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Intrinsic Efficiency and Critical Power Deposition in the *e*-Beam Sustained Ar : Xe Laser

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Abstract. Experimental investigations on an *e*-beam sustained near infrared Ar : Xe laser have been carried out to determine the intrinsic efficiency at optimized conditions. A parametric study at different sustainer currents reveals a maximum output energy depending on current density. Up to 8 bar the optimized laser output power per unit volume increases linearly with 1.1 MW/l bar. Intrinsic efficiencies of up to about 8% are feasible.

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The near infrared Ar : Xe laser has attracted much interest because this type of laser shows a high intrinsic efficiency and a high specific energy. It uses rare gases for the active medium resulting in a long gas lifetime. The wavelengths due to transitions between the 5*d* and 6*p* levels of Xe are between 1.73 and 3.51 μm and are short compared to that of a CO_2 laser. There is no gas dissociation and no thermal population of the lower laser level so that cooling provisions are less critical. In this paper results will be presented from measurements on an *e*-beam sustained electrical discharge Ar : Xe laser.

This technique has been successfully applied in the past for excimer laser studies [1] and for the Ar : Xe laser [2–4]. It uses the *e*-beam both to ionize the medium and to maintain the stability of the discharge. The sustainer discharge ionizes the xenon atoms again from the metastable (6*s*) state. In this way the system works as a four-level system with the metastable state as the ground state in the excitation scheme. The *e*-beam excitation from the atomic ground state assures sufficient replenishment for metastable atoms that are quenched to the ground state.

In the present studies we investigated the optimum conditions with respect to efficiency and laser output as a function of experimental parameters such as gas pressure and current densities of *e*-beam and sustainer.

1. Experimental Configuration

The experiments are carried out using an *e*-beam sustained electrical discharge laser head. A cross-sectional view of the laser is given in Fig. 1. The *e*-beam enters the active volume through a $5 \times 55\,\mathrm{cm}^2$ window made of a 25 μm titanium foil supported by a Hibachi structure. We used in our studies two different *e*-beam parameters. One *e*-beam has a peak electron energy of 90 keV, a maximum current density of $40\,\mathrm{mA/cm}^2$ and a pulse duration of 0.8 μs after passing the foil. The other one has a peak energy of 180 keV, a current density of $120\,\mathrm{mA/cm}^2$ and

