

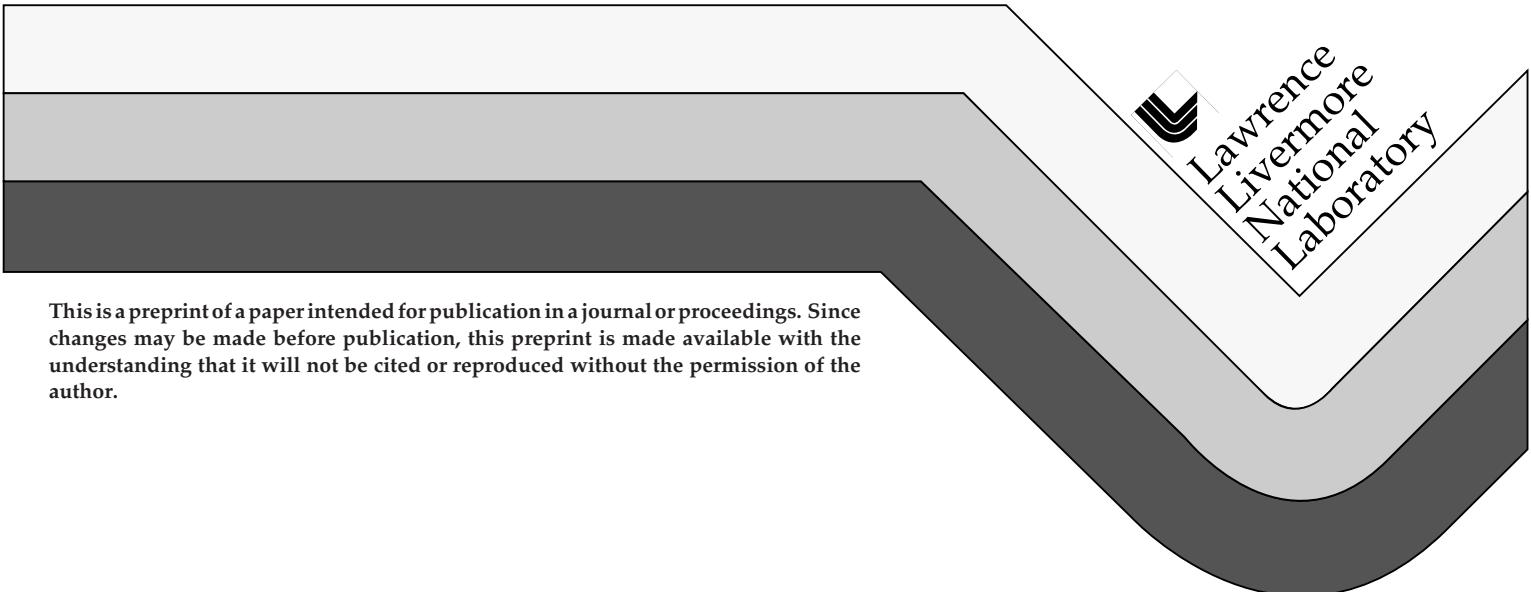
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# Measurement of spatial gain profiles in multiple-pulse driven Ne-like Ge lasers

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## ABSTRACT

We present the first direct spatial measurement of the two dimensional gain profiles for a Ne-like ion using a slab target illuminated by the multiple pulse technique. To understand the spatial dependence of the gain in Ne-like Ge on the 19.6 nm laser line for plasmas driven by a series of 100 ps pulses 400 ps apart we did a series of Nova experiments backlighting short Ge amplifiers. Two-dimensional, high-resolution, spatial images of the 19.6 nm laser emission from the output aperture of the amplifiers were measured to determine the spatial position of the gain. The amplifier lengths were chosen to be short enough to avoid significant refraction of the beam. In previous imaging experiments which measured the near field output of the Ge laser, the position of the laser output was dominated by refraction effects. To assure good temporal overlap, we used the traveling wave geometry to illuminate both the amplifier and backscatter. The amplifier design included a wire fiducial which provided an absolute spatial reference and avoided the usual difficulty of determining the location of the target surface. We compare the measured gain with simulations done using LASNEX, which calculates the hydrodynamic evolution of the plasma, and XRASER, which uses the temperature and densities from LASNEX to do the gain and kinetics calculations.

