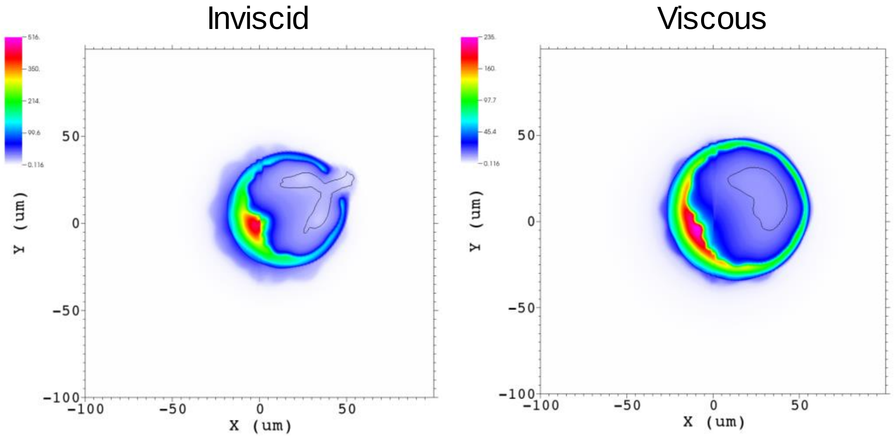
Modeling the Effects of Ion Viscosity on the Dynamics of OMEGA Direct-Drive Cryogenic Implosions

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



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

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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

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[1] Igumenshchev *et al*., Phys. Plasmas **23**, 052702 (2016).

Collaborators

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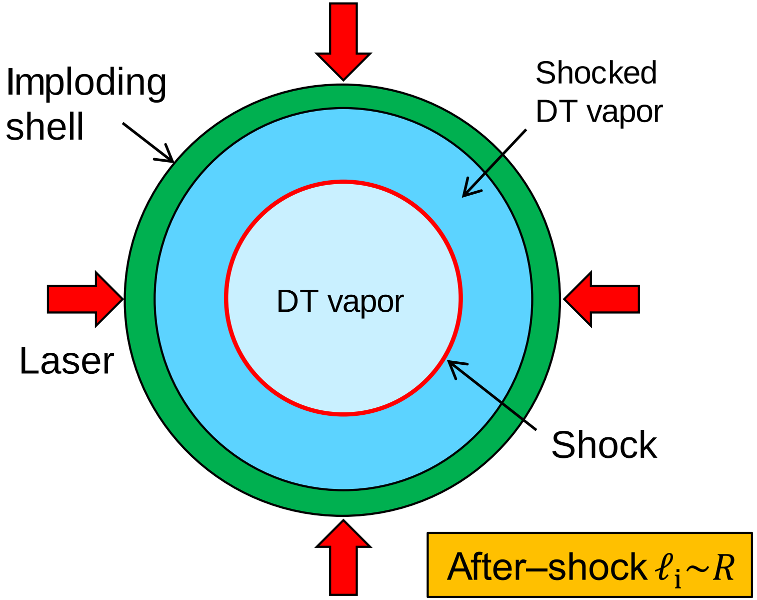
Effects of ion viscosity are important in ICF implosions

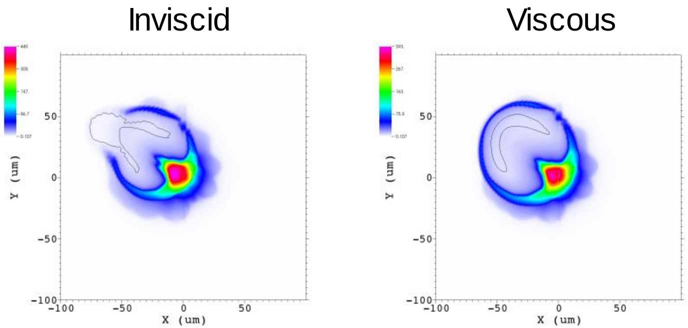
Affect the shock in DT vapor[1]



After–shock $\ell_{\mathrm{i}} \sim R$

Affect the formation of hot spot[2]

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



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[1] e.g., Vold *et al*., Phys. Plasmas **22**, 112708 (2015).