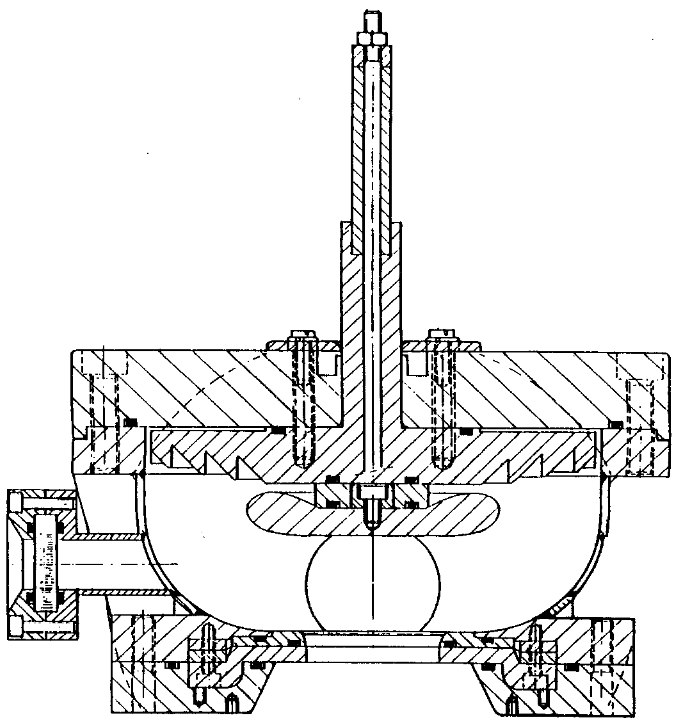

Fig. 1. Cross-section of the laser head

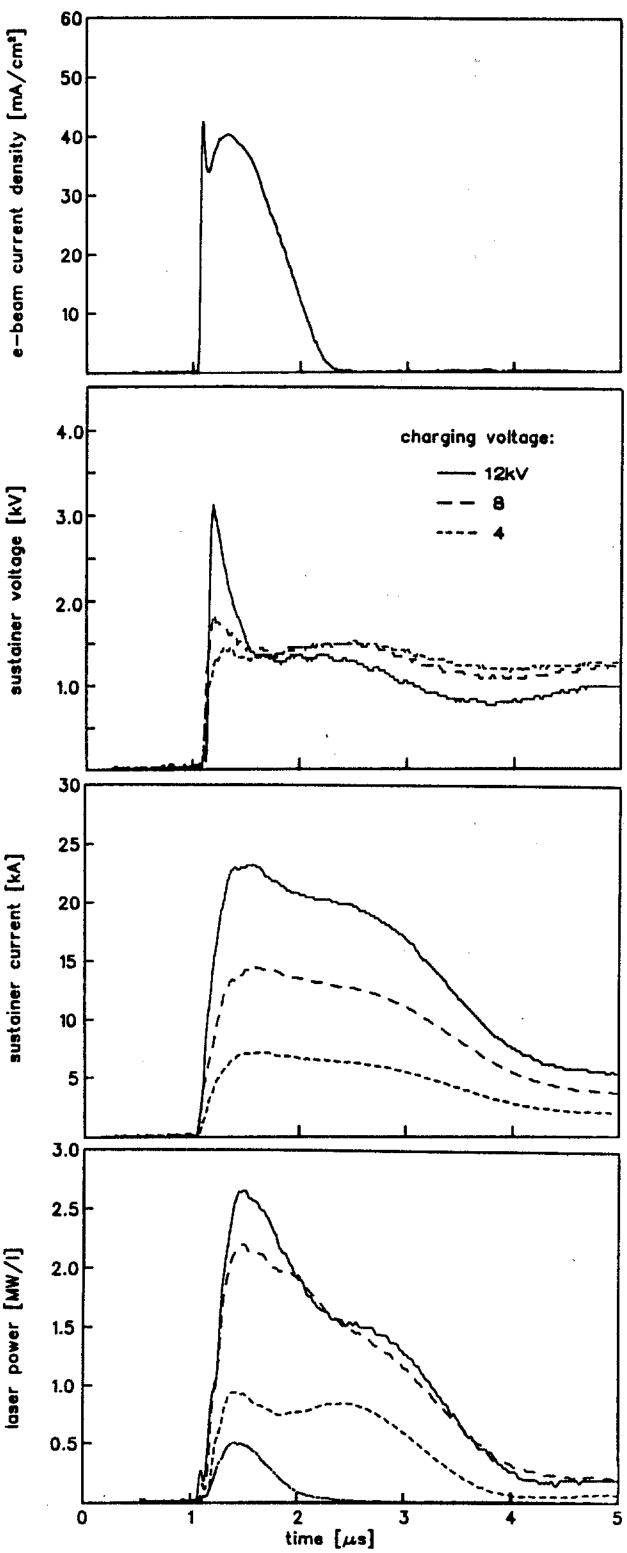

Fig. 2. Typical shapes of the e-beam current, the sustainer voltage, the sustainer current and the laser output power ($p = 4\,\mathrm{bar}$, $R_s = 0.36\,\Omega$, $C_s = 5.4\,\mu\mathrm{F}$ and e-beam: 90 keV)

a duration of 1.1 µs. The active volume is 0.33 l and can be filled with gas at a total gas pressure up to 8 bar. Since it was found that for an Ar : Xe gas mixture the output energy has a broad maximum around 0.4% of Xe, all studies were carried out with 0.4% Xe in Ar.

The optical cavity consists of one total reflecting gold mirror with radius of curvature of 2 m and one flat ZnSe output coupler with 50% reflectance. The aperture is 5.9 cm^2. The electrical discharge circuit consists of a capacitor C_s connected in series with a sodium-chloride solution resistor R_s. By changing the charging voltage or by changing R_s and/or C_s the discharge conditions and the amount of power deposition can be varied. The sustainer capacitor C_s is switched to the electrode by two spark gaps operating in parallel. In this way the self-inductance of the discharge circuit is kept around 100 nH. The spark gaps are triggered by a 100 kV pulse with a 2 ns rise time, which is generated by a small coaxially shaped mini-marx generator. The electrical discharge electrode with a length of 60 cm is shaped according to an Ernst profile [5]. The distance of the electrode to the foil is 2 cm.

