Inertial Confinement Fusion
Experiments & Modeling

Using X-ray Absorption Spectroscopy of Thin Tracer Layers to Diagnose the Time-Dependent Properties of ICF Ablator Materials

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Outline

I. What is Fusion?

II. How does Inertial Fusion work?

The physics of indirect-drive ICF

III. What is the OMEGA Laser?

IV. Our Research Program

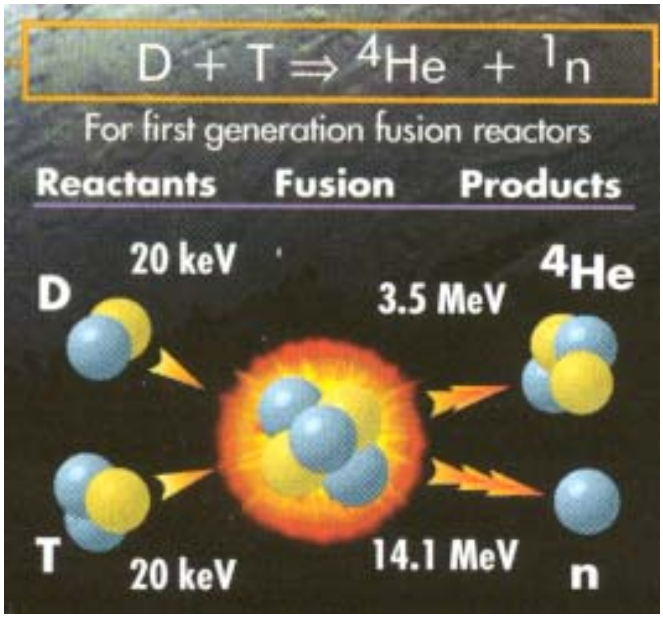
X-ray Absorption Spectroscopy

Tracer Spectroscopy

Ablator Characterization

What is Fusion?

Fusion is the joining together of small, light nuclei to form a larger, more massive nucleus



deuterium-tritium is the most popular reaction, but there are others

⇒ since the incredibly powerful nuclear force is involved (as opposed to the electromagnetic force involved in chemical reactions) huge amounts of energy are released:

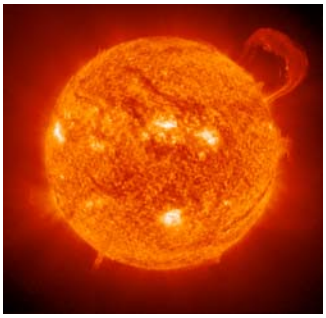
→ the final products of a fusion reaction weigh 0.7% less than the initial ingredients, thus 0.7% mc^2 is converted into energy: *One gram of fuel yields 175,000 kW-hours of energy*

Different Fusion Methods

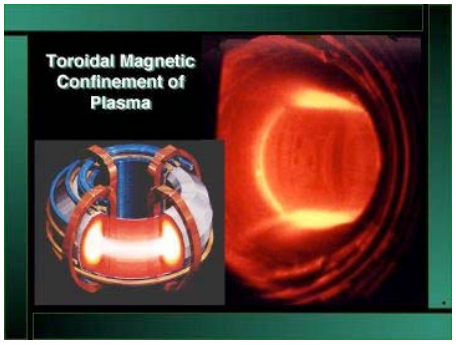
Practical problem: combination of high temperatures and densities are required to force positively charged nuclei together, but the resulting high pressure will tend to blow fusion plasma (hot ionized gas) apart

3 primary plasma confinement methods

I. Gravitational confinement -- astrophysical contexts

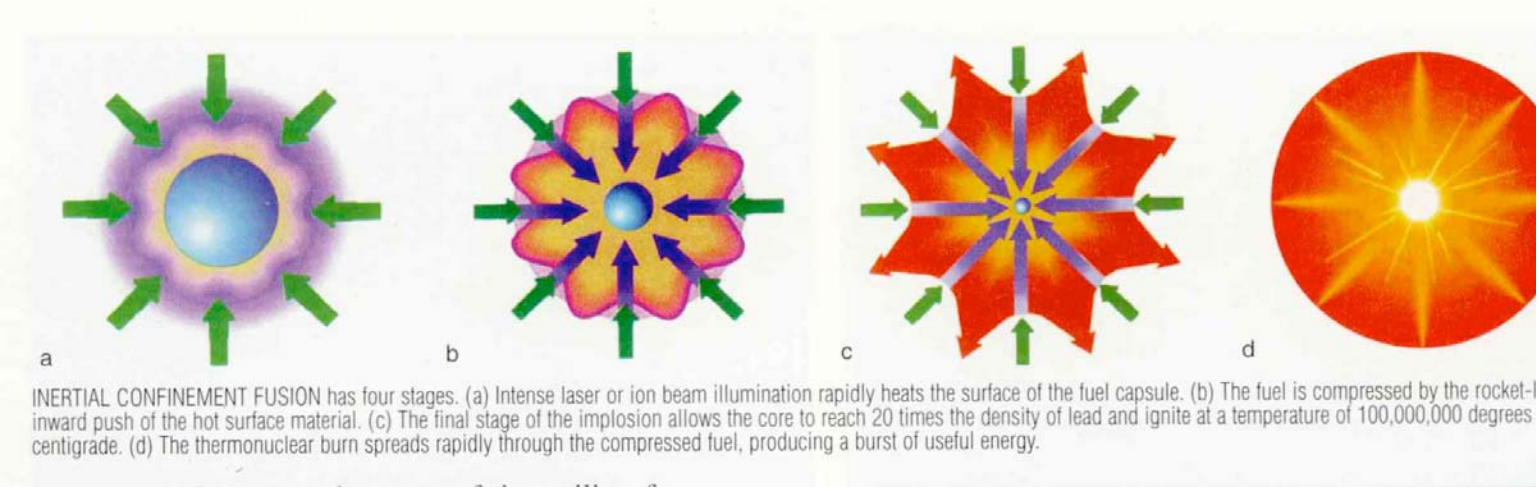


II. Magnetic confinement



III. Inertial confinement -- inertia of the fuel confines it for the nanoseconds (10^{-9} s) required for the fusion reaction to proceed

How Does Inertial Confinement Fusion (ICF) Work?