[2] e.g., Weber *et al*., Phys. Rev. E **89**, 053106 (2014).

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

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

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u} = 0 \\[2ex] \dfrac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u}\vec{u}) = -\nabla P + \boxed{\nabla \cdot \hat{\sigma}} + \cdots \\[2ex] \dfrac{\partial}{\partial t}\left(\rho \dfrac{u^2}{2} + \rho\varepsilon\right) + \nabla \cdot \left[\vec{u}\left(\rho\dfrac{u^2}{2} + \rho\varepsilon + P\right)\right] = \boxed{\nabla \cdot (\vec{u} \cdot \hat{\sigma})} + \cdots \end{cases}$$

Optional nonconservative scheme for viscosity:

$$\left[\frac{\partial}{\partial t}(\rho\varepsilon)\right]_{\text{visc}} = Q_{\text{visc}} \equiv (\hat{\sigma} \cdot \nabla)\vec{u}$$

To compare with other codes

Viscous stress tensor:

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

η – ion viscosity

Ion viscosity uses the Barginskii formula

$$\eta_0^{\mathrm{i}} = 0.96 n_{\mathrm{i}} T_{\mathrm{i}} \tau_{\mathrm{i}} \qquad \text{at} \quad \Gamma = \frac{Z_{\mathrm{i}}^2 e^2}{a k_{\mathrm{B}} T_{\mathrm{i}}} \ll 1$$

and fit to MD simulations[1] at $2 < \Gamma < 160$

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[1] Wallenborn & Baus, Phys. Rev. A **18**, 1737 (1978).

Limitation of viscous stress can be required to avoid unphysical solutions when the ion free path $\ell_\mathrm{i} \sim R$

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

- Limitation of the ion free path ℓ_i is one possible way to limit the viscous stress

$$\eta_0^\mathrm{i} = 0.96 n_\mathrm{i} T_\mathrm{i} \tau_\mathrm{i} \equiv 0.96 n_\mathrm{i} m_\mathrm{i} \ell_\mathrm{i}^2 / \tau_\mathrm{i}, \qquad \text{where} \quad \ell_\mathrm{i} = v_{T\mathrm{i}} \tau_\mathrm{i}, \quad v_{T\mathrm{i}} = \sqrt{T_\mathrm{i}/m_\mathrm{i}}$$

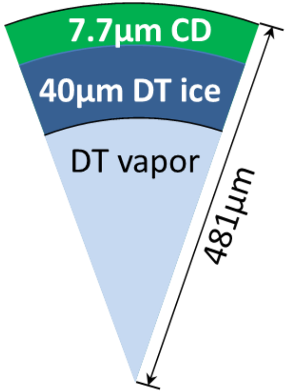
$$\eta_0^\mathrm{i} = 0.96 n_\mathrm{i} m_\mathrm{i} \frac{\left[\min\left(\ell_\mathrm{i}, \ell_\mathrm{i}^\mathrm{max}\right)\right]^2}{\tau_\mathrm{i}},$$

ℓ_i^{max} is the parameter of limitation ($\ell_\mathrm{i}^\mathrm{max} = 10\ \mu\mathrm{m}$)

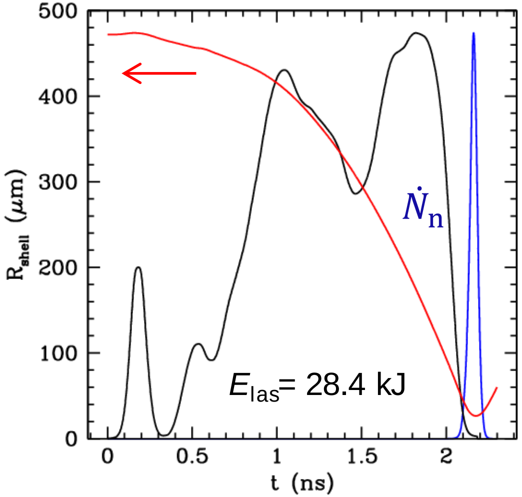
$$\eta_0^\mathrm{i} \propto T_\mathrm{i}^{5/2} \quad \longrightarrow \quad \left(\eta_0^\mathrm{i}\right)_\mathrm{lim} \propto T_\mathrm{i}^{-3/2}$$

