Saturated and Near-Diffraction-Limited Operation of an XUV Laser at 23.6 nm

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Amplification of spontaneous emission (ASE) at 23.6 nm has been studied in a Ge plasma heated by a 1 TW infrared laser pulse. The exponent of the axial gain reached 21 in a geometry with Fresnel number ≤ 1. Two plasma columns of combined length up to 36 mm were used with an extreme ultraviolet mirror giving double-pass amplification. Saturation of the ASE output was observed. The beam divergence was about 8× diffraction limited with a brightness estimated at 10^{14} $\mathrm{W\,cm^{-2}\,sr^{-1}}$. The feedback from the mirror was significantly reduced probably by radiation damage from the plasma.

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A significant objective in the development of extreme ultraviolet (XUV) lasers is to maximize their brightness and coherence in order to produce sources suitable for applications in fields such as biological microscopy [1] and holography [2]. From the Van Cittert–Zernike theorem [3] it follows that the output will have maximum brightness and spatial coherence when the aperture-to-length ratio gives a Fresnel number less than unity and the gain is sufficient to reach saturation of ASE. We report here an experimental study under approximately these conditions with the 23.6 nm Ge XXIII laser equipped with a multilayer-mirror half cavity.

The shortest wavelength at which saturated amplication of spontaneous emission (ASE) has previously been reported is 109 nm using traveling-wave excitation in the Xe III Auger laser [4]. High gain at shorter wavelengths has been produced in laser-generated plasmas through their thermal electrons exciting neonlike ions ranging from Ti XIII to Ag XXXVIII at wavelengths from 32.6 to 8.0 nm, and in nickel-like ions from Sm XXXV to Au LII at wavelengths from 7.3 to 3.56 nm [5]. The laser power P required to produce the gain exponent gl in these systems increases rapidly for shorter wavelength operation. It can conveniently be characterized by an efficiency parameter gl/P ranging from 0.3 to 70 TW^{-1} [6]. Saturation of gain is achieved when the ASE intensity exceeds the saturation intensity $I_s = h\nu/\sigma\tau$, where σ is the cross section and τ the gain recovery time. Saturation occurs in a homogeneous column of laser material for gain length $gl > \ln(4\pi\alpha\beta\gamma l^2/a^2)$, where l is the length, a is the radius, α is the ratio of spontaneous to ASE spectral linewidth, β is the ratio of the radiative lifetime of the laser level to the gain recovery time, and γ is the population inversion fraction [7]. gl values in the range 15 to 20 are typically required to reach saturation in XUV lasers. The possibility of XUV lasers with gain length approaching the saturation level has been restricted by their gl/P levels to a few of the longer wavelength transitions driven by the largest laser facilities. To date, experiments have been with plasma columns of large Fresnel number and fully saturated operation has not been clearly demonstrated.

The first evidence of near-saturated behavior in an XUV laser was with the 20.6 nm Se XXV laser with an exploding foil target driven by 0.53-μm radiation [8]. Subsequent work showed that the 23.6 nm Ge XXIII laser could be operated with a 1.05-μm driver and a slab target [9]. The approximately twofold reduction of energy requirement through elimination of harmonic conversion and inherently higher gl/P of the Ge laser was a major advantage. Several groups have reported operation of this laser [10–12] which is becoming established as the collisionally excited laser of highest efficiency for producing gain with gl/P up to 70 TW^{-1} [6].

We have previously measured both time and angularly resolved spectra from the Ge laser [10], and have studied the gain as a function of irradiance [13]. We found optimum efficiency at 1.2×10^{13} $\mathrm{W\,cm^{-2}}$ in 100-μm-wide line foci giving $g = 3.8$ $\mathrm{cm^{-1}}$ in plasmas up to 3 cm long. This initial work used three beams of the six-beam Vulcan Nd:glass laser.

Deploying the additional three beams 180° opposed in another line focus enabled a double-plasma experiment with compensation for refractive deviation of the beam [11,13–15]. In our work 200-fold enhancement of the emission from a 22-mm-long source plasma was demonstrated with an additional 14-mm amplifying plasma.

We now report the use of this double-plasma configuration with an XUV mirror to double-pass the double plasma. The mirror increased the laser output by a factor of typically 30× which is much larger than has been observed in previously reported experiments with XUV mirrors [16–18] and similar to another recent observation [19].

