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XeF PUMP LASER

FINAL TECHNICAL REPORT

March 1980

prepared for

UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE LABORATORY
Livermore, CA 94550

under Subcontract No. 012/C03

AVCO EVERETT RESEARCH LABORATORY, INC.

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1.0 INTRODUCTION

There is a requirement for high repetition rate lasers at the 1 kW power level for use as a dye pump to provide high-power tunable lasers and for other applications. The available data of the single-pulse characteristics of the XeF laser operating at 350 μm suggested that this laser would be applicable for further development. The desired repetition rates and power outputs can be obtained by flowing the gas out of the laser cavity between pulses. Economic constraints dictate that the flow system must be a closed loop and that low pressure drop throughout the flow channel is required. There were two major issues which might have limited the utility of this laser system. These were: (1) the feasibility of achieving sufficient damping of the acoustic disturbances between consecutive pulses consistent with the requirements of low pressure drop in the flow loop, and (2) the attainment of laser efficiency and output energy of sufficient magnitude under flowing conditions. Answers to these questions were required for evaluation of the potential of the XeF laser system. These issues were examined experimentally without the complexity of an actual closed-loop flow system and extensive power conditioning system through the use of a blow-down flow facility and burst mode electrical excitation. The goal of this program was to demonstrate operation of an XeF laser of adequate energy, efficiency and beam quality at high repetition rates. The specific design goals were:

PRF	$\geq 10 \text{ kHz}$
Energy output	$\geq 50 \text{ mJ/pulse}$
Efficiency	$\geq 0.3\%$
Beam divergence angle	$\leq 20\times \text{ diffraction limited}$

In the following sections of this report we will discuss how these goals have been met.

2.0 DESCRIPTION OF AERL SUPPLIED FACILITIES

Figure 2.1 is a diagram of the blowdown facility which was designed for this experiment. The laser gas is mixed and stored in a 4 cu ft tank. To accelerate mixing, a small circulation pump (1.3 CFM) is provided. A 2-inch ball valve with 25 ms operating time is used to initiate the flow and a throttle hand valve is used to regulate the flow. The gas then enters a plenum and passes through a sonic orifice flow plate before entering the laser cavity. After the laser cavity the gas passes through the diffuser to a check valve which permits the system to be evacuated before starting. The gas flow is then exhausted to the atmosphere.

A new configuration for UV preionized discharge pumped excimer lasers has been developed at AERL. Previous discharge pumped excimer lasers have not been compatible with high-speed transverse gas flow required for high repetition rate operation. The AERL design uses preionizers located behind a screen electrode, thus permitting gas flow transverse to the laser axis. Inductance is minimized by current returns, which are spaced to permit gas flow, located on both sides of the discharge.

The UV for preionization passes through a 100 mesh stainless steel screen which is spot welded to the anode. There are a number of advantages to this laser configuration:

- . it offers the possibility of high-speed transverse gas flow;
- . the preionizers are not in the gas flow when transverse flow is used, thus permitting much more rugged spark sources such as modified automobile sparkplugs to be used;
- . arcs may occur between the preionized and main discharge electrodes if they are not connected together electrically. In this design one electrode of the preionizers is attached to one of the main discharge electrodes, thus eliminating this problem;
- . the gradient of ion density is parallel to the electric field, thus reducing the probability of arcing;

H 2172-1

Fig. 2.1 Diagram of Blowdown Facility

the preionizers are located closer to the main discharge, thus reducing the intensity required, even with a 50% transmission screen on the anode.

Figure 2-2 is a cross section of the laser cavity showing the location of the electrodes, preionizers, electrical feed-throughs, acoustics, capacitors, thyatron and gas flow inlet and outlet. This design uses only metal, ceramic and teflon, and is therefore highly resistant to attack by fluorine.

Figure 2-3 is a block diagram of the XeF laser electronics for burst mode operation. The valve pulser starts the operating sequence by opening the 2-inch ball valve on the supply tank for a time adjustable from 0.1 to 1.5 s. An adjustable delay which may be set for any time during the valve opening provides a pulse to trigger the 10 kHz burst generator. The burst generator triggers the 1002 charging thyatron for the preionizer and the 1802 charging thyatron for the laser discharge. The 1802 preionizer thyatron is triggered after a 50 μ s delay to allow charging time. The output of the 50 μ s delay generator also feeds the discharge delay which drives the Cober 605P pulser which triggers the HY-53 main discharge circuit. The energy required in the burst mode operation is stored in capacitor banks. A crowbar circuit is provided to protect the HY-53 if it goes into continuous conduction.

Figure 2-4 is a detailed circuit diagram of the modulator charging circuit. The major problem with circuits of this type is to prevent the charging thyatron and the discharge thyatron from conducting simultaneously due to triggering by noise. If this occurs, the 14 μ F energy storage capacitor is discharged and no further pulses can occur. As is usual with problems of this nature, it yielded only to a tedious trial and error solution. Careful attention was required to grounds, bypassing, shielding and isolation. Figure 2-5 shows five charge-discharge cycles at 10 kHz repetition rate.

Fig. 2.2 Cross Section of Laser Cavity

Fig. 2.3 Block Diagram of Laser Electronics

H7350

CHARGING CIRCUIT

Fig. 2.4 Schematic Diagram of Modulator Charging Circuit

VOLTAGE $\uparrow$
(10 kV/MAJOR DIV)

TIME $\rightarrow$
(50 μ s/MAJOR DIV)

H7149

Fig. 2.5 Laser Discharge Pulse Modulator

3.0 SINGLE PULSE PERFORMANCE

3.1 SINGLE PULSE PERFORMANCE

Single-pulse tests were performed using a shaped aluminum electrode 6 cm wide by 1 m long. In order to minimize hot gas clearing time the discharge width was initially set at 3 mm by means of a slot in the anode which controlled the area illuminated by the preionizers (1-2).

The number of 600 pf capacitors was optimized as shown in Fig. 3.1. At the optimum of 12 capacitors on the switched side of the circuit and 28 on the storage side, a maximum output of 36 mJ was obtained. Increasing the reflectivity of the output mirror to 24% further increased the output to 40 mJ.

Since this seemed to be about the best that could be obtained from the 3 mm wide discharge volume, the slot in the anode was increased to 6 mm wide, increasing the discharge width correspondingly. The input energy was also increased by increasing the number of capacitors to 24 on the switched side and 44 on the storage side of the discharge circuit. This increased the output to 56 mJ with the 24% reflector. Figure 3.2 shows the output as a function of input for the 3 mm and 6 mm discharges. As can be seen, the saturation effect shown in the 3 mm wide discharge does not appear for the 6 mm wide discharge. Thus, the saturation observed for the 3 mm wide discharge seems to be purely a volumetric effect. The single-pulse performance under flowing conditions was essentially the same as under static conditions.

