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Prospects for fluorescence based imaging/visualization of hydrodynamic systems on the National Ignition Facility

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The next generation of large, high power lasers, such as the National Ignition Facility (NIF) [1] in the United States, Laser Mega Joule [2] in France or Helen Successor [3] in the United Kingdom offer the prospect of x-ray fluorescence based diagnosis of hydrodynamic experiments The x-ray fluorescence could be pumped by at least two techniques One technique is to use a sizable fraction of these facilities' high power to efficiently make multi-kilovolt x-rays which, in turn, causes dopants placed in experimental packages to fluoresce We call this "externally pumped x-ray fluorescence" The second technique is to use the sizable multi-kilovolt photon background that we expect to be present in many hohlraum based experiments, while the driving laser is on, to pump x-ray fluorescence The fluorescing medium could be a dopant in an experimental package or, possibly, a relatively thick slab of material in the hohlraum wall which could serve as a backlighter We call this "hohlraum hot-corona pumped fluorescence".

Externally pumped x-ray fluorescence

Extensive modeling and theory [4] supported by ongoing Nova experiments [5,4,6], indicate that lasers such as NIF will be able to make multi-kilovolt x-rays with unprecedented efficiency. Figure 1 shows projected conversion efficiency of laser energy into multi-keV photons for a few types of "underdense radiators" The theoretical NIF efficiencies shown in the figure came from numerical simulations using the Lasnex computer code The multi-kilovolt sources assumed in the modeling were cylindrical berryllium containers 2mm in diameter, 1 6mm long, filled with 0.01g/cc of the indicated material and irradiated at 60TW The physical basis for this significant improvement in efficiency over "traditional discs" (also shown) has been previously discussed [4,5]

The high efficiencies shown in figure 1, coupled with the inherently large energy of a NIF class laser (~2MJ) means that 100's of kilojoules of multi-keV x-rays could be available for applications [4] One of these applications is the pumping of fluorescent dopants strategically placed in experimental packages such as those used in the study of hydrodynamic instabilities. Of particular interest is the possibility of using fluorescence based diagnosis to visualize a slice through an experimental package, providing an image which might be very similar to contour plots produced by numerical simulations Figure 2 shows two approaches for producing such images. One, somewhat familiar technique is to dope only a region of width ℓ inside the target with fluorescent dopant. Conceptually, this is identical to backlighting based approaches for producing sliced images However, it has the possible advantage of working for systems with $\rho\ell K<<1$, as we shall discuss below. Like backlighting based approaches, it has the disadvantage of making the experimental packages rather costly and difficult to fabricate The second technique for producing a slice-image is schematically shown in figure 2b It uses a highly collimated source to pump only a relatively thin slice of a target which may be uniformly doped This is analogous to optical fluorescence visualization of hydrodynamics experiments pumped by sheets of laser light.

For the two types of slice imaging, the number of fluorescent photons per resolution element that would be collected by a detector of solid angle $\Delta\Omega$ is approximately given by

$$\#\gamma's = \frac{\eta_> P_L}{4\pi d^2} w \cdot h \frac{K_> \rho \ell}{E_>} \frac{\eta_f}{4\pi} \delta\tau \cdot \Delta\Omega \cdot \begin{cases} 1 \\ \ell / D_{source} \end{cases} \qquad (1)$$

where η_x is multi-keV source efficiency, P_L is the laser power driving the source located distance d away from the physics package, w and h are the resolution width and height seen by the imaging camera, ℓ is the length of the doped/pumped region, $K_>$ is the opacity of the material at the pump energy $E_>$ (which is above the K-shell edge), ρ is the dopant density, η_f is the probability a K-shell vacancy will fluoresce into a given line, and $\delta\tau$ is the temporal resolution For the collimated source we assume that only a fraction of the multi-keV source power, given by ℓ/D_{source}, actually pumps the desired slice where D_{source} is the source diameter The table summarizes K_E (opacity at the K-edge), η_f and $E_{>min}$ [7] for possibly important dopants

Material	K_E	$E_{>min}$	η_f
Cl	1700cm^2/g	2 9keV	02
Fe	400	7	17
Cu	300	10	25

Using expression 1, typical numbers for a NIF experiment look promising Consider a 2mm diameter Ge source of 10% efficiency pumped by 100TW located 0 5cm from a package doped with 0 2g/cc of Cu If we try to take a slice with ℓ=50 microns, spatial resolution w=h=10microns and time resolution of 100ps, then the number of photons per resolution element going at the imaging system will be

Slice via dopant location 1.2e9/(10micron)^2/100ps/sr

Slice via collimated source: 3e7/(10micron)^2/100ps/sr

Note that it my be possible to significantly increase the collimated number by re-optimizing sources for collimated output power, probably at the expense of total energy output.

