NOV 08 1985

TITLE COMPARISON OF THE RESULTS OF THEORETICAL CALCULATIONS
 WITH EXPERIMENTAL MEASUREMENTS FROM THE LOS ALAMOS
 FREE-ELECTRON LASER OSCILLATOR EXPERIMENT

AUTHOR(S): John C. Goldstein, X-1
 Brian E. Newnam, CHM-6
 Roger W. Warren, AT-7
 Richard L. Sheffield, AT-7

LA-UR--85-3556

DE86 002382

SUBMITTED TO: Proceedings of the 1985 Free-Electron Laser Conference
 to be held 9/9-13 in Tahoe City, CA

MASTER

By acceptance of this article the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

MR

COMPARISON OF THE RESULTS OF THEORETICAL CALCULATIONS
WITH EXPERIMENTAL MEASUREMENTS FROM THE LOS ALAMOS FREE-ELECTRON LASER
OSCILLATOR EXPERIMENT*

John C. Goldstein, Brian E. Newnam, Roger W. Warren and Richard L. Sheffield
Group X-1, MS E531
Los Alamos National Laboratory
University of California
Los Alamos, NM 87545

ABSTRACT

A comparison between some of the measurements made with a uniform wiggler during the Los Alamos free-electron laser oscillator experiment and the results of one-dimensional pulse propagation calculations using the mathematical model of Colson and Ride will be presented. Small-signal gain data will be discussed. Calculated output power vs. optical resonator length will be compared with data. Time-integrated optical spectral data, which show clear evidence for Raman sidebands, will be compared with calculated spectra as a function of resonator length. The calculated electron energy distribution function, using the measured electron-beam micropulse shape, and the associated extraction efficiency will be compared with measurements.

*Work performed under the auspices of the U. S. Department of Energy and supported by the U. S. Army Ballistic Missile Defense Organization.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Comparison of the Results of Theoretical Calculations with
Experimental Measurements from the Los Alamos Free-Electron
Laser Oscillator Experiment

John C. Goldstein, Brian E. Newnam, Roger W. Warren, and Richard L. Sheffield
Los Alamos National Laboratory

Introduction

This paper presents a comparison of experimental measurements made during the Los Alamos untapered wiggler free-electron laser oscillator experiment [1]-[4] with theoretical calculations made using the time-dependent, one-spatial-dimensional, pulse-propagation theory [5], [6] of free-electron laser action. The model of Colson and Ride [5] was used, with slight changes for a plane-polarized wiggler [7]. A general review of previous theoretical results from the one-dimensional theory, as well as comparisons with data from the Stanford free-electron laser oscillator experiments, is given in ref. [8].

Not all of the data collected during the experiments will be compared, in this paper, with theoretical calculations. For example, data on the relative magnitudes of higher optical harmonics and on the quality of the optical beam, as determined from its focal spot dimensions, will not be discussed. Specifically, calculations and measurements of the output power and optical spectrum versus optical resonator length will be compared. The results of another calculation of the extraction efficiency and electron energy spectrum, using a more accurate representation of the electron beam in the theory, will be compared with measurements. Finally, the effects of electron energy fluctuations on the optical output will be discussed.

Applicability of the Theory

Before such comparisons are made, it is necessary to determine whether or not the conditions of the experiment satisfied the basic assumptions and approximations of the theory, and, if so, what specific numerical values of theoretical parameters pertained during the time that measurements were being recorded. The basic assumption of the theory is that the electron beam transverse dimension be small compared to that of the optical beam so that all electrons interact only with the on-axis component of the electric field of the light. That is, the size of the electron beam, averaged over the length of the plane-polarized wiggler magnet, should be small compared to the focal spot size of the theoretically-assumed lowest order Gaussian mode of the optical resonator. In fact, for the electron beam, wiggler, and optical resonator parameters of this experiment, the average size of the electron beam is about equal to the optical mode's focal spot size. Hence, one of the basic assumptions of the theory is not very well satisfied. Since the one-dimensional theory ignores the transverse variation of all physical quantities, it cannot address questions related to the transverse-mode content of the light (e.g., optical quality, the effects of misalignment of the optical resonator, electron beam, and wiggler axes, etc.).

