Observation of Gain-Narrowing and Saturation Behavior in Se X-Ray Laser Line Profiles

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We report on the first successful measurements of the spectral width of an x-ray laser line. The experiments observed the 206.38-Å laser in Ne-like Se and indicate an unamplified width of 50 mÅ, show gain narrowing to 10 mÅ in intermediate length amplifiers, and show no significant rebroadening in saturated amplifiers. The unamplified width is 1.4 times the expected Doppler width, and the lack of rebroadening leads to speculation that collisional effects may play a significant role in determining the line profiles.

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The field of x-ray laser research has been characterized by rapid progress since the first successful proof of principle demonstrations [1-3]. Collisional-excitation amplified-spontaneous emission (ASE) x-ray lasers, which rely on collisional excitation of highly stripped ions in high-temperature laser-produced plasmas, have generated much interest due to their brightness and wavelength versatility [4]. Neonlike collisional excitation lasers, which are isoelectronic to Ne I and lase on $3p$-$3s$ transitions, have been produced worldwide in many elements with wavelengths as short as 80 Å (Desenne *et al.* in [5] and Fields *et al.* in [5]). The analogous Ni-like collisional excitation lasers, lasing on $4d$-$4p$ transitions, have also been produced in a number of elements with wavelengths as short as 36 Å (MacGowan *et al.* in [5]). Preliminary holography experiments have been performed [6] with Ne-like Se, and ≈ 500-Å resolution microscopy experiments have been performed [7] with Ni-like Ta.

However, in spite of this rapid progress, many of the basic physics issues of x-ray lasers remain poorly understood. The lack of substantial amplification of the $(2p_{1/2}3p_{1/2})_0$-$(2p_{1/2}3s_{1/2})_1$ line in Ne-like lasers (the "$J=0$-1 anomaly") has never been conclusively explained, though calculations predict it to have large gain [1,2,8]. Lasing in F-like analogs to Ne-like lasers, while predicted [9], has never been observed, in contrast to the observation of lasing in Co-like analogs to Ni-like lasers [10]. The effects of driver beam nonuniformities and plasma turbulence remain difficult to calculate and potentially important [11], and, in particular, the laser linewidths have previously never been measured, in spite of their fundamental importance to gain and radiative transport calculations, due to the difficulty in obtaining soft-x-ray spectra with sufficient resolution. Ne-like Se x-ray laser linewidths have heretofore generally been assumed [1] to be dominated by Doppler broadening, based on a predicted [1,2] ion temperature of 400 eV.

The intrinsic (unamplified) spectral profile of a plasma line is determined predominantly by spontaneous emission rates, electron collisional rates, and Stark broadening and Doppler broadening [12], with possible complications due to ion turbulence [12,13] and ion-ion interactions [13,14]. The observed profile is also modified by radiative transport effects. Amplified lines narrow as the square root of the gain-length product in the small-signal regime [15]. As the laser saturates, the line can rebroaden to its intrinsic width if the intrinsic profile is dominated by inhomogeneous (i.e., caused by inhomogeneities such as Doppler shifts or turbulence), rather than homogeneous (i.e., Fourier transform limited by collisions, etc.), effects [16-18]. There have been few reported experiments which have measured the amplifier length dependence of ASE (mirrorless) laser linewidths through saturation, and these have generally used the high-gain 3.51-μm xenon laser transition [17,19,20]. Previous attempts to measure the spectral widths of x-ray laser lines [21-23] have been inconclusive; in each case, instrument resolutions were insufficient to accurately measure the linewidths, and no variations with amplifier gain-length product were reported.

We report in this Letter on the first successful measurements of ASE laser line profiles in the soft-x-ray wavelength region. The experiments used the 206.38-Å $(2p_{3/2}3p_{3/2})_2$-$(2p_{3/2}3s_{1/2})_1$ laser from Ne-like Se exploding foils [1,2]. Eight experiments using 30-35-μg/cm^2 Se/Lexan foils with lengths between 0.42 and 6.3 cm were performed. Each foil was irradiated by two superimposed line foci, with 120-μm widths and variable lengths, from Lawrence Livermore National Laboratory's Nova laser. The total irradiance on each target was 7×10^{13} W/cm^2 in a 600-ps Gaussian pulse. The resulting x-ray laser beam was observed along the axis of the line foci by a high-resolution, grazing incidence grating spectrometer [24] and the spectra were time resolved by an x-ray streak camera with 40-ps time resolution. Thin (0.2-2.8 μm), free-standing Al filters were inserted into the beam path on most of the expeirments to avoid saturating the streak camera.

