Steady-state model for the electron beam pumped KrF laser

W.J. WITTEMAN

Department of Applied Physics, Twente University of Technology, Enschede, The Netherlands

Abstract. In this paper the kinetics of excitation, quenching, and absorption in an e-beam pumped KrF laser is discussed. It is argued that under usual experimental conditions the steady-state approximation can be applied. For that case a comprehensive kinetic model can be treated analytically. The model simulates quite well the experimental results obtained so far. It predicts the maximum performance conditions, limiting behaviour, and scaling properties of e-beam pumped KrF lasers.

1. Introduction

Rare-gas fluoride exciplexes (KrF*, XeF*, and ArF*) are used as active media to obtain the most powerful and efficient UV lasers to date. An output energy of 24 Joule/liter has been obtained with KrF* at an efficiency of about 8 percent [10]. The exciplexes can be produced in a gas mixture containing the rare gas, fluorine and a buffer gas. The excitation is achieved by irradiation with a relativistic electron beam, an electron beam controlled discharge or an UV preionized discharge. The best results are obtained by pure electron-beam excitation. The usual gas mixture for an electron-beam pumped KrF laser is 2–6 Torr F2, 100–200 Torr Kr and 2–4 atm Ar. The lasing species, KrF*, is mainly formed from ions in the reaction

\[ \text{Kr}^+ + \text{F}^- \rightarrow \text{KrF}*. \]

The krypton ions are either produced directly by the interaction of the electron beam with Kr or at the end of a reaction chain starting from ionized argon. The secondary electrons from the ionization process undergo easily dissociative attachment with F2 to form F* ions.

Although there is in principle also a ‘neutral channel’, starting with metastable atoms to form KrF*, this channel is not important, because only a fraction (15–20%) of the electron energy is used to produce metastable states. Moreover, the sequence reactions in the neutral channel are relatively slower than those with ions, so that an even smaller part of the electron energy goes through the neutral channel. Numerical calculations show that for an electron beam pumped system the formation kinetics in the case of short pulses (25–50 ns) goes for more than 90% through the ion channel. Therefore we consider only the ion channel. The kinetic of the KrF* is characterized by a chain of many chemical reactions. The most important reactions and rate constants have been extensively studied in the past and are described in literature [6, 7, 13]. In the following we shall use the knowledge of these reactions to describe a model that includes the most important kinetic processes in the laser mechanism. It will be argued that under the...
Table 1. Dominant formation rate constants

