Beam divergence studies on a long pulse XeCl excimer laser

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ABSTRACT

The focusability of a long pulse XeCl excimer laser has been improved using confocal positive branch unstable resonators where the outcoupling is done through the convex mirror. For the outcoupler different reflectivity profiles are used. A near diffraction limited output beam is obtained from hard edge unstable resonators. A beam with only one central spot in the focus of a lens can be obtained with a resonator fitted with a Gaussian outcoupling mirror.

1 INTRODUCTION

For the application field of our 1 kHz, 1 kW XeCl excimer laser, developed by the Nederlands Centrum voor Laser Research (NCLR),[1] the divergence of the optical beam is extremely important. Therefore research is being done on the beam quality of our long pulse (250 ns) XeCl excimer laser. The experiments are performed on a single shot base using a system having a similar performance as the high repetition rate system.[2]

With a stable plano-concave resonator a homogeneous square beam of approximately 22 mm x 22 mm can be obtained with a pulse energy of approximately 500 mJ. However the divergence of this beam is 7 mrad (full angle), while in the diffraction limited case 38 μrad should be possible. The active medium of the excimer laser has in practice large transverse dimensions. Thus it is difficult to have a fundamental Gaussian beam that fills the total discharge volume. The beam from a stable plano-concave resonator is therefore multimode having a relatively poor divergence. To decrease the divergence the beam waist of the fundamental mode has to be increased. With an unstable resonator it is possible to have a fundamental mode that covers the total active volume, due to the magnification in the resonator.

In the past different unstable resonator configurations have been successfully applied for short pulse excimer lasers.[3–14] These lasers are characterized by high current and short stability discharges, which means a high gain and only a few cavity round trips for the optical pulse. The optical output from these short pulse lasers is given by the superposition of outputs from each cavity round trip.[15] The divergence of those pulses can be decreased considerably if instead an active medium with a lower gain and longer stability period is used, so that more round trips are used to reach saturation. With such a system the output beam can be formed before saturation of the gain medium, resulting in a beam with a lower divergence. Our investigations are carried out for this discharge regime. In the field of these long pulse XeCl lasers only a few results have been published yet.[16–18]

For our system, having a relatively low gain ($3-4$ % cm^{-1}) and a long gain lifetime (approximately 250 ns),

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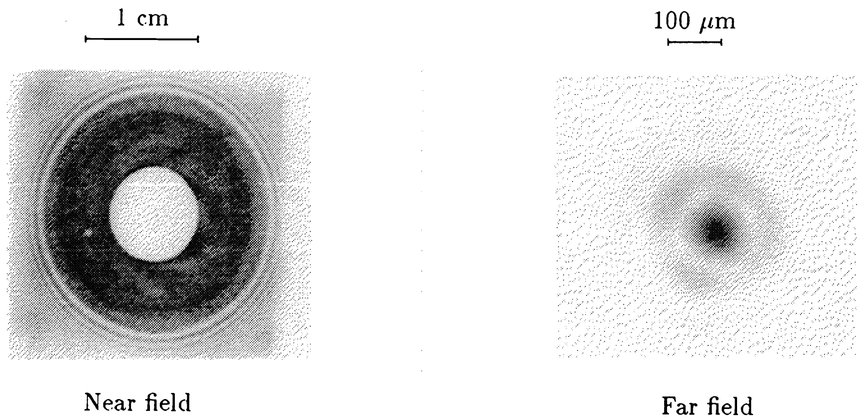

Figure 1: Near field beam profile (left) and focus profile (right) of the beam from a hard edge unstable resonator (M=2.375) with a central HR spot of 8 mm diameter focussed by a 10 m radius concave mirror

a positive branch confocal unstable resonator is found to be an excellent choice. The negative branch unstable resonators have an intracavity focus which might lead to problems with optical breakdown. The outcoupling from the positive branch unstable resonator is done at the convex mirror to get a collimated output beam. The present article deals with experimental studies of various resonator configurations for a low gain, long optical pulse system.

