A passive higher-harmonic cavity may be used to suppress parasitic longitudinal coupled-bunch instabilities. Our analytic modeling already predicts whether a parasitic higher-order mode (HOM) will cause longitudinal coupled bunch instability for a worst-case scenario where a synchrotron sideband has the same frequency as the HOM. An analytic prediction of whether a broadband HOM will cause microwave instability has also been added to the modeling.

The capability to include a higher-order mode (HOM) has also been added to a simulation code that models Robinson instabilities with a higher harmonic cavity. To speed the computations, the fundamental modes in the RF cavities and the HOM wake fields are represented by in-phase and quadrature components.

The analytic modeling and simulations are compared for passive harmonic-cavity operation of Aladdin with the base lattice and low-emittance lattice, for the UVSOR ring, and for MAXlab rings. For the parasitic coupled bunch instability, the analytic predictions are in approximate agreement with simulations. For the microwave instability, the analytic predictions are in rough agreement with simulations.

For low-emittance operation of the Aladdin ring, the bunchlength in simulations of the microwave instability is consistent with experimental measurements. This suggests that our estimate of the reduced longitudinal broadband impedance (5.7 Ω) is reasonable.

In modeling of MAX-II, a typical parasitic coupled-bunch instability is suppressed by the harmonic cavity in the new 100-MHz/500-MHz RF system and the previously installed 500-MHz/1500-MHz RF system. Both RF systems are expected to show little or no evidence of microwave instability at full ring energy, provided that the reduced longitudinal broadband impedance is less than 4 Ω.

The simulations confirm that a passive harmonic cavity may be used to suppress parasitic coupled bunch instabilities, in approximate agreement with the analytic model.
1. INTRODUCTION

A passive harmonic radiofrequency (RF) cavity may be utilized to lengthen the bunch and suppress longitudinal parasitic coupled bunch instabilities. The harmonic cavity voltage required to suppress the parasitic coupled bunch instabilities may be predicted analytically [1]. For harmonic-cavity operation at Aladdin (in high- and low-emittance lattices) and UVSOR, the analytic predictions are in approximate agreement with experiment [1, 2].

We have now added an analytic prediction of whether a broadband HOM will excite the microwave instability. This prediction considers the negative-mass instability of a coasting beam whose current equals the peak current in a bunch. If the negative-mass instability excited at angular frequency $\omega = 1/\sigma_t$ (where $\sigma_t$ is the rms bunch length) has frequency shift larger than the phase-mix damping from the beam’s velocity spread, instability is predicted. This is the criterion that is used by the ZAP code [3].

The suppression of parasitic coupled bunch and microwave instabilities by a harmonic cavity may also be simulated [4]. Since we have already developed a simulation code to study Robinson instabilities [1], we added the capability of simulating a HOM to the existing code. To speed computations, all wake fields are represented by in-phase and quadrature components [5].

Instabilities observed in simulations are compared with analytic predictions of parasitic coupled bunch instability for several lattices and rings. Approximate agreement in observed. The simulations confirm that a passive harmonic cavity may be used to suppress parasitic coupled bunch instabilities.

A comparison of microwave-instability predictions and simulations shows rough agreement. In simulations of the Aladdin low-emittance lattice, microwave instability occurs throughout the operating current range of 90–280 mA; the energy spread is increased above the natural value by more than 100% for ring currents exceeding 200 mA. As a result, the simulated bunchlength increases with current, in approximate agreement with experimental measurements of bunch length. This suggests that our estimate of the reduced longitudinal broadband impedance (5.7 $\Omega$) [6] is reasonable.

For MAX-II, the parasitic coupled-bunch instability we considered may be suppressed by using the harmonic cavity in the new 100-MHz/500-MHz RF system and the previously installed 500-MHz/1500-MHz RF system. Both RF systems are expected to show little or no evidence of microwave instability at full ring energy, provided that the reduced longitudinal broadband impedance is less than 4 $\Omega$.

2. COMPUTATIONAL METHODS

A. Analytic estimates of instability thresholds

Consider a HOM with angular resonant frequency $\omega_3$, resonant impedance $R_3$, and quality factor $Q_3$. When the width of the HOM resonance, $\omega_3/2Q_3$, is smaller than $2\omega_0$, where $\omega_0$ is the ring’s angular recirculation frequency, the HOM impedance may be excited by a single rotation sideband [7] to cause parasitic coupled-bunch instability. The worst-case scenario is when the HOM resonant frequency equals a sideband frequency. To approximate this case, we extrapolate an approximate criterion for a mostly quadratic synchrotron potential to the non-quadratic potentials obtained with a harmonic cavity [1]. For single-hump bunch shapes, instability thresholds are expected to be approximated within ~10%, while the accuracy for double-hump bunches may be less.

For resonant interaction with a parasitic cavity mode, the complex frequency shift is imaginary with magnitude equaling the coupled bunch growth rate, given by

$$|\Delta \Omega_{CB}| = \frac{e\alpha \omega_3 R_3 F_{\omega_3}}{2E\gamma \omega_0}$$

(1)
where $F_{\omega_3}$ is the bunch form factor at frequency $\omega_3$. Here, $e$ is the magnitude of the electron charge, $I$ is the magnitude of the ring’s average current, $\alpha$ is the momentum compaction, $E$ is the ring energy, $T_o$ is the ring’s recirculation time, and $\omega_R$ is the rigid-dipole oscillation frequency [1]. If the growth rate remains positive after subtracting the radiation-damping rate $\tau_L^{-1}$, it is compared with the approximate dipole Landau damping rate [1] to estimate whether Landau damping is sufficient to prevent instability. If the estimated Landau damping is insufficient, parasitic coupled bunch instability is predicted.

