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Some Thoughts on the Role of non-LTE Physics in ICF

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LLNL Report #---

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Some Thoughts on the Role of Non-LTE Physics in ICF[1]

Jeff Colvin

I have been leading an effort to develop sub-critical-density high-Z metal-doped and pure metal foams as laser-driven x-ray sources for various national defense applications. The main idea here is that the laser beams preferentially heat the electrons, and if the plasma is sufficiently low density so that the heating rate is greater than the equilibration rate via electron-ion collisions, then the electron temperature in the plasma is much greater than the ion temperature as long as the laser is on. In such a situation the plasma is not in local thermal equilibrium (LTE), it heats supersonically and volumetrically, and the conversion efficiency of laser beam energy to multi-keV L-shell and K-shell radiation is much higher than what it would be in LTE plasma.

This is not a new idea [1, 2], but the development of accurate computational models for the atomic processes in non-LTE plasma is relatively new [3]. In the course of this work I adapted the work of Scott and Hansen [3] and developed a new computational model that provides reasonably good agreement between simulated and measured L-shell and K-shell emissivity from Ge-doped silica foams in Omega experiments [4]. It turned out that the model I developed and benchmarked with Omega data was identical to a model independently and simultaneously developed for NIF hohlraums and referred to as the “high-flux” model [5, 6].

The original model, though, had some approximations in it, and at least one adjustable parameter (the flux limiter on the temperature-gradient-driven electron thermal transport), and was found to be somewhat less accurate in matching NIF data of x-ray source targets [7]. The original model underwent a number of revisions and was benchmarked against data from Kr gas targets on NIF [8]. The new revised model -- now our standard model for x-ray source targets -- has been remarkably successful in matching data from a new generation of Cu-loaded foams that have been developed in the project that I lead [9]. Figure 1, taken from Reference 9, shows a comparison between simulated and measured Cu K-shell x-ray conversion efficiency for a series of experiments conducted on the Omega laser with newly developed Cu-loaded carbon nanotube (CNT) foams. The small systematic offset between the simulated and measured points in this figure is, we think, a signature of an effect of the foam microstructure on the laser beam absorption and propagation, as discussed in Reference 9. There may be even greater microstructure effects in the newer generation of pure Cu and pure Ag foams with which we are

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now experimenting on NIF. Data analysis and post-shot simulations are still in progress, and the effects of foam microstructure is still an open question.

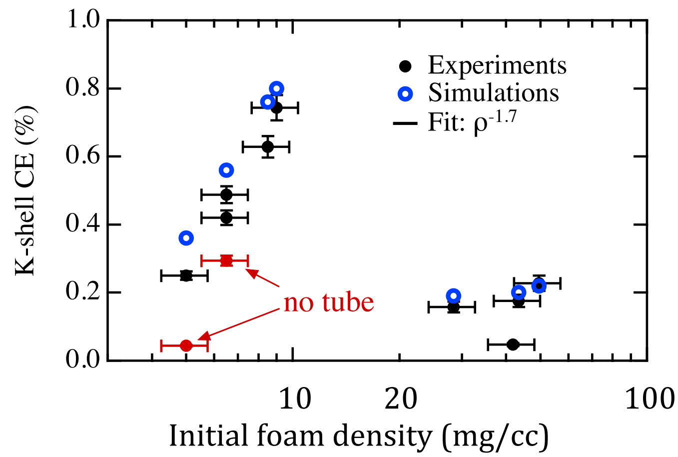

Figure 1. Simulated and measured Cu K-shell x-ray conversion efficiencies for Omega Cu-loaded CNT targets. Figure taken from Reference 9.

Nonetheless, this work has given me an appreciation for just how difficult it is to get an accurate calculation of plasma conditions and spectral emissivities in non-LTE high-Z plasma. Because of the very different time scales for the hydrodynamics and the radiative processes, the solution of the conservation of energy difference equation with the radiation coupling term is only conditionally stable, and the solution converges only for very small time steps. We are finding that in order to match NIF data requires tens of thousands of cycles and hundreds of hours CPU time per typical run, which, of course, necessitates parallel operation. Scott has developed what he calls an "extended algorithm" to address the convergence problem in non-LTE in the presence of strong matter-radiation coupling [10], but this algorithm is not in either of the ICF codes because there is currently no criterion by which the codes can decide when and where the extended algorithm is valid and when and where it is not.

Everything said here about non-LTE physics in x-ray source targets almost certainly applies also to NIF hohlraums. These hohlraums fill with sub-critical-density high-Z plasma with which the incident laser beams interact. The same considerations of calculational stability, convergence, and accuracy that apply to the x-ray source targets surely apply to hohlraum plasmas as well. Getting the non-LTE plasma conditions and spectral emissivities right is necessary to getting the drive asymmetries right in the simulations. Drive asymmetries are one of the principal obstacles we face in getting indirect drive ICF ignition to work.

Even if we can get the drive asymmetries right in the simulations, with the current hohlraum designs there is no way to eliminate them entirely. Indeed, the current focus of advanced hohlraum design, as I understand it, is to reduce the time dependence of the drive asymmetries by employing various means to tamp the wall blow-off, such as lining the inside wall with low-density Au foam. These approaches may help, but we will still be left with the difficulties of accurately simulating the spectral drive in the non-LTE plasma, and we still will not have eliminated the drive asymmetries.

