

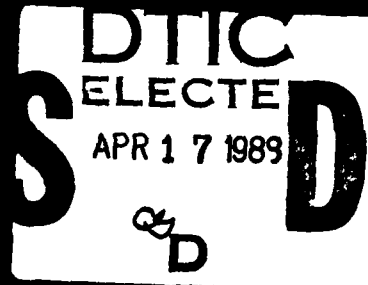
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Kibbutz Ramat Rachel, JERUSALEM, ISRAEL

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August 29 - September 2, 1988



PROGRAM AND ABSTRACTS

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PROGRAM AND ABSTRACTS

Grant No. N00014-88-J-1092

**TENTH INTERNATIONAL
FREE ELECTRON LASER CONFERENCE**

Kibbutz Ramat Rachel

Jerusalem, Israel

August 29 - September 2, 1988

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- * Israel Academy of Sciences and Humanities.
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PROGRAMME

Monday, August 29

09:00-10:20 Session 1

Opening Session

Chairman : A. Szoke (LLNL)

- (1) - 09:00-09:10 A. Gover V. Granatstein : Greetings
- (2) - 09:10-09:30 G. Bekefi (MIT): Recent Free Electron Laser Experiments at MIT.
- (3) - 09:30-09:50 L. Elias (CREOL): Electrostatic Accelerator FELs.
- (4) - 09:50-10:15 L. Shenggang (Chengdu): Survey of FEL Activity in China.

COFFEE BREAK

10:50-12:20 Session 2

Experimental Status Reports I

Chairman : M. Poole (Daresbury)

- (1) - 10:50-11:10 R. Warren (LANL): Near-Ideal Lasing with a Uniform Wiggler.
- (2) - 11:10-11:30 J.A. Edighoffer (TRW-LANL): The Results of the Paladin 15-M Experiment.
- (3) - 11:30-11:50 T. Smith (Stanford): Program and System Development at the SCA-FEL.
- (4) - 11:50-12:15 Y. Kawarasaki (JAERI): Japanese Activities on Storage Ring and RF Linac FEL Development.

LUNCH

15:00-16:30 Session 3

Experimental Status Reports II

Chairman : M.J. Van der Wiel (FOM)

- (1) - 15:00-15:20 K. Mima (Osaka): Experiments and Theory on Induction Linac.
- (2) - 15:20-15:40 R.A. Jong (LLNL): IMP, a Free-Electron Laser Amplifier for Plasma Heating in the Microwave Tokamak Experiment.
- (3) - 15:40-16:00 H. Freund (SAIC-NRL): A Review of Free-Electron Laser Research at the Naval Research Laboratory.
- (4) - 16:00-16:20 A. Bhattacharjee (Columbia): Sideband Instabilities and Optical Guiding in a Free-Electron Laser: Experiment and Theory.

16:50-18:20 Session 4
Theory I

Chairman : R. Warren (LANL)

- (1) - 16:50-17:10 B. Levush (UMD): A Novel Method for Achieving Coherence and Maximum Efficiency in a High Power FEL Oscillator.
- (2) - 17:10-17:30 I. Kimel (CREOL): Mode Competition in Long Pulse FELs.
- (3) - 17:30-17:45 W.M. Sharp (LLNL): Simulation of Superradiant Free-Electron Lasers.
- (4) - 17:45-18:00 D. Oepts (FOM): Simulations of Mode Reduction with an Intracavity Etalon in an RF-Linac Based FEL.
- (5) - 18:00-18:15 J. Elgin (Imperial College): Modulational Instability in the Free-Electron Laser.

Tuesday, August 30

08:30-10:00 Session 5
Experimental Status Reports III

Chairman : C. Roberson (ONR)

- (1) - 08:30-08:50 R. Temkin (MIT): A High-Power, 140 GHz, CARM Amplifier Experiment.
- (2) - 08:50-09:10 E. Fliflet (NRL): Experimental CARM Oscillator Research at NRL.
- (3) - 09:10-09:30 B. Buzzi (Echelle Poly.): High Efficiency Millimeter-Wave Free-Electron Laser Experiments.

COFFEE BREAK

10:30-12:00 Session 6
Poster I

LUNCH

13:00 Tour of Tel Aviv University and Weizmann Institute of Science, followed by Reception and Dinner at Chaim Weizmann House.

Wednesday, August 31

08:30-10:00 Session 7
Experiments

Chairman : R. Temkin (MIT)

- (1) - 08:30-08:50 A.M. Fauchet (BNL): The Transverse optical Klystron Experiment at NSLS: Status Report.
- (2) - 08:50-09:10 D.J. Bamford (Stanford): Measurement of the Coherent Harmonics Radiated in the Mark III Free Electron Laser.
- (3) - 09:10-09:30 M.E. Couprie (LURE): Spontaneous Emission of the Super-Aco FEL Optical Klystron Domino.
- (4) - 09:30-09:50 B. Newnam (LANL): Free-Electron Laser Applications in the Ultraviolet: Report of the OSA Cloudcroft Conference.

COFFEE BREAK

10:30-12:00 Session 8
Theory II

Chairman :

- (1) - 10:30-10:50 T. Scharleman (LLNL): Modeling the Results of the Paladin 15-M Experiment.
- (2) - 10:50-11:10 H.D. Shay (LLNL): Tapering Free-Electron Laser Amplifiers in Wiggler Period and Field.
- (3) - 11:10-11:30 J. Goldstein (LANL): Numerical Simulations of Free Electron Laser Oscillators.
- (4) - 11:30-11:50 H. Takeda (LANL): One Dimensional Simulation of a Free-Electron Laser Oscillator using a Diffraction Grating as a Cavity Mirror.

LUNCH

13:00 Tour of Jerusalem preceded by Introductory Talk.

20:00-21:30 Session 9
Round Table Discussion

Chairman : K.J. Kim (Berkeley)

Thursday, September 1

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- (2) - 08:50-09:10 J.M. Ortega (LURE): CLIO: Collaboration for an Infra-Red Laser at Orsay.
- (3) - 09:10-09:30 A.H. Lumpkin (LANL): Time-Resolved Spectral Measurements of the Boeing Free-Electron Laser Experiments.
- (4) - 09:30-09:50 K.J. Kim (LBL): Generation of Intense, Coherent VUV Radiation with High-Gain FELs and Non-Linear Optical Techniques.
- (5) - 09:50-10:10 R. Temkin (MIT): Gyrotron-Powered Electromagnetic Wigglers for Compact Free-Electron Lasers.
- (6) - 10:10-10:30 Z. Sheena (TAU): Experimental Study of the Interaction of an Electron Beam with the Ponderomotive Potential of Laser Beats.

COFFEE BREAK

11:00-13:00 Session 11

Technology, Wigglers, Unconventional Schemes

Chairman : J.M. Ortega (LURE)

- (1) - 11:00-11:20 D. Quimby (Spectra): Development of a 10-Meter Wedged-Pole Undulator.
- (2) - 11:20-11:40 I. Alexeff (Tennessee): Recent Advances in Orbitron Experiments and Theory.
- (3) - 11:40-12:00 W. Zakowicz (Polish Academy): Model of Passive Waveguide for FEL.
- (4) - 12:00-12:15 R. Hofland (Aerospace): Optically-Pumped Free-Electron Laser with Electrostatic Reacceleration.
- (5) - 12:15-12:30 L. Schächter (Technion): Smith-Purcell Amplifier in a Regime of Exponential Gain.
- (6) - 12:30-12:45 X.K. Maruyama (NPS Monterey): Bremsstrahlung Radiation Effects in Rare Earth Permanent Magnets.

LUNCH

15:00-16:30 Session 12

Theory III

Chairman : K. Mima (Osaka)

- (1) - 15:00-15:20 L.H. Yu (BNL): Output Power in Guided Modes for Amplified Spontaneous Emission in a Single Pass Free Electron Laser — 3D Treatment Including the Effect due to Betatron Oscillation.
- (2) - 15:20-15:40 A. Fruchtman (WIS): The Effects of Diffraction, Waveguide, and Density Nonuniformities on the FEL Interaction.
- (3) - 15:40-15:55 E. Jerby (TAU): Three Dimensional Effects in Raman FELs.
- (4) - 15:55-16:10 J. Wurtele (MIT): Effects of Electron Prebunching on the Radiation Growth Rate of a Collective (Raman) Free-Electron Laser Amplifier.
- (5) - 16:10-16:25 J. Wachtel (Elta): Computation of Emittance Growth in a Focusing Wiggler FEL.

16:50-18:20 Session 13

Poster II

Friday, September 2

08:30-10:00 Session 14

Applications/Experiments

Chairman : I. Ben Zvi (WIS)

- (1) - 08:30-08:50 V. Granatstein (UMD): Free Electron Laser with Small Period Wiggler and Sheet Electron Beam: A Study of the Feasibility of Operation at 300 GHz with 1 MW cw.
- (2) - 08:50-09:10 W. Colson (Berkeley Assoc.): Optical Focusing in a Free Electron Laser for Inertial Confinement Fusion.
- (3) - 09:10-09:30 A.H. Lumpkin (LANL): Potential Application of the Los Alamos Free-Electron Laser: High-Temperature Superconductors.
- (4) - 09:30-09:55 G. Ramian (UCSB): The User-Oriented FEL Development Program at UCSB: 1) FEL Development; 2) User Applications.

COFFEE BREAK

10:30-12:00 Session 15

Applications

Chairman : J.W. Humphreys (SDIO)

- (1) - 10:30-10:55 A. Louis (Hebrew University): Review on Laser-Tissue Interaction.
- (2) - 10:55-11:20 T. Meyer (SDIO): The Ground Based Free Electron Laser: Challenges and Solutions.
- (3) - 11:20-11:45 C.L. Houston III (SDIO): Applications of the Free Electron Laser: The Medical Free Electron Laser (MFEL) Program.
- (4) - 11:45-12:00 A. Gover (SAIC-TAU): Applications of Electrostatic Accelerator FELs.

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- 1.4 FEL Research in China
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RECENT FREE ELECTRON LASER EXPERIMENTS AT MIT*

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ABSTRACT

Recent experimental work at MIT on free electron laser devices will be described. The studies will include: the construction and testing of a novel microwiggler; the radiation characteristics of a high power, 600 μ m wavelength free electron laser amplifier; prebunching and optical guiding in a Raman FEL; and the radiation characteristics of a 35GHz Cyclotron Auto Resonance Maser (CARM) amplifier.

*This work was supported by the Air Force Office of Scientific Research, the National Science Foundation, and the Lawrence Livermore National Laboratory.

Electrostatic-Accelerator Free-Electron Lasers

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ABSTRACT

Because electrostatic accelerators are well suited to generate high quality electron beams and as a result of high beam recovery demonstrated by these machines, it will be possible to construct compact, single stage FELs which can operate with excellent wall power efficiency in the infrared, far-infrared and millimeter region. A discussion is presented of some possible designs and of their potential operating capabilities.

Survey of FEL Activity in China

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Abstract

A brief survey of FEL activity in the People's Republic of China is presented. It is reported that some results on Roman type FEL have been obtained and experimental work on Compton type FEL was also started. Some theoretical studies on FEL carried out will be reported as well.

NEAR-IDEAL LASING WITH A UNIFORM WIGGLER*

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ABSTRACT

Over the years the Los Alamos National Laboratory Free-Electron Laser (FEL) team has reduced or eliminated many of the experimental problems that resulted in non-ideal lasing. The major problems were accelerator instabilities that caused noise and fluctuations in current, energy, and timing. Wakefield effects, which introduced fluctuations in the beam's energy and emittance, were also encountered in the wiggler and beamline. Finally, mirror nonlinearities, caused by free carriers produced in the mirror by the high light levels, caused extra light losses and interfered with the diagnostics. Lasing is now thought to be ideal in that it lacks major disturbing effects and is limited only by emittance, energy spread, and peak current.

In this paper, we describe the features of lasing that we have observed over a range of optical power of 1000, from the onset of lasing to the threshold of the sideband instability, to the organization of regular optical spikes, and to the region of chaotic spikes.

Detuning the cavity length is proposed as an ideal technique, in most circumstances, to completely suppress sidebands. With detuning, one can easily switch operating modes from high efficiency (chaotic spiking) to narrow spectral line (no sidebands). Alternate techniques for sideband suppression normally use some kind of wavelength selective device (e.g., a grating) inserted in the cavity. With detuning, there is no need for such a device. This avoids the conflict between

wavelength control exerted by the extra optical component and that exerted by the energy of the electron beam. Lasing, therefore, starts easily, the wavelength chirps readily as the optical power saturates, and the power and efficiency do not suffer seriously from fluctuations in electron beam energy.

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THE RESULTS OF THE PALADIN 15-M EXPERIMENT

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ABSTRACT

PALADIN is a 10.6 μm amplifier experiment at the 45 MeV Advanced Test Accelerator of the Lawrence Livermore National Laboratory. Operating with 15 meters of wiggler, PALADIN produced 27 dB of exponential gain from 14 kW of input power; with 5 MW of input power, the untapered wiggler saturated. This paper summarizes the experimental parameters and results, and presents evidence for the observation of gain guiding by the electron beam in the amplifier.

* Work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory, for the Strategic Defense Initiative Organization and the U. S. Army Strategic Defense Command.

Program and System Development at the SCA/FEL

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ABSTRACT

The Superconducting Linear Accelerator driven Free Electron Laser (SCA/FEL) at Stanford University has been established as a facility for producing picosecond photon beams. Experimental areas for biomedical and materials science research have been developed, and users are currently in the process of setting up their apparatus for initial experiments to take place using near infrared photons.

Much of the group's efforts during the past year has been devoted to the development and installation of improved diagnostic systems for the electron beam and the wiggler. An emittance-measuring system for the electron beam has been tested, and a variable dispersion electron spectrometer/10 kW beam dump is being installed. Improved measurement capability of the rf phase stability of the SCA has improved the operating stability of the FEL, and has allowed the beam bunch length to be compressed to about 2 ps (1 deg at 1.3 GHz). Motivated by the degradation of the TRW wiggler, a stretched wire system^{1,2} has been used to make *in-situ* measurements of the field profile. This system will allow us to monitor the wiggler's performance, and will assist in any magnet re-adjustments.

A particularly exciting development for the SCA/FEL, which we would like to implement in the near future, is the capability of producing two substantially different wavelengths of photons "simultaneously." In this mode, the SCA will produce an electron bunch train in which the energy alternates between a high and a low value. The beams will be separated by a magnetic system, then steered through independent wigglers. With the presently installed TRW wiggler and the on-site #2 wiggler built by Spectra Technology, Inc., photons produced by the low-energy beam will be adjustable to any wavelength between about 15 microns and 2 microns, while photons produced by the high energy beam will be independently adjustable from the near infra-red through the visible. The power in each beam will be about 50 watts, and each beam will consist of a train of picosecond pulses separated by about 90 ns. The precise synchronization of the two beams, guaranteed by the fact that they are produced at the same time by the same linac, will allow dynamic studies of biological and chemical systems to be undertaken which would be impossible using conventional photon sources.

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Japanese Activities on Storage Ring
and RF Linac FEL Development

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Status of Japanese activities on FEL research is briefly summarized. These activities are conveniently categorized into four groups from view points of their developmental stages and forms of the beam source utilized:

- 1) Two storage rings parasitically used now are more advancing than remainings. Both have already made several experiments.
 - a) The 800 MeV TERAS ring at the Electrotechnical Laboratory in Tsukuba, equipped with an optical klystron, aiming at oscillation at a visible(579 nm) wavelength.
 - b) The 750 MeV UVSOR ring at the Institute of Molecular Science, in Okazaki, equipped with an ordinary undulator, also at a visible (488 nm) wavelength.
- 2) Two RF-linacs(normal conducting) are modified for the purpose.
 - a) The 35 MeV SANKEN linac in Osaka is a L-band(1300MHz) one, being used for a gas-load undulator experiment including beam diagnosis. Besides this, another 145 MeV S-band linac is under construction.
 - b) The 25 MeV TODAI linac(S-band) in Tokai is now modified through replacement of traveling wave accelerating tubes by standing wave tubes and with an improvement of the injector system.
- 3) Two dedicated accelerators are;
 - a) The 35 MeV NICHIDAI double-sided microtron (2450MHz) of normal conducting and in C.W. operation in Narashino is under construction.
 - b) The 25 MeV JAERI superconducting linac(508MHz) in Tokai is now ready for R&D installation in Phase-I.
- 4) Three proposals;
 - a) The 1.3 GeV KYUSHYU storage ring with a high gain FEL undulator in Fukuoka.
 - b) The 1.5 GeV TOHOKU beam stretcher/storage ring with insertion devices in Sendai.
 - c) The X-band KEK FEL linac in Tsukuba.

