SHORT RAYLEIGH LENGTH FREE ELECTRON LASERS

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Abstract

Conventional free electron laser (FEL) oscillators minimize the optical mode volume around the electron beam in the undulator by making the resonator Rayleigh length about one third of the undulator length. This maximizes gain and beam-mode coupling. In compact configurations of high-power infrared FELs or moderate power UV FELs, the resulting optical intensity can damage the resonator mirrors. To increase the spot size and thereby reduce the optical intensity at the mirrors below the damage threshold, a shorter Rayleigh length can be used, but the FEL interaction is significantly altered. A new FEL interaction is described and analyzed with a Rayleigh length that is only one tenth of the undulator length, or less.

INTRODUCTION

For several decades, it has been suggested that a free electron laser (FEL) oscillator can optimize the electron-optical coupling by minimizing the optical mode volume around the smaller relativistic electron beam. The origin of the idea was stated in Madey's initial paper inventing the FEL concept [1], and has lead to the common practice of designing the FEL's optical resonator so that its Rayleigh length Z_0 is about half of the undulator length L. That assumption is studied in this paper and it is found that there are several possible advantages to much shorter Rayleigh lengths including increased gain.

In Madey's original paper, the FEL gain was estimated using a "Filling factor" F in order to describe how the smaller electron beam exchanged energy with the slightly larger optical mode. The filling factor is defined as the ratio of the electron beam area to the optical mode area with both assumed to be constant along the interaction length L. FEL gain G is then estimated as proportional to the filling factor, and the usual practice was to minimize the optical mode volume around the smaller electron beam. Since that time, it has been common practice to design an FEL oscillator with minimum optical mode area along the undulator length L. A further refinement is to average the filling factor over L so that $G \propto (z_0 + 1/(12z_0))^{-1}$. The normalized Rayleigh length is defined as $z_0 = Z_0/L$ and the actual Rayleigh length is $Z_0 = \pi w_0^2/\lambda$, λ is the optical wavelength, and w_0 is the optical mode waist radius. The optimum weak field gain is then found by minimizing the mode volume over the undulator length L for $z_0 = 12^{-1/2} \approx 0.29$ [2]. Common practice uses values $z_0 \approx 0.3 \rightarrow 0.5$.

The short Rayleigh length FEL design is an alternative that makes use of a resonator cavity with a short Rayleigh length resulting in a larger laser spot at the mirrors [3]. Scientific, industrial, and military applications of FEL oscillators benefit from a more compact design. Laboratory space is always valuable. When the application also requires moderate to high power at infrared or shorter optical wavelengths, the conventional FEL oscillator design leads to high intensity at the mirrors and possible mirror damage.

A couple of examples illustrate how this common practice ($z_0 \approx 0.3 \rightarrow 0.5$) can limit an FEL performance. Take the mirror separation of the resonator to be $S = 12$ m with 10% output coupling. Typical mirrors can be damaged by a high laser intensity $\sim 10\,\mathrm{kW/cm^2}$ in the infrared and $\sim 1\,\mathrm{kW/cm^2}$ in the UV. Taking the electron beam and optical mode to be about 1mm in diameter in the undulator, the commonly used design criteria would lead to a limitation in output power of 150 W in the infrared and only 3 W in the UV. The UV FEL is a particular problem since the longer Rayleigh length Z_0 associated with the shorter UV wavelength λ increases mirror intensity further by decreasing the mirror spot size. Both FELs would benefit from a shorter Rayleigh length resonator in order to reduce the intensity on the mirrors and keep the system compact. The conventional estimate for gain would lead to $G \propto z_0$ for small Rayleigh length $z_0 \ll 1$. The research presented here shows that this is incorrect, and that there is little or no loss in gain for small $z_0 \ll 1$. The design option is illustrated in Figure 1 below.

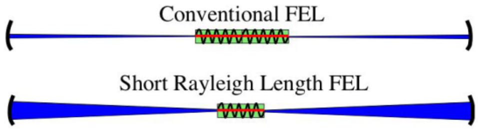

Figure 1: Schematic comparison of the conventional and short Rayleigh length FEL designs.

The FEL interaction is altered in the short Rayleigh length FEL because the optical field amplitude and phase change significantly along the undulator [4]. The field amplitude $a(\tau)$ and phase $\phi(\tau)$ at the mode center $r = 0$ are shown in Figure 2 and are given by

$$a(\tau) = a_0(1 + (\tau - \tau_w)^2/z_0^2)^{-1/2} \quad (1)$$

$$\phi(\tau) = -\arctan((\tau - \tau_w)/z_0) \quad (2)$$

where $\tau = ct/L$ is the dimensionless time of interaction along the undulator length L, c is the speed of light, a_0 is the dimensionless optical field amplitude at the mode focus, and τ_w is the location of the mode focus along the undulator. When z_0 is small, the field amplitude and phase change rapidly along the undulator. While the rapidly changing field would appear to be detrimental to the bunching process, it may improve coupling by focusing laser light to a small waist to intensify the field strength.

