ROBINSON MODES AT ALADDIN*

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Abstract

A fourth harmonic radiofrequency (RF) cavity improves the beam lifetime of the Aladdin electron storage ring. When the harmonic cavity is operated with a low-emittance lattice, coupling between the dipole and quadrupole Robinson modes may cause instability. During stable operation, damped Robinson modes are observed in the spectrum of phase noise upon the beam.

1 PASSIVE HARMONIC CAVITY

The Aladdin 800-MeV 300-mA electron storage ring is now being operated with a low-emittance lattice [1]. When the bunches are lengthened by a fourth harmonic RF cavity, the small value of the momentum compaction results in coupling of the dipole and quadrupole Robinson modes [2]. A Robinson instability may result, in which all bunches oscillate longitudinally in unison.

The operation of a harmonic cavity may be described by a parameter ξ that is proportional to its voltage, where ξ equals 1 for an "optimally lengthened" bunch whose linear synchrotron frequency is zero [2, 3]. For $\xi << 1$, a quadratic synchrotron potential provides a Gaussian bunch shape, while $\xi > 1$ describes a double-hump bunch shape in a double-well synchrotron potential.

To analytically model Robinson instabilities with two RF cavities, the calculated frequency of a rigid bunch oscillation may be substituted for the synchrotron frequency in a formula describing Robinson instabilities in a quadratic RF potential [2]. For $\xi \leq 1$, quantitative agreement with simulations and measurements is obtained when coupling between the dipole and quadrupole Robinson modes is included in the analytic model. For double-hump bunches with $\xi > 1$, qualitative agreement is obtained in which some instabilities may occur that are not predicted by the analytic model.

For passive operation of a harmonic cavity, varying its resonant frequency (characterized by a "tuning angle" [2]) changes the value of ξ. Instability predictions for passive operation are shown in Fig. 1(a), for the case where an RF circulator (required for active operation) is attached to the harmonic cavity. An RF-coupling β_2 of 1.5 describes the circulator, while a momentum compaction of 0.006 (obtained from the measured low-current synchrotron frequency) describes the imperfect experimental implementation of the low-emittance lattice. The remaining parameters are theoretical low-emittance parameters given in Table 1 of Ref. [2]. We consider the case where power is supplied to the fundamental RF cavity by operation in the "compensated condition," in which the RF generator current is in phase with the cavity voltage [4].

In Fig. 1, a curved line shows the harmonic-cavity tuning angle that gives an optimally lengthened bunch with $\xi = 1$; double-hump bunches with $\xi > 1$ occur on the right hand side of this curve. For optimally lengthened bunches, a fast mode-coupling instability is predicted. Figure 1(b) shows instabilities observed in 500,000-turn longitudinal simulations of 900 macroparticles, which are injected at the synchronous phase within a single revolution [2]. An energy spread that exceeds the natural value by more than 10% is taken to indicate instability. Approximate agreement between analytic modeling and simulations is obtained.

The modeling and simulations agree with experimental observation of Robinson instabilities [2]. Experiments show that bunches with $\xi << 1$ also suffer from coupled-bunch instabilities driven by parasitic modes of the RF cavities. For ring currents exceeding ~100 mA, double-hump bunches with $\xi \approx 1.2$ do not suffer from Robinson

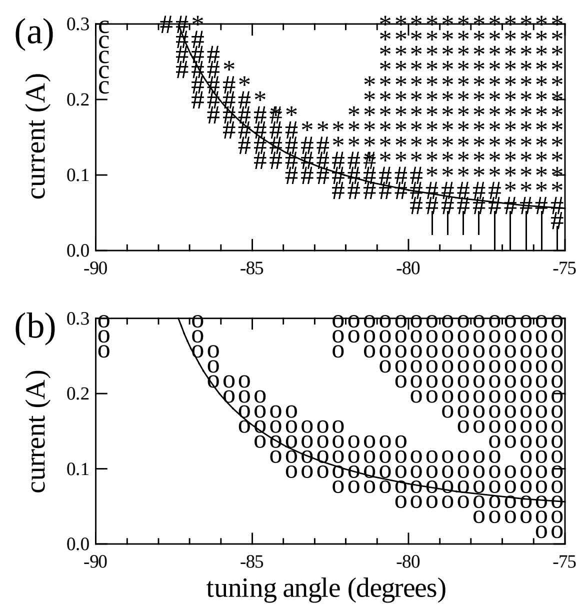

Figure 1. (a) Analytic instability predictions for passive harmonic-cavity operation with a low-emittance lattice. A solid curve shows the parameters for optimal bunch lengthening. |: coupled dipole Robinson instability; *: coupled quadrupole Robinson instability; #: fast mode-coupling Robinson instability; c: coupled-bunch instability with longitudinal mode number of 1. (b) Instabilities observed in 500,000 turn simulations.

* Work supported by NSF grant DMR-0084402.

