Initial Operation of the Vanderbilt Free Electron Laser *

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Since their inception in the mid 1970's Free Electron Lasers (FELs) have proven to be unique light sources. For many applications, the problems caused by the complexity of the FEL is greatly outweighed by its flexibility as a research tool. In 1987 Vanderbilt University committed itself to the development of a user-intensive FEL research facility. This facility will be available to Vanderbilt and other institutions to conduct research in Biomedicine and Materials Science. This FEL incorporates a 45 MeV traveling-wave linac with a 2.3 cm period, Halbach-type, permanent magnet wiggler. In the initial configuration this system will selectively lase within the range of 2-8 μm. It will operate with a 0.05% duty factor and with an average power of ~6W. The FEL assembly was completed during the winter of 1990-91. Testing and operation of the FEL were subsequently initiated. The initial operation and performance of the FEL are reported at this time. It is expected that the laboratory will become available for research by users during summer 1991.

1. Introduction

As in more conventional lasers, FELs create coherent, monochromatic light by stimulated emission amplification[1]. The interaction of an electron beam with specialized magnetic fields replaces the conventional laser medium. Due to the tunability of magnetic field strength and electron-beam energy, the FEL is continuously tunable over wide ranges of the spectrum. The available field strengths and electron-beam characteristics allow FELs to operate in unlased parts of the spectrum and avails to very large beam powers. By combining this tunability with operation on the harmonics it has been possible to tune several FELs over more than an order of magnitude in wavelength[2]. This distinguishes them as the most broadly tunable laser available.

Vanderbilt has successfully operated its new FEL at several frequencies. Spectral data, power measurements and operational stability are discussed in this paper.

2. The FEL System

The Vanderbilt University FEL was built and installed by Sierra Laser Systems. This laser is a compact, predominantly infrared, FEL. It is similar to the Stanford University Mark III FEL[3]. The FEL is controlled by three local STD bus, IBM-type computers located in the klystron equipment racks. These computers communicate via Arcnet with the operator interface computer located in the control room or in one of the experimental laboratories. The operator computer is a SUN Microsystems 386i workstation. The computer control software was partially supplied by Sierra in cooperation with researchers at Vanderbilt.

The electron beam is produced by an rf travelling-wave electron linac operating at 2.856 GHz. This beam is created in an rf-extracted electron gun with a LaB6 cathode[4]. The ~1 MeV beam is then transported through an alpha magnet that compresses the pulse temporally and clips the energy tails[5]. After the alpha magnet, the beam is transported to the entrance of the accelerator. The maximum energy of the rf linac is ~45 MeV. The electron beam parameters are displayed in Table 1.

The wiggler is a 2.3 cm period, Halbach type, hybrid design, using permanent magnets with steel pole pieces. The wiggler parameters are shown in Table 1. There are 208 SmCo permanent magnets used in the wiggler.

Table 1 also shows the expected laser performance. Tuning of the electron energy and the wiggler field strength will allow lasing from 2 to 8 μm. To lase below 2 μm the laser cavity length will be moved to the proper length to facilitate lasing on the third harmonic of the fundamental. More extensive modifications discussed later in this paper will allow lasing

Table 1: Operation Parameters of the Vanderbilt University Free-Electron Laser.

Accelerator:	
Maximum electron energy (MeV)	45
Micropulse peak current (A)	20-40
Macropulse average current (mA)	100-200
Energy spread (%)	0.5
Horizontal Normalized emittance ($\pi mm \cdot mrad$)	4
Vertical Normalized emittance ($\pi mm \cdot mrad$)	10
Wiggler:	
Type	Hybrid
Length (cm)	120
Wiggler Period (cm)	2.3
Number of magnets	208
Type of magnet	SmCo
Magnet energy product (kJ/m^3)	180 - 210
Maximum rms wiggler field (T)	0.47
Laser:	
Wavelength (μm)	1 - 8
Micropulse peak power (MW)	0.5 - 2
Micropulse duration (ps)	0.5 - 3
Micropulse energy (μJ)	1 - 4
Micropulse repetition rate (GHz)	2.856
Macropulse average power (kW)	5 - 25
Macropulse duration (μs)	0.5 - 8
Macropulse energy (mJ)	1 - 200
Macropulse repetition rate (Hz)	0 - 60
Overall average power (W)	0 - 6

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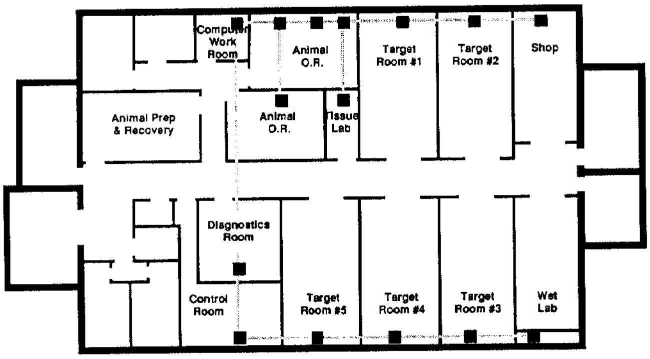

Figure 1. Plan view of the laboratory level of the Vanderbilt University FEL facility.

in different regimes of the spectrum.

