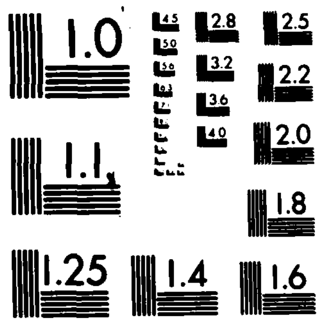
AD-A139 593 A HIGH-GAIN 35 GHZ FREE-ELECTRON LASER AMPLIFIER EXPERIMENT(U) NAVAL RESEARCH LAB WASHINGTON DC S H GOLD ET AL. 20 MAR 84 NRL-MR-5301

1/1

UNCLASSIFIED F/G 20/5 NL

END
DATE FILMED
4-84
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(2)

NRL Memorandum Report 5301

AD A139593

A High-Gain 35 GHz Free-Electron Laser Amplifier Experiment

S. H. GOLD, D. L. HARDESTY, AND A. K. KINKEAD

High Power Electromagnetic Radiation Branch
Plasma Physics Division

L. R. BARNETT

Department of Electrical Engineering
University of Utah
Salt Lake City, UT 84112

V. L. GRANATSTEIN

Electrical Engineering Department
University of Maryland
College Park, MD 20742

March 20, 1984

This work was supported by the Office of Naval Research.

NAVAL RESEARCH LABORATORY
Washington, D.C.

AD-A139 593

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 5301	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory — 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State and ZIP Code) Washington, DC 20375	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research — 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State and ZIP Code) Arlington, VA 22217	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
61153N		RR011-09-41	47-0866-04

11. TITLE (Include Security Classification) A HIGH-GAIN 35 GHz FREE-ELECTRON LASER AMPLIFIER EXPERIMENT

12. PERSONAL AUTHOR(S) S.H. Gold, D.L. Hardesty, A.K. Kinkead, L.R. Barnett,* and V.L. Granatstein**

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Interim	FROM ____ TO ____	March 20, 1984	13

16. SUPPLEMENTARY NOTATION *University of Utah, Salt Lake City, UT 84112
**University of Maryland, College Park, MD 20742 This work was supported by ONR.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Free-electron laser (FEL) Amplifier

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A new intense-beam free-electron laser experiment, operating as a short-pulse amplifier at 35 GHz, has demonstrated linear growth rates of 1.2 dB/cm, total gain of 50 dB, and coherent emission of 17 MW, corresponding to an experimental efficiency of greater than 3%.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☒ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
Steven H. Gold	(202) 767-3358	Code 4740

DD FORM 1473, 83 APR   EDITION OF 1 JAN 73 IS OBSOLETE.

SECURITY CLASSIFICATION OF THIS PAGE

i

A HIGH-GAIN 35 GHz FREE-ELECTRON LASER AMPLIFIER EXPERIMENT

The collective-interaction free-electron laser (FEL), using an intense relativistic electron beam of moderate voltage (~1 MeV) and low axial velocity spread ($\Delta\beta_{\parallel}/\beta_{\parallel} \lesssim 0.1\%$) offers the potential of devices capable of producing extremely high power density continuously tunable millimeter-wave emission.[1] Such devices may have important applications as oscillators for plasma heating[2], and as amplifiers for millimeter-wave communications, and for improved high-gradient particle accelerators.[3] For this reason, there has been substantial interest in demonstrating the feasibility of practical FEL devices.

Recently, collective FEL experiments have reported very high power superradiant millimeter-wave emission (75 MW near 75 GHz), with broad tunability (25 to 100 GHz) and good saturated efficiencies (~6%).[4-6] However, superradiant FEL experiments have several important drawbacks, including lack of coherence (emission linewidths $\gtrsim$ 5%), and difficulty of theoretical modeling. In addition, since starting conditions, radiation growth, and saturation are all intimately linked by the choice of experimental parameters, it is difficult to accurately characterize and optimize these properties separately.

We report here on a new FEL experiment which amplifies an injected coherent wave. This experiment is free from the drawbacks mentioned above for the superradiant FEL, and additionally has the advantage of extrapolating more naturally to practical FEL amplifier devices. While there have been intense beam amplifier experiments based on the cyclotron maser instability[7], this is the first reported high-gain FEL amplifier using an intense relativistic electron beam. At substantially lower

Manuscript approved January 16, 1984.

currents and voltages, millimeter-wave ubitron amplifiers based on similar physical principles were first reported by Phillips.[8] In addition, several recent 10 μm FEL amplifier experiments have been reported.[9] Operating in the Compton regime, at very high voltages and low currents, these devices are characterized by extremely low single pass gains (~1%).