3.2 TESTS WITH OTHER GASES

Other gases which exhibited laser output in static tests were krypton fluoride, fluorine, pure nitrogen, nitrogen in helium, and neon. Argon fluoride was tested but did not lase. Nitrogen in helium at atmosphere pressure was used in high repetition rate runs as discussed above.

An output of ~20 mJ was obtained from krypton fluoride at 10 J input; however, conditions were not optimized.

Figure 3.3 shows the output from nitrogen and helium-nitrogen mixtures as a function of pressure with charging voltage as a parameter. In pure N_2 the output peaks at ~110 torr and in 1 atm N_2 -He mixtures at 20-25 torr. The maximum output was near

J3182

Fig. 3.1 Output Energy vs Number of Capacitors

Fig. 3.2 Output Energy (mJ)/Charging Voltage (kV)

Fig. 3.3 Output from Nitrogen and Helium-Nitrogen Mixtures

the lower limit of the joule meter used for measurements but is estimated to be ~3 mJ. Since argon fluoride did not lase, the N₂-He mixture was used as a low cost mix for repetitive pulse and beam divergence tests. The results of the repetitive tests are discussed in that section.

Although the argon fluoride mix (0.2% F₂, 10% Ar, balance He) did not exhibit lasing output at the 1930 Å line of ArF, strong lasing was observed at the 7000 Å lines of fluorine. The output was estimated to be several millijoules.

Lasing was observed in pure neon at lower pressures with low output intensities. Lasing was observed only when the preionizers were not used. This is probably due to a reduction in breakdown voltage when preionization is used. Attempts to lase Ne-He mixtures were not successful.

3.3 PREIONIZATION

It has been found necessary to add a seed material to the XeF laser mix to assist preionization and obtain the maximum output. The vapor from RTV silicon rubber has been found to be effective seed material; however, it is not very convenient to use in the blowdown facility. Therefore, a number of materials were tested, as listed in Table 3.1, to determine their suitability for use in the laser. The tests were not extensive and some of the materials listed that did not work under the conditions given might work when optimized. As indicated in the table, benzene was found to work equally as well as RTV vapor.

Figure 3.4 shows laser output as a function of benzene pressure which peaks at about 0.03 torr. Benzene has a vapor pressure of 40 torr at room temperature, thus making it easy to add benzene vapor to the gas mix when it is prepared. It was also observed that when no seed material was present the laser intensity was highest near the anode screen where the UV preionization light entered the discharge region. The intensity decreased near the cathode. When the seed material was present the intensity was uniform across the beam. Thus, an alternative to using seed gas might be to provide preionizers on both sides of the discharge. This same effect was observed in a KrF laser at AERL and the installation of preionizers on both sides was effective in making the beam uniform and in increasing the output by a factor of 2.

The distance of the preionization source from the laser discharge has a strong effect on laser output as shown in Fig. 3.5. Although a number of different types of preionization sources were used, as indicated by the arrows in Fig. 3.5, it appears that the distance from the discharge is the dominant parameter. This data was taken using the KrF laser mentioned

TABLE 3.1
PERFORMANCE OF SEED MATERIALS

MATERIAL	PERFORMANCE
Dibutyltin Dilaurate	No effect
Glacial Acetic Acid	No effect at low concentration 0 at high concentration
Medical Adhesive Silicone Type A	Same as GE #102 RTV
Acetic Anhydride	No effect
Water	0 output
GF #664A	No effect
GF #664B	Same as GE #102 RTV
Methyltriacetoxysilane	No effect (Concentration not optimized)
Benzene	0 at high concentration Same as GE #102 at 0.2 torr
Xylene	0 at high concentration
Toluene	0 at high concentration

J3183

Fig. 3.4 Output Energy (mJ)/Benzene Concentration

FIG. 3.5 Output Energy vs Distance of Preionizer from Laser Channel

previously in which no additives were used. As can be seen, when no additives are used, the output drops rapidly as the preionizers are moved away from the discharge.

This result was confirmed in the XeF laser after the repetitive pulse runs were completed, when the spark plug preionizers were replaced by a corona bar consisting of a Pyrex capillary tube with a tungsten wire inside it. The capillary tube was mounted with its surface 1.5 mm from the back of the anode screen and the tungsten wire was connected, electrically, to the cathode. Thus, when the main discharge thyatron is fired a rapidly rising voltage appears on the tungsten wire and causes a corona discharge to occur from the surface of the Pyrex tube to the back surface of the anode screen. This discharge charges the capacitance between the tungsten wire and the surface of the Pyrex tube which is covered with a plasma. The cathode for this experiment consisted of a 1.9 cm diameter rod. Using this preionizer and no additives, the output was the highest ever achieved for the test conditions. When benzene was added the output decreased, probably due to absorption.

From the above data we conclude that the wavelengths responsible for preionization when additives are not present are below 1300 Å, which corresponds to the 9.2 eV ionization potential of benzene.

It was also found that the spark plug preionizers had no effect on the laser output with the 1.9 cm diameter electrode. Although the spark plug preionizers made no difference the laser output was still enhanced by the addition of benzene vapor to the gas mix. Without benzene vapor the output was 70% of that with benzene vapor on the first pulse but on subsequent pulses the output dropped very rapidly when no benzene vapor was present. This rapid drop in output was probably due to the decomposition of the trace impurities present which were responsible for the preionization. Preionization was probably provided by the corona discharge from the insulated current returns located 7.5 cm upstream and downstream. The output did not drop because the electric field shaping provided by the 1.9 cm diameter electrode restricted the discharge volume to near the optimum value.

4.0 REPETITIVE PULSE PERFORMANCE

4.1 REPETITIVE PULSE PERFORMANCE

4.1.1 Repetitive Pulse Test of Preionizers

In order to determine if the UV preionization sources would function at 10 kHz, an experiment was set up to test one of the spark sources which had been chosen for the XeF laser. The same circuit which was used for the 10 kHz laser tests was used. This consists of an EGG 1802 thyatron discharging a 600 pf capacitor into a 15 ft length of 50 Ω cable connected to the spark plug. The applied voltage was ~15 kV. The light output was observed with an S5 biplanar photodiode. Figures 4.1(a) and 4.1(b) show the light output for a burst of 10 pulses at 1 kHz and 10 kHz, respectively, in air. As can be seen from the pictures, the light output at 10 kHz is higher than at 1 kHz. In order to see if the higher output was due to a difference in discharge voltage, the pictures in Fig. 4.2 were taken. Figure 4.2(a) is the discharge voltage at 1 kHz and Fig. 4.2(b) is the discharge voltage at 10 kHz. These photographs show that the voltage is actually higher at 1 kHz. This is due to the resonant charging circuit which, in this case, rings at 6 kHz. After the last pulse in Fig. 4.2(b), the voltage has time to fully double to twice the applied voltage. Also, the first two pulses are just about equal to the charging voltage, which accounts for the two lower intensity pulses in Fig. 4.1(b).