INERTIAL CONFINEMENT FUSION has four stages. (a) Intense laser or ion beam illumination rapidly heats the surface of the fuel capsule. (b) The fuel is compressed by the rocket-l inward push of the hot surface material. (c) The final stage of the implosion allows the core to reach 20 times the density of lead and ignite at a temperature of 100,000,000 degrees centigrade. (d) The thermonuclear burn spreads rapidly through the compressed fuel, producing a burst of useful energy.

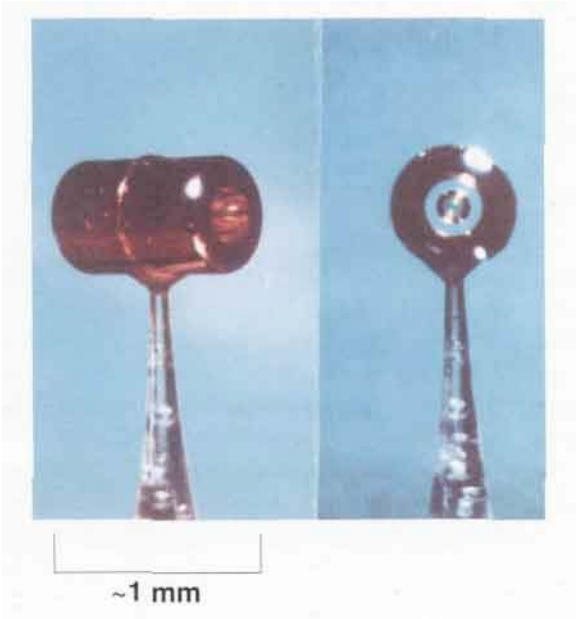
A spherical capsule filled with fuel (deuterium and tritium–isotopes of hydrogen) is bombarded with energy, *compressing* and *heating* a small region in the center of the fuel to values that allow the electrostatic repulsion of the nuclei to be overcome.

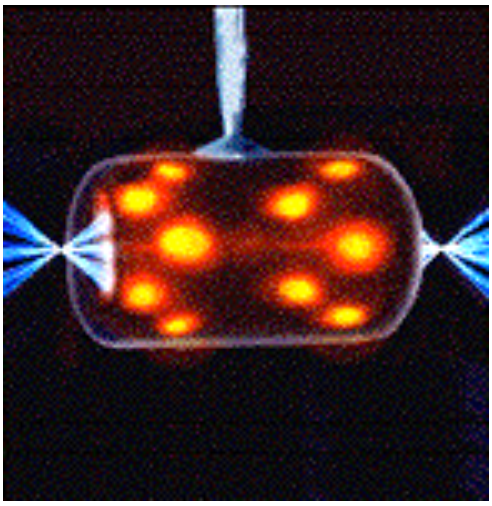
The fusion reactions from this central “hot spot” deposit enough energy in the rest of the fuel that fusion occurs there too–this process is referred to as **ignition**. Ignition hasn’t been achieved yet, but should be at the new National Ignition Facility (already 6 years behind schedule and $2B over budget).

Note that during the very short period of ignition (a few nanoseconds, or a billionth of a second) the fuel is pushed inward, so its own inertia acts to impede its disassembly; hence the term

Indirect-Drive ICF

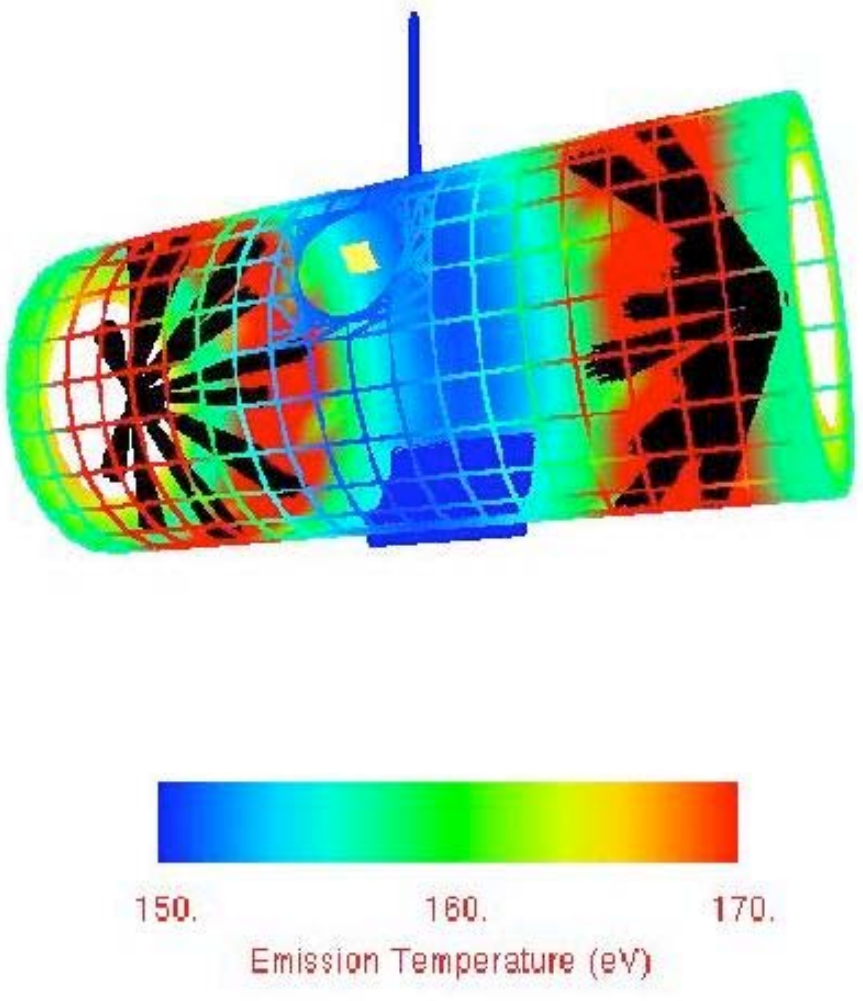
Indirect-drive ICF delivers the energy of a laser (or ion beam) not directly to the fuel capsule, but rather to an enclosure, or **hohlraum**, in which it is thermalized (converted to an equilibrium radiation field, with emission at all wavelengths, instead of the one wavelength of a laser). This thermal radiation is typically characterized by temperatures of 2 to 3 million K, so it is primarily X-rays.





