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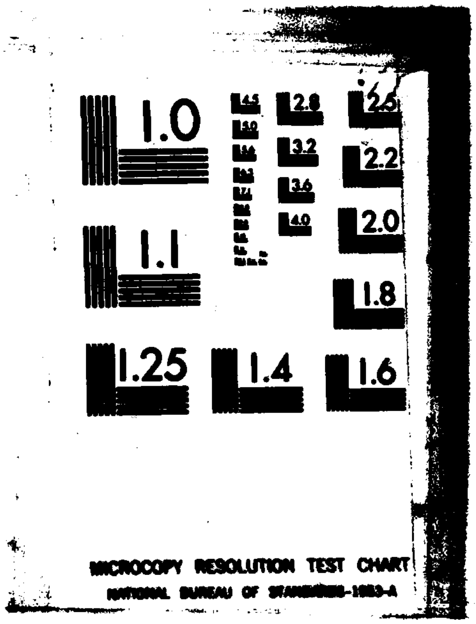

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A review was made of various pulse propagation theories and comparison to the Stanford experiment. Quantum noise effects were theoretically derived for free electron lasers in optical resonators and found to be small. Control of the synchrontron instability with selective mirrors was examined. A comprehensive Lagrangian description of the gain surfaces for various free electron laser designs was made. A theory was developed for the electron dynamics and optical wavefronts in Gaussian resonators.

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AFOSR-TR- 83-0783

Theory of Pulse Propagation and Coherence in Free Electron Lasers

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[redacted] **Scientific Report (AFOSR-81-0061): W. B. Colson, Principal Investigator**

Free electron lasers (FELs) amplify the radiation present in a resonant optical cavity with a co-propagating relativistic electron beam traveling along the axis of a long, undulating magnetic field. For the periodic undulator, we describe the electron dynamics with the self-consistent pendulum equation. A sampled electron at a site (x,y) in the optical wave has an equation of motion of the form:

$$\dot{\nu}_{(z-st)} = \ddot{\zeta}_{(z-st)} = \frac{1}{2}\left[a_z\, e^{i\zeta_{(z-st)}} + a_z^{*}\, e^{-i\zeta_{(z-st)}}\right] \quad . \tag{1}$$

The complex optical field strength is $a(\vec{x},t)$ and the electron phase is $\zeta(\vec{x},t)$. In (1) all variables have been reduced to a dimensionless form and are of order unity; their complete definitions are given in the enclosed publications. The electron phase (or position) with respect to an optical wavelength is $\zeta(x,y,z-st,t)$ and its resonance parameter (or dimensionless velocity) is $\nu(x,y,z-st,t)$ The slippage of the optical field a_z over electrons is described by subscript $z-st$ on the electron coordinates. The optical wave envelope is described by the parabolic wave equation:

$$\left[-\frac{i}{4}\nabla^2_{trans} + \frac{\partial}{\partial t}\right]a(x,y,z,t) = -\langle je^{-i\zeta}\rangle_{(x,y,z-st,t)} \quad . \tag{2}$$

where the dimensionless current density is $j(x,y,z,t)$ and ∇_{trans} is the transverse gradient. In many FELs where the electron pulse interacts with an accelerating R.F. wave, as in a linac or storage ring, the optical field is amplified by a short electron pulse so that the dimensionless slippage factor $s > 0$. When $s \ll 0$, we have observed that the synchrotron instability leads to complex multimode structure along the wave envelope. Also, when the electron beam and optical mode coupling is optimized, the transverse wavefront changes significantly over the interaction length. Therefore, a theory that adequately

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characterizes optimized FELs will need to be self-consistent, nonlinear, and contain a multimode representation of the wave in each spatial dimension. This is a much harder problem than for a typical atomic laser where the driving medium has no structure on the scale of the optical mode. Except for special cases, the entire multimode problem requires large amounts of CPU time. We are now using an array processor (AP120B) on the UCSB computer.

Theoretical Progress

The goal of this theoretical work has been to provide a clear, intuitive description of free electron laser phenomena so that we have a foundation for future experiments and FEL designs. Our previous papers show how the pendulum equation can be simply generalized to include the effects of collective Coulomb forces, collective high-gain phenomena, higher harmonics, and specialized magnet designs like the tapered undulator, the optical klystron, and the transverse gradient "gain- expansion" magnets. We have continued and expanded the scope of this line of thought during the last year.

Optical pulse propagation in FELs with a tapered wavelength undulator was studied further in collaboration with J. Goldstein of Los Alamos National Lab. The parameters were chosen to characterize their proposed oscillator experiments. We found a severe sychrotron instability which would cause chaotic multimode structure along the Los Alamos optical pulse. The reference is:

> J.C. Goldstein and W.B. Colson, "Pulse Propagation in Free Electron Lasers with a Tapered Undulator," Proceedings of the 1981 International Conf. LASERS '81, New Orleans LA (Dec. 14-18, 1981).

In another paper written with Pascal Elleaume of Orsay, France, we study the electron phase-space evolution and gain of free electron lasers whose short-wavelength radiation has Gaussian spherical wavefronts. Several free electron laser designs are considered: the undulator, tapered wavelength undulator, and the optical klystron. We show that the optical phase shifts along the magnet length are more important than the changes in the optical amplitude. These changes cause a shift and distortion in the gain curves toward higher frequencies. We find that the gain spectrum is no longer proportional to the slope of the forward spontaneous emission spectrum, and we find the design of the Gaussian mode which maximizes the energy extraction from the electron beam. Several magnet designs were studied including the simple undulator, the tapered undulator, and the optical klystron. We found that gain is optimized by making the resonator's Rayleigh length approximately one fifth of the magnet length. This result helped us decide that transverse mode structure is always important in optimized FELs. The reference is:

W.B. Colson and P. Elleaume, "Electron Dynamics in Free Electron Laser Resonator Modes," Applied Physics B **29**, 101 (1982).

