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**COLD-CATHODE, ELECTRON-BEAM-SUSTAINED
CO₂ AMPLIFIER GAIN STUDIES**

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January 28, 1975

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COLD-CATHODE, ELECTRON-BEAM-SUSTAINED CO₂ AMPLIFIER GAIN STUDIES

Abstract

Measurements of small-signal gain coefficients have been made on electron-beam-sustained CO₂ laser amplifiers, having clear apertures of 11 × 11 cm and

operated at 1520 Torr. Gain uniformity over the full aperture, gain as a function of E/p, gas mixture, and rotational line have been investigated.

Introduction

A number of authors have described large-aperture CO₂ amplifiers built to operate at pressures of one or more atmospheres.¹⁻⁵ Generally these units have been designed for high spacial uniformity of the small-signal gain coefficient, α , to avoid degradation of the quality of the laser beam passing through them. That is, the gain measured at all points within the amplifier's usable aperture should be as nearly equal as possible. At LLL well-known techniques have been used to investigate the gain of one 10-cm- and two 11-cm-aperture, cold-cathode, electron-beam-sustained CO₂ amplifiers.⁶ Besides establishing operating parameters for these three units, our measurements provide a reliable data base against which CO₂ amplifier models may be compared.

The devices studied are shown in the cutaway drawing in Fig. 1. Two identical power amplifiers of this design make up the output stages of the LLL short-pulse CO₂ laser system shown in the insert in Fig. 1. The 10-cm-aperture device was the prototype for these amplifiers, and

data taken on the prototype guided the design of the other two units. The cylindrical electron-gun vacuum vessel shown in Fig. 1 is evacuated to about 10⁻⁶ Torr. At $t = 0$, 200 kV are impressed on the array of tantalum strips that constitute the electron gun's "cold" cathode. As a result, a sheet beam of electrons about 10 cm wide by 1 m long emerges through a 1-mil-thick titanium foil window, supported by the hibac structure drawn in Fig. 1.

After penetrating the titanium foil window, the electron beam passes through a coarse-mesh stainless-steel screen, not shown, and produces a partial ionization of about 10⁻⁶ in the 11 × 11 × 100-cm discharge volume located between this cathode screen and the large profiled graphite anode in Fig. 1. The graphite anode is connected to a capacitor bank charged to provide an E/p ratio of about 4 kV/cm-atm in the discharge volume filled with a mixture of He, CO₂, and N₂. In normal operation the primary electron-beam current is terminated after 2 μ sec by crowbarring the electron-gun's Marx

Fig. 1. Cutaway drawing of a cold-cathode, electron-beam-sustained CO_2 amplifier.

bank. The discharge bank is crowbarred simultaneously, with the net result that about 200 J/liter-atm are deposited in

the laser gas. The following is an account of several measurements made to characterize these amplifiers.

Electrical Parameter Measurements

The 10-cm-aperture prototype was plagued by minor electrical problems which prevented the accumulation of reliability data. Foremost were timing problems, i.e., crowbars would fire or not seemingly at random. Nonetheless, a sequence of 840 shots was fired without a foil window failure. The two 11-cm-aperture amplifiers were designed to eliminate these problems. Among other things, the discharge cavity was redesigned to insure uniform electric fields in the gain region and to avoid sharply reduced structures that might cause arcing.

The electron-gun's Marx bank and the discharge bank of the 11-cm-aperture amplifier may be modeled as simple RLC circuits with the following circuit components: electron-gun inductance $\approx 2 \mu\text{H}$, capacitance $\approx 0.45 \mu\text{F}$, and resistance $\approx 1 \Omega$; discharge inductance $\approx 0.3 \mu\text{H}$, capacitance $= 4.5 \mu\text{F}$ for 2-atm operation, and resistance $\leq 0.01 \Omega$. The electron gun was typically operated with a 13-cm anode-to-cathode spacing at 200 kV for a pulse duration of 2 μsec . Current and voltage sensors built into these circuits

provided diagnostic traces like those in Fig. 2 on every firing. These oscillographs were digitized and the data reduced with a small computer. The time history of the primary electron-beam current was measured by using the graphite discharge anode as a Faraday cup. The nearly rectangular pulse so obtained is displayed in Fig. 3.