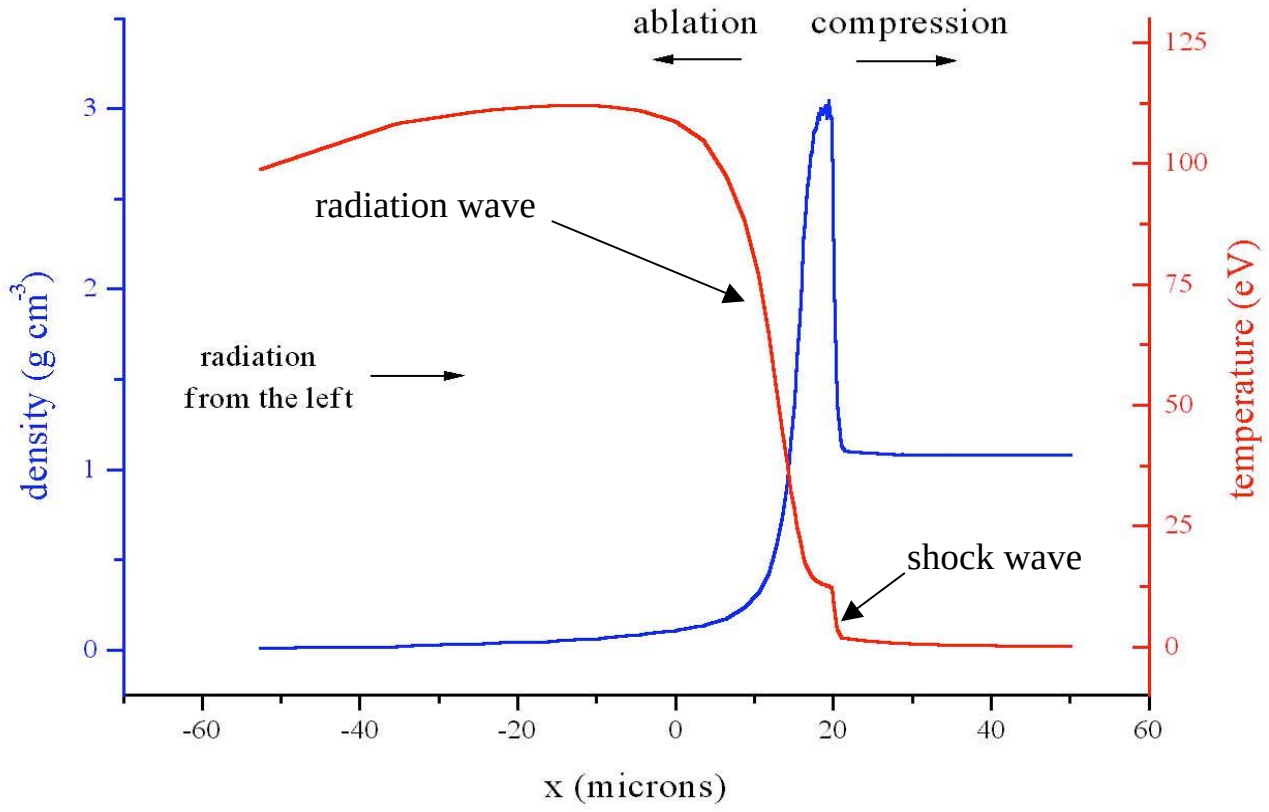
Images of a gold hohlraum used at the NOVA laser at Livermore. The picture on the right was taken in X-rays and shows the laser hotspots on the *interior* of the hohlraum radiating through the hohlraum walls.

We can model the interactions of the laser beams with the hohlraum interior in order to determine the heating at any point in the interior of the hohlraum as a function of time. In this way we can optimize the placement of the laser beams in order to achieve a given temperature and degree of radiation symmetry (you want your target to be compressed as symmetrically as possible).



This calculation was carried out using *symrad*, a viewfactor code written by Joe MacFarlane. It calculates the radiation temperature at any point

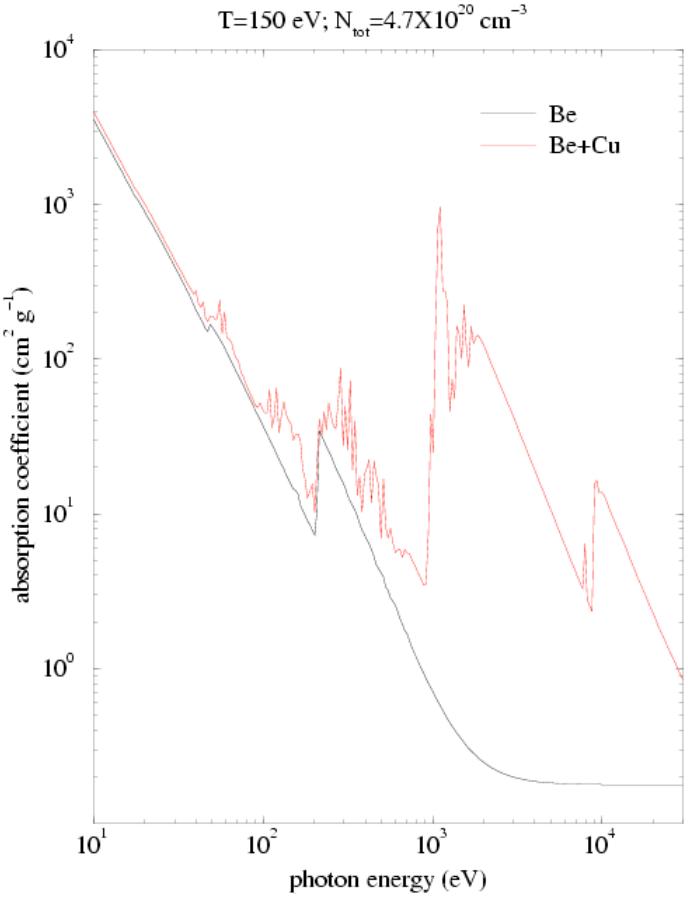
The X-rays that fill the hohlraum bathe the fuel capsule at its center, depositing energy on the outside of the capule and heating the outer capsule layers (referred to as the **ablator**). This hot plasma rushes away from the capsule into the relative vacuum of the hohlraum. Conservation of momentum causes compression of the interior of the capsule, with an inward moving shockwave converging on the fuel in the capsule's center.



A hydrodynamical simulation of the ablation and compression of a solid plastic samp by thermal X-rays. The X-rays are incident from the left. Hot, tenuous material expa

Clearly, controlling the interaction of the X-rays with the outer ablator layer of the fuel capsule is crucial for generating an efficient implosion and subsequent ignition of the fusion fuel.

