LARP Contributions to the LHC RF system

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History of the LARP involvement

- 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 (project started in 2008)
  - The tools have been used for commissioning in Nov '09, Feb '10, Feb '11
  - Both groups (SLAC, CERN) are interested in expanding the capabilities and functions
- In 2009 we started studying the effects of RF noise on beam diffusion. Measurements were conducted in 2010
- I continued working on these topics after the start of the Toohig fellowship (October 2010), but also got more involved with other RF issues

Summary of contributions

- Cavity Controller (LLRF) commissioning tools
- Longitudinal coupled-bunch instabilities
  - Estimates for high current operations
  - May 2011 MD Data Analysis
- Diagnostic tools for cavity monitoring
  - Cavity 4B1 noise issues
- Beam Diffusion Studies

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4 Diagnostic tools for cavity monitoring

5 RF Noise Induced Beam Diffusion

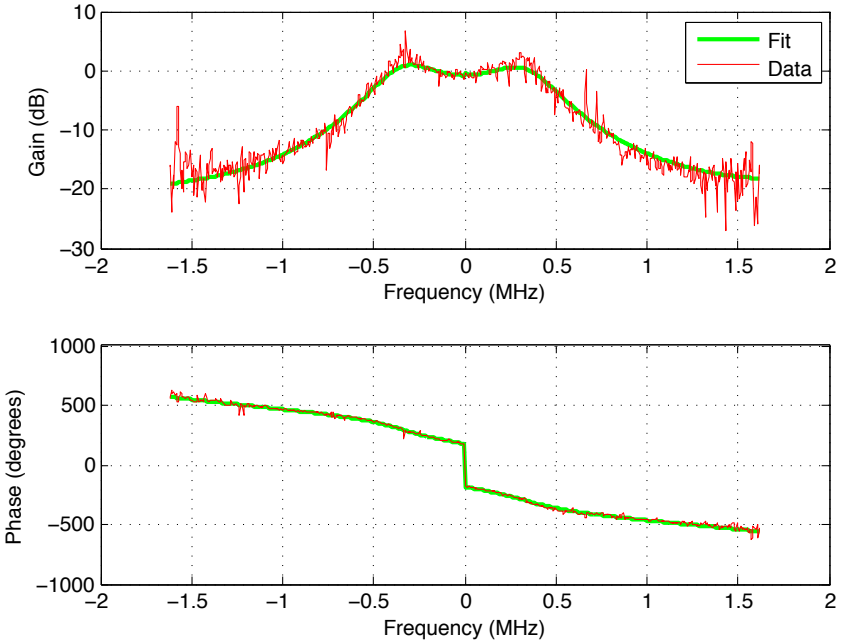
6 Future Directions

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 have been used in commissioning since November 2009
  - Tools reduced commissioning from 1.5 days/station to 1.5 hours/station, increased consistency and reliability.

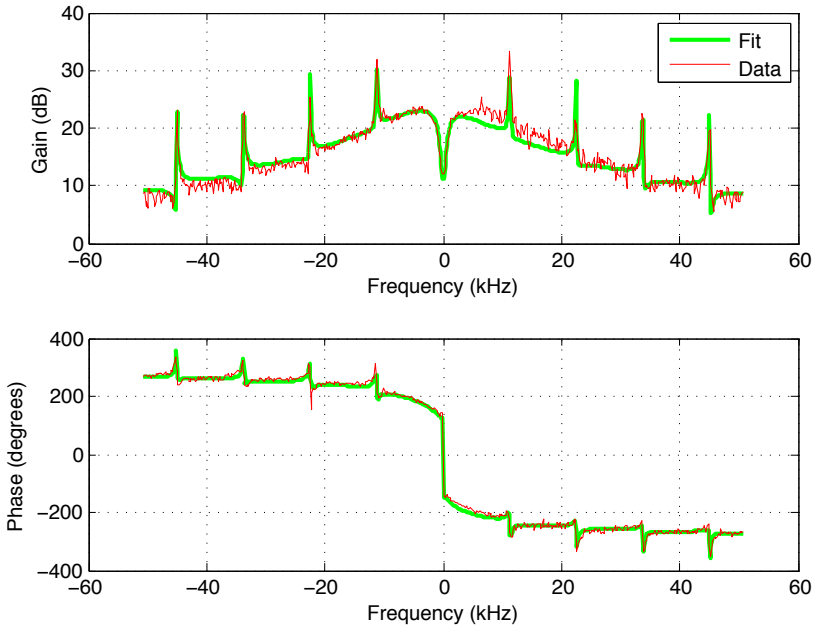
Cavity Controller commissioning tools - Future Steps

