

High-Repetition-Rate Grazing-Incidence Pumped X-Ray Laser Operating at 18.9 nm

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We have demonstrated a 10 Hz Ni-like Mo x-ray laser operating at 18.9 nm with 150 mJ total pump energy by employing a novel pumping scheme. The grazing-incidence scheme is described, where a picosecond pulse is incident at a grazing angle to a Mo plasma column produced by a slab target irradiated by a 200 ps laser pulse. This scheme uses refraction of the short pulse at a predetermined electron density to increase absorption to pump a specific gain region. The higher coupling efficiency inherent to this scheme allows a reduction in the pump energy where 70 mJ long pulse energy and 80 mJ short pulse energy are sufficient to produce lasing at a 10 Hz repetition rate. Under these conditions and by optimizing the delay between the pulses, we achieve strong amplification and close to saturation for 4 mm long targets.

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When the x-ray laser was first demonstrated nearly 20 years ago [1], kilojoules of laser pump energy were required to generate a laser at ~ 20 nm. Two developments led to improved efficiency of these collisional pumped Ne- and Ni-like ion x-ray lasers. The first was the prepulse technique [2] where the target was irradiated with a low energy prepulse a few nanoseconds before the main pulse to form a preplasma. This gave better absorption of the main pulse, reduced density gradients, and improved propagation and amplification of the x-ray laser beam along the plasma column [3–5]. The second advance came with transient collisional excitation, where a nanosecond prepulse is followed by a short picosecond pulse which pumps the population inversion [6], with reported saturated output at 14.7 nm [7] and 7.3 nm [8]. These achievements have used the transverse pumping geometry where the laser beams are incident at normal incidence and the laser energy is absorbed over a wide range of plasma densities. Recent work has shown further progress towards a high-repetition-rate soft x-ray laser based on longitudinal pumping with optical field ionization followed by collisional excitation [9]. High gain has been measured for Pd-like Xe at 41.8 nm and Ni-like Kr at 32.8 nm pumped with energy < 1 J and at a repetition rate of 10 Hz [10]. A longitudinal pumped Ni-like Mo x-ray laser at 18.9 nm has also been demonstrated [11], with a total pump energy of 150 mJ, and produced a highly directional output but not in saturation. A saturated x-ray laser based on a tabletop capillary discharge operating at 46.9 nm has produced millijoule level laser pulses at a repetition rate of 4 Hz [12] and has led to many applications.

We report the first demonstration of a novel pumping scheme using the excitation pulse incident on the plasma column at a grazing-incidence angle to create an 18.9 nm Ni-like Mo $4d-4p$ x-ray laser operating close to saturation at 10 Hz repetition rate. This pumping geometry allows improved laser coupling efficiency into a predetermined optimum gain region of the plasma by using refraction to

turn the pump laser at an electron density below the critical density, thus increasing the path length and absorption in this specific region of the plasma. This higher efficiency requires only a very low energy laser pump (~ 150 mJ), available at a 10 Hz repetition rate and represents more than an order of magnitude reduction in the pumping energy compared to the conventional transverse scheme. A systematic optimization of the pump parameters has been carried out showing strong lasing in targets of 4 mm in length for certain conditions. The x-ray laser gain is determined to be 55 cm^{-1} and appears to go into saturation for targets above 2 mm in length showing continued increase in intensity up to 4 mm. The x-ray laser exhibits small beam divergence and low deflection angles expected for the chosen gain region of $\sim 10^{20} \text{ cm}^{-3}$ and supports the physical basis for the novel geometry.

In the grazing-incidence pumping (GRIP) scheme the same two stage pumping is used as in the conventional transient scheme but with a significant difference. A long pulse, 200 ps in this case, focused on a slab at normal incidence preforms a plasma column to create a tailored density profile. After a certain delay when the plasma conditions, particularly the electron density profile, are correct, the short pulse is incident at a grazing angle to the target surface in a line focus. The short pulse beam is refracted in the plasma at a chosen electron density, well below critical, and is strongly absorbed. The required angle of incidence of the short pulse, measured relative to the target surface, is chosen to allow the laser pump to be refracted in the plasma. This is obtained from $\phi_r = \sqrt{n_{e0}/n_{ec}}$, where n_{e0} is the maximum density within the gain region and n_{ec} is the critical density for the optical pump [13]. This has several advantages that increase the laser coupling into the gain region. The grazing angle gives a longer path length to increase absorption within a specific plasma region. Refraction causes the short pulse to turn back into the gain region, thus allowing the laser pump to

traverse this region twice. The short pulse beam has an inherent traveling wave very close to the speed of light. For these reasons, a sub-20-nm x-ray laser should be able to be generated on a small, high-repetition rate laser.

