RF Feedback Simulation for the PEP-II B Factory*

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Abstract

A model of the beam and RF system for PEP-II has been developed to allow both time-domain simulation and frequency-domain analysis of the complete system. The model includes the full set of feedback loops and nonlinear elements such as the beam and klystron. The model may be used to predict beam and feedback stability in the presence of nonlinearities through time-domain simulation as well as system frequency response about a given operating point.

1. INTRODUCTION

The heavy beam loading of PEP-II requires feedback systems to reduce the fundamental cavity impedance seen by the beam. Two feedback systems are to be used to control the fundamental impedance of the RF cavities. Direct feedback and a comb filter feedback with one turn delay reduce the driving impedance of the cavity as seen by the beam by 45dB. The principles of these systems have been well documented elsewhere[1],[2],[3].

The presence of nonlinear elements such as a klystron close to saturation and the inherently nonlinear dynamics of the beam dictates that time-domain simulation be carried out in order to fully explore the RF system behavior.

An ion clearing gap introduces large transients in the cavity. Through the partial filling of the matching portion of the positron ring, the phase transients that result are matched in both rings to keep the bunches in collision.

The Low Energy Ring (LER) has the greater beam loading of the two PEP-II rings and the simulation concentrates on that ring.

2. SIMULATION GOALS

A system in which both time-domain simulations and frequency-domain analysis may be done is desired. The time-domain simulation should ideally operate fast enough to allow rapid turn around time to simulation tests. Presently, the simulation takes approximately 1 minute per millisecond of beam time to run on a SPARC 10. Since the cavity presents a narrow band impedance to the beam, the longitudinal coupled bunch growth rates are proportional to the impedances at the pairs of upper and lower sidebands centered about the fundamental. Several low order coupled-bunch modes are strongly driven due to the highly detuned cavity resonance and the close spacing of the revolution harmonics at 136 kHz. From this we can limit the number of bunches in the simulation to a relatively small number that will allow excitement of those modes yet be computationally reasonable.

3. CONSTRUCTING THE MODEL

Methods of element inclusion

The commercial simulation application Simulink[4] is used to construct the model. This package works in conjunction with Matlab which contains industry standard control system design and analysis tools as well as built-in graphics capabilities. A previous simulation done at Chalk River Laboratory[5] was written entirely in C routines and lacked flexible output and analysis tools.

There are two ways in which elements are added to the system model. The user may graphically represent the operation of the system using built-in elements such as integrators, gains, and summing nodes. Certain dynamic elements (continuous or discrete) may be described as either transfer functions or in their state-space form. Nonlinear devices are also available; for example saturation, switches, etc.

Simulink also provides a means for integrating C-coded elements into a block diagram. For certain operations it may be desirable to produce the element as a block that calls compiled C-code. Devices that contain many states or are sampled frequently may run faster if written in this fashion. For this simulation the beam dynamics including the tracking of the longitudinal oscillations of all the bunches are written in C. The high sampling rate comb filter feedback is implemented in C also.

Figure 1 is the outermost level of the graphical representation of the model. Functional block diagram elements representing common operations are arranged so as to form a representation of the dynamical system. Nested within each block is the necessary realization to carry out that block's function, either another block diagram possibly consisting of only elementary items, or a reference to C code.

4. COMPONENTS AND THEIR VERIFICATION

Individual components of the simulation should be testable in order to verify their behavior. Time and frequency domain responses are generated and compared to the predicted behavior.

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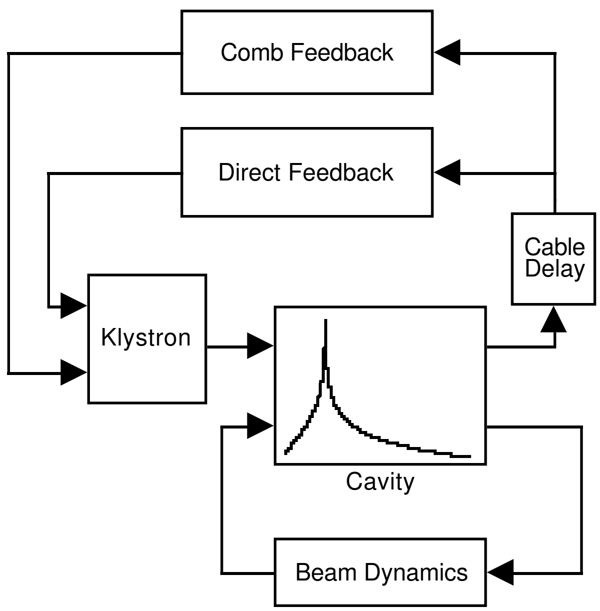

Figure 1. Simulation block diagram.

