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TITLE: EVOLUTION OF LONG PULSES IN A TAPERED WIGGLER-FREE ELECTRON LASER

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Evolution of Long Pulses in a Tapered Wiggler Free Electron Laser*

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Abstract

The evolution of a long pulse (pulse length much greater than the slippage distance) in a tapered wiggler free electron laser oscillator is studied by numerical solution of the one dimensional theoretical model for a realistic set of magnet, electron beam, and optical resonator parameter values. Single pass gain curves are calculated for low and high light intensities. It is found that an initial, low amplitude, incoherent pulse grows into a coherent pulse whose growth rate agrees with the calculated small signal gain curve. The transient evolution of coherent pulses is calculated for several different cavity length detunings, and a quasi-steady-state desynchronism curve is obtained. Various pulse features for two points along the desynchronism curve are given. The frequency changing behavior ("chirping") of the optical pulse during transient evolution is examined.

Introduction

Several different one-dimensional theoretical models have been developed to treat the evolution of temporally-finite pulses in a free electron laser (FEL) oscillator.[1-3] Comparisons of the results of numerical evaluations of these theoretical models with data from the Stanford University uniform wiggler FEL experiment seem to show semiquantitative agreement.[1-4] The theoretical models have been slightly extended to treat tapered wiggler FELs[1,5] and predictions of the performance of such FELs have been made.[5-7] In this work, we use another slight modification of the theory[8] for plane polarized wigglers to predict the performance of a tapered wiggler oscillator driven by a long electron pulse. That is, the length of the electron pulse is much longer than the slippage distance that characterizes the amount by which electrons slip behind a point on the envelope of the optical pulse as they make one transit through the wiggler.

Optical Properties

We assume a typical linear accelerator driven Compton regime FEL oscillator in which the linac produces short pulses of electrons which are magnetically guided down the axis of an optical resonator containing a coaxial plane polarized tapered wiggler magnet. After interacting with the optical pulse during their passage through the wiggler, the electrons are magnetically guided out of the device and a new pulse of electrons from the linac enters in time to meet the optical pulse on its next passage through the wiggler region. The condition of exact synchronism occurs when the interval between successive electron pulses from the linac equals the round trip time of light in the resonator. Usually the time between electron pulses is fixed so that the deviation of the resonator length from that at exact synchronism strongly determines the properties of this type of laser.

We shall calculate the properties of the system specified by the parameter values given in Table 1. The wiggler magnet is 100 cm long with an 11% taper in wavelength. The precise variation of the wavelength and magnetic field amplitude along the wiggler's axis is shown in Fig. (1). The synchronous particle would decrease in energy by 7.35% in this magnet. The optical resonator has a Rayleigh range of 62.5 cm and the mirror losses are taken to be 7%. The electron beam is taken to be monoenergetic with a peak current of 40 A in a 30 ps (FWe^{-1}) pulse. The difference between the velocity of light and the electrons' axial velocity in the wiggler of Fig. (1) implies that the electrons slip a distance of 0.038 cm relative to a point on the envelope of the optical pulse on each transit through the wiggler. This distance is about 4% of the electron pulse length; the corresponding figure for the Stanford experiments is about 48%.

The one dimensional theoretical model of Ref. (8), modified to include the axial variations of the wiggler shown in Fig. (1), yields the CW (i.e., for long pulses, neglecting slippage) single pass gain curves shown in Fig. (2). Note the difference between the wavelength of maximum small signal gain, 10.35 μm from Fig. (2a), and the wavelength of maximum large signal gain, 10.7 μm from Fig. (2b). This behavior requires that the optical pulse change its spectrum during the course of its evolution from low intensity to high

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intensity. The way in which this "chirping" occurs is addressed below. Fig. (2c) is a plotof the maximum single pass CW gain (at whatever wavelength it occurs) versus intensity. From this plot one might guess that the optical pulse will reach an intensity of 3×10^{10} w/cm^2 in order for the saturated gain to equal the 2% cavity losses.

<u>Table 1: System Parameters</u>

WIGGLER	
Length	100 cm
Field Strength	0.3 T
Wavelength Range	2.73 - 2.43 cm
Energy Taper	7.35%
RESONATOR	
Rayleigh Range	2.5 cm
Filling Factor	0.78
Design Resonant Wavelength	10.59 microns
Round Trip Intensity Loss	2%
ELECTRON BEAM	
Peak Current	40 A
Pulse Length	0.9 cm
Beam Diameter	0.18 cm
Slippage Distance	0.038 cm
Initial Energy	20.85 MeV

The theoretical model used here to calculate pulse evolution assumes coherent light. Initially, light is emitted spontaneously by the first pulse of electrons to transit the wiggler and is in fact incoherent. A detailed treatment of the growth of light from spontaneous emission in a uniform wiggler FEL has been given by Georges.[6] While we have not repeated that calculation for the tapered wiggler of Fig. (1), we have calculated the evolution of a very low intensity, initially incoherent, pulse. Such a pulse has zero average electric field but nonzero average intensity. Choosing the amplitude and phase randomly using Gaussian statistics produces a pulse with an approximately constant spectrum (white noise). We have observed that such a pulse will grow from an intensity equal to the spontaneous emission level into a coherent pulse. By "coherent pulse" we mean that after 100 to 150 passes the spectrum is narrow and centered about the small signal gain point of 10.35 μm, and the rate of growth of the pulse is equal to that given in Fig. (2a), namely about 15% per pass (minus the cavity losses). Hence, we have some confidence that the laser system specified in Table 1 will start up from spontaneous emission. However, we emphasize that these results do <u>not</u> constitute a rigorously correct modeling of the startup problem for a tapered wiggler; rather, they indicate that one should add perhaps 150 passes to the time evolution curves to be presented below to account for growth from spontaneous emission.

<u>Pulse Evolution</u>

Figure (3) shows the evolution of the energy of a coherent optical pulse which initially has a small amplitude (which is nevertheless 4 or 5 orders of magnitude above the spontaneous emission intensity) and a wavelength corresponding to the peak small signal gain of Fig. (2a). The different curves correspond to cavity lengths shorter by the indicated amounts than the length for exact synchronism with successive electron pulses from the linac. For the shortest cavity lengths, the light intensity builds up to a relatively low value and reaches a steady state. For small values of cavity length change, the optical pulse rises to high intensity in about 1500 passes. A true steady state is not reached within 2000 passes for these cases as the pulses continue to evolve slowly, as evidenced by the oscillations of their energies. We refer to such oscillatory states as quasi-steady-states.

Figure (4) summarizes the optical pulse energies versus cavity length detuning for the quasi-steady-states achieved after 1750 passes. One expects the laser output to fall quickly to zero at positive values of cavity length detuning (cavity length increases) so that this FEL system is expected to have appreciable output only over about 20 microns of cavity detuning. The maximum energy extraction efficiency from the electrons, corresponding to the peak of the curve of Fig. (4), is 2.6%.

Figure (5) compares specific pulse characteristics after 1750 passes for two different detunings: -18 μm and -[illegible].3 μm. Figures (5a) and (5b) show the intensity profiles at the end of the wiggler. Note that the abrupt termination of the intensity in Fig. (5a) is an artifact of the calculation: the pulse should have an exponentially decreasing leading edge which varies as $\exp(-[(1 - \ell)/2\delta L](z - z_o))$ where $\delta L = 1.5 \times 10^{-3}$ cm, $\ell = .02$, and $z_o = 101.16$ cm. The light ahead of z_o ($z > z_o$) never overlaps any electrons and therefore experiences only cavity losses. It is neglected to simplify the numerical calculations. Note further that the intensity of the $\delta L = -1.5$ μm case is strongly modulated and much higher than that for $\delta L = -18$ μm. The optical spectra of these two pulses are shown in Figs. (5c) and (5d) where one observes that the low intensity pulse's spectrum is at the wavelength of peak small signal gain, while the high intensity pulse has a complicated spectrum whose peak is shifted to about 10.9 μm. The corresponding electron energy spectra are shown in Figs. (5e) and (5f) where one sees that the low intensity pulse has scarcely modified the initially monoenergetic electron beam while the high intensity pulse yields the characteristic double-peaked energy distribution expected for a saturated tapered wiggler FEL.[8,10] Hence, one has a considerable variation of expected phenomena over the cavity length detuning range of this device.

