Analysis of Techniques to Infer Hot-Spot Mix using Absolute X-ray Emission for OMEGA Direct-Drive Layered Implosions

OMEGA Cryo Implosion Scenarios

- Mode 1 (No Mix)
- Mode 1 (Hot-spot Mix Added)

Inferred vs. Actual Mix

- Ice-Block Approx. Model
- 1D Sim Ref. Model
- Actual

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Summary

Accurate hot-spot mix estimates are obtained when using a yield ratio reference $Y_v/Y_n$ from 1D simulations

- We analyzed two methods that infer hot-spot mix using a no-mix estimate of $Y_v/Y_n$ (X-ray/Neutron yield)
  1. Ice-block approximation model\(^1\)
  2. 1D sim. reference approximation model

- In tests where $T_e \neq T_i$, the ice-block approximation model was found to overestimate mix

- In contrast, inferring mix using a $Y_v/Y_n$ reference from 1D simulations not only takes non-equilibrium into account, but also applied well to non-1D scenarios

\(^1\)T. Ma et al., PRL 111, 085004 (2013)
Collaborators

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Our goal is to infer mix in a variety of implosions on OMEGA

- X-ray emission yield $Y_\nu$ has a strong $Z$ dependence for fully-ionized plasmas$^1$:

  $$\varepsilon_\nu \propto n_i^2 \left( \frac{\chi_H}{kT_e} \right)^\frac{1}{2} \langle Z \rangle \left[ \langle Z^2 g_{FF} \rangle + 2 \left( \frac{\chi_H}{kT_e} \right) \langle Z^4 e^{-\frac{(\chi-\Delta\chi)}{kT}} g_{BF} \rangle \right] e^{-\frac{h\nu}{kT}}; \quad Y_\nu = \int \varepsilon_\nu dV dt$$

- Mix is inferred by seeing how much higher $Y_\nu,exp$ is above $Y_\nu(Z=1)$ and back-calculating the resulting $\langle Z \rangle$
  - Requires having an estimate for $Y_\nu(Z=1)$

- We analyzed two methods for approximating $Y_\nu(Z=1)$ to infer mix
  1. Ice-block approximation model$^2$
  2. 1D simulation-reference model

$^2$T. Ma et al., PRL 111, 085004 (2013)
The ice-block approximation model\(^1\) compares a measured yield ratio \(Y_v/Y_n\) to a no-mix, ice-block expectation to infer mix

- Advantage: Ice-block model assumes uniform conditions in hot-spot
- A yield ratio is used so that density, volume, and emission times can be ignored:

\[
\left(\frac{Y_v}{Y_n}\right)_{\text{exp}} = \frac{\left(\frac{Y_v}{Y_n}\right)_{\text{ice-block}}^{*}}{\left(\frac{Y_v}{Y_n}\right)_{\text{ice-block}}^{*}} = \frac{\langle Z \rangle}{g_{H,FF}} \left[ \langle Z^2 g_{FF} \rangle + 2 \left( \frac{\chi_H}{kT_e} \right) \langle Z^4 g_{BF} \rangle \right]
\]

\(Z\) dependency is now isolated

\(^1\)T. Ma et al., PRL 111, 085004 (2013)

*Yield formulas use measured \(T_e\) and \(T_i\)
The ice-block approximation model\(^1\) compares a measured yield ratio \(Y_v/Y_n\) to a no-mix, ice-block expectation to infer mix

\[
\left(\frac{Y_v}{Y_n}\right)_\text{exp} = \frac{\left(\frac{Y_v}{Y_n}\right)_\text{ice-block}^{(Z=1)}}{C_0 g_{Fe} e^{-\frac{h\nu_0}{k\langle T_e \rangle}} n_i^2 V \Delta t}{f_D f_T \langle \sigma v \rangle_{DT} n_i^2 V \Delta t}
\]

If no mix in “exp”, yield ratios should be equal and inferred \(\langle Z \rangle\) matches \(Z_H = 1\)

\*Yield formulas use measured \(T_e\) and \(T_i\)

\(^1\)T. Ma et al., PRL 111, 085004 (2013)
Ice-block mix model breaks down during non-equilibrium conditions (stronger on OMEGA than on NIF)

Test case (No Mix):

$$\langle Z \rangle = 1$$
$$h\nu = 15 \text{ keV}$$

Larger x-ray emission volume (normalized) compared to neutron volume

$$(\frac{Y_v}{Y_n})_{\text{profile}}$$

$$C_0 e^{-\frac{h\nu_0}{k(T_e)}} \frac{\eta^2 V\Delta t}{\int D_f T(\sigma v) DT}$$

Bad assumption. $$V_v > V_n$$

$$V_i > V_e$$
We can bypass the ice-block model limitations by using a simulation approximation for $Y_v/Y_n$

- A monotonic relation between $Y_n$ and $Y_v$ exists in simulation
  - Higher implosion velocity groups have slightly different $Y_v/Y_n$ ratio
  - *These ratios account for non-equilibrium effects*

- To exploit these relations for inferring mix, we simply assume:

\[
\left( \frac{Y_v}{Y_n} \right)_{\text{exp}}^{\text{(No Mix) 1D Sim.}} = \left( \frac{Y_v}{Y_n} \right)_{\text{1D Sim.}}
\]

\[\text{Values from 1D cryo simulations database}^1\]

\[\text{Simulated X-ray Emission } Y_v \text{ (hv=15keV) (J/ster/keV)}\]

\[\text{Simulated Neutron Yield } Y_n\]

\[\text{200-400 km/s}\]

\[\text{1E+15}\]

\[1^V. \text{Gopalaswamy et al, Nature 565, 581 (2019)}\]
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- To exploit these relations for inferring mix, we simply assume:

$$\left( \frac{Y_v}{Y_n} \right)_{\text{exp (No Mix)}} = \left( \frac{Y_v}{Y_n} \right)_{1D \text{ Sim.}}$$

of similar $v_{\text{imp}}$

[Graph showing simulated X-ray emission and neutron yield with different velocity groups.]

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With the no-mix reference for $Y_v/Y_n$ based on 1D simulations, mix can then be inferred in a similar way to ice-block approximation method.

\[
\begin{align*}
\frac{(Y_v/Y_n)_{\text{exp}}}{(Y_v/Y_n)_{\text{Ice-Block (No-Mix)}}} & \approx \frac{\langle Z \rangle}{g_{H,FF}} \left[ Z^2 g_{FF} + 2 \left( \frac{X_H}{kT_e} \right) Z^4 g_{BF} \right] \\
\frac{(Y_v/Y_n)_{\text{exp}}}{(Y_v/Y_n)_{1D \, Sim.}} & \approx \frac{\langle Z \rangle}{g_{H,FF}} \left[ Z^2 g_{FF} + 2 \left( \frac{X_H}{kT_e} \right) Z^4 g_{BF} \right]
\end{align*}
\]

- $Z$ dependency remains proportional to ratio between yield ratios and assumed uniform.
In tests with single-mode perturbation simulations, 1D reference model can offer more accurate mix estimates for implosions on OMEGA. More tests will be done with stronger and wider variety of perturbations.
Accurate hot-spot mix estimates could be obtained when using a yield ratio reference $Y_v/Y_n$ from 1D simulations

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Summary

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