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Optimization of multiple-pass off-axis KrF amplifiers

G. Almási[1,*], S. Szatmári[2,**]

[1] Laser-Laboratorium Göttingen e.V., P.O.Box 2619, D-37016 Göttingen, Germany
[2] Max-Planck-Institut für biophysikalische Chemie, Abt. Laserphysik, P.O.Box 2841, D-37018 Göttingen, Germany

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Abstract. Multiple-pass short-pulse off-axis amplification using spherical and cylindrical expansion schemes has been analyzed for different conventional discharge-pumped KrF gain modules. It is shown that using a single-gain module in a three-pass optimized off-axis arrangement, output energies up to several 100 mJ can be reached with excellent contrast, starting from 10–20 μJ input energies.

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High-power UV dye-excimer laser systems [1–8] are promising candidates to reach the highest ever focused intensity with medium peak power [9–11] due to the short wavelength and excellent beam quality. KrF is shown as an efficient short-pulse amplifier [12] whose bandwidth allows the amplification of pulses with a duration of a few times ten femtosecond [5, 13, 14]. Comparing excimer and solid-state amplifiers there are important differences how the stored energy can be extracted by a short pulse. This makes it necessary to use special short-pulse amplification techniques for both schemes. The main problem in excimers is the short lifetime of the excited state, which causes a limited energy storage capability. Since pumping of the excited state is always longer than its lifetime, a continuous depletion of the amplifying medium – simultaneously with pumping – is required in a multiple-pass or multiple-beam arrangement in order to optimize efficiency. Due to the large stimulated emission cross-section and – correspondingly a high gain – a strong Amplified Spontaneous Emission (ASE) background is expected. This can only be suppressed by saturable absorbers, which show at this wavelength limited performance [15]. The most practical way to avoid this background is to keep the signal to ASE ratio high during amplification by proper choice of the operational conditions in the amplifier. The high small-signal gain coefficient of the excimers and the correspondingly small saturation energy density [12, 16] also leads to an early saturation of the amplifier resulting in poor signal to noise ratio in the conventional amplification schemes. In multiple-pass amplification the delay between the successive passes is chosen to be longer than the recovery time of the gain. On the other hand, in case of "pencil-like" discharge geometries the high on-axis small-signal-gain causes strong ASE, which stabilizes the gain. Therefore the initial small-signal gains for the successive amplification passes can be regarded equal. The characteristic recovery time for a commercial KrF gain module is about 2 ns. In the case of KrF, the presence of non-saturable absorption determines the optimum energy density where amplification is optimum with respect to the efficiency and contrast. This is found to be only at a few times the 2 mJ/cm^2 saturation energy density [17]. Then the only way to increase the output energy – while operating the amplifier around the earlier defined optimum – is to increase the cross-section of the beam. Unfortunately the construction of discharge pumped amplifiers with large homogeneous cross-section is very difficult, imposed by the stringent requirements for the necessarily small inductance of the discharge loop of the KrF laser head.

A new, so called off-axis amplification scheme presented in [18, 17] overcomes the above mentioned difficulties and can tailor the effective width and length of an amplifier to the theoretical optimum. In this amplification scheme the signal beam encloses an angle with the electrodes, resulting in an increase of the effective cross section and a decrease of the gain length. The relationship of the old and new geometrical parameters can be seen in Fig. 1a. The figure shows that the old coordinate system (xz) is rotated by α around the y axis. If the off-axis angle α is bigger than $\arctan(L/W)$ (this

Permanent addresses:
* Janus Pannonius University, Department of Physics, Ifjúság u. 6, H-7624 Pécs, Hungary
** JATE University, Research Group on Laser Physics of the Hungarian Academy of Sciences, Dóm tér 9, H-6720 Szeged, Hungary

