Low Level Radio Frequency - Beam Dynamics Interaction in Circular Accelerators

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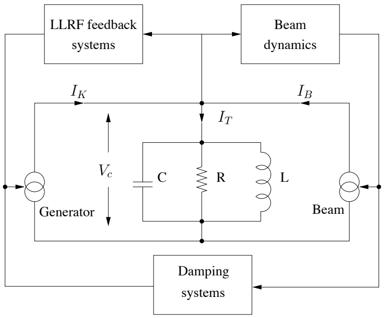
Why do we need LLRF systems?

- Beam dynamics and RF station have a strong interaction through the accelerating cavity. This interaction leads to coupled-bunch instabilities.
- Low Level RF (LLRF) feedback loops are added to reduce the cavity fundamental impedance experienced by the beam.

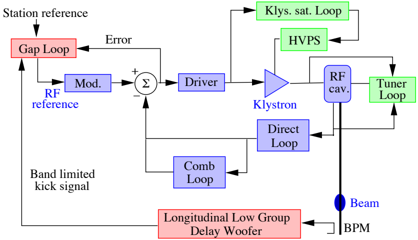


- Limitations in the LLRF feedback cap the impedance reduction. For sufficiently high beam current, the beam can still be unstable.
- Damping systems are then employed to control the instabilities.
- Cavity HOM driven instabilities are a separate subject and talk.

Why is this interaction so critical?

The system is unstable for sufficiently high beam current.

- Stability of **BOTH** the RF loop and the beam are necessary conditions
  - Beam Dynamics: Beam loss, degradation of beam characteristics such as the beam emittance, driven motion of beam.
  - RF Loop Dynamics: Loss of stability/regulation of MW RF stations, saturation of power systems.



Coupled-bunch instabilities

- The beam dynamics for an even fill pattern of N bunches is defined by the superposition of N modes. We study the system in the modal domain.
- With this representation the driving term for the modal oscillations can be shown to be proportional to the effective impedance of the accelerating structures:

$$Z^{\|\text{eff}}(\omega) = \frac{1}{\omega_{\text{rf}}} \sum_{p=-\infty}^{\infty} (pN\omega_o + \omega) Z^{\|}(pN\omega_o + \omega)$$

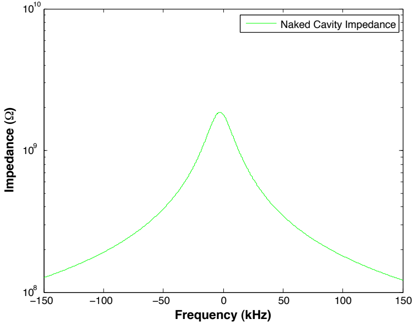
- For systems with low interaction (LLRF on), the eigenvalue for mode n is

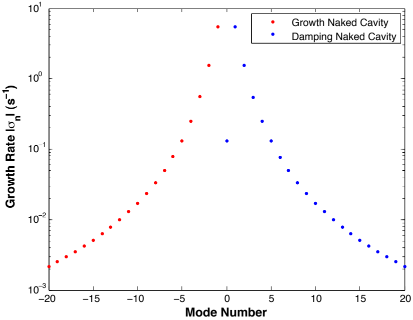
$$\Lambda_n = -d_r + \omega_s + \frac{\eta\, q\, I_0 \omega_{\text{rf}}}{2E_o T_o \omega_s} \left(Z^{\|\text{eff}}(n\omega_0 + \omega_s) - Z^{\|\text{eff}}(0) \right) = \sigma_n + j\omega_n$$

  where σ_n is the modal growth rate and ω_n is the oscillation frequency for mode n.
- It is important to note that that the main interaction between beam/RF station is at $(n\omega_0 + \omega_s)$.

Impedance control systems (LLRF)

- For both LHC and PEP-II, the LLRF feedback system consists of a direct (analog/digital for LHC) and a comb loop to reduce the impedance sampled by the beam, and subsequently the modal growth rates.
- Controller settings critical for machine performance: achieve optimal impedance reduction without exceeding RF feedback loop gain and phase margins.





