Space- and time-resolved investigation of short wavelength x-ray laser in Li-like Ca ions

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(Received 21 September 1992; accepted for publication 9 June 1993)

We have demonstrated the soft x-ray amplification for lithium-like Ca^{17+} $4f$-$3d$ transition at 57.7 Å with 900 ps, 1.05 μm drive laser pulse. The spatial distribution of the gain coefficient and temporal history of the lasing line emissions were also obtained.

X-ray lasers in recombination pumped Li-like ions were initially demonstrated by Jamelot *et al.* in 1985 with Mg^{9+} and Al^{10+} ions.[1] Because of its advantages in requiring lower drive energy, scaling faster to shorter wavelength, and hence being less expensive, the Li-like recombination scheme has attracted many scientists around the world.[1-10] Although great progress has been achieved in shortening the lasing wavelength and raising the gain coefficient, some problems still remain unresolved for understanding the lasing mechanism.

Recombination pumped Li-like x-ray lasers originate from mainly nf-$3d$ transitions in the Li-like ions. The nf levels are populated through a direct collisional recombination from the ground state of He-like ions. The nf-$3d$ population inversion is maintained by fast radiative decay from the $3d$ to the $2p$ levels while the radiative decays of nf levels to lower states are slower. Thus, a higher density of the plasma is needed to ensure the nf level populations, and a fast cooling is needed to increase the recombination of nf level and to avoid the collisional excitation of $3d$ levels. As the atomic number of the lasing ions increases, this condition becomes more restricted. If free expansion is the dominant cooling mechanism, for $Z=20$, the drive pulse was predicted to be less than 100 ps at 1.05 μm drive wavelength by a self-similar code coupling with a collision-radiation model.

Recently in a new round of x-ray laser experiment, we have successfully demonstrated the soft x-ray amplification for $4f$-$3d$ (57.7 Å) transition of the Li-like Ca ions in slab CaF_2 targets irradiated by 900 ps, 1.05 μm optical laser pulses. One of the reasons we use this long drive pulse is that shorter pulses are not available on the LF12 Facility at present. We have also obtained a set of time- and space-resolved spectra, which may provide some valuable information for understanding the lasing action. A simplified numerical simulation was performed to meet the experimental results, showing the possible important role of other cooling mechanisms beside adiabatic expansion in long laser pulse drived experiments.

The experiment was carried out at the two-beam LF12 laser system. Each beam delivers $\sim$600 J energy at 1.05 μm with a 900 ps-duration full width at half-maximum (FWHM) quasi-Gaussian pulse. In the experiment, the north beam was line-focused by a six-element cylindrical-lens array to form a 12.5 mm$\times$120 μm uniform focus on the target surface, with a corresponding intensity of $\sim 4\times 10^{13}$ W cm^{-2}. Length of the slab CaF_2 target with polished surface varied from 2 to 10 mm.

A flat field grazing incidence grating spectrograph (FFGIGS)[11] with a grazing incidence pre-optics consisted of a cylindrical mirror and a spherical mirror was aligned to the axis of the line focus. One dimensional spatially resolved spectra were recorded on x-ray film or by a soft x-ray streak camera.[12] Because only relative calibration of the film and no calibration of the spectrograph and the camera have been performed, we are not able to measure the absolute intensities of the output x-ray laser, hence the energy. But for gain demonstration, knowing the relative intensity is enough. For the same reason, time resolved gain cannot be deduced. When the streak camera (time resolution about 50 ps) was used, it was so adjusted that its scanning slit in front of the photocathode was set parallel to the dispersion axis of the spectrum and to cover the desired part of the spectrum from 40 to 90 Å. By precisely controlling the position of the scanning slit or the target, time-resolved spectra at different distances from the target surface can be obtained.

