RF Noise Induced Beam Diffusion in the LHC

and Cavity Controller commissioning tools

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1. Cavity Controller commissioning tools

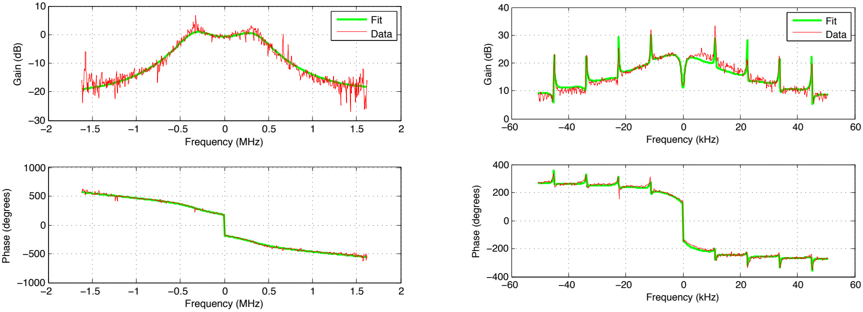
2. RF noise effects on LHC longitudinal beam emittance

Cavity Controller commissioning tools - Achievements

- Coupled-bunch instabilities are defined by the impedance and associated circuitry of RF stations.
  - Cavity Controller (LLRF) feedback loops are employed to reduce the accelerating fundamental impedance to achieve stable operation.
  - Cavity Controller settings are critical for the stability of both the beam and the RF station.
- With LARP support and in collaboration with the CERN BE-RF group, SLAC personnel have successfully developed a suite of tools to remotely commission and optimally configure the LHC RF stations.
  - Remote operation was crucial under the new stricter CERN policies which prevented tunnel access when the magnets are energized.
- The tools were essential for the Winter 2010 commissioning (also used in Nov '09 startup).
  - Tools reduced commissioning from 1.5 days/station to 1.5 hours/station, increased consistency and reliability.

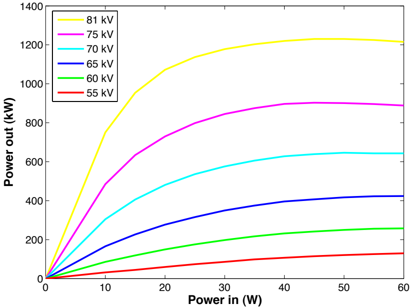
Cavity Controller commissioning tools - Future Steps

- Coupled-bunch instabilities are not an issue currently, but they do scale with beam current.
  - 1-turn feedback will be commissioned in the beginning of the 2011 LHC run.
- Work is in progress to test the 1-turn feedback functionalities of the commissioning tools.



Cavity Controller commissioning tools - Future Steps

- The BE-RF group has proposed an expansion of the tools to control the smooth increase of the High Voltage and Klystron current with beam, from 450 GeV conditions to ramping/physics.
  - This is a necessary step for high intensity
- Once again, our PEP-II experience will be useful for the development of this functionality.
  - This is a natural extension of the tools, we are eager to collaborate. The LARP/SLAC LLRF funding for 2011 is reduced. Reevaluate?



1 Cavity Controller commissioning tools

2 RF noise effects on LHC longitudinal beam emittance

RF noise effects on LHC longitudinal beam emittance

- The noise power spectrum of the RF accelerating voltage can strongly affect the longitudinal beam distribution and contribute to beam motion and diffusion.
- During the design phase, the use of klystrons in a hadron collider were questioned and reviewers doubted the feasibility of the configuration due to the klystron noise levels. Of particular concern was the synchrotron frequency f_s crossing of the ripple line at 50 Hz [J. Tuckmantel, 1] during the ramp.
- The choices of technical and operational configurations can have a significant effect on the noise sampled by the beam. The motivation at this commissioning/low current phase is to identify the sources of noise that are most damaging with the intent to selectively improve the responsible equipment.

How did we get involved

- Having developed the Matlab tools for setting-up the Cavity Controller loops we had a a good understanding of the various hardware components, had developed time-domain simulations that included the characteristics of the Cavity Controller, and time for these studies (not busy commissioning a machine).
    - These simulations are complementary to the original simulations done at CERN [J. Tuckmantel, 2]. The earlier simulations are more comprehensive in the description of the beam dynamics, whereas our goal was to include a more realistic model of the RF and Cavity Controller with their limitations and imperfections.