Experiments and Theory on Induction Linac

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We have developed an induction linac (Reiden I-A) of which beam energy and current are 6MeV and 10kA. The Reiden I-A is composed of 4MeV injector and 2MeV accelerator. In this accelerator, by-path loads are set in the induction cavity in order to get a flat-top acceleration voltage pulse. As the result, the accelerated electron energy fluctuation is suppressed with in 3% during 70ns. The beam emittance is going to be reduced by the emittance selector.

The preliminary experiments on amplified spontaneous emission have been carried out. In the experiments, the beam energy and current are 1.5MeV and 100A, and the wiggler period is 30mm. The peak radiation power at about 1mm wavelength is about 1MW. The distributed feed back wave guide was also applied to make the radiation spectrum narrow. The detail results will be given in the conference.

As for FEL theory, we developed a 3D FEL simulation code which can describe many wave guide mode effects on the amplification and saturation. In particular, the conversion efficiency for a tapered wiggler is found to be degraded by the multi-mode excitation.

IMP, A FREE-ELECTRON LASER AMPLIFIER FOR PLASMA HEATING IN THE MICROWAVE TOKAMAK EXPERIMENT *

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Abstract

The Intense Microwave Prototype (IMP) is an induction-linac based free-electron laser (IFEL) amplifier system that is presently under construction at the Lawrence Livermore National Laboratory. It will produce up to two megawatts of average power at a frequency of 250 GHz for electron cyclotron resonance heating experiments in the Microwave Tokamak Experiment (MTX). The electron beam for the IFEL will be provided by the ETA-II accelerator. This accelerator is designed to produce an electron beam with a current of 3 kA at an energy of 10 MeV and a brightness of over 10^8 A/(m - rad)². In addition, it is designed to produce 50 ns wide pulses at a repetition rate of 5 kHz. The high magnetic field and wide tunability capabilities required for the FEL will be provided by a permanent magnet-laced electromagnetic wiggler with a 10 cm period and an overall length of 5.5 m. We shall present the physics design and expected performance of the FEL, along with a description of the experiment and the phased development to high average power.

* Work performed under the auspices of the US Department of Energy by the Lawrence Livermore National Laboratory under W-7405-ENG-48.

A REVIEW OF FREE-ELECTRON LASER RESEARCH AT THE NAVAL RESEARCH LABORATORY[†]

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ABSTRACT

A combined experimental and theoretical research program on the Ubitron/Free-Electron Laser is in progress at the Naval Research Laboratory. The theoretical program includes a three-dimensional nonlinear analysis of two specific experimental configurations: a helical wiggler/axial guide field in combination with a cylindrical waveguide, and a planar wiggler in combination with a rectangular waveguide. The simulations include the modeling of the injection of the beam into the wiggler, effects of the wiggler inhomogeneity on the particle orbits, efficiency enhancement through a tapered wiggler design, beam thermal effects, and harmonic interactions. The planar wiggler model includes the effect of magnets with parabolic pole faces. The theoretical program provides support in the design, optimization, and interpretation of the Ubitron experiments. A 15 GHz Ubitron amplifier experiment is in progress which employs a 250 keV/30 A electron beam propagating through a cylindrical waveguide in the presence of a helical wiggler and an axial guide field. A comparison of theory and observations of the experiment will be presented. In addition, a third harmonic Ubitron experiment is in the design stage. The purpose of this experiment is to demonstrate that operation at high frequencies can be achieved with substantial reductions in the beam voltage. The experiment will involve a planar wiggler and rectangular waveguide configuration. The use of a tapered wiggler is under consideration to enhance the efficiency at the third harmonic. In addition, as shown in simulations of the fundamental interaction¹, the effect of a tapered wiggler is to reduce the sensitivity of the interaction to beam velocity spread. This is critically important in a harmonic experiment since the sensitivity of the interaction to thermal effects increases with the harmonic number.²

[†]Work supported by the Office of Naval Research and the Office of Naval Technology.

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¹H.P. Freund, H. Bluem, and C.L. Chang, Phys. Rev. A 36, 2182 (1987).

²H.P. Freund, C.L. Chang, and H. Bluem, Phys. Rev. A 36, 3218 (1987).

SIDEBAND INSTABILITIES AND OPTICAL GUIDING IN A FREE-ELECTRON LASER:
EXPERIMENT AND THEORY*

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ABSTRACT

We report experimental and theoretical results on the effect of optical guiding on sideband instabilities. A preliminary calculation by Johnston et al.¹ in the exponential gain ("linear") regime suggests that optical guiding can modify the group velocity of the radiation, and thereby suppress the sideband instabilities. We have developed 1-D and 2-D codes to study the effect of optical guiding on sidebands in the linear as well as the saturation regime, with and without waveguides. The results of the 1-D code in the linear regime agree reasonably well with the sideband frequency shift calculated in Ref. 1. In the saturation regime, the shift is smaller. When the effect of space charge is included, the shift is reduced further. 2-D simulations are done with the parameters of the Columbia Raman FEL. Appreciable sideband shifts due to optical guiding are observed in both linear and saturation regimes.

Experimental studies were done using the Columbia Raman FEL facility (1.9 mm wavelength, megawatt power, 800 kv pulse-line accelerator), using a small electron beam (4 mm diameter) in a large drift tube (17 mm diameter). High resolution spectra of the FEL oscillator are obtained showing the carrier as well as the short- and long-wavelength sidebands. Observations are taken at saturation or at the end of the exponential gain regime. Data shows, in qualitative agreement with theory, that optical guiding causes an increase in the separation between the carrier and sidebands in the linear regime, but the separation decreases as saturation sets in.

* This work is supported by the U.S. Office of Naval Research, Grant No. N0014-796-0769, and the National Science Foundation, Grant No. ECS-87-13710

¹ S. Johnston, A. M. Sessler, Y. -J. Chen, W. M. Fawley and E. T. Scharlemann, unpublished

A NOVEL METHOD FOR ACHIEVING COHERENCE
AND MAXIMUM EFFICIENCY
IN A HIGH POWER FEL OSCILLATOR*

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ABSTRACT

One of the most important problems in the design of high power generators of coherent radiation is the competition of the many eigenmodes of the resonator for the beam energy. The effect of multimode interaction on the efficiency of a low gain FEL oscillator fed by a continuous electron beam is investigated. Calculations that enable one to design a device in such way that it will operate at a single frequency with maximum efficiency are presented.

In the framework of the stationary theory with only one mode present in the system, it is shown that the state with the maximum efficiency corresponds to a current four times larger than the start-oscillation current. Linear multimode analysis indicates that this state is subject to instability. It has been shown that the state with the maximum efficiency corresponds to a current about three times larger than the start-oscillation current. In addition it has been found that many single mode equilibrium states exist with this current while only one state corresponds to the maximum efficiency.

Multimode simulations have been carried out to determine the conditions under which the system will reach the state with maximum efficiency. It has been found that by changing the last few percent of the voltage pulse slowly enough as it approaches the design value a single mode equilibrium state with the maximum efficiency is accessible.

* This work is supported by ONR and DOE

MODE COMPETITION IN LONG-PULSE FELS

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ABSTRACT

The short electron pulses in most FELs mode-lock a large number of optical modes. In long-pulse FELs on the other hand, the mode structure only depends on the intrinsic, nonlinear mode interaction. This interaction is studied in an analytic perturbative framework, both for low as well as high gain regimes. The mode coupling depends on the saturation terms which are obtained from third order perturbation. Both self and crossed saturation are obtained and the ratio crossed/self characterizes the strength of the mode coupling. The mode competition is analyzed by studying the two-mode problem. Mathematically, this entails a stability analysis of a system of two coupled integro-differential equations. In FELs the crossed saturation is twice as strong as the self saturation. As a result, a dominant mode is able to suppress the other mode and the result is single mode operation.

SIMULATION OF SUPERRADIANT FREE-ELECTRON LASERS*

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It has been suggested that the use of very short electron pulses in a single-pass free-electron laser would generate an output signal with a peak amplitude many times greater than the value expected for a long pulse.¹ The growth of such "superradiant" pulses in a helical-wiggler FEL is characterized here using 1-D and 2-D numerical simulations. The 1-D calculations show the effects of detuning, energy spread, and the axial current distribution on superradiant pulses, while the 2-D simulations illustrate the effects of betatron motion and the radial structure of the electron beam. The efficiency of superradiant pulse generation and the consequences of retaining second-derivative terms in the field equations are also studied.

* Performed jointly under the auspices of the US DOE by LLNL under W-7405-ENG-48 and for the DOD under SDIO/SDC-ATC MIPR No. W31RPD-8-D5005.

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SIMULATIONS OF MODE REDUCTION WITH AN INTRACAVITY
ETALON IN AN RF-LINAC BASED FEL

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Coherence between successive light pulses from an RF-LINAC based FEL can be induced by means of an intracavity interferometric element such as an etalon. This procedure considerably reduces the number of active cavity modes and facilitates the selection of a single narrow line from the laser output.

Results of computer simulations for the operation of an etalon in the FELIX [1] design will be shown.

The model based on the wave equation driven by single particle currents has been applied in simulations using a small number (up to six) of independent electron pulses. The case with 40 separate pulses in the cavity is treated with a simpler model.

[1] P. W.van Amersfoort *et al.*, this conference.

[2] W.B.Colson, in 'Free Electron Lasers: Critical Review of Technology', B.E Newnam, Ed.,
Proc. SPIE 738 (1988) pp 2-27

ABSTRACT

Modulational Instability in the Free Electron Laser

by

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The standard linear stability analysis of the Free Electron Laser published elsewhere is shown to be in error. Specifically, there is an omission in the mechanism normally put forward to describe sideband instability: as well as the nonparametric Stokes and AntiStokes processes usually considered, there is also an equally important parametric four-wave mixing process in which the Stokes, AntiStokes and pump modes are strongly coupled. This alters the gain coefficient describing the growth of the sideband modes. Results will be presented and discussed in detail.

A High-Power, 140 GHz, CARM
Amplifier Experiment

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A 140 GHz cyclotron autoresonance maser (CARM) amplifier experiment is planned and nearing operation. The experimental design will be described in detail, and theoretical simulation will be presented. The experiment will employ a 50-100 A, 450 keV electron beam from a Pierce-type gun and a bifilar helical wiggler to produce the solid axicentered e-beam with $v_{\perp}/v_{\parallel} = 0.3 - 0.6$. The driver for the amplifier will be either an extended interaction oscillator or a gyrotron. The experimental and theoretical research will address the issues of gain, efficiency, bandwidth, and the CARM sensitivity to beam velocity spread and absolute instabilities.

This work is supported by the Innovative Science and Technology Office of the Strategic Defense Initiative Organization and managed by Harry Diamond Laboratories.

EXPERIMENTAL CARM OSCILLATOR RESEARCH AT NRL*

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ABSTRACT

The Cyclotron Auto-Resonance Maser (CARM) is under investigation at the U.S. Naval Research Laboratory as an efficient source of high power millimeter-wave and submillimeter-wave radiation for applications such as plasma heating, advanced rf accelerators, and space-based radars. This talk will summarize ongoing and planned CARM experiments at NRL. A short-pulse 100 GHz CARM oscillator experiment based on a 600 kV, 200 Amp, 70 nsec electron beam is underway. The mode selective, high-Q waveguide cavity with rippled-wall Bragg reflectors is designed to operate in the TE_{61} mode. A novel cold cathode diode is used to produce a high quality ($\Delta v_z/v_z \leq 3\%$) annular beam with a momentum pitch ratio of 0.6. The cathode features nonemitting focussing electrodes and an annular velvet emitter. The main objective of the experiment is to demonstrate high efficiency $\sim 20\%$ at a power of approximately 20 MW. In addition, a long pulse 250 GHz CARM oscillator experiment based on a 500 kV, 100 Amp, 1 μ sec MIG-type thermionic cathode electron gun is planned. The design of this experiment will be discussed.

*Supported by the U.S. Office of Naval Research.

⁺Science Applications International Corporation, McLean, VA

HIGH EFFICIENCY MILLIMETER-WAVE FREE-ELECTRON LASER EXPERIMENTS

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A Free-Electron Laser (FEL) experiment is currently underway at PMI. The electron beam is produced by a cold cathode immersed in a uniform axial magnetic field ($B_{||} = 0 - 12$ kG) and energized by a PI 110 A accelerator. The electron beam parameters are the following : voltage $V = 0.4 - 1.0$ MV, current $i_b = 0 - 400$ A and radius $r_b = 0 - 3$ mm. The bifilar helical wiggler periodicity is $l_w = 20$ mm, with a maximum strength $B_w = 600$ G. A novel design^[1] for the adiabatic entrance to the wiggler interaction region, 10 periods long, will be described. We have obtained high efficiency enhancement^[2] (from 6.5 % to 20 %) of our FEL, operating @ 120 GHz ($\lambda = 2.5$ mm, $V = 600$ kV, $B_{||} = 9.6$ kG, $B_w = 300$ G), by reducing the beam radius (from 3 mm to 1 mm) and current (from 300 A to 30 A). The measured electric field growth rate for the parameters given above is 1.44 dB/cm, yielding an estimated theoretical efficiency of 16 %. In addition, we have observed continuous voltage tuning of the FEL, between 75 GHz and 270 GHz, at power levels around 10 MW and efficiencies > 5%. These results are obtained with an untapered wiggler.

[1] F. Hartemann, H. Lamain and J.M. Buzzi, accepted for publication in Applied Physics Letters.

[2] F. Hartemann, J.M. Buzzi and H. Lamain, submitted for publication to Physical Review Letters.

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STATUS OF THE DARMSTADT NEAR-INFRARED FEL PROJECT

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ABSTRACT

The near infrared FEL project planned with the superconducting 130 MeV electron accelerator at the Nuclear Physics Institute at the Technische Hochschule Darmstadt will be carried out with electron energies between 35 and 50 MeV corresponding to wavelengths between 5.24 and 2.57 μm respectively. For this purpose the injector system will be modified in order to achieve a peak current of 2.7 A. The design and some measured data of the injector components (high brightness electron gun, subharmonic chopper and prebuncher cavities) will be presented. Detailed numerical simulations of the FEL performance have been carried out. The results of these simulations are compared with theoretical predictions. The resulting requirements for the hybrid undulator with $K=1$ and $\lambda=3.2$ cm with respect to the field errors will be discussed.

EXPERIMENTS

with a

35 GHz CYCLOTRON AUTORESONANCE MASER (CARM) AMPLIFIER*

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ABSTRACT

Studies of a cyclotron autoresonance maser (CARM) are presented. The measurements are carried out at a frequency of 35GHz using a mildly relativistic electron beam of $\sim 1.5\text{MeV}$ energy and 5 to 300Amp current. The beam is generated by a field emission electron gun ($\sim 1.5\text{MeV}$, $\sim 20\text{kA}$) followed by an emittance selector that removes $\sim 99\%$ of the outer, hot electrons. The entire system length (~ 2.0 meter), including the field emission gun, is immersed in a uniform solenoidal guide field that can vary from 0 to 15KG. Perpendicular energy is imparted to the electrons by means of a bifilar helical wiggler having a period of 7cm and a length of 56cm. The cyclotron radiation is generated in a 1 meter long wiggler free region. Initial superradiant measurements give a small signal gain of 45dB/m and an unsaturated power output of 1.3MW. Experiments are also underway in which a 35GHz, 100kW magnetron is used as the driver for our CARM amplifier.

*This work is supported by the Air Force Office of Scientific Research.

EFFECT OF OPTICAL GUIDING ON SIDEBAND INSTABILITIES IN A FREE-ELECTRON LASER*

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ABSTRACT

Sideband instabilities¹ in free-electron lasers are caused by the slippage between the optical beam and the electron beam. Since optical guiding occurs due to the modifications in the refractive index (of the electron beam) which in turn determines the group velocity of the radiation, it is natural to expect that optical guiding should have a strong effect on the slippage and the sideband shifts. Preliminary calculations by Johnston et al.² in the exponential gain regime indicate that optical guiding can have a stabilizing effect on sidebands by reducing their growth rate and shifting them away from the carrier frequency.

We have developed 1-D and 2-D computer codes to study the effect of optical guiding on sidebands in the exponential gain and saturation regimes, including space-charge effects and boundary conditions for waveguides.