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



Cavity Controller commissioning tools - Challenges

- 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
- Updates of the one-turn feedback firmware are necessary (complications)



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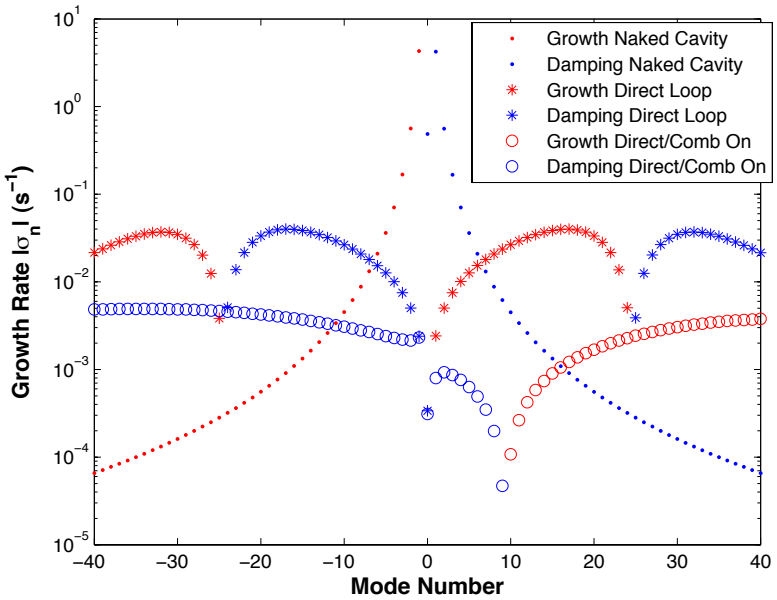
Estimates for high current operations

- 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.



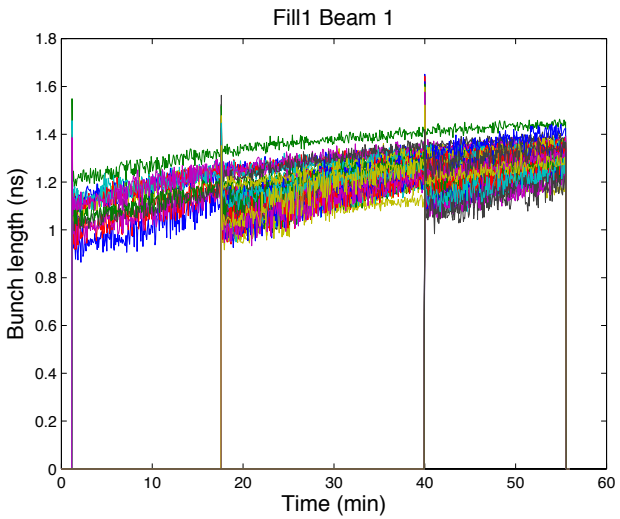
Estimates for high current operations

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
- 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

May 2011 MD Data Analysis

- In early May, MDs were conducted to study single and multi bunch longitudinal instabilities. The two major goals are to:
  - Determine Landau damping limits
  - Study a not yet explained injection transient:
  - Longitudinal instabilities are observed right after injection
  - The damping time (15-30 minutes) is way too long to be the result of capture mismatch
  - Instabilities are independent of total current (not driven by narrowband impedance)



