Invited Paper

Development of an injection controlled high power XeF (C→A) excimer laser

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ABSTRACT

The performance of a scaled, repetitively pulsed injection controlled XeF (C→A) laser system is reported. A 1 Hz electron beam pumped XeF (C→A) laser system produced 0.8 J per pulse with an intrinsic efficiency of 1.5 %. Details of a compact halogen compatible flow loop will be reported. Various unstable resonator geometries were evaluated. A minimum beam divergence of 150 μrad (full angle) corresponding to a 3 times diffraction limited beam was determined from far field measurements.

1.INTRODUCTION

An efficient high power laser with wavelength tunability and spectral bandwidth control in the visible region is of importance for applications such as optical communication and remote sensing. In recent years, Raman conversion of UV excimer laser output[1] and frequency doubled solid state lasers[2] have been demonstrated in the visible blue green spectral region. In addition to these laser systems, the XeF (C→A) excimer laser has a unique broadband blue green spectrum. Moreover, this system is an attractive laser source in view of both wavelength tunability and scalability. The XeF (C→A) laser has been developed using different pumping methods such as photolytical pumping[3,4], discharge pumping[5], electron beam pumping[6,7]. At a low excitation rate (< 1 MW/cm^3) by an electric discharge or a long pulse electron beam, the net gain is fairly low (< 1 %/cm) and the free-running laser emits at 485 nm with a spectral width of 15~20 nm. In the high excitation rate regime with a short pulse electron beam, the gain of this system exceeds 3 %/cm. By using an unstable resonator, the XeF (C→A) laser can be operated with narrow linewidth with the suppression of the broad band free running spectrum and the output exhibits good beam quality.

Recent scaling experiments have been performed in which the active volume was increased from ~0.02 ℓ to ~0.5 ℓ [8,9]. Using a multi-component high pressure gas mixture composed of F_2, NF_3, Xe, Kr, and Ar[10], a specific energy density of 1.8 J/ℓ and an intrinsic efficiency of 1.5 % were achieved at 490.7 nm, corresponding to a 1.1 J output energy. Also the spectral characteristics have shown that the short pulse electron beam excited XeF (C→A) is continuously tunable between 450 and 530 nm, the entire blue green region, with a band width as narrow as 0.001 nm[11].

The pulse repetition rate of the XeF (C→A) laser as reported in reference 8 was initially limited to 0.1 Hz by the transient gas turbulence since the gas flow rate was insufficient to exchange the pumped gas volume between discharges of the intense e-beam pump pulses depositing ~120 J/ℓ in the laser gas mixture. Thus, a compact, fast gas flow system (2.5 m/s) with a transverse in-line fan was designed and incorporated. Significantly improved 1 Hz repetitively pulsed laser performance was achieved.

The near and far field output beam characteristics of the electron beam pumped XeF (C→A) laser with various unstable resonator magnifications between 1.7 and 3.0 were investigated from the point of view of beam uniformity and beam divergence. These configurations, however, were conventional on-axis unstable resonators whose energy extraction efficiency may have been limited by the mismatch between the intensity build up region and the highest gain region in the pumped volume produced by single sided transverse electron beam excitation. Furthermore, the beams from on-axis resonators typically have an annular near field flux that has a dark hole at the center in it. This annular contour is not ideal to achieve optimum brightness in the far field for many applications. However, an off-axis resonator increases the area of uniform flux for this laser system. A performance comparison based on near and far field characteristics of such unstable resonators will be reported.

2. EXPERIMENTAL SETUP

2.1 Electron beam generator and laser cell

The electron beam generator produces a 650 keV, 90 kA pulse in 10 ns (FWHM) with a current density of 250 A/cm^2 with repetitive operation of up to 1 Hz. This generator has been described in detail elsewhere[8,9,12]. A 25 μm titanium foil with a 5 μm thick layer of ion vapor deposited aluminum which prevents interaction with reactive fluorine in the laser gas mixture was installed as a pressure window between e-beam diode and laser chamber. The average electron beam energy deposited in a laser gas mixture was measured to be 120 J/ℓ.