The results of the 1-D code in the linear regime agree reasonably well with the shift in the sideband frequency calculated in Ref. 2 in the exponential gain regime. In the saturation regime, where the formula for the refractive index based on Kramers-König relations is not strictly valid, the shift is smaller. When the effect of space charge is included, the sideband shift is reduced further.

While the results of 1-D studies are qualitatively correct, 2-D effects introduce important quantitative differences. We couple the space-time dependent radiation equation to single-particle, Hamiltonian equations for electrons. The radiation amplitude is expanded in a complete set of waveguide eigenmodes, and a periodic boundary condition in time is imposed. For the parameters of the Columbia Raman FEL, appreciable sideband shifts are observed both in the linear and saturation regimes. Results on the effects of tapering will be reported.

* This work is supported by the U.S. Office of Naval Research, Grant No. N0014-796-0769, and the National Science Foundation, Grant No. ECS-87-13710

¹ N. M. Kroll and M. N. Rosenbluth, *Physics of Quantum Electronics* 7, 197 (1980)

² S. Johnston, A. M. Sessler, Y. -J. Chen, W. M. Fawley and E. T. Scharlemann, unpublished

A PROPOSED SUPERCONDUCTING PHOTOEMISSION SOURCE OF HIGH BRIGHTNESS

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ABSTRACT

We report on the design criteria and the initial layout of a photoemission electron source for an intense beam with high brightness. A cesium antimonide photocathode deposited on a superconducting niobium substrate is used as an integral part of a 500 MHz superconducting reentrant resonator. It will be illuminated by a commercially available, frequency doubled, and mode locked Nd:YAG or Nd:YLF laser operated in a cw or burst mode, i.e. with medium intensity and high (125 MHz) repetition rate or with high intensity and low (100 Hz) repetition rate. The intensity of the electron beam will be limited by the power of the rf klystron or the intensity of the laser beam. First results of the calculated beam properties will be discussed. The experimental layout of the source and the beam diagnostic system will be described.

SHORT PERIOD UNDULATORS FOR FREE-ELECTRON LASERS*

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ABSTRACT

We describe a new scheme of fabricating micro-undulators capable of producing kilogauss fields on axis. In this magnetic structure, each period consists of two channels (electro magnets) energized by current with opposite polarities, hence the magnetic field in each half period is independently controllable. The unique flexibility of this configuration, in principle, allows one to tune out random errors associated with field variations in individual channels, and also permits tapering for efficiency enhancement studies.

The construction of the micro-undulator is similar to that of the magnetic recording heads manufactured for precision applications. It is assembled in two half brackets, each with 60 precision-cut slots, held together with epoxy and bolts. AlFeSi cores, wound with 160 turns of 40 gauge wire, are loaded into the slots in the half-brackets and potted. Terminal boards (electrical interfaces) are connected to the core windings and inserted into the half-brackets. The whole assembly is then lapped and gapped to the final configuration. All mechanical tolerances are held to within 0.3 mil. such that an undulator period error of less than 1% is achieved. Using this technique we have constructed a 30 period prototype wiggler having a periodicity of 2.4 mm and yielding a magnetic field of 100G per ampere on axis. Preliminary field measurements of the undulator, and the design parameters of a submillimeter FEL experiments will also be presented.

*This work was supported by the National Science Foundation, and the Air Force Office of Scientific Research.

PHOTO-INJECTOR, ACCELERATOR CHAIN AND WIGGLER DEVELOPMENT PROGRAMS
FOR A HIGH PEAK POWER RF - FREE ELECTRON LASER

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ABSTRACT

Strong constraints are imposed on the main components of a RF linac to reach high peak power in a free electron laser. To get high beam qualities, development programs and prototype realizations have been engaged on the following topics :

- a low-frequency photo-injector running at 144 MHz,
- an accelerator chain prototype at 433 MHz including a 6 MW peak klystron with 200 μ s pulse duration, a hard tube modulator and a 3-cell cavity,
- an adjustable hybrid tapered wiggler with online feedback control.

The status of these developments will be presented.

PROPOSAL FOR A RACE-TRACK MICROTRON WITH HIGH PEAK CURRENT

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ABSTRACT

In order to obtain high gain in a free electron laser a high-quality electron beam with high peak current is required. It is well-known that a microtron is able to produce a high-quality beam having low emittance and small energy spread (10^{-3}). Because a circular microtron has a limited high current capability a race-track design is adopted for providing flexibility, better beam quality and of course higher peak current in the microbunch.

Space charge problems may be severe in a microtron. It can be shown that bunching on certain specific subharmonic frequencies will lead to a strong reduction of the space charge problems. The general lay-out of our microtron design will be presented. The characteristics are: energy 25 MeV, micropulse 10^{-9} of the RF frequency of 3 GHz. Our aim is to come beyond the present state of the art with the following characteristics: relative energy spread 0.001, emittance 3 mm mrad, current in the micropulse 100 A, macropulse length 50 μ s and subharmonic bunching at 1:64.

*This work is supported by Ultra Centrifuge Nederland, The Netherlands.

**Universal Relations Between Gain and Spontaneous
Emission of Free Electrons in Wave Guides***

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Abstract

We derive universal relations between spontaneous emission, thermal noise and stimulated emission of quasi-free electrons in a waveguide. The formulation is based on quantum electrodynamics principles.

These relations result in interesting practical expressions in the classical regime, where the electron recoil due to emission or absorption of a photon is negligible. The relations apply to a wide range of radiation effects which are based on quasi-free electrons. Such as Free Electron Laser, Cyclotron Resonance Laser, and Smith Purcell radiators.

A simple expression is given that yields the relation between the gain and the spontaneous emission for each waveguide mode, based on the characteristic angle of the mode. We further simplify our expression in the case of a rectangular waveguide. We utilize the formulation in two examples in order to calculate the gain on the basis of previously calculated expression for spontaneous emission and the expression for the ratio between spontaneous and stimulated emission which we have developed. One case is the FEL and the other is the CRM.

*This work is supported in part by ONR contract #N00014-87-C-0362.

NONLINEAR THEORY AND DESIGN OF A HARMONIC UBITRON/FREE-ELECTRON LASER

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ABSTRACT

A fully three-dimensional nonlinear analysis of the harmonic Ubitron/Free-Electron Laser is discussed which is valid for arbitrary harmonic number. The analysis has been performed for a configuration consisting in a beam propagating through a rectangular waveguide in the presence of a planar wiggler field. The wiggler model includes an adiabatic entry taper to model the injection of the beam into the wiggler, parabolic pole pieces to provide additional focussing in the plane normal to the wiggler motion, and an amplitude taper downstream from the entry region for efficiency enhancement. The advantage of harmonic operation is that relatively high operating frequencies can be achieved with relatively low voltage electron beams; however, this occurs at the expense of a greater sensitivity to beam thermal effects. In addition to enhancing the extraction efficiency, a tapered wiggler has been shown^{1,2} to reduce the sensitivity of the interaction to beam thermal spread. Thus, the tapered wiggler compensates for the increased thermal sensitivity of the harmonic interaction. Specific design criteria for a third harmonic Ubitron experiment will be discussed. The experiment will employ a 55 keV/15 A electron beam with a 1 kG/3 cm wiggler field, and operate as an amplifier at 15 GHz.

[†]Work supported by the Office of Naval Technology.

¹H.P. Freund, H. Bluem, and C.L. Chang, Phys. Rev. A 36, 2182 (1987).

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THE PLASMA CHERENKOV MASER WITH FINITE AXIAL MAGNETIC FIELD

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ABSTRACT

The linearized Maxwell's and fluid equations are used to investigate the stability properties of a tenuous relativistic electron beam propagating in a cylindrical waveguide filled with a background plasma and guided by a finite magnetic field. It is assumed that the electron beam fills the waveguide and both the electron beam and background plasma are cold. In general, the presence of a finite magnetic field in a beam or plasma loaded waveguide will couple the TM and TE modes of the system so that both E_z and B_z field components exist simultaneously. Use of the linearized Maxwell's and fluid equations results in a set of coupled wave equations for the E_z and B_z field components which lead to a dispersion relation for the electron beam-plasmaguide system. The dispersion relation is then used to calculate the growth rate of the slow-wave plasmaguide modes (Trivelpiece-Gould modes; $\omega < \omega_p < \omega_c$ or $\omega < \omega_c < \omega_p$ where ω_p and ω_c are the background plasma frequency and cyclotron frequency, respectively) due to the interaction with the relativistic electron beam.

MODELING SIDEBAND SUPPRESSION IN AN FEL USING A LITTROW GRATING

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The sideband instability has been observed in the Los Alamos FEL [1] and is expected on theoretical grounds to be a source of efficiency degradation when tapered wiggler FEL operation is desired. A frequency selective optical cavity element, such as a Littrow grating or a grating rhomb, has been theoretically shown to yield spectral purity and high efficiency. This research reports both 1D and 3D simulations of FEL behavior when a grating mounted in the Littrow configuration is ruled onto one of the resonant cavity mirrors. The Littrow configuration is oriented so that the first order diffraction from the grating is aligned with the resonant cavity axis. In both the 1D and 3D simulation codes, the effect of the Littrow grating is modeled by including wavelength dependent diffraction. We have modeled uniform and tapered wiggler FEL designs and included grating rulings in the range from 1 to 24 lines/mm. The calculations show that the FEL pulse is temporally stretched and spectrally pure. Simulations of the Los Alamos 12% tapered wiggler show that high efficiencies, of the order of 2 to 4 percent, are possible with experimentally accessible e-beam parameters.

*Work performed under the auspices of the United States Department of Energy, and supported by the United States Army Strategic Defense Command.

[1] R.W. Warren, B.E. Newnam & J.C. Goldstein, "Raman Spectra and the Los Alamos free-electron-laser," IEEE J. Quant. Elecs. Vol. QE-21, No. 7, pg. 882, 1985.

A HIGH POWER, 600 μm WAVELENGTH FREE-ELECTRON LASER*

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ABSTRACT

We report high-power emission (18 MW) at a wavelength of $\lambda = 640 \mu\text{m}$ and a bandwidth $\Delta\lambda/\lambda < 0.04$ from a superradiant free electron laser (FEL) excited by a 2 MeV, 1 kA electron beam. Comparison of the experiment with a nonlinear simulation yields good agreement. Theoretical extrapolation to a tapered wiggler experiment shows that power levels of ~ 140 MW could be achieved with an efficiency of $\sim 7\%$.

*Work supported by the Air Force Office of Scientific Research and the National Science Foundation.

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SUPERFLUORESCENT EMISSION OF CHANNELING X-RADIATION

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Relativistic electrons and positrons channeled in crystals are good sources of monochromatic, tunable and collimated X-radiation. This lends itself to the conjecture that they might be used to construct an X-ray laser. Theoretical treatments⁽¹⁻³⁾ indicate that the regime of steady-state X-ray lasing in this scheme requires current densities above MA/cm², in excess of the present limit of beam technology. A much more promising alternative is the generation of X-ray bursts of superfluorescence (SF) from channeled electrons and positrons. The intensity of such bursts scales quadratically rather than linearly with the beam intensity, owing to their cooperative character. In FELs similar cooperative emission (superradiance) is not realizable at X-ray wavelengths, since it would require pre-bunching of the beam on scale of Ångströms. Our theoretical analysis of SF⁽³⁾ is based on the same principles as those used by us for stimulated channeling radiation⁽²⁾, namely, Maxwell-Bloch equations for moving dipoles. It is shown that 10-fold SF enhancement at a wavelength of 10Å is attainable at current densities of ~100A/cm², by GeV positrons or electrons, channeled in crystals or artificial structures. This estimate indicates that X-ray SF based on this scheme is within the present state of the art.

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SUPPRESSION OF SIDEBANDS BY DIFFRACTION IN A FREE-ELECTRON LASER

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ABSTRACT

The effect of diffraction on the growth of sideband instabilities in free electron lasers is investigated. It is found that for situations where the fundamental is strongly guided the gain of the sidebands is not significantly modified from the one dimensional result except for the appearance of a high frequency tail for the growth rate due to radiation damping. On the other hand, if the fundamental is weakly guided (radiation waist larger than beam waist) the sideband growth rates are suppressed and their gain may become less than the gain of the fundamental.

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OPTICAL TRANSITION RADIATION MEASUREMENTS FOR THE LOS ALAMOS AND
BOEING FREE-ELECTRON LASER EXPERIMENTS

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Abstract

Characterization of the electron-beam driving a Free-Electron Laser (FEL) is an important aspect of optimizing such systems. In particular, good electron-beam emittance can be a critical issue ensuring spatial overlap of the optical and electron beams in the wiggler. An effective, newly developed technique for measuring electron-beam emittance on a single macropulse (and, perhaps, a few micropulses) of the high current and high-energy electron beams uses the unique properties of Optical Transition Radiation (OTR). This radiation is emitted when a charged-particle beam transits an interface between two media of different dielectric constants. Radiation is emitted in both forward and backward lobes and, in addition, the backward lobe includes a functional relationship to the Fresnel reflection coefficients so that detection at 90 degrees to the beam direction is practical.

Two sets of measurements were successfully performed at Los Alamos. Beam profiles and beam divergence patterns from a single screen were recorded using our two intensified Charge-Injection Device (CID) television cameras and an optical beamsplitter. Data were recorded with and without polarization effects on both x and y axes. The separation and width of the OTR angular

distribution lobes ($\theta \sim 1/\gamma$) agreed with the measured electron-beam energy, and, pending analysis of the data, with the expected divergence of a few mrad, respectively. The beam-spot detector was also used in conjunction with the standard technique of varying the fields in a quad doublet and measuring the spatial profiles. These data will allow a comparison of the OTR single-shot technique to the multishot quad-scan results.

A two-screen OTR interference experiment was also performed. The first foil was a thin Kapton film spaced 1/2 mm in front of an aluminized fused silica screen. The predicted three fringes were observed with no filter, a 600-nm bandpass filter, and with the polarizer oriented on both x and y axes. The comparison of these various emittance measurements will be discussed. Based on these results and further calculations, an OTR experiment for the Boeing FEL will be planned.

Chirping for Efficiency Enhancement of the Free-Electron Laser^{*}

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Theoretical and numerical studies have been made of FEL's driven by picosecond pulses in which the electron energy decreases as a function of time over the pulse length. Such electron pulses could be produced by an RF linac which accelerates electrons on the high gradient phase of the microwave field. Such electron pulses lead to frequency chirping of the laser field and efficiency enhancement in the high-power trapped-particle regime.

Cavity length detuning adversely affects the efficiency, since the chirped optical pulse is pushed off resonance more and more on successive passes. On the other hand, this detuning serves to compensate for laser lethargy during the optical pulse build-up. By initiating lasing on an unchirped front portion of the electron pulse and then setting the detuning to zero, efficient operation (5% or better for the LANL uniform wiggler) can be obtained over hundreds of passes.

^{*}Research supported by the Division of Advanced Energy Projects, U.S. Dept. of Energy

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ASYMMETRIES OF THE GAIN CURVE

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Numerical calculations of the gain curve, based on a one dimensional simulation algorithm of the coupled system of electron bunch and radiation field, show two types of significant asymmetries. First, there is the asymmetry of strong FELs due to the variation of the radiation field during one passage through the undulator magnet. Second, there is an asymmetry in the gain curve of FELs with only a few undulator-periods. The reason for this asymmetry is that the expansion of the energy to first order in calculating the Small-Signal-Gain curve no longer holds, since the width of the gain curve of such lasers is not negligible. Therefore, terms of higher order in energy deviation are necessary. Both asymmetries are described quantitatively with correction terms.

PROPAGATION OF PICOSECOND ELECTRON BEAMS FOR GAS-LOADED FELS

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ABSTRACT

Gas-loaded free electron lasers have the advantages of shorter wavelength and higher gain operation over vacuum ones. However, the presence of the gas might be expected to have detrimental effects on electron beam propagation. This paper describes the experimental and calculational results on propagation of picosecond electron pulses in neutral gases. Also its effects on free electron laser performance are analyzed.

The electron beam propagation is observed through neon gas at pressures from 80 to 760 Torr. The 25 MeV electron beams from an rf linear accelerator are injected into a 1.4 m glass tube with conducting screen. The longitudinal increase of the beam's diameter is determined by processing images of optical emission profiles which is recorded with a TV camera and a VTR. The plasma effects, such as the inward beam pinching and the instabilities, are not observed.