To determine whether microwave instability will be caused by a broadband HOM (when $\omega_3/2Q_3$ is larger than $2\omega_0$), we consider the negative-mass instability growth rate for a coasting beam whose current equals the peak bunch current. For ring energies large compared to the transition energy, the complex instability frequency for mode frequency $\omega$ obeys

$$\Omega^2 = \frac{i\alpha I_p \omega Z(\omega)}{E T_o}$$

(2)

where $I_p$ is the peak current (equaling $(2\pi)^{1/2} I / \omega R \sigma_t$ for a Gaussian bunch) and $\omega_R$ is the RF frequency. Here $Z(\omega)$ is the broadband impedance at the mode frequency $\omega$. To overcome the phase-mix damping from the velocity spread of a coasting beam requires that

$$|\Omega| > |k\Delta v| = \frac{\omega}{c} \left| |\alpha| \frac{\sigma_E}{E} \right| = |\omega \alpha| \frac{\sigma_E}{E}$$

(3)

where $k = \omega/c$ is the instability wavenumber and $\sigma_E/E$ is the beam’s relative energy spread. Equations (2) and (3) predict that the ring’s average current must exceed a threshold for instability given by

$$I_{\text{threshold}} = \frac{\omega_R \sigma_t}{\sqrt{2\pi} \ e} T_o \left| \alpha \left( \frac{\sigma_E}{E} \right)^2 \frac{\omega}{Z(\omega)} \right|$$

(4)

For typical broadband impedance models, the threshold current increases with increasing $\omega$. For a bunch of length $\sigma_t$, we estimate that the smallest possible mode frequency has $\omega \approx 1/\sigma_t$, which is the same estimate used in the ZAP code [3]. Thus, the threshold current for a mode characterized by $\omega_3$, $R_3$, and $Q_3$ is estimated to be

$$I_{\text{threshold}} = \frac{\omega_R \sigma_t}{\sqrt{2\pi} \ e} T_o \left| \alpha \left( \frac{\sigma_E}{E} \right)^2 \frac{1 + Q_3^2 \left( \omega_3 \sigma_t - \frac{1}{\omega_3 \sigma_t} \right)}{R_3} \right|^{1/2}$$

(5)

If the ring current exceeds the predicted threshold current, microwave instability is predicted.

The analytic prediction of coupled-bunch instability excited by the harmonic cavity has been extended to include longitudinal mode numbers of $\pm 2$ and $\pm 3$, in addition to the mode numbers of $\pm 1$ that were previously considered [1]. In addition, our codes can now model cavities in which the RF generator power is supplied with a nonzero load angle [2].

**B. In-phase and quadrature components of wake fields**

When a particle of charge $q < 0$ passes through an RF cavity at time $t = 0$, the physical wake field at time $t$ from a resonant cavity mode with resonant frequency $\omega$ obeys for $0 < t < \infty$ [7]
\[ \Delta V(t) = q \frac{2R}{\tau} e^{t/\tau} \left[ \cos \omega t - \left( \frac{1}{\omega} \right) \sin \omega t \right], \]  

where \( R \) is the impedance at resonance, \( Q \) is the quality factor, \( \tau \equiv 2Q/\omega \) is the mode’s damping time constant, and \( \omega \equiv \omega_0 \sqrt{1 - (1/2Q)^2} \). The physical wake field is causal, equaling 0 for \( t < 0 \) and one-half the value given by eq. (6) for \( t = 0 \). In our computations, we consider an “analytic” wake field given by eq. (6) for \(-\infty < t < \infty\). By using the analytic wake field, the effect of a particle’s wake may be accounted for by its contribution to the cavity voltage at an arbitrary reference time, which may precede the particle’s passage through the cavity. Provided that the analytic wake field is only used to compute forces for \( t > 0 \), the analytic wake field gives the correct forces.

Consider the superposition of analytic wake fields from numerous macroparticles. Let \( \omega_g \) represent the ring’s RF frequency, with RF period \( t_g \equiv 2\pi/\omega_g \). Let \( t = 0 \) correspond to a synchronous phase of the steady-state RF voltage. For non-negative integer \( \nu \), the cavity mode’s field may be represented by in-phase and quadrature components [5] relative to the harmonic frequency \( \nu \omega_g \)

\[ V(t) = V_c(t) \cos(\nu \omega_g t) - V_s(t) \sin(\nu \omega_g t). \]  

Here, \( V_c(t) \) is called the in-phase component while \( V_s(t) \) is called the quadrature component. When a particle passes through the RF cavity at time \( t = 0 \), these components are modified by

\[ \Delta V_c(t) = q \frac{2R}{\tau} e^{t/\tau} \left[ \cos \Delta \omega t - \left( \frac{1}{\omega} \right) \sin \Delta \omega t \right], \quad \Delta V_s(t) = q \frac{2R}{\tau} e^{t/\tau} \left[ \sin \Delta \omega t + \left( \frac{1}{\omega} \right) \cos \Delta \omega t \right], \]  

for \(-\infty < t < \infty\), where \( \Delta \omega \equiv \omega - \nu \omega_g \). For a high-\( Q \) mode, an approximation to eq. (8) is given in Ref. [8]. For integral \( n \), the analytic wake produced at synchronous time \( nt_g \) by a particle passing through the cavity at time \( nt_g + tm \) has in-phase and quadrature components

\[ \Delta V_c(nt_g) = q \frac{2R}{\tau} e^{nt_g/\tau} \left[ \cos \Delta \omega t_m + \left( \frac{1}{\omega} \right) \sin \Delta \omega t_m \right] \cos(\nu \omega_g t_m) \]

\[ + \left[ \sin \Delta \omega t_m - \left( \frac{1}{\omega} \right) \cos \Delta \omega t_m \right] \sin(\nu \omega_g t_m) \]

\[ \Delta V_s(nt_g) = -q \frac{2R}{\tau} e^{nt_g/\tau} \left[ \sin \Delta \omega t_m + \left( \frac{1}{\omega} \right) \cos \Delta \omega t_m \right] \cos(\nu \omega_g t_m) \]

\[ + \left[ \cos \Delta \omega t_m + \left( \frac{1}{\omega} \right) \sin \Delta \omega t_m \right] \sin(\nu \omega_g t_m) \]

The cavity field experienced by a macroparticle passing through the cavity at time \( nt_g + tm \) is related to the in-phase and quadrature voltages at the synchronous time \( nt_g \) by

\[ V(nt_g + tm) = e^{-tm/\tau} \left[ V_c(nt_g) \cos \Delta \omega t_m - V_s(nt_g) \sin \Delta \omega t_m \right] \cos(\nu \omega_g t_m) \]

\[ + e^{-tm/\tau} \left[ V_s(nt_g) \cos \Delta \omega t_m + V_c(nt_g) \sin \Delta \omega t_m \right] \sin(\nu \omega_g t_m). \]  

Letting \( tm = t_g \) in eq. (10) shows that the in-phase and quadrature fields at the synchronous time \((n + 1)t_g \) are related to those at the synchronous time \( nt_g \) by

\[ V_c[(n+1)t_g] = e^{-t_g/\tau} \left[ V_c(nt_g) \cos \Delta \omega t_g - V_s(nt_g) \sin \Delta \omega t_g \right], \]

\[ V_s[(n+1)t_g] = e^{-t_g/\tau} \left[ V_s(nt_g) \cos \Delta \omega t_g + V_c(nt_g) \sin \Delta \omega t_g \right]. \]  

**C. Dominant modes of the RF cavities**

Consider the high-\( Q \) dominant mode of an RF cavity whose resonant angular frequency \( \omega \) is near to \( \nu \omega_g \). For Aladdin, \( \nu = 1 \) describes the fundamental RF cavity while \( \nu = 4 \) describes the harmonic RF
cavity. We describe the wake fields using the in-phase and quadrature voltage relative to the frequency \( \nu \omega_g \), where computations are speeded by making the following approximations.

