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PEP-II RF Feedback System Simulation

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A model containing the fundamental impedance of the PEP-II cavity along with the longitudinal beam dynamics and RF feedback system components is in use. It is prepared in a format allowing time-domain as well as frequency-domain analysis and full graphics capability.

Matlab and Simulink are control system design and analysis programs (widely available) with many built-in tools.
The model allows the use of compiled C-code modules for compute intensive portions.

We desire to represent as nearly as possible the components of the feedback system including all delays, sample rates and applicable nonlinearities.

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Components

Cavity

A baseband representation of the total number of cavities of the ring. Baseband: A DC input representing the klystron RF input leads to a DC value representing the cavity voltage. Modulations to the cavity are made within a small (10 MHz) bandwidth around the center frequency. Forward and reflected power signals are recorded.

Beam

Longitudinal dynamics with enough macro bunches (36) to simulate coupled-bunch motion throughout the range excited by the cavity and feedback. Includes ion clearing gap.

Two macro-bunches are left empty in HER to represent the ion clearing gap (2/36 = 5.56%). Two bunches are partially filled in the LER for transient matching.

Direct RF Feedback

Reduces the cavity impedance seen by the beam.

Comb Filter Feedback

Periodic structure applying gain at the synchrotron sidebands; one-turn delay. Further reduces the impedance seen by the beam. Sample rate: 10MHz, same as in hardware.

Group delay equalizer

Mitigates the effects of the in-band and out-of-band delay differences.

Delays

Signal delays in system prevent the application of unlimited gain. Loop delay including waveguide, cable, klystron, and feedback components is approximately 550ns.

Saturating Klystron

Contains group delay and bandwidth behavior.
Saturation characteristics of klystron. AM gain decreases when running into saturation.
The klystron operating point is nominally set to 90% of saturated power (95% of saturated voltage) in order to compromise between operating efficiency and feedback headroom.

Longitudinal (Bunch-by-Bunch) Feedback

Two aspects: Implemented as additional term in beam dynamics akin to radiation damping; also connection from B-by-B system to RF feedback system.

Adaptive Feedforward

A profile corresponding to 20MHz samples is generated by sampling the klystron drive signal over many turns, averaging, and modifying the feedforward values in order to produce a more constant klystron output. The feedforward signal adapts slowly and will not interfere with the operation of the feedback loops. An RF reference is generated to allow gap induced cavity transients to occur without feedback intervention. This reduces power fluctuation in the presence of gap transients to less than 2%.

Analysis and Predictions

Gain, phase, delay setting

Analytic frequency-domain representation used to determine gains, phases, margins. The phase margin of the combined direct and comb feedback loops is set to 45°.

Modal impedance based on system

Expected modal impedance may be calculated based on linear system components.

Performance

Presently takes 3min/1ms of beam time on a SPARC 10.

Operation

The model runs with full current at startup. The assumption is that the B-Factory will be free of large injection transients due to the gradual injection scheme. Slow loops (tuner and gap voltage) are preset and disabled.

Uses:

System stability with linear and nonlinear operation

Klystron saturation and gap transients. The effect of the nonlinear klystron saturation is what largely requires the use of time-domain simulations.
Adaptive Gap Voltage program to follow gap transient.

System parameter variation:

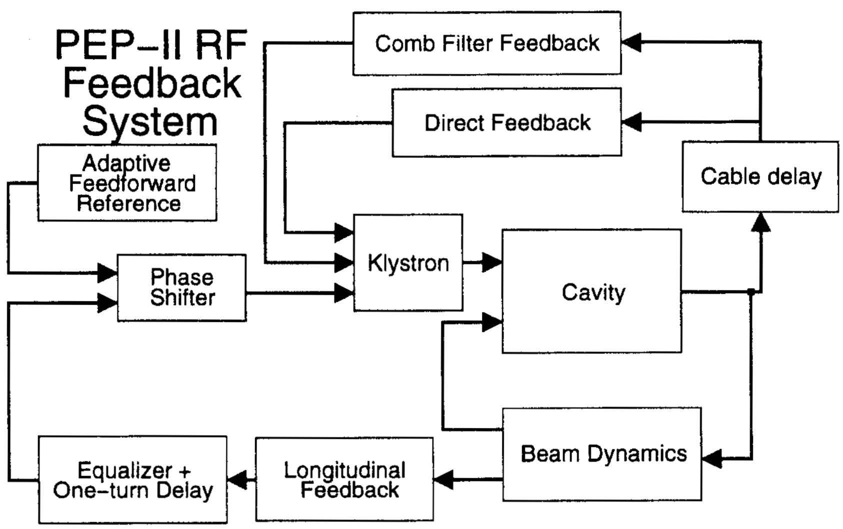
Klystron delay and bandwidth were varied to validate the klystron purchase specification.