2 HARD EDGE UNSTABLE RESONATORS

Hard edge unstable resonators are resonators where the outcoupling mirror has a step in the reflectance profile. These mirrors can be made by putting a mask over the substrate while depositing the dielectric layers on the substrate in a chemical vapour deposition process.

2.1 High reflectance hard edge unstable resonators

If the central spot on the outcoupling mirror has a high reflectance (HR) the outcoupled near field is ring-shaped with practically no energy in the center of the beam. Figure 1 shows the near field beam profile, measured with a gated CCD camera and a scintillator, for a resonator with a magnification m of 2.375 (the resonator feedback is approximately 18 %, which is near the minimum for our system to obtain saturation) and a central HR spot of 8 mm diameter. The diffraction pattern at the beam edge is caused by the reflection at the substrate outside the central reflecting area which does not contain an antireflection coating.

The far field of this beam is also shown in figure 1. This measurement has been performed by focussing the beam with a mirror of 10 m radius on a scintillator and using a fast gated CCD camera equipped with a microscope objective to obtain the image. The far field shows the ring structure as expected from the diffraction of a cylindrical beam. The focussed intensity profile is shown in fig. 2. For comparison we plotted also the diffraction limited far field pattern of a homogeneous cylindrical beam with an inner diameter of 8 mm and an outer diameter of 20 mm. It is seen that there is a good correspondence between the measured profile and the calculated profile based on diffraction only. Thus our beam is near the diffraction limit.

The M^2 parameter[19,20] of the beam from this resonator can be determined from the measurement of the

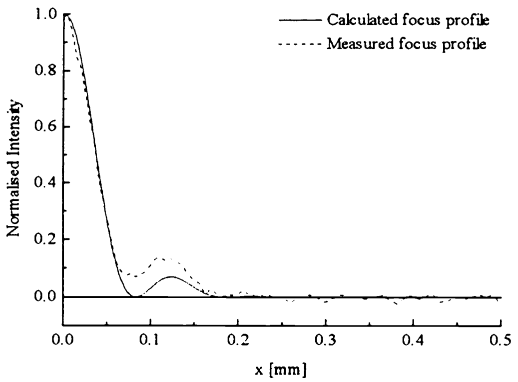

Figure 2: Comparison between far field profiles from theory and experiments

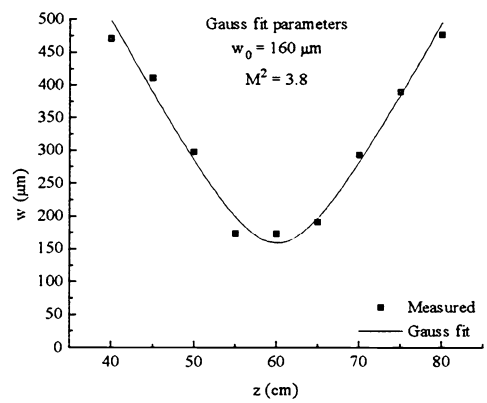

Figure 3: Determination of M^2 parameter of the beam from the beamwidth at different positions

beamwidth at several positions around the focus.

$$W^2(z) = W_0^2 + M^4 \left(\frac{\lambda}{\pi W_0}\right)^2 (z - z_0)^2 \tag{1}$$

where $W(z)$ is the beamwidth at position z, W_0 is the beamwidth at the focus, λ is the wavelength, z the position and z_0 the position of the focus. The beamwidth is defined as the radius which contains approximately 90 % of the energy. The result is shown in figure 3. It is found that M^2 for this beam is 3.8. From calculations it is found that the expected value for M^2 is 3.9, so there is again a good correspondence between theory and experiment.

The M^2 parameter characterizes the optical quality and can be considered as a comparison with the perfect gaussian beam. In the case of a gaussian beam M^2 is 1. When we reduce the side lobe energy the M^2 value decreases. Calculations predict that the side lobe energy can be reduced by lowering the reflectance of the central spot on the outcoupling mirror.