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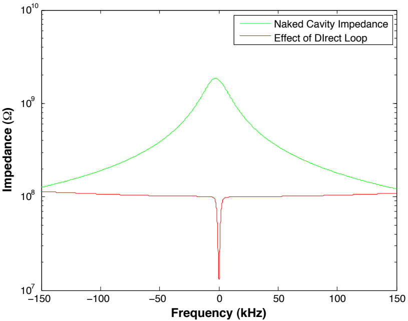

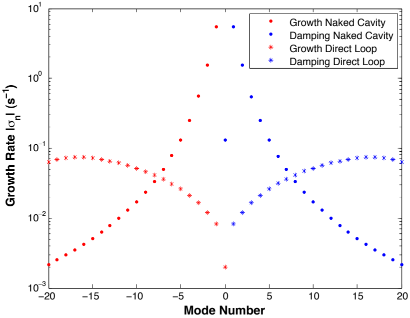

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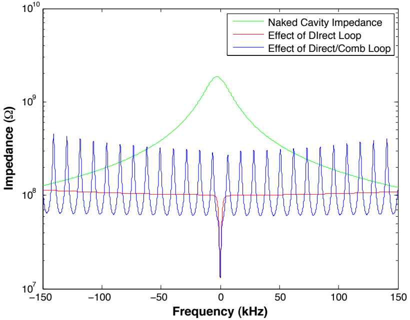
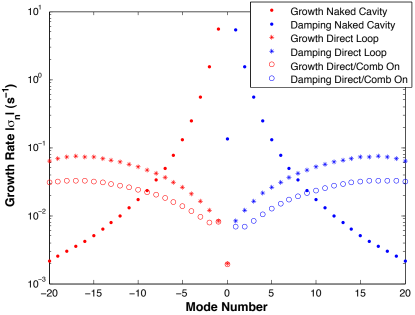
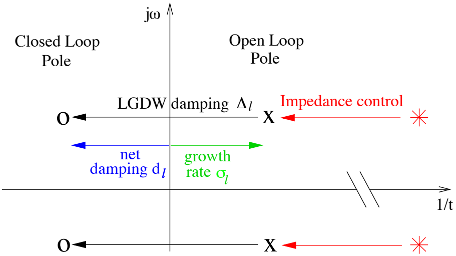




Impedance control systems (LLRF)

- The impedance control feedback loops set the most unstable low-order beam mode close to the imaginary axis.
- For high beam currents these dominant modes are still unstable.
- Application of a dedicated damping feedback channel (Low Group Delay Woofer) stabilized these modes at PEP-II.



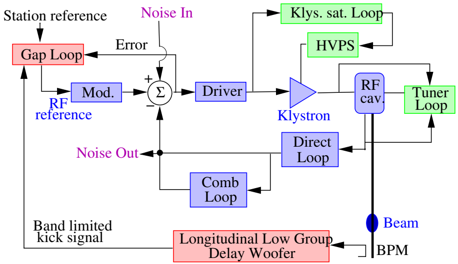
- From our studies, we determined that the LGDW can stabilize the system for growth rates up to 3 ms^{-1} due to the processing delay.
- The LLRF system has to reduce the growth rate of the most unstable mode to less than 3 ms^{-1}. The growth rates can be used as a metric of LLRF performance and as an instability threshold.

Configuring the LLRF system

- The RF station is a non-linear system. The stability and performance strongly depend on the operation point.
- Each operation point is defined by the RF station parameters:
  - Beam parameters, such as the beam energy and average beam current,
  - High-Level RF station settings: the klystron operation point, the cavity voltage, detuning, and quality factor Q,
  - LLRF parameters: Direct loop gain and phase, Comb gain, phase, and delay.
- The LLRF parameters have to be selected to maximize RF feedback loop and beam stability.
- Multiple RF stations, varying number of cavities per station further increase the complexity.

Characterizing the LLRF system

- To design the LLRF or to set the LLRF parameters it is necessary to characterize the RF station:
    - Transfer function measurements are made using a novel noise injection base band network analyzer.
- The transfer function measurements are numerically fit to a linear model of the system, which includes the High and Low Level RF parameters mentioned above.