A formal, 190-shot test sequence was conducted to establish the reliability of

these units with the following results

($\sigma \equiv$ standard deviation):

Electron-gun current $\bar{J} = 0.68 \text{ A/cm}^2$
 $\sigma_J = 0.002 \text{ A/cm}^2$

Peak discharge current $I_{pk} = 35 \text{ kA}$
 $\sigma_I = 1.2 \text{ kA}$

Pulse width $\Delta t = 2.04 \text{ } \mu\text{sec}$

Energy deposited $\bar{\epsilon} = 203 \text{ J/liter-atm}$
 $\sigma_{\epsilon} = 9 \text{ J/liter-atm}$

a

Upper trace: electron-gun voltage
 (140 kV/cm)

Lower trace: electron-gun current
 (3 kA/cm)

b

3:1:2 gas mix at 760 Torr

Upper trace: discharge voltage for
 44-kV charge (35 kV/cm)

Lower trace: discharge current
 (15 kA/cm)

c

3:1:2 gas mix at 1520 Torr

Upper trace: discharge voltage for
 88-kV charge (35 kV/cm)

Lower trace: discharge current
 (15 kA/cm)

Fig. 2. Voltage and current traces; horizontal scales = $1 \text{ } \mu\text{sec/cm}$.

Fig. 3. Time history of the primary electron-beam current for a 13-cm electron-gun anode-to-cathode spacing and a roughing pump vacuum in the discharge chamber. Max voltage = 300 kV, $J = \sim 0.5 \text{ A/cm}^2/\text{cm}$, and time = 1 $\mu\text{sec/cm}$.

Reliability	0.92 at 50% confidence (failures were premature crowbars or misfires)
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No. of shots	190
Repetition rate	1 ppm
Gas mix	$\text{He:N}_2:\text{CO}_2 \approx 3:1:2$
E/p	4 kV/cm-atm
Pressure	760 Torr

Subsequent tests have been made at about 1520-Torr operating pressure and circuit modifications improved the reliability, but the formal test sequence was not repeated.

A Faraday cup array was used to establish the primary electron-beam current density distribution in vacuo 1 cm from the foil windows. The variation

was slight along the 1-m dimension, but important variations were observed transverse to the electron gun along the 10-cm dimension, as shown in Fig. 4. Separate measurements at three locations with a shielded Pearson probe confirmed these data. Summarized, the electron-beam uniformity measurements made at a charge voltage of 200 kV and an electron-gun anode-to-cathode separation of 13 cm revealed that the mean primary beam current density was

$$\bar{J} = 0.68 \text{ A/cm}^2 \text{ with standard deviation,}$$

$$\sigma_J = 0.11 \text{ A/cm}^2 \text{ over a } 10 \times 100\text{-cm area,}$$

and

$$\sigma_J = 0.08 \text{ A/cm}^2 \text{ over an } 8 \times 100\text{-cm area.}$$

Fig. 4. Variation of primary electron-beam current transverse to the electron-gun along the 10-cm dimension.

Variation of Small-Signal Gain with E/p and Gas Mixture

A gain measuring apparatus was assembled and used to study the spacial and temporal properties of CO_2 laser ampli-

fiers.⁶ An 8-W TEM₀₀ cw probe laser beam operating on the P20 rotational transition of the 10.4- μm band was passed

through the amplifier. Using a single detector, we recorded the amplitude of the emerging beam before, during, and after the amplification producing discharge. The detector and oscilloscope were carefully checked for calibration and linearity before each run.

While an exhaustive parameter study required more time than was available, the operating parameters of the amplifiers were explored using five gas mixtures. During each experimental run, a gas sample was taken and subjected to mass spectrometric analysis to establish the mixture. Pressure was measured by two Wallace and Tiernan gauges, which always agreed within reading accuracy.

Figures 5 through 9 are typical data sets taken at each of the five gas mixtures. The upper trace in Fig. 5(a) shows the chopped probe laser-beam amplitude at a slow sweep rate, while the lower trace records the amplified probe laser beam at 2 $\mu\text{sec}/\text{division}$. The gain measurements in the other figures should be interpreted similarly.

To change the discharge E/p ratio, the charging voltage on the discharge bank was varied from 76 to 96 kV. This resulted in a static E/p variation of 3.46 to 4.36 kV/cm-atm. No attempt was made to measure the electric field, pressure, or temperature variations in the presence of the discharge plasma, so that E and p refer to $t = 0$ values only. To explore a range of energy depositions at each charging voltage, the pulse duration was varied from 0.5 to 3.0 μsec with a fixed gas mixture at 1520 Torr. It was found, as shown in Fig. 10, that small-signal gain usually increased as

pulse width and discharge voltage increased. The numbers for the curves in Fig. 10 are initial values of E/p in kV/cm-atm.