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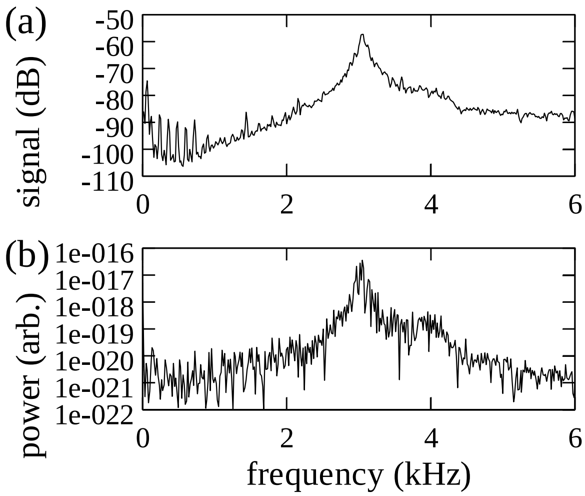

Figure 2. (a) Experimental spectrum of phase noise for a double-hump bunch with ξ = 1.2 and current of 144 mA. (b) Spectral power density of the average bunch centroid position in a simulation.

instabilities or parasitic coupled-bunch instabilities. These double-hump bunches are used routinely for stable operation with a long Touschek lifetime.

For ring parameters where stability is attained, the damped Robinson modes influence the beam's response to noise generated by the RF master oscillator and power supply. A large response is expected at the frequency of the Robinson modes, resulting in a peak in the phase noise on the beam [5, 6]. When a fourth harmonic RF cavity is used to increase the Aladdin low-emittance bunch length, coupling between the dipole and quadrupole Robinson modes gives two noise peaks in the longitudinal phase spectrum [2]. Figure 2(a) shows the spectrum of phase noise observed under normal operating conditions (ξ = 1.2) with a beam current of 144 mA, when an Agilent E4400B signal generator is used as our master oscillator.

We performed a 900-macroparticle simulation of 500,000 turns with $\alpha = 0.006$ for the parameters of Fig. 2(a). A fast Fourier transform was performed of the bunches' average centroid position, sampled every 100 turns during the final 409,600 turns. The simulation's spectral power density, shown in Fig. 2(b), is similar to the experimental noise spectra. This suggests that damped Robinson oscillations are excited in simulations by transients and "shot" noise from the finite number of macroparticles.

The spectrum of phase noise was observed experimentally when the resonant frequency of the passive fourth harmonic cavity was varied, for a ring current of 150 mA. For $0.88 < \xi < 1.08$, the beam is unstable and a large-amplitude 3 kHz signal is observed, consistent with a fast mode-coupling Robinson instability [2]. For harmonic-cavity voltages where Robinson instability is not observed, the frequency of peaks in the experimental phase noise spectrum are plotted in Fig. 3.

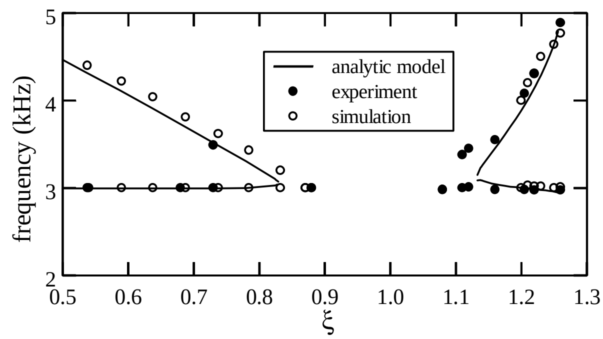

Figure 3. Measured noise peaks on a phase detector circuit agree with noise peaks observed in macroparticle simulations and with calculations of the coupled dipole and quadrupole Robinson modes.

The coupled dipole and quadrupole Robinson frequencies calculated for $\alpha = 0.006$ are also plotted in Fig. 3, in agreement with the measured peaks.

The spectral power density in simulations was also studied. Unstable simulations with $0.88 < \xi < 1.18$ display a large 3 kHz peak. Stable simulations with $\xi < 0.88$ or $\xi > 1.18$ display two peaks. The higher-frequency peak is more prominent in fast Fourier transforms of the RMS bunch length. The peaks observed in stable simulations are plotted in Fig. 3, in agreement with the measured peaks and the calculated Robinson frequencies.

We performed simulations to study feedback that counteracts Robinson oscillations of the bunch centroids. Simulations show that an ideal feedback system with damping time of 0.5 ms reduces phase noise at 3 kHz by 20 dB, with much less effect upon the coupled-quadrupole-mode noise around 4 kHz. This agrees with experimental tests of such a feedback system, which is now routinely employed.

2 ACTIVE HARMONIC CAVITY

By powering the harmonic cavity in the "compensated condition" [4], one may attempt to produce an optimally lengthened bunch at all values of the ring current. Initially, the RF feedback at Aladdin was insufficient to prevent dipole-quadrupole Robinson mode coupling in this case [2]. To overcome this limitation, we installed additional feedback that produces an effective coupling of $\beta_2 \approx 750$ for bunch oscillation frequencies below ~5 kHz.