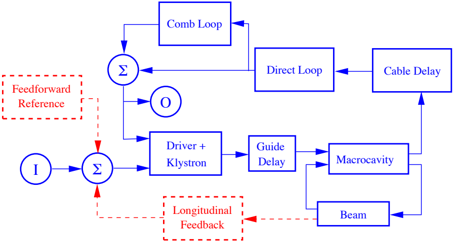


Motivation for this work

- The theoretical study of the beam-LLRF interaction is difficult due to the complexity of the multiple feedback loops and the non-linear nature of the system.
- An empirical 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.
- In this work, we wanted to look at the RF system and the beam as one dynamic system, rather than as two separate interacting systems.
- This work includes:
  - Theoretical formalisms and models that determine the longitudinal beam dynamics based on the LLRF implementation
  - Time domain simulations that capture the dynamic behavior of the beam-LLRF interaction
  - Measurements from PEP-II and LHC that validate the models and simulations.

Time-domain Simulation

- The Simulation is based on a reduced model of the longitudinal system
  - Beam Dynamics: Includes 'macrobunches' to study the low-order beam modes.
  - RF Stations: Models the RF power and fundamental blocks of the Impedance Control feedback.
- This tool is developed as a block system in Simulink, which uses the system parameters calculated in MATLAB to set the initial conditions of the slow loops.



- The frequency-dependent elements in the LLRF processing are implemented in the model, as are features which allow nonlinear responses (such as the klystron saturation effects).

Time-domain Simulation

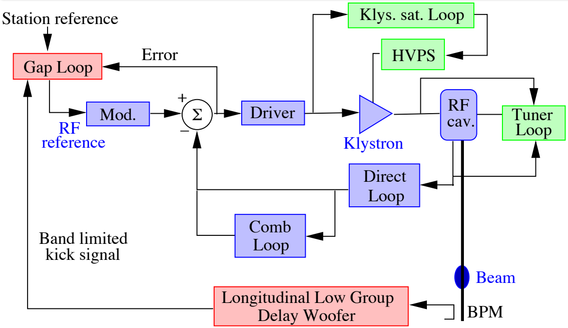
- The simulation is run for the equivalent of a few tens of milliseconds of machine time.
- It is then possible to extract valuable parameters to characterize the beam dynamics.
- The simulation uses the same tools to optimally configure the RF stations and measure the growth/damping rates of the beam as used in the real machine.
- The synergy between the real machine and the simulation allows us to study the impact of parameter sensitivity and LLRF imperfections in the beam stability.
- These simulation studies are performed without spending machine time and predict the ultimate limits of the configurations so that hardware can be developed before these limits are reached.

Applications

- The close similarities in RF architectures among circular accelerators allowed us to use these simulations and models for various machines, such as PEP-II, PEP-X, LHC.
- The focus of this presentation will be on PEP-II and LHC, since we did more extensive work and got the most interesting results from these machines.

PEP-II System

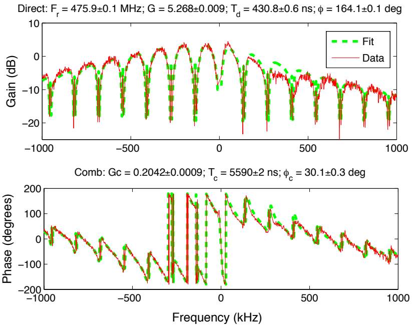
- Slow dynamic loops define the operation point for the fast model. Associated variables do not change in the time frame set in the simulation.
- Fast Dynamics are modeled.
- Not modeled components are also shown (but considered through the comparison of growth and damping rates in the analysis).



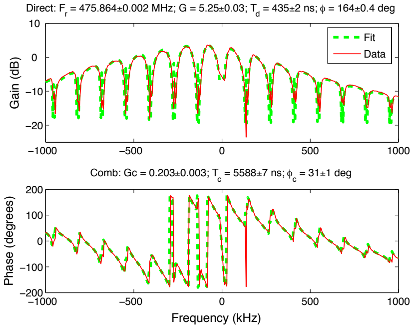
The direct and comb loops are necessary to reduce the impedance of the cavity as seen by the beam → control the growth rates.