Depositing more than 300 J/liter-atm did not increase the measured gain because of either thermal population of the lower laser level or perhaps even probe laser-beam scattering due to pump-induced turbulence. A maximum energy deposition of about 400 J/liter-atm was measured at 96 kV and a 3- μsec pulse width. Other workers have found that such an input energy density can lead to gas temperatures in excess of 600°K and this alone is sufficient to explain the observed roll off in gain.⁵ Figure 11 is an alternative way of presenting some of these data. Notice that the small-signal gain coefficient, α , is an almost linear function of E/p if the pulse duration is held constant over the range explored.

From the plot of gain vs energy deposited in the gas in Fig. 12, it becomes evident that the amplifiers studied are still in the range of increasing pumping efficiencies for high E/p. Further, experience suggests that for a fixed energy deposition of 200 J/liter-atm, the highest gains are achieved with gas mixtures having the property,

$$0.5 \leq \left(\frac{\psi_{\text{CO}_2}}{\psi_{\text{CO}_2} + \psi_{\text{N}_2}} \right) \leq 0.7,$$

as indicated in Fig. 13. However, too few mixtures have been explored to establish this as more than a supposition.

Upper trace: probe laser amplitude
Vertical scale = 2 mV/div
Horizontal scale = 100 μ sec/div

Lower trace: gain = 5.17%/cm
Vertical scale = 0.2 V/div
Horizontal scale = 2 μ sec/div

Upper trace: electron-gun voltage
Vertical scale = 140 kA/div
Horizontal scale = 1 μ sec/div

Lower trace: electron-gun current
Vertical scale = 3 kA/div
Horizontal scale = 1 μ sec/div

Upper trace: discharge voltage
Vertical scale = 35 kV/div
Horizontal scale = 1 μ sec/div

Lower trace: discharge current
Vertical scale = 15 kA/div
Horizontal scale = 1 μ sec/div

Fig. 5. Oscillographs showing (a) gain, (b) voltage, (c) current histories for a discharge bank charging voltage of 88 kV and a gas mixture of 52.0% He, 17.5% N_2 , and 29.8% CO_2 at 1520 Torr.

Upper trace: probe laser amplitude
Vertical scale = 2 mV/div
Horizontal scale = 100 μ sec/div

Lower trace: gain $\approx 4.99\%/cm$
Vertical scale = 0.2 V/div
Horizontal scale = 2 μ sec/div

Upper trace: electron-gun voltage
Vertical scale = 140 kV/div
Horizontal scale = 1 μ sec/div

Lower trace: electron-gun current
Vertical scale = 3 kA/div
Horizontal scale = 1 μ sec/div

Upper trace: discharge voltage
Vertical scale = 35 kV/div
Horizontal scale = 1 μ sec/div

Lower trace: discharge current
Vertical scale = 15 kA/div
Horizontal scale = 1 μ sec/div

Fig. 6. Oscillographs showing (a) gain, (b) voltage, (c) current histories for a discharge bank charging voltage of 96 kV and a gas mixture of 53.4% He, 23.9% N₂, and 22.6% CO₂ at 1520 Torr.

Upper trace: probe laser amplitude
Vertical scale = 2 mV/div
Horizontal scale = 100 μ sec/div

Lower trace: gain = 4.68%/cm
Vertical scale = 50 mV/div
Horizontal scale = 2 μ sec/div

Upper trace: electron-gun voltage
Vertical scale = 140 kV/div
Horizontal scale = 1 μ sec/div

Lower trace: electron-gun current
Vertical scale = 3 kA/div
Horizontal scale = 1 μ sec/div

Upper trace: discharge voltage
Vertical scale = 35 kV/div
Horizontal scale = 1 μ sec/div

Lower trace: discharge current
Vertical scale = 15 kA/div
Horizontal scale = 1 μ sec/div

Fig. 7. Oscilloscopes showing (a) gain, (b) voltage, (c) current histories for a discharge bank charging voltage of 96 kV and a gas mixture of 38.2% He, 31.9% N₂, and 29.8% CO₂ at 1520 Torr.

