UV GAS LASER STUDIES

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Northrop Research and Technology Center

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Prepared by

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Temporal narrowing of the optical pulse in an E-beam excited high pressure xenon laser substantiates the evidence of laser oscillations in molecular xenon reported earlier. Using a hole coupled output mirror, an energy of 0.1J was measured in a calorimeter; this corresponds to a peak power of 10 MW demonstrating that a high power laser in the vacuum ultraviolet has been achieved.

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1.0 SUMMARY

Experiments were carried out to substantiate the evidence of laser oscillations in molecular xenon, first reported in the previous semiannual report NRTC 73-16R. These experiments were performed after making several improvements in the experimental setup including an increase in the E-beam energy.

In addition to the observation of spectral line narrowing with a thousandfold increase in spectral intensity reported earlier, the present series of experiments clearly demonstrated temporal narrowing of the optical pulse which provides additional evidence for laser oscillations. Using hole coupled output mirrors, an energy output of 0.1 joule was measured in a calorimeter. The corresponding pulse width was 10 nsec so that the peak power was on the order of 10 MW which was also corroborated by the signals from the calibrated photodiode.

The fluorescence pulse was observed to reach a maximum before the peak of the excitation current pulse and the laser pulse terminated even before the fluorescence attained the peak. This premature termination of light output is believed to be due to increased absorption and thermal deactivation at elevated temperatures produced as a result of intense excitation of the gas.

The above experiments were carried out jointly with the Los Alamos Scientific Laboratory and Maxwell Laboratories and a major part of the results was published in two papers. Copies of the papers are attached in the appendix. A more versatile xenon laser facility has now been installed at the Northrop Research and Technology Center. A description of the new facility together with preliminary xenon laser test results obtained in the facility are also reported.

2.0 RESULTS AND DISCUSSIONS

In the classic paper of Schawlow and Townes[1] in which the first proposal for a laser was described, the authors suggested that laser oscillations should lead to (1) spectral line narrowing with increase in spectral intensity, (2) nonlinear intensity buildup resulting in a pulse shortening, (3) coherence in the electromagnetic field, and (4) sharp directionality of the radiation leaving the laser cavity. The first criterion was demonstrated very clearly for the xenon laser in our previous investigations, and also the existence of mode patterns suggesting coherence was inferred from the mirror burn patterns. Additional experiments have now been completed to demonstrate the second criterion, viz, the temporal narrowing.

Several improvements were made in the experimental configuration before the additional experiments were performed. First, the electron beam energy was increased to approximately 0.7 MeV peak by raising the diode impedance. This was done at the cost of peak current resulting in a 90 kA beam. The total energy delivered to the high pressure gas in this series of experiments was about 2 kJ. Two solar blind planar photodiodes were mounted on the laser to simultaneously observe the side light fluorescence and the laser light. The optical output couplers were changed to hole coupled mirrors with geometric output coupling coefficients of 10% and 30%. Finally, a laser calorimeter (cone-thermopile type) was connected through vacuum plumbing to intercept most of the energy leaving the cavity. The calorimeter and measuring circuity were capable of resolving 10 mJ.

Figure 1 shows the modified experimental configuration. Side light leaving the gas cell at right angles to the optical axis and electron beam passed through an aperture onto the planar photodiode No. 2. Light parallel to the optical axis was directed to the calorimeter. Two lithium fluoride flats, each reflecting approximately 10%, diverted a part of the laser output to the photodiode No. 1 and the spectrometer entrance slit. Both photodiodes were

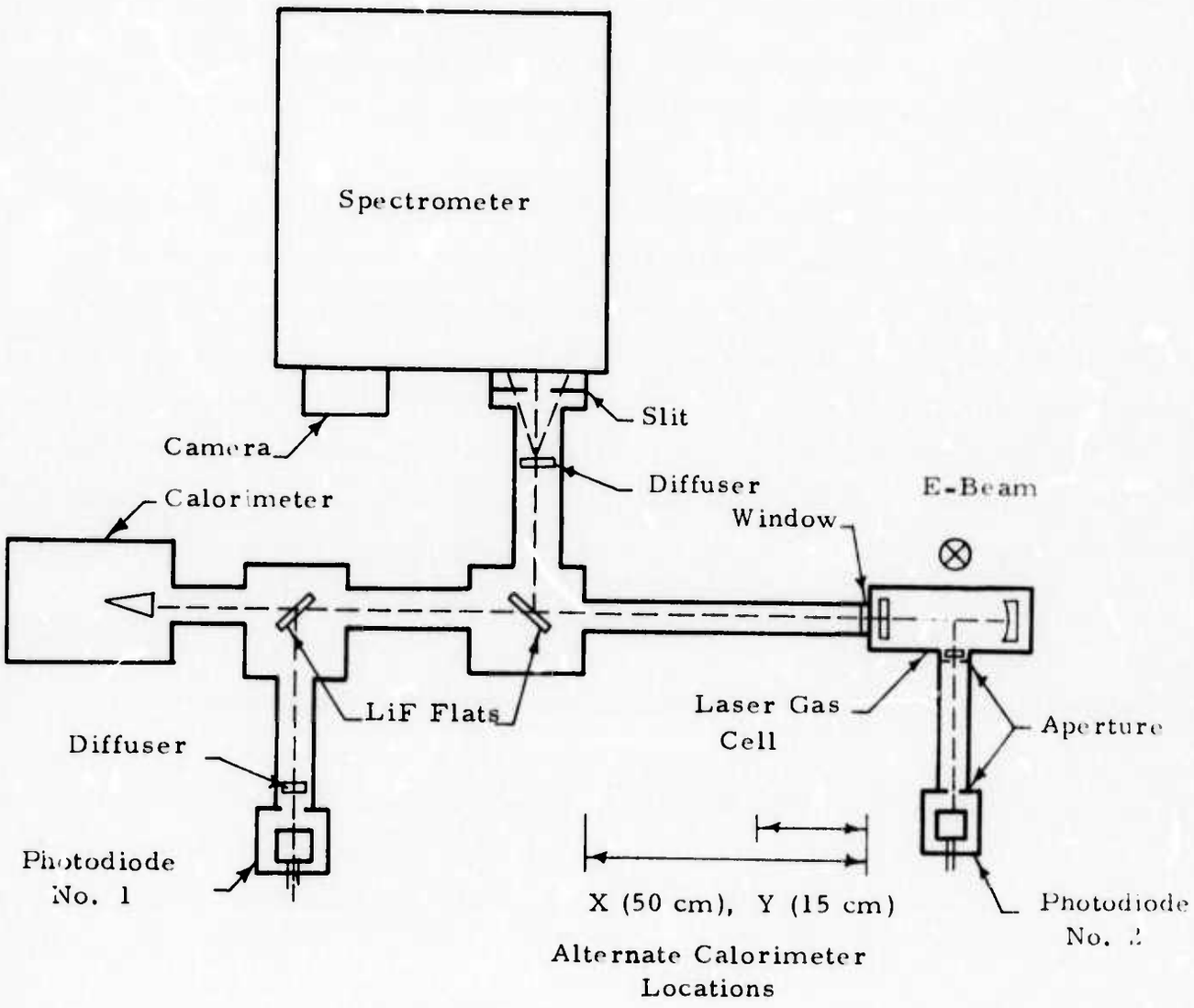


Figure 1. Modified experimental configuration.

appropriately apertured to prevent saturation. In addition, a sandblasted lithium fluoride diffuser was placed in front of diode No. 1 to further reduce the light intensity. The remaining laser light (about 80%) was absorbed by the calorimeter. Thus, each shot provided spectral, temporal, and energy output information.

The laser output and fluorescence (side light) are shown as functions of time in Figure 2. These are also compared to the electron gun current and voltage. In this case the laser output power is estimated from the quantum efficiency of the detector (diode No. 1) to be 6 MW. It is assumed that the diffuser screen is Lambertian for this estimate. The fast turn-on characteristic of the laser after threshold is evident from the response of the photodiode No. 1 presented in Figure 2. For this shot the peak signal from this photodiode increased by a factor of ~320 with a 30% transmitting mirror in contrast to the case with no mirror. Such an enormous increase in temporal intensity along the cavity axis, with no similar increase in the fluorescence sidelight, can only occur due to laser oscillations.

It is significant to note that the laser pulse terminates very early compared to the E-beam pulse. This may be ascribed to a variety of causes including mirror damage, thermal effects, etc. Even the fluorescence sidelight terminates prematurely and this is quite likely due to thermal deactivation at elevated temperatures.