2.2 Partial reflecting hard edge unstable resonators

Table 1 shows the characteristics of different resonators used in the experiments. The magnification m is determined by the radii of curvature of the mirrors

$$m = -\frac{R_1}{R_2} \tag{2}$$

where R_1 is the radius of curvature of the concave rear mirror and R_2 the radius of curvature of the convex outcoupling mirror. R in table 1 is the reflectivity and D_r the diameter of the reflecting area. The *geometrical* feedback is determined by the magnification m and the reflectivity of the central area R and is independent of the size of the reflecting area.

$$\text{Feedback} = R\frac{1}{m^2} \tag{3}$$

The pulse energy is the energy in the ring of the beam. If we block the diffraction pattern at the beam edge with a diaphragm the energy loss is about 1/6 of the total energy. The beam was focussed with a mirror having a radius of curvature of 10 m. The size of the spot in the focus given in table 1 is the radius of the first minimum.

The position of the focus field, i.e. the point of the highest intensity, shows some small shot-to-shot variations. The origin of these variation is expected to lie in the start-up of the optical pulse. The optical field in the resonator builds up from the noise. If there are enough round trips in the resonator between the start of the gain and its saturation the intracavity field will only consist of resonator eigenmodes. Calculations have shown that if the gain medium saturates before the moment is reached at which only resonator eigenmodes exist, the field depends on the starting field. This can lead to a small variation of the optical axis of the output beam which results in small variations of the position of the focus. Pointing-x is the angle variation of the optical axis transverse to the electrodes. Similarly is pointing-y defined for the optical axis variation parallel to the electrodes.

Figure 4 shows the intensity profiles of the foci for the three resonators mentioned in table 1. These resonators are identical (same radii of curvature for both mirrors and same resonator length) except for the reflectivity of the central spot (100, 72 and 45 %). It is seen that lowering the central reflectivity of the spot on the convex mirror from 100 % to 72 % an improvement of the profile occurs: the energy is the side lobe is lowered. At 45 % reflectivity the side lobe energy increases to a level above the 100 % reflection case. This is probably caused by the outcoupler: due to the coating used to obtain the reflectivity profile there will exist a phase difference between the central transmitted part and the edge of the beam. This results in more energy in the side lobe. The phase difference introduced by the coating can be reduced by using phase unifying mirrors.[21,22] This will be discussed in paragraph 2.3

We observed that, in spite of what we expected, the M^2 parameter is not reduced by the lower side lobe energy but has increased. The reduction of the side lobe energy leads to a focus that is slightly larger, so the beamwidth used for the determination of M^2 is also slightly larger resulting in a higher value for M^2.

m [−]	R [%]	D_r [mm]	Feedback [%]	Energy [mJ]	Spot size [μm]	M^2 [−]	Pointing x [μrad]	Pointing y [μrad]
2.4	100	8	17.7	255	79	3.8	4	7
2.4	72	8	12.5	226	92	4.5	3	7
2.4	45	8	7.8	226	77	4.8	6	5

Table 1: Characteristics of and results obtained with different unstable resonator configurations with the same magnification

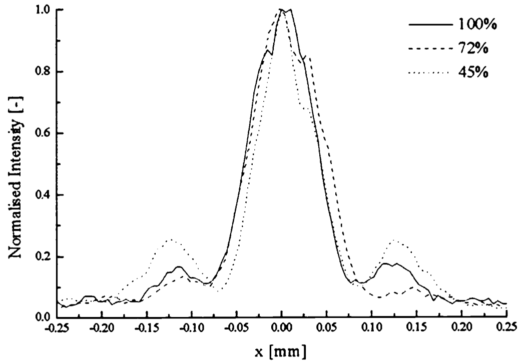

Figure 4: Focus profiles from resonators with different central reflectances (100, 72 and 45 %). The magnification $m = 2.4$ for all resonators

The pointing stability is found to be approximately equal for all three resonators. Apparently the pointing stability is not influenced by the reflectivity of the central area.