Fluorescent slice imaging might prove to be particularly useful for peering into rotationally symmetric, or even 3D, objects such as turbulent hydrodynamics experiments However, in any experiment we need be concerned about background emission overwhelming the fluorescent signal. Two source of background we have considered are thermal emission and fluorescence pumped by a hohlraum's hot-corona emission

Background thermal emission because the physics package is heated to a temperature Te has a Planckian limit given by

$$\frac{\#\gamma's}{cm^2} = \frac{5\times10^{15} \mathcal{E}_{keV}^3 \Delta\mathcal{E}_{keV} \delta\tau \Delta\Omega}{(e^{\mathcal{E}/T}-1) \cdot \mathcal{E}_{keV} \cdot 1.6\times10^{-16}}$$

For the Cu doped example above, the numbeı of thermal photons/$(10\mu m)^2$/100ps/sr collected by an imaging instrument of bandwidth ΔE would be

T	#/ıesolution element
200eV	0 85ΔE
300eV	5 2e5ΔE

both of which, for any reasonable bandwidth, are much less than the 1 2e9 and 2 9e7 from the slice example Thus background thermal emission from the experimental package does not appear to be an obvious problem if it is kept below, say, 300eV.

Pumping of the fluorescent dopant by hohlraum hot-corona emission while the laser is on does prove to be a major source of background and will limit the utility of slice imaging via a collimated source For example, figure 3 shows our estimate, from a 2D Lasnex simulation, of the average radiation energy density inside a typical scale 1 0 Nova hohlraum at 1ns, Tr~230eV We observe that the multi-keV radiation energy density is hugely greater than the radiation energy density of the equivalent Planckian The number of detected fluorescent photons produced by this radiation field is approximately given by

$$\#\gamma's = \left(\int_{E_{thresh}}^{\infty} \frac{c}{4\pi} u(\varepsilon) \frac{K(\varepsilon)\rho l}{\varepsilon} d\varepsilon\right) 2\pi\, w \cdot h \frac{\eta_f}{4\pi}\, \delta\tau\, \Delta\Omega \qquad (2)$$

Where E_{thresh} is the energy of the K-shell edge of the dopant, c is the speed of light and u(E) is the energy density per keV of the radiation field For the Cu example we have been considering, the number of hot-corona pumped fluorescent photons/sr from the 10x10x50 micron x 100ps resolution element would be

For a 50micron wide doped region	2e9/sr
For a 500 micron wide doped region	2e10/sr

Thus, hot-corona emission pumped fluorescence would be comparable to the externally pumped signal (2e9/sr) if we formed the slice by spatially localized doping and it would be >> than the externally pumped signal (2 9e7/sr) if we formed the slice with a collimated source pumping a uniformly doped experimental package Our simulations indicate that it will take somewhat more than a nanosecond after the laser turns off for the hot-corona emission to drop to the point where collimated slice imaging would work

Discussion of externally pumped x-ray fluorescence

We believe that externally pumped fluorescence my have a diagnostics niche It may be useful for directly driven experiments with negligible hot-corona background and for hohlraum based hydrodynamics experiments long after the drive laser is off. In these regimes the technique has the potential to provide images approximately equivalent to contour plots of material density (and, possibly, temperature by taking advantage of temperature induced spectral shifts However, here we only consider cold fluorescence) A fundamental limitation for hohlraums will be background fluorescence pumped by hot corona emission while the hohraum drive laser is on However, as we discuss in the next section, we may be able to capitalize on this for diagnostic purposes.

Hohlraum hot-corona pumped x-ray fluorescence

Pumping of fluorescence by hot corona may have diagnostic applications not only on NIF class lasers, but it might also have some utility on current lasers such as Omega [8] and Nova We might use hot-corona emission to pump dopants placed in targets or to pump a slab of cold material in the hohlraum wall to provide a form of self-backlighting Coupled with highly tuned, narrow band imaging systems [9], this might provide a way to provide relatively high photon energy backlighting in hohlraums Our calculations indicate that very bright sources are possible, especially with higher energy density hohlraums Figure 4 shows our estimates of radiation energy density near the center of a 280eV and 395eV Nova hohlraum Also shown is opacity (/100) of cold Mo, which has a K-line at 17 4keV with a fluorescence yield of 47% Using equation (2) above, we find the number of 17 4keV photons from each 10x10x50 micron x 100ps resolution element of molybdenum at density 0 2g/cc (i e $\rho_{Mo}\ell$=0 001) to be 2 4e7 photons/sr in the 280eV hohlraum and 3 8e8 photons/sr in the 395eV hohlraum Again, it is worth noting this technique may render diagnosable a dopant layer which is optically thin, $K\rho\ell$~0 01 to 0 1 on either side of the K-edge

