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False gain in x-ray laser experiments due to axial plasma expansion

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Large systematic errors entering soft x-ray gain coefficients, evaluated by observing the nonlinear increase of spectral intensity with plasma lasing length, are investigated. Time-resolved observations reveal a faster decay in the intensity of the off-axis N Balmer α line for plasmas with shorter lasing lengths, which will cause intrinsically spontaneous emissions to appear amplified. Numerical investigations also reproduce this false gain, which is attributed to the effects of axial expansion, resulting in an enhanced cooling for plasmas with reduced lasing lengths. These observations suggest the necessity of reevaluating gain coefficients obtained using plasmas with excessively short lasing lengths.

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A convincing and most straightforward method of demonstrating soft x-ray laser amplification is by observing the exponential growth of spectral intensities with increasing lasing length of the gain medium. This technique has been widely used to evaluate gain coefficients in laser plasmas, pumped by electron collisional excitation [1–4] and three-body recombination processes [5–9]. Gain saturation of Ne-like soft x-ray lasers has been demonstrated by observing the change from exponential to linear growth of the output with plasma lasing length [10,11]. This technique has also been employed to evaluate gain coefficients in longitudinally pumped plasmas, where large amplification has been reported for an optical-field-induced ionization x-ray laser [12].

The same method has also been adopted in our studies on recombination pumped H-like and He-like systems [13,14]. Space-resolved and time-resolved gain coefficients were evaluated by observing the spectral intensity of potential lasing lines with various lengths from plasmas, ranging from 1.6 to 7.8 mm, and fitting the data to a gain formula for amplified spontaneous emissions [15]. Amplification in a laser-produced boron nitride plasma was confirmed for the He-like N $3\,^1D$–$2\,^1P$ line. At the same time, a weaker amplification for the H-like N Balmer α line was also identified under specific conditions. In the course of these investigations, positive gain coefficients were occasionally observed which could not be explained by conventional recombination laser theory [14]. These apparent amplifications were initially discovered in space-resolved time-integrated experiments, in which the evaluated gain coefficient for the N Balmer α line increased consistently with increasing distance from the target surface. Gain coefficients exceeding 2 cm^{-1} were obtained in regions of the plasma where only weak emission could be observed. Similar amplification was recognized in time-resolved experiments for large times after the incidence of the pump pulse, where again spectral emissions were weak. However, population inversions in such dilute plasmas should be small due to a reduced pumping of the upper laser level through three-body recombination. It would therefore be natural to expect amplifications to diminish as the spectral intensity approaches zero. Such a systematic error has also been observed in earlier works with C Balmer α lasers [6], where the possibility of a consequent overestimation of gain coefficients was indicated for late times.

The present paper describes the results of experimental and numerical studies on apparent amplifications observed in soft x-ray laser experiments. The mechanism underlying the onset of large systematic errors in the gain evaluation process is investigated, by observing the temporal change in the intensity of spontaneous emission lines emitted from boron nitride plasmas with various lasing lengths. Results suggest an enhanced cooling for the plasma with shorter lasing length, due to the additional effects of expansion in the axial direction. Numerical simulation is also performed to verify experimental observations.

A single beam line of the multiterawatt neodymium doped phosphate glass (Nd:glass) laser system at the Institute for Solid State Physics of the University of Tokyo was used in the experiment. The 90-mm-diam aperture beam line is capable of delivering a 40 J, 100 psec width laser pulse, operating at the fundamental wavelength of 1.053 μm. A lens system composed of aspherical and toric lenses line-focuses the incident laser onto a boron nitride target. The dimensions of the line-focus are 7.8 mm long and 100 μm in width, resulting in a maximum peak intensity of 4.3×10^{13} W/cm^2. The thickness of the slab boron nitride target used in the present experiment is 1 μm, deposited on a solid graphite disk. Off-axis soft x rays emitted in a direction perpendicular to the axis of the cylindrical plasma are observed by a flat-field Harada-type spectrograph [16], equipped with a 1200 lines/mm Hitachi varied-pitch grating as the dispersive element. Stigmatic imaging of the plasma in the direction vertical to the target surface is obtained by a grazing incidence gold-coated cylindrical mirror. The slit of the spectrograph was adjusted so that the central 1.6 mm lasing length portion of the elongated plasma is observed. An x-ray streak camera (Hamamatsu Photonics C1936 demountable photocathode type) is used as the detector for time-resolved observations. The temporal resolution of the streak camera is approximately 100 psec at the sweep range used, limited by the finite width of the photocathode slit.

