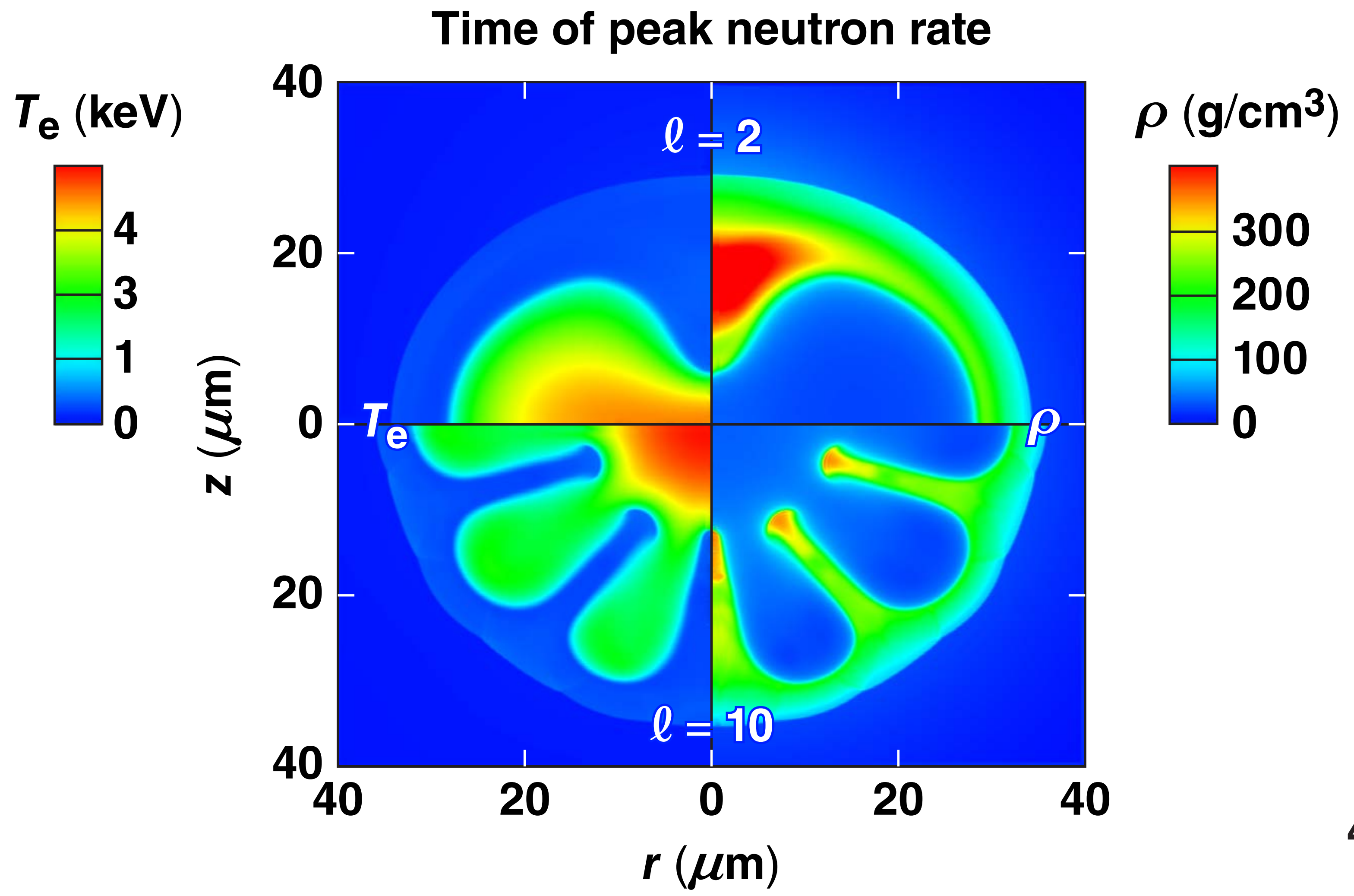
Effects of Long- and Intermediate-Wavelength Asymmetries on Hot-Spot Energetics