For a high-\( Q \) mode, we approximate \( \Delta \omega \approx \omega - \nu \omega_g \). For a macroparticle in the \( n \)th bunch with arrival time \( nt_d + t_m \) (where \( |t_m| < t_d/2 \)), we approximate \( \cos(\Delta \omega t_m) \approx 1 \), \( \sin(\Delta \omega t_m) \approx 0 \) and \( \exp(-t_m/\tau) \approx 1 \). Applying these approximations to eq. (9) gives the analytic wake field in-phase and quadrature components at the reference time \( nt_d \)

\[
\Delta V_c(nt_d) = q[(2R/\tau)\cos \nu \omega_g t_m + (R/\nu Q \tau)\sin \nu \omega_g t_m],
\]

\[
\Delta V_s(nt_d) = q[(R/\nu Q \tau)\cos \nu \omega_g t_m - (2R/\tau)\sin \nu \omega_g t_m].
\]

Applying these approximations to eq. (10) gives the cavity field at time \( nt_d + t_m \) as

\[
V(nt_d + t_m) = V_c(nt_d)\cos(\nu \omega_g t_m) - V_s(nt_d)\sin(\nu \omega_g t_m).
\]

The use of eqs. (11)–(13) in tracking is described in eqs. (23)–(31) of Ref. [1], for the case where the cavity mode may also be excited by an RF generator current.

For steady-state operation, the wake field’s in-phase and quadrature components relative to the frequency \( \nu \omega_g \) are constant, given by [1]

\[
V_c = -2FIR \cos^2 \phi, \quad V_s = FIR \sin 2\phi,
\]

where \( F \) is the bunch form factor for frequency \( \nu \omega_g \), \( I \) is the magnitude of the ring current, and \( \phi \) is the cavity’s tuning angle, defined by \( \tan \phi \equiv 2Q(\nu \omega_g - \omega)/\omega \). By describing wakefields with in-phase and quadrature components relative to the frequency \( \nu \omega_g \), a simulation may be initiated with these components equal to their steady-state values. This decreases the loss of macroparticles at the beginning of simulations [2].

D. Higher order modes

To model an HOM of arbitrary \( Q \), we cannot use the approximate equations (12)–(13). We instead use the in-phase and quadrature voltage relative to the harmonic with \( \nu = 0 \), which is equivalent to the method described in Ref. [9]. In this case, the cavity field equals the in-phase component, while the quadrature component is required to relate fields at different times. For \( \nu = 0 \), \( \Delta \omega \) equals \( \overline{\omega} \), and a macroparticle’s wake at the synchronous time \( nt_d \), given by eq. (9), obeys

\[
\Delta V_c(nt_d) = q(2R/\tau)e^{i\omega t_d}\left[\cos(\overline{\omega} t_m) + (1/\overline{\omega} \tau)\sin(\overline{\omega} t_m)\right],
\]

\[
\Delta V_s(nt_d) = -q(2R/\tau)e^{i\omega t_d}\left[\sin(\overline{\omega} t_m) - (1/\overline{\omega} \tau)\cos(\overline{\omega} t_m)\right].
\]

The cavity field experienced by a particle passing the cavity at time \( nt_d + t_m \) is given by eq. (10) as

\[
V(nt_d + t_m) = e^{-i\omega t_m}\left[V_c(nt_d)\cos(\overline{\omega} t_m) - V_s(nt_d)\sin(\overline{\omega} t_m)\right].
\]

The cavity field at synchronous time \((n + 1)t_d\) is related to that at time \( nt_d \) by eq. (11), which becomes

\[
V_c\left[nt_d\right] = e^{-i\omega t_d}\left[V_c\left(nt_d\right)\cos(\overline{\omega} t_m) - V_s\left(nt_d\right)\sin(\overline{\omega} t_m)\right],
\]

\[
V_s\left[nt_d\right] = e^{-i\omega t_d}\left[V_s\left(nt_d\right)\cos(\overline{\omega} t_m) + V_c\left(nt_d\right)\sin(\overline{\omega} t_m)\right].
\]

Equations (15)–(17) are applied to tracking a HOM in the same way that eqs. (11)–(13) are used for the dominant cavity modes.
E. Initial conditions

In the first versions of our simulation code [1], the macroparticle tracking was initiated with all macroparticles at the calculated synchronous phase with no energy offsets. The synchronous phase was calculated for the steady-state RF fields, which include the steady-state RF wakefields. However, the initial value of the RF wakefields was zero.

In simulations of the UVSOR storage ring with ring currents exceeding 240 mA, the macroparticles’ phase changed at nearly a constant rate from the start of the simulations, resulting in their loss [2]. (In our code, a macroparticle with $|t_m| \geq t_g/2$ is considered lost. After a macroparticle is “lost,” it is not tracked, and its wakefield no longer contributes to the computed cavity fields.) These losses resulted from the initial conditions, in which the contribution of the macroparticle wakes to the RF voltage was zero. Consequently, confining RF buckets may not exist until the RF voltages from the macroparticle wakes approach steady state. If the macroparticle phases change sufficiently during this time period, the RF bucket may not form and the macroparticles may be lost.

To remedy this situation, the code was changed so that the initial values of the RF wakefields equal their steady-state values for the dominant RF modes of the fundamental and harmonic cavities. The values of these wakefields are given by eq. (14). This allowed successful simulations for UVSOR.

The initiation of simulations with all macroparticles at the same phase may also be problematic, since their combined wakefield exceeds the steady-state value for cases where the steady-state form factor is $<< 1$ (e.g., over-stretched double-hump bunches). To decrease macroparticle losses from this effect, the code was modified so that the macroparticles are first tracked for two radiation-damping times with the calculated RF wakefields of the dominant RF cavity modes in the two cavities. This creates an initial macroparticle distribution that approximates the steady-state distribution.

At this point, the simulation begins with the excitation of wakefields by the macroparticles and their decay from finite quality factors. The effects of HOM wakefields are also included at this point, with the HOM impedance ramped linearly from zero over the first two radiation-damping times of the simulation. This allows the macroparticles to gradually adjust to the presence of the HOM wakes.

These modifications of the initial conditions have reduced the loss of macroparticles in simulations.