Forward and reflected power information
Tracking of reflected voltage in waveguide ahead of cavity allowed testing worst-case trip scenarios (beam dump, klystron trip) confirming best window placement.

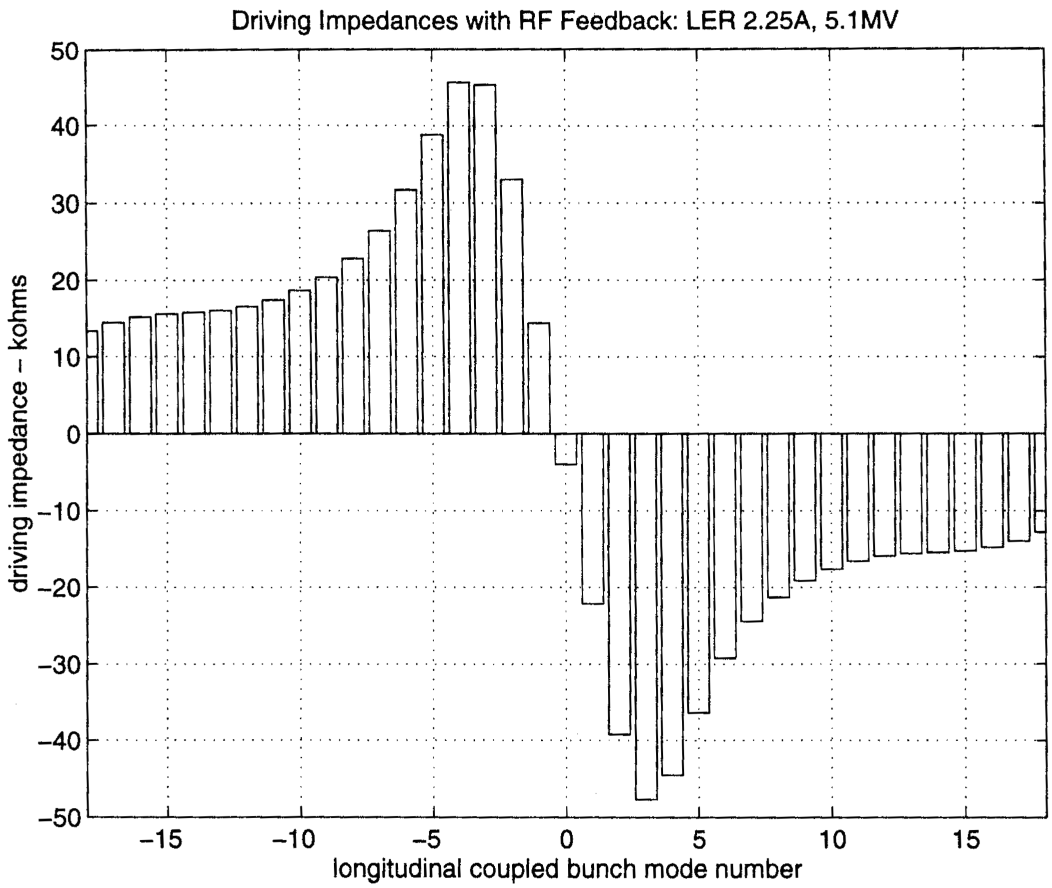
Test bed for additional components

Summary:

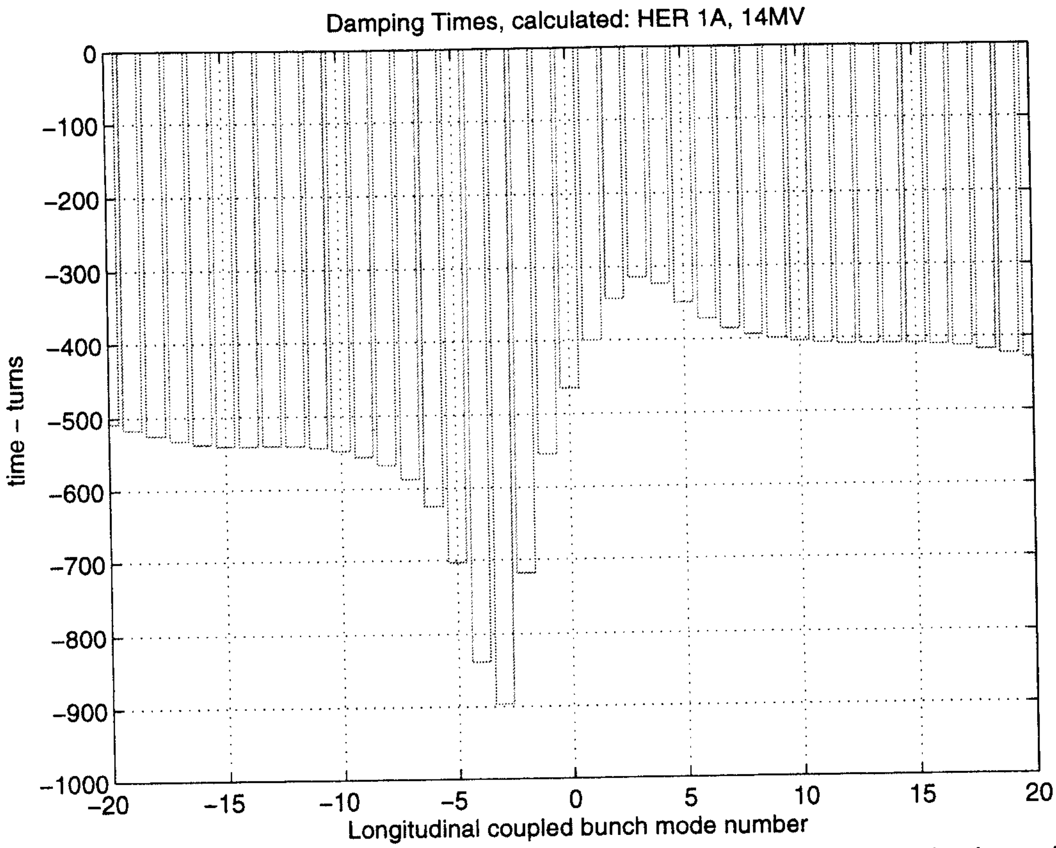
System has shown stable operation for PEP-II nominal HER and LER configurations.