Spectrometer resolution was measured using quasi-monochromatic line emission from a Penning plasma source [25], while the line-spread function of the streak camera was measured separately by shining broadband x

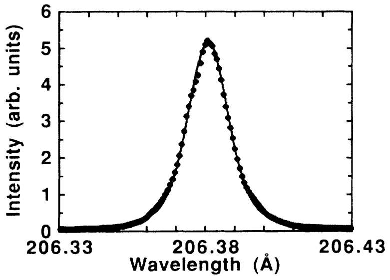

FIG. 1. Spectral profile (points) from a 6.3-cm target fitted by a Voigt function (solid line). Data points represent individual pixels in the digitized image, averaged over a 75-ps time window near the temporal peak of the line.

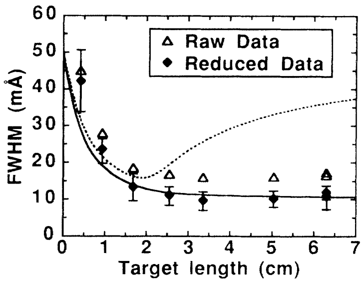

FIG. 2. Measured and reduced linewidths as a function of target length. The error bars for the shortest target are due to background level uncertainties; for the others, they represent the spread in reduced widths obtained using different fitting functions. Also shown is the expected target-length scaling for inhomogeneous saturation (dashed curve) and homogeneous saturation (solid curve) with a 50-mÅ intrinsic width.

rays through a narrow (35 μm) slit placed just in front of the cathode. Separate measurements were necessary because the Penning source emission was too weak to be observed with the streak camera. Convolution of the measured spectrometer resolution function with the measured streak camera line-spread function gave total instrument resolving powers ($\lambda/\Delta\lambda$) of 14000 and 17000 near 206 Å for the two different spectrometer settings used in the experiments.

The x-ray laser data were collected on TMX-3200 film and digitized on a PDS microdensitometer for analysis. After applying a calibrated film density/intensity correction, each raw data profile (Fig. 1) was fitted by a variety of functional forms. The corresponding instrument resolution profile, fitted by the same functional forms, was then deconvolved analytically; the resulting full widths at half maximum (FWHM) of the spectral profiles are plotted against target length in Fig. 2 along with the raw data. The raw data profiles were measured near the temporal peak of the $\approx$200-ps duration line emission; we note that no significant time dependence to the linewidths was seen or expected due to the weak dependence of the linewidth on intensity over the dynamic range ($\approx$100) of the streak camera.

Extrapolation of the reduced data to $L=0$ gives an intrinsic linewidth of 50 ± 10 mÅ, 1.4 times wider than the 400-eV Doppler width of 35 mÅ. The shorter targets exhibit spectral narrowing roughly consistent with the expected $(gL)^{-1/2}$ dependence for a gain of ≈ 6 cm^{-1}, derived from peak intensity scaling data (Fig. 3). The measured gain is somewhat higher than the 4.5-5.5-cm^{-1} gain found in previous spectrally, temporally, and spatially integrated measurements [1,26]. We note that spatial integration of the gain distribution, which can affect the measured intensities and linewidths if there is significant emission from a large, low-gain region surrounding the central 100-200-μm peak [27], is essentially negligible in the present work due to the small (30 by 300 μm) region of the plasma being imaged by the spectrometer. This may account for the higher measured gain.

The longer targets (up to 6.3 cm in length) showed no significant saturation rebroadening, implying that there may be a significant homogeneous contribution to the intrinsic profile. Evidence for the fact that the laser is actually saturating, i.e., that the stimulated emission rate is affecting the level populations, can be seen in previous Se data [26] which observed that the intensity of the 182.43-Å laser line continued to exponentiate from targets as long as 6.3 cm while the higher-gain 206.38-Å laser line did not, implying that refraction of the beam out of the gain region is not the cause of the rolloff in 206.38-Å line intensity from long targets (Fig. 3). As expected, no line-splitting stimulated emission effects, predicted [28,29] for very long seeded amplifiers but not for ASE sources, were observed.

