RF Noise Induced Beam Diffusion in the LHC

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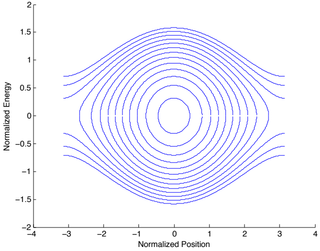
Longitudinal Emittance

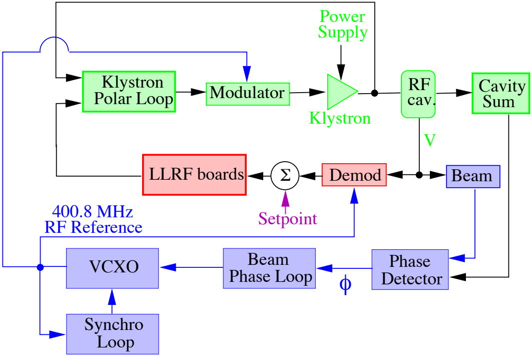
- The longitudinal emittance is a measure of the area in phase space occupied by the beam
  - Intrabeam scattering and RF noise lead to emittance increase
  - Energy lost to synchrotron radiation reduce the emittance



- 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
  - Increased bunch length decreases luminosity and eventually leads to beam loss due to the finite size of the RF bucket

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

Motivation

- 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 be able 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
  - For example, we can use measurements and system models to predict noise spectral density in the cavity. We can estimate the growth in longitudinal emittance

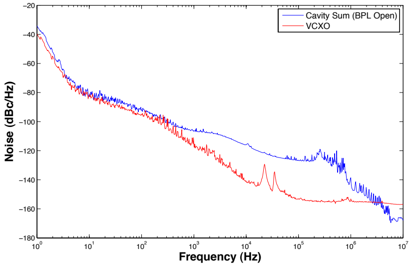
Beam dependence on RF Noise

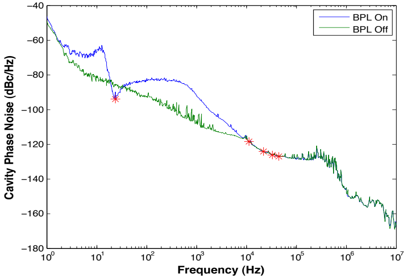
- The beam is a very high Q resonator at the synchrotron frequency f_s
- The bunch length growth rate is approximately given by [1], [2]

$$\frac{d\sigma_\phi^2}{dt} = 2\pi f_s^2 S_\phi(f_s)$$

  where $S_\phi(f)$ is the phase noise spectral density experienced by the beam (in rad^2/Hz).
- 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) [3]

Performance limiting components at LHC

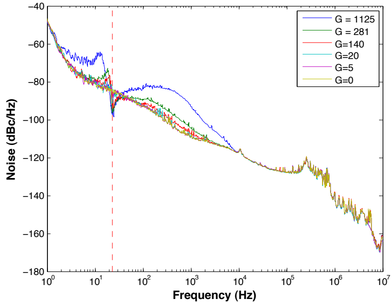




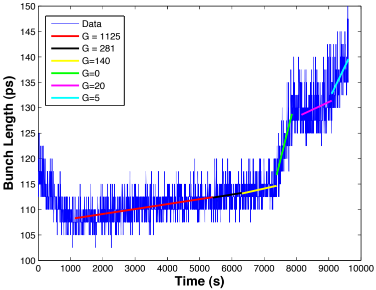
- Phase noise PSD of the RF sum (through an 8-way combiner) of the cavity voltage seen by the beam (no interfering electronics).
- The accelerating voltage phase noise is dominated by the 400 MHz reference up to 300 Hz, the Cavity Controller at higher frequencies
- The Beam Phase Loop (BPL) reduces the 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

Measurement/Estimate comparison (protons)