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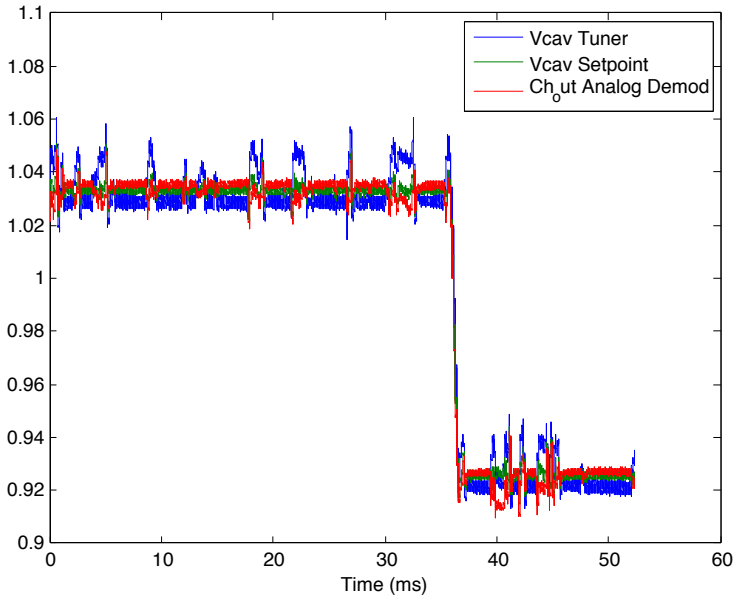
Diagnostic tools for cavity monitoring

- During 2010, cavity 4B1 was permanently parked due to spurious noise
- A tool was developed to monitor the cavity during the 2011 run
- With the tool and the efforts of the BE-RF group, the source of the problem was narrowed down to the connections from the cavity antennas to the setpoint module or the serial link between the setpoint and RF feedback modules
  - Cables were replaced and the cavity has been used with no problems in normal operations since February



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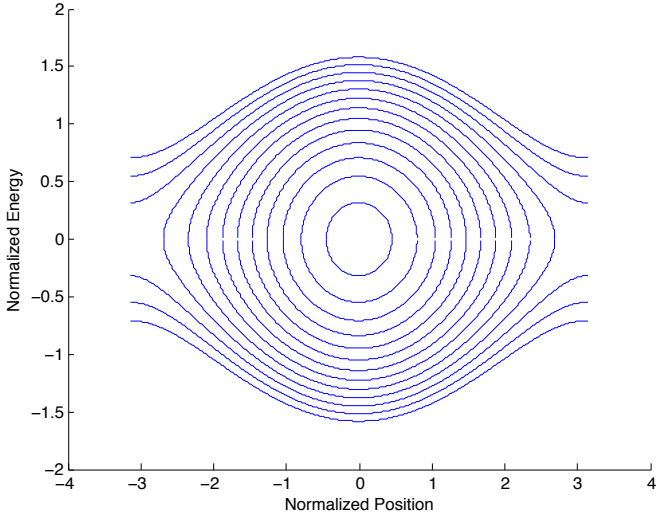
Longitudinal Emittance

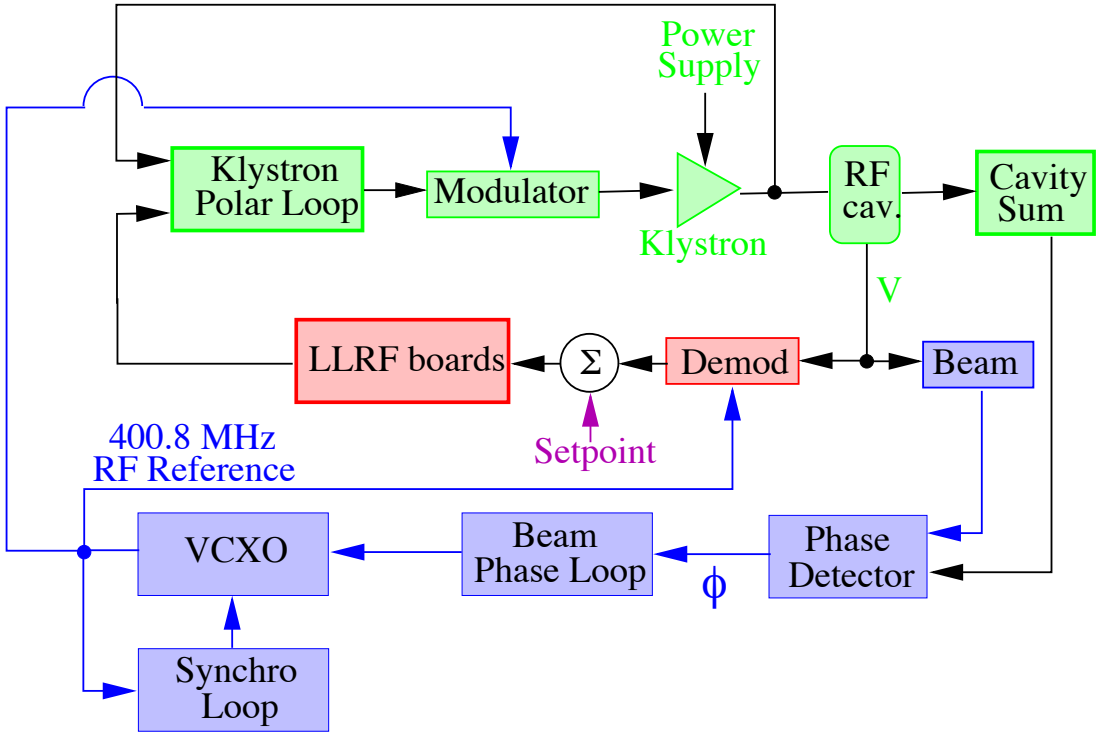
- The longitudinal emittance is a measure of the area in phase space occupied by the beam
  - Intrabeam scattering and RF noise lead to emittance increase
  - Energy lost to synchrotron radiation reduce the emittance