Values of many different physical parameters are needed to carry out numerical calculations based on the theoretical model. Parameter values for the wiggler magnet and the optical resonator can be determined from measurements made separately on these components when the FEL is not operating (although measurements of the total round-trip loss of the optical cavity were made using light from the FEL itself) and it is thought that these values are constant during the operation of the experiment. Parameter values for the

electron beam are largely determined by the operating conditions of the rf-linac [9]-[12]. Since the linac can be operated under many different conditions, the parameters of the electron beam can be changed and therefore need to be characterized as they existed during a specific set of FEL experiments. Additionally some of the electron-beam parameter values (peak micropulse current and average energy) were not constant during the generation of light in the optical resonator: they exhibited slow changes ("drifts"), or rapid changes ("fluctuations"), or both. Although in principle, all of these effects can be included in the numerical calculations, the "fluctuations" are stochastic in nature and have not been included because not enough is known about their statistics.

Despite the one-spatial-dimensional character of the theoretical model, the numerical calculations are quite long and expensive, primarily due to the fact that the electron micropulse is about twenty slippage distances long (the slippage distance s is related to the wiggler length L_w and the electron's axial velocity $\beta_z = v_z/c$ by $s = L_w(1 - \beta_z)$) and the electron macropulse drives the oscillator over a time duration that corresponds to 2000 round trips of the optical pulse in the resonator. It is necessary to resolve the optical pulse on a length scale much smaller than s if the modulation due to the sideband instability is to be accurately calculated. Therefore, two major simplifications were made in calculations of the desynchronism curve, presented below, in order to reduce the cost of the numerical computations: the electron micropulse shape was taken to be parabolic, and the electrons, prior to interaction in the FEL, were taken to be monoenergetic. The consequences of these approximations are discussed below.

Previous theoretical calculations [13] have predicted FEL performance on the basis of anticipated values for electron-beam and optical resonator

parameters. The approach taken to analyze the results of this experiment has been to calculate the desynchronism curve using a simplified representation of the electron beam in order to reduce the required time and cost of the numerical calculations. Several special calculations which included a better representation of the electron beam micropulses, including drifts and fluctuations of the mean electron energy during the macropulse, were then performed. The results of these calculations will be discussed separately.

Small-Signal Gain and Electron Beam Parameters

The small-signal gain is an important parameter of any laser. Comparison of the measured value of the small-signal gain with the calculated value (calculated, in the case of a free-electron laser, from the separately measured characteristics of the wiggler magnet and the electron beam) provides a test of the validity of the theory under weak signal conditions. Such conditions usually hold during the initial stage of the evolution of a laser oscillator that starts up from spontaneous emission. A calculation of oscillator evolution basically consists of self-consistently computing the growth of the radiation field and the accompanying reduction of the gain (i.e., gain saturation) until a steady-state optical intensity is reached for which the single-pass gain equals the total round-trip optical cavity loss. A comparison of measured and calculated steady-state laser performance (or time-integrated output, as was measured in this experiment) will probably not be very good if the theoretical calculation starts with a small-signal gain different from that in the experiment.

The net round-trip optical gain was routinely measured by directly observing the change from pass to pass of the detected optical signal at early times in the electron beam macropulse while the light intensity was several

orders of magnitude below its final saturated value. However, it was observed that small-signal gain data varied by $\pm 50\%$ for the same accelerator operating conditions. Hence, these measurements could not be compared with calculated values, and they could not be used to fix the initial gain of an oscillator calculation. The reason for the wide variations in the small-signal gain data appears to be that, at early times in the macropulse, accelerator turn-on transients had not completely died out: the peak micropulse current showed some initial ringing and the mean electron energy may have changed by several percent during the gain measurements. Hence, the measured gain values did not reflect the steady-state conditions of the electron beam which obtained later on in the macropulse. Similar problems with initial accelerator transients were observed at Stanford [14].