4.1.2 Electrode Design for Repetitive Tests

In order to determine if downstream arcing in the heated gas from preceeding pulses would be a problem, a series of tests were conducted at 10 kHz repetition rate and 100 m/s flow velocity before installing the acoustics. At the time of these tests the 4.5 cm wide electrode was still in place and downstream arcing did occur. This indicated that the breakdown voltage of the hot gas, even after 100 μ s, was lower than the preionized cold gas. Therefore, a narrow electrode 6 mm wide, and comparable to the discharge with a semicylindrical contour, was installed with the acoustic damping as shown in Fig. 4.3. With this configuration downstream arcing still occurred at 10 kHz repetition rates and 100 m/s flow velocities. Double pulse experiments gave a maximum repetition rate of 4 kHz. Examination of the electrode configuration suggests that this is probably due to a capacitive discharge occurring from the extensions on the sides of the cathode, through the Teflon and acoustic material and through the hot gas to the opposite wall. A discharge can then occur along the

H3289

Fig. 4.1 Preionization Spark Source Light Output at
a) 1 kHz, b) 10 kHz

H3288

Fig. 4.2 Preionization Spark Source Charging Voltage at
a) 1 kHz, b) 10 kHz

Fig. 4.3 Laser Configuration with 6 mm Wide Electrode and Acoustic Damping

surface of the acoustic foam to the tip of the cathode. This was confirmed by observation. The output energy was also substantially lower with this electrode due to the narrowing of the discharge caused by the relatively small radius (3 mm). This can be seen in Fig. 4.4, which shows interferograms taken at various times (given in microseconds) after the discharge. As can be seen in the first interferogram taken at 1 μ s, the discharge is constricted near the cathode which results in a reduction of discharge volume and a corresponding loss in efficiency.

The second electrode was 1.9 cm wide with the center flat and the edges with a 5 mm radius. As can be seen in the interferograms of Fig. 4.5, the discharge occurs from the two edges of the electrode where the electric field intensity is high and very little energy is deposited in the center.

An electrode was then designed following the technique described by Chang(3). This results in the curves shown in Fig. 4.6. As is shown, however, a round rod of 1.9 cm diameter deviated less than 0.25 mm from the calculated electrode profile. Therefore, a length of round brass rod was used for the electrode. Figure 4.7 shows interferograms taken using this electrode. The measured output energy was the same as with the 4.5 cm wide electrode, but the reduced width permits more rapid hot gas clearing. This electrode was, therefore, selected for use in future tests.

4.1.3 Repetitive Pulse Tests

After optimizing the electrode design a series of tests was undertaken to evaluate the performance of the laser under repetitive pulse conditions. Figure 4.8 shows the effect of varying the spacing between the two pulses at ~100 m/s flow velocity. The upper trace is the voltage on the thyatron and the lower shows the integrated light output for each pulse. Note the change of horizontal sweep speed from 50 μ s/division to 100 μ s/division for the 350 μ s and 400 μ s pulse spacings. As can be seen, the intensity of the second pulse is a function of the pulse spacing. This phenomenon may be due to a glow discharge occurring downstream.

Figure 4.9 shows some typical high repetition rates runs at different flow velocities using XeF gas mix. Because the data is highly variable from shot to shot, a least squares fit to all of the data points was performed and is displayed in Fig. 4.10, which plots the amplitude ratio of the second pulse of a pulse train to the first pulse against flush factor. The flush factor, F, is defined as:

$$F = \frac{U_{\infty} t}{W} \quad (4.1)$$

H9040

Fig. 4.4 Interferograms of Laser Discharge with 6 mm Wide Electrode

H8039

Fig. 4.5 Interferograms of Laser Discharge with 1.9 cm Wide Flat Electrode

*T.Y. CHANG, REV. OF SCI. INSTR. 44, 405 (1973)

Fig. 4.6 Comparison of Chang Electrode Profile with $K=0.53$ with Round Rod

Fig. 4.7 Interferograms of Laser Discharge with 1.9 cm Diameter Electrode

200 μ s

250 μ s

300 μ s

350 μ s

400 μ s

H8041

Fig. 4.8 Effect of Pulse Spacing on Amplitude of Second Pulse

Fig. 4.9 Typical Performance at Various Repetition Rates
(Note changes in sweep speed)

Fig. 4.10 Ratio of Pulse 2 to Pulse 1 vs Flush Factor

where U_∞ = flow velocity,
 t = time between pulses,
 w = discharge width.

The discharge width is taken as 0.8 cm for XeF and 1.2 cm for N_2He . This data was taken at velocities ranging from less than 100 m/s to over 400 m/s. The higher flush factors therefore tend to be at higher velocities. As can be seen, the improvement in performance at higher velocities (flush factor) is not as great as one might expect from data taken at constant velocity. This can be seen from Fig. 4.11 which shows the effect of flush factor on the pulse ratio for a constant velocity of 100 m/s in XeF gas mix. At high velocities the time between pulses will be shorter for a given flush factor than at low velocities, thus allowing less time for the gas conductivity to decay.

After the discharge occurs the electrons will be rapidly attached by fluorine or NF_3 . The number of fluorine ions, n , remaining after time, t , is:

$$n = \frac{1}{1/n_0 + at} \quad (4.2)$$

for the conditions in the laser at $at \gg 1/n_0$, hence:

$$n \approx \frac{1}{at} \quad (4.3)$$

$$\text{for } t = 100 \mu s, n \approx 10^{10}/cm^3. \quad (4.4)$$

This is greater than the level produced by preionization and can therefore provide an alternate path for conduction of the discharge current.

In order to determine if a visible discharge was occurring which caused the reduction in amplitude of the second pulse, photographs were taken through the end windows of the laser of the discharge as shown in Fig. 4.12. The diagram at the top of Fig. 4.12 shows the perspective of the photographs. At 167 μs visible streamers and arcs can be seen on the downstream side to the left of the discharge, whereas at 200 μs no streamers are apparent.

Another factor which degrades performance is turbulence and wakes from the current return rods which results in spreading of the hot gas region. The velocity defect behind a cylinder may be calculated as follows(4):

Fig. 4.11 Ratio of Pulse 2 to Pulse 1 vs Flush Factor for
 $V = 100 \text{ m/s}$

PERSPECTIVE VIEW

H8042

Fig. 4.12 Photographs of Discharge at 167 μs and 200 μs of Pulse Spacing

$$\frac{u_1}{U_\infty} = 0.976 \left(\frac{x}{C_D d} \right)^{-1/2} \left[1 - \left(\frac{y}{b} \right)^{-3/2} \right]^2 \quad (4.5)$$

where U_∞ = free-stream velocity
 $u_1 = U_\infty - u$
 $\bar{u}$ = mean velocity downstream of cylinder
 x = distance downstream
 C_D = drag coefficient
 d = diameter of cylinder
 b = half width of wake
 y = distance from center line of cylinder

$$\text{then for } y = 0, u_1 = 0.31 U_\infty. \quad (4.6)$$

The rms velocity fluctuation, u' , is then⁽⁵⁾:

$$u' = 0.35 u_1 \quad (4.7)$$

For the conditions in the laser

$$u' = 0.11 U_\infty \quad (4.8)$$

The diffusion distance, d , in time, t , is then:

$$d = \sqrt{u' t \ell} = \sqrt{0.11 U_\infty t \ell} \quad (4.9)$$

where ℓ = integral length scale = $\sim 1/2$ channel width.

