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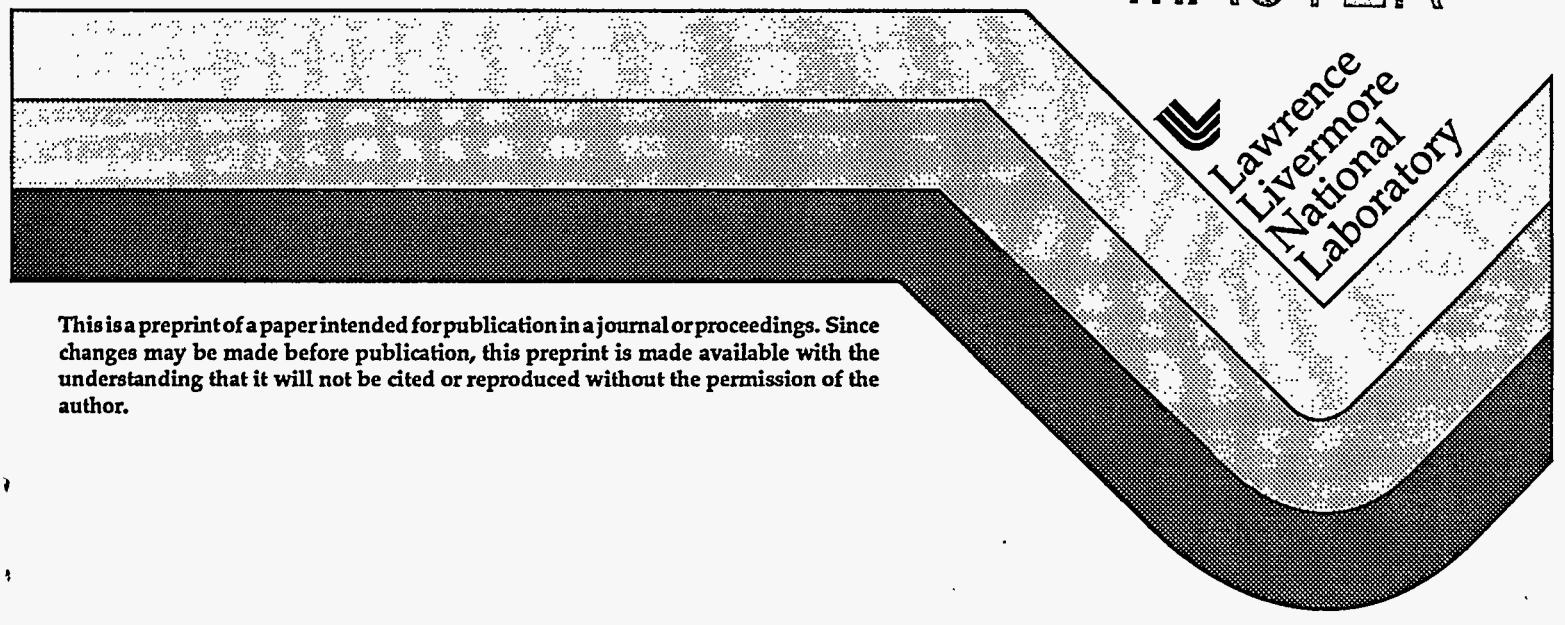

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Efficient production of 2-10keV xrays by laser heated "underdense radiators"

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The next generation of high power lasers offers the prospect of creating multi-kilovolt x-rays with >10% efficiency. Such efficiencies are achieved with "underdense radiators", a non-traditional source of laser generated x-rays. Applications of these sources with the proposed National Ignition Facility (NIF) include volume preheating of experiments; bright, multi-keV backlighting; pumps for flourscent imaging of capsule dopants and doppler velocimetry; uniform irradiation of large test objects.

Within the next decade very high power laser facilites may be constructed in Europe and the United States. Two-dimensional (2D) numerical simulations with the Lasnex code [1] indicate that these high power lasers may produce multi-kilovolt x-rays with unprecedented efficiency. For example, consider the two types of sources, shown in figure 1. The source of figure 1a is a column of gas or foam irradiated from one end by a 0.35 micron (blue) laser beam. In simulations using 0.01g/cc of Xe gas irradiated by a 2ns flattop pulse at an intensity of 10^{15}w/cm^2 we find efficiencies into photons of energy >4keV (L-shell Xe and continuum) to be 19% with a 10TW beam. Since a cluster of four "beamlets" of the proposed National Ignition Facility (NIF) [2] will deliver 10TW in the geometry of figure 1a, good efficiency may be achievable with such gas-column sources. Simulations indicate that higher efficiencies and photon energies require more than 10TW. Figure 1b shows a higher power source; a low-Z container, transparent to x-rays of interest, filled with an appropriate Z, low density gas or foam. In simulations using Xe gas at 0.01g/cc, we find near optimal performance for containers 2mm diameter, 1.6mm long with 1mm diameter laser entrance holes. For 2ns pulses, simulated, >4keV efficiencies range from 17% at 20TW to 30% at 60TW.