Desynchronism Curve and Optical Spectra

Since the initial conditions for oscillator calculations were not fixed by the data (a calculation follows the reduction of the initial gain due to rising light intensity until an equilibrium is reached between the saturated gain and the optical cavity losses) a series of calculations was done at zero cavity length detuning with various peak currents. On comparing the results with data, it was decided that the calculation using a peak current of 33 amps resembled the data most closely. Using this current, a full desynchronism curve was then calculated. The parameter values used in the calculations are given in Table 1. It should be noted that two major simplifications have been used in making these calculations: the electron beam was taken to be monoenergetic, and the temporal shape of the electron micropulse was taken to be parabolic. In addition, neither drifts nor fluctuations of the electron beam energy were included in these calculations. Other than the value of the

peak micropulse current, the only difference between these calculations and earlier ones [13] is that the present calculations start from, and include on each successive pass through the optical resonator, spontaneous emission. Figure 1 shows the spectrum of spontaneous emission, averaged over 100 passes, produced by the numerical model. Figure 2 shows the measured and calculated desynchronism curves. The maximum calculated laser output occurs at a cavity length $L=L_0+\delta L$ such that the round trip time of light, $2L_0/c$, is exactly equal to the time T between successive electron micropulses. The experimental data have been plotted such that the peak occurs at $\delta L=0$, but measurements do not identify the cavity length of exact synchronism. The calculated maximum output power is about 20% lower than the measured value, but the full width of the desynchronism curve at half height is about twice as large as that for the measured curve. This discrepancy may be caused by three-dimensional effects which are left out of the present calculations.

As has been pointed out in previous theoretical papers [8], [13], the characteristics of the optical pulse at a cavity length corresponding to the peak of the desynchronism curve differ substantially from those of optical pulses generated in the wings of the desynchronism curve. The primary difference, besides the magnitude of the intensity, is in the spectrum of the light which, for the conditions of this experiment, was predicted to exhibit a complex multiple-line structure at $\delta L=0$. As δL either increases or decreases, the optical spectrum is predicted to simplify progressively until only a single narrow line is present on the extreme wings of the desynchronism curve. This behavior is caused by the generation of sidebands due to the nonlinear motion of electrons in ponderomotive potential wells in the presence of very high optical intensities [8].

Clear evidence for sidebands [15], which were hitherto not observed experimentally, is one of the major accomplishments of the present experiment. In fact, there appears to be more structure in the experimental spectra than there is in the calculated spectra. The experiment did not measure the spectrum of a single optical micropulse but rather the time-integrated (over the total duration of the electron-beam macropulse) optical spectrum. Theoretically, the spectrum of a single optical micropulse would be expected to change substantially over this time interval: at very early times, the optical spectrum is that of spontaneous emission; later, the spectrum becomes narrowed into a single peak by the repeated action of the frequency-dependent gain; still later in the macropulse, sidebands appear (for a cavity length detuning δL near zero) and produce a broadened, multiple-peaked spectrum. Of course, the mean intensity of the light increases by some ten orders of magnitude during this spectral evolution, so that the experimental data are heavily weighted by the optical micropulse spectra at high intensity. Figs. 3a and 3b show calculated time-integrated spectra for $\delta L=0$ and $\delta L=-20\mu\text{m}$, while measured spectra at the detunings labelled A and B of Figure 2 are shown in Figs. 3c and 3d respectively. Although substantial shot-to-shot variations of the spectra occurred in the experiment, the data exhibited in Figs. 3c and 3d represent two different single shots - no averaging was done.

What is the effect of adding an energy spread to the initial electron beam in the theory? If the peak current is held fixed, the small-signal gain drops, and the laser will saturate at a lower intensity for the same optical resonator loss. However, a calculation with the same small-signal gain (68%) and a $2\frac{1}{4}\%$ energy spread was done by raising the peak current to 98A. Under other conditions as given in Table 1, the result for the integrated spectrum is shown in Figure 4. Under these conditions, the resonator loss is low

enough to allow the light intensity to reach high enough levels that the effective bucket full height (10.6%) is greater than the intrinsic energy spread. Hence, the energy spread does not detract from the high-intensity optical gain and, since the peak current is three times higher than the monoenergetic case, the total laser output is substantially increased (by a factor of 3.9).