Time-resolved off-axis spectra of the Balmer α line of H-like N are shown in Fig. 1, for plasmas with full lasing lengths of 7.8, 1.6, and 0.8 mm. The origin of the abscissa is

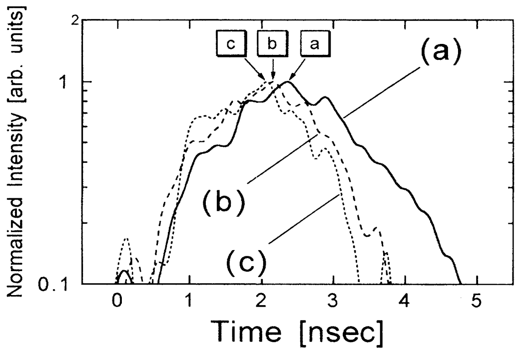

FIG. 1. The time dependence of the off-axis N Balmer α line intensity emitted from plasmas with lasing lengths of (a) 7.8, (b) 1.6, and (c) 0.8 mm. The maximum intensity of each spectrum is normalized to unity. The time of maximum emission for each spectrum is indicated by an arrow.

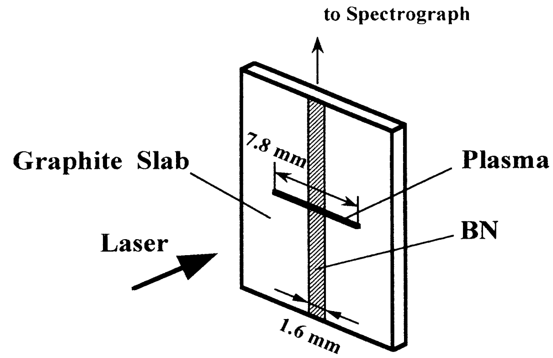

FIG. 2. Schematic diagram of the striplike boron nitride target. The 7.8 mm long line-focused laser perpendicularly intersects the 1.6 mm width, 1 μm thick boron nitride strip. The optical axis of the spectrograph is in the vertical direction.

taken to be the incidence time of the pump laser pulse. These spectra correspond to a region of the plasma at $z=200$ μm, where the z axis is taken to be normal to the target surface. Each spectrum in the figure is normalized so that the peak intensity equals unity. Two points can be noticed from this result. The first is that the temporal change of the spectral intensity after 2 nsec is significantly different for plasmas with different lasing lengths. The spectrum corresponding to the plasmas with shorter lasing lengths decreases to 10% of the peak intensity at times between 3 and 4 nsec, while that for the plasmas with longer lasing lengths is postponed until approximately 5 nsec. The second involves the time at which maximum spectral intensity is observed, which is shown in the figure for each spectrum by an arrow. It can be seen that a peak is reached at earlier times for plasmas with shorter lasing lengths. Similar results were obtained with time-resolved spectra for regions of the plasma at $z=100$ μm, although the difference was less significant. The reduction in the normalized spectral intensities observed in Fig. 1 for plasmas with reduced lasing lengths will cause essentially spontaneous emissions to show spurious amplifications. The magnitude of such false gain, which adds onto the intrinsic gain coefficient causing a consequent overestimation, can be estimated by fitting the results of Fig. 1 to the gain formula of Linford *et al.* [15]. Data analysis reveals systematic errors exceeding 1 cm^{-1} after 2.7 nsec from the pump pulse, at $z=200$ μm. The magnitude of the error gradually increases with increasing time, and reaches 3 cm^{-1} at 3.3 nsec. Data sets at $z=100$ μm also exhibit false gains beginning at earlier times, reaching a value of 2 cm^{-1} at 2.6 nsec.

