Density maps at neutron peak (t=2.16 ns) from 3D Aster simulations

I. V. Igumenshchev  
University of Rochester  
Laboratory for Laser Energetics

\[ A_{\ell=1} = 6.5\% \]  
\[ \langle V \rangle_n = 193 \text{ km/s} \]  
\[ Y_n = 1.6 \times 10^{14} \]

\[ A_{\ell=1} = 6.5\% \]  
\[ \langle V \rangle_n = 175 \text{ km/s} \]  
\[ Y_n = 2.0 \times 10^{14} \]
Summary

Ion viscosity can limit the compressibility of OMEGA cryogenic implosions and mitigate asymmetry effects

- Effects of ion viscosity in cryogenic OMEGA implosions were studied using the 3-D hydrodynamic code ASTER\(^1\)

- Ion viscosity modifies the shock in DT vapor and affects the formation of hot spot in symmetric and asymmetric (with mode \(\ell =1\)) implosions

- Simulations show sensitivity of the results to numerical implementations of the ion-viscosity model

---

\(^1\) Igumenshchev et al., Phys. Plasmas 23, 052702 (2016).
Collaborators


University of Rochester
Laboratory for Laser Energetics

D. S. Clark and M. M. Marinak

LLNL

B. M. Haines

LANL
Effects of ion viscosity are important in ICF implosions

1 Affect the shock in DT vapor

2 Affect the formation of hot spot

- More efficient conversion of the shell kinetic energy into the internal energy of hot spot in symmetric and asymmetric implosions

Effects of ion viscosity were simulated using the hydrodynamic ICF code ASTER

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \]

\[ \frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla P + \nabla \cdot \vec{\sigma} + \cdots \]

\[ \frac{\partial}{\partial t} \left( \frac{\rho u^2}{2} + \rho \epsilon \right) + \nabla \cdot \left( \vec{u} \left( \frac{\rho u^2}{2} + \rho \epsilon + P \right) \right) = \nabla \cdot (\vec{u} \cdot \vec{\sigma}) + \cdots \]

ASTER is an Eulerian hydrodynamic code using the energy conservative scheme:

Viscous stress tensor:

\[ \delta_{ik} = \eta \left( \nabla_i u_k + \nabla_k u_i - \frac{2}{3} \delta_{ik} \nabla \cdot \vec{u} \right) \]

\[ \eta - \text{ion viscosity} \]

Ion viscosity uses the Barginskii formula

\[ \eta_0^i = 0.96 n_i T_i \tau_i \quad \text{at} \quad \Gamma = \frac{Z_i^2 e^2}{a k_B T_i} \ll 1 \]

and fit to MD simulations\(^1\) at \(2 < \Gamma < 160\)

\[ \frac{\partial}{\partial t} (\rho \epsilon) \]

\[ = Q_{\text{visc}} \equiv \langle \vec{\sigma} \cdot \nabla \rangle \vec{u} \quad \text{To compare with other codes} \]

Limitation of viscous stress can be required to avoid unphysical solutions when the ion free path \( \ell_i \sim R \)

- Simulations show that viscous heating can result in a runaway increase of the after-shock \( T_i \)

- Limitation of the ion free path \( \ell_i \) is one possible way to limit the viscous stress

\[
\eta_0^i = 0.96 n_i T_i \tau_i \equiv 0.96 n_i m_i \frac{\ell_i^2}{\tau_i}, \quad \text{where} \quad \ell_i = v_{Ti} \tau_i, \quad v_{Ti} = \sqrt{\frac{T_i}{m_i}}
\]

\[
\eta_0^i = 0.96 n_i m_i \frac{\left[ \min(\ell_i, \ell_i^{\text{max}}) \right]^2}{\tau_i}, \quad \ell_i^{\text{max}} \quad \text{is the parameter of limitation} \quad (\ell_i^{\text{max}} = 10 \ \mu\text{m})
\]

\[
\eta_0^i \propto T_i^{5/2} \quad \xrightarrow{\text{}} \quad (\eta_0^i)_{\text{lim}} \propto T_i^{-3/2}
\]
Simulations of OMEGA shot 94712 were used to study the effects of ion viscosity.

- Degraded performance, YOC = 17%
- Large neutron-inferred flow velocity $141\pm15$ km/s*
- Imprint is not the major degradation mechanism (simulated yield reduction ~30%)
- The role of ion viscosity in 1-D and 3-D?

