# Simulations and Results of the Longitudinal Dynamics for PEP-II Rings

## Low-Order Mode Longitudinal Dynamics Behavior

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# Outline

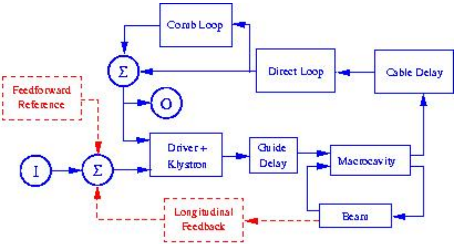
# Introduction

- We developed a time domain simulation tool to model the longitudinal low-order mode dynamics in PEP-II Rings (an expansion of an earlier work by R. Tinghe).
- Simulation tool captures the dynamic behavior of both the low-order modes of the beam and the RF stations, including their nonlinearities and principal feedback loops used in the control feedback impedance.
- Understand the discrepancy between fast growth rate measured in HER-LER with respect to the one predicted by ideal models.
- Tool to analyze different RF configurations and operative conditions in the machine.
- Quantify stability and performance for future high beam current operations.

# Outline

# Reduced Model - Simulation

The Reduced Model used in the simulation captures the dynamic interaction between the RF stations and the beam.
Beam Model: 1746 bunches are reduced to 18-72 Macrobunches. Captures beam low-order dynamics. Preserves beam filling pattern.
RF Station Model: All 2 cavity stations are grouped into one Macrostation, all 4 cavity stations are grouped in another.




- Macrostations include the principal loops used in the control feedback impedance.
- Slow dynamic loops define the operation point for the fast model.

# Reduced Model - Simulation

Macrostations can describe the composite behavior of the RF stations included in the ring or the behavior of an individual RF station.

- The individual RF stations included in the ring do not have identical behavior or operation points. There are some differences due to the different behavior of components.
- The composite effect of all RF stations can be captured by defining a macrostation that average the behavior of the individual stations. This model does not describes the effect in the bean dynamics of a particular station.
- The effect on the beam dynamics of a particular RF station can be analyzed considering that the macrostation represents the behavior of that particular station. This topology is equivalent to assume that the ring is composed by RF stations equal to the analyzed station.

# Outline

# Modal Growth Rates and Cavity Impedance

- In the simulation time frame, the system is mainly reduced to two interacting dynamics: the beam and the RF stations.
- To assess system stability and performance for the low-order mode beam dynamics, a combined design of the RF stations and the Longitudinal Low-Group Delay Woofer is necessary.
- The interaction between the beam and the RF stations is defined by the effective impedance $Z^{\|\mathrm{eff}}(\omega)$ presented by the RF stations to the beam. $Z^{\|\mathrm{eff}}(\omega)$ is calculated in the simulation by a non-linear model of the RF station defined by 7 characteristic parameters.
- To represent $Z^{\|\mathrm{eff}}(\omega)$, the simulation configures the model using the same techniques and tools than those used in the RF station.
- RF station control loops are designed to be stable and to present the minimum impedance $Z^{\|\mathrm{eff}}(\omega)$ to the beam.
  - There is a trade-off between those criteria. Consequently, between RF station and beam stability.

# Modal Growth Rates and Cavity Impedance

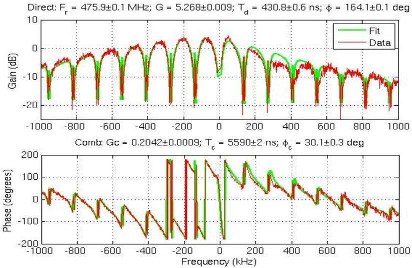
- The low-order mode behavior of the beam is quantified by the Modal Growth Rate (GR) and Damping Rate.
- Growth Rates are measured by opening the Longitudinal Feedback for a sort period of time, such that the operation point becomes transiently unstable.
- During this transient, the modal growth rate $\sigma_l$ and the syncrotron frequency $\omega_l$ are

