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Nearly 10 years of Nova experiments and analysis have lead to a relatively detailed quantitative and qualitative understanding of radiation drive in laser heated hohlraums. Our most successful quantitative modelling tool is 2D Lasnex numerical simulations. Analysis of the simulations provides us with insight into the details of the hohlraum drive. In particular we find hohlraum radiation conversion efficiency becomes quite high with longer pulses as the accumulated, high Z blow-off plasma begins to radiate. Extensive Nova experiments corroborate our quantitative and qualitative understanding.

High Z cavities or hohlraums are an essential part of the indirect drive approach to inertial confinement fusion [1]. They convert intense laser light into xrays which can symmetrically implode capsules or be used for a wide variety of other experiments. Figure 1 shows a typical laser heated hohlraum. The laser beams enter through laser entrance holes (LEH) at the ends of a cavity which is typically gold. On the Nova laser 5 beams per side enter with cylindrical symmetry. These beams strike the walls of the hohlraum at intensities of 10^{14} to 10^{15} w/cm2 where they heat the gold, producing xrays. These xrays can heat the unilluminated walls which become hot and, in turn, efficiently reemit xrays. Later in time, the laser must also propagate thru hot, low density plasma which has blown off from the laser spots. One of the most fundamental questions we must answer about a given hohlraum is how much radiation flux ($T_R{}^4$), or "drive", does it produce?

One of the ways in which we can view drive is in terms of simple power balance where the radiation source is balanced by the radiation sinks [2,3,4]. That is, radiation production = wall losses + hole losses + diagnostic losses. We write this balance as

$$\eta P_L=(1-\alpha)A_{wall}\sigma T_R{}^4+ A_{LEH}\sigma T_R{}^4 + A_{diag}\,\sigma T_R{}^4 \quad \text{[eq. 1]}$$

Here P_L is the absorbed laser power and η is the "conversion efficiency" of laser light into xray power. $T_R{}^4$ is the hohlraum radiation flux we wish to understand. A_{wall} is the hohlraum area, α is the "albedo" of the wall (ratio of reemitted flux/incident flux; so $1-\alpha$ is the fraction absorbed). A_{LEH} is the area of the laser entrance holes, A_{diag} is the area of diagnostic holes, σ is the Stephan-Boltzmann constant. In this simple view of hohlraum energetics, the laser power which is not converted to xrays, $(1-\eta)P_L$, becomes hot plasma which can fill the hohlraum.

The key parameters in this model of hohlraum energetics are η and α. Typical values for a Nova "scale 1.0" hohlraum irradiated with a 1ns pulse at 20TW are $\alpha=0.79$, $\eta=0.75$ and $T_R=225$eV.

If hohlraum energetics were really so simple this would be a short paper. In practice we find the albedo, α, a quantity which we can experimentally isolate and generalize. However the radiation conversion efficiency, η, is not so simple. We find it to vary with several parameters, including pulse shape and geometry. Consequently, our most successful means for quantitatively predicting hohlraum T_R is not the simple model, but rather detailed 2D numerical simulations with our Lasnex code [5]. Figure 2 compares measured radiation temperature (filled squares) from 1ns Nova hohlraums [6] with simulated temperature (open circles). These comparisons will be discussed in more detail later. Here we make the point is that Lasnex in it's "black box" mode can successfully predict drive in hohlraums.

We can more deeply analyze our Lasnex simulations to gain insight into the details of drive physics. One approach to separately ascertain the radiation power absorbed by each of the sinks and then use equation 1 to find total radiation power . We isolate losses to the walls and diagnostics by first extracting a time dependent radiation temperature $T_R(t)$ from the 2D simulation. Then, in a separate 1D planar slab simulations we calculate how much radiation power is absorbed by the gold wall and by the diagnostic. Finally, the radiation power escaping from the LEH's is taken directly from the 2D Lasnex simulation. The sum of these three powers should be the total radiation power produced in the hohlraum. Figure 3 plots this radiation budget analysis for a simulated Nova hohlraum driven by a 2.2ns long shaped laser pulse (ps26). The most prominent feature of this plot is that the late time radiation power approaches and then slightly exceeds the absorbed laser power.

The above analysis assumes that the simple model of sources and sinks really works in Lasnex simulations of Nova hohlraums. One check is to directly extract the wall power from the Lasnex simulation [7] and compare that with the power estimated by the separate, 1D simulation. We find the two estimates of wall losses are the same to a few percent. This is evidence that the wall in the 2D simulation behaves like a planar slab and that radiation is the dominant wall heating mechanism in a Lasnex simulation. A consequence of this is that experiments which attempt to isolate wall losses can be generalized; we have no theoretical basis for thinking them dependent on aspects of the experiment other than the time dependent radiation temperature.

In contrast to wall losses, our Lasnex simulations show that the radiation production cannot be generalized. Figures 4a and 4b contrasts the radiation production in a hohlraum simulation with that from a disc simulation, illuminated at the same intensity as the hohlraum wall (since the hohlraum is heated by 10 beams while the disc is only heated by 1, the disc radiation power has been scaled up by 10 to allow more convenient comparison of the radiation powers). We see that at early times both disc and hohlraum have about the same radiation production. Later in time the hohlraum radiation production becomes larger than the disc's. With sufficiently long pulse length, the hohlraum radiation production can approach or exceed the laser power.

