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Phoenix I Energy Extraction Experiment

James M. Hoffman, Edward L. Patterson, Gary C. Tisone, James B. Moreno

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PHOENIX I ENERGY EXTRACTION EXPERIMENT

UC-34

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ABSTRACT

Energy extraction experiments are reported for the Phoenix I amplifier driven by a discharge-initiated oscillator-preamplifier system operating on mixtures of either $\text{SF}_6\text{-HI}$ or $\text{SF}_6\text{-C}_2\text{H}_6$ and an electron-beam-initiated intermediate amplifier ($\lambda\text{-3}$) fueled with H_2 and F_2 mixtures. Input intensities in this experiment were as large as those provided in the previous energy-extraction experiments where the oscillator operated with mixtures of H_2 and F_2 . When the oscillator-preamplifier system operated with mixtures of $\text{SF}_6\text{-HI}$ the input spectrum to the Phoenix I amplifier contained ~ 28 P-branch vibrational-rotational lines which were almost identical to the input spectrum from the $\text{H}_2\text{-F}_2$ fueled oscillator. In this case the energy extraction measurements were essentially the same as the results obtained with the spectrum produced using H_2 and F_2 mixtures. For an input intensity of 10^7 W/cm^2 , 170 J were extracted from the amplifier. Energy-extraction measurements made with the oscillator-preamplifier operating with $\text{SF}_6\text{-C}_2\text{H}_6$ mixtures with 20 P-branch lines gave values of extracted energy which were only 16% lower than the values obtained with similar intensities using the $\text{SF}_6\text{-HI}$ spectrum. With the $\text{SF}_6\text{-C}_2\text{H}_6$ spectrum, extraction was only obtained from the first three excited vibrational levels. This result indicates that most of the energy in the amplifier could be extracted on the first three excited vibrational levels. It is shown that the extraction results can be fit with a simple two level model. Calculations using this simple model as well as a comprehensive HF code indicate that parasitic oscillations must be included when modeling the energy extraction characteristics of the Phoenix I amplifier.

Amplified spontaneous emission was reduced by a factor of 2 to 3 when the input intensity was increased from 0 to $1 \times 10^6 \text{ W/cm}^2$. Further increases in the input intensity did not further reduce the amplified spontaneous emission.

The radius of curvature of the beam was estimated using a lateral shearing interferometer. It was found that the Phoenix I amplifier altered the radius of curvature.

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I. Introduction

In previous extraction experiments¹ using a master-oscillator, power-amplifier (MOPA) arrangement, it was shown that it was possible to extract greater than 90% of the available energy from the Phoenix I amplifier. The input intensity required to obtain this extraction efficiency was 2×10^7 W/cm². In those experiments both the oscillator and the amplifier were operated with similar gas mixtures of H₂ and F₂, which assured a good spectral match between the oscillator and amplifier.

In another experiment,² energy extraction and beam-quality measurements for the Phoenix I amplifier were reported for which the electron-beam-initiated oscillator was replaced by an oscillator and preamplifier chain utilizing fast electrical discharges in SF₆-HI mixtures. This oscillator-preamplifier system produced a spectrum that did not contain the same vibrational-rotational lines as the H₂-F₂ spectrum. For input intensities of 7.4×10^4 and 1.5×10^5 W/cm², the output energy from Phoenix I was 33 J and 46 J, respectively. The corresponding extraction efficiencies (19% and 26%) were in good agreement with the results obtained using the H₂-F₂-fueled oscillator at the same input intensities. In this earlier experiment² the beam quality was inferred from the encircled energy distribution determined by measuring the energy transmitted through various size pinholes located at the focus of an off-axis parabolic mirror. The encircled-energy measurements demonstrated that the spot size for which 84% of the incident energy was transmitted was 154 μ m corresponding to 2.7 times the diffraction-limited diameter for the same fraction of encircled energy. The corresponding diameter for the unamplified beam was 100 μ m which is about 1.8 times the diffraction-limited diameter. The source of the apparent increase in spot size in the amplified beam is not known at this time. The wavefront curvature was determined by

use of lateral-shearing interferometry.³ Measurement of the rotation of the fringes with respect to the reference wire on the lateral shearing interferometer indicated that both beams (input and amplified) had a radius of curvature of 350 ± 50 m. This corresponds to a full-angle divergence of 200 ± 30 μ rad. These results demonstrated that at these input intensities the amplifier did not change the radius of curvature of the wavefront.

