Studies of intensity noise at the Synchrotron Ultraviolet Radiation Facility III

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(Presented on 22 August 2001)

Suppression of beam instabilities has become an important goal at synchrotron radiation light sources, where highly sensitive applications like metrology, Fourier transform spectroscopy, and microscopy are now in use. We describe measurements connecting beam size and position changes to the onset of the saw-tooth instability and an instability generated by attempts to enlarge the vertical beam size for lifetime improvements. [DOI: 10.1063/1.1436538]

I. INTRODUCTION

Most earlier applications of synchrotron radiation were not very sensitive to source intensity fluctuations. Fourier transform spectroscopy,[1–5] however, is very sensitive to intensity noise in the audio frequency range, depending on the scanning speed of the instrument. A Fourier transform infrared spectrometer installed at the Synchrotron Ultraviolet Radiation Facility (SURF) II in 1997[6] indicated a significant amount of intensity noise. Much of that noise was attributed to bunch length oscillations[7] or the saw-tooth instability,[8,9] which is driven by the higher-order modes of the radio-frequency cavity. Later it was discovered, that the intentional excitation of the vertical betatron oscillation with a broadband noise source caused intensity noise as well. This oscillation is driven to increase the electron bunch volume and thereby the beam lifetime.[10] The saw-tooth instability causes both changes in the transverse and longitudinal beam size, as well as changes in the orbit radius. The excitation of the vertical betatron oscillation using the broadband noise source causes the vertical beam size to fluctuate, because of amplitude and phase variations at a given frequency. The changes in transverse beam size and orbit radius induce intensity noise in the collected synchrotron radiation. Through several improvements to the radio-frequency system and an increase in the electron energy, leading to more efficient damping, we can now tune the upgraded SURF III machine[11] to suppress the saw-tooth instability. Replacing the broadband noise source with a narrow-band frequency generator, tuned automatically with a feedback loop to keep the vertical beam size constant, solved the second problem. After eliminating these two contributions to the intensity noise, SURF is now providing synchrotron radiation with unprecedented stability.

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II. ORIGIN OF INTENSITY NOISE

The equilibrium bunch length is given by[12]

$$\sigma_s=\frac{\beta_c|\eta_c|}{2\pi f_{\rm syn}}\frac{\sigma_E}{E_0}, \tag{1}$$

with electron speed β_c, momentum compaction $|\eta_c|$, synchrotron oscillation frequency $f_{\rm syn}$, and relative energy spread σ_E/E_0. During the saw-tooth instability the bunch length oscillates[9] and the longitudinal bunch distribution will not be Gaussian anymore. Therefore we use a root-mean-square definition of the bunch length for the nonsteady case

$$\langle\sigma_s(t)\rangle_{\rm rms}\approx\frac{\beta(t)c|\eta_c|}{2\pi f_{\rm syn}(t)}\frac{\sigma_E(t)}{E(t)}. \tag{2}$$

The energy spread, beam energy, and synchrotron oscillation frequency change during the relaxation oscillations. The fluctuation in beam energy translates into a change in the orbit radius, because of the constant magnetic guide field B:[12]

$$\rho(t)=\frac{E(t)\beta(t)}{eBc}. \tag{3}$$

The changes in beam energy spread and energy cause variations in the horizontal beam size, which is given by[12]

$$\sigma_x(t)=\sqrt{\epsilon_x(t)\overline{\beta}_x(t)+\left(\frac{\sigma_E(t)}{E(t)}\right)^2\overline{\eta}(t)^2}, \tag{4}$$

with the horizontal emittance ϵ_x, the average horizontal betatron function $\overline{\beta}_x$, and the average horizontal dispersion function $\overline{\eta}$.

In summary the bunch length oscillations are accompanied by changes in the synchrotron oscillation frequency and beam energy spread. The changes in beam energy spread cause both changes in the equilibrium orbit or energy because of the constant guide field and changes in horizontal beam size. Both the changes in the horizontal beam size as well as the orbital radius cause intensity noise in the collected synchrotron radiation.

III. DIAGNOSTICS DEVICES

A. Intensity noise detection

Beam size and position variations will affect instruments that depend on the brightness or the radiance of the source. To some degree, most applications are sensitive to this quantity. In the optical setup we used, the synchrotron radiation is imaged onto an aperture, overfilling it, and a photodiode is placed behind the aperture to determine the amount of radiation passing through its opening. Obviously, the amount of radiation passing through the overfilled aperture will depend on the image size and position, thus the size and position of the actual beam. Experiments performed in which an underfilled aperture was used, showed little or no noise. The photodiode current is amplified and displayed on an oscilloscope (Fig. 1, top), but also fed into a spectrum analyzer (Fig. 1, bottom) to analyze the beam stability. For SURF it has been shown that the saw-tooth instability coincides with greatly enhanced microwave emission in the *x*-band microwave range,[9] which is caused by spontaneous microbunching.