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Reaction constant</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Ar}^+ + 2\text{Ar} \rightarrow \text{Ar}^+_2 + \text{Ar} )</td>
<td>( k_1 = 2.5 \times 10^{-31} \text{ cm}^6 \text{ S}^{-1} )</td>
<td>[2]</td>
</tr>
<tr>
<td>( \text{Ar}^+_2 + \text{Kr} \rightarrow \text{Kr}^+ + 2\text{Ar} )</td>
<td>( k_2 = 7.5 \times 10^{-16} \text{ cm}^6 \text{ S}^{-1} )</td>
<td>[8]</td>
</tr>
<tr>
<td>( \text{Kr}^+ + \text{F}^- \rightarrow \text{KrF}^* )</td>
<td>( k_3 = 3 \times 10^{-4} \text{ cm}^3 \text{ S}^{-1} )</td>
<td>[5]</td>
</tr>
<tr>
<td>( \text{Ar}^+ + \text{F}^- \rightarrow \text{ArF}^* )</td>
<td>( k_4 = 3 \times 10^{-4} \text{ cm}^3 \text{ S}^{-1} )</td>
<td>[5]</td>
</tr>
<tr>
<td>( \text{Ar}^+_2 + \text{F}^- \rightarrow \text{ArF}^* + \text{Ar} )</td>
<td>( k_5 = 3 \times 10^{-4} \text{ cm}^3 \text{ S}^{-1} )</td>
<td>[5]</td>
</tr>
<tr>
<td>( \text{Kr}^+ + \text{Kr} + \text{Ar} \rightarrow \text{Kr}^+_2 + \text{Ar} )</td>
<td>( k_6 = 2.5 \times 10^{-31} \text{ cm}^6 \text{ S}^{-1} )</td>
<td>[9]</td>
</tr>
<tr>
<td>( \text{Kr}^+_2 + \text{F}^- \rightarrow \text{KrF}^* + \text{Kr} )</td>
<td>( k_7 = 3 \times 10^{-4} \text{ cm}^3 \text{ S}^{-1} )</td>
<td>[5]</td>
</tr>
<tr>
<td>( \text{ArF}^* + 2\text{Ar} \rightarrow \text{Ar}_{2}^* \text{F}^* + \text{Ar} )</td>
<td>( k_8 = 5 \times 10^{-32} \text{ cm}^6 \text{ S}^{-1} )</td>
<td>[7]</td>
</tr>
<tr>
<td>( \text{ArF}^* + \text{Kr} \rightarrow \text{KrF}^* + \text{Ar} )</td>
<td>( k_9 = 3 \times 10^{-10} \text{ cm}^9 \text{ S}^{-1} )</td>
<td>[9]</td>
</tr>
<tr>
<td>( \text{ArF}^* + \text{F}_2 \rightarrow \text{Ar} + \text{F} + \text{F}_2 )</td>
<td>( k_{10} = 1.9 \times 10^{-9} \text{ cm}^3 \text{ S}^{-1} )</td>
<td>[12]</td>
</tr>
<tr>
<td>( \text{KrF}^* + \text{Ar} \rightarrow \text{Kr} + \text{Ar} + \text{F} )</td>
<td>( k_{11} = 1.8 \times 10^{-15} \text{ cm}^3 \text{ S}^{-1} )</td>
<td>[4]</td>
</tr>
<tr>
<td>( \text{KrF}^* + 2\text{Ar} \rightarrow \text{ArKrF}^* + \text{Ar} )</td>
<td>( k_{12} = 8 \times 10^{-32} \text{ cm}^6 \text{ S}^{-1} )</td>
<td>[9]</td>
</tr>
<tr>
<td>( \text{KrF}^* + \text{Ar} + \text{Kr} \rightarrow \text{Kr}_2 \text{F}^* + \text{Ar} )</td>
<td>( k_{13} = 6.5 \times 10^{-31} \text{ cm}^6 \text{ S}^{-1} )</td>
<td>[9]</td>
</tr>
<tr>
<td>( \text{KrF}^* + \text{F}_2 \rightarrow \text{Kr} + \text{F} + \text{F}_2 )</td>
<td>( k_{14} = 5.2 \times 10^{-10} \text{ cm}^9 \text{ S}^{-1} )</td>
<td>[4]</td>
</tr>
<tr>
<td>( \text{KrF}^* + \text{e} \rightarrow \text{products} )</td>
<td>( \alpha = 2 \times 10^{-7} \text{ cm}^3 \text{ S}^{-1} )</td>
<td>[15]</td>
</tr>
<tr>
<td>( \text{ArF}^* + \text{e} \rightarrow \text{products} )</td>
<td>( \gamma = 2 \times 10^{-7} \text{ cm}^3 \text{ S}^{-1} )</td>
<td>[15]</td>
</tr>
<tr>
<td>( \text{Ar}_2 \text{F}^* + \text{Kr} \rightarrow \text{ArKrF}^* + \text{Ar} )</td>
<td>( k_{15} = 1 \times 10^{-10} \text{ cm}^9 \text{ S}^{-1} )</td>
<td>[7]</td>
</tr>
<tr>
<td>( \text{Ar}_2 \text{F}^* + \text{F}_2 \rightarrow 2\text{Ar} + \text{F} + \text{F}_2 )</td>
<td>( k_{16} = 1 \times 10^{-10} \text{ cm}^9 \text{ S}^{-1} )</td>
<td>[7]</td>
</tr>
<tr>
<td>( \text{ArKrF}^* + \text{Kr} \rightarrow \text{Ar}_2 \text{F}^* + \text{Kr} )</td>
<td>( k_{17} = 2 \times 10^{-11} \text{ cm}^9 \text{ S}^{-1} )</td>
<td>[9]</td>
</tr>
<tr>
<td>( \text{KrF}^* + 2\text{Ar} \rightarrow 2\text{Kr} + \text{F} + 2\text{Ar} )</td>
<td>( k_{18} = 2 \times 10^{-11} \text{ cm}^9 \text{ S}^{-1} )</td>
<td>[1]</td>
</tr>
<tr>
<td>( \text{KrF}^* + \text{F}_2 \rightarrow 2\text{Kr} + \text{F} + \text{F}_2 )</td>
<td>( k_{19} = 1 \times 10^{-10} \text{ cm}^9 \text{ S}^{-1} )</td>
<td>[7]</td>
</tr>
<tr>
<td>( \text{F}_2 \rightarrow \text{F}^- + \text{F} )</td>
<td>( \beta = 2 \times 10^{-9} \text{ cm}^3 \text{ S}^{-1} )</td>
<td>[9]</td>
</tr>
</tbody>
</table>
Table 2. Dominant radiation interaction