Upper trace: probe laser amplitude
Vertical scale = 2 mV/div
Horizontal scale = 100 μ sec/div

Lower trace: gain = 4.67%/cm
Vertical scale = 0.1 V/div
Horizontal scale = 2 μ sec/div

Upper trace: electron-gun voltage
Vertical scale = 140 kV/div
Horizontal scale = 1 μ sec/div

Lower trace: electron-gun current
Vertical scale = 3 kA/div
Horizontal scale = 1 μ sec/div

Upper trace: discharge voltage
Vertical scale = 35 kV/div
Horizontal scale = 1 μ sec/div

Lower trace: discharge current
Vertical scale = 15 kA/div
Horizontal scale = 1 μ sec/div

Fig. 8. Oscillographs showing (a) gain, (b) voltage, (c) current histories for a discharge bank charging voltage of 96 kV and a gas mixture of 35.5% He, 16.0% N₂, and 48.3% CO₂ at 1520 Torr.

Upper trace: probe laser amplitude
Vertical scale = 2 mV/div
Horizontal scale = 100 μ sec/div

Lower trace: gain = 3.1%/cm
Vertical scale = 20 mV/div
Horizontal scale = 2 μ sec/div

Upper trace: electron-gun voltage
Vertical scale = 140 kV/div
Horizontal scale = 1 μ sec/div

Lower trace: electron-gun current
Vertical scale = 3 kA/div
Horizontal scale = 1 μ sec/div

Upper trace: discharge voltage
Vertical scale = 35 kV/div
Horizontal scale = 1 μ sec/div

Lower trace: discharge current
Vertical scale = 15 kA/div
Horizontal scale = 1 μ sec/div

Fig. 9. Oscillographs showing (a) gain, (b) voltage, (c) current histories for a discharge bank charging voltage of 96 kV and a gas mixture of 19.5% He, 16.1% N₂, and 64.3% CO₂ at 1520 Torr.

Fig. 10. Gain vs pulse width for five gas mixtures. Numbers for curves are initial values of E/p in $\text{kV}/\text{cm-atm}$.

Fig. 11. Gain vs E/p for five gas mixtures. Numbers for curves are pump pulse durations. Solid lines fit data; dashed lines connect data points for clarity.

Fig. 12. Gain vs energy deposited for five gas mixtures. Numbers for curves refer to E/p ratio in kV/cm-atm.

Fig. 13. Small-signal gain vs gas mixture for a constant energy deposition of 200 J/liter-atm and a fixed discharge bank charging voltage of 96 kV.

Gain Uniformity Measurements

The amplifier's gain at several locations within its aperture may be determined by carefully translating the probe laser beam. Early measurements on the 10-cm-aperture prototype revealed a disappointingly non-uniform gain profile, shown in Fig. 14. These data were taken using a gas mixture of $\text{He:N}_2:\text{CO}_2 = 3:1:2$ at 760 Torr. The nearly linear reduction in α from anode to cathode was attributed to a corresponding static electric-field variation as shown in Table 1. Readily achievable geometry changes were incorporated into the design of the 11-cm-aperture amplifiers to guarantee high static electric-field uniformity.

To evaluate the 11-cm-aperture amplifiers' gain uniformity, a 3:1:2 gas mixture of $\text{He:N}_2:\text{CO}_2$ at 1520 Torr, an E/p of 4 kV/cm-atm, and a 2- μ sec pulse

duration were used. Five shots were taken in each of the 17 positions indicated in Fig. 15. The electrostatic field was calculated for each position probed and these values, together with the measured peak gains, are given in Table 2. The gains reported for Unit No. 1 are larger than those for Unit No. 2, although the devices were supposedly identical. This discrepancy was traced to a poorly calibrated voltmeter, which allowed the first unit to be charged about 2% more than the 88 kV required to provide an E/p of 4 kV/cm-atm.

All shots were charged to an indicated 88 kV and crowbarred after 2 μ sec. An energy of 212 ± 6 J/liter-atm was deposited on each shot. This data is displayed in Fig. 16 to indicate the gain uniformity

Fig. 14. Prototype gain uniformity for gas mixture of 50.0% He, 16.7% N₂, and 33.3% CO₂ at 760 Torr. (Top) Energy deposition ~220 J/liter-atm and discharge bank voltage ~37 kV. (Bottom) Energy deposition ~180 J/liter-atm and discharge bank voltage ~37 kV.

along vertical and horizontal directions. The remaining gain nonuniformities must be due to primary electron-beam current nonuniformities, dynamic electric field changes, fluid dynamic motion in the gain medium, or a combination of the three.