3. RESULTS

A. Parasitic coupled bunch instability

Analytic predictions of parasitic coupled-bunch instability were considered for the Aladdin ring operated in base lattice and low-emittance tunings, UVSOR, the MAX-II ring with two RF systems, the MAX-III ring, and preliminary designs of the MAX-IV ring operated at 1.5 GeV and 3 GeV ring energies. A damped parasitic mode with $Q_3 = 3000$, $R_3 = 10$ kΩ, and $\omega_3 \approx 2\pi \times 10^9$ radians/s was modeled. In each case, the resonant frequency of the higher-order mode ($\omega_3$) was adjusted to equal a multiple of the ring’s revolution frequency, to approximately obtain worst-case instability growth with longitudinal mode number different from 0, 1 or $-1$. Parameters are given in Appendixes A–H. For each case, a variety of ring currents and passive harmonic-cavity tuning angles were considered. If instability is predicted analytically, a symbol is plotted in part (a) of Figs. 1–8. The instability symbols used are $-$: parasitic coupled-bunch instability; $|$: coupled-dipole Robinson instability; $*$: coupled-quadrupole Robinson instability; #: fast dipole-quadrupole Robinson mode-coupling instability; c: coupled-bunch instability with longitudinal mode number of $\pm 1$, $\pm 2$ or $\pm 3$; /: equilibrium phase Robinson instability; \: zero-frequency coupled dipole-quadrupole Robinson instability.

Simulations of 500,000 turns were then performed for the same ring currents and tuning angles as the analytic predictions. In part (b) of Figs. 1–8, an “o” is plotted when the electrons’ energy spread is
increased above the natural value by more than 10%. A “/” is plotted when the bunch centroids are shifted (on average) by more than 2.35\(\sigma\) from their initial calculated equilibrium positions, while a “\" is plotted when any macroparticles are lost. The appearance of an “o” in part (b) may be taken as an indication of instability, while a “/” may result from equilibrium phase instability \[10\] (or potential well distortion, in the case of a broadband HOM). A “\" is inconclusive, since macroparticles may be lost at the initiation of a simulation or as a result of instability.

In part (c) of Figs. 1–8, an “o” is plotted when the electrons’ energy spread is increased above the natural value by more than 30%, while an “o” is plotted in part (d) when the electrons’ energy spread is increased above the natural value by more than 100%. The appearance of an “o” in parts (c) and (d) may be taken to indicate instabilities that are not saturated by energy-spread increases of 30% and 100%, respectively.

In all cases, there is approximate agreement between the analytic predictions of part (a) and the simulated instabilities observed in part (b). Although the agreement is fairly good, the analytic model tends to slightly underestimate the occurrence of parasitic coupled-bunch instabilities. In several cases, the analytic predictions of part (a) agree better with part (c), indicating that the analytic model may underestimate the energy spread required to damp instability by as much as 30%.

A comparison of Figs. (1) and (2) indicates that parasitic coupled-bunch instabilities are more easily suppressed with the Aladdin base lattice than with the low-emittance lattice. In MAX-II modeling, the parasitic coupled-bunch instability is suppressed by using the harmonic cavity in the 100-MHz/500-MHz RF system or the 500-MHz/1500-MHz RF system.

Our simulations confirm that parasitic coupled bunch instabilities may be suppressed by using a passive harmonic cavity. The simulations also indicate that our analytic predictions of this suppression are approximately valid. For the Aladdin and UVSOR rings, experimental observations also support the approximate validity of the analytic predictions and simulations \[1, 2\].

B. Microwave instability

For the Aladdin base lattice and low-emittance lattice, the microwave instability may be driven by the reduced longitudinal broadband impedance of the vacuum chamber, estimated to be \(|\frac{Z_p}{p}| \approx 5.7\) ohms with cutoff frequency \(\approx 1.27\) GHz \[6\]. We model this impedance by a mode with \(Q_3 = 1\), \(\omega_3 = 8 \times 10^9\) radians/s, and \(R_3 = 2148\) \(\Omega\). In part (a) of Figs. 9–10, an “m” is plotted when the microwave instability is predicted analytically. The results of simulations are shown in Figs. 9–10, parts (b)–(d), where 60 macroparticles per bunch were simulated. Rough agreement between the analytic predictions and simulations are obtained. The microwave instability occurs at lower values of the ring current with the low-emittance lattice.

For the low-emittance lattice, the energy spread in simulations is significantly increased when the ring current is \(\geq 40\) mA, thereby affecting the entire operating range of 90–280 mA. For ring currents exceeding 200 mA, the energy spread in simulations is more than twice the natural value. The harmonic cavity has a modest effect upon the microwave instability.

The increased energy spread in simulations of currents exceeding \(\approx 2\) mA/bunch is consistent with measurements of bunch length in single-bunch operation, where the bunch length exceeds its natural value and increases with bunch current. Figure 11 shows bunch length measurements obtained by observing synchrotron radiation with a photodiode, and by observing the voltage induced upon a 0.365-m stripline. Also shown are simulated bunch lengths for single-bunch operation with the harmonic cavity detuned (tuning angle = \(-90^\circ\)), for \(|\frac{Z_p}{p}| = 2.85\) \(\Omega\), 5.7 \(\Omega\), and 11.4 \(\Omega\). Since the unstable bunch length fluctuates, an average over the final 500,000 turns of a 1,000,000-turn simulation is plotted for each current. Within the experimental uncertainty, the simulated bunch lengths for \(|\frac{Z_p}{p}| = 2.85\) \(\Omega\) and 5.7 \(\Omega\)
are in agreement with the measurements, suggesting that the impedance estimate of $|Z_p/p| \approx 5.7$ ohms is reasonable.

For the MAX-II ring with a 100-MHz/500-MHz RF system, the vacuum chamber dimensions are comparable to Aladdin. Thus, we again considered microwave instability excitation by broadband impedance with $Q_3 = 1$ and $\omega_3 = 8 \times 10^9$ radians/s. To model $|Z_p/p| = 1$ or $2$ $\Omega$, resonant impedances $R_3$ of 382 and 764 $\Omega$ were considered. For ring currents less than the operating maximum of 300 mA, microwave instabilities were not predicted analytically or observed in simulations of 30 macroparticles per bunch. To model $|Z_p/p| = 4$ $\Omega$, a resonant impedance of 1528 $\Omega$ was modeled. Analytic predictions and simulation results for $|Z_p/p| = 4$ $\Omega$ are shown in Fig. 12. In many of the simulations for currents exceeding 200 mA, the energy spread was increased, in approximate agreement with the analytic modeling. Therefore, reduced broadband impedance below 4 $\Omega$ appears desirable for stable operation of MAX-II. Broadband impedances of 8, 16 and 32 $\Omega$ are modeled in Figs. 13–15, showing increased instability.