The actual flush factor, F' , is then degraded by the wakes and turbulence from the current return rods. Then from Eqs. (4.1), (4.6), and (4.9)

$$F' = 0.69F - \sqrt{\frac{0.11 F \ell}{W}}$$

This is plotted in Fig. 4.13 which shows that the flush factor is degraded by a factor of ~ 2 at most values of interest. Experimental evidence for this is shown in Fig. 4.14 which gives interferograms of the flow at 50 μ s after the discharge at flow velocities of ~ 100 m/s and ~ 200 m/s. As can be seen, the hot gas region is much wider at the higher flush factor.

This effect is not as important in the N_2 -He mix due to the larger initial discharge width which is observed.

Fig. 4.13 Reduction in Flush Factor Due to Turbulence and Wakes

100/ms

200/ms

J2763

Fig. 4.14 Interferograms of Hot Gas 50 μ s After Discharge

5.0 ACOUSTICS

5.1 INTRODUCTION AND SUMMARY

A relatively simple acoustic suppression concept has been investigated analytically and experimentally and found to provide the required attenuation of the waves generated in the XeF laser device. This device, in addition to the waves generated by the reaction of the gases, has waves generated by the spark-preionizers. The initial waves are of two types, those along and normal to the laser gas flow axis. The reactive nature of the laser gas mixture requires material compatibility considerations. In the concepts considered, two approaches were considered. One wherein the acoustic treatment is removed from the mainstream of the reacting gas flow, while the other was directly in the flow. The latter would require materials which have been passivated or inert to the gas mix time; Teflon was considered as a candidate.

The concept with the acoustic treatment removed from the flow can and was found to be less sensitive to the material compatibility consideration. This concept is designated a sidewall attenuator. This concept also results in a configuration with minimum pressure loss which is very desirable. Since this approach positions the acoustic material at the sidewalls all flow paths through it are dead-ended. The only gas flow is that associated with the wave pressure. Further development of this concept might incorporate a fringe flow of neutral gas which would provide protective gas film.

The concept evaluated incorporated the acoustic material (Scotfoam) at one sidewall only; however, both the upstream and downstream regions were treated acoustically.

In the following subsections the constraints and requirements governing the acoustic design (Section 5.2.1), the acoustic environment (Section 5.2.2), the design approach (Section 5.3.1), an alternative concept (through flow absorber Section 5.3.2), and also the test results (Section 5.4) will be discussed.

5.2 ACOUSTIC SUPPRESSION REQUIREMENTS

5.2.1 Medium Homogeneity

The medium homogeneity requirements are discussed in detail in Section 6.1. In summary, it was found that a $\Delta\rho/\rho$ of 0.02 will satisfy the beam quality requirement of $20\lambda/d$.

5.2.2 Acoustic Environment

The wave history in the absence of acoustic attenuators is presented in Fig. 5.1. The history is given in terms of nondimensional time ($\tau_p = at/Lc$) and space ($\xi = x/Lc$) where a is the undisturbed acoustic speed ($a = 92100$ cm/s) and Lc is the cavity width in the flow direction ($Lc = 0.6$ cm). Since, in this analysis there is no acoustic treatment, the upstream waves propagate unattenuated with no reflections. The downstream waves encounter the hot gas slugs from previous pulses (three previous pulses are shown) and complex interactions result as illustrated in the figure. The time necessary to fully expand the energized gas to the final state is very short ($6 \mu s$). The initial wave and its interactions with the previous pulses results in the generation of additional compression waves.

A screen may be selected to disperse the hot gas interfaces and thereby minimize the interactions with the previous pulses. In addition, the screen can partially compensate the first interaction with the previous pulse hot gas interface. This interaction would otherwise result in an underpressure (less than atmospheric) with subsequent oscillations in pressure until the waves are damped (see Fig. 5.2).

On the basis of analysis of the waves associated with the pulsed reactions, the following has been concluded:

1. The final $\Delta\rho/p$ wave which is acceptable is approximately 10% of that which is initially generated. (The medium homogeneity requirement is $\Delta\rho/p = 2 \times 10^{-2}$.) However, the wave which produces an entropy disturbance can be as strong as 15%.
2. The current return rods must be acoustically isolated from the optical cavity.
3. Hot gas interface reflections are approximately 14%. In addition, the characteristic scale for these reflections are that of the cavity flow length (6 mm).

J5529

Fig. 5.1 XeF Pump Laser Wave History

Fig. 5.2 Wave Pressure History

5.3 ACOUSTIC SUPPRESSION CONCEPT

The approach implemented for acoustic suppression was the sidewall attenuator. The very low pressure drop for the laser gas flow and relative ease of fabrication when using acoustic foam material make this concept very attractive. An alternative design comprising acoustic wedges downstream of the laser cavity and reflecting rods upstream of the laser cavity was also investigated and described below.

5.3.1 Acoustic Suppression System Design

Figure 5.3 presents this concept, illustrating the treatment for the spark and end wave acoustics which is an adaptation of the AERL Humdinger aerowindow mufflers. The relative positions of the current return rods are shown in addition to the sidewall absorber treatment.

The selection of the acoustic material involves consideration of the compatibility with fluorine. The applicable materials identified to date are acoustically dense; however, available acoustic foam was evaluated analytically as well as experimentally. The duration of the tests were such that no noticeable deterioration occurred. Prolonged operation might require special wall treatment such as with perforated Teflon. An alternative approach could use the acoustic foam with a protective gas layer of nonreacting gas. There is space in the configuration to accommodate absorbers upstream and downstream, each of which is 1.3 cm deep and nearly 6 cm long. The full depth, 1.3 cm, will be utilized. If necessary, further refinement in the design can be considered by optimizing the absorber depth (within a constraint of 1.3 cm maximum).

The analysis for this concept consisted of treating the waves as sinusoidal with an estimated spectral distribution based on limited experimental data. In addition, an analysis of the attenuation, reflection and entropy disturbance associated with repetitive pulsing was conducted for pressure waves traveling upstream in the duct passage (only the upstream attenuator will generate entropy disturbances which will appear in the active cavity region since these disturbances travel with the flow. This analysis considers perforated wall attenuators requiring the determination of an equivalent open area ratio for the acoustic foam which, for the selected foam was one percent.

