FEEDBACK TO SUPPRESS PHASE NOISE AT ALADDIN*

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Abstract

The performance of the Aladdin infrared beamline is adversely affected by a Robinson mode in which all bunches move in unison with a frequency of 3 kHz. To decrease these oscillations, feedback has been installed in the radiofrequency system to damp longitudinal motion of the bunch centroids. Simulations indicate that at frequencies around 3 kHz, the phase noise generated by Robinson modes may be reduced 20 dB by feedback with a damping time of 0.3 ms. This agrees with the measured performance of feedback circuitry. Since the feedback greatly improves operation of the infrared beamline, it is now incorporated into the standard operation of Aladdin.

INTRODUCTION

The Aladdin 800-MeV 300-mA electron storage ring is now operated with a low-emittance lattice [1]. When the fifteen identical bunches are lengthened by a passive fourth harmonic radiofrequency (RF) cavity, the small value of the momentum compaction results in coupling of the dipole and quadrupole Robinson modes [2, 3]. To obtain long bunches without exciting a fast mode coupling instability, standard operation utilizes double-hump bunches confined in a double-well synchrotron potential, as shown in Fig. 1. These stable bunches are "overstretched" by a harmonic cavity voltage 20% larger than that required to obtain optimally lengthened bunches in a cubic + quartic synchrotron potential [2].

During standard operation, the phase noise on the beam displays peaks at 3 kHz and 4 kHz, which are the calculated frequencies of coupled dipole and quadrupole Robinson modes [3]. This suggests that the beam has a large response to noise generated by the RF master oscillator and power supply at the frequencies of the damped Robinson modes [4, 5]. The infrared beamline [6] is adversely affected, since the associated transverse electron oscillations cause oscillations in the photon flux transported through the beamline [7].

To reduce the noise peak at 3 kHz, feedback may be installed that counteracts Robinson oscillations of the bunch centroids; i.e., "Robinson dipole" feedback [8]. In this paper, simulations are presented to predict the performance of this feedback. The predictions are consistent with experiments on a feedback system that was subsequently installed. The successful operation of this feedback system agrees with simulations in which a feedback damping time of ~0.3 ms causes a 20-dB suppression of the 3-kHz noise peak.

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INSTABILITY MODELING

To assess the impact of feedback that counteracts dipole Robinson oscillations, we first studied whether the feedback would destabilize the double-hump bunches lengthened by our passive harmonic cavity. We modeled a momentum compaction of 0.006 (obtained from the measured low-current synchrotron frequency) and fundamental RF voltage of 50 kV, while an RF-coupling to the harmonic cavity of $\beta_2 = 1.5$ describes an attached RF circulator. The remaining parameters are the low-emittance parameters given in Table 1 of Ref. [2]. In 500,000-turn simulations of 900 macroparticles 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.

To include the feedback in simulations, we defined a "measured" energy offset with a measurement response time of 100 turns. This corresponds to the time response we can obtain experimentally by measuring the bunches' average RF phase. Letting *ebar* denote the macro-particles' average energy offset during a single turn, the "measured" offset is incremented each turn according to:

$$ebar\_measured = 0.99(ebar\_measured) + 0.01ebar \quad (1)$$

The damping provided by feedback is modeled by adding the term $(-2T_o/\tau_{feedback})(ebar\_measured)$ to the right hand side in eq. (29) of Ref. [2], where T_o is the ring recirculation time and $\tau_{feedback}$ is the damping time from the feedback.

In simulations that include feedback, the double hump bunches that are utilized for standard operation remain stable.

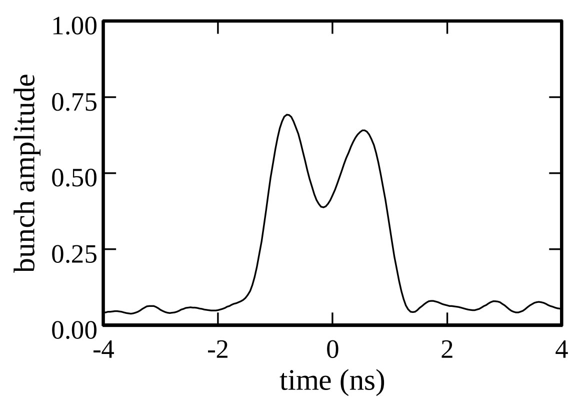

Figure 1. Data from the Q-electrode show the double-hump bunch shape during standard operation of the LF15 low-emittance lattice. Effects of the Q-electrode capacitance and cable dispersion have been corrected by software.