Figure 4(a) displays analytic predictions for $\beta_2 = 750$. For currents > 200 mA, a coupled bunch instability excited by the harmonic cavity is predicted for short bunches with $\xi << 1$; Robinson instability is predicted to disrupt optimally lengthened bunches with $\xi = 1$.

Figure 4(b) shows instabilities observed in simulations. An "o" is plotted when the energy spread at the end of a simulation exceeds the natural value by >10%. However, this criterion does not detect an equilibrium phase Robinson instability where the bunches move to a different phase and then attain a stable equilibrium [7].

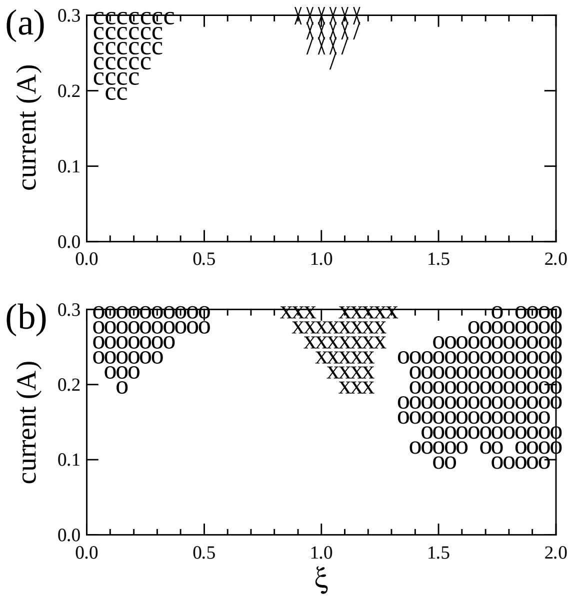

Figure 4. (a) Instability predictions for active harmonic-cavity operation with a low-emittance lattice. /: equilibrium phase instability; \: zero-frequency coupled dipole-quadrupole Robinson instability; c: coupled-bunch instability with longitudinal mode number of 1. (b) Instabilities observed in 500,000 turn simulations.

To detect this manifestation of instability, an "x" is plotted when the energy spread is within 10% of its natural value and the bunch centroids are shifted from their initial synchronous phase by more than 2.35 times the RMS bunch length. For a Gaussian bunch shape, this corresponds to a change in bunch position exceeding the FWHM of the bunch length. When the equilibrium phase instability occurs in simulations, the bunch becomes much shorter than a stable optimally lengthened bunch.

For single-hump bunch shapes, the simulations and analytic predictions are in agreement. For double-hump bunch shapes, instabilities that are not predicted by the analytic model may occur. Consistent with the modeling and simulations, active harmonic-cavity operation with currents exceeding 200 mA has been unsuccessful.

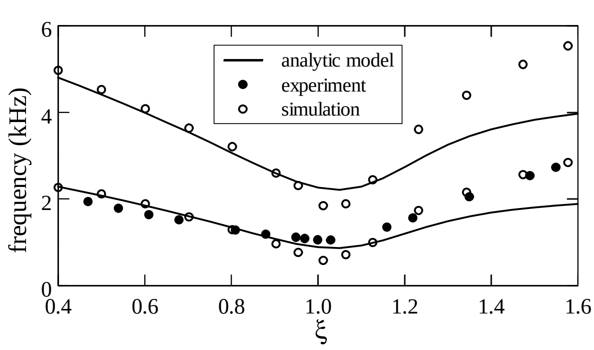

Figure 5. Measured noise peaks on a phase detector circuit are compared with noise peaks observed in simulations and with calculations of the coupled dipole and quadrupole Robinson modes.

For a ring current of 155 mA, the peaks in the experimental spectrum of phase noise are plotted in Fig. 5. Double peaks were not observed. Also shown are the calculated coupled dipole and quadrupole Robinson frequencies for $\alpha = 0.006$. From simulations, we plot the noise peaks from fast Fourier transforms of bunch position and length. Quantitative agreement is obtained for single-hump bunches, while the calculated frequencies for double-hump bunches differ significantly from those observed in simulations and experiment.

The phase noise observed in active operation exceeds that in passive operation. This may be a result of the low Robinson-mode frequency of ~1 kHz in active operation. The fundamental cavity's RF oscillator and power supply are expected to produce more noise at lower frequencies [5], while the power supply for the harmonic cavity provides additional noise during active operation. With a low Robinson frequency, the beam responds to this noise.

It is expected that the equilibrium phase instability may be avoided in active operation by using a higher RF voltage [2], but the Touschek lifetime will be reduced. The reduced lifetime and increased noise make active operation unattractive.

3 SUMMARY

For passive harmonic-cavity operation with a low-emittance lattice, optimally lengthened bunches are destabilized by coupling of the dipole and quadrupole Robinson modes, necessitating the use of stable double hump bunches. In this case, the coupled dipole and quadrupole Robinson frequencies are around 3–4 kHz. Active operation of the higher harmonic cavity gives a lower coupled dipole Robinson frequency (~1 kHz) with increased noise. We routinely employ passive operation with double-hump bunches, reducing noise with feedback that damps oscillations of the bunch centroids.

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