As noted above in the discussion of the CW single pass gain curves for this system, the wavelength of maximum gain shifts progressively to longer wavelengths as the intensity of the light in creases from small signal values to saturated values. To maintain maximum growth rates, the optical pulse's frequency must change during the evolution toward steady state. Figure (6) shows how the optical spectrum evolves during an early stage of the chirping process. The spectrum does not move smoothly; rather, a sideband first developes, as seen in Fig. (6a). The sideband amplitude grows until it equals the main peak, Fig. (6b), and finally the main peak decays leaving most of the light at the sideband wavelength, Fig. (6c). Hence, the spectrum evolves in a stepwise fashion, not shifting continuously but rather through a series sidebands to progressively longer wavelengths. The final state of evolution is shown in Fig. (5d), and the latter stages of evolution are more complicated than the initial stages shown in Fig. (6). The wavelength of the sideband in Fig. (6) is shifted by about 2.5% from that of the small signal gain peak of 10.35 μm. This shift is consistent with an electron synchrotron period about aqual to the magnet length[8], a condition which implies that the modulation of the envelope of the optical field is about equal to the slippage distance.[8] This modulation is indeed present, and the average intensity of the pulse is approximately consistent with a synchrotron period equal to the magnet length. This type of sideband generation was observed for a uniform wiggler FEL as well.[8]

Summary

A tapered wiggler free electron laser oscillator has been studied within the limitations of a one-dimensional theoretical model. A realistic set of parameter values for the magnet, electron beam, and optical resonator where used. CW gain curves were calculated at low and high light intensity. A low-amplitude incoherent pulse was found to develop coherence and subsequently grow at the expected small signal rate. The growth of a coherent pulse from low amplitude to saturation was calculated for various cavity length detunings. High intensity pulses were observed to reach a quasi-steady-state within 2000 passes through the resonator. The width of the corresponding desynchronism curve was seen to be about 20 microns. A maximum energy extraction efficiency from the electron beam of 2.6% was observed. The process by which the light adjusted its frequency to follow the change of the gain maximum with increasing light intensity was observed to occur approximately by successive discrete steps involving the generation of sidebands with frequency steps related to the electron synchrotron frequancy.

Acknowledgment

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Figure Captions

Fig. (1) : Wiggler wavelength and field amplitude vs. axial position.

Fig. (2a): CW single pass gain at 10^6 w/cm^2.

Fig. (2b): CW single pass gain at 10^{10} w/cm^2.

Fig. (2c): Maximum CW single pass gain vs. intensity.

Fig. (3) : Optical pulse energy vs. pass number for several different cavity lengths.

Fig. (4) : Quasi-steady-state optical pulse energy vs. cavity detuning.

Fig. (5a): Intensity profile for $\delta L = -18$ µm.

Fig. (5b): Intensity profile for $\delta L = -1.5$ µm.

Fig. (5c): Spectrum for $\delta L = -18$ µm.

Fig. (5d): Spectrum for $\delta L = -1.5$ µm.

Fig. (5e): Electron spectrum for $\delta L = -18$ µm.

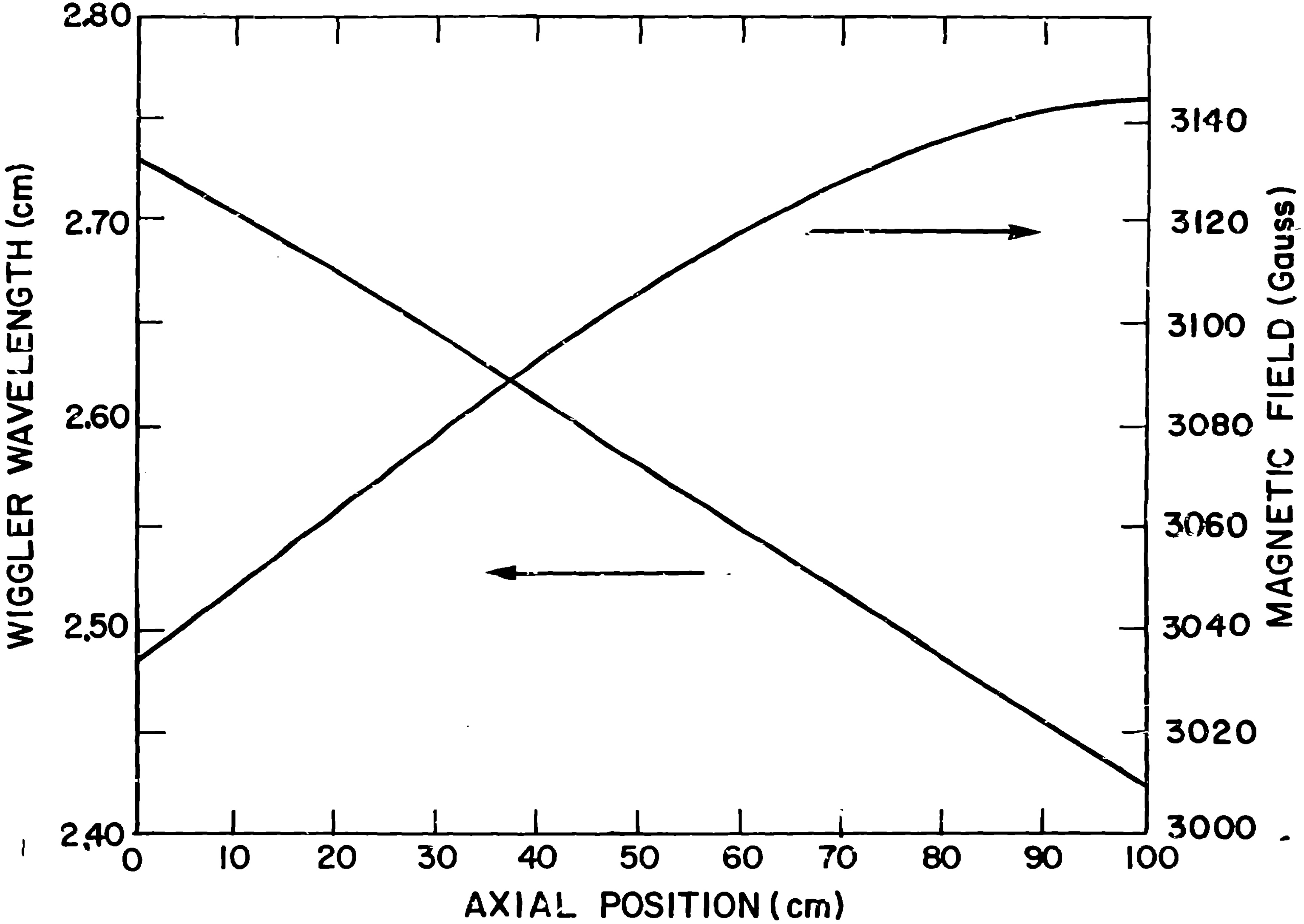
Fig. (5f): Electron spectrum for $\delta L = -1.5$ µm.

Fig. (6a): Spectrum after 775 passes.

Fig. (6b): Spectrum after 850 passes.

