LA-UR -85-4034

CONFIDENTIAL - 18

RECEIVED BY OSN

DEC 06 1985

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

LA-UR--85-4034

DE86 003665

TITLE: SPIKING MODE OPERATION FOR A UNIFORM-PERIOD WIGGLER

AUTHOR(S): R. W. Warren, J. C. Goldstein, B. E. Newnam

SUBMITTED TO: Seventh International Free Electron Laser Conference,
Tahoe City, California, September 8-13, 1985

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.

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

MASTER

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

SW

SPIKING MODE OPERATION OF A UNIFORM-PERIOD WIGGLER*

ROGER W. WARREN, JOHN C. GOLDSTEIN, and BRIAN E. NEWMAN

MS J579

Los Alamos National Laboratory

Los Alamos, NM 87545

ABSTRACT

The onset of saturation in a uniform-period wiggler has been examined experimentally and through numerical simulations. Models have been constructed that explain the observations in simple and consistent ways. The models are based upon the development of strong frequency and amplitude modulation of the optical wave as a way to increase extraction efficiency and optical power.

*This work was performed under the auspices of the US Department of Energy and supported by the US Army Ballistic Missile Defense Organization.

1. Introduction

The Los Alamos free-electron laser (FEL) oscillator experiment [1-5] was completed in 1984. During the experiment, over 100 hours of lasing experience was accumulated with a uniform-period wiggler. Our copious measurements have been compared with the results of both simple single-pass numerical simulations [6] and with much more complex self-consistent multipass calculations. In general, agreement with the complex calculations is good; but is poor with the simple calculations. In spite of their general agreement with experiment, however, the multipass calculations provide little physical insight into the phenomena taking place and the reasons why.

Accordingly, we have devoted considerable time to examining the results of the experiment and the multipass calculations for the uniform-period wiggler and constructing simple physical models describing what happens and why. Much further work of an approximate, analytical form would be useful to test and extend these models. We present the results of this examination in this paper, which is divided into five sections covering the items listed below:

- The simple theory
- The experimental results
- The multipass theory
- A model for the Raman regime
- A model for the spiking regime

2. Simple theory

At Los Alamos we use computer code FELMOV [6] to design wigglers and to explore their performance under various conditions. FELMOV is a one-dimensional, single-pass code that employs the equations and philosophy of Kroll, et al. [7]. Other wigglers have been built by other investigators following the same simplified design techniques. Implicit in this design approach is the belief that the assumptions built into the code or applied to its use are approximately valid in practice. With FELMOV, the most important of these assumptions are as listed below.

- A. The optical power will build up during lasing as a smooth, single-frequency wave.
- B. The new light generated on each pass can be added to the old in the lowest order empty cavity mode; that is, no mode distortion, focusing, or bending of the beam occurs.
- C. The pulsed nature of our FELs does not introduce new features that invalidate the use of FELMOV in the design of its wigglers.

Various attempts have been made to remove these assumptions, but this has only been accomplished in a piecemeal manner because of the complexity of more general codes and the time and expense of running them. Colson [8], Goldstein [9], Tang and Sprangle [10], and Quimby, et al. [11] have written codes explicitly including the pulsed nature of the electron beam. Quimby [12] and others have in various ways included the generation of higher order cavity modes. Focusing of the beam has been included in the codes by Quimby [12] and by Scharlemann, et al. [13]. Misalignment and bending have been

discussed by Bismik and Cover [14]. Modulation of the laser power by Raman instabilities has been included in calculations by Rosenbluth, et al. [15], Goldstein [9], Tang and Sprangle [10], Colson [16] and Quimby, et al. [11].

A uniform-period wiggler was designed by FELMOV to operate with an electron beam of 20-MeV energy. Its small-signal gain peaks at 10- μ m wavelength. The gain and extraction efficiency were also evaluated at higher optical powers to examine the onset of saturation. In fig. 1, we have selected several different power levels and show how the extraction efficiency varies with position (Z) down the length of the wiggler. Energy is extracted rather uniformly at low optical power (25 MW); whereas above about 100 MW, extraction oscillates strongly with Z. Wherever the extraction efficiency increases with Z, new light is generated in the wiggler; wherever it decreases, light is absorbed. The oscillation reflects the passage of the electrons through a series of synchrotron oscillations where the phase of their wiggles changes sign compared to the phase of the optical field, periodically changing the interaction of the electrons from decelerating to accelerating. At the higher power levels of fig. 1 the wiggler is being used inefficiently because light is absorbed and not generated over a significant part of its length. In spite of this nonuniform generation, the overall effect of the wiggler is to produce a smooth, single-frequency optical wave at all power levels in agreement with the assumptions of FELMOV.

