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Section A

Wavelength shifting in the Stanford FEL ☆

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Abstract

The time evolution of FEL wavelength in response to small perturbations of the electron energy was measured in the Stanford FEL for a range of operating parameters. The dependence of the wavelength response on the cavity Q, desynchronism, and electron pulse length was also measured. A simple model of the wavelength shifting mechanism is presented which explains the observed behavior.

1. Introduction

Since its realization in 1976 [1], the Free Electron Laser (FEL) has become widely used as a scientific instrument [2]. In such use, the requirements for optical beam quality and stability are stringent. One of these requirements is stability of the FEL wavelength to a small fraction of the optical spectral width. Though this requirement has been met [3] by negative feedback from the optical beam wavelength to the electron beam energy, the dynamic behavior of the FEL wavelength during electron energy changes has not been well understood. In this paper, we present time dependent measurements of the FEL wavelength following sudden changes in electron beam energy. We also present a model of FEL wavelength shifting which provides insight into the observed behavior.

2. A simple model for FEL wavelength shifting

A simple model of the wavelength shifting mechanism for short pulse FELs can be generated by considering the evolution of the optical pulse. The FEL resonance condition states that the electron bunch must slip back over the optical field by one optical wavelength each wiggler period. Thus, as the two pulses travel the length of the wiggler, the electron bunch slips backward with respect to the optical pulse by a distance $N\lambda$ where N is the number of wiggler periods and λ is the optical wavelength. Since the electrons must be bunched by the optical field before they can efficiently exchange energy into the field, slippage leads to preferential optical gain near the trailing edge of the pulse. This effect, known as lethargy, reduces the effective group velocity of the optical pulse. To compensate for this, the FEL cavity length must be slightly detuned from resonance. This detuning, also referred to as desynchronism, shortens the round trip time of the optical pulse in the laser cavity such that, in a reference frame that is co-moving and synchronized with the electron bunches, the optical pulse is moved forward with respect to the electron bunch by a small distance each pass.

As a result of slippage and desynchronism, on each pass there are electrons at the back of the optical pulse which spontaneously radiate into a region of low optical energy. This spontaneous optical field is moved forward into the electron pulse by desynchronism on subsequent passes and is amplified until saturation is reached or until it is moved ahead of the electron pulse and decays from cavity losses. The optical field in the FEL pulse can therefore be viewed as growing from the back of the pulse as it moves forward at the rate of one desynchronism distance per pass.

Considering this description of optical pulse evolution, it seems likely that one mechanism for wavelength shifting is for changes in the electron energy to result in instantaneous changes in the wavelength of spontaneous radiation at the back of the electron pulse, and for this wavelength change to propagate into the pulse one desynchronism distance per pass. Though mode competition in the bulk of the optical pulse may also contribute to wavelength shifting, the FEL gain dependence on wavelength at saturation is so small that this is likely to be a slow process. Therefore, in this model it is assumed that propagation by desynchronism is the dominant mechanism for wavelength shifting in optical pulses that are of length comparable to the slippage distance.

Considering this assumption, the wavelength response as a function of pass number is the convolution of the

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electron energy as a function of pass number with the optical pulse shape. If the center wavelength of the optical pulse is defined as

$$\lambda(n)=\frac{\int_0^\infty \lambda(n,z)P(z)\,\mathrm{d}z}{\int_0^\infty P(z)\,\mathrm{d}z}, \tag{1}$$

where $\lambda(z)$ and $P(z)$ are the optical wavelength and power as a function of position in the optical pulse, and we define normalized wavelength and energy changes as

$$\Delta\lambda(n)=\frac{\lambda(n)-\lambda(0)}{\lambda(\infty)-\lambda(0)},\quad \Delta\gamma(n)=\frac{\gamma(n)-\gamma(0)}{\gamma(\infty)-\gamma(0)}, \tag{2}$$

then

$$\Delta\lambda(n)=\frac{\int_0^{nd}\Delta\gamma\left(n-\frac{z}{d}\right)f(z)\,\mathrm{d}z}{\int_0^\infty f(z)\,\mathrm{d}z}, \tag{3}$$

where n is the number of passes, d is the desynchronism distance, and z is distance along the FEL axis in the optical pulse frame.