Simulation Validation: Transfer Function

The initial simulation validation was through transfer function comparison between the real machine and the simulation for the same operation points



RF station Transfer Function

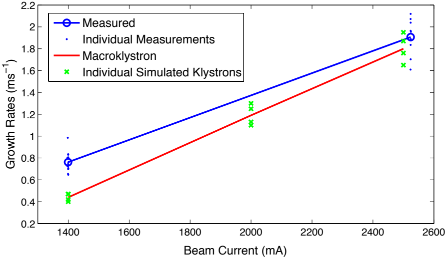


Simulated Transfer Function

The trace in green is a fit of a linear model to the data that help us extract valuable station parameters from the data trace in red.

Simulation Validation: Growth Rates

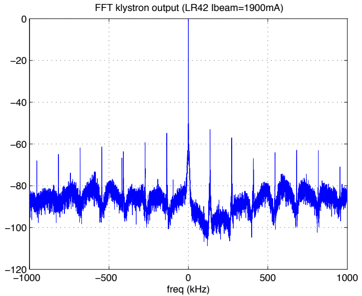
- The PEP-II modal growth rates had been consistently higher than the theoretically estimated values during the machine design.
- An early motivation for the simulation was to estimate the growth rates for given operational scenarios and compare with the real RF stations.
- The simulation reproduced the form of the most unstable growth rates for various beam currents, and also agreed with the physical system in the number of the most unstable mode (-3).



- But the simulated growth rates were still lower than the measured values.

Amplifier Distortion

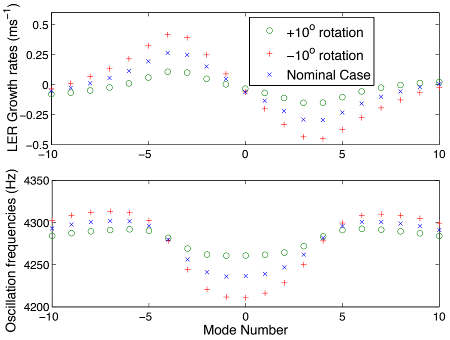
- To locate the discrepancy, we compared the simulation and machine frequency responses of RF components, leading to a surprising discovery on the performance of the klystron pre-amplifiers.
- These amplifiers and the klystron operate over a very large dynamic range, since they deliver a large carrier at the RF frequency, and small modulating signals around the revolution harmonics.
- Amplifiers performed as expected for a single tone input, but did not have a flat frequency response in the useful bandwidth for a two tone input.



- This distortion prevents configuring the RF station to the minimum impedance, leading to increased growth rates.
- The amplifiers were replaced based on this discovery, with great performance improvement (results on later slides).

Stability trade-off

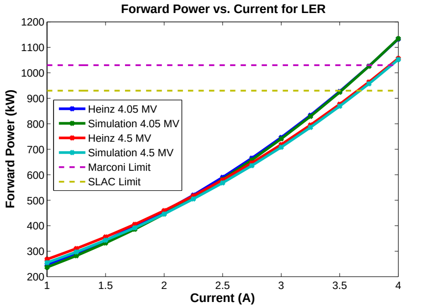
- The RF feedback loop had been historically configured to achieve set gain and phase margins.
- We investigated with the simulation the trade-offs between RF feedback loop and beam stability, and discovered that we had one more degree of freedom for increased beam stability through RF configurations.

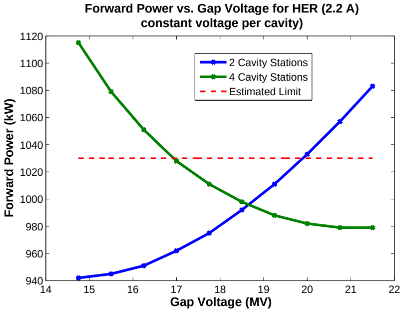


- During these studies, it was determined that a small reduction on the phase margin for the comb loops (reducing station stability) can lead to a substantial reduction in Growth Rates.
- A rotation of the comb phase by 10° was implemented in the LER.

Estimate Operation Point Limitations

- As the PEP-II currents were increased, the operational margins were getting smaller. Loss of control was anticipated for foreseeable currents.
- The simulation was used to test the effectiveness of different operational scenarios. We looked into operation point limitations (sufficient klystron power, cavity voltage etc.), and growth rate limitations.

