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# Modeling and simulation of longitudinal dynamics for LER-HER PEP II Rings<sup>1</sup>

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## Abstract

A time domain modeling and simulation tool for beam-cavity interactions in LER and HER rings at PEP II are presented. The motivation for this tool is to explore the stability margins and performance limits of PEP II RF systems at higher currents and upgraded RF configurations. It also serves as test bed for new control algorithms and can define the ultimate limits of the architecture.

The time domain program captures the dynamical behavior of the beam-cavity interaction based on a reduced model. The ring current is represented by macro-bunches. Multiple RF station in the ring are represented via one or two macro-cavities. Each macro-cavity captures the overall behavior of all the 2 or 4 cavity RF station. Station models include nonlinear elements in the klystron and signal processing. This allows modeling the principal longitudinal impedance control loops interacting with the longitudinal beam model.

Validation of simulation tool is in progress by comparing the measured growth rates for both LER and HER rings with simulation results. The simulated behavior of both machines at high currents are presented comparing different control strategies and the effect of non-linear klystrons in the growth rates.

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# MODELING AND SIMULATION OF LONGITUDINAL DYNAMICS FOR LER-HER PEP II RINGS\*

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A time domain dynamic modeling and simulation tool for beam-cavity interactions in LER and HER rings at PEP II are presented. The motivation for this tool is to explore the stability margins and performance limits of PEP II RF systems at higher currents and upgraded RF configurations. It also serves as test bed for new control algorithms and can define the ultimate limits of the architecture.

The time domain program captures the dynamical behavior of the beam-cavity-LLRF interaction based on a reduced model. The ring current is represented by macro-bunches. Multiple RF stations in the ring are represented via one or two macro-cavities. Each macro-cavity captures the overall behavior of all the 2 or 4 cavity RF stations. Station models include nonlinear elements in the klystron and signal processing. This allows modeling the principal longitudinal impedance control loops interacting with the longitudinal beam model.

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## SYSTEM AND MODEL DESCRIPTION

The PEP-II RF stations comprise 1.2 MW 476 MHz klystrons with either 2 or 4 normal-conducting RF cavities with HOM dampers [1]. The LLRF systems include comb (a second order IIR filter) and direct loop feedback paths to reduce cavity impedances seen by the beam. Despite the LLRF feedback, the beam exhibits low mode coupled-bunch instabilities at operating currents due to the fundamental impedance, and a special "woofers" feedback channel is required to control low mode instabilities [2]. The stations also incorporate numerous slow regulating loops which control cavity tuners, HV power supply voltage, compensate for gap transient effects, etc. [1]. The system described is depicted in the simplified block diagram in Fig. 1.

The simulation is focused on understanding the dynamic interaction among the beam, the cavities and the fast LLRF feedback loops. This tool is developed as a block diagram in Simulink, which uses the system parameters calculated in Matlab [3]. The simulation is an update of a previous

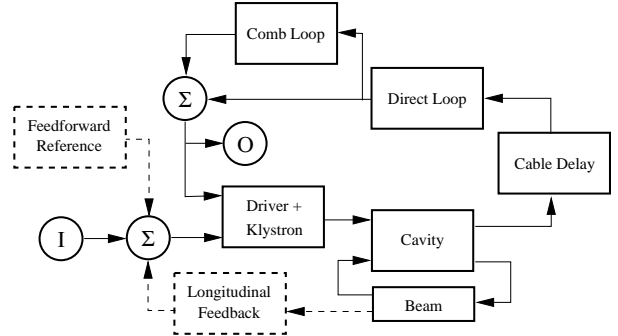


Figure 1: Simplified System Block Diagram. Transfer Function measured between I(input) & O(output).

work developed by Rich Tighe [4]. To optimize computation time and complexity only elements in Fig. 1 with dynamics in the order of the low-order mode beam dynamics are included. Slow feedback and control systems are considered as constant, defining the operation point of the system in the time frame where the simulation is performed. The particle beam is represented via a variable number of macrobunches comparable to the comb samples per turn, rather than the 1746 physical bunches, which fully resolves the low frequency beam modes (*e.g. modes: -18 to 17, for the 36 macrobunch case*) and interactions with the RF fundamental impedance.

Growth rates depend on the real part of the effective impedance presented to the beam by all the RF cavities included in the ring [5]. The growth rate corresponding to the  $l^{th}$  characteristic beam mode is given by

$$\sigma_l = \mathcal{R}(\Lambda_l) = -d_r + \frac{\pi \alpha e f_{rf}^2 I_0}{E_0 h \omega_s} \mathcal{R}(Z^{\parallel \text{eff}}(l\omega_0 + \omega_s)), \quad (1)$$

where  $\mathcal{R}(Z^{\parallel \text{eff}}(\omega))$  represents the effective impedance presented by all the stations to the beam. Detailed models of klystrons, including non-linearities and the frequency response, were considered to analyze both the limits in growth rate reduction due to the feedback system and discrepancies between stations. The simulation can be used to predict stability in future operation points, as well as study the effectiveness of possible additions and modifications to the RF stations.