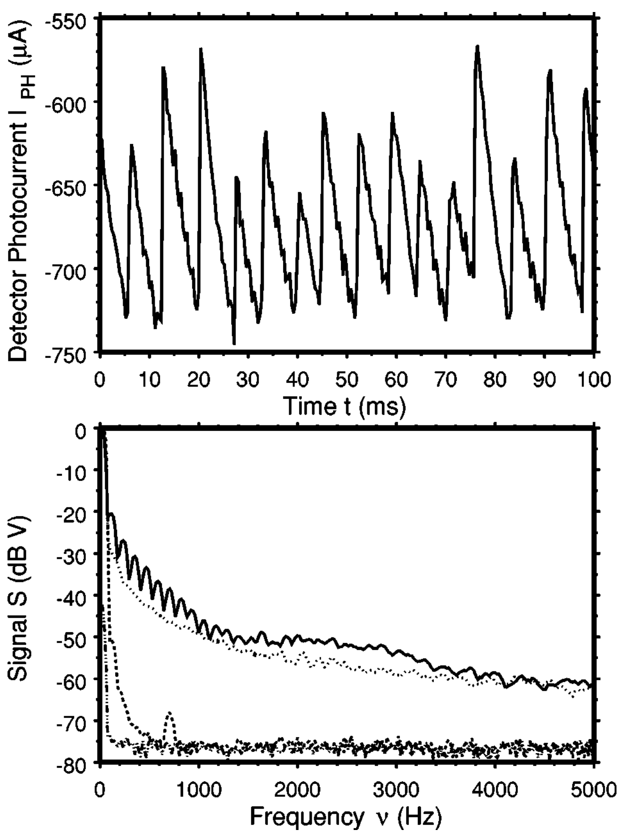

FIG. 1. (Top) Photodiode signal vs time during the saw-tooth instability as detected with our noise detector. (Bottom) Frequency analyzed photodiode signals for different operating conditions of SURF at 361 MeV. Saw-tooth instability abundant and broadband excitation of the vertical betatron oscillation (—); saw-tooth instability suppressed and broadband excitation (···); saw-tooth instability suppressed and narrow-band excitation (— — —); same measurement with synchrotron radiation blocked to determine the noise floor (-···-).

In Fig. 1 the two origins of intensity noise in the collected synchrotron radiation at SURF are clearly illustrated: the saw-tooth instability and the broadband excitation of the vertical betatron oscillation. By tuning the accelerator and replacing the broadband excitation with a narrow-band frequency generator we could all but eliminate intensity noise at SURF. This opens the way for noise sensitive synchrotron radiation applications as, e.g., Fourier transform spectroscopy.

B. Triggered beam imaging

The data in Fig. 1 unambiguously show that intensity fluctuations are caused by both the saw-tooth instability and the broadband excitation of the vertical betatron oscillation. In addition, direct visual inspection and captured beam images[13] showed large scale transverse size fluctuations during the noisy periods.

Our discussion in Sec. II connects horizontal size variation to orbital radius variation during the saw-tooth oscillation. Our beam imaging instrument (Ref. 13) was capable of measuring both quantities simultaneously. To capture the maximum variation of both beam size and orbital position, we triggered this instrument off the microwave bursts that accompany the saw-tooth instability. Using a delay generator the image acquisitions were done at various times after the microwave emission, checking for correlation of beam size and position with the delay time. The charge coupled device camera used was capable of progressive scan imaging and short integration times down to 1.25 μs. This is faster than the synchrotron oscillation period of about 2.5 μs. However, as already stated in Ref. 9, the quadrupole mode of the bunch oscillation is dominating thus operating at twice the synchrotron radiation frequency, which is too fast for our imaging system. Anyway, we did observe a very large variation in beam size and a strong correlation between instantaneous beam size and orbit radius (see Fig. 2). Other measurements during stable operation of SURF using the same instrument showed an undetectable variation in beam size.