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Absorption Conference
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Summary

Low and intermediate-mode nonuniformities lead to different degradation mechanisms of inertial confinement fusion (ICF) implosion performance

- **Low-mode ($\ell \sim 2$) asymmetries show a drop in hot-spot pressure while the hot-spot volume is unchanged**
- **Intermediate-mode ($\ell \sim 10$) asymmetries result in a smaller hot-spot volume, while the pressure is not significantly degraded**
- **Large-amplitude intermediate modes exhibit a "secondary-piston effect," allowing for a secondary conversion of the shell's kinetic energy to hot-spot internal energy**
- **The signatures of single-mode nonuniformities can provide physical insight into the understanding of implosion results**

Collaborators

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Implosion performances are quantified using the following hydrodynamic and burn parameters

- **Yield (Y), neutron rate ($\dot{Y}$) and burnwidth (τ) :**

$$Y = \int dt \int dV \frac{n^2 \langle \sigma v \rangle}{4} \rightarrow \dot{Y} = \int dV \frac{n^2 \langle \sigma v \rangle}{4}$$

- **Neutron-averaged quantities: Temperature (T), and pressure (P)**

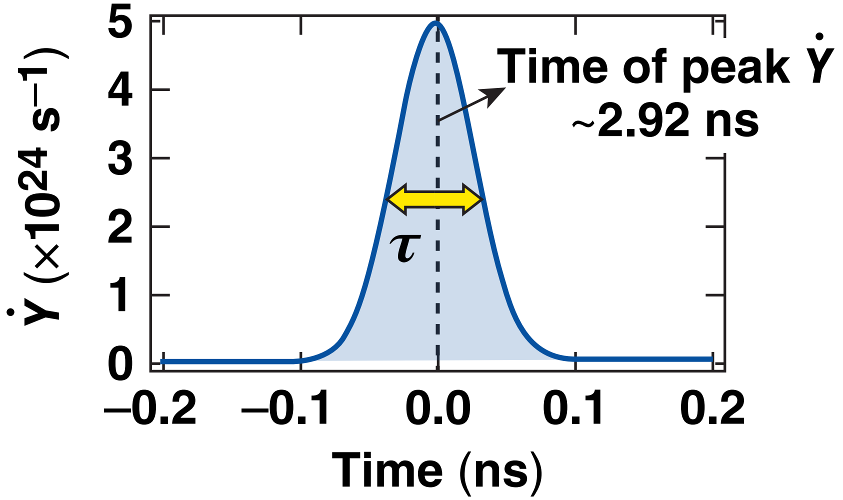
$$\langle Q \rangle = \frac{\int dt \int dV \frac{n^2 \langle \sigma v \rangle}{4} Q}{Y}$$

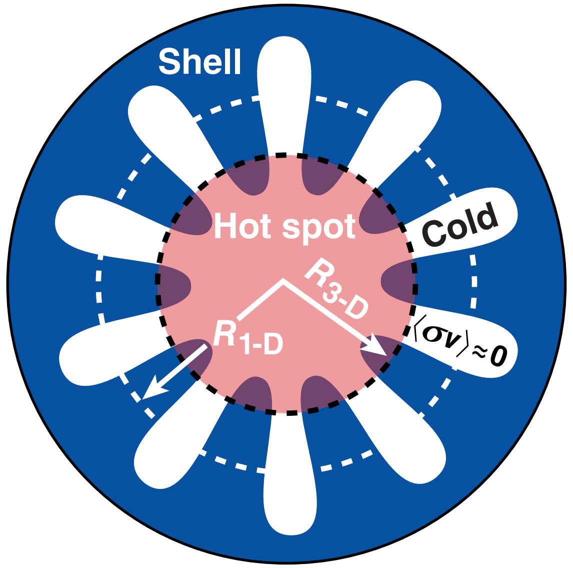
- **YOC * $\equiv \left(\frac{Y \text{ from experiments or 3-D/2-D simulations}}{Y \text{ from 1-D simulations}} \right)$**