The purpose of this experiment is to test the predictions of theory for the collective FEL, optimize gain and saturated efficiency, and produce a powerful short-pulse source of coherent 35 GHz radiation. In this experiment, a narrowband 35 GHz signal is injected into an FEL interaction and coherently amplified to extremely high power. The experimental setup is illustrated in Fig. 1. A high power magnetron ($\lesssim$20 kW, ~500 nsec pulse) operating at 35.02 GHz is used as the signal source. The signal is either sent directly through standard K_a-band waveguide to the FEL input coupler, or it first transits a high power attenuator to allow controlled variation of the amplitude of the injected signal. The signal is transmitted through a thin mylar vacuum window and injected into the FEL interaction tube in a vertically-polarized TE_{11} mode by means of a directional sidewall coupler (directivity ~20 dB) constructed of two resonant slots separated by 3/4 wavelength and fed by a short-slot hybrid coupler. This microwave signal is launched codirectionally in a 10.8 mm drift tube with a 6-mm-diameter intense relativistic electron beam (~900 keV, 600 A, 60 nsec FWHM) of very low parallel velocity spread ($\Delta\beta_\parallel/\beta_\parallel \ll 1\%$) produced by the VEBA pulseline accelerator.

The interaction region consists of a helically-varying transverse wiggler magnetic field of 3 cm period and 63 cm uniform field length (plus input and output wiggler field tapers of 21 and 15 cm), whose magnitude is adjustable up to 4 kG. In addition, there is an applied axial magnetic field of up to 20 kG that serves both to confine the electron beam and to cause gyroresonant enhancement of the effects of the wiggler magnetic field. This axial field also affects the nature of the FEL instability[10], can directly enhance its saturated efficiency[11], and can be tapered in strength to compensate for the loss of beam-wave synchronism due to kinetic energy extraction from the electron beam and thus further enhance the amplifier saturated efficiency.[6,12] At the end of the interaction, the electron beam is disposed of to the drift tube wall, and the radiation is propagated into the lab via a large microwave horn that tapers smoothly up to a 30 cm i.d. polyethylene window. The radiation emerging from the experiment is sampled by a standard gain K_a-band horn located 1 m from the output horn and is conducted through 10 m of standard waveguide into a screen room. There, it is attenuated by a 30 dB directional coupler, a calibrated rotary-vane attenuator, and an adjustable bandpass filter centered at 35 GHz, and is detected by a calibrated crystal detector terminated in 50 Ω.

The achievement of accurate power and gain measurements is greatly simplified for an amplifier experiment, compared to measurements of single pulse superradiant emission. The procedure is as follows. Two crystal detectors are absolutely calibrated at 35 GHz against a conventional thermistor power meter. (Two power meters were checked against each other to verify their correct operation.) One is used, via a directional coupler and attenuators, as the shot-to-shot monitor of the driver magnetron output, and this is checked directly against the other detector and attenuators which are placed in the line leading to the input coupler. The propagation loss to the input coupler (0.7 dB), through the input coupler (0.9 dB) and to the end of the interaction region (1.5 dB) are determined by substitution measurements against a calibrated attenuator. Thus a particular signal on the first detector corresponds to a known injected signal level. This signal is then detected in the screen room on the second crystal detector after transiting experiment, output horn, pickup horn, waveguide, attenuation, and filter. The system is now absolutely calibrated, and experimental measurement of the vertically-polarized output power of the FEL can be performed at an approximately constant signal level by changing only the setting on the calibrated microwave attenuator in series with the second detector. Rotation of the pickup horn via a waveguide twist permits sampling of the horizontally-polarized emission. This is important because the circularly-polarized wiggler field is expected to amplify only one circularly-polarized component of the injected linearly polarized mode, which should cause equal output signals in each linear polarization. The last experimental requirement is to differentiate between the amplified signal, near 35 GHz, but somewhat broadened by short-pulse effects and possibly by the interaction, and the much broader band superradiant output that has been seen at very high power levels in earlier experiments under somewhat different conditions. For this purpose, a step-twist filter[13] was constructed and used to select a 3-dB bandwidth of 500 MHz centered at 35 GHz. This filter also ensures the accuracy of the total power determination, since crystal detectors are typically somewhat frequency-sensitive.

