# First Observation of Spiking Behavior in the Time Domain in a Free-Electron Laser

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The spiking behavior of free-electron lasers, or sideband instability, has been observed for the first time in the time domain using an autocorrelator on the MKIII free-electron laser at Stanford University. The measurement is compared with simulations and qualitative theory.

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It is important to understand the spiking behavior or sideband instability in order to maximize the performance of the free-electron laser (FEL). This is especially true for applications that require high power and high optical-beam quality. The theory of the sideband instability has been thoroughly discussed. Both qualitative theory and computer simulations have been presented,[1-5] and the effects of tapering[3,5] and energy spread[3] on the sideband instability have been studied. The change in extraction efficiency[1,2] is perhaps the most important aspect of the sideband instability. Other items of importance for FEL operation are transverse- and longitudinal-mode quality, and overall stability of the laser power.

In this paper we present the results of autocorrelation measurements done on the MKIII FEL at Stanford University. These measurements show clearly the existence of power spikes within the laser pulses brought about by the sideband instability. Although evidence for the sideband instability has previously been obtained from measurements of the optical power spectrum,[6,7] the spectral data obtained in those measurements were not sufficient to determine the time dependence of the variations in intensity caused by this instability. The autocorrelation measurements reported here provide the first direct experimental evidence for the existence of the intensity spikes predicted by theory.

The equations of motion which describe the behavior of the FEL[8] are given by

$$\dot{a}(t) = -r\langle e^{-i\zeta(t)}\rangle_{\nu_0}\,, \tag{1a}$$

$$\ddot{\zeta}(t) = |a(t)|\cos(\zeta+\phi)\,, \tag{1b}$$

where $\zeta(t)=(k+k_0)\bar{z}(t)-\omega t$ is the relative phase between an electron and the laser field, $\bar{z}(t)$ is the longitudinal position of the electron averaged over one wiggler oscillation, and derivatives are with respect to normalized time $\tau=ct/L$. The normalized magnetic field is $K=eB/k_0mc^2$, $\xi=K^2/4(1+\frac{1}{2}K^2)$ is the planar wiggler normalized strength, and $\mathcal{H}(\xi)=J_0(\xi)-J_1(\xi)$ is the planar wiggler interaction strength. Here $a=2\pi N \times e\mathcal{H}(\xi)LE(t)/\gamma_0^2mc^2$ is the normalized laser field envelope, where $a=|a|e^{i\phi}$ and $E(t)$ is the complex electric field envelope. The normalized current density is given by $r=4\pi^2Ne^2\mathcal{H}^2(\xi)L^2\rho_0/\gamma_0^3mc^2$, where $\rho_0$ is the average current density. The brackets $\langle\,\rangle_{\nu_0}$ mean an average over all electrons within an optical wavelength. FEL sideband theory has been discussed previously at length.[1,2]

Equations (1a) and (1b) are the familiar self-consistent pendulum equations. Figure 1 shows the graphical representation in the $(\zeta,\nu)$ phase space.[8,9] Saturation of the laser is achieved when most of the electrons are contained within the separatrix. The electrons close to the centers of the separatrix oscillate around the center with frequency $\Omega=(c/L)|a|^{1/2}$. This is the synchrotron frequency which leads to the development of sidebands. In an oscillator, total saturation is reached at the fundamental laser frequency when the intensity causes the electrons to execute one full synchrotron oscillation as they travel the entire length of the wiggler. However, this oscillation mixes nonlinearly with the fundamental laser frequency and results in gain at the sideband $(\omega-\Omega)$. This can also be examined in the time domain. As the high-intensity laser field passes over the electrons, it extracts energy from them until it no longer can. After many round trips, optical spikes develop each of which extracts the maximum possible energy out of one segment of the electron beam equal to one slippage distance in length $(N\lambda)$, the distance by which the optical pulse overtakes the electrons over the length of the