*YOC: yield over clean

- **Burn volume (V)**

Neutron rate for OMEGA target





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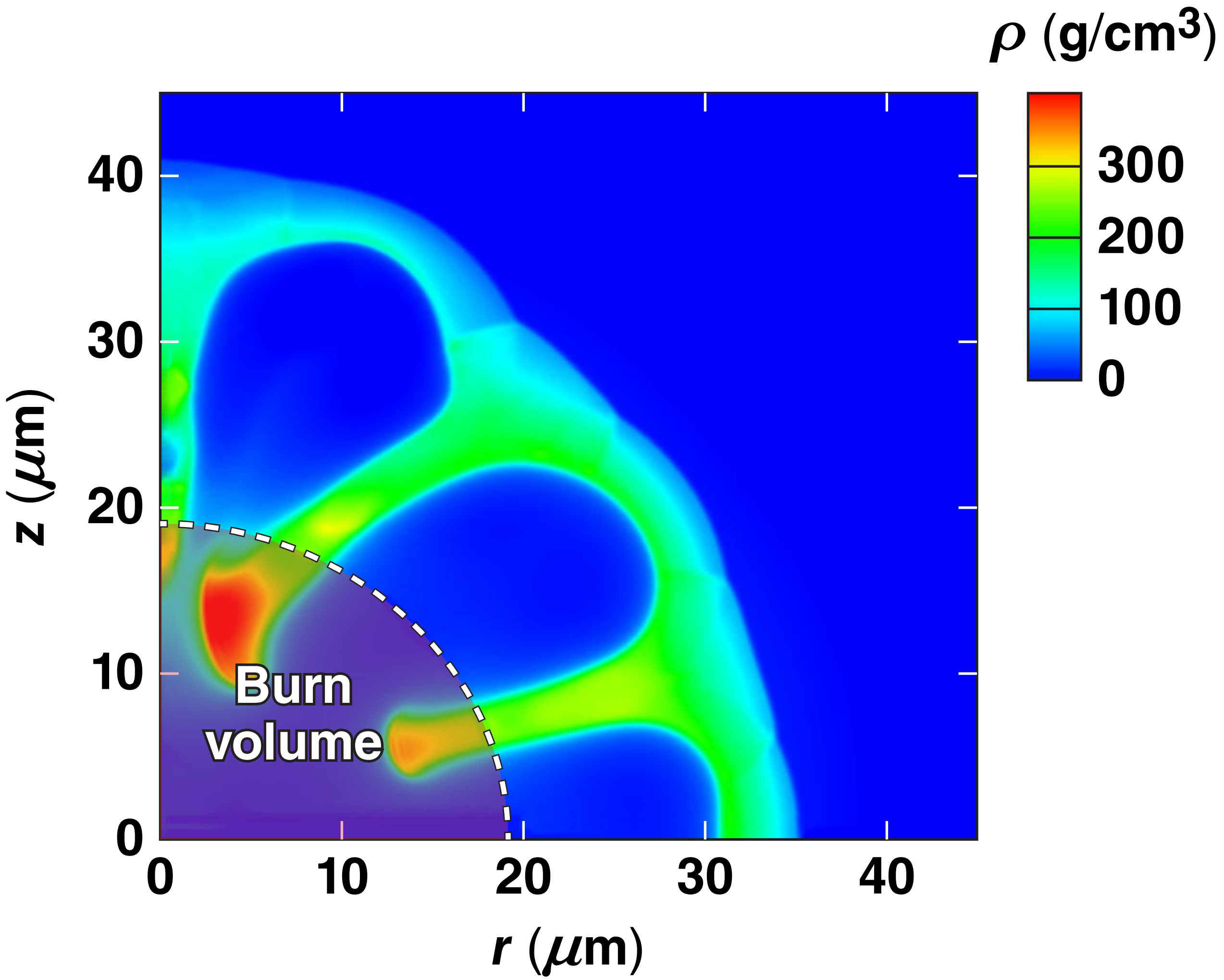
*R. Betti *et al*., Phys. Plasmas 17, 058102 (2010).
P. Y. Chang *et al*., Phys. Rev. Lett. 104, 135002 (2010).