To test the GRIP x-ray laser principle, the experiment was performed on an 800 nm wavelength, 100 fs Ti:sapphire facility at the Lawrence Livermore National Laboratory. This laser typically produces a maximum of 300 mJ uncompressed laser energy per pulse at a repetition rate of 10 Hz. The energy was split with 33% into the long pulse arm and 66% into the short pulse arm. The long pulse, 200 ps in duration, was focused onto the Mo target at normal incidence as shown in Fig. 1 using a combination of a spherical and cylindrical lens. A total energy of 70 mJ was focused on target in a line of 5 mm long by 15 μm full width at half maximum (FWHM), at an intensity of $5 \times 10^{11} \text{ W cm}^{-2}$. The short pulse arm was compressed under vacuum where a pulse length of 125 fs to 8 ps could be produced. The short pulse was focused to a line using a 91.4 cm focal length on-axis parabola tilted to produce the required grazing angle of incidence to the target as shown in Fig. 1. RADEX simulations [14] predicted that the optimum turning point of 10^{20} cm^{-3} electron density was required for the Ni-like Mo x-ray laser operating at 18.9 nm. From the above equation, this determined the 14° angle of incidence considering the critical density of $1.74 \times 10^{21} \text{ cm}^{-3}$ for the 800 nm short pulse laser pump. The parabola produced a line focus 4 mm long by $\sim 30 \mu\text{m}$ (FWHM) wide with a maximum energy on target of 80 mJ. The typical pulse duration of 1.5 ps on target gave an incident intensity of $4 \times 10^{13} \text{ W cm}^{-2}$. This focusing geometry gave a traveling wave velocity of $0.98c$. The long pulse arm was sent through a delay line that could adjust the separation of the two pulses from 0–1 ns. A surrogate optically transparent scatter film was placed at the target position to align the beams. The line foci were measured and overlapped using a laser achromat to image the target plane at high magnification onto a charge-coupled device (CCD) detector. The beams were incident onto a slab of polished Mo up to 4 mm in length.

The main diagnostic was an on-axis 1200 lines/mm variable-spaced grating flat-field spectrometer, operating over a 10–25 nm wavelength range. The spectrometer was

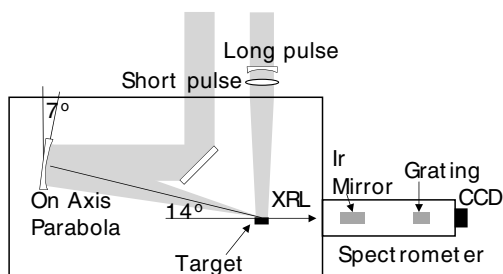


FIG. 1. Experimental setup showing grazing-incidence pumping of short pulse laser beam.

set up to image the target position, via a flat Ir-coated mirror, onto a back-illuminated 1024×1024 pixel CCD positioned 1 m from the source. The detector had an angular view of 25 mrad in the horizontal direction and the spectrometer collected the central ~ 4 mrad in the vertical direction determined by the effective height of the grating. Fiducial wires were placed close to the spectrometer entrance aperture and aligned relative to the target surface to give the deflection and beam divergence angles of the x-ray laser. Aluminum foils of 0.2–2 μm thickness were used as a light tight filter and to reduce the x-ray laser from saturating the CCD. The spectrometer was used to acquire the spectrum of a single shot. An on-axis soft x-ray Mo:Si multilayer-coated mirror imaging system, consisting of a 12.5 cm focal length mirror in combination with a 45° mirror, was used to image the near-field pattern of the 18.9 nm Mo x-ray laser at $17\times$ magnification onto a second back-illuminated CCD. Many laser near-field image x-ray laser shots could be recorded in one CCD frame by synchronizing the repetition rate of the laser with the CCD readout.

Some careful adjustment of the pumping conditions was required to achieve the soft x-ray laser line. Reducing the laser energy by more than 10% in each beam resulted in a strong fall in x-ray laser intensity. The optimized pump conditions were found to be a 1.5 ps short pulse delayed by 500 ps after the peak of the long pulse. Figure 2(a) shows a typical spectrum in a single shot for 150 mJ total energy incident on a 4 mm target. The wavelength dispersion direction is along the vertical axis while the horizontal