Simulations of OMEGA shot 94712 were used to study the effects of ion viscosity

Target dimensions



Laser pulse and simulated shell trajectory and neutron history of shot 94712



Adiabat $\alpha \approx 4.5$

- Degraded performance, YOC = 17%
- Large neutron-inferred flow velocity 141±15 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 *

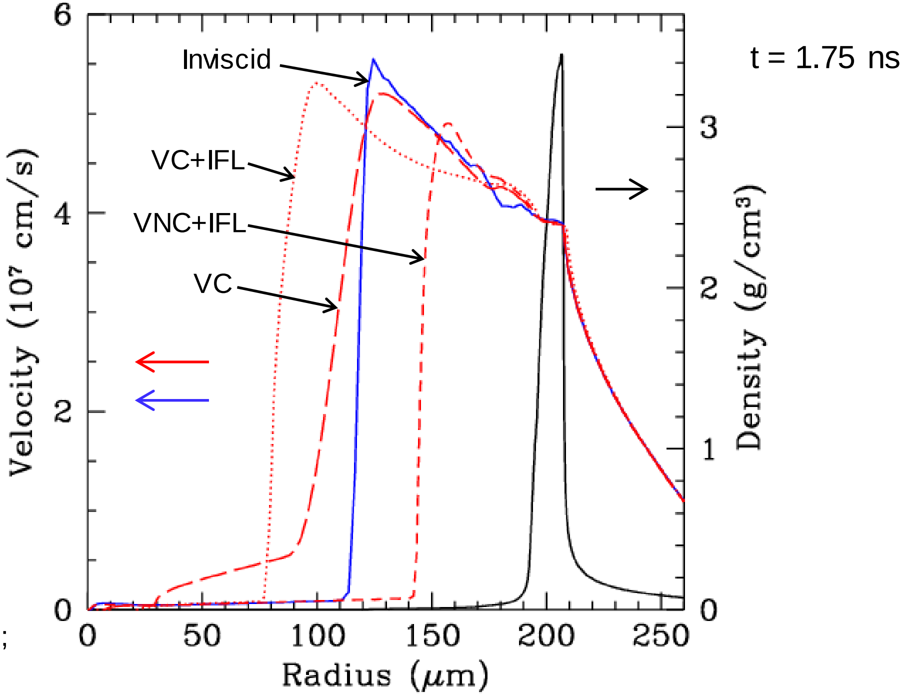
(3) VC **

Viscous energy conservative scheme (VC)

Viscous energy nonconservative scheme (VNC)

Ion heat-flux limitation (IFL)

The effect of ion viscosity on the shock in DT vapor



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* 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

Model	**Neutron yield**	**Hot-spot pressure (Gbar)**	$\langle T_\mathrm{i} \rangle_\mathrm{n}$ **(keV)**	$\langle \rho R \rangle_\mathrm{n}$ **(mg/cm^2)**
Inviscid (+ IFL)	4.6×10^{14}	130	4.84	201
(1) VC + IFL	3.3×10^{14}	58	4.87	116
(2) VNC + IFL	4.1×10^{14}	122	4.63	196
(3) VC	4.1×10^{14}	91	4.89	157
Experiment	$(7.69 \pm 0.54) \times 10^{13}$	36±7	4.13–5.78	162±15

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

⇦ Similar to the code *HYDRA**

⇦ Similar to the code *xRAGE***

Viscous energy conservative scheme (VC)

Viscous energy non-conservative scheme (VNC)