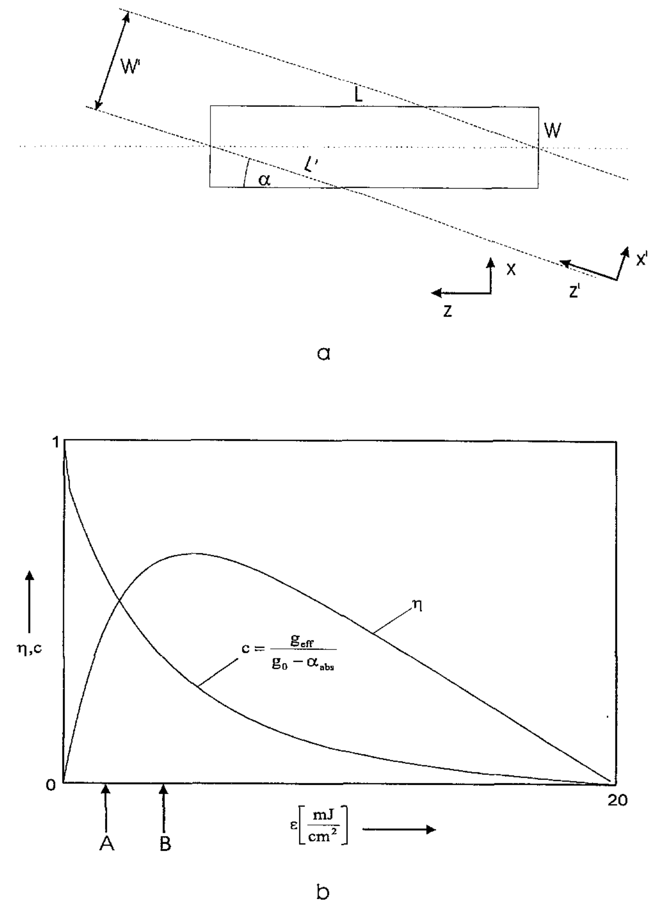

Fig. 1. **a** The off-axis amplification geometry. **b** Local extraction efficiency and gain contrast versus energy density in a KrF amplifier

case has practical importance) the new effective amplifier length L' and width W' of the amplifier can be calculated as

$$L' = \frac{W}{\sin\alpha}, \tag{1}$$

and

$$W' = \frac{LW}{L'}, \tag{2}$$

where L and W are the original length and width of the discharge.

For small angles, W' is a linear function of α. The optimum operational condition of a KrF amplifier is defined in [17] with respect to efficiency and contrast. From the Frantz-Nodvik theory [19] including nonsaturable absorption [20]

$$\frac{d\varepsilon}{dz'} = g_0\left[1-\exp(-\varepsilon)-\frac{\alpha_{abs}}{g_0}\varepsilon\right], \tag{3}$$

where g_0 is the small signal gain coefficient and α_{abs} is the absorption coefficient, ε is the energy density normalized to the saturation energy density. The local energy efficiency can be defined as

$$\eta(\varepsilon) = \frac{1}{g_0}\frac{d\varepsilon}{dz'}. \tag{4}$$

The definition of the local gain contrast coefficient c is also given in [17] as

$$c = \frac{g_{eff}}{g_0-\alpha_{abs}}, \tag{5}$$

where g_{eff} is the effective gain coefficient.

The local quantities defined above are only dependent on the energy density (ε). This dependence on ε is shown in Fig. 1b (taken from [17]). The local efficiency has a maximum at $\varepsilon = \ln(g_0/\alpha_{abs})$ and goes to zero at $\varepsilon = 0$ and $\varepsilon = g_0/\alpha_{abs}$. The local gain contrast is a monotonic function of the energy density having a maximum value of 1 at $\varepsilon = 0$ and goes to 0 at $\varepsilon = g_0/\alpha_{abs}$. In [17] using (4) and (5) an optimum operational condition is defined both for preamplifiers and final amplifiers. (The optimum operation with regard to both efficiency and contrast for a preamplifier and a power amplifier is marked by A and B, respectively.) This optimum for a preamplifier is when it is working around the saturation density. In a power amplifier, where the importance of the efficiency is more pronounced the optimum energy density is about twice the saturation density. From these general consideration and from a case study of a commercial amplifier (also in [17]) it is shown that the off-axis amplification geometry is superior to the conventional on axis schemes for pencil-like amplifier geometries. The off-axis amplification scheme is expected to be also ideal for multiple-pass amplification, since in the successive passes one can tailor the virtual size of the amplifier seen by the signal beam to meet always the optimum amplification conditions by changing the off-axis angle from one amplification pass to the next.

