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Spatially Resolved X-ray Laser Spectra and Demonstration of Gain in Nickel-Like Systems

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ABSTRACT

A recent series of experiments have provided spatially resolved near field images of several candidate x-ray lasing transition in neon-like, nickel-like, and hydrogen-like ions from laser-produced plasmas. From these time-gated, spatially, and spectrally resolved measurements the source size for the J-0-1 and the J-2-1 transitions in Ni-like selenium have been determined. Source regions as small as 50 μm have been observed on transitions with gain-length products >9 . In addition, we have obtained the first experimental evidence for the amplification of spontaneous emission in the nickel-like ions of europium and ytterbium. Gains of order 1 cm^{-1} and gain-length products of up to 3.8 are observed on the J-0-1, 4d-4p transitions in Eu^{+35} at 65.83 and 71.00Å. Analogous transitions in Yb^{+42} have been identified and some evidence for ASE has been observed.

1. INTRODUCTION

Since the demonstration of soft x-ray lasing in neon-like selenium by Matthews, et al.¹ and Rosen, et al.,² our research has been directed towards the understanding of Amplified Spontaneous Emission (ASE) in higher Z laser-produced plasmas, the development of a high gain ASE source below the carbon K absorption edge at 43.7Å, and ultimately, the application of x-ray lasers to produce holographs of living biological specimens. In this paper we present a detailed study of ASE in neon-like selenium, the first demonstration of gain in nickel-like europium, a lasing scheme which readily scales to sub-44Å, and the initial results of recombination lasing schemes involving hydrogen-like and lithium-like ions.

The investigations into neon-like systems have focused on the 3p-3s J-0-1 (182.4Å) transition and the higher gain J-2-1 (206.4, 209.8, 220.3, and 262.9Å) transitions in selenium.^{1,2} To this end we have developed an instrument which can provide a spatially-resolved, spectrally-resolved, and time-resolved measurement of the on-axis emission. The instrument allows us to better understand the dynamical properties and the inversion physics of high density x-ray laser plasmas. In addition, the instrument can operate in an alternate mode, one which measures the time-gated, spectrally resolved far-field radiation pattern. The one-dimensional near-field image measures the x-ray intensity as a function of position within the laser plasma, thus identifying the source region and its associated size for each wavelength. The far-field radiation pattern measures the angular distribution of radiation emitted from the entire plasma, thus providing the divergence of each lasing transition, as well as a precise measure of any refractive bending of the x-rays due to plasma density gradients. These measurements taken together provide a measure of the x-ray specific intensity emitted from the laser plasma.

Typical space and time scale lengths for these exploding foil targets are 100 μm and 200 ps, respectively. Thus, it is easy for weak gain transitions to become obscured without space and time resolution. Imaged spectra from nickel-like systems has allowed the rapid identification of weakly amplified transitions, by their localization to small regions within the plasma column. The nickel-like systems are analogous to the neon-like systems, with gain occurring between the 4d-4p levels of Ni-like ions.^{3,4,5} Experiments with nickel-like europium have unambiguously demonstrated gain on the J-0-1 transitions. The significance of this scheme is better appreciated when one examines the pump laser irradiance required to achieve a sub-44Å laser using a neon-like scheme, as compared to the more efficient Ni-like ions. An irradiance in excess of $1 \times 10^{10}\text{ W/cm}^2$ is required to produce neon-like Gd, where as nickel-like W is expected to produce gain at 43.15Å with a pump laser irradiance of $4 \times 10^4\text{ W/cm}^2$.⁷

We have also investigated hydrogen-like, helium-like, and lithium-like recombination lasers, which are an alternate path to the demonstration of gain below 44Å. These schemes should scale readily to sub-44Å, and the Li-like ions in principle can be more efficient

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converters. Preliminary experiments have focused on identifying the candidate lasing lines and understanding the global ionization balance.