A new definition for the burn volume is introduced, it is the volume of the confined plasma that produces neutrons



$$V = \frac{\int \mathrm{d}t \left[\int \mathrm{d}V \frac{n^2 \langle \sigma v \rangle}{4} \right]^2}{\int \mathrm{d}t \int \mathrm{d}V \left(\frac{n^2 \langle \sigma v \rangle}{4} \right)^2}$$

- The burn volume is an essential simulation diagnostic to explain neutron yields

TC12190

The effect of instabilities are studied by rewriting the yield in terms of the hot-spot quantities

- Yield: $Y \sim P^2 \dfrac{\langle \sigma v \rangle}{T^2} V\, \tau$
- The temperature dependence of the fusion reactivity in the range of $2 < T < 7$ keV follows*:

$$\frac{\langle \sigma v \rangle}{T^2} \sim T^{1.72}$$

- The yield and YOC can be written as $Y \sim P^2 T^{1.7} V\, \tau$

$$\boxed{\mathrm{YOC} \simeq \left(\frac{P_{\text{3-D}}}{P_{\text{1-D}}}\right)^2 \left(\frac{V_{\text{3-D}}}{V_{\text{1-D}}}\right) \left(\frac{T_{\text{3-D}}}{T_{\text{1-D}}}\right)^{1.7} \left(\frac{\tau_{\text{3-D}}}{\tau_{\text{1-D}}}\right)}$$

TC12189

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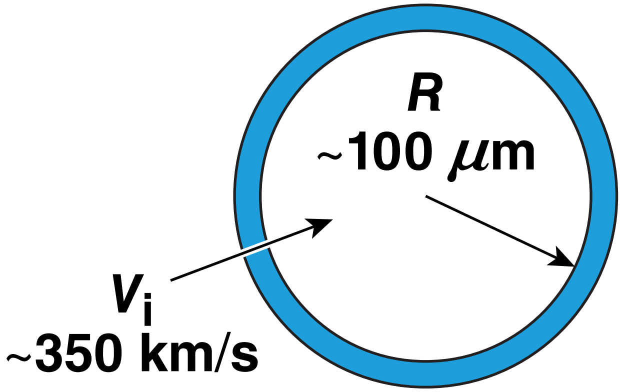
*R. Betti *et al*., Phys. Plasmas 17, 058102 (2010).

The radiation–hydrodynamic code *DEC2D/3D** is used to simulate the deceleration phase of implosions

- This is a Eulerian code with a moving mesh that shrinks radially to maintain high resolution during the compression
- Hydrodynamic-profiles at the end of the acceleration phase (from the 1-D code *LILAC***) are used as the starting point, followed by a simulation of the deceleration phase in multidimension
- *Single-or multimode velocity perturbations are introduced to the inner surface of the shell*