Are there other sources of spectral broadening? Yes - if the mean energy of the electron-beam changes during the macropulse, the resonance condition changes and one might expect the light frequency to also change. Figure 5a shows the calculated integrated spectrum at $\delta L = -40 \mu\text{m}$ for the parameters listed in Table 1. Figure 5b shows the calculated integrated spectrum for identical conditions except that the electron beam energy increased linearly in time by 2% over the duration of the macropulse. Obviously, the light was "dragged" by the electrons to show an integrated spectral width of about 4%. Again, in both cases, individual optical micropulses show a single narrow-line spectrum with no evidence of sidebands. We note that great care was taken during the experiments to minimize the drift in the mean electron-beam energy. It was kept to less than 0.5% and was always monitored on the slow deflector [9]-[12]. Also, the shapes of the experimental spectra are different from that shown in Fig. 5b. Hence, the experimental spectra shown above are thought to reflect sidebands and not the drift of the mean electron energy.

Another striking feature of the experimental results is the irregular variations of the light output after quasi-steady-state conditions at high intensity have been reached. This effect has been named the "Rocky Mountain effect" [1]-[4] and has been traced to small fluctuations ($\approx 0.1\%$) of the mean electron beam energy due to fluctuations of the fields in the accelerator.

The electron-beam transport channel from the accelerator to the wiggler contains a dispersive section in which the path length taken by high energy electrons is shorter than that taken by low energy electrons (approximately 0.75 cm shorter for a 1% difference in energy). Fluctuations in the mean electron energy therefore cause fluctuations in the arrival times of successive pulses at the entrance to the wiggler. These arrival time fluctuations cause the overlap between the light and electron pulses, as they traverse the wiggler, to fluctuate, thus resulting in fluctuations of the light output. Calculations of periodic (with 10 μ s period) arrival time errors show substantial (10%) modulation of the light output, in qualitative agreement with data, for small (+3ps) timing errors. Calculations with stochastic variations of timing errors have not been done.

Calculation Using Exact Micropulse Shape

Measurements of the exact electron-beam micropulse shape have been made with the "fast deflector" [10]. After performing a deconvolution of the data, the shape of an individual micropulse was seen to be as in Fig. 6. This shape differs significantly from the parabolic shape used in most of the theoretical calculations in that very long Lorentzian-like wings are observed. These low-current wings do not have enough gain to exceed the cavity losses - and hence do not contribute to laser action - but contain ~20% of the total charge and therefore reduce the measured extraction efficiency. One long (approximately ten times longer than usual) numerical calculation was done using both the measured electron beam micropulse shape and the measured 2 1/4% intrinsic energy spread. Other changes from Table 1 for this single calculation are listed in Table 2. Note that the calculated extraction efficiency (1.15%)

listed in Table 2. Note that the calculated extraction efficiency (1.15%) agrees well with the measured value (1.0% $\pm$ 0.2%). The measured energy distributions with and without laser action are shown in Fig. 7a. In Figs. 7b and 7c, the electrons' relativistic factor γmc^2 , is plotted: $\bar{\gamma}_i$ is the average value of γ before interaction, $\bar{\gamma}_f$ is the average value after interaction, and the extraction efficiency is $(\bar{\gamma}_i - \bar{\gamma}_f)/\bar{\gamma}_i$. Fig. 7b shows the calculated energy distribution for the entire micropulse. The initial distribution was taken to be rectangular, 2 1/4% wide, and was simulated in the code by six columns of particles rather than a uniformly-filled rectangular region. The remnants of the initial distribution can be seen in the upper right side of Fig. 7b; these electrons, which have not changed their initial energies, correspond to electrons in the long, low-current wings of the electron micropulse which never see strong optical fields. If the extraction from the central region is examined, where $I \geq 0.2 I_{\max}$ (which contains 68% of the total charge), an extraction efficiency of 1.58% is observed and the distribution is shown in Fig. 7c. Individual zones of the calculation near the peak current show extraction efficiencies of up to 2.8%. A physical picture of sideband generation which is consistent with these results is given in Ref. [16]. Figure 8a shows the calculated optical pulse shape, inside the optical resonator at the exit of the wiggler, with the electron micropulse (dotted line) superimposed. Modulation due to the sideband instability is apparent, although more structure is shown in Fig. 8b which is a plot of the electric field amplitude at the same physical location. Note, from Table 2, that the optical resonator losses matched the experimental value of 1.6% (1/4% output coupling) and so were quite different from the conditions of Table 1 and the detuning curves in Fig. 2.

