Modulated desynchronism in a free-electron laser oscillator

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Abstract

We study experimentally and theoretically, the effects of desynchronism modulation on short pulse free-electron laser (FEL) oscillators. We find that the output power and the micropulse length of the FEL beam oscillate periodically at the modulation frequency and the minimum micropulse length can be significantly shorter than that obtained without modulation. The FEL can operate during part of the modulation cycle in the normally inaccessible portion of the output power curve where the FEL gain is less than the cavity loss.

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1. Introduction

During the past few years there has been much interest in the topic of generating and controlling short FEL pulses [1–3]. To date, short pulse generation has been achieved while maintaining the two fundamental FEL parameters (the cavity detuning \( \delta L \), and the losses \( \alpha_0 \)) constant. In this work we show a new method of controlling the pulse length of an FEL by modulating the cavity detuning [4,5]. We begin with the experimental observation that when \( \delta L \) is modulated by a few microns at a rate of 40kHz, our FEL micropulse length varies from a minimum of 300fs to a maximum of 800fs. When the modulation is turned off, the micropulse length is 700fs.

Throughout this paper the FEL wavelength is taken to be 5\( \mu \)m.

2. Experimental results

The Stanford FEL parameters are shown in Table 1. Here the optical power signal is recorded as a function of time in Fig. 1(a) and (b) for different modulation levels. The flat signals were taken without modulation and are shown for comparison. At high modulation level (\( \delta L_m = 3.7 \mu m \)), the measured micropulse length ranges from 300 to 800fs (FWHM).

The magnetic chicanes in the FEL beam line are non-isochronous, i.e., electron pulses with a higher energy will have a shorter transit time through the chicanes than lower energy pulses. The effect is calculated to be 0.03 ps/keV. Therefore modulation of the beam energy is translated into modulation of the electron bunch repetition...
frequency. Since the change in the repetition frequency has the same effect as the cavity length detuning, the total cavity detuning can be written as \( \delta L = \delta L_0 + \frac{1}{2} \gamma^2 \frac{\partial^2 A}{\partial \xi^2} + \frac{\gamma^4}{2} \frac{\partial^4 A}{\partial \xi^4} + \frac{\gamma^6}{2} \frac{\partial^6 A}{\partial \xi^6} \) (A = B) (1)

\[
\frac{\partial B}{\partial \xi} = -iD, \quad \frac{\partial D}{\partial \xi} = -A - iSB - 2iQD + 2iQ^2 B
\]

\[
\frac{\partial Q}{\partial \xi} = -[AB^* + c.c.], \quad \frac{\partial S}{\partial \xi} = -[AD^* + c.c.].
\]

We use the short pulse FEL oscillator equations [3,5].

In these equations, \( A \) is the optical field, \( \xi = (ct - z)/L_0 \) is the position within the optical pulse in units of the slippage length, \( \tau = \gamma n \), where \( n \) is the pass number, and \( \nu = 2\delta L/(L_{0\gamma}) \) is the normalized cavity detuning which can be written as \( \nu = \nu_0 + (\Delta \nu_{m}/2) \sin (\omega_{m}\tau/(FEL)) \). We have used in these equations a collective variable description [6]: \( B = \langle \exp(-i\theta) \rangle, \quad D = \langle p \exp(-i\theta) \rangle, \quad Q = \langle p \rangle, \) and \( S = \langle p^2 \rangle \), with \( p = \partial e \theta \), and \( \theta \) the electron phase. The second derivative terms in Eq. (1) were introduced in a previous work [5], and they were found to be relevant to explaining the behavior of the system when the cavity detuning was modulated with large amplitude.

