Low-energy pumping of a 108.9-nm xenon Auger laser

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We report extensive measurements of gain in the Xe III system initially observed by Kapteyn *et al.* [Phys. Rev. Lett. 57, 2939 (1986)]. The dependence of this gain on pressure, pumping-pulse length, and pump energy is presented. By optimizing these parameters we have achieved a gain of exp(3.2) by using only 0.56 J of 1064-nm energy on target, representing an efficiency improvement of nearly 100. Total gains as high as exp(6.6) have been measured when using higher energies. Our data indicate that effective laser-produced plasmas can be created with applied power densities as low as 5×10^{10} W cm^{-2}.

Kapteyn *et al.*[1] recently reported the first observation of gain at 108.9 nm in Xe^{2+} pumped by incoherent x rays from a laser-produced plasma. Total gains of exp(3.6) were measured using a natural isotopic mix of Xe. We have studied the dependence of this gain on pressure, pumping-pulse length, and pump energy. By optimizing these parameters we have achieved a gain of exp(3.2) using only 0.56 J of 1064-nm energy on target. This represents an efficiency improvement of nearly 100 over that of Ref. 1. Using higher energies, we have measured total gains as large as exp(6.6).

The key to this optimization is the discovery that laser-produced plasmas can efficiently produce the required ~75-eV incoherent pumping x rays even when the applied laser power density is only 5×10^{10} W cm^{-2}. Thus moderate-energy lasers can be used to create a line plasma of significant length. In addition, the gain region can be located close to the target without exceeding reasonable pumping flux densities. This geometry can increase the aspect ratio and reduce the effects of amplified spontaneous emission[1] (ASE); in addition, higher pressures can be used efficiently to stop the pumping x rays in the region of interest.

Parameters of the relevant Xe levels have been reported[2]; a simplified energy-level diagram is shown in Fig. 1. Soft x rays emitted by the laser-produced plasma photoionize a $4d$ inner shell electron of neutral Xe, producing a Xe^+ $4d^95s5p^6\ {}^2D_{3/2,5/2}$ population. Rapid Auger decay produces a population inversion between the Xe^{2+} $5s^05p^6\ {}^1S_0$ and the Xe^{2+} $5s^15p^5\ {}^1P_1$ levels. The calculated Auger yield to the upper laser level is 5%, and the gain cross section is 3×10^{-13} cm^2.

Our experimental configuration is similar to that of Ref. 1 and is shown in Fig. 2. The 1064-nm plasma-producing laser is focused by a 30-cm focal-length cylindrical lens onto a solid Ta target in the Xe cell. The focal spot is a line 30 mm long by ~100 μm wide, as determined by measuring the resulting target pits. A 2 mm × 2 mm U-shaped channel and an aperture determine the pumped region observed by the detection system. The channel is positioned 2 mm from and parallel to the target, and thus the target surface effectively forms the fourth side of the channel. The detection system consists of a 1-m normal-incidence vacuum spectrometer with a microchannel plate detector having a rise time of 350 psec. A 1-mm-thick LiF window separates the Xe chamber from the spectrometer.

The length of the open side of the channel is limited to 28 mm by fixed shields in order to minimize end effects. In addition, three equal-length movable shields permit us to vary the length of the pumped region without varying the properties of the plasma pumping source. Measurements of the 108.9-nm output energy as a function of length were used to determine gain: the frequency-integrated superfluorescence output energy can be approximated as[3]

$$E \propto \frac{[\exp(\alpha l) - 1]^{3/2}}{[\alpha l \exp(\alpha l)]^{1/2}}, \qquad (1)$$

where α is the gain per unit length and l is length. The points in Fig. 3 are measured values of 108.9-nm energy, and the curve is the best fit of relation (1) to those points. In this case the fit indicates $\alpha = 2.36$ cm^{-1} and a total gain of exp(6.6). This curve-fitting method was used to determine all the gain values presented here. This technique, the slow time response of the

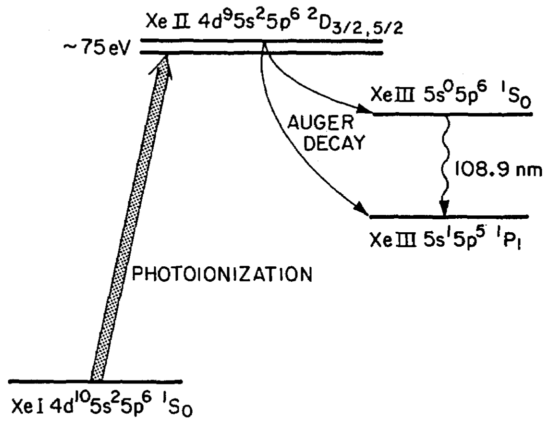

Fig. 1. Simplified energy-level diagram of Xe.