The experimental strategy was to choose a beam voltage (~800 kV) that would permit approximate "grazing incidence" operation at 35 GHz at a value of transverse velocity ($\beta_{\perp}$) that had proved optimal in earlier superradiant experiments. Grazing incidence corresponds to the tangent intersection of the curves $\omega^2=\omega_{co}^2+k^2c^2$ and $\omega=(k+k_w)v_\parallel$, where (ω,k) are the angular frequency and wavenumber of the output radiation, ω_{co} is the cutoff frequency of the mode of interest (TE_{11}) in the drift tube, $k_w \equiv 2\pi/\lambda_w$, where λ_w is the wiggler period, and c is the velocity of light. For FEL operation above gyroresonance, the intersection of these curves predicts the approximate resonant frequency of the interaction.[4,10] Since saturation can depend strongly on axial field, initial values of B_z were chosen to yield $\beta_\perp \approx .3$ at values of wiggler field (600 G to 1.4 kG) that had proved desirable in the superradiant experiment.

An initial parameter search demonstrated that very high power operation was possible, and that, as noted in previous superradiant experiments[4,6], the introduction of an axial field end-taper near the end of the uniform wiggler interaction region enhanced this power. In addition, pushing to slightly higher beam voltages appeared to improve the performance of the device. In this situation, operating at 900 keV, B_z=11.75 kG, B_r=1.15 kG, a 15 nsec amplified signal was observed that shows a gain of 30.8 dB, referred to the output of the interaction, over the 7 kW injected signal. Correction upward by 3 dB, since the signal was found to be equal in both linear polarizations, produced a peak power of 17 MW, corresponding to an experimental efficiency of ~3.25%. This output was found to be reproducible within 20% over many experimental discharges.

An important consideration in amplifier operation is that the output power track the injected signal. More fundamentally, one would like to establish a region of stable linear amplification, in which the output power is a linear multiple of the input power. To begin such an investigation, the effect of interaction length on the power gain was investigated by progressively reducing the length of the axial field magnet in 6 cm decrements. The use of this procedure is discussed in detail elsewhere.[6] The results are shown in Fig. 2, which plots vertically-polarized output power at two different input power levels as a function of total system length L, arbitrarily defined as the distance from the start of the wiggler entrance taper to the half-field point of the axial field exit taper.

The first data set was taken at an injected signal level of 40 W. These data show a simple exponential growth of power with increasing system length. The best fit line, $P_{out} = \exp[.276(L-32\ cm)]\ P_{in}$, tracks this data well. The expression (L-32 cm) corrects the effective interaction length for those portions of the total system length, namely the entry and exit field tapers, that do not contribute to the linear gain, and also for the effect of launching loss into the growing mode in the interaction. This growth rate corresponds to 1.2 dB/cm, a value about one third lower than values inferred at higher currents, voltages, and microwave frequencies from an experiment operating in a superradiant configuration.[6] No sign of saturation appears in this data set, and the peak gain at L=72 cm is ~50 dB. The true amplifier gain should probably be corrected upwards by an additional 6 dB, since only one circular polarization is expected to grow, while both are injected equally, and since only one linear polarization is detected.

The second data set was taken at an injected signal level of 8 kW. In this case, clear signs of saturation appear, beginning at L=54 cm. From that point onward, output power increases by no more than 50% over the next three 6 cm increments in length. Using the same best-fit formula, a second line is drawn corresponding to P_{in}=8 kW. It fits the remaining (unsaturated) data well. This result demonstrates that gain is a linear function of interaction length. It also demontrates that unsaturated output power is a linear function of input power, as expected in a true traveling-wave amplifier, over a factor of 200 variation in input power.

The functional relationship of unsaturated output power to input power is shown more explicitly in Fig. 3. These data, taken at a fixed system length and at slightly higher voltage than the previous two data sets, show the input varied by a factor of almost 1000, from 8.5 W to 8 kW. A clear linear relationship between P_{out} and P_{in} exists until saturation effects limit further increases in the output power.

It should be emphasized that these signals are true amplified signals, and not the broadband superradiant emission seen in previous experiments. The emission is coherent, and passes easily through the 500 MHz bandpass filter. While the magnetron signal is very narrowband (<5 MHz), the short output pulse length implies a minimum emission linewidth of 10 MHz. The amplified linewidth is expected to be of this order. The superradiant emission can be measured in the absence of an injected signal, and is a function of L. At L=72 cm, the spectral power density of the peak amplified signal is at least 34 MW/GHz, based on transmission through the 500 MHz bandpass filter, and may exceed this by an order of magnitude. The measured superradiant signal through this filter is of order 10 kW, or 20 kW/GHz, more than three orders of magnitude less.