For a thick "backlighting" slab, possibly behind some thin layer of wall material, the approximate expression for the number of fluorescent photons collected by an imaging detector is

$$\#\gamma's = \left(\int_{E_{Thresh}}^{\infty} \frac{c}{4\pi} \frac{U(\varepsilon)}{\varepsilon} d\varepsilon \right) 2\pi\, w \cdot h \frac{\eta_f}{4\pi}\, \delta\tau\, \Delta\Omega \qquad (3)$$

For Mo at 17 4keV, the number of "backlighter" photons per 10x10micron x 100ps resolution element would be 5e8 photons/sr/resolution element in the 280 eV hohlraum and 7e9 photons/sr/resolution element in the 395eV hohlraum. Hohlraum hot corona pumped fluorescence may be a way of providing almost "free" diagnostic photons up to many 10's of keV in high energy density hohlraums. The table below lists the number of photons/sr/$(10\mu m)^2$/100ps for a variety of materials pumped by the radiation field estimated for a 395eV Nova hohlraum.

Material	photon energy	thick slab	$\rho\ell$=0.001
Cu	8keV	1e11	2e10
Kr	13	2e10	1.5e9
Mo	17.4	9e9	4e8
Nd	35	6e8	9e6

For hot-corona x-ray fluorescence to be a useful diagnostic this emission needs to be much greater than the hohlraum background emission along the diagnostic line of sight We believe this will be true for two reasons. First, within our simulations, the typical midplane line of sight passes through a much cooler region of the hohlraum For example, simulations indicate that in the 395eV hohlraum the 17 4keV emission along the midplane line of sight is nearly five orders of magnitude less than the emission near the LEH where virtually all the hot corona emission is created. The background 17.4keV emission at the midplane is equivalent to 4e5 photons/sr/keV/($(10\mu m)^2$/100ps ; quite a bit lower than the estimated fluorescent signal for any reasonable bandwidth However, even if the imaging were to include the hot-corona emission it is possible that a properly tuned very narrow bandwidth detector would see mostly fluorescence signal This is because the nature of fluorescence is to integrate pump radiation over a fairly wide bandwidth but emit over a very narrow bandwidth For cold fluorescence, the natural linewidth ranges between 1 7eV for Cu, 6eV for Mo and 20eV for Nd Figure 5 plots fluorescent line intensities per keV for the 395eV hohlraum It shows the lines, especially for the thick slabs, to be significantly brighter/keV than the average radiation field pumping the fluorescence It also indicates that these lines are ~1/1000 of the planckian limit determined by the temperature that characterizes the slope of the pumping spectrum between 8 and 20keV

A concern we have investigated for the thick slab is whether L-shell vacancies on the surface of the slab, which are also pumped by the hot-corona, will resonantly reabsorb K-shell fluorescence from deeper inside the slab We find that by shielding the slab to eliminate pumping by photons <4keV, the probability that a K-shell photon will be resonantly reabsorbed is <~1% for both Cu and Mo when pumped by the 395eV hot-corona spectrum Consequently, the fluorescent intensities shown in figure 5 should be approximately correct

Discussion of hohlraum hot-corona pumped x-ray fluorescence

Pumping of fluorescence by hohlraum emission has already been seen on Nova and the level was about as expected Phillion [10] used CH slabs doped with Cl and Na, placed over a hole on the side of a scale 1 0 Nova hohlraum, to gather a second-opinion of gold M-band preheat inside a Nova hohlraum The fluorescent Cl and Na lines were measured with a time integrating, crystal spectrometer The fluorescent yield proved to be consistent with viewfactor estimates of hohlraum M-band levels made by combining estimates of laser spot M-band emission (as seen on disc experiments) and wall M-band emission (as measured by dante on the hohlraum midplane [11, 12])