In this paper a method is shown how to optimize a multiple-pass off-axis amplification scheme for subsequent pre- and power amplification. A comparison has been made by model calculations for three different expansion schemes (for spherical, cylindrical and for parallel beams) in order to find an overall optimum for a given number of passes with respect to maximum output energy and the highest possible contrast. Calculations were carried out for amplifiers with different momentarily stored energies.

1 Comparison of the different expansion schemes

In order to show the importance of the increase of the cross-section during amplification, an example will be given for the dependence of the efficiency and contrast on the gain length of the amplifier of constant cross-section. If one compares amplifiers of different gain length operating at an input energy range in the order of the saturation density it is seen that the sensitivity of the efficiency on the length of the amplifier is not sharp; over

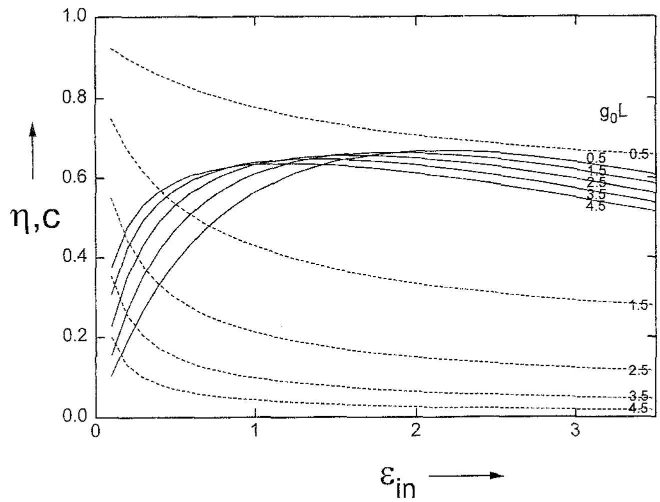

Fig. 2. Efficiency *(solid lines)* and contrast *(broken lines)* vs normalized input energy density for gain-length products of 0.5–4.5

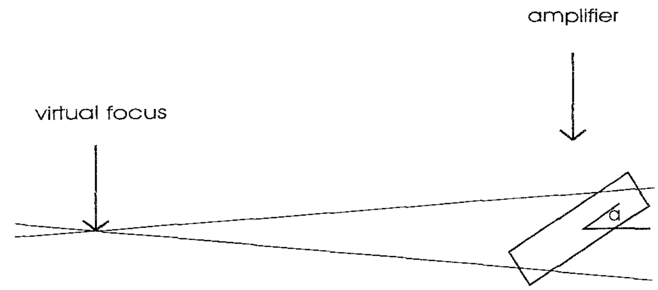

Fig. 3. Schematics of the optical arrangement used for the comparison of the different expansion schemes

