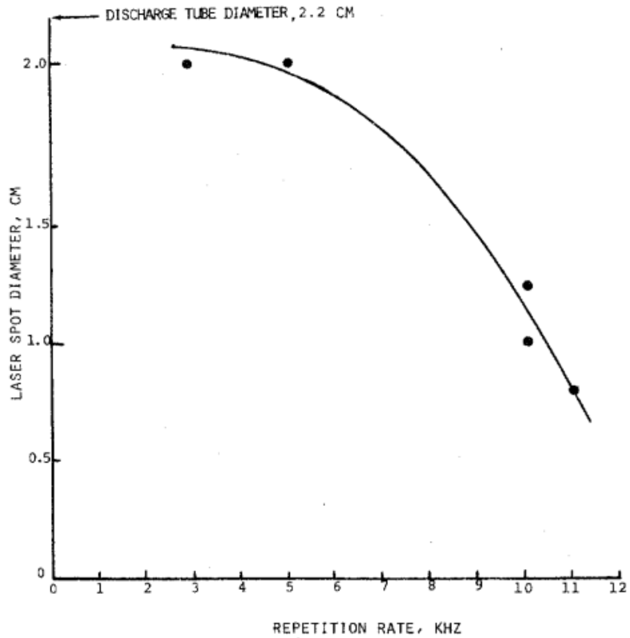

Fig. 2. Contraction of laser spot with increased repetition rate.

copper where a toroidal beam distribution can be found, particularly near threshold, but never a reduced spot diameter. Evidently, the molecular source of the free copper atoms must be involved in producing the reduced diameter. We suggest that at low (400°C) temperatures recombination takes place most rapidly near the wall, causing the reduced beam diameter when the interpulse period grows comparable to the recombination time. This effect is enhanced because the temperature on the axis can be substantially hotter than the walls [13], and thus the dissociation rate will be greater on the axis than near the walls. This should result in much higher copper density and laser intensity on the axis, as long as the interpulse period is significantly shorter than the time required for diffusion to allow free copper atoms to reach the wall and recombine.

IV. Summary

These results show that steady-state discharge-heated radiation-cooled laser operation can be maintained for hours with both copper chloride and copper iodide lasants. This operation, in contrast to other reports, can be maintained at tube temperatures up to 800°C. Furthermore, there are conditions which cause substantial reduction in the beam diameter. It is suggested that this is related to enhanced dissociation of the copper halide on the tube axis and recombination at the wall.

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Avalanche Initiating Electron Produced by Laser-Induced Tunneling

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***Abstract*—We have been able to eliminate all extrinsic sources of avalanche initiating electrons in ultrapure N_2 and He gas. Plasma formation is therefore inhibited until the laser intensity grows high enough to produce tunnel ionization of a molecule in the focal volume. This permits a record CO_2 laser intensity, as high as 10^{13} W/cm^2 in a high-pressure gaseous target. For the first time the electron tunneling limit has been approached in a dense medium.**

There has been great interest [1] recently in the tunnel limit of laser ionization. At sufficiently low frequency ω and high field strength $\mathcal{E}$, the ionization is best described [2] as a tunnel effect rather than a multiphoton ionization. The parameter γ separates the two regimes:

$$\gamma = \frac{\omega \sqrt{2mE_0}}{e\mathcal{E}}.$$

For $\gamma < 1$, the zero frequency description, electron tunneling is most appropriate. For $\gamma > 1$ the multiphoton ionization picture is more suitable.

In practice, for gas pressures above [3] a few torr the plasma formation occurs by impact ionization rather than by the direct action of the light field as described above. Impact ionization leads directly to an avalanche [4], but it relies on the presence of a free electron in the focal volume to initiate [5] that avalanche. Therefore, plasma formation requires *both* an initiating electron and a fast avalanche growth rate.

Unless special precautions are taken, there will always be a small density of free or readily ionizable electrons in a gas. The threshold intensity which is usually measured, I_{th}^{aval}, is that which produces a fast enough avalanche growth rate [4] during the laser pulse duration. If the gas is very pure, however, there may be no extrinsic sources of avalanche initiating electrons [5], and the measured threshold, I_{th}, is that which is required to produce the initial free electron. In general, I_{th} may be much greater than I_{th}^{aval}.

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By using the ultraclean boil-off vapors of cryogenic liquids, we have raised the threshold intensity for plasma formation to I_{th}^{tunnel}, the intensity required to ionize the initial electron by tunneling [2]. $I_{th}^{tunnel} \approx 10^{13}$ W/cm², which exceeds the avalanche threshold I_{th}^{aval} by as much as four orders of magnitude, depending on the gas pressure [4].

These threshold intensities are particularly important for laser plasma interaction in a gaseous target. The interaction intensity cannot simply be raised by arbitrarily increasing the power output of the laser. In fact it can never exceed I_{th}, the intensity at which the plasma first forms. Further increase in laser intensity merely causes the ionization front [6] to move backward along the laser beam to a point where the intensity is $\leqslant I_{th}$. Since we have now raised I_{th} to $\approx 10^{13}$ W/cm², it becomes reasonable to consider gaseous targets for laser compression applications [7].

A description of the experiment is shown in Fig. 1. The laser source was an oscillator-amplifier system [8] which used optical free induction decay [9] to generate ultrashort CO_2 laser pulses. The output was a diffraction limited beam of 0.1 J and 500-ps duration. It was focused by an $f/1$, two-element germanium lens [10] well corrected for spherical aberration. The focal region was imaged by a second identical lens onto a graphite covered index card placed several meters away.