The cell length was minimized to ~0.57 m so that the short gain duration could be fully available during the optical round trips. The materials of the laser cell was made of stainless steel 316. The other

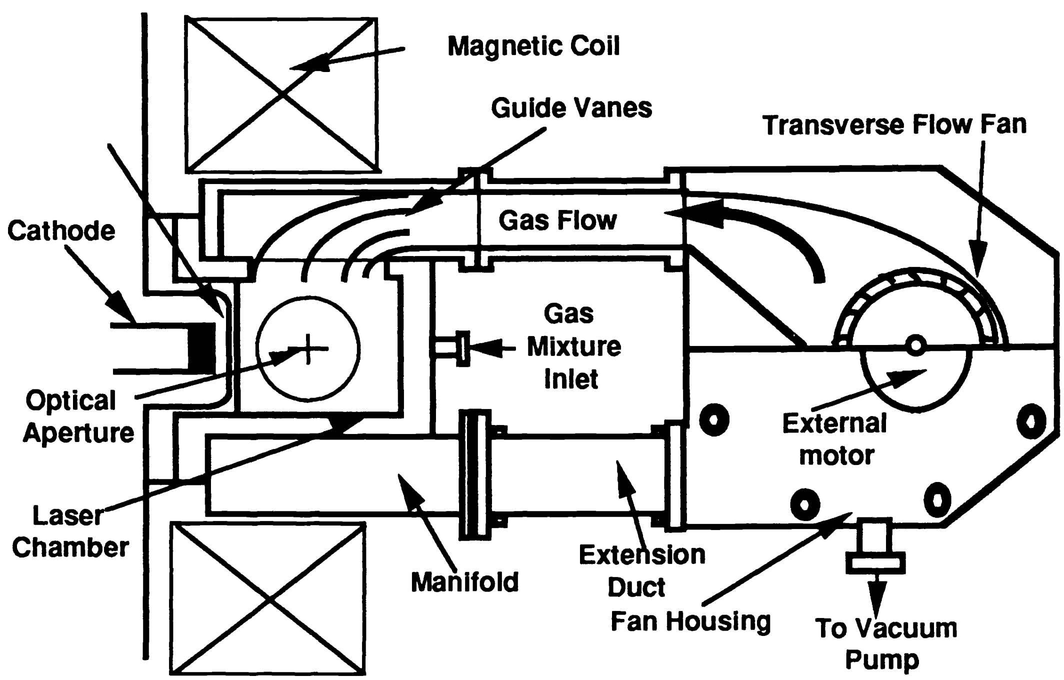


Fig. 1 Cross-sectional schematic of a compact gas circulation system for an single side electron beam pumped XeF(C→A) laser

Table-I Design parameters of the compact flow system for the XeF(C→A) laser

1. Repetition Rate : 1 Hz
2. Fluid: Ar buffer, 6.5 bar
3. Flow Rate: 5 ℓ/s
4. Clearance Factor: 5
5. Velocity and Reynold's Number:

Velocity	Reynold's Number
0.25 m/s	7730

flow parts were fabricated from aluminum alloy and were assembled with Viton vacuum seals for good halogen compatibility. A cross-sectional schematic of this flow system is depicted in Fig. 1. Gas flow is achieved by a transverse flow fan with a compact, external induction motor (~200 W) coupled magnetically to the fan.

The flow loop design was, to a large degree, determined by several critical constraints since the present electron beam diode and the B-field coil configuration could not be changed at this time. Table I summarises the design parameters of this system. A required flow rate of 5 ℓ/s at 6.5 bar Ar, assuming a clearance ratio of 5 for the laser cell at 1 Hz operation, is conventional. However, a 90 degree bend of the flow duct between the magnet coils can induce a turbulent eddy flow inside the laser cell even if the flow velocity is slow. Therefore, four concentric guide vanes whose representative radii are approximately 18 mm, 24 mm, 32 mm, and 44 mm, respectively, have been placed effectively minimizing in the bending portion reduces intense turbulence inside the laser chamber. Additionally, this bending contour has a diffuser shape because the width of the optical clear aperture should be expanded to 38 mm compared to 22 mm of the duct height.