A highly tuned, spherical crystal imager [9,13, 14] might be a particularly good instrument to use for imaging hot-corona pumped x-ray fluorescence With a spectral resolution $\Delta E/E$ ~ 1e-5 and a collection solid angle $\Delta\Omega$~ 1e-5 to 1e-3, such an instrument could collect a large number of photons per 10x10μm x 100ps resolution element. For thick fluorescers pumped by the 395eV hot-corona, we would expect to gather 5e4 to 5e6 Cu K-alpha photons (per resolution element) at 8keV, 2e3 to 2e5 Mo K-alpha photons at 17 4keV, 90 to 9e3 Nd K-alpha photons at 34keV

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1- J T Hunt, K. R Manes, J R Murray, P A Renard, R. W Sawicki, J B. Trenholme, and W. Williams, "A Design Basis for the National Ignition Facility," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-117399 (1994)
2- M. Andrè, M. Novaro, D Schirmann, "Technologie pour un Laser Megajoule", Chocs, Review Scientifique et technique de la Direction des applications militaires, Numèro 13, 73, Avril 1995.
3- J MacMordie, private communication (AWE, Aldermaston, UK, 1995)
4- L. J Suter, R L Kauffman, J. F Davis, M S Maxon, Efficient Production and Applications of 2 to 10-keV X-rays by Laser Heated "Underdense Radiators", ICF Quarterly Report, April-June 1996, Volume 6, Number 3, Lawrence Livermore National Laboratory, UCRL-LR-105821-96-3 (1996)

5- R L Kauffman, L J Suter, H N Kornblum, D S Montgomery, "X-ray Production in Laser-Heated Xe Gas Targets", ICF Quarterly Report, April-June 1996, Volume 6, Number 3, Lawrence Livermore National Laboratory, UCRL-LR-105821-96-3 (1996)
6- C A Back, J Grun, C Decker, L J Suter, to be published
7- S T Perkins, D E Cullen, M H Chen, J H Hubbel, J Rathkopf, J Scofield, Tables and Graphs of Atomic Subshell and Relaxation Data Derived from the LLNL Evaluated Atomic Data Library (EADL), z=1-100, UCRL-50400 Vol 30, October 31, 1991
8- J M Soures, et al, Phys Plasmas 3, 2108 (1996)
9- J Koch, Journal of Applied Optics, April, 1998
10- D Phillion, LLNL, private communication 1987
11- H N Kornblum and R L Kauffman, Rev Sci Instrum 57, 2179 (1986)
12- R L Kauffman, L J Suter, C B Darrow, J D Kilkenny, H N Kornblum, et al, Phys Rev Lett 73, 2320 (1994)
13- F J Marshall, J Ortel, A Framed Monochromatic X-Ray Microscope for ICF, Rev Sci Instrum Vol 68, No 1, 735 (1997)
14- S A. Pikuz, T. A Shelkovenko, V M Romanova, D. A. Hammer, A Ya Faenov, V M Dyakin, and T A Pikuz, High-Luminosity Monochromatic X-Ray Backlighting Using Incoherent Plasma Source to Study Extremely Dense Plasma, Rev Sci Instrum Vol 68, No 1, 740 (1997)