LHC Studies at SLAC

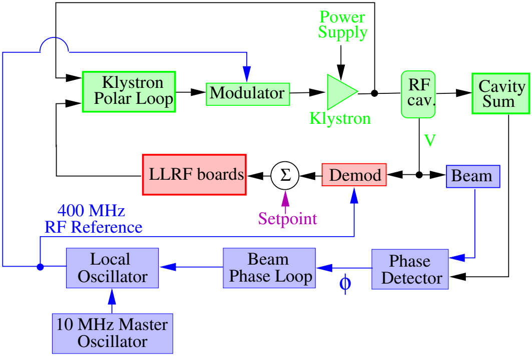
- To address the need to fully understand the RF-beam interaction we developed a theoretical formalism relating the bunch length growth with beam dynamics, accelerating voltage noise, and RF system configurations [T. Mastorides, 4].
- We could then estimate the bunch length growth for various operational configurations by:
  - Evaluating the RF noise sources based on the layout and components of the RF system
  - Modeling these noise sources through our time-domain simulation of the LHC RF to estimate the noise in the accelerating cavity and subsequently the bunch length growth.
  - Study the variation of the bunch length growth with RF and Cavity Controller configurations.
- We also estimated the noise thresholds in the Cavity Controller system for specific bunch lengths and RF station configurations.

Initial Measurements

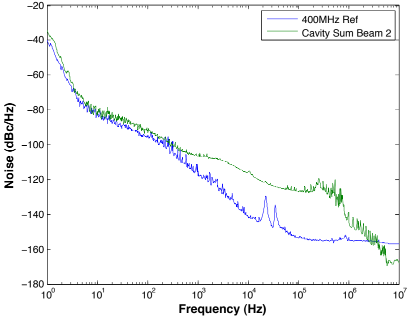
- Measurements were then conducted at the LHC to support the above theoretical formalism and simulation studies.
  - May $7^{th} - 13^{th}$
  - Single bunch 9e9 per ring
  - 3.5 TeV, 8 MV
  - No squeeze, no collision
  - Initial bunch length of 450 ps for both rings (BQM measurement).
- The goals were to:
  - Identify the dominating RF component for beam diffusion
  - Correlate RF noise and longitudinal beam emittance
  - Study the Cavity Controller noise contributions.

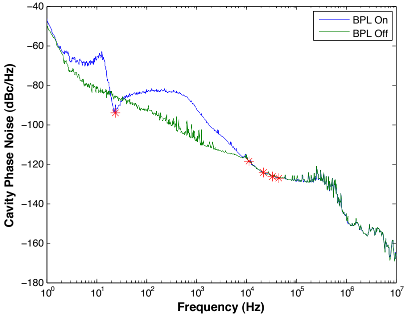
Performance limiting components at LHC

- 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 ≈ 400 kHz, extending over 35 f_{rev} bands.



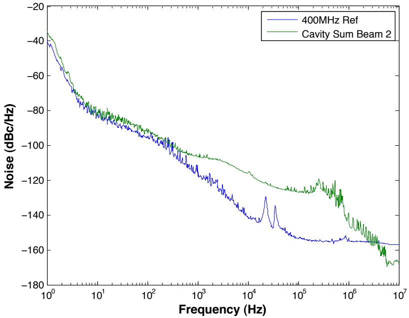
Performance limiting components at LHC

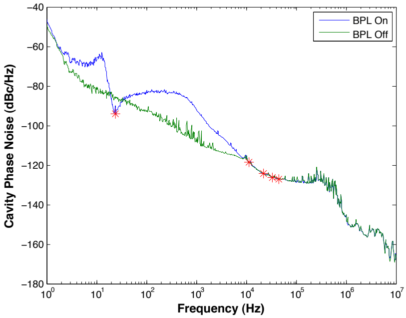




- Phase noise PSD of the RF sum (through an 8-way combiner) of the cavity voltage seen by the beam. The beam time of flight delay has been inserted.
- There are no interfering electronics, so we can trust that this is the signal experienced by the beam.
  - We are only limited by the resolution of the instrument, which is essential when we try to determine the beam phase loop notch.