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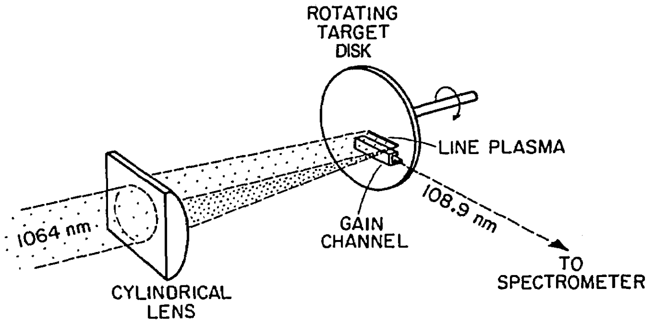

Fig. 2. Schematic of the experimental configuration. Not shown are the aperture limiting the field of view of the spectrometer to the volume inside the channel and the shields used to vary the active length.

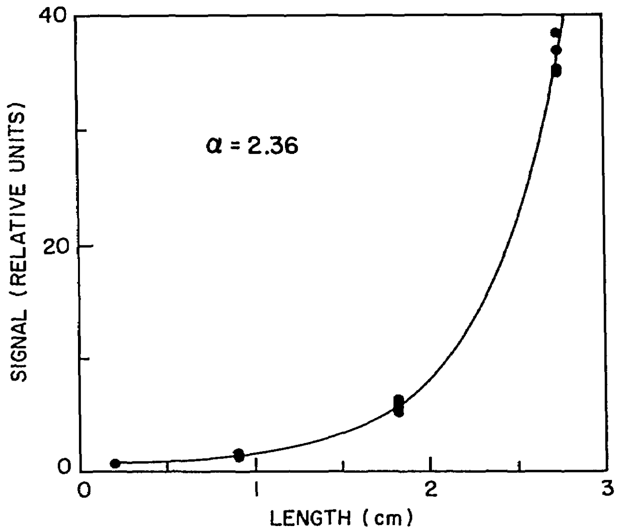

Fig. 3. Output energy at 108.9 nm as a function of pumped length for a plasma-producing laser energy of 10 J in a 600 psec pulse length at 2.5-Torr Xe pressure. The points are measured values; the curve is a plot of relation (1) with $\alpha = 2.36$.

detector, and shot-to-shot variations in pumping intensity combine to limit our minimum detectable gain to $\alpha \sim 0.5\ \mathrm{cm}^{-1}$.

Ideally, total gain is proportional to the product of active length, pumping flux, and Xe density, but a number of processes can interact to limit the gain. We have measured the gain under a wide range of conditions in order to determine the optimum conditions. Figure 4 shows α versus pressure for two pulse lengths at constant laser power density on target. There is an optimum pressure for a given pulse length, and the optimum pressure is higher for the shorter pulse. This indicates that electron quenching and/or Stark broadening may be important since raising the pressure increases not only the excited-state density but also the electron density. (Reduction of the pumping flux by absorption before it reaches the active region is unimportant in our geometry.) The observed increase, however, is somewhat less than the factor of 3 expected from these effects.

Figure 5 plots gain as a function of laser energy for a 600-psec pulse length. It is evident that some process is acting to limit the gain to $\alpha \approx 2.3$ at high energies. Faster electron quenching at the higher pumping flux densities, parasitic ASE, Stark broadening, or a combination is likely. At the other end of the scale, the gain decreases faster than linear between the 2- and 1-J data points. This indicates that the laser-produced plasma at the lowest applied power density is less effective in pumping the system because of a lower radiating efficiency and/or because of a shift in spectrum. The 1064-nm power density at this point is $5 \times 10^{10}\ \mathrm{W\ cm}^{-2}$, 20 times lower than used previously.[1] If we assume that the plasma is a blackbody we can estimate its temperature from our measured gains by using the parameters of the Xe system. This yields a