* O. Mannion et al. KI02.00001, this meeting
Three implementations of the ion viscosity scheme have been tested in simulations of shot 94712

(1) VC + IFL
(2) VNC + IFL *
(3) VC **

Viscous energy conservative scheme (VC)
Viscous energy nonconservative scheme (VNC)
Ion heat-flux limitation (IFL)

* Similar to the code HYDRA (Marinak et al., Phys. Plasmas, 2001); D. S. Clark & M. M. Marinak, private communication
** Similar to the code xRAGE (Gittings et al., Comp. Sci. & Discovery, 2008); B. M. Haines, private communication
Effects of ion viscosity result in reduction of performance of 1-D implosions

Summary of 1-D spherically symmetric *ASTER* simulations of shot 94712

<table>
<thead>
<tr>
<th>Model</th>
<th>Neutron yield</th>
<th>Hot-spot pressure (Gbar)</th>
<th>$\langle T_i \rangle_n$ (keV)</th>
<th>$\langle \rho R \rangle_n$ (mg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inviscid (+ IFL)</td>
<td>$4.6 \times 10^{14}$</td>
<td>130</td>
<td>4.84</td>
<td>201</td>
</tr>
<tr>
<td>(1) VC + IFL</td>
<td>$3.3 \times 10^{14}$</td>
<td>58</td>
<td>4.87</td>
<td>116</td>
</tr>
<tr>
<td>(2) VNC + IFL</td>
<td>$4.1 \times 10^{14}$</td>
<td>122</td>
<td>4.63</td>
<td>196</td>
</tr>
<tr>
<td>(3) VC</td>
<td>$4.1 \times 10^{14}$</td>
<td>91</td>
<td>4.89</td>
<td>157</td>
</tr>
<tr>
<td>Experiment</td>
<td>$(7.69\pm0.54) \times 10^{13}$</td>
<td>36±7</td>
<td>$4.13$–$5.78$</td>
<td>$162\pm15$</td>
</tr>
</tbody>
</table>

Viscous energy conservative scheme (VC)

Viscous energy non-conservative scheme (VNC)

Ion heat-flux limitation (IFL)

Mass release inside the implosion shell because of increased after-shock $T_i$

Similar to the code *HYDRA*

Similar to the code *xRAGE*

* D. S. Clark & M. M. Marinak, private communication

** B. M. Haines, private communication
Ion viscosity can mitigate the effects of mode $\ell = 1$ asymmetry

Simulated and measured flow velocity* and neutron yield in shot 94712

* O. Mannion et al. K102.00001, this meeting
Ion viscosity can mitigate the effects of mode $\ell = 1$ asymmetry

Simulated and measured flow velocity* and neutron yield in shot 94712

* O. Mannion et al. K102.00001, this meeting
Ion viscosity can mitigate the effects of mode $\ell = 1$ asymmetry

Simulated and measured flow velocity* and neutron yield in shot 94712

* O. Mannion et al. KI02.00001, this meeting
Ion viscosity can mitigate the effects of mode $\ell = 1$ asymmetry

Simulated and measured flow velocity* and neutron yield in shot 94712

* O. Mannion et al. KI02.00001, this meeting
Ion viscosity can mitigate the effects of mode $\ell = 1$ asymmetry

Simulated and measured flow velocity* and neutron yield in shot 94712

* O. Mannion et al. KI02.00001, this meeting
Ion viscosity can mitigate the effects of mode $\ell = 1$ asymmetry (continued)

Density maps at neutron peak ($t = 2.16$ ns) in simulations of shot 94712

**Inviscid**

$A_{\ell=1} = 6.5\%$

$\langle V \rangle_n = 193 \text{ km/s}$

$Y_n = 1.6 \times 10^{14}$

**VC + IFL**

$A_{\ell=1} = 6.5\%$

$\langle V \rangle_n = 175 \text{ km/s}$

$Y_n = 2.0 \times 10^{14}$
Ion viscosity can limit the compressibility of OMEGA cryogenic implosions and mitigate asymmetry effects.

- Effects of ion viscosity in cryogenic OMEGA implosions were studied using the 3-D hydrodynamic code ASTER\textsuperscript{1}.

- Ion viscosity modifies the shock in DT vapor and affects the formation of hot spot in symmetric and asymmetric (with mode $\ell = 1$) implosions.

- Simulations show sensitivity of the results to numerical implementations of the ion-viscosity model.

Kinetic simulations are required to find which implementation is better.

\textsuperscript{1} Igumenshchev \textit{et al.}, Phys. Plasmas 23, 052702 (2016).