- 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

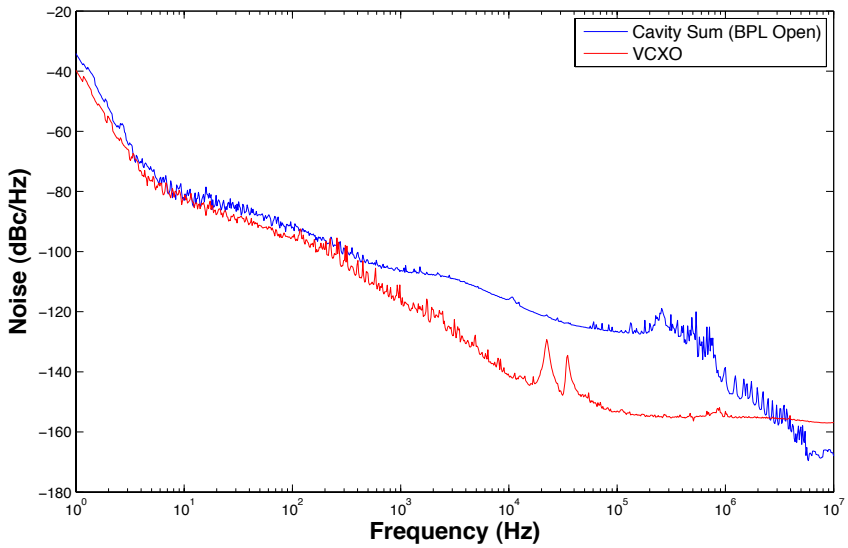
Beam dependence on RF Noise

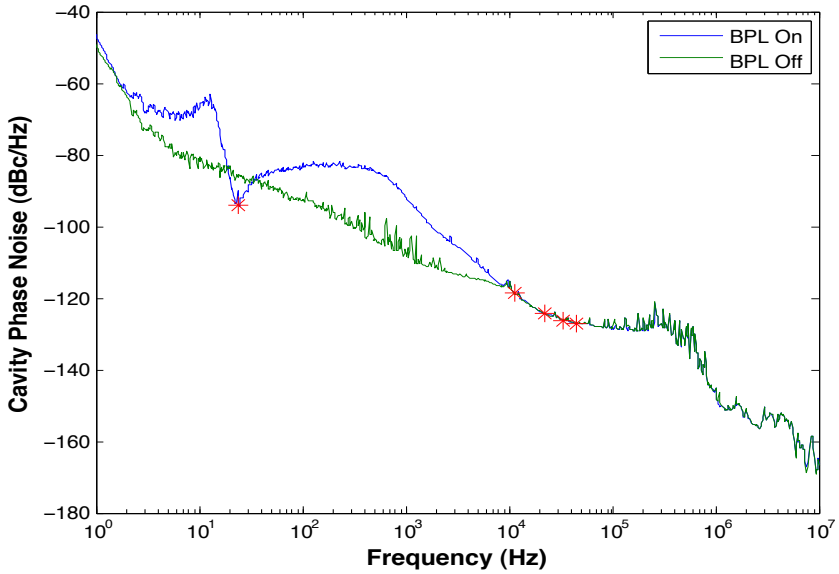
- The beam is a very high Q resonator at the synchrotron frequency f_s
- The bunch length growth rate is approximately given by [1], [2]