The results of these previous experiments can be summarized as follows:

1. Energy can be efficiently extracted from the Phoenix I amplifier with an input intensity of about 2×10^7 W/cm² from an oscillator operating on mixtures of H₂ and F₂.
2. The extraction efficiency at low input intensities (1×10^5 W/cm²) utilizing mixtures of SF₆-HI in a discharge-initiated system is just as good as with electron-beam-initiated H₂ and F₂ mixtures.
3. The encircled-energy measurements indicate that amplification of the beam increased the focal spot size from 100 μ m to 154 μ m.

Results 2 and 3 were obtained at relatively low input intensities, and the effect of utilizing an SF₆-HI or SF₆-C₂H₆ input spectrum at higher intensities was unknown. Therefore, a third extraction experiment on the Phoenix I amplifier was performed. The objective of this experiment was to determine the efficiency of energy extraction from the Phoenix I amplifier using the discharge-initiated oscillator-preamplifier system operating on mixtures of SF₆-HI or SF₆-C₂H₆, and an electron-beam-initiated intermediate amplifier fueled with H₂ and F₂ mixtures, to generate a saturating input for the Phoenix I amplifier. This arrangement was designed to deliver sufficient input intensity to saturate Phoenix I but in a different spectrum than was provided by the H₂-F₂-fueled oscillator.

II. Experimental Details

The Phoenix I oscillator-preamplifier-amplifier chain used in this experiment is shown schematically in Fig. 1. The electrical-discharge-initiated oscillator and preamplifier system is similar to that described by Arnold and Wenzel.⁴ The λ -3 intermediate amplifier⁵ and Phoenix I amplifier⁶ have been described previously. The oscillator and preamplifiers produced a near-diffraction-limited beam with an energy output of about 1 J with a pulse width of 120 nsec. In these extraction experiments the oscillator-preamplifier system was operated with gas mixtures of SF_6 and HI or SF_6 and C_2H_6 . The SF_6 and HI mixture was chosen because the reaction $\text{F} + \text{HI} \rightarrow \text{HF} + \text{I}$ has been shown to result in formation of HF molecules in excited vibrational levels up to $v' = 6$.⁷ The HF molecules formed with the SF_6 and C_2H_6 mixture are in excited vibrational levels up to $v' = 3$.

The output beam from the oscillator-preamplifier was expanded and propagated a distance of 31.5 meters to the λ -3 electron-beam-initiated intermediate amplifier.

The timing between the oscillator-preamplifier and the λ -3 intermediate amplifier was chosen to maximize the number of vibrational-rotational lines in the input spectrum for the duration of positive gain in the λ -3 intermediate amplifier. The duration of positive gain in the λ -3 can be obtained from the total output signal shown in Fig. 2. The time correlation between the λ -3 electron-beam current, total laser output and various P-branch transitions are shown in Fig. 2. The start of positive gain in the λ -3 system occurs about 35 nsec after the start of the electron-beam current. As can be seen from the data, the vibrational-rotational lines from $P_1(7)$ up to $P_3(5)$ are lasing almost simultaneously. This information was used to determine when an input signal into λ -3 should occur. The time chosen for this input signal

Fig. 1. Schematic representation of saturated amplifier experiment.

Fig. 2. Time correlation for the λ -3 intermediate amplifier between electron-beam current, total output and various P-branch transitions for the λ -3 system configured as an oscillator.

was about 30 nsec after the start of the electron-beam current. The temporal behavior of the strongest vibrational-rotational lines from the oscillator-preamplifier has been measured and the principal features are shown in Fig. 3. The X's shown in Fig. 3 indicate the time of peak signal at each line. The time derived over which the intensity levels are greater than 10% and 5% of the maximum are also indicated in Fig. 3.

