LA-UR- 98-4556

Approved for public release; distribution is unlimited.

Title: FIRST LASING OF THE REGENERATIVE AMPLIFIER FEL

Author(s): Dinh C. Nguyen, Richard L. Sheffield, Clifford M. Fortang, John C. Goldstein, John M. Kinross-Wright, and Nizar A. Ebrahim

Submitted to: Nuclear Instruments and Methods A
and Proceedings of FEL 98 Conference, Williamsburg, VA
August 17-21, 1998

Los Alamos
NATIONAL LABORATORY

First Lasing of the Regenerative Amplifier FEL

Dinh C. Nguyen[†], Richard L. Sheffield, Clifford M. Fortgang, John C. Goldstein,
John M. Kinross-Wright, and Nizar A. Ebrahim,

Los Alamos National Laboratory, MS H851, Los Alamos, NM 87545

ABSTRACT

The Regenerative Amplifier Free-Electron Laser (RAFEL) is a high-gain RF-linac FEL capable of producing high optical power from a compact design. The combination of a high-gain and small optical feedback enables the FEL to reach saturation and produce a high optical power and high extraction efficiency without risk of optical damage to the mirrors. This paper summarizes the first lasing of the Regenerative Amplifier FEL and describes recent experimental results. The highest optical energy achieved thus far at 16.3 μm is 1.7 J over an 9-μs macropulse, corresponding to an average power during the macropulse of 190 kW. We deduce an energy of 1.7 mJ in each 16 ps micropulse, corresponding to a peak power of 110 MW.

[†] Further author information -
D.C.N. (correspondence): Email: dcnguyen@lanl.gov; Telephone: 505-667-9385; Fax: 505-667-8207

1. Regenerative Amplifier FEL

High-gain RF-linac FELs operating in the self-amplified spontaneous emission (SASE) regime have recently emerged as a potentially viable technology for generating short-wavelength coherent radiation. High-power FELs, prone to optical damage to resonator mirrors because of high intracavity power, can also benefit from the single-pass nature of SASE. A variation of SASE, which we call Regenerative Amplifier FEL, uses mirrors to provide a small amount of optical feedback to restart the amplification process in a high-gain wiggler [1]. The large single-pass gain allows the optical intensity to build up in a few passes to a sufficiently high level for efficient energy extraction. Using a large outcoupling allows most of the optical power to exit the cavity, thereby reducing the risk of optical damage and increasing the amount of light that exits the cavity as useful power.

The Regenerative Amplifier FEL offers a number of unique attributes: very large cavity detuning length (on the order of millimeters), fast build-up and ring-down (a factor of 3 in successive passes), broad output spectra (>5%), a high extraction efficiency (>2%), and very high peak power (hundreds of MW). This paper summarizes the experimental conditions for realizing the RAFEL concept and describes the first lasing results as well as some recent accomplishments.

2. Experimental Setup

The experimental setup of the Regenerative Amplifier FEL has been described in detail elsewhere [1]. A schematic of the experiment is shown in Fig. 1 of Ref. 2 in these proceedings. Table I summarizes the RAFEL experimental conditions. The electron beam is generated by a compact, 1.2-m-long, 1300-MHz photoinjector/linac capable of producing maximum beam energy of 20 MeV. Cesium telluride (Cs_2Te) photocathodes coated with a thin film of CsBr have been used successfully with the fourth harmonic at 263 nm of a mode-locked Nd:YLF drive laser. The quantum efficiency for Cs_2Te cathodes, approximately 10% for freshly made cathodes, is reduced to 7% after application of the coating. The QE remains unchanged for more than two months of operation without any sign of degradation. The Cs_2Te photocathodes for this experiment have been enlarged so that they can be uniformly illuminated with a 7-mm-radius drive laser spot. The large emission radius reduces space charge effects and results in a high peak current directly from the linac [2].