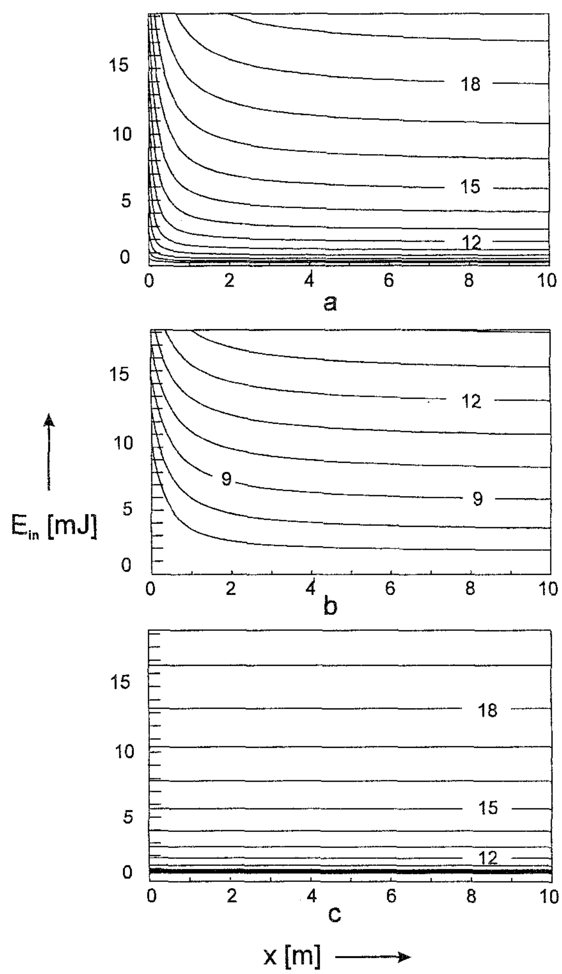

Fig. 4a–c. Output energy [mJ] versus input energy and distance using (**a**) cylindrical, (**b**) spherical expansion, and using (**c**) parallel beams. The *curves* connect the points of the energy surface with equal elevation given by the labels

a wide range of the gain length efficient amplification of input energies $0.8\,E_{sat} < E_{in} < 3\,E_{sat}$ can be realized, as shown by the efficiency curves (solid lines) in Fig. 2. This is due to the relatively broad maximum of the local extraction efficiency function on ε (Fig. 1b). The sensitivity of the gain contrast is more pronounced on the gain length as shown in Fig. 2 (broken lines). The calculations have been carried out assuming parallel beams. If $\varepsilon \approx \varepsilon_{sat}$ in the amplifier, one has a chance to keep the reduction of gain at a tolerable level only in that case if the gain length product is smaller than 2. (See also the consideration for the maximum amplifier length in [11]).

In the first pass the complete filling of the pumped region with the signal is not so important since the input energy is negligibly small compared to the momentarily stored energy of the amplifier (given by the $E_m = \varepsilon_{sat} g_0 LA$ equation, where LA is the product of the length and cross-section of the amplifier), therefore, the extraction efficiency is expected to be limited. However, in the further amplification passes the efficiency will be a critical function of ε. In a multiple-pass amplification scheme there are different optical arrangements to match the beam cross-section to the aperture of the amplifier in the subsequent passes. In previous investigations [17] spherically expanding beams were always used to compensate for the increase of energy during amplification, in order to maintain the optimum energy density in the amplifier. The spherical expansion has a disadvantage that a significant part of the stored energy is lost in the previous passes (not using the whole pumped region) if complete filling of the useful aperture in the final pass is required. If this condition is achieved in one of the previous passes, part of the energy will not reach the final amplification pass, thus deteriorating the efficiency. Therefore other expansion schemes, like cylindrical expansion, and expansion by telescopes – resulting in parallel beams in the amplifiers – have to be considered. The effect of expansion of the beam on the energy density can be accounted for by the introduction of a correction factor in (3), as:

$$\frac{d\varepsilon}{dz'} = g_0 \left[1 - \exp(-\varepsilon) - \left(\frac{\alpha_{abs}}{g_0} - \frac{k}{z'_0 + z'} \right) \varepsilon \right], \qquad (6)$$

where z'_0 is the distance of the virtual focus measured from the entrance of the actual pass and k is 0, 1, 2 for a parallel beam, and for cylindrical and spherical expansions respectively. However, in a typical experimental situation where z'_0 is in the range of a few meters the effect of the last term is negligible compared to the absorption term.

