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## An Investigation of the Role of Ne, Ar, and Kr as Buffer Gas in a Coaxial $e$ -Beam Pumped KrF Laser

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**Abstract**—The role of Ne, Ar, and Kr as a buffer gas was investigated in a KrF laser pumped by a coaxial  $e$ -beam. The coaxial diode has a length of 20 cm and the anode tube diameter is 1 cm. The tube can be pressurized with the laser gas mixture up to 12 bar while a current density of 250 A/cm<sup>2</sup> can be achieved. It is found that both the maximum energy extraction and the optimized gas pressure with each buffer gas increase in the sequence Kr–Ar–Ne. From the experimental results, the quenching parameters of Kr, Ar, and Ne are deduced.

### I. INTRODUCTION

FOR  $e$ -beam pumped excimer systems, the stopping power is only a fraction of the electron beam energy. Since the stopping power is proportional to the gas density, it is important to optimize the energy extraction density with respect to the gas density. We have treated this problem in the past for the conventional mixture of Ar, Kr, and F<sub>2</sub> [1]. It was argued that for practical situations, the analysis can be simplified by following the complicated chain of many kinetic reactions as a quasi-stationary process. The predictions obtained in this way are suitable for comparison to results of different experiments.

Although the energy transfer from the  $e$ -beam is proportional to the gas density, this density must be limited because of its quenching effect and the production of absorbing species. The density of KrF\* is determined by the optical quality of the resonator and the absorption of the medium. The latter is mainly dependent on the partial gas densities and current density. This means that the density of KrF\*, and consequently the quenching losses, can be decreased by decreasing the outcoupling. The stimulated emission process will then overcome the quenching losses by a stronger intracavity laser flux. The more intense laser flux on its turn causes increased absorption. Therefore, the system can be optimized. It was found that the optimized densities of all individual gas components increase with the current density, and that in a large range, the outcoupling is not a sensitive parameter. These results were found in good agreement with our experiments [2], [3] where we investigated laser cavities of different volumes and current densities.

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Since for high performance we have to optimize the balancing process between the excitation of the gas and its quenching and radiation losses, it is interesting to investigate mixtures with different buffer gases that are expected to show large differences in their quenching and absorption properties. Recently, some calculations and experiments have been reported on this subject. Measurements with high-pressure Ne mixtures have been described [4], whereas a growing interest can be seen in low-pressure Kr buffered gas mixtures [5]–[7]. In the present contribution, we study the radiation energy extraction density for, respectively, Ar, Kr, and Ne as a buffer gas. The experiments allow us to estimate the quenching parameters of these gases.

### II. DESCRIPTION OF THE LASER SYSTEM

The laser system, consisting of a coaxial vacuum diode driven directly by a low-inductance ten-stage Marx generator, has been described in detail previously [3]. In the present situation, the laser chamber is made of Ti-foil of 50  $\mu$ m instead of 25  $\mu$ m, so that it can be used at pressures up to 12 atm under discharge conditions. The thicker foil causes a lower current density and electron energy in the gas. The diameter of the chamber is 10 mm and the pumped length is 20 cm, resulting in an active volume of 16 cm<sup>3</sup>. The chamber is ended with two plane parallel MgF<sub>2</sub> flats. At one side, a quartz prism is attached as a total reflector.

All experiments described below have been performed at a diode voltage of 280 kV and a current of 7.5 kA in 30 ns pulses. From this, we estimate a maximum current density of approximately 375 A/cm<sup>2</sup> and an average current of about 250 A/cm<sup>2</sup>. The maximum electron energy inside the laser tube is approximately 170 keV.

### III. EXPERIMENTS

The classical mixture of an  $e$ -beam pumped KrF laser consists of Ar, Kr, and F<sub>2</sub>. This mixture has been well established, and the results are all based on the thorough investigations by many researchers of fundamental processes such as formation rate constants and radiation interactions. It was found that for maximum extracted energy, depending on the current density, the Ar pressure should be between 3 and 5 atm and the Kr pressure between 0.2 and 0.5 atm [1]–[3].