Typical waveforms of the e-beam current, the sustainer electrode voltage, the sustainer current and laser power are given in Fig. 2. These waveforms are obtained with the 90 keV e-beam and a sustainer setup with $R_s = 0.36\,\Omega$ and $C_s = 5.4\,\mu\mathrm{F}$ at a total gas pressure of 4 bar. Self-regulation of the voltage between the electrodes to a more-or-less steady state value of a glow discharge is observed during the e-beam current. The corresponding electrical field in this steady state given by E/p is found to be $0.2\,\mathrm{V\,cm^{-1}\,Torr^{-1}}$. It is seen that during the e-beam the output is much higher than after its termination. Furthermore the output power more or less follows the e-beam. After the e-beam has ended the output follows the sustainer pulse at a reduced level. Laser action is most efficient when both e-beam current and discharge current are present simultaneously. Since the discharge voltage between the electrodes does not change as a function of time the output is apparently limited by the sustainer current density.

Time evolutions of the sustainer voltage, current and laser power are measured with a Philips PM 3350 digitizer. The laser power is detected by a uncooled InSb ORP-10 photodiode with a risetime of 100 ns.

Total laser energy is measured with an ED 500 Gentec Joule meter. As the photodiode waveform is proportional to the laser power, integration of the ORP-10 output yields the laser energy, apart from a calibration factor. This factor is found by comparing the integrated ORP-10 output to the Gentec reading. In this way our ORP-10 output is calibrated in Watts.

2. Experimental Results

Below a total gas pressure of 3 bar the discharge impedance is very low. This resulted in a ringing discharge in our system with $R_s = 0.10\,\Omega$. In such a ringing discharge lasing occurred only at the zero-crossing points of the discharge current. At a total gas pressure of 4 bar a maximum output energy of 1.3 J was found. When the 180 keV e-beam was used the output energy was 1.8 J at 4 bar and increased to 3.2 J at the highest pressure of 8 bar under optimized discharge conditions.

In Fig. 3 the laser output energy is plotted against the charging voltage of the sustainer capacitor for two discharge configurations. A constant part of the output energy results from direct e-beam excitation, the remainder of the energy results from the sustainer discharge. The contribution of the 180 keV e-beam to the laser en-

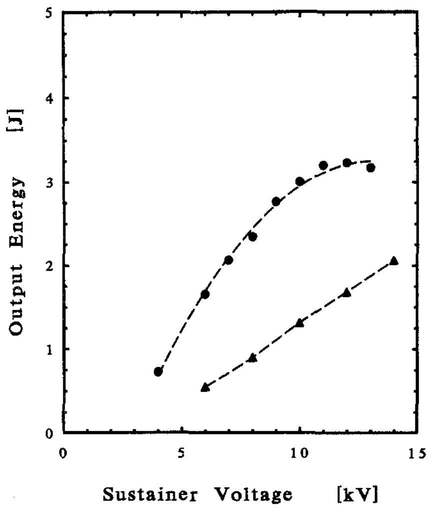

Fig. 3. Laser output energy as a function of the sustainer voltage at $p = 8$ bar and with $R_s = 0.10\,\Omega$. (▲: $C_s = 1.8\,\mu F$; •: $C_s = 5.4\,\mu F$; 180 keV *e*-beam)

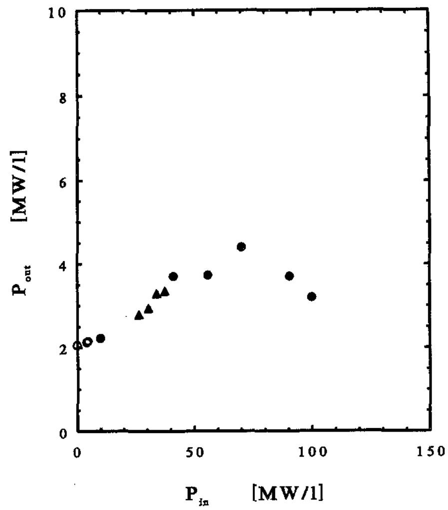

Fig. 4. Laser output power vs input power at $p = 4$ bar and with a 180 keV *e*-beam. (○: $R_s = 1.0\,\Omega$, $C_s = 5.4\,\mu F$; •: $R_s = 0.10\,\Omega$, $C_s = 5.4\,\mu F$; ▲: $R_s = 0.36\,\Omega$, $C_s = 5.4\,\mu F$)

