Another regime of operation for a 18.2 nm recombination laser using a capillary-discharged carbon plasma

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Another regime of operation for the significant amplification of C VI H_α radiation in a capillary-discharged carbon plasma is proposed. This suggested regime of operation features the existence of gain at the axis of a capillary, the large gain region (several hundred micrometers in diameter), and the hollow electron density profile for the better guiding of the radiation being amplified. All these features help to overcome the previous problems and favor the high amplification of the radiation. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1406554]

There have been significant efforts which have demonstrated the amplification of extreme ultraviolet (EUV) radiations using high-density and high-temperature plasmas produced by high power lasers irradiation.[1,2] Currently, due to its compactness and efficient energy coupling, a capillary discharge has been used to produce a lasing medium. The amplification due to the lasing action of Ne-like Ar IX($j=0-1$) line at 46.9 nm in a capillary discharge of Ar gas was successfully demonstrated[3] and later led to the saturation of the radiation in a longer gain medium.[4] A true table-top x-lay laser at 46.9 nm is at hand.[5] Shin *et al.* have achieved the gain of C VI H_α radiation at 18.2 nm in a wall-ablated carbon capillary discharge[6] and Wagner[7] has observed the lasing of Li-like O VI $4f-3d(52.0\,\mathrm{nm})$ and $4d-3p(49.8\,\mathrm{nm})$ radiations using an oxygen-filled capillary discharge but in these experiments, the amplification was limited due to either the short gain length[6] or the low gain.[7] The recent observation of an enhancement of C VI H_α radiation in a C_2H_2-filled capillary discharge by Boboc *et al.*[8] was attributed to a guiding effect. The failure in the significant amplification using the electron-collisional recombination pumping scheme (CRPS) in a capillary discharge still demands the further understanding of the dynamics of capillary plasmas including the atomic kinetics.

In this letter, we present another regime of operation for the amplification of C VI H_α radiation in a capillary discharge plasma. The detailed dynamics for the parameter which gives a maximum gain is also discussed. This regime of operation features the existence of gain at the axis of a capillary, the large gain region (several hundred micrometers), and the hollow electron density profile for the better guiding of the radiation being amplified. All these features are advantageous over the previous experiments by Shin *et al.* where the gain region existed around the wall of a capillary, making alignment very difficult, and the nongain region around the center absorbed the lasing radiation, preventing the significant amplification.

Contrary to the Oraevskii's proposal,[9] Lee *et al.* noticed that a rapid adiabatic expansion following a high density and temperature plasma state (pinch) can provide the sufficient cooling for the formation of gain for C VI H_α (18.2 nm) radiation.[10,11] Recombination processes are enhanced in high density plasmas.[12] The enhancement of the recombination rate has to be adequately included and was done in this work since it is critical in a C VI recombination laser that the cooling time should be shorter than the recombination time of C VII–C VI ion.

The one-dimensional Lagrangian magnetohydrodynamic (MHD) code[10] in a cylindrical symmetry, which was developed to study the dynamics of a Z-pinch plasma,[13,14] has been used to evaluate a discharge-produced carbon capillary plasma. This code solves single-fluid and two-temperature MHD equations.[15] During the calculation of MHD, the population densities of ionization stages are also evaluated by a time-dependent ionization balance equation with the collisional-radiative (CR) rate coefficients which include the contributions of excited levels in addition to the direct ground-to-ground process. The populations of the excited levels of C VI ions are calculated using a quasisteady state approximation[16] as a postprocessor of the MHD code. The radiative trapping of the C VI L_α line is included with the escape probability approximation,[17,18] taking into account the Doppler shift caused by a velocity gradient in the radial direction. To account for an anomalous behavior of the opacity, the suggestion by Pert *et al.*[19] is adopted. For the calculation of the gain of C VI H_α (18.2 nm) line, the Doppler broadening[2] is used.

An initial radius (R), initial density (N_o) and external current pulse, $I(t)=I_o\sin(2\pi t/T)$, which can be controlled in real experiments, are adopted as simulation parameters. The simulation has been performed by varying N_o and I_o for two sets of R and T: $T/4=20$ ns, $R=1$ mm and $T/4=100$ ns, $R=2$ mm. The peak current I_o is varied according to the snowplow model,[20] keeping the pinch time to be in the range of $0.5\times T/4-1.5\times T/4$ for different initial densities.