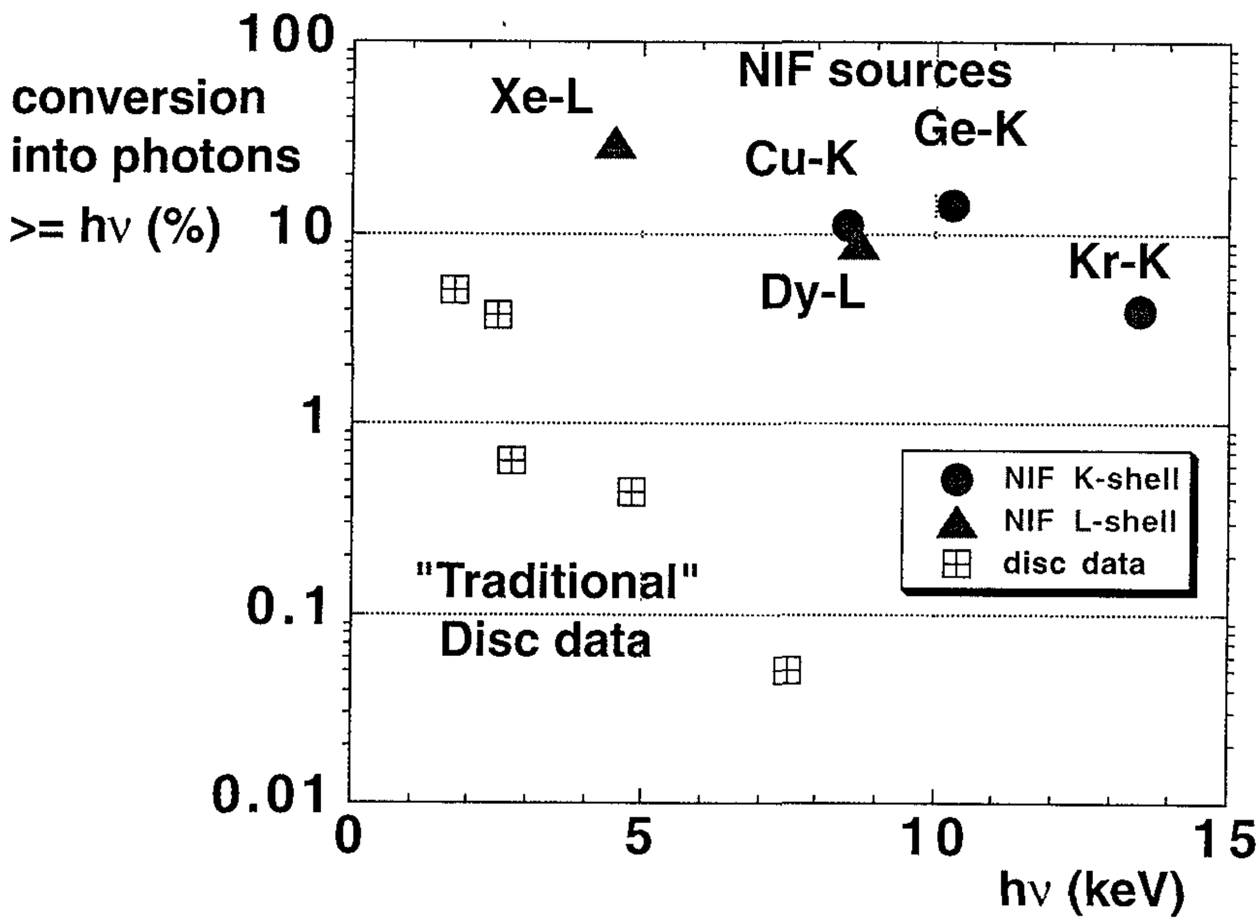

Figure 1- Theory and modeling, supported by experiment, indicates that NIF will be able to convert a very significant fraction of its laser energy into mult-kilovolt radiation using "underdense radiators". The efficiencies are very much greater than from a traditional disc.