For the MAX-II ring with the previously installed 500-MHz/1500-MHz RF system, we modeled the same broadband impedances, using 20 macroparticles per bunch in simulations. For ring currents less than the operating maximum of 300 mA, microwave instability was not predicted analytically or observed in simulations for $|Z_p/p| \leq 4$ $\Omega$. Figure 16 shows results for $|Z_p/p| = 8$ $\Omega$. Microwave instability is not predicted analytically. In simulations, microwave instability from the broadband impedance is observed for currents of 280 and 300 mA, when the harmonic-cavity tuning angle is $-88.25^\circ$.

Figure 17 shows results for $|Z_p/p| = 16$ $\Omega$. Microwave instability is predicted analytically for double-hump bunches when the ring current exceeds 200 mA. In simulations, the microwave instability occurs for single-hump bunches with ring currents $\geq 260$ mA, in rough agreement with the analytic model. Figure 18 shows the increased instability with $|Z_p/p| = 32$ $\Omega$. For our broadband impedance model, the 500-MHz/1500-MHz RF system is less prone to the microwave instability.

Since the MAX-II vacuum chamber has button-type beam-position monitors rather than the high-impedance striplines of Aladdin, its broadband impedance may be somewhat less than the value of 5.7 $\Omega$ estimated for Aladdin. Thus, the microwave instability is expected to have little effect at full ring energy with either of the MAX-II RF systems.

4. SUMMARY

For RF systems with a passive higher harmonic cavity, analytic predictions of parasitic coupled bunch instability and microwave instability have been compared with simulations. For parasitic coupled bunch instabilities, approximate agreement is obtained, in which the analytic predictions slightly underestimate the occurrence of instability. For the microwave instability, rough agreement is obtained between the analytic predictions and simulations for the Aladdin ring and MAX-II. Tuning in a harmonic cavity has a modest effect upon the microwave instability.

For low-emittance operation of the Aladdin ring, the bunchlength in simulations of the microwave instability is consistent with experimental measurements. This suggests that our estimate of the reduced longitudinal broadband impedance (5.7 $\Omega$) is reasonable.

In modeling of MAX-II, a typical parasitic coupled-bunch instability is suppressed by the harmonic cavity in the new 100-MHz/500-MHz RF system and the previously installed 500-MHz/1500-MHz RF system. Both RF systems are expected to show little or no evidence of microwave instability at full ring energy, provided that the reduced longitudinal broadband impedance is less than 4 $\Omega$.

The analytic predictions and simulations both confirm that a passive harmonic cavity may be used to suppress parasitic coupled bunch instabilities, consistent with experiments [1, 2].


Figure 1. Modeling for the Aladdin base lattice with the harmonic cavity’s circulator detached. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including worst-case parasitic coupled bunch instability. (b) Results of 500000-turn simulations of 60 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding $2.35\sigma_t$, and “\” indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased by more than 100%.
Figure 2. Modeling for the Aladdin standard low-emittance lattice with the harmonic cavity’s circulator attached. A solid curve shows parameters for optimal bunch lengthening. (a) Analytic predictions including parasitic coupled bunch instability. (b) Results of 500000-turn simulations of 60 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding $2.35 \sigma_t$, and “\" indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 3. Instability modeling of UVSOR with a third-harmonic cavity. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including worst-case parasitic coupled bunch instability. (b) Results of 500000-turn simulations of 60 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding 2.35σt, and “\” indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 4. Instability modeling for MAX-II with a 100-MHz/500-MHz RF system. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including worst-case parasitic coupled bunch instability. (b) Results of 500000-turn simulations of 30 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding $2.35\sigma_t$, and “\" indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 5. Instability modeling for MAX-II with the previously installed 500-MHz/1500-MHz RF system. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including parasitic coupled bunch instability. (b) Results of 500000-turn simulations of 10 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding 2.35σ_t, and “\” indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 6. Instability modeling for MAX-III with a 100-MHz/500-MHz RF system that uses two harmonic cavities. A solid curve shows optimal bunch lengthening. (a) Analytic predictions including parasitic coupled bunch instability. (b) Results of 500000-turn simulations of 75 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding 2.35σt, and “\” indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 7. Instability modeling for MAX-IV at 1.5 GeV with a 100-MHz/500-MHz RF system. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including worst-case parasitic coupled bunch instability. (b) Results of 500000-turn simulations of 10 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding $2.35\sigma_t$, and “\” indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 8. Instability modeling for MAX-IV at 3 GeV with a 100-MHz/500-MHz RF system. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including worst-case parasitic coupled bunch instability. (b) Results of 500000-turn simulations of 10 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding $2.35\sigma_t$, and “\" indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 9. Modeling for the Aladdin base lattice with the Landau cavity’s circulator detached. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including microwave instability for $|Z/p| = 5.7 \Omega$. (b) Results of 500000-turn simulations of 60 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding $2.35\sigma_i$, and “\” indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 10. Modeling for the Aladdin standard low-emittance lattice with the harmonic cavity’s circulator attached. A solid curve shows optimal bunch lengthening. (a) Analytic predictions including microwave instability for $|Z_p/p| = 5.7 \, \Omega$. (b) Results of 500000-turn simulations of 60 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding $2.35\sigma_t$, and “\" indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 11. Bunchlength of the standard low-emittance lattice (LF15) for single-bunch operation with an RF voltage of 50 kV, where the harmonic cavity is detuned. Bunchlength measurements were obtained by using a photodiode to observe synchrotron radiation, and by measuring the voltage induced upon a 0.365-m stripline. The bunchlength from simulations shows the rms bunchlength averaged over the final 500,000 turns of 1,000,000-turn simulations of 60 macroparticles, with harmonic-cavity tuning angle of $-90^\circ$. Simulation results for $|Z_{p}/p| = 2.85 \, \Omega$, 5.7 $\Omega$, and 11.4 $\Omega$ are displayed.
Figure 12. Instability modeling for MAX-II with a 100-MHz/500-MHz RF system. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including microwave instability for $|Z_p/p| = 4 \, \Omega$. (b) Results of 500000-turn simulations of 30 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding $2.35\sigma_t$, and “\" indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 13. Instability modeling for MAX-II with a 100-MHz/500-MHz RF system. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including microwave instability for $|Z_p/p| = 8 \Omega$. (b) Results of 500000-turn simulations of 30 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding $2.35\sigma_t$, and “\” indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 14. Instability modeling for MAX-II with a 100-MHz/500-MHz RF system. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including microwave instability for $|Z_p/p| = 16 \, \Omega$. (b) Results of 500000-turn simulations of 30 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding 2.35$\sigma_t$, and “\" indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 15. Instability modeling for MAX-II with a 100-MHz/500-MHz RF system. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including microwave instability for $|Z/p| = 32 \, \Omega$. (b) Results of 500000-turn simulations of 30 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding $2.35\sigma_t$, and “\” indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 16. Modeling for MAX-II with the previously installed 500-MHz/1500-MHz RF system. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including microwave instability for $|Z_p/p| = 8 \, \Omega$. (b) Results of 500000-turn simulations of 20 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding $2.35\sigma_t$, and “\” indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 17. Modeling for MAX-II with the previously installed 500-MHz/1500-MHz RF system. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including microwave instability for $|Z_p/p| = 16 \, \Omega$. (b) Results of 500000-turn simulations of 20 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding $2.35 \sigma_t$, and “\” indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Figure 18. Modeling for MAX-II with the previously installed 500-MHz/1500-MHz RF system. A solid curve shows the parameters for optimal bunch lengthening. (a) Analytic predictions including microwave instability for $|Z_p/p| = 32$ Ω. (b) Results of 500000-turn simulations of 20 macroparticles/bunch, where “o” indicates that the energy spread has increased more than 10%, “/” indicates a shift in bunch position exceeding 2.35σt, and “\” indicates lost macroparticles. (c) Simulation results: “o” indicates that the energy spread has increased more than 30%. (d) Simulation results: “o” indicates that the energy spread has increased more than 100%.
Appendix A. Input file with parameters for the Aladdin Base Lattice at 800 MeV