The laser is housed in the second basement or vault of the Vanderbilt FEL center. This building is in immediate proximity with the Medical School, Engineering School and the Physics, Chemistry and Biology Departments. The laser light is brought up to the first basement and distributed to the laboratories via an optical beam delivery system(figure 1.) The laboratory level includes a beam-diagnostic room, control room, five laser target rooms, a medical suite and support rooms. The medical suite includes two operating rooms, locker rooms, a computer work room and an animal care facility. Initially, one operating room will be equipped with an articulated arm beam delivery system to manipulate the laser during surgery.

3. The Applications Program

The FEL center at Vanderbilt University is intended to be a national resource for bio-medical and materials science research. Presently six schools and departments at Vanderbilt are collaborating in a broad-based research program. In the future, the program will expand to include users worldwide.

The core applications are characterized by close relationships between experiments. There is also a large degree of collaboration between the scientists on various projects. The experiments on materials science concentrate on the interaction of the FEL light with optical materials, crystals, mammalian tissue, and adsorbates on surfaces. In biophysics, there will be experiments on the vibrational spectroscopy of biopolymers such as DNA, and the effect of crosslinking of RNA on the synthesis of proteins in cells. Molecular biology experiments will explore the dynamics and function of different components of cell membranes. Surgery and medical imaging will be the initial focus of the medical applications portion of the program.

The center also will support a broad group of external users. Research proposals will be accepted in medical research, biology and materials science. Presently several well known scientists have expressed interest in coming to Vanderbilt to do research.

4. Initial Results

The electron and optical-beam parameters of the initial operation of the Vanderbilt FEL program are shown in Table 2. We have observed laser operation at 2.5 μm and at 4.4 μm. The maximum power observed at the second wavelength was 11 kW during the macropulse. The electron energy measurement was obtained by simple dipole deflection from a calibrated steering coil. The current was measured by a beamline current toroid. The optical power of the laser pulse was determined using a calibrated pyroelectric energy meter. The wavelength and spectrum data were obtained using a McPherson 0.3 m monochromator and a gold-doped germanium detector.

Table 2: Operation Parameters of Initial Vanderbilt FEL Lasing.

Initial Lasing:	
Electron beam energy (MeV)	42±7
Electron beam pulse length (μs)	~6
Accelerator repetition rate (Hz)	5.4
Electron peak current (mA)	180
Lasing wavelength (μm)	2.53
Laser pulse duration (μs)	~2
Laser energy per pulse (mJ)	15
Corresponding peak power (kW)	8
Most recent data:	
Electron beam energy (MeV)	42±7
Electron beam pulse length (μs)	~6
Accelerator repetition rate (Hz)	10.1
Electron peak current (mA)	190
Lasing wavelength (μm)	4.4
Laser pulse duration (μs)	~2
Laser energy per pulse (mJ)	22
Corresponding peak power (kW)	11

Figure 2a shows the most recent spectrum of the laser at 4.4 μm. The shoulder on the low wavelength side of the peak was not understood initially. By taking an expanded spectrum, figure 2b, it was determined that the laser was lasing at two different frequencies. By setting the monochrometer at each peak, and looking at the laser intensity during the macropulse, it was determined that the laser was initially lasing at the longer wavelength, shutting off, and re-starting at the shorter wavelength. It is believed that this behavior is due to a slewing of the energy during the macropulse. This slewing could be easily caused by self-heating of the cathode, thus changing the energy of the electrons into the alpha magnet. The path of the electrons would also change and thus the phase between the gun and the accelerator would be affected. Figure 3 shows the laser intensity during the macropulse when the energy was slightly reduced. This shows the laser cycling on and off three times.