The calculations had been carried out with the following parameters. The test beam had an off-axis angle of 0.8°. We assumed an amplifier of $8\times30\times840$ mm^3 ($W\times S\times L$) discharge dimensions with a small signal gain coefficient of 0.11 cm^{-1} and an absorption coefficient of 0.011 cm^{-1} (S is the gap separation). The input energy was varied from 0 to 20 mJ, the distance of the amplifier from the virtual focus was varied in the range of 0.1–10 m. The half angle of the expansion was chosen so that the beam always filled the free off-axis aperture at the output. The schematics of the optical layout is seen in Fig. 3. The results of the calculations can be illustrated by the contour map of the 3D-surface (output energy versus input energy and distance) for the different expansion schemes in Figs. 4a–c. Comparing the graphs of the collimated and cylindrical arrangements one can see that at a distance longer than 2 m there is no significant difference in the achievable energy. In the case of a near focus position and at higher input energies the parallel scheme gives higher output energy. The reason of this is the loss of the pumped region at the entrance region of the amplifier for diverging beams. Increasing the distance from the entrance the loss becomes smaller and this is also the case for smaller input energies. Comparing the cylindrical and spherical expansion schemes one sees similar performance with the exception of a 30% less output energy in the spherical case. The origin of this loss of efficiency is caused by the mismatch between the active volume and the spherically expanding beam: this leaves part of the stored energy unextracted at the entrance, and cuts the signal beam at the output. From these results one can conclude that the cylindrical expansion scheme is the most preferable because of its simplicity and being able to produce the necessary surface growth without loosing energy by unavoidable mismatch of the beam and of the pumped region. These requirements can hardly be fulfilled by the use the spherical expansion. With parallel beams similar results can be obtained, however the complexity of the optical system increases. Moreover, by the use of beam expanders one has to take care of the avoidance of pulse front distortions [21, 22].

2 Characterization of an off-axis amplifier

The most important chacterization of an amplifier can be given by its Input-Output (I–O) characteristics. The contrast, the efficiency, the gain and the output energy can be obtained from the I–O curve. The situation for an off-axis amplifier is somewhat different. The off-axis angle is a new independent variable. Then the run of the two independent variables (the input energy and the applied off-axis angle) produce a surface, which gives the output energy. This output energy surface can be calculated by integrating (6) for the different expansion schemes over the range determined by the two independent variables. During the simulations we used the following geometry. The beam to be amplified was cylindrically expanded with a half angle of 0.2°. This entered the tube with various distances from the virtual focus of the beam. This distance was chosen so that the beam just filled the output of the free off-axis aperture. Roughly a linear relationship is found between the distance of the virtual focus and the applied off-axis angle. Different discharge geometries were tested with the parameters listed in Table 1. The global efficiency, contrast and output energy are shown in Fig. 5a–c for an amplifier of 2.7 cm gap separation, whose parameters are indicated

Table 1. Discharge parameters of the amplifiers

Length L [cm]	Gap separation S [cm]	Width W [cm]	Gain coefficient g_0 [cm^{-1}]	Stored energy E_m [mJ]
86	2.7	0.85	0.11	45
86	4.0	1.2	0.11	90
86	8.0	2.2	0.11	330
86	12.0	3.1	0.11	700