Eq. (3) can be simplified using a simple approximation of the optical pulse shape $f(z)$. One such model is shown in Fig. 1. The region of the optical pulse where the optical field interacts with the electron bunch is modeled as a constant amplitude region of length $\alpha=\sigma_z+N\lambda$ where σ_z is the width of the electron bunch. Though such a "square" model of what is obviously a rounded region is crude, this approximation keeps the model simple without compromising its essential features. The optical field region ahead of this interaction region consists of an optical field that has been moved forward out of the interaction region by desynchronism, and is attenuated exponentially by the optical cavity loss. The shape of this passive region can be written as an exponential. The optical pulse shape as a function of longitudinal distance can then be expressed as

$$f(z)=[u(z)-u(z-\alpha)]+u(z-\alpha)\,\mathrm{e}^{-(z-\alpha)/(dQ)}, \tag{4}$$

where $\alpha=\sigma_z+N\lambda$ is the length of the interaction region, d is the desynchronism distance, Q is the optical cavity Q, and $u(x)$ is the step function ($u(x)=0$ for $x<0$, $u(x)=1$ for $x>=0$).

Using Eqs. (3) and (4), the wavelength $\lambda(t)$ as a function of time can be predicted for an arbitrary electron energy change $\gamma(t)$. For a step change in the electron energy the wavelength response can be written as

$$\Delta\lambda(t)=\frac{t}{\tau(\alpha/d+Q)},\quad t<\tau\frac{\alpha}{d}, \tag{5}$$

$$\Delta\lambda(t)=\frac{\alpha/d+Q(1-\mathrm{e}^{-t/(\tau Q)})}{\alpha/d+Q},\quad t\geq\tau\frac{\alpha}{d}, \tag{6}$$

where τ is the round-trip time in the optical cavity ($\tau=85$ ns in the Stanford FEL).

It is evident from the above equations that the time required for the optical wavelength to respond to a sudden electron energy change will increase with increasing Q, increase with longer pulses (larger α), and decrease with larger desynchronism. For very large desynchronism, α/d becomes small with respect to Q and the desynchronism and pulse length dependence of the response time must vanish. In this limit, the response time is only dependent on the optical cavity Q.
The model is valid in the range of medium to large Q and electron pulse lengths comparable to, or shorter than, a few slippage distances. For very low Q, the model of the optical pulse shape we have described no longer resembles the actual shape of optical pulse and some inaccuracy in the model predictions can be expected. For very long electron bunches, wavelength shifting effects which originate in the bulk of the interaction region can no longer be ignored and the model predictions are likely to overestimate the response time.

In the following section, measurements of wavelength response to step changes in electron energy are presented along with the predictions of this model. For the model predictions, the measured electron energy change $\Delta\gamma(t)$ was substituted into Eqs. (3) and (4) to calculate $\Delta\lambda(t)$.

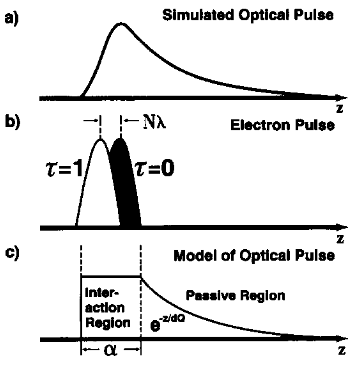

Fig. 1. (a) Simulated [4] optical pulse shape for $Q=50$, $d=0.03N\lambda$ and $\alpha=3N\lambda$ with relevant electron pulse shape and position (b). (c) Two-region model of the optical pulse.

3. Wavelength response measurements

Measurements of the FEL wavelength response to electron energy changes were made by suddenly decreasing the electron energy by 0.1%. This was accomplished by electronically changing the set-point for the RF amplitude stabilization loop in one accelerator structure. The RF field amplitude in this structure was measured as a function of

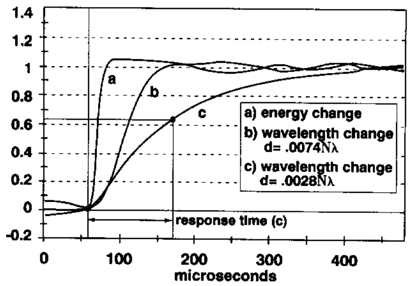

Fig. 2. Measured wavelength response to a sudden perturbation in electron energy as a function of time for $Q = 190$, $\alpha = 4.6$. (a) Normalized electron energy. (b) Normalized wavelength as a function of time for $d = 0.0074N\lambda$. (c) Normalized wavelength as a function of time for $d = 0.0028N\lambda$. The steady state relative wavelength change is approximately 0.2% of 4.9 μm.

