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BENDING AND FOCUSING EFFECTS IN AN FEL OSCILLATOR: (I) SIMPLE MODELS*

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ABSTRACT

The combination of wiggler, electron beam, and optical beam produces not only gain, but also refractive effects. These effects have been modeled for an oscillator configuration with a simple prism and lens. An instability is found to occur whenever the focal strength of the electron beam is sufficiently large. An estimate has been made of the magnitude of these effects and we present a discussion of the likely consequences.

1. Introduction

The Los Alamos free-electron laser (FEL) operates [1] at 10 μm and employs either a uniform or tapered wiggler. The FEL frequently displays a regular modulation in the amplitude of its output with a period near 400 ns. This modulation is observed only when there is misalignment of the electron beam with the axis of the optical cavity and the optical signal is either rapidly increasing at the beginning of a macropulse or freely decaying at the end. An example of a modulated growth is shown in fig. 1. We are able to explain these observations in terms of the interaction of the optical beam with an electron beam that is misaligned with the axis of the optical cavity. The interaction contains the same physics as the guiding effect discussed by Scharlemann, et al. [2], for free beams not constrained to an optical cavity. Our explanation takes two forms: (1) In sec. II of this paper, we present a simple model where the optical signal is represented by its central ray and the bending effect of the misaligned electron beam is represented by a prism. With this model we can demonstrate the kinds of phenomenon that have been observed as well as predict

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other important phenomenon not yet seen. In sec. III, we then describe the cavity modes and represent the focusing effect of an aligned electron beam by a lens. Focusing has not yet been observed. In sec IV, we estimate the magnitude of the effects, describe the limits to the simple models, and discuss the likely consequences of the effects. (2) In companion paper II, we model the interaction of the optical and electron beams with a computer simulation where we have included 3-D effects in detail with good qualitative agreement between these two approaches.

Previous theoretical and experimental works have been performed to investigate lenses and focusing media contained within an optical cavity. Pierce [3], for example, discussed sequences of lenses used to propagate coherent light over long distances. Kogelnik [4] and Tien et al. [5], cover lens-like media such as gas with index variations produced by acoustic waves or temperature gradients. Berreman [6] performed guiding experiments in cells with temperature gradients. Kogelnik [7] discussed resonant cavities with internal lenses and lens-like media. Louisell [8] included some of these index-varying effects for a CO_2 laser medium. Finally, Quimby and Slater [9], Slater and Lowenthal [10], Tang and Sprangle [11], and Bhowmik and Cover [12], and Colson and Richardson [13] all made numerical simulations for FELs that display mode displacements and distortions resulting from focusing effects. The new features included in this paper are

- The focusing effect in an FEL occurs only when the optical beam is propagating in the same direction as the electron beam.
- Focusing results from the interaction of the light and electron beams in the wiggler. The index variations that lead to focusing are not fixed to the wiggler, to the electron beam, or to the optical beam, but depend on the positions and strengths of all three.

- The lens-like region is usually smaller in diameter than the optical beam.
- The magnitude of the focusing effects in FELs is quite large and can effect the stability of the resonator.

2. Walking Mode

Figure 2 represents a near-concentric optical cavity (stability factor 0.93) like that used in our experiments. Suppose that a light ray is injected into the cavity through its center at an angle α relative to the optical axis. One can easily calculate the path followed by the ray after successive reflections from the two mirrors and evaluate the development of interesting quantities with time; for example, the angles T and B where T represents the tilt angle of a reverse ray (moving counter to the electron beam), and B represents the intersection angle of successive forward rays. In general, all of these quantities oscillate around zero in an approximately sinusoidal fashion with the same period and related amplitudes. Using ray optics, we have calculated the period in terms of the number of round trips (NRT) the optical pulse must experience before the angle α repeats itself. We find that $NRT = \frac{\pi}{2} \sqrt{D/\delta}$ to first order in δ/D , where δ is the separation of centers of curvature of the identical mirrors of radius R, and D is the mirror separation given by $D = 2R - \delta$. We call this oscillatory motion the walking mode.