The generated electron beam is focused to the entrance of the wiggler by two solenoids, one around the first accelerator cell and one at a location 0.4 m in front of the wiggler. The wiggler is designed to provide two-plane sextupole focusing to maintain the same electron beam radius through the wiggler. The wiggler has a constant period of 2 cm, with a 1-m uniform section (peak field = 0.7 T) and a 1-m tapered section (peak magnetic field tapered from 0.7 to 0.5 T). The wiggler is bracketed with two annular mirrors that form part of the feedback cavity. The electron beam converges through a 5-mm-diameter hole in the first annular mirror to a 0.2-mm-radius spot at the wiggler entrance. Both the electron and the FEL beams go through a 12-mm-diameter hole in the downstream annular mirror. Part of the optical beam is reflected off the downstream annular mirror, collimated by a pair of spherical and cylindrical mirrors (approximating a 90° paraboloid), and then refocused to the wiggler entrance by the second paraboloid. Most of the high-power optical beam exits through the large hole in the downstream annular and expands to a 7-mm X 4-mm elliptical beam at the KBr vacuum window. The optical beam is measured with a Molectron J50 energy meter, a slow HgCdTe detector, or a fast Cu:Ge detector. After traversing the second annular mirror, the electron beam enters a spectrometer dipole, turns 120°, and terminates in the beam dump located in the ground.

3. Experimental Results

The RAFEL small-signal gain was measured in a SASE experiment that is described in detail elsewhere [3]. From the best fit to the data, we obtained a value of the gain coefficient that indicates there were 8 power gain lengths in the wiggler. This gives a single-pass gain of 330 (33,000%). The large-signal gain as measured by optical build-up is as high as 300%. Immediately after installing the feedback optics, we observed an optical power that exceeded the single-pass SASE power by more than six orders of magnitude. The measured HgCdTe signal in the large signal regime follows the transmitted current macropulse closely and exhibits considerable more fluctuations than the single-pass signal (Fig. 1). By adjusting the feedback cavity length, we measured a detuning length FWHM greater than 1 mm (Fig. 2). The large detuning length greatly relaxes the mechanical stability requirements for the feedback cavity.

The optical buildup to saturation was recorded with a high-speed copper-doped germanium detector that integrated the optical energy over each micropulse and yielded the pulse energies of individual micropulses. Because the round trip cavity length is twice the micropulse separation, two optical micropulses exist in the cavity length when the laser is on. These two sets of micropulses build up from intrinsically different gain conditions and achieve saturation at different times (Fig. 3). Regardless of the gain conditions, both sets of micropulses achieve the same saturation level. When the electrons are turned off, they decay together as a pair of micropulses (Fig. 4). Because of the large outcoupling, the cavity ringdown is fast: the FEL power drops by a factor of 3 in successive passes. From the ringdown measurements, we estimate the feedback cavity has an outcoupling of 66%. Only 25% of the total power reflected back into the feedback cavity gets injected into the wiggler. The actual feedback fraction is thus only 8%.

The output spectrum was measured with a Jarrell-Ash monochromator and a fast HgCdTe detector. The signal was integrated over the portion of the macropulse where the cavity field is stable to within 1%. The spiky nature of the spectrum is similar to those predicted by FELEX simulations at the 9th and 10th passes (Fig. 5). The breadth of the measured spectrum compared to prediction may be due to the fact that the measurement was integrated over several passes.

During the first lasing experiment, the micropulse charge was limited to 3 nC or less, and the measured energy integrated over a 9-μs macropulse (~1000 micropulses) was 0.5 J, yielding a micropulse energy of 0.5 mJ in each 10-ps micropulse. More recently, with a higher micropulse charge of 4.5 nC, we achieved a macropulse energy of 1.7 J over a 9-μs macropulse, corresponding to a micropulse energy of 1.7 mJ in approximately 16 ps. The corresponding average power during the macropulse is 190 kW and the peak power during a micropulse is estimated at 110 MW. Since these results were obtained with 4.5 nC of charge at 16.7 MeV, corresponding to 75 mJ of energy in each electron micropulse, we deduced 2.3% of the beam power was converted to FEL light exiting the cavity. The measured micropulse energy is plotted versus micropulse charge in Fig. 6. For comparison, the FELEX prediction at 6 nC is included, together with our estimates of the maximum micropulse energy that can be obtained (solid line).