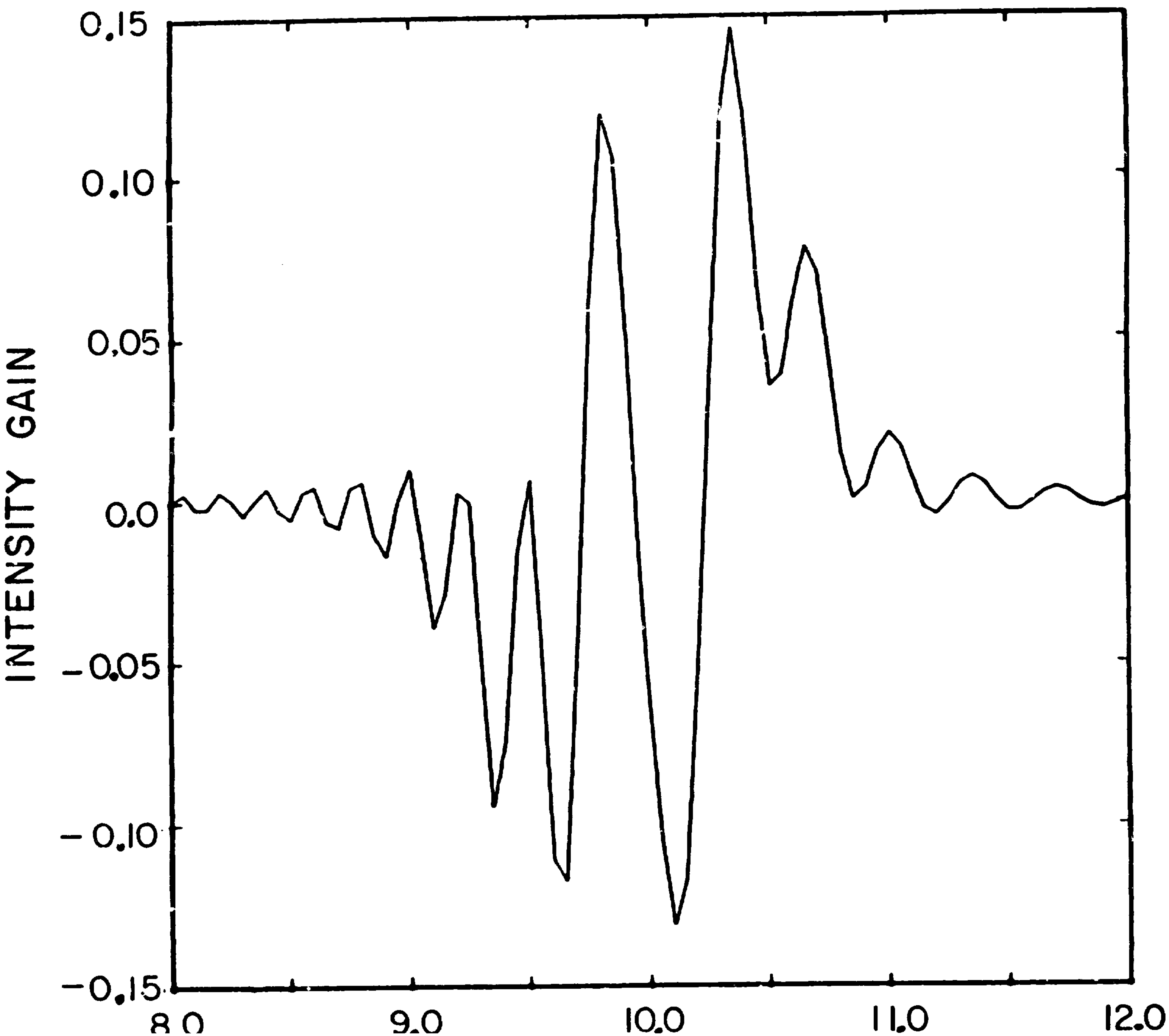
Fig. (6c): Spectrum after 925 passes.

FIGURE 1

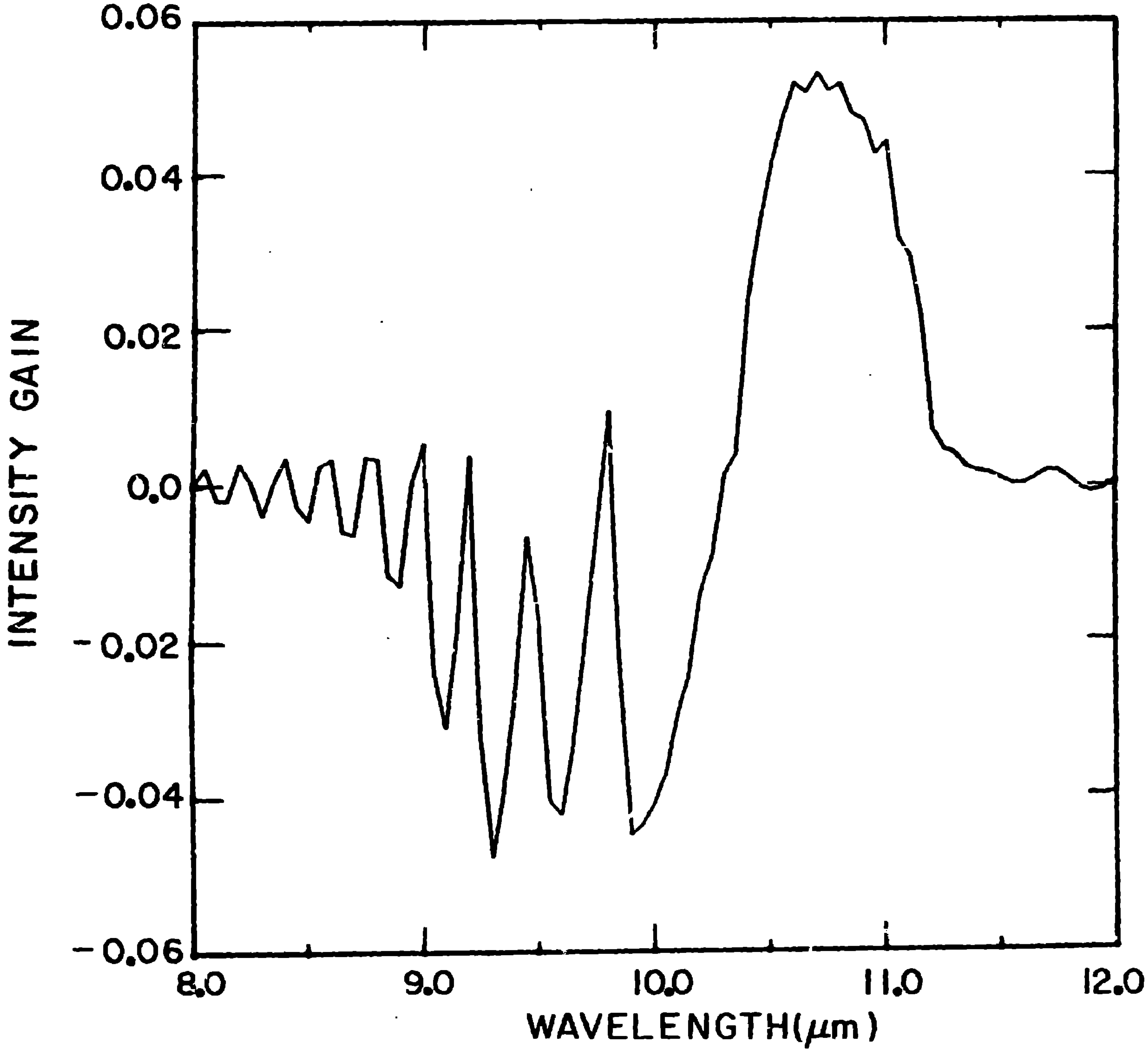


WIGGLER WAVELENGTH (cm)
2.80
2.70
2.60
2.50
2.40
MAGNETIC FIELD (Gauss)
3140
3120
3100
3080
3060
3040
3020
3000
0
10
20
30
40
50
60
70
80
90
100
AXIAL POSITION (cm)