The estimated temperature rise of the Xe gas after the full electron pulse is ~2000^{o}K which is equivalent to ~0.2 eV thermal energy per atom or ~0.3 eV relative collisional energy. Since this is a significant fraction of the binding energy of the excimers,[2] thermal dissociation leading to the quenching of fluorescence is highly probable. Other effects that may also contribute to the premature termination of the fluorescence are deactivating collisions with electrons, Penning ionization, etc. Furthermore,

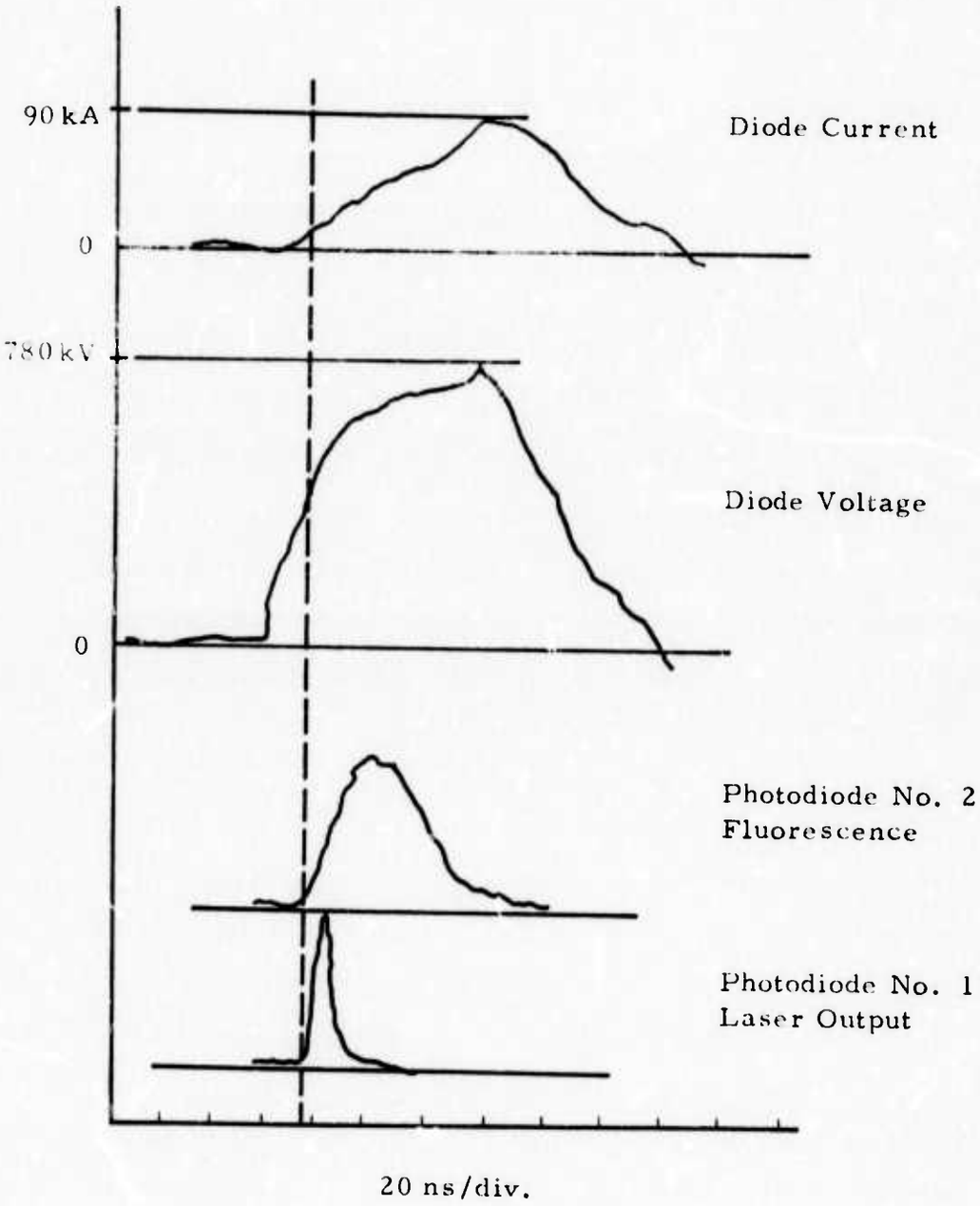


Figure 2. Laser output pulse compared to side light and electron gun current/voltage. (Pressure 12 atm.)

Kosinskaya and Polozova[3] have reported increased absorption at elevated temperatures due to formation of pseudomolecules having large Frank-Condon factors with the excited states. Such an absorption would cause radiation trapping, thus effectively increasing the lifetime of the excimers so that the effect of the de-excitation processes will become more pronounced.

The absorption at elevated temperatures may also be responsible for the early termination of the laser pulse. Even before the gas temperature becomes high enough to cause thermal deactivation of the excimers, the heating during the earlier part of the excitation pulse may increase the absorption sufficiently to cause a termination of the laser pulse by reducing the gain.

The time delay for laser initiation was a function of pressure and a minimum of ~7 nsec was observed at ~185 psia. Severe mirror damage with obvious mode structure was observed in the mirror burn pattern for all laser shots. The mirror damage might also offer an explanation for the premature termination of the laser pulse, if the degradation of the mirror occurred as soon as the laser started to build up in intensity.

As the Xe pressure was varied, the laser pulse showed little change in amplitude and width but the mirror burn pattern indicated a large variation in electron energy deposition. Figure 3 shows the total reflectors after a single shot each for decreasing pressures (left to right). The image of the hole coupled mirrors burned into the surfaces of these is easily visible.

For the high pressure case the electrons could penetrate only ~1 cm into the gas. As the pressure decreased, an optimum pressure of ~170 psia was reached and the damage occurred over almost the entire area exposed to the lasing gas volume. The edges of all the mirrors were shielded by the mounts leaving a 1.7 cm diameter aperture. At 120 psia, only the back

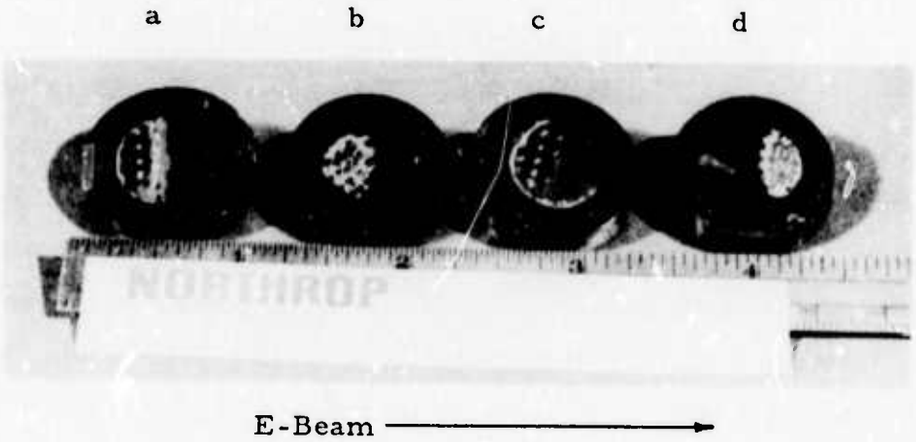


Figure 3. Total reflectors for 4 shots at decreasing pressure: (a) 275 psia, (b) 200 psia, (c) 170 psia, (d) 120 psia.

edge was obviously damaged, indicating that the optimum electron energy deposition was beyond the edge of the optical cavity.

Closer inspection of the surfaces revealed that the entire aperture showed mirror damage in all of these shots; but only where the energy flux was largest did the aluminum coating evaporate. Also, the centers of the holes imaged on these total reflectors from the hole couplers showed minimal damage. This may indicate that lasing did not occur within the holes, i.e., only the light that walked off the edges of the holes was coupled out. This was expected since the holes are much larger than the fundamental Gaussian mode waist for such a short cavity (12 cm) at this wavelength (1730A). Therefore, varying the hole size would not alter the coupling coefficient in the way one would expect from simple area ratio considerations. In addition, the output beam was expected to diverge rapidly, giving a poor far-field energy distribution. This indeed was the case. With the calorimeter in the location shown in Figure 1, the energy collected was not observable above the noise level of 10 mJ. Removing the LiF flats and their mounts that vignetted part of the beam and moving the calorimeter to position X (50 cm) noted in Figure 1, allowed 30 mJ to be measured. Moving to position Y (15 cm from the output coupler) allowed 100 mJ to be captured. This energy with the 10 nsec FWHM gives an average power of 10 MW for 10 nsec, which is in reasonable agreement with the previous measurement of 6 MW estimated from the photodiode signals.

Finally, the spectra (see Figure 4) showed a doublet structure similar to that seen in our first series of experiments. The increased width of the lines is possibly due to the poor resonator quality obtained with the hole coupled mirrors. The central minimum was shallower in this series of experiments.