**Keywords:** X-ray laser, multiple pulse technique, plasma imaging

## 1. INTRODUCTION

With most researchers now using shaped pulse techniques[1], such as the prepulse technique[2], the multiple pulse technique[3], or other variations[4], the neon-like  $3p\ 1S_0 \rightarrow 3s\ 1P_1$  laser line now dominates the laser output in neon-like systems as was originally predicted twenty years ago[5]. To understand the reason why this line now lases so well, imaging experiments have been done to measure the near field spatial dependence of the laser output under various illumination conditions[6-8]. However, those experiments were unable to measure the spatial position of the gain directly because the spatial distribution of the laser emission was determined primarily by refraction for the long lasers used. In this work we overcome the refraction limitation by imaging the near field output of short neon-like germanium amplifiers which are backlit with output from a long neon-like germanium laser. These measurements are compared with calculations.

## 2. EXPERIMENTAL SETUP

The experiments were conducted on the Nova 2 beam laser facility laser at Lawrence Livermore National Laboratory (LLNL). The Nova laser produced a series of three 100 ps full-width half maximum (FWHM)Gaussian pulses which were 400 ps apart (peak to peak). The second harmonic,  $\lambda = 0.53\ \mu\text{m}$ , was used. Each pulse produced 400 J of energy in a 120  $\mu\text{m}$  wide (FWHM) by 4.5 cm long line focus, resulting in a peak intensity of  $74\ \text{TW}/\text{cm}^2$ .

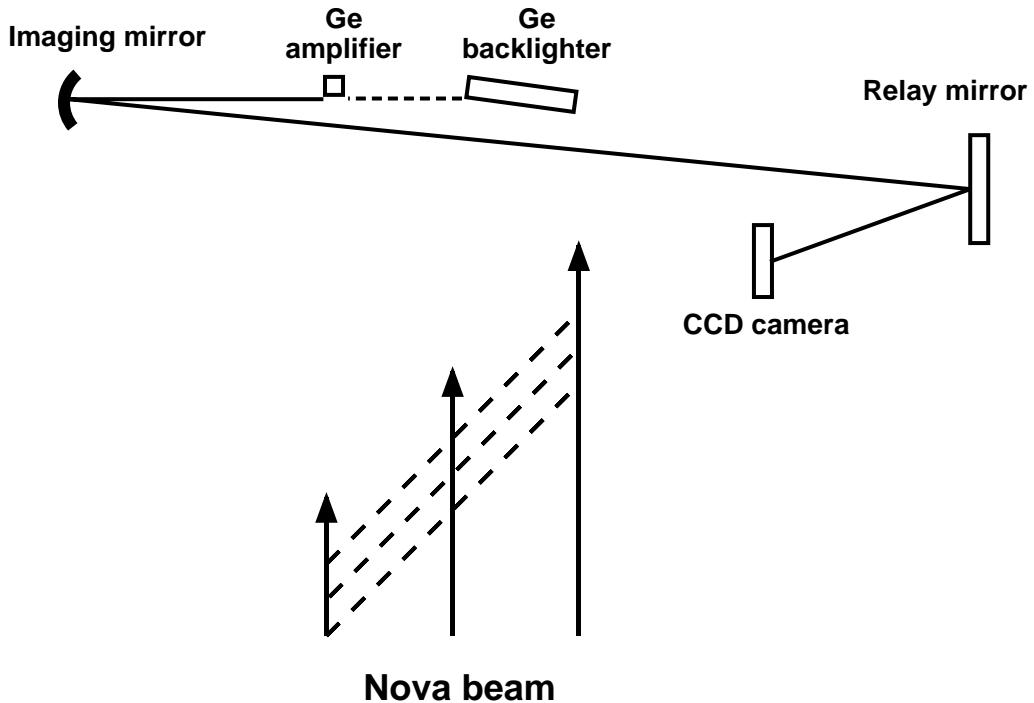


Fig. 1. Schematic of the experimental setup.

Figure 1 shows a schematic of the experiment. The target consisted of two parts; a 1.89 cm long germanium laser which served as the backscatterer and a short germanium amplifier which was varied in length from 0 to 0.6 cm. Solid germanium slabs of 0.1 cm thickness were used to fabricate the target. The overall length of the target from the back end of the long backscatterer to the output end of the short amplifier was held fixed at 4.5 cm. For the 0.3 cm long amplifier, this corresponds to a gap of 2.31 cm between the backscatterer and the amplifier. Because the typical laser output of a germanium laser is refracted off axis we tilted the 1.89 cm long germanium laser by 9 mrad so that it would more uniformly illuminate the amplifier. The short germanium amplifier had a 25  $\mu\text{m}$  diameter aluminum wire centered above the target surface several hundred microns from the output end of the laser to serve as an absolute spatial fiducial in the measurements. The position of the wire was carefully measured for each target. The target was illuminated using the traveling wave setup[3] so that the Nova beam would illuminate the target from end to end at a phase velocity equal to the speed of light with the Nova beam first illuminating the 1.89 cm long section which would simultaneously backlight the amplifier as it was being driven by the Nova laser.

