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THE SANDIA X-RAY LASER PROGRAM


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Abstract - The Sandia X-ray Laser Program is based on the use of intense keV radiation produced by gas puff, Z-pinch implosions to photoionize Ne-like ions to F-like ions. A 3p-3s population inversion is generated via recombination processes. An annular stagnation shell is used to separate the imploding pump source from the lasant. We are also developing a converter technology for examining the Na-Ne line matching scheme. Design considerations and some computational results are presented.

Discussion

The Sandia x-ray laser program is based on the availability of large pulsed-power drivers developed for our light ion beam ICF program. When thin cylindrical foils are imploded in a pulsed-power diode, the implosions are observed to be unstable. Calculations have indicated that annuli of comparable mass/length, but greatly increased thickness (reduced density) would have improved stability properties. But the same calculations have indicated anomalously intense photon emission at 1 keV and above. This emission, nominally 10 kJ in 10 ns from a cylindrical stagnation region of radius 0.1 cm and length 2 cm, produced an intensity at the center line of the cylinder of about 2 TW/cm$^2$ of 1 keV X-rays. If this radiation pulse were to rise to its maximum in 5 ns, the rate of increase of pump power would be 0.4 TW/cm$^2$-ns. In the first publication on x-ray lasers, Duguay and Rentzepis estimated a requirement of 0.004 TW/cm$^2$-ns for 3s-2p lasing at 372 Å in Na$^+$, and 0.25 x 10$^{13}$ TW/cm$^2$-ns for a Cu K$_\alpha$ laser at 1.54 Å. Clearly, we have a respectable pump for a soft x-ray laser, but are orders of magnitude below that required for a hard x-ray laser. (The estimates in Ref. (2) suggest pump power scaling as inverse laser wavelength to the sixth power.)
To simulate low density, thick-shelled "foils" we use annular gas puffs produced by high (4-8) Mach number nozzles. The gas is preionized and imploded. Figs. (1) and (2) show time integrated spectra from Ne and Xe gas puff implosions using the Proto II accelerator. Because the nozzle does not produce a true annulus, intense photon emission is observed first at the nozzle end of the diode, advancing along the azimuthal axis of symmetry with increasing time. A variety of schemes are being examined to reduce this "zippering" phenomenon.

1) Spectral intensity for a Ne gas puff imploding on itself.

2) Spectral intensity for a Xe gas puff imploding on itself.
Because pulsed-power technology inherently produces high-power pulses of a few ns or longer time duration, and because of "zippering", we desire a laser medium that might show a population inversion on a ns or longer time scale. The \((2p)^5(3p) - (2p)^5(3s')\) transition in Ne-like ions is an appealing candidate. The population inversion is produced by photoionizing Ne-like ions with our imploding gas puff source, and developing the population inversion via recombination of F-like ions and the disparity of radiative lifetimes of the upper and lower laser levels. Fig. (3) shows the ionization energy of Ne-like ions as a function of nuclear \(Z\), and the range of high energy photon emission observed for various gases. The intersection identifies suitable \(Z\) for laser media. (Pump power requirements are not included in these calculations.)

3) Graphical determination of laser medium to match pump spectrum

![Graphical representation](image)

Fig. (4) shows an idealized target design, with a 1 mm radius gas puff stagnation layer surrounding a laser medium. The stagnation layer is introduced to delay shock wave disruption of the laser medium until lasing has occurred. Experiments have shown that a stagnation layer made of CH foils or low density foam does not significantly change the high energy output from the stagnating gas puff. Given the geometry, and assuming that the laser medium is composed of ground state Ne-like ions, the pumping requirement is the high energy output \((J)\) required for an ionization time constant of 0.1 ns, 1.0 ns, and 10 ns. The required energies are called \(J_{100}\), \(J_{10}\), and \(J_1\), respectively. If we assume that the high energy output
4) Idealized laser target

X-RAY LASER CONFIGURATION

![Diagram of X-ray laser configuration]

is a delta function in energy located at the threshold for \((2p)^6\) photoionization, we calculate the dashed curves in Fig. (5). If we use realistic photoionization cross sections and broad spectral distributions (e.g. Fig. 2) for the various gases, we calculate the hooked shaped curves in Fig. (5) (i.e. there is an optimum \(Z\) for each gas puff spectrum). A \(J_1\) criterion is likely to determine a lower energy limit, while with \(J_{100}\) and a broad pump, one will rapidly photoionize F-like ions to 0-like ions, etc. Thus \(J_1-J_{10}\) establishes a reasonable criterion for pump energy. The results in Figs. (3) and (5) suggest a pump power scaling with inverse wavelength to the fourth power, neglecting the energy required to produce the Ne-like plasma. Also shown in Fig. (5) are outputs from various modifications of the Proto II accelerator, and a projected future driver. We are currently using a diode designed by PSI to optimize our gas puff photon source; we have measured > 20 KJ at or above 1 keV with imploding Ne gas puffs. Thus we can examine laser media near \(Z = 30\).