The optimized gas mixture consisted of 1.3 mbar F_2, 16 mbar NF_3, 16 mbar Xe, and 1 bar Kr and completed to a total pressure of 6.5 bar with Ar as a buffer[13].

2.2 Optical Resonators

The optical cavities investigated in these experiments were positive branch confocal unstable resonators as illustrated in Fig. 2 (a). The back reflector was a plano concave lens with the spherical concave surface (radius=R1) coated to achieve maximum reflectivity from 465 to 505 nm. A centered 1.5 mm aperture to couple an injection seeding laser pulse was provided either by drilling a hole through the substrate or by masking a spot on the coating. The output coupler was a double meniscus lens (R1=-R2) with a maximum reflectivity coated spot centered on the convex surface. For each cavity magnification (M=R1/R2, or D1/D2), the size of this spot was chosen so that the same resonator active volume was designed to be either 35mm in diameter or 31mm square. The spacing between mirrors was adjusted to the confocal position of ((R1-R2)/2). For M=1.7, the mirrors are internally mounted, and for the other magnification (M=2.0-3.0), an external mount which permits flexibility in the experiments was used.

The difference of geometry and near field beam pattern between an on-axis and off-axis resonator is shown in Fig. 2 (a) and (b). A square reflection coated mirror was used as an output coupler . The square resonator volume is more attractive because it coincides with the e-beam pumped volume. In this experiment, the key adjustable parameter is the position of the reflection coating. Thus the output coupler was designed so that the reflection coating could be located anywhere in the optical clear aperture. When off-axis resonator geometries were studied, the injection dye laser beam was coupled with a small prism through the edge of the reflection coating.

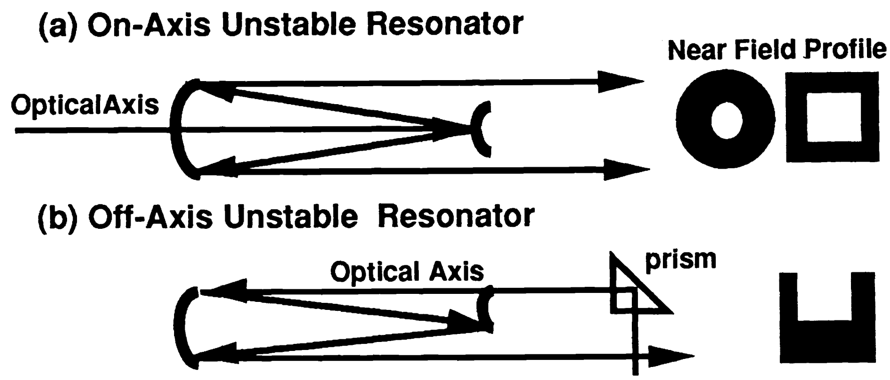


Fig. 2 Various geometries of injection controlled positive branch confocal unstable resonators

2.3. Diagnostics

The gas flow velocity was probed by using a 2 mm outer-diameter pitot tube, and the differential pressure was measuresd by a capacitance manometer (MKS Baratron H77-3) for 6.5 bar Ar. Also, the medium flow homogenity were assesed in one arm of a Mach-Zehnder interferometer in the 0.5 ℓ active region. Interferometer sensitivity (per fringe shift) corresponds to a gas density variation ($d\rho/\rho$) 4×10^{-4} for 6.5 bar Ar. An image of the interferometric pattern was acquired by the CCD camera system mentioned above.