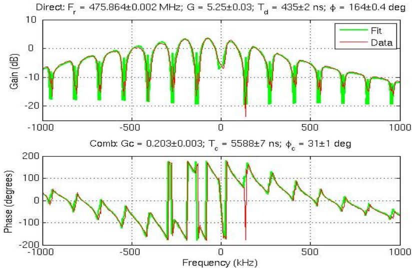
$$
\begin{aligned}
\sigma_l &\approx -d_r + \frac{\alpha\, e\, I_0 \omega_{\mathrm{rf}}}{2E_o T_o \omega_s} \mathcal{RE}\left(Z^{\|\mathrm{eff}}(l\omega_0 + \omega_s) - Z^{\|\mathrm{eff}}(0)\right) \\
\omega_l &\approx \omega_s + \frac{\alpha\, e\, I_0 \omega_{\mathrm{rf}}}{2E_o T_o \omega_s} \mathcal{IM}\left(Z^{\|\mathrm{eff}}(l\omega_0 + \omega_s) - Z^{\|\mathrm{eff}}(0)\right), \\
\text{with} \quad & Z^{\|\mathrm{eff}}(\omega) = \frac{1}{\omega_{\mathrm{rf}}} \sum_{p=-\infty}^{\infty} (pN\omega_o + \omega) Z^{\|}(pN\omega_o + \omega).
\end{aligned}
$$

# Outline

# $Z^{\|\mathrm{eff}}(\omega)$ Validation

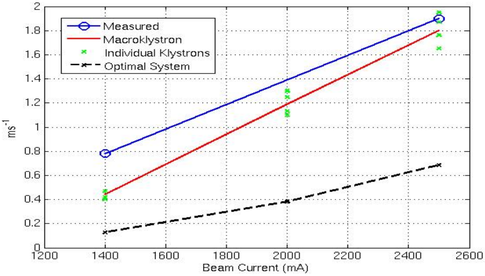
The simulation was validated with measurements in LER, comparing the growth rates and the RF station impedance. For example, the agreement between the closed-loop transfer function of an RF station measured (left) and simulated (right) in LER, as well as, the 7 fitted parameters, are shown



# Growth Rate Validation

- RF stations in LER and macrostations in the simulations are configured such the same close-loop transfer function is fitted to both systems.
- The same technique and tools are used in the simulation and the machine to measure the growth rates.
- The GRs reported in the measurement are the result of averaging multiple individual measurements. (fastest growing mode).




Simulations using individual klystron characteristics in the macrostation show different Growth Rates.

- Blue: Averaged measurements.
- Green: Simulated Growth Rate for individual stations.
- Red: Averaged value of the individual Growth Rates simulated.
- Black: Ideal System.

# Outline

# Growth Rate - Sensitivity Analysis

Discrepancies between GRs measured and predicted by ideal models were analyzed studying the GR sensitivity to parameter variations. Gains in the Direct and Comb loops, $G_D e^{i\phi_D}$, $G_C e^{i\phi_C}$ were changed.

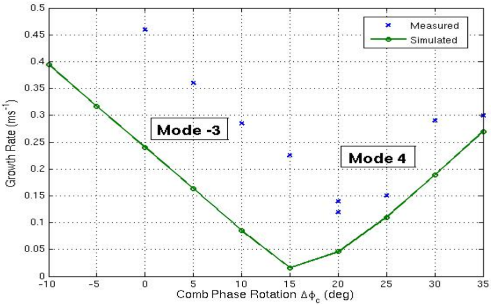
| Param. | Adjust. | GR | Change |
|---|---|---|---|
| Nom. | - | 0.263 | |
| $G_D$ | +20% | 0.233 | -11% |
| $G_C$ | +20% | 0.221 | -16% |
| $\tau_C$ | +50 ns | 0.258 | -2% |
| $\phi_D$ | $+10^\circ$ | 0.119 | -55% |
| $\phi_D$ | $-10^\circ$ | 0.408 | +55% |
| $\phi_C$ | $+10^\circ$ | 0.106 | -60% |
| $\phi_C$ | $-10^\circ$ | 0.415 | +58% |

Using an ideal model to simulate LER operating at $I_{BEAM} = 1400mA$ and defining it as the nominal case, (GR $= 0.263\,ms^{-1}$), parameters are changed to analyze the impact in the growth rates.

