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<b>University of Wisconsin-Synchrotron Radiation Center TECHNICAL NOTE</b>	<b><u>File No.</u> 205</b>	<b><u>Page</u> 1 of 7</b>
<b><u>Subject:</u>  Instability modeling for passive harmonic-cavity operation at UVSOR</b>	<b><u>Author(s):</u> R. A. Bosch</b>	
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### ABSTRACT

Instability modeling is performed for third harmonic cavity operation at the 600 MeV UVSOR electron storage ring. The analytic predictions are in approximate agreement with simulations of 960 macroparticles and experimental observations at UVSOR.

## 1. Introduction

The UVSOR 600-MeV electron storage ring utilizes a passive third harmonic radiofrequency (RF) cavity for suppression of parasitic longitudinal coupled bunch instabilities and increased lifetime [1]. Measurements of longitudinal beam stability have been recently performed with a streak camera for a current of 200 mA and several tuning angles of the harmonic cavity [2].

In this note, analytical modeling and simulations predict instabilities for harmonic-cavity operation with the UVSOR parameters, using computer codes described in References [3] and [4]. The UVSOR parameters are shown in Table I, in the notation of Ref. [3]. The parameters  $\omega_{CB}$  and  $Z(\omega_{CB})$  are estimates of the angular frequency and impedance of a typical higher-order cavity resonance that may excite a parasitic coupled bunch instability at Aladdin [5]. Since the UVSOR fundamental RF frequency of 90.115 MHz is comparable to that of Aladdin (50.582 MHz), we use these estimates for UVSOR.

The analytical modeling and simulations are in approximate agreement, and consistent with the UVSOR measurements.

## 2. Modeling of Robinson instabilities

### (a) Analytic modeling

We first consider coupled dipole and quadrupole Robinson modes that may be excited by the dominant resonances of the fundamental and harmonic RF cavities. We also consider the possibility of exciting a dipole coupled bunch instability with longitudinal mode numbers of 1 or  $M - 1$ , where  $M = 16$  is the number of bunches. At UVSOR, the fundamental RF cavity is operated with a “load angle”  $\theta_{v1}$  of  $-40^\circ$ , i.e., the total RF voltage lags the generator current by  $40^\circ$ . To model this case requires modification of our codes, which assume operation in the “compensated condition” where the load angle is zero. The required modification of our algorithm is obtained by generalizing eq. (21) of Ref. [3], which determines the tuning angle of the fundamental cavity  $\phi_1$ . In the notation of Ref. [3], the generalized equation is [6]

$$\phi_1 = \tan^{-1} \left[ 2F_1 IR_1 \sin \psi_1 / V_{T1} - \tan \theta_{v1} (1 + 2F_1 IR_1 \cos \psi_1 / V_{T1}) \right] \quad (1)$$

For operation in the compensated condition ( $\theta_{v1} = 0$ ), eq. (1) reduces to eq. (21) of Ref. [3].

Analytic instability modeling is shown in Fig. 1(a). As in the case of Aladdin operation with the standard “base” lattice, optimally lengthened bunches are predicted to be stable for ring currents exceeding  $\sim 120$  mA, while additional bunchlengthening is predicted to excite a coupled-quadrupole Robinson instability. For lower ring currents, optimally lengthened bunches are predicted to be unstable.

For a ring current of 200 mA, the coupled quadrupole Robinson instability is predicted to onset when the harmonic cavity voltage is 2% larger than optimal ( $\xi = 1.02$  in the notation of Ref. [3]) with a frequency of 12.7 kHz. For  $\xi = 1.05$ , the predicted frequency is 13.2 kHz, in agreement with the observed unstable 13 kHz bunch length oscillation shown in Fig. 1 of Ref. [2] for  $\xi \approx 1.05$ .

### (a) Simulations

We simulated UVSOR harmonic cavity operation by longitudinal tracking of 500,000 turns with 960 macroparticles, which gives 60 macroparticles/bunch. To model the nonzero load angle, eq. (1) was used to compute the tuning angle of the fundamental RF cavity.