3. Experimental results

Our experimental results have been fully described elsewhere [5]. Briefly, we observed different kinds of spectral behavior in three regions of optical power:

A. At very low optical power, achieved either by low electron current or by cavity length detuning, we detected a single, narrow spectral line, indicating a pure continuous optical wave in agreement with the assumptions and conclusions of FELMOV.

B. Above a threshold of about 25 MW, we observed a long-wavelength sideband that grew in magnitude and separation from the main line with increasing optical power. Figs. 2a - 2c show the development of the sideband as the power was increased by changing the cavity length. These observations are in qualitative agreement with the models for a Raman instability, as outlined in refs. [7-11], but are in disagreement with FELMOV.

C. Above a second threshold of about 100 MW, the single-sideband character of the spectra changed; the sideband broadened, splitting and stretching to longer wavelengths. Fig. 2d shows such a spectrum. These observations are in general agreement with the simulations of Colson [16] and Goldstein [9], but it is not clear what is happening physically. The experimental spectra, unfortunately, did not contain phase information. Therefore, we cannot construct temporal pulse shapes solely from the data to help our understanding. Instead, we have depended mostly on simulations to guide us in developing a satisfactory model for this regime.

4. Multipass calculations

We have performed new simulations corresponding in detail to the experimental parameters. A discussion of these simulations and their agreement with experiment is presented in another paper in this volume [17]. An example of the results is given in fig. 3, showing the optical

electric field in a micropulse as a function of Z after 2000 electron micropulses have passed and saturation has been reached (for zero cavity length detuning). Corresponding phase information was also generated. Clearly evident within each micropulse are four regimes of optical power:

A. A distinctive part of the micropulse is found without amplitude modulation. This occurs in the wings of the micropulse at low optical power and corresponds to the low-power regime observed and discussed in Sec. 3A above.

B. A second part occurs at intermediate optical powers where weak modulation at different frequencies is seen. This part corresponds to the Raman regime discussed in Sec. 3B.

C. A third part occurs at high optical power and is very strongly and regularly modulated, that is, "spiked," giving a broad spectrum like that discussed in Sec. 3C.

D. A fourth part occurs at the highest optical powers. It is also strongly spiked, but more frequently and less regularly. This part also gives a spectrum like that of Sec. 3C.

In the discussions presented above, we have identified various parts of a micropulse, for example, low-power wing, and made comparisons with the experimental measurements made over an entire macropulse, that is, a set of 2000 full micropulses. This type of comparison was made for the sake of convenience. We have also made a more appropriate comparison between simulated macropulses and experimental macropulses and reached the same conclusions presented here. It is remarkable that the various parts of a micropulse are isolated from one another well enough so that the average power of each part can be used to characterize its spectrum and modulation.

In general, the agreement between experiment and the multipass simulation is good at all power levels. In contrast, the simple FELMOV predictions are poor except at low optical power.

5. Model for the Raman regime in uniform-period wigglers

We have constructed simple models for the Raman and spiking regimes, discussed above, from examination of the multipass simulations. In building these models, our primary approach has been to look for ways to modify the considerations of the simple theory to increase its energy extraction efficiency without compromising agreement with the multipass calculations. The logic of this technique cannot be rigorously defended, but it has been decidedly useful in practice. It identifies saturation as a particularly crucial process that limits uniform-period wigglers to power levels and efficiencies considerably below those of tapered wigglers. In our models there are two strategies used to escape the limits imposed by saturation: frequency modulation (in the Raman regime) and pulse modulation (in the spiking regime).

Frequency modulation can be understood by examining the approximate formula for the resonance condition, $\lambda_L = \lambda_W / \gamma^2$, where λ_L and λ_W are the wavelength of the light and the wiggler, and γ represents the normalized electron energy. Saturation occurs in a uniform-period wiggler when sufficient energy is removed from the electrons to alter γ significantly and upset the resonance condition. A tapered wiggler maintains resonance by tracking the changes in γ with corresponding changes in λ_W . The frequency modulation we have in mind holds λ_W constant, but tracks the changes in γ with corresponding changes in λ_L .