GRs are very sensitive to changes in $\phi_D$ and $\phi_C$.

# Growth Rates - Measurements at LER

For LER operating with 3 RF stations at 4.5$MV$ and 1400$mA$, measured and simulated GRs of fastest modes are compared for different Comb Phase rotations $\Delta\phi_C$.
Comb phase rotation $\Delta\phi_C$ is measured respect to the design value $\phi_C$, calculated to achieve the stability margins in the RF loops.



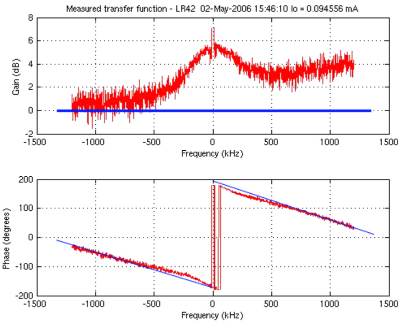

Based on these studies, since April 2006, LER RF stations operate with $\Delta\phi_C = +10°$ with the corresponding GR improvement.
Further $\Delta\phi_C$ rotations are limited by imperfections in the RF stations

# System Imperfections

- The limits on the maximum $\Delta\phi_C$ rotation at high currents, compatible with the RF station stability, are being studied using simulation.
- The synergy between the simulation tool and the machine gave insights to locate imperfections in the RF stations that affects their stability and ultimately increases the modal growth rate.
- Imperfections in the RF stations do not allow to set the optimal direct and comb loop parameters in the station when it operates at high current due to a reduction in stability margins.
- Comb Phase Rotation ($\Delta\phi_C$) and Asymmetric Combs have not been fully implemented due to those imperfections.
- System imperfections or discrepancies between the model used in the simulation and the real RF stations are located in the RF processor (RFP), driver amplifier and klystron frequency response.

# System Imperfections

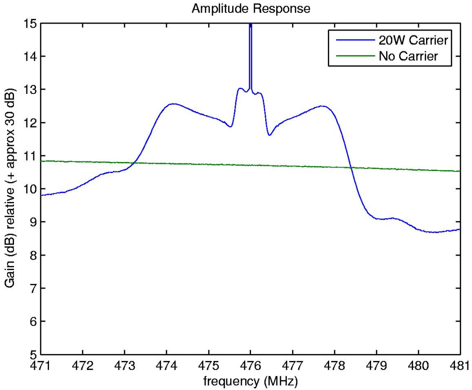
- The model assumes that the composite subsystem is a pure delay (blue).
- The frequency response of some stations show different behavior than a pure delay. *e.g.*, for LER 4-2, the transfer function of the composite system is (red)




Part of the distortion is due to the driver amplifier. The distortion in the RF processor is under study.

# System Imperfections

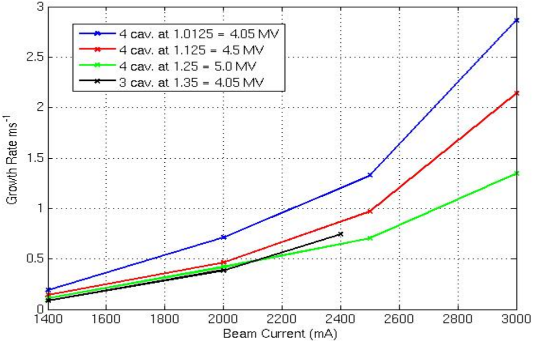
Distortion in amplifiers: The system operates driven by a signal composed by a carrier plus side-bands.




- When the driver amplifier is tested using only a carrier signal the frequency response is flat.
- When the driver amplifier is tested using a signal composed by the carrier plus side-bands, the frequency response is not flat in the range of interest.

# Growth Rates for existing RF configurations

Low-Energy Ring operating at different Gap Voltages and configured with 3 or 4 RF stations.

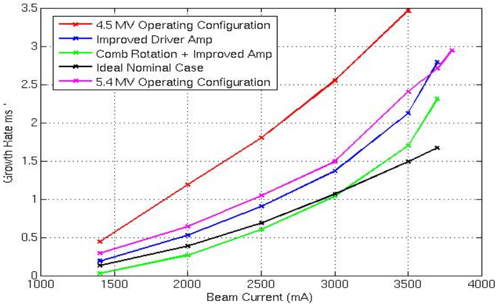



Displayed simulated results correspond to the fast modal growth rate (l=-3).

