

# SIMULATION OF THE APS STORAGE-RING RF SYSTEM

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## Abstract

A simulation model for the APS storage ring rf system has been developed that includes the effects of cavity impedances, longitudinal beam dynamics, and generator klystrons. The model predicts multiple-bunch longitudinal beam behavior and is used for feedback system design and stability analysis.

## 1 INTRODUCTION

Presented here is a description of a computer-based model used to simulate the Advanced Photon Source (APS) 7-GeV storage ring rf system. Relevant system parameters are given in Table 1. The Matlab<sup>®</sup>-Simulink<sup>®</sup> software package was used for implementing the model. Some useful features of this package used for this model include the ability to have subsystem components or blocks that are nonlinear, time-varying, and/or mixed (discrete with continuous time). Also, different blocks can have different sampling rates. The overall model includes the cavity, the beam, the generator (klystron), and feedback and feedforward electronics (Figure 1).

The motivation behind the simulation effort is two-fold. First, simulation is required in order to predict the beam's longitudinal dynamics, especially when there are significant gaps in beam current between bunches or between groups of bunches and when the charge significantly varies from bunch to bunch [1]. Second, the efficacy of the present and proposed low-level control schemes can be tested with such a model.

Table 1: RF System Parameters

Bunch revolution frequency, $f_0$	271.56 kHz	
Harmonic number, $h$	1296	
Cavity shunt impedance, $R$	5.6 M $\Omega$	
Unloaded Q, $Q_0$	40000	
Cavity coupling, $\beta$	3.5	
Number of cavities	16	
Number of klystrons	4	
Momentum compaction, $\alpha$	2.28 E-4	
	<b>OPERATION</b>	
Average beam current, $I_0$	100 mA	300 mA
Gap voltage (whole ring), $V_{rf}$	8.0 MV	12.0 MV
Stable phase (from rf crest)	47.1 $^\circ$	63.0 $^\circ$
Synchrotron frequency	1.70 kHz	2.30 kHz
Cavity detuning from fundamental, $\Delta f$	-7.22 kHz	-17.6 kHz

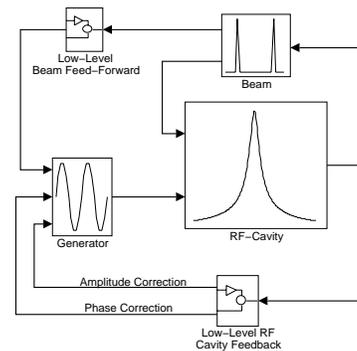


Figure 1: Overall block diagram used in the simulation.

In order to meet these requirements, the model simulates the continuous-time cavity voltage, as powered by both the (controllable) generator and the beam image-current, and the turn-by-turn, multiple-bunch difference equations of longitudinal motion that describe the effect of the cavity on the beam. Work is in progress to include cavity higher-order mode (HOM) resonances, so that a complete picture of beam stability can be obtained through simulation.

Several simplifications are made in order to speed up computer run-time. To avoid running the simulation at MHz frequencies, all signals are decomposed into their baseband, in-phase and quadrature (I and Q) projections in the vector plane that rotates at the angular radio-frequency  $\omega_{rf}$  [2]. Rather than directly simulating error-inducing beam injection, the cavity fields are set in an errorless steady state, and the beam bunch phases are then allowed to oscillate, using some initial phase-error condition(s). In addition, the number of bunches used in the simulation is intentionally limited, so as to speed up the run-time.

## 2 MODEL COMPONENTS

### 2.1 Cavity

The cavity fundamental-resonance impedance is modelled as a linear, second-order harmonic oscillator, or RLC circuit, parameterized in the complex frequency domain (s) by:

$$Z = \frac{2\sigma R s}{s^2 + 2\sigma s + (\omega_{rf} + 2\pi\Delta f)^2}, \quad (1)$$

where  $\sigma = \frac{(\omega_{rf} + 2\pi\Delta f)}{2Q}$ . Other parameter values for

Eq. (1) used in the simulation can be found in Table 1. The linear, time-invariant property of this model permits a superposition of the rf and beam image-current as inputs to the cavity block of Figure 1.