By adding mid-Z dopants (like bromine, copper, or germanium) to the plastic or beryllium capsule ablator, we can control the density and opacity of the ablator. This in turn controls the ablation/compression physics in the fuel capsule.



Comparison of the calculated opacity of pure beryllium to a mixture of beryllium with 1% copper. The copper dopant increases the density of the ablator and also, as can be readily seen in the figure, increases the opacity significantly. This strongly affects how the radiation field inside the hohlraum interacts with the ablator

Tracer Spectroscopy for Ablator Characterization:

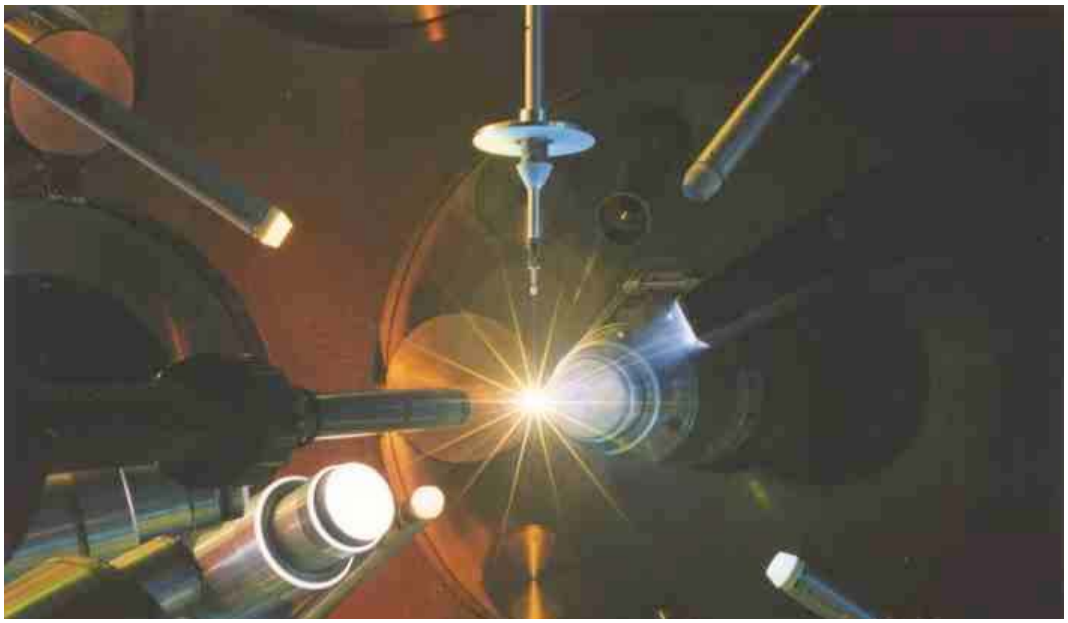
Experiments at the OMEGA Laser

Since the goal is to better control the ablation physics, and thus the implosion of an ICF fuel capsule, via the mixing of high-opacity dopants into the ablator materials, we need a means for measuring the time-dependent properties in the interior of ablator materials as the radiation- and shock-waves are burning through them.

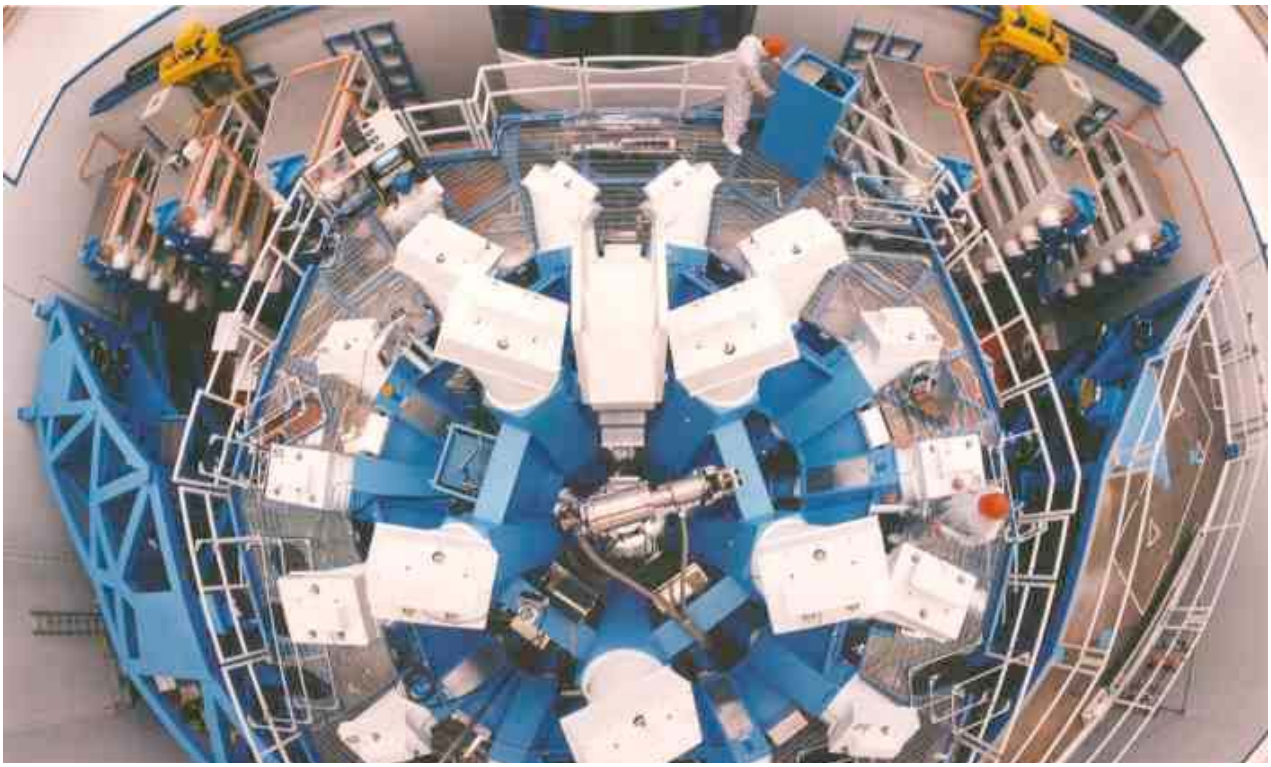
Over the past several years we have designed and carried out a series of experiments with the goal of using backlit X-ray absorption spectroscopy of thin tracer layers to characterize the physical conditions within doped and undoped ablator materials. These experiments have been performed out at the OMEGA laser at the University of Rochester, New York.