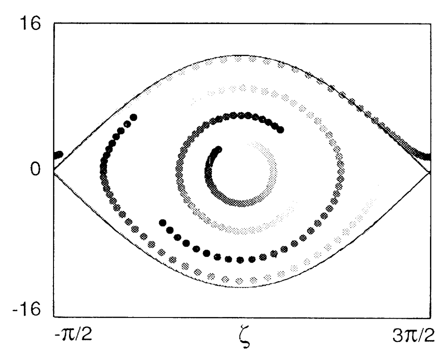


FIG. 1. Electron trajectories in phase space under highly saturated conditions. Time progresses from light gray to dark. Note the nearly circular orbits of some electrons [harmonic oscillation at $\Omega=(c/L)|a|^{1/2}$]. This is the origin of the sidebands which result in the spiking behavior of free-electron lasers. (Courtesy W. Colson.)

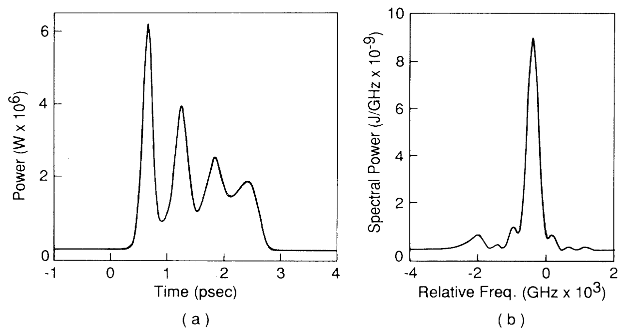


FIG. 2. Results of computer simulations using the MKIII parameters in Table I (Ref. 10). (a) Optical intensity profile as a function of time within a single micropulse. (b) Spectral power distribution as a function of difference in frequency from the laser fundamental.

wiggler. Then separation of these pulses should be equal to one slippage distance.

Computer simulations for short electron pulses give more exact results.[1,2,4,5,10] For short micropulses, two main regions within the pulses develop: tails where the intensity is not high enough to support sidebands, and the middle where there is a regular modulation of the optical fields. At the transitions between these, the level of saturation—and hence the period and amplitude of the modulation—changes from near zero amplitude toward the tail to maximum toward the middle. This behavior was also observed in simulations based directly on the MKIII operator parameters.[10] Figure 2(a) shows the calculated optical pulse shape and Fig. 2(b) shows the calculated spectrum after 170 round-trip passes.

The MKIII linac[11] has an rf gun and an alpha-magnet buncher before the accelerator, the field of which was set to give an electron micropulse length at the entrance to the accelerator of approximately 2.5 psec. The relative

TABLE I. Electron-beam and laser parameters for the MKIII free-electron laser system during the spiking-behavior autocorrelation measurements.

| | |
|---|---|
| Electron beam | |
| Energy | 37.8 MeV |
| Energy spread | ~0.5% full width |
| Peak current | 30 A |
| Micropulse length | 2.5 psec |
| Normalized horizontal emittance | $8\pi$ mm mrad |
| Normalized vertical emittance | $4\pi$ mm mrad |
| Laser | |
| Number of periods | 47 |
| Wiggler period | 2.3 cm |
| $\langle K^2 \rangle$ field strength | 0.45 |
| $\lambda$ | 3.05 $\mu$m |
| Output coupling | 2.4% |
| Total losses | 11% |

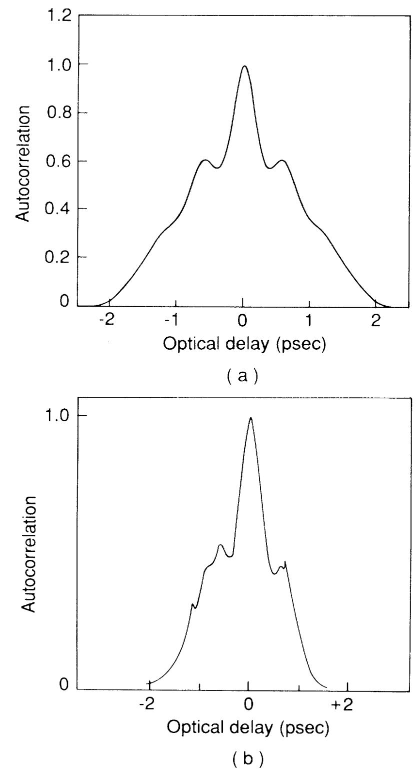


FIG. 3. (a) Autocorrelation function for the computed laser micropulse shown in Fig. 2. (b) Observed autocorrelation function during experiment, showing side lobes resulting from the spikes within the micropulse.