In-flight target

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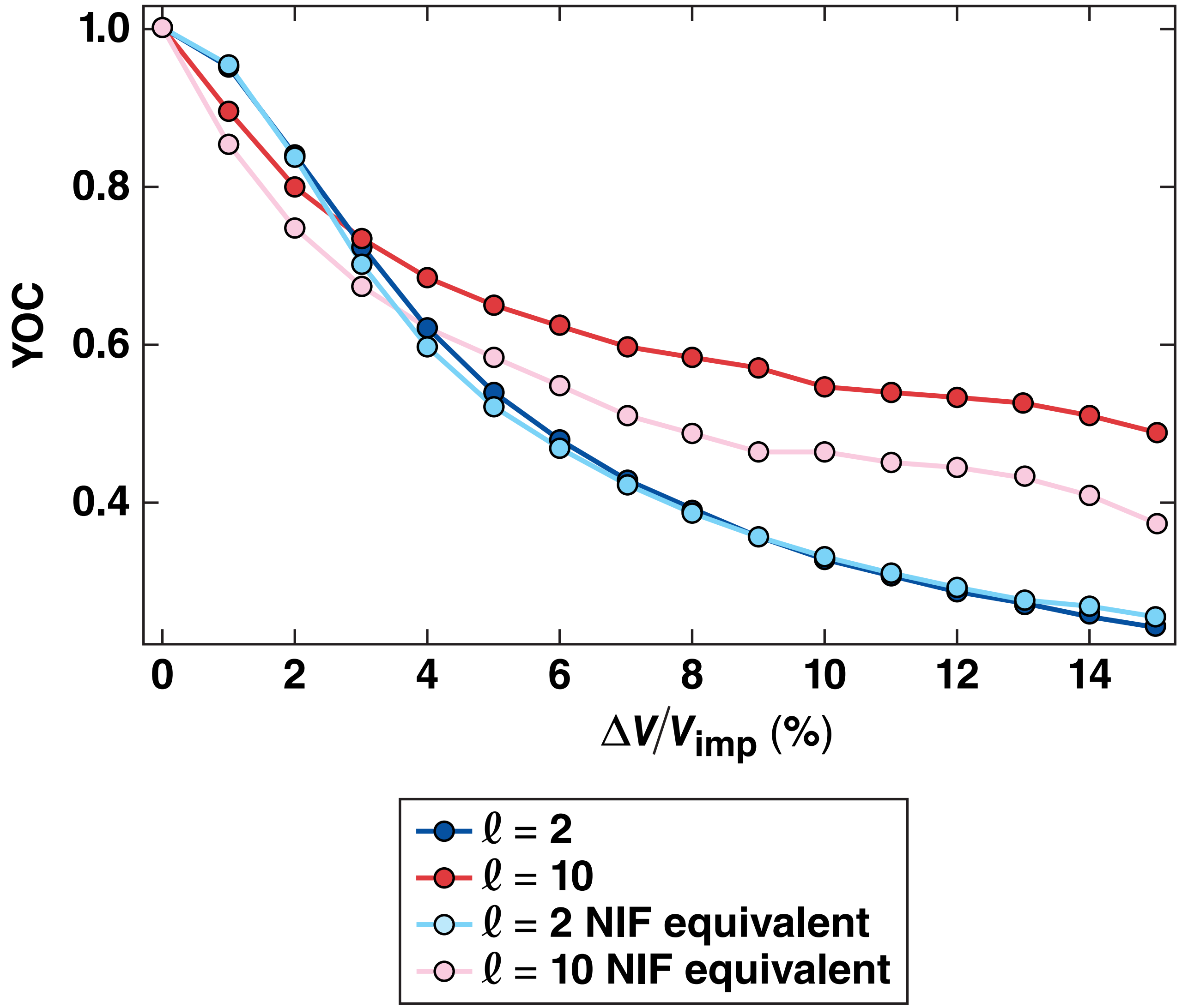
*K. Anderson, R. Betti, and T. A. Gardiner, Bull. Am. Phys. Soc. 46, 280 (2001); A. Bose *et al*., "Hydrodynamic Scaling of the Deceleration-Phase Rayleigh–Taylor Instability," submitted to Physics of Plasmas; K. M. Woo *et al*., Bull. Am. Phys. Soc. 59, 354 (2014).

**J. Delettrez *et al*., Phys. Rev. A 36, 3926 (1987).

TC12203

OMEGA and extrapolated ignition targets show similar trends;* therefore, the analysis is applicable to both scales



- Low modes ($1 \leq \ell \leq 5$) arise mainly because of target offset**
- Intermediate modes ($5 \leq \ell \leq 60$) can arise because of multiple effects, including surface defects***
- Some intermediate modes ($\ell \sim 10$ and $\ell \sim 18$) can be seeded in excess by the overlap intensity arising from the beam geometry***