We have efficient 2-D designs up to ~10keV. Table 1 summarizes our study. For all these sources the densities are 0.01g/cc and the target is that of figure 1b.

material	power	fraction of energy> hν	
Kr	60TW	4%>13keV	30%>2keV
Ge	60TW	14%>10	26%>2
Ge	50TW	10%>10	26%>2
Ge	30TW	7%>10	20%>2
Cu	40TW	11%>8.5	26%>2
Cu	30TW	10%>8.5	24%>2
Dy	60TW	9%>8	24%>2
Xe	60TW	30%>4	48%>1
Xe	50TW	26%>4	48%>1
Xe	30TW	22%>4	40%>1
Xe	20TW	17%>4	37%>1

Figure 2 summarizes these source efficiencies vs. photon energy and compares them with current disc backlighter efficiencies [3]. "Underdense radiators" (so called because the fill density is < critical density) heated by powerful lasers could be far more efficient multi-keV sources than current backlighters.

Analysis of Lasnex simulations shows underdense radiators to be much more efficient than discs because of the way the plasma is heated. Compare the underdense source of figure 1a with a disc of the same material heated by the same laser. In underdense material, the heating front can move supersonically (bleaching front). However, a disc's heating front moves subsonically (ablative front). Analysis shows that a bleaching front, as compared to an ablative front, creates far more hot plasma which is denser and, therefore, is more efficient in producing multi-keV x-rays. In particular, we find:
*In producing a given mass of hot plasma, more energy is lost to low photon energy radiation (a parasitic loss) when the heating occurs in a dense ablation front, than when the matter is heated in the uncompressed bleaching front.
*The material in the ablation front rises to higher pressure. This ends up as more kinetic energy per unit of mass heated.
*More kinetic energy causes the hot blow-off behind an ablative heating front to be less dense than behind a bleaching front. Consequently, the blow-off behind the bleaching front produces more of the coronal, multi-keV x-rays per unit mass.

We have tested our ability to predict multi-keV efficiencies against several databases [4,5,6,7]. Figure 3 compares simulated and experimental absolute multi-keV efficiencies. These data include Xe

filled "gas bags" specifically shot at Nova to examine multi-keV production by underdense radiators [7]. Except for two low intensity points ($1.4x10^{14}w/cm^2$) there is general agreement between experiment and simulations, lending credibility to the projections.

Applications of efficient multi-keV x-ray sources.

1-Preheat sources: The preheat temperature, T_e, we can produce in an experimental package a distance d away from the source will be given by

$$\eta_> E_L/(4\pi d^2\lambda)=(3/2)\rho*(Z+1)T_e/A*9.6x10^4$$

Here $\eta_>$ is the multi-keV efficiency; E_L is the laser power; λ is the scale-length over which absorption occurs in the experimental package; ρ, Z and A are the density, atomic number and weight of the experiment we are preheating. Using $\eta_>=30\%$, $E_L=10^6$j, d=1/2cm, ρ=1g/cc, (Z+1)/A=0.33, gives $T_e=2eV*cm/\lambda$. Depending on λ, it may be possible to preheat ρ=1 samples to ~5eV up to several 10's of eV. NIF applications for preheat include off-hugoniot equation of state measurements and low-temperature hydrodynamics.

Backlighter sources: Sources like these could serve as the bright, high photon energy, large area backlighters needed for bigger targets. Consider, for example, the 60TW Ge source listed in table 1 scaled up to 100TW (14%>10keV). Viewed from the end of the 2mm diameter cylinder, the >10keV emission/cm^2/sr will be $3.5x10^{13}$ w/cm^2/sr . This is equivalent to viewing a 10keV hemi-isotropic disc source of 1% efficiency irradiated by 700TW at an intensity of ~$2.2x10^{16}w/cm^2$.