FIGURE 2a

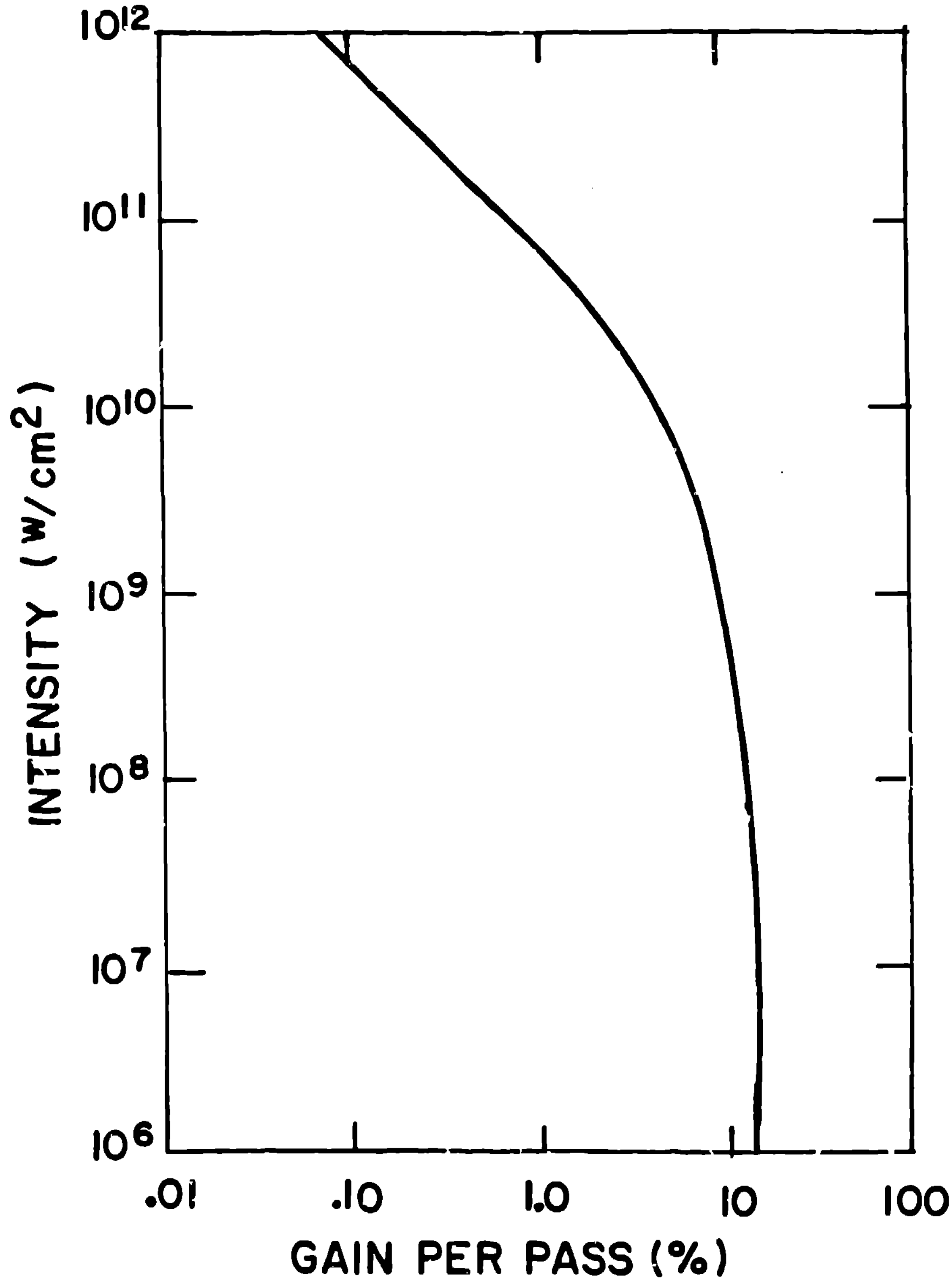


F1 URE 2b



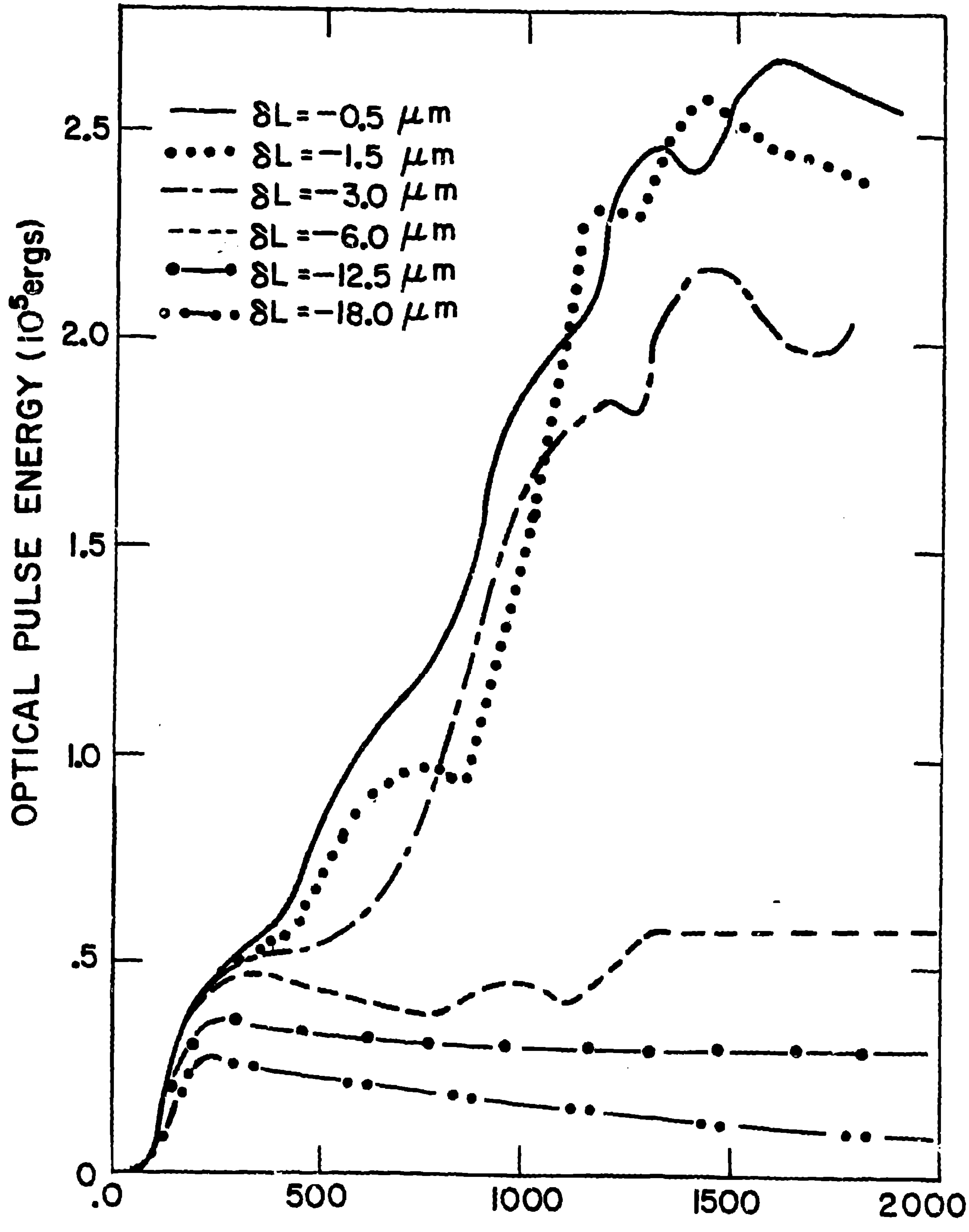
0.06
0.04
0.02
0.0
-0.02
-0.04
-0.06
INTENSITY GAIN
8.0
9.0
10.0
11.0
12.0
WAVELENGTH(μm)

FIGURE 2c



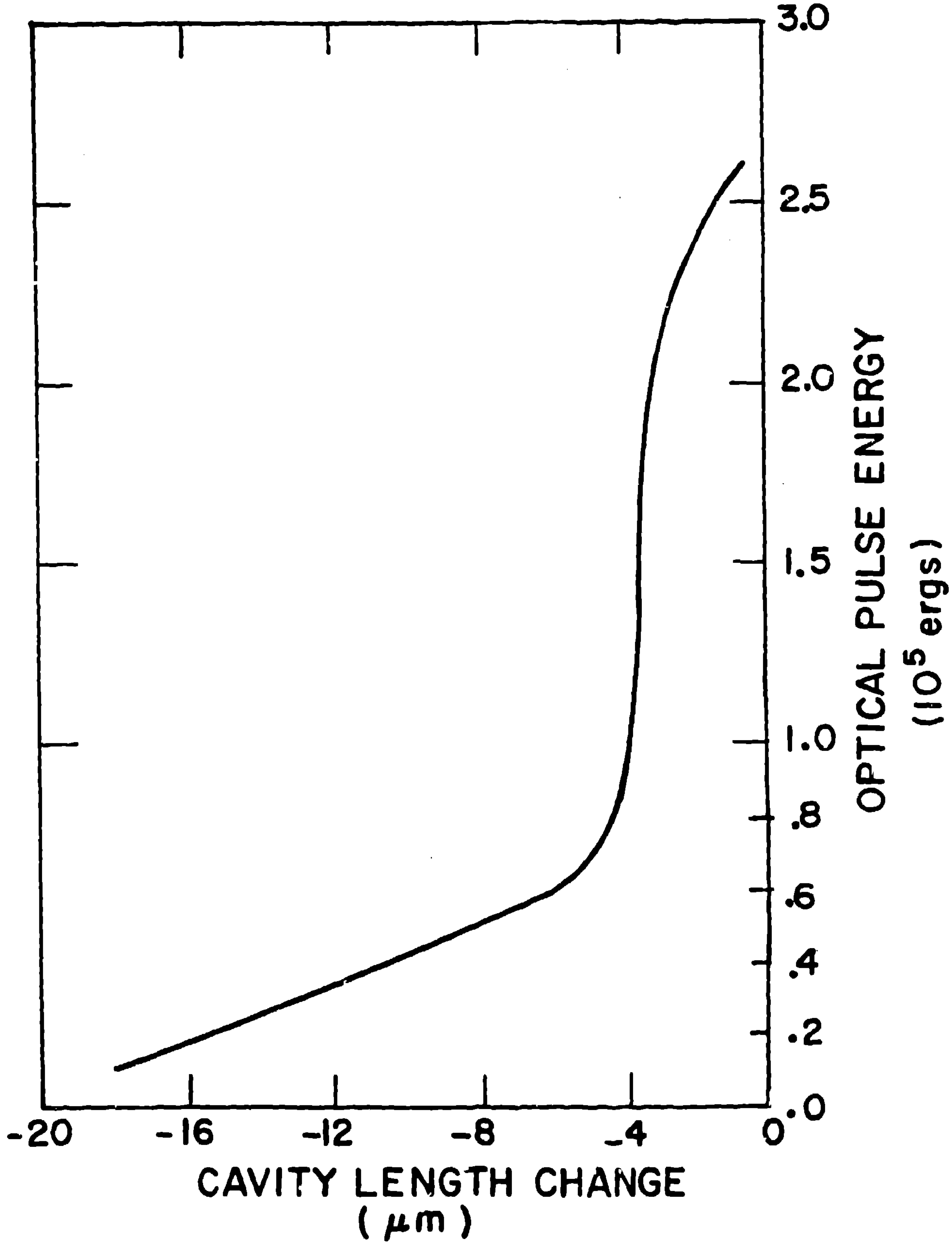
10^12
10^11
10^10
10^9
10^8
10^7
10^6
INTENSITY (W/cm²)
.01
.10
1.0
10
100
GAIN PER PASS (%)