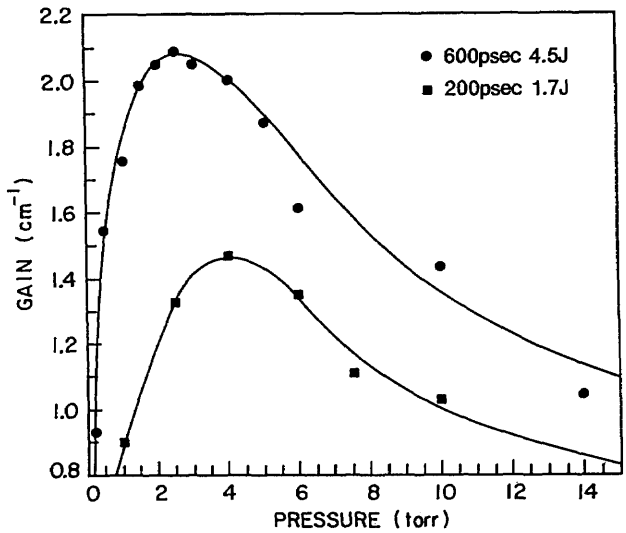

Fig. 4. Gain coefficient as a function of pressure for excitation pulse lengths of 200 and 600 psec; the laser power density on target is about $1.4 \times 10^{11}\ \mathrm{W\ cm}^{-2}$ in both cases.

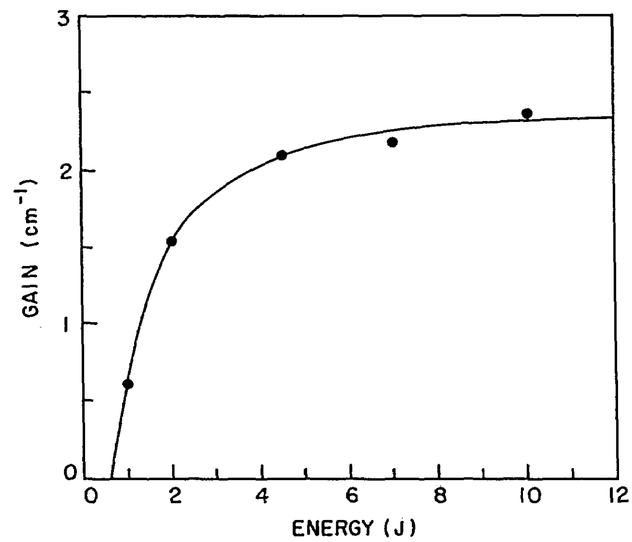

Fig. 5. Gain coefficient as a function of 1064-nm laser energy on target; the pulse length was 600 psec and the pressure was 2.5 Torr.

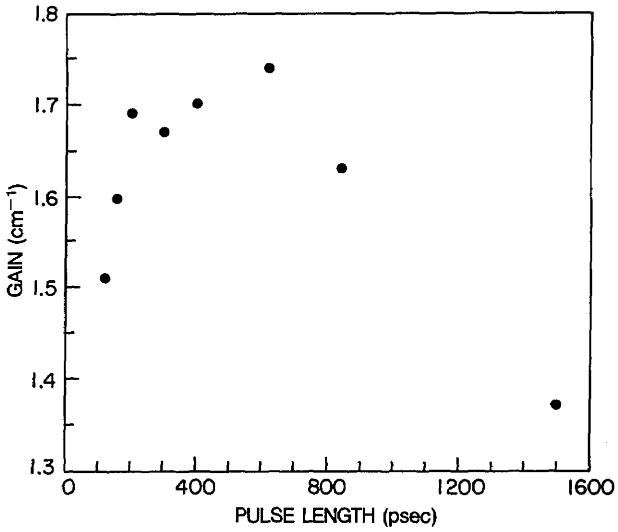

Fig. 6. Gain as a function of pulse length for a constant energy of 2.5 J and 4-Torr Xe pressure.

temperature of ~16 eV at an applied power density of 5×10^{10} W cm^{-2} and a corresponding conversion efficiency of about 5% from laser to incoherent x-ray energy.

Because of the decreasing effectiveness of a plasma produced by low applied power densities, further reductions in energy can be made only by decreasing the pulse length. Figure 6 shows the gain as a function of pulse length for constant energy. At short pulse lengths the gain falls because the transit time along the channel exceeds the excitation time. For pulse lengths greater than 800 psec the gain is also reduced, probably for two reasons. First, the power density on target at 800 psec is 5×10^{10} W cm^{-2}; as seen above, at this value the plasma is probably becoming less effective in pumping the system. Second, 800 psec is comparable with the effective lifetime of the upper laser level at these gains.

Gain measurements were made using isotopically enriched Xe (84% ^{136}Xe). Gain increases of only ~10% were observed, even under low-gain conditions where ASE limiting was not a problem.

This work is the first reported demonstration of the predictions of Mendelsohn and Harris[4] and of Walker *et al.*[5] that Auger lasers could be constructed using only several joules of laser pumping energy.

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