A typical on-axis time-integrated CaF_2 spectrum from the FFGIGS spectrograph is shown in Fig. 1. The spec-

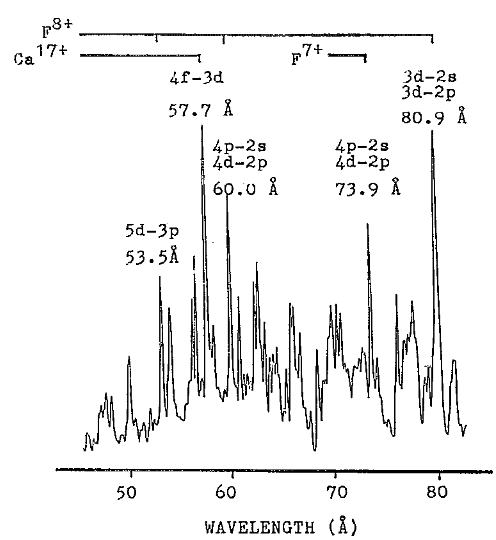

FIG. 1. Density trace of a time integrated typical spectrum from a 10 mm long CaF_2 plasma column obtained with the on-axis FFGIGS.

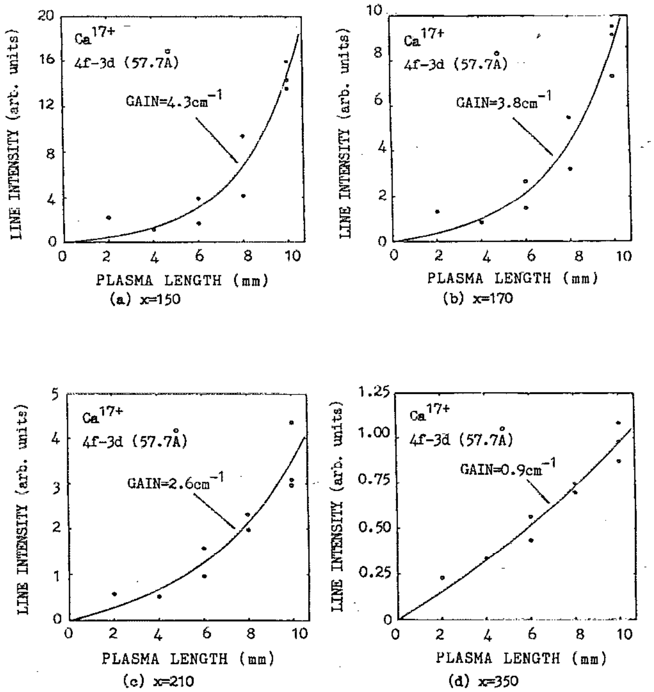

FIG. 2. Time integrated line intensities of Ca^{17+} $4f$-$3d$ transitions at 57.7 Å as functions of plasma length at different distances $x(\mu m)$ from the target surface from the on-axis FFGIGS.

trum is dominated by strong line emissions originated from Li-like Ca^{17+} and H-like F^{8+} ions. There are spectral lines from other ions, but they are much weaker. In the experiment, amplifications were demonstrated for the Ca^{17+} $4f$-$3d$ transition at 57.7 Å, and the F^{8+} 3–$2H_\alpha$ transition at 80.9 Å.

The time integrated line intensities for the Ca^{17+} $4f$-$3d$ transition at different distances from the target surface from the FFGIGS are plotted in Fig. 2 as functions of target length. They are fitted with the formula for the emission from distributed source of amplified spontaneous emission from Linford *et al.*[13] The highest gain was found to be 4.3 ± 0.9 cm^{-1} at 150 μm from the target surface. The error is mainly caused by fluctuations in output parameters of the drive laser system from shot to shot. Other errors like those produced in data handling processes are estimated to 10% and well below this error, hence we do not show them in Fig. 2. Our previous experiments on the Li-like Si x-ray laser[9] revealed that there exists a spatial distribution of the gain coefficient along the normal of the target. Starting from the target, a negative gain appears first, then amplification emerges and reaches its peak value, and then gradually decreases with increasing distance from the target surface. Obviously the peak gain position of the Ca^{17+} $3d$-$4f$ line is 200–300 μm closer to the target surface than those of Si^{11+} lines, and the region of amplification is narrower.