Since the oscillator pulse width is much greater than the positive gain duration of the λ -3 intermediate amplifier, we had to choose a time for insertion of the signal into λ -3 which contained a maximum number of vibrational-rotational lines. The time chosen as indicated in Fig. 3 was 40 to 50 nsec, so that the actual oscillator signal had to be inserted into the λ -3 preamplifier about 10 to 20 nsec before the start of the electron-beam current.

After amplification in the λ -3 intermediate amplifier (operating with a total pressure of 620 Torr with a $F_2:O_2:H_2$ mixture of 1.0:0.3:0.25), the pulse had a width (FWHM) of about 60 nsec and an energy of about 25 J. This optical beam was then expanded and propagated to the Phoenix I amplifier. In the case for which maximum energy was required at the input to Phoenix I, the optical beam out of the λ -3 intermediate amplifier was propagated directly to the Phoenix I amplifier. For that case, to ensure that the optical beam filled the aperture of the Phoenix I amplifier, the beam expander at the output of the oscillator-preamplifier was adjusted so that the beam was slightly diverging. The input intensity to the amplifier was varied by an attenuator utilizing front surface reflections from various combinations of small-angle wedges made of quartz, CaF_2 and ZnSe.

The input beam intensity profile was determined using an infrared-pyroelectric Vidicon camera equipped with an F/0.7 Ge lens. A NaCl scatter plate was used

Fig. 3. Temporal behavior of the strongest vibrational-rotational lines from the oscillator-preamplifier. The time of the maximum periods over which the intensity levels are greater than 10% and 50% are indicated. The shaded area indicates the time chosen for the oscillator signal and the start of positive gain in the intermediate amplifier to overlap.

to reduce the intensity incident on the camera. The input beam relative intensity profile is shown in Fig. 4. The full-width-half-maximum for the input beam was 5.8 cm. The aperture of the Phoenix I cell was 7.54 cm so the edge intensity was about one-fourth of the center intensity.

The temporal behavior of the pulses from the oscillator-preamplifier, the λ -3 intermediate amplifier and the Phoenix I amplifier was measured with Au:Ge detectors cooled by liquid nitrogen. The electron-beam currents for the λ -3 intermediate amplifier and the Phoenix I amplifier were also monitored. All of the signals were time correlated to the center of the Phoenix I amplifier cell. A set of time correlated data are shown in Fig. 5. These data were obtained with the oscillator-preamplifier operating with mixtures of SF₆-HI.

The input energy into the Phoenix I amplifier was measured using a quartz beam splitter and a 20-cm-diameter calorimeter. This system was calibrated by comparison with another calorimeter which was placed directly in the input beam. This measurement was corrected for the transmission of the sapphire input window of the Phoenix I amplifier.

The collimated output energy from the Phoenix I amplifier was measured with a 20-cm-diameter total-absorbing calorimeter. In order to separate the collimated output energy from radiation emitted at large angles by amplified spontaneous emission (ASE), the calorimeter used to measure the collimated output was apertured and was located 5.6 meters from the center of the amplifier.

The energy due to ASE in the forward and backward directions was measured using quartz beam splitters and 20-cm-diameter calorimeters. The collimated beam energy was eliminated from the forward ASE measurement by placing a mask in front of the calorimeter. This calorimeter then measured energy which was proportional to the energy in forward ASE.

Fig. 4. Relative intensity profile of input beam into Phoenix I amplifier. The vertical profile and horizontal profile are indicated. The horizontal profile has been shifted so that both profiles can be distinguished. One marked division of the abscissa is equal to one centimeter.

Fig. 5. Time correlated signals from the saturated amplifier experiment. The input and output energies are indicated.

III. Results

The results of the energy extraction experiment are shown in Fig. 6. The data points show the extracted energy from the Phoenix I chain. That is, $E_{\text{extracted}} = E_{\text{out}} - E_{\text{in}}$. The data points indicated by an X are measurements made with the oscillator-preamplifier system operating on mixtures of $\text{SF}_6\text{-HI}$. The results of the previous experiment where the oscillator used mixtures of H_2 and F_2 are indicated by the open circles. The results from these two different experiments are the same within the estimated experimental error of 15%. These results indicate that an oscillator-preamplifier system, operating on mixtures of $\text{SF}_6\text{-HI}$ is just as effective at extracting energy from an amplifier operating with $\text{H}_2\text{-F}_2$ as is an oscillator operating with $\text{H}_2\text{-F}_2$ mixtures.