When the reflection of the central part is lowered the geometrical feedback, which is given by eq. (3), is also lowered. From experiments with stable plano-concave resonators it is found that for a feedback below approximately 15 % the laser output drops dramatically. So to keep the feedback high enough the magnification has to be decreased.

Figure 5 shows the focus profiles obtained with unstable resonators with different central reflectances, but with a magnification chosen such that the geometrical feedback is approximately the same. This is done by using different radii of curvature for the mirrors. The characteristics of these resonators can be found in table 2. A smooth focus profile with practically no side lobes is obtained for the resonator with an outcoupler of 72 % reflectivity. Again the resonator fitted with an outcoupler having a central reflectivity of 45 % leads to more side lobe energy than the resonator with a 100 % reflecting area.

It is found that the pointing stability decreases with decreasing magnification. This can be expected as the number of round trips that should take place before the saturation of the gain medium increases with decreasing magnification. We observed that for the three configurations indicated in table 2 the gain medium saturates approximately the same moment due to the equal feedback for all three resonators. The output beam shows

m [−]	R [%]	D_r [mm]	Feedback [%]	Energy [mJ]	Spot size [μm]	M^2 [−]	Pointing x [μrad]	Pointing y [μrad]
2.4	100	8	17.7	255	79	3.8	4	7
2.0	72	10	17.5	252	105	4.7	7	10
1.6	45	12	17.5	245	84	7		

Table 2: Characteristics of and results obtained with different unstable resonator configurations with the same geometrical feedback

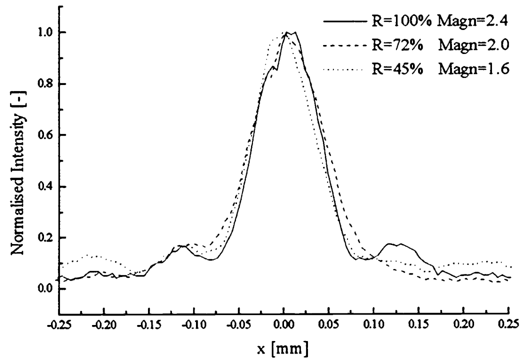

Figure 5: Focus profiles from resonators with different central reflectances but with approximately the same feedback (17.5 %)

more shot-to-shot variation resulting in a lower pointing stability. The larger number of round trips needed in low magnification resonators can be explained from the lower mode discrimination of the transverse resonator modes. The mode competition is stronger due to this lower mode discrimination, so it takes more round trips for the lowest loss mode to build up from the noise and dominate the other modes.

2.3 Phase unifying unstable resonators

The transmission phase difference between the central spot and the rest of the mirror can be decreased by using so-called phase unifying mirrors.[21,22] Experiments were performed with a resonator with a magnification of $m = 1.6$ having a phase unifying mirror with a central reflectance of 45 %. Figure 6 shows typical results. The phase unifying mirror gives a smaller focus than the non phase unifying mirror. However its focus profile and its pointing position are not very stable.

During the start-up of the system several modes try to oscillate. Due to different losses the respective modes have strong competition. In general the mode with the lowest losses will reach the highest intensity and will suppress the weaker modes. For the survival of this strongest mode with the lowest losses several oscillations between the mirrors have to take place before saturation of the gain medium. It turns out that in the case of a low magnification system there are relatively lower losses for the higher order modes so that the competition process becomes slower and it takes more oscillations for the lowest loss mode to dominate. If the gain medium saturates before the end of the mode competition, as in pulsed systems like ours, the output beam still contains higher order modes. This means that the far field has a larger spot size and a more unstable pointing position.