The mirror was a Mo/Si multilayer with a measured reflectivity at 23.6 nm of 28% [20]. It was concave with a radius of curvature of 13 cm and was positioned 2 cm from the 22-mm plasma, which in turn was separated 0.6 mm axially from the 14-mm plasma. The targets were evaporated stripes of germanium on glass substrates. They were in a preadjusted assembly with a lateral separation of 200 μm ± 10 μm (determined from previous work to give the best coupling between the two plasmas) [15]. The mirror was also prealigned to the axis of the x-ray laser which was shown from previous measurements [15] to be shifted by refraction by 10 mrad from the plane of the target surface. The line foci were placed on the germanium stripes with ±15 μm and ±1 mrad accuracy.

Three beams produced the 22-mm-long line focus. Their 18-mm line foci were displaced axially to form a line focus up to 26 mm long in which a 22-mm-long and 120-μm-wide Ge stripe target was placed. The other three beams had 18-mm line foci superimposed to irradiate a 14-mm-long 160-μm-wide Ge stripe target. The intensity in the line foci was $(2.3\pm0.5)\times10^{13}$ W cm^{-2} and the 1.05-μm laser pulses were of duration 0.5 ns.

A flat field grazing-incidence XUV spectrometer with a 1200-line/mm grating recorded the axial spectrum [10]. Overlap of higher orders was eliminated by use of two parallel Au mirrors at 8° grazing incidence which cut out radiation at wavelengths <5 nm. The mirrors were located behind the 80-μm-wide entrance slit of the spectrometer and the slit was 15 cm from the end of the plasma. Variable attenuation up to $\times10^5$ was obtained with aluminum filters. A potassium acid phosphate crystal spectrometer recorded the x-ray resonance spectra of Ge XXIII with spatial resolution along the plasma [13]. The uniformity of the irradiation along the line focus was optimized by observation of the ratio of the neonlike to fluorinelike spectral lines [13].

Axial spectra were recorded in three ways. Time-averaged spectra with angular resolution were obtained using Kodak 101 XUV film in the focal plane. Time-resolved spectra were obtained by placing an XUV streak-camera slit across the spectrum at the angular peak of emission. In addition, a novel observation was made in which the 23.6-nm spectral line was aligned along the slit of the streak camera so that the streak displayed the temporal variation of the angular distribution of the emission of this line only.

Time-resolved spectra were obtained for single plasmas of 22 mm length with and without the mirror and for double plasmas (22+5 mm, 22+9 mm, and 22+14 mm) with and without the mirror. Relative intensities were obtained by densitometry of streak records as in our previous work [10,13]. The intensity data for the most intense (23.6 nm) $J=2$-1 transition are plotted in Fig. 1 against the effective gain length gl of the system. For the single target plasmas, the effective gl is simply the length multiplied by the gain coefficient 4 ± 0.5 cm^{-1}. The gain coefficient was determined from the exponential form and fitted slope of the data in Fig. 1. Data from our previous study [10] of gain in a single plasma are also included in Fig. 1 to show the similarity of their exponential growth of intensity. Intensities are shown with an arbitrary normalizing factor between the two sets of data. It is important to note that with the mirror and double-target combination the 23.2-nm line was up to 2:1 more intense than the 23.6-nm line, in contrast to the typically 0.7:1 ratio observed for low gl. The change in intensity ratio occurs mainly in the rollover region of Fig. 1 and is not explicable if the rollover is due to refraction limiting the gain length as both lines would be affected identically. It is, however, consistent with saturation because the ratio of the saturated intensity for the 23.2:23.6-nm lines is 2:1 as seen experimentally and the change of ratio due to saturation is then expected to occur in the rollover region.

The relative intensities of unsaturated ASE from single plasmas were used to determine the effective feedback

