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 A research program has been carried out to advance the science and technology of free-electron lasers and their applications. The overall objectives of the program were the following were i) development of free-electron lasers in the millimeter and far-infrared region. ii) facilitate the application of far-infrared free-electron lasers to research in frontier science and technology and iii) training of researchers in the development, operation and application of free-electron lasers. A free electron laser facility, unique in the world, has been developed which is operational from 200 GHz, (6.6 cm⁻¹), to 4.8 THz, (160 cm⁻¹), tunable under computer control and able to deliver kilowatts of millimeter wave and far-infrared power. An important part of this facility is a well equipped user lab that has been used to perform ground breaking experiments in scientific areas as diverse as bio-physics, bio-medicine, magnetism, semiconductors and laser physics. Nine graduate students and post doctoral researchers have been trained in the operation, use and application of these free-electron lasers.

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Development and Scientific Utilization
of the
University of California, Santa Barbara
Free-electron Laser

Final Technical Report for the Period
15 September 1986 - 14 September 1991

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OVERVIEW

A research program has been carried out to advance the science and technology of free-electron lasers and their applications. The overall objectives of the program were the following were

- i) development of free-electron lasers in the millimeter and far-infrared region,
- ii) facilitate the application of far-infrared free-electron lasers to research in frontier science and technology and
- iii) training of researchers in the development, operation and application of free-electron lasers.

A free electron laser facility, unique in the world, has been developed which is operational from 200 GHz, (6.6 cm^{-1}), to 4.8 THz, (160 cm^{-1}), tunable under computer control and able to deliver kilowatts of millimeter wave and far-infrared power. An important part of this facility is a well equipped user lab that has been used to perform ground breaking experiments in scientific areas as diverse as bio-physics, bio-medicine, magnetism, semiconductors and laser physics. Nine graduate students and post doctoral researchers have been trained in the operation, use and application of these free-electron lasers.

There were three main thrusts to the UCSB Free-electron laser program. 1. FEL development. 2. Facilitation of the usage of the UCSB FEL. 3. Training of graduate students and post-doctoral researchers. In the following report we detail the program objectives and use them as a guide as we document the accomplishments of this program.

FEL DEVELOPMENT PROGRAM

The most important achievement of the program was the development and operation of two reliable Free-electron lasers that can be used to deliver radiation for a wide variety of scientific experiments; the first covering the spectral range from 313 to 62 microns and the second from 2.5 millimeter to 338 microns. The electron beam is provided by a single 6MV electrostatic accelerator and directed to the appropriate laser by a "switch yard" like beam line. The beam line is computer controlled to allow the operator and user to readily change from one laser to the other and to control the lasing frequency. Under the best conditions the computer can cause the frequency of the laser to scan about a set frequency, covering bandwidths as large as 10% of the set point. Power levels in the kilowatt range are transported out of the FEL vault into the user lab via a computer controlled, evacuated, free space optical transport system.

Below we discuss, point by point, the detailed objectives of the FEL development program and how the objectives were met. These detailed objectives were important milestones and research activities during the development of the UCSB but the full measure of the success of the program is the existing facility which includes two fully operational and "user friendly" FEL's and a well equipped user lab to facilitate scientific research with the FEL's.

Reduced funding curtailed "next generation" development of free-electron lasers. In particular, neither the UCSB or Hughes plans for a "two stage FEL" were completed and the plans for a high current electron gun were not pursued. The initial design and construction of a compact 2MV electrostatic accelerator and undulator were undertaken but not completed for the same reason.

Precise measurement of the laser bandwidth and center frequency in each pulse.

In collaboration with scientists from the Plasma Fusion Center at M.I.T., direct spectral measurements were obtained of the spectral and temporal response of the free-electron laser. The observed data agreed reasonably well with theory. About 30% of the time the spectra had a single longitudinal mode but even in the regime of multi-mode operation the laser signals were only weakly modulated in time. This observation was consistent with phase-locking of the modes. (B.G. Danly, S.G. Evangelides, T.S. Chu, and R.J. Temkin, "Direct Spectral Measurements of a Quasi-cw Free-electron Laser Oscillator", Phys. Rev. Lett. **65**, 2251 (1990).)

Measurements were also performed on the pulse to pulse jitter. At a frequency of 50 cm^{-1} the pulse to pulse variation showed a spread 3.1×10^{-4} .

Development of pulse to pulse frequency stabilization methods.