FIGURE 3



δL = −0.5 μm
δL = −1.5 μm
δL = −3.0 μm
δL = −6.0 μm
δL = −12.5 μm
δL = −18.0 μm
OPTICAL PULSE ENERGY (10⁵ergs)
0
.5
1.0
1.5
2.0
2.5
.0
500
1000
1500
2000
NUMBER OF PASSES

FIGURE 4



3.0
2.5
2.0
1.5
1.0
.8
.6
.4
.2
.0
OPTICAL PULSE ENERGY
(10^5 ergs)
-20
-16
-12
-8
-4
0
CAVITY LENGTH CHANGE
(μm)

FIGURE 5a

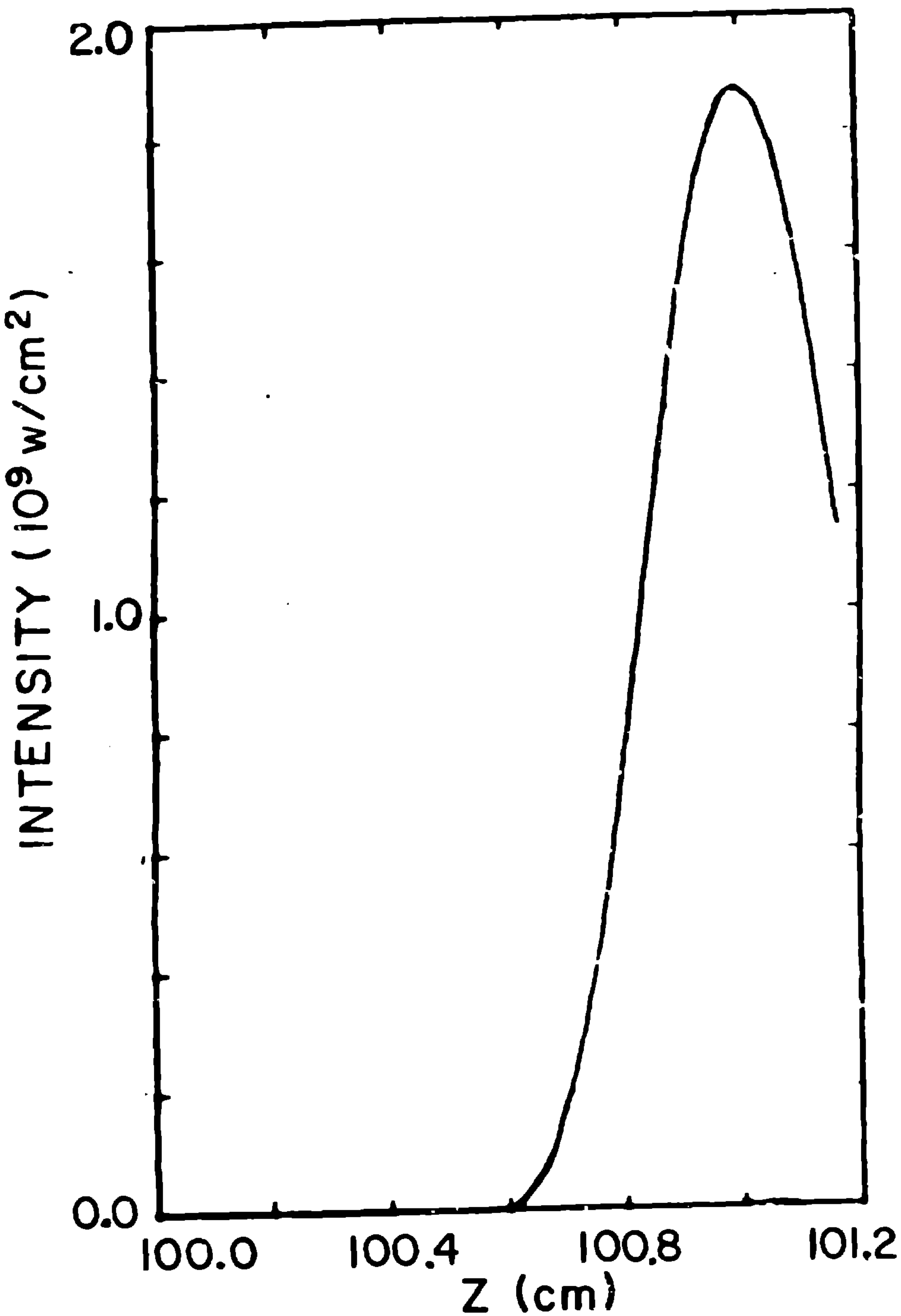


FIGURE 5b