In our hohlraum simulations radiation production rises because the hot blow-off plasma is confined. To see this first consider, figure 5 which shows the scaling of radiation production by hot, underdense gold plasma with electron density. The values shown are TW of xrays produce by a volume equal to the volume of a scale 1.0 Nova hohlraum. We see that at 10^{21}/cc the underdense plasma alone can produce ~9TW of radiation. Now initially in a hohlraum a the unconverted laser power $(1-\eta)P_L$ produces hot blow-off. Unlike a disc, where this blow-off is free to expand, the blow-off in a hohlraum is confined. Both energy and plasma accumulate, causing the density to rise. Figure 6 plots average corona electron density vs. time for the pulse shaped hohlraum and disc of figure 1. This is a plot of material which is hotter than 1keV. In a disc the average density of the blow-off drops in time while in a hohlraum the density rises above 10^{21}/cc. Compared to a disc, this accumulation of blow-off qualitatively changes the way in which plasma energy is dissipated. It provides a pathway for deposited energy to be converted into radiation much faster than hydro losses. Analysis of our simulations corroborates this picture by showing that at late time much radiation is produced over a very substantial volume of the hohlraum. This is also in contrast to early time when the radiation production volume is at the wall and is "disc-like".

Summarizing our analysis of Lasnex hohlraum simulations, we find:

1- Wall losses in hohlraum simulations are approximately slab-like. Experiments to isolate wall losses can be generalized.

2- Radiation production in hohlraums has at least two phases. Disc-like at early time and greater than disc-like at late time. This implies that experiments to isolate radiation production are less generalizable.

3- At densities > 10^{21}/cc radiation is efficiently produced in the hot, dense plasma that accumulates. This provides an avenue for producing radiation not present in discs. High late time conversion efficiencies are possible in hohlraums of average density >~0.1n_c.

Extensive Nova experiments corroborate the quantitative and qualitative picture of drive formed by our modelling and analysis. We have carried out four major types of experiments. They are:

*Experiments to isolate the wall losses in gold slabs. These are the foundation of our quantitative understanding of drive in laser heated hohlraums.

*Measurements of radiation temperature in laser heated hohlraums. These experiments test our ability to integrate many pieces of coupled physics.

*Studies of radiation production in slabs

*Studies of radiation production in high Z, underdense plasmas.

Wall loss experiments

So called burn-thru experiments provide fundamental information on wall losses for benchmarking wall physics models. In these experiments [8], we place thin pieces of Au (<~1.5μm) over a hole drilled in the side of a well characterized, laser heated hohlraum. We observe the time at which the radiation diffusion wave burns thru the thin foils. The basic idea is that

burn-thru depth(t) ~ mass heated(t) ~ net energy deposited(t).

The basic information provided by these experiments can be used to test any wall model. In particular, we use it to benchmark our Lasnex wall model; the average atom model called XSN [9].

The experiments to date have been done in hohlraums heated by a 1ns pulse which achieve a peak radiation temperature of 260±10eV. Our analysis of these experiments indicate that the wall losses are approximated by an "XSN opacity multiplier" of 1.0±0.2. In our numerical simulations this range of opacity multiplier causes a variation in simulated peak temperature of ~±3eV. At 260eV the XSN wall losses are quite close to those estimated by a much better physics model, STA [10]. Consequently, a multiplier of ~1.0 agreeing with experiments is not too surprising. At lower temperatures, however, XSN opacities become significantly less than STA opacities. Experiments to investigate this at 150eV are in progress, to be followed by still lower temperature experiments.

Radiation temperatures in laser heated hohlraums

Measurements of radiation temperature in laser heated hohlraums have been performed at many institutions [11] and are the most visible type of drive experiments. They also provide the greatest challenge for our understanding since they require us to successfully integrate many pieces of coupled physics. We have two basic techniques for measuring hohlraum radiation temperature. In the "witness plate" technique [12], we infer T_R from the velocity of a radiation driven shock in an Aluminum sample exposed to the radiation drive. An Al plate, which is either wedged shaped or stepped, is placed over a hole drilled in the side of the hohlraum. An optical streak camera records the visible light created as the radiatively driven shock breaks out of the plate, from which we can extract the shock velocity. This technique measures flux <u>into</u> the hohlraum wall.

In the second technique, T_R is inferred from a measurement of absolute xray emission thru a hole drilled in the center of the hohlraum. An instrument, called Dante [13], consisting of filtered xray diodes and fast scopes records the radiation flux coming out of the hole. In the simplest hohlraums, Dante measures the flux coming out of the opposite hohlraum wall. This measurement of drive is time dependent and complementary to the witness plate since the Dante flux (the flux out of the wall) should be equal to the albedo times the witness plate flux (the flux into the wall).

We have measured drive in pure gold scale 1.0 Nova hohlraums with a number of pulse shapes. We have used 1ns flattop pulses, a shaped pulse, "ps26", shown in figure 3 and third, shaped pulse similar to ps26 but having a 18TW peak (ps22).

Our detailed Lasnex modelling [14] of these experiments is in rather good agreement with the observations. Figure 2 shows the comparison between 2D Lasnex simulated T_R's (open circles) and experimentally measured T_R's (filled squares) for scale 1.0 Nova hohlraums irradiated with 1ns pulses. The hohlraum diameter is 1.6mm and the length is 2.55mm. The LEH diameter is 0.8mm. We measured the drive in these hohlraums with stepped witness plates. The Lasnex temperatures shown represent peak, simulated radiation flux into the wall, as would be measured by the witness plate.

Peak drive from our pulse shaped experiments is also quite close to our simulations. Figure 7 shows $T_R(t)$ measured by Dante on a ps26 pure gold drive experiment. The corresponding Lasnex simulation is also shown. The drive from our standard modelling, produced by post-processing the simulation to mock-up the Dante diagnostic, properly estimates the peak radiation temperature. However, the foot is clearly off. This likely is related to our suspicion that Lasnex's XSN opacities are too low at T_R~150eV, as mentioned earlier. Figure 7 also indicates the simulated foot drive would be very close to observations if real Au opacities at ~150eV were better approximated by an XSN opacity multiplier of 3. Figure 8 compares the peak experimental Dante temperatures against peak Lasnex Dante temperature for a number of ps22 and ps26 pure Au hohlraums. In general, our simulations are quite close. All the ps22 experiments were done in pure gold hohlraums 1.6mm diameter, 2.75mm long with 1.2mm diameter LEH's. The ps26 hohlràum is 2.4mm long. The range in temperatures is due to variations in delivered laser power.