Figure 1(a) shows that the experimental condition for the

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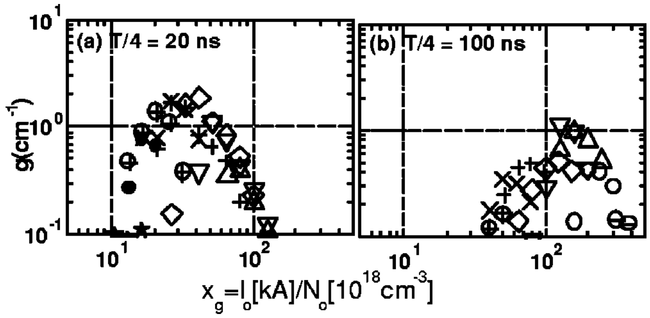

FIG. 1. Gain of C VIH_α(18.2 nm) line is plotted as a function of I_o/N_o with 30% of theoretical optical trapping for the cases of (a) $T/4 = 20$ ns, $R_o = 1$ mm, and (b) $T/4 = 100$ ns, $R_o = 2$ mm. The symbols represent initial densities in $10^{18}\ \mathrm{cm}^{-3}$: (⊖):0.16, (○):0.25, (△):0.40, (▽):0.63, (◇):1.0, +:1.6, (×):2.5, (⊕):4.0, (●):6.3, and (★):10.

amplification of C VI H_α (18.2 nm) line in a capillary discharge has a wide range if a current pulse is as short as $T/4 = 20$ ns. For a current pulse of $T/4 = 20$ ns, the gain larger than $1\ \mathrm{cm}^{-1}$ is achieved for $N_o = 6.3\times10^{17}-4\times10^{18}\ \mathrm{cm}^{-3}$ and $I_o = 12.6-240$ kA with a maximum gain of $2\ \mathrm{cm}^{-1}$ at $N_o = 10^{18}\ \mathrm{cm}^{-3}$ and $I_o = 41.6$ kA. However in the case of $T/4 = 100$ ns [Fig. 1(b)], even though it is possible to achieve a gain as high as $1\ \mathrm{cm}^{-1}$, the condition is severer: larger currents by an order of magnitude are demanded. This is due to the longer cooling time, which approximately depends on the current rising time, $T/4$.

It should be noticed that initial densities in this simulation are higher than in previous capillary experiments.[3,4,7,8] In the case of the Ar experiment which uses the electron-collisional excitation pumping scheme, an adequate lasing condition can be achieved by producing a high density and temperature plasma through a pinch. Thus even if the initial density is low, the pinch state produces a density high enough for the sufficient amplification. However in the case of CRPS using the H- and Li-like ions, a high density and temperature plasma state should be followed by fast cooling phase. An adiabatic expansion, which plays a cooling role, reduces not only the temperature but also the density. To get a sufficient density for a high gain in such an expansion phase, a higher initial density is required. From this point of view, the low gain value in the Li-like oxygen experiment[7] can then be attributed to its low initial density.

For a set of parameters which results in a maximum gain of $2\ \mathrm{cm}^{-1}$ ($T/4 = 20$ ns, $R = 1$ mm, $N_o = 10^{18}\ \mathrm{cm}^{-3}$, and $I_o = 41.6$ kA), the temporal variations of the plasma at axis are shown in Fig. 2(a). The abrupt increase of the electron density and temperature is caused by implosion, and the following fast cooling by adiabatic expansion. Figure 2(b) clearly shows that the cooling time is shorter than the recombination time of C VII to C VI ion. In Fig. 2(c), the temporal behavior of the gain at axis is plotted, which shows a higher gain peak of ~5 ns duration and an additional small gain peak. The second gain peak arises by the reduction of the optical trapping of C VI L_α line [dashed line in Fig. 2(c)]. The increased opacity (or decreased escape probability) due to the decrease of the ion temperature reduces or terminates the first gain pulse, even though other conditions are still adequate for the gain formation. A further expansion of plasma and the recombination of C VI to C V makes the opacity decrease,