SIMULATIONS OF PHASE NOISE

To model standard operation, we considered a ring current of 150 mA and harmonic cavity tuning angle of –80.725°. For this case, the harmonic cavity voltage is 20% larger than that required for optimal bunch-lengthening. For a 500,000-turn simulation, a fast Fourier transform [9] was performed of the bunches' average centroid position (in units of seconds), sampled every 100 turns during the final 409,600 turns. The spectral power was obtained by adding the squares of the real and imaginary components of the Fourier transform.

For the case where no feedback is applied, the spectral power in simulations approximates the measured spectrum of phase noise, as shown in Fig. 2. Because of the coupling between the dipole and quadrupole Robinson modes, two noise peaks are observed. Consequently, the phase noise spectrum does not agree with formulas for uncoupled dipole Robinson oscillations [4, 8]. However, the similarity between parts (a) and (b) of Fig. 2 suggests that the effect of feedback upon phase noise may be studied with simulations.

Figure 3 shows the spectral noise in simulations of Robinson dipole feedback for several values of the feedback damping time, for standard double hump bunches with a ring current of 150 mA. For $\tau_{feedback}$ = 10 ms, the feedback damping time is only slightly smaller than the radiation damping time of 13.5 ms, so that little suppression of the 3-kHz phase noise is observed. With a larger amount of feedback, the 3 kHz coupled-dipole peak is suppressed while the 4 kHz coupled-quadrupole peak is only slightly affected. By using a feedback damping time of 0.3 ms, the 3 kHz peak is reduced by a factor of 100 (20 dB). These simulations predict that a feedback system may effectively reduce the phase noise during standard operation, provided that the feedback damping time is much smaller than the radiation damping time of 13.5 ms.

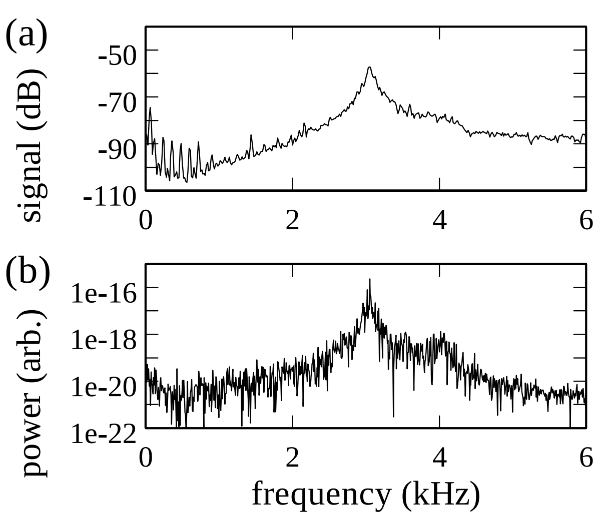

Figure 2. (a) Experimental spectrum of phase noise for standard double-hump bunches with a current of 144 mA, when an Agilent E4400B signal generator is used as the master oscillator. (b) Spectral power density of the average bunch centroid position in a 500,000-turn simulation.

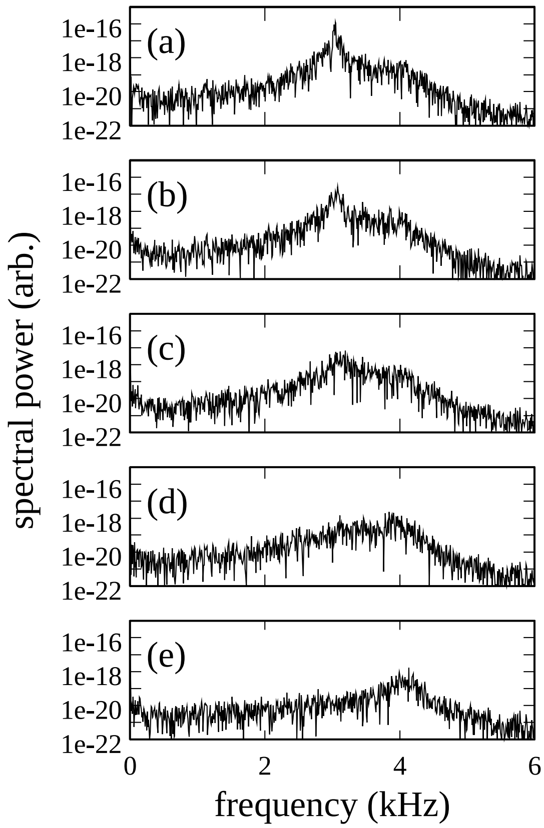

Figure 3. Spectral power in simulations of Robinson dipole feedback for a current of 150 mA. (a) $\tau_{feedback}$ = 10 ms. (b) $\tau_{feedback}$ = 3 ms. (c) $\tau_{feedback}$ = 1 ms. (d) $\tau_{feedback}$ = 0.3 ms. (e) $\tau_{feedback}$ = 0.1 ms.

