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Beam characteristics of a large-bore copper laser with a radiatively cooled plasma*

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ABSTRACT

In a large-bore copper vapor laser (CVL), excessive gas heating at the axial region of the discharge lowers its efficiency by thermally populating the metastable lower laser levels. The associated lower gas density also lengthens the discharge field-diffusion time, leading to weaker axial pumping and undesired beam characteristics. Our Laboratory has developed a novel approach to circumvent this obstacle by cooling the plasma radiatively via a series of segmented metal plates (septa) placed vertically along the length of the tube. This improved tube design significantly lowers the average gas temperature and shortens the radial delay. A 27% increase in laser power was observed with the addition of septa. We have characterized the beam intensity profile, spatial and temporal pulse variation, and beam polarization through extensive laboratory measurements. A detailed computational model of the laser has been used to characterize and interpret the laboratory results.

1. INTRODUCTION

Because of the expanding applications of copper lasers, there has been considerable effort directed towards improving their performance. Volumetric scaling for higher laser power can be attempted either by lengthening the discharge tube or by increasing the tube diameter. Length scaling, however, is limited by high voltage constraints and pulsed power technology. Attempts to scale in diameter are limited by excessive central gas heating, which degrades the laser efficiency by thermally populating the metastable lower laser levels ($^2D_{3/2}$ and $^2D_{5/2}$ states).¹ In addition, the decreased central gas density lowers the plasma impedance, thus lengthening the time for the discharge field to diffuse to the center. This leads to insufficient axial pumping and a nonuniform beam profile.

To circumvent these problems, we have developed a new method for improving laser performance. In this approach, a number of segmented metal plates (septa) are placed vertically along the length of the tube. The decreased gas temperature associated with the septa plays two beneficial roles. First, the prepulse electron temperature is allowed to equilibrate to a lower value, thus lowering the prepulse metastable densities. Second, the increased gas density gives rise to an increased discharge impedance. This is manifested, for example, in a shorter radial delay in field penetration and a better coupling between the laser head and the pulse power modulator.

Working with an 8 cm bore laser containing neon buffer gas, we have made extensive measurements of its output power, beam intensity profile (spatial and temporal variation), radial delay and polarization. Comparison is also made with the results obtained in a similar laser without septa. We have used a detailed computational model of the laser, which includes kinetics, gas heating in the presence of septa, and field diffusion in the laser plasma to anticipate and interpret these results.

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2. GAS TEMPERATURE CONSIDERATION

In view of the large thermal inertia of the gas, the gas temperature profile changes little during a pulse. Thus, the temperature distribution T is described by the steady-state heat conduction equation,

$$\nabla \cdot (k \nabla T) = -P \quad (1)$$

with k the conductivity of Ne gas, and P the time-averaged power per unit volume deposited in the gas, given by a sum over momentum transfer collisions between electrons and heavy species. Under the reasonable assumptions of uniform power deposition and uniform wall temperature, one can analytically calculate the temperature profile. The radial temperature distribution without septa was given in Ref. 1. In the presence of septa (S-laser), one solves for the two-dimensional temperature distribution $T(r, \theta)$, after expanding in a Fourier series with respect to θ , the angle with respect to a septum plate. From the solution, one can verify that a radiatively consistent septum temperature would be only a few percent higher than the wall temperature.

Figure 1. Calculated gas temperature profile for both C-laser (without septa) and S-laser (with septa) at a buffer gas pressure of 75 Torr. The tube wall temperature is 1490°C.

The difference between the two cases is illustrated in Fig. 1, which shows calculated radial temperature distributions at 75 Torr buffer gas pressure (Ne with 0.5% H_2), with a power deposition as given by the model (cf. Appendix). The presence of septa lowers the central temperature by about 1370 K. In the case without septa (cylindrical laser or C-laser), our profile calculations agree with the copper ground state density profile measured in the same size laser.² (In this case, the calculated central gas temperature lies some 1300 K below that illustrated in Ref. 1. The main reason for the difference is that our calculated deposition is 0.64 W/cm³ as opposed to 1 W/cm³ used there. Our deposited ohmic power is 0.85 W/cm³, of which 0.21 W/cm³ is converted to radiation. Another factor is that our thermal conductivity² is about 40% higher than in Ref. 1.