2. EXPERIMENTAL ARRANGEMENT

The experiments are carried out in the Nova Two Beam Laser Facility, using two frequency doubled (KDP) laser arms with a wavelength of $.53 \mu\text{m}$. A dual-cylindrical lens pair provide a variable length line focus geometry (Figure 1), with focus spots of $100\text{-}300 \mu\text{m}$ in width and $0.5\text{-}5 \text{ cm}$ in length. Pulse widths of 100 ps to 1 ns and irradiances up to $1 \times 10^{14} \text{ (5 cm targets)}$ are available. The thin foil targets are composed of $10 \mu\text{g cm}^{-2}$ lexan substrate, with $50\text{-}100 \mu\text{g cm}^{-2}$ of Se, EuF_2 , or Yb deposited on one side.

Figure 1. Experimental set-up showing x-ray laser axis and diagnostics. On-axis McPigs at top is fitted with reentrant fore-optic to allow imaging.

The primary diagnostics are three 1-meter diameter Rowland circle, grazing-incidence spectrometers (McPigs), two of which were positioned to view along the target axis, and 45° off the target axis. The third spectrometer was fitted with reentrant fore-optics to allow spatial imaging in the sagittal plane of the spectrometer, and it was also aligned to view along the target axis. Additional diagnostics included a streaked x-ray crystal spectrograph, time integrated x-ray crystal spectrographs, and two x-ray pinhole cameras.

The McPigs spectrometers have a spectral resolving power of 1 part in 2000. The detector consists of a $75 \times 16 \text{ mm}$ micro-channelplate image intensifier aligned to the Rowland circle. The active areas of the detector designed to function as a 60 nm transmission line. This transmission line geometry allows the propagation of 100 ps , one kilovolt pulses, thus enabling the micro-channelplate detector to be turned on and off in a 100 ps (a 100 ps shutter!). The detectors are currently operated in a gate off mode, where the detector is active and integrating the incident photons for a fixed time interval and then gated off (50 ps transition time). The active area of the detector is coated with a thin layer of Cesium Iodide to enhance the sensitivity to XUV photons.

The one-dimensional imaging is accomplished with the use of a grazing-incidence cylindrical mirror. A diagram of relevant optics is shown in Figure 2. The axis of the cylindrical optic and the x-ray laser target are aligned, and then the mirror is rotated 3 degrees about the transverse axis to provide the correct focal length. This maps a one-dimensional image of the laser plasma transverse to the target axis onto the detector plane. The spatial magnification of the instrument can be varied from 2 to 4, and has a measured resolution of $20 \mu\text{m}$ (50% MTF) in the object (target) plane. Thus, the instrument can provide a spectrally resolved image of the x-ray emission from regions as small as $20 \mu\text{m}$ within a plasma whose dimensions are typically $600 \mu\text{m}$. The Imaging McPigs can also be configured to focus the light collected by the cylindrical optic at infinity (as opposed to focusing at the detector plane), thus allowing a spectrally resolved measure of the far field radiation pattern. The angular coverage is typically 45 mr .

Figure 2. Pictorial diagram of imaging optics and relevant components of McPigs spectrograph. A one dimensional image of the plane normal to the x-ray laser axis is formed on the detector plane.

3. IMAGED SPECTRA OF NEON-LIKE SELENIUM X-RAY LASER

We have recently begun a study of the spatial dependence of amplified spontaneous emission in neon-like selenium. This is our highest gain system demonstrated to date, exhibiting up to 16 gain lengths.^{1,2} The plasma is produced by a 500 ps, 3×10^{13} W cm⁻² pulse, incident on a 100 μ g cm⁻² selenium target. Figure 3 shows an imaged spectra from a 2 cm length Se target. The brightness displayed in the image is proportional to the logarithm of the emission intensity. The 3p-3s lasing transitions can be clearly identified in the imaged spectrum, by their small spatial extent in comparison to the non-lasing transitions as well as by their brightness. The insets in Figure 3 show the narrow spatial dependence of two lasing transitions, the J-0,1 (182.4Å) and the J-2,1 (206.4Å), and can be contrasted to an optically thick sodium-like line (201.0Å, a non-lasing transition) which shows a broad spatial extent. All of the lasing lines are well above the spontaneous emission level and are localized to the central plasma region, with sizes of approximately 200 μ m.

Figure 3. Enlargement of actual raw film data of 2 cm Se x-ray laser target. Image taken looking along laser axis, providing the radial intensity dependence of lasing transitions. 1 mm scale is in the object plane.