The output dependence on the total pressure of the clas-

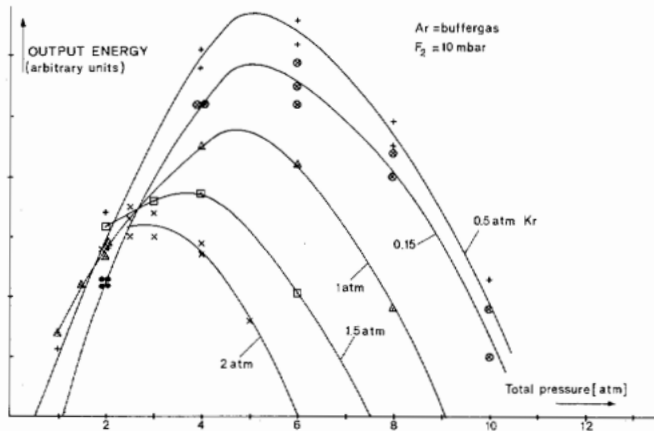


Fig. 1. The dependence of laser output in arbitrary units on Ar pressure. Each curve has constant Kr pressure as indicated in the figure.

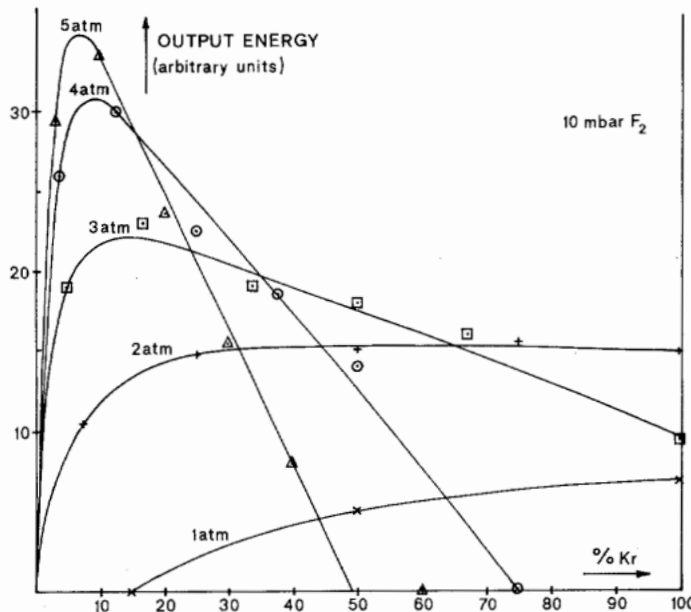


Fig. 2. The output energy in arbitrary units is plotted versus the Kr percentage for the three-component mixtures. Each curve follows the data for total pressures as indicated.

sical mixture is shown in Fig. 1. For each curve, the Kr and  $F_2$  partial pressures are kept constant as parameters. All mixtures have shown that the output is not sensitive to  $F_2$  concentrations around its value of about 10 mbar, so that all experiments have been performed for this partial pressure of  $F_2$ . The experiments show clearly that the optimized values of the three-component system for a current density of approximately  $250 \text{ A/cm}^2$  are 4.5 atm Ar and 0.5 atm Kr. Increasing the Kr concentration shows a lower extraction energy, but also a shift to lower total pressure for better energy extraction. Further, it is seen that the lower the total pressure, the less sensitive the extraction energy is on the Kr pressure, and below 2 atm the maximum is even obtained for a mixture without Ar, i.e., a two-component system.

This is also shown in Fig. 2 where the output is plotted as a function of the Kr percentage in  $F_2$ -Ar-Kr mixtures with total pressures of 1, 2, 3, 4, and 5 atm, respectively.

The results of the two-component system Kr- $F_2$  are

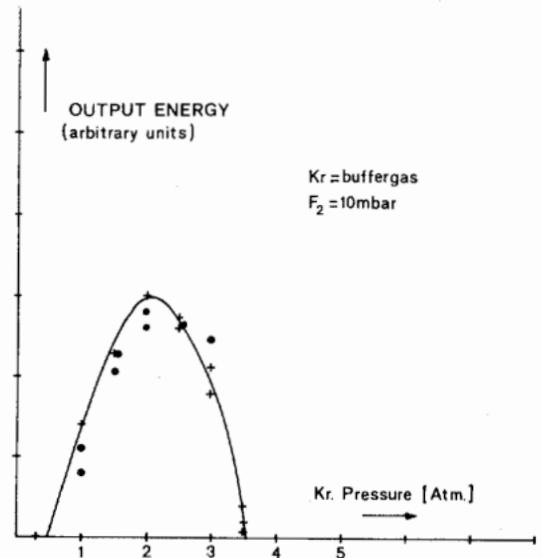


Fig. 3. The output energy in arbitrary units of the two-component system Kr- $F_2$  as a function of the Kr pressure.  $F_2$  pressure is 10 mbar.