In order to empirically verify the standard [1] cavity model of Eq. (1), a cold-model-cavity measurement near

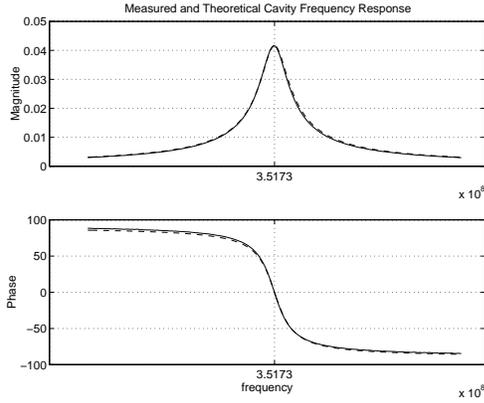


Figure 2: Measured frequency response (solid) and theoretical (dashed).

the rf fundamental was performed using an HP network analyzer. The resulting observed resonant frequency,  $Q$ , and gain were then used as parameters for Eq. (1). Plots of both data sets are given in Figure 2, showing that the model is well borne out by experiment.

For the simulation, the cavity shunt impedance is scaled so that the effects of all sixteen cavities (on the beam) are lumped into one resonance. This simplification is justified given the small synchrotron tune (Table 1); i.e., for a given bunch, effectively small longitudinal motion occurs within one revolution, therefore the even smaller motion that occurs between successive cavities can be ignored.

## 2.2 Beam

As each bunch passes through the cavity, the beam block shown in Figure 1 inputs a sample of the cavity voltage in order to update that bunch's phase, as governed by the following difference equations (modified from [3] to allow for time-varying cavity voltage):

$$\Delta\phi_{n+1}^i = \Delta\phi_n^i - \frac{\alpha\omega_{rf}T_o}{V_o}\Delta V_{n+1}^i \quad (2)$$

$$\Delta V_{n+1}^i = \Delta V_n^i + (V_a)_n^i - V_c \cos\phi_s \quad (3)$$

All quantities denoted with a superscript (bunch number) and a subscript (that bunch's pass through the cavity) refer to bunch-sampled continuous-time (rf) parameters. Otherwise, variables refer to constants, such as  $V_o$ , the stable beam energy (7.0 GeV) given here in volts, and  $\phi_s$ , the stable phase w.r.t. the peak of the cavity voltage set-point  $V_c$ . For the  $i^{\text{th}}$  bunch at its  $n^{\text{th}}$  turn,  $\Delta V_n^i$  denotes the deviation from  $V_o$ , and  $\Delta\phi_n^i$  denotes the *beam* phase deviation from its nominal zero-reference [1]. The quantity  $(V_a)_n^i$  thus represents the accelerating voltage for bunch  $i$  at its turn  $n$ , and it is given by the I/Q projection of  $(V_c)_n^i$  onto  $\Delta\phi_n^i$ .

The beam block outputs beam-image current, partitioned into a number of segments corresponding to the number of bunches being simulated and the number and size of gaps in current. The amplitude of a given bunch over all turns is taken as constant, i.e., no quadrupole oscillations are assumed; however, the phase varies as

described above. In addition, the amplitude of the image current over each revolution period is, of course, fill-pattern dependent.

For example, in typical operation 36 or 48 bunches may be uniformly concentrated in four groups about the ring, thereby creating a uniform, but gapped, fill pattern. Also used are non-uniform gapped fill patterns, for example, ones with a small leading group of successive bunches (i.e., no empty buckets between them) followed by a small gap, and then a large number of bunches and a large trailing gap. Such a fill pattern and the AM and PM modulations it induces on the cavity voltage are shown in Fig. 3(a-c), respectively. The stable, steady-state synchronous phases of individual bunches are thus also fill-pattern-dependent, and the simulation is a tool to determine these [1]. Certain fill patterns are empirically known to induce coupled-bunch instabilities, for which certain cavity HOMs have been implicated [4]. Although the HOM effects have not been (as yet) included in the simulation model, some fill patterns have been shown to cause instability even through the cavity fundamental.

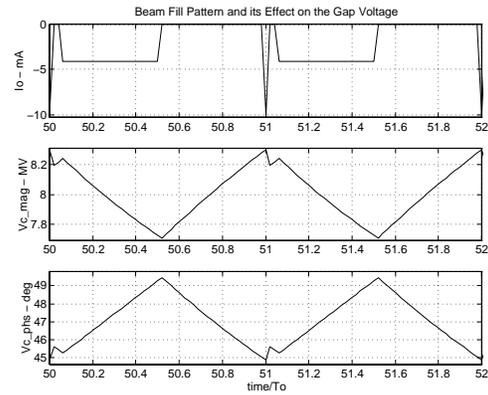


Figure 3: The asymmetric gapped fill pattern, shown over two revolutions (a), induces AM and PM modulations of the cavity gap-voltage shown in (b) and (c), respectively. The nominal cavity set points are 8.0 MV and  $47.1^\circ$ .