In order to investigate the reason for this false gain, boron nitride targets with a striplike form deposited on a graphite slab were used. A schematic diagram of the target is shown in Fig. 2. The dimensions of the boron nitride strip are 1.6 mm in width and 1 μm thick. The axis of the 7.8 mm long line-focused laser is aligned perpendicular to the major axis of the boron nitride strip and the optical axis of the spectrograph. Laser irradiation of this target results in a 1.6 mm lasing length boron nitride plasma sandwiched on both ends by carbon plasmas.

The time-resolved spectra of the N Balmer α line for strip and slab targets irradiated by 7.8 mm line-focus lasers are shown in Fig. 3. The peak intensity of each line is again normalized to unity. The stronger spectral intensity observed for strip targets at earlier times is due to a continuum which is not observed with pure boron nitride targets, and can therefore be attributed to emissions from the surrounding carbon plasma. Such emissions were not significant for later times, and it was confirmed that the Balmer α line intensity was not influenced by this continuum in the time region of concern in this work. The spectra in Fig. 3 obtained using strip and slab targets show an excellent agreement for times after 2 nsec. From a comparison with the results shown in Fig. 1, one also notices a distinct difference between spectral emissions from 1.6 mm lasing length boron nitride plasmas produced on slab and strip targets. This deviation of the spectral intensities can be explained by the different hydrodynamical behavior of the plasmas produced on the two targets. The carbon plasma present for strip targets acts to restrict expansion of the boron nitride plasma in the axial direction. Plasmas produced with slab targets, however, are allowed to expand freely in this direction, resulting in an enhanced cooling and a consequently faster decay of emission. The results

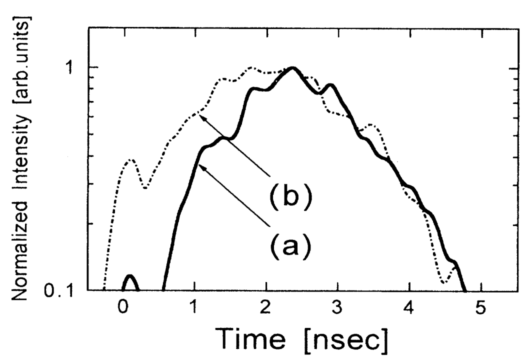

FIG. 3. The time dependence of the off-axis N Balmer α line intensity emitted from plasmas produced on (a) slab and (b) strip targets, both irradiated by 7.8 mm long line-focus lasers. The maximum intensity of each spectrum is normalized to unity.

observed in Fig. 1 can also be explained in the same manner. Axial expansion is inherent to all elongated laser plasmas. However, the rate of change in the volume will be larger for plasmas with reduced lasing lengths. As a result, the adiabatic cooling rate increases with decreasing lasing length, causing line emissions to decay faster for the plasmas with shorter lasing lengths.

To support the above conclusion, numerical simulations of the experiment were performed. The hydrodynamics of the plasma was calculated assuming a self-similar expansion [17], and a collisional-radiative model was used for the atomic kinetics. Since conventional self-similar models for cylindrical plasmas cannot simulate axial expansions, the calculation of the hydrodynamics was divided into two steps. The angle between the velocity at the ends of the elongated plasma with and without axial expansion is assumed constant, whose tangent we denote as α. For a single time step, radial expansion of the plasma is first calculated using the self-similar model. An increase in the lasing length of the plasma at the boundary due to axial expansions is calculated using α and the radius of the plasma. The densities and temperature are then modified to compensate for the change in the plasma volume, assuming adiabatic expansion. Atomic kinetics calculations include ion species from completely ionized to Li-like ions. The excited states are taken into account only for the H-like species, for levels with principal quantum numbers $n=2$ to 15. Familiar hydrogenic rates were used for the collisional and radiative processes [18]. Opacity was not included in the present simulation, since Balmer α lines can be considered to be optically thin for emission in the off-axis direction.