The highest gain for F^{8+} 3–$2H_\alpha$ transition is demonstrated to be 1.4 cm^{-1} at 220 μm from the target surface from the FFGIGS data, much lower than expected.

The time-resolved line intensities of those two line

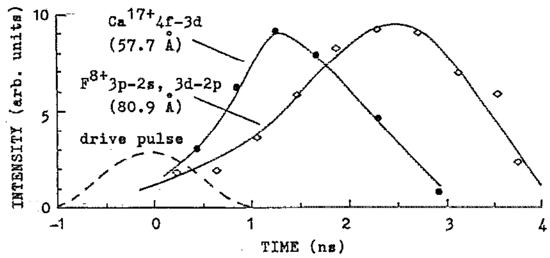

FIG. 3. Temporal history of Ca^{17+} $4f$-$3d$ transitions at 57.7 Å and the F^{8+} 3–$2H_\alpha\alpha$ transition at 80.9 Å, from 200 to 300 μm region with respect to the surface of a 10 mm target slab, with laser intensity of $\sim 2.0\times 10^{13}$ W cm^{-2}.

emissions are plotted in Fig. 3. The delay of the Ca^{17+} $4f$-$3d$ emission relative to the drive laser pulse is about 1 ns, 1.4 ns earlier than that of the F^{8+} 3–$2H_\alpha$ transitions, and the durations of the two transitions are 1.6 and 2.2 ns (FWHM), respectively. The long delay and long duration of the H_α line emission from F^{8+} ions is of the characteristics of recombination lasing although only low gain was demonstrated by the time integrated intensity. Time resolved measurements of the gain should be deduced in the future experiments.

From the pumping mechanism, long drive pulse is unfavorable for the recombination x-ray laser. There must be some other cooling mechanism besides free expansion that makes the plasma cool rapidly in our experiment. To make sure, we have performed a simple theoretical simulation by coupling a self-similar model in cylinder geometry with a collisional-radiational model. In the model, if no additional cooling is adopted, the electron temperature is

$$T_e = T_{e0}\left(\frac{t}{t_p}\right)^{-5/3},$$

where t_p and T_{e0} are the duration of the drive pulse and the electron temperature at the ends of the drive pulse, respectively. This formula represents the cooling rate of the plasma through adiabatic expansion. For Ca^{17+} $4f$-$3d$ transitions at 57.7 Å, with a 600 ps drive laser pulse duration, the simulated gain peaks at 250 μm from the target surface, 2 ns after the drive pulse, and the maximum value is only 0.6 cm^{-1}. Phenomenologically increasing the cooling rate with

$$T_e = T_{e0}\left(\frac{t}{t_p}\right)^{-2.2},$$

and taking the same input conditions, the maximum gain turns out to be 2.6 cm^{-1} at about 200 μm from the target surface and 1.5 ns after the peak of the drive laser pulse. This result is qualitatively in agreement with the experiment. The additional cooling may originate from heat conduction and radiation losses, which becomes important in high Z plasmas. More diagnostics should be employed to show the efficient cooling mechanisms responsible for that.

In conclusion, we have demonstrated the soft x-ray amplification of Li-like Ca^{17+} ion $4f$-$3d$ transitions at 57.7 Å. We have also obtained the spatial distribution of the gain and the temporal history of the lasing line emissions. The experiment demonstrated possibility of shortening the lasing wavelength in recombination Li-like ions with long drive pulses, and offered information for better understanding of the recombination lasing scheme.

The authors gratefully acknowledge the LF12 Laser Facility Operation Group for their assistance and cooperation and Shanghai Film factory for providing Shanghai 5F x-ray film without supercoating. This work was supported by the National Nature Science Foundation and the National High Technology Program.

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