The OMEGA laser is currently the world's largest laser

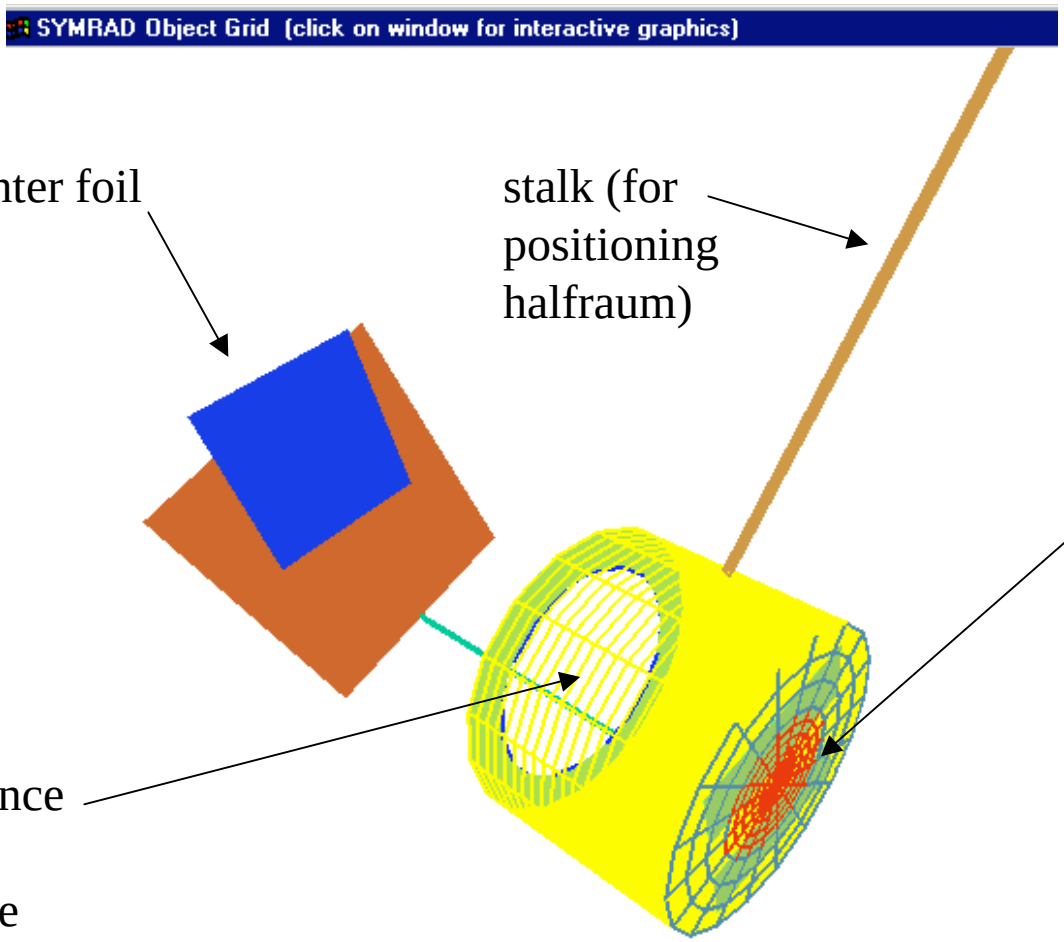
A Nd glass laser produces 60 beams of IR light, which are frequency-tripled into the ultraviolet. The total energy is 30 kJ, which can be delivered to a spot as small as 50 microns square in the target chamber (below) in less than 1 ns, for a total power of tens of terawatts, and a flux of 10^{18} W/cm^2.



The beams are generated in the laser bay (above) and deliverd to the target bay (below).



In order to focus on the ablator physics, and to simplify the modeling, we use planar samples of ablator materials (as opposed to spherical fuel capsules).

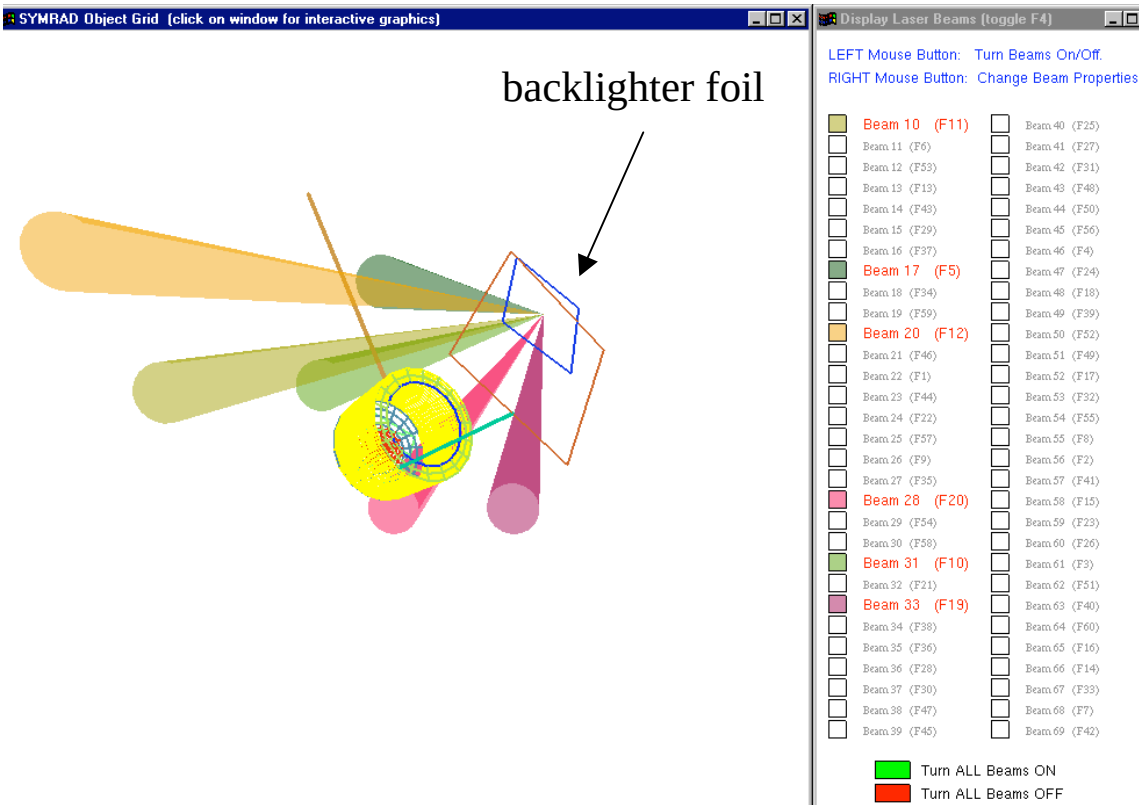


And we mount these planar samples over holes on the exterior of hohlraums, rather then suspending them in the middle of the hohlraum interiors.