In modeling these systems with broadband pumps such as shown in Fig. (2), one finds that a \(J_{10}\) criterion produces a maximum F-like ion population in 2-3 ns, after which it decreases as the 0-like and N-like populations increase because the intense broadband pump can photoionize F-like and 0-like ions. To avoid this waste of both photons and F-like ion population we are developing low \(Z\)-converters to produce output spectra similar to Fig. (1), i.e. emission on the \(K_\alpha\) lines from the H-like and Ne-like ions of the low \(Z\)-converter. This is done by coating the outer surface of the stagnation layer with the low-\(Z\) material. The laser medium is produced by thermally exploding a solid coating on the inner surface of the stagnation layer. Schematics of some current targets are shown in Fig. (6).

With \(K_\alpha\) radiation from H-like Al, one can photoionize the \((2p)^6\) shell of the Ne-like ion of both Cu and Ni. But while this pump wavelength can photoionize the \((2p)^5\) shell of F-like Ni, it cannot photoionize the \((2p)^5\) shell of F-like Cu. Thus, with an Al converter and a Cu target one can prevent the photoionization of F-like ions, and by varying the target from Cu to Ni, one can test the hypothesis experimentally. By varying the
converter material one can examine other possible lasants, provided the conversion process is efficient. Preliminary measurements with Ne gas puffs and Al converters show about 25% of the output above 1 KeV in Al H- and He-like Kα lines. Fig. (7) shows a time integrated spectrum from a thin foil stagnation layer coated with Al on the outside and Cu on the inside. Emission from Ne-like Cu is observed. Use of a Na converter would allow experiments on the Na-Ne line matching laser scheme.

5) Graphical determination of laser medium to match pump energy

6) Schematic of current targets
The size of the laser target can be estimated from radiation trapping considerations. The background blackbody radiation can destroy a \((2p)^5(3p)-(2p)^5(3s)\) population inversion by pumping the \((2p)^5(3p)-(2p)^5(3d)\) transition with the subsequent rapid radiative decay of the \((2p)^5(3d)\) to the \((2p)^6\) ground state. A critical blackbody flux can be defined as

\[
F_{BB} = 1.75 \left[ 5A_{3s,2p}^6A_{3d,2p}^{3p} / (5A_{3d,2p}^6-3A_{3s,2p}^6) \right] kT_R^{-4} \left[ \exp(\Delta E/kT_R) - 1 \right] / f_{23}(\Delta E)^2
\]

where \(A_{ij}^k\) is the Einstein coefficient, \(kT_R\) is the radiation temperature in Ry and \(f_{23}(\Delta E)\) is the 3p-3d oscillator strength (energy difference in Ry).

The critical blackbody flux is shown in Fig. (8) as a function of radiation temperature for a variety of \(Z\). Also shown are critical blackbody fluxes associated with our geometry, pulse width, and \(J\) values. For 80 kJ and a 40 eV radiation temperature, Fig. (8) shows that the blackbody background could destroy a population inversion at \(Z=23\), while for \(Z=29\) and 34 the same blackbody background is below critical by a factor of 3-5. However, background blackbody radiation is not a serious problem unless the \((2p)^5(3d)-(2p)^6\) radiation can escape from the system. Using a crude radiation trapping criterion \(N[(2p)^6]R_{2p,3d}\), then a cross section and \(Ne\)-like ion density define a minimum target radius. However, since one does not want the \((2p)^5(3s)-(2p)^6\) line trapped, a similar radiation trapping criterion determines a maximum target radius. In Fig. (8) minimum and maximum \(N[(2p)^6]R\) are shown as a function of \(Z\), for a 20 eV Doppler width.
8) Critical blackbody flux as a function of $Z$ and $kT_R$.

9) Critical radius-ion density product determined by radiation trapping.
The maximum electron density and, hence, the maximum Ne-like ion density is determined as the critical electron density for destruction of a 3p-3s population inversion due to the excess of superelastic 3p-3s over inelastic 3s-3p collisions. For a system pumped by recombination a critical electron density is given by

$$n_{ec} = \frac{4}{3} \left( \frac{A_{3s,2p}}{C_{3s,3p}} \right) \left[ \exp(\Delta E_{3p,3s}/kT_e) - 1 \right]$$

where $C_{i,j}$ is a velocity weighted electron excitation cross section. In Fig. (10) $n_{ec}$ is shown as a function of $Z$ for various electron temperatures ($kT_e$). Peak gain occurs for $n_e$ about $n_{ec}/2$. With $kT_e=40$ eV and $kT_e=125$ eV, Figs. (3) and (8)-(10) suggest targets of V pumped directly with Ne gas puff radiation, Ni or Cu pumped with radiation from an Al converter, and possibly Se pumped with radiation from a S converter. For such laser media created from solid coatings on the inside of the stagnation layer the coating thickness should be 100 Å or less.

The approach followed in the Sandia X-ray laser program is traditional in that we separate the pump source from the laser medium. Much of our effort so far has been on source development; laser experiments are planned for the coming year.

References