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

  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

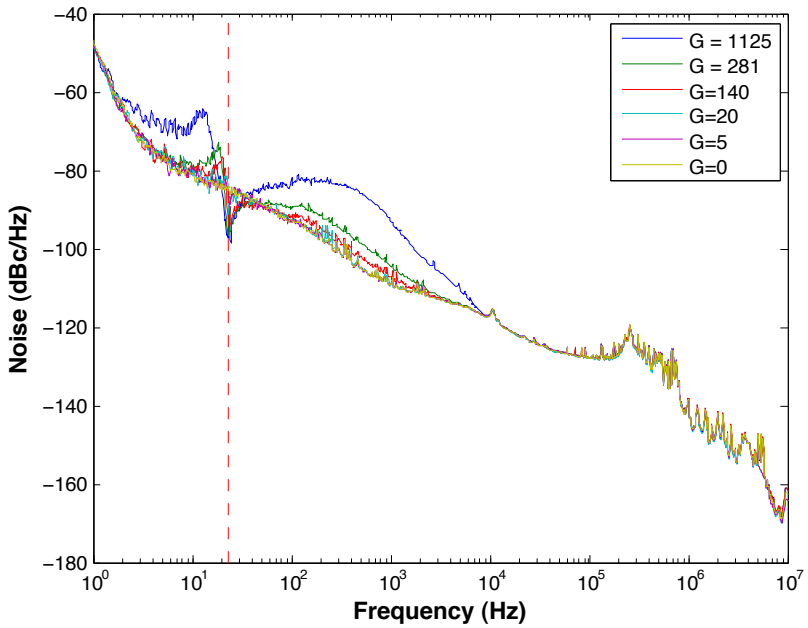




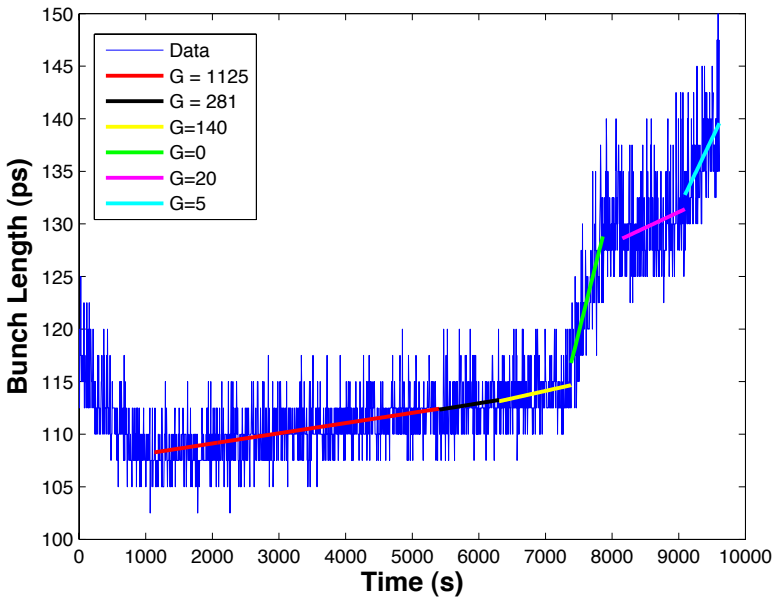
- Phase noise PSD of the RF sum (through an 8-way combiner) of the cavity voltage seen by the beam (no interfering electronics).
- The accelerating voltage phase noise is dominated by the 400 MHz reference up to 300 Hz, the Cavity Controller at higher frequencies
- The Beam Phase Loop (BPL) reduces the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