C data for 4th harmonic cavity, base lattice
90.e3 ! vt1 = Cavity 1 peak voltage
11. ! beta1 = Cav. 1 RF coupling coefficient
8000. ! q1o = Cavity 1 quality factor (unloaded)
0.5e6 ! r1o = Cavity 1 impedance at resonance (unloaded)
0. ! loadangle1 (deg) > 0 when generator current lags cavity volts
0.0335 ! alpha = momentum compaction
2.96e-7 ! t = recirculation time
15 ! Nbucket = total number of buckets, including empty buckets
0.8e9 ! Ee = electron energy/charge, i.e. energy in eV
4.8e-4 ! sigmaeo = relative energy spread from synchrotron radiation
17.4e3 ! vs = energy loss/revolution from synchrotron radiation (volts)
13.8e-3 ! t_L = longitudinal radiation damping time (seconds)
4 ! nu = Cavity 2 harmonic number
0. ! beta2 = Cav. 2 coupling coefficient
20250. ! q2o = Cavity 2 quality factor (unloaded)
1.24e6 ! r2o = Cav. 2 resonant impedance (unloaded)
3000. ! q3 = HOM quality factor (parasitic or broadband)
10.e3 ! R3 = HOM mode resonant impedance (ohms)
6.28319e9 ! w3 = HOM mode angular frequency
0.020 ! imin, current (mA) to be modeled
0.305 ! imax, placeholder not needed by passive_15
0.020 ! delta_i, placeholder not needed by passive_15
-89.75 ! phi2_degrees = min Cav. 2 tuning angle to be modeled (degrees)
-74.75 ! phi2_max, placeholder not needed by passive_15
0.5 ! delta_phi2, placeholder not needed by passive_15
1. ! damp: 1 to consider Landau damping of Robinson modes, 0: w/o
0. ! t_feedback: dipole-mode damping time (seconds); 0. for no feedback
100 ! Nturn_ubar: response time (in turns) for measuring bunch energy
60 ! M = number of macroparticles/bunch
15 ! Nbunch = number of bunches (i.e., filled buckets)
500000 ! Nturnmax = number of turns to track
100 ! Nturnwrite = number of turns to skip between writing output
Appendix B. Input file with parameters for the Aladdin low-emittance lattice

```plaintext
C  data for 4th harmonic cavity, alpha = .006
50.e3  ! vt1 = Cavity 1 peak voltage
11.    ! beta1 = Cav. 1 RF coupling coefficient
8000.  ! q1o = Cavity 1 quality factor (unloaded)
0.5e6  ! r1o = Cavity 1 impedance at resonance (unloaded)
0.    ! loadangle1 (deg) > 0 when generator current lags cavity volts
0.006  ! alpha = momentum compaction
2.96e-7  ! t = recirculation time
15    ! Nbucket = total number of buckets, including empty buckets
0.8e9  ! Ee = electron energy/charge, i.e. energy in eV
4.8e-4  ! sigmaeo = relative energy spread from synchrotron radiation
17.4e3  ! vs = energy loss/revolution from synchrotron radiation (volts)
13.5e-3  ! t_L = longitudinal radiation damping time (seconds)
4    ! nu = Cavity 2 harmonic number
1.5  ! beta2 = Cav. 2 coupling coefficient
20250.  ! q2o = Cavity 2 quality factor (unloaded)
1.24e6  ! r2o = Cav.2 resonant impedance (unloaded)
3000.  ! q3 = HOM quality factor (parasitic or broadband)
10.e3  ! R3 = HOM mode resonant impedance (ohms)
6.28319e9  ! w3 = HOM mode angular frequency
0.020  ! imin, current (mA) to be modeled
0.305  ! imax, placeholder not needed by passive_15
0.020  ! delta_i, placeholder not needed by passive_15
-89.75  ! phi2_degrees = min Cav. 2 tuning angle to be modeled (degrees)
-74.75  ! phi2_max, placeholder not needed by passive_15
0.5  ! delta_phi2, placeholder not needed by passive_15
1.  ! damp: 1 to consider Landau damping of Robinson modes, 0: w/o
0.  ! t_feedback: dipole-mode damping time (seconds); 0. for no feedback
100  ! Nturn_ebar: response time (in turns) for measuring bunch energy
60  ! M = number of macroparticles/bunch
15  ! Nbunch = number of bunches (i.e., filled buckets)
500000  ! Nturnmax = number of turns to track
100  ! Nturnwrite = number of turns to skip between writing output
```
Appendix C. Input file with parameters for UVSOR

C data for UVSOR, 3rd harmonic cavity (values from Masahito Hosaka)