4. Conclusion

We have achieved very efficient lasing with the Regenerative Amplifier Free-Electron Laser. This experiment demonstrates the utility of optical feedback to achieve saturation in a high-gain SASE FEL. From the fit of the measured SASE signal versus current to an exponential function of, we inferred a single-pass gain of about 330 at 16.3 μm. The highest optical energy achieved thus far is 1.7 J over a train of 1000 micropulses. We deduced a pulse energy of 1.7 mJ in each 16-ps micropulse, corresponding to a peak power of 110 MW. This new FEL has operated at high peak power without optical damage to the cavity mirrors. The RAFEL also exhibits a very large feedback cavity detuning length. The FEL output efficiency, defined as the efficiency of conversion from electron beam energy to light outside the FEL cavity, is 2.3%. Work is in progress to improve the RAFEL efficiency and to explore the lasing characteristics of this new FEL.

References

1. D. C. Nguyen et al., Proceedings of SPIE, **3154**, 39 (1997).

2. R. L. Sheffield et al., Proceedings of SPIE, **2988**, 28 (1997).

3. D. C. Nguyen et al., "High-gain SASE experiments in the infrared", these Proceedings.

Table I

Summary of Parameters for Standard RAFEL Operating Conditions

Beam energy	E_b	16.7 MeV
Peak current	I	280 A
Micropulse charge	Q	4.5 nC
Bunch length	τ	16 ps
Normalized emittance*	ε_n	7 π-mm-mrad
Energy spread	$\Delta\gamma/\gamma$	0.5%
rms beam radius inside wiggler	r_b	0.2 mm
Wiggler period (fixed)	λ_w	2 cm
Wiggler length	L_w	2 m (1-m uniform, 1-m tapered)
On-axis field	B_w	(0.7 - 0.5) Tesla
Wiggler parameter	a_w	0.92 - 0.65
Wiggler gap	g_w	(5.9 - 9.5) mm
Betatron period	λ_β	1 m
Wavelength	λ	16.3 μm
Pierce parameter	ρ	0.02
Gain length (measured)	L_G	15 cm
Micropulse energy	W_μ	1.7 mJ
Micropulse peak power	P_{peak}	110 MW
Micropulse separation	T	9.23 ns
Macropulse average power	P	190 kW
Macropulse length	T_{macro}	9 μs

* Inferred from the measured matched beam radius.

Figure Captions

Fig. 1 Oscilloscope traces of: a) Cavity RF field; b) Beam current; c) HgCdTe voltage in the large-signal (lasing) regime.

Fig. 2 RAFEL cavity detuning length.

Fig. 3 Cu:Ge detector signals of individual micropulses showing fast optical build-up near saturation.

Fig. 4 Cu:Ge detector signals of individual micropulses showing fast ring-down.

Fig. 5 Output optical spectra: measured (solid) and calculated with FELEX (dashed).

Fig. 6 Output micropulse energy versus micropulse charge; experimental measurements (solid circles), FELEX prediction (square) and extrapolation to lower charge based on FELEX (line).