Also, we use “halfraums”, with just one opening for laser beams. This simplifies the geometry and also

In order to study the physical conditions inside the ablators, we manufacture them with a thin (0.5 μm) layer of salt (NaCl) at a specific depth (5 to 10 μm).

The chlorine in the salt has a distinctive set of spectral features between 4 Å and 5 Å – when our spectrometers see these features, we know that we're looking at the conditions at the depth of the salt tracer.

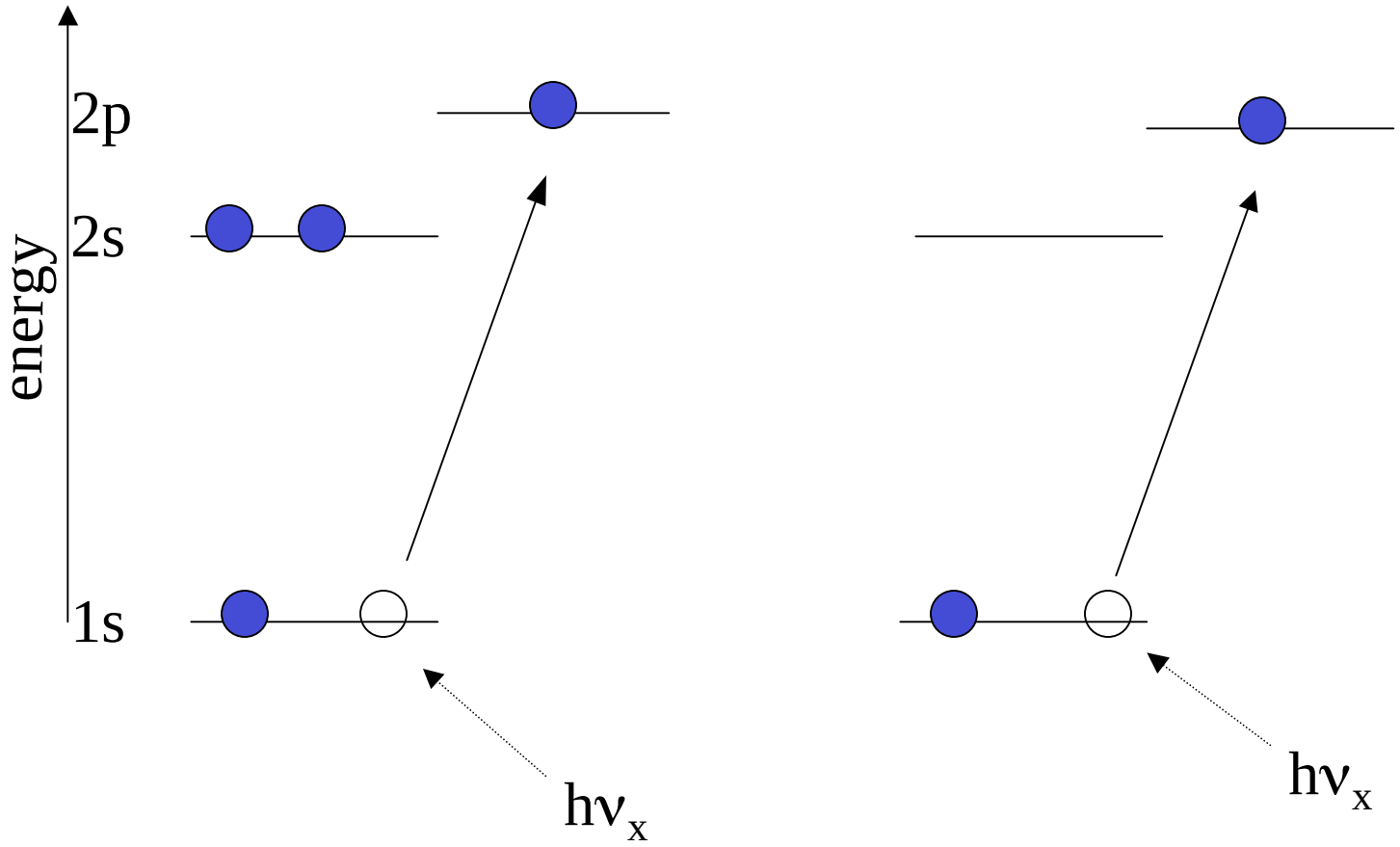


The chlorine spectral features are best seen in *absorption*, so we need a strong source of continuum X-rays to be absorbed by the chlorine in the tracer salt. This is provided by diverting several laser beams onto a bismuth (Z=83) foil, referred to as the