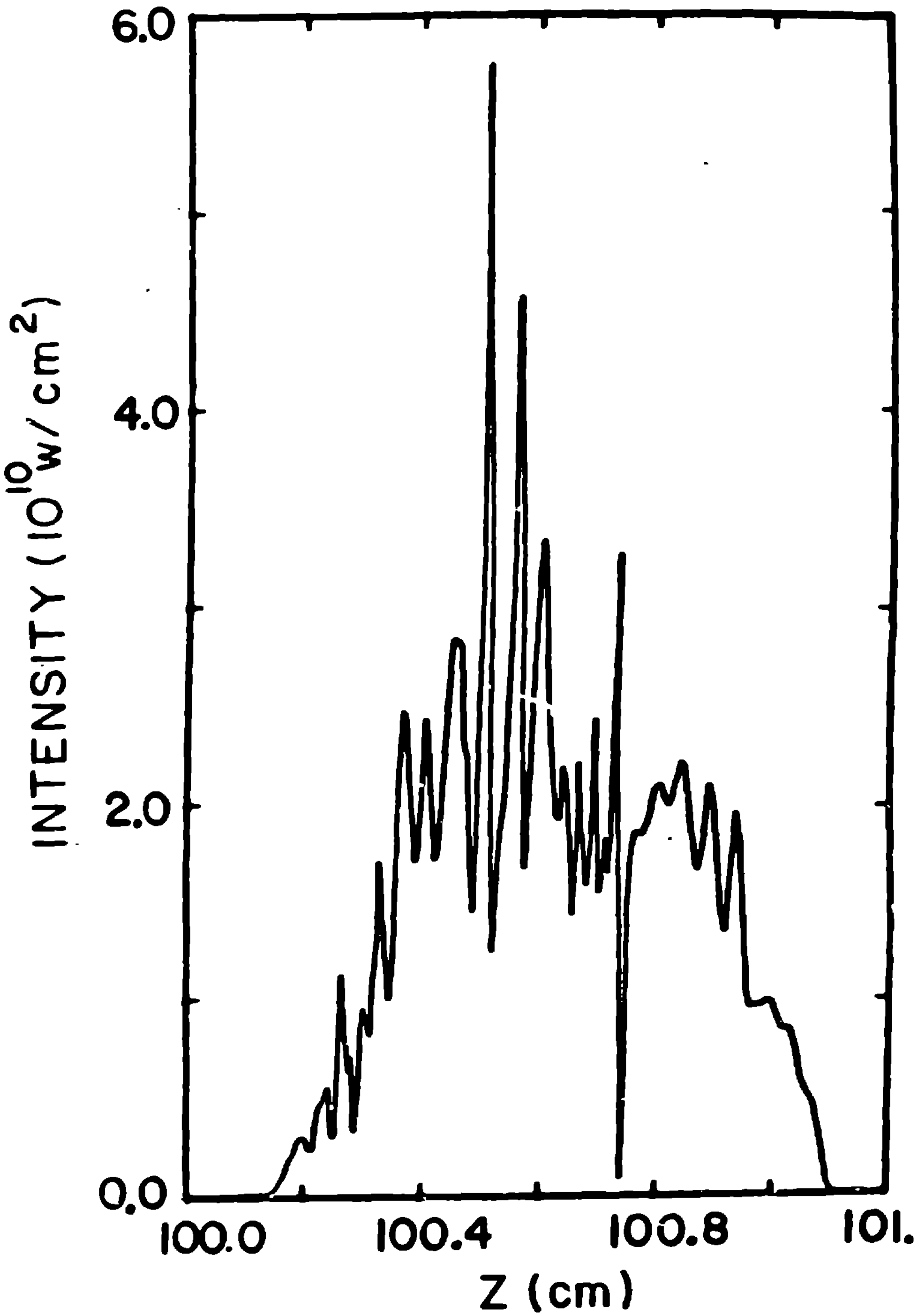


FIGURE 5c

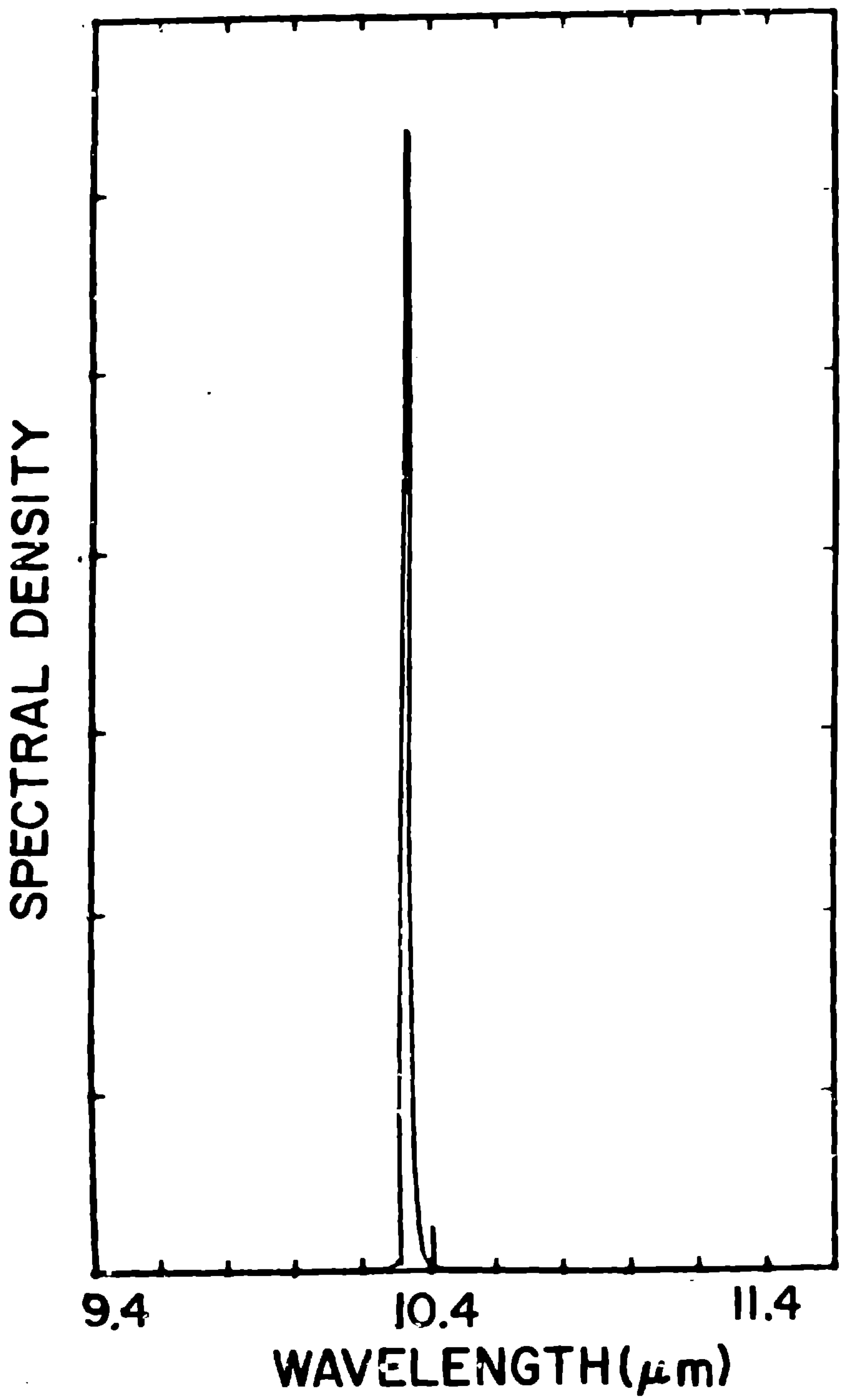


FIGURE 5d

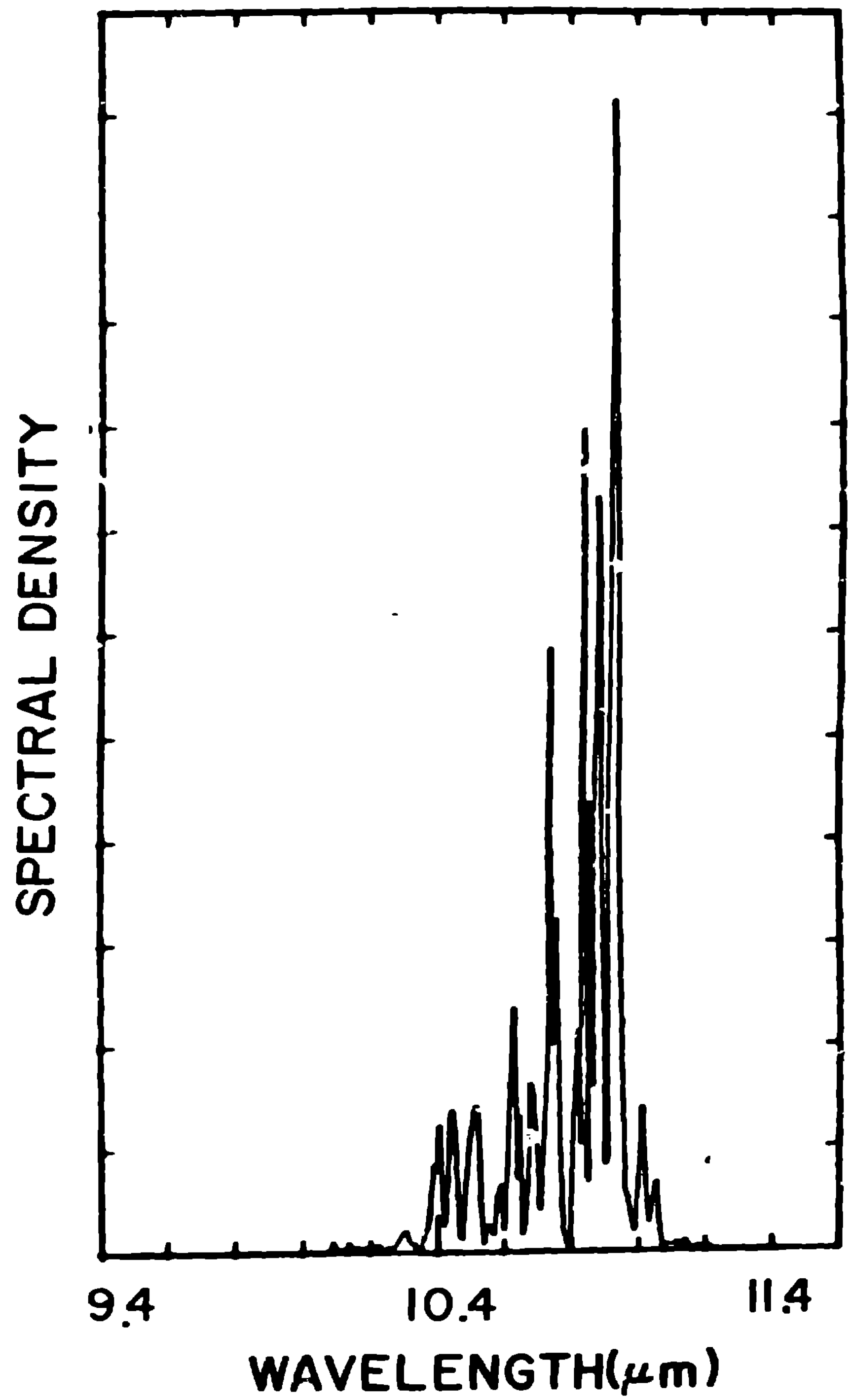


FIGURE 5e

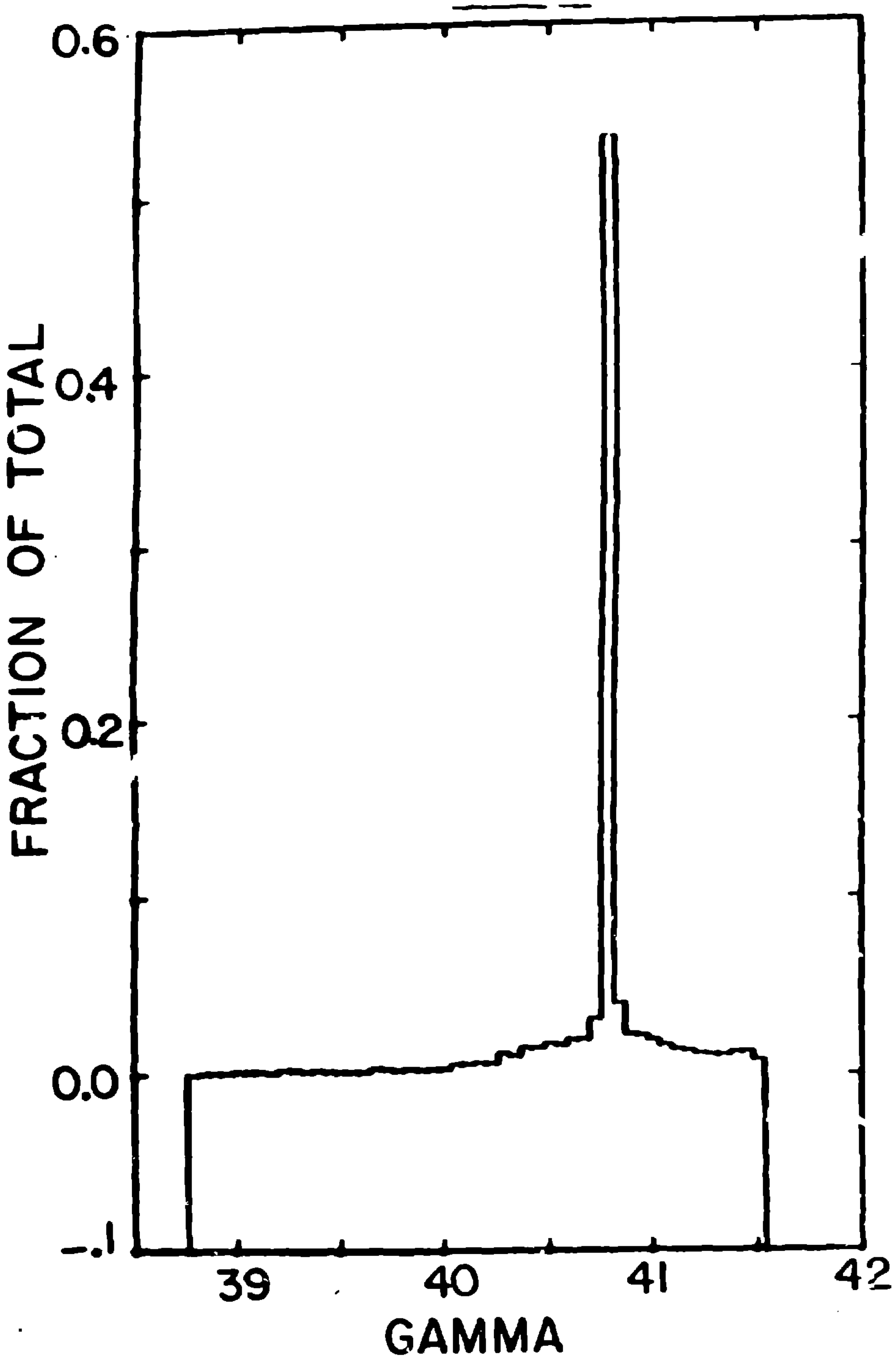


