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Joseph Nilsen, Juan C. Moreno, Luiz B. Da Silva,
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Lasing at 79 \AA in Ni-like Nd Using Multiple Pulse Illumination and Other New Results

Joseph Nilsen, Juan C. Moreno, Luiz B. Da Silva, and Jeffrey A. Koch

Lawrence Livermore National Laboratory
P. O. Box 808, Livermore, California 94550

ABSTRACT

We present results which show lasing at 79 \AA in nickel-like neodymium ($Z=60$) when a series of short 100 - 150 ps pulses which are 400 - 500 ps apart are used to illuminate slab targets of neodymium. This multiple pulse technique was first used successfully with germanium and selenium targets where strong lasing was observed on the neon-like $3p \rightarrow 3s(J = 0 \rightarrow 1)$ transitions at 196 and 182 \AA , respectively. We also will present results which use this technique on both higher and lower Z targets of neon-like ions. For the higher- Z ions such as yttrium, zirconium, and molybdenum we observe the usual lasing dominated by the pair of $3p \rightarrow 3s(J = 2 \rightarrow 1)$ transitions as seen in other experiments using single pulse illumination. For lower- Z ions such as iron, nickel and zinc we see dominant lasing from the $3p \rightarrow 3s(J = 0 \rightarrow 1)$ transition however it is relatively weak for iron and increases with Z to become quite strong for zinc. We present results which show the advantages of coupled slab targets and of using a traveling wave geometry to drive targets with these short pulses. The main result of this work is combining the advantages of the double slab targets, the traveling wave geometry, and the multiple pulse technique to improve the output of the nickel-like neodymium laser at 79 \AA .

Keywords: X-ray laser, multiple pulse technique, neodymium

1. EXPERIMENTAL SETUP

Experiments were conducted at Lawrence Livermore National Laboratory (LLNL) on the Nova laser using $\lambda = 0.53 \text{ \mu m}$. Figure 1 shows the experimental geometry for the neodymium targets which yielded the best results. One beam of the Nova laser illuminated the 1 \mu m thick neodymium coating on a 3.0 cm long copper slab which had a

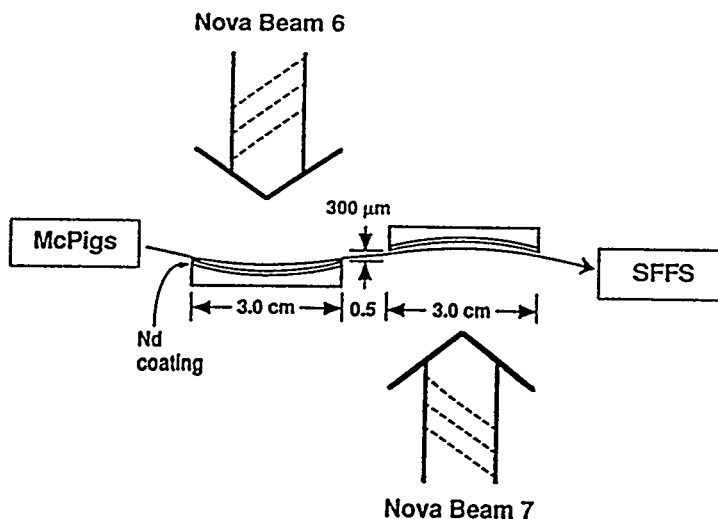


Fig. 1. Schematic of the double slab neodymium target.

0.48 cm gap in the middle resulting in an actual length of 2.52 cm. A second Nova beam illuminated a similar slab target which was coupled lengthwise with the first target but illuminated from the opposite direction using a 300 μm gap between targets in the plasma expansion direction. To help compensate for the effects of refraction the target surfaces were curved using a 250 cm radius of curvature. The Nova laser produced a series of 150 ps FWHM Gaussian pulses which were 500 ps apart. Each pulse produced 600 J of energy in a 120 μm wide by 3.6 cm long line focus, resulting in a peak intensity of 110 TW/cm². A traveling wave geometry¹ was used so that both Nova beams would illuminate the target from left to right at a phase velocity equal to the speed of light. Nova beam 7 was delayed by 117 ps to account for the transit time from the left end of the first slab target to the left end of the second target, which were 3.5 cm apart. For the neon-like ions we used a single flat slab target instead of the curved double slab targets shown in Fig. 1 and used three 100 ps pulses separated by 400 ps.