The effect of gas temperature on field penetration follows from the behavior of the resistivity, as manifested in the field diffusion equations. Neglecting axial gradients, the field components are $B_\theta(r, t)$ and $E_z(r, t)$. The magnetic field diffuses according to

$$\frac{\partial B_\theta}{\partial t} = \frac{\partial E_z}{\partial r}, \quad E_z = \frac{D}{r} \frac{\partial (r B_\theta)}{\partial r}, \quad (2)$$

with diffusion coefficient $D = \rho/\mu_0$, with μ_0 the permeability. The penetration time varies inversely with the resistivity, $\rho = m_e v/c^2 n_e$, with v the electron momentum transfer frequency, n_e the electron density. There is an enhancement of the resistivity due to electron gyro frequency which is proportional to B_0^2 , but it typically is small in this laser. During the pulse, v is dominated by electron-neon collisions and, hence, increases as the gas temperature is lowered. In addition, our simulations show that, during the time of initial field penetration, the electron density is closer to its quiescent value than to its peak value (achieved a few hundred nanoseconds later), and that the latter is not too sensitive to the gas temperature. Since a lower gas temperature gives rise to a lower quiescent electron density, this is another mechanism for raising the resistivity. According to the model, the two effects are of comparable importance.

Figure 2 shows the calculated electric field versus time at three radii, with and without septa, at pressure of 75 Torr. The presence of septa decreases the field penetration time by about 30%, which in turn raises the peak electric field at center by 50% as shown. The ratio of peak electric field at $r = 3.8$ cm to $r = 0.2$ cm also improves from 2.24 to 1.78, leading to a more uniform beam profile.

Figure 2. Calculated electric field versus time, at a buffer gas pressure of 75 Torr; (a) C-laser, (b) S-laser.

3. CONSTRUCTION OF LASER HEAD

The head design of an S-laser is illustrated in Fig. 3. The septa are constructed of axially spaced plates along the length of an 8 cm bore alumina tube. The tube was made with grooves on its top and bottom for holding the segmented septa. Alumina plates have been tried as the septa but cracked very often because of severe thermal stress, especially in the colder region of the plasma tube near the ends. Molybdenum plates, which are properly separated to prevent localized discharge between them, have been successfully used as the septa. Since the electrical field of the discharge is highest at the tube wall because of field diffusion (cf. Fig. 2), the separation between plates needs to be larger at these regions. Septum plates with an egg-shape geometry are therefore used as shown in Fig. 3. Originally, the use of electrically conductive plates in a plasma generated by an axial electric field raised some concern about potentially shorting out of the discharge. In practice, a current path through a septum is not probable since one side of the septum must act as a cathode for electron emission that requires a cathode-fall voltage of a few hundred volts.³ This high-impedance nature of the cathode sheath required for glow discharge effectively reduces the bypass current in the metal plates to a negligible level. We have observed no noticeable difference in laser performance between lasers using alumina or molybdenum septa.

The emissivity ϵ of the septum has some effect on the amount of radiation transferred to the alumina tube, but it makes only a small difference in septum temperature which is very close to the tube wall temperature (with a temperature difference ΔT). Our approximation using radiation view factors shows that ΔT decreases from ~ 70 K to ~ 15 K as ϵ increases from 0.4 (emissivity of molybdenum) to 1. This change is only a few percent of the average gas temperature (~ 2100 K) of an S-laser and its effect on laser performance is very small. The spacing between septa is also minimized for a more efficient radiation coupling between septa and tube. The axial region of the laser plasma is, thus, effectively cooled by the septa, leading to a lower gas temperature and improved laser efficiency.

Figure 3. Schematic of an 8 cm S-laser head with septum plates lined up along the axis of the plasma tube; (a) side view, (b) end view.