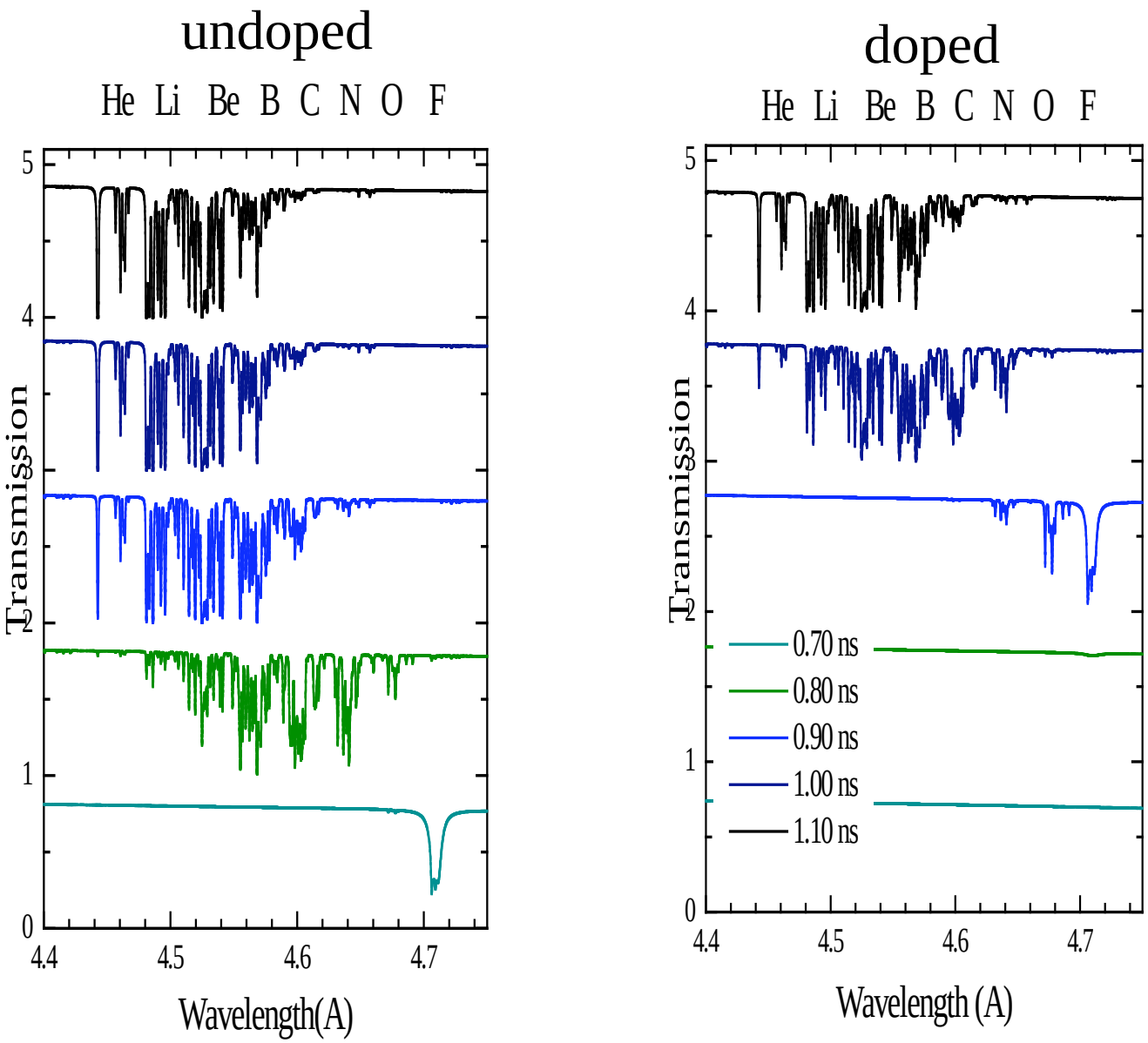
How do we learn things by looking at the chlorine spectra in absorption?

We take advantage of the affinity that X-rays have for *inner shell* electrons.

And the fact that transition energies for these so-called K_α lines depend very little on the ionization stage; in other words, the outer electrons hardly affect the wavelengths of these lines at all



These K_α absorption features for different ionization stages of the same element are right next to each other in a spectrum, with their wavelengths being inversely proportional to the ionization stage.



These simulated chlorine K_α absorption spectra show features from helium-like through fluorine-like

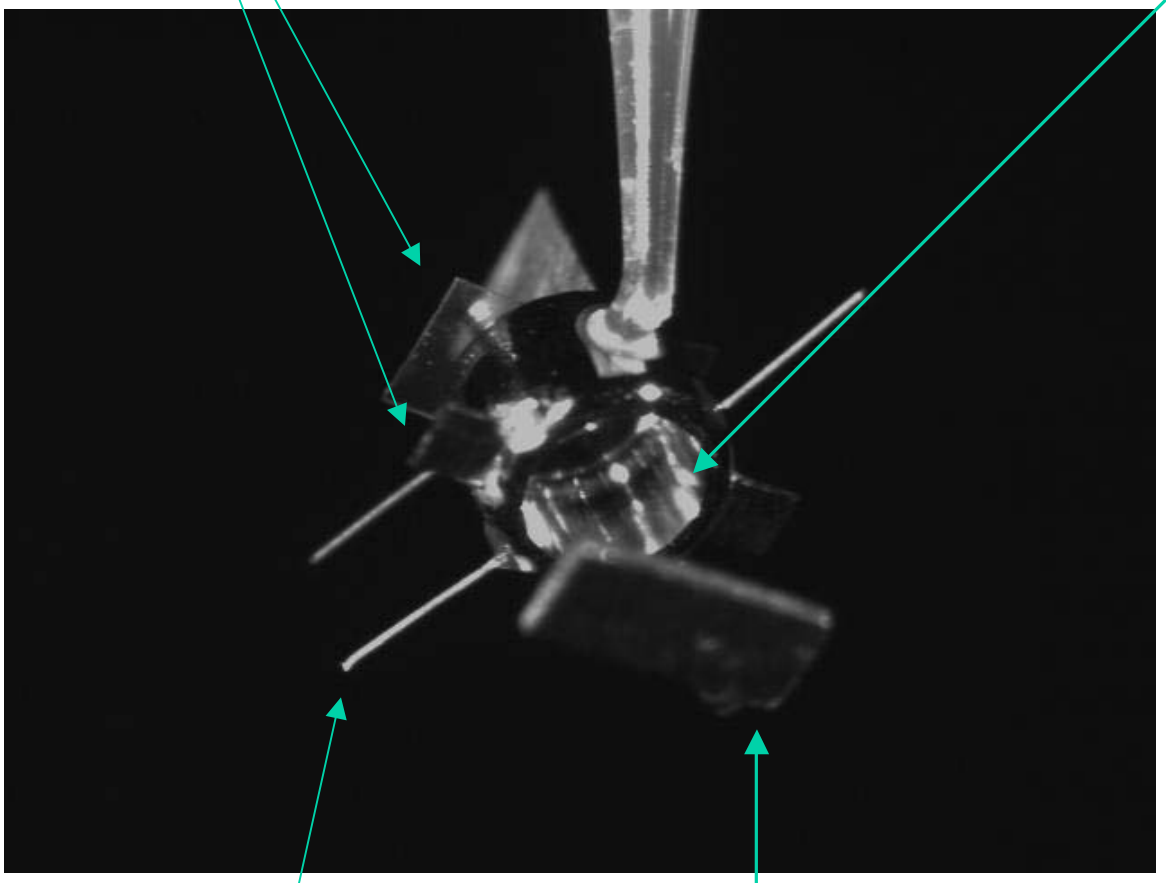
Experimental Goals

When the hohlraum radiation reaches the depth of the salt tracers in the planar ablator patches on our hohlraums, we expect to see a sudden “turn-on” of K_α absorption lines from high ionization stages of the chlorine. The delay in this turn-on time between doped and undoped ablators gives a direct measurement of the effect of the dopant on the coupling between the radiation field and the ablator material.