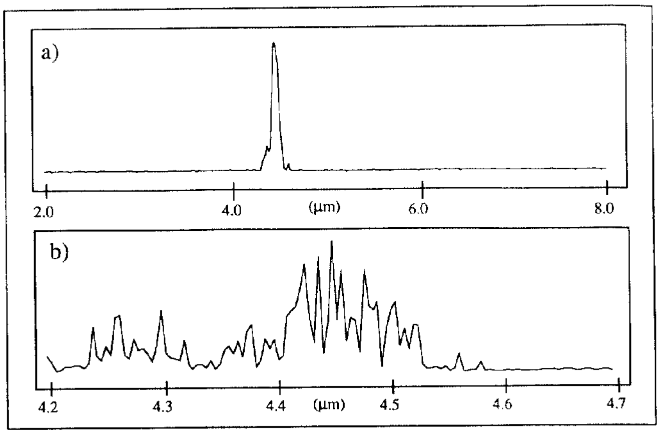

Figure 2. Initial spectrum of the laser operation. a) shows the spectrum from 2.0 to 8.0 μm. b) shows expansion of a) from 4.2 to 4.7 μm. This spectrum shows lasing at two different frequencies.

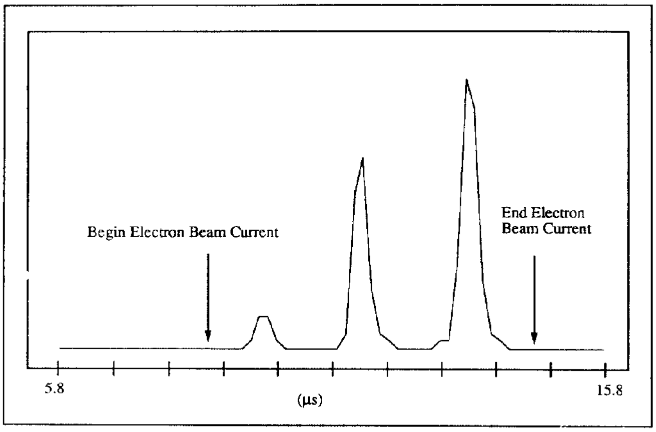

Figure 3. Laser intensity during macropulse. Begining and ending of electron beam current are labeled. The three peaks show the laser cycling on and off during the macropulse.

5. Present Expansions

Bringing the laser to design performance is the main thrust of the Vanderbilt FEL team at this time. Work has also begun on many improvements to the basic laser system to broaden the functionality of the center.

In order to reach the longer wavelengths in the far infrared, a Cerenkov resonator will be built and installed on the beamline after the wiggler. This will allow lasing in the wavelength region from 50 to 200 μm. A Cerenkov FEL operates by interacting an electron beam with a travelling electromagnetic wave. The phase of the e-m wave is synchronized to the electron velocity by use of a dielectric-loaded waveguide[6]. The micropulse peak power is predicted to be of the order of 10MW.

Using an alternate electron beam line that will start after the wiggler, the electron beam can be directed toward a secondary beam chase that leads to the laboratory level. By transporting the laser light to collide with the electron beam, intense, monochromatic, yet incoherent, X-rays can be created with Compton backscattering[7]. After the interaction, the electrons are returned to the beam line just before the beam dump. These X-rays are important for a variety of applications including microscopy, medical imaging and therapy. The X-ray facility will initially operate at wavelengths from 3nm (40 eV) to 0.06 nm (20 keV.) Figure 4 shows the available power versus the available spectrum for the Vanderbilt FEL center.

Incorporation of laser-irradiated cathodes will be another important modification to the present gun configuration. This will include laser heated cathodes and photoelectric cathodes. This improvement will allow greater control over the FEL pulse structure and will increase the beam brightness and therefore FEL gain. Other improvements will facilitate shorter macropulses, shorter wavelengths and shorter micropulses.

6. Conclusions

The Vanderbilt University free electron laser facility has begun operation. While the initial data are sparse the operation of the machine is improving. Further analysis of the energy slewing is presently being accomplished. Other than excessive delays due to parallel debugging of the computer system and the FEL, the project has progressed nominally. This summer, the facility will be made available to the initial users. This center is expected to become a national resource for research in biomedical and materials science research. With the facility upgrades that are planned, this FEL center will offer a powerful array of wavelengths, pulse structures and beam powers for a myriad of experiments.

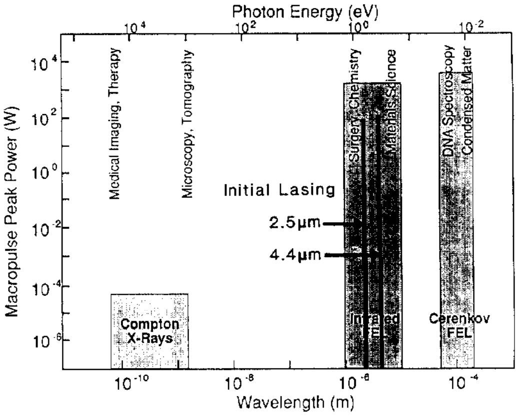

Figure 4. Available power versus available wavelength for the Vanderbilt free electron laser center. This plot includes the machine upgrades that are presently funded.

8. Acknowledgements

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