Successful experiments were carried out to reduce the pulse to pulse frequency jitter by injection seeding of the FEL. The pulse to pulse frequency bandwidth was reduced from 1.6 to 0.16 GHz. (A. Amir, J.F. Knox-Seith and M. Warden, "Narrow-Bandwidth Operation of a Free-electron Laser Enforced by Seeding", Phys. Rev. Lett. **66**, 29 (1991). A. Amir, J.F. Knox-Seith and M. Warden, "Bandwidth narrowing of the UCSB FEL by

injection seeding with a cw laser", Nuclear Instruments and Methods in Physics Research, A304, 12 (1991).)

Complete the computer control system to permit continuous tuning of the FEL.

A computer control system has been developed that greatly facilitates operation and control of the FEL. Data files store the control parameters for particular wavelengths. Under the best conditions the FEL can be scanned under complete computer control. The steering and focusing magnetic fields are scaled with the electron beam energy and computer controlled tuning over 10% bandwidths can be achieved.

B.R. Wallace, "UCSB FEL Real-time Control System", submitted to "Glockenspiel Newsletter" and to "Windows Magazine".

Design and test short period undulators to improve efficiency and access high frequencies.

Research was carried out to test the efficacy of micro-undulators produced by cutting grooves in a single magnet block. Although the micro-undulator demonstrated greater ease in fabrication and assembly of short period undulators the research revealed several serious problems. These were smaller fields than pure permanent magnet undulators, dc and long period errors and large end fields. (K.P. Paulson "Micro-undulator Research at UCSB", Nuclear Instruments and Methods in Physics Research, A296, 624 (1990).)

Design and test a high current (100 Amp) low emittance electron gun and electron collector.

This objective was not achieved during the contract period due to curtailed funding.

Develop and test two-stage FEL concepts.

Two concepts were proposed to extend the short wavelength limit of FEL's driven by electrostatic accelerators. Both involved producing a wiggler with intense standing electromagnetic wave fields, a "two stage" FEL. This part of the program was not pursued due to the reduced funding.

Develop a 2MV compact electrostatically driven accelerator.

Initial design and construction was carried out on this objective but curtailed funding prevented completion of this part of the program.

Perform theoretical analyses on a variety of advanced FEL concepts in collaboration with the Plasma Physics Division of the Naval Research Laboratory.

Reduced funding curtailed development of advanced FEL concepts and the planned for theoretical analysis was not pursued.

FACILITATION OF THE USAGE OF THE UCSB FEL.

A user friendly facility is in place capable of providing tunable sub millimeter wave and far-infrared radiation from 2mm to 60 microns. Operation is readily achieved with the aid of computer files that set the operating conditions of the beam line to obtain the appropriate frequency. Under the best conditions the computer can sweep the electron energy in

such a way that the laser can be tuned about a 10% bandwidth. Kilowatts of power are readily available over the range covered by the two FEL's.

The following objectives were targeted and met in the FEL usage part of the program.

Facilitate the use of the UCSB Free-electron lasers.

The recent and continuing thrust of the UCSB free-electron laser program has been directed at providing a user friendly system that will enable ground breaking experiments in diverse scientific fields. Experiments have been performed in magnetism, semiconductor physics, bio-physics, bio-medical research and laser physics.

Beyond the in-house user program a number of users have taken advantage of the UCSB's FEL's. By research discipline , they are the following:

Bio-physics

M. Berns, University of California at Irvine

R. Austin, Princeton University

Semiconductor Physics

J. Kotthaus, University of Munich

W. Prettl, University of Regensburg

W. Wenckebach, F.O.M. Holland

B.D. McCombe, SUNY Buffalo

FEL Physics

J. Burghoorn, Holland

Provide services and collaborative support for scientists planning to use the FEL.

The staff of the UCSB Center for Free-electron Laser Studies is balanced to provide continued improvement of the facility and to support ongoing experiments. Two full time staff support operations for users and four staff split their time between development and maintenance and operations support.

Acquire , develop, test and maintain the auxiliary instrumentation necessary for the experiments to be performed with the FEL.

A variety of instruments have been acquired to facilitate experiments on the FEL. Liquid helium cryostats are available with variable temperature sample space and optical access for far-infrared or optical radiation. Magnetic fields are available to 8 Tesla.

Each of the six optical ports of the FEL far-infrared beam transport system in the user lab is equipped with an optical bench and a supply of FIR optical components. A double monochromator with photon counting detection is available for use with either Raman scattering or detection of the effects of FIR pumping by the FEL.

Since the FEL pulse length is of the order of microseconds, and that of the cavity dump coupler 30 nanoseconds, reasonably fast electronics are available.

Several other lasers can be used in conjunction with the FEL; a Nd:YAG/dye laser, a CO₂ TEA laser with pulsed molecular gas FIR laser and a cw CO₂ pumped FIR ,molecular laser.