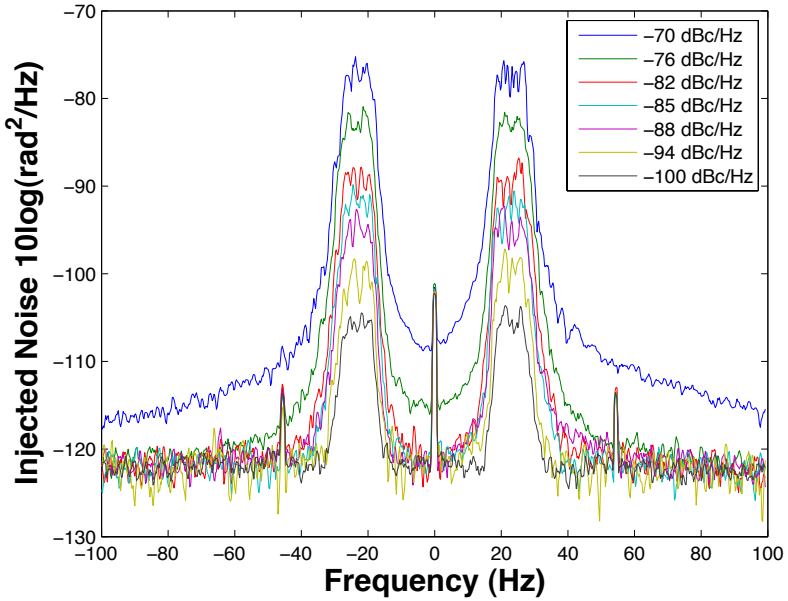
BPL gain	Estimated $d\sigma_\tau^2/dt$ (ps^2/hr)	Measured $d\sigma_\tau^2/dt$ (ps^2/hr)	Measured $d\sigma_\tau/dt$ (ps/hr)	Integrated RF Noise (mrad)
0	19000	22500	91	2.2
5	12800	12900	47	2.1
20	5500	2800	8	2
140	2900	1200	5	2.1
281	1250	800	4	2.2
1125	1000	800	3	3.1

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

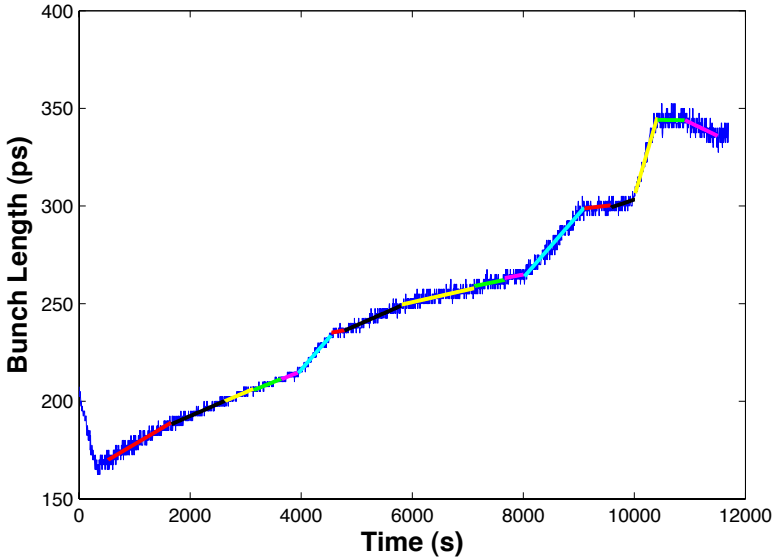
- Clear correlation between the estimated and measured bunch length growth
- For a BPL gain of more than approximately 30, there is no significant reduction in beam diffusion:
  - Intrabeam Scattering effects become comparable
  - LLRF contributions are at similar levels
  - The BPL gets saturated
- 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	B1 $d\sigma_\tau/dt$	B2 $d\sigma_\tau/dt$	Estimated
(dBc/Hz)	(ps/hr)	(ps/hr)	(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 of noise on beam loss and the bunch distribution are evident

Future Direction (by P. Baudrenghien)

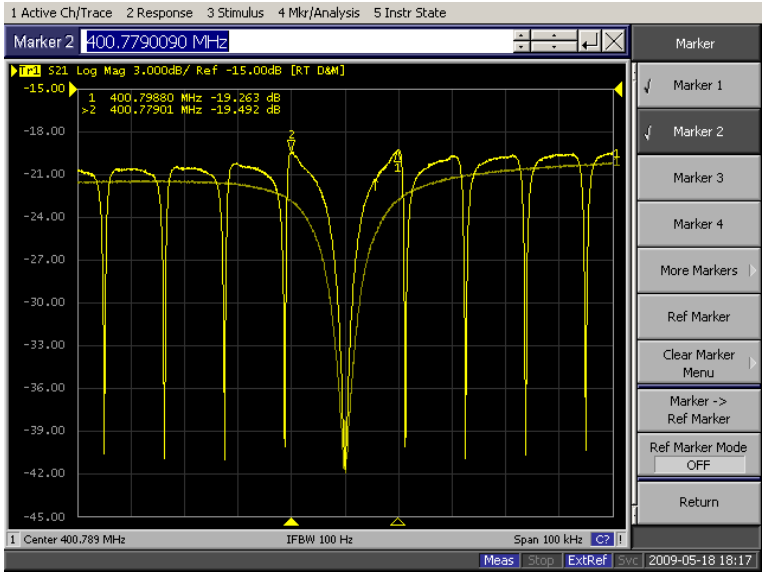
Topics

- 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

Future Direction (by P. Baudrenghien)