For the 1ns hohlraums, measurements of laser light backreflected by Stimulated Raman and Brillioun Scattering (SRS & SBS) are quite small, ~1% [15, 16]. However, for the pulse shaped experiments, the scattered fractions are higher; ~9%. An important part of modelling the drive experiments to the accuracy shown in figure 8 is to reduce the incident laser power by the measured backreflected light.

In addition to pure Au hohlraums, we have also measured drive in gas filled hohlraums [17]. These hohlraums are part of a comprehensive effort to understand drive in hohlraums similar to ones we plan to use on NIF [18]. Our experiments use scale 1.0 gold hohlraums which are filled with either methane or propane. 3500A thick polyimid windows cover the 1200μm diameter laser entrance holes. With either gas we find the drive is reduced compared to a gold hohlraum. Table 1 summarizes the changes of radiation flux caused by gas and compares them with the changes we expect from simulation. Although these experiments are still in progress, we think we understand the drive reduction caused by gas to ~10% in flux. In our modelling, gas hohlraum drive is reduced for two reasons. First, there is slightly less radiation production in a gas filled hohlraum. This accounts for ~4-6eV of the observed drop. A bigger reduction is due to decreased absorption. With "unsmoothed" Nova beams the average SRS+SBS rises from ~9% in pure Au to ~16% in methane and ~23% in propane. MacGowan, et. al. [16] have shown that these scattered light fractions can be reduced to the 1% level by proper beam smoothing and/or Landau damping. We plan to smooth all 10 of Nova's beams in the coming year and redo these drive experiments.

Table 1

gas	n_e(0ns)	Δflux expt	Δflux modeling
methane	2.5e20	-32%	-21-28%
propane	6.5e20	-40%	-30-34%

Disc conversion efficiency experiments

Experiments measuring the radiation produced by laser heated gold discs have long been a staple of ICF facilities throughout the world. The filled triangles of figure 9 are Nova measurements of 1ns Au disc conversion efficiency [19]. The solid line shows a typical disc scaling from Lasnex simulations. Except at the highest intensities, where poor focal spot quality may be playing a role, there is general agreement between simulation and experiment. One of the original roles of disc experiments was to empirically provide a conversion efficiency, η, which we could use in the power balance model of equation 1. However, subsequent measurements of Au burn-thru, described earlier, constrained our wall models to the point where equation 1 would not work with disc conversion efficiencies. The lower solid line in figure 2 shows the estimated scaling of 1ns hohlraum T_R using these disc conversion efficiencies and "benchmarked" XSN wall losses. This model clearly does not work. The other solid line passing thru the data results from the benchmarked wall model and a fixed, 75% conversion efficiency.

The filled squares of figure 9 plot conversion efficiencies inferred from 1ns drive experiments. They're plotted at the intensity the beams would have at the wall of the hohlraum without refraction, absorption, etc. by the blow-off. These conversion efficiencies are very different from the discs'. Also plotted on figure 10 are hohlraum conversion efficiencies inferred from the peak drive temperatures of ps22 and ps26 pure Au drive experiments. These are ~85% when we include the correction to the incident laser power due to SBS+SRS losses [16]. This scattering of experimental conversion efficiencies forms a sensible pattern when compared with the conversion efficiencies inferred from our Lasnex simulations. As we discussed in the beginning of the paper, blow-off confinement effects cause simulated hohlruam conversion efficiencies to become greater than disc efficiencies.

Radiation production by underdense plasmas

Our analysis of Lasnex simulations highlights the importance of radiation production in underdense, blow-off plasma once a hohlraum fills. Because it scales as density squared (figure 5) underdense plasma radiation can be an avenue for channeling energy into radiation instead of hydro losses. Recently we have begun measuring radiation production in high Z, underdense plasmas. These experiments utilized 2.4mm diameter balloons inflated with 1atm of 75% Xe and 25% propane (partial pressures). The balloon wall was ~3500A of polyimide. Propane was included to provide C and H ions which are thought to suppress Brillioun backscatter. When ionized, the fill gas has an electron density of ~1.1×10^{21}/cc. We irradiated them with 1ns pulses of ~22TW and inferred the total xray production of these bags by measuring the soft-xray and Xe L-shell xray emission along single lines of sight perpendicular to the Nova axis of symmetry. Assuming isotropic emission from the bags, we find a total conversion efficiency of 80% at ~3×10^{14}w/cm^2 and 70% at ~7×10^{14}w/cm^2. The intensities are approximate because we employed a very 3D irradiation scheme for these bags. These conversion efficiencies are as high as we have measured on Nova from "open geometry" targets and higher than 1ns discs at the same intensities. These efficiencies are also somewhat higher than the η ~49-65% we calculate with Lasnex and XSN non-LTE atomic physics. The simulated range results our attempts to bracket the illumination geometry of these 3D experiments.

NIF radiation budget

We have performed a radiation budget analysis of the NIF ignition hohlraum simulations of Pollaine [18]. Qualitatively, they are extremely similar to the ps26 Nova radiation budget of figure 3. The time integrated conversion efficiency for the NIF simulation is 81%. For Nova ps26 it is 82%. The general similarity indicates that we are not asking NIF hohlraums to perform in a manner very different from what we have already done on Nova.