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Cross-section/Time constant</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>KrF* + hv → Kr + F + 2hv</td>
<td>$\sigma_1 = 2.4 \times 10^{-16}$ cm(^2)</td>
<td>[7], [14]</td>
</tr>
<tr>
<td>Ar* + hv → Ar* + Ar</td>
<td>$\sigma_1 = 1.5 \times 10^{-17}$ cm(^2)</td>
<td>[8]</td>
</tr>
<tr>
<td>Kr* + hv → Kr* + Kr</td>
<td>$\sigma_4 = 1.5 \times 10^{-17}$ cm(^2)</td>
<td>[7], [14]</td>
</tr>
<tr>
<td>Kr*F* + hv → products</td>
<td>$\sigma_2 = 5 \times 10^{-18}$ cm(^2)</td>
<td>[7]</td>
</tr>
<tr>
<td>F* + hv → 2F</td>
<td>$\sigma_5 = 1.5 \times 10^{-20}$ cm(^2)</td>
<td>[8]</td>
</tr>
<tr>
<td>F* + hv → F + e</td>
<td>$\sigma_6 = 5.6 \times 10^{-18}$ cm(^2)</td>
<td>[8]</td>
</tr>
<tr>
<td>KrF* → Kr + F + hv</td>
<td>$\tau_1 = 6 \times 10^{-9}$ sec</td>
<td>[7], [14]</td>
</tr>
<tr>
<td>ArF* → Ar + F + hv</td>
<td>$\tau_2 = 4 \times 10^{-9}$ sec</td>
<td>[3]</td>
</tr>
<tr>
<td>Ar*F* → 2Ar + F + hv</td>
<td>$\tau_3 = 5 \times 10^{-9}$ sec</td>
<td>[7]</td>
</tr>
<tr>
<td>ArKrF* → Ar + Kr + F + hv</td>
<td>$\tau_4 = 2 \times 10^{-8}$ sec</td>
<td>[7]</td>
</tr>
<tr>
<td>Kr*F* → 2Kr + F + hv</td>
<td>$\tau_4 = 1.5 \times 10^{-8}$ sec</td>
<td>[7]</td>
</tr>
</tbody>
</table>

Figure 1. Flow diagram representing the most important kinetics of an e-beam pumped KrF laser

\[
\frac{d[A_{\star}]}{dt} = P[Ar] + a_1 [Ar_2^+] I - k_1 [Ar^+] [Ar]^2 - k_3 [Ar^+] [F^-],
\]

where $k_1$ is the formation constant of molecular argon ions, $a_1$ the absorption cross-section, and $k_3'$ the formation constant for ArF\*.