The two-dimensional(2D), high-resolution, spatial imaging diagnostic consisted of a 25 cm focal length (50 cm radius of curvature) molybdenum/silicon multilayer mirror placed 25.9 cm from the output end of the germanium laser at near normal incidence. The multilayer mirror consisted of twenty layer pairs with a spacing of 10.3 nm which gave the mirror a peak reflectivity of approximately 40% and bandwidth of 1.5 nm for 19.6 nm radiation at normal incidence. This mirror imaged the output aperture of the short germanium amplifier onto an X-ray CCD camera which was placed 720 cm from the mirror. A second flat molybdenum/silicon multilayer mirror was used between the imaging mirror and CCD to relay the image and block additional background. Aluminum filters with 3  $\mu\text{m}$  total thickness were used to attenuate the signal and further eliminate shorter and longer wavelength signals which could be reflected off the mirrors. The CCD consisted of a 1024 by 1024 array of 24  $\mu\text{m}$  pixels. The magnification was 27.8, resulting in spatial resolution of better than 1  $\mu\text{m}$ .

### 3. EXPERIMENTAL RESULTS

From our previous experiments[3,7] we know that for long lasers, like the 1.89 cm long germanium backscatter, lasing occurs during the second and third Nova drive pulse with X-ray laser pulse durations of approximately 50 ps and that lasing during the third pulse is an order of magnitude brighter than during the second pulse. For that reason, the time integrated data recorded by the CCD camera is primarily a snapshot at the time of the third Nova drive pulse with the 1.89 cm germanium laser acting as a 50 ps gate for the CCD camera. Using the setup shown in Fig. 1 we did a series of experiments using different length amplifiers. Figure 2 shows a 2D image of the near field emission from a backlit 0.3 cm amplifier. The Nova laser is incident from above with the target surface at zero on the vertical axis. The plasma is expanding upwards in the vertical direction.

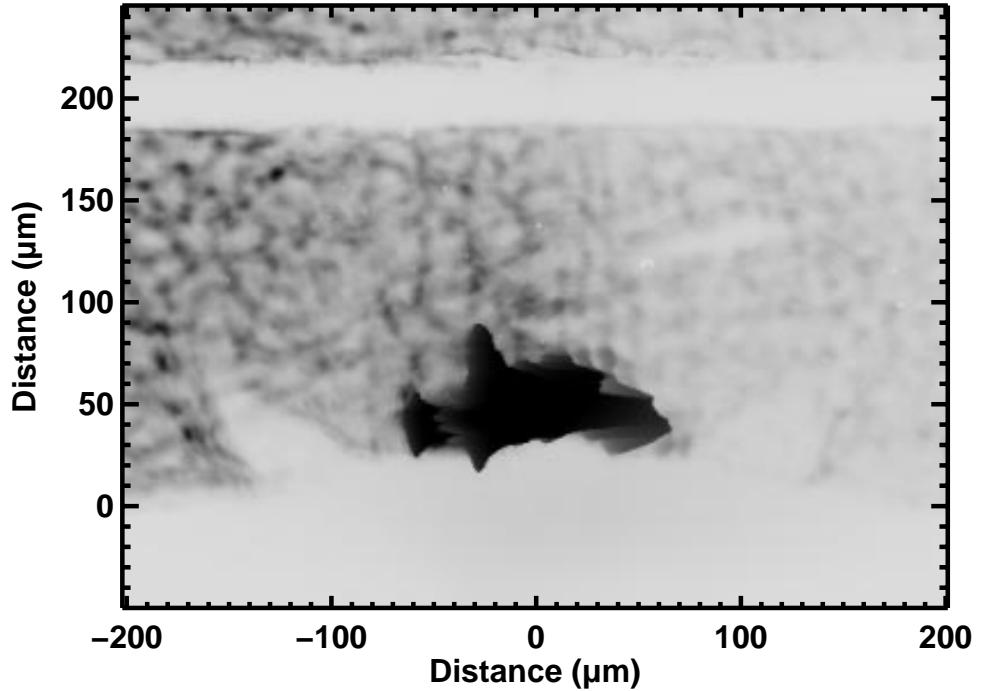


Fig. 2 2D image of the near field 19.6 nm laser emission from a backlit 0.3 cm amplifier.

