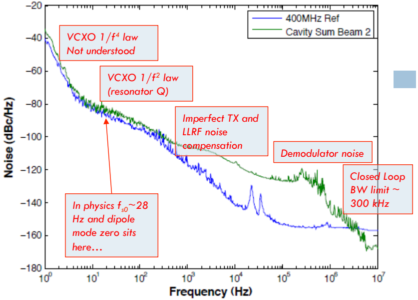
- The Beam Phase Loop (BPL) is a narrow bandwidth loop updated once a turn, that modulates the RF reference to achieve damping of mode zero beam motion around the synchrotron frequency f_s

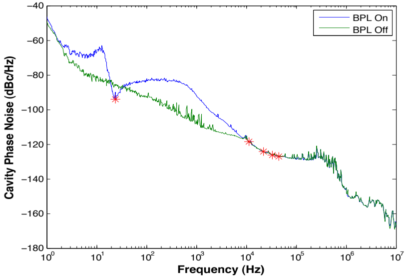
LHC RF Noise Sources



- Two major noise sources for beam diffusion:
  - 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.

Performance limiting components at LHC

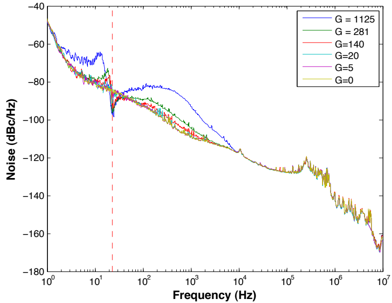




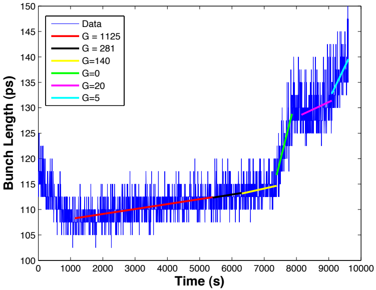
- Phase noise PSD of the RF sum (through an 8-way combiner) of the cavity voltage seen by the beam (no interfering electronics).
- The accelerating voltage phase noise is dominated by the 400 MHz reference up to 300 Hz, the Cavity Controller at higher frequencies
- The Beam Phase Loop (BPL) reduces the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

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.



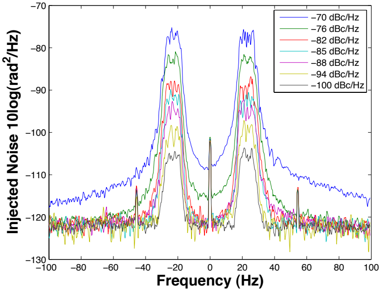
RF station 6B2 noise spectral density with BPL gain



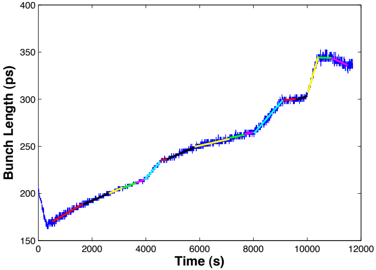
Beam 2 Bunch Length with time

Ion Measurements

- For a more quantitative and accurate study, a technique was developed (talk by J. Molendijk yesterday) 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 $f_{rf} + f_{rev}$

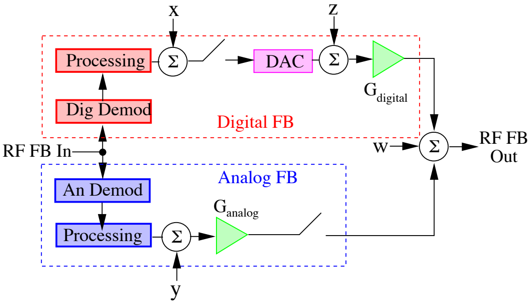


Beam 1 bunch length growth

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 a noise threshold of approximately -93 dBc/Hz for a single cavity (SSB) for acceptable performance
  - Acceptable performance set to $\frac{d\sigma}{dt} = 2.5$ ps/hr (Intrabeam Scattering levels between 1 and 3.5 ps/hr at 3.5 TeV)
- The cumulative single-sideband noise power level *per cavity* is approximately -102 dBc/Hz for LHC (assuming *uncorrelated* noise sources) – 9 dB margin [4]
- 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

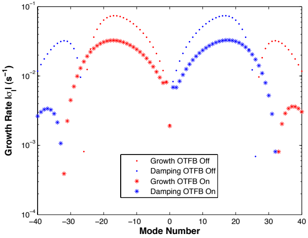
Design Analysis



- To better understand the contributions of the LLRF components, we terminated the input of the RF Feedback, switched the analog and/or digital path on and off, and adjusted the analog and digital gains
- As such, we identified the dominant LLRF noise contributions
  - Digital path: differential amplifier driving the ADC and digitizing noise of the ADC
  - Analog path: the large amplification stage after the analog demodulator
- Since the digital path is narrowband, in the end we have a single gain stage in the analog demodulator that dominates the RF noise contributions to beam diffusion!