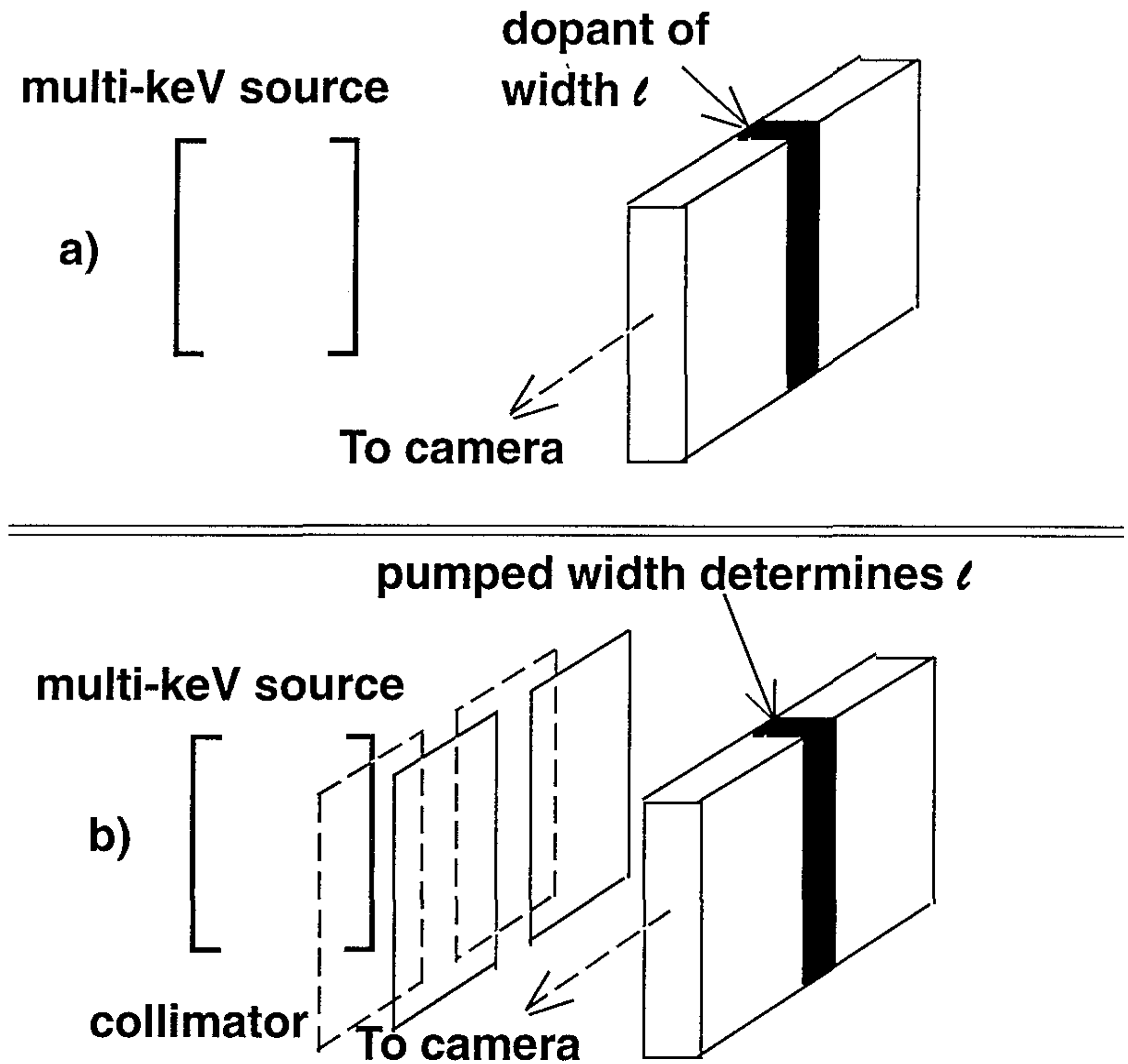

Figure 2- Two approaches for causing only in a "slice" thru the experimental package to fluoresce.

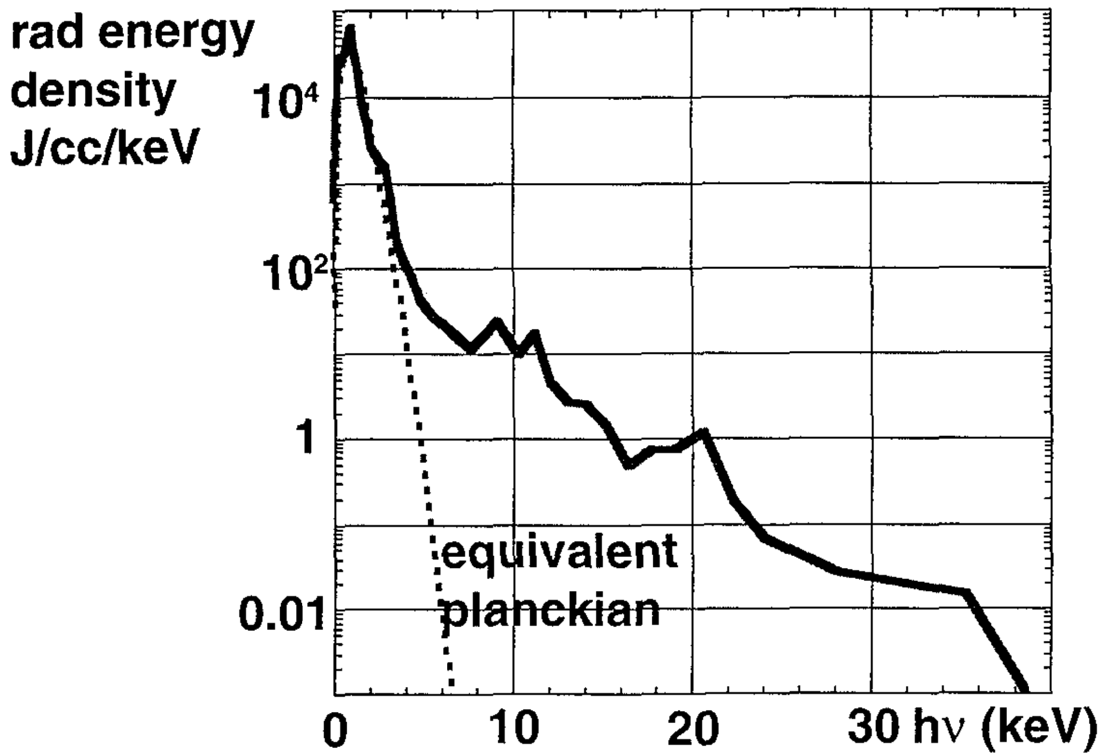

Figure 3- Average radiation field inside a simulated scale 1.0 Nova hohlraum, at 1ns, when the hohlraum temperature is ~230eV. The hot corona emission from near the LEH causes the high energy radiation field to be >> the equivalent planckian which describes the spectrally integrated radiation energy density (J/cc).