Furthermore, the actual distribution of ionization stages at any given time reflects the temperature at the depth of the tracer.

Using this information, we can optimize the design of capsule ablators in order to most efficiently ignite a fusion reaction.

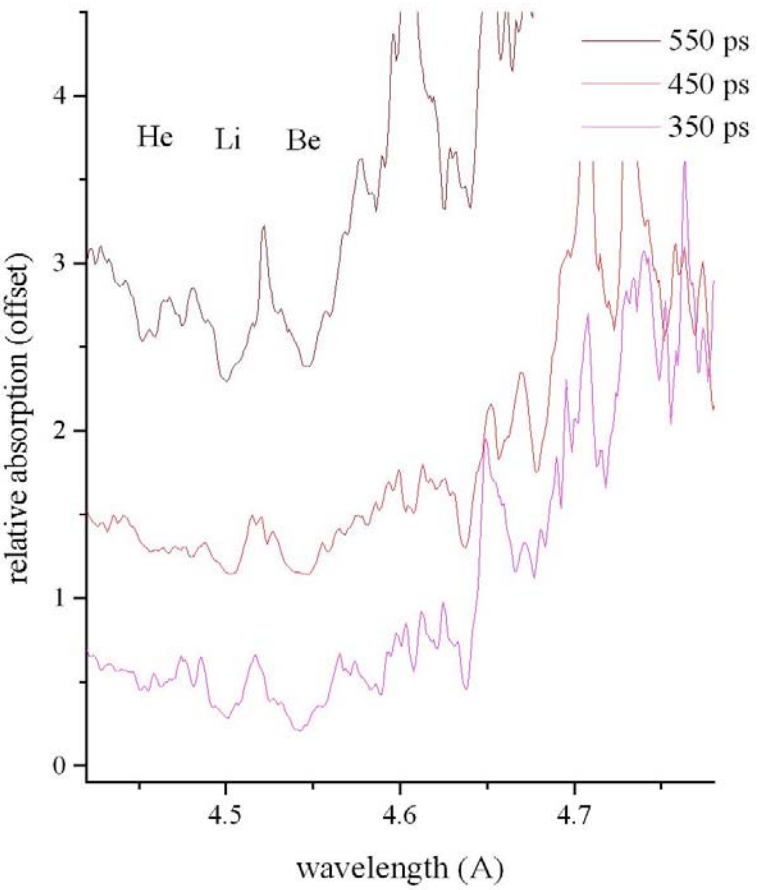
Image of an Experimental Hohlraum



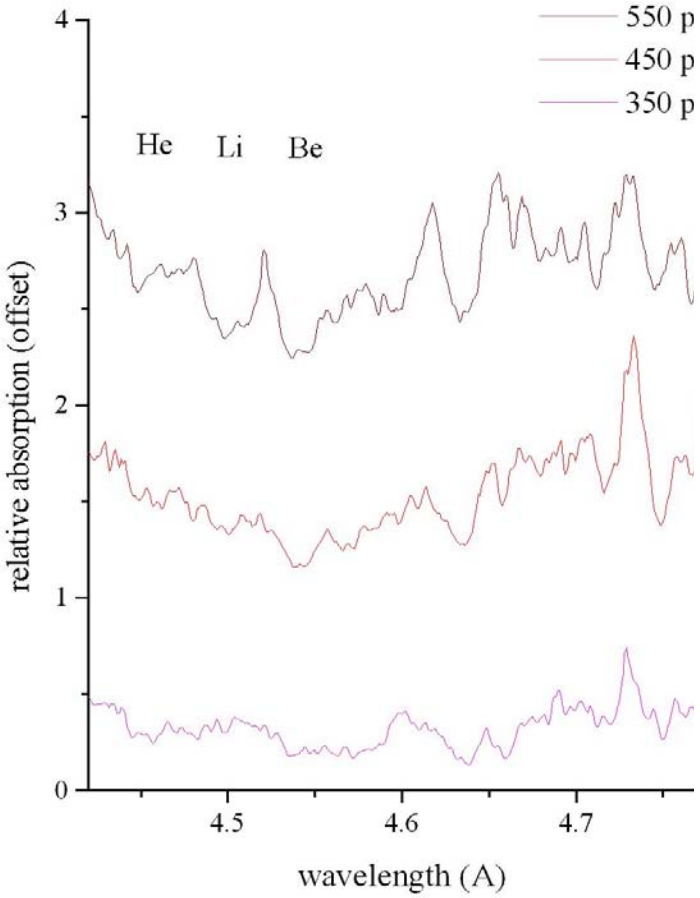
The ablator patch is mounted on the back of the hohlraum. The positioning fibers allow us to properly align the hohlraum in the OMEGA target chamber. This hohlraum is a

From our April 2000 campaign: We've got time-dependent spectra from a germanium-doped plastic ablator (right) and an undoped ablator (left)

undoped plastic



1.5% germanium dopant



In these figures we're focusing in on the times when the tracer signals turn on. There's a delay of between 100 and 200 ps in the appearance of K_α absorption signals on the doped and undoped sides. Note that you can also see the ionization balance moving toward

Conclusions

Ablator samples can be precision manufactured with thin (sub-micron) salt tracer layers

These tracer layers can provide information about *local*, time-dependent properties on the interiors of solid samples in ICF environments

Samples inside or attached to hohlraums can be backlit from the outside in order to perform point-projection spectroscopy

Chlorine K_α features can be clearly seen and measured in hohlraum targets using bismuth backlighters

Time-depend K_α absorption spectroscopy can be used to diagnose the physical conditions inside solid materials exposed to X-ray radiation fields

Germanium (even at the 1.5% level) can measurably modify the radiation hydrodynamics of ICF capsule ablator materials