Extraction measurements were also made with the discharge-initiated oscillator and preamplifiers operating on mixtures of $\text{SF}_6\text{-C}_2\text{H}_6$. The energy extracted for two different inputs are shown as triangles in Fig. 6. As shown in Fig. 6, the results with $\text{SF}_6\text{-C}_2\text{H}_6$ are only about 16% lower than the results obtained with $\text{SF}_6\text{-HI}$. This result is very useful because use of $\text{SF}_6\text{-C}_2\text{H}_6$ avoids the increased difficulty in using HI, which will photodissociate and thermally dissociate.

With no input into the Phoenix I amplifier, the calorimeter signals which are proportional to the ASE in the forward and backward directions were 4 and 7 J, respectively. With an input of $1.6 \times 10^6 \text{ W/cm}^2$, these signals were reduced to 1.5 and 2.3 J, respectively. Increasing the input intensity above $1 \times 10^6 \text{ W/cm}^2$ did not further reduce the amplified spontaneous emission. These results are similar to the first extraction experiment¹ where a factor of two reduction was obtained for 10^4 W/cm^2 but an increase in input intensity above that value did not further decrease the amplified spontaneous emission. The ASE results are not understood, but they may be influenced by parasitic

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Fig. 6. Energy extraction from Phoenix I as a function of input intensity. The error in measurement of the extracted energy is estimated to be $\pm 10\%$ and the error in determining the input intensity is estimated to be $\pm 20\%$. The total available extracted energy from the amplifier is indicated to be 180 J. The solid curve is the result of a simple parasitic model with the following parameters: $g_o L = 23$, $g_t L = 5.5$, and $R_{eff} = 0.004$. The curve marked "No Parasitics" indicates the simple model predictions for energy extraction when the reflection parameter is set equal to zero.

modes that are not dominated by the input radiation.

An energy-gain curve can be obtained from the extraction data, where the energy gain has been defined as

$$G_E = \frac{E_{out}}{E_{in}} \quad (1)$$

The energy-gain curve is shown in Fig. 7. The open circles are the gain data obtained from the first extraction experiment. The data marked X in Fig. 7 show the energy gain obtained from the experiment using an oscillator-preamplifier system operating with SF₆-HI mixtures. For about 90% energy extraction from the Phoenix I amplifier, the energy gain is about 5.

The HF laser is a complicated system which requires a rather sophisticated computer model to adequately describe the system. For quick estimates of performance of a system, it is advantageous to have some simple models. In an effort to develop a simple model, we first attempt to analyze the Phoenix I results using a simple model describing extraction in a quasi-steady-state amplifier that neglects amplified spontaneous emission and parasitic oscillations. The model considered is two level, steady state with homogeneous broadening.⁸ From this model the effective small-signal-gain-length product is given by

$$g_o L = \ln \left(\frac{I_{ext}}{I_{in}} + 1 \right) / \left(1 - \frac{I_{ext}}{g_o L I_s} \right)$$

where I_{ext} is the extracted intensity, I_{in} is the input intensity and I_s is the saturation intensity. From the published extraction data for Phoenix I,¹ the values of $g_o L$ at various input intensities have been

ENERGY GAIN CURVE VS. INPUT ENERGY

Fig. 7. Energy gain of Phoenix I as a function of input energy.

calculated and are listed in Table I.

Table I. Small-Signal-Gain-Length Product Obtained from Phoenix I Data Using a Two-Level Steady-State Amplifier Model

<u>I_{in} (W/cm²)</u>	<u>E_{ext} (J)</u>	<u>$g_o L$</u>
8.9×10^3	5.11	5.7
5.7×10^4	28.0	6.4
3.2×10^5	61.0	6.7
2.0×10^6	99.0	6.9
1.2×10^7	159.0	16.5
2.2×10^7	157.0	11.2

Results from the present experiment are listed in Table II.