To account for multiple scattering in the gas, Monte-Carlo simulation studies are done. The multiple scattering results in trajectory changes for the electrons and causes deterioration of electron beam quality. The prediction is compared with experimental results. These degradation of the beams causes a lowering of interactions between electron and light beams. Calculations of lasing performance are done taking into account the beam propagation through the gases. The most significant factor influencing the process is the current density decrease of the electron beams.

3-D MAGNETIC FIELD CALCULATIONS FOR WIGGLERS USING MAGNUS-3D

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ABSTRACT

The recent but steady trend towards increased magnetic and geometric complexity in the design of wigglers and undulators, of which tapered wigglers, hybrid structures, laced electromagnetic wigglers, magnetic cladding, twistors and magic structures are examples, has caused a need for reliable 3-D computer models and a better understanding of the behavior of magnetic systems in three dimensions. The capabilities of the MAGNUS-3D Group of Programs are ideally suited to solve this class of problems and provide insight into 3-D effects. MAGNUS-3D can solve any problem of Magnetostatics involving permanent magnets, linear or nonlinear ferromagnetic materials and electric conductors of any shape in space. The magnetic properties of permanent magnets are described by the complete nonlinear demagnetization curve as provided by the manufacturer, or, at the user's choice, by a simpler approximation involving the coercive force, the residual induction and the direction of magnetization. The ferromagnetic materials are described by a magnetization table and an accurate interpolation relation. An internal library with properties of some common industrial steels is available. The conductors are independent of the mesh and are described in terms of conductor elements from an internal library. MAGNUS-3D uses the finite element method and the two-scalar-potentials formulation of Maxwell's equations to obtain the solution, which can then be interactively used to obtain all kinds of tables and plots and to calculate quantities needed in Magnetic Engineering. This includes tables of values of the field components at specified points or lines, plots of field lines in 3-D or of the magnetic bodies seen from any point of view in space, function graphs representing a field component plotted against a coordinate along any line in space (such as the beam line), and views of the conductors and the mesh. All views feature color, perspective, and partial or full hidden surface removal. The magnetic quantities that can be calculated include the force or torque on conductors or magnetic bodies, the energy, the flux through a specified surface, line integrals of any field component along any line in space, and the average field or potential harmonic coefficients. This paper describes the programs with emphasis placed on their use for wiggler design, and an example of mesh generation and calculations for an advanced undulator concept.

Pulsed Wire Magnetic Field Measurements on the Stanford-TRW FEL Wiggler

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ABSTRACT

The magnetic field profile of the Stanford-TRW electron laser wiggler has been measured *in situ* using a 20 microsecond 4 ampere current pulse in a stretched wire and measuring the displacement of the traveling acoustic wave generated.¹ Both the technique and our results are discussed. The 120 period wiggler in its present configuration has rms errors of 1.3% in the half-period field integral and .04 radians in phase. The measurements have been used to set steering coils to cancel steering errors; residual steering errors are about .45 milliradians rms under typical operation. Our analysis indicates that the phase errors are unimportant and that the errors in field integrals only matter to the extent that they result in steering errors.

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ANIMATION OF ELECTRON MOTION IN THE PONDEROMOTIVE POTENTIAL OF LASER BEATS

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July 16, 1988

Abstract

The behavior of an electron in the beat wave field of two counter-propagating pulsed CO_2 laser beams, operating at different frequencies is usually studied by solving the equation of motion of the electron numerically. These solutions give the energy spectrum of the electrons at the end of the interaction. The present paper describes a computer program that animates the motion of the electron, giving a real time picture of its motion during the whole interaction process. This program can be used to understand several trapping mechanisms of an electron moving in a ponderomotive field superimposed on a DC axial field. The first one is the case in which the electron is created inside the ponderomotive field. In this case the program can be used to show visually that such an electron can get trapped only if its energy is around the synchronization energy. In the second case the program can be used to understand the trapping mechanism for the case in which there is a temporal rise in the ponderomotive field. For the case in which an abrupt axial field jump is used to trap the electron in the ponderomotive wells, numerical simulations show periodicity in the relation between the energy of the electron and the trapping fraction. This periodicity and also the trapping mechanism can be clearly understood using the animated motion of the electron together with the varying ponderomotive potential. The program can also be used to understand the detrapping of trapped electrons in the case where there is a temporal fall of the field.

Coaxially Fed Folded Foil Electromagnet Wiggler

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ABSTRACT

A simple electromagnet wiggler, constructed of Copper foil windings, is presented. The design is based on a concept proposed by Granatstein *et al.* [1]. By combining two wigglers of this kind, back and forth, we obtained a co-axial current feeding that cancels asymmetrical fringe fields at both ends of the wiggler.

Analytical expressions for the off-axis magnetic fields are given and compared to exact numerical results and to experimental measurements. Both comparisons show high accuracy of the analytical expressions in the entire wiggler volume. Electron trajectories in the wiggler and optimal injection conditions are described and considered in this paper.

A wiggler construction of $\lambda_w = 2\text{cm}$ that produces 345 Gauss peak on-axis at 1 kA feeding current is presented. The feasibility of a miniature wiggler based on this concept is discussed, and a scheme of $\lambda_w = 3\text{ mm}$, $B_w = 0.5\text{ Tesla}$ ($a_w = 0.1$), fed by a current of $I = 1.4\text{ kA}$, is proposed.

Reference

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Submitted to the Tenth International FEL Conference, Jerusalem, 1988.

SIDEBAND SUPPRESSION FOR THE LOS ALAMOS

FREE-ELECTRON LASER

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ABSTRACT

Theoretical calculations suggest that a higher extraction efficiency can be achieved for a tapered wiggler FEL if some means of narrowband wavelength filtering can be found to suppress sidebands. Different techniques to suppress sidebands will be assessed.

Any method using refractive media is prone to optical damage due to the high fluences inside the cavity. When the fluence is low enough that optical distortion, due to the thermal loading of normal incidence optics is within acceptable limits, a Littrow grating may be used. For much higher fluences where a ring resonator with grazing incidence is required, either a single planar grating, or a grating rhomb can be used.

The Littrow grating emerges as a likely candidate for the conditions of the LANL FEL. Practical design considerations will be discussed, and details of different fabrication techniques will be presented.

ELECTRON BEAM MEASUREMENTS ON THE FIRST STAGE OF THE HPMC HIGH BRIGHTNESS GUN*

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ABSTRACT

The TRW High Power Modular Components program is developing the use of superconducting RF cavities at high average current ($I_{avg} = 100$ mA) for FEL applications. To test the cavities a high brightness injector system is under construction. The injector incorporates a cw 500 kV high voltage electron gun and a pre-accelerator to raise the energy to 1 MeV where the beam may be finally bunched with minimum emittance growth in the face of the large space charge in the bunch. The injector gun cathode is grid modulated to produce beam pulses with 2 A peak current, 500 ps flat-top at 100 MHz repetition rate. The gun was modeled using both steady state (E-GUN) and time dependent (MASK) codes. The modelling using the MASK code showed that the imbalance of space charge in the beam during the rise and fall of the pulse results in large differences in the beam trajectories during these periods compared to that during the peak period. This will inevitably lead to emittance growth in downstream focussing elements. We have therefore designed for the rise and fall periods to be as short as possible with a flat-top peak current. We have constructed a test stand to simulate the first stage of the gun, which operates at 100 kV. On the test stand we have demonstrated 500 ps wide flat-topped beam pulses with rise and fall times of approximately 300 ps. This was accomplished using a pulser configured with custom built, differentially biased step recovery diodes connected to a 180 degree hybrid. The pulser is capable of repetition rates of up to 100 MHz. Measurements of the beam emittance, using a pinhole and fluorescent screen technique, yielded values for normalized emittance of approximately 15 $\mu\text{mm-mrad}$. Comparisons between measured and computed values for emittance will be presented.

*Work supported by U.S. Office of Naval Research contract #N00014-87-C-0165

**The Influence of the Equilibrium Self-Fields
on the Betatron Oscillations in a Sheet-Beam FEL**

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Abstract

A general formalism for non-neutral cold relativistic planar steady flows is applied to the study of the betatron oscillations of a sheet electron beam in a planar wiggler FEL. The full transverse dependence of the wiggler field as well as the equilibrium self-fields of the beam are included. For a thick beam equilibrium with a particular density profile it is shown that the betatron oscillations are eliminated. For a thin beam configuration we employ the paraxial approximation and we also show that for some critical density there are no betatron oscillations. If the density is larger than this critical density the beam oscillates with the betatron frequency but there are no trajectory crossings and the beam preserves its cold fluid nature. We also consider the single particle equations of motion in the presence of both planar wiggler and planar self-fields. We show that in some cases the particles oscillate with a reduced betatron frequency, in contrast to the previous case of cold fluid motion where the self-fields do not change the betatron frequency. For the study of the betatron oscillations in the thick beam equilibrium a two space scale method is employed. For the thin beam within the paraxial approximation we use the Floquet theory for equations with periodic coefficients.

THE TRANSVERSE OPTICAL KLYSTRON EXPERIMENT AT NSLS*

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ABSTRACT

A transverse optical klystron (TOK) is a device in which a relativistic electron beam produces coherent visible and ultraviolet radiation by interacting with a high power laser beam inside a wiggler. The interaction induces spatial bunching of the electron beam at the laser wavelength as well as at its harmonics and the modulated electron beam radiates coherently at these wavelengths.

This paper reports the first measurements done on the TOK installed on the VUV storage ring at NSLS. The main components of the TOK are a 6.5 kG, 10 cm period wiggler, a Q-switched, doubled Nd:YAG laser ($\lambda_L = 5320 \text{ \AA}$) as the modulating laser and the storage ring electron beam at an energy of approximately 400 MeV. The laser modulates the electron beam at the third harmonic of the wiggler. We have observed bunch lengthening of the electron beam synchronous with the high power laser pulse, which is a measurement of the energy spread induced by the laser on the electron beam. We are presently looking for coherent enhancement of the wiggler radiation at the third harmonic of the laser wavelength.

The TOK wiggler can also be used as the central component of a storage ring FEL. To evaluate this possibility we have attempted to measure the optical gain at $\lambda_L = 5145 \text{ \AA}$ and $E = 650 \text{ MeV}$. We will discuss this preliminary measurement.

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MEASUREMENT OF THE COHERENT HARMONICS RADIATED IN THE MARK III
FREE ELECTRON LASER*

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ABSTRACT

The generation of harmonics within the electron beam medium of a free electron laser raises the possibility of producing coherent VUV and XUV radiation when the fundamental wavelength lies in the visible. This radiation can be beneficial for scientists desiring short-wavelength coherent radiation. However, the harmonic radiation can also damage the optics within the laser cavity. Ideally one would like to know, and have control over, the amount of radiation in each of the harmonics. Experiments are needed to test the validity of theoretical descriptions of the harmonic generation process. We have measured the absolute energies, growth rates, cavity losses, and time-resolved spectral distributions for each of the first eight harmonics of the Mark III free electron laser at Stanford University. Several of the quantities measured so far are in significant disagreement with elementary theory. In this paper we present the basic experimental results and discuss implications.

*This work is supported by the U.S. Office of Naval Research.

SPONTANEOUS EMISSION OF THE SUPER-ACO FEL OPTICAL KLYSTRON DOMINO

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ABSTRACT

The permanent magnet optical klystron DOMINO is composed of two undulators separated by a dispersive section, which gaps can be moved separately. Each undulator is constituted by 10 periods of 12,9cm long, the maximum peak magnetic field is 0,48T providing a K value of 5,75. The magnetic measurements and the pairing has been done very carefully. It was set-up on a straight section of the new Orsay Storage Ring Super-ACO in January. It is injected in positrons and the horizontal emittance is $3 \cdot 10^{-8}$ m.rad, the vertical one is 10^{-9} m.rad.

The spontaneous emission has been studied experimentally while varying different parameters such as the current, the energy of Super-ACO, the undulator or dispersive section gaps (the minimum being 38mm). The nominal energy of the ring is 800 MeV, but experiments are performed at lower machine energies for FEL in order to increase the gain and to limit mirrors degradation. The interesting parameter we can deduce from the spontaneous emission spectrum is the modulation rate f of the interference between the two undulators. The evolution of f versus the dispersive section gap provides the energy dispersion of the storage ring. Recording f versus the current (the maximum current per bunch is 20mA) gives information about bunch lengthening (typical bunch length at low current at 800 MeV is 90ps). The variation of f versus the position of the observation pinhole position is linked to the angular dispersion of the positron bunch. Mainly, f is lowered by the positrons energy dispersion and some angular dispersion, as predicted by the theory, but it is not really affected by small residual imperfections of the magnetic field.

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FREE-ELECTRON LASER APPLICATIONS IN THE ULTRAVIOLET:
REPORT OF THE OSA CLOUDCROFT CONFERENCE

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In March, 1988, the Optical Society of America sponsored the First Topical Conference on Free-Electron Laser Applications in the Ultraviolet at Cloudcroft, New Mexico. The objectives of this conference were to identify and discuss significant examples of applications that await future FEL devices operating below 300 nm. The contributors were most interested in the unique combination of FEL radiation properties that should exceed or are not offered by other light sources. These include broad tunability, narrow bandwidth, high peak- and average powers, ps-pulse structure, high spectral brightness, coherence, and polarization purity.

Approximately fifty papers proposed applications in atomic and molecular spectroscopy, spectroscopy of highly ionized gases and ion beams, solid-state spectroscopy, surface physics, materials and surface processing, photochemical processes, biological structures and radiation effects, and medical applications. In addition, representatives of four FEL facilities (Los Alamos National Laboratory, Duke University, National Bureau of Standards, and Stanford University) described the operating parameters that they hope to attain.

Of particular concern to the spectroscopists was how tightly controlled the wavelength will be from micropulse to micropulse. The corresponding challenge to FEL builders is how well the sources of phase- and amplitude noise in the accelerating fields can be controlled. Also, the solid-state and surface scientists indicated that there will be a limit on the peak intensity that can be tolerated before a test sample is altered by the FEL radiation probe.

The conference organizers expect that publication of the proceedings digest¹ by the Optical Society of America will stimulate additional applications as well as encourage the timely development of FEL user facilities.

¹ *Free-Electron Laser Applications in the Ultraviolet*, 1988 Technical Digest Series, Vol. 4, (Optical Society of America, Washington, D.C. 1988), 233 pages.

* This work was supported by the Advanced Energy Projects Division/OBES, U. S. Department of Energy, the Air Force Office of Scientific Research, and the Optical Society of America.

MODELING THE RESULTS OF THE PALADIN 15-M EXPERIMENT

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ABSTRACT

The PALADIN experiment, operating at 10.6 μm with a 15-m wiggler at LLNL's Advanced Test Accelerator (ATA), demonstrated very high gain in a single-pass optical FEL amplifier. The experimental results were dominated by the transverse phase space of the electron beam in the wiggler. We have been able to simulate a close approximation to the experimental results with FRED, one of the LLNL FEL simulation codes, by using data from the emittance selector upstream of the wiggler to determine the details of the transverse phase space.

This paper briefly summarizes the PALADIN data from the 15-m wiggler and describes the procedure used to determine the transverse phase-space distribution. The FRED simulations that result with this distribution are compared with experiment.

* Performed under the auspices of the U. S. Department of Energy by LLNL under W-7405-ENG-48 and for the Department of Defense under SDIO/SDC-ATC MIPR No. W31RPD-8-D5005.

TAPERING FREE-ELECTRON LASER AMPLIFIERS
IN WIGGLER PERIOD AND FIELD*

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April 28, 1988

ABSTRACT

Tapering a free-electron laser (FEL) amplifier to improve extraction after gain saturation can be accomplished by variations in both the wiggler period and the wiggler field.¹ The paper considers specific FEL designs and demonstrates the improvement in extraction efficiency which can be achieved by utilizing both variations. Fabrication considerations make a continuously varying wiggler period impractical for long wigglers, and so this technique entails discontinuous steps in the wiggler period. Such steps in wiggler period must be introduced in a manner so that they do not induce steering in the electron beam for reasonable ranges of transverse velocities and energies nor induce a large spread in phase shifts. We discuss such techniques.

¹D. Prosnitz, A. Szoke, and V.K. Neil, Phys. Rev. A 24, 1436 (1981).

*Performed jointly under the auspices of the U.S. DOE by LLNL under W-7405-ENG-48 and for the DOD under SDIO/SDC-ATC MIPR No. W31RPD-8-D5005.