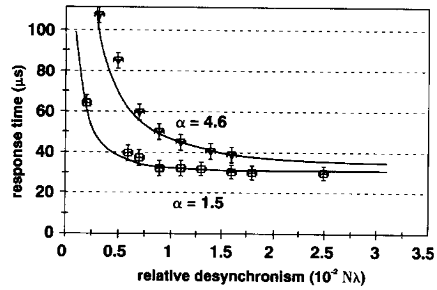

Fig. 3. Response time versus desynchronism for $\alpha = 1.5N\lambda$ and $\alpha = 4.6N\lambda$. $Q = 190$. The crosses represent measured values while the continuous lines represent the predictions of the model.

time to determine the time evolution of the electron energy during the change. The rate of change of the electron energy is limited by the high loaded Q of the accelerator structures. The response time of the electron energy, defined in Fig. 2, was typically 6 μs to 12 μs.

The time evolution of the FEL wavelength was recorded using a spectrometer and an array detector [3]. A typical set of measurements is shown in Fig. 2. Trace (a) is the normalized perturbation in the electron energy as a function of time. The relative amplitude of ripple seen on the energy is approximately 1×10^{-4} of the total electron beam energy. Trace (b) and (c) are the normalized FEL wavelength as a function of time for desynchronism $d = 0.0074N\lambda$ and $d = 0.0028N\lambda$ respectively. Both wavelength traces were obtained for $Q = 190$, $\alpha = 4.6N\lambda$, and $\lambda = 4.9$ μm.

To explore the dependence of wavelength response on parameters such as Q, α, and d, we define a " response time" which is the time interval from the beginning of the energy step to the point where the wavelength has reached 0.63 of its steady state value (see Fig. 2). The optical cavity Q was varied by appropriate choice of cavity mirrors and was determined by measuring the optical energy decay time. The desynchronism was varied by controlling a motorized mirror and was measured using an LVDT linear motion sensor with 0.1 μm resolution. The position of zero desynchronism was estimated from observation of the sharp decrease in optical power which occurs near $d = 0$. All desynchronism values are relative to this point. The length of the interaction region α was varied by changing the length of the electron bunch. The length α, however, was estimated by obtaining autocorrelation measurements of the optical pulse length at various values of desynchronism; α was calculated by extrapolating these measurements to zero desynchronism. All wavelength response measurements were made at $\lambda = 4.9$ μm with energy steps that resulted in a 10 nm wavelength increase.

The response time as a function of desynchronism at $Q = 190$ is shown in Fig. 3. The continuous lines are the predictions of the model for the wavelength response as calculated using the measured energy step. The measurements and the model show that the response time decreases for larger values of desynchronism. This results from the fact that the wavelength shift must propagate through the optical pulse at a rate of one desynchronism distance per pass; an increase in desynchronism increases the propagation rate and decreases the response time. The two measurement sets shown in Fig. 3 correspond to two different interaction region lengths. The separation between the two curves indicates that the response time increases for longer pulse lengths at a given value of desynchronism. This results from the fact that the time required for the wavelength change to propagate through the optical pulse must increase with pulse length if the propagation rate is fixed. For large desynchronism, the optical pulse length is dominated by the exponential $e^{-z/dQ}$ and increasing the desynchronism increases both the pulse length and the propagation rate. In this region, the response time is only dependent on the optical Q.

The response time as a function of desynchronism for large values of d and for three different values of Q is shown in Fig. 4. The length of the interaction region is $1.5N\lambda$. The response time decreases for smaller values of

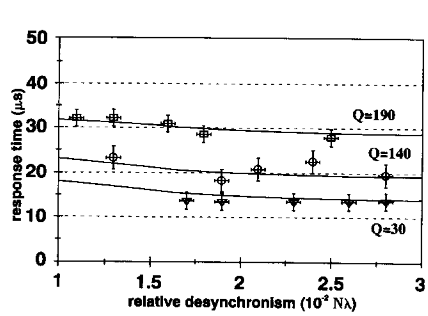

Fig. 4. Response time as a function of desynchronism for $Q = 30$, 140, and 190. $\alpha = 1.5$. The crosses represent measured values while the continuous lines represent the predictions of the model.

Q as expected. For the case where $Q = 30$, the wavelength response time is limited by the finite slew rate of the energy step. However, as the predicted response time is calculated using the measured slew rate, the comparison is still valid.

4. Conclusion

Time dependent measurements of the FEL wavelength in response to sudden perturbations of the electron energy indicate that lower optical cavity Q, shorter electron pulses, and large values of desynchronism all lead to a faster wavelength response. A simple analytic model has been shown to be successful in predicting the wavelength response. The electron energy slew rate can in principle be increased by an order of magnitude over that used in these studies, allowing the validity of the model to be tested with very low optical cavity Q. An improved approximation of the optical pulse shape may be required to extend the validity of the model to this regime.

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