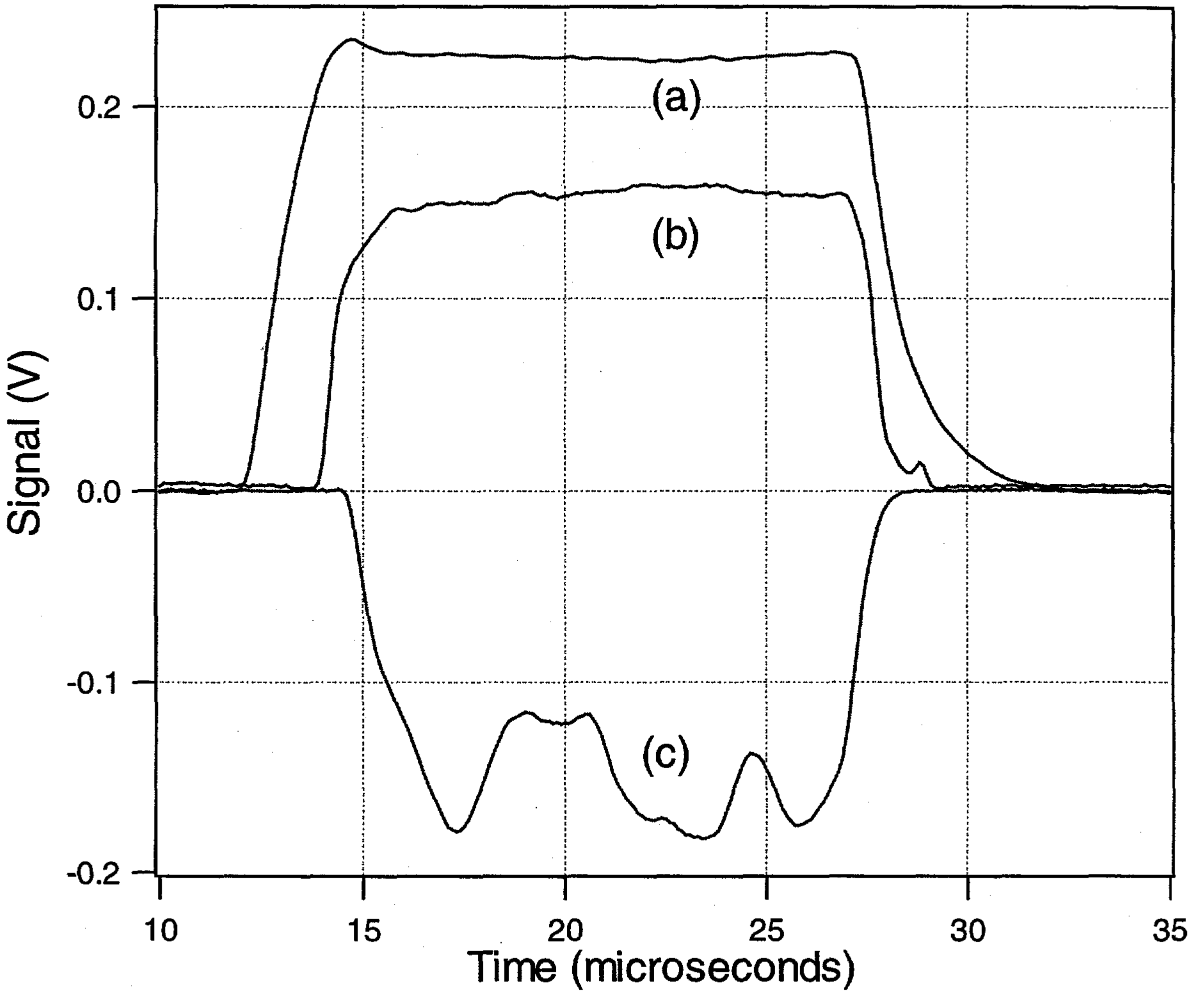

Figure 1

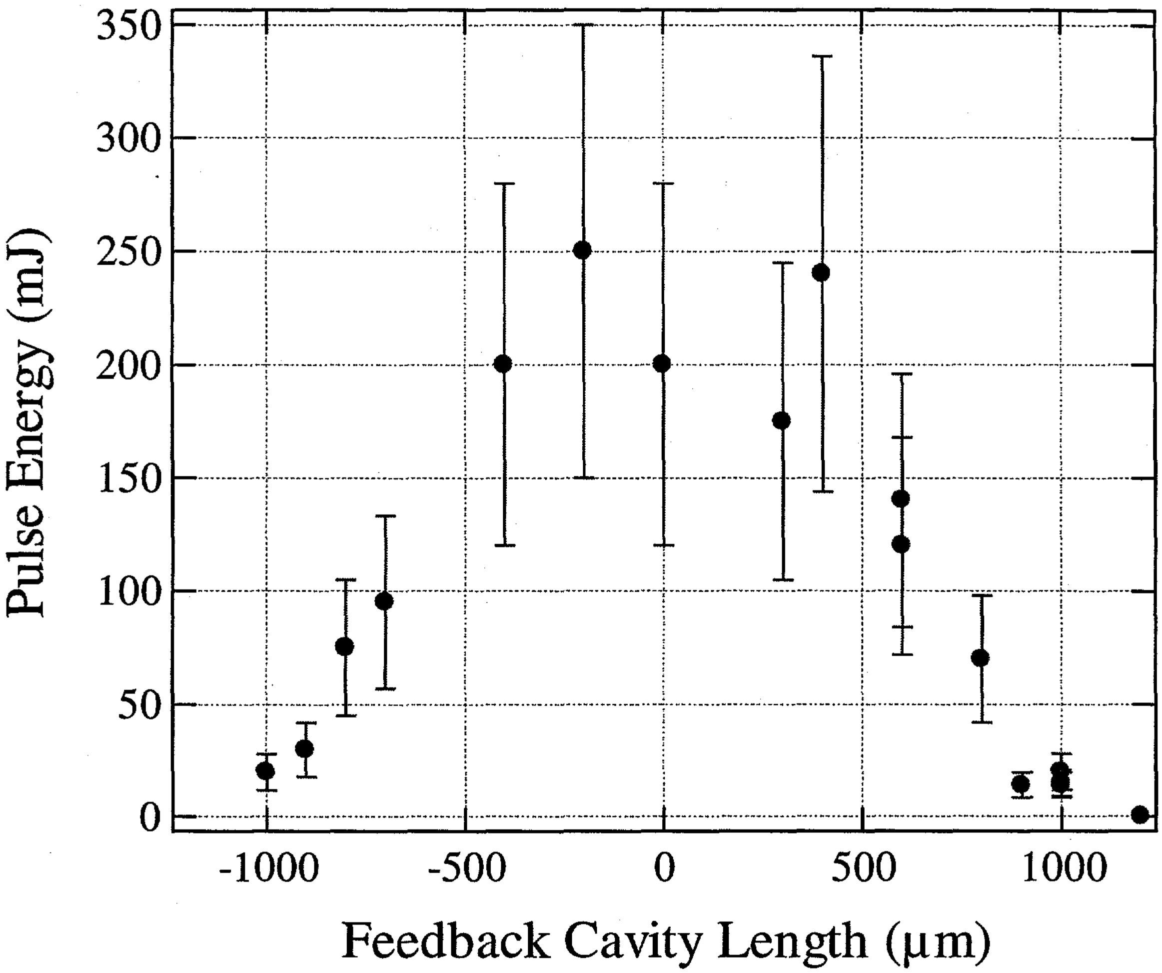
350
300
250
200
150
100
50
0
Pulse Energy (mJ)
-1000
-500
0
500
1000
Feedback Cavity Length (μm)