For this target the fiducial wire is centered 202  $\mu\text{m}$  above the target surface and is visible as a white horizontal stripe in the figure. The horizontal axis is the transverse direction of the Nova line focus. The black area is the position of the laser emission at 19.6 nm from the germanium amplifier. The lasing peaks about 45  $\mu\text{m}$  from the target surface and has a horizontal width of approximately 130  $\mu\text{m}$ , which corresponds closely to the width of the Nova line focus. In previous experiments with 3 cm long lasers, the laser emission peaked 160  $\mu\text{m}$  from the target surface and calculations showed that refraction was bending the beam away from the surface, making it impossible to measure the actual position of the gain region. In this experiment, the amplifier is an order of magnitude shorter and refraction should be a very small effect since refraction is proportional to the propagation distance squared. The laser emission in Fig. 2 is a measurement of the location of the gain region with some small corrections. Experiments were also done for amplifier lengths of 0.1, 0.2, and 0.6 cm. Very

similar results were seen. For the 0.6 cm length the data was saturated while it was very weak for the 0.1 cm length. The best data was obtained for 0.2 and 0.3 cm lengths.

To determine a gain from this data we need to know the intensity of the backscatterer, the self emission of the amplifier, and other backgrounds. We did experiments with no amplifier to characterize the backscatterer and an experiment with a 0.3 cm amplifier without a backscatterer to look at the self emission from the plasma. Because our backscatterer was so close to the amplifier there was significant variation across the backscatterer at the position of the amplifier. This can be seen in Fig. 2 as the variation from left to right and is a factor of two across the width of the amplifier. One also notices what appears to be laser speckle from the backscatterer. The backscatterer actually peaks several hundred microns to the left of the amplifier position. This seems to be due to the Nova line focus not producing a perfectly straight line focus. The self emission is evident as the weak emission which extends below the target surface and is no doubt due to very late time emission as the crater is created in the germanium slab from the hydrodynamic expansion of the hot material. The non uniformity of the backscatterer, the uncertainty in the background subtraction of the self emission and other background, as well as slight saturation of the CCD make it difficult to determine the actual gain from the data. However, from the 0.2 and 0.3 cm amplifier experiments we can put a lower bound of  $8 - 12 \text{ cm}^{-1}$  on the peak gain.

To produce a more uniform backscatterer other experiments[9] have used a separate backscatterer which was collimated by a multilayer mirror and produced a larger more uniform backscatterer which was propagated at least 50 cm before illuminating the amplifier. However those experiments used much longer drive pulses (600 ps) from Nova and the  $J = 2 \rightarrow 1$  laser line from a neon-like yttrium laser. The yttrium laser is complicated because the  $J = 2 \rightarrow 1$  and  $J = 0 \rightarrow 1$  laser lines overlap and the relative contributions are unknown. This line overlap no doubt helps to explain why the yttrium laser tends to be quite bright compared to other nearby elements but also makes it difficult to use to understand the physics of a particular laser transition. Since the laser gain duration is typically at least half of the drive pulse duration this made it practical in Ref. [9] to time the backscatterer with the amplifier even with 100 ps timing uncertainties between the two Nova beams. Even though the yttrium laser being used as a backscatterer had only a 75 ps duration because of the high gain, the short backlit yttrium amplifier had gain durations of many 100's of psecs. With the much shorter Nova drive pulses (100 ps) used in this work and the use of the  $J = 0 \rightarrow 1$  laser line, which has a shorter gain duration, the use of a separate backscatterer would have made it very difficult to accurately time the arrival of the backscatterer with the Nova drive on the amplifier. By using the traveling wave geometry with one Nova beam illuminating both the backscatterer and amplifier we insure that the backscatterer is illuminating the amplifier at the same time as the gain is being created. We should also point out that our work uses a simple imaging system with two multilayer mirrors to measure the absolute position of the gain region for a slab target at the time of peak lasing. In contrast, Ref. [9] was a proof of principle experiment which looked at exploding foil targets with a complex interferometer which used a minimum of six multilayer optics and which needed to be rebuilt after every experiment because some of the optics, such as the beam splitters, were destroyed after each shot. The experiments in Ref. [9] had neither an absolute time nor spatial fiducial.