The dependence of source size with target length is shown in Figure 4. The transition shown is the brightest lasing transition, J-2,1 at 206.4 Å, and its width can be seen to narrow from 250 μm at 1 cm target length to 50 μm at 3 cm target length. There appears to be no further narrowing of the source size for 4 cm target lengths. The J-0-1 at 182.4 Å exhibits a similar narrowing with target length, continuing to decrease in size for up to 4 cm target length, the longest target measured. This decrease in source size is observed for the other lasing transitions and appears to be a function of gain-length product.

Previous gain measurements have shown that the Ne-like Se systems have a saturation length of approximately 4 cm, with a total output energy of a 160 μJ in a 170 ps FWHM pulse, with the energy split equally between the 206.4 and 209.8 lines. A total energy of 500 μJ from our longest target (5 cm) has been demonstrated though. From these data, the saturation intensity of the x-ray laser can be calculated using the measured source size of 50 μm, giving a saturation intensity of 1.6×10^{13} W cm⁻² for the 206.4 line. The predicted saturation intensity is 1.3×10^{13} W cm⁻², in close agreement with the experimental value. We are currently examining this data with regard to the spatial dependence of the gain coefficient in hopes of a better understanding of the inversion physics.

We have also measured the spectrally resolved far field radiation pattern for a 3 cm target length. This was accomplished by focusing the image at infinity on the spectrograph. The data for three lines is shown in Figure 5. The intensity of all the amplified lines (J-0,1, J-2,1) exhibit the same qualitatively behavior. The bimodal pattern can be partially attributed to refraction of the radiation by the plasma density profile, bending the x-rays off-axis. The data shows the same angular displacement on all lasing transitions, which is inconsistent with a wavelength dependent refraction. This inconsistency may be attributed to the time integrated measurement technique, convolved with a complex, wavelength dependent time behavior of the gain media. Future experiments will examine the time dependent spectrum in the far field.

Figure 4. Near field image of high-gain lasing transition for four target lengths. Source size is 50 μm for longest target length.

Figure 5. Far field radiation pattern for three transition.

4. DEMONSTRATION OF GAIN IN NICKEL-LIKE SYSTEMS

The recent series of experiments on nickel-like ions of europium (Z-63) and ytterbium (Z-70) have achieved gain at the shortest wavelengths demonstrated to date. This technique, although qualitatively similar, is expected to have several advantages over the neon-like systems. For nickel-like ions, gain is predicted for the 4d-4p transitions through collisional pumping. Neon-like systems, in contrast, operate in the n-3-3 manifold (3p-3s transitions), and the experimentally observed gain is larger on the J-2-1, instead of the J-0-1 transitions.^{1,2,6,8} The sub-shell splitting for the n=4 shell in Ni-like ions is larger than the n-3 shell in Ne-like ions. This leads to a shorter lasing transition for a given ionization potential in nickel-like systems, and therefore, inherently a more efficient scheme.

Typical on-axis and off-axis spectra for a 3 cm, 50 $\mu\text{g cm}^{-2}$, EuF_2 target, produced with a 1 ns pulse at an irradiance of $7 \times 10^{13} \text{ W cm}^{-2}$ show predominate lines of copper-like and nickel-like europium. The optically thick Cu-like 4s-4p lines have been identified by their on-axis and off-axis behavior. The previously unobserved 4d-4p Ni-like lines are seen at 65.83, 71.00, 100.39, and 204.56 Å, and are identified by the proximity of their wavelengths to theoretical values and their dependence on target length.

The non-linear behavior of the highest gain 4d-4p, J-0-1 Ni-like transitions are shown for three target lengths in Figure 6. The line at 71.00 Å is seen to gain in intensity with target length more rapidly than 65.83 Å line. Both the optically thick Cu-like line and the optically thin continuum are observed to scale as expected with target length, (constant and linear, respectively). The length scaling of the lines at 100.39 Å (J-2-1) is approximately linear. The observed gain for the 71.00 and the 65.83 Å lines are $1.11 \pm 0.12 \text{ cm}^{-1}$ and $0.61 \pm 0.14 \text{ cm}^{-1}$, respectively. The low gain observed on the J-1-1 and the J-2-1 transitions is believed due to trapping, thus consistent with their overall brightness (i.e., large source function and no gain).