In conclusion, we have demonstrated for the first time an extremely high power, high gain true FEL amplifier using an intense relativistic electron beam. In operation at 35 GHz, it has demonstrated coherent amplification, with peak powers of ~20 MW at >3% efficiency, high gain per unit length (~1.2 dB/cm), and very high total gain ($\gtrsim$50 dB). We hope to further characterize and optimize its output in future studies. It is already a unique source of coherent short-pulse microwave radiation, and *shows the great potential of FELs as high gain amplifiers, and as powerful* coherent millimeter-wave sources.

This work was supported by the Office of Naval Research.

REFERENCES

1. See e.g. V.L. Granatstein, et al., in Handbook of Laser Science and Technology, edited by M.J. Weber (CRC, Boca Raton, 1982), Vol. I, p. 441.
2. D. Arnush, et al., Int. J. Electron. 53, 605 (1982).
3. A.M. Sessler, in Laser Acceleration of Particles, edited by P.J. Channell (AIP, New York, 1982), p. 154.
4. S.H. Gold, et al., Phys. Fluids 26, 2683 (1983).
5. R.H. Jackson, et al., IEEE J. Quantum Electron. QE-19, 346 (1983).
6. S.H. Gold, et al., Phys. Fluids, to be published. (March, 1984)
7. V.L. Granatstein, et al., J. Appl. Phys. 46, 3800 (1975).
8. R.M. Phillips, IRE Trans. Electron Devices ED-7, 231 (1960), and Proc. 4th Int. Congress on Microwaves Tubes (Centrex, Eindhoven, 1963), p. 371.
9. See e.g. B.E. Newnam, et al., LANL Report No. LA-UR-83-2492, to be published in Proc. 1983 Free-Electron Laser Workshop, Orcas Island, WA.
10. H.P. Freund and P. Sprangle, Phys. Rev. A28, 1835 (1983).
11. H.P. Freund, Phys. Rev. A27, 1977 (1983).
12. H.P. Freund and S.H. Gold, submitted to Phys. Rev. Lett.
13. B.C. DeLoach, Jr., IRE Trans. Microwave Theory Tech. 9, 130 (1961).