The output energy was monitored by Gentec pyro-electric detector and the temporal pulse duration, typically 10 ns in FWHM, was detected by a fast vacuum diode. The wavelength was measured by an OMA III system. The imaging sensor to monitor the beam profile was a 2 dimensional charge coupled Device (CCD) array with 240 x 240 pixcels in 5.5 mm x 6.5 mm dimension (COHU4800) with saturation light level of 1 μJ/cm2 in the visible blue green wavelength. As shown in Fig. 3, by using a combination dimension. For far field measurements, the beam reflected by a surface

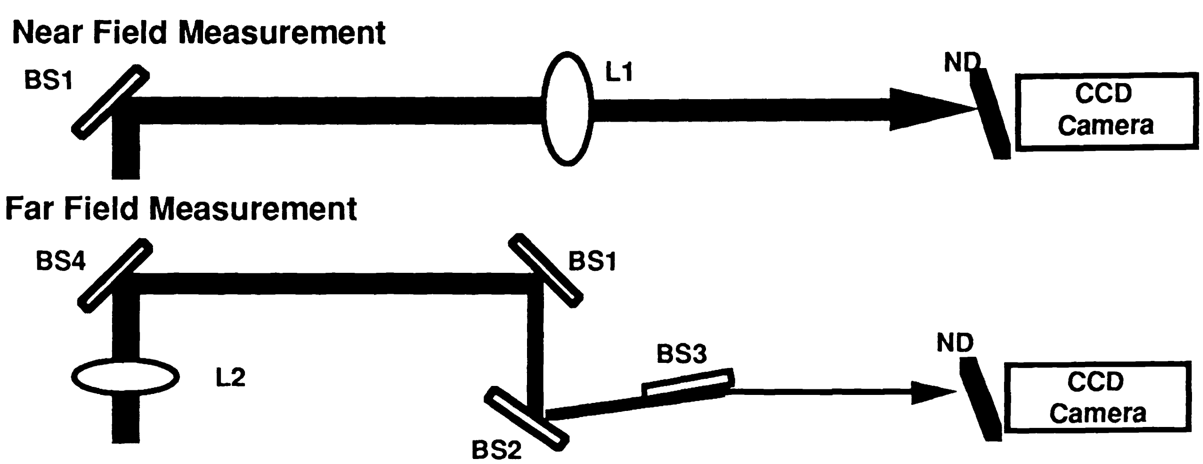


Fig. 3 Schematic diagram of beam profile experiment

of an AR coated BK7 (BS4) and of successive surface reflections of uncoated quartz beam splitters and and anti-reflection (AR) coated BK7, the intensity of an XeF (C→A) laser was attenuated to obtain a good dynamic range for the CCD detector. For near field measurements, the beam was reflected by a beam splitter surface (BS1) and then passed through a 500 mm focal length lens (L1) so that the image is reduced in size to fit the ditector array three beam splitter (BS1-BS3) surfaces entered a 4000 mm focal length lens was used to make an appropiate image size onto the CCD detector pixels (more than 30 pixels). The fine attenuation of the beam intensity is completed by the neutral density (ND) filters located in front of the CCD camera.

3. RESULTS AND DISCUSSION

3.1 Initial flow measurements

Flow characteristics of this system were first evaluated without electron beam shots. Two pitot tubes were situated inside the flow chanel prior to the laser chamber. One was at the center, the other was located at the edge (50 mm from the wall of a rectangular [22 mmx550 mm] flow channel). The flow velocity distribution was measured to be 5.7 m/s and 5.2 m/s, at the center and at the edge, respectively for 6.5 bar Ar resulting the good velocity distribution within 10 % across the flow channel. This velocity corresponds to 2.5 m/s in the laser chamber and the exchange of approximately 45 laser cell fills between the shots at 1 Hz.

In general, an inhomogenity of the flow is caused in a 90 degree sharp bending portion and it can degrade the overall optical quality. However, an interferometric measurement showed that the gas density variation ($d\rho/\rho$) in an active region of laser chamber under 6.5 bar Ar was approximately 1×10^{-4} (a quater fringe shift) at 632.8 nm.

3.2 Repetitive Operation with electron beam shots

An internal unstable resonator was used in this experiment with a magnification of 1.34 which has a reflectivity of 99% even in the wings of XeF (C→A) gain region. The injected wavelength was chosen to be at 490.7nm in view of both the peak of the gain spectrum and good reflectivity of the mirrors. The injection intensity coupled into the resonator was 3 MW/cm^2 (~2 mJ).