EXPERIMENTAL IMPLEMENTATION

Rather than measuring the energy offset directly, a Robinson dipole feedback system has been constructed that detects the average bunch phase with a time response of ~100 turns. Sending this signal through an "all pass" filter gives a 90-degree phase shift for oscillations with frequency around 3 kHz, providing a signal proportional to the average energy offset. The variation of phase shift with frequency is sufficiently small to have little impact upon the feedback performance. An RF voltage proportional to the phase-shifted signal counteracts the Robinson oscillations. This feedback method is similar to that described in Ref. [8].

The feedback gain may be varied to change the damping time provided by the feedback. For example, a feedback gain 6 dB below maximum gives a damping time twice as large as that obtained with maximum feedback, while a feedback gain 12 dB below maximum gives a damping time four times as large as that obtained with maximum feedback. The precise damping time

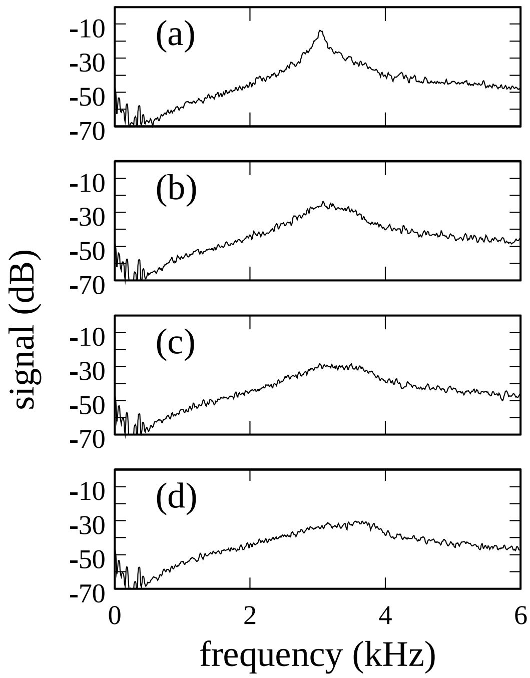

Figure 4. Experimental phase noise at a ring current of 150 mA, when an Agilent E4400B signal generator is used as the master oscillator. (a) Robinson dipole feedback off. (b) Robinson dipole feedback gain 12 dB below maximum. (c) Robinson dipole feedback gain 6 dB below maximum. (d) Maximum Robinson dipole feedback.

given by maximum feedback is unknown, but it is expected to be in the range of 0.1–1 ms.

Experiments to characterize the Robinson dipole feedback were performed with the low-emittance LF15 lattice. Throughout the normal operating current range of 85–280 mA, the stability of standard double hump bunches was observed to be unaffected by the feedback, in agreement with simulations.

For comparison with the broadband noise generated in simulations, experiments were performed with the Agilent E4400B signal generator used as the ring's master oscillator. Figure 4 shows experimental measurements of phase noise without Robinson dipole feedback, with feedback gain 12 dB below maximum, with feedback gain 6 dB below maximum, and with maximum feedback gain. At frequencies near 3 kHz, a 20-dB noise reduction is observed experimentally with the maximum feedback gain. The smaller noise peak at 3.7 kHz is not suppressed, consistent with the simulation results showing that the coupled-quadrupole Robinson mode is not suppressed by the dipole feedback.

The experimental spectrum with maximum feedback is approximated by the simulated spectrum for feedback damping time of 0.3 ms, consistent with our expectation that this damping time is in the range of 0.1–1 ms.

SUMMARY

Simulations predict that Robinson dipole feedback will not destabilize the double hump bunches now used for standard low-emittance operation; this is confirmed by experiment. With a feedback damping time of ~0.3 ms, the feedback reduces the 3-kHz peak in the simulated phase noise by 20 dB for standard double hump bunches. This agrees with experiments that characterize the recently installed feedback system.

The Robinson dipole feedback greatly improves the quality of data acquired on the infrared beamline [10] with no apparent effect upon other beamlines. Therefore, feedback to counteract dipole Robinson oscillations is now incorporated into the standard operation of Aladdin.

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