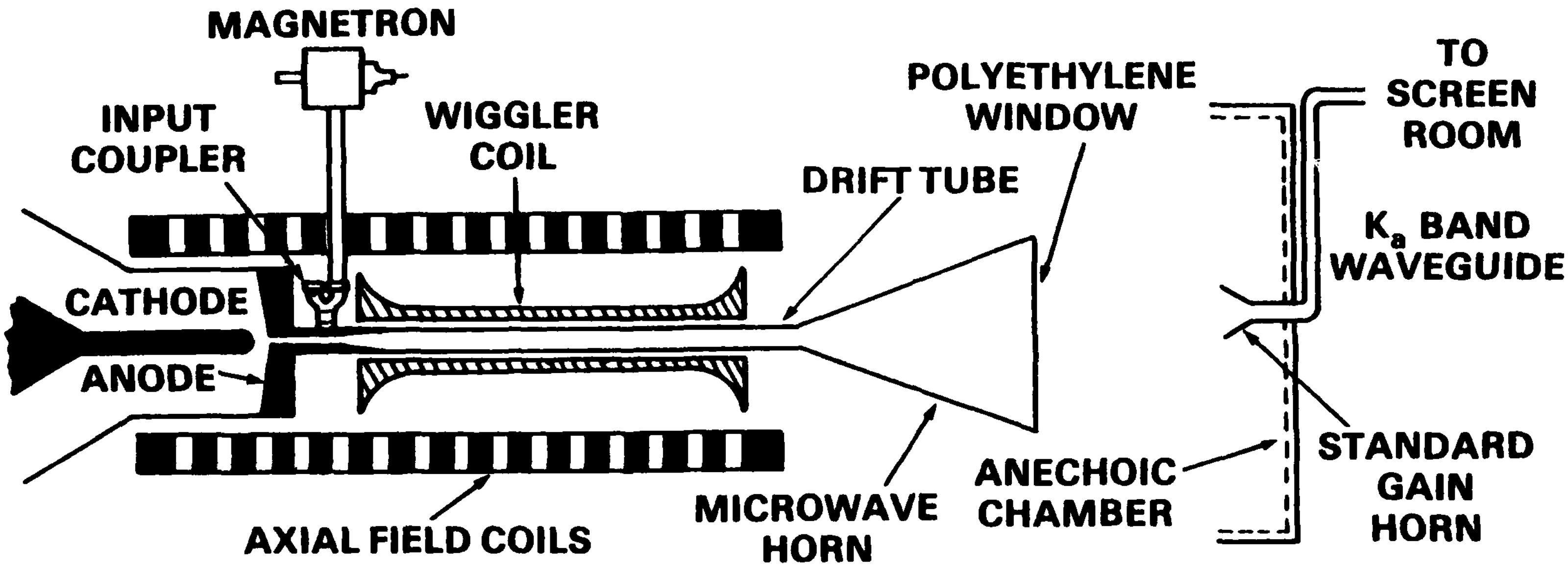


Fig. 1. Free-electron laser amplifier experimental configuration.

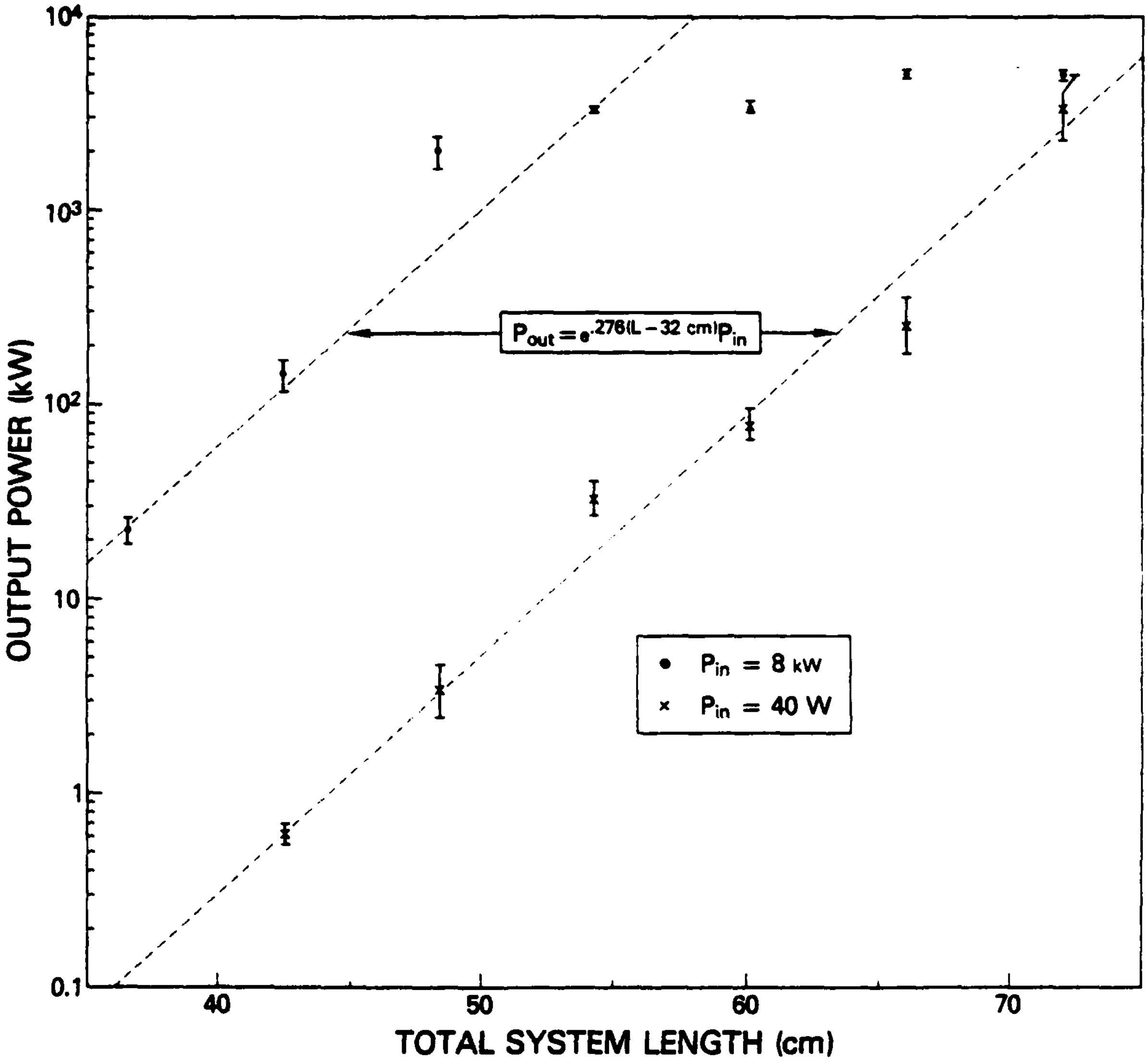


Fig. 2. FEL output power versus system length for input power levels of 40 W and 8 kW.