The main processes suffered by the molecular argon ions are the ionization of krypton, with a rate constant $k_2$, the formation of ArF\*, with a rate constant $k_3''$, and the photoabsorption by the intracavity radiation field (cross-section $\sigma_1$):

\[
\frac{d[Ar_2]}{dt} = k_1 [Ar^+] [Ar]^2 - \sigma_1 [Ar_2^+] I - k_2 [Kr] [Ar_2^+] \\
- k_3'' [Ar_2^+] [F^-].
\]
The rate equation for Kr⁺ contains the direct production by the electron beam and the formation by Ar⁺. The ions form KrF* by the Coulomb interaction with F⁻. Further some ions produce Kr₂⁺ in collisions with Ar and Kr. The rate constants are respectively $k_3$ and $k_{10}$:

$$\frac{d[\text{Kr}^+]}{dt} = 2P[\text{Kr}] + k_2 [\text{Ar}^+] [\text{Kr}] - k_3 [\text{Kr}^+] [\text{F}^-] - k_{10} [\text{Kr}^+] [\text{Kr}] [\text{Ar}].$$  (3)

The ionization rate per Kr atom is about twice that for Ar, hence the factor 2 in the first term.

The formed Kr₂⁺ species have also Coulomb interaction with F⁻ to create KrF* with rate constant $k_3''$. There is also absorption by the radiation (cross-section $\sigma_2$):

$$\frac{d[\text{Kr}^+_2]}{dt} = k_{10} [\text{Kr}^+] [\text{Kr}] [\text{Ar}] - k_3'' [\text{Kr}^+_2] [\text{F}^-] - \sigma_2 [\text{Kr}^+_2] I.$$  (4)

The ArF* species form KrF* in a replacement reaction with Kr with a rate constant $k_{11}$. Further, ArF* is lost by three body collisions with Ar to produce Ar₂F* with a rate constant $k_{13}$, by quenching in collisions with F₂ (rate constant $k_8$) and electrons (density $[n]$ and rate constant $\alpha$), and through radiative decay (time constant $\tau_2$):

$$\frac{d[\text{ArF}^*]}{dt} = k'_3 [\text{Ar}^+] [\text{F}^-] + k''_3 [\text{Ar}^+_2] [\text{F}^-] - k_{11} [\text{ArF}^*] [\text{Kr}] - \alpha [\text{ArF}^*] [n] +$$

$$- k_{13} [\text{ArF}^*] [\text{Ar}]^2 - k_8 [\text{ArF}^*] [\text{F}_2] - \frac{1}{\tau_2} [\text{ArF}^*].$$  (5)

The lasing species KrF* formed in the above mentioned processes are balanced by the process of stimulated emission, with cross-section $\sigma_s$, quenching by electrons, two and three body collisions with Ar, Kr, and F₂, and by radiative decay with time constant $\tau_1$:

$$\frac{d[\text{KrF}^*]}{dt} = k_3 [\text{Kr}^+] [\text{F}^-] + k''_3 [\text{Kr}^+_2] [\text{F}^-] + k_{11} [\text{ArF}^*] [\text{Kr}] +$$

$$- (\alpha I + Q_1) [\text{KrF}^*],$$  (6)

where

$$Q_1 = \alpha [n] + k_4 [\text{Ar}] + k_5 [\text{Ar}]^2 + k_6 [\text{Kr}] [\text{Ar}] + k_7 [\text{F}_2] + \frac{1}{\tau_1}$$  (7)

is the parameter describing quenching and radiative decay.

The Ar₂F* species are quenched by Kr, Ar, and F₂ and have a radiative decay time of $\tau_3$ sec:
\[
\frac{d[\text{Ar}_2\text{F}^*]}{dt} = k_{13} [\text{ArF}^*] [\text{Ar}]^2 + k_{18} [\text{ArKrF}^*] [\text{Ar}] + \\
- \left( k_{14} [\text{Kr}] + k_9 [\text{F}_2] + \frac{1}{\tau_3} \right) [\text{Ar}_2\text{F}^*].
\]