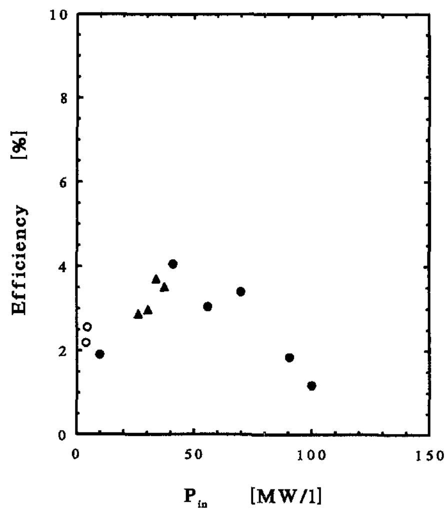

Fig. 5. Intrinsic efficiency as a function of the input power (see text)

ergy is relatively low and about 0.2 J at a pressure of 8 bar. With increasing charging voltage of the sustainer capacitor the output energy increases showing that the discharge electrons contribute to the laser action. A maximum specific output energy of 10 Jl^{-1} is obtained for $R_s = 0.1\,\Omega$, $C_s = 5.4\,\mu F$ and 12 kV charging voltage. Under these conditions higher charging voltages result in less output. The output energy is 1% of the energy stored in the sustainer capacitor. This low efficiency is due to the dissipation in the resistor R_s and to the mismatch between the duration of the *e*-beam current (1.1 µs FWHM) and that of the discharge current (1/e time is 2.4 µs).

From the above-described experiments it is observed that the presence of the *e*-beam is essential for obtaining efficient laser action. During the *e*-beam pulses with respective durations of 0.8 and 1.1 µs the laser process seems to be quasi stationary. This is in agreement with observations described in [3]. It is also observed that the output reaches a maximum as a function of the current density. Increasing the current density further causes a decrease in the output energy. At the same voltage and total gas pressure the current density is directly related to the power deposition. The optimum current density is in this way related to the so called critical power deposition. It is found that this critical power deposition increases linearly with the total gas pressure. The best performance is thus obtained in a configuration for which the *e*-beam coincides with a sustainer pulse of constant current density at the optimized value with respect to current and gas density. These values of the optimized parameters can be deduced from the present experiments.

3. Discussion

For each experiment we now consider only that part of the pulse for which the *e*-beam is more or less constant, i.e. we do our measurements during an interval of 0.25 µs starting 0.4 µs after the onset of the *e*-beam pulse. In this interval the laser power is maximum and easily calculated from the ORP-10 photodiode waveform. For each combination of charging voltage, R_s and C_s, the electrical input power and the optical output power can be obtained in this way. The results are plotted in Fig. 4 for a total gas pressure of 4 bar and an *e*-beam energy of 180 keV. The figure shows that there is a point of critical power deposition (≈ 70 MW/l) which is independent of the sustainer parameters.

The intrinsic efficiency (which is the quotient of the laser power and the power deposited by the sustainer in this 0.25 µs interval) can be calculated directly from Fig. 4. The result is shown in Fig. 5. It is seen from Fig. 4 that for a pressure of 4 bar the maximum power is obtained at the critical power deposition of about 70 MW/l. At this critical power deposition the intrinsic efficiency is slightly less than its optimum value of 4.1% but the maximum output power is produced for this critical power deposition.