LLRF alignment tools (1/2)

- 1-Turn feedback
  - Hdw installed on all cavities (VME modules in UX45)
  - Setting-up must be done remotely and during a short technical stop
  - Tools must first be commissioned on a test-cavity in SM18
  - Availability of test-stand postponed to June 2011
  - Trips to CERN planned in Summer and Fall 2011
  - Commissioning on the machine in Fall 2011 or begin 2012

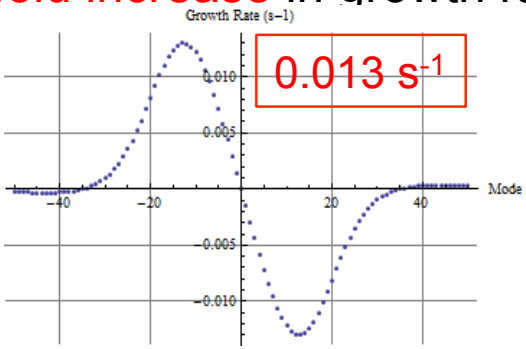


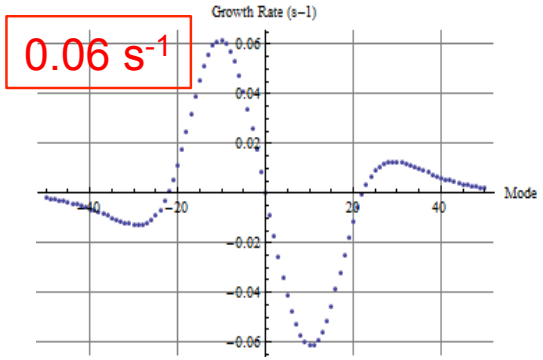
Effective cavity impedance without 1-T fdbk and with 1-T fdbk, measured on the SM18 test-stand. Centre 100 k Hz span. The 1-T feedback acts in a +-0.5 MHz band around the RF frequency.

Future Direction (by P. Baudrenghien)

LLRF alignment tools (2/2)

- Alignment optimization with circulating beams
  - Done at PEP II
  - Can be done at the LHC if we place notches in the excitation noise spectrum on the synchrotron side-bands
  - Motivation is the high sensitivity of Coupled-Bunch instability growth rates with RF feedback phase offsets. A 5 degrees error results in a five-fold increase in growth rate



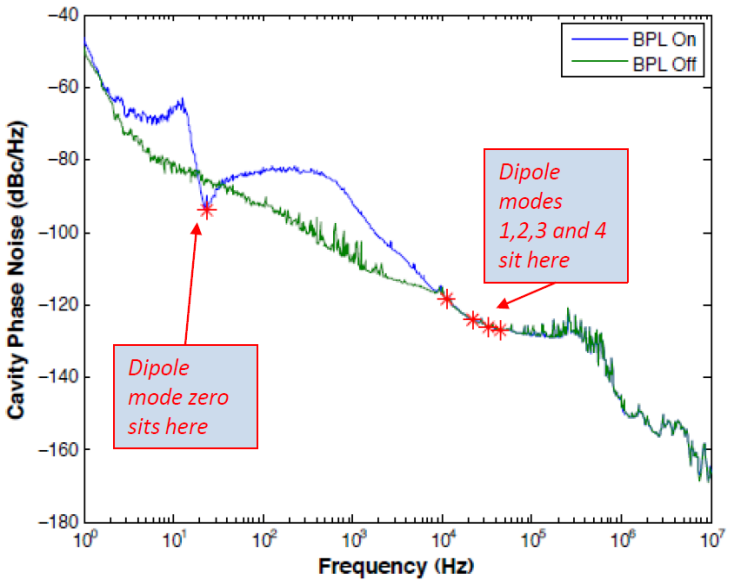


Longitudinal Coupled-Bunch instability growth rates (dipole) caused by the impedance at the fundamental of one cavity at 3.5 TeV. Left: RF fdbk phase optimized, 0.013 s^{-1} max. Rigth: 5 degrees error, 0.06 s^{-1} max. Notice different scales. *Chamonix 2011, "The LHC RF: Is it working well enough?", P. Baudrenghien et al.*