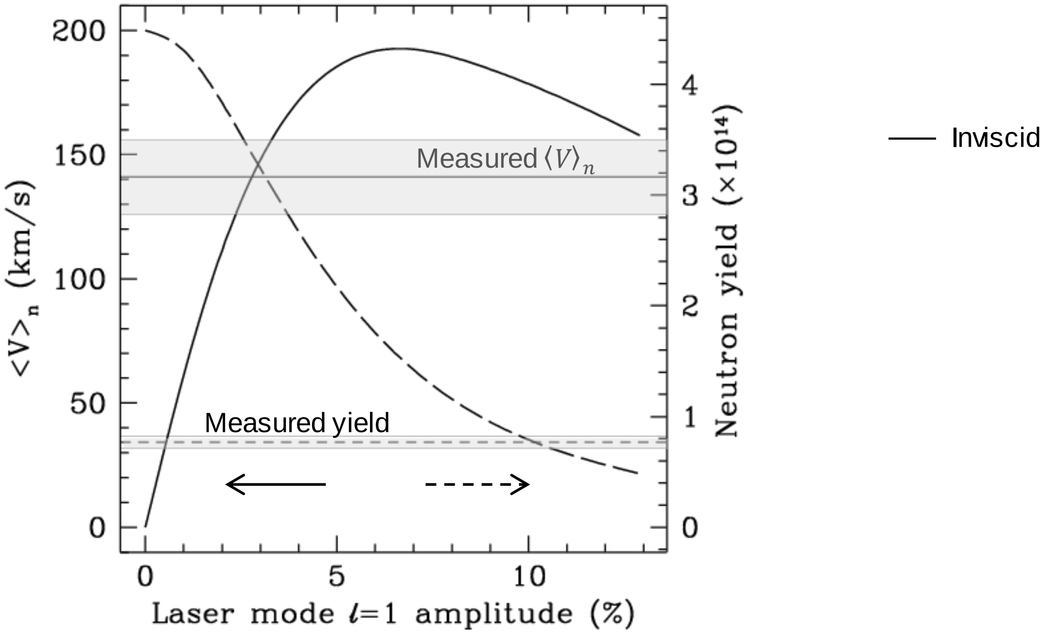
Ion heat-flux limitation (IFL)

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

** B. M. Haines, private communication

Ion viscosity can mitigate the effects of mode ℓ = 1 asymmetry

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



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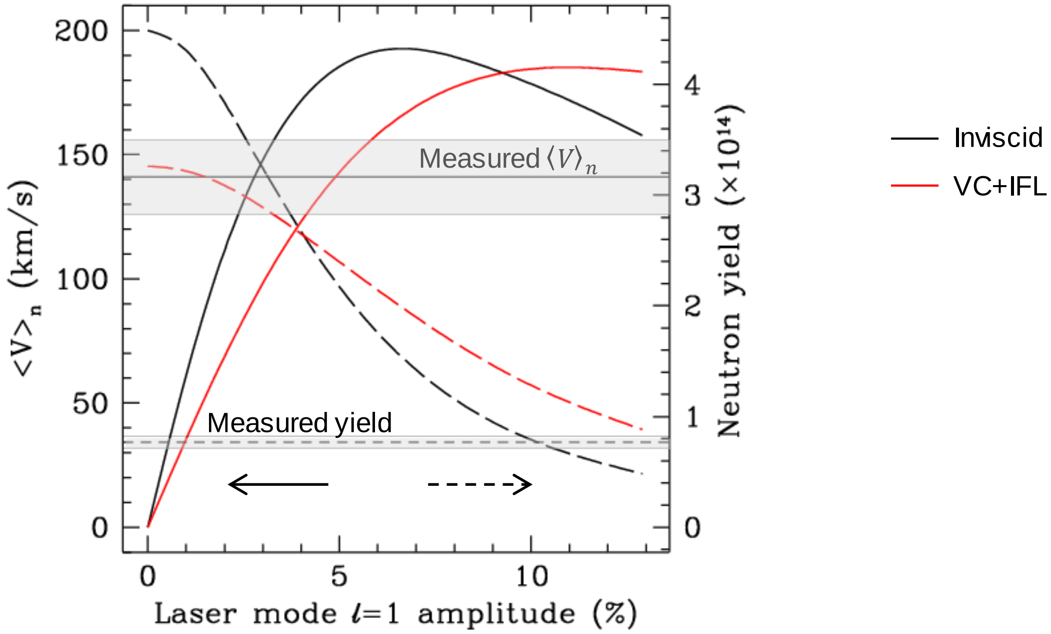