System Block Diagram

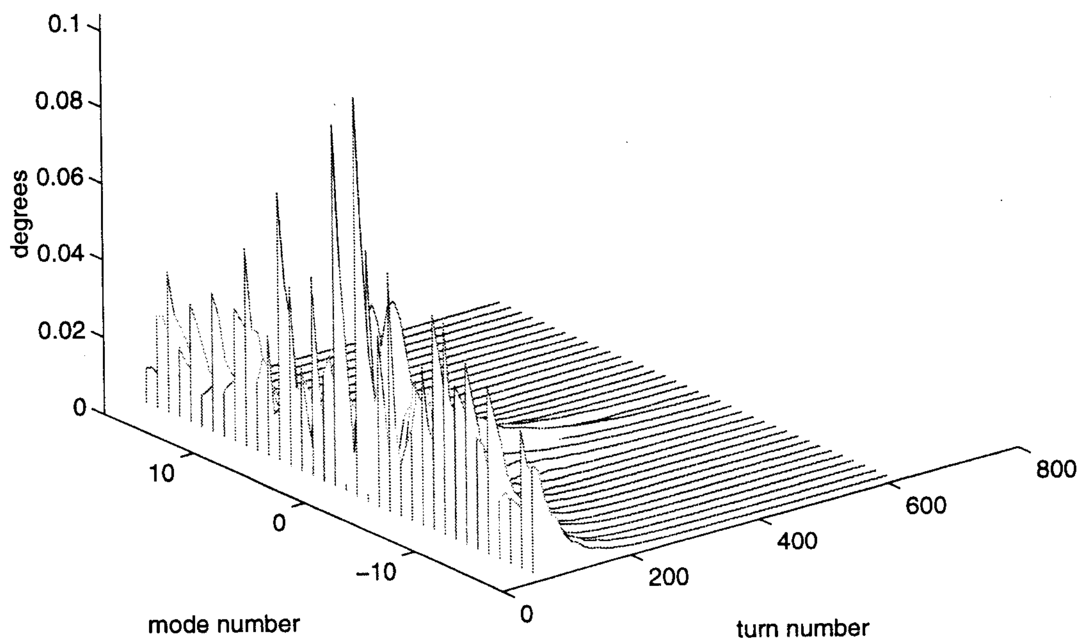


From a linear impedance calculation the coupled-bunch driving impedances for the modes affected by the RF cavity fundamental and feedback may be found.

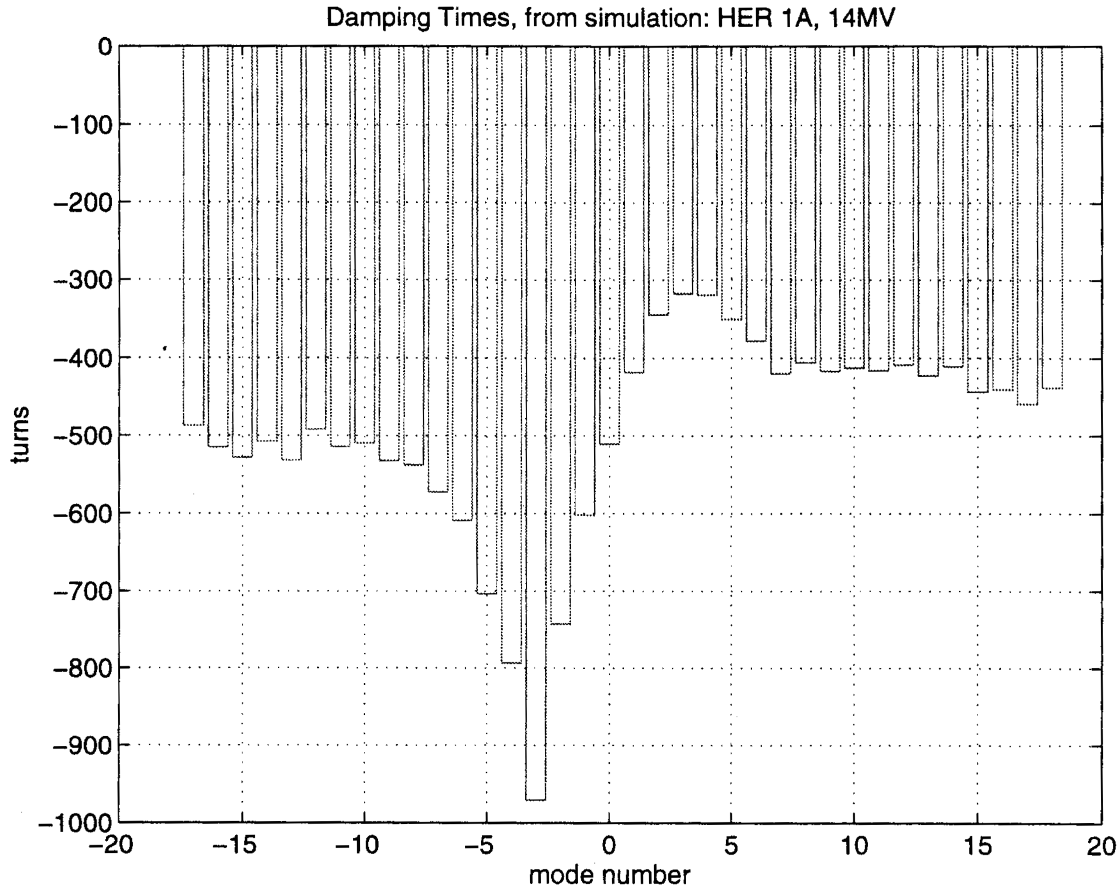


The results of the linear driving impedance calculation is converted to expected growth rates for a given configuration.