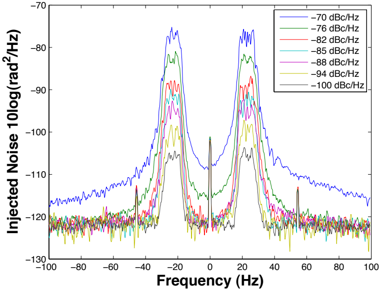
BPL gain	Estimated $d\sigma_\tau^2/dt$ (ps^2/hr)	Measured $d\sigma_\tau^2/dt$ (ps^2/hr)	Measured $d\sigma_\tau/dt$ (ps/hr)	Integrated RF Noise (mrad)
0	19000	22500	91	2.2
5	12800	12900	47	2.1
20	5500	2800	8	2
140	2900	1200	5	2.1
281	1250	800	4	2.2
1125	1000	800	3	3.1

Table: Bunch Growth Rate Dependence on BPL gain and Noise Power for B2 (protons)

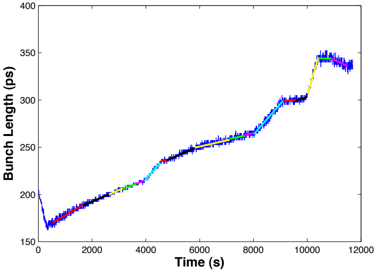
- Clear correlation between the estimated and measured bunch length growth
- For a BPL gain of more than approximately 30, there is no significant reduction in beam diffusion:
  - Intrabeam Scattering effects become comparable
  - LLRF contributions are at similar levels
  - The BPL gets saturated
- The rms RF station voltage phase noise is NOT a useful metric.

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

Measurement/Estimate comparison (ions)

PSD (dBc/Hz)	B1 $d\sigma_\tau/dt$ (ps/hr)	B2 $d\sigma_\tau/dt$ (ps/hr)	Estimated (ps/hr)
-70	352	580	380-450
-76	119	140	125
-82	45	49	35
-85	21	26	20

Table: Bunch length growth as a function of the Power Spectral Density (PSD) of the injected noise – referred to a single sideband (SSB).

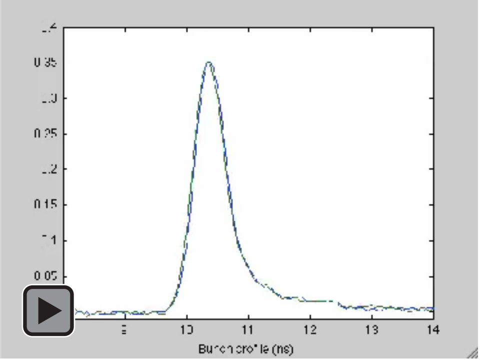
- Clear correlation between the estimated and measured bunch length growth

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) [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

Longitudinal Profile

- Longitudinal profile over 80 minutes



- The effects on noise on beam loss and the bunch distribution are evident

Conclusions

Conclusions/Future Directions

- We can estimate the effect of different operational and technical RF configurations on the LHC beam diffusion
- A noise threshold was set for the LHC for acceptable lifetime
- With this formalism and RF simulation tools [5] we can design future RF systems and budget the allowed noise
- The work and analysis presented uses the bunch length as the primary metric. As the bunch distribution deviates from a gaussian, this description becomes less accurate.
  - Work is in progress to relate the measured cavity noise spectrum with a diffusion coefficient and subsequently with the evolution of the beam distribution.

Acknowledgements

- The CERN BE-RF group
- LHC operations for allowing these MDs

References

[1] D. Boussard, CERN 84-15, 1984, p. 283.

[2] J. Steimel *et. al.*, “Effects of RF Noise on Longitudinal Emittance Growth in the Tevatron”, Proc. PAC 2003, May 12-16 2003, Portland, OR.

[3] T. Mastorides *et. al.*, “RF system models for the LHC with Application to Longitudinal Dynamics", Phys. Rev. ST-AB, 13, 102801 (2010).

[4] T. Mastorides *et. al.*, “RF Noise Effects on Large Hadron Collider Beam Diffusion", in preparation for submission to Physical Review ST-AB.

[5] T. Mastorides *et. al.*, “Modeling and Simulation of the Longitudinal Beam Dynamics - RF Station Interaction in the LHC Rings", Proc. EPAC 2008, 23-27 June 2008, Genoa, Italy.