This calculation can be performed in a more persuasive manner by recognizing that a slightly off-axis Gaussian optical beam can be accurately represented by the sum of an on-axis Gaussian beam plus the admixture of a small amount of the next higher odd optical mode. These two modes have different phase velocities in the cavity and thus progressively slip out of phase with each other. The phase slippage causes the centroid of the combined modes to oscillate with a

characteristic period. This is the walking mode. Again, we can calculate NRT, the number of round trips for the combined modes to replicate themselves. From the data of Kogelnik and Li [14], we have calculated,

$$NRT = \pi / \left[2 \tan^{-1} \left(\sqrt{\frac{\delta/R}{2 - \delta/R}} \right) \right] ,$$

and to first order in δ/D

$$NRT = \frac{\pi}{2} \sqrt{D/\delta} .$$

For our experimental parameters, i.e., $\delta = 23$ cm and $D = 6.9$ m, we find $NRT = 8.6$. This is in good agreement with the measured value of 8.5 from fig. 1.

3. The Electron Beam - A Prism

Bending caused by the electron beam can be modeled by a one-way prism that acts only when the optical beam moves in the direction of the electrons and not on the return path. A steady-state description of the optical beam in the presence of such a prism can be derived by using ray diagrams such as fig. 2. Point X of fig. 2 represents the crossing of rays #2 and #4. If a prism of the correct strength were placed at X, ray #4 could be bent so as to fall on ray #2. Then the triangular trajectory, including ray #3 and parts of rays #2 and #4, would represent the steady-state mode with this prism at X. If a prism of twice this strength were placed at X, a modified steady-state trajectory could be drawn with all angles doubled in size. The steady-state mode that results from placing a prism of any strength anywhere within the optical cavity can be determined by this kind of ray matching.

Several important conclusions can be reached from these constructions.

- The steady-state mode is characterized by two angles: a bend angle, B, and a tilt angle, T.

- The bend angle is proportional to the strength of the prism.
- The tilt angle is proportional to the strength of the prism, its longitudinal displacement from the center of the cavity, and the number of round trips needed to reproduce the angles. Thus, the tilt angle increases as the cavity gets longer and becomes more nearly concentric.
- If the prism were suddenly removed (electron beam turned off), the steady-state optical mode would cease to reproduce itself and would instead start cycling through the pattern of fig. 2.
- The amplitude of this cycle would be proportional to the strength of the prism and NRT. The phase of the cycle within the walking mode would depend upon the prism's longitudinal placement.

4. Breathing Mode

If an optical ray were injected into the cavity directly on axis, a walking motion would not be established. If, however, the injection were not carefully performed (e.g., a misplaced focus), the mode excited would not be in steady state and a different kind of oscillation, which we call the breathing mode, would result. A discussion of the Gaussian modes in a cavity of this type can be found in Kogelnik and Li [14]. If the mode is not in steady state, two waists occur, one in the forward direction and one in the reverse. The waists oscillate around the center of the cavity with a characteristic amplitude and period. The period can be evaluated, as before, using either a modified ray or mixed wave-mode description. Using the latter approach, we find that the mode-mixture required involves the lowest order mode and the next higher even mode. The period that results is one-half the period of the walking mode.

If, as before, we select three consecutive passes from the breathing mode, two in the forward direction and one in the reverse, we can find the

intersection of the two forward passes, i.e., the position where their radii are the same. A lens of appropriate strength placed at this position will focus one forward pass into the other and produce a steady-state mode that includes one reverse path and parts of two forward passes of the breathing mode. Figure 3 illustrates this kind of mode matching. As was found for the prism, if the lens is suddenly removed (electron beam turned off), an oscillation is produced, this time in the breathing mode.

4.1. Stability

In contrast to the prism case, we cannot always find three passes of the breathing mode to match to any lens. There is an upper limit to the focal strength of the lens, equal roughly to the combined strengths of the mirrors, beyond which a steady-state mode does not exist. When this limit is approached, the waist of the reverse mode and its footprint on the mirror become very large. The forward mode then has two small waists and a large diameter in the wiggler. Figure 4 is an approximation of this limiting case. Also shown in fig. 4 is the empty cavity mode. Obviously, little light is transmitted through a wiggler near the limit.