Figure 2

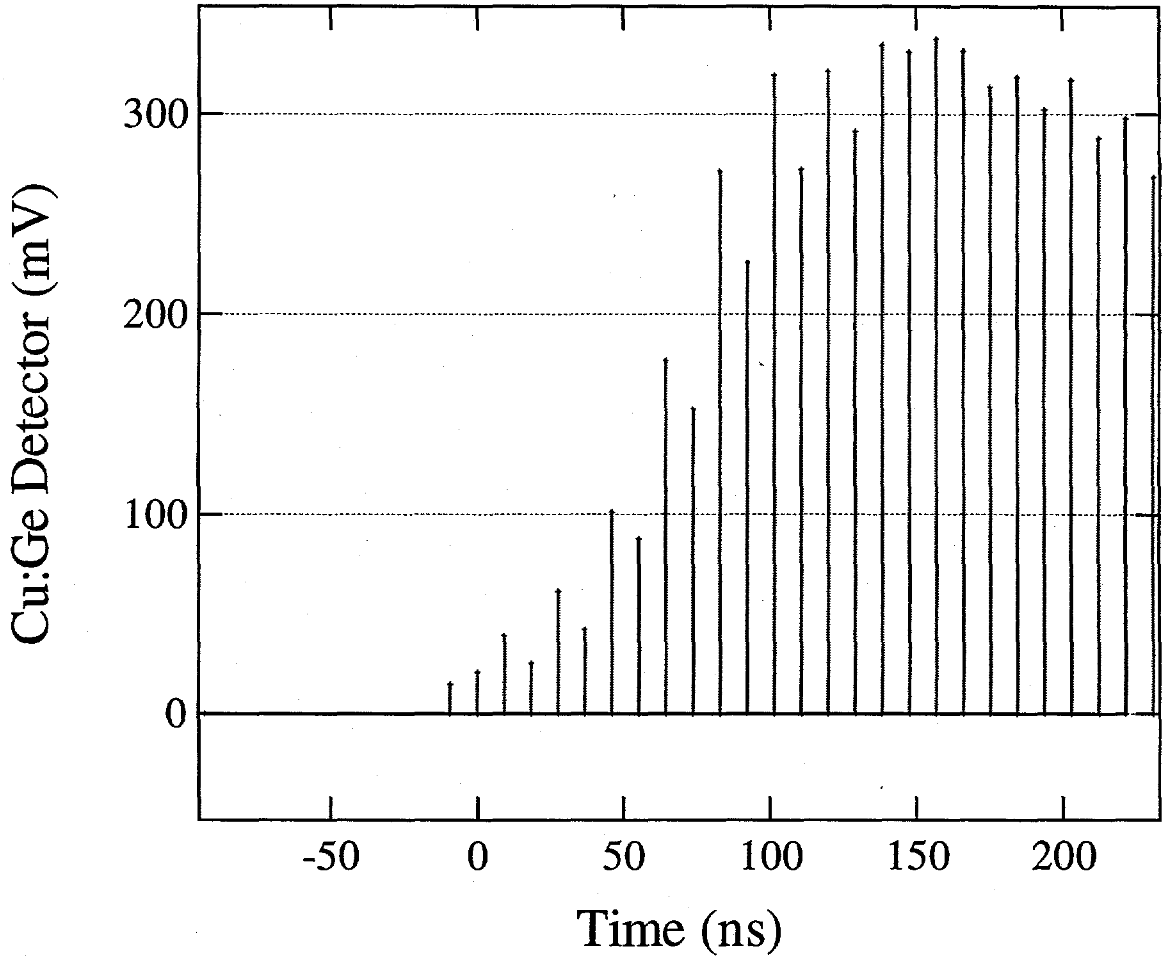

Figure 3

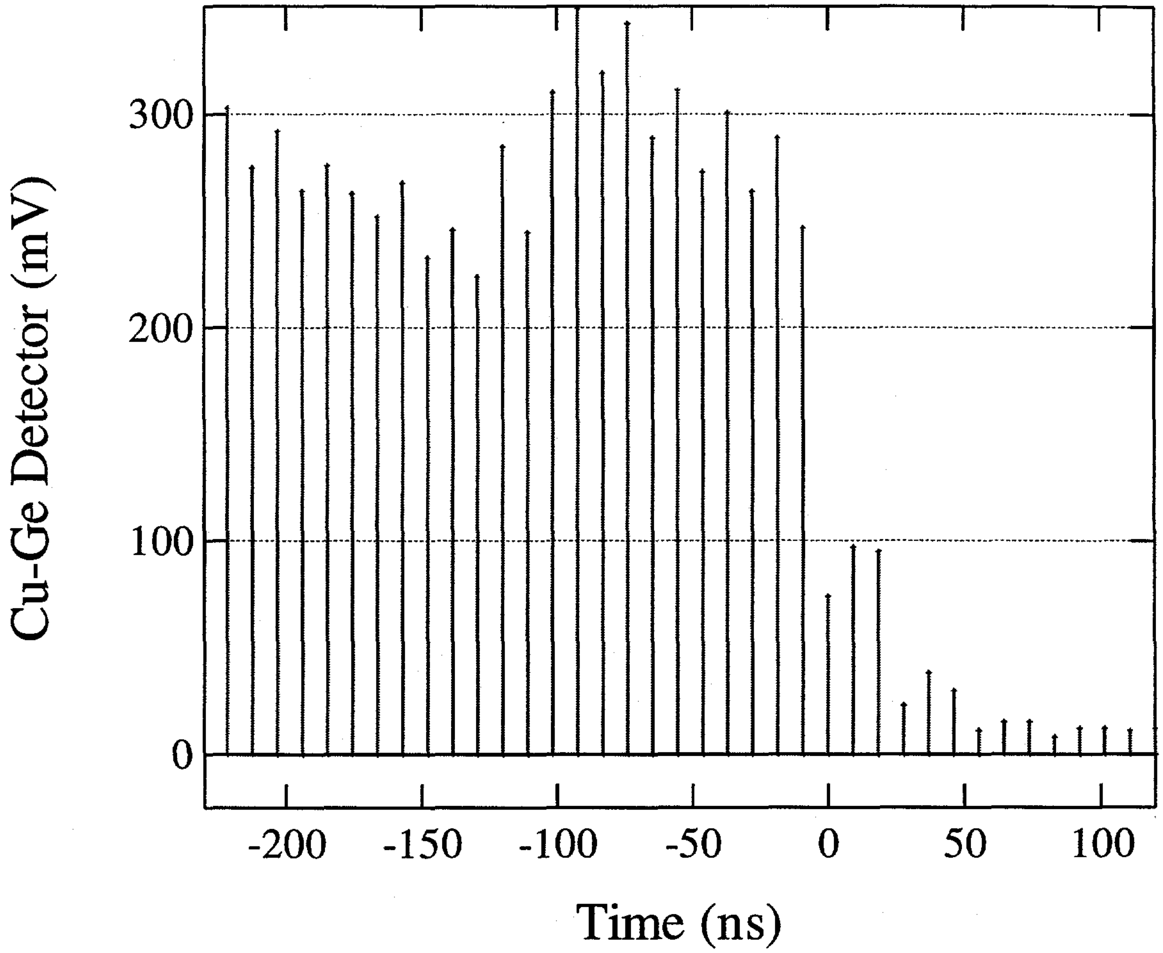

Figure 4