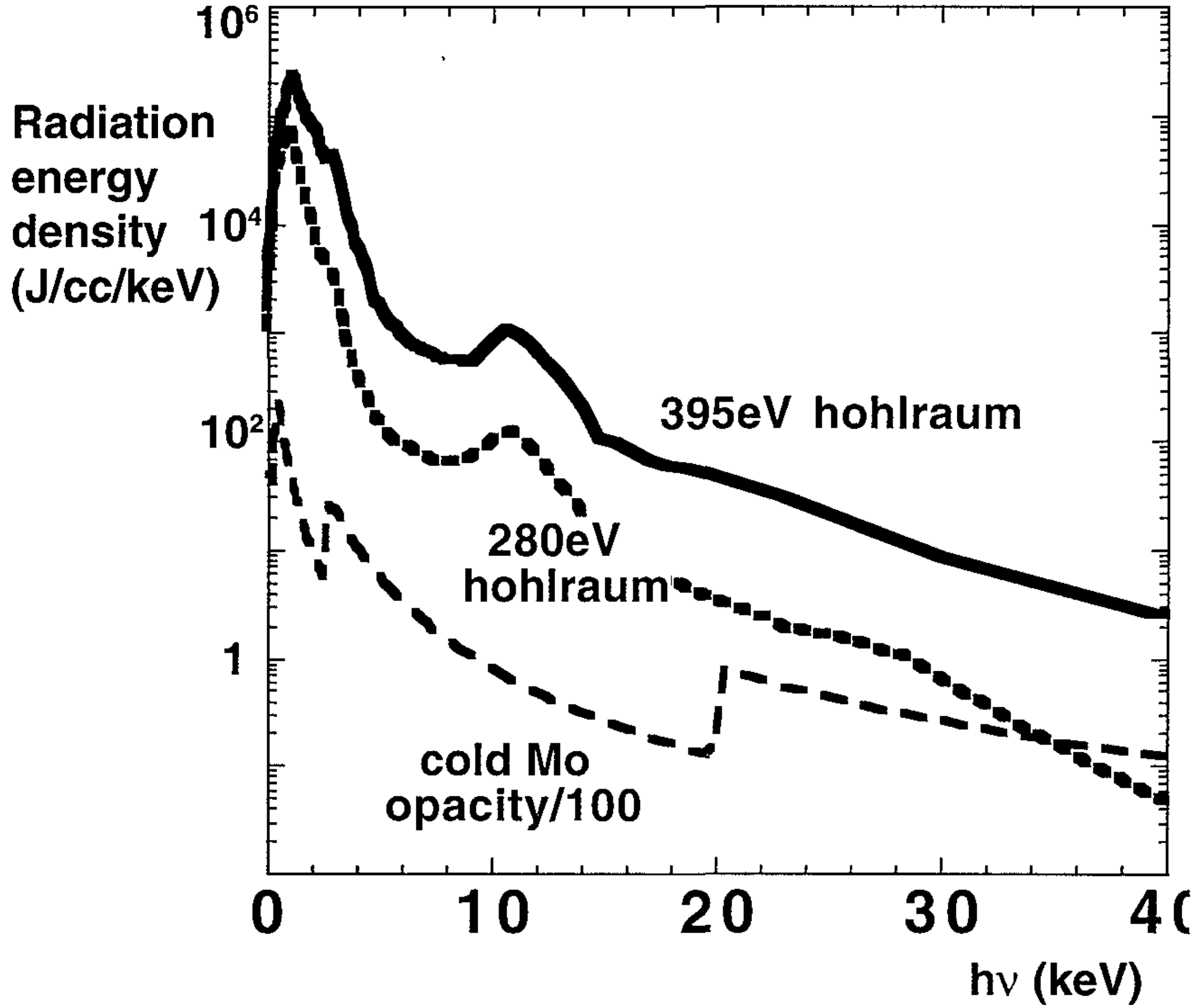

Figure 4- Estimated radiation energy density near the center of a 280eV and a 395eV Nova hohlraum. Also shown is the opacity of cold Mo (/100) which has a K-line at 17.4keV with 47% fluorescent yield due to radiation absorbed above the 20keV K-edge.