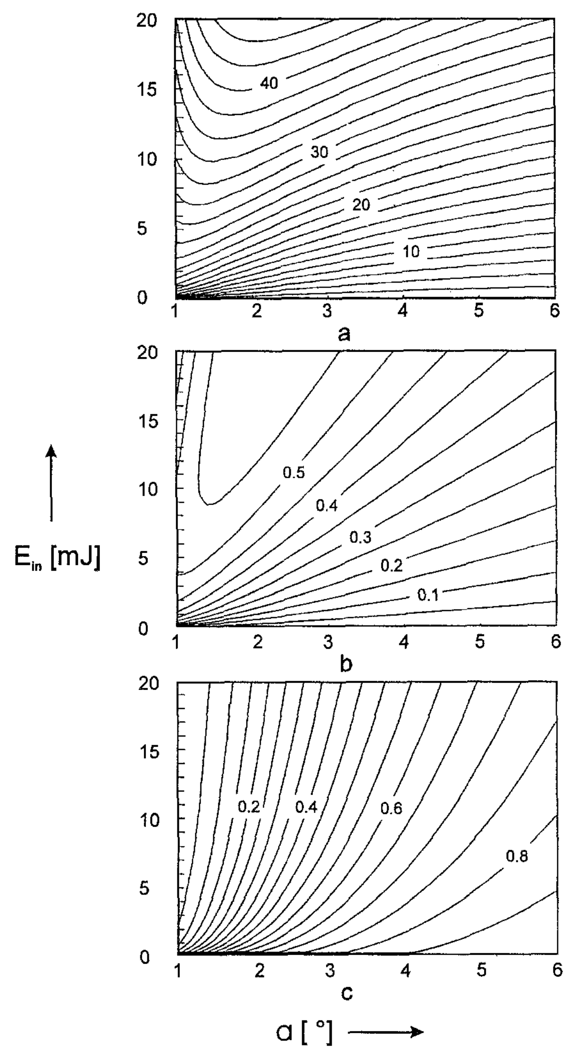

Fig. 5. **a** Output energy, **b** energy extraction efficiency, **c** gain contrast vs off-axis angle and input energy. The *curves* connect the points of the surfaces with equal elevation given by the labels

in the first row of Table 1. In Fig. 5a it is seen that a certain output energy can be reached with a wide variety of off-axis angle – input energy pairs. The minima of a certain contour line gives the so-called optimum off-axis angle from the point of view of energy extraction efficiency, where the most energy can be extracted with minimum input energy. With more input energy available, the same output energy can be reached at two different angles. Smaller off-axis angles belong to higher input energy densities due to the smaller free off-axis aperture. If the experimental geometry makes it possible it is better to use an arrangement with larger off-axis angle. This relaxes the nonlinear effects in the window material [23, 24] and improves the contrast. The efficiency curves in Fig. 5b are basically similar to that of Fig. 5a. The contrast shown in Fig. 5c is a monotonic function of both α and E_{in}. The larger the off-axis angle or the smaller the input energy the better the contrast.

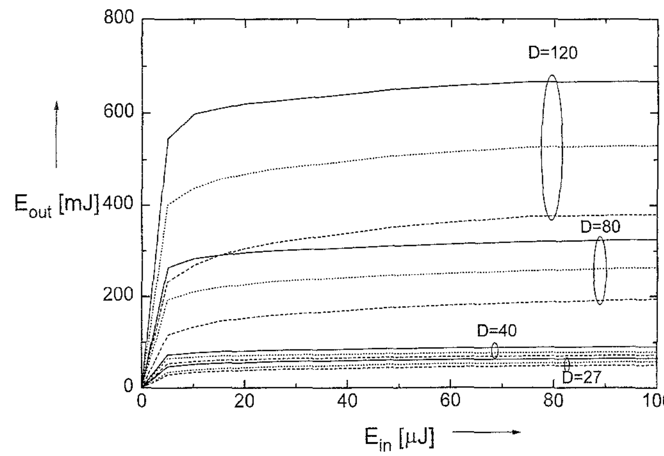

Fig. 6. Input-output characteristics of KrF gain modules of different electrode separation for different overall contrast values. (*Solid, dotted* and *broken lines* represent $C = 0.03$, $C = 0.06$ and $C = 0.12$ overall contrast, respectively)

3 Multiple-pass amplification

With these curves the optimization of a multiple-pass KrF amplifier can be done in the following way. The contrast-values for the different passes have to be determined with regard to the required overall contrast, and to the slightly different requirement in the subsequent passes. (In the first and the final passes somewhat worse contrasts are tolerated in order to keep amplification and efficiency high). With respect to the contrast requirements one can determine a working point for the first pass for a given input energy. The output energy will serve as the input energy for the next pass considering some losses caused by the optical components (windows, beam steering mirrors). Then one can proceed in a similar manner for the subsequent passes. The last amplification step is reached, when the output energy is already more than the momentarily stored energy of the amplifier. A further amplification pass would result in an energy gain of only 1.5 regarding the roughly 50% extraction efficiency in a practical case (Fig. 1b), and this gain would be compensated for by the unavoidable losses.