For ring currents exceeding 240 mA, the macroparticles' phases changed at nearly a constant rate from the beginning of the simulations. This may be attributed to the initial conditions of the simulations, in which the contribution of the macroparticle wakes to the RF voltages was zero. Consequently, confining RF buckets may not exist until the RF voltages from the macroparticle wakes approach equilibrium. If the macroparticle phases change sufficiently during this time period, the RF bucket may not form and the macroparticles will not be confined. To remedy this effect, the code was changed so that the initial RF voltages include the equilibrium wake from the macroparticles. In the notation of Ref. [3], the initial RF in-phase and quadrature voltage contributions from wake fields were changed from zero to

$$V_{bc1} = -2F_1IR_1 \cos^2 \phi_1, \quad V_{bs1} = F_1IR_1 \sin 2\phi_1, \quad V_{bc2} = -2F_2IR_2 \cos^2 \phi_2, \quad V_{bs2} = F_2IR_2 \sin 2\phi_2 \quad (2)$$

This remedy allows successful UVSOR simulations for currents exceeding 240 mA, with little effect upon UVSOR simulations at lower currents. We verified that this remedy also has little effect upon simulations of Aladdin.

In these 500,000-turn simulations of bunches injected at the synchronous phase, a final energy spread that exceeds the natural value by more than 10% is taken to indicate the presence of instability. A shift in phase of stable bunches by more than 2.35 times the rms bunch length is taken to signify that an equilibrium phase instability has previously occurred [4, 7]. Simulation results are shown in Fig. 1(b), in which an “o” is plotted when the final energy spread exceeds the natural value by  $> 10\%$ . The equilibrium phase instability did not occur. The simulation results are in close agreement with the analytic modeling shown in Fig. 1(a).

For a ring current of 200 mA, the unstable simulation for a tuning angle of  $-89.75^\circ$  showed a sinusoidal dependence of bunch phase shift upon bunch number, consistent with the analytic prediction of coupled bunch instability with longitudinal mode number of 1. For the unstable simulation at a current of 200 mA and tuning angle of  $-81.75^\circ$  ( $\xi = 1.095$ ), fast Fourier transforms [8] were performed of the bunches' average centroid position and bunchlength, sampled every 100 turns during the final 409,600 turns. The fast Fourier transforms peak at a frequency of 13.8 kHz, in approximate agreement with the frequency computed analytically for coupled-quadrupole Robinson instability (14.2 kHz) and the frequency of bunchlength oscillations observed at UVSOR (13 kHz) [2].

### 3. Parasitic coupled bunch instabilities

The analytic modeling also predicts whether radiation damping and Landau damping will suppress a parasitic dipole coupled bunch instability caused by resonant interaction with the impedance  $Z(\omega_{CB})$  at frequency  $\sim \omega_{CB}$ . Figure 2 displays analytic predictions of parasitic coupled bunch instabilities in addition to the instability predictions of Fig. 1(a). According to Fig. 2, operation without Robinson or parasitic coupled bunch instabilities may be obtained for currents of 100–300 mA by using near-optimal bunchlengthening. This is consistent with UVSOR observations that stable operation may be obtained for currents of 110–300 mA [9].

For a current of 200 mA, sufficient Landau damping to suppress parasitic coupled bunch instabilities is predicted by our analytic code for  $\xi > 0.87$ . This threshold is consistent with UVSOR observations of parasitic coupled bunch instability suppression for  $\xi \geq 0.9$  [2].

## 4. Summary

For UVSOR parameters, analytic modeling and simulations of Robinson instabilities are in approximate agreement, and consistent with experiments. Analytic predictions of parasitic coupled bunch instabilities are also consistent with UVSOR observations.

This study resulted in code modifications that allow modeling of nonzero load angles, and improved initial conditions in simulations. Comparison with UVSOR experiments suggests that our analytic modeling and simulations are approximately valid.