To illustrate this process, we show in fig. 4 a frequency modulated optical wave and its spectrum. The wave is moving to the right, overtaking electrons as it goes; λ_S identifies the position on the wave of shortest wavelength, λ_L the longest, and λ_N the normal (equal to the resonance condition at the entrance to the wiggler). Different electrons are initially exposed to this wave at every point on it and end their exposure after a slippage distance L_{SL} , which for our wiggler is 40 wavelengths or 400 μm . Now consider the two electrons initially exposed at λ_N and λ_N' and marked at the top of fig. 4 by vertical bars. The electron at λ_N slips to the left in the wave and continually feels an increasing wavelength. If the increase in wavelength matches the electron's loss of energy, the electron will stay in resonance over its whole path, in the way described above, and lose a maximum of energy without saturation. The second electron, at λ_N' , suffers the opposite fate and converts less of its energy to light than if the wave were unmodulated.

When averaged over all electrons, two features become apparent:

A. The total energy extracted from all the electrons is increased in second order by the modulation.

B. The extracted energy is converted to light and added nonuniformly to the optical wave, causing an amplitude modulation like that shown at the bottom of fig. 4.

This correlated amplitude and frequency modulation modifies the original spectrum, emphasizing the long-wavelength sideband at the expense of the short-wavelength one. The new light can also shift the frequency of the modulations, balancing the inertial effects of the electrons against the growth of the optical field. The physical effects contained in this balance are the same as those involved in synchrotron motion. Thus we believe (but

have not proved) that the sideband frequency eventually establishes an equilibrium value equal to the synchrotron frequency. It should be noted, however, that the electrons undergo only a fraction of a complete synchrotron cycle and should in no way be considered to "oscillate to and fro in the ponderomotive potential."

As the optical power grows, the frequency and amplitude of the modulations increase until they reach a limit, shown in fig. 2c, where the sideband is as large as the main line; that is, the amplitude modulation is 100%. The simulation shows that this condition occurs when an electron no longer feels a small change in λ_L over its slippage distance, but instead experiences a large fraction of a complete cycle. At this point, the synchrotron period T_{SY} and slippage time L_{SL}/c are approximately equal. This transition point signals the beginning of the spiking mode whose most characteristic features are already evident at the transition point: the breakup of a continuous optical wave into a train of isolated pulses of length L_{SL} and the interaction of each electron with a single optical pulse as it moves through approximately one complete synchrotron cycle.

6. Spiking model

From our examination of the experimental data and the simulations, we have been able to extract six important features concerning the spiking regime discussed above in Sec. 4C.

- A. It is characterized by regions of periodic "spikes" of optical power.
- B. The extent of the modulation of the optical power in a spike is very large ($\sim 10:1$).

C. Spiking only occurs at high optical power, starting at the optical power for which the synchrotron period equals the slippage time.

D. For powers above this level, the spiking period stays approximately fixed, equal to the slippage time (not the synchrotron period, which varies as the fourth root of the optical power).

E. The frequency of the optical pulse chirps during a spike.

F. There is a marked jump in the phase of the optical fields in adjacent spikes.

We have incorporated features A-D in the simplified model for the optical field shown in fig. 5. Later we will complicate the model by including features E and F. In fig. 5, the optical field in the model is shown pulsed on or off. The pulses, hereafter called spikes, are separated by the slippage time T_{SL} , and we have chosen the spike width to be one-half of T_{SY} , a synchrotron period. The behavior and advantages of this arrangement are immediately obvious. As the electrons pass through the wiggler, they are overtaken by the spikes of fig. 5. Because of the choice of spike duration and period, almost all of the electrons feel only one of the spikes and undergo exactly one-half a synchrotron oscillation, that is, lose as much energy as they possibly can. Different electrons experience the spikes at different places in the wiggler, but because of the translational symmetry of the wiggler, each behaves similarly. As optical power increases, the spike width narrows, maintaining one-half a synchrotron oscillation and, thus, a maximum extraction. Because there is no region where light is absorbed, the saturation characteristics during spiking are much different and occur at higher powers than FELMOV would indicate.

The situation is unusual from the perspective of the optical spikes. As each spike sweeps through the wiggler, it successively overtakes all of the

electrons within a space equal to a slippage distance. All of these electrons concentrate their energy into the spike, which steadily narrows as its power rises. This situation rapidly leads to very narrow spikes of very high peak power.