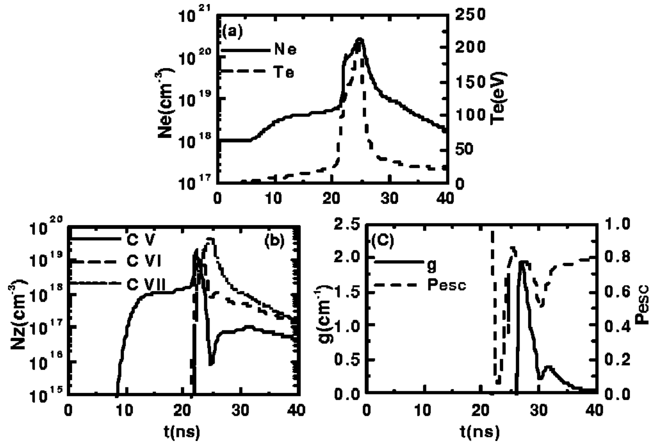

FIG. 2. The temporal variations at axis for the case of maximum gain, $T/4 = 20$ ns, $R = 1$ mm, $N_o = 10^{18}\ \mathrm{cm}^{-3}$, and $I_o = 41.6$ kA: (a) electron density (N_e) and the temperature (T_e); (b) the population densities of ground states, and (c) the gain of C VIH_α(18.2 nm) line (g) and the escape probability for the C VIL_α line (P_{esc}).

causing the appearance of the second gain peak.

Figure 3(a) shows the radial distribution of the gain at a maximum gain time of 26.7 ns for the same parameter as in Fig. 2. Note that the gain is radially stratified into two regions: one region near axis with a diameter of 150 μm where the gain is uniform and high, and the other outer region where the gain decreases gradually. This radial dependence of the gain is closely related to the radial distribution of temperature [Fig. 3(b)]. The smaller Doppler broadening and the higher recombination pumping rate are due to a lower temperature near axis build a higher gain, even though the ionic distributions are not much different from those in the outer region [Fig. 3(c)]. The optical depth is also longer in the low temperature as $\sim T^{-1/2}$ but the expanding velocity profile [Fig. 3(d)] reduces such an effect. The hollow profile of the electron density keeps a propagating beam from being divergent, reducing the refraction loss. Considering that a beam propagates on an $r-z$ plane [Fig. 4(a)] where the index of refraction is uniform along the z axis, the deflected angle per unit length can be derived from the ray equation in Ref. 21:

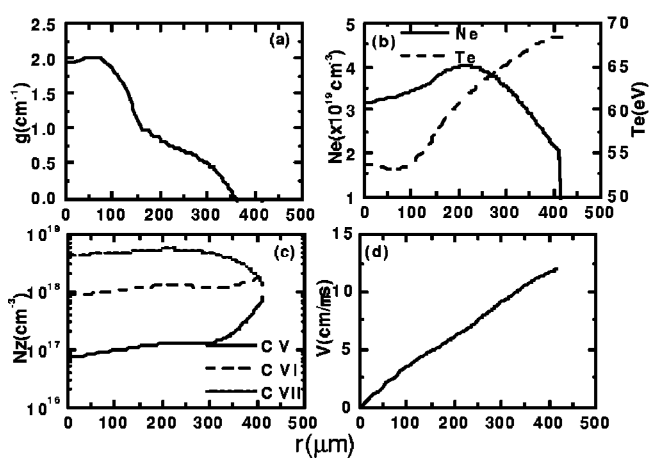

FIG. 3. The radial distributions of plasma quantities at the time of maximum gain, 26.7 ns for the case of Fig. 2: (a) gain of C VIH_α(18.2 nm) line (g), (b) the electron density (N_e) and the temperature (T_e), (c) the population densities of ground states, and (d) the radial velocity.

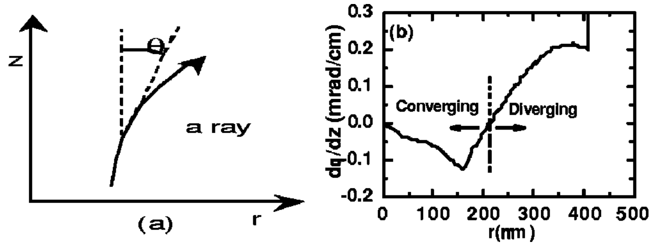

FIG. 4. (a) Schematic drawing of a beam propagation in the $r-z$ plane; (b) deflected angle per unit length for the case of Fig. 3.

$$\frac{d\theta}{dz}=\frac{1}{n}\frac{dn}{dr}, \tag{1}$$

where n is the index of refraction of a plasma with the plasma frequency, $\omega_p^2=4\pi n_e e^2/(m_e)$,

$$n=\sqrt{1-\left(\frac{\omega_p}{\omega}\right)^2}. \tag{2}$$

For the electron density profile shown in Fig. 3(b), the deflection angle of a ray per unit length along the z direction is plotted in Fig. 4(b). This shows that a beam in an inner region, where the gain is also high, is guided, leading to a high amplification.