The performance of the XeF(C→A) laser is shown in Fig. 4. The signal from a pyroelectric energy monitor is displayed with a charging voltage of the capacitors in Marx generator. These traces are the first four shots of a sequence. The slight degradation of the output energy of the second shot was caused by lower charging voltage during the transitional stage in Marx generator. However, from the third shot, the output was recovered to the same as the first shot. Average energy of 0.8J resulted when the laser was being operated at 1 Hz. Both the high energy per pulse and repetitively pulsed operation have been achieved in the scaled XeF (C→A) laser system.

3.3 Resonator Performance Comparison

For this performance comparison, a laser cell with a smaller volume was used[8,10]. The intensity injected into these unstable resonator cavities were adjusted to approximately 3 MW/cm^2 at a wavelength of 486.8 nm. Typical energies of on-axis circular geometries are 740 mJ, 430 mJ, 290 mJ, and 210 mJ for M=1.7, 2.0, 2.5, and 3.0 respectively and the pulsewidth was ~10 ns FWHM. These energy variations have been predicted by model calculations taking into account cavity losses[13]. In addition, significant differences were not observed in the output energy between circular and square geometries for M=2.0. Also the output energy and a temporal profile were the same for an on-axis and off-axis resonator configuration.

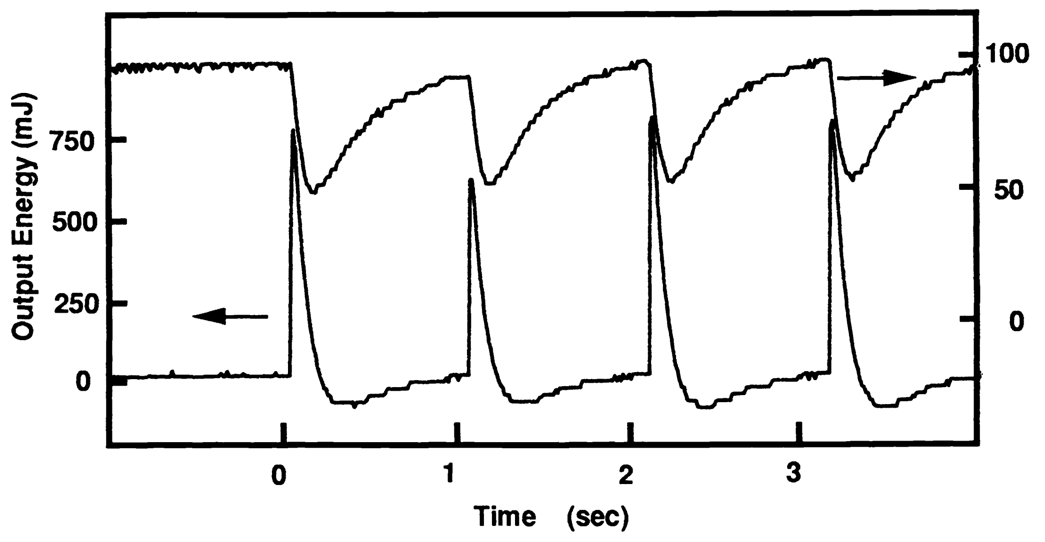
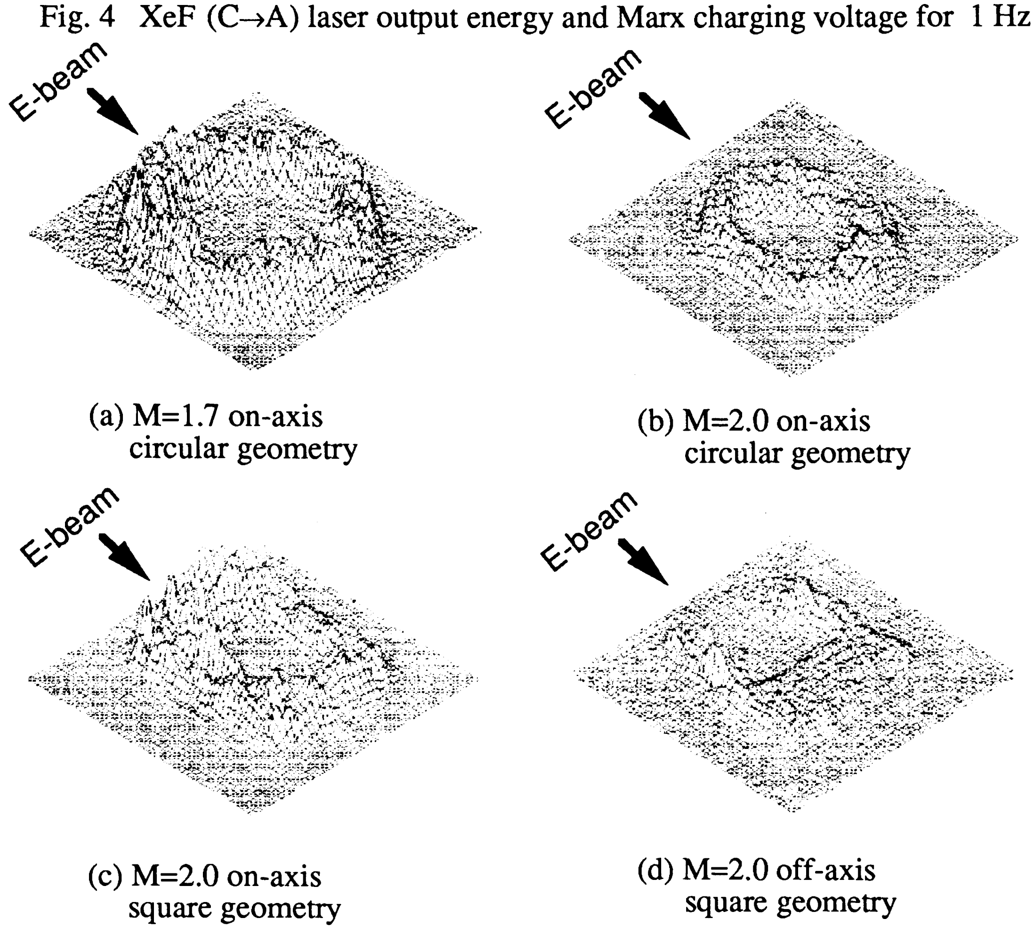