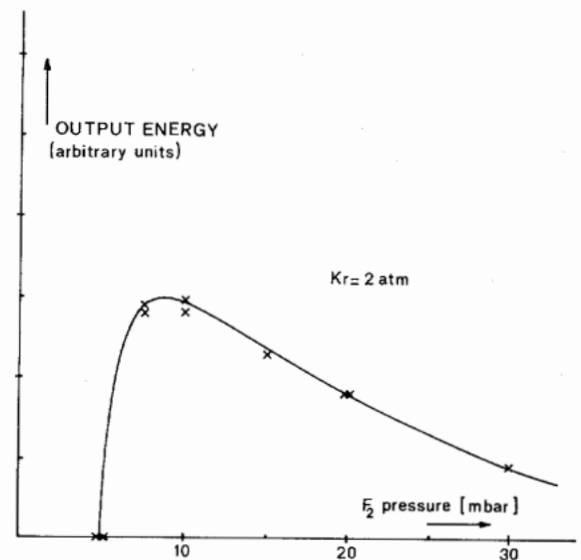


Fig. 4. The output energy in arbitrary units of the  $F_2$ -Kr mixture as a function of  $F_2$ . The Kr pressure is 2 atm.

shown in Fig. 3. The  $F_2$  concentration of 10 mbar is kept constant. The maximum extraction energy is more sensitive to the gas pressure, is much smaller, and reaches its value at a much lower pressure than in the case of the three-component system. The  $F_2$  dependence of this system is shown in Fig. 4. The optimized value of the  $F_2$  concentration has a relatively broad range around 10 mbar, similar to the three-component system. Apparently, at 10 mbar, sufficient  $F^-$  ions are produced by the interaction of  $F_2$  and secondary electrons. Higher  $F_2$  concentrations lead to increased absorption of radiation by photodissociation.

Since in the absence of Ar the optimized gas pressure and maximum output are much smaller than in the presence of Ar, one may wonder whether this difference is related to stronger quenching and absorption phenomena in

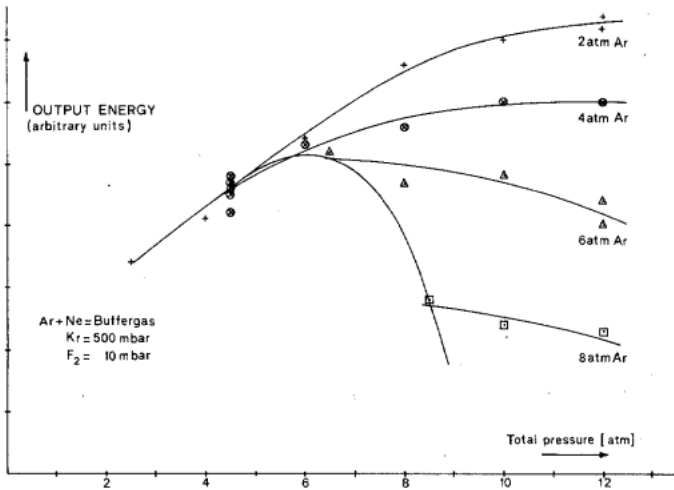


Fig. 5. The output energy of the four-component mixture Ar-Kr-Ne-F<sub>2</sub> as a function of the Ne pressure with the Ar pressure as a parameter. The F<sub>2</sub> pressure is 10 mbar and the Kr pressure 0.5 atm.