FIGURE 5f

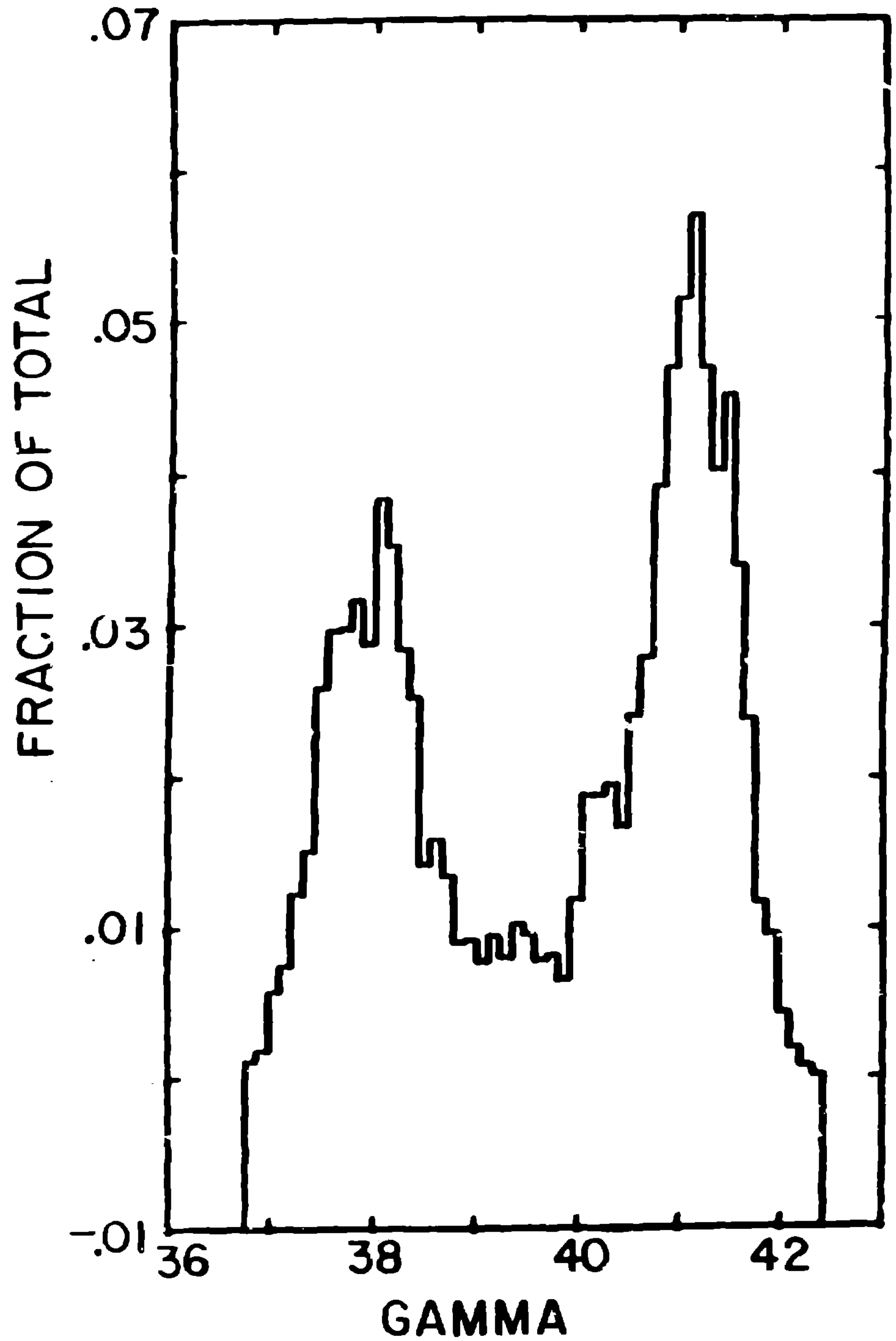


FIGURE 6a

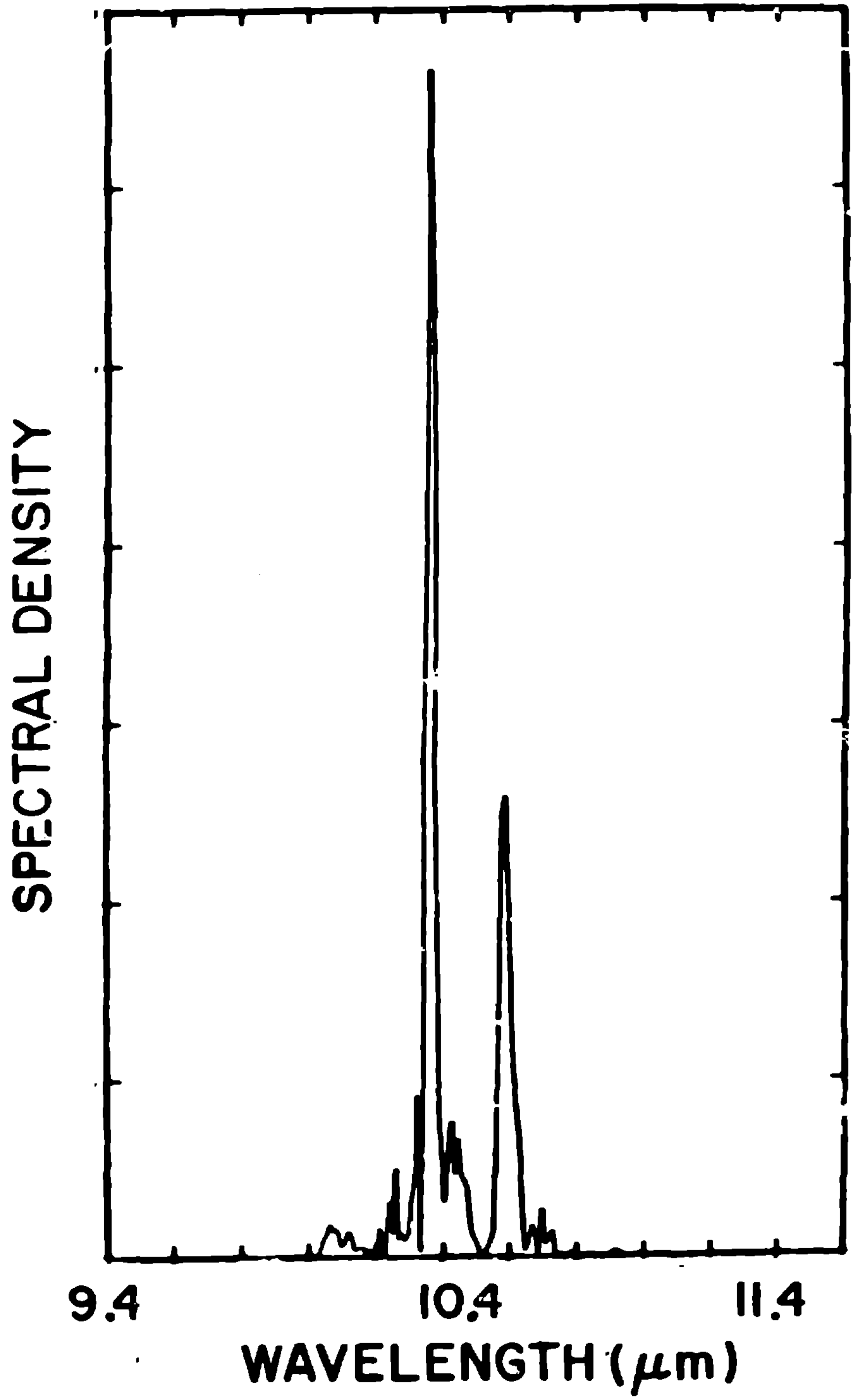


FIGURE 6b

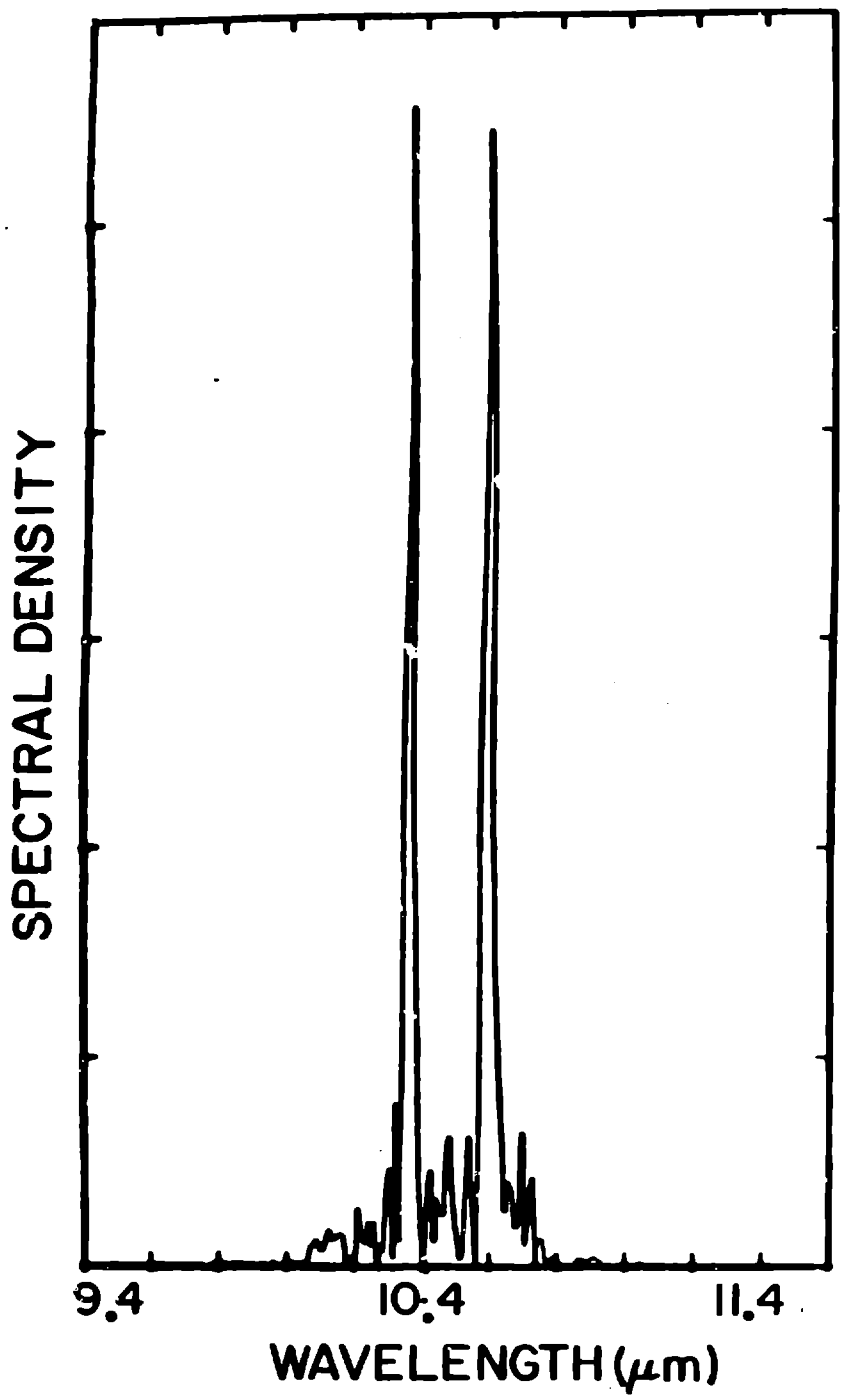


FIGURE 6c