Table II. Small-Signal-Gain-Length Product Obtained from Present Phoenix I Extraction Data Using a Two-Level Steady-State Amplifier Model

<u>I_{in} (W/cm²)</u>	<u>E_{ext} (J)</u>	<u>$g_o L$</u>
1.6×10^6	86	5.9
3.5×10^6	150	16.6
6.3×10^6	162	23.5
8.0×10^6	166	27.0
1.1×10^7	170	30.0

From Table I and Table II it is apparent that this simple amplifier model does not yield a single value of $g_o L$ for this amplifier. The fact that this simple amplifier model does not yield a single value of $g_o L$ may indicate that parasitic oscillations are perturbing the operational characteristics of the laser amplifier.

The evaluation of the effect of parasitic oscillations on the operating characteristics of an HF laser amplifier requires that a second model be

developed. The model we choose to consider is illustrated in Fig. 8. Each window is assumed capable of reflecting light emerging from the amplifier back into the active medium. The reflected light is also assumed not to be coaxial with the input beam.

For this particular case the transport equation is

$$\frac{dI^{\pm}}{dx} = \pm \frac{g_o I^{\pm}}{1 + \frac{I}{I_s}} \quad (3)$$

where $I = I^+ + I^-$. This equation can be solved for the given boundary conditions and the solution is the following equation:

$$g_o L = \ln G + \frac{I_i^+}{I_s} \left[(1 - R_o G)(G - 1) \right] \quad (4)$$

where $G = I^+/I_i^+$, and R_o is the effective reflectance of the output window. This equation can be put into a more tractable form if the following identity relating extraction efficiency and I_i^+ is used:

$$\eta_{\text{ext}} = \frac{I_i^+(G - 1)(1 - R_i R_o G^2)}{g_o L I_s} \quad (5)$$

where R_i is the effective reflectance of the input window and $(1 - R_i)$ and $(1 - R_o) \approx 1.0$. Combining the above two expressions in order to eliminate I_i^+ , the extraction efficiency is given by

$$\eta_{\text{ext}} = \frac{1 - R_i R_o G^2}{(1 + R_o G)} \left[1 - \frac{1}{g_o L} \ln G \right] \quad (6)$$

The required input intensity for this extraction efficiency at the given value of G , $g_o L$, R_i and R_o is given by the identity

$$I_i^+ = I_p^+ (1 - R_i) + R_i I_i^-$$

$$I_i^- = R_o G^2 I_i^+$$

$$I_o^- = R_o I_i^+ G$$

$$I_o^+ = I_i^+ G (1 - R_o)$$

Fig. 8. Schematic representation of steady-state parasitic model. R_i and R_o are the reflectivity of the input and output window, respectively. I_p^+ is the input intensity into the amplifier and I_o^+ is the amplifier output intensity. I_o^- is the intensity reflected along the amplifier optical axis from the output window. I_i^- is the amplified backward intensity on the input window and I_i^+ is the total intensity in the forward direction.

$$I_p^+ = \frac{\eta_{\text{ext}} g_o L I_s}{(G - 1)} \quad (7)$$

By varying G from $\exp g_o L$ to 1.0 in Eqs. (6) and (7), one can vary η_{ext} versus I_p^+ for an amplifier which has parasitic oscillations. For the case of symmetric effective window reflectance, $R_o = R_i = R$, Eq. (6) becomes

$$\eta_{\text{ext}} = (1 - RG) \left[1 - \frac{1}{g_o L} \ln G \right] \quad (8)$$

The value of effective window reflectance R is obtained from the relation

$$g_t L = -\ln R \quad (9)$$

where $g_t L$ is the parasitic controlled gain-length product, and for this case it can be obtained from the gain curve for small-signal input (see Fig. 7). The gain $G = e^{-\ln R}$ is about 250 for small-signal input, and this leads to an effective window reflectance of 0.004. This is not the actual reflectance of the windows of the laser amplifier but is the fraction of the output intensity which is reflected in the direction of the optical axis either by scattering from the windows or reflections from the windows being redirected by the cell walls. The value of $g_o L$ used in this calculation is taken to be approximately the average of values of the last two entries in Table II and the three entries in Table II. It was found that the shape of the predicted energy extracted curve is not very sensitive to the assumed value of $g_o L$.