The principal instruments were a time-gated, microchannel plate intensified grazing-incidence grating spectrograph(MCPIGS) and a streaked flat field spectrograph(SFFS); both of these instruments observed the axial output of the X-ray laser. The MCPIGS provided angular resolution over 10 mrad near the X-ray laser axis, while the SFFS integrated over an angular acceptance of 10 mrad. The angular resolution of both instruments was perpendicular to the target surface. The MCPIGS used a 2400 line/mm grating and had spectral coverage of approximately 37 to 170 \AA for the neodymium experiments and used a 600 line/mm grating with 150 to 660 \AA coverage for most of the neon-like experiments. Figure 1 shows the traveling wave setup with the X-ray laser output pointing at the SFFS. This could be flipped over so that the X-ray laser beam would go from right to left and point at the MCPIGS spectrograph instead.

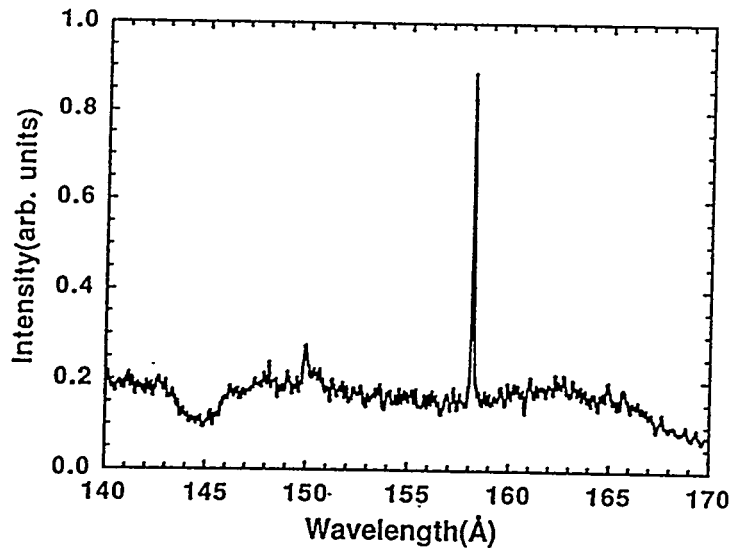


Fig. 2. MCPIGS spectra of the double slab neodymium target.

2. EXPERIMENTAL RESULTS

For the 6 cm long double slab neodymium target illuminated with three pulses as described above, Fig. 2 shows a spectrum from the MCPIGS spectrograph for the case of the traveling wave oriented toward this spectrograph. A single strong nickel-like neodymium $J = 0 \rightarrow 1$ laser line at 79 \AA , seen in second order at 158 \AA , dominates the emission spectrum. To calibrate the wavelength of the neodymium laser line, several experiments with single neodymium slab targets were done which had zirconium or molybdenum targets glued to the backside and oriented so that the neodymium spectrum and the zirconium or molybdenum spectrum would both be seen on the MCPIGS spectrograph. We used the fitted wavelengths² for the neon-like zirconium and molybdenum laser lines as reference lines to estimate the wavelength of the 2nd order neodymium laser line at 158.13 \AA . This gives a value of 79.06 \AA for the wavelength of the

neodymium laser line with an estimated uncertainty of 0.1 \AA . This is described in more detail in Ref. 3.