NUMERICAL SIMULATIONS OF FREE ELECTRON LASER OSCILLATORS *

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ABSTRACT

A numerical simulation capability has been developed to model the physics and realistic design constraints of free electron laser oscillators driven by RF linac accelerators. Two computer codes have been written, FELEX and FELP. The code FELEX is a three spatial dimension code with limited time or spectral resolution. The code FELP is a one spatial dimension code with essentially unlimited time or spectral resolution. The codes are complementary and their use is dependent upon the problem being addressed. The code FELP is used to model optical and electron micropulse structure, broadband noise, and the sideband instability. As an example, the code was used to assist in the design of a grating rhomb for the Boeing burst mode experiment. In this experiment, the grating rhomb provides optical filtering of the sideband instability. The code FELEX models accelerator generated electron beam distributions, the transport of these distributions through wigglers with misalignments and field errors, self-consistent interaction with the optical field, and propagation of the optical field through resonators with realistically modelled components. For example, FELEX is routinely used to match resonator designs to the optical parameters of the electron beam, and used to investigate the physics of 3-D micropulse effects. Some details of the codes will be presented along with various examples of simulation results.

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

⁺ Mission Research Corporation, 127 Eastgate Drive, Los Alamos, New Mexico.

ONE-DIMENSIONAL SIMULATION
OF FREE-ELECTRON LASER OSCILLATOR
USING A DIFFRACTION GRATING AS A CAVITY MIRROR*

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ABSTRACT

In a tapered undulator oscillator, sidebands reduce the extraction efficiency significantly. To achieve a high extraction efficiency, the sidebands may be eliminated by deflecting the light in the cavity selectively according to the wavelength. This can be done by making one of mirrors into a diffraction grating. We cant the optical axis of the mirror so that the axis of first-order diffraction from the grating coincides with the cavity optical axis. In this configuration, sidebands are diffracted to angles according to wavelength. The optical power loss at the mirror with grating depends on the density of grating lines. The diffracted light pulse is also stretched temporally, which reduces the optical intensity. The three-dimensional effects of the grating have been folded into one-dimensional pulse code FELP. Using this code, the free-electron laser performance is calculated and compared for different line densities of grating for the following three wigglers: a 12% wavelength tapered wiggler, a wiggler tapered in wave number by 30%, and an untapered wiggler. The wavelength aperture, defined as the overlap of the optical mode with the electron beam at the wiggler, is also studied as a function of line density.

* Work supported and funded by the US Department of Defense, Army Strategic Defense Command, under the auspices of the US Department of Energy.

STATUS OF THE DUTCH FREE ELECTRON LASER FOR INFRARED EXPERIMENTS

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We review the status of the Dutch Free Electron Laser for Infrared eXperiments (FELIX), with which radiation in the range between 3 μm and 3 mm will be generated. Among our research objectives are (i) rapid tunability and (ii) mode reduction by means of an intracavity etalon. The first stage of the project deals with generation of radiation with a wavelength between (at least) 8 and 80 μm ; the undulator of the former UK-FEL project will be used in this stage. The design of the accelerator, with which 70-A, 3-ps bunches are accelerated to a maximum energy of 45 MeV, is presented. It consists of a triode, a 4-MeV buncher, and two travelling-wave linac structures. Gain calculations leading to the best choice for the number of undulator periods are discussed.

CLIO: COLLABORATION FOR AN INFRA-RED LASER AT ORSAY

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ABSTRACT :

The CLIO collaboration has started in 1986 in order to build an infra-red laser at LURE at Orsay. It includes the design and construction of a new FEL dedicated RF linear accelerator. The goal is to make a broadly tunable laser (at least in the range 2-20 μm), of high peak power (MWatt range), and "medium" average power (a few tens of Watts). It will be utilized as a "user facility" as well as for FEL fundamental studies.

The linac uses a gridded dispenser cathode gun, a 500 MHz pre-buncher, a fundamental buncher and one accelerating section powered by a 3 GHz klystron (with 12 μs long pulses). The final energy will be adjustable between 30 and 75 MeV. The desired characteristics are : peak current > 50 A, total energy spread $\approx 1\%$, normalized emittance < 150 $\pi\text{mm.mrad}$. The numerical simulations made with PARMELA indicate that these performances will be reached with an emittance better by a factor of 2 to 4. The accelerator is followed by an achromatic and nearly isochronous 60° bend. It will allow to select the particles within a given energy spread, before the undulator, and to analyse, with respect with time, their energy distribution after the undulator.

The optical cavity is 4.8 m long (32 nsec roundtrip time), compatible with the laser risetime (typically 100 passes) and the klystron pulse length of 12 μs . The undulator is made of 2 independently adjustable identical parts, 0.96m long (24x4 cm) each, the second one can be tapered. This will allow to optimize both the optical gain and energy extraction at different wavelengths. The laser is scheduled to operate by the end of 1990.

TIME-RESOLVED SPECTRAL MEASUREMENTS FOR THE BOEING FREE-ELECTRON
LASER EXPERIMENTS

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Abstract

The operations of a RF-Linac-driven Free-Electron Laser (FEL) in the visible portion of the spectrum provides the opportunity to measure the time evolution of the spectral output on both the macropulse (50-100 μ s) and micropulse (10-ps) timescales. Such information can be used both to optimize the FEL performance and to provide tests for modeling efforts on electron-photon interactions.

A time-resolved spectrometer based on the integration of a versatile streak camera and a Jarrel Ash 1/4-m spectrometer has been proposed by Los Alamos and integrated into the Boeing FEL Burst Mode experiment in collaboration with Boeing staff. The streak camera can be operated with a fast-sweep plug-in to provide 2 to 5-ps resolution or a slow-sweep plug-in that has a time coverage of up to 600 μ s. The electron-beam properties of the Boeing FEL are 110-MeV energy, 80 to 130- μ s macropulse, 10-ps micropulse, and 258-ns micropulse spacing. The streak camera can, thus, address the time regimes of interest. The Jarrel Ash 1/4-m spectrometer offers two gratings of different blaze and groove spacing. Initial calibrations with a Hg light source have shown that a span of 90 nm with 2 to 3-nm resolution or a span of 20 nm with about 1-nm resolution (first order, high groove

number) are available when the dispersed spectrum is directed onto the entrance slit of the streak camera.

Preliminary results include the following:

- (1) Observation of the spontaneous emission micropulse duration with electron beam bunched (8-10 ps)
- (2) Observation of the spontaneous emission micropulse duration with electron beam debunched (~16 ps)
- (3) Observation of the lasing micropulse duration (8-10 ps)
- (4) Observations of the FEL spectral output in a micropulse
 - (a) single wavelength
 - (b) two wavelengths at same time
 - (c) two wavelengths with 8-ps time difference
- (5) Observation of the FEL spectral output during a macropulse (6-, 30-, and 60- μ s coverage)
 - (a) single wavelength (to resolution limit)
 - (b) two distinct wavelengths (probably not sidebands)

throughout the latter portion of the macropulse

We believe that the micropulse measurements of Item 4 may be the first ever achieved on a FEL. Also, the macropulse measurements can provide an ideal diagnostic for detection of sidebands since they should develop after high powers are attained in the cavity. These results will be compared to complementary diagnostic information, as available.

GENERATION OF INTENSE, COHERENT VUV RADIATION
WITH HIGH-GAIN FELS AND NON-LINEAR OPTICAL TECHNIQUES*

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Abstract

We discuss methods of generating intense, tunable, coherent VUV radiation between 1000 and 300Å through combined use of high-gain FEL amplifiers and optical harmonic generation techniques. For a concrete example, we consider a high-gain FEL in the bypass that has been considered for the Advanced Light Source -- a 1.5 GeV synchrotron radiation facility under construction at Lawrence Berkeley Laboratory. With the ring operating at 750 MeV, the single-pass gain with a suitable undulator will be about one thousand for wavelengths between 1000 and 700Å, and higher at longer wavelengths. At these wavelengths, several kilowatts of coherent radiation can be produced using harmonic generation, four wave mixing, and pulse shortening techniques. With this as the input, several megawatts of coherent power will appear at the output end of the FEL. For shorter wavelengths, down to 300Å, non-linear optical techniques can convert the FEL output to several kilowatts of coherent power.

*This work is supported by the Office of Basic Energy Sciences of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Gyrotron-Powered Electromagnetic
Wigglers for Compact Free-Electron Lasers

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An experimental and theoretical investigation of the application of high-power gyrotrons for the generation of intense electromagnetic waves for use as wigglers in free-electron lasers will be presented. The use of high frequency EM wigglers (100-300 GHz) can substantially reduce the electron beam energy required for FEL operation at a given frequency, thus resulting in compact low-voltage FEL systems capable of operating in the infrared and visible regions of the spectrum. A series of experiments on a 130 GHz standing wave electromagnetic wiggler have been carried out at MIT. In the 130 GHz wiggler experiment, EM wiggler fields of field strength $a_w = 0.003$ have been obtained experimentally, as compared with the design value of $a_w = 0.008$. A second set of experiments will employ a higher power electron beam and wiggler field strengths of $a_w = 0.05 - 0.1$ should be achievable. Details of the experimental results will be presented. Theoretical work on EM wiggler pumped FELs will also be described.

This work is supported by the U.S. Department of Energy, San Francisco Office.

EXPERIMENTAL STUDY OF THE INTERACTION OF AN ELECTRON BEAM WITH THE PONDEROMOTIVE POTENTIAL OF LASER BEATS

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June 29, 1988

Abstract

An experimental setup in which a non relativistic electron beam interacts with the ponderomotive potential of two counter-propagating pulsed CO_2 laser beams, operating at different frequencies in a stimulated Compton scattering scheme, was used to investigate various interaction phenomena. The effect of several test parameters on electron trapping and phase area displacement was inspected using a scheme in which electron trapping was achieved by applying a strong abrupt axial DC field along their path. This field is superimposed on a weak axial DC field that is used to separate the trapped electrons from the untrapped ones. In this scheme the effect of the ponderomotive and axial field strengths on the amount of energy exchange between the electrons and the field, and on the fraction of electrons affected was experimentally acquired. The effect of the temporal variation of the laser fields on the interaction was studied using a scheme in which an electron beam intersects the laser beam fields at a small and varying angle. In this scheme the spatial variation of the ponderomotive field resulting from the intersection is seen by the moving electron as a temporal variation of the field. The results of all these tests were processed and compared to the theory, and then used to build a mathematical model that describes the test environment as closely as possible. This model was later applied in a computer program that predicts the collected current from the interacting electron beam after being passed through a low potential drift tube. In the majority of cases these predictions are identical to the ones measured.

DEVELOPMENT OF A 10-METER WEDGED-POLE UNDULATOR*

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A 10-meter rare-earth permanent magnet hybrid undulator [1] called NISUS (Near-Infrared Scalable Undulator System) is under construction at Spectra Technology for use in the Boeing FEL program series. The design was optimized for operation at a 1 micron wavelength with the Boeing accelerator parameters. A remotely-adjustable compound taper is utilized to achieve optimum startup gain and high saturated extraction. A major goal was to build NISUS from modules which would allow easy scaling to longer lengths without redesign. Prototype tests for verification of field strength and quality are complete with initial module deliveries expected in the fall of 1988.

Improvements relative to the technology used in the earlier tapered hybrid undulator (THUNDER) [2] will be highlighted. The wedged-pole configuration [3] is employed for a major increase in field strength while operating the poles farther from saturation. The new magnetic structure is seamless to eliminate the drift spaces used to accommodate steering stations in THUNDER. This simplifies construction since careful tuning of the drift length to eliminate phase slippage is no longer needed. An important development is the finding that magnetic field errors can be substantially reduced using thin iron shims attached to the permanent magnets. A shimming algorithm has been demonstrated which allows arbitrary dipole steering errors to be redistributed into a constant dipole error. This residual uniform steering error can be easily canceled with an applied bias field. Steering correction is provided in NISUS by an efficient distributed coil system which is mounted directly on the vacuum chamber. Primary e-beam focusing is supplied by canted poles with focusing trim provided by the same steering coils.

* This work was supported in part by the U.S. Army Strategic Defense Command through Boeing Aerospace Company contracts GR5166 and GT8052.

- [1] K. Halbach, J. de Physique (Paris) 44, C1-211 (1983).
- [2] K.E. Robinson, D.C. Quimby, and J.M. Slater, IEEE J. Quantum Electron. QE-23, 1497 (1987).
- [3] D.C. Quimby and A.L. Pindroh, Rev. Sci. Instr. 58, 339 (1987).

RECENT RESULTS ON THE ORBITRON MASER*

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(With Fred Dyer and Mark Rader)

Recent results include the steady-state operation on the Orbitron Maser, both in the vacuum and the gas-filled mode. In both modes, the emission consists of a spectrum of narrow lines. These lines do not shift in location as the voltage, current, or gas pressure is varied. However, the amplitude of an individual line can vary as a function of the above parameters. The highest frequency observed always lies below the cut-off frequency as computed by orbit theory. In the gas-filled tube, electron bombardment causes the anode wire to become incandescent, suggesting that the wire is at a considerable positive potential relative to the plasma. All these observations support the orbit model of microwave emission, at least in our experiments.

* Work supported by the Air Force Office of Scientific Research under Contract #86-0100.

MODEL OF PASSIVE WAVEGUIDE FOR FEL

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It was shown, that within the Kirchhoff diffraction theory a periodic system of lenses with central holes may guide radiation beams with very small losses (#). This may be an attractive property for application in the FEL as such waveguide does not obstacle the electron beam. This passive waveguide may be an alternative to active guidance by wiggling electron beam.

In (#) only the radiation field in the lenses' planes was derived. Solving numerically the Helmholtz equation we get the radiation in the space between lenses. We establish the phase velocity distribution which is an important quantity for the FEL.

In addition to the discrete system of lenses we investigate hollow dielectric waveguides with transverse gradient of the refraction index. Preliminary analysis shows that a confinement of radiation in the hole, similar as for lenses, is possible.

#. W. Zakowicz, A. Błędowski, will be published in Journal of Applied Physics.

OPTICALLY-PUMPED FREE-ELECTRON LASER WITH
ELECTROSTATIC REACCELERATION*

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ABSTRACT

A numerical model of a two-stage free-electron laser (FEL) was developed that considers optical pumping and time-dependent electrostatic acceleration in the laser interaction region. Analytical solutions were obtained in weak- and strong-signal limits that provide confidence in the predictions of the numerical model. The validated model predicts attractive FEL performance when a Van de Graff accelerator is used as the electron source for the proposed two-stage concept. Although the model neglects diffraction, three-dimensional, and collective effects, their inclusion would not be expected to change the general conclusions reached in our study.

*presented at the Fifth International Symposium of the Soc. of
Photo-Optical and Instrumentation Engineers, San Diego, 9-13 Sept.
1984.

SMITH-PURCELL AMPLIFIER IN A REGIME OF EXPONENTIAL GAIN

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ABSTRACT

When an electromagnetic (EM) wave impinges on an open periodic structure, it is scattered into a manifold of harmonics, which are propagating along the structure but are either decaying (evanescent waves) or propagating in the direction perpendicular to the periodicity surface. The phase velocity of evanescent harmonics is smaller than c . Therefore a beam of electrons whose average velocity is close to one of these harmonics (synchronous) can exchange energy with it. In this process, the amplitude of the synchronous harmonic is changed. This change can be understood as a new wave impinging on the grating; and the latter scatters it into the entire manifold of harmonics, including the synchronous one; this process may go on and on. This process can be formulated in terms of the reflection matrix of the periodic structure, when calculating the response function of the system when working as an amplifier. The expression which describes this process in the response function also determines its poles. To carry out the poles analysis, it is necessary to know the reflection matrix explicitly and this is generally very difficult. Nevertheless the properties of the response function near the poles, can be roughly estimated, since they are determined by a *single* component of the reflection matrix, namely, the one which corresponds to the reflection of the synchronous wave into itself. Assuming that our surface supports the propagation of this evanescent wave, it is shown that the dispersion equation is analogous to the one which corresponds to a similar wave supported by another open slow wave structure, namely, a dielectric slab placed above an high conductivity surface. Its electric and geometric parameters are chosen, in such a way, that it supports the same kind of wave. It is found that one of the poles corresponds to an exponential gain; the necessary conditions for this regime to develop are discussed. Within the limits of this model we find the dependence of these poles on the beam thickness and height.