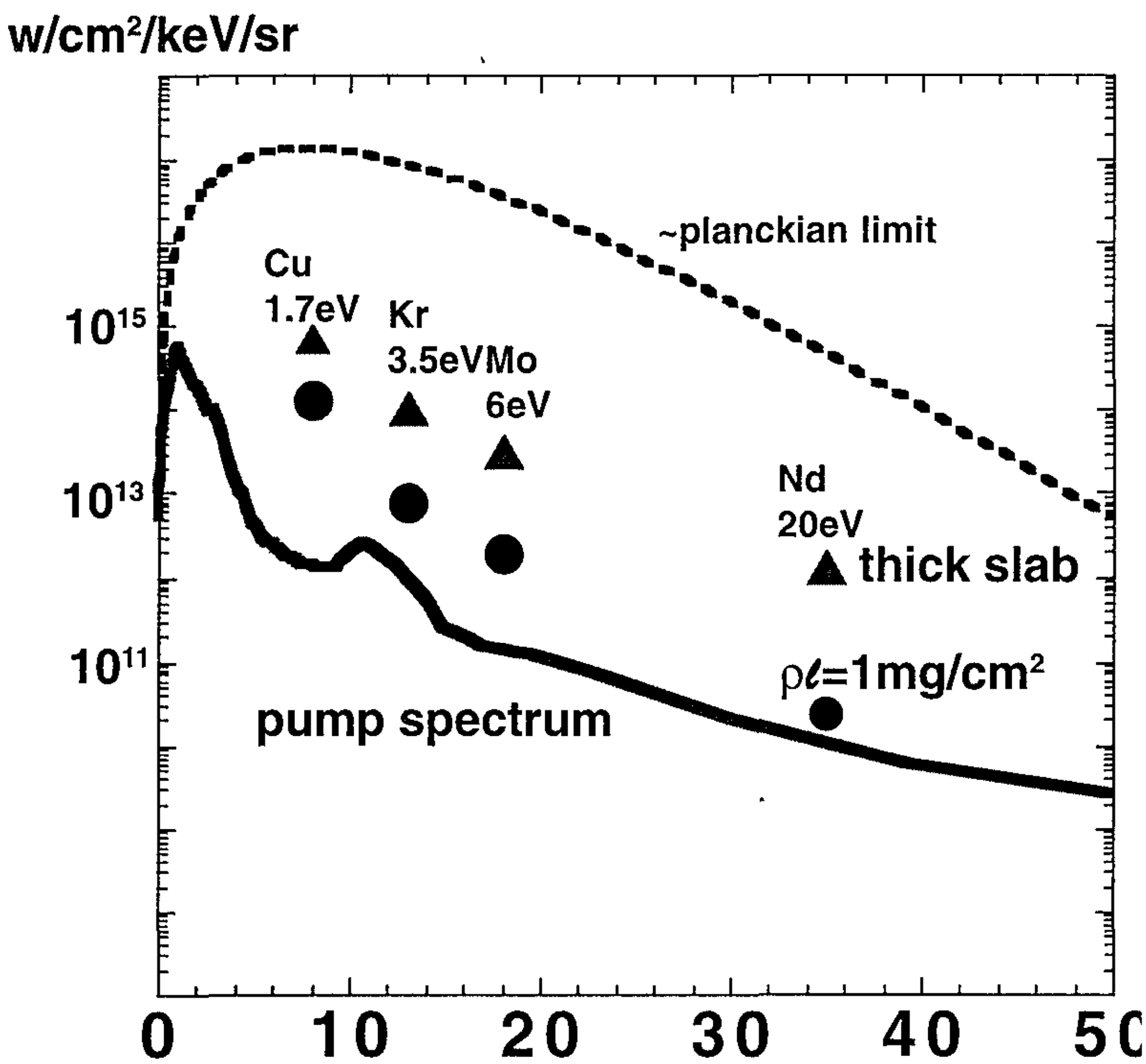

Figure 5- Filled triangles are fluorescent line intensities we expect from thick slabs of material pumped by a 395eV hohlraum's spectrum. Dots are fluorescent line intensities from a dopant layer of $\rho\ell$=1mg/cm^2.

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