The $\text{ArKrF}^*$ species formed in collisions of $\text{Ar}_2\text{F}^*$ and $\text{KrF}^*$ with $\text{Kr}$ and $\text{Ar}$ are also quenched in collisions with $\text{Kr}$ and $\text{Ar}$ to produce $\text{Kr}_2\text{F}^*$ (rate constant $k_{17}$) and $\text{Ar}_2\text{F}^*$ (rate constant $k_{18}$). Further there is radiative decay with a time constant $\tau_4$:

\[
\frac{d}{dt} [\text{ArKrF}^*] = k_{14} [\text{Ar}_2\text{F}^*] [\text{Kr}] + k_5 [\text{KrF}^*] [\text{Ar}]^2 + \\
- k_{17} [\text{ArKrF}^*] [\text{Kr}] - k_{18} [\text{ArKrF}^*] [\text{Ar}] + \\
- \frac{1}{\tau_4} [\text{ArKrF}^*];
\]

\[
\frac{d}{dt} [\text{Kr}_2\text{F}^*] = k_6 [\text{KrF}^*] [\text{Ar}] [\text{Kr}] + k_{17} [\text{ArKrF}^*] [\text{Kr}] + \\
- k_{19} [\text{Kr}_2\text{F}^*] [\text{Ar}]^2 - k_{20} [\text{Kr}_2\text{F}^*] [\text{F}_2] + \\
- \frac{1}{\tau_5} [\text{Kr}_2\text{F}] - \sigma_3 [\text{Kr}_2\text{F}^*] I.
\]

In the discharge medium we assume neutrality. The dominant loss of secondary electrons is rapid dissociative attachment with $\text{F}_2$ with rate constant $\beta$, resulting in $\text{F}^-$ formation. So we can write for the electron density:

\[
\frac{d[n]}{dt} = P[A + 2K] - \beta [n] [\text{F}_2],
\]

where the electron density is given by

\[
[n] = [\text{Ar}^+] + [\text{Ar}_2^+] + [\text{Kr}^+] + [\text{Kr}_2^+] - [\text{F}^-].
\]

The radiation field within the cavity is mainly subjected to stimulated emission, outcoupling, and absorption by $\text{Ar}_2^+$, $\text{Kr}_2^+$, $\text{F}^-$, $\text{Kr}_2\text{F}^*$ and $\text{F}_2$. We obtain the following equation for the photon density flux:

\[
\frac{1}{c} \frac{dI}{dt} = \sigma_4 I[\text{KrF}^*] - \gamma I - \sigma_1 I[\text{Ar}_2^+] - \sigma_2 I[\text{Kr}_2^+] - \sigma_3 I[\text{Kr}_2\text{F}^*],
\]

where

\[
\gamma = \gamma_0 + \gamma_a.
\]

$\gamma_0 = (-\ln R)/2L$ is the well-known outcoupling factor for a cavity having a value $R$ for the product of the reflectivities of the mirrors separated at a distance $L$. 


Figure 2. The time behaviour of a current pulse of about 50 nsec (solid line) and the corresponding laser output pulse (broken line)

\[ \gamma_a = \sigma_{F^-}[F^-] + \sigma_{F_2}[F_2] \]  \hspace{1cm} (14)

being the absorption loss by the fluorine ions and molecules.

The absorption of \( F^- \) and \( F_2 \) turns out to be very small compared to those of \( \text{Ar}_2^+ \) and \( \text{Kr}_2^+ \). Moreover, the calculations show that \( F^- \) is practically independent of the excitation parameter \( P \). For these reasons we take the losses due to \( F^- \) and \( F_2 \) and the outcoupling together.

For the laser parameters used in the range of maximum operation performance it is found that the time constants for the species and the output power following the excitation pulse is in the order of a few nanoseconds. This is found by a numerical evaluation of the above equations, but also from experiments. In fact, we observed that the radiation pulse follows rather accurately the shape of the excitation pulse (Figure 2). This means that for an excitation process during a time larger than those time constants the laser process can be considered quasi-stationary. The stationary process yields the great advantage of an analytic treatment of the complicated kinetics of this laser process. This allows us to determine directly the effects of the partial pressure of gas components, excitation density and cavity on the various formation, quenching and absorption processes. In this way optimum performance conditions are easily obtained.