Feature E, mentioned above, also falls into our model in a natural way. The spike width was initially set equal to one-half a synchrotron period, for the electron has then slowed enough to be wiggling 90° out of phase with the optical field at the end of a spike, contributing nothing to its amplitude. This condition on the spike length can be relaxed if we allow the frequency within each spike to chirp to longer wavelengths with time. Such a frequency chirp within a spike would increase its extraction efficiency if carried out with moderation. Thus a compromise situation is found in which some, but not too much, spike lengthening and chirp occur. The simulations confirm that a chirp of this kind within each spike does exist.

Finally, the extra complications of feature F, presented above, should be mentioned because of their important effect on the spectra. We consider what happens to those few electrons that "split" the optical spike, that is, enter the wiggler in the middle of one spike and leave in the middle of the next. At first glance it appears that these electrons are unlikely to perform in the ideal way of the majority of electrons. We have explored this topic by calculating the efficiency of these split electrons as a function of two variables: the exact period of a spike and the relative phase of the optical fields of adjacent spikes. We find that by shifting the period slightly from the slippage time and by choosing the right phase difference between adjacent spikes, we can achieve an extraction efficiency for the split electrons even greater than that experienced by the average

electron. There is an "optical-klystron" effect where the electrons are bunched by the first half-spike and then drained of energy by the second half-spike. This beneficial effect depends critically on the interspike phase difference, explaining feature F mentioned above.

The spiking model presented above agrees with the experimental data and is based upon features found in the numerical simulations, but the physical arguments so far presented in its favor are weak, emphasizing the improvement in extraction efficiency that results from spiking. More persuasive would be a description of the natural evolution of an unmodulated wave into a spiked wave, illuminating the forces that cause this evolution or, as a minimum, a discussion illustrating the forces that maintain the stability of a spiked wave. In the next two paragraphs we describe the forces that maintain the stability of the critical parameters of the model: the spike length and spike period.

Suppose that our model gives the spike length and period representing a certain set of experimental parameters. Now let one of the parameters change; for example, let the output coupling be reduced. The spike length and period will initially be unchanged, but the optical power in a spike will gradually increase because of the reduced optical losses. The increased power will shorten the synchrotron period and cause absorption of light by the electrons on the trailing edge of each spike. The trailing edge will erode and the spike will increase in amplitude until a new equilibrium is reached with a shorter spike.

In a second example, suppose that the optical power reaches the boundary between Raman sideband and spiking mode; that is, the synchrotron period equals the slippage time. Let the optical power increase as above. The synchrotron period will now be less than T_{SL} , and our initial expectation

is that the period of the frequency and amplitude modulation will shorten and continue to equal T_{SY} . If this happens, however, electrons will begin to be "used" twice by two adjacent spikes in their pass through the wiggler. On their second use, they will have a lower energy and a larger energy spread and will not give up energy readily. This second use will cause the leading edge of the spikes to be low in amplitude, and their separation will tend to drift towards longer times, that is, to T_{SL} —in agreement with our model.

7. Discussion of results

All of the complex considerations presented above can be fit into a consistent picture. The FELMOV calculations describe an equilibrium situation. If one assumes a continuous optical wave going into the wiggler, one gets back a continuous optical wave coming out of the wiggler. Although this solution is mathematically correct, it does not always represent a stable equilibrium; for example, fluctuations can upset it. At low optical powers, the equilibrium is stable and FELMOV is valid. At moderate powers, the Raman effect occurs, signalling the onset of instability. At high power, instability of the FELMOV solution has occurred and an entirely different solution, the spiking mode, is now the stable state. It seems unlikely that this is the end of developments. From the simulation it appears that a new, more random, more closely spaced spiking mode occurs at the highest optical powers. This is the regime discussed in Sec. 4D, and is the "Chaos" region found earlier by Colson [16]. We believe that in this regime the forces, described above, stabilizing the spike length are still operating but that the forces stabilizing the spike period are no longer effective.

An onset of instability of some sort is likely to occur, we believe, whenever a wiggler is operated inefficiently, far from its design conditions. Unstable conditions might occur with tapered wigglers operated well above saturation or in the small-signal regime. We have not yet examined this possibility.