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Figures

1- Typical laser heated hohlraum

2- Radiation temperatures in a scale 1.0 Nova hohlraum. Experiment (filled squares), Lasnex (open circles), equation 1 using disc conversion (lower line) and 75% conversion (line thru data).

3- Radiation power budget analysis of a simulated Nova hohlraum irradiated by a shaped pulse known as ps26.

4- a) Radiation production in a simulated ps26 hohlraum (irradiated by 10 beams) compared with the 10X the radiation production of a gold disc irradiated by a single ps26 beam. b) Same for a hohlraum and disc irradiated by a 1ns flattop.

5- Electron density scaling of xray production in hot, underdense Au plasma The plasma volume equals the volume of a scale 1.0 Nova hohlraum.

6- Average electron density of the blow-off in a ps26 hohlraum and disc vs. time. Here blow-off is defined as material hotter than 400eV.

7- Comparison of measured Dante $T_R(t)$ and simulated $T_R(t)$ for ps22.

8- Peak experimental Dante temperatures vs. peak Lasnex Dante temperature for a number of ps22 and ps26 pure Au hohlraums.

9- Conversion efficiency of laser light into xrays for discs and hohlraums, experiment and modelling.

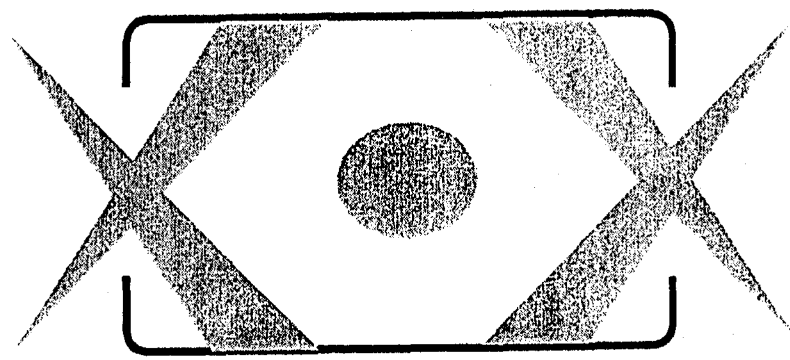

Figure 1

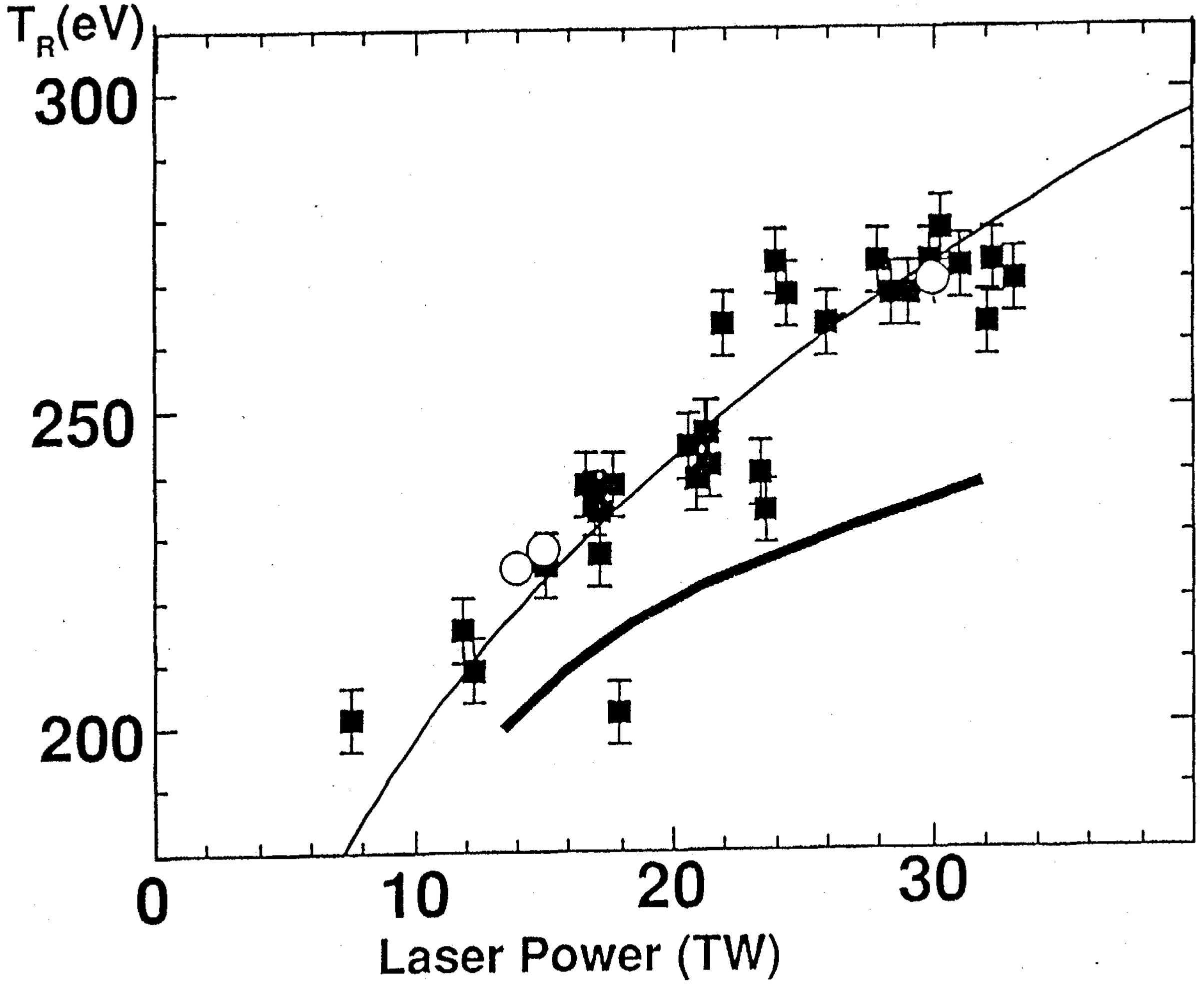

Figure 2

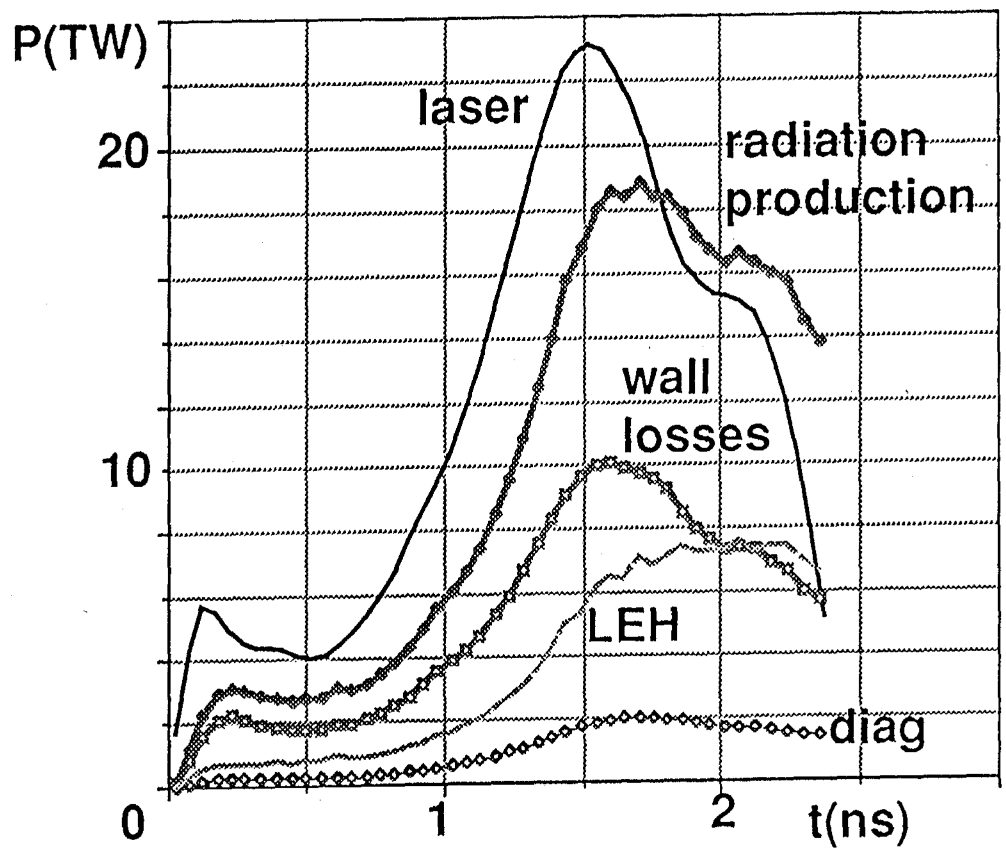
P(TW)
20
10
0
1
2
t(ns)
laser
radiation production
wall losses
LEH
diag