4. LASER BEAM CHARACTERISTICS

4.1. Output power

The S-laser head was driven by a pulse modulator with three-stage magnetic compression⁴ that delivered a peak voltage of approximately 40 kV, with a rise time of less than 50 ns. The peak discharge current was measured to be approximately 2.5 kA at the optimized lasing condition. The neon buffer gas was mixed with 0.5% hydrogen to improve the laser efficiency.⁵ To maximize the laser output, the laser was run as an amplifier with a 10 W injection beam.⁶ The pulse width of the injected beam, more than 70 ns, was sufficient to extract the 60 ns amplifier pulse. At a repetition rate of 4.4 kHz, amplifier power extraction measurements were made at a selection of buffer gas pressures. The results are plotted in Fig. 4.

Figure 4. Extracted output power of 8 cm copper laser amplifiers with septa (S-laser) and without septa (C-laser) at various buffer gas pressures.

In this experiment, the optimum laser input power decreases at higher pressures because of increased head impedance. The charging voltage of the storage capacitor (40 nF) was reduced from 19.5 kV at 25 Torr to 16 kV at 100 Torr. Similar power measurements were also made for an 8 cm copper laser without septa (C-laser) as plotted in Fig. 4. The optimized

gas pressure for each case is between 70-80 Torr. At this optimized lasing condition, the extracted laser power increased from 255 W with a C-laser to 325 W with an S-laser, a 27% improvement. A small reduction (~5%) in required input power was also observed when septa were used because of the lower gas temperature that improved coupling between the laser head and the pulse modulator. A laser efficiency of 1.38% was achieved at 75 Torr, based on the energy stored in the initial capacitor.

4.2. Beam intensity profiles

The beam intensity profile of the S-laser output was measured at different pressures with a CCD camera. As illustrated in Fig. 5, the profiles are highly nonuniform at lower pressures but improve dramatically at higher pressures, as also observed in large-bore copper lasers without septa.⁷ The relative beam intensity near the axis, although improved slightly from the case without septa, is still much lower than that at the wall at lower pressures. The use of septa, which bring the axial gas temperature down to that of wall temperature as shown in Fig. 3, does not increase the laser gain of the axial region sufficiently to flatten the beam profile at lower gas pressures. This result illustrates the dominant role of field diffusion in large-bore copper lasers, especially at lower operating gas pressures.

Figure 5. Beam intensity profile of an 8 cm S-laser amplifier at buffer gas pressures of 25, 50, and 100 Torr.

4.3. Radial delay

To examine the effect of a cooler plasma on field diffusion, we measured the radial delay with a fast photo diode placed behind a 1 mm pinhole and positioned at different locations across the amplifier beam. Since the injection beam has a pulse duration that is more than 10 ns longer than the amplifier pulse, proper delay between the injection beam and the amplifier gain was used to optimize the laser output and to diminish the effect of a small radial delay (less than 5 ns) in the injection beam. Figure 6 shows the laser output pulse at different beam locations for gas pressures of 25, 50, and 100 Torr. The reduction in radial delay at higher pressures shown in this figure has been discussed in Ref. 7 and is a result of higher gas density as described by Eq. (2). A comparison of radial delay between lasers with and without septa is plotted in Fig. 7. The smaller radial delay with the use of septa evidently arose from faster field penetration, as illustrated in Fig. 2, and lower population of metastable lower laser levels. Note that we measure the time delay of the optical signal rather than of the electric field. However, our code prediction and lab measurement show similar trends in lowering radial delay when septa are used.

Figure 6. Laser output pulse measured at four different locations across the middle of the beam; 1: at the outer edge, 2: 1 cm from the outer edge, 3: in the middle between the outer edge and the septum, 4: close to the shadow of septa.

Figure 7. Comparison of measured radial delay between an S-laser and a C-laser at various buffer gas pressures.

We measured the S-laser output pulse with an integrating sphere. The pulse temporal profile changed at different gas pressures, with the faster rise times occurring at higher pressures. This is similar to what was observed without septa.⁷ The temporal pulse profile of an S-laser, although similar to that of a C-laser pulse, is actually shortened from 70 ns to about 60 ns because the use of septa improved the field penetration.