The solid curve in Fig. 3 shows the intensity versus time for the 79 \AA laser line as recorded by the SFFS spectrograph for the case of the 6 cm long double slab neodymium target illuminated by the traveling wave oriented toward this spectrograph. The dotted line shows the time history of the continuum radiation in a 6 \AA wide band centered at 70 \AA . The 79 \AA lasing has a FWHM duration of 38 ps and occurs during the rising edge of the second pulse 140 ps before the peak of the continuum emission. For this experiment the Nova energy fell by 30% on the third pulse so no lasing was observed. In experiments done with single slab targets we have seen lasing on the second and third pulse, as expected. The group at Osaka has seen lasing on this same transition with a duration of 70 ps which occurs before the peak of the second 100 ps drive pulse.⁴ As discussed later, we do not expect to see any lasing on the first pulse, whose main purpose is to prepare the plasma. A big advantage of using the traveling wave geometry, in addition to allowing longer targets, is the removal of the transit time effect which greatly complicates the measurement of pulse durations and timing issues. For a typical 3 cm long target, the 100 ps transit time is comparable to the pump duration.

For the SFFS spectrograph the lasing disappears when the traveling wave setup is oriented away from the SFFS and towards the MCPIGS spectrograph. On the MCPIGS we observe the 79 \AA lasing line for both cases, but it does become about 6 times brighter when the traveling wave setup is oriented towards the MCPIGS. From calculations of integrated intensity for a laser going with versus against the traveling wave, as described in Ref. 1, we estimate the gain to be approximately 1 cm^{-1} .

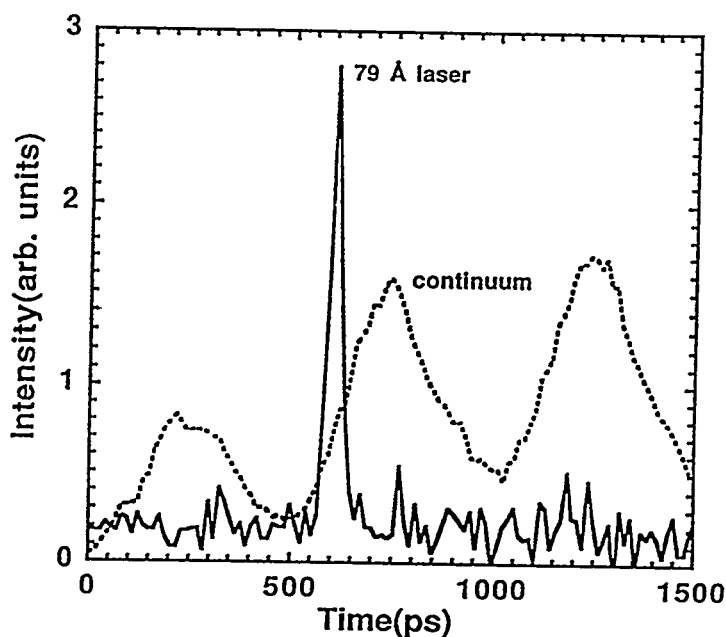


Fig. 3. Intensity of the 79 \AA neodymium laser line and continuum radiation vs time.

The multiple pulse technique was applied to the nickel-like neodymium after it had been used quite successfully on neon-like ions of germanium and selenium.^{1,5,6} In recent experiments we tried the multiple pulse technique on lower-Z ions of zinc, nickel, iron, and chromium. Recall that these ions have all lased very well on the $J = 0 \rightarrow 1$ line using the prepulse technique.⁷ For the multiple pulse experiments we used a series of three 100 ps pulses 400 ps apart. The targets were two 1.9 cm long slab targets which were combined lengthwise to make a single 4.5 cm long target. This way, two elements, such as nickel and ion could be looked at simultaneously on the MCPIGS and SFFS. We used 50 TW/cm^2

peak intensity on target. Figure 4 shows time integrated spectra from the SFFS for two targets, selenium and zinc, and nickel and iron. The spectra are integrated over the lasing duration during illumination by the second Nova pulse. For the selenium and zinc target, strong lasing on the $J = 0 \rightarrow 1$ line at 212 \AA is seen. The selenium does not lase because the Nova intensity is too low. For the nickel and iron target the nickel lases quite strongly at 231 \AA while the iron lases weakly at 255 \AA . The nickel also lases very weakly on the other $J = 0 \rightarrow 1$ line at 176 \AA . A third experiment done with an iron and chromium target shows weak iron lasing and no lasing in chromium. Other experiments done at higher intensity with yttrium, zirconium, and molybdenum targets show strong lasing only on the usual pair of $J = 2 \rightarrow 1$ lines. These experiments suggest that our choice of the parameters for the multiple pulse technique seems optimum for neon-like ions near $Z = 28 - 34$ while the prepulse technique works better for lower- Z ions.^{1,5-8}