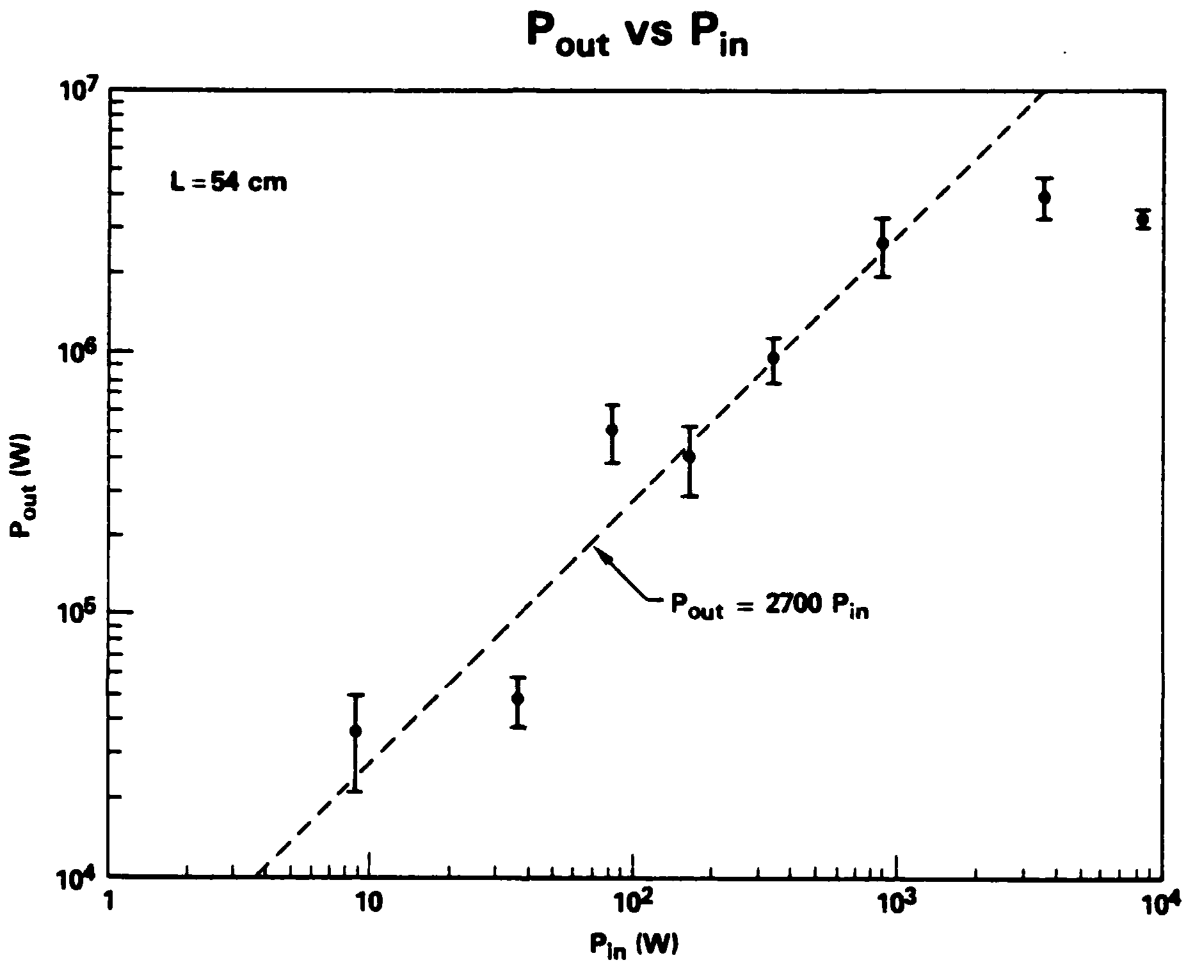


Fig. 3. FEL output power versus input power at L=54 cm.

DA

FILM