Spectroscopic Investigations of Implosions on the National Ignition Facility
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The National Ignition Facility (NIF) is a 192 beam laser system in operation at LLNL since 2009

NIF target chamber + positioner

Indirect-drive Inertial Confinement Fusion (ICF) at the National Ignition Facility (NIF)

- NIF uses 192 laser beams to deliver 1-2 MJ of energy over several ns
- ~75% of the energy is converted to X-rays in the hohlraum
- Radiation field inside the hohlraum is ~thermal at \( T_e \approx 300 \) eV

NIF also provides a platform for High Energy Density (HED) experiments

National Ignition Facility (NIF) overview

Ignition will require a convergence ratio of ~35

This requires extreme precision and control to maintain symmetry
NIF uses a graded-doped CH capsule with a layer of frozen DT fuel inside a high-Z hohlraum.

Significant improvements have come from better stability.

The amount of material mixed into the hot spot correlates with the implosion yield.

Recent implosions have achieved significant &alpha;-heating.

Material interfaces are Rayleigh-Taylor unstable during compression (either acceleration or deceleration).

Hydrodynamic growth is larger than we simulate. Either seeds are larger than we think or hydrodynamic growth is larger than we simulate.

We are developing methods to measure growth and mix in the late stages of the implosion.

The spectrum reflects emission over a wide range of conditions and the effects of radiation transport.

Perturbations which grow too large can inject material into the hot spot, resulting in cooling.

Diagnosing / verifying hydrodynamic growth of perturbations is critical to understanding implosions.

Perturbation growth brings Ge dopant into the hot spot.

Mix mass inferred from X-ray emission relative to neutron yield - T. Ma et al, PRL 111 (2013)

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"K-shell" features provide information on mix.
The basic 0D analysis method counts photons:

- Count photons emitted at a given frequency $N_i$.
- Infer total atom population $N_i$ from
  \[ N_i = N_i \eta_i (n_i, T) \Delta t \]

Complications:
- Emission rate per atom, $\eta_i$, depends strongly on $T$.
  \[ \text{estimate } T, n_i \text{ from spectral features} \]
- Optical depth effects (lines + shell)
  \[ \text{approximate with escape factors, shell } \rho R \text{ fitting parameter} \]
- Non-uniformity in space and/or time
- Non-emitting mass is invisible (but likely unimportant)

**The resulting mass estimates have large uncertainties**

Monochromatic imaging accentuates features

Experimental spectra show optically thick features similar to simulations

**Fluorescence is locally weak but extends over a large area**

This 0D analysis only addresses the “He-α” emission

The features are sensitive to physical parameters and models:

- “He-α” emission – hot spot $T$, $n_i$
- He-α red wing – “ice” $T$, $n_i$
- K-shell jump – shell $\rho R$
- K-shell position, slope – shell $T$, $n_i$ + continuum lowering model
- K-α fluorescence – shell $T$

**Simulated diagnostics diagnose the shell $\rho R$**

Intensity jump across K-edge provides information on $\rho R$

\[ I_j = B_j (T) e^{-\tau_j} \]

Analysis requires $T$ of hot spot
- provided by spectroscopy
- Integrate over filter response function
- $\rho R$ of ablated material estimated from simulation

Averaging over shell $\rho R$

Analysis of a synthetic spectrum reproduces the $\rho R$ variations of a rippled shell
Initial experiments look promising

- Target with pre-imposed ripples
- Inhomogeneity along ripples due to machining imperfections
- Spectra show emission from shock bounce and peak compression
- Spacing, $\rho R$ vs time give capsule velocity, growth factors

Recent work has focused on the effect of the “tent” – a thin plastic membrane which supports the capsule

- Rayleigh-Taylor growth is seeded where the tent leaves the capsule
- The tent can induce large (~40%) defects in the shell $\rho R$

An improved spectrometer (coming soon) will enable better quantitative analysis of $\rho R$

In a DT target, a jet of CH penetrates the shell and cold DT enters the hot spot

CH does not quite reach the hot-spot

Yield is reduced by ~50%

An appropriate dopant could provide a spectroscopic signature of the jet / bubble resulting from the tent scar

These simulations are of a Symcap, in which DT ice is replaced by an equivalent mass of CH

The tent scar allows radiation to escape the hot spot

Radiative energy loss may also be significant

Spectroscopy is providing information on NIF implosions

- Spectral features
  - Ly- and He- emission, K-α fluorescence
  - K-edge absorption
  - Continuum shape
  - Time-dependence
- Diagnostics for
  - Hot spot temperature
  - Shell optical depth
  - Shell velocity, growth factors

Spectroscopic simulations are an important part of the experimental design process