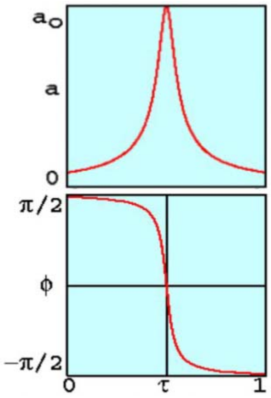

Figure 2: Optical field amplitude $a(\tau)$ and phase $\phi(\tau)$ as functions of dimensionless time $\tau = ct/L$.

SIMULATION RESULTS

As an example consider an FEL having an undulator of $N = 22$ periods with total length $L = 52$ cm, rms undulator parameter $K = 1$, and period $\lambda_0 = 2.36$ cm. The FEL with a shorter Rayleigh length requires a shorter undulator length so that the expanding mode does not scrape the undulator magnets. In this case the undulator gap is $g = 1$ cm and there is no significant scraping of the focused electron beam or optical mode. At the end of the undulator the optical mode radius is $w_u \approx (\lambda L/4\pi z_0)^{1/2} \approx 0.2 z_0^{-1/2}$mm in this case. In order to keep $w_u < 0.2g = 2$ mm to avoid even the slightest scraping, we keep $z_0 > 0.01$. An electron micropulse of $I = 400$ A peak current and energy of 80 MeV is focused to a small waist radius of $r_b = 0.06$ mm. The FEL resonance condition defines the optical wavelength as $\lambda \approx \lambda_0(1 + K^2)/2\gamma^2 = 1\,\mu$m in a resonator with mirror separation $S = 12$ m and 25% output coupling. FEL gain is evaluated from simulations following the electron beam dynamics and optical mode self-consistently [2].

Figure 3 is the result for this FEL, varying the dimensionless Rayleigh length over the range $z_0 = 0.1 \to 1$. The most dramatic result is that gain does not decrease like $G \propto z_0$ for small z_0, but remains roughly constant around $z_0 \approx 0.01$. This is due to optical mode distortion that is allowed to occur self-consistently in the simulations, but not in the simple estimate using the filling factor F. The single pass gain is large for this example (nearly 400%), but the trend shown here has been confirmed for much smaller gain as well. To the right are examples of the optical mode shape plotted in (x, y) as they are slightly distorted from their Gaussian fundamental shape. The distortion is not large, but sufficient to significantly increase the gain when the Rayleigh length is small. In these cases, the electron beam has been focused to a waist size of $r_b \approx 0.06$ mm so that it remains inside the focused optical mode waist. The normalized emittance required for this case is $\epsilon_n = 3$ mm-mrad, but larger emittances have been explored finding the same trend: there is no significant decrease in gain at small Rayleigh length when mode distortion is allowed. Also, the location of the optical mode focus is found to be optimum for $\tau_w = 0.5$, in the middle of the undulator.

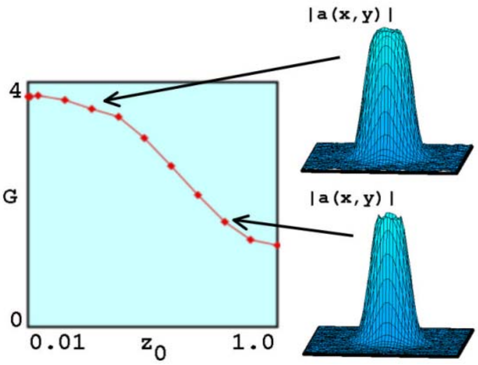

Figure 3: FEL gain as a function of Rayleigh length z_0.

If the electron beam focal radius r_b is made too large, some of the electron beam is outside of the optical mode waist, decreasing coupling and gain. If the electron beam focal radius is made too small, the larger angular spread resulting from fixed emittance ϵ_n results in some of the electron beam drifting outside of the optical mode at the ends of the undulator, so that again gain decreases. There is typically an optimum electron beam focal radius $r_b \sim 0.1$ mm for the short Rayleigh length designs examined.

The effects of mirror vibration and positioning are more critical in the short Rayleigh length design, but we find that they are still within normal design tolerances [5].

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