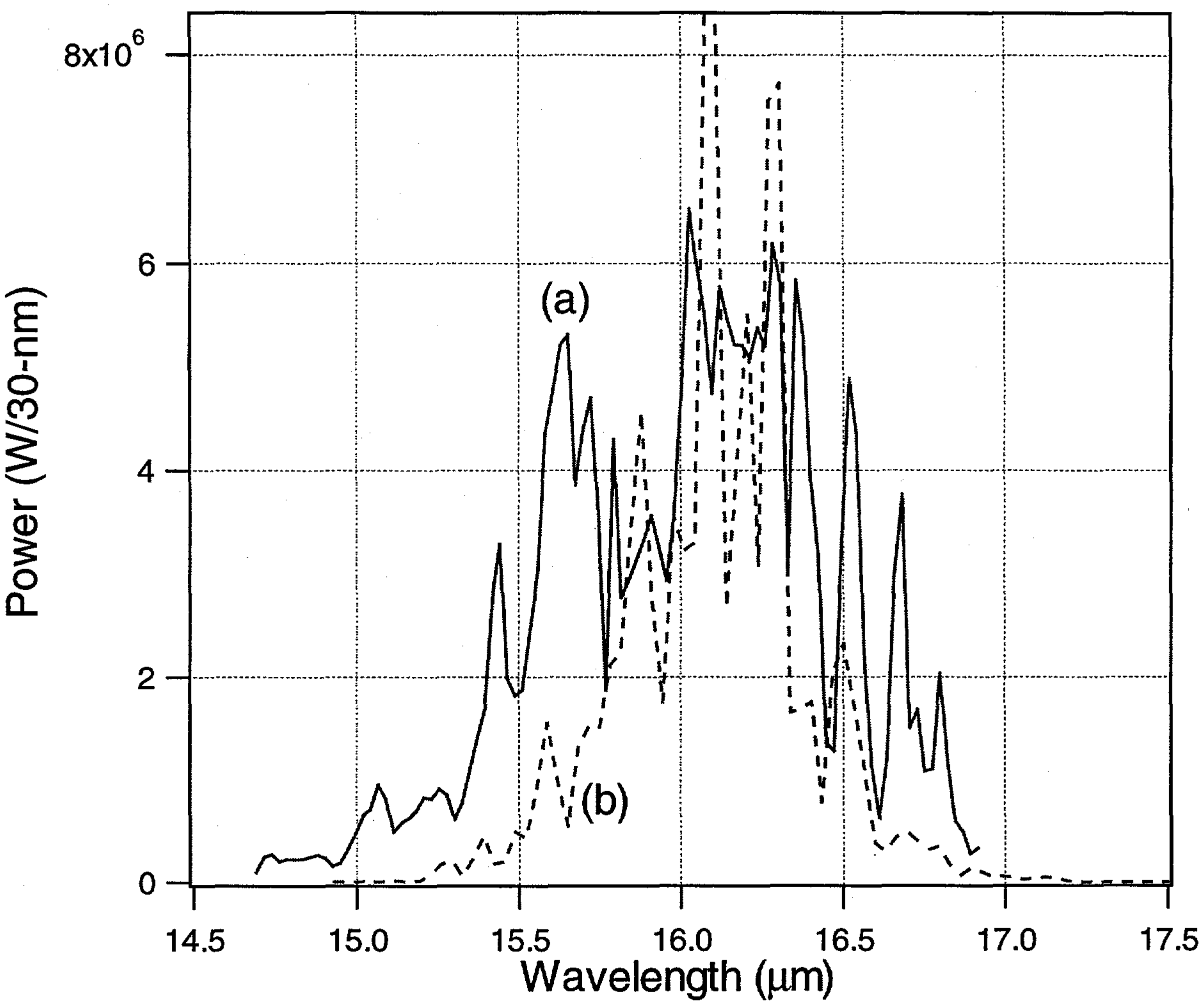
8x10^6
6
4
2
0
Power (W/30-nm)
14.5
15.0
15.5
16.0
16.5
17.0
17.5
Wavelength (µm)
(a)
(b)