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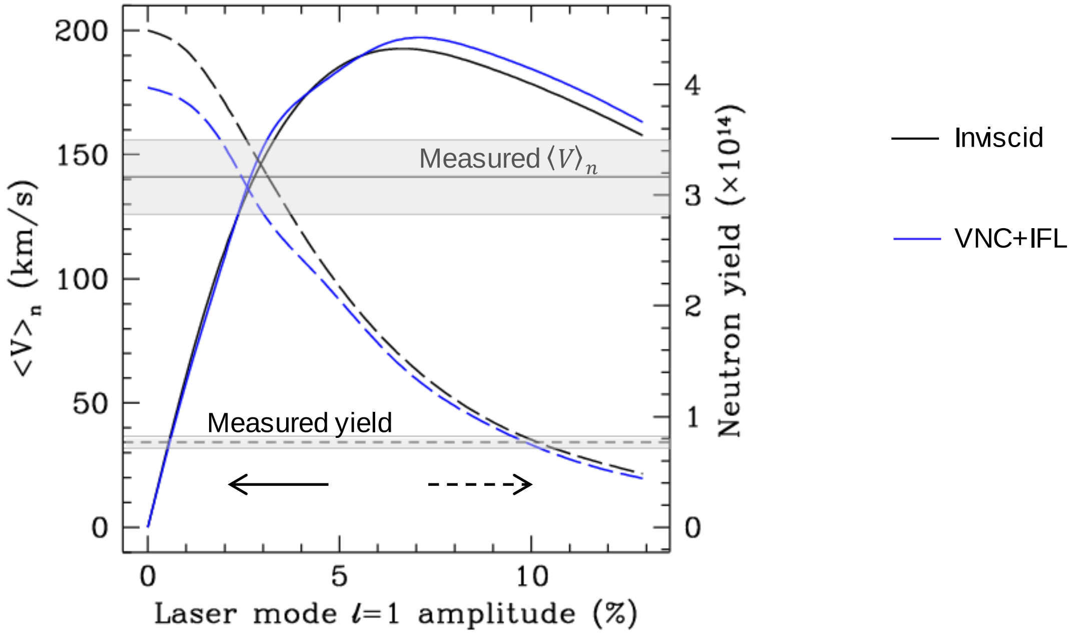

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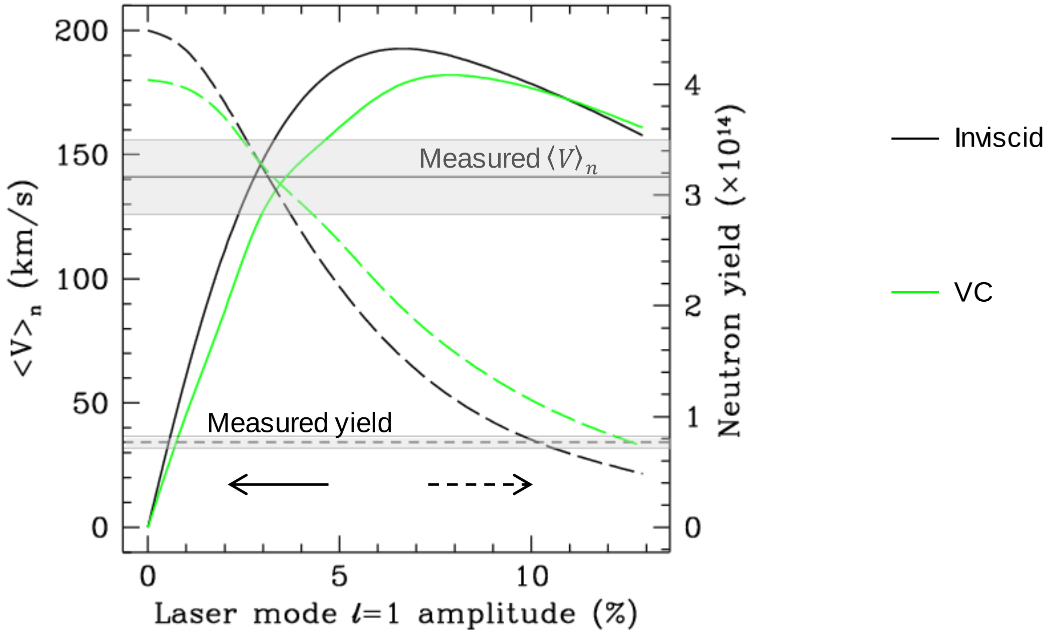