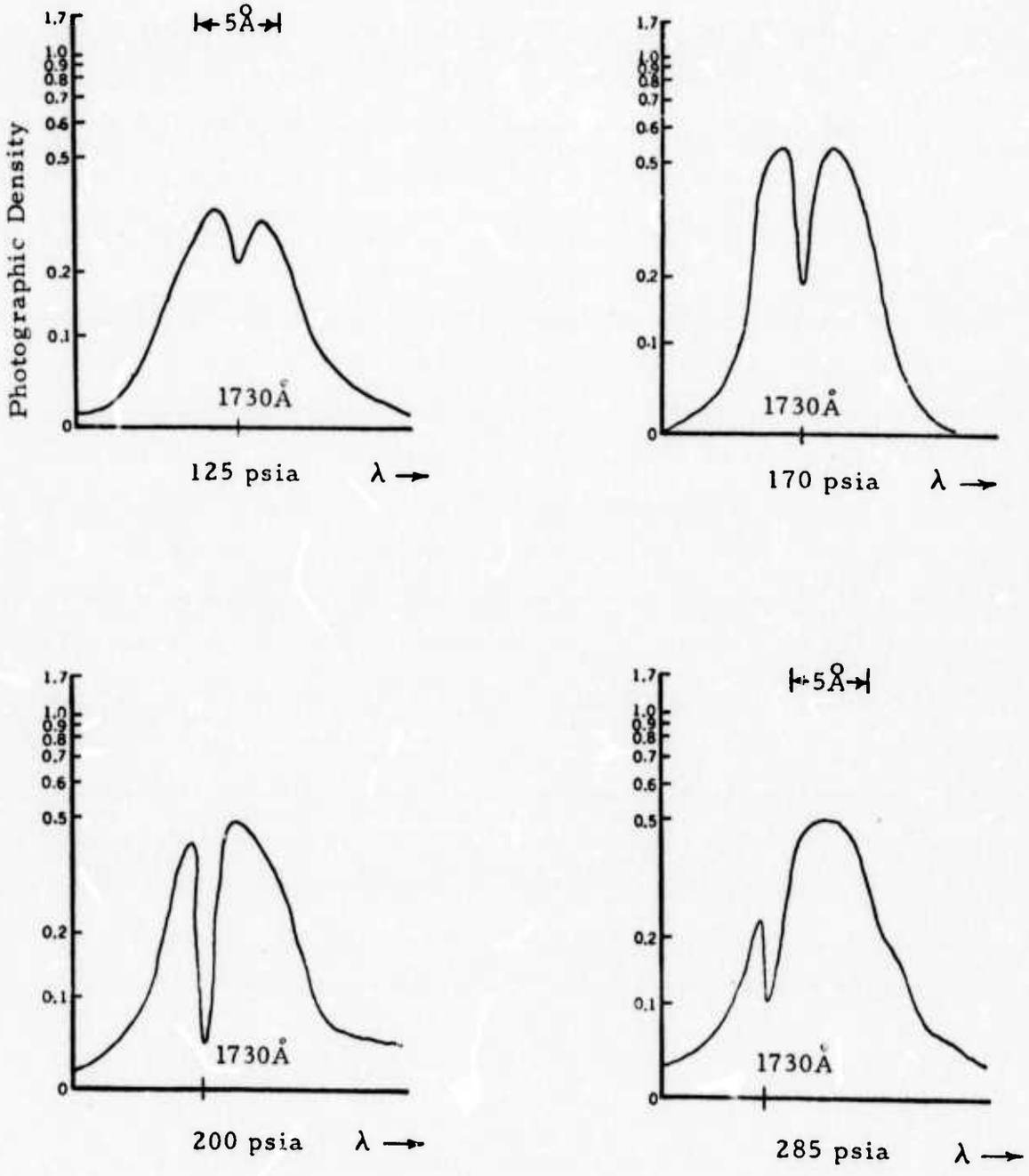


Figure 4. Densitometer traces of xenon laser spectra. Center wavelength 1730 ±10Å.

The origin of the minimum in the laser spectrum is still not clear, although there is a possibility that it is due to absorption by an impurity. A careful inspection of the fluorescence spectrum was made to see if any absorption at this wavelength could be seen. No absorption near the maximum of the fluorescence could be found to within the film noise which would allow for up to 6% absorption per pass. However, even 6% absorption with mirrors in place could give rise to a sizable reduction in laser intensity. At a given wavelength λ, the reduction would be $\gamma(\lambda) \lesssim e^{B(\lambda)\ell}$ (assuming the gain per double pass is much greater than unity) where B is the absorption per unit length at λ and ℓ is the distance the laser radiation field travels. For this experiment $B \leq 6 \times 10^{-3}$ cm^{-1} and $\ell \leq 3 \times 10^{2}$ cm, thus allowing for a maximum possible reduction of laser intensity at λ of $e^{1.8}$, or about a factor of 6. (ℓ was computed from the photodiode signal.) The reduction in intensity may be further accentuated by the lasing process itself, since the laser buildup tends to occur preferentially in the spectral regions having larger gain, at the cost of the intensity buildup at regions where the gain has been effectively reduced by absorption. Therefore the possibility of this feature being due to absorption cannot be ruled out. However, at this time no source of absorption has been identified. Also, another possibility should be examined, viz, that the metal vapor from the damaged mirror coatings might be a source of absorption since, with one mirror removed, no damage to the coating occurs at just the fluorescence intensity and no structure is observed in the continuum at the center wavelength. Absorption by Mg at 1730Å is a possibility.

A variation of the laser peak wavelength was observed as a function of pressure and is shown in Figure 4. A shift to longer wavelengths was seen with increasing gas pressure. This shift is probably due to the increased absorption occurring through ground state collisions. The photographic plates were not calibrated and we have assumed that the wavelength of the band edge of the absorption feature as seen in Figure 4 is invariant over the experimental conditions.

The results of the second series of experiments substantiate the earlier evidence demonstrating that Xe_2 is a high intensity laser in the vacuum uv. Pulse shortening, line narrowing, accompanied by as much as a thousand-fold spectral intensity increase and burn patterns characteristic of high intensity optical damage provide conclusive proof of laser oscillations in Xe_2^*. Even with a premature cutoff in laser emission, poor output coupling, and inefficient use of the total E-beam energy, a peak power of 10 MW was achieved. This is based on the measurement of total output of 0.1 joule. The measured energy in fact was a small part of the laser energy that came out through the edges of the holes of the output mirror. As evidenced by the mirror burn pattern, most of the laser energy in the pulse was still responsible for burning off the mirror coatings. Therefore, the estimate of 0.7 joule of total laser energy from the initial set of experiments appear to be reasonable. This leads to a peak power of $\sim$70 MW/cm^2 since the laser cross sectional area was $\sim$1 cm^2.

3.0 NEW XENON LASER FACILITY

The first successful demonstration of the high power vacuum uv xenon laser was accomplished using a Maxwell Laboratories POCO electron accelerator. This facility was limited for a more thorough and extensive investigation of the xenon laser. First, the electron beam had a high percentage of low energy electrons which, when absorbed by the gun foil as well as by the laser cavity foil, caused foil disintegration in every shot thus limiting the experimental capability to nearly one shot per day. Secondly, the E-beam had to be shaped in a magnetic field to obtain the proper excitation geometry and the laser cell had to be inside the coil producing the magnetic field. This provided undesirable additional constraints for experimentation. Thirdly, the beam energy could be raised only up to ~0.7 MeV which limited the range of pressures that could be studied.

To alleviate these difficulties a new E-beam was procured from Physics International Company. A photograph of this device is shown in Figure 5. This new E-gun, Pulserad 110A, has now been installed with necessary radiation shielding and diagnostic equipment. The gun utilizes a rectangular, shaped cathode to provide an E-beam of cross sectional area 1 cm x 10 cm without the use of any magnetic field. The electron energy distribution is such that there is very little absorption by the foil windows. Therefore the gun operates for 10 to 15 shots without foil failure. The current density, measured by a Faraday cup and shown in Figure 6a, has a peak of ~1 kA/cm^2 at ~1 MeV. The corresponding diode current as measured by an integrated current loop is shown in Figure 6b. The machine can be operated up to 2 kA/cm^2 at 1.5 MeV. The beam current is quite reproducible from shot to shot.