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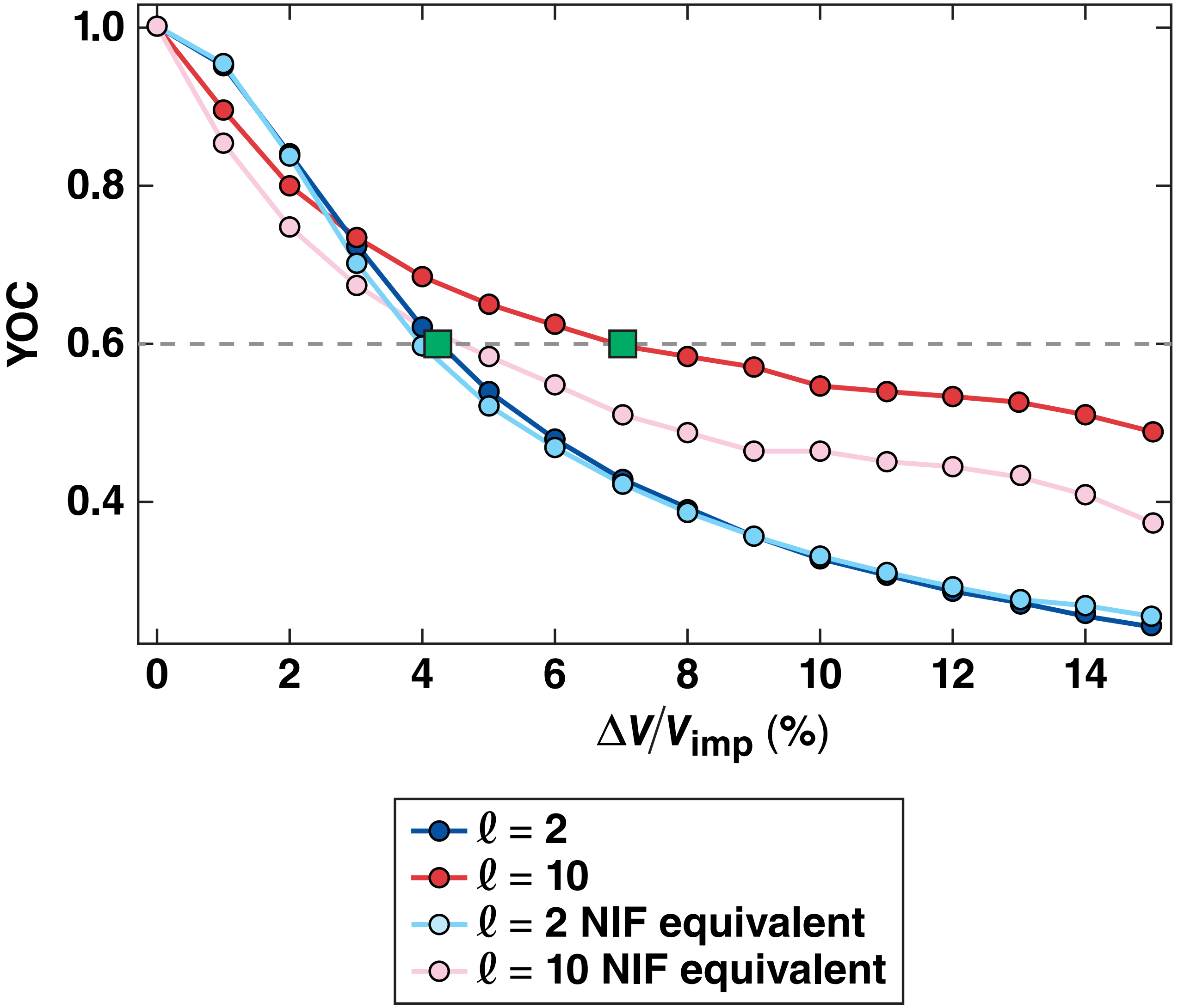
*A. Bose *et al.*, "Hydrodynamic Scaling of the Deceleration-Phase Rayleigh–Taylor Instability," submitted to Physics of Plasmas.