The simulation models the RF signals in baseband and uses the in-phase/quadrature formalism to represent them. The fast feedback loops at each RF station modify the cavity impedance as

$$Z_i^{\parallel \text{eff}}(\omega) = (I + G(\omega)H(\omega))^{-1} Z_{st_i}(\omega), \quad (2)$$

where  $G(\omega)H(\omega)$  corresponds to the return ratio of the sta-

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tion. Parameters in the control loops and the stations define the frequency response of the system.

## RF CAVITY IMPEDANCE CONTROL

Eq. 1 expresses the particle beam stability whereas the term in parentheses of Eq. 2 corresponds to the stability of the RF feedback loops. The LLRF station feedback parameters (direct and comb loop gain and phase) are optimized to minimize the overall station impedance  $Z_i^{\text{eff}}(l\omega_0 + \omega_s)$  at frequencies  $l\omega_0 + \omega_s$ , corresponding to the beam perturbation, compatible with stability performance criteria for the RF loops (e.g. *gain/phase margins*). In PEP-II operations they are calculated using a non invasive method that starts with the identification of the transfer function of each station [6]. A similar method is used in the simulation to adjust the parameters of the macrostation. To achieve good agreement between the simulation and the physical system, it is important to define in the simulation an effective impedance interacting with the beam equal to the real impedance presented by the RF stations to the beam. From (1) and (2), it is important to observe that this is possible only if there is agreement between the transfer function measured per station and the transfer function and return ratio defined in the simulation.

Since the transfer function relationship tracks the growth rate consistency, it is reasonable to use the transfer functions for verifying the simulation model. This was done for different operating points, but the analysis below is in LER at 1400 mA. The transfer function is measured by playing a noise file in the input and reading the response at the output as marked in Fig. 1. The time domain simulation includes klystron non-linearities and frequency response. In Fig. 2 and Fig. 3 the collected data are shown in red for measured and simulated transfer functions respectively. These are fitted to the same 5 parameter linear system model [6] shown in green. The value of the model is to compare the resulting

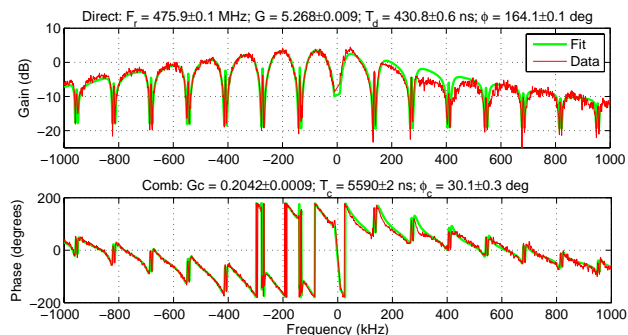


Figure 2: Transfer Function and parameters of operating station in LER at 1400 mA.

sets of parameters extracted from the physical system and simulation; thus, providing evidence of convergence. From these figures we can clearly see the agreement between the data and fit, which shows the accuracy of the fitting tools. The measured and simulated transfer functions as well as the fitted parameters are very close, providing confidence

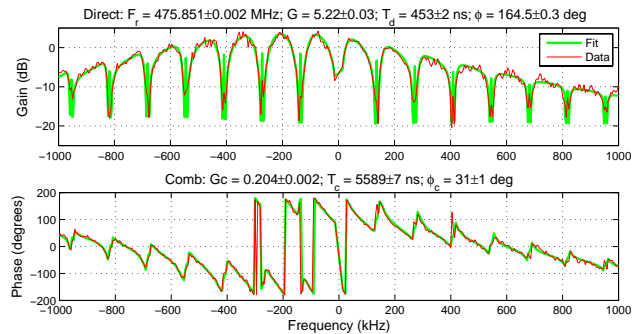


Figure 3: Transfer Function and parameters of macrostation from non-linear simulation in LER at 1400 mA.

that the growth rates will also be comparable. The small discrepancies can be attributed it to parasitic coupling between the in-phase and quadrature components to be analyzed in a subsequent publication.

It is important to note that the klystron frequency responses are different among physical stations. One result of the simulation was to show that the growth rates are very sensitive to these variations. Thus, either the growth rates have to be computed for each station and averaged or a macroklystron has to be developed that will represent the whole ring. The later case is presented.