The frequency at maximum attenuation is given as ⁽⁶⁾

$$f_0^2 = \frac{a^2}{5.97 H h}$$

FIG. 5.3 Acoustic Damping Configuration

where a is the acoustic velocity (9.21×10^4 cm/s),
 H is twice the passage height (5 cm),
and h is the absorber depth (1.3 cm).

This frequency is determined to be 14.8 kHz for the geometry specified above. The maximum attenuation is obtained when the foam resistance is

$$R = 2.76 H \rho f_0 = 40.6 \text{ Rayls (c.g.s.)}$$

where ρ is the gas density (1.99×10^{-4} gm/cm³).

With these characteristics the anticipated attenuation (op. cit.) has been evaluated and is presented in Fig. 5.4 along with the estimated initial spectral distribution. Predicted attenuation is presented for an optimum sidewall treatment. This optimum requires a resistive lining of 95 Rayls/cm and a thickness of 1.6 mm. A material which satisfies these requirements as well as compatibility with the device has not been identified. The attenuation has also been predicted for an available material (34.6 Rayls/cm acoustic foam). The latter requires a 4.4 mm thickness sheet. The results for this material are also shown in Fig. 5.4. These are the attenuation predictions for sinusoidal waves; the strong waves are easier to attenuate. In order to evaluate the strong wave attenuation the effective porosity of the material is necessary for use in an AFRL code.

The equivalent perforated wall resistance is

$$R_w = 2 \frac{1-\sigma}{\sigma} \sqrt{4\pi\sigma\mu f} = 15.2$$

where σ is the open area ratio
and μ is the gas viscosity (2.02×10^{-4}) poise.

The open area ratio is 0.01 for 38.4 kHz, the characteristic frequency of the pressure pulse. The code predicts a greater attenuation for the pressure pulse than the analysis for the sinusoidal waves. The pressure and entropy variations are shown in Fig. 5.5. The peak reflected wave amplitude results in a $\Delta p/p_0$ given by

$$\frac{\Delta p}{p_0} = \frac{1}{2\gamma} \left(\frac{\Delta p}{p_0} \right)_{QR} = -1.2 \times 10^{-5}$$

The peak entropy disturbance builds up with the number of pulses stabilizing after eight pulses. The density inhomogeneity after the eighth pulse is

Fig. 5.4 Results - 34.6 Rayls/cm Acoustic Foam

Fig. 5.5 Pressure and Entropy Variations

$$\frac{\Delta p}{\rho} = \frac{\gamma-1}{\gamma} \left(\frac{\Delta p}{p} \right)_0 \quad s = -1.8 \times 10^{-6}$$

The code is one dimensional and takes the absorbed gas (during the pressure pulse) from the absorber and distributes this uniformly into the flowing gas as it is expired from the absorber. The disturbances to be expected will be higher than predicted if the entropy disturbance is not mixed and appears as a layer; however, in this case the disturbed region will be local and at the absorber side of the cavity. The reflected waves are seen to be insignificant.

The analyses indicate that the approach is feasible and can be easily implemented. The acoustic foam thickness for a resistance of 34.6 Rayls/cm should be varied to determine an optimum. The desired resistance for the preionizer attenuator is 5.1 Rayls, based on a similar analysis. However, the frequency at peak attenuation is lower at 9220 Hz since the cathode/anode waves reverberate across the cavity at this lower frequency.

5.3.2 Alternative Approach

This consisted of acoustic components which would be directly exposed to the reacting gases. Acoustic elements which were established were the upstream reflector, the downstream disperser and the downstream absorber. (See Figs. 5.6 and 5.7) All acoustic elements configured result in in-depth or distributed reflections in addition to satisfying the amplitude constraints dictated by the required medium homogeneity and the desired pulse rate.

The upstream acoustic element is a reflector since absorption of acoustic energy will result in the transport of entropy disturbances into the active laser cavity at subsequent pulses. The concept selected consists of Teflon rods distributed in a matrix similar to that in a heat exchanger tube core. Since the desire is to reflect the waves downstream, a high reflection coefficient is desired; however, the high blockage required would result in high flow pressure losses. A rod matrix configuration was selected which is 41 percent porous resulting in a reflection per row of 26 percent. Since the rod diameter of 8 mm is large compared to the laser cavity flow length (3 mm), this reflection is distributed as will be those of the other rods. There is an additional dispersion of the incident waves because of the shear flow between the rods. The row of rods nearest to the cavity are streamlined to reduce the flow pressure losses and wakes from the reflector. All flow disturbances from the rods are normal to the laser optical axis. In addition, an upstream screen will be utilized to remove the flow shear. The screen would be made of Teflon with a mesh of 67 and a porosity of 44 percent.

J3524

Fig. 5.6 Acoustic Attenuator Schematic

J3525

Fig. 5.7 Acoustic Attenuator Concepts

The downstream disperser is a coarse screen also of Teflon. Results of the analysis of the flow distortion are presented in Fig. 5.8. The purpose of the disperser is to eliminate the hot/cold gas interfaces. Since the intermittent slugs of hot and cold gas are 3-4 mm wide, the distortion created by the wakes of the coarse screen should be comparable. The coarsest Teflon screen is 17 mesh with filament diameters of 0.04 cm which yields only half the desired distortion. Coarser screens with filament diameters of 1 mm are available and will be examined for possible use.

The downstream absorber is a modification of a through flow absorber demonstrated on the AERL Humdinger small-scale device and consists of acoustic absorbing wedges. The wedges will be fabricated from porous Teflon. Figure 5.9 presents the results of the analyses for the absorber attenuation of the waves transmitted through the absorber as well as those which would be reflected from downstream impedance mismatches. The requirement on these waves is 17.2 db (initial peak SPL of 189.2 db with a maximum acceptable disturbance of 169.3 db rms). The design nearly satisfies this requirement on the transmitted wave and gives a round trip attenuation of 25.7 db. It is important to note that at the pulse frequency (where the structural noise may be generated) the attenuation is 5 db.

5.4 TEST RESULTS

Tests were conducted with and without acoustic treatment. The acoustic suppression concept evaluated was the sidewall attenuator consisting of acoustic foam.

Initial tests using helium gas were conducted for single-pulse discharges. The configuration for these tests had two sections of the cathode-sidewall removed. The medium quality for the base flow was excellent in spite of the wall irregularity. The cavity acoustics were as to be expected. During the early post discharge period cathode and anode waves are generated which travel normal to the flow. These waves are cylindrical and attenuate rapidly as they reverberate from the sidewalls and spread in the flow direction.

The shock waves generated during the discharge interact with the current return rods and the sonic orifice plate. The resulting reflected wave history was established and the time for the disturbance to appear at the cavity determined. The current rod interaction both upstream and downstream should appear at the cavity at 156 and 159 μ s respectively.