In summary, another regime of operation for the amplification of H-like C VI H_α (18.2 nm) line in a capillary discharge is obtained using one-dimensional MHD simulation. The results show that there is a wide range of experimental conditions for a gain as high as 1 cm^{-1} with a current pulse of 20 ns quarter period. The temporal behavior in the case of a maximum gain shows that the capillary discharge plasma has adequate dynamics for recombination x-ray lasers. This regime has new features: the existence of gain at the axis of a capillary, the large size of a gain region, and the hollow electron density profile for the better guiding of the radiation being amplified.

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[1] *X-Ray Laser 1998*, edited by Y. Kato, H. Takuma, and H. Daido (Institute of Physics, Bristol, 1999), Vol. 159; C. H. Skinner, Phys. Fluids B **3**, 2420 (1991).
[2] R. C. Elton, *X-Ray Lasers* (Academic, New York, 1990), pp. 100, 146 and 26.
[3] J. J. Rocca, V. Shlyaptsev, F. G. Tomasel, D. D. Cortazer, D. Hartshorn, and J. L. A. Chilla, Phys. Rev. Lett. **73**, 2192 (1994).
[4] J. J. Rocca, D. P. Clark, J. L. A. Chilla, and V. N. Shlyaptsev, Phys. Rev. Lett. **77**, 1476 (1996).
[5] B. R. Benware, C. H. Moreno, D. J. Burd, and J. J. Rocca, Opt. Lett. **22**, 796 (1997).
[6] H. J. Shin, D. E. Kim, and T. N. Lee, Phys. Rev. E **50**, 1376 (1994).
[7] T. Wagner, E. Eberl, K. Frank, W. Hartmann, D. H. H. Hoffmann, and R. Tkotz, Phys. Rev. Lett. **76**, 3124 (1996).
[8] T. Boboc, F. Weigand, and H. Langhoff, Appl. Phys. B: Lasers Opt. **70**, 399 (2000).
[9] A. N. Oraevskii, O. G. Semenov, and B. N. Chickkov, Sov. J. Quantum Electron. **17**, 1274 (1987).
[10] K. T. Lee, S. H. Kim, D. Kim, and T. N. Lee, Phys. Plasmas **3**, 1340 (1996).
[11] K. T. Lee and D. Kim, J. Korean Phys. Soc. **32**, 304 (1998).
[12] K. Lee and D.-E. Kim, Phys. Rev. E **60**, 2224 (1999).
[13] S. H. Kim, K.-T. Lee, D.-E. Kim, and T. N. Lee, Phys. Plasmas **4**, 730 (1997).
[14] K.-T. Lee, S. H. Kim, and D.-E. Kim, Phys. Rev. Lett. **85**, 3834 (2000).
[15] V. F. D'yachenko and V. S. Imshennik, in *Review of Plasma Physics*, edited by M. A. Leontovich (Plenum, New York, 1970), Vol. 5, p. 462.
[16] R. W. P. McWhirter, *Plasma Diagnostic Techniques*, edited by R. H. Huddlestone and S. L. Leonard (Academic, New York, 1965), Chap. 5, p. 222.
[17] Y. T. Lee, R. A. London, G. B. Zimmerman, and P. L. Hagelstein, Phys. Fluids B **2**, 2731 (1990).
[18] A. I. Shestakov and D. C. Eder, J. Quant. Spectrosc. Radiat. Transf. **42**, 483 (1989).
[19] G. J. Pert, in *X-Ray Lasers 1990*, edited by G. J. Tallent (Institute of Physics, New York, 1990), p. 143.
[20] N. A. Krall and A. W. Trivelpiece, *Principles of Plasma Physics* (McGraw-Hill, New York, 1973), p. 123.
[21] M. Born and E. Wolf, *Principles of Optics* (Cambridge University Press, Cambridge, 1999), Chap. 3, p. 130.