5. Discussion

5.1. Estimate of Magnitudes

A crude attempt will be made here to assess the magnitude of the bending and focusing effects for the Los Alamos laser. A more detailed calculation using computer simulations is presented in the companion paper. When our tapered wiggler is operating at saturation, its resonant phase angle is about 45° and its optical power gain about 10%. A simple vector diagram shows that in each forward pass of the optical beam, the electron beam adds to the old field a new

field that is 7% as large as the old field and is shifted 45° behind it in phase. The new combined signal is delayed by about 4° behind the old field. If the electron beam had been shifted sideways so that it interacted with only half of the old beam, that part would have been shifted in phase by 4° with respect to the other half. This causes a distortion, i.e., a tilt of the wavefront that leads to a bend in the beam given roughly by

$$\frac{4^\circ}{360^\circ} \approx \frac{\lambda}{r}$$

where r is the radius of the electron beam. Using $r \approx 1$ mm, we find a bend of about 100 μ rad.

We can make a similar estimate of the focusing effect. If the new field is added to the old only in the central one half of its profile, the wavefront will become curved in a focusing manner. A crude estimate of its radius of curvature, i.e., the focal length of the effective lens, gives 2.5 m. This estimate is close to the stability limit, S , discussed above and defined as $S = \frac{R}{4} = 0.86$ m, where R is the radius of curvature of the mirrors. It appears likely that the stability limit will be approached or exceeded at high currents with long cavities.

5.2. Limits to the Model

The simulation of an electron beam by a simple prism or lens is reasonably good if the effective length of the electron beam (the wiggler's length) is short compared to the cavity length and if the electron beam's cross section is large compared to that of the optical beam. The different parts of a wiggler (bunching section, tapered part, etc.) contribute differently to the bending and focusing effects so a more accurate representation would include multiple prism or lensing elements. Even if the wiggler is centered in the optical cavity, the effective prism or lens will generally not be centered.

The gain of a wiggler is maximized if every electron passing through it interacts with the maximum optical field. This leads to designs where the electron beam has a cross section small compared to that of the optical beam, violating the condition stated above. In such a situation, mode distortion may become significant. Such distortions will not be acceptable in many cases, i.e., when near-optimum focusing is required. A sacrifice in gain may then be acceptable if it reduces distortion. This reduction can be accomplished by broadening the electron beam's cross section to meet the requirements given above.

5.3. Consequences of Instability

The small size of the electron beam may not be all bad. On first sight, it appears that instability would be catastrophic; i.e., above some limiting current, the electron's focal strength would exceed the stability limit and all light would be forced to the cavity walls. Actually, there are several mechanisms that save us from this fate. First, at moderate electron currents, the focal strength will be below the limit but will cause a moderate reduction in mode stability, i.e., a moderate increase in period of the walking and breathing modes, a moderate increase in mode size at the wiggler, etc. These effects were observed in companion paper II. The increased mode size will reduce the focal strength of the electron beam and provide a natural buffer against instability (as well as reduce gain and extraction efficiency). Second, at high electron currents, the mode will be unstable on axis but stable off axis, where the electron beam is weak and the focal strength low or even negative. A hollow doughnut-like mode will result with a low optical field on axis having low gain and efficiency. This was observed in a number of simulations in companion paper II. Finally, at very high currents, vignetting on the walls may become

significant and will help to stabilize the mode but, again, produce low gain and efficiency.

6. Conclusion

The bending and focusing effects caused by the active medium in an FEL oscillator can be quite large. The focusing effect can upset the stability of near-concentric resonators and lead to mode distortions, vignetting losses and low gain. Bending and focusing effects can be identified by oscillations of the cavity modes at different characteristic frequencies.

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FIGURE CAPTIONS

1. Series of optical pulses leaving cavity, one on each pass. The exponential growth is modulated in amplitude by the walking mode.
2. Ray reflecting off mirrors in walking mode. Shown is about one fourth of a complete cycle. Ray #3 and parts of #2 and #4 are drawn as heavy lines. This triangular pattern can be a stable mode if a prism of the correct strength is placed at X.
3. Gaussian mode reflecting off mirrors. Three modes are combined to represent the steady-state mode resulting when a lens of the correct strength is placed at X.
4. Diagram representing the mode pattern near the stability limit.

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