A picture at 150 μ s (the wave moves one cm every 10 μ s) clearly shows a disturbance from the upstream reflection entering the cavity region with a $\Delta\rho/\rho = 0.015$. The other important interaction with the flow plate should appear as a disturbance at the

Fig. 5.8 Results of Analysis of Flow Distortion

Fig. 5.9 Results of Analyses for Absorber Attenuation

cavity at 290 μ s. The interferometer picture at 300 μ s indicates a disturbance of $\Delta\rho/\rho = 0.007$. The interaction with the cathode edge should appear at the cavity at 45 μ s; however, the hot gas interface in the cavity region precludes identifying its presence.

These disturbances are less than would be expected for a shock strength of 1.083 when considering the wave to be infinite in depth. The depth of the disturbed region is of the order of the cavity width (0.6 cm). Since the geometry of the interaction is comparable, the finite wave should be expected to give different results. In addition, the stepped wall at the cathode in the tests should have a significant effect on the waves and their attenuation. The flow over these steps is separated and will diffract the wave causing spreading and attenuation. The flow plate jet mixing region is also of the scale of the wave which results in high wave attenuation.

The magnitude of the disturbances at 150 and 300 μ s is important for the repetitively pulsed situation since these disturbances will accumulate. At 10 kHz the pulses are repeated every 100 μ s, which means these disturbances appear at the cavity during subsequent pulses. In addition, the entropy disturbance for the test configuration should appear at the cavity at 1.6 ms after the pulse. Missing from these initial single-pulse tests are the interactions with the previous hot gas slugs downstream of the cavity. These interactions will send waves back into the cavity every 10-20 μ s.

The evaluation of the acoustic foam sidewall attenuation indicated that the above disturbances were attenuated as well as redistributed. The latter effect is also important since, if it is repeatable in time from pulse to pulse (accumulative effects included) then the disturbances can be accommodated by a steering correction.

The interferograms were made using a Twyman-Green interferometer and a Xenon laser at a wavelength, λ_I , of 526 nm. The measured fringe shifts, F_I , will then be:

$$F_I = 2 \frac{\lambda}{\lambda_I} F = 1.33F$$

The factor of 2 is due to the double pass through the medium in the Twyman-Green interferometer.

The shifts corresponding to the cases discussed in Section 6.1 are then:

1. Small-scale disturbances $F_1 = 0.35$

2. Large scale

a. Tilt, $F_I = 2.7$

b. Lenslike disturbances $F = 3.3$

The fringe shift observed may be related to the density fluctuations:

$$\frac{\Delta \rho}{\rho} = \frac{\lambda_I}{2\beta} \frac{F_I}{L}$$

A shift of one fringe is then $\Delta \rho/\rho = 7.3 \times 10^{-3}$.

5.4.1 Acoustic Behaviour in the Absence of Attenuators

The initial test configuration is presented in Fig. 5.10. Two sections of the cathode sidewall were removed for these tests and results in a step of 1.5 cm upstream and downstream of the solid cathode. The anode consisted of a screen over the preionizer. The acoustic environment for a constant volume heating process in the discharge region (2.5 cm height and 0.6 cm width in the flow direction) results in a wave disturbance of $\Delta \rho/\rho = 0.21$ (shock Mach number equal to 1.083) for the test gas (helium).

In addition to the steps in the wall contour, other obstructions in the flow are the current return rods and the sonic orifice plate. The interaction of the acoustic waves with the rods and orifice plate should be identifiable in the interferometer pictures at the appropriate time after the discharge. Since the rods are adjacent to the wall steps, these interactions are merged.

Waves are introduced at the cathode and anode because of the cathode layer drop and because of the preionizer chamber behind the anode screen. The wave from the cathode is a compression wave whereas that from the anode is an expansion wave. These waves are clearly identifiable in the interferograms as well as their progression in time since they are always in the field of view prior to their attenuation within 70 μ s.

The hot gas interface does not appear to be restricted to a narrow zone and in fact is ~0.5 cm in thickness. This softens the interaction and results in a more distributed reflection which is desirable. In addition, the downstream mixing by the screens (if required for the downstream hot gas interface scrambling) should be more effective in minimizing these interactions.

Figure 5.11(a) is an interferogram of the laser without flow and Fig. 5.11(h) is with flow. The slight curvature (~ 0.7 fringe) of the fringes is due to the beamsplitter used in the Twyman-Green interferometer. In any case, 0.7 fringe is substantially less than the ~ 3 fringe tolerance for large-scale disturbances calculated above. There is about 0.5 fringe shift between Figs. 5.11(a) and 5.11(b). This could be due to several causes:

1. Thermal motion of the air in the laser,
2. Change of the gas in the laser from air to helium under flow.

However, even if the 0.5 fringe shift is due to the flow, it may be neglected, since it is sufficiently less than the 3 fringe tolerance.

Figure 5.12 shows the development of the acoustic waves for the first 25 μ s after the discharge. The first picture shows the disturbed region 1 μ s after the discharge. At 3 μ s the acoustic waves have moved upstream and downstream and the anode and cathode waves can be observed moving in from the top and bottom of the picture. At 5 μ s the anode and cathode waves can be seen more distinctly about a quarter of the way from the top and bottom of the picture. At 7 μ s a second reflection from the back side of the anode plate is just entering the picture at the top.

At 8 μ s and 9 μ s the development continues and at 10 μ s the initial anode and cathode waves have met halfway between the anode and cathode and the hot gas region, starting just to the left of the center of the photo, can be distinguished from the acoustic disturbance. At 15 μ s the anode and cathode waves have passed each other and the leading edge of the upstream wave has moved out of the picture. At 20 μ s the cathode wave has weakened considerably due to expansion and is not clearly visible; however, the anode wave is still strong near the lower part of the picture. At 25 μ s the anode and cathode waves have reached the opposite electrodes and have not yet been reflected.

In Fig. 5.13 interferograms covering the range from 30 to 130 μ s are shown. At 30 μ s the anode wave has been reflected from the cathode and is traveling back towards the anode. At 35 μ s the anode wave has almost reached the center of the field of view and a weak disturbance due to the residual cathode wave is visible in the upper half of the picture. At 40 μ s the anode and cathode waves have crossed the center again and at 45 μ s they are approaching the electrodes. At 50 μ s the waves have again reached the electrodes and the region to the left of the hot gas looks relatively undisturbed. At 60 μ s there is a small amount

Fig. 5.10 Laser Configuration for Interferograms

a

b

H6060

Fig. 5.11a Interferogram without Flow
 5.11b Interferogram with Flow

H6061

Fig. 5.12 The structure Development from 1 to 25 μs

H6062

Fig. 5.13 Acoustic Wave Development from 30 to 130 μs

of distortion to the left of the hot gas, but the anode and cathode waves have lost most of their energy. At 75, 90, 100 and 130 μ s, the upstream area steadily improves as the hot gas is carried downstream. As can be seen, the medium has recovered adequately at 100 μ s for the next pulse.