The weak field oscillator problem was explored with R. A. Freedman of UCSB under the support of the Office of Naval Research (H. Pilloff). From a comprehensive viewpoint we developed the Lagrangian for the simple periodic undulator, the tapered undulator, the two-stage optical klystron with a dispersive section, and the transverse gradient "gain-expander" magnet. The gain surface shows the dependence of gain on the optical field strength and the resonance parameter. This is instructive in pointing out the relative merits of each design and indicates the individual characteristics of start-up in each laser. For instance, it is easy to see how the optical wavelength varies to follow the maximum available gain in each of the designs. Possible startup problems in some designs are also indicated. We include the use of dielectric mirrors which narrow the bandwidth of the resonator. These are useful in suppressing weak field multimode behavior in the more complex magnet designs. We also comment on some recent papers by Bonifacio which predict chaotic solutions to the single-mode version of (1) and (2). Their parameters translate into extremely high current densities which could not be adequately characterized by (1) and (2) alone, without Coulomb forces included. The reference is:

W. B. Colson and Roger A. Freedman, "Oscillator Evolution in Free Electron Lasers," Physical Review A **27**, 1399 (1983).

A graduate student in our group, P. Bosco, has begun a Ph.D. thesis on the topic of noise in FEL oscillators. He is supported by a small NASA grant. The spectrum and angular distribution of the radiation emitted by relativistic electrons in a tapered undulator is studied both analytically and numerically for higher harmonics and varied tapering. Tapering the magnet wavelength or field strength has the effect of spreading the spectral line to higher frequencies and interference over this broader spectral range results in a more complex line shape. The angular dependence on the other hand, is shown to be unaffected by increasing tapering. The characteristic features of the radiation patterns predicted here are distinct from untapered undulators, and although they have not yet been observed, their detection is presently feasible. These features will also provide useful diagnostics of electron trajectories in the undulating fields, and information about the threshold behavior in free electron laser oscillators using tapered undulators. The reference is:

P. Bosco and W. B. Colson, "Spontaneous Radiation from Relativistic Electrons in a Tapered Undulator," Physical Review A **27**, June 1 (1983).

The problem of oscillator evolution and mode competition in free electron lasers is studied. Much of the foundation for this problem was my Ph.D. thesis, but a new mode evolution equation is presented and analyzed in the paper. Relativistic quantum field theory is used to calculate electron wave functions, the angular distribution of spontaneous emission, and the transition rates for

stimulated emission and absorption in each mode. The photon rate equation for **the weak-field regime is presented.** This rate equation is applied to oscillator **evolution with** a conventional undulator, a two-stage optical klystron, and a tapered undulator. The effects of noise are briefly discussed. The reference is:

> P. Bosco, W. B. Colson, and Roger A. Freedman, "Quantum/Classical Mode Evolution in Free Electron Laser Oscillators," IEEE J. Quantum Electronics **QE-19** , 272 (1983).

In probably the most important paper we have generated this year, we provide an accurate and efficient solution to the transverse mode evolution in FEL oscillators. This work was done in collaboration with John Richardson of the Institute of Theoretical Physics at UCSB. The non-linear, self-consistent theory of short pulse free electron lasers can now be extended to include transverse diffraction within the optical resonator mode. The theory provides efficient solutions to the three-dimensional parabolic wave equation coupled to the Lorentz force equation. The approach introduces no extra gain or loss in the solution and is efficient enough to allow low-cost numerical studies of the transverse mode evolution problem. However, when coupled to the longitudinal pulse codes, the problem becomes difficult. The method is general enough to include arbitrary magnet designs, optical mirror arrangements and driving currents. We have made predictions in collaboration with J. Edighoffer of TRW for the upcoming experiments at Stanford. In particular, we suggest that the electron beam be moved off-axis by about 1 mm so that higher-order modes with a distinct structure of four peaks may be detected. The reference is:

> **W. B. Colson and John L. Richardson, "Multimode Theory of Free Electron Laser Oscillators," Physical Review Letters 50 ,1050 (1983).**

In another paper with John Goldstein the time evolution, from low intensity small signal gain conditions to high intensity saturated gain steady state

conditions, of long pulses (pulse length much larger than the slippage distance) in an untapered-wiggler free electron laser is calculated. It is found that the optical pulse envelope becomes severely modulated with the initial spatial period of the modulation equal to the slippage distance. Three modes of laser operation which avoid the severely modulated steady state pulses are discussed. The reference is:

J.C. Goldstein and W.B. Colson, "Control of Optical Pulse Modulation due to the Sideband Instability in Free Electron Lasers," Proceedings of the 1982 International Conf. LASERS '82, New Orleans LA (Dec. 13-17, 1982).

A review paper was written with Dr. A. Renieri on the main features relevant to pulse propagation in free electron lasers together with a comparison of the Stanford oscillator experimental data. The reference is:

W. B. Colson and A. Renieri, "Pulse Propagation in Free Electron Lasers," Bendor Free Electron Laser Conf., J. de Physique, 44, C1-11 (1983).

Throughout these studies, graphical representations of optical pulse propagation and electron phase-space evolution has been helpful in understanding free electron laser physics. The graphs not only help in the research, but make communication of our results much easier

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