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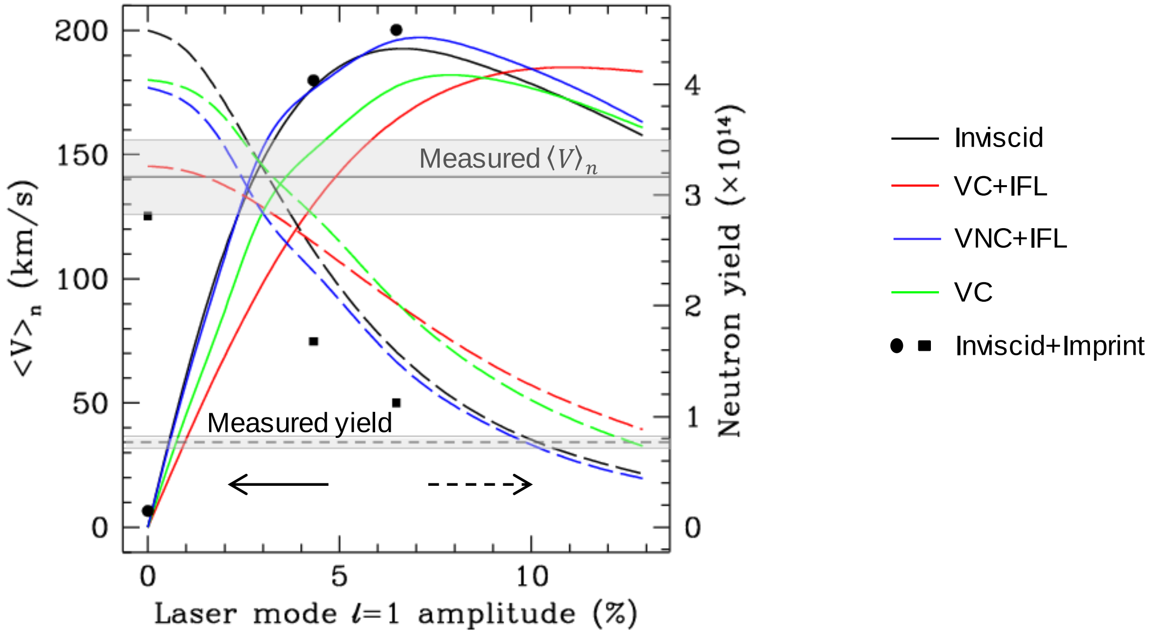

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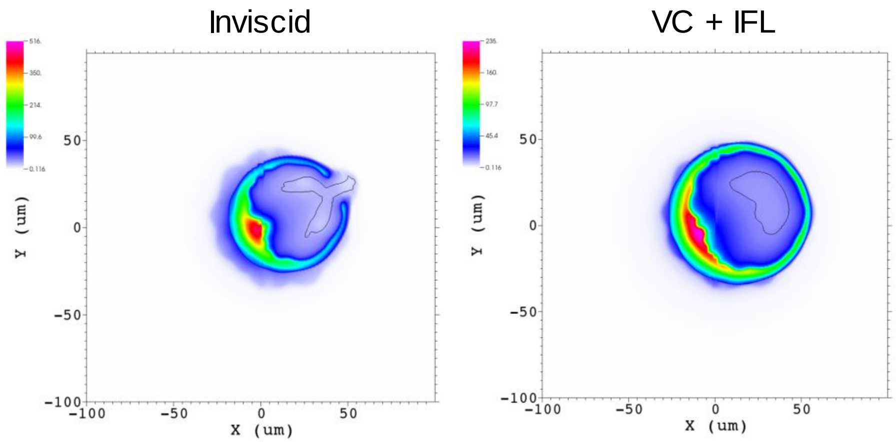
Ion viscosity can mitigate the effects of mode ℓ = 1 asymmetry (continued)

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



Inviscid:

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VC + IFL:

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

Kinetic simulations are required to find which implementation is better

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[1] Igumenshchev *et al*., Phys. Plasmas **23**, 052702 (2016).