3. Quasi-stationary solution of the rate equations

Adding equation (1) to (6) we obtain for the stationary state:

\[ P\{2[\text{Kr}]+[\text{Ar}]-[\text{ArF}^*]\} - [\text{ArF}^*]\left( k_{13}[\text{Ar}]^2 + k_8[\text{F}_2] + \frac{1}{\tau_2} + \alpha[n] \right) + \]

\[ -Io_2[\text{Kr}_2^+] = (Io_s + Q_1)[\text{KrF}^*]. \]  \hspace{1cm} (15)

From the radiation equation for the cavity (12) we obtain:

\[ [\text{KrF}^*] = \frac{1}{\sigma_s} \left( \gamma + \sigma_1[\text{Ar}_2^+] + \sigma_2[\text{Kr}_2^+] + \sigma_3[\text{Kr}_2^*F^*] \right). \]  \hspace{1cm} (16)
Substituting (16) into (15) we finally obtain:

\[
\frac{W}{P} = \frac{\gamma[(\text{Ar}) + 2(\text{Kr}) - Q_2(\text{ArF}^*)]P^{-1} - Q_1\alpha^{-1}(\gamma + \sigma_1(\text{Ar})P^{-1} + \sigma_2(\text{Kr})P^{-1} + \sigma_3(\text{KrF}^*)P^{-1})]}{\gamma + \sigma_1(\text{Ar})P^{-1} + 2\sigma_2(\text{Kr})P^{-1} + \sigma_3(\text{KrF}^*)P^{-1}}
\]  

(17)

where \( W = \gamma I \) is the production rate of photons per unit volume, \( \gamma = \gamma/P \), and

\[
Q_2 = k_{13}[\text{Ar}]^2 + k_{14}[\text{F}_2] + \alpha[n] + \frac{1}{\tau_2}
\]  

(18)

is the quenching parameter of \( \text{ArF}^* \).

From equation (17) we can calculate \( \frac{W}{P} \) as a function of \( P/\gamma \) with the gas densities as parameters. Then we find \( \frac{W}{P} \) to depend strongly on the densities of \( \text{Ar} \) and \( \text{Kr} \) but little on \( \text{F}_2 \), if we substitute for \( \text{F}_2 \) the usual experimental pressures of a few Torr. Therefore we have kept \( \text{F}_2 \) constant and equal to \( 10^{17} \text{ cm}^{-3} \).

We also calculated the maximum produced photons per excitation or the maximum values of \( \frac{W}{P} \) as a function of \( P/\gamma \) together with the corresponding densities of \( \text{Ar} \) and \( \text{Kr} \). In Figure 3 the maximum values of \( \frac{W}{P} \) are plotted versus \( P/\gamma \) with \( P \) as parameter. It is seen that the output has a maximum for \( P/\gamma \), but its dependence on \( P/\gamma \) is only significant for low pumping rates or high outcoupling. The corresponding densities of \( \text{Ar} \) and \( \text{Kr} \) for which the maxima are obtained are plotted in Figures 4 and 5 respectively.

The most important species \( \text{Ar}^+ \), \( \text{Ar}_2^+ \), \( \text{Kr}^+ \), \( \text{Kr}_2^+ \), \( \text{F}^- \) and \( n \) (electron density) formed in the laser mixture under the maximum output conditions are plotted in Figures 6, 7, 8, 9, 10 and 11 respectively, again versus \( P/\gamma \) with \( P \) as parameter. The corresponding \( \text{Ar} \) and \( \text{Kr} \) densities are those indicated in Figures 4 and 5 respectively.