Figure 5

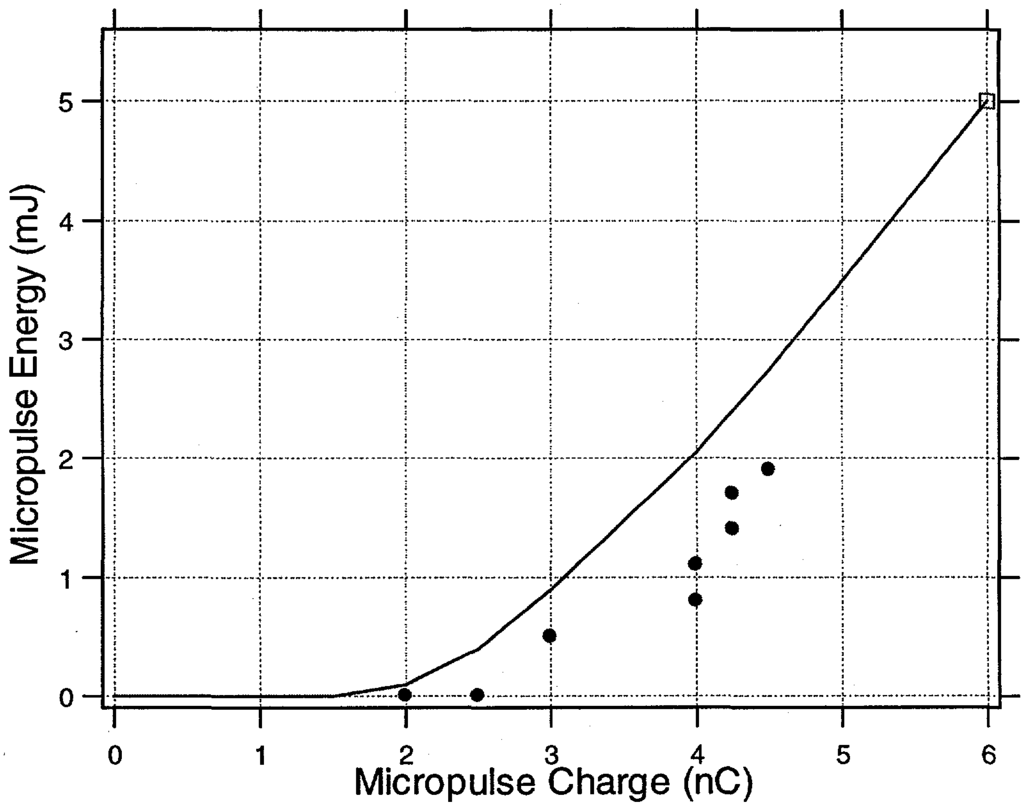

Figure 6