Summary and Conclusions

Calculations made using the one-dimensional pulse-propagation theory of free-electron lasers have been compared with measured results from the Los Alamos untapered wiggler free-electron laser oscillator experiment. Several qualifications should be noted before interpreting the degree of agreement between the measured and calculated desynchronism curves and associated optical spectra: the theory does not treat three-dimensional effects at all, and the transverse size of the electron beam is comparable to the focal spot size of the optical mode, thus bringing the one-dimensional approximation into doubt for the conditions of this experiment. In addition, experimental data do not determine very well the electron-beam conditions (e.g., small-signal gain) at the beginning of the evolution of radiation in the oscillator. Hence, the appropriate values of some of the theoretical parameters cannot be accurately determined. However, known properties of the electron-beam lead to very long numerical calculations; hence, the micropulse shape and the distribution of initial electron energies have been approximated in the calculations.

Despite these uncertainties and approximations, the calculated desynchronism curve is in good agreement with the measurements: the maximum output power is 20% below the measured value, and the full width at half height of the calculated detuning curve is twice as large as that obtained from experimental data. It is known [17] that the width of this curve is proportional to the electron current. Part of the discrepancy may be due to three-dimensional effects not included in the calculations. The time integrated optical spectra, at different values of cavity length detuning, are similar, but not identical, in the measurements and the calculations. Measurements of time-resolved optical spectra, from one or a few optical

micropulses rather than the entire macropulse, are needed to completely demonstrate theoretically predicted sideband generation as such measurements could not be confused by drifts or fluctuations of the electrons' mean energy. The difference between the calculated and measured peak extraction efficiency is probably due to the presence of low current wings on the electron micropulse which were not in these calculations. Electrons in these wings do not generate intense light but do reduce the measured extraction efficiency.

Several special calculations were made to simulate other experimental conditions such as drift of the mean electron energy during the macropulse and variations in the times of arrival of successive electron pulses at the wiggler due to fluctuations of the mean electron energy and the characteristics of the beam transport system. Qualitative agreement with observations was achieved. The result of a single calculation which used the measured electron micropulse shape and energy distribution is in good agreement with extraction efficiency measurements. The calculation shows that long, low-current wings of the electron micropulse do not significantly contribute to laser action but do detract from the measured extraction efficiency; hence, accelerator design and operation should avoid such shapes. It is thought that the present level of agreement between theory and experiment is sufficient to allow for the design of future experiments. Finally, theoretically predicted sidebands have, for the first time, been observed in this experiment and exhibit spectra similar to calculated spectra.

Acknowledgement

One of the authors (J.C.G.) would like to thank Brian D. McVey for assistance with the numerical calculations.