A new laser cell and cavity has been designed and constructed for use with this gun facility. Figure 7 shows the assembled laser with the gun. Xenon

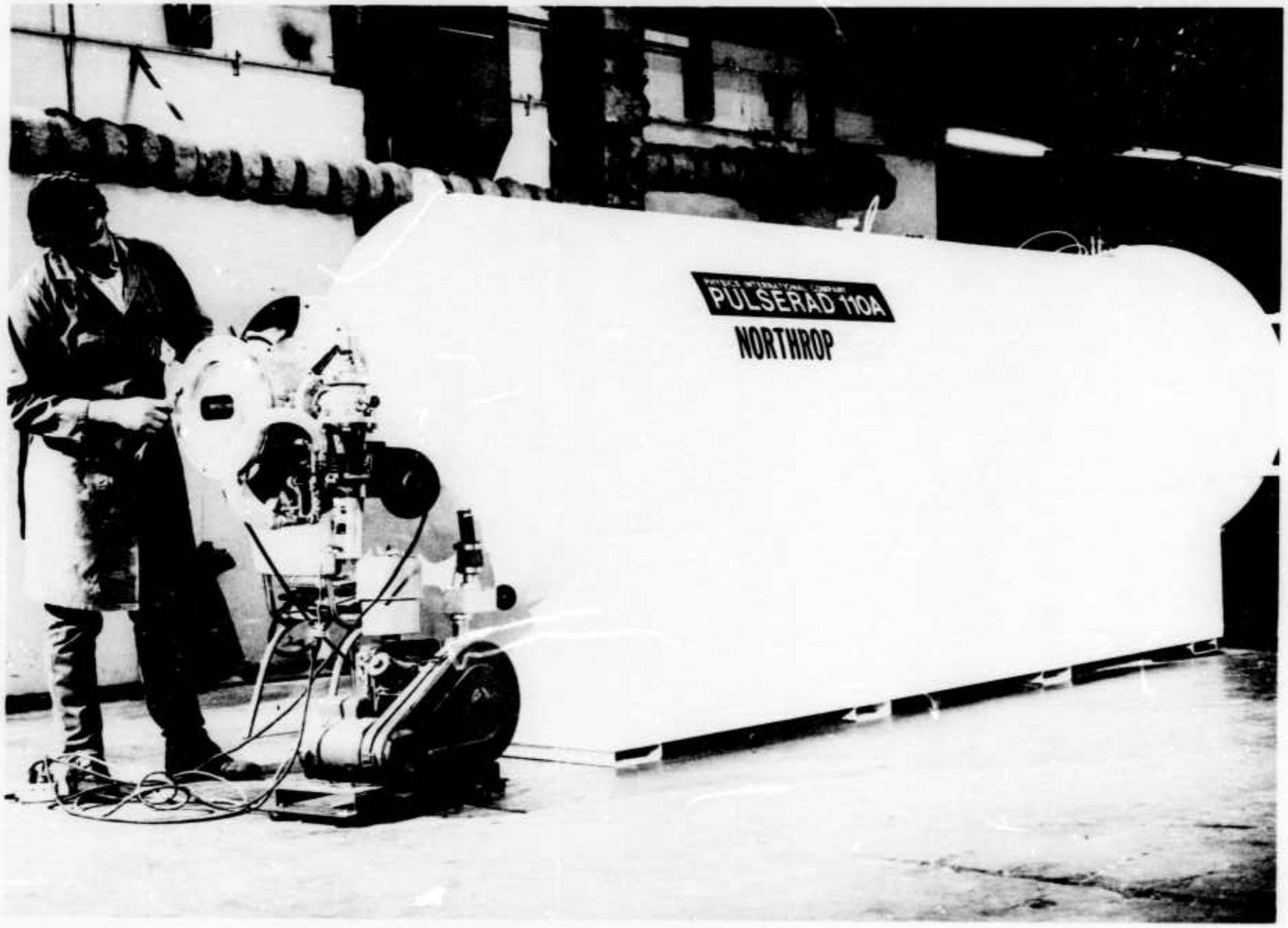
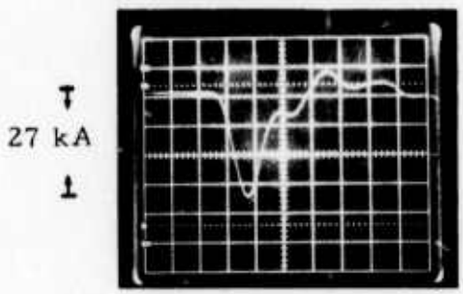


Figure 5. Photograph of Pulserad 110A capable of delivering 20 kA at 1 MeV over an area 1 cm x 10 cm in a 20 nsec pulse.

1.1 kA/cm^2

20 ns/div.

Figure 6a. Faraday cup signal of Pulserad 110A.



20 ns/div.

Figure 6b. Diode current as measured by a current loop signal.

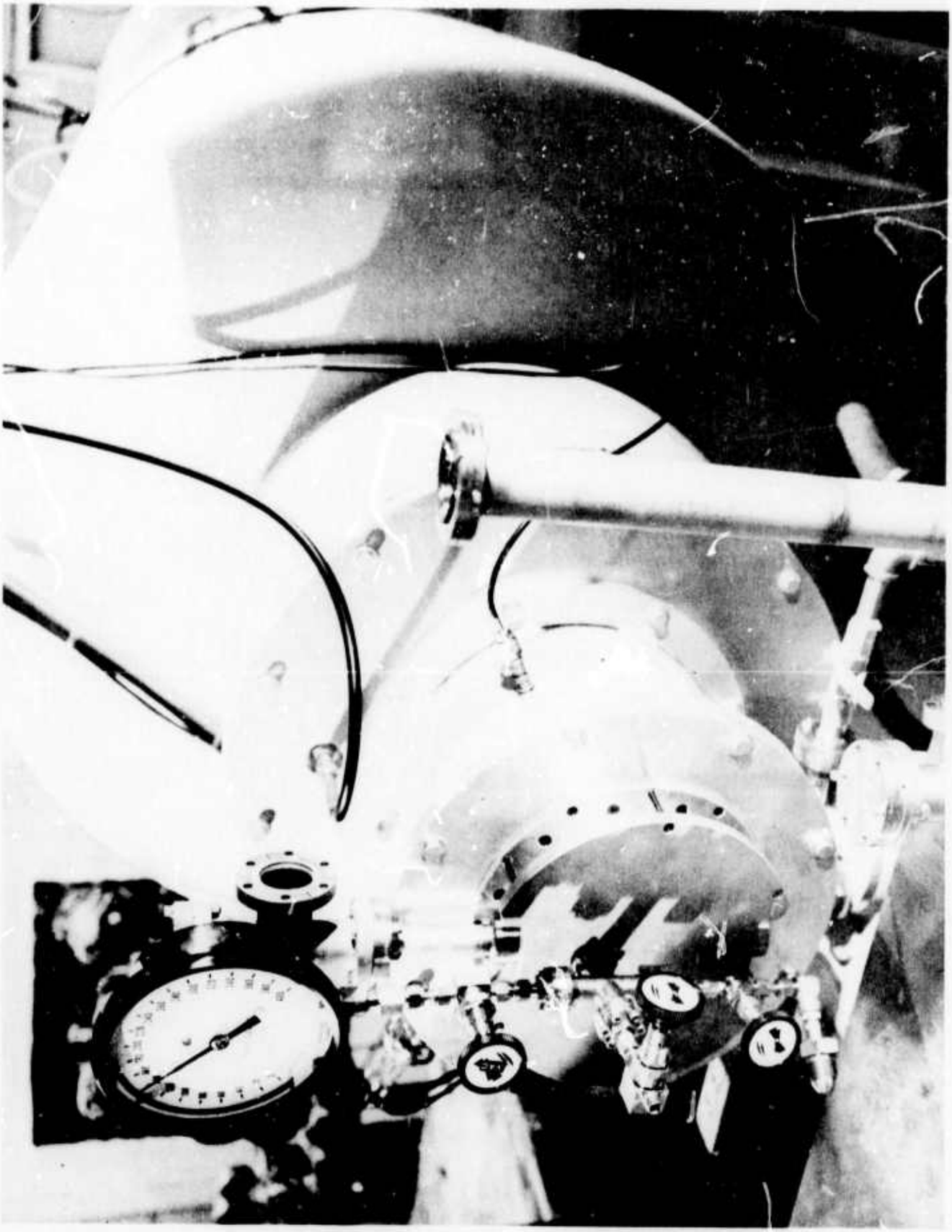


Figure 7. Xe laser with Pulserad 110A.

laser operation has been achieved using this new facility. Figure 8 shows a typical result of xenon laser spectrum together with a fluorescence spectrum recorded in a SPEX 1500 spectrograph obtained with this system. The laser cavity is now being redesigned to operate with external mirrors so that gain measurements and determination of mirror damage can reliably be performed.