## 2.3 Klystron

In present operations, with DC beam current less than 160 mA, there is no need to drive the klystrons into power-saturation. However, this AM-limiting saturation effect, due to the klystron, its power supply, or both, is foreseen as operation approaches the full available power (3 MW). The saturation effects are under study and will be incorporated into the model. Presently, a linear klystron is assumed.

## 2.4 Low-Level RF System [5]

Two cavity feedback loops are now in operation in the storage ring: a low-bandwidth cavity tuning loop and a cavity-phase-sum feedback loop. The first loop is omitted from the model. Its has a relatively low bandwidth (less than 1 kHz) requiring too much additional simulation time to resolve its dynamic effect on the beam. Moreover, beam phase errors induced during injection (transient beam load-

ing) are well accounted for as perturbations to the cavity and beam steady state, as already mentioned.

The actual cavity-phase-sum loop compares the sum-signal of a group of four cavity phase measurements to a setpoint and feeds back the error through a PID controller to adjust the phase of their dedicated klystron. For the simulation the summing nature of the phase loop is of course omitted. The loop bandwidth has been measured to be near 7 kHz [6], corresponding roughly to the cavity bandwidth. The time-delay for the largest rf-station-to-cavity distance is 6  $\mu$ s; it is included in the model as the nominal cable delay.

To date, a simple gain-scheduling algorithm has proven sufficient to insure the magnitude of the cavity gap voltage. However, since a cavity-amplitude feedback is foreseen, this loop is added to test its effect. To demonstrate the added utility of a beam phase-error feedforward, this loop has been added as well. Presently, the longitudinal motion of the beam is monitored using a dedicated storage ring BPM pickup button, so that a beam-phase signal could be incorporated into the overall low-level system with relative ease.

### 3 SOME SIMULATION RESULTS

Figures 4-5 are useful to visualize operation with 100 mA and 300 mA. For a given  $V_{rf}$  (Table 1) and an optimally detuned cavity (i.e. zero loading-angle), one can see the limit on stored beam due to the Robinson stability criterion (shaded area) and the limit due to available power (dashed line). Thus, while stability for dipole oscillations is guaranteed, still a beam feedforward aids in damping these oscillations more quickly as can be seen from Figure 6 (dash-dot case). Of course, for arbitrary beam offsets across all bunches and for cases when each bunch has its own synchronous phase, such a system may damp the oscillations of one bunch while driving those of another bunch. A bunch-by-bunch feedback system then becomes an attractive solution.

### 4 ACKNOWLEDGMENTS

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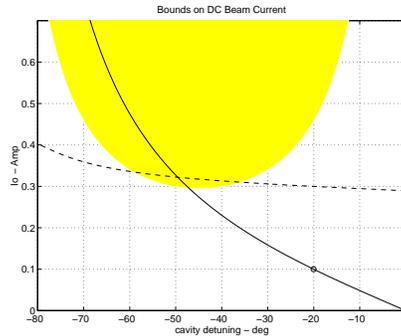


Figure 4: Bounds on beam current  $I_0$ , when cavities are detuned optimally (solid line), assuming  $V_{rf} = 8.0$  MV. The shaded area is due to the Robinson instability, and the dashed curve is due to the available power (assumed  $< 3$  MW). The o marks operation at 100 mA.

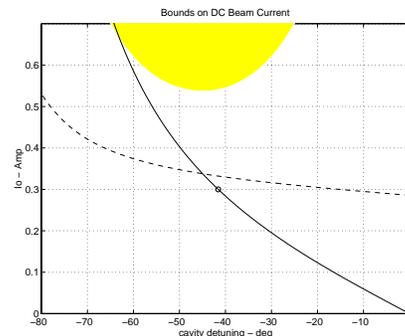


Figure 5: Bounds on beam current  $I_0$ , when cavities are detuned optimally (solid line), assuming  $V_{rf} = 12.0$  MV. The shaded area is due to the Robinson instability, and the dashed curve is due to the available power (assumed  $< 3$  MW). The o marks operation at 300 mA.

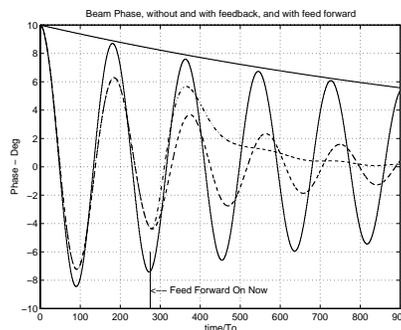


Figure 6: When all bunches are offset by  $10^\circ$ , the error oscillates (solid), damped with an envelope given by  $10e^{-t/Td}$  (also shown). With LLRF feedback the damping improves (dashed), and even more so with the beam feedforward on (dash-dot).