The results of the parasitics model are shown by the solid curve in

Fig. 6. The simple model calculations are in reasonably good agreement with the experimental energy extraction data. This agreement maybe fortuitous since there is some doubt about how well a simple steady state model represents a pulsed HF amplifier. The dashed curve in Fig. 6 marked "no parasitics" indicates the predicted energy extraction as a function of input intensity obtained from this model if no parasitic oscillations are permitted in the amplifier.

The Sandia comprehensive HF code was also used to predict the amplifier behavior with and without parasitics. The version of the comprehensive HF code in which parasitic oscillations are modeled has been described previously.⁷ The parasitics are approximated by transverse oscillations between the laser walls. In reality, the parasitic modes are probably more complicated so that an effective wall reflectivity is appropriate. This value is determined by assuming that parasitics dominate at the lowest measured input intensity. There the amplifier gain is just $\exp\left\{-(L/\ell)\ln R\right\}$, where ℓ and L are the amplifier width and length, respectively, and R is the effective wall reflectivity. Matching this expression to the measured gain at the lowest input intensity determined R . Figure 9 shows the computed results for Phoenix I, using a value of $R = 0.41$. Also shown are results computed with $R = 0$ and the experimental results. The value of R used in the comprehensive code is different than the value used in the simple model, because the two models consider different parasitic modes and, therefore, use reflectivities characteristics of different surfaces and geometries. The smooth transition between poor extraction at low input and good extraction at high power is correctly predicted. These results from the simple model and the comprehensive HF code lend credence to the assumption that energy extraction in the Phoenix I amplifier is strongly influenced by parasitic oscillations.

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Fig. 9. Extracted energy as a function of input intensity for Phoenix I. The discrete points are measured values; the dashed and solid curves are calculations using the comprehensive code. The predictions are based on an approximate accounting for parasitic oscillations.

Time integrated spectral data were acquired from the oscillator-preamplifier system, the λ -3 intermediate amplifier when driven by the oscillator, and the Phoenix I amplifier when driven by the complete chain. These results are listed in Table III. Spectral data are shown for the oscillator-preamplifier system when operating with mixtures of both SF_6 -HI and SF_6 - C_2H_6 . Spectral data from the first extraction experiment, in which an H_2 - F_2 fueled oscillator was used, are also listed. No relative intensities are given but a visual inspection of the spectra indicates that most of the energy extracted from the Phoenix I system was contained in the vibrational-rotational lines $P_1(7)$ up to $P_4(6)$ when SF_6 -HI was used in the oscillator. This observation is confirmed by the SF_6 - C_2H_6 data where only vibrational-rotational lines with $v' \leq 3$ are extracted, yet the energy extracted from the amplifier is almost the same as that obtained with SF_6 -HI. These data show that most of the energy extracted from an electron-beam-initiated HF amplifier operating with mixtures of H_2 and F_2 are contained within vibrational levels $P_1(7) - P_4(6)$, and that 85% of the energy can be extracted with an input spectrum originating from the first three excited vibrational levels.

A lateral shearing interferometer³ was used to determine the change in the radius of curvature of optical beam produced by the Phoenix I amplifier. Interferograms were obtained at the input of the Phoenix I amplifier and at the output of the Phoenix I amplifier. The input interferogram was taken 8.33 m in front of the Phoenix I input window. The output interferogram was located 11.6 m behind the location of the input interferogram. A reproduction of the output interferogram is shown in Fig. 10. From the tilt of the interference lines with respect to the cursor wire, the radius of curvature of the wavefront was determined to be 67.8 m at the input and 88.5 m at the output. For a spherical wave