Figure 5.14 covers the period from 150 to 300 μ s. At 150 μ s an acoustic disturbance is observed which is probably a reflection from the current returns. At 190 μ s another reflection is observed, probably from the step in the wall at 8.2 cm from the center of the discharge. The reflection from the orifice plate is visible at 300 μ s. This is shown more clearly in Fig. 5.15 where the negatives of the interferograms with flow only and at 300 μ s after the discharge have been superimposed to give Moiré fringes showing the wavefront.

A search was made for entropy disturbances, which move at the flow velocity, out to 2.4 ms in steps of 200 μ s. No large-scale disturbances stronger than a fraction of a fringe were observed and small-scale disturbances were below the sensitivity limit of the interferometer. This indicates that the sonic orifice plate and associated screen were acting as a depth reflector for the acoustic waves, causing the waves to be stretched out in time and reduced in amplitude.

Figure 5.16 shows the acoustic wave from the preionizer in air. Since air has a β which is 8.3 times higher than that of helium and also a breakdown voltage two times higher, the fringe shift observed in air is 33 times that in helium. The disturbance in helium would therefore be about 0.2 fringe, which is why it is difficult to observe. The large volume between the preionizer and discharge region permits expansion of the shock and spreads the disturbance in time thus reducing its peak intensity. For this reason the preionizer disturbance does not appear to present a problem.

5.4.2 Effect of Acoustic Foam Sidewall Attenuators

Two sidewall configurations were evaluated, which came close to the desired 40.6 Rayls at the appropriate gas velocity. The results are presented as interferometric pictures (Figs. 5.17-5.19). In addition to the acoustic variation, there were electrode modifications. The tested configuration with acoustic treatment was shown in Fig. 5.3. These results should be compared with those presented for the untreated (acoustically) configuration above.

The acoustic treatment effect is best indicated by comparing the interferometer pictures at comparable times after discharge. The electrode wave attenuation performance is indicated qualitatively at 40 μ s where previously a sharp discontinuity

M6063

Fig. 5.14 Acoustic Wave Development from 150 to 300 μs

H6058

FLOW →

Fig. 5.15 Moiré Fringes of Flow Plate Reflection

H6059

Fig. 5.16 Preionizer Wave in Air

H8040

/ Fig. 5.17 Interferograms of Laser Gas with 6 mm Wide Electrode

H8039

Fig. 5.18 Interferograms of Laser Gas with Flat 2 cm Wide Electrode

Fig. 5.19 Interferograms of Laser Gas with 1.9 cm Diameter Round Rod

was evidenced. At 60 μ s these waves have been attenuated with the preionizer acoustics, whereas they still appear in the untreated condition. Acoustic waves appear as strong disturbances as late as 300 μ s. The acoustic treatment results in acceptable medium in the discharge medium after 100 μ s, with hot gas clearing precluding prior discharge. This is remedied by a higher flush factor (higher flow velocity). The short electrode configuration results in a smaller discharge region, hence higher temperatures and wave strength. The final "Chang" electrode gives the best performance in combination with the acoustic attenuator. Further optimization of the acoustics is possible, particularly for multi-pulse operation; however, further diagnostics such as pressure transducers are desired to assist in data interpretation and final acoustic treatment selection, in addition to the interferometer.

5.4.3 Acoustic Material Characterizations

Various grades of foam were characterized for possible implementation of the acoustic suppression concepts proposed. The characterization consisted of determining the acoustic resistance of the various absorbing samples.

The aerodynamic test rig for evaluating the acoustic sample flow resistance consisted of a square duct with a sample holder, a pressure transducer to measure the pressure drop across the sample, a flow meter and a gas supply. The pressure drop divided by the flow velocity establishes the acoustic resistance in Rayls. Figures 5.20 and 5.21 present the results for the samples tested, and illustrate the broad range of resistance available among the samples as well as the nonlinearity of the pressure drop with velocity.

These materials were used for sidewall attenuators as well as within the preionizer for electrode wave suppression. The previous analyses had indicated the desire for a 40.6 Rayl resistance for the sidewalls and 5.1 Rayls for the preionizer.

Fig. 5.20 Scotfoam Flow Resistance

Fig. 5.21 Flow Resistance for Scotfoam No. 264A

6.0 BEAM QUALITY

6.1 MEDIUM HOMOGENIETY

In the following discussion on medium homogeneity the disturbances are divided into two groups: 1) Small scale -- those much smaller than the laser aperture, and 2) Large scale -- disturbances comparable to the laser aperture or larger.

6.1.1 Small-scale Disturbances

The Strehl intensity S is defined as the ratio of far-field axial intensity for arbitrary phase and amplitude at an output aperture normalized to the far-field axial intensity for uniform phase and amplitude over the clear aperture. The Strehl intensities S for ordered (Case I), and random (Case II) phase aberrations $\epsilon(x,y)$ transverse to the optical axis are given by (7)

$$S = \begin{cases} [I_0 / \overline{I_0}]^2, & \text{sinusoidal phase distribution (Case I)} \\ \exp(-\epsilon_{\text{rms}}^2), & \text{Gaussian probability phase distribution (Case II)} \end{cases} \quad (6.1a) \quad (6.1b)$$

The number $F(x,y)$ of fringes or waves aberration are related to the phase aberration $\epsilon(x,y)$:

$$F(x,y) = \epsilon(x,y)/2\pi \quad (6.2)$$

Since a beam divergence of $20\lambda/d$ is required, the Strehl intensity is:

$$S = \frac{I}{I_0} = \left(\frac{1}{20}\right)^2 = 2.5 \times 10^{-3} \quad (6.3)$$

From Eqs. (6.1a) and (6.1b), the requirement $S = 2.5 \times 10^{-3}$ corresponds to a peak wave aberration F given by

$$F = \begin{cases} 0.26, & \text{sinusoidal phase distribution (Case I)} \\ 0.244, & \text{Gaussian probability phase distribution (Case II)} \end{cases} \quad (6.4)$$

The corresponding fluctuations in density, ρ , are:

$$\frac{\Delta \rho}{\rho} = \frac{\lambda}{2\pi B} \frac{C}{L} \quad (6.5)$$

where λ = laser wavelength

B = Gladstone-Date constant = $(n-1)$

L = length of laser discharge

For the present case, $\Delta \rho/\rho = 3.6 \times 10^{-3}$.

6.1.2 Large-scale Disturbances

Large scale disturbances in the medium, comparable in size to the laser aperture, may be treated by geometric optics.

a. Tilt

Since the beam divergence requirement is $20\lambda/d$, a wedge of 20λ over the aperture would be required to displace the beam by this amount. A beam pointing stability 10% of the beam divergence would be desirable, corresponding to 2λ , or from (6.5), $\Delta \rho/\rho = 0.02$.

b. Lenslike Disturbances

The focal length, f , of a lens is

$$f = \frac{R}{2} \quad (6.6)$$

where R = radius of curvature. The thickness, x , of a lens is related to its radius of curvature as follows:

$$x = \frac{r^2}{2R} \text{ for } R \gg x \quad (6.7)$$

where $r = d/2$ (d = lens diameter).