Future Direction (by P. Baudrenghien)

Beam diffusion caused by RF noise

- Very important issue in an Hadron Collider
- Work started begin 2010
- Intensive studies and 3 dedicated Machine development sessions in 2010 (2 with protons, one with ions)
- Reaching a good understanding of the major noise sources and effects on beam. Several publications
  - *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", Proc. IPAC 2010, 23-28 May 2010, Kyoto, Japan*
  - *T. Mastorides et al., "Studies of RF Noise Induced Bunch Lengthening at the LHC", PAC 2011*
- Studies of diffusion to be continued in 2011 and 2012
- Can also contribute to the optimization of longitudinal blow-up



SSB Phase noise *L(f)* (in dBc/Hz) of the Vector Sum of the eight cavities B2 with Beam Phase Loop OFF (green) and ON (blue). Circulating beam at 3.5 TeV. *Chamonix workshop 2011, "The LHC RF: Is it working well enough?", P. Baudrenghien et al.*

Future Direction (by P. Baudrenghien)

Stability margin for the impedance at the fundamental

- Using the very detailed LHC RF model developed at SLAC for the alignment of the Cavity Controllers we derive predictions on the collective effects stability margin
- The sensitivity of the LLRF settings on the stability has been computed
- Machine Development sessions are planned to confirm the predictions

Parameter Nominal Value	Adjustment	Growth rate 0.033	Change
f_d	± 1 kHz	0.038/0.028	$+15/-15\%$
G	± 3 dB	0.028/0.043	$-16/+31\%$
ϕ	$\pm 10°$	0.23/0.19	$+\mathbf{590}/+\mathbf{490}\%$
G_c	± 3 dB	0.026/0.039	$-20/+20\%$
ϕ_c	$\pm 10°$	0.12/0.10	$+270/+220\%$

Growth rate sensitivity on the LLRF parameters. *T. Mastorides et. al., "RF system models for the LHC with Application to Longitudinal Dynamics", Physical Review ST-AB, Oct 2010*

Configuration	Detuning (kHz)	Growth rate simple model σ (s^{-1})	Growth rate exact model σ (s^{-1})	Tune shift $\Delta\omega/2\pi$ (Hz)	Tune spread Δf_s (Hz)	$\Delta\Omega_s/4$ (s^{-1})
1 cav with fdbk	3	0.013	0.005	0.07	4.4	7
1 cav fdbk off	3	1	0.87	1	4.4	7
8 cav with fdbk	3	0.1	0.04	0.56	4.4	7
7 cav with fdbk + 1 cav fdbk off	3	**1.1**	**0.91**	**1.49**	**4.4**	**7**

3.5 TeV conditions with nominal beam and RF. Maximal growth rate and Landau damping for various configurations. *Chamonix workshop 2011, "The LHC RF: Is it working well enough?", P. Baudrenghien et al.*

Conclusions/Acknowledgements

- A very exciting year for LHC
- The Matlab tools were used during commissioning and they are being upgraded for high-current operation (one-turn feedback)
- Through the beam diffusion studies, a noise threshold was set for acceptable lifetime
- Contributions on future longitudinal stability limits, analysis of MD data, and software diagnostic tools
- There is interest from both sides (SLAC Feedback and Dynamics, CERN BE-RF groups) to continue this collaboration. Possibility for a new Toohig Fellow?
- This work is supported by the US-LARP program and DOE contract #DE-AC02-76SF00515

Conclusions/Acknowledgements

- Many thanks to LARP for the support in the later stages of my PhD and these 8 months of the fellowship
- As many of you know, I will be transitioning to the BE-RF group starting June 1st
- I am grateful for the Toohig Fellowship opportunity, which allowed me to develop skills, build strong research relationships, and get involved with exciting projects
- Many thanks to John, Claudio, Tom, and Eric for their support
- I would be very interested in being a CERN contact for new fellows, as well as for new and existing LARP projects

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.