Cavity

The ten cavities of the LER are modeled as a single cavity with ten times the impedance and gap voltage. The large detuning is evident in the shift of the resonant frequency to 206 kHz below the 476 MHz RF drive frequency for the design parameters of the LER. The bandwidth of the cavity should be verifiable. In short, all the behavior of the real cavity operating at 476 MHz should be discernible but instead at baseband frequencies. That is, the baseband cavity output should be the envelope of the real cavity's output[6]. Figure 2 shows the frequency response of the baseband cavity. It can be seen as simply the response of the real cavity with the RF frequency mixed out. The cavity accepts inputs in the form of currents. In this way the contributions from the klystron and the beam are treated as currents and the common model of the cavity as an RLC circuit may be referenced. The cavity is modeled in such a way as to allow tracking of the reflected voltage as well as the cavity gap voltage.

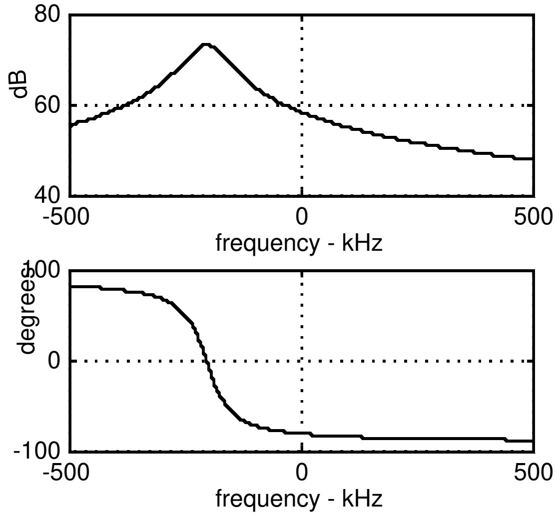

Figure 2. Baseband cavity frequency response.

Klystron

The klystron is to be modeled with the correct bandwidth and delay characteristics. The modeled klystron will saturate at approximately 1.2 MW of output power so that in transient situations the power output is limited.

Beam

The beam is modeled as a set of discrete bunches. At each bunch's passage it's energy change is instantaneous and the charge of each bunch is converted into an equivalent current to be injected into the cavity during that bunch's passage through the cavity. Figure 3 shows synchrotron oscillations of 4 bunches with small random initial energy and phase offsets (the synchronous phase is with respect to the cavity voltage).

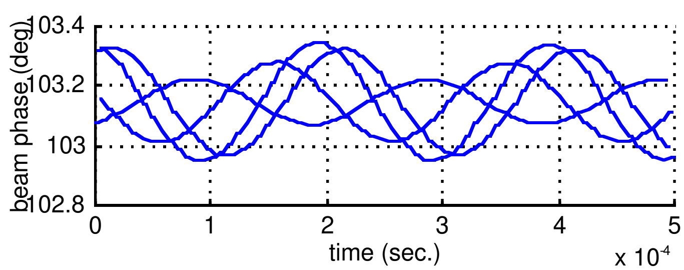

Figure 3. Beam oscillations.

5. FEEDBACK ELEMENTS

Direct Feedback

The direct feedback is straightforward in it's implementation. A sample of the cavity voltage is subtracted from the RF reference with the proper gain and phase. This loop acts as a voltage follower and reduces the peak cavity impedance by a factor of about 6-8. The delays in the system prevent the application of higher gain. It is very effective in reducing the driving impedance of the most strongly driven longitudinal modes. The remainder of the driving impedance reduction is obtained by the use of the comb filter feedback.

Comb Filter Feedback

The comb filter with one-turn delay is modeled as a digital filter sampling the cavity voltage followed by a digital delay line such that the propagation through the combined system is one revolution period. Figure 4 is a portion of the frequency response of the comb filter including one-turn delay. The filter is periodic with a sampling rate of approximately 10 MHz allowing feedback at the synchrotron sidebands for the first 20 coupled bunch modes. Finer delay resolution is obtained by a short section of digital delay line clocked at 40 MHz.

Equalizer

A phase equalizer is placed in line with the comb filter to increase the linear phase response range. As in the actual system, the equalizer is implemented as a 16 tap FIR filter.

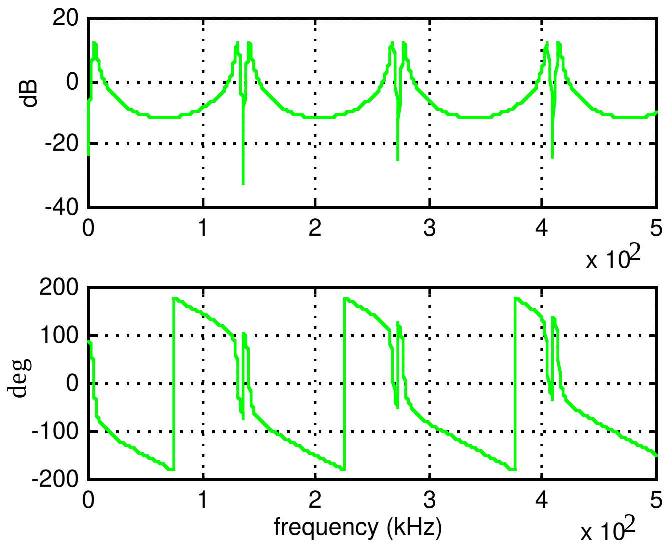

Figure 4. Comb filter frequency response.