## GROWTH RATE MEASUREMENTS

The essential measurements from the simulation are the modal growth rates since these are used to determine beam stability. The system is perturbed from equilibrium and the beam modes evolve in time. In PEP-II operations the modal growth rates are estimated via grow/damp experiments opening the longitudinal feedback loop [7]. Similarly in the simulation, we let the beam modes evolve and study the interaction between the RF station and the beam [2]. To achieve consistency between the physical system and the simulation, the same growth rate extraction tools are used to determine the growth rates in each case. For the simulation case, the growth rates are then compared to the expected damping rates from the longitudinal feedback loop, providing a quantitative measure of stability margins for each mode, in contrast to earlier work [4]. The natural complex frequency, whose real part corresponds to the growth rate and the imaginary to the oscillation frequency, is fitted to the evolving modes (shown on the left in Fig. 4). Thus, we differentiate between stable/unstable modes and can select the beam mode with the highest growth rate. The growth rates for modes -10 to 10 and their oscillation frequencies can be seen on the right in Fig. 4 for LER at 2500 mA. Modes -3 to -5 are usually the most unstable modes due to cavity detuning with increasing beam current. Fig. 5 compares the growth rates from the physical system and the simulation for both the macrostation and the individual station (due to different klystron responses) at 1400 and 2500 mA. The simulation not only reproduces the form of the most unstable growth rates for various beam currents, but it also agrees with the physical system in the number of that most unstable mode. The

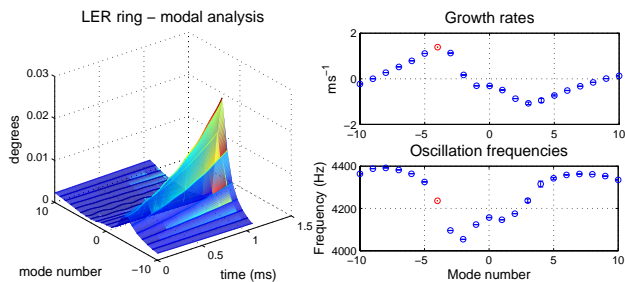


Figure 4: Low Frequency Beam Modes (LER at 2500 mA).

discrepancy at low currents will be investigated conducting dedicated measurements on the physical system.

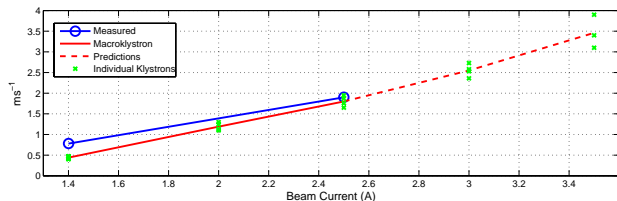


Figure 5: Measured and Simulated Growth Rates (Simulated for each station as well as the macroklystron). Extrapolated GRs are dashed. Most unstable mode is  $-3$ .

## APPLICATIONS AND PREDICTIONS

The value of this simulation tool is the ability to study the effect of different parameters in the stability and performance of the system without requiring time from the real machine. Additionally, simulations allow analysis of different system configurations and parameter combinations that are not directly applicable to the physical machine without major changes. These studies have helped to understand the sensitivity of the growth rates on certain parameters included in the control loops.

An example is the study of the impact of the comb filter phase rotation on the growth rates. The original criterium used to configure the direct and comb loops was to maximize the stability margin (gain and phase margins) of the RF feedback loop. The studies showed that this criterium comes with a tradeoff to the growth rates. We now understand that achieving great improvement in the growth rates with a relatively small reduction of the stability margin is possible. Details of this study are summarized in Fig. 6, where the growth rate of the dominant unstable mode is plotted versus the comb filter phase rotation. This plot combine simulation results with the average growth rate measured from the LER ring operating at 1400 mA. The comb filter phase of  $0^\circ$  is defined by the maximum stability margin criterium. These results have already been applied allowing increased beam stability margin. The consistency of the error margin between measured and estimated growth rates give a certain confidence to predict the growth rates of the machine at higher currents. Growth rates at higher currents are calculated by simulation and depicted in Fig. 5. The dashed lines show the prediction at beam currents larger than 2500 mA in the LER ring.

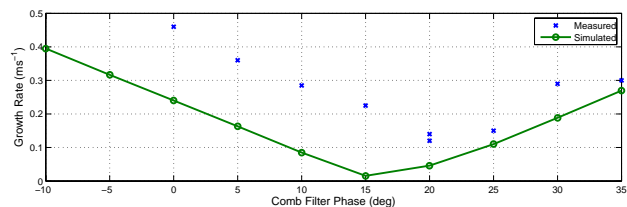


Figure 6: Measured and simulated growth rates vs. comb phase rotation. Agreement in both the general form and most unstable mode number.

These numbers can be compared to the expected damping rates for the corresponding operation point [2] and provide a sense for the stability of the beam at those higher currents.

## CONCLUSIONS

The simulation of the PEP-II rings is a close representation of the actual system. As such, it can predict the performance limits of the LLRF systems at higher currents and study the effectiveness of upgrades or their optimal configurations. It also provides insight of the system and suggestions for optimal tuning, as with the comb rotation, the analysis of the effect of the variations in the klystron responses as well as the ability to separate the stability of the particle beam from that of the LLRF. There are many further applications after the presented verification which will be studied in the future.

One of the important features of this tool is the adaptability to simulate the interaction between the RF stations and the beam for other systems. The interaction between the different parts of the algorithm and Simulink is through a parameter structure, which can be easily modified. Thus, the simulation was easily adapted to be used for modeling SPEAR to study Robinson instability and it was also modified to help with the design of the Klystron Linearizer [8].

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