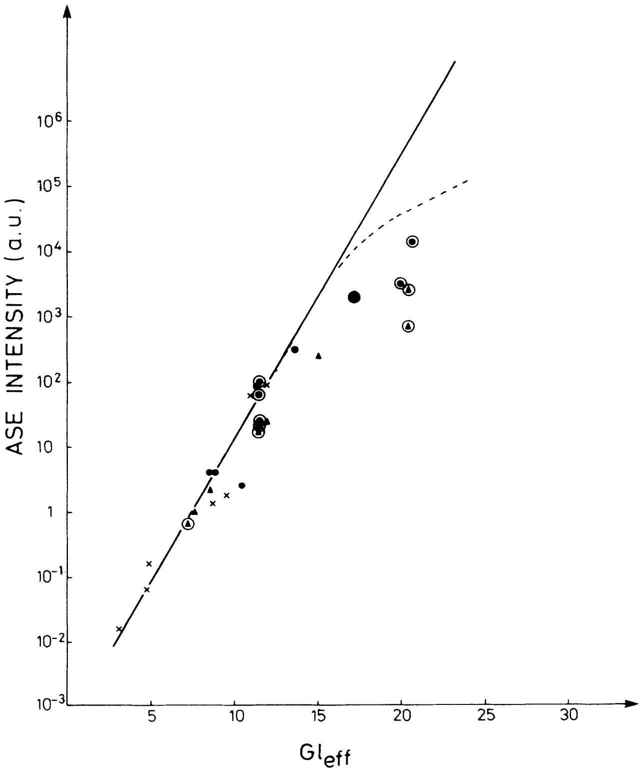

FIG. 1. Ordinate: peak ASE intensity in arbitrary units; abscissa: effective gain length $gl_{\rm eff}$. Solid circles are from time-resolved spectra. Triangles are from time-resolved angular distribution of emission. Those shots with mirrors are circled. Crosses are from our previous experiment [10]. The solid line shows intensity proportional to $\exp(gl_{\rm eff})$ and the broken line shows our model calculations of the effect of saturation.

fraction from the mirror into the plasma by matching outputs with a mirror to those without. With the mirror and a single plasma of length l_1 the effective gl was $2gl_1+\ln\eta$, where η is the feedback fraction from the mirror. From the typically 30-fold increase in output brightness for the 22-mm plasmas obtained by adding the mirror, it was established that the effective feedback from the mirror was $\eta=(1.7^{+1}_{-0.7})\times10^{-2}$. This is significantly less than the measured 28% reflectivity [20] of the mirror. Damage spots equal in size to the protective aperture in front of the mirror were produced on every shot. It is evident that damage during the laser pulse significantly reduced the effective reflectivity in operation from its initial value. The mechanism has not been identified but thermal radiation seems the most probable cause.

The temporal variation of the gain was also considered in determining the effective gl. It was deduced from the time variation of the ASE brightness for the 22-mm plasmas. The proportionality $I(t)\sim\exp[g(t)l]$ was used with the maximum g value being 4 cm^{-1}. The finite transit time of the radiation through the system for the double plasmas and with the mirror was then used to deduce the slightly reduced effective gain coefficient for the different cases in order to plot effective gl values in Fig. 1. This correction was limited to a maximum reduction of time-averaged gain from 4 to 3.4 cm^{-1} for the longest double plasma and mirror combination.

The data in Fig. 1 show an exponential increase for effective gl values less than about 14, above which they roll over into saturated behavior for effective gl values up to 20.5. We believe this is the first unequivocal demonstration of saturation of an XUV laser and of the effective use of a mirror to significantly increase the gain length of the laser.

Confirmation of the saturated behavior was obtained by numerical modeling [7] of the relative intensity of ASE in a homogeneous plasma column with the same length and transverse dimensions of the gain region [13,15] (100 μm×60 μm) as used in this experiment. In this model the value of α was 5 and β was 270, the former appropriate for gain narrowing of ASE at gl values giving saturation and the latter specific to Ge XXIII [21]. The results in Fig. 1 show reasonable consistency between the observed gain saturation and that predicted. The model computes the laser output in units of the saturation intensity and its results have been scaled to fit the experimental data in the unsaturated range of gl in Fig. 1.

The exit aperture of the gain region (100 μm×60 μm) [13,15] and the length and mirror curvature establish a Fresnel number for the system of 0.8. At this Fresnel number the radiation field at the exit from the system would be approximately diffraction limited in a homogeneous plasma for saturated gain. The optical system is effectively semiconfocal with the focal point of the mirror (focal length $L=6.5$ cm) close to the exit end of the second plasma. The diffraction-limited beam waist of a confocal Gaussian beam is of diameter $(2\lambda L/\pi)^{1/2}$ which for the present example is 44 μm, i.e., similar to the aperture of the gain region.

Measurement of the time-resolved divergence in the plane of the target normal gave the results shown in Fig. 2. For a single plasma of length 22 mm the divergence of 8.8 mrad is about twice that computed for an optically uniform gain medium of 60 μm width and 22 mm length with $gl=8.4$. In Fig. 2 the double plasma with the mirror shows a burst of emission (superimposed on a broader