a Kr dominating mixture. Further, if this is the case, it is interesting to investigate the effect of a lighter rare gas as a buffer that is expected to have a smaller quenching effect. This has been done by considering again the curve of the optimized three-component system with 500 mbar Kr and 10 mbar F<sub>2</sub>. At the positions of, respectively, 2, 4, 6, and 8 bar Ar of this curve, the gas has been further mixed with Ne. This is shown in Fig. 5. At points where we start to add Ne instead of Ar, we find indeed that Ne has a favorable effect on the energy extraction. The lower the Ar concentration, the higher the maximum energy extraction. The result also shows that for Ar below 4 atm, a further decrease of Ar results in an increase of total pressure for which maximum energy is obtained, indicating that absorption and quenching of Ne are much less than those for the Ar gas. The next step by substituting Ne for Ar is to investigate the Kr dependence in this mixture because Kr is essential for producing the lasing molecules. It is most likely that, similar to the case with Ar, the Kr<sup>+</sup> ions are formed in collisions with Ne<sub>2</sub><sup>+</sup>. We studied the relation between the partial pressures of Kr and Ne.

In Fig. 6, we plotted the extraction energy as a function of the total pressure with Ne as a buffer gas. In all experiments, we used a constant F<sub>2</sub> pressure of 10 mbar which was observed to be the optimized concentration of F<sub>2</sub>. Each curve describes the measurements with constant Kr pressure and a constant Ar pressure of 490 mbar. This presence of Ar is due to the fact that the available F<sub>2</sub> was diluted in Ar gas. The curves of Fig. 6 show that the maximum of each curve increases with decreasing Kr concentration and reaches a maximum for 500 mbar, similar to the three-component system. The higher maximum is again obtained for higher total pressure. We also noticed that if one chooses a maximum pressure below 4.5 atm, a higher Kr pressure is more favorable. In this pressure range below 4.5 atm, the use of Ar is even more favorable. The maximum admissible pressure of our system is 12 atm. We may extrapolate the optimized Ne pressure at about 15 atm.

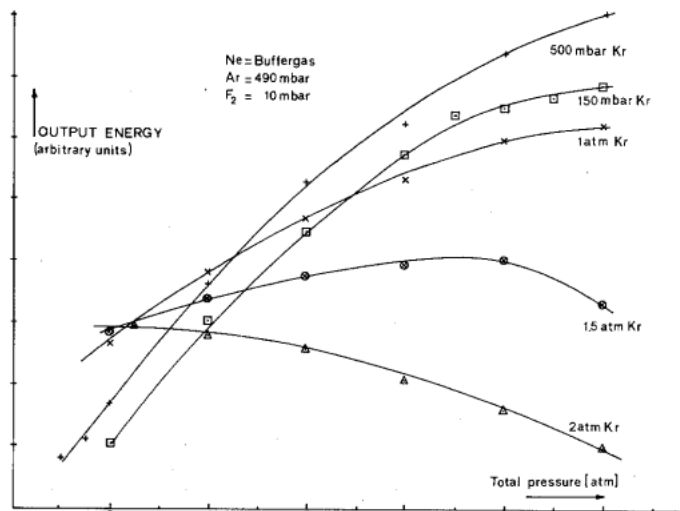


Fig. 6. The output energy of the four-component mixture Ar-Kr-Ne-F<sub>2</sub> as a function of the Ne pressure with the Kr pressure as a parameter. The F<sub>2</sub> pressure is 10 mbar and the Ar pressure is 490 mbar.

#### IV. DISCUSSION OF THE RESULTS

The above-described experiments were performed with Kr, Ar, and Ne as a buffer gas. It was found that the lighter the buffer gas, the higher the maximum extracted energy density is from the *e*-beam, but also that this higher energy is extracted at a higher pressure of the buffer gas. The heavier gas, however, has a large stopping power so that the excitation density per unit pressure is higher. Since there is a balancing process between the excitation of the gas and the losses (quenching and absorption), it is clear that the losses of a lighter gas are much smaller than those of a heavier gas. The experimental results can be used to estimate the quenching parameters of the buffer gases. We proceed as follows. The experiments with the high *e*-beam current density show that the output power is very insensitive to the reflectivity of the outcoupling mirror. For the steady state, which is reached after a few nanoseconds, we have per unit length the condition that the stimulated emission is equal to the outcoupling and absorption losses:

$$\sigma_s I[\text{KrF}] = I(\gamma + \alpha) \quad (1)$$

where  $I$  is the intracavity photon intensity,  $[\text{KrF}]$  is the density of the lasing molecules,  $\gamma$  is the outcoupling per unit length,  $\alpha$  is the absorption per unit length, and  $\sigma_s$  is the cross section for stimulated emission. The production of the inversion density  $P$  depends on the gas pressure and *e*-beam current density. For steady state, we have

$$P = [\text{KrF}] Q + I(\gamma + \alpha) \quad (2)$$

where  $Q$  described the quenching of a lasing molecule per second. The output power per unit length, given by  $\gamma I$ , can be calculated from (1) and (2):

$$\gamma I = \frac{\gamma P}{\gamma + \alpha} - \frac{\gamma}{\sigma_s} = Q. \quad (3)$$