Table III. Spectral Comparison with Various Gas Mixtures

λ (microns)	Ident	(a)			(b)			(c)	
		OSC	λ -3	Phoenix	OSC	λ -3	Phoenix	OSC	Amp
2.64	P ₁ (4)	x	x	-	x	x	-		
2.67	P ₁ (5)	-	-	-	x	x	-		
2.71	P ₁ (6)	x	x	x	x	x	x	x	x
2.74	P ₁ (7)	x	x	x	x	x	x	x	x
2.78	P ₁ (8)	x	x	x	x	x	x	x	x
2.82	P ₁ (9)	-	-	-	x	x	x	x	x
2.73	P ₂ (3)	-	-	-	x	-	-		
2.76	P ₂ (4)	x	-	-	x	x	-		
2.80	P ₂ (5)	x	x	x	x	x	x	x	x
2.83	P ₂ (6)	x	x	x	x	x	x	x	x
2.87	P ₂ (7)	x	x	x	x	x	x	x	x
2.91	P ₂ (8)	x	x	x	x	x	x	x	x
2.95	P ₂ (9)	x	x	x	x	x	x	x	x
2.85	P ₃ (3)	-	-	-	x	-	-		
2.89	P ₃ (4)	x	x	-	x	x	-	x	x
2.93	P ₃ (5)	x	x	x	x	x	x	x	x
2.96	P ₃ (6)	x	x	x	x	x	x	x	x
3.00	P ₃ (7)	x	x	x	x	x	x	x	x
3.05	P ₃ (8)	x	x	x	x	x	x	x	x
3.09	P ₃ (9)	x	x	-	x	x	x	x	x
3.03	P ₄ (4)	x	-	-					
3.07	P ₄ (5)	x	x	x				x	x
3.11	P ₄ (6)	x	x	x				x	x
3.15	P ₄ (7)	x	x	x				x	x
3.19	P ₄ (8)	x	x	x				x	x
3.24	P ₄ (9)	x	x	x				x	x
3.14	P ₅ (3)	x	-	-					
3.17	P ₅ (4)	x	x	-				x	x
3.21	P ₅ (5)	x	x	x				x	x
3.26	P ₅ (6)	x	x	x				x	x
3.30	P ₅ (7)	x	x	x				x	x
3.35	P ₅ (8)	x	x	x				x	x
3.40	P ₅ (9)	x	x	-				x	x
3.33	P ₆ (4)	x	-	-				x	x
3.38	P ₆ (5)	x	x	-				x	x
3.42	P ₆ (6)	x	x	-				x	x
3.47	P ₆ (7)	x	-	-					

(a) The oscillator-preamplifier was operated with SF₆-HI.

(b) The oscillator-preamplifier was operated with SF₆-C₂H₆.

(c) These results are from the first extraction experiment and the oscillator was operated with H₂-F₂. There are some very weak lines out of the amplifier which have been identified but are not listed. These lines are the following: P₁(14-18), P₁(21), P₂(4), P₄(4), P₅(10), P₆(7).

Fig. 10. Phoenix I shear plate interferogram.

the radius of curvature of the wavefront should change by 11.6 m in going between between the two interferometer locations. The measured radius of curvature of the output beam indicates that the amplifier is alter the radius of curvature of the wavefront.

IV. Summary

The results presented here show that energy extraction from the Phocnix I amplifier is as efficient when the input signal is generated from an oscillator operating with mixtures of SF_6 -HI as when the oscillator operates with H_2 and F_2 . For an input intensity of 10^7 W/cm^2 , about 170 J were extracted from the amplifier. This corresponds to an extraction efficiency of 94%. It was also shown that it is possible to develop a simple parasitic model which gives an adequate fit to the experimental extraction data. At low input intensity, models that were constructed indicate that parasitic oscillations strongly affect energy extraction.

Time-integrated spectral results showed that most of the energy extracted from the amplifier was contained in vibrational-rotational lines from $P_1(7)$ up to $P_4(6)$. This result suggests that if the oscillator-preamplifier were operated with SF_6 - C_2H_6 mixtures, then the energy extraction should be somewhat less than when operated with SF_6 -HI. Two extraction measurements made with the oscillator-preamplifier operating with SF_6 - C_2H_6 mixtures were about 16% lower than the results obtained with SF_6 -HI.

An attempt was made to determine if ASE was reduced as the input intensity was increased. As in the previous energy extraction experiments, the ASE was reduced by a factor of 2 or 3 at low input intensities ($1 \times 10^6 \text{ W/cm}^2$) but was not further reduced as the input intensity was increased.

The beam wavefront curvature before and after amplification was determined with a lateral shearing interferometer. The wavefront curvature was altered in passing through the Phoenix I amplifier.

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