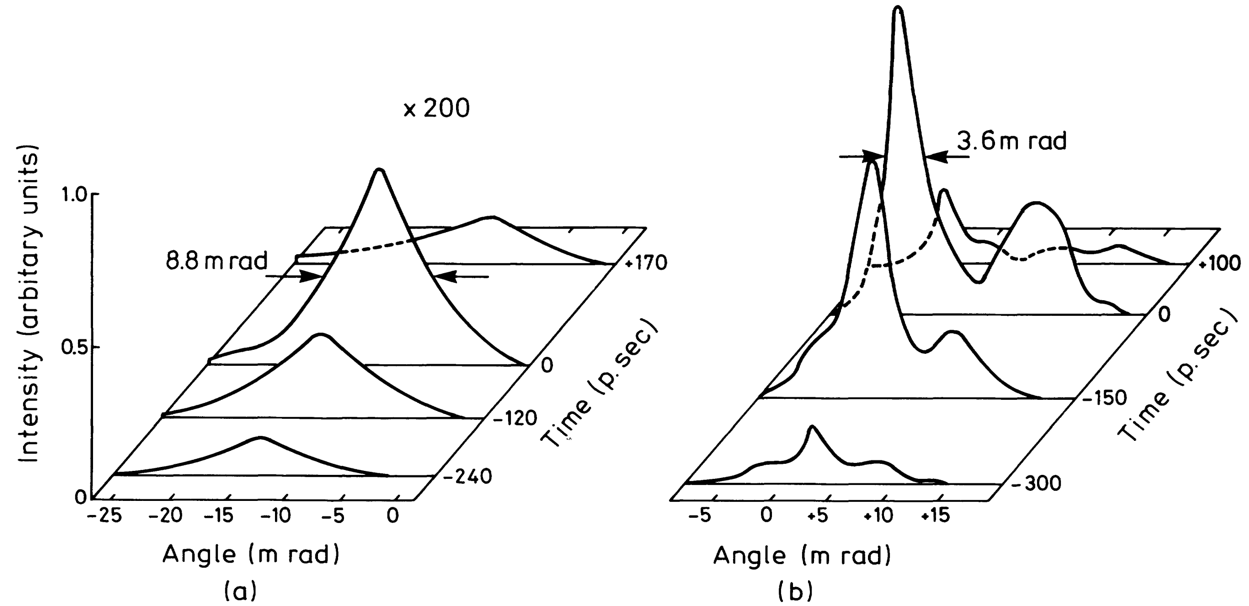

FIG. 2. ASE intensity (in arbitrary units) plotted as a function of both angle and time from streak-camera data. (a) 22-mm single target without mirror [sensitivity 200× greater than (b)]; (b) double target (22+14 mm) with mirror.

background) which is significantly more localized in angle and time with an angular width of 3.6×10^{-3} rad and a duration of 150 psec. This angular divergence is approximately 8× the angular width of an ideal semiconfocal mode implying an approximately 5-μm spatial coherence length.

The brightness of the source was deduced from time-integrated spectra recorded on Kodak 101 film of calibrated sensitivity [10]. The spectral intensities provide a value for the emitted energy per steradian which, with the estimated source aperture of 60 μm × 100 μm, gives a source brightness of 1.3×10^{14} W cm^{-2}sr^{-1}. The accuracy of this value is limited by the uncertainty in the film calibration, grating reflectivity, and beam divergence in the dispersion plane to within a factor of 4. The output pulse duration was assumed to be 250 psec as observed in the streaked spectra.

The increase of beam divergence above the level expected for an optically uniform medium can be qualitatively understood through refraction producing changes in angle of the order of the observed divergence (3.6 mrad) over a transverse scale of the order of the inferred mode size (5 μm). Further, more detailed analysis of the divergence data is planned in order to relate it to numerical modeling of the plasma hydrodynamics and gain production process.

The time and angularly resolved brightness data for different lengths of plasma with and without mirrors were used to give a third set of values of brightness as a function of effective gain × length product which is included in Fig. 1, with an arbitrary intensity scaling to match the unsaturated data from the time-resolved spectra. The additional brightness values measured at the time and angle of maximum brightness give further support to the observation of saturation.

In conclusion we have shown that by use of a double plasma and an XUV mirror, gain saturation has been reached in an XUV laser at 23.6 nm. The system has been operated with a Fresnel number close to unity and the beam divergence is about 8× that of an ideal semiconfocal mode. The brightness of the source reached values of approximately 1.3×10^{14} W cm^{-2}sr^{-1}.

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[20] The mirror was coated by C. M. Falco, J. M. Slaughter, and D. Schulze, Laboratory for X-ray Optics, Optical Sciences Center, University of Arizona, Tucson, on an ultrasmooth substrate machined by Carl Zeiss, Ltd. Its reflectivity was measured by M. Kühne of Physikalish-Technische Bundesanstalt Institut, Berlin, to be 30% at the 24.00-nm spectral peak and 28% at 23.60 nm.

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