A Bomem Fourier transform interferometer with resolution of $.002 \text{ cm}^{-1}$ is available for use in conjunction with FEL experiments. It is equipped with cryogenic and magnetic field capabilities in addition to a liquid He^3 cooled bolometer detector.

Coordinate FEL development advances with the requisite needs of scientific users.

The overall focus of the FEL program at UCSB is on facilitating the use of these lasers in important scientific areas.

Develop a strong in-house program in condensed matter physics and surface science to form a base for collaborative efforts in these fields.

At present three faculty in the physics department, Mark Sherwin, Beth Gwinn and Jim Allen have committed their time and energy to experiments that take advantage of the unique properties of the UCSB FEL. The arena in which most of the activity centers is the non-linear dynamics of semiconductor nano-structures and devices.

TRAINING OF GRADUATE STUDENTS AND POST-DOCTORAL FELLOWS

The following have gained their Ph.D. degrees through the FEL program.

James Hu, Spring 1986 - Design and Performance of Undulators at the UCSB Free-electron Laser

Avner Amir, Spring 1986 -

Spontaneous Emission and Laser Mode Structure at the UCSB Free-electron Laser

Joseph S. Spector, February 1988 -

The First Condensed Matter Studies Using the UCSB Free-electron Laser

Daniel Gregoire, December 1988 -

Measurement of Longitudinal Channeling Radiation with the UCSB-CFELS Electrostatic Accelerator

Jann Kaminski, May 1989 -

Semiconductor Studies Using the UCSB Free-electron Laser

Abbas Nikroo, November 1990 -

Frequency, Temporal and Spatial Evolution of Large K Magnons in MnF₂

Finn Knox-Seith, October 1990,

Injection Seeding of an Electrostatic Accelerator Driven FEL.

Kevin Paulsen, October 1990 -

Evaluation of a 4 mm Period UCSB Microundulator

John Plombon (pending) -

Stochastic Ionization of Electrons in GaAs/AlGaAs Heterostructures

Bill Bewley (pending) -

Parametric Amplification of the FEL by Difference Frequency Generation in the I. R.

PUBLICATIONS PRODUCED IN WHOLE OR IN PART BY THIS PROGRAM

"Narrow-Bandwidth Operation of a Free-electron Laser Enforced by Seeding", A. Amir, J.F. Knox-Seith and M. Warden, Phys. Rev. Lett. 66, 29 (1991).

"Direct Spectral Measurements of a Quasi-cw Free-electron Laser Oscillator", B.G. Danly, S.G. Evangelides, T.S. Chu, and R.J. Temkin, Phys. Rev. Lett. 65, 2251 (1990).

"Bandwidth narrowing of the UCSB FEL by Injection Seeding with a CW Laser" A. Amir, J.F. Knox-Seith and M. Warden, Nucl. Inst. and Meth. in Phys. Res., A304, 12 (1991).

"Micro-undulator Research at UCSB", K.P. Paulsen, Nucl. Inst. and Meth. in Phys. Res., A296, 624 (1990).

"Transvers Optical Mode Trapping in a Free-electron Laser", Nucl. Instr. and Meth. in Phys. Res., A272, 505 (1988).

"High-current Beam Transport in Electrostatic Accelerator Tubes", G. Ramian and L. Elias, Proc. of the 1987 Partical Accelerator Conf., IEEE 1, 307 (1987).

"Two-stage Free-electron Laser Driven by an Accelerator", I. Kimel, L. Elias, and G. Ramian, Proc. of the 1987 Partical Accelerator Conf., IEEE 1, 227 (1987).

"Injection Locking Experiment at the UCSB FEL", A. Amir, R.J. Hu, F. Kielmann, J. Mertz and L. Elias, Nucl. Instr. and Meth. in Phys. Res., A272, 174 (1987).

"Perturbative Analytical Study of Long Pulse FEL's: Mode Competition for a High Gain Compton Regime", I Kimel and L. Elias, Phys. Rev. A38, 2889 ().

"The New UCSB Compact Far-infrared FEL", G. Ramian and L. Elias, Nucl. Instr. and Meth. in Phys. Res., A272, 81 (1988).

"Optical and Electron Beam Requirements for an Optical Undulator FEL", Y. Tsunawaki, A. Amir, J.C. Gallardo and L.R. Elias, Jap. J. of Appl. Phys., 27, 675 (1988).

"The Application of Recirculating-beam Electrostatic Accelerators to Free-electron Lasers", G. Ramian, Nucl. Instr. and Methods in Phys. Res. B40/41, 1058 (1989).