4.4. Beam polarization

In some high power CVL applications, such as laser materials processing and second harmonic generation, the polarization state of the beam is essential for efficient use of laser power. In principle, beam polarization of a copper laser amplifier can be easily controlled by the injection beam. Nonetheless, our measurement with a cross polarizer indicates that depolarization occurs within the amplifier. This depolarization typically generates a butterfly pattern after the cross polarizer, as illustrated in Fig. 8. Note that the vertical dark line exists even in the absence of septum plates. The

depolarized signal, although accounting for only about 4% of a single amplifier output, increases through amplification in a three-amplifier chain system, leading to a ~10% beam depolarization at the end of the chain output.

Figure 8. CVL amplifier beam pattern after passing a cross polarizer with laser between the polarizers. The injection beam was vertically polarized. The vertical dark line exists even in the absence of septum plates.

Two mechanisms, namely, stress-induced birefringence in laser windows and Zeeman effect in laser plasma, have been considered as the possible causes of the beam depolarization. The former, mainly due to window heating, was found to be too small to account for the 4% beam depolarization. In addition, the beam depolarization disappeared immediately after the laser discharge was turned off when the laser windows were still under the same stress. Further investigation indicates that the magnetic field established by the high current discharge is sufficiently large to induce substantial depolarization associated with Zeeman effect.⁸ The peak discharge current of the 8 cm CVL, about 2.5 kA, generates a concentric magnetic field in the laser plasma with a peak strength of 125 Gauss. The resulting Zeeman splitting of the laser transition lines leads to different gain coefficients g_{π} and g_{σ} as illustrated in Fig. 9. Consequently, spatially dependent polarization rotation occurs, except along the X and Y axes, where only one gain coefficient is seen by the vertically polarized laser beam. Although this mechanism partly explains the dark cross of the depolarized beam, a more detailed analysis is required to understand the butterfly pattern.

Figure 9. Zeeman splitting of laser gain g and g induced by CVL discharge; B: concentric magnetic field induced by discharge; E: polarization of the injection beam represented by the dash lines.

5. CONCLUSIONS

A new tube design has been introduced to improve the efficiency and beam characteristics of a large-bore copper laser. The use of septum plates cools the plasma and, according to our computations, reduces the peak gas temperature from 2870°C to 2130°C and the average gas temperature from about 2250°C to 1800°C. The decreased gas temperature leads to lower metastable copper populations and to faster field diffusion and, consequently, to more efficient axial pumping. The beam intensity profile, although radially flatter than that of a C-laser, still has a characteristic "V" shape at lower gas pressures associated with field diffusion. The shorter radial delay in an S-laser leads to an output pulse shorter by 10 ns than that in a C-laser. The maximum output power of 325 W, obtained at 75 Torr, represents a 27% improvement over that in a C-laser. This result translates to a laser efficiency of 1.34% based on the energy stored in the initial capacitor. A beam depolarization of 4% was observed in both S-laser and C-laser. It is believed to result from the Zeeman effect in the magnetic field established by the high peak plasma current.

6. APPENDIX

6.1. Summary of CVL model

Briefly, our model contains rate equations for the densities of seven copper species (including the ground state, the two pairs of lasing levels, an aggregate higher excited state, and the copper ion), three neon species, and several species of atomic and molecular hydrogen. There are also equations for the electron temperature and the green and yellow laser intensities. The rate equations contain terms describing all relevant atomic processes. The atomic rates are taken from detailed tabulations of available reaction data and, where necessary, from calculations. The model also follows the radial diffusion of the magnetic field across the discharge and the associated penetration of the electric field. The resistivity is a radially averaged quantity, since the densities and electron temperature are not resolved radially. The steady-state gas temperature profile is computed from the power deposition in the gas. The laser model is driven by a modulator model (See Refs. 9 and 10) which contains a detailed description of the magnetic compression switches. Its predicted waveforms are in satisfactory agreement with experiment.

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