In either the inhomogeneous or homogeneous limits, the simple one-dimensional, time-independent radiative transfer equations [16] for the single-direction spectral intensity I_ν from a steady-state ASE laser can be approximated as

$$\frac{dI_\nu}{dz}=j\left(1+\frac{g}{j}I_\nu\right)\frac{\phi(\nu)/\phi(\nu_0)}{1+K/I_{\mathrm{sat}}}\,, \qquad (1)$$

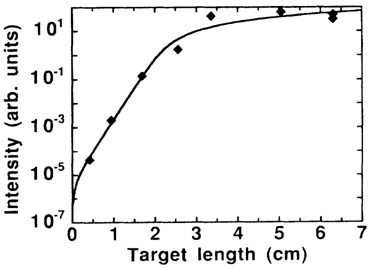

FIG. 3. Peak intensities as a function of target length (points), corrected for measured filter transmissions and instrument slit settings. The solid curve is obtained by fitting the data by Eq. (1) with either inhomogeneous or homogeneous broadening. Saturation intensity is reached at approximately fifteen gain lengths.

where I_{sat} is the peak saturation intensity, g is the peak small-signal gain, j is the peak spontaneous emissivity, and $\phi(\nu)$ is the area-normalized intrinsic line profile function. In the homogeneous (e.g., collisional) limit, K is the spectral intensity averaged over the intrinsic line profile function, and Eq. (1) must be solved numerically. In the inhomogeneous (e.g., Doppler) limit, K is simply the spectral intensity, and Eq. (1) can be solved analytically. Inferring a gain, saturation intensity and spontaneous emissivity from Fig. 3 (ordinate units are arbitrary), the expected target-length scaling behavior for the linewidth can be calculated both homogeneously and inhomogeneously assuming Lorentzian and Gaussian intrinsic profiles, respectively. It can be seen from Fig. 2 that the data are consistent in this model with an intrinsic line profile which is dominated by homogeneous, rather than inhomogeneous, effects. Essentially identical results were found when both right- and left-propagating beams were included [18], albeit with slightly different saturation intensities. We have also performed calculations for the mixed homogeneous and inhomogeneous case [16–18], using a 10-mÅ Lorentzian homogeneous component due to finite-state lifetimes [2] in addition to a 35-mÅ Doppler width; the results showed less dramatic but still significant rebroadening. We note that the apparent slight discrepancy in Fig. 2 between the calculated curves and the reduced data points from short targets may be partly due to bulk Doppler shifts driven by axial pressure gradients near the edges of the plasma. These shifts would slightly reduce the effective amplifier length, giving a slightly broader line profile. We estimate that this effect would be less than (5–10)% for the 0.5-cm data point, becoming negligible for targets longer than 2 cm.

The implications of these data are important for a clear theoretical understanding of x-ray laser physics. Previous gain calculations for the 206.38-Å Se laser and, likely, other $J=2$-1 Ne-like lasers which relied on a Doppler width estimate for the intrinsic linewidth should be divided by 1.4, as the small-signal gain is inversely proportional to the linewidth and any additional effects of the increased width on the level kinetics should be negligible. In addition, the lack of saturation rebroadening despite convincing evidence of gain saturation [26] implies that a significant fraction of the broad intrinsic profile may be homogeneous in nature. That Doppler broadening for x-ray laser lines may be compromised by collisional narrowing [14,30] and at least partly replaced by homogeneous ion-ion collisional contributions has been suggested previously [13]. This scenario also lends some support to a proposed [13] explanation of the $J=0$-1 anomaly which relies on the prediction that the homogeneous replacement of Doppler broadening is not present in the $J=0$-1 laser. We note, however, that an additional experiment we performed with Se indicated a gain-narrowed linewidth for the 182.43-Å $J=0$-1 laser which was consistent with the 206.38-Å linewidth measurements; both narrow to $\lambda/\Delta\lambda \approx 14000$ when amplified through $\approx$ ten gain lengths. Investigation of the possible rebroadening of this laser in longer targets is unfortunately not possible at Nova due to energy and line-focus length limitations.

In conclusion, we have measured the magnitude and target-length dependence of the spectral width of the dominant 206.38-Å laser transition in Ne-like Se x-ray lasers. The data show a somewhat broad unamplified profile and the target-length scaling indicates that the unamplified profile may be dominated by homogeneous broadening mechanisms, suggesting that the theoretical understanding of line broadening and radiative transport in x-ray laser plasmas may need to be reconsidered.

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