Coupled-bunch instabilities

- Impedance reduction is of fundamental importance at the LHC since there is no dedicated bunch-by-bunch longitudinal feedback system.
- The substantial bunch length leads to stability through Landau damping.
- The effective cavity impedance though depends strongly on the LLRF configurations.
- The system models and simulations allow us to include non-linearities in the system and more accurately reflect the system configuration in the growth rate estimation.
    - In particular, the simulations employ the same parameter structure used at the station setting-up.



Growth Rate sensitivity to LLRF parameters

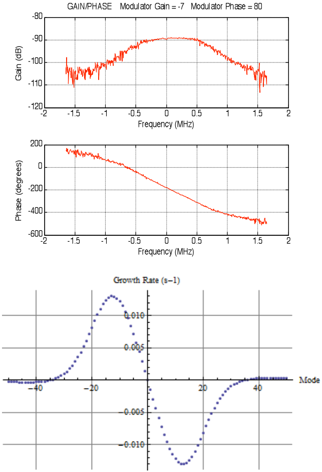
- One of the important features of the LHC time-domain simulation is the ability to study alternative configurations of the RF and LLRF system, without requiring time from the real machine.
- As such, it can be used to analyze the sensitivity of the modal growth rates to variations of the LLRF parameters.
- These studies provide insight on the limits of the implementation, on the operational margins, and on the parameters most essential to reliable operations.

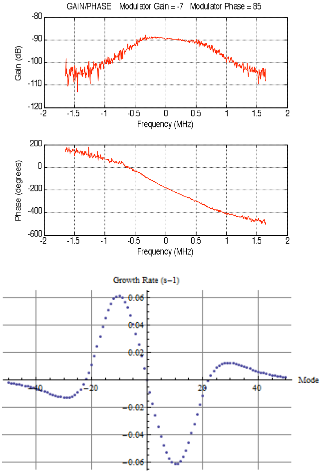
LLRF Parameter	Adjustment	Growth Rate	Change
Nominal Value	-	0.033	-
Cavity Detuning	± 1 kHz	0.038/0.028	$+15/-15\%$
FB Gain	± 3 dB	0.028/0.043	$-16/+31\%$
Loop phase	$\pm 10^\circ$	0.23/0.19	$+\mathbf{590}/+\mathbf{490}\%$
1-turn FB Gain	± 3 dB	0.026/0.039	$-20/+20\%$
1-turn FB phase	$\pm 10^\circ$	0.12/0.10	$+270/+220\%$

Table: Growth Rate Sensitivity on LLRF parameters.

Growth Rate sensitivity to LLRF parameters

Effect of 5 degree loop phase rotation (RF Modulator) on effective impedance and growth rates





1. RF System models
2. Longitudinal diffusion due to RF noise
3. Coupled-bunch instabilities
4. Conclusions

Conclusions

Conclusions/Future Directions

- The RF system models can help optimize the RF/LLRF configurations, estimate the effect of the LLRF implementations on critical beam dynamics, and provide insight on alternative hardware designs
- A noise threshold was set for the LHC for acceptable lifetime and a margin of operation was estimated for RF noise
  - The dominant components for beam diffusion were identified
  - With this formalism and RF simulation tools [1] we can design future RF systems and budget the allowed noise
- Estimates of coupled-bunch instabilities reveal significant margin of operation, but also great sensitivity to RF/LLRF configurations.

Acknowledgements

Acknowledgements

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- LHC operations for allowing these MDs
- SLAC collaborators

Thank you for your attention

References

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- [2] C. Rivetta *et. al.*, “Modeling and Simulation of Longitudinal Dynamics for Low Energy Ring-High Energy Ring at the Positron-Electron Project”, Phys. Rev. ST-AB, 10, 022801 (2007) and SLAC-PUB-12374, February 2007.
- [3] T. Mastorides *et. al.*, “Analysis of Longitudinal Beam Dynamics Behavior and RF System Operative Limits at High Beam Currents in Storage Rings”, Phys. Rev. ST-AB, 11, 062802 (2008) and SLAC-PUB-13287.
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