Fig. 4 XeF (C→A) laser output energy and Marx charging voltage for 1 Hz operation



(a) M=1.7 on-axis circular geometry

(b) M=2.0 on-axis circular geometry

(c) M=2.0 on-axis square geometry

(d) M=2.0 off-axis square geometry

Fig. 5 3-D near field beam profiles of various unstable resonator geometries

The uniformity of near field pattern was investigated by using the CCD imaging system described in section 2.3. 3-D beam profiles are illustrated in Fig. 5. where (a) M=1.7 and (b) M=2.0 are the typical near field patterns of circular on-axis unstable resonator geometries. Hot spots in the near field pattern were observed in every resonator even when the resonators were re-adjusted. These hot spots near the electron beam foils are appatrerently associated with single sided electron beam pumping and they show approximately 1.5~2-folded higher intensity than for the more uniform pump region. The uniformity of the beam flux in the near field was also compared between on- and off-axis resonator with a magnification 2.0 square geometry. The results are shown in Fig.5 (c) on-axis and (d) off-axis. The intensity distribution was found to be a more uniformly illuminated pattern for off-axis geometry. In addition, the obscuration near the electron beam foil resulted in a higher flux. Thus, a primary objective to increase the uniform flux portion was achieved with off-axis resonator.

The beam divergence angles obtained from far field pattern by the CCD array were analyzed with the 'top-hat' method. The spot size diameter is given by 86.5 % of the total energy of the beam energy diameter assuming the laser beam is a Gaussian beam. The resuts are shown in Fig.6 together with diffraction limited curve. A minimum beam divergence of 150 μrad was achieved for a M=3.0 circular resonator geometry. Since the output energy was decreased for higher magnification, the intensity in the far field was optimized with M=2.5 for this scheme. The total angle of 150~280 μrad corresponds to 3~4 times of a diffraction limited output beam. Square plots in Fig. 6 show the results of on- and off-axis in the far field resulting that off-axis geometries for a square resonator geometry reduced beam divergence about 30%.

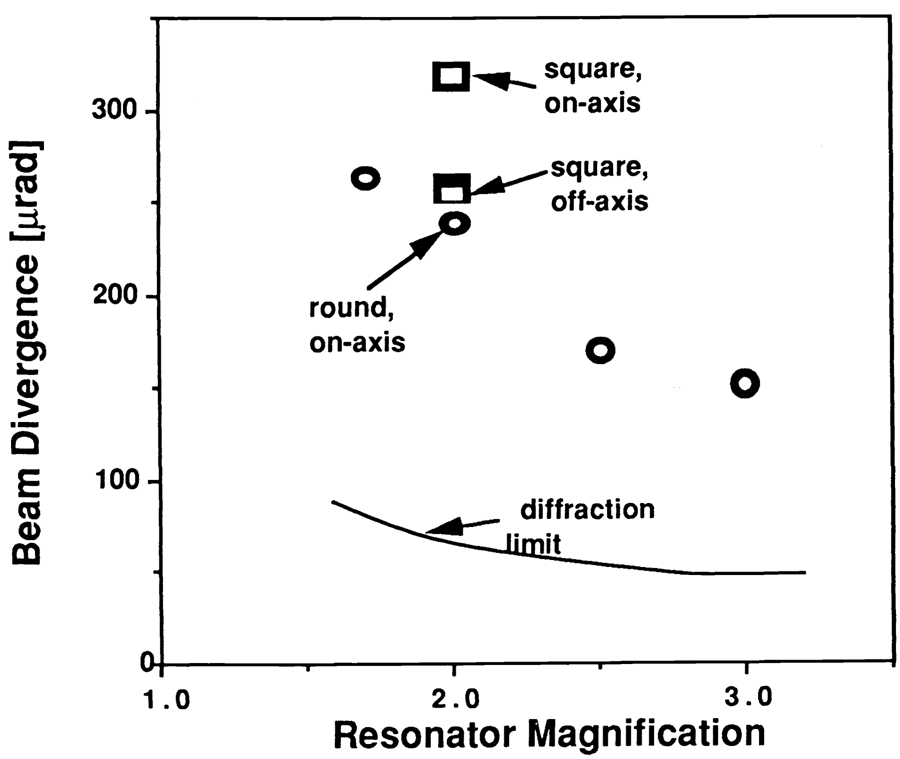


Fig. 6 Dependence of beam divergence on the resonator magnification for various resonator geometries

4. CONCLUSION

Scaling of the XeF (C→A) laser system has demonstrated not only at a high energy per pulse of ~1 J but also with repetitively pulsed operation that utilizes a compact flow system incorporating a transverse in-line fan. A 1 Hz electron beam pumped XeF (C→A) laser produced 0.8 J per pulse and an intrinsic efficiency of 1.5 %, which was achieved with a magnification 1.3 unstable resonator at 490.7 nm.

A veratile beam profiling technique for the pulsed excimer laser beam based on CCD array has developed. Using this imaging system, the output beam characteristics of several unstable resonator geometries were investigated. Despite a slightly nonuniform near field intensity pattern, a minimum beam divergence of 150 μrad (full angle) corresponding to 3 times of diffraction limited beam was obtained with a magnification 3 circular geometry resonator. The square off-axis unstable resonator configuration was found to illuminate a more uniform near field pattern. Moreover, this off-axis geometry also resulted in a reduction of the beam divergence.

5. ACKNOWLEDGEMENTS

The authors would like to thank Jim Hooten at Rice University for his technical assistance. This work is supported by the Office of Naval Research ,the Robert Welch Foundation and the National Science Foundation.

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