References

1. R. W. Warren, B. E. Newnam, W. E. Stein, J. G. Winston, R. L. Sheffield, M. T. Lynch, J. C. Goldstein, M. C. Whitehead, O. R. Norris, G. Ludemann, T. O. Gibson, and C. M. Humphry, "First Operation of the Los Alamos Free-Electron Laser Oscillator," in Proceedings of the International Conference on Lasers '83, R. C. Powell ed. (S.T.S. Press, McLean, VA, 1985), pp. 316-320.
2. B. E. Newnam, R. W. Warren, R. L. Sheffield, J. C. Goldstein, and C. A. Brau, "The Los Alamos Free Electron Laser: Optical Performance," Nuc. Instr. and Methods in Phys. Res. A237 (1985), pp. 187-198.
3. R. L. Sheffield, R. W. Warren, B. E. Newnam, W. E. Stein, J. C. Goldstein, and M. T. Lynch, "Recent Results of the Los Alamos Free-Electron Laser Oscillator Experiment," in Proceedings of the International Conference on Lasers '84, K. M. Corcoran, D. M. Sullivan, and W. C. Stwalley eds. (STS Press, McLean, VA, 1985), pp. 648-656.
4. B. E. Newnam, R. W. Warren, R. L. Sheffield, W. E. Stein, M. T. Lynch, J. S. Fraser, J. C. Goldstein, J. E. Sollid, T. A. Swann, J. M. Watson, and C. A. Brau, "Optical Performance of the Los Alamos Free-Electron Laser," IEEE J. of Quantum Electronics QE-21 (July, 1985), pp. 867-881.
5. W. B. Colson and S. K. Ride, "The Free-Electron Laser: Maxwell's Equations Driven by Single-Particle Currents," in Free-Electron Generators of Coherent Radiation, Physics of Quantum Electronics vol. 7, S. F. Jacobs, H. S. Pilloff, M. Sargent III, M. O. Scully, and R. Sptizer eds. (Addison-Wesley, Reading, MA, 1980), pp. 377-414.
6. H. Al-Abawi, J. K. McIver, G. T. Moore, and M. O. Scully, "Pulse Propagation in the Tapered Wiggler," in Free-Electron Generators of Coherent Radiation, Physics of Quantum Electronics vol. 8, S. F. Jacobs, G. T. Moore, H. S. Pilloff, M. Sargent III, M. O. Scully, and R. Spitzer eds. (Addison-Wesley, Reading, MA, 1982), pp. 415-456.
7. John C. Goldstein, "Evolution of Long Pulses in a Tapered Wiggler Free-Electron Laser " in Proceedings of the 1983 Free-Electron Laser Conference, SPIE 453, C. A. Brau, S. F. Jacobs, and M. O. Scully eds. (Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1984), pp. 2-10. Note that a factor $a_w(\tau)$ was inadvertently deleted from the right-hand-sides of Eqs. (9) and (10), and that, for an untapered wiggler, none of the magnetic field quantities depend on τ .
8. W. B. Colson and A. Renieri, "Pulse Propagation in Free Electron Lasers," J. de Physique, Colloque C1, pp. 11-27 (February, 1983).
9. R. W. Warren, W. E. Stein, M. T. Lynch, R. L. Sheffield, and J. S. Fraser, "The Los Alamos Free Electron Laser: Accelerator Performance," Nuc. Instr. and Methods in Phys. Res. A237 (1985), pp. 180-186.

10. R. L. Sheffield, W. E. Stein, R. W. Warren, J. S. Fraser, and A. H. Lumpkin, "Electron-Beam Diagnostics and Results for the Los Alamos Free-Electron Laser," IEEE J. Quant. Electron. QE-21 (July, 1985), pp. 895-903.
11. W. E. Stein, R. W. Warren, J. G. Winston, J. S. Fraser, and L. M. Young, "The Accelerator for the Los Alamos Free-Electron Laser," IEEE J. Quant. Electron. QE-21 (July, 1985), pp. 889-894.
12. M. T. Lynch, R. W. Warren, and P. J. Tallerico, "The Effects of Linear Accelerator Noise on the Los Alamos Free-Electron Laser," IEEE J. Quant. Electron. QE-21 (July, 1985), pp. 904-908.
13. J. C. Goldstein and W. B. Colson, "Control of Optical Pulse Modulation Due to the Sideband Instability in Free-Electron Lasers," in Proceedings of the International Conference on Lasers '82, R. C. Powell ed. (STS Press, McLean, VA, 1983), pp. 218-225.
14. S. Benson, D. A. G. Deacon, J. N. Eckstein, J. M. J. Madey, K. Robinson, T. I. Smith, and R. Taber, "Review of Recent Results from the Stanford 3 μ m Free Electron Laser," J. de Physique, Colloque C1, pp. 353-362 (February, 1983).
15. R. W. Warren, B. E. Newnam, and J. C. Goldstein, "Raman Spectra and the Los Alamos Free-Electron Laser," IEEE J. Quant. Electron. QE-21 (July, 1985), pp. 882-888.
16. R. W. Warren, J. C. Goldstein, and B. E. Newnam, "Spiking Mode Operation of A Uniform Wiggler," these proceedings.
17. J. N. Eckstein, J. M. J. Madey, K. Robinson, T. I. Smith, S. Benson, D. Deacon, R. Taber, and A. Gaupp, "Additional Experimental results from the Stanford 3 μ m FEL" in Free-Electron Generators of Coherent Radiation, Physics of Quantum Electronics vol. 8, S. F. Jacobs, M. O. Scully, and M. Sargent III eds. (Addison-Wesley, Reading, MA, 1982), pp. 49-75.