Figure 3

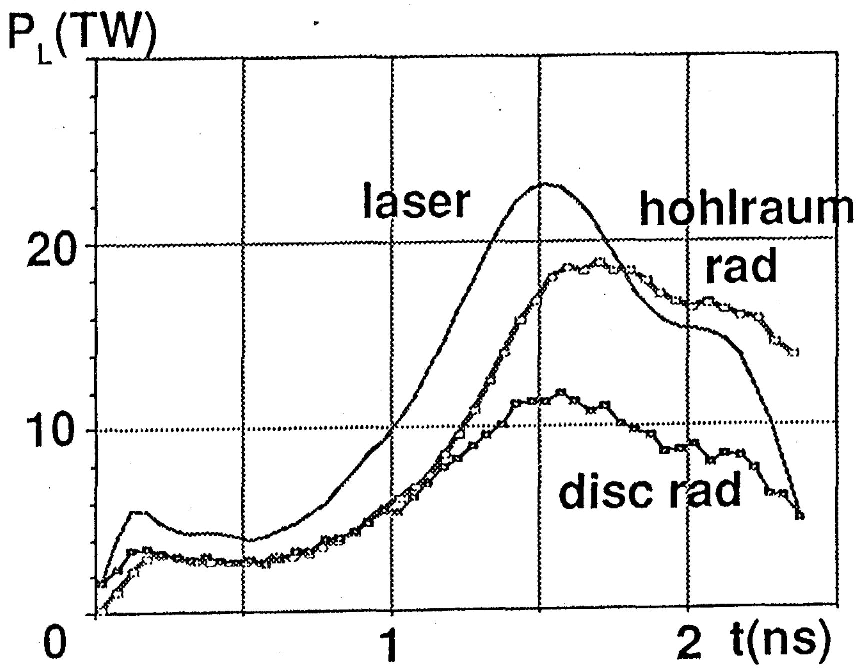

Figure 4a

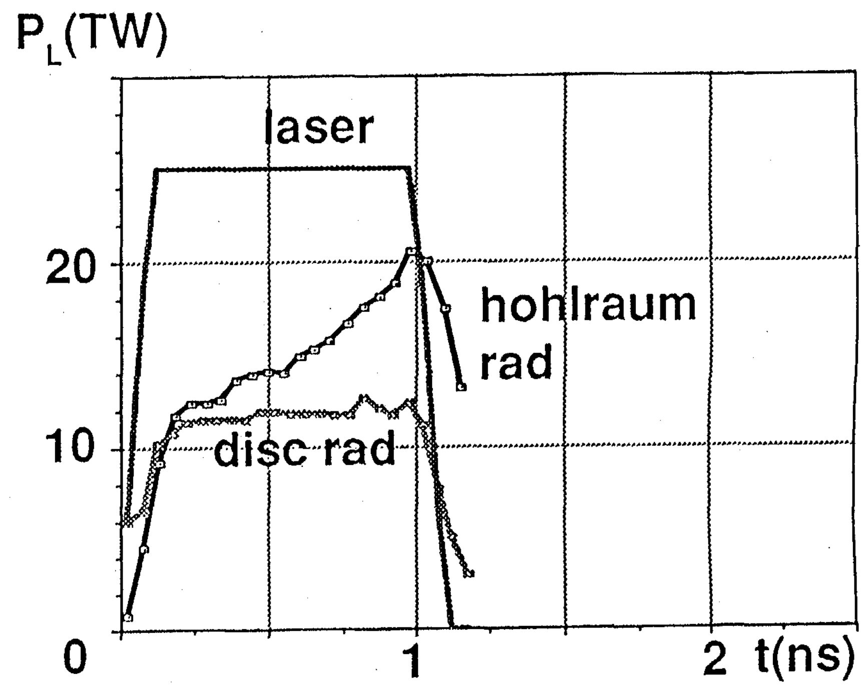

Figure 4b

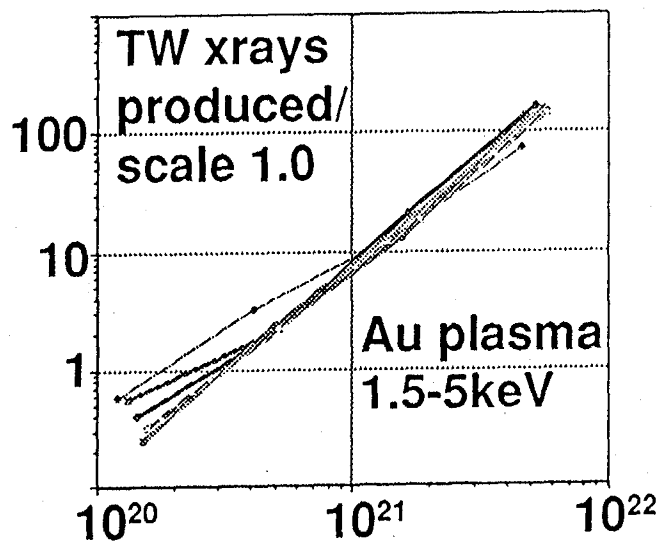
TW xrays
produced/
scale 1.0
Au plasma
1.5-5keV
100
10
1
10^{20}
10^{21}
10^{22}