Performance limiting components at LHC

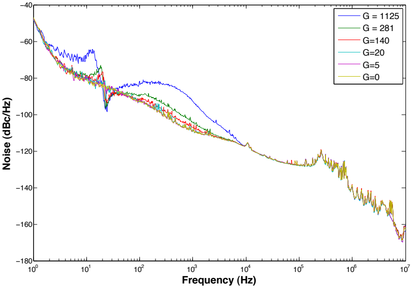


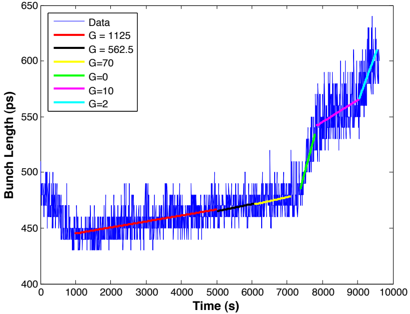


- The accelerating voltage phase noise is dominated by the 400 MHz reference up to 300 Hz, the Cavity Controller at higher frequencies.
- The Beam Phase Loop (BPL) reduces the noise around the synchrotron frequency. It is a narrow bandwidth loop that modulates the RF reference to achieve damping of mode zero beam motion around the synchrotron frequency.
- Most of the noise power contribution is around the synchrotron frequency.

Longitudinal beam emittance dependence on RF noise

- This result allowed us though to conduct some quantitative experiments.
- By varying the BPL inverse time constant τ^{-1}, we could change the noise level around the synchrotron frequency and look at the result on the longitudinal beam emittance.





Beam Growth Dependence on BPL and Noise Power

BPL τ^{-1}	Estimated σ_∞ (cm)	$d\sigma_z/dt$ (ps/hr)	**rms RF Station Noise (mrad)**
1125	4.6	14	3.1
281	5.1	15	2.2
140	7.2	20	2.1
20	8.1	42	2
5	13	189	2.1
0	18.2	364	2.2

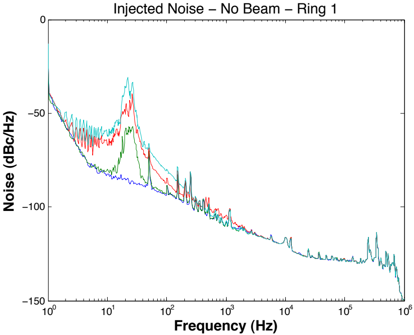
- Clear correlation between the scaled bunch length **as estimated by our theoretical formalism** and the longitudinal emittance growth.
- For a BPL τ^{-1} of more than approximately 30, there is no significant reduction in beam diffusion:
  - This is close to the synchrotron period (1/24)
  - The BPL gets saturated?
- The rms RF station voltage phase noise is NOT a useful metric.

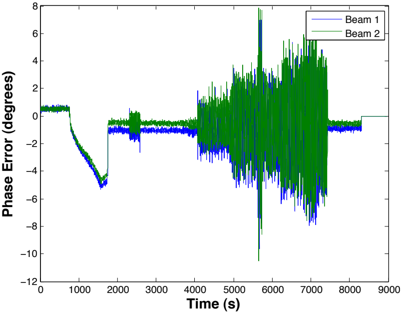
Early Conclusions

- RF noise does not seem to be a big problem...for now
- However, two new systems will be introduced for the higher intensity runs next year: The longitudinal damper (active only at injection) and the 1-Turn feedback (active all the time). These will add RF noise. We wanted to assess the current margin of operation and compare with the estimated noise increase.
- Also, we wanted to track the bunch distribution during noise injection rather than just the bunch length.
- An MD was conducted two weeks ago which answered some questions, opened new ones.
  - October 18^{th}
  - Single bunch 3.5e10 per ring
  - 3.5 TeV, 8 MV
  - No squeeze, no collision
  - Initial bunch length of 450 ps for both rings (BQM Measurement).