The output energy from the resonator fitted with the phase unifying mirror is higher (350 mJ) than with the non phase unifying resonator. The diffraction patterns at the beam edge of the near field have now a lower energy (< 25 mJ). Figure 7 shows the near field profiles of the phase unifying and non phase unifying resonators. It is clearly seen that less diffraction effects occur with the phase unifying resonator. This can be explained by the somewhat smoother nature of the edge of the reflecting central area on the outcoupler. This has to do with the in-house fabrication process of the mirror. The distance between the mask and the substrate (few mm) in the chemical vapour deposition process causes a small shadow effect of the mask on the substrate, which results in a

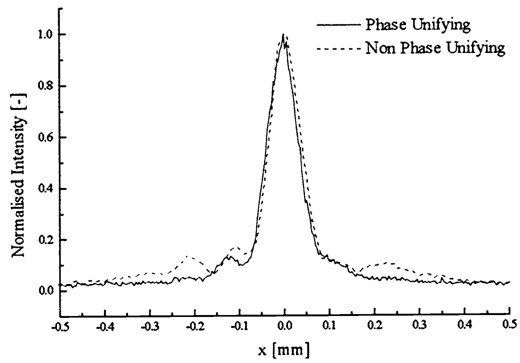

Figure 6: Comparison of focus profiles from a hard edge resonator with magnification of 1.6 and a central spot reflectance of 45 % fitted with a standard mirror and fitted with a phase unifying mirror

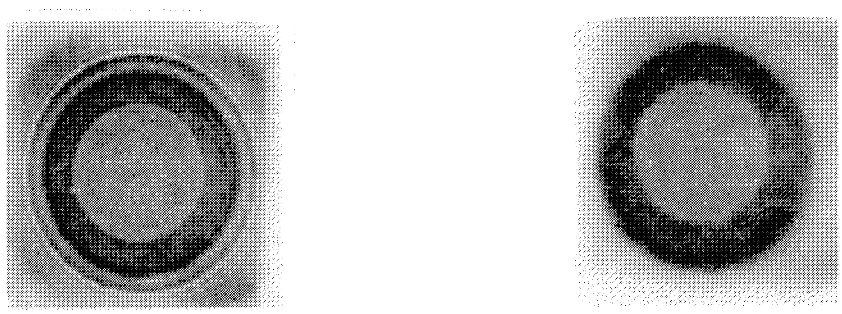

Figure 7: Near field profiles of the non phase unifying unstable resonator (left) and the phase unifying resonator (right)

smooth edge of the reflecting area.

3 SOFT EDGE UNSTABLE RESONATORS

With a hard edge outcoupling mirror one will always get a side lobe in the focus due to the diffraction at the hard edge. This extra ring, which results in loss of useful energy in the focus as only the energy in the central lobe will be used when using the focussed beam in applications, can be eliminated by using an outcoupling mirror with a smooth reflectivity change: a so-called soft edge outcoupling mirror. The most common soft edge mirror is a mirror with a gaussian reflectivity profile. A resonator fitted with a mirror with a gaussian reflectivity profile will have Laguerre-gaussian modes, which can be analysed using the complex ABCD method. The intensity profile just before the outcoupling mirror has a gaussian shape with a width w that can be approximated by[23]

$$w^2 \approx (m^2 - 1)w_R^2 \tag{4}$$

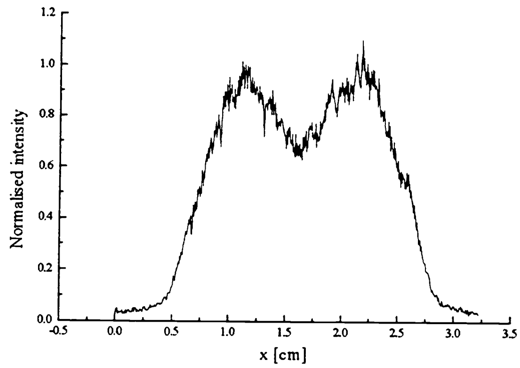

Figure 8: Measured near field profile of the output beam from a resonator fitted with a gaussian outcoupling mirror

where m is the magnification of the resonator (eq. (2)) and w_R the width of the gaussian reflectivity profile. The profile of the outcoupled beam is the multiplication of the radially increasing transmission of the mirror and the radially decreasing gaussian beam profile

$$I_{out}(r) = I_0 \left[1 - R_0 e^{-2r^2/w_R^2}\right] e^{-2r^2/w^2} \tag{5}$$

where $I(r)$ is the radius dependent intensity, I_0 the central intensity of the intracavity field, R_0 the central reflectivity and w_R and w the width of the reflection profile and the intracavity field respectively.