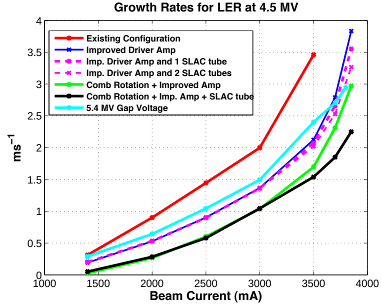


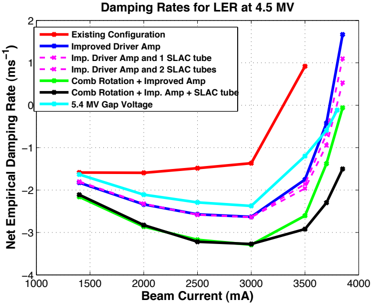


Estimate Beam Current Limits due to Growth Rates

Growth Rates were the most critical limitation

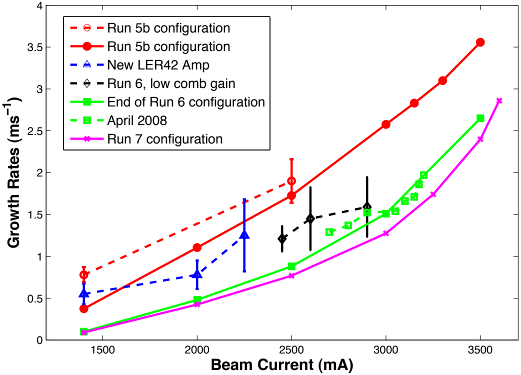
- We wanted to identify biggest performance return for investment.
- We looked into effect of new klystrons, new driver amplifiers, comb rotation, higher total accelerating voltage.





Effect of technical upgrades on real machine performance

- With these studies, the new driver amplifiers, and the comb rotation, a world record current of 3213 mA was achieved at the LER.
- Measurements were conducted to quantify the growth rate reduction and the agreement with the predictions.

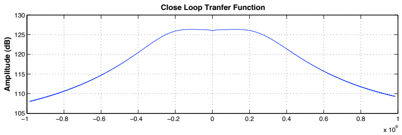


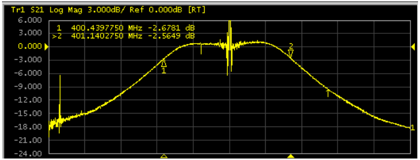
- Solid lines from simulation, dashed lines measured growth rates.

LHC Simulation Motivation

- The success of the PEP-II studies and the similarities between the LHC and PEP-II LLRF systems motivated the adaptation of the existing time-domain models and simulations to the LHC implementation to study both single-bunch and multi-bunch beam dynamics, as well as the dynamics of the station.
- The simulation was used in the development of the LHC identification and configuration tools, a set of tools for configuring the RF system remotely and consistently. The tools were used for January 2010 startup.
- With these tools, the commissioning time for the RF stations was reduced from multiple days to a few hours.

Initial Simulation Validation: Closed Loop RF station Transfer Functions





RF noise effects on LHC longitudinal beam emittance

- Even though the RF architecture is very similar, there is a fundamental difference in the beam dynamics. The synchrotron radiation for protons in the LHC is significantly less (6 keV per turn out of 7 TeV nominally).
- As a result, the noise power spectrum of the RF accelerating voltage can strongly affect the longitudinal beam distribution and contribute to beam motion and diffusion.
- The choices of technical and operational configurations can have a significant effect on the noise sampled by the beam.
- To address the need to fully 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

LHC Studies

- The formalism states that the equilibrium bunch length σ_z is given by

$$\sigma_z^2 = 2\frac{c^2}{\omega_{RF}^2}\int_0^\infty S_x(f)df$$

where the power spectral density $S_x(f)$ is a function of the beam frequency response and the accelerating voltage phase noise.