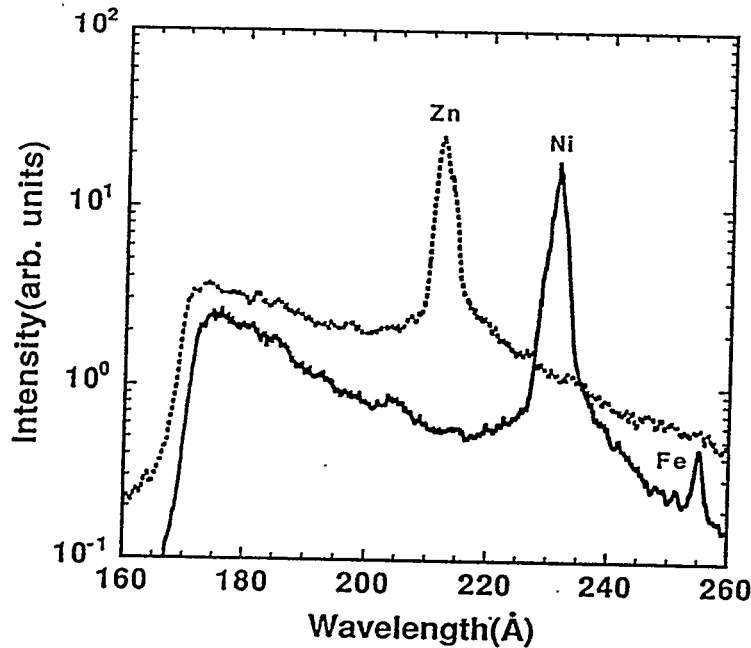


Fig. 4. SFFS spectra of zinc, nickel, and iron targets

3. ANALYSIS

For nickel-like systems our modeling of the laser-plasma interaction suggests that the multiple pulses are creating a larger, more uniform density plasma, at the densities required for lasing at these short wavelengths. The first pulse heats, ionizes, and expands the plasma. At this time the gradients in the electron density are too steep for any significant laser propagation and the gain region is very small. Between pulses, the plasma cools and recombines to nickel-like. In addition, this cooler plasma is not as transparent to the optical drive laser and energy from the subsequent optical pulses can be directly absorbed by the lasing region of the plasma during the rising edge of the optical pulse. The pulses can rapidly heat the plasma but do not have sufficient time to ionize the plasma significantly in the lasing region. During the second and third pulse stable regions of nickel-like ions are created which are at the right densities for gain and laser propagation. A complete description of the modeling for the case of neon-like selenium can be found in Ref. 5.

4. CONCLUSIONS

With the use of the multiple pulse technique we show that the $3p \rightarrow 3s$ ($J = 0 \rightarrow 1$) transition is greatly enhanced and dominates the output of the neon-like lasers with $Z = 28 - 34$. The success of the multiple pulse technique with neon-like ions is then extended to nickel-like slab targets. We achieve lasing in nickel-like ions using slab targets,

thereby overcoming the previous limitation which required the use of thin exploding foil targets illuminated from both sides to achieve lasing. We combine the use of coupled slab targets and curved surfaces with the traveling wave geometry to maximize the laser output. Finally we demonstrate lasing with a pulse duration of 38 ps on the $J = 0 \rightarrow 1$, $4d \rightarrow 4p$ transition at 79.06 Å in nickel-like neodymium when slab targets are illuminated by a series of 150 ps pulses.

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