The discussions presented in this paper are meant to serve two purposes: to show, through numerical simulations and through experimental results, that free-electron lasers often operate in a complex fashion that is outside the scope of simple considerations and, second, to present simple models to help our understanding of the physical processes that are contained, but hidden, in the numerical simulations. The models are qualitative and incomplete, but will, we hope, stimulate ideas and further work by others.

8. Summary

The onset of saturation in a uniform wiggler has been examined experimentally and through numerical simulations. Physical models have been constructed that explain in simple and consistent ways the observations. The models are based upon the development of strong frequency and amplitude modulation of the optical wave as a way to increase extraction efficiency and optical power.

9. Acknowledgment

Our thanks to the team who worked together to perform the oscillator experiment from which these data were derived.

References

- [1] 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, IEEE J. Quantum Electron. QE-21 (1985) 867.
- [2] R.W. Warren, B.E. Newnam, and J.C. Goldstein, IEEE J. Quantum Electron. QE-21 (1985) 882.
- [3] B.E. Newnam, R.W. Warren, R.L. Sheffield, J.C. Goldstein, and C.A. Brau, Nucl. Instrum. and Methods A237 (1985) 187.
- [4] R.L. Sheffield, R.W. Warren, B.E. Newnam, W.E. Stein, J.C. Goldstein, and M.T. Lynch, Proc. Int. Cong. on Lasers '84, K.M. Corcoran, D. M. Sullivan, and W.C. Stwally, Eds. (STS Press, McLean, Virginia, 1985) 648.
- [5] B.E. Newnam and R.W. Warren, these Proceedings.
- [6] C.A. Brau and R.K. Cooper, in: Free-Electron Generator of Coherent Radiation, Vol. 7, S.F. Jacobs, H.S. Pilloff, M. Sargent III, M.O. Scully, and R. Spitzer, Eds. (Addison-Wesley, Reading, Massachusetts, 1980) 647.
- [7] N.M. Kroll, R.L. Morton, and M.N. Rosenbluth, IEEE J. Quant. Electron. QE-17, (1981) 1436; or similar paper from the Physics of Quantum Electronics, Vol. 7, (1979 FEL Conf. Telluride).
- [8] W.B. Colson, in: Free-Electron Generators of Coherent Radiation, Vol. 8, S.F. Jacobs, G.T. Moore, H.S. Pilloff, M.S. Sargent III, M.O. Scully, and R. Spitzer, Eds. (Addison-Wesley, Reading, Massachusetts, 1982) p. 457.
- [9] J.C. Goldstein, in: Free-Electron Generators of Coherent Radiation, C.A. Brau, S.F. Jacobs and M.O. Scully, Eds. Proc. SPIE, Vol. 453 (1984) 2.
- [10] C.M. Tang and P. Sprangle, *ibid.*, 11.
- [11] D.C. Quimby, J.M. Slater, and J.P. Wilcoxon, IEEE J. Quantum Electron. QE-21 (1985) 979.
- [12] D.C. Quimby, Nucl. Instrum. and Method A237 (1985) 10..
- [13] E.T. Scharlemann, A.M. Sessler, and J.S. Wurtele, "Optical Guiding in a Free-Electron Laser," Lawrence Livermore National Laboratory report, USRL-91476 (1984).
- [14] A. Bhowmik and R.A. Cover, in Free-Electron Generators of Coherent Radiation, Proc. SPIE, vol. 453, op. cit., 218
- [15] M.N. Rosenbluth, H.V. Wong, and B.N. Moore, *ibid.*, 25.
- [16] W.B. Colson, *ibid.*, 290.

[17] J.C. Goldstein, B.E. Newnam, R.W. Warren, and R.L. Sheffield, these Proceedings.

Figure Captions

Fig. 1. Integrated extraction efficiency versus position in the wiggler for three optical power levels.

Fig. 2. Optical power versus wavelength deviation for four different optical power levels, showing dependence of sideband strength and deviation on peak power:

- (a) power = 25 MW
- (b) power = 45 MW
- (c) power = 65 MW
- (d) power = 110 MW

Fig. 3. Optical field and power versus position in the last micropulse of a macropulse. Regions A - D are labeled and discussed in the text.

Fig. 4. Waveform and spectra of (a) frequency modulated wave and (b) frequency and amplitude modulated wave.

Fig. 5. Schematic diagram of optical field illustrating spiking.

Fig 1

RAMAN SIDEBANDS GROW UNTIL THEY DOMINATE THE SPECTRA

MODULATION

SPECTRA

Fri, 4