IV. CONCLUSION

A noise detection system to determine intensity noise in synchrotron radiation beams was introduced and applied to understand the beam noise at SURF III. Using this detection system we were able to tune the accelerator in a way to suppress the saw-tooth instability. Furthermore it was discovered, that the intentional excitation of the vertical betatron oscillation using a broadband noise generator introduced noise as well. This led to the introduction of a narrow-band frequency generator, which is used together with an automatic beam size measurement system to keep the vertical beam size constant by adjusting the excitation frequency. Through timed imaging we could prove that our explanation for the origin of the intensity noise during the saw-tooth instability is correct: bunch length fluctuations cause changes in the beam energy spread, beam energy, and synchrotron oscillation frequency. The changes in beam energy spread cause fluctuation of the horizontal beam size. The changes in beam energy cause variation in the orbit radius. Both of these

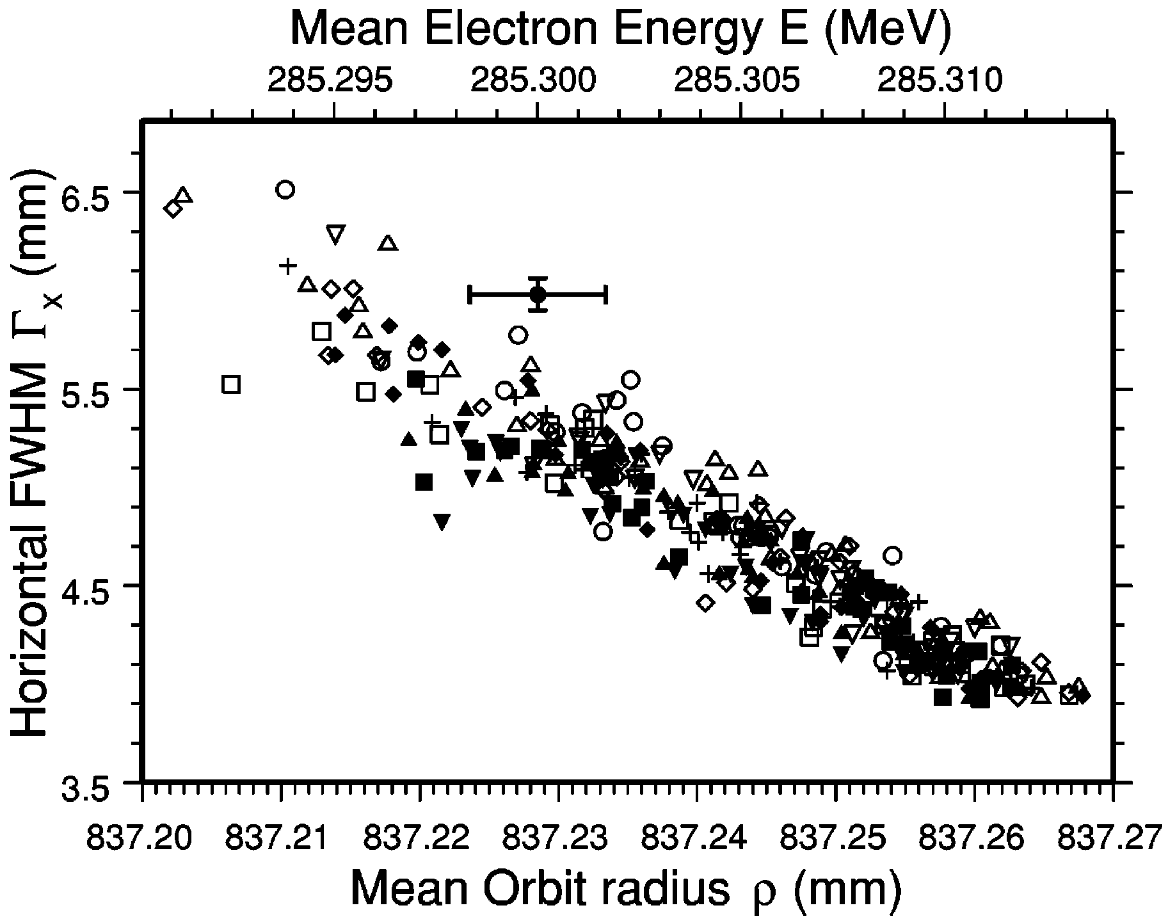

FIG. 2. Horizontal full width at half maximum vs mean orbit radius or energy [connected through the constant magnetic guide field, see Eq. (3)] for various delays between microwave emission and image acquisition. We did not detect any correlation between time delay and beam position or size, presumably because our imaging system did not have sufficient time resolution. Clearly visible, however, is the correlation between orbit radius and beam size for an unstable beam: stable beam (●), unstable beams at Δt: 0 ms (○); 0.1 ms (■); 0.3 ms (□); 0.5 ms (▲); 0.7 ms (▼); 1 ms (△); 2 ms (▲); 3 ms (♦); 4 ms (◇); and 5 ms (+).

effects can cause noise in the collected synchrotron radiation. The broadband excitation introduces noise because of amplitude variations at any given frequency as well as phase changes, also causing changes in the transverse beam size.

ACKNOWLEDGMENT

Support by the staff of the SURF III facility, especially Alex Farrell, is gratefully acknowledged.

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