The normalized spectral intensity of the N Balmer α line emitted from the total volume of the plasma is calculated as a function of time for various plasma lasing lengths. An example of the results is shown in Fig. 4 for 7.8, 1.6, and 0.8 mm lasing length plasmas with $\alpha=1$, and also for null axial expansion ($\alpha=0$). The initial radius of the plasma is assumed to be equivalent to the width of the line focus, which was evaluated to be 100 μm. The initial electron density and temperature, which were 1×10^{21} cm^{-3} and 100 eV, respectively, for the present calculation, were chosen so that a relatively large gain coefficient developed for the N Balmer α line under optically thin conditions. Simulation results are found to show similar tendencies in the temporal profile of the Balmer α line with those obtained in experiments, exhibiting faster decay of spectral intensities for shorter plasma lasing lengths. The data for the 7.8 mm lasing length plasma follow closely those for plasmas with $\alpha=0$, implying a nearly cylindrical expansion. Calculations also show an earlier time of peak emission for the plasmas with shorter lasing lengths, consistent with our experimental observations. This is also a result of enhanced cooling and rapid dilution of plasmas with reduced lasing lengths.

It is interesting to note that simulations also reveal the existence of negative false gains, which occur at the rise of emission. This is due to a larger spectral intensity emitted per unit length for the plasmas with shorter lasing lengths in this time region, which is a consequence of the faster cooling. The magnitude of this false absorption coefficient obtained from calculation is 0.6 cm^{-1} at maximum. A sign of such a systematic error was observed in our gain evaluation experiments with the Balmer α line of H-like N, [14] although errors arising from shot-to-shot variations in the pump laser intensity concealed the phenomena. Some evidence of false absorption can also be seen in works with C ions [6], where the Balmer β line showed a larger spectral intensity per unit plasma lasing length for earlier times.

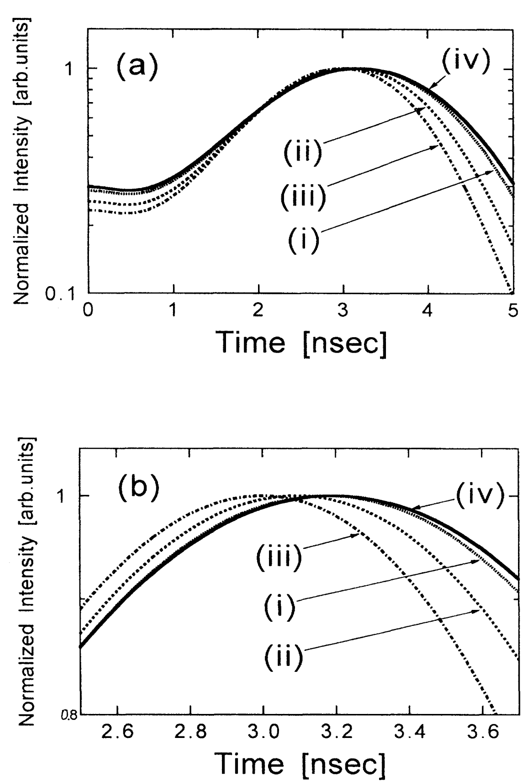

FIG. 4. (a) Calculated spontaneous emission of the N Balmer α transition for plasmas with lasing lengths of (i) 7.8, (ii) 1.6, and (iii) 0.8 mm with axial expansion ($\alpha=1$), and also (iv) without axial expansion ($\alpha=0$). (b) An enlarged view of (a) in the vicinity of peak emission, shown to indicate the shift in the time of maximum spectral intensity for the various calculated spectra.

In conclusion, we have reported on the observation of false gains appearing in soft x-ray laser experiments pumped by 100 psec pulse width Nd:glass lasers. Experimental results with special strip targets show that expansion of the plasma in the axial direction is the main cause of this systematic error. Simulations support the above experimental observations, and also reveal the existence of a false absorption occurring at the rise of emission. Such a systematic error can severely influence the accuracy of gain evaluation procedures, resulting in an overestimation of the gain coefficients when using plasmas with small lasing lengths. The present work may help to explain discrepancies between experiment and calculation observed in works on optical-field-ionized x-ray lasers [19], in which a faster than linear growth of the Lyman α transition of H-like Li was observed out to a plasma lasing length of 1.5 mm, although temporal resolution of the spectra did not show enhanced emission compared with calculated spontaneous emissions.

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