In Figs. 6 and 7 we plotted similar results obtained with a 180 keV *e*-beam at a total laser gas pressure of 8 bar. It is seen that an intrinsic efficiency of 8% can be achieved and that the critical power deposition has increased considerably. At 8 bar the critical power deposition is 130 MW/l and the maximum output power

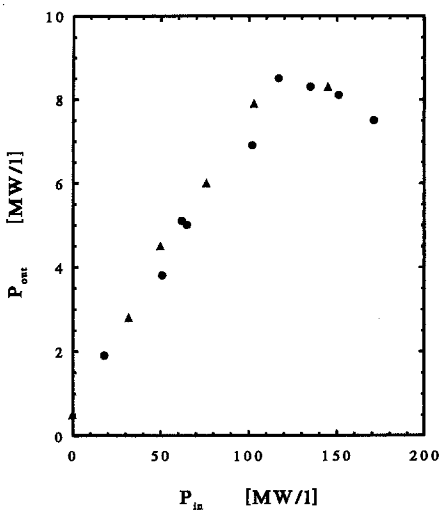

Fig. 6. Laser output power vs input power at $p = 8$ bar and with a 180 keV *e*-beam. (▲: $R_s = 0.10\,\Omega$, $C_s = 1.8\,\mu F$; •: $R_s = 0.10\,\Omega$, $C_s = 5.4\,\mu F$)

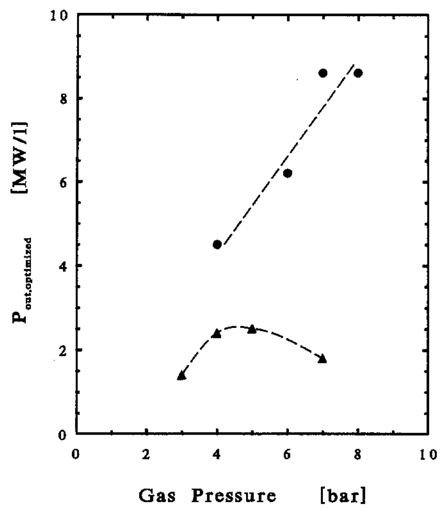

Fig. 8. Optimized output power as a function of total gas pressure (▲: 90 keV *e*-beam; •: 180 keV *e*-beam)

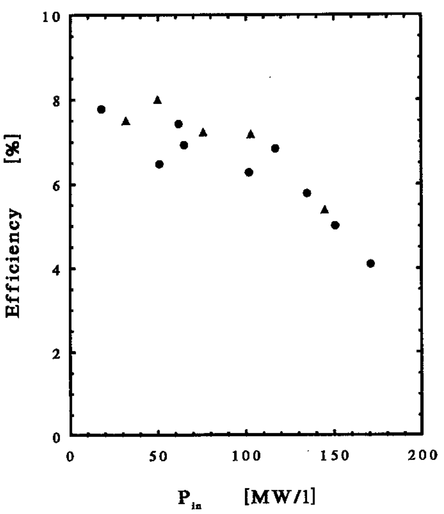

Fig. 7. Intrinsic efficiency vs input power as derived from Fig. 6

8.5 MW/l. Note that Figs. 3 and 6 represent the same experimental conditions. Two totally different discharge conditions lead to two separate lines in Fig. 3. But when input power and output power are computed (in a 0.25 µs interval) all measured data form one curve as can be seen in Fig. 6.

We observed that in a pressure range of 3–8 bar the critical power deposition is proportional to the gas density. The optimized extracted power density as a function of gas pressure is plotted in Fig. 8. We see a linear increase with pressure up to 8 bar for the 180 keV *e*-beam. The values for the 90 keV *e*-beam saturate and decrease above a total gas pressure of 5 bar due to the insufficient penetrating power of the electron beam.

We also observed that the output reached a maximum with increasing current density. This phenomenon may be attributed to the so called electron collision mixing process. It was pointed out by Ohwa et al. [6] in a theoretical analysis that a high electron density may cause a strong coupling between the 5*d* and 6*p* levels of Xe and in this way quench the laser process. This fact is reflected in the occurrence of the critical power deposition. Increasing the current density (electron density) above this critical value this electron collision mixing effect causes a decrease in the laser output power as observed in our measurements.

By increasing the gas density at constant current density the production rate of the upper laser level density increases so that the fractional losses by electron collision mixing are relatively lower. This means that the optimized current density will increase with the gas density in agreement with our measurements.

4. Conclusion

An experimental analysis of the *e*-beam sustained Ar : Xe laser has shown that an intrinsic efficiency of 8–9% is feasible for a system having an *e*-beam pulse duration that coincides with a sustainer pulse of constant current at the critical power deposition. This critical power deposition of 13 MW/l bar is proportional to the gas density. An optimized output power of 1.1 MW/l bar is obtained.

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