Pumps for flourescence based diagnosis: Efficient multi-keV sources and high-power lasers may allow us to field flourescence based diagnostics; a qualitatively new way of studying hydrodynamics. The principle is simple. A multi-keV source, at distance d, pumps a dopant in a capsule. In imaging, the number of photons collected from a resolution element r is:

$$\#photons= (\eta_> P_L/4\pi d^2)r^2(r/\lambda)\eta_F(1/4\pi)d\Omega\eta_{det}d\tau/E_>$$

Here, P_L is the laser power; $E_>$, the source's average photon energy; η_F, the dopant's flourescent efficiency, $d\Omega$, η_{det}, $d\tau$, the camera's solid

angle, efficiency and time resolution. Using r=10μm, P_L=60TW, $\eta_>$=10%, $E_>$=10keV, d=1/2cm, dτ=100ps, η_F=0.2 (eg. 8keV Cu-K) gives

$$\#photons=3.2x10^9(10\mu m/\lambda)d\Omega\eta_{det}$$

For a 10μm pinhole at 1cm and the dopant concentration arranged so (r/λ)~0.01 to 0.1, we collect 40-400 photons from each 10μm resolution element. For a curved crystal/Rowland circle system, the number photons could be ~300-3000, at 1% crystal reflectivity.

A compelling possibilty is using flourescence to produce cutaway pictures of capsule mix, similar to those used to visualize mixing in 3-D simulations. At a velocity of 10^7cm/s or more narrowband doppler imaging with a camera of spectral resolving power 1500 or greater could image only one side of the imploding pusher. Related to this, doppler spectroscopy of flourescent lines could measure pusher velocity and, possibly, show the evolution of turbulence, via line broadening, at stagnation. A requirement for this will be an efficient spectrometer which sees only diametrically opposed parts of a doped capsule.

Large fluence-area products with good unifomity: If we require the flux over a test object to be uniform to +-10% the fluence*area product we can generate will be source output times the solid angle we can collect from each source and still get +-10% uniformity. This last term is a strong function of geometry. If all the emission is concentrated at a single point, we can collect only 0.45sr. However, if we produce x-rays in a number of properly distributed sources the utilized solid angle increases. With four souces we can collect up to 1.6sr from each source and with 25 sources, 4.5sr. On NIF, the estimated fluence*area products with four sources are: 1-5keV; 50,000j*cm^2; 5-15keV; 14,000j*cm^2. With 25 sources: 1-5keV; 140,000j*cm^2; 5-15keV; 40,000j*cm^2.

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Figures:

Figure 1- Two types of underdense radiators. a) is a gas column irradiated from one end with a single, large f-number beam. b) a transparent container filled with underdense gas or foam, irradiated with several beams.

Figure 2- Projected multi-keV efficiencies with sources shown in figure 1b, irradiated at ~60TW, are much higher than current disc efficiencies.

Figure 3- Comparison of simulated and experimental multi-keV conversion efficiencies from several databases.

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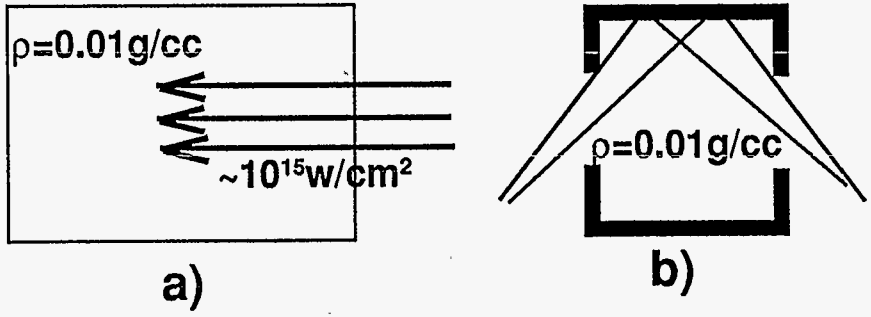