46.e3 ! vt1 = Cavity 1 peak voltage (volts)
1.5  ! beta1 = Cav. 1 RF coupling coefficient
7500. ! q1o = Cavity 1 quality factor (unloaded)
500000. ! r1o = Cavity 1 impedance at resonance (unloaded) (ohms)
-40. ! loadangle1 (deg) > 0 when generator current lags cavity volts
0.03 ! alpha = momentum compaction
1.77e-7 ! t = recirculation time (s)
16 ! Nbucket = total number of buckets, including empty buckets
0.600e9 ! Ee = electron energy/charge, i.e. energy in eV
3.4e-4 ! sigmaeo = relative energy spread from synchrotron radiation
5.4e3 ! vs = energy loss/revolution from synchrotron radiation (volts)
19.e-3 ! t_L = longitudinal radiation damping time (seconds)
3. ! nu = Cavity 2 harmonic number
1. ! beta2 = Cav. 2 RF coupling coefficient
9200. ! q2o = Cavity 2 quality factor (unloaded)
0.79e6 ! r2o = Cav. 2 resonant impedance (unloaded)
3000. ! Q3 = HOM quality factor
10.e3 ! R3 = HOM impedance (ohms)
6.354182e9 ! w3 = HOM angular frequency (rad/s)
0.020 ! imin = min current (mA) to be modeled
0.305 ! imax = maximum ring current to be calculated (A)
0.020 ! delta_i = ring current increment between calculations (A)
-89.75 ! phi2_min = minimum Landau tuning angle to model (degrees)
-69.75 ! phi2_max = maximum Landau tuning angle to model (degrees)
0.5 ! delta_phi2 = Landau tuning angle increment between calculations
1. ! damp=1: consider Landau damping of Robinson modes, 0: w/o
0. ! t_feedback: dipole-mode damping time (seconds); 0. for no feedback
100 ! Nturn_ebar: response time (in turns) for measuring bunch energy
60 ! M = number of macroparticles/bunch
16 ! Nbunch = number of bunches (i.e., filled buckets)
500000 ! Nturnmax = number of turns to track
100 ! Nturnwrite = number of turns to skip between writing output
Appendix D. Input file with parameters for MAX-II with a 100-MHz/500-MHz RF system

C data for MAXII, nu=5, updated at MAXlab 2/16/04, new format 6/23/04
450.e3 ! vt1 = Cavity 1 peak voltage (volts)
3. ! beta1 = Cav. 1 RF coupling coefficient
19000. ! q1o = Cavity 1 quality factor (unloaded)
4.8e6 ! r1o = Cavity 1 impedance at resonance (unloaded) (ohms)
0. ! loadangle1: generator current lags cavity voltage by loadangle1 (deg)
0.004 ! alpha = momentum compaction
3.0e-7 ! To = recirculation time (s)
30 ! Nbucket = number of buckets, including empty buckets
1.5e9 ! Ee = electron energy/charge, i.e. energy in eV
7.e-4 ! sigmae = relative energy spread from synchrotron radiation
140.e3 ! vs = energy loss/revolution from synchrotron radiation (volts)
3.2e-3 ! t_L = longitudinal radiation damping time (seconds)
5 ! nu = Cavity 2 harmonic number
24000. ! q2o = Cavity 2 quality factor (unloaded)
1.7e6 ! r2o = Cav. 2 resonant impedance (unloaded)
3000. ! Q3 = HOM quality factor
10.e3 ! R3 = HOM impedance (ohms)
6.220353e9 ! w3 = HOM angular frequency (radian/s)
0.020 ! imin = minimum ring current to be modeled (A)
0.300 ! imax = maximum ring current to be modeled (A)
0.020 ! delta_i = ring current increment between calculations (A)
-89.75 ! phi2 min = minimum Landau tuning angle to be modeled (degrees)
-69.75 ! phi2 max = maximum Landau tuning angle to be modeled (degrees)
0.5 ! delta_phi2 = Landau tuning angle increment between calculations
1. ! damp=1: consider Landau damping of Robinson modes, 0: w/o
0. ! tfeedback: dipole-mode damping time (seconds); 0. for no feedback
1 ! Nturn_ebar: number of turns to measure energy offset
30 ! M = number of macroparticles per bucket
30 ! Nbunch = number of consecutive buckets in bunch train
500000 ! Nturn_max = number of turns to track
100 ! Nturnwrite = number of turns to skip between writing output
Appendix E. Input file for MAX-II with previously installed 500-MHz/1500-MHz RF system

C data for MAXII 500 MHz system, nu=3, 7/12/04
600.e3 ! vt1 = Cavity 1 peak voltage (volts)
3. ! beta1 = Cav. 1 RF coupling coefficient
40000. ! q1o = Cavity 1 quality factor (unloaded)
10.e6 ! r1o = Cavity 1 impedance at resonance (unloaded) (ohms)
-10. ! loadangle1: generator current lags cavity voltage by loadangle1 (deg)
0.004 ! alpha = momentum compaction
3.0e-7 ! To = recirculation time (s)
150 ! Nbucket = number of buckets, including empty buckets
1.5e9 ! Ee = electron energy/charge, i.e. energy in eV
7.e-4 ! sigmae = relative energy spread from synchrotron radiation
140.e3 ! vs = energy loss/revolution from synchrotron radiation (volts)
3.2e-3 ! t_L = longitudinal radiation damping time (seconds)
3 ! nu = Cavity 2 harmonic number
0. ! beta2 = Cav. 2 RF coupling coefficient
16000. ! q2o = Cavity 2 quality factor (unloaded)
4.0e6 ! r2o = Cav. 2 resonant impedance (unloaded)
3000. ! Q3 = HOM quality factor
10.e3 ! R3 = HOM impedance (ohms)
6.220353e9 ! w3 = HOM angular frequency (radian/s)
0.020 ! imin = minimum ring current to be modeled (A)
0.300 ! imax = maximum ring current to be modeled (A)
0.020 ! delta_i = ring current increment between calculations (A)
-89.75 ! phi2_min = minimum Landau tuning angle to be modeled (degrees)
-70. ! phi2_max = maximum Landau tuning angle to be modeled (degrees)
0.5 ! delta_phi2 = Landau tuning angle increment between calculations
1. ! damp=1: consider Landau damping of Robinson modes, 0: w/o
0. ! tfeedback: dipole-mode damping time (seconds); 0. for no feedback
1 ! Nturn_ebar: number of turns to measure energy offset
10 ! M = number of macroparticles per bucket
150 ! Nbunch = number of consecutive buckets in bunch train
500000 ! Nturn_max = number of turns to track
100 ! Nturnwrite = number of turns to skip between writing output
Appendix F. Input file with parameters for MAX-III with two harmonic cavities