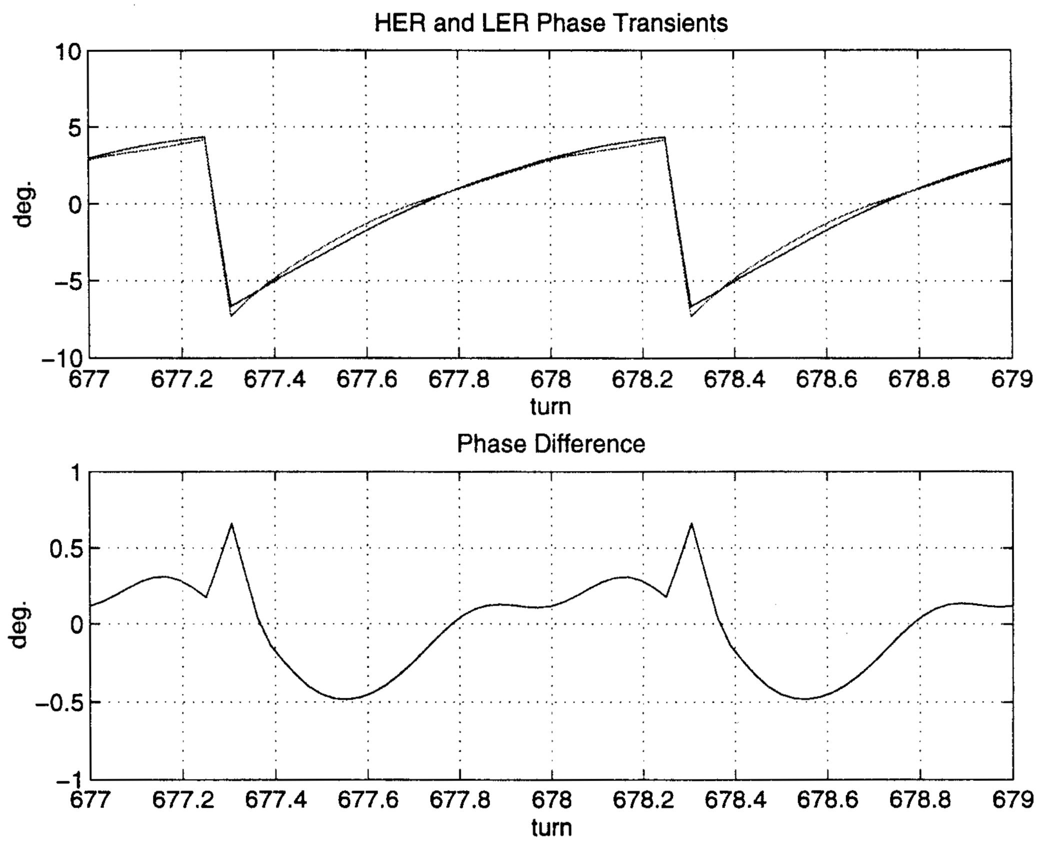
Spectral Analysis of 2.25A LER, 5.1MV



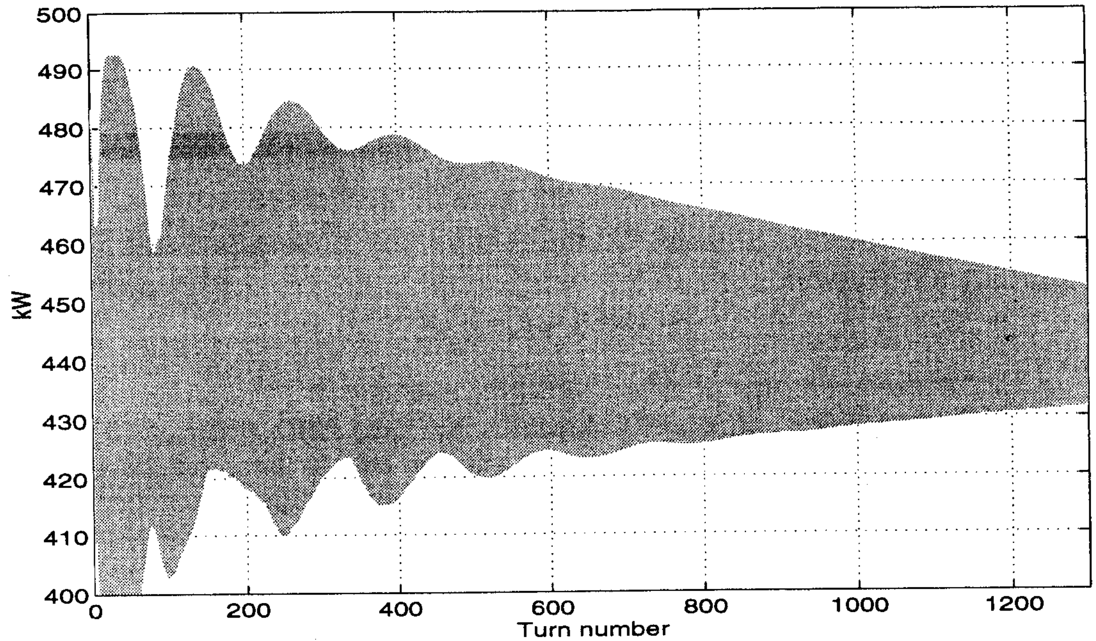
After completing the simulation, the bunch signals are converted to their modal components. Here we see all modes damping within 500 turns. In fact, the slowest mode to damp has a damping time of 150 turns. The radiation damping time is 3500 turns.



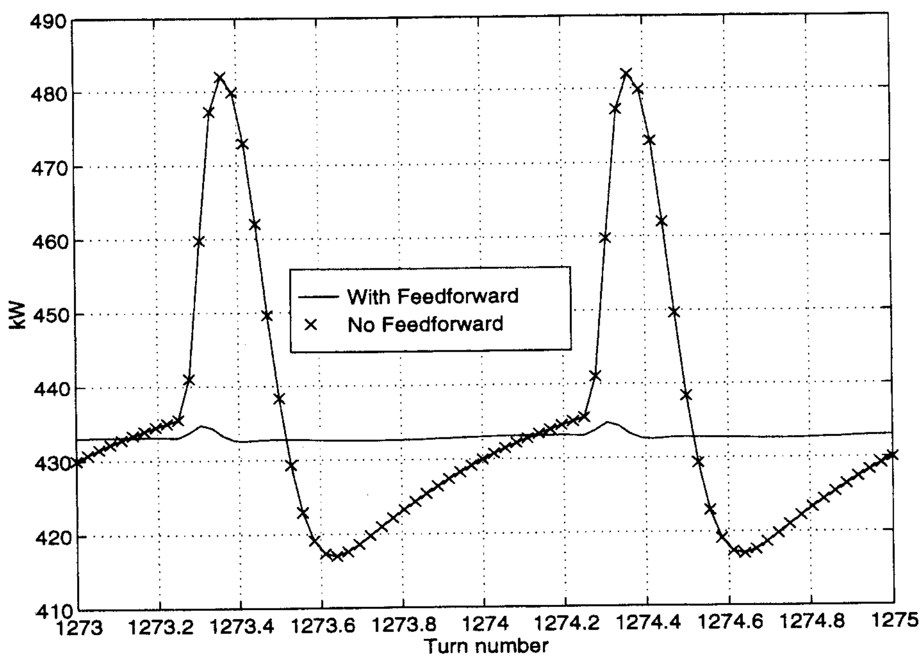
The results of the linear time-domain simulation give good agreement with the expected values. This allows us to proceed and add the saturation effect.



The gap induced transients in the two rings must be matched to prevent excessive collision point variation. Here the transients from the two rings are matched to within 0.6° (0.1 σ_Z). Fine tuning of the simulation parameters is possible to reduce this further. Theoretically, the transients may be perfectly matched (assuming equal cavity coupling in the two rings)



Forward Power Envelope During Adaptation



Forward Power Variation, with and without Feedforward.