In the case where the output is insensitive to variations of the outcoupling, we have  $\partial/\partial\gamma (I\gamma) \approx 0$ . Using (3), we

obtain

$$\frac{\alpha P}{\gamma + \alpha} = (\gamma + \alpha) \frac{Q}{\sigma_s} \quad (4)$$

Substituting (1) and (2) into (4), we obtain

$$\alpha I = \frac{\gamma}{\gamma + \alpha} Q[\text{KrF}] = \beta Q[\text{KrF}] \quad (5)$$

where  $\beta < 1$ .

The last expression shows that the intracavity absorption is smaller than the quenching.

In order to make an estimate of the quenching parameters of the various buffer gases, we again consider (2) for the optimized high-pressure gas densities. At these pressures, the quenching mainly occurs by three-body collisions which allow the formation of a new species with a large probability of transferring the relatively small excess energy into the translational motion of the colliding particles. The quantity  $Q$  for high pressure can then be expressed as

$$Q_R = k_R [R]^2 \quad (6)$$

where  $k_R$  and  $[R]$  are, respectively, the quenching parameter and the density of the rare gas.

The production term  $P$  is proportional to both gas density and current density  $i$ . This can be expressed as follows:

$$P_R = B_R i [R]. \quad (7)$$

Substituting (5), (6), and (7) into (2), we obtain

$$\gamma I = B_R i [R] - (1 + \beta) [\text{KrF}] k_R [R]^2. \quad (8)$$

For the maximum energy extraction as a function of  $[R]$ , we have

$$\frac{d(\gamma I)}{d[R]} = 0$$

or from (8)

$$B_R i = 2(1 + \beta) [\text{KrF}] k_R [R] \quad (9)$$

where the dependence of  $\beta$  on  $[R]$  is expected to be negligible. The quenching parameter is now given by

$$k_R = \frac{\sigma_s B_R i}{2(2\gamma + \alpha) [R]} \quad (10)$$

where we have used (1).

The pumping rate  $B_R$  can be deduced from the stopping

TABLE I  
QUENCHING CONSTANTS OF Kr, Ar, AND Ne FOR KrF

	$B_R$	$R$ [cm <sup>3</sup> ]	$[\text{cm}^6 \cdot \text{s}^{-1}]$ $k_R$
Kr	111	$5.2 \times 10^{19}$	$4.6 \times 10^{-31}$
Ar	55.5	$1.35 \times 10^{20}$	$9 \times 10^{-32}$
Ne	28	$3.9 \times 10^{20}$	$1.5 \times 10^{-32}$

power as given by Berger and Seltzer [8]. The values are  $B_{\text{Kr}} = 111$ ,  $B_{\text{Ar}} = 55.5$ , and  $B_{\text{Ne}} = 28 \text{ cm}^2 \cdot \text{A}^{-1} \cdot \text{s}^{-1}$ .

The outcoupling  $\gamma$  for an outcoupling reflectivity of about 10 percent and a length of 20 cm for the active medium is  $5.75 \times 10^{-2} \text{ cm}^{-1}$ . The cross section for stimulated emission is  $\sigma_s = 2.4 \times 10^{-16} \text{ cm}^2$  [9].

The absorption losses  $\alpha$  near the maximum output can be calculated with (4). The optimized values of  $[R]$  can be deduced from the experimental data. The quenching parameter  $k_R$  for the three gases can now be estimated with (10) where the used value of  $[\text{KrF}]$  is obtained from (1). The results are presented in Table I.

To our knowledge, the quenching constants of Kr and Ne are not known in the literature. The three-body quenching of Ar is quoted as  $8 \times 10^{-32} \text{ cm}^6 \cdot \text{s}^{-1}$  [10], which is in good agreement with our results.

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