Figure 5

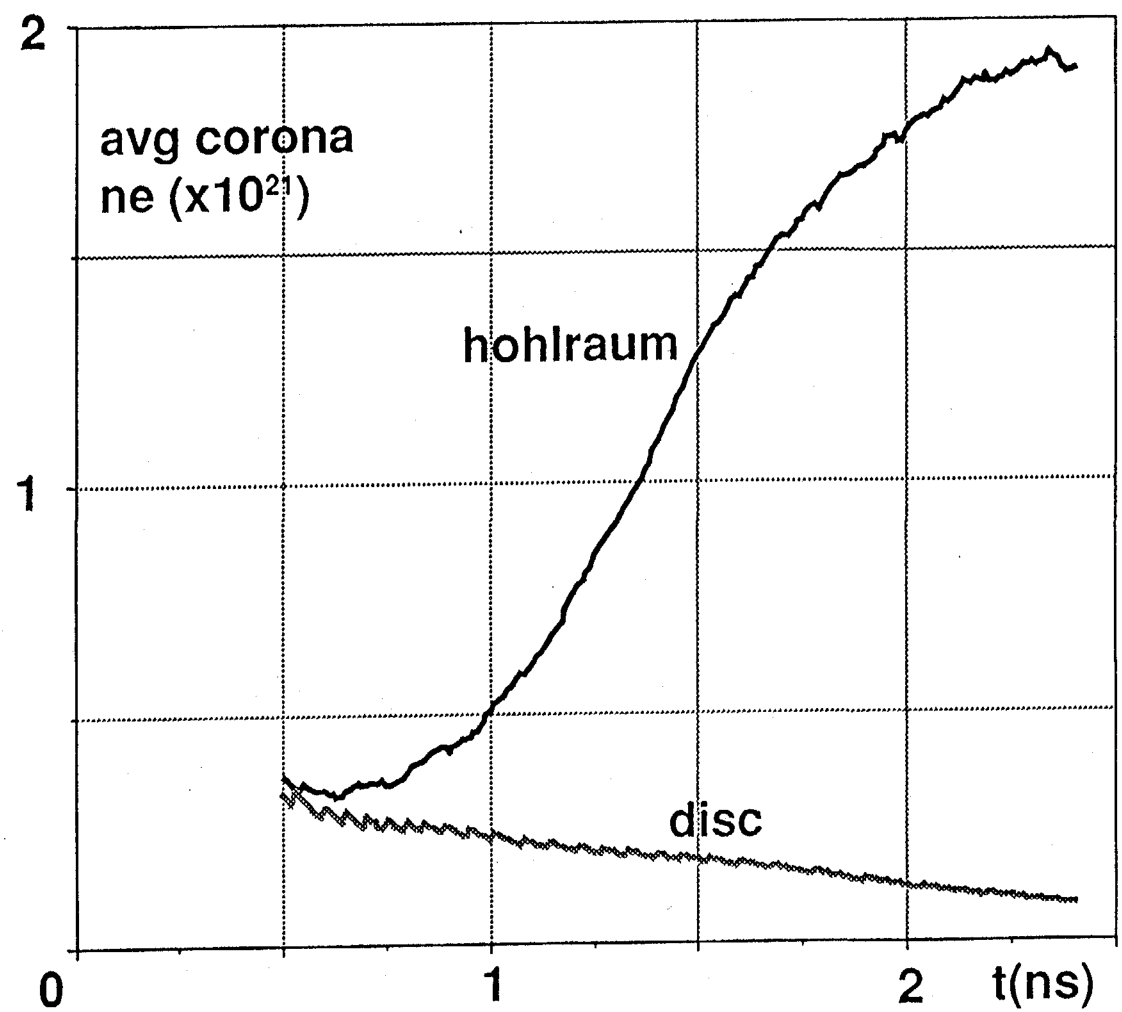

Figure 6

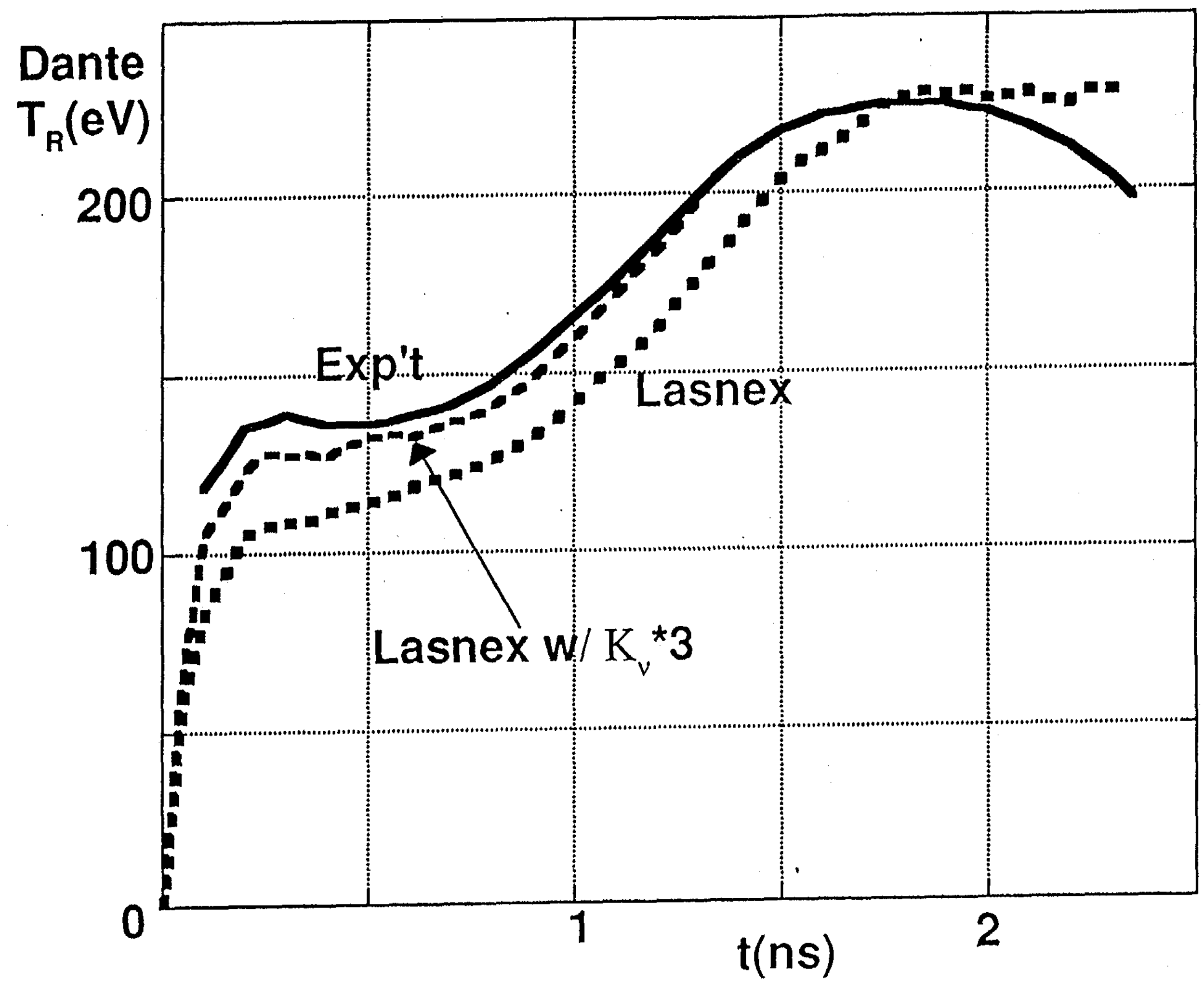

Figure 7

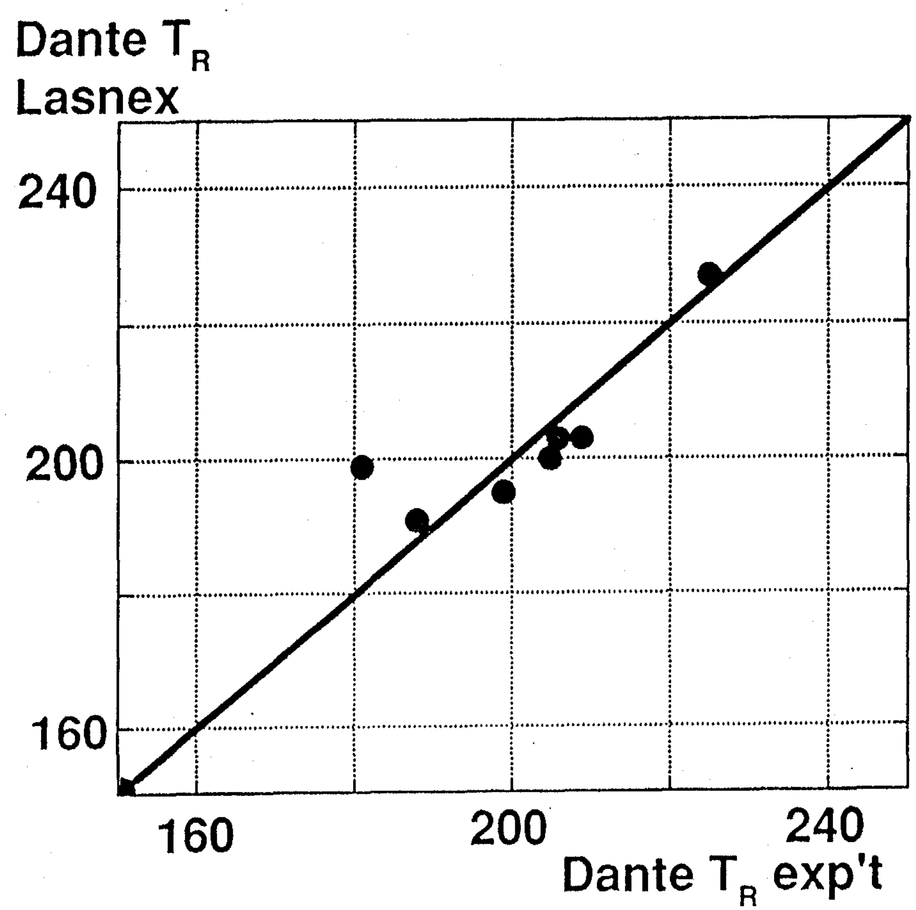

Figure 8