Figure 6. On-axis spectrum for three target lengths is shown. Gain of order 1 cm^{-1} for the Ni-like lines at 65.9 Å and 71.04 Å are observed.

The nickel-like systems are expected to scale favorably with increasing Z to shorter wavelengths. Preliminary experiments with Ni-like ytterbium have identified the J=0-1 lines at 50.26 and 56.09 Å. Figure 9 shows the on-axis spectra for two target lengths. The line at 50.26 Å exhibits a non-linear increase with length, with a gain of order 1 cm^{-1} . The line at 56.09 shows little or no gain. The results were obtained with targets of $100 \mu\text{g cm}^{-2}$ Yb on $10 \mu\text{g cm}^{-2}$ CH irradiated at $1.4 \times 10^{14} \text{ W cm}^{-2}$ in a 1 ns pulse.

Figure 7. On-axis spectrum of Ni-like Yb for two target lengths. Gain can be seen on the J=0-1, 50.26 Å line.

An imaged spectrum for a 2 cm Yb target was measured with the detector gated on for 0.75 ns of the 1 ns drive pulse. Figure 10 shows the spatial dependence for the J=0-1 transitions at 50.26 and 56.09 Å and the continuum at 50.1 Å. The spatial profiles for the J=0-1 lines is obtained by subtraction of the continuum near each line from its profile. The dotted line represents the best estimate of the CH-Yb boundary and was estimated by the sharp increase in the continuum. The 50.26 Å line is seen clearly above the noise and localized to the high density/continuum region. Its FWHM is seen to be $100 \mu\text{m}$ in the target plane. The 56.09 Å line is localized to the same region and shows similar width.

Figure 8. Spatial line-outs for two transitions in Yb plasma, and the underlying continuum gain is seen on the J=0-1 at 50.24 Å and exhibits a source size of $100 \mu\text{m}$. The x-axis zero is estimated to be the location of the center of mass of the exploding foil, obtained by comparison with simulation data.

5. RECOMBINATION EXPERIMENTS

Achieving amplification of soft x-rays below the carbon K absorption edge (43.7Å) using recombination plasmas is currently being explored. Our initial experiments have examined aluminum (H-, He-, Li-like), calcium (Li-like), and chromium (Li-like) ions. Recombination lasers are relatively simple and lend themselves to rapid scaling to short wavelengths.

The candidate lasing lines in Li-like ions of Cr and Ca are the 4f-3d at 38.6Å and 57.7Å, respectively, and the 5f-3d transition at 26.4 and 39.5Å, respectively. The H-like aluminum 3-2 transition at 39Å, as well as the 4f-3d and 5f-3d transitions (90Å-155Å) of He-like and Li-like Al are being explored. A spatially imaged spectrum for an Al foil target is shown in Figure 11. The spectral coverage does not include the line at 39Å. The H-like 4-3 line at 110.8Å is relatively bright and confined to the central 100 μm region. The 5f-3d transitions of He-like (88.9Å) and Li-like (105.7Å) Al are found over a much broader region (400 and 800 μm, respectively). The spatial dependence for the 88.9Å line is indicative of small gain. Data from the crystal spectrographs indicate that the plasma conditions have produced predominately H-like ions, as opposed to the fully stripped plasma needed for inversion in H-like ions.

Figure 9. Imaged Al spectrum showing identified candidate lasing transitions. Spatial reference scale is in the object (target) plane.

6. SUMMARY

We have achieved the first demonstration of gain in a plasma of nickel-like ions, at wavelengths as short as 50Å. The scaling of this scheme to wavelengths below the carbon K absorption edge will be attempted in the near future with nickel-like tungsten. This system is predicted to show gain at 43.15Å.

The studies of neon-like ions has demonstrated the saturation of a soft x-ray ASE source. The source size of the lasing transitions are measured to be 50 μm, 4 times smaller than previous estimates. Further, we have developed an Imaging McPig Spectrograph, which is uniquely suited to measure the gain in an ASE source. This instrument allows the measurement of the specific intensity and source size, with temporal resolution suitable for laser plasmas. In addition, the spatial dependence of the gain coefficient and the effects of refraction can be measured in x-ray lasers. Upcoming experiments will focus on detailed near-field and far field measurements for several target lengths and plasma conditions.

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