6. SAMPLE BEHAVIOR AND USES

Given the running conditions, a set of calculations is presented indicating key power and voltage values for the simulation. Table 1 is the output for the design parameters of the LER. It has been possible to obtain useful results from the model without requiring that the beam dynamics be fully implemented. For example, it was necessary to explore certain situations involving beam loss to determine proper window placement[7]. Figure 5 shows three voltage envelopes along the waveguide leading from the klystron to the cavity. All three are the result of the forward voltage and the reverse voltage. During the beam loss the magnitude of the peak field can be seen to reach levels of almost five times nominal in some portions of the waveguide.

Figure 6 is the bunch spectrum from the simulation showing peaks at the synchrotron sidebands of the revolution harmonics.

Table 1. Calculated Output Values

<u>The summary of the operating parameters:</u>
The beam loading feedback gain, H = 6
The comb filter gain = 0.6
The gap voltage = 5.9 MV
The synchrotron freq. = 5 kHz
The beam loading ratio, Y = 5.803
IB = 4.5 , phib = 166.9
IG = 1.799 , phil = 0
IT = 4.45 , phiz = -79.96
Cavity Power Dissipation (per cavity) = 49.73 kW
Active Beam Power = 301.9 kW
Beam induced voltage at res. = 3424 kV
Beam induced voltage = 596.6 kV
Generator Power (per cav.) = 393.3 kW
Generator Voltage (at res.) = 1369 kV
Generator Voltage = 238.5 kV

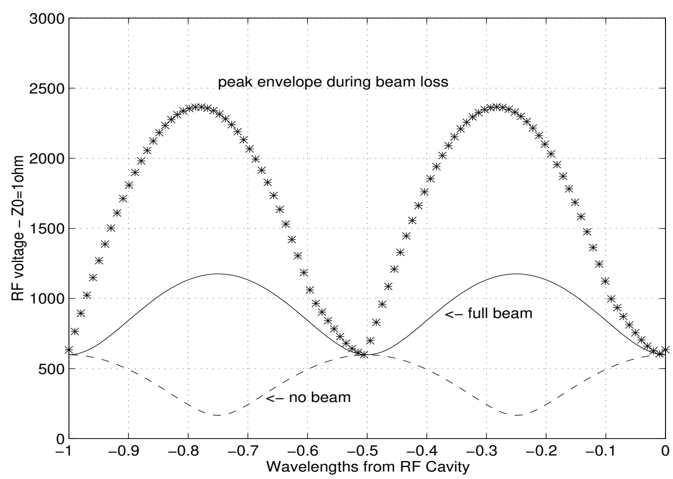

Figure 5. Waveguide voltage envelope.

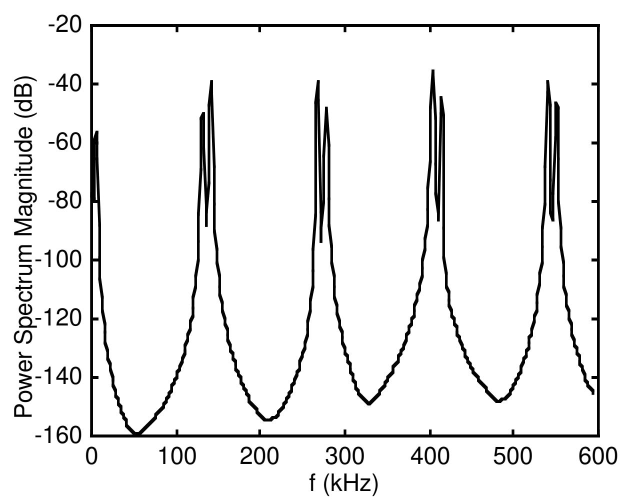

Figure 6. Bunch Spectrum

7. CONCLUSIONS

A model of the PEP-II RF feedback including the beam is in use to verify the stability, through time domain simulations, of the PEP-II system. It is possible to obtain both time-domain as well as frequency-domain responses from the same model. In this way one can be more confident that the system being simulated has the desired properties. It should be possible to also test other feedback schemes using this model, for example, adaptive feedback to control gap transients. The model is nearing the completion of testing and will be run to verify the stability of the LER beam and RF parameters.

8. REFERENCES

[1] D. Boussard, "Control of Cavities with High Beam Loading", IEEE Trans. Nucl. Sci. NS-32, p.1852, 1985.

[2] F. Pedersen, "A Novel RF Cavity Tuning Feedback Scheme For Heavy Beam Loading",IEEE Trans. Nucl. Sci. NS-32, p.2138, 1985.

[3] F. Pedersen , RF Cavity Feedback, SLAC 400, 1992.

[4] Simulink, The Mathworks, Natick, MA 01760 USA

[5] S.T. Craig, "RF Cavity Control System for the SLAC/LBL B Factory, AECL 10776

[6] B.R. Cheo, S.P. Jachim, Dynamic Interactions Between RF Sources and LINAC Cavities with Beam Loading, IEEE Trans. on Elec. Dev., Vol 38, No. 10, Oct 1991.

[7] H. Schwarz, R. Rimmer, "RF System Design for the PEP-II B Factory", this conference.