## Acknowledgments

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Parameter	Value
$E$	600 MeV
$\sigma_E/E$	$3.4 \times 10^{-4}$
$V_s$	5.4 kV
$T_o$	$1.77 \times 10^{-7}$ s
$\omega_g$	$5.67 \times 10^8$ rad/s
$M$	16 bunches
$R_1^\circ$ (unloaded)	0.5 M $\Omega$
$Q_1^\circ$ (unloaded)	7500
$\beta_1$	1.5
$\nu$	3
$R_2^\circ$ (unloaded)	0.79 M $\Omega$
$Q_2^\circ$ (unloaded)	9200
$\beta_2$ (passive)	1
$\omega_{CB}$	$6.28 \times 10^9$ rad/s
$Z(\omega_{CB})$	10 k $\Omega$
$V_{T1}$	46 kV
$\alpha$	0.03
$\tau_L$	19 ms
load angle $\theta_{v1}$	$-40^\circ$

Table I. UVSOR parameters (courtesy of M. Hosaka).

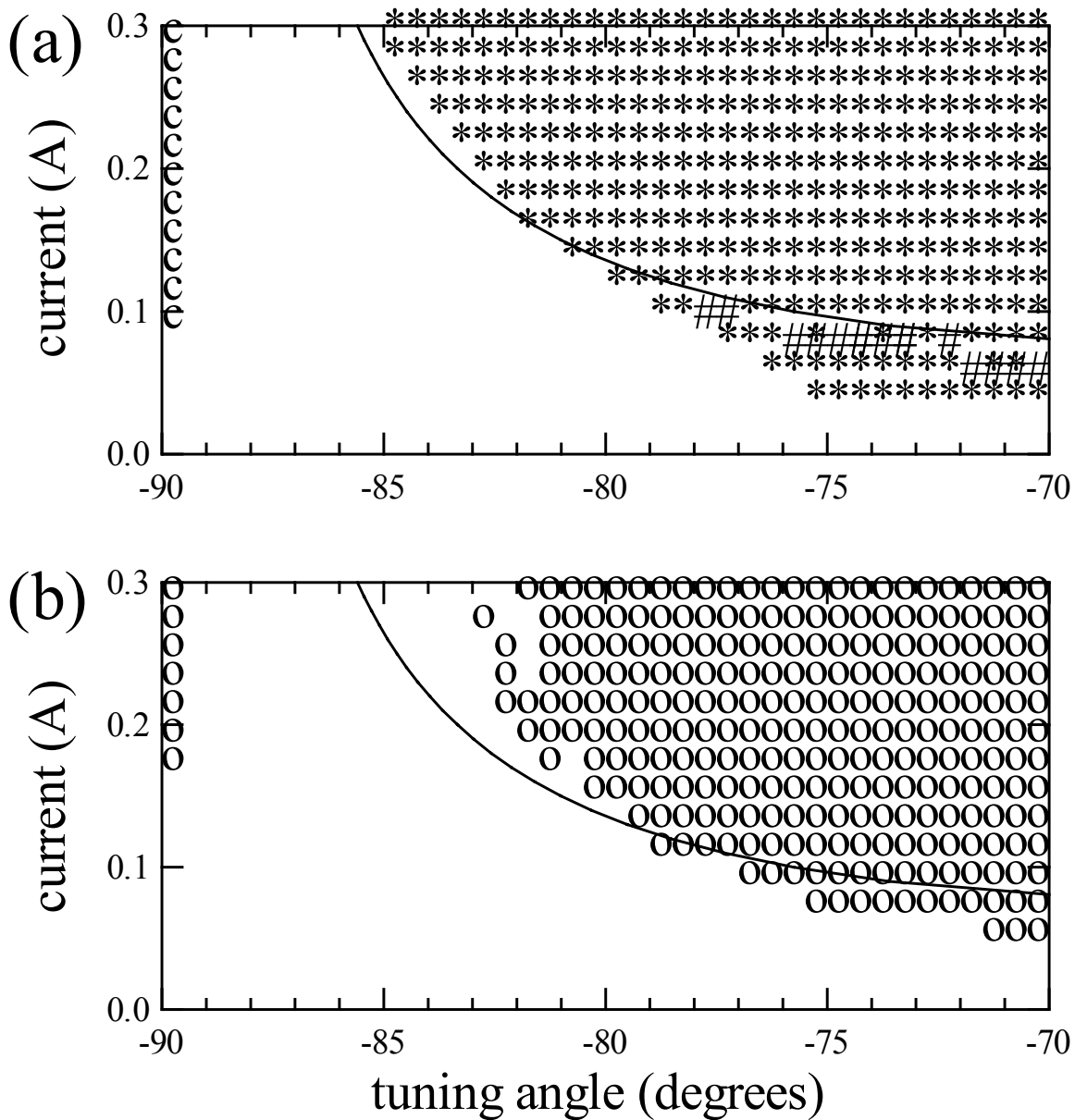


Figure 1. Instability modeling for passive harmonic-cavity operation at UVSOR. A solid curve shows the parameters for optimal bunch lengthening. To the left of this curve, the bunches