Fig. 15. Location of gain measurements within the amplifier's aperture.

Table 1. Prototype gain uniformity.

Position (cm)		α (%/cm)		σ_{α} (%/cm)	Calc static e-field (kV/ cm-atm)
x	y				
Horizontal scan					
0.4	0.0	4.72	0.08		4.44
1.4	0.0	4.72	0.08		4.36
2.4	0.0	4.44	0.10		4.19
4.4	0.0	3.92	0.12		3.72
6.5	0.0	3.44	0.04		3.33
7.5	0.0	3.24	0.05		3.18
8.5	0.0	2.96	0.06		3.07
9.3	0.0	2.90	0.04		3.00
Vertical scan					
5.0	-1.0	4.04	0.12		3.61
5.0	0.0	4.12	0.10		3.62
5.0	1.0	4.12	0.08		3.61
5.0	2.0	3.84	0.10		3.59
5.0	3.0	3.70	0.16		3.54
5.0	4.0	3.35	0.08		3.47
5.0	4.5	3.10	0.12		3.45

Table 2. Gain uniformity for 11-cm-aperture amplifiers.

Position ^a	Unit 1			Unit 2		
	α (%/cm)	σ_α (%/cm)	Calc static e-field (kV/cm-atm)	α (%/cm)	σ_α (%/cm)	Calc static e-field (kV/cm-atm)
00	5.45	0.08	4.08	5.14	0.22	4.00
01	5.21	0.10	4.05	5.22	0.17	3.97
02	5.20	0.09	4.03	4.80	0.09	3.95
03	5.25	0.09	4.05	4.91	0.04	3.97
04	5.09	0.17	4.00	4.87	0.27	3.92
05	5.52	0.14	4.10	5.21	0.06	4.02
06	4.90	0.11	4.07	4.44	0.15	3.99
07	5.37	0.24	4.15	5.25	0.12	4.07
08	5.21	0.16	4.24	5.04	0.02	4.16
09	5.65	0.04	4.17	5.30	0.04	4.09
10	5.62	0.07	4.19	5.27	0.09	4.11
11	5.36	0.15	4.15	5.28	0.19	4.07
12	5.12	0.06	4.24	5.35	0.22	4.16
13	5.34	0.08	4.10	5.17	0.12	4.02
14	4.77	0.14	4.07	4.54	0.05	3.99
15	5.11	0.15	4.05	5.00	0.05	3.97
16	4.79	0.03	4.00	4.84	0.10	3.92
Av overall locations	5.23	0.26	4.10	5.04	0.27	4.02

^aSee Fig. 15.

Fig. 16. Gain uniformity along (a) vertical and (b) horizontal directions.

Variation of Small-Signal Gain with Rotational Quantum Number

Anomalously high gains have been reported for the P20 transition in the 10.4- μm band.^{7,8} The gain on transitions near P20 was studied by simply tuning the grating in the probe laser. Data were taken on the P16, P18, P20, P22, and P24 transitions, as well as on the P20 transition of the 9.4- μm band. Operating conditions were chosen to be those typical of normal system usage, i. e., a 3:1:2 gas mixture of $\text{He:N}_2:\text{CO}_2$, $E/p = 4 \text{ kV/cm-atm}$, 1500 Torr, and a 2- μsec pump duration.

The mean α 's measured on the amplifier's axis in five shot sequences for each line studied are plotted in Fig. 17. The error bars represent the extreme measurements and demonstrate the high quality of these data. These data indicate an increase of about 6% in the P20 and 3% in the P18 gain over the prediction of a Boltzmann rotational distribution with a rotational temperature of $T_R = 435^\circ\text{K}$.

Fig. 17. Gain vs P-transitions in five shot sequences.

The 9.4- μm P20 transition peak gain was $\alpha = 3.84 \pm 0.03\%/cm$ as expected from the lower cross section of this transition.