Figure 1

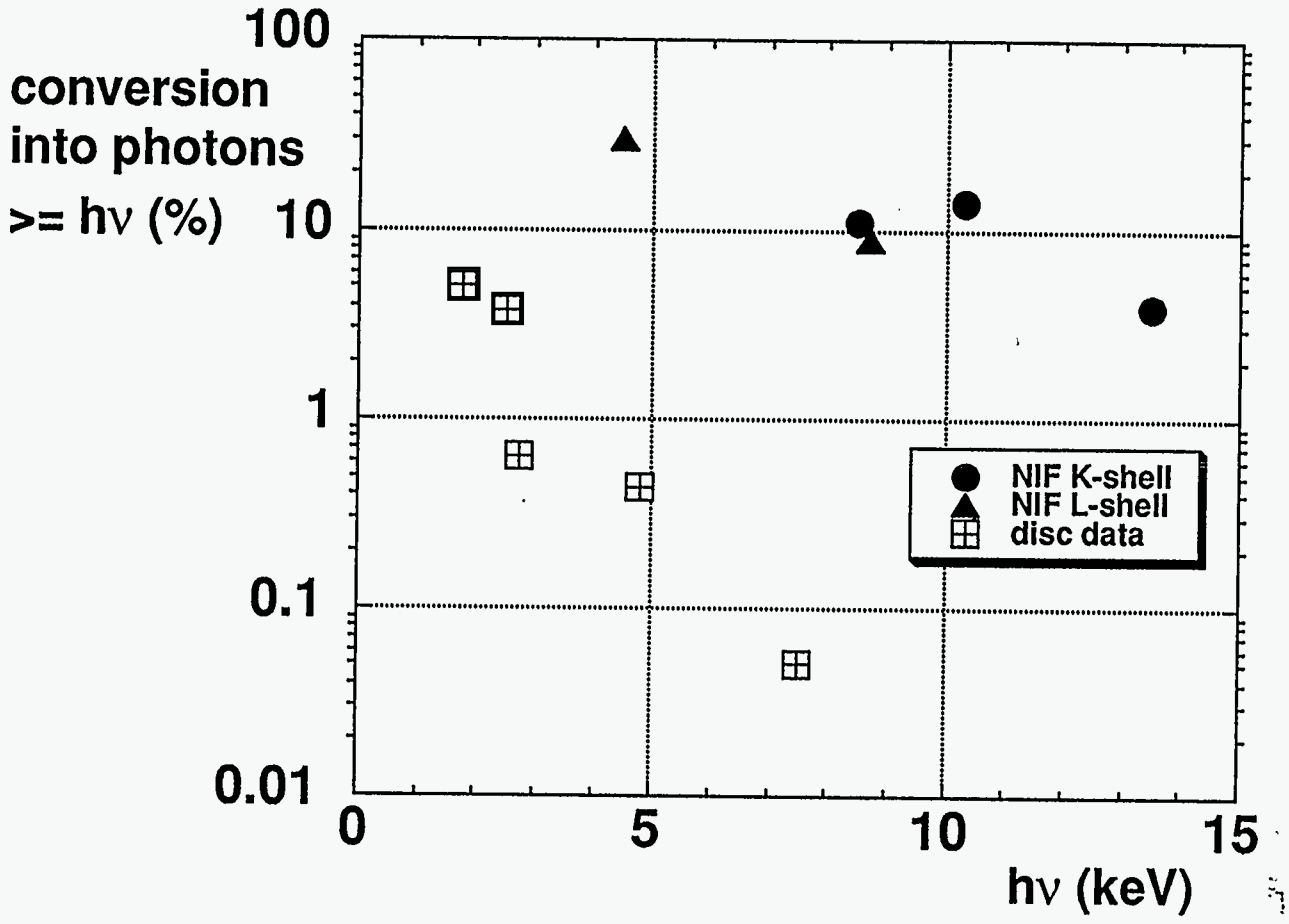
100
conversion
into photons
>= hν (%)
10
1
0.1
0.01
0
5
10
15
hν (keV)
NIF K-shell
NIF L-shell
disc data