Figure 8. The upper spectrogram shows the Xe_2 laser spectrum obtained at a pressure of 169 psi in a stable cavity and excited by 500 kA/cm^2 at ~0.8 MeV. The lower spectrogram shows the fluorescence spectrum. The laser spectrum was highly attenuated before recording.

4.0 REFERENCES

1. A. L. Schalow and C. H. Townes, Phys. Rev. 112, 1940 (1958).

2. R. S. Mulliken, J. Chem. Phys. 52, 5170 (1970).

3. I. V. Kosinskaya and L. P. Polozova, Optics and Spectroscopy 30, 458 (1970).

5.0 APPENDIX

XENON MOLECULAR LASER IN THE VACUUM ULTRAVIOLET

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ABSTRACT

Vacuum ultraviolet emission from high pressure Xe gas under excitation by a pulsed electron beam has been investigated. When cavity mirrors were provided, significant line narrowing and a thousandfold increase in spectral intensity occurred at 1730 ±10Å. This was accompanied by severe mirror burning and provides strong evidence that an associative molecular Xe laser has been achieved.

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Evidence of laser emission in the vacuum ultraviolet from molecular xenon was first reported by Basov, et al.[1] using E-beam excitation of liquid xenon. Recently, Koehler, et al.,[2] and Ault, et al.[3] have presented evidence of stimulated emission from gaseous xenon, including spectral line narrowing. We wish to report the observation of stimulated emission from gaseous xenon with increased line narrowing and with thousandfold enhancement in spectral intensity relative to the fluorescence emission. The optical emission inside the cavity was sufficiently intense to evaporate ~1 cm^2 area of the mirror coating providing symmetric burn pattern on the mirrors which only occurred in coincidence with the line narrowing and the increase in spectral intensity.

The experimental arrangement consisted of an optical cavity inside a high pressure gas cell excited transversely by an E-beam. The optical resonator was comprised of a 5m total reflector on a Pyrex substrate and a plane output mirror on a MgF_2 substrate. The mirrors were spaced 12 cm apart, and were prepared by aluminum coating followed by a MgF_2 overcoat. Each mirror was mounted on adjustable mirror mounts and the alignment was accomplished by a He-Ne laser. The optical cavity was housed within the pressure cell so that the static pressure on both sides of the cavity mirrors would be the same. This greatly reduced the mechanical requirements on the optical components and their mounts. The E-beam was supplied by a Maxwell Laboratories POCO electron accelerator delivering ~150 kA at 0.5 MeV. The circular beam was shaped in a 15 kilogauss magnetic field into a rectangular cross section of 9 cm x 3.5 cm. The average current

density inside the high pressure gas cell was estimated to be ~1000A/cm^2 providing about 1200J of input energy to the gas.

Diagnostics were primarily accomplished by spectral measurements to observe line narrowing. The spectral measurements were performed with a SPEX 3/4 meter VUV spectrograph model 1500 provided with a 1200 lines/mm grating blazed at 1500Å. The dispersion of the spectrograph near 1700Å was ~10Å/mm with a maximum resolution of 0.1Å. Radiation from the laser cell was directed by a 45° mirror through an evacuated chamber to the spectrograph and was recorded on Kodak 101-01 special uv film. In most of the spontaneous emission experiments the spectrograph slit width was kept at 200μ, limiting the resolution to 2Å. The target chamber was evacuated by a LN_2 trapped, oil diffusion pump before filling with Xe gas. The spectrograph camera was shielded to reduce any possible fogging due to x-rays.

The densitometer trace of the spectrum obtained from 12 atm xenon gas inside the optical cavity is shown in Fig. 1a. The corresponding spontaneous emission spectrum obtained without the mirrors is shown in Fig. 1b. The intensity of the spectrum in Fig. 1a was larger by over a factor of 1000 compared to that in Fig. 1b. Such an enormous increase in spectral intensity can only occur by laser emission. The densitometer traces show that the laser spectrum exhibits two peaks of ~2.5Å width separated by ~5Å. The spectrometer resolution for the laser traces was ~0.25Å. Each trace represents the time integrated spectrum of a single shot.

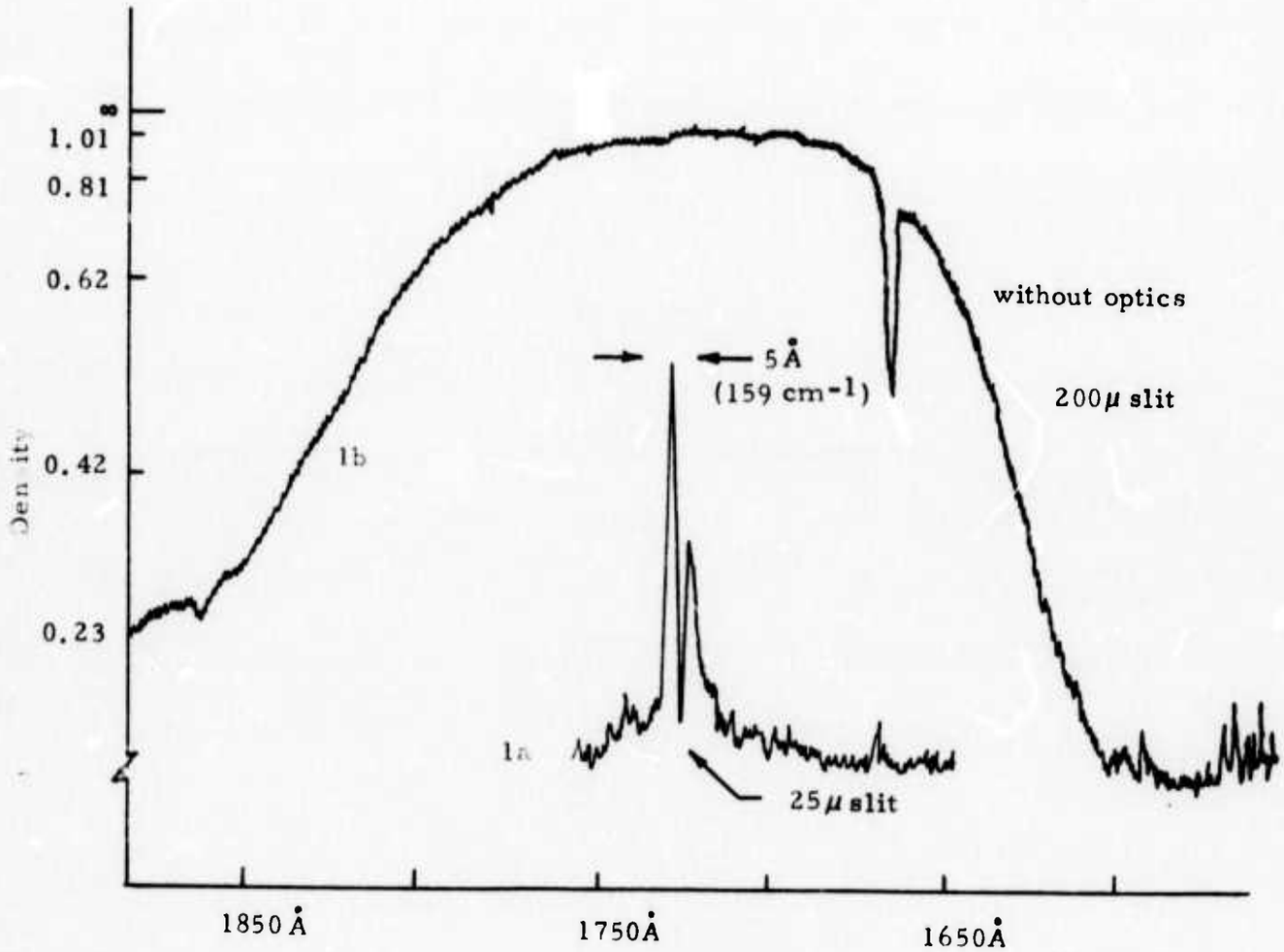

Fig. 1a. Laser spectrum (attenuated by ~1000 compared to Fig. 1b). Spectrometer slit width 25μ → 0.25Å resolution. Output coupling ~1%. Absorption losses 35% and 27% for the flat and spherical mirrors, respectively. (Photographic density on vertical axis.)

Fig. 1b. Typical fluorescence spectrum for Xe gas at ~12 atm without optics (200μ slit → 2Å resolution).

The cross sectional area of the excited volume which demonstrated strong lasing as indicated by the symmetric burn pattern on both mirrors, is shown in Fig. 2. The mirror burn spot became smaller and moved towards the E-beam entrance window when the pressure was raised to 15 atm causing a reduction in electron range and consequently the excitation volume.