phase of the rf field between the gun and the accelerator was adjusted for a minimum electron-beam energy spread (~0.3% full width instantaneous). The energy of the beam was 37.8 MeV and the magnets of the MKIII FEL were opened to give a $\langle K^2 \rangle$ of 0.45 and a 3-$\mu$m output. Table I shows a complete set of the operating parameters for this experiment. The laser macropulses were 2.5 $\mu$sec long. The laser output coupling was 2.3% into one of four beams and total losses were 11%. The energy per macropulse in one beam was 12 mJ. Before taking the autocorrelations, the laser spectrum was observed (with a monochromator) to have some power in a lower sideband (although much less than the power in the primary wavelength).

The time-domain spiking behavior on the MKIII was measured with an autocorrelation method. The autocorrelator (Interactive Radiation model 5.14-LD-3.6X) has a 10° external angle crossed-beam arrangement with a $LiNiO_3$ doubling crystal and a 1-mm germanium detector (Judson model J-16-18). A boxcar integrator averaged the autocorrelator output signal over ten entire macropulses while the autocorrelator optical delay was scanned. The laser macropulse energy was maintained to within ±5% of the mean of each scan.

The theoretical autocorrelation function $C_{auto}$ in Fig.

3(a) can be calculated from the equation

$$C_{\text{auto}}(\Delta t) = \int_{-\infty}^{+\infty} I(t)I(t+\Delta t)dt \,,$$

where $I(t)$ is the instantaneous intensity $[|E(t)|^2]$ of the optical pulse shown in Fig. 2(a). The sideband has about 5% of the total power, and its frequency is about 1.8% lower than the main frequency. Note that a small modulation of the autocorrelation corresponds to nearly complete amplitude modulation of the optical pulse. This is because most of the pulse is in the transition region where the modulation period is varying, washing out the modulation of the autocorrelation function.

Figure 3(b) shows the experimentally measured autocorrelation trace. The general triangular shape of the curve was very reproducible for several autocorrelator scans. It indicates that the laser micropulses were very square and about 2 psec, or 200 wavelengths, in length. The humps on the sides of the curve are clear evidence of spiking within the laser micropulses. These humps seemed to change in prominence randomly from scan to scan. Note that there are two humps on one side of the curve. This indicates that the micropulses had at least three internal spikes. These spikes were separated by 0.8 psec, which gives a modulation frequency of 1.3% of the laser frequency. This compares with a maximum modulation frequency of $1/N = 2\%$ (where $N$ is the number of wiggler periods), which is approached if there are many spikes within the laser pulses.

These results compare well with the results of simulations from a one-dimensional code derived by Benson.[10] They predict a pulse length of about 2 psec as observed. They also show three major spikes within the optical pulses, separated by $\sim 0.7$ psec, and the associated sideband. The minimum separation for the MKIII should be 47 wavelengths, or $\sim 0.5$ psec, so the spiking is in the transition regime, where the intensity is not quite enough to develop narrow spikes with the minimum separation.

The spiking behavior in free-electron lasers has been observed in the time domain for the first time. Autocorrelation measurements on the MKIII indicate the existence of three spikes within otherwise square-shaped micropulses, separated by 240 $\mu$m, where the minimum theoretical separation is 150 $\mu$m. This agrees very well with computer simulations performed using similar operating parameters, which predicted three spikes separated by 200 $\mu$m. The simulation predicted a sideband with $\sim 10\%$ of the power of the fundamental wavelength, which also matched the observed spectrum.

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