Figure 2

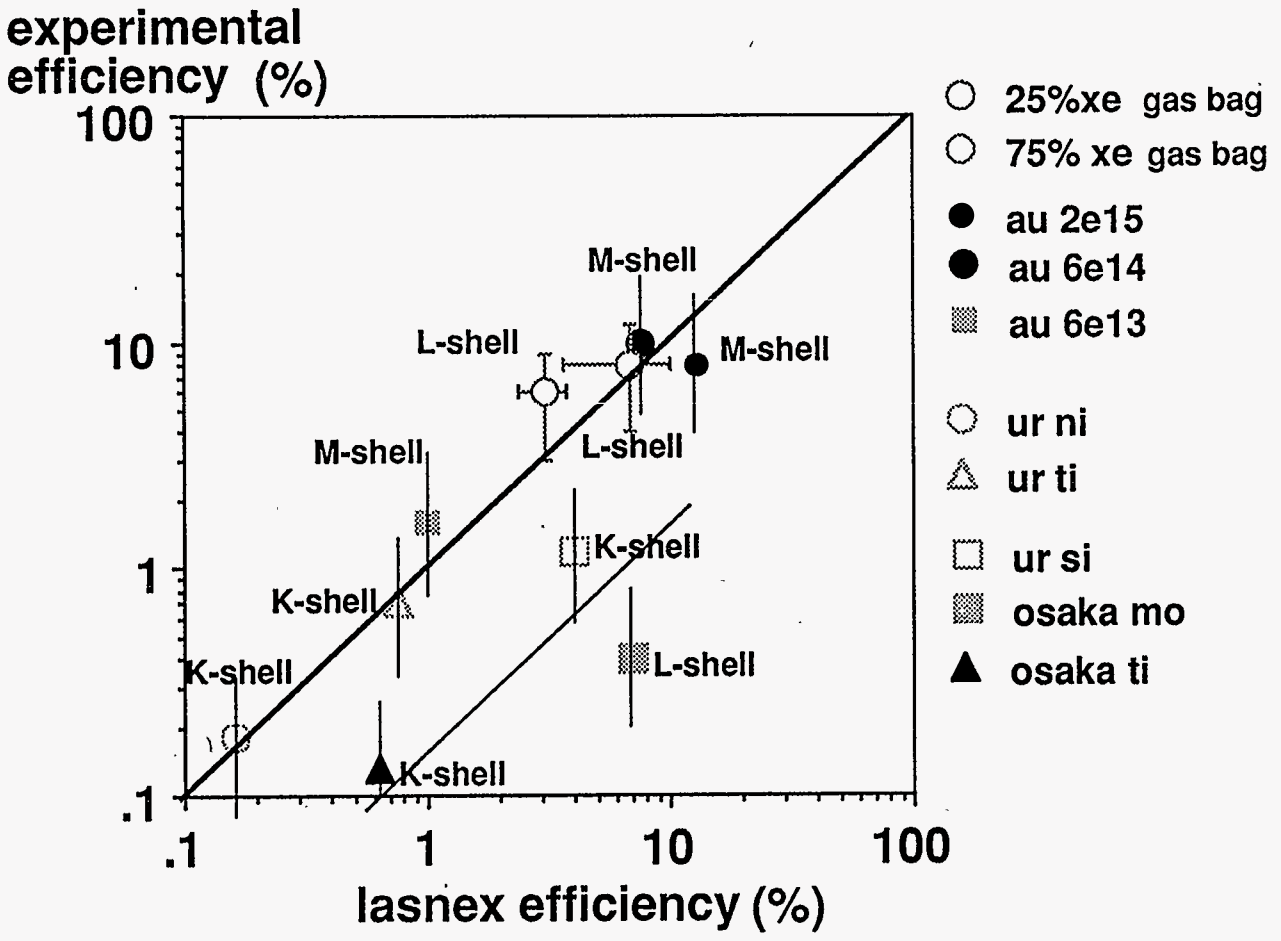
experimental
efficiency (%)
100
10
1
.1
.1
1
10
100
lasnex efficiency (%)
M-shell
L-shell
M-shell
M-shell
L-shell
K-shell
K-shell
K-shell
L-shell
K-shell
25%xe gas bag
75% xe gas bag
au 2e15
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Figure 3

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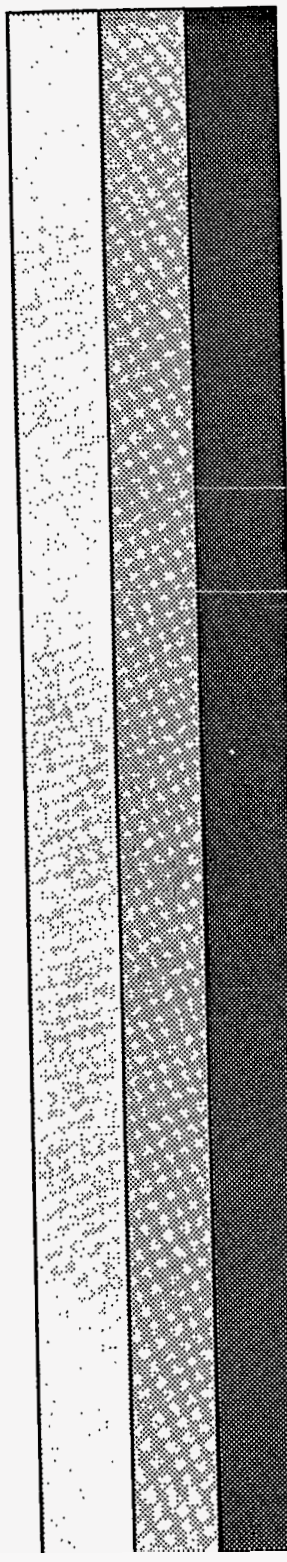

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