**S. X. Hu *et al.*, Phys. Plasmas 16, 112706 (2009).

***P. B. Radha *et al.*, Phys. Plasmas 12, 032702 (2005).

TC12188

OMEGA and extrapolated ignition targets show similar trends;* therefore, the analysis is applicable to both scales



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TC12188a

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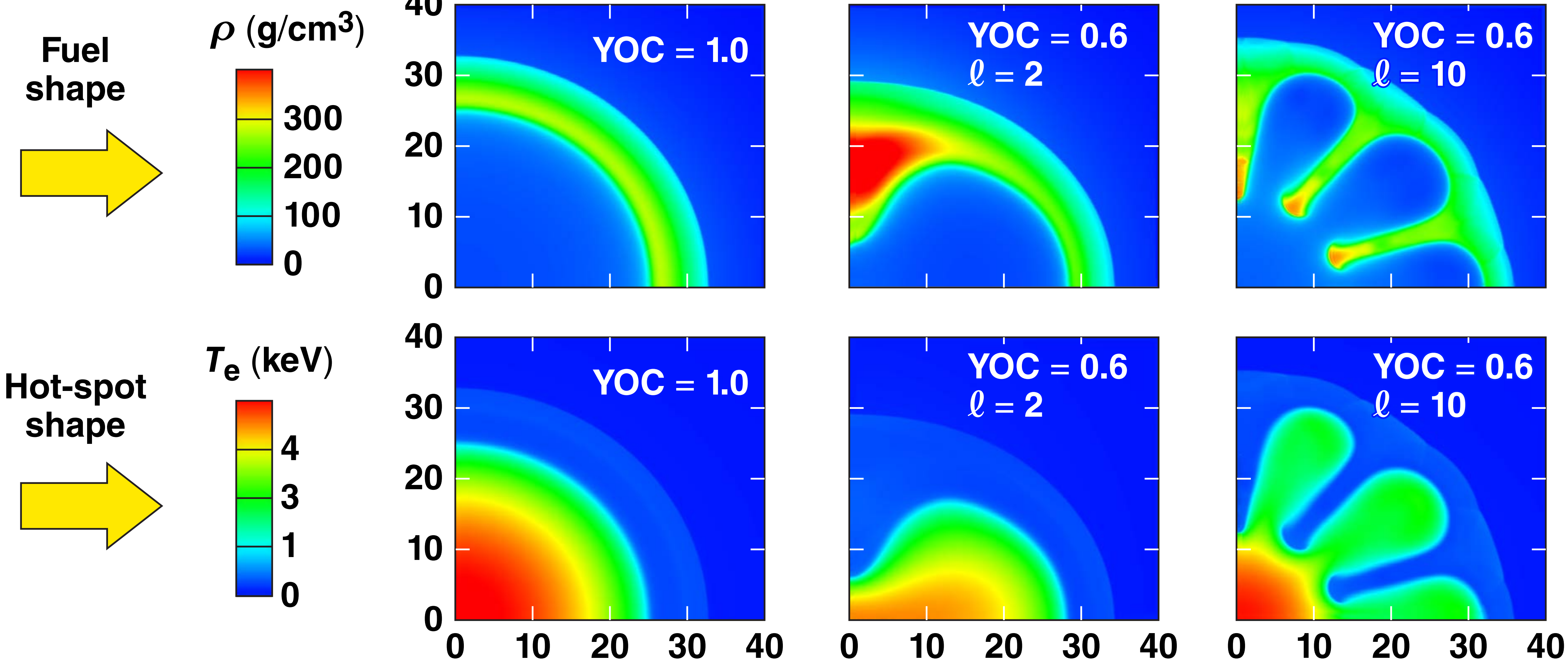
**S. X. Hu *et al*., Phys. Plasmas 16, 112706 (2009).