BREMSSTRAHLUNG RADIATION EFFECTS IN RARE EARTH PERMANENT MAGNETS

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ABSTRACT

Advances in rare earth permanent magnet (REPM) technology have made possible new applications. Two such applications are the use of permanent magnetic lenses for accelerator and beam transport systems and the expanding use in undulators and wigglers of synchrotron radiation and free electron laser systems. Both applications involve potential exposure of REPM's to high radiation fields.

We have investigated the radiation hardness of several different varieties of REPM's up to 2 Giga rads of absorbed dose from a mixed electron-photon field. $\text{Sm}_2\text{Co}_{17}$, $\text{Nd}_2\text{Fe}_{14}\text{B}$ and an experimental REPM, $\text{Pr}_{15}\text{Fe}_{79}\text{B}_6$, from several different manufacturers have been investigated. Of the samples irradiated, $\text{Sm}_2\text{Co}_{17}$ proved to be the most resistant to bremsstrahlung radiation. However, details of manufacturing techniques produced significantly different results. We observed that REPM's of nominally identical stoichiometric composition from different manufacturers did not show the same rate of remanence loss.

We present details of our experiment and absorbed dose modeling and a summary of radiation effects measurements of which we are aware. Our study of these radiation damage experiments lead us to the empirical observation that the order of radiation hardness is $\text{Sm}_2\text{Co}_{17}$, SmCo_5 and $\text{Nd}_2\text{Fe}_{14}\text{B}$, regardless of the source of radiation, i.e., gammas, electrons, protons or neutrons.

OUTPUT POWER IN GUIDED MODES FOR AMPLIFIED SPONTANEOUS EMISSION
IN A SINGLE PASS FREE ELECTRON LASER --- 3D TREATMENT INCLUDING THE EFFECT
DUE TO BETATRON OSCILLATION*

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ABSTRACT

We use a dispersion relation derived from the Vlasov-Maxwell equations to study the three-dimensional initial value problem determining the start-up of a single-pass free electron laser from shot noise in the electron beam, including the diffraction effect and the effect of betatron oscillations on the gain of guided mode in a free electron laser operating in the high gain regime before saturation.

Our solution of the initial value problem is based upon a Green's-function technique, and our results are derived despite the lack of orthogonality and completeness of the guided modes. The Green's function is expanded in terms of an orthonormal set of eigenfunctions of a two-dimensional Schrodinger equation with nonselfadjoint Hamiltonian. The output power is then determined with use of the Green's function.

Using perturbation theory and assuming the betatron oscillation phase advance in one gain length is small, we derived the gain reduction formula due to the transverse phase variation of the electromagnetic wave, i.e. the electrons interact with the electromagnetic field at different transverse phases when they are at different transverse position, even if their longitudinal coordinate are the same.

*Work performed under the auspices of the U.S. Department of Energy.

The effects of diffraction, waveguide, and density nonuniformities on the FEL interaction

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Abstract

Analytic expression for the gain and for the transverse wave profiles in the free electron laser (FEL) are presented for the opposite asymptotic limits of strong optical guiding and large diffraction, in both the strong-pump and the Raman regimes. Scaling laws are derived which express the gain reduction due to diffraction losses. The diffraction losses depend on the shape of the electron beam and the gain scales differently for a cylindrical beam and for a sheet beam. We also examine the influence of transverse density nonuniformities on the gain. In the Raman regime, when the density gradients are large, the gain is expressed as a sum of contributions from individual resonant layers, where each such contribution is inversely proportional to the density gradient at the respective resonant layer. A different scaling is obtained if the density gradient vanishes at the resonant layer. Also studied is an FEL where the electron beam propagates along the axis of a waveguide. A dispersion relation is derived and analytic expression for the wave transverse profile is obtained. It is shown that the FEL interaction couples the waveguide modes and there are no pure TE or TM modes.

Three Dimensional Theory for Raman FELs

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ABSTRACT

In this talk we present a linear three-dimensional kinetic theory for FEL amplifiers that is valid in all Raman and the Compton regimes. The 3-D model is based on expansion of the Maxwell and Boltzman equations by Fourier decomposition in the t, x, y dimensions and Laplace transform in the z dimension. This leads in general to a matrix gain-dispersion relation which is solved numerically. The 3-D model is applicable to an arbitrary electron beam distribution in free-space or in a waveguide.

Wave profile modification effects due to optical guiding, and due to excitation of space-charge waves with transverse field components, are numerically analyzed using our model. The features of both effects are discussed and their relative strength are compared through exemplary parameters based on previous FEL experiments. It is shown that the space-charge fields may have a significant effect on the field profile measurement of Raman FEL and they may interfere with the measurement of the optical guiding effect.

The theoretical model includes the effect of higher odd and even harmonic interaction, due to the transverse finiteness of the FEL interaction. This effect may lead to a further modification of the fundamental harmonic profile.

This work was supported in part by the U.S. ONR contract 1-624-03-686-00.

* On leave from Tel Aviv University.

EFFECTS OF ELECTRON PREBUNCHING ON THE RADIATION GROWTH RATE
OF A COLLECTIVE (RAMAN) FREE-ELECTRON LASER AMPLIFIER*

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ABSTRACT

Experiments¹ are reported on the effects of electron prebunching in a mildly relativistic, low current (200kV, 1A) free electron laser amplifier operating in the collective (Raman) regime at a frequency of ~10GHz. Prebunching is established by injecting an electromagnetic wave into a bifilar helical wiggler and then transporting the bunched beam into a second magnetic wiggler region. The wave growth rate is deduced from measurements of the radiation intensity as a function of interaction length. Observations show that prebunching can increase the radiation growth rate manyfold as compared with a system without prebunching. Studies are presented both in the small signal (linear) regime, and in the nonlinear (saturated) regime. The experimental results are compared with computer simulations,² and analytical calculations.

¹C. Leibovitch, K. Xu, and G. Bekefi, IEEE J. Quant. Electronics (to be published, Sept. 1988).

²J. Fajans and J.S. Wurtele, IEEE J. Quant. Electronics (to be published, Sept. 1988).

*This work was supported by the National Science Foundation, the Air Force Office of Scientific Research and the Office of Naval Research.

COMPUTATION OF EMITTANCE GROWTH IN A FOCUSING WIGGLER FEL

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ABSTRACT

Computed electron trajectories in a free electron laser show significant emittance growth in the wiggle plane when there are wiggler field gradients. For a low gain free electron laser using a focusing planar wiggler, phase space plots show the development of this 3-dimensional effect as well as rotation of the phase space region occupied by the beam due to betatron oscillations in the focusing wiggler field. Matching the input electron beam to the wiggler eliminates emittance growth.

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A COMPARITIVE STUDY OF PARTICLE SIMULATION AND
LINEAR MODEL ANALYSIS OF FELIX

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ABSTRACT

For the design of FELIX [1] computer simulations are done with two different codes, G3DH and TDA, to estimate three dimensional effects in the amplification process in the undulator.

G3DH [2] solves a 3D matrix gain dispersion equation. TDA [3] is a nonlinear 3D particle simulation code. Both codes take into account energy spread and emittance of the electron beam, Rayleigh length and waist position of the EM beam, and the planar undulator form. The finite length of the electron beam micro-bunches is not considered.

The two methods to calculate the evolution of the beam profiles along the undulator will be compared. Beam guiding and other effects will be presented for various input conditions.

References:

1. P.W. v. Amersfoort et al., this conference.
2. E. Jerby, A. Gover, Proc. of the 9th FEL Conf.
3. T.-M. Tran, J.S. Wurtele, unpublished.

ACCELERATION OF PARTICLES DUE TO LASER-PLASMA INTERACTIONS
IN AN INVERSE FREE-ELECTRON LASER*

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ABSTRACT

An interesting variant of the beat-wave acceleration mechanism has been proposed by Bobin¹. The essential idea is to couple the beat wave generated by a laser and the wiggler (which in the electron beam frame appears to be an electromagnetic wave) to the plasma oscillations generated by the electron beam streaming through a plasma. The longitudinal electric field thus produced is expected to enhance greatly the accelerating capabilities of the inverse free-electron laser (IFEL). We have undertaken a detailed theoretical analysis of the proposed acceleration scheme, with due attention to the instabilities caused by the beam-plasma interactions. We develop fluid equations in the beam frame, and calculate growth rates and saturation amplitudes for the plasma instabilities. Since the saturation amplitude for the electric field in the original calculation is taken to be due to relativistic effects which detunes the beating waves, it is important to choose the plasma density in such a way that the beat wave is the only wave that grows to saturation. Due attention will also be given to the radiation generated by beam-plasma interactions, and the evolution of particle distribution functions.

* This work is supported by the U.S. Office of Naval Research, Grant No. N0014-796-0769, and the Department of Energy

¹ J. L. Bobin, Optics Comm. 55, 413 (1985)

QUASI-LINEAR ANALYSIS OF A SMITH-PURCELL FREE ELECTRON AMPLIFIER

by

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Abstract

We present an analysis of a Smith-Purcell Free Electron Amplifier. The study is based on a scheme known as the quasi-linear theory which enables us to consider non-linear effects. The model consists of a non-relativistic electron beam which moves above a corrugated periodic structure. An electromagnetic wave is incident on the combined system. The wave is reflected from the structure and a manifold of radiating and evanescent waves is generated. One evanescent mode which is synchronous with the velocity of the beam, interacts with the electrons and can be amplified. The amplified wave is scattered from the structure, thus the radiating waves are also amplified. Expressions for the gain of the device and the form of the radiating waves are obtained. The interaction with the wave alters the characteristics of the beam. We find a non-linear diffusion equation to describe these changes, and analyse their effects on the gain of the device. It is shown that in the non-linear regime the gain depends both on the first and second derivatives of the velocity distribution function.

NEW PHOTOELECTRIC INJECTOR DESIGN FOR THE LOS ALAMOS
NATIONAL LABORATORY XUV FEL ACCELERATOR*

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ABSTRACT

The injector for the Los Alamos National Laboratory XUV FEL accelerator has been redesigned in order to provide more charge to the wiggler. The new design can deliver 8 nC of charge within 20 ps with a normalized 90% emittance of < 25 n-mm-mrad to the wiggler at an energy of 200 MeV. In addition to the new design of the injector, we analyze the emittance growth and subsequent reduction through the injector, including the different mechanisms for emittance growth and the methods used to eliminate the correlated emittance.

*Work supported by the Division of Advanced Energy Projects of the US Dept. of Energy, Office of Basic Energy Science, and the Los Alamos National Laboratory.

OPTIMIZATION OF THE OPTICAL KLYSTRON DOMINO FOR THE SUPER-ACO STORAGE RING FEL

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ABSTRACT

The permanent magnet optical klystron DOMINO is composed of two undulators separated by a dispersive section, which gaps can be moved separately. Each undulator is constituted by 10 periods of 12,9cm long, the maximum peak magnetic field is 0,48T providing a K value of 5,75.

Two kinds of magnetic measurements are available: Hall probe and turning coils; and they were employed together or successively, depending on the element to be measured. The optimization of the optical klystron was done gradually: the magnets, the pairs, the periods, the dispersive section, the undulators were studied separately. A constant relationship was established between the measurements and the previsions from the pairing.

The optimization of the trajectory can be done by adjustable side magnets. The final measurements on the three elements of the optical klystron allowed us to predict the effect on the new Storage Ring set-up at Orsay, Super-ACO, which was in good agreement with the experimental values.

The spontaneous emission of the Optical Klystron has been studied experimentally on Super-ACO (which nominal energy is 800 MeV). The obtained modulation rate of the characteristic interference pattern of the optical klystron is lowered by the positrons energy dispersion and some angular effects, as predicted by the theory, but it is not affected by the small residual imperfections of the magnetic field. Therefore, appreciable FEL gain (even more than 10%) in the visible and UV spectral ranges can be expected.

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PULSE QUALITY OPTIMIZATION ON A
LINEAR INDUCTION ACCELERATOR TEST STAND

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In recent years, induction linear accelerators became increasingly attractive for various applications such as radiation processing, radiography and drivers of free electron lasers. For the FEL application, the quality of the accelerated electron beam-characterized principally by its brightness and energy regulation is of great importance. To obtain efficient extraction in the wiggler of a free electron laser, the accelerating voltage waveform as seen by the electron beam should have a flat top with a negligible voltage variation.

An induction linac module test stand was developed at Maxwell Laboratories. The test stand includes a high voltage pulse power driver capable of driving high pulse quality low impedance electrical pulses in the 100 to 400 kV range with a 100 ns pulse width. The driver uses a combination of a Marx generator, water Blumleins and a switch and is capable of driving a few induction cells. The induction cell is designed mechanically to allow a simple assembly processes and to ensure high mechanical accuracies which are imperative for high quality electron beam acceleration.

A model for predicting propagation of electrical pulses into induction modules was developed by Maxwell. This model takes into account the non-linear behavior of magnetic core materials. This model is used to optimize the pulse quality applied to the beam in the accelerating gap of the induction cell. Measurements of electrical pulse propagation along different sections of the pulse power system and into the induction cell will be presented and compared to theoretical predictions.

HIGH-EXTRACTION EFFICIENCY EXPERIMENTS WITH THE LOS ALAMOS FREE-ELECTRON LASER*

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ABSTRACT

Recently the injector, RF power system, wakefield effects in the beam transport, and cavity optics of the Los Alamos free-electron laser system have significantly improved. As a result of these improvements, the experimental performance of our uniform period wiggler and the experimental results of cavity-length detuning are in reasonable agreement with theory.

In this paper we report on experiments to determine the results of these improvements on extraction efficiency. The experiments used wigglers with 12% and 30% wavelength taper. Measurements were made with and without a prebuncher, and with sideband suppression using both cavity-length detuning and with a Littrow grating. The prebuncher was a short (three-period) wiggler in front of the primary wiggler. It is designed to optimize the capture of electrons at the entrance of the wiggler to enhance its efficiency.

*Work supported and funded by the US Department of Defense, Army Strategic Defense Command, under the auspices of the US Department of Energy.

Characterization of Undulator Radiation for a Non Synchronized Low Emittance Beam*

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For a low emittance beam ($\epsilon < \lambda$), the undulator radiation can be best characterized by the Wigner Distribution of the electromagnetic field:

$$W(x, k_x) \equiv \int d\chi \tilde{E}\left(x + \frac{\chi}{2}\right) \cdot \tilde{E}\left(x - \frac{\chi}{2}\right) e^{ik_x \chi}$$

where $\tilde{E}$ is the electric field phasor.

This distribution shows both the spatial and the angular distribution of the radiation. Earlier work was done by K.J. Kim to calculate numerically the W.D. undulator radiation for an on-axis synchronized electron beam:

$$\frac{\omega}{v_z} - \frac{\omega}{c} - \frac{2\pi}{\lambda w} = 0.$$

The calculation of the W.D. in that work relied on a paraxial approximation. By contrast the work reported in the present paper is based on an exact solution of the Maxwell equations and therefore is applicable also for an electron beam which is not synchronized on axis and its radiation is not concentrated around the axis ($x = 0, k_x = 0$).

A highly vectorized computer code that calculates the exact W.D. was written by the authors, and the results are animated and shown in this computer paper.

*This work is supported in part by ONR contract #N00014-87-C-0362.

Optical Guiding by a Cylindrical Electron Beam in a Waveguide

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Abstract

Optical guiding in an FEL which employs a cylindrical electron beam, a cylindrical waveguide and a helical wiggler is studied. We consider a small-signal, high-gain FEL which operates in the collective ("Raman") regime. We derive an analytical dispersion relation and find the eigenvalues and the actual eigenmodes of the system. The radial profile of the electromagnetic wave is modified by the FEL interaction and the wave is more confined to the electron beam. It is shown that the FEL interaction couples the waveguide modes. In contrast to vacuum waveguide modes, the eigenmodes of the FEL in the waveguide are not pure TE or TM modes and the axial components of both the electric and the magnetic fields of the wave are non zero.

FREE-ELECTRON LASER WITH LASER UNDULATOR

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ABSTRACT

The Max-Planck-Institute for Quantum Optics is planning an experimental program to investigate a free-electron laser for the xuv and soft x-ray regime which employs a laser pulse as the undulator. This concept only requires a fairly small accelerator (< 10 MeV) which, on the other hand, must provide an extremely high-quality electron beam. Due to recent progress in building compact and efficient high-power infrared lasers for very short pulses (for example, Nd-lasers with 1 ps and 1 TW), the entire soft x-ray FEL would be rather compact.