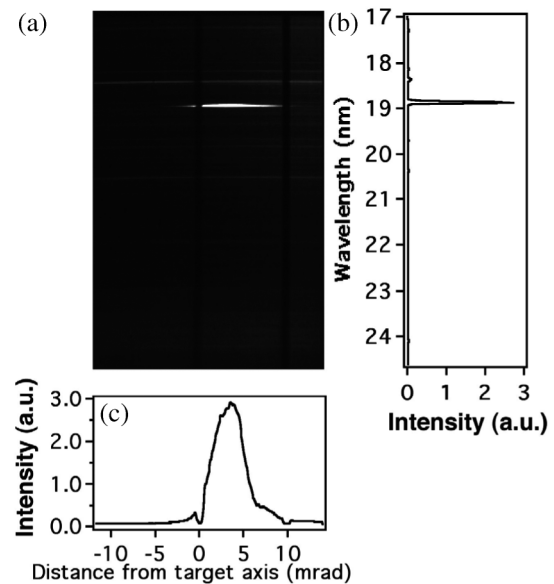


FIG. 2. (a) Soft x-ray spectrum from on-axis flat-field spectrometer. The two vertical lines are the fiducial wires used to calibrate the x-ray laser deflection angle relative to the target surface. (b) (right) Intensity lineout showing strong lasing at 18.9 nm from Ni-like Mo $4d-4p$ transition. (c) Horizontal lineout showing narrow angular profile of x-ray laser beam.

axis gives the angular pointing of the x-ray emission perpendicular to the target. A lineout in the vertical direction, Fig. 2(b), shows intense output at 18.9 nm many orders of magnitude higher than any other feature. Figure 2(c) shows a narrow divergence angle of 3.6 mrad (FWHM) in the horizontal direction with a deflection angle of 3.2 mrad from the target. For the most intensely peaked shots the average deflection and divergence angles were 3 and 4.5 mrad, respectively. The above formula to calculate the required pumping angle can also be applied very approximately to the measured peak of the deflection angles for the 18.9 nm x-ray laser and indicate the x-ray laser is emitted at an electron density of $(3-5) \times 10^{19} \text{ cm}^{-3}$ and up to a maximum of 10^{20} cm^{-3} . This is consistent with the maximum density chosen by the grazing-incidence angle for the turning point of the short pulse beam. However, it should be noted that the incidence angle of laser pumping is not constant along the line focus because of the range of beam angles from the focusing optic. This results in laser coupling to different electron densities. It would be expected that a grazing angle between 10° and 20° , corresponding to densities 5×10^{19} and $2 \times 10^{20} \text{ cm}^{-3}$, respectively, would produce x-ray laser output for Ni-like Mo.

The x-ray laser output was repeatable but was found to have some sensitivity to the overlap of the two line foci of the two beams, both with narrow widths. This was clearly observed in the near-field imaging, with up to ten individual shots obtained spatially separated on the CCD image, where maximum x-ray laser output was observed for good overlap of the beams. In Fig. 3 we show the total output of the Ni-like Mo 18.9 nm line, recorded from the near-field imaging system, as a function of the delay between the short pulse and the long pulse. The output is strongly peaked at a delay of 500 ps for a short pulse of 1.5 ps duration. The temporal window for the delay is extremely narrow at ~ 50 ps (FWHM) and different from recent

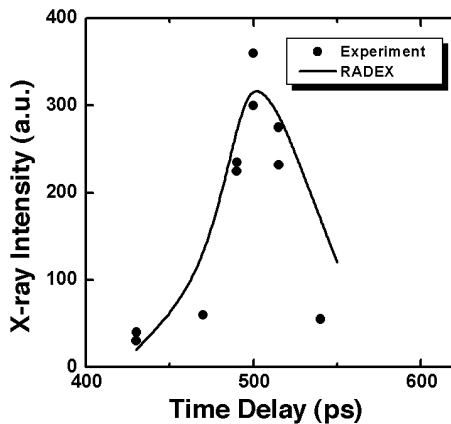


FIG. 3. Measured x-ray laser intensity (solid circles) as a function of time delay between the long pulse and the short pulse for a 1.5 ps short pulse together with RADEX modeling (solid line) under similar laser pumping conditions.

characterization experiments of the Ni-like Pd x-ray laser pumped in the transverse geometry [15]. RADEX simulations indicate this high sensitivity to delay is attributed to the resultant plasma produced by the narrow focal width of $\sim 15 \mu\text{m}$ (FWHM) and the relatively short pulse duration of 200 ps of the long pulse. Both of these laser parameters are several times smaller than previously described in transverse pumping designs and affect the inversion process for grazing-incidence pumping. The plasma density gradients present at $\sim 10^{20} \text{ cm}^{-3}$ continue to relax with the onset of lasing at approximately 450 ps after the peak of the long pulse, Fig. 3. The simulations show the plasma region containing the active medium Ni-like ions passes very quickly through the optimal density of $\sim 10^{20} \text{ cm}^{-3}$ selected by the grazing angle. At around 500 ps the peak of Ni-like ion relative abundance passes through this density region and gives the strongest x-ray laser output. At longer delays of $\sim 600-650$ ps the active ions have moved away from the target and the pumping region while the overall electron density has dropped substantially with reduced laser coupling. The modeling shows good agreement with the observed peak of the delay for best lasing conditions. The predicted time history after the peak and the width of the time window for lasing is very sensitive to the initial long pulse pump conditions and is under further study.