The gas in the focal volume comes directly from a liquid nitrogen or liquid helium Dewar. A small 30-W heater mounted at the tip of a hard copper tube provides the boil-off vapor. The ultraclean gas flows through a 3/8-in OD soft copper tube, warming up before entering the focal region. Most of the experiments were conducted at 1 atm, but some additional experiments were done in a gas cell [11] at pressures as high as 100 atm. Also some work was done with 100-ns-long CO_2 laser pulses with results similar to those reported below.

The purpose of imaging the focal volume with a second lens was to check the spherical aberrations and to ensure that no nonlinear beam distortion was occurring. It is well known that the spherical aberrations of two lenses in series will add. Therefore, the image quality of the second recollimating lens is a conservative measure of the spherical distortion of each lens individually. It was found that the spherical aberration satisfied the manufacturer's specification, which claimed a focal spot size only 17 μ in diameter. In addition, no nonlinear beam distortion was observed up to the instant of plasma formation.

A variable-thickness CaF_2 attenuator adjusted the intensity for a 50 percent probability of plasma formation. The threshold was very sharp, since a 30 percent increase in the incident intensity would raise the breakdown probability from 0 percent to 100 percent. We define the threshold as the intensity at which the breakdown probability was 50 percent. Measured at the center of the focal volume, this turned out to be 10^{13} W/cm², and was the same in both N_2 gas and He gas. This is the threshold intensity for producing an initiating electron, since I_{th}^{aval} is orders of magnitude less [4] than 10^{13} W/cm².

The ionization rate due to the tunnel effect [2] may be written as:

$$W_0 \approx \frac{\sqrt{6\pi}}{4}\,\omega\left(\frac{\sqrt{2}\,N}{\gamma}\right)^{1/2} \exp\left\{-\frac{4}{3}N\gamma\left(1-\frac{\gamma^2}{10}\right)\right\} \tag{1}$$

where $N = E_0/\hbar\omega$. To produce a single electron in 10^{-9} s in a focal volume containing 10^{11} molecules, we require an ionization rate of $W_0 \approx 10^{-2}$/s. The exponent in (1) can be estimated quite accurately with only a crude determination for the prefactor and the ionization rate. We find that

$$\frac{4}{3}N\gamma\left(1-\frac{\gamma^2}{10}\right) \approx 40 \tag{2}$$

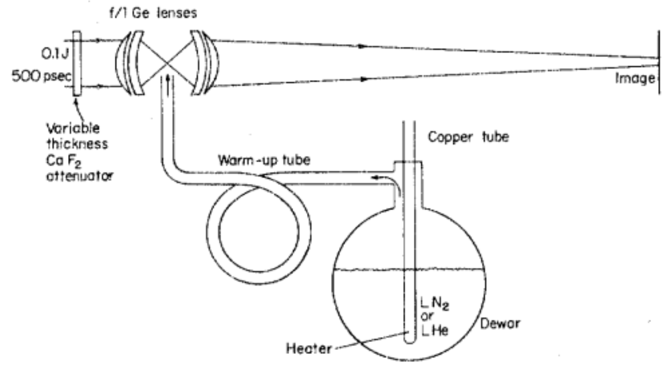

Fig. 1. The experimental layout. The focal region was imaged with a second lens as a check on the spherical correction of the lenses. The ultrahigh purity of the boil-off vapors inhibited plasma formation below 10^{13} W/cm².

is the appropriate threshold condition. In the tunneling limit $\gamma \ll 1$, and so the small correction factor $\gamma^2/10$ may be dropped from (2). Finally, the peak electric field threshold reduces to

$$\mathcal{E} = \frac{\sqrt{2m\,E_0}\,E_0}{30\,e\hbar}. \tag{3}$$

For an ionization potential $E_0 = 13.5$ eV, the electric field is 8.5×10^7 V/cm, corresponding to a laser intensity of 10^{13} W/cm².

The effective ionization potential $E_0 = 13.5$ eV matches well with the ionization potential [12] of the N_2 molecules, 15 eV. The small difference is probably accounted for by the fact that the derivation of (1) made no allowance for the bound excited states of N_2. Under these experimental conditions γ was approximately 0.25, placing us squarely in the low-frequency tunneling limit.

A further effort was made to purify the boil-off vapors. The gas was flowed through a small dc electric field designed to sweep out charged ions, if any. Also it was flowed through a zeolite cold trap to remove any lower vapor pressure molecules. Neither technique had any further influence on the plasma formation threshold, beyond 10^{13} W/cm².

The threshold intensity measured for He gas was the same as that measured for nitrogen, this, in spite of its higher ionization potential, 24.6 eV. The explanation, we feel, is that the He gas is inevitably contaminated with a very small amount of air outgassed from the connecting lines. Tunnel ionization of one of the air molecules probably provided the avalanche initiating electron.

In conclusion, a record intensity, 10^{13} W/cm² has been achieved in high-pressure gaseous laser targets. The boil-off vapors of cryogenic liquids provide the necessary degree of purity. The maximum intensity is then limited by intrinsic tunnel ionization, an effect which cannot be avoided. On the other hand, 10^{13} W/cm² is sufficiently high that high-pressure gaseous targets may now be regarded as serious candidates for laser compression and fusion applications [7].

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