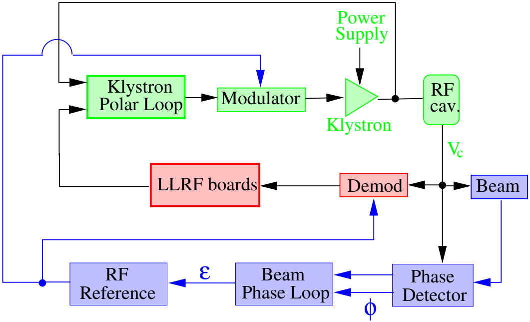
- With this formalism, we estimated the equilibrium bunch length for various operational configurations by:
  - Evaluating the RF noise sources based on the layout and components of the RF system
  - Determining the ratio between these noise sources and the noise in the accelerating voltage through our simulation and models
- Using the above information, we can also estimate the anticipated growth rate of the bunch length.
- We also estimated the noise thresholds in the LLRF system for specific bunch lengths and RF station configurations.

LHC Measurements

- Measurements were conducted at the LHC to support the above theoretical formalism and simulation studies:
  - Identify the dominating RF component for beam diffusion
  - Correlate RF noise and longitudinal beam emittance
  - Study the LLRF noise contributions.

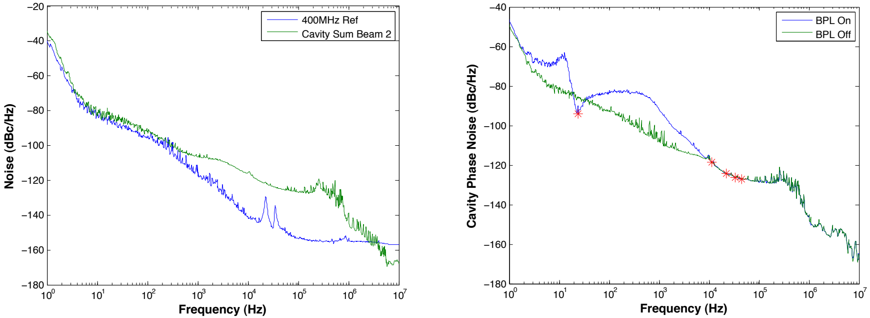
Performance limiting components at LHC

- Two major noise sources:
  - Intrinsic noise in baseband from the LLRF feedback boards.
  - The RF reference noise introduced during the LLRF modulation/demodulation process.



- The BPL is a narrow bandwidth loop that drives the RF reference to achieve mode 0 beam correction.

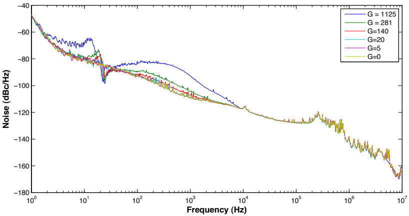
Performance limiting components at LHC

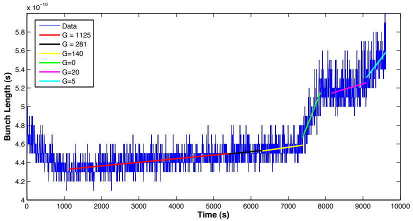


- The accelerating voltage phase noise is dominated by the 400 MHz reference up to 300 Hz, the LLRF controller at higher frequencies.
- The Beam Phase Loop (BPL) reduces the noise around the synchrotron frequency.
- 98% of the contribution to bunch lengthening is from around the first revolution harmonic.

Longitudinal beam emittance dependence on RF noise

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





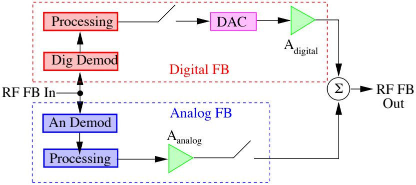
Beam Growth Dependence on BPL and Noise Power

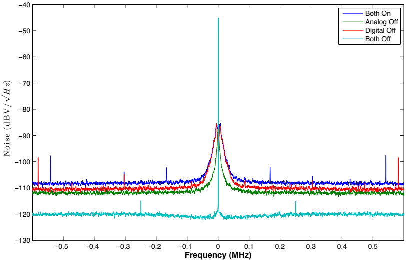
BPL τ^{-1}	**Scaled σ_z^2**	$d\sigma_z/dt$ (ps/hr)	**rms Cavity Noise (mrad)**
1125	9.2	14	3.1
281	11.6	15	2.2
140	22.6	20	2.1
20	28.7	42	2
5	74.7	189	2.1
0	146	364	2.2

- 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:
  - The BPL gets saturated
  - The longitudinal emittance growth due to intrabeam scattering of about 5 ps/hr starts getting comparable to the RF noise induced growth.
- The rms RF station voltage phase noise is NOT a useful metric.