The mirror burn spot attendant with line narrowing and increase in spectral intensity was repeatable each time in a series of seven shots. When the mirrors were misaligned or the total reflector was taken out, there was neither a burn spot on the mirror nor any significant line narrowing. This indicates that the observed mirror burn spot is not due to damage by scattered E-beam, pressure wave or superradiant emission.

Since an energy measurement was not available for these experiments, an attempt was made to estimate the laser energy from the mirror burn spots. This was on the assumption that the mirror burning occurred by heating due to laser energy absorption and as such constitutes merely a first order estimate. The mass of the removed 1.25 cm^2 x 800Å coating on the semi-transparent window is 2.7×10^{-5} gm. The amount of energy required to evaporate this mass of Al is ~0.38 joules. Considering the evaporation of the Al coatings from both the mirrors along with the protective MgF_2 coating, the total laser energy absorbed by the mirrors was estimated to be approximately 1J. This corresponds to an energy extraction of ~0.1J/cm^3.

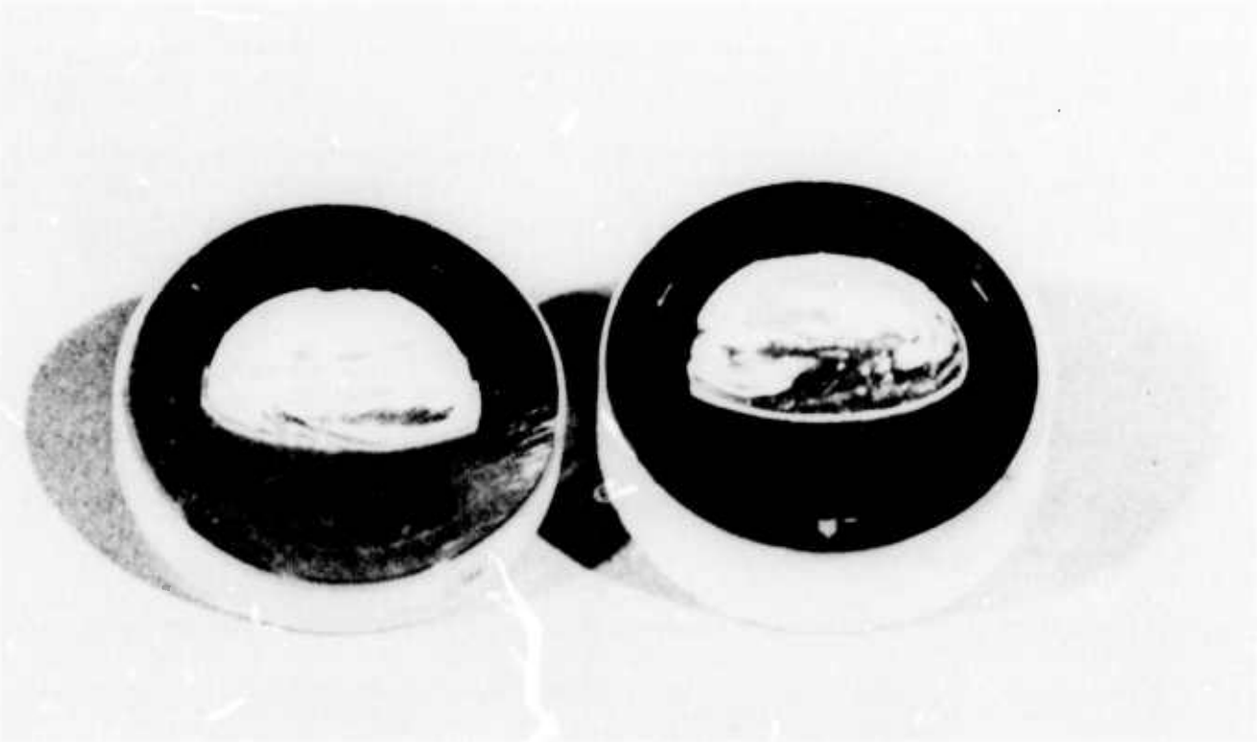

Fig. 2. Photographs of the output mirror (MgF_2) on the left and the spherical (5 meter radius) total reflector on the right. The electron beam direction is from top to bottom in this picture.

The results presented here leave little doubt that laser emission has been observed from molecular xenon in the VUV region. Since the emitted photon has enough energy to ionize an excited xenon molecule, it is not obvious that laser emission in the VUV could actually be achieved with this type of laser medium. These results demonstrate that sufficient net gain for laser emission from molecular xenon is possible in spite of the competition with photoionization.

REFERENCES

1. N. G. Basov, V. A. Danilychev, and Yu. M. Popov, "Stimulated emission in the vacuum ultraviolet region," Sov. J. Quant. Elect. 1, 18-22 (1971).

2. H. A. Koehler, L. J. Ferderber, D. L. Redhead, and P. J. Ebert, "Stimulated VUV emission in high-pressure xenon excited by high-current relativistic electron beams," Appl. Phys. Letters 21, 198-200 (1972).

3. E. R. Ault and M. L. Bhaumik, "UV Gas Laser Studies," Northrop Report No. NRTC 72-14R, November 1972.

HIGH POWER ULTRAVIOLET LASER RADIATION FROM MOLECULAR XENON

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ABSTRACT

Experiments have been conducted on a high pressure Xe laser excited by a high current, pulsed, relativistic electron beam. Spectral, temporal and calorimetric diagnostics were performed. The results establish that lasing in molecular Xe has been achieved with the highest laser power yet obtained in the vacuum ultraviolet. Premature termination of light output indicates the possibility of significant effects due to thermal collisions.

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Evidence of stimulated emission in high pressure Xe gas undergoing excitation by a pulsed high current relativistic electron beam, as originally suggested by Basov and Danilychev,[1] was reported in previous investigations[1a] and is now established in experiments with more complete diagnostics.[2]

A schematic of the apparatus is shown in Fig. 1. The electron beam was obtained from a Maxwell POCO facility. Diode voltage and diode current were recorded for every shot. The electron beam drifted horizontally through a low pressure chamber where it was shaped into a rectangular cross section of ~3 x 9 cm and delivered ~2 kJ to the target chamber (TC) through a supported 1 mil titanium foil. The entire electron trajectory was immersed in a longitudinal magnetic field of ~10 kG.

Fluorescence from the Xe was monitored in the vertical direction by a photodiode (FPD).[3] Emission was also monitored in the horizontal direction transverse to the electron beam trajectory by a SPEX 3/4 m vacuum spectrograph operated in the photographic mode.[4] A fraction of the transverse emission was split off by a LiF flat and monitored by a photodiode (TPD). The FPD and TPD were individually biased using 1 kV battery stacks. All signals were monitored in a screen room.

One inch diameter mirrors could be mounted internally in such a way that they supported no static pressure gradient. The mirrors were fabricated by evaporating aluminum onto metal substrates followed by an overcoat of MgF_2. Reflectivities of ~70% could be expected. The optical cavity was

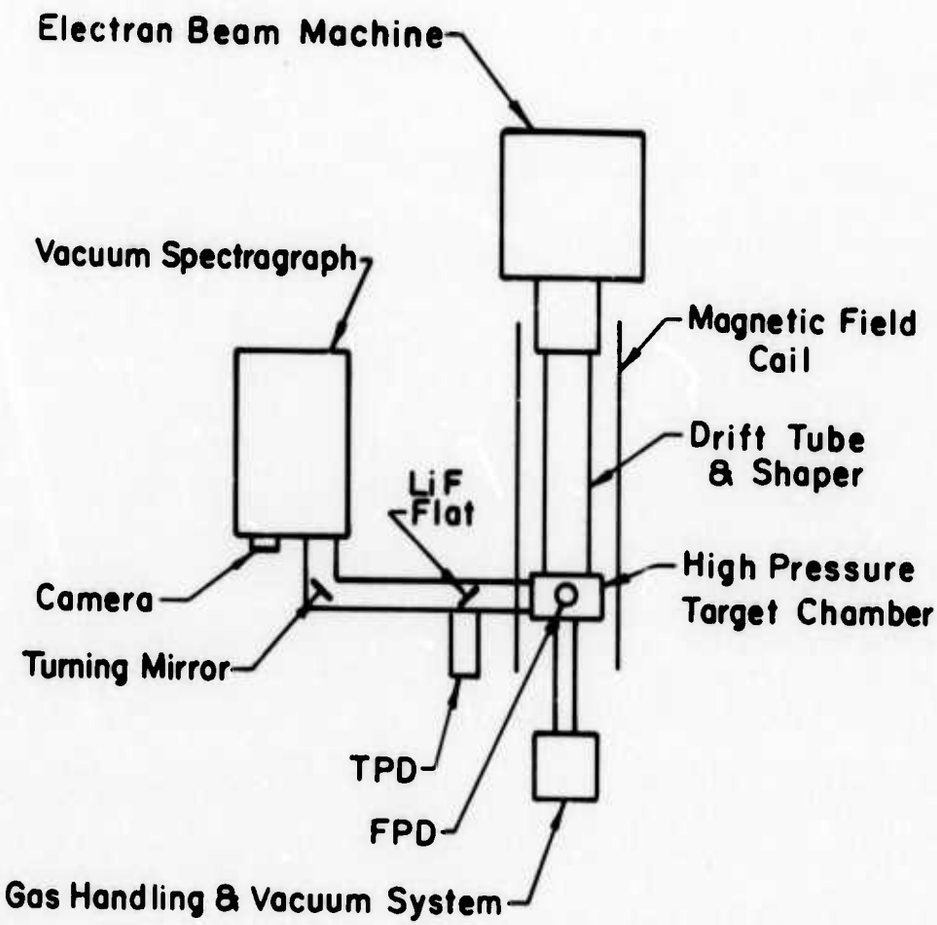

Fig. 1. Schematic of apparatus.

formed using a 4 m sphere and a flat which had an array of holes on 0.1 inch centers. Output couplings of 10% and 30% were used. Alignment was accomplished with a helium-neon laser before pressurization of the TC.