Eqs. (1) have been solved numerically. The initial beam is assumed to be monochromatic and unbunched, and the initial beam energy satisfies the FEL resonant condition. Hence the initial conditions are \( B = D = Q = S = 0 \) at \( \xi = 0 \). For \( \nu < 0 \) or \( \nu > 0 \) we assume \( A(\xi = 0, \tau) = A_0 \) or \( A(\xi = 1, \tau) = A_0 \), where \( A_0 \) characterizes the level of spontaneous emission, \( A(\xi, \tau = 0) = A_0 \). We define the dimensionless output energy \( P \) as

\[
P(\tau) = \int_{-\infty}^{+\infty} d\xi |A(\xi, \tau)|^2.
\]

The theoretical optical power signal is shown in Figs. 1(c) and (d) as a function of time for two different modulation levels. These signals exhibit a periodic oscillation with the same frequency as the modulation. At \( \delta L_m = 3.7 \mu \text{m} \) calculations show that the micropulse length varies between 300 and 800 fs. This is in good agreement with the experimental result.
In order to understand the role of the modulated desynchronism in FEL dynamics, we show in Fig. 2 the output power versus desynchronism curve obtained without modulation. The horizontal lines represent the range of detuning values due to various modulation amplitudes. When modulation is applied, the FEL must evolve as it attempts to follow the changing conditions. It is reasonable to assume that it moves toward the steady condition corresponding to the instantaneous detuning value. Therefore, for small modulation around detuning $v_0$ the power will decrease when $v > v_0$ and will increase when $v < v_0$. This explains the periodicity observed in the output power. When the modulation amplitude becomes large enough such that the detuning reaches very small values ($v < v_{\text{max}}$) outside the emission region, the equilibrium power is no longer monotonic in $v$, and the output power curve develops higher frequency structures (see Figs. 1(b) and (d)). The transient evolution in a short pulse FEL oscillator with perfect synchronism ($v = 0$) has been analyzed by Piovella [7].

3.2. Operation in the inaccessible region

The dynamics of the FEL operating in the normally inaccessible region ($v < v_{\text{max}}$) are very complex. To qualitatively understand these dynamics, we investigate numerically the case where the cavity detuning changes as a step function. The detuning is initially set to a constant detuning $v_1 > v_{\text{max}}$. After the FEL reaches a steady state, the detuning is abruptly changed to a value $v_2 < v_{\text{max}}$. Fig. 3 shows the evolution of the optical micropulse shape during this process. As the change is applied, there is a strong tendency for all the optical energy to concentrate at the trailing edge of the electron bunch, causing the micropulse length to decrease. An interesting observation is that during a short period of time of approximately 6 $\mu$s, while the micropulse length is decreasing, the micropulse energy rises briefly above the steady state value before decreasing to zero. After choosing different combinations of the initial and final detuning values, we find that the highest micropulse energy occurs when the initial detuning is set to $v_{\text{max}}$, which corresponds to the maximum steady-state power, and the final detuning is set close to zero. Specifically for our case, the initial and final values are $v_1 = 0.017$ and $v_2 = 0.0001$, respectively. The evolution of the micropulse energy is shown in Fig. 4. The initial increase of the micropulse energy is clearly visible.

This phenomenon provides us the possibility to operate the FEL with average micropulse energy higher than that obtainable in the steady-state operation. A possible scheme is to employ a periodic step function as shown in Fig. 5(a).

Fig. 2. Output power versus cavity detuning. The modulation amplitudes (a) $\Delta v_m = 0.006$, (b) $\Delta v_m = 0.07$ used in the simulation, the average cavity detuning $v_0 = 0.03$ and the maximum power cavity detuning $v_{\text{max}}$ are shown.

Fig. 3. Optical micropulse shape, $|A|^2$, versus the optical pulse position, $\xi$, recorded at different instances within a modulation cycle.
Plotted are the simulated results of the micropulse energy and the macropulse length. Here the operation time in the normally inaccessible high-power region is about 4 µs, while the operation time in the steady-state region is about 43 µs. Another interesting application will be the possibility to obtain a very short micropulse with a relatively high energy (see Fig. 5(b)). In that case a longer operation time in the normally inaccessible region is required.

4. Conclusions

We demonstrated a new method of controlling the micropulse length of a short pulse FEL oscillator by modulating the cavity detuning. Numerical simulations based on short pulse FEL equations show good agreement between experiment and theory. The dynamics of the FEL micropulse in the normally inaccessible region is investigated by studying a step-function change in cavity detuning. A correlation is found between optical pulse duration and optical energy when modulation is applied, i.e., shorter pulses are possible at the expense of reduced optical energy. Possible application of this technique is discussed.

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References