Theoretical results for an FEL with electromagnetic-wave undulator will be presented, including examples for the required parameters of the single FEL components. Special attention will be drawn to effects which originate from the focusing of the undulator pulse, as well as to quantum effects.

A laser undulator would not only allow a compact, short-wavelength FEL, but would also be a means of generating intense monochromatic (spontaneous) gamma radiation. A possible application of this radiation could be the detection of some of the most elusive effects predicted by relativistic quantum electrodynamics: electron-positron pair creation by light and the scattering of light by light. The cross section of photon-photon scattering is the largest for photon energies in the order of 1 MeV. Radiation of this energy could, for example, be generated by an electron beam of about 130 MeV and an undulator pulse generated by an FEL which is driven by the same electron beam.

INTEGRATED NUMERICAL MODELING OF FREE-ELECTRON LASER OSCILLATORS*

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ABSTRACT

The nonideal characteristics of the electron beam have largely determined the performance of all free-electron laser (FEL) oscillators that have operated up to the present time. A realistic quantitative theoretical assessment of FEL oscillator performance must therefore include a viable representation of the electron beam's characteristics, as well as the properties of the wiggler magnet and the optical resonator. This paper presents results of integrated numerical modeling of the Los Alamos FEL oscillator, using as input to the 3-d FEL simulation code FELEX, a numerically-generated electron pulse obtained from the accelerator code PARMELA as a solution of a full model of the Los Alamos accelerator system (electron gun, accelerator cavities, and beam transport line).

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

PROPOSAL FOR A X-BAND SINGLE-STAGE FEL

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ABSTRACT

A single stage X-band FEL with a high repetition rate ($\sim$ KHz) has been designed and is now under construction at the KEK FEL facility. The microwave FEL will be driven with a kiloamp electron beam of 1 MeV which is generated in the induction gun energized by a pulsed power system employing magnetic switches. A 9.4 GHz microwave signal introduced from the 50 KW magnetron is expected to be amplified to $\sim$ 300 MW as a result of interaction with the above electron beam of quiver motion caused by the tapered planar wiggler field. Detail of the design including the induction gun, post accelerator, wiggler magnet and RF measuring system are described. Status of preliminary operation of the pulsed power system are presented.

**A PROPOSED LINAC CAVITY RF DRIVE SYSTEM FOR THE LOS ALAMOS
EXTREME ULTRAVIOLET FREE-ELECTRON LASER***

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ABSTRACT

Since 1979, scientists and engineers at the Los Alamos National Laboratory have designed, constructed, and operated a radio frequency-linac Free-Electron laser (FEL) at wavelengths from 9 - 45 μm . Coupled with the success of other research centers investigating wavelengths from the visible to far-infrared, Los Alamos is now proposing a vacuum-ultraviolet and soft x-ray (referred to henceforth as extreme ultraviolet, XUV) FEL oscillator/Self-Amplified Spontaneous Emission amplifier with beam energies ranging from 100 MeV to 1 GeV.

This report shall focus on the first milestone of the proposed Los Alamos XUV project, i. e., a 250-MeV linac with approximately 30-mA average current, producing photons with wavelengths below 1000 Å. Additionally, the type of modulator for the klystrons and its subsequent effects on the accelerator field phase and amplitude control module shall be described.

*This work was performed with Los Alamos National Laboratory Institutional Research and Development Support of the U. S. Department of Energy.

INDUCTION LINAC BASED FREE-ELECTRON LASER AMPLIFIER FOR FUSION APPLICATIONS *

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Abstract

We describe an induction linac based free-electron laser (FEL) amplifier design for producing multi-megawatt levels of microwave power for electron cyclotron resonance heating of tokamak fusion devices such as the Compact Ignition Tokamak (CIT) or the International Thermonuclear Experimental Reactor (ITER). The wiggler design strategy incorporates a tapering algorithm suitable for FEL systems with moderate space charge effects and minimizes spontaneous noise growth at frequencies below the fundamental, while enhancing the growth of the signal at the fundamental. In addition, engineering design considerations of the waveguide wall loading and electron beam fill factor in the waveguide set limits on the waveguide dimensions, the wiggler magnet gap spacing, the wiggler period and the minimum magnetic field strength in the tapered region of the wiggler. This FEL is designed to produce an average power of about 10 MW at frequencies in the range from 280 GHz to 560 GHz. The achievement of this average power at a reasonable cost requires a high duty factor which affects some of the component design. In addition, the desire to obtain a high extraction efficiency pushes the beam energy up and requires magnetic field strengths in the wiggler that are near or possibly larger than the Halbach limit. Several wiggler configurations were studied including those using superconducting coils. It was found that the Halbach limit could be exceeded in all cases considered, but the complexity of the design changed with coil current density and the maximum saturation field allowed in the pole material. The baseline design for the electron beam transport uses an Enge magnet to turn the beam out of the microwave line of sight. At the high duty factor, the average current is large and a rotating graphite absorber is used to collect and remove the energy from the e-beam. The basic design of these components and the calculations which define the baseline FEL design will be discussed.

* Work performed under the auspices of the US Department of Energy by the Lawrence Livermore National Laboratory under W-7405-ENG-48.

LINAC FOR A FREE ELECTRON LASER OSCILLATOR

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Further reconsiderations on the main parameters of the linac, taking the cost-performance optimization into account lead to;

- 1) As a main part of the accelerator, two units of 508MHz five-cell super-conducting array cavities, contained in one cryostat will be adopted, which is the same one as used in the Main Ring(MR) of TRISTAN(KEK).
- 2) The injector system consists of;
 - a) a 300kV D.C.(or>1ms, 10Hz pulse) thermoelectron gun with the net cathode diameter of 2mm and the grid which is pulsed of 2ns(micro-pulse) width, in separation of 80 ns during 1ms(macro-pulse) width.
 - b) a normal conducting 127MHz(1/4 of fundamental frequency) subharmonic and a harmonic buncher with the adequate space separation(6~10m).
 - c) two super-conducting single cavity pre-accelerators, the former one of which is so designed that its β is less than 1(~0.9).
- 3) Solid-state RF power amplifiers will preferably be used, since less RF power is required for the main accelerator(s) in an energy-recovery system (Phase-2 and 3).

Detailed design study is in progress.

INVESTIGATION OF THE FREE-ELECTRON LASER INSTABILITY IN
CURVILINEAR GEOMETRY

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ABSTRACT

The fundamental relationship defining the wavelength of a free-electron laser is a statement of equality between the electron velocity and the phase velocity of the beating between the amplified electromagnetic wave and the static wiggler field. Shorter wavelengths are reached either by increasing the electron energy, which is known to result in a steep gain decrease, or by lowering the phase velocity of the electromagnetic wave, for example through propagation in a gas with a refraction index slightly greater than one¹.

In this work, I study the effect of the phase velocity decrease which is obtained by vacuum propagation of a cylindrical electromagnetic mode², below critical radius, in the case of cylindrically symmetric electron beam and wiggler. A first, order of magnitude, estimate shows that the transverse variations of all physical quantities must be explicitly taken into account in order to be able to use a realistic value of the beam width. This calculation is presented in the second part of the paper.

¹ J. Feinstein *et al*, Phys. Rev. Lett. 60, 18 (1988).

² O. Larroche and R. Pellat, Phys. Rev. Lett. 59, 1104 (1987).

HARMONIC COMPETITION IN A TAPERED FEL AMPLIFIER*

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ABSTRACT

It is known that in an FEL the generation of harmonics of the radiation field is possible. Harmonic generation in an FEL with a linearly polarized wiggler is particularly pronounced. A set of reduced, non-linear equations has been derived to describe the competition among harmonics in a tapered FEL. The effect of space charge has also been included. A numerical code has been developed to solve these equations. We will present our study of the distribution of the radiated power among the different harmonics as the input electromagnetic wave is amplified.

* Work supported by US SDIO

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PROPOSED EXTENDED TUNING RANGE FOR THE LOS ALAMOS MID-INFRARED
ADJUSTABLE, COHERENT LIGHT EXPERIMENT (MIRACLE) FACILITY

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ABSTRACT

The Los Alamos Free-Electron Laser Facility (FEL) has been in operation as an oscillator in the 10- μm wavelength regime since 1983. Our efforts have been concentrated on high power operations, although tunability had been demonstrated from 9 to 35 μm previously. A projected extension of this range from 3 μm to 160 μm would provide a needed complement to the existing FEL applications research facilities in the U.S. that operate in the visible, (Stanford SCA), the few micron (Stanford), and the sub-millimeter regimes (U. C., Santa Barbara).

Recently, we re-demonstrated the tunability of the Mid-Infrared Adjustable, Coherent Light Experiment (MIRACLE) Facility and extended our operations to 45 μm . We used copper mirrors with a 1-mm-diameter outcoupling hole in one of the mirrors. The present ZnSe windows (λ cut off at 22 μm) on the end of the cavity and the Hg:Ge detector (sensitivity to 15 μm) constrained our experiment. We therefore relied on detection of the first, second, and/or third harmonics of the FEL output as we varied the electron beam energy. Extraction of energy from the electron-beam was monitored on our electron spectrometer as well as by the optical measurements.

We propose to change the cavity window to allow longer wavelength transmission (diamond is one candidate), obtain a zinc or

copper-doped Germanium detector for extended wavelength coverage, and modify our IR spectrometer for operations at the longer wavelengths. We would then tune to longer wavelengths and ultimately establish an optical path up to the user laboratory.

Potential applications in material science and medical physics for this wavelength regime will be addressed.

MONOCHROMATIC X-RAY EMISSION BY A FULLY IONIZED HYDROGEN PLASMA

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A B S T R A C T

Subnanosecond emission phenomena of high energy particle beams, nonthermal infrared and microwave emission as well as anisotropic soft x-rays have been studied at a modified 1kJ Mather type plasma focus device. Using hydrogen gas, a high density plasma of nearly cylindrical shape is produced. The onset of a hydrodynamical instability of the $m = 0$ type leads to a final radius of $r \approx 50 \mu\text{m}$ and a length of $l = 500 \mu\text{m}$, through which a current of $I = 200 \text{ kA}$ is enforced by the external electrical circuit. As the electron drift energy in this phase is about 800 eV and the temperature is about 20 eV, the plasma is far beyond thermal equilibrium. The further evolution is determined by the onset of microinstabilities which modulate the plasma density periodically. According to a particle-wave interaction, electrons and ions are accelerated to energies beyond 1 MeV. The emission time of the beams is 300 ps. The electron beam is emitted in pulses with a pulse period of about 10 to 30 ps and a pulse width in the range of 1 to 3 ps. The energy spectrum of the ion beam reaching up to 3.5 MeV, shows regular fine structures with half widths of less than 5 keV. Simultaneously, the emission of anisotropic soft x-rays with a wavelength of about $\lambda = 1 \text{ nm}$ into a cone angle $\theta = 0.2$ is observed. The narrow relative line width $\Delta\lambda/\lambda = 2 \cdot 10^{-3}$, indicates a temporarily coherent emission of X-radiation by the fully ionized Hydrogen plasma. Assuming a process similar to an FEL as generation mechanism of the soft x-rays, the period length of the periodical density structure and the relativistic factor γ of the electron beam were determined as $\Lambda = 17 \text{ nm}$ and $1 < \gamma < 4$, by measuring the wavelength λ of the x-radiation and the cone angle θ . The selforganization of the plasma is theoretically described as three-wave coupling in a beam plasma system. The measured data are in agreement with the plasma parameters, indicating that the occurrence of the plasma modulation is due to a cyclotron-driftinstability.

THREE-DIMENSIONAL MODELING OF ELECTRON BEAM TRANSPORT IN A HYBRID
STEEL-PERMANENT-MAGNET WIGGLER*

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Free electron lasers are being designed with wigglers tens of meters long that would transport beam currents on the order of a kiloampere. These lasers could be operated thousands of hours per year. A very small fraction of the electron current is expected to hit the wall of the vacuum vessel. The cumulative result of this beam spill is induced radioactivity and degradation of the magnetic properties of the steel pole pieces and permanent magnets. The objective of our work is to model the beam spill for a long steel-permanent-magnet wiggler with canted-pole pieces for wiggler-plane focusing.

The 3-D finite-element magnet design code MAGNUS was used to model the field of segments of the wiggler. A program was written to assemble these segments into a complete wiggler and graphically display the components of the assembled wiggler field. A three-dimensional electron beam transport code was used to transport electrons through the wiggler. Injection conditions for on-axis propagation in the wiggler and the amount of canting required for equal two-plane focusing of resonant electrons along the wiggler were determined. Trajectories were run to determine the conditions under which electrons would hit the wall of the vacuum tube, and the fraction of electrons hitting the wall was obtained given the nominal electron beam radius and beam emittance, assuming a gaussian distribution of electrons in the radial direction and a gaussian distribution of transverse electron velocities. Results of beam spill calculations will be presented.

*This work is supported by the U.S. Office of Naval Research and Los Alamos National Laboratory.

SIDEBAND SUPPRESSION IN THE LOS ALAMOS
FREE-ELECTRON LASER USING A LITROW GRATING

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ABSTRACT

Diffraction gratings provide a means of narrowband wavelength filtering to suppress sidebands that result from synchrotron oscillations. A Littrow grating may be used when intracavity power is low enough to allow the use of normal incidence optical elements for the resonator. The grating works by dispersing the unwanted sidebands laterally so they cannot overlap the electron beam in the center of the wiggler and experience gain. The Littrow grating is also a pulse stretcher. The optical pulse is lengthened by a wavelength of light for every "working" groove in the grating. The lengthening must be limited because of the loss in gain due to poor overlap with the electron beam. As the pulse is lengthened in time clearly the spectrum of the pulse narrows.

The accelerator for Los Alamos Free-Electron Laser (LANL FEL), operates at 20 MeV with 200-500 Amperes peak current during the 10 picosecond micropulses. The pulse repetition rate is 1 macropulse per second. The electron macropulse is adjustable up to 100 μ sec. Within the macropulse are micropulses, each 10 psec long separated by 46 nsec, the round trip time of the resonator. When used with our untapered, 1m- long wiggler, the FEL system generates light at 10 μ m with prolific sidebands that cover a wavelength range in excess of 10%.

We have used a 6 V/mm diffraction grating in a Littrow configuration to suppress the sidebands at an intracavity peak power in excess of 100 Mw. The spectrum obtained was a single sharp line of 0.3% FWHM. In a pulse 10 ps long of wavelength 10 μ m, there are about 300 cycles. The spectral bandwidth of a smooth pulse of this length is proportional to the inverse of the number of periods or about 0.3%. Thus the spectrum we observe approximates the transform of the pulse length. The resonator length could be changed and still maintain lasing without a grating for 150 μ m. With the 6 V/mm grating the resonator could be tuned over 440 μ m. The lasing frequency and the orientation of the mode depend upon cavity length in ways that will be described.

SPECTRAL AND ANGULAR DISTRIBUTION OF RADIATION FROM
ADVANCED WIGGLERS WITH SHARPLY PEAKED MAGNETIC FIELDS

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ABSTRACT

An obvious device for the production of highly collimated high frequency radiation is a wiggler with a sharply peaked magnetic field of high peak value B_0 . Such a wiggler is already operating at Novosibirsk [1], but no data on the actual radiation output are yet available. Therefore, a study of a transverse model wiggler with a magnetic field given over one half period by $B(z) = B_0 \cosh^{-2}[w(z - \frac{1}{2}\lambda_0)]e_y$ was performed, with an adjustable "width" parameter w , and the Novosibirsk values $B_0 = 1.6$ Tesla and $\lambda_0 = 0.22m$. The advantage of this choice of the magnetic field is that large portions of the analysis can be carried through analytically by continuing the integrand of the radiation integral into the complex plane, followed by an asymptotic evaluation by means of well-established asymptotic methods [2]. By virtue of their asymptotic character, increasing values of the wiggler parameter K make the calculations progressively simpler, while a purely numerical approach would be absolutely hopeless in view of K being as large as 32.9 [3]. Along the lines sketched in [2], the spectral and angular distribution of the emitted single electron signal can be efficiently calculated for various "width" parameters.

The divergence of the emitted radiation is found to agree well with the estimate $\Delta\theta \approx 4\pi K \tanh(\frac{1}{2}w\lambda_0)/(w\lambda_0\gamma)$. In addition, the approach furnishes an analytic formula for the frequency at which the emitted intensity peaks in every direction, $\omega_{\max}(w, \theta, \varphi, \gamma, B_0, \lambda_0)$. One can estimate that in storage ring operation, the consequences of the non-transverse nature of the magnetic field chosen can be left out of account due to the small electron beam diameter of these machines. The semi-analytical approach also enables one to incorporate a velocity distribution at injection, and it forms a convenient basis for performing an integration over all angles of the differential cross section.