Noise Injection

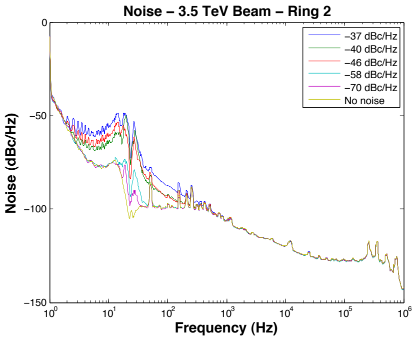
- We injected noise of narrow bandwidth around the synchrotron frequency.
- We could see this noise in the cavity (without beam), and later in the phase error between the beam and the cavity sum.

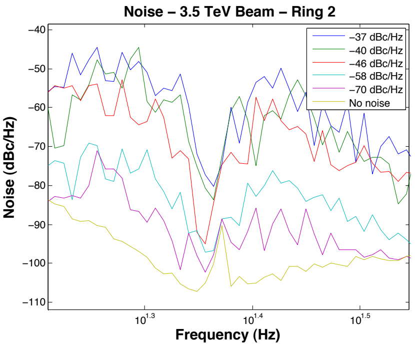




Noise Injection with beam

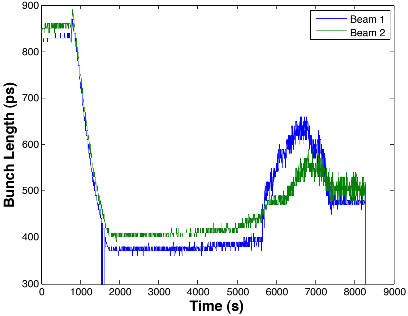
- The BPL though strongly reduced the noise right at f_s.
- Even though we were driving very strongly around the f_s, the notch did not seem to change significantly – hard to judge due to the instrument resolution.

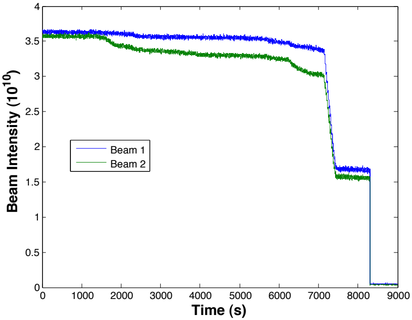




Bunch length growth

- We saw various levels of bunch length growth, at times seemingly uncorrelated with the noise power injected.





Longitudinal Profile over 80 minutes

- Due to the filtering of the excitation by the BPL it seems that in this MD we excited the tails much more than the core of the bunch.
- At some point we drive the core, populate the tails, which are then quickly lost (rapid decrease in beam intensity).

Future steps

- It seems that we need to review our noise injection scheme. Currently the BPL is canceling the noise excitation right at f_s. One option is to inject outside the bandwidth of the BPL for cleaner measurements $(n * f_{rev} + f_s)$.
- The middle-term goal is to estimate whether the RF noise can become excessive with the addition of the necessary loops for high current operation, and if so, use the model/formalism to identify which RF equipment to upgrade.
- A methodology is being developed to inject noise at specific frequencies and with varying amplitudes in a second round of measurements. This way, it will be possible to better quantify the relationship between the RF noise and longitudinal emittance blowup.
- We would like to develop a formalism to estimate more accurately the time evolution of the bunch length growth with the simulation and models.

Acknowledgements

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- LHC operations for allowing these MDs.

Thank you for your attention

- J. Tuckmantel, *Synchrotron Radiation Damping in LHC and Longitudinal Bunch Shape, LHC Project Report 819, June 2005.*
- *J. Tuckmantel, Simulation of LHC Bunches under Influence of 50 Hz multiple Lines on the Cavity Field, LHC Project Note-404, June 2007.*
- *T. Mastorides, J.D. Fox, C.H. Rivetta, D. Van Winkle, P. Baudrenghien RF system models for the LHC with Application to Longitudinal Dynamics, Phys. Rev. ST-AB, 13, 102801 (2010).*
- *T. Mastorides, J.D. Fox, C.H. Rivetta, D. Van Winkle, LHC Beam Diffusion Dependence on RF Noise: Models and Measurements, in preparation for submission to Physical Review ST-AB.*