Simple Gain Uniformity Model

Detailed numerical models for CO_2 amplifiers and oscillators like Ref. 9 are available; however, the nearly linear relationship observed between α and E/p in our operating range yields a convenient rule of thumb. The small-signal gain coefficient, α , is related to the cross section, σ , and the inversion density, ΔN , by $\alpha = \sigma \Delta N$. Also, $\sigma \approx$

$\lambda^2/4\pi^2\tau_s\Delta\nu_L$, where λ is the laser wavelength, τ_s is the spontaneous lifetime of the laser transition, and $\Delta\nu_L$ is the homogeneous linewidth of the laser transition. Thus, σ is not strongly dependent on E/p or energy deposition, so variations in α across an amplifier's aperture reflect variations in ΔN .

ΔN is given by

$$\Delta N \equiv \left[N_{00^0 1} P(J) - \left(\frac{\partial J}{\partial J + 1} \right) N_{10^0 0} P(J + 1) \right],$$

where $N_{00^0 1}$ and $N_{10^0 0}$ are the populations of the participating vibrational levels, $P(J)$ is the translational temperature-dependent occupation probability of the J th rotational level, and θ_J is the level degeneracy.

These populations may be written in terms of the energy density stored in the symmetric stretch mode, U_S , the bending mode, U_B , and the antisymmetric stretch mode, U_A ; their fundamental frequencies, f_S , f_B , and f_A ; and the molecular density of CO_2 , N_{CO_2} :

$$N_{00^0 1} = \frac{N_{\text{CO}_2}}{Q} \left[\frac{U_A}{hf_A N_{\text{CO}_2} + U_A} \right]$$

and

$$N_{10^0 0} = \frac{N_{\text{CO}_2}}{Q} \left[\frac{U_S}{hf_S N_{\text{CO}_2} + U_S} \right],$$

where

$$\frac{1}{Q} = \left[\frac{hf_S N_{\text{CO}_2}}{hf_S N_{\text{CO}_2} + U_S} \right] \left[\frac{hf_B N_{\text{CO}_2}}{hf_B N_{\text{CO}_2} + U_B} \right]^2 \times \left[\frac{hf_A N_{\text{CO}_2}}{hf_A N_{\text{CO}_2} + U_A} \right].$$

Pumping of these modes, and hence the laser levels, in the CO_2 molecule depends on the product of secondary electron density and E/p -dependent dynamic ex-

citation rates.^{10,11} The secondary electron density in the laser gas goes approximately as the square-root of the primary beam current density, J .¹

A simple model arises from assuming that E/p changes only slightly from the static case during the discharge and that the dynamic excitation rates are almost linear functions of E/p . U_S and U_B equilibrate with the translational temperature of the gain medium in a time short compared to the 2- μsec pumping time, while U_A and the energy stored in nitrogen do not. We imagine two more or less independent thermal baths with the upper laser level coupled tightly to the hotter one and the lower laser level coupled to the cooler one at the translational temperature. With these assumptions,

$$U_A \approx \int_0^{\Delta t} hf_A N_{\text{CO}_2} N_e(t) X_A(E/p) dt,$$

where $N_e(t)$ is proportional to $\sqrt{J(t)}$ and X_A is a linear function of E/p .

Given a similar expression for U_S and neglecting small terms, we arrive at a semiempirical formula:

$$\alpha \approx \sqrt{J} [A(\Delta t) + B(\Delta t)(E/p)],$$

where A and B are parameters that depend on pumping time (or energy deposition) and gas mixture and can be obtained for our pumping conditions from our data, i.e., Fig. 11. The ability of such a simple formula to fit our measured gain profiles is displayed in Figs. 18, 19 and 20.

Fig. 18. Comparison of simple gain uniformity model to prototype amplifier gain measurements. Fit is made to the axial measurement.

Fig. 19. Comparison of simple gain uniformity model to first 11-cm-aperture unit. Fit is made to the axial measurement.

Fig. 20. Comparison of simple gain uniformity model to the second 11-cm-aperture unit. Fit is made to the axial measurement.

Summary

The gain history of a cold-cathode, electron-beam-sustained CO₂ laser amplifier has been measured for several gas mixtures and excitation conditions. The spacial variation of the gain in three such units has also been established and a simple formula to estimate gain uniformity in similar systems has been

provided. While the thermal saturation evident in Fig. 10 suggests that gain uniformity may be improved simply by pumping hard, it should be clear that care must be taken in configuring discharge electrodes and electron guns if uniform gain profiles are to be achieved.

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The address for G. Loda is Systems, Science and Software, Hayward, California.

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