are “understretched” with a Gaussian profile. To the right, the bunches are “overstretched” double-hump bunches. (a) Analytic instability predictions. |: coupled dipole Robinson instability; \*: coupled quadrupole Robinson instability; #: fast mode-coupling Robinson instability; c: coupled-bunch instability with longitudinal mode number of 1. (b) Instabilities observed in 500,000-turn simulations.

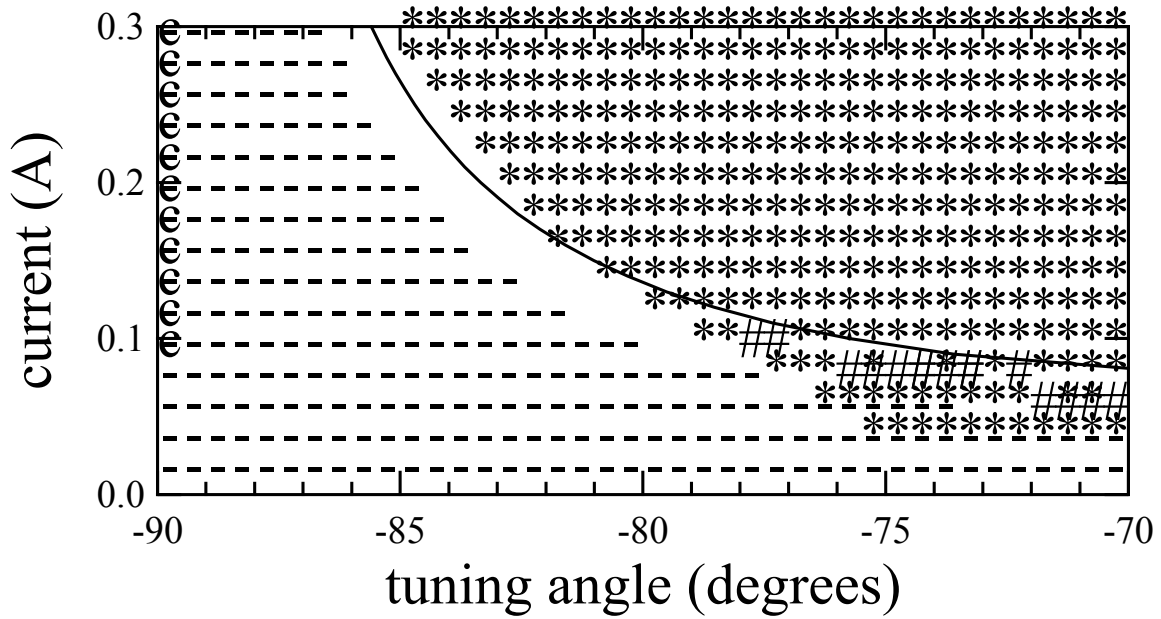


Figure 2. Analytic instability predictions for passive harmonic-cavity operation at UVSOR. A solid curve shows the parameters for optimal bunch lengthening. |: coupled dipole Robinson instability; \*: coupled quadrupole Robinson instability; #: fast mode-coupling Robinson instability; c: coupled-bunch instability with longitudinal mode number of 1; -: parasitic coupled bunch instability.