Table 1: Experimental and Theoretical Parameters for
Desynchronism Curve Data

	Experiment	Theory
Wiggler		
length, cm	100	100
wavelength, cm	2.73	2.73
peak field, kg	3.0	3.0
dimensionless vector potential a_w	0.7647	0.7647
coupling constant G	0.94	0.94
Optical resonator		
total round-trip intensity loss	7.5%	8%
output coupler transmission	5.2%	5%
Rayleigh range, cm	63.16	63.16
resonant wavelength, μm	9.85	9.85
focal spot diameter, cm	0.199	0.199
Electron beam		
initial energy, Mev	21.813	21.813
energy spread	2%	0%
peak current, A	39.32	33
FWHM, cm	1.091	1.17
shape	"Lorentzian"	parabolic
slippage distance, cm	0.03608	0.03608
emittance, cm-rad	$2.5\pi \times 10^{-4}$	--
average diameter, cm	0.21	0.21
Laser Output		
small-signal energy gain	--	68%
cavity tuning range, μm	60	>80
maximum optical energy output, mj	390	341
average output power, kw	5	4
extraction efficiency	0.6%	1.09

Table 2: Experimental and Theoretical Parameter
Changes for Extraction Efficiency Data
Experiment

	Experiment	Theory
Optical resonator		
total round-trip		
intensity loss	1.6%	1.6%
output coupler		
transmission	0.25%	0.25%
Electron beam		
energy spread	2.25%	2.25%
peak current, A	39.32	39.32
FWHM, cm	1.091	1.091
shape	"Lorentzian"	"Lorentzian"
Laser output		
small-signal gain	--	23%
maximum optical		
energy output, mj	90	128
average output		
power, kw	1.3	2.0
extraction efficiency	1.0 <u>±</u> 0.2%	1.15%

Figure Captions

- Figure 1. Spectrum of spontaneous emission from an untapered wiggler from the numerical model, averaged over 100 passes.
- Figure 2. Measured (open circles) and calculated (closed circles) desynchronism curve.
- Figure 3a. Calculated time-integrated optical spectrum at $\delta L=0$.
 3b. Calculated time-integrated optical spectrum at $\delta L=-20\mu\text{m}$.
 3c. Measured time-integrated optical spectrum at point A of Fig. 2.
 3d. Measured time-integrated optical spectrum at point B of Fig. 2.
- Figure 4. Calculated time-integrated optical spectrum at $\delta L=0$ for 98A peak current and $2\frac{1}{4}\%$ initial electron energy spread.
- Figure 5a. Calculated time-integrated optical spectrum for $\delta L=-40\mu\text{m}$.
 5b. Calculated time-integrated optical spectrum for $\delta L=-40\mu\text{m}$ and initial energy increasing by 2% during macropulse.
- Figure 6. Measured electron micropulse shape.
- Figure 7a. Measured electron distributions.
 7b. Calculated electron energy distribution for entire micropulse showing 1.15% extraction efficiency.
 7c. Calculated electron energy distribution for central 68% of micropulse showing 1.58% extraction efficiency.
- Figure 8a. Calculated power inside resonator and electron micropulse.
 8b. Calculated electric field inside resonator and electron micropulse.

Figure 1

Figure 2

Figure 3 a

CHM-VG-6947

Figure 3b

Figure 3c

Figure 3d

Figure 4

Figure 5a

Figure 5b

Figure 6

Figure 7a

Figure 7b

Figure 7c

Figure 8a

Figure 8b