# Growth Rates for various possible new RF configurations

## Simulated results for Low-Energy Ring.

- LER operating with 4.5MV Gap Voltage. Different improved configurations.
- LER operating with 5.4MV Gap Voltage.

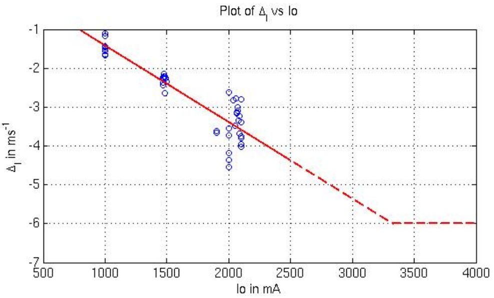



The maximum beam current simulated is set by the maximum power delivered by the klystrons installed at LER.

Cases: 'Improved Driver Amp.' and 'Comb Rotation + Impr. Amp.' do not include imperfections in the RFP module.

# Operational Limits due to Longitudinal Stability

For overall stability, the Modal Growth Rate values estimated for different RF configurations and future beam currents have to be compared with the achievable damping from the Longitudinal Low-Group Delay Woofer.

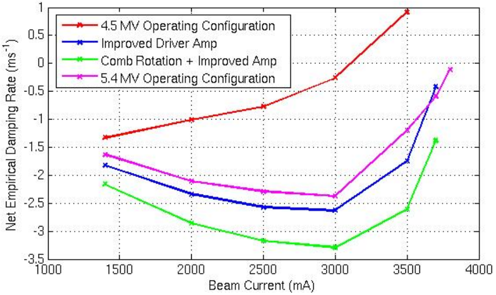



From measurements in LER, the damping for the fast growing mode $\Delta_l$ is plotted vs. beam current $I_0$.

The achievable maximum damping is estimated from experience during operation.

# Operational Limits due to Longitudinal Stability

Combining the estimated fast modal growth rate ($\sigma_l$) with the damping due to the Longitudinal LGDW ($\Delta_l$), the net system damping for future operation can be analyzed.




## Net System Damping

Assuming for operation a safety margin (SM) equal to $SM = \sigma_l$

$$\begin{aligned} \sigma_{NET_l} &= \Delta_l - \sigma_l - SM \\ &= \Delta_l - 2\sigma_l. \end{aligned}$$

# Work in progress

- Fix Driver Amplifiers for LER - HER. Replace driver units.
- Analysis of imperfections in the RF processing unit.
  - Define new calibration for the unit.
  - Evaluate the final limitation introduced in growth rate reduction.
- Analysis of maximum operative Comb Loop Phase rotation at high beam currents.
  - Apply comb phase rotation to HER.
  - Design Asymmetric Comb Filter.
- Quantitative analysis of limits in the Longitudinal stability introduced by Low-Group Delay Woofer.
  - Define region of stability. Influence of parameters and klystron nonlinearity.

# Future Work

- Simulation for the HER system is ready.
  - Validate with growth rate measurements.
- Analysis stability limits for HER.
  - Effect of new RF stations.
- Quantify the impact of system imperfections and uncertainties in the growth rates.
  - Define operative limits for HER-LER.
  - Generalize limits for future high current rings.
  - Define the impact of parameters in the region of stability
- Define limitations in the architecture and design for future digital RF processors.

# Conclusions

- A time domain simulation program has been developed to quantify the performance and the behavior of PEP-II ring at higher beam currents.
  - Results on effective impedance $Z^{\|\mathrm{eff}}(\omega)$ and the growth rate estimation for LER have close agreement with measurements in the machine.
- The synergy between the simulations and the machine measurements have helped understand operational limitations, have pointed to imperfections which cause higher growth rates, and have offered new control techniques (Comb Phase Rotation).
- The modeling helps define realistic operational limits for PEP-II, allows the development of new control techniques. It also can be useful to evaluate other accelerators with similar impedance controlled RF systems.