***P. B. Radha *et al*., Phys. Plasmas 12, 032702 (2005).

Single-mode nonuniformities have a distinct effect on the shape of the fuel and hot spot

OMEGA target at time of peak neutron rate



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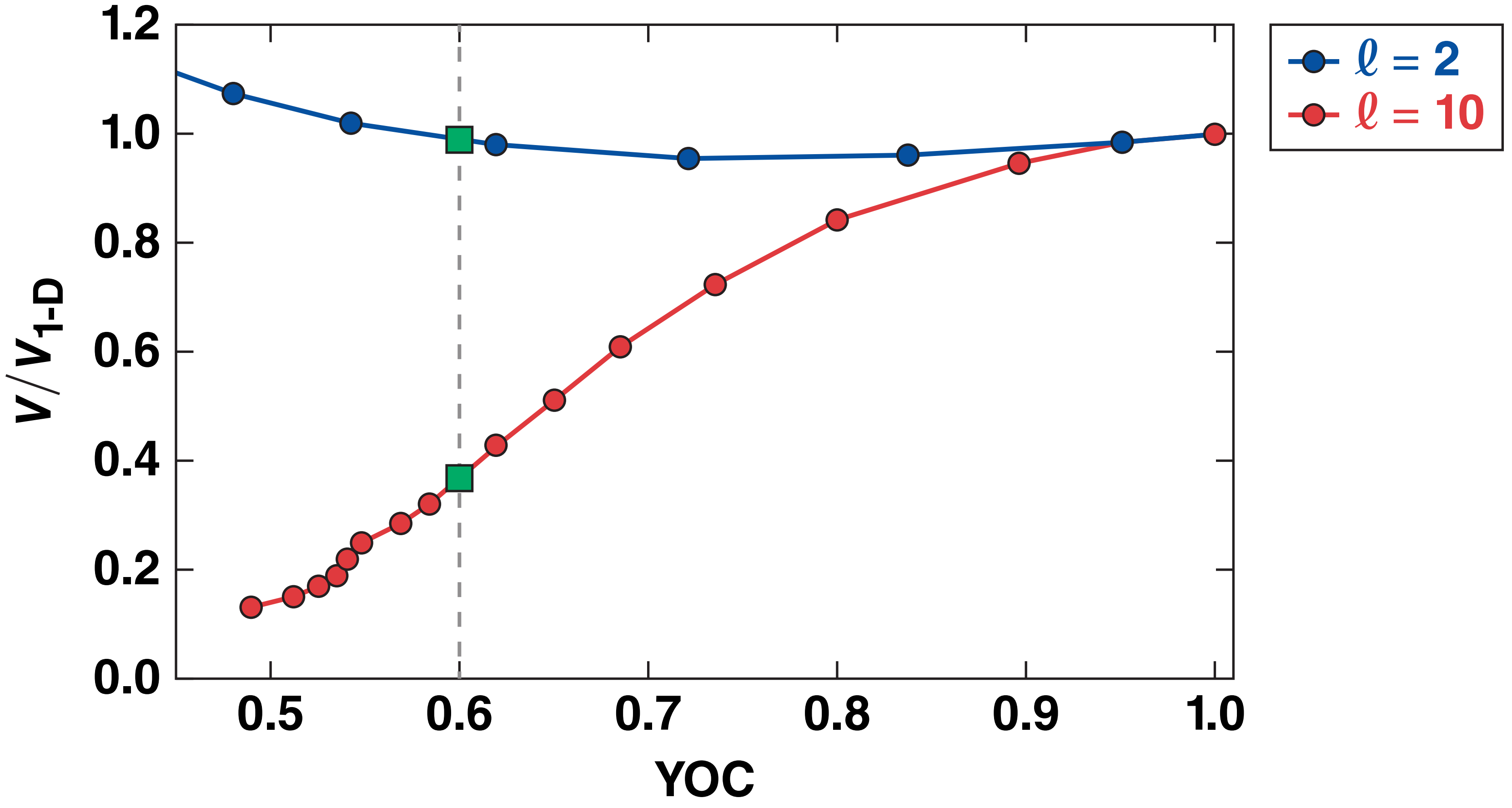