Ni-like Mo experiments have shown laser action in recent years to varying degrees with small pump energies [11,16,17]. An earlier experiment using a short pulse beam incident at an oblique geometry on a Mo target was reported to form plasma jets but no x-ray laser output [18]. An important objective in this work was to determine the gain for the GRIP scheme with traveling wave pumping and show continued increase in x-ray laser output as a function of target length. Single shots were taken with data recorded through imaging and on the spectrometer for lengths up to 4 mm, Fig. 4. It should be noted the x-ray laser intensity increases by approximately 3 orders of magnitude from the threshold of detection for 1.5 mm

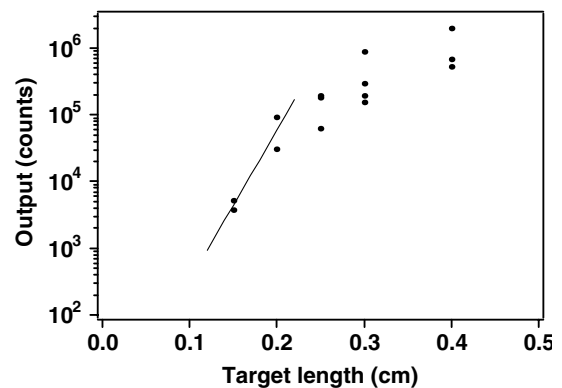


FIG. 4. X-ray laser intensity versus target length showing strong output with increasing target length. A gain of 55 cm^{-1} is inferred from 1.5 to 2 mm targets.

targets to the maximum of 4 mm. The x-ray laser output continues to increase at the longest targets but at a lower rate. The highest gain is determined to be 55 cm^{-1} for targets up to 2 mm with no output detected for targets below 1.5 mm. For a 2 mm target the gain length (GL) product of 11 is achieved with the output rolling over indicating a saturationlike behavior. The gradual roll-off at longer target lengths may be due to reduced amplification at the ends of the 4 mm line focus. The intensity still increases by a further factor of 20 for targets up to 4 mm long, which determines an upper limit of the GL ~ 14 and is close to saturation. For the laser conditions studied here the gain region cross section is fairly small $\sim 9 \times 20 \mu\text{m}^2$ and the mean electron density is expected to be in the range of $(4\text{--}8) \times 10^{19} \text{ cm}^{-3}$. RADEX simulations indicate that for 4 mm target lengths and the relatively low electron density, refraction should not be a significant problem for the x-ray laser propagation along the plasma column. For the above beam size and assuming ~ 2 ps pulse duration, the saturation intensity of $\sim (0.5\text{--}1.0) \times 10^{10} \text{ W cm}^{-2}$ would be achieved with an output of approximately 10–20 nJ. The relatively low output is in part due to the small pumped volume as a result of the narrow laser line focus. Pumping longer targets and generating a larger gain region by widening the line foci on the long and short pulse could substantially improve the output of this x-ray laser while keeping the pump laser operating at 10 Hz. Additional details of the grazing-incidence scheme, including the RADEX computed hydrodynamic parameters, refraction of laser radiation, and detailed analysis of the scheme's advantages and disadvantages, will be described in a separate publication.

In conclusion, the new grazing-incidence pumping scheme has allowed lasing for Ni-like Mo at 18.9 nm to be demonstrated with only 150 mJ total energy on target with a pump laser operating at 10 Hz. The angle of incidence of the short pulse is chosen such that the short pulse experiences the optimum maximum electron density for pumping the inversion and is then refracted back into the gain region. This allows pumping at much lower energy as the short pulse is absorbed more effectively in the density region where gain occurs. High gain has been inferred at short target lengths. The sensitivity to delay between the long pulse and the short pulse is in part due to the available long pulse pump energy determining the line focus parameters. These are the first experiments to utilize this new geometry, and it is expected that further improvements will be made in the near future. The grazing-incidence pumping is another step forward in the improvement in efficiency of x-ray laser that will lead to new applications that require high average power at a high-repetition rate and low pump energy.

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