C data for MAXIII, 5th harmonic cavity, updated at MAXlab 2/17/04
200.e3 ! vt1 = Cavity 1 peak voltage (volts)
2. ! beta1 = Cav. 1 RF coupling coefficient
19000. ! qlo = Cavity 1 quality factor (unloaded)
1.6e6 ! rlo = Cavity 1 impedance at resonance (unloaded) (ohms)
0. ! loadangle1: generator current lags cavity voltage by loadangle1 (deg)
0.035 ! alpha = momentum compaction
1.2e-7 ! To = recirculation time (s)
12 ! Nbucket = number of buckets, including empty buckets
0.700e9 ! Ee = electron energy/charge, i.e. energy in eV
6.e-4 ! sigmaeo = relative energy spread from synchrotron radiation
13.e3 ! vs = energy loss/revolution from synchrotron radiation (volts)
11.e-3 ! t_L = longitudinal radiation damping time (seconds)
5 ! nu = Cavity 2 harmonic number
0. ! beta2 = Cav. 2 RF coupling coefficient
24000. ! q2o = Cavity 2 quality factor (unloaded)
3.4e6 ! r2o = Cav. 2 resonant impedance (unloaded)
3000. ! Q3 = HOM quality factor
10.e3 ! R3 = HOM impedance (ohms)
6.126106e9 ! w3 = HOM angular frequency (rad/s)
0.020 ! imin = minimum ring current to be modeled (A)
0.305 ! imax = maximum ring current to be modeled (A)
0.020 ! delta_i = ring current increment between calculations (A)
-90. ! phi2_min = minimum Landau tuning angle to be modeled (degrees)
-79.75 ! phi2_max = maximum Landau tuning angle to be modeled (degrees)
0.25 ! delta_phi2 = Landau tuning angle increment between calculations
1. ! damp=1: consider Landau damping of Robinson modes, 0: w/o
0. ! tfeedback: dipole-mode damping time (seconds); 0. for no feedback
1 ! Nturn_ ebar: number of turns to measure energy offset
75 ! M = number of macroparticles per bunch
12 ! Nbunch = number of consecutive bunches in bunch train
500000 ! Nturn_max = number of turns to track
100 ! Nturnwrite = number of turns to skip between writing output
Appendix G. Input file for the MAX-IV, 1.5-GeV electron storage ring

C data for MAXIV-1.5 GeV, nu=5, updated at MAXlab, 2/20/04
500.e3  ! vt1 = Cavity 1 peak voltage (volts)
2.      ! beta1 = Cav. 1 RF coupling coefficient
19000.  ! q1o = Cavity 1 quality factor (unloaded)
6.8e6   ! r1o = Cavity 1 resonant impedance (unloaded)(ohms) for 4 cavities
0.      ! loadangle1: generator current lags cavity voltage by loadangle1(deg)
0.000738 ! alpha = momentum compaction
9.5e-7  ! To = recirculation time (s)
95      ! Nbucket = number of buckets, including empty buckets
1.5e9   ! Ee = electron energy/charge, i.e. energy in eV
4.927e-4 ! sigmae = relative energy spread from synchrotron radiation
42.2e3  ! vs = energy loss/revolution from synchrotron radiation (volts)
51.78e-3 ! t_L = longitudinal radiation damping time (seconds)
5      ! nu = Cavity 2 harmonic number
0.      ! beta2 = Cav. 2 RF coupling coefficient
24000.  ! q2o = Cavity 2 quality factor (unloaded)
1.7e6   ! r2o = Cav. 2 resonant impedance (unloaded) for 1 cavity
3000.   ! Q3 = HOM quality factor
10.e3   ! R3 = HOM impedance (ohms)
6.263344e9  ! w3 = HOM angular frequency (rad/s)
0.040  ! imin = minimum ring current to be calculated (A)
0.800  ! imax = maximum ring current to be calculated (A)
0.040  ! delta_i = ring current increment between calculations (A)
-90.   ! phi2_min = minimum Landau tuning angle to be calculated (degrees)
-70.   ! phi2_max = maximum Landau tuning angle to be calculated (degrees)
0.5    ! delta_phi2 = Landau tuning angle increment between calculations
1.      ! damp=1: consider Landau damping of Robinson modes, 0: w/o
0.      ! t_feedback: dipole-mode damping time (seconds); 0. for no feedback
1      ! Nturn_ebar: number of turns to measure energy offset
10     ! M = number of macroparticles per bucket
95     ! Nbunch = number of consecutive buckets in bunch train
500000  ! Nturn_max = number of turns to track
100    ! Nturnwrite = number of turns to skip between writing output
Appendix H. Input file with parameters for the MAX-IV, 3-GeV electron storage ring.

C data for MAXIV-3GeV nu=5, 2 Landau cavities, updated at MAXlab, reformatted 7/12/04
2250.e3  ! vt1 = Cavity 1 peak voltage (volts)
2.       ! betal = Cav. 1 RF coupling coefficient
19000.   ! q1o = Cavity 1 quality factor (unloaded)
17.e6    ! r1o = Cavity 1 impedance at resonance (unloaded) (ohms), 10 cavities
0.       ! loadangle1: generator current lags cavity voltage by loadangle1 (deg)
0.000738 ! alpha = momentum compaction
9.5e-7   ! To = recirculation time (s)
95       ! Nbucket = number of buckets, including empty buckets
3.0e9    ! Ee = electron energy/charge, i.e. energy in eV
9.854e-4 ! sigmae = relative energy spread from synchrotron radiation
675.1e3  ! vs = energy loss/revolution from synchrotron radiation (volts)
6.47e-3  ! t_L = longitudinal radiation damping time (seconds)
5        ! nu = Cavity 2 harmonic number
0.       ! beta2 = Cav. 2 RF coupling coefficient
24000.   ! q2o = Cavity 2 quality factor (unloaded)
3.4e6    ! r2o = Cavity 2 resonant impedance (unloaded) for 2 cavities
3000.    ! Q3 = HOM quality factor
10.e3    ! R3 = HOM impedance (ohms)
6.263344e9  ! w3 = HOM angular frequency (radian/s)
0.040   ! imin = minimum ring current to be calculated (A)
0.800   ! imax = maximum ring current to be calculated (A)
0.040   ! delta_i = ring current increment between calculations (A)
-90.    ! phi2_min = minimum Landau tuning angle to be calculated (degrees)
-70.    ! phi2_max = maximum Landau tuning angle to be calculated (degrees)
0.5     ! delta_phi2 = Landau tuning angle increment between calculations
1.      ! damp=1: consider Landau damping of Robinson modes, 0: w/o
0.      ! t_feedback: dipole-mode damping time (seconds); 0. for no feedback
1       ! Nturn_ebar: number of turns to measure energy offset for feedback
10      ! M = number of macroparticles per bucket
95      ! Nbunch = number of consecutive buckets in bunch train
500000  ! Nturn_max = number of turns to track
100     ! Nturnwrite = number of turns to skip between writing output