In view of all the considerations outlined above, it may be time to re-think our approach to indirect-drive ICF. It seems to me that we will always have difficulty making indirect-drive ignition work in any geometry in which the capsule sees the laser spots. Perhaps we should look at hohlraum designs, such as chambered hohlraums, in which the capsule never sees the laser spots (that is, the “hot spots” in the sub-critical density wall blow-off plasma where the laser beams deposit their energy).

Fortunately, we do not have to start from scratch. There are already existing designs for chambered hohlraums (hohlraums with internal shields) that have already been tested. Lindl presents two types of chambered hohlraum design in his review paper [11]. At the time of publication of Reference 11 only the Type A chambered hohlraum, shown schematically in Figure 55a of Reference 11, had been tested on Nova. In the Type A chambered hohlraum internal shields are placed so as to reduce radiation losses out the laser entrance holes, which results in a higher radiation drive temperature in the center chamber where the capsule is placed. Some experiments with the Type A chambered hohlraum were conducted on Nova and confirmed the (small) gain in drive temperature that was predicted.

In the Type A chambered hohlraum, though, the capsule still sees the laser spots. In the Type B chambered hohlraum, shown schematically in Figure 55b of Reference 11, the internal shields are placed so that the capsule, in principle, never sees the laser spots.

A variant of the Type B chambered hohlraum was designed and tested on Nova as part of the original Rayleigh-Taylor material strength experiments in the mid-1990s [12, 13]. It was a scale-2.15 Nova hohlraum with the Rayleigh-Taylor experiment package mounted on the wall of the center chamber specifically to shield it from the Au M-band preheats from the laser spots. This hohlraum is shown schematically in Figure 2, taken from References 12 and 13.

This hohlraum was designed to produce a slowly rising drive pulse that reached a peak radiation drive temperature at the wall of the center chamber of ~85 eV at 8.5 ns. Measurements showed a reduction of the Au M-band at the mid-plane of the hohlraum by more than a factor of three over the equivalent-scale hohlraum without the internal shields, consistent with simulations. At the time I did this hohlraum design we were not concerned about radiation drive asymmetries in the center of the central chamber, and I can find no information about drive asymmetries in my surviving notes. References 12 and 13 are the only publications that resulted from this particular work; the indirect-drive approach to the material strength experiments was soon after abandoned in favor of developing techniques for isentropic compression.

As far as I am aware, there has been no other work on chambered hohlraums until just this past year. Amendt has done some work on a spherical chambered hohlraum design for NIF that he has dubbed a "ballraum" [14]. The basic notion is shown schematically in Figure 3.

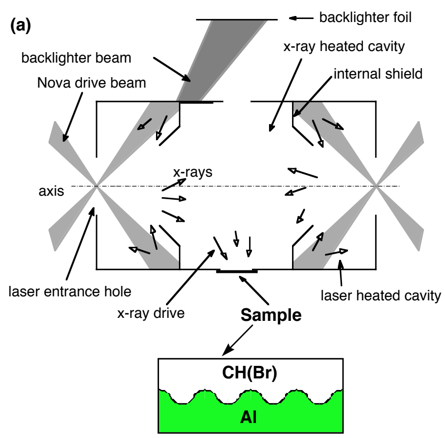

Figure 2. Schematic of the scale-2.15 Nova chambered hohlraum designed for the original Rayleigh-Taylor experiments in 1998. Figure taken from Reference 12.

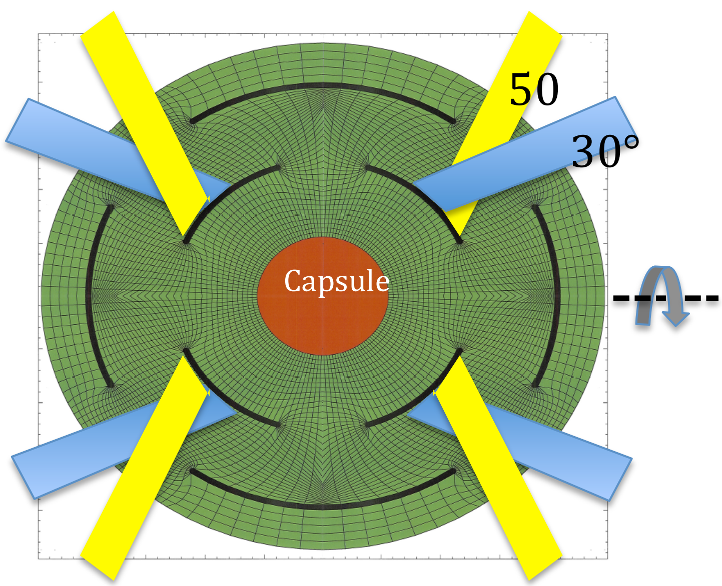

Figure 3. Schematic of a "ballraum" (spherical chambered hohlraum).

Such a hohlraum would likely require more beam energy, but that could still be possible with NIF if we re-visit the old idea of using 2ω instead of 3ω light. Indeed, the chambered hohlraum shown in Figure 2 was driven with 2ω light on Nova. It may turn out that neither of the notional hohlraums shown in Figures 2 and 3 will work on NIF because there is not enough beam energy for ignition, but perhaps some alternate chambered hohlraum design could be made to work at NIF energy.

Let me be clear: I am not proposing that we abandon any of the current approaches to making indirect-drive ignition work on NIF. I am proposing instead that, in view of the difficulties with the current approaches and the constraints imposed by non-LTE physics, it would be prudent to put some effort in to a serious exploration of an alternate approach. Chambered hohlraums show some promise for an alternate approach to indirect-drive ICF. I think it is worth a closer look.

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