In our numerical calculations we considered a system based on our hybrid excimer-dye laser seed pulse generator producing input pulses of a few times 10 μJ energy. The amplifier parameters were varied as listed in Table 1. The calculated I–O characteristics for different amplifiers operating in a three-pass arrangement and for different overall contrast are shown in Fig. 6. The neighboring curves (bounded with an oval) belong to one amplifier characterized by a gap separation of 27, 40, 80 and 120 mm, respectively. The three curves which belong to one amplifier represent arrangements with different contrast conditions. The curve with the smallest energy in one group always belongs to the highest overall contrast of $C = 0.12$ (broken line). This is shared by the passes as $C_1 = 0.4$, $C_2 = 0.6$, $C_3 = 0.5$. The middle curve (dotted line) is with a medium contrast of $C = 0.06$ (where $C_1 = 0.3$, $C_2 = 0.5$ and $C_3 = 0.4$). The last one (solid line) had a poor contrast of $C = 0.03$ (where $C_1 = 0.2$, $C_2 = 0.4$ and $C_3 = 0.3$). The listed shares of the contrast for the different passes are the results of a rough optimization. The relatively poor contrast values in the first passes are necessary to boost up the energy quickly to the mJ range in order not to use more passes for preamplification. The share of the contrast between the second and third passes is determined with regard to the optimum efficiency in the final pass. However in the energy density range close to the maximum of efficiency (Fig. 1b) the efficiency is not a critical function of the contrast, so one can use somewhat different shares in the second and third passes with almost the same characteristics. Our main goal was with these contrast share sets to test systems with very different overall contrasts. In Fig. 6 one sees that 10–20 μJ seed energy is enough to drive a three-pass off-axis amplifier into saturation and to reach roughly the momentarily stored energy of the gain module. In a typical KrF gain module having a gain window of 15 ns one could realize even more passes in principle. However, one need not to increase the number of passes any longer, because the relatively small addition of energy in the subsequent passes is immediately compensated by the losses.

An optimized, multiple-pass, short-pulse excimer amplifier should have the following features. During the first amplification the input has to be boosted up to the same magnitude as the momentarily stored energy. This is the necessary condition for possible optimization of the efficiency of the amplifier in the subsequent passes. The amplifier gain length should make it possible to do this in one amplification pass. The optimum energy density for the power amplification can be determined from the small-signal gain and the absorption coefficient. With cylindrical expansion scheme one should avoid the loss of the useful aperture in the second and third passes. The final output aperture should be enough to keep the energy density at moderate values (about two times the saturation energy density) for the desired final output energy. In the final amplification pass the gain must be more than 2, in order to get a positive net gain with respect to optical losses. According to our theoretical considerations and experimental results, from an amplifier having similar geometrical discharge properties like commercial KrF lasers, one can expect somewhat more output energy than the momentarily stored energy with the overall contrast of 5–10% in a three-pass arrangement.

4 Conclusion

The off-axis amplification scheme has been proven as an efficient way to optimize multiple-pass amplifiers both for efficiency and contrast. Multiple-pass off-axis amplification in discharge pumped KrF gain modules has been analyzed by computer model calculations in order to optimize for maximum gain contrast and energy extraction efficiency. Different expansion schemes have been modeled and the cylindrical one has been found to be the best fitted to the needs of multiple-pass off-axis amplification. Amplifiers of different discharge parameters have been investigated. It has been shown that in a wide range of momentarily stored energy a three-pass amplification scheme is enough to reach the theoretically extractable energy with 10–20 μJ input energy with an overall contrast of 5–10%.

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