LLRF Noise Contributions

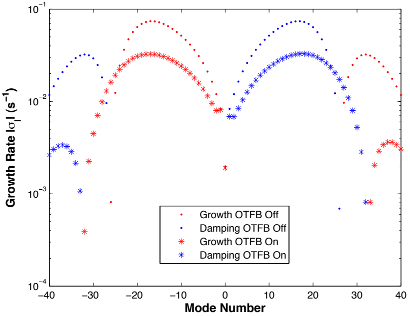
- Four sources of noise: the Analog feedback path, the Digital feedback path, the Digital to Analog Converter (DAC), and the backend processing.
- The Digital and Analog modules dominate the noise contributions.
- The dominant components on the digital path are the differential amplifier driving the Analog to Digital Converter (ADC), and the digitizing noise of the ADC.
- For the analog path of the RF feedback the noise level is dominated by the large gain stage in the last stage of the analog demodulator





LHC longitudinal coupled-bunch instabilities studies

- The coupled-bunch instabilities were estimated for various RF configurations, beam energies, and future higher currents for the LHC.
- The effect of the LLRF parameter variation was studied, and the results agreed with the theoretical expectations.



- Growth rates were compared with the anticipated Landau damping (incoherence mechanism) for LHC.
- We do not anticipate coupled-bunch instabilities to be a critical issue for LHC operations.

Conclusions

- The LHC RF and LLRF models and simulation are valuable tools in the study of the RF station/Beam dynamics interaction. The configuration/optimization tools are also imperative for LHC operations due to the new no-access policy when magnets are on.
- The PEP-II studies provided great insight of the system, helped us develop new algorithms, identify big impact upgrades, and finally reach a world record current of 3213 mA in the High Energy Ring.
- With the simulation, models, and now theoretical tools (formalism), we are in a great position to estimate the effect of RF configurations, alternative designs, or next generation systems on the LHC longitudinal dynamics.
- We can study any other possible configuration, proposed design, algorithm, or next generation system
- Results can be helpful for noise allocation and specification of technical components in future designs

Future Directions

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.
- The 1-Turn Feedback hardware has not been commissioned yet for all RF stations. The optimization tools will be used to complete the hardware commissioning and will then be tested.
- Final validation measurements of the complete software suite will be conducted.
- After that, it will be discussed with the CERN RF group whether to include new features to the tool for future operations.

Future Directions

RF Noise Effect on Beam Diffusion Studies

- Initial measurements have validated our theoretical formalism, simulation and studies.
- 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.
- Our earlier measurements identified the RF reference (Local Oscillator distribution) as the dominating component affecting the beam diffusion. Studies are being conducted to identify possible alternative algorithms 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.
- Coupled-bunch instabilities studies at 3.5 TeV would be useful since growth rates increase with lower beam energy, and the updated LHC schedule calls for an extensive run at 3.5 TeV.

Toohig Fellowship

- The Toohig Fellowship would give me the opportunity to broaden my exposure with the LLRF studies, and possibly pursue a few of these directions.
- We have had a great collaboration with the BE-RF group at CERN, and it would be exciting to continue building the ties between US labs and CERN.
- I would also be very interested to learn more about LARP projects at other laboratories, developing new accelerator physics skills, and expanding my experiences in the field.
- I have experience with feedback control and instabilities, I am interested in beam dynamics, and I believe I can contribute in feedback projects (tune, orbit). I am an experimentalist, so I would also be interested in commissioning of new instruments and systems (coupled-bunch or fast e-cloud/TMCI feedback).

Acknowledgments

- I would like to thank my advisor John Fox for his help and guidance all these years. I am also grateful to the present and past members of our group, Claudio Rivetta, Dan Van Winkle, and Dmitry Teytelman.
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- The SLAC AARD department has always been very supportive, and in particular Sami Tantawi, Ron Ruth, and Alex Chao.
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Thank you for your attention