The average reflectivity of the gaussian mirror is determined by the central reflectivity R_0 and the resonator magnification m

$$\bar{R} = \frac{R_0}{m^2} \tag{6}$$

The output beam will show the smoothest and most uniform profile if the central reflectivity satisfies the maximally flat condition[23]

$$R_0 = \frac{1}{m^2} \tag{7}$$

From the experiments with hard edge unstable resonator as described before it is found that the magnification m should be at least 2 to be sure that the lowest loss mode dominates over the higher order modes. If we want to satisfy the maximally flat condition (7) the central reflectivity should be 25 %. However then the average reflectivity becomes rather low (appr. 6 %) so it was decided to take a larger central reflectivity (45 %) so that the feedback would be appr. 11 %. There will be a central dip in the near field profile now, but calculations predict that this will not affect the focus profile dramatically.

The gaussian reflectivity profile of the outcoupling mirror can be produced by varying the thickness of one layer in the dielectric coating.[24]

Figure 8 shows the near field profile of an unstable resonator having a magnification $m = 2$, fitted with a gaussian outcoupling mirror having a central reflectance of 45 % and a width $w_R = 12.6$ mm. The central dip caused by the outcoupling mirror is clearly seen. Figure 9 shows the beam profile in the focus of a 10 m concave mirror. For comparison also the focus profile from the hard edge resonator with full central reflector from table 1

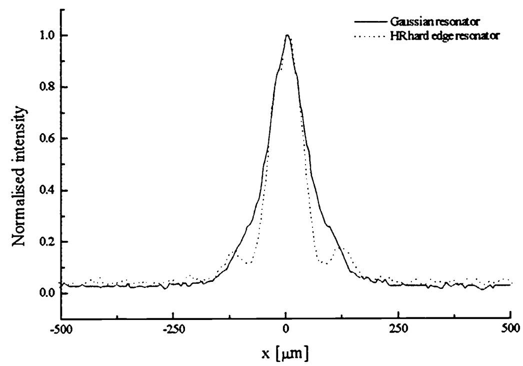

Figure 9: Focus profile of the output beam from a gaussian resonator and a hard edge resonator

is plotted. It is seen that there is now only one spot with all the energy and as the pulse energy is equivalent the energy density is higher. However the width of this spot is somewhat larger, thus leading to an M^2-parameter that is unexpectedly high: $M^2 = 5$.

The pointing stability of the beam from the gaussian resonator is comparable to the pointing stability of the hard edge resonator with the same magnification: pointing-x = 8 μrad and pointing-y = 10 μrad for the gaussian resonator (compare with data in table 2 for the hard edge resonators).

4 CONCLUSIONS

For the different hard edge unstable resonators used in our experiments it is found that the results are in good agreement with theory. The best results with hard edge resonators with respect to the focus profile and the output energy are obtained with the phase unifying mirror. However due to the fact that the magnification was too low the far field intensity profile and pointing position are less stable. From the measurement of the output energy of the different hard edge resonators it was seen that a geometrical feedback of 7.8 % is still enough to get a good output beam, although from the stable resonator measurements it was found that the feedback should be larger than 15 %.

With the gaussian resonator the beam profile in the focus shows only one spot with all the energy. The pointing stability of the gaussian resonator is found to be comparable to the hard edge resonator with the same magnification so the pointing stability does not seem to depend on the reflectivity profile of the outcoupling mirror.

The pointing stability seems to depend mainly on the magnification of the resonator. Neither the central reflectivity nor the reflectivity profile seems to influence the pointing stability.

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