References

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DESIGN OF A HIGH FIELD TAPERABLE HELICAL WIGGLER

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ABSTRACT

The need for a high field strength tunable and taperable helical wiggler is emphasized by the trend toward construction of increasingly higher gain Free Electron Lasers (FEL). The proposed helical wiggler is an electromagnetic device where the field strength and the taper are completely adjustable. A ferromagnetic core which provides accurate wiggling field definition is segmented into so-called helical dipoles. Unique coil and core geometry together with a careful choice of materials make it possible to produce fields over 5 kG in a bore diameter of 2.5 cm. A further increase in field strength can be achieved by inserting permanent magnets which drive the core material out of saturation. Control over excitation of the helical dipoles is used to adjust the field and to implement a steering free taper. The paper discusses theoretical as well as practical aspects of the proposed device.

WAVE PROFILE MODIFICATION OBSERVED IN A COLLECTIVE
(RAMAN) FREE ELECTRON LASER*

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ABSTRACT

Modification of the spatial electric field intensity distribution and phase of a single electromagnetic waveguide mode ($TE_{1,0}$) during free-electron laser (FEL) interaction has been measured. The studies were carried out at a microwave frequency of $\sim 10\text{GHz}$ in a FEL using a mildly relativistic electron beam of $\sim 200\text{keV}$ energy and 1-4A current. The probing of the RF-fields was accomplished by a small movable electric dipole antenna inserted in the interaction region. Substantial modification of the $TE_{1,0}$ mode occurs, in particular near and within the electron beam.

In addition, we also present measurements of the electric field and phase associated with the space charge wave of the bunched electron beam. This was carried out by means of a second movable antenna probe polarized orthogonally to the RF probe. Experiments show that the space charge electric field is zero at the electron beam center and reaches its maximum value near the beam edge, in agreement with expectations.

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Effect of dc Space-Charge Fields on Free-Electron Lasers

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Abstract

Starting from 3-D model, this paper investigates the effect of dc space-charge fields on free-electron lasers. Calculation shows an appearance of a new unstable range of the equilibrium electron orbit due to the dc space-charge fields. It is found that both FEL mode and gyrotron mode may be simulated, and dc space-charge fields make the FEL growth rate decrease and gyrotron growth rate increase.

Equilibrium Electron Orbit

According to 1 and 2, the dc space-charge fields of equilibrium e-beam, 3-D wiggler fields and guide field may be written as

$$\vec{E} = -\frac{m_0}{2e} R \omega_p^2 \hat{e}_R \quad (1)$$

$$\vec{B} = -\frac{m_0}{2e} \beta_w R \omega_p^2 \hat{e}_\theta + B_0 \hat{e}_z + 2B_w [I_1'(\lambda) \cos \lambda \hat{e}_R + \lambda^{-1} I_1(\lambda) \sin \lambda \hat{e}_\theta + I_1(\lambda) \sin \lambda \hat{e}_z] \quad (2)$$

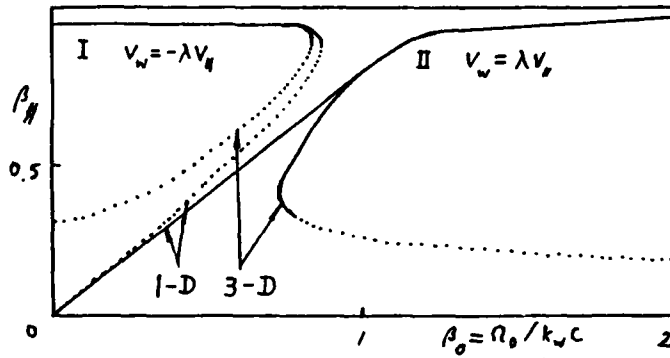
A helical orbit requires $v_1 = v_w$, $v_2 = 0$, $v_z = v_{||}$, $\chi = \pm \pi/2$ and $\lambda = \mp v_w/v_{||}$, where

$$v_w = \frac{2\Omega_w v_{||} I_1(\lambda) / \lambda + \omega_p^2 (2\gamma k_w)^{-1} (1 - \beta_w^2)}{\Omega_0 - k_w v_{||} \pm 2\Omega_w I_1(\lambda)} \quad (3)$$

Fig.1 (a) and (b) show the relations of β_w vs normalized guide field $\beta_0 = \Omega_0/k_w c$ without and with dc space-charge fields.

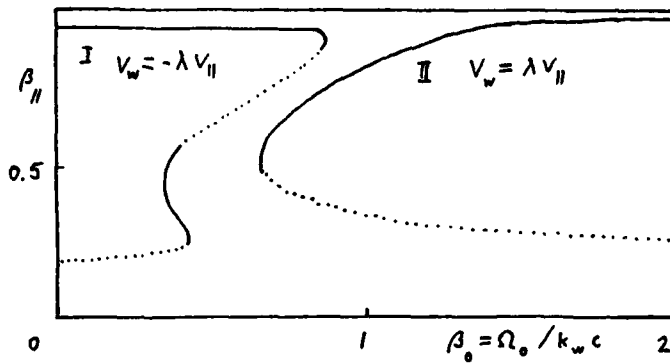
Dispersion Equation

A dispersion equation for TEMn mode is derived. Fig.2 (a) and (b) show the dispersion of TE1,1 mode without and with dc space-charge fields. It can be seen that both FEL and gyrotron modes may be simulated, and dc space-charge fields make FEL growth rate decrease and gyrotron growth rate increase, where $k_c = 2.301/\text{cm}$, $R_w = 0.8 \text{ cm}$, $k_w = 2/\text{cm}$, $\gamma_0 = 2.37$, $R_{\text{beam}} = 0.15 \text{ cm}$, $\beta_{||} = 0.75$, $B_w = 800\text{G}$, $B_0 = 8100\text{G}$ and $\omega_p = 64358 \times 10^{10} \text{ Hz}$.



(a)

Fig.1. Graph of the axial velocity versus axial guide field (a) without (b) with dc space-charge fields taken into account.



(b)

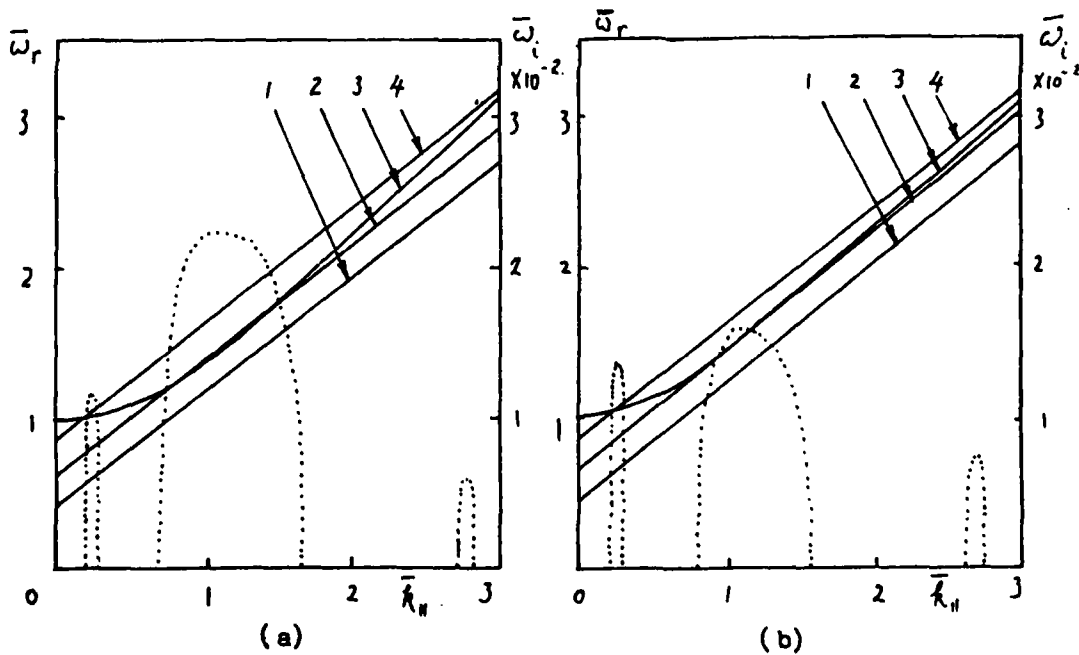


Fig.2. Dispersion relation of TE_{1,1} mode (a) without (b) with space-charge fields taken into account: 1 $\rightarrow \omega = k_{\parallel} v_{\parallel} - \Omega_0$; 2 $\rightarrow \omega = (k_{\parallel} + k_w) v_{\parallel}$; 3 $\rightarrow \omega^2 = c^2 (k_{\parallel}^2 + k_w^2)$; 4 $\rightarrow \omega = k_{\parallel} v_{\parallel} + \Omega_0$.

FREE ELECTRON LASER WITH SMALL PERIOD WIGGLER AND SHEET ELECTRON BEAM;
A STUDY OF THE FEASIBILITY OF OPERATION AT 300 GHz
WITH 1 MW CW OUTPUT POWER*

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The use of a small period wiggler ($\lambda \lesssim 1$ cm) together with a sheet electron beam has been proposed as a low cost source of power for electron cyclotron resonance heating (ECRH) in magnetic fusion plasmas. There may also be application to space-based radar systems. We have experimentally demonstrated stable propagation of a sheet beam (18 A, 1 mm $\times$ 20 mm) through a ten-period wiggler electromagnet with peak field of 1.2 kG. Calculation of microwave wall heating and pressurized water cooling have also been carried out, and indicate the feasibility of operating a near-millimeter, sheet beam FEL with an output power of 1 MW CW (corresponding to power density into the walls of 2 kW/cm²). Based on these encouraging results, a proof-of-principle experiment is being assembled, and is aimed at demonstrating FEL operation at 120 GHz with 300 kW output power in 1 μ s pulses; electron energy would be 410 keV. Preliminary designs of 250-300 GHz, 1 MW FEL's with untapered as well as tapered wigglers will also be presented.

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Optical Focusing in a Free Electron Laser for Inertial Confinement Fusion

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ABSTRACT

Many of the recognized attributes of the free electron laser (FEL) make it an attractive candidate for the radiation driver in Inertial Confinement Fusion (ICF). The FEL conversion efficiency has been demonstrated at several tens of percent and could supply sufficient energy for an ICF application. In addition to the high power qualities of the FEL, it provides a continuously tunable radiation source for ICF experiments. A plausible ICF FEL design scales so as to give roughly the same dimensionless current density as in the LLNL ELF microwave experiments. The increased current density and undulator length for the ICF case are roughly compensated by the larger electron beam energy that is necessary to reach the shorter ICF wavelengths.

The intense laser field within the normal FEL interaction region could not be handled by any known optical elements without damage. We explore the possibility that the end of a long FEL undulator be used to focus the optical wavefront to a smaller area, at the target, a short distance beyond the end of the undulator. Using the same optical phase-shift mechanism that is responsible for the optical guiding effect, it appears possible to prepare the wavefront at the end of the undulator so that free-space propagation brings the optical beam to a focus about 10m beyond the end of the interaction region. Such an FEL focusing section at the end of a long undulator would avoid conventional optical elements in an ICF experiment.

POTENTIAL APPLICATION OF THE LOS ALAMOS FREE-ELECTRON
LASER: HIGH-TEMPERATURE SUPERCONDUCTORS

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ABSTRACT

Realizing the tremendous potential for the development and application of the new High-Temperature Superconductors (HTSCs) requires an improved understanding of the fundamental mechanisms that are involved in these unusual mixed oxide materials. One of the most significant questions involves the nature of the energy gap that evidently develops as the sample temperature is reduced below the critical temperature (T_c). Characterization of the magnitude of this gap and its behavior under a variety of parameter changes could be a key to developing these materials further.

It is proposed that this issue can be investigated by the adaptation of the classic microwave transmission experiments on low-temperature superconductors of Biondi and Garfunkel. However, in this case, one would use a pulsed, tunable, monochromatic, coherent, and linearly polarized source of mid-infrared (MIR) and far-infrared (FIR) radiation, i.e., the Los Alamos Free-Electron Laser (FEL). A projected extension of its previously demonstrated tuning range of 9 to $35\mu\text{m}$ out to $160\mu\text{m}$ would allow the scanning of any HTSC gaps whose magnitudes are from 8 to 140 meV. This range spans the present theoretical estimates and/or preliminary reported measurements in materials with T_c 's from about 30 to 300 K. Sample preparation/availability remains a key issue for the technique's widespread use, but a new physical measurement data base could result that is directly related to the pairing mechanisms involved.

THE USER-ORIENTED FEL DEVELOPMENT PROGRAM AT UCSB[†]

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ABSTRACT

A number of FEL related activities are being carried out at the UCSB Center for Free-Electron Laser Studies. A 6 MV electrostatic accelerator based FEL is being operated, development work is being performed, and student training is taking place under an ONR administered URI contract. A scientific user's facility was built and is being operated under an SDI MFEL contract.

The UCSB FEL has been highly successful in opening the relatively unexplored FIR region of the spectrum to research with a tunable, high-power, coherent source. Despite this, it is becoming apparent that the true potentials of both the present 6MV FEL and the user's facility have not been fully realised. At the same time, there is a growing recognition that FEL development has reached a level of maturity such that, with the exception of a few specific DOD projects, future support will be available only to the extent that FELs are proven useful to the scientific community and public. We have, therefore, restructured the FEL development program into what is referred to as "user-oriented" development. This means that a focussing and consolidation of resources into an ambitious development program, specifically designed to enhance the usefulness and attractiveness of the user's facility for scientific research, has taken place. The key goals of this program include extension of operating wavelength beyond the present limit of 115 μm , operation in a short-pulse high-power mode, and operation with extremely narrow average linewidth. The wavelength extensions will be carried out in three phases representing increasing levels of difficulty and risk. Their success will eventually result in complete coverage of wavelengths from 800 μm to 8 μm . Since the 6 MV machine is the foundation for this work, a full characterization will be undertaken including measurement and modeling of the mode competition, complicated time-frequency behavior, and line-narrowing previously observed. Progress is also continuing on the 2 MV compact "next generation" FEL but more emphasis will be placed on it's use in the development of technology for the 6 MV wavelength extensions.

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The Ground Based Free Electron Laser: Challenges and Solutions

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ABSTRACT

In the decade since its first successful operation, the free electron laser has evolved and matured to the point where a broad range of potential applications are envisioned for it. This wide variety of uses spans such diverse areas as medical research, photochemistry, material processing, etc.; but perhaps the most stressing requirement for the FEL is in the area of strategic defense. This paper will focus on technical progress in the free electron laser and associated beam control elements that have made it the leading candidate for strategic defense.

Two different FEL approaches are currently being pursued for strategic defense applications. Radio frequency linear accelerator driven FEL's have recently extended the wavelength of operation of these devices as oscillators to .5 microns using respectively the superconducting accelerator (in a double pass recirculation mode) at Stanford and the new 120 MeV accelerator at Boeing. Also an RF FEL has been operated in a master oscillator power amplifier configuration (MOPA). Induction linear accelerator driven FEL's have previously been operated at microwave wavelengths with high extraction efficiencies. Recently, operation of these devices has been extended to 10.6 microns using the 50 MeV Advanced Test Accelerator (ATA).

APPLICATIONS OF THE FREE ELECTRON LASER:
THE MEDICAL FREE ELECTRON LASER (MFEL) PROGRAM

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ABSTRACT

In 1984 the United States Congress recognized the potential of the free electron laser for application in medical and materials science research and asked the SDIO to manage the effort. Over the past four years the program expanded to include research in four major areas: (1) FEL Sites and FEL Technology - support was provided to enhance existing FEL locations and to create new regional centers; (2) Biomedical Research - this includes pre-clinical and clinical research; (3) Biophysical Research - comprised of research in basic biological mechanisms and interactions; (4) Materials Science - studies in optical and materials research which support FELs and basic materials research which could not be accomplished without the FEL are in progress. Brief descriptions of the on-going research will be presented and potential future directions of the MFEL Program will also be discussed.

Applications of Electrostatic Acceleration FELs

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Abstract

We review future development prospects of high power FELs based on high current electrostatic accelerators. Applications considered include material processing, photochemistry, medicine, inertial and confined plasma fusion, energy transmission, atmospheric and space propulsion.

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