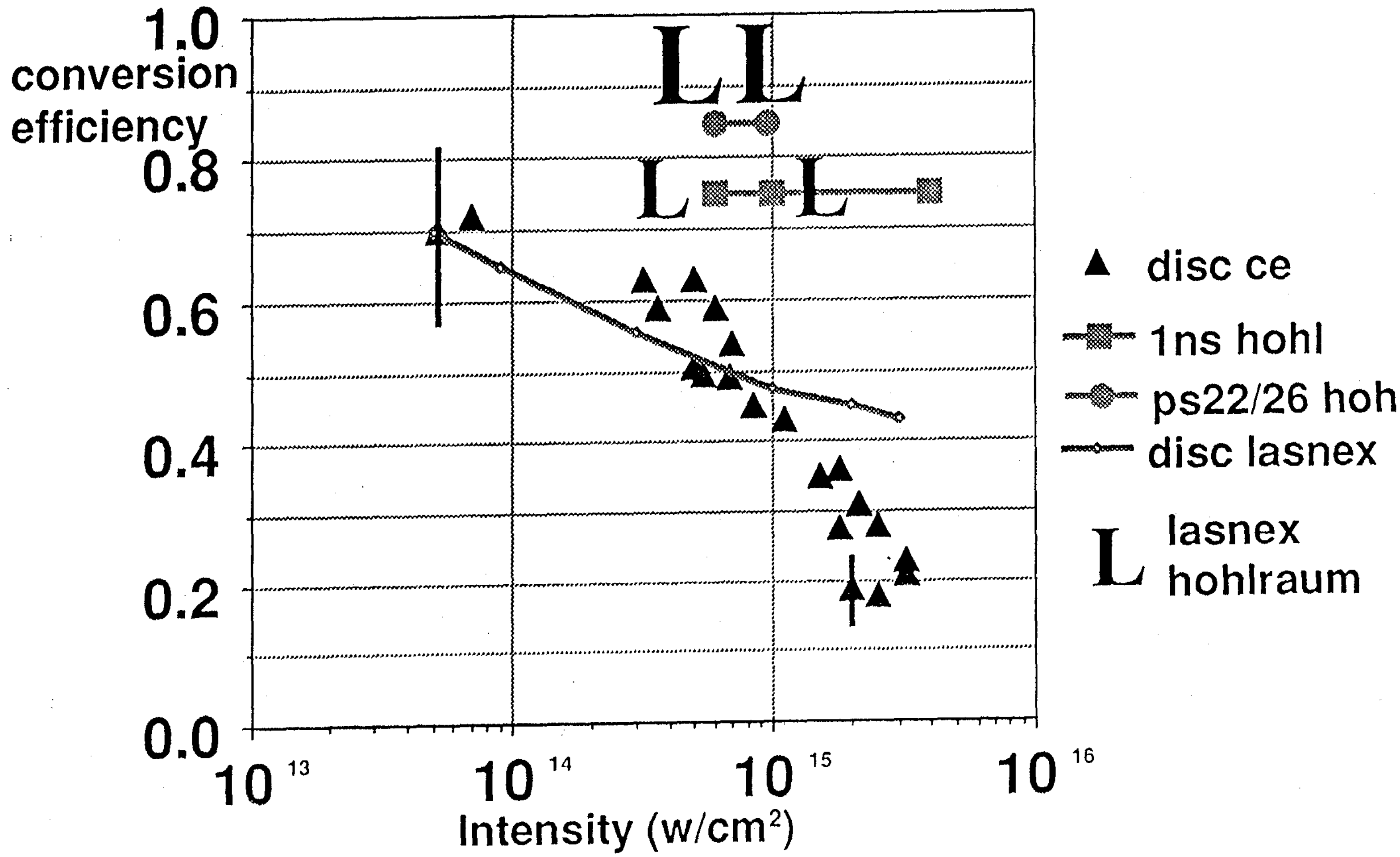
1.0
conversion
efficiency
0.8
0.6
0.4
0.2
0.0
10 13
10 14
10 15
10 16
Intensity (w/cm2)
disc ce
1ns hohl
ps22/26 hohl
disc lasnex
lasnex
hohlraum

Figure 9