A turbomolecular pump was used to evacuate the TC and gas handling system typically to lower than 3×10^{-6} torr. A new charge of research grade Xe was added to the TC for each shot. In an attempt to enhance gas purity, the Xe was frozen at liquid nitrogen temperature and evacuated by using the turbomolecular pump; finally, each fill of the TC was done with the Xe reservoir at dry ice temperature.

Fluorescence was monitored over a pressure range from 150 to 325 psia. The linewidth varied from ~160A at lowest pressures and excitation energy[1] to ~80A at 280 psia. Maximum FPD and TPD signals were registered at 280 psia and had a qualitatively different shape from those at lower pressures. There was an additional rapidly rising and falling feature superimposed on the slowly varying signals seen at lower pressures, which is attributed to the effects of enhanced stimulated emission. The "additional" signal was more noticeable from the TPD, as would be expected, since the gain length in that direction is >2X that in the FPD direction.

When mirrors were introduced to form an optical cavity, significant line narrowing and increase in the TPD signal were observed. Figure 2 shows the voltage and current waveforms from the electron beam machine temporally related to the FPD and TPD signals. In contrast to the no-mirrors

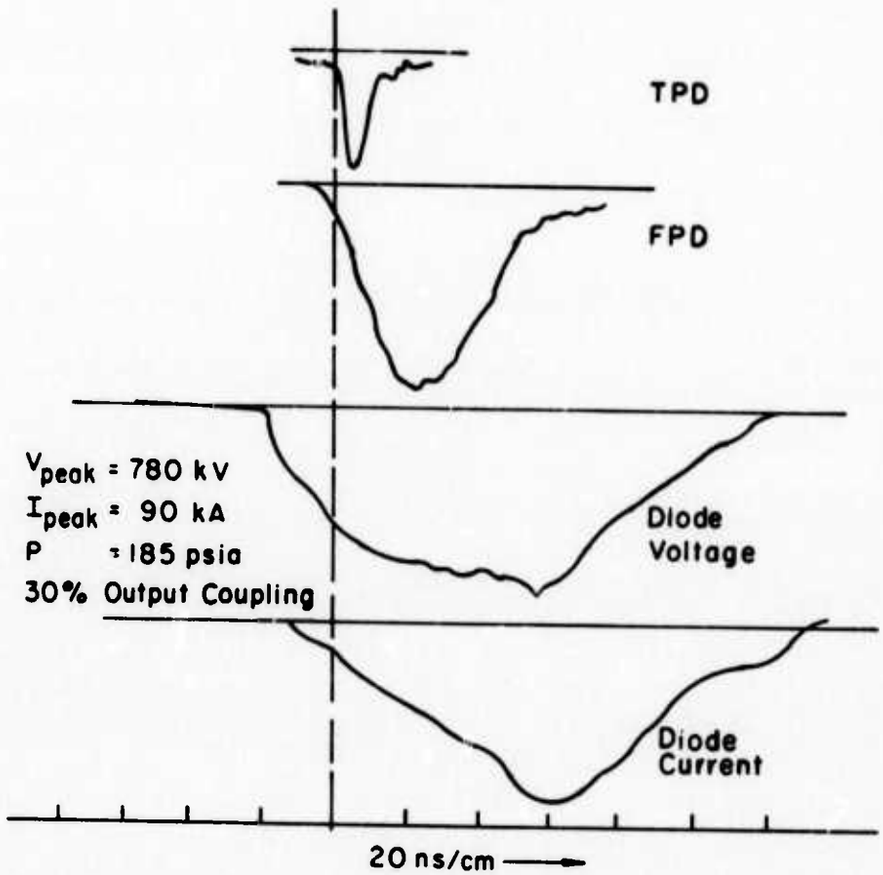

Fig. 2. Temporally related laser and fluorescent photodiode signals (arbitrary scales) and electron beam signals.

case, the TPD signal exhibits a sharp turn-on characteristic. The peak TPD signal increased by ~320X when using the 30% transmitting mirrors. The TPD signal terminates early in the electron beam pulse and may be due to a variety of causes including mirror damage, thermal collisions, etc. More notably, even the FPD signal terminates prematurely and this is ascribed to the effects of thermal collisions.

The estimated temperature rise of the Xe gas after the full electron pulse is ~2000K which is equivalent to ~0.2 eV thermal energy per atom. The estimated density of ground state pseudomolecules having large Franck-Condon factors with the excited states may be as large as $10^{19}/cm^3$ and would lead to considerable radiation trapping.[5,6] Therefore, the fluorescence light intensity would be reduced, giving the appearance of a terminating signal, and would be emitted in a characteristic time $\tau' = \sqrt{n\tau}$, where n is the number of absorptions that occur in the viewing direction and τ is the true excited state lifetime. Additionally, since the excited state lifetime is effectively increased, then collisional destruction of the excimer will become more important.

Other effects that may be significant and lead to premature termination of light output are thermal dissociation of the excited state, larger collisional rates at the elevated temperature, and deactivating collisions with primary (relativistic current) and secondary (reverse current) electrons.

The time delay for laser initiation was a function of pressure, and a minimum of ~7 nsec was observed at ~185 psia. Severe mirror damage with obvious mode structure was observed for all laser shots. The region of most severe mirror damage was observed to move toward the electron input window as the pressure was increased, indicating the change of electron range.

When using mirrors, laser action was achieved over the full pressure range tested from 120 to 280 psia, but due to the limited number of mirrors available threshold pressures were not determined. Figure 3 shows a densitometer trace of the laser spectrum at 280 psia. The laser peak wavelength is 1730 ± 20Å. The linewidth is ~18Å and was approximately the same for all mirrors and gas pressures tested. The spectral feature on the blue side of the laser line is probably due to an impurity absorption having a relatively sharp band edge and is degraded toward the red. In order to determine whether an impurity in the gas caused the absorption, a careful inspection of the fluorescence spectrum was made. No absorption near the maximum of the fluorescence curve could be found to within the film noise, which would allow for up to 6% absorption per pass. The fractional reduction in laser intensity, at a given wavelength λ, due to absorption is $\gamma(\lambda) \leq \exp[B(\lambda)\ell]$ (assuming the gain per double pass is much greater than unity), where B is the absorption per unit length at λ and ℓ is the distance the laser radiation field travels. For this experiment $B \leq 6 \times 10^{-3}$ cm^{-1} and $\ell \leq 3 \times 10^{2}$ cm, thus allowing for a maximum possible reduction of laser intensity at λ of e,[1,8] a potentially sizable effect. ℓ was calculated from the TPD signal. It is