#### 4. PLASMA MODELING

We modeled these experiments using LASNEX one-dimensional (1D) and two-dimensional (2D) computer simulations[10] of the germanium slab illuminated by three 100 ps pulses. The 1D LASNEX calculations included our usual expansion angle of 15 degrees in the dimension perpendicular to the primary expansion so as to simulate 2D effects. The densities and temperatures calculated by LASNEX were used as input to the XRASER code[11], which calculated the gains of the laser lines including radiation trapping effects on the  $3s \rightarrow 2p$  transitions in neon-like germanium. The XRASER calculations also included the Bulk Doppler effects due to the expansion of the plasma. For the 2D LASNEX calculation we used a 1D slice from the middle of the line focus as input to the 1D XRASER calculation. Figure 3 shows a lineout(solid line) of the intensity of the laser emission for the 0.3 cm long amplifier which is averaged over a  $86 \mu\text{m}$  stripe through the middle of the amplifier versus distance in the plasma expansion direction. The sharp drop in intensity centered at  $202 \mu\text{m}$  clearly

shows the position of the 25  $\mu\text{m}$  diameter aluminum wire fiducial. This experimental data is compared with the calculated gain(dotted lines) for the 19.6 nm line at the time of peak gain for the third Nova drive pulse versus distance from the target surface in the plasma expansion direction as calculated by XRASER using the 1D and 2D LASNEX calculations as input. The gain peaks at 60  $\mu\text{m}$  for the 1D case and 50  $\mu\text{m}$  for the 2D case. One sees that the laser emission is closer to the surface than either calculation and points out the need for more detailed calculations which have finer spatial zones near the critical density surface and better temporal resolution. More complete 2D calculations are also needed to see how the gain varies transversely across the line focus.

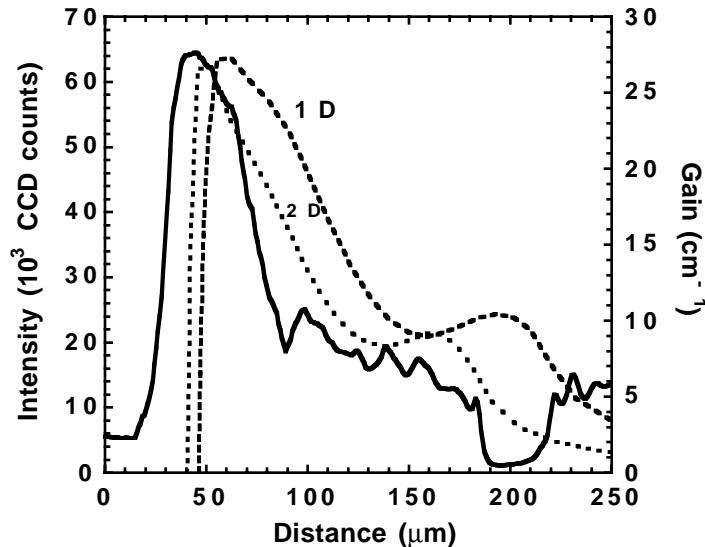


Fig. 3. Spatial dependence of the average 19.6 nm laser emission(solid line) from the 0.3 cm long amplifier versus distance in the plasma expansion direction. This is compared with the calculated gain(dotted lines) for the 19.6 nm line at the time of peak gain for the third Nova drive pulse versus distance from the target surface in the plasma expansion direction as calculated by XRASER using the 1D and 2D LASNEX calculations as input.

## 5. CONCLUSIONS

In conclusion, we present high-resolution, two-dimensional, spatial images of the 19.6 nm neon-like germanium laser emission at the output aperture of short amplifiers backlit by longer germanium lasers. The backscatterer and amplifier are both created by illuminating the targets by a series of 100 ps pulses from the Nova laser. The images show the peak of the laser emission, which corresponds to the gain region, to occur about 45  $\mu\text{m}$  from the target surface. The simulations show the gain peaking 50 to 60  $\mu\text{m}$  from the surface. This is an important first step in understanding where the gain is originating in these plasmas and more experiments are needed to quantitatively map out the gain profiles and to measure other plasma parameters such as the temperature and density to compare with calculations.

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