The number of fringes, F , change in path length is:

$$F = \frac{Bx}{\lambda} \quad (6.8)$$

The beam spread, θ , is

$$\theta = \frac{d}{f} \text{ (FULL ANGLE)} \quad (6.9)$$

Combining (6.5) - (6.8)

$$\theta = \frac{8}{d} F \quad (6.10)$$

then, for $\theta = 20^\circ/d$, $F = 2.5$, and from (6.5),
 $\Delta \theta = 0.024$.

6.2 OPTICAL RESONATOR DESIGN

The output beam dimensions for the XeF pump laser are 3 mm x 25 mm. In the 3 mm direction the beam divergence will be limited by geometry to:

$$\theta = \frac{w}{2L} = 2.1 \text{ mr.}$$

where w = beam width = 6 mm
 L = spacing between mirrors
 = 140 cm

The required divergence is:

$$20^\circ/w = 1.2 \text{ mr.}$$

Therefore, a stable resonator is close to meeting the required divergence in the 6 mm direction. However, in the 25 mm direction, an unstable resonator is required. Therefore, a cylindrical unstable resonator is used which is a stable resonator in the 6 mm direction and unstable in the 25 mm direction.

An attractive choice of unstable resonator for this laser is a positive branch confocal design. The positive branch has no focal points within the cavity and the confocal resonator yields a collimated beam at the exit aperture together with good medium utilization. Having made this choice, we can select an output coupling based on the available gain, and a cavity mirror separation. The remainder of the design is then fully determined.

The resonator consists of two mirrors. Mirror 1 is concave with radius of curvature R_1 ; mirror 2 is convex with radius of curvature R_2 . The mirrors are separated by a distance L . If t_c is the required output coupling, then the magnification m can be obtained from

$$t_c = 1 - \frac{1}{m}$$

Also

$$R_1 = \frac{2m}{m-1}L$$

$$R_2 = \frac{2L}{m-1}$$

It may be necessary to modify unstable resonator designs for use with short-pulse lasers. This is due to the finite time taken for a laser mode to build up in the resonator. The number of passes, i_0 , required for a mode to be established is: (8)

$$i_0 = 1 + \frac{\ln M_0}{\ln M}$$

where M is the magnification

$$\text{and } M_0 = \frac{D^2}{\lambda R}$$

where D = beam diameter

R = radius of curvature of the primary mirror in the unstable resonator
 λ = wavelength

Figure 6.1 is a plot of this equation which shows that as the magnification increases the number of passes required for the mode to develop decreases. However, the output coupling, t_c , also increases with magnification. Therefore, since beam divergence will be best at the highest magnification, but the output coupling is optimum at a lower value, a trade off is required between beam quality and power output. A resonator design with $M = 10$, which means $i_0 = 4$, which takes about 20 ns at a mirror spacing of 1.5 m was found to be unsatisfactory. Therefore, to reduce the build up time to a value closer to the pulsewidth (~10 ns), a resonator with $m = 270$ ($i_0 = 2.1$) was designed. Then for $m = 270$ and $R_1 = 312$ cm, $R_2 = 1.15$ cm and $L = 155$ cm. Making mirror 1 ($R_1 = 312$ cm) spherical will insure that the cavity is stable in the 3 mm direction and will not cause significant degradation of the beam divergence in the 3 mm direction since the radius (312 cm) is much greater than the mirror spacing (155 cm). This permits a standard spherical mirror to be used and a commercially available mirror with a 312 cm radius of curvature was selected. The convex surface of the cylindrical lens can then be used for mirror 2. A cylindrical lens with a radius of 1.1 cm was chosen. By mounting mirror 2 off axis, performance of the unstable resonator will be unaffected and an unobscured aperture is obtained.

FIG. 6.1 Magnification vs Number of Resonator Passes

The unstable resonator with a magnification of 270 was used to give beam divergence of $20\lambda/d$ to meet the program requirement. The output with this resonator was reduced to ~ 10 mJ per pulse.

Beam divergence measurements were made with and without acoustic damping in the laser. Bursts of up to 10 pulses were used but deterioration of the thyatron prevented repetition rates of greater than 2.5 kHz in bursts of this length. Shorter bursts were used up to 7 kHz. Figure 6.2 shows the burn pattern at the focus of a 25 cm focal length lens with the stable resonator and with the unstable resonator. In the direction corresponding to a line between the electrodes, the beam divergence is 12 mr with the stable resonator and 0.3 mr with the unstable resonator. In the direction at right angles to the above, the beam divergence is 1.6 mr with the stable resonator and with the unstable resonator. The beam divergence with the unstable resonator meets the $20\lambda/d$ requirement of the program, indicating that the medium homogeneity is satisfactory.

Figure 6.3 shows a sequence of 10 burn patterns taken at 2 kHz repetition rate without acoustic damping in the laser cavity. These burn patterns do not differ significantly from the single-shot result shown in Fig. 6.2 or from data taken with acoustic damping. No significant deterioration is seen on pulses subsequent to the first. Unfortunately, it was not possible, due to problems with the thyatron, to make 10 pulse runs at 10 kHz. Under these conditions a different result may be obtained.

(a)

(b)

Fig. 6.2 Burn Pattern at Focus of 25 cm Focal Length Lens

Fig. 6.3 Sequence of 10 Burn Patterns at Focus of 10 cm Focal Length Lens -- 2 kHz Repetition Rate

7.0 CONCLUSIONS

As a result of the experimental work performed during this program we have met the requirements for repetition rate, output energy, efficiency and beam quality. However, as shown in the preceeding discussion, flush factors of 6 to 8 are required to achieve this performance. The impact of flush factor on laser efficiency may be seen from the following formula for the ratio of blower power input to laser power input using parameters achieved during the program:

$$\frac{\text{BLOWER POWER INPUT}}{\text{LASER POWER INPUT}} = \frac{n\rho(E_L f)^2 F^3}{2e_s^3 A^2} = 1$$

where n	= number of dynamic heads	} fixed
	pressure drop ~5	
ρ	= gas density ~0.2 Kg/M ³	
E_L	= laser energy out = 0.05J	
f_L	= repetition rate = 10 ⁴ Hz	
F	= flush factor = 4	
η	= efficiency = 3 x 10 ⁻³	
e_s	= specific energy output = 300 J/M ³	
A	= area = 0.03 M ²	

Therefore, efficiency is degraded by a factor of 2 for the given conditions. In order to improve efficiency, future work should concentrate on improving flush factor, laser efficiency and specific energy output. As discussed in the preceeding material, flush factor may be improved by a reduction in turbulence. Experiments on a single-pulse XeF laser have shown that laser efficiency and specific energy output may be improved by reducing the risetime of the discharge voltage. This may be achieved by using a new low inductance thyatron which has become available since the start of the program.

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