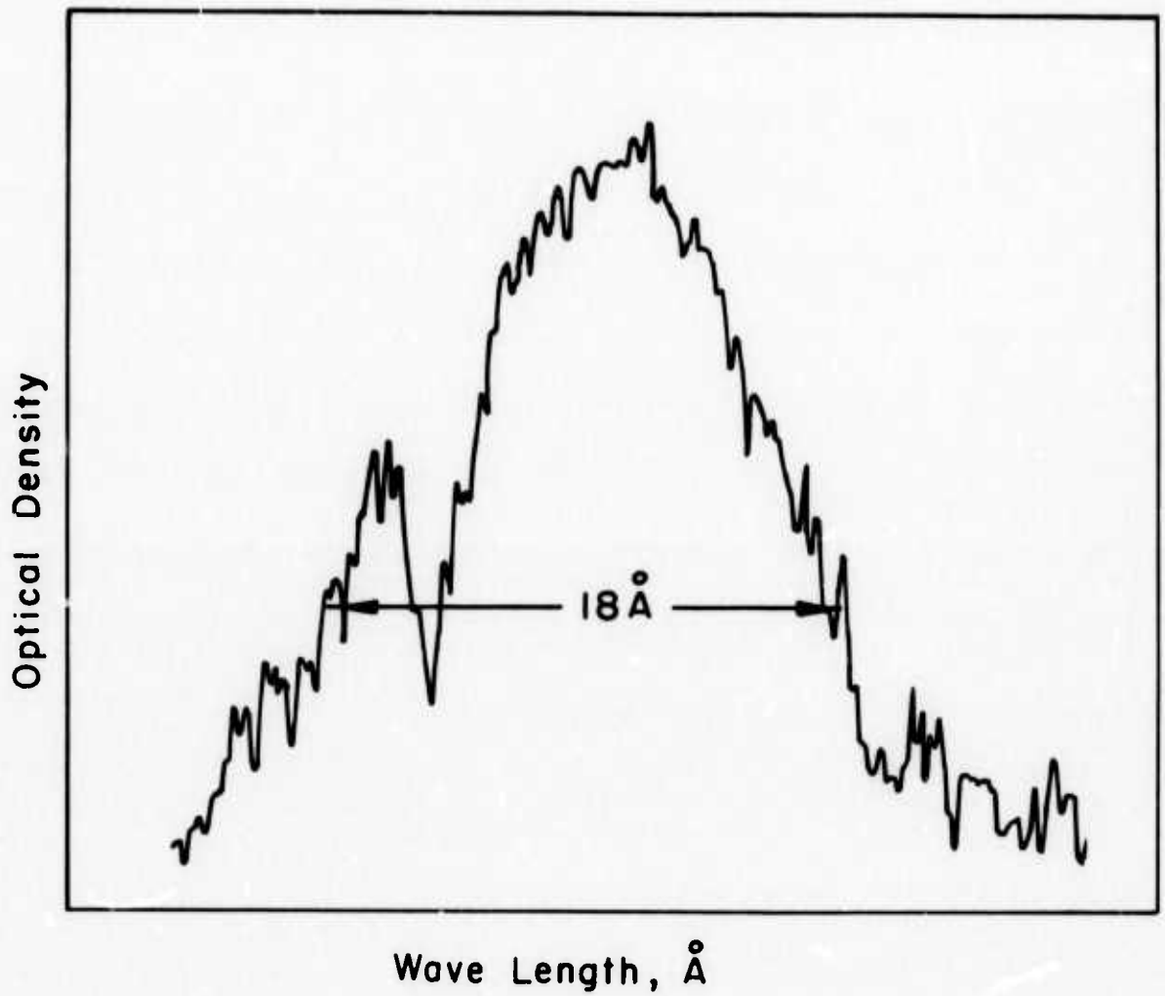

Fig. 3. Densitometer scan of laser spectrum. 280 psia of Xe.

also possible that the mirrors may absorb in a relatively narrow band in the presence of the high intensity VUV radiation due to mirror damage.

A variation of the peak intensity laser wavelength was observed as a function of pressure and is shown in Fig. 4. A shift to the red was seen with increasing gas pressure. This shift may be due to the higher rate of vibrational relaxation in the excited state or to absorption occurring through ground state collisions. The photographic plates were not calibrated, and we have assumed that the wavelength of the band edge of the absorption feature as seen in Fig. 4 is invariant over the experimental conditions.

Laser emission at 185 psia was measured calorimetrically to be 0.1J when using 30% output coupling. Using the above energy and the temporal behavior as determined by the TPD signal from another laser shot leads to a peak output power of $\sim$20 MW or $\sim$60 MW/cm^2. Calculations performed to estimate the efficiency conversion into fluorescent output E_f, and laser output, E_L, yield $E_f \approx 6\%$ and $E_L \approx 1\%$. The full energy delivery was used in calculating E_f. Calculations of E_L included only the energy delivered to the volume between the mirrors up until the termination of the laser output. This value of E_L is probably conservative since the laser emission would not be expected to fill the geometrical output holes completely.

In conclusion, electron beam excitation has resulted in the demonstration of laser action in high pressure Xe gas. When mirrors are included, substantial line narrowing, significant increase in light output, mode pattern

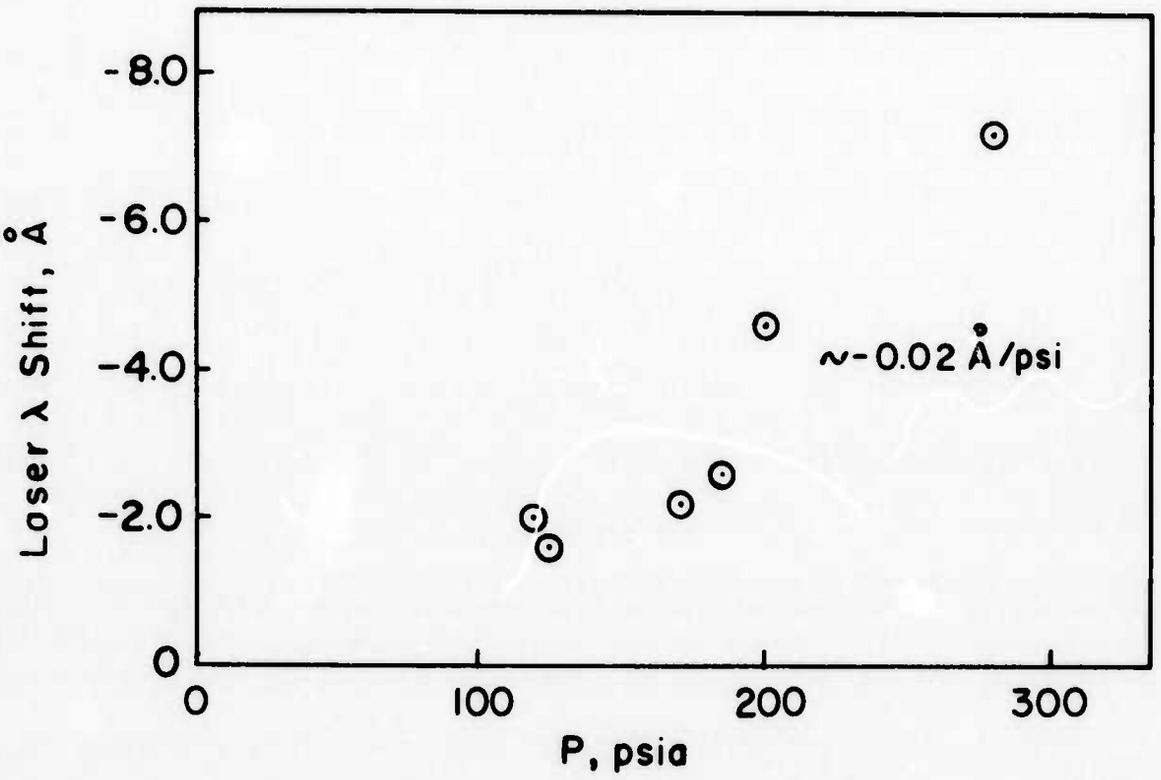

Fig. 4. Shift of laser peak intensity wavelength versus gas pressure, $\lambda = \lambda_0 + \Delta\lambda$.

damage to the mirrors, and drastic change in the temporal character of the light emission occur. Calorimetry and temporal behavior establish the molecular Xe laser as having the highest output power in the vacuum ultraviolet.

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REFERENCES

1. N. Basov, V. Danilychev, and Y. Popov, Sov. J. Quantum Electron. 1, 18 (1971).

1a. E. R. Ault, M. L. Bhaumik, W. M. Hughes, R. J. Jensen, C. P. Robinson, A. C. Kolb, and J. Shannon, IEEE J. Quantum Electron. 9, 1031 (1973).

2. Also see, H. A. Koehler, J. J. Ferderber, D. L. Redhead, and P. J. Ebert, Appl. Phys. Lett. 21, 198 (1972); J. Gerardo and A. W. Johnson, J. Appl. Phys. (to be published). P. W. Hoff, J. C. Swingle, C. K. Rhodes, Opt. Commun. (to be published).

3. ITT Type F 4115 photodiode with a MgF_2 entrance window and CsTe photocathode.

4. Kodak Type SC 7 ultraviolet film was used. The spectrometer dispersion was 11Å/mm when using a 1200-grooves/mm grating blazed at 1500Å.

5. For potential energy curves, see R. S. Mullikan, J. Chem. Phys. 52, 5170 (1970).

6. I. V. Kosinskaya and L. P. Polozova, Optics and Spectroscopy 30, 458 (1970).