We define the efficiency of the laser process as

\[
\eta = \frac{W}{P} ([\text{Ar}] + 2[\text{Kr}])
\]  

(19)

being the ratio of the photon density rate and the excitation rate density. In other words the efficiency describes the change that an atom ionized by the fast electrons leads to the production of a photon that is coupled out. This is not exactly true because \( W \) includes both the outcoupled photons and those absorbed by the species \( \text{F}^- \) and \( \text{F}_2 \). However the latter two absorptions are in the range of interest about two orders of magnitude smaller than the out-coupling. The values of \( \eta \) for optimum output versus \( P/\gamma \) are plotted in Figure 12 with \( P \) as parameter. The efficiency describing the relation between radiation output and electrical input energy is smaller because the energy loss per argon ionization is estimated as about 26 eV, whereas the outgoing photon has an energy of 5 eV. Thus with a quantum efficiency of about 0.2 we predict an overall efficiency for the electron energy between 8 and 10 percent.
Figure 3. The ratio of maximum extracted photon density to the average excitation rate versus the ratio of the excitation rate to the outcoupling. The parameter is the excitation rate per atom.

Figure 4. The argon densities for which the maximum output is obtained versus the ratio of the excitation rate to the coupling.
Figure 5. The krypton densities for which the maximum output is obtained versus the ratio of the excitation rate to the outcoupling.

Figure 6. The argon ion density divided by $P$ for optimum output conditions as a function of $P/\gamma$. 
Figure 7. The molecular argon density divided by $P$ for optimum output conditions versus $P/\gamma$

Figure 8. The krypton ion density divided by $P$ for optimum output conditions versus $P/\gamma$
Figure 9. The molecular krypton density divided by $P$ for optimum output conditions versus $P/\gamma$.

Figure 10. The density of $F^-$ for optimum output conditions versus $P/\gamma$. It is found that $F^-$ is practically constant and independent on $P$. 
Figure 11. The electron density divided by $P$ for optimum output conditions versus $P/\gamma$

Figure 12. The efficiency $\eta$ that corresponds with the maximum output power versus $P/\gamma$
4. Discussion of the model

The predictions described in the previous section are in good agreement with our experiments, which are reported in ref. [10, 11, 16]. It is observed that the maximum output energy is not very sensitive to the Kr density. The observed maximum density is about $3 \times 10^{18}$ cm$^{-3}$ and in substantial agreement with the model. It should be noted that Kr has a broad maximum. Similarly we observed that at maximum operation conditions the argon density is around $9 \times 10^{19}$ cm$^{-3}$ (3.6 atm). This is in good agreement with our model. Further increase of the excitation current density does not require higher argon densities as expected. Also the outcoupled photon density and overall efficiency between 8 and 10 percent are in excellent agreement with our observations.

For the optimum performance conditions with respect to output we found from the model that most excimer energy of KrF* is lost by quenching. The losses by radiation absorption are minor. For low values of $P/\gamma$, say smaller than $2 \times 10^5$ cm/sec, the system is inefficient due to quenching by Ar and Kr. At higher values the system has a broad maximum for $P/\gamma$. This was also observed experimentally by increasing the reflectivity of the outcoupling mirror from 8 to 16 percent for a system with high excitation density. The decrease of $W/P$ at the right of the maxima in Figure 3 is due to increasing photon absorption by Ar$^+$ and Kr$^+$.

It is seen that the maximum values of $W/P$ are primarily dependent on $P/\gamma$. The relatively small decrease of the values of $W/P$ with increasing value of the excitation parameter $P$ is due to electron quenching.

In order to compare the calculated $W/P$ values with those obtained experimentally for a 50 nsec pulse at about 3.75 atm total gas pressure we multiply $W/P$ by the corresponding $P/\gamma$ value. We then find for our curves that $W/P$ at maximum Ar gas pressure is about $10^{25}$, which corresponds to $8 \cdot 10^6$ Watt per cm$^2$. Using the experimental outcoupling factor of about $3 \cdot 10^{-2}$, a volume of 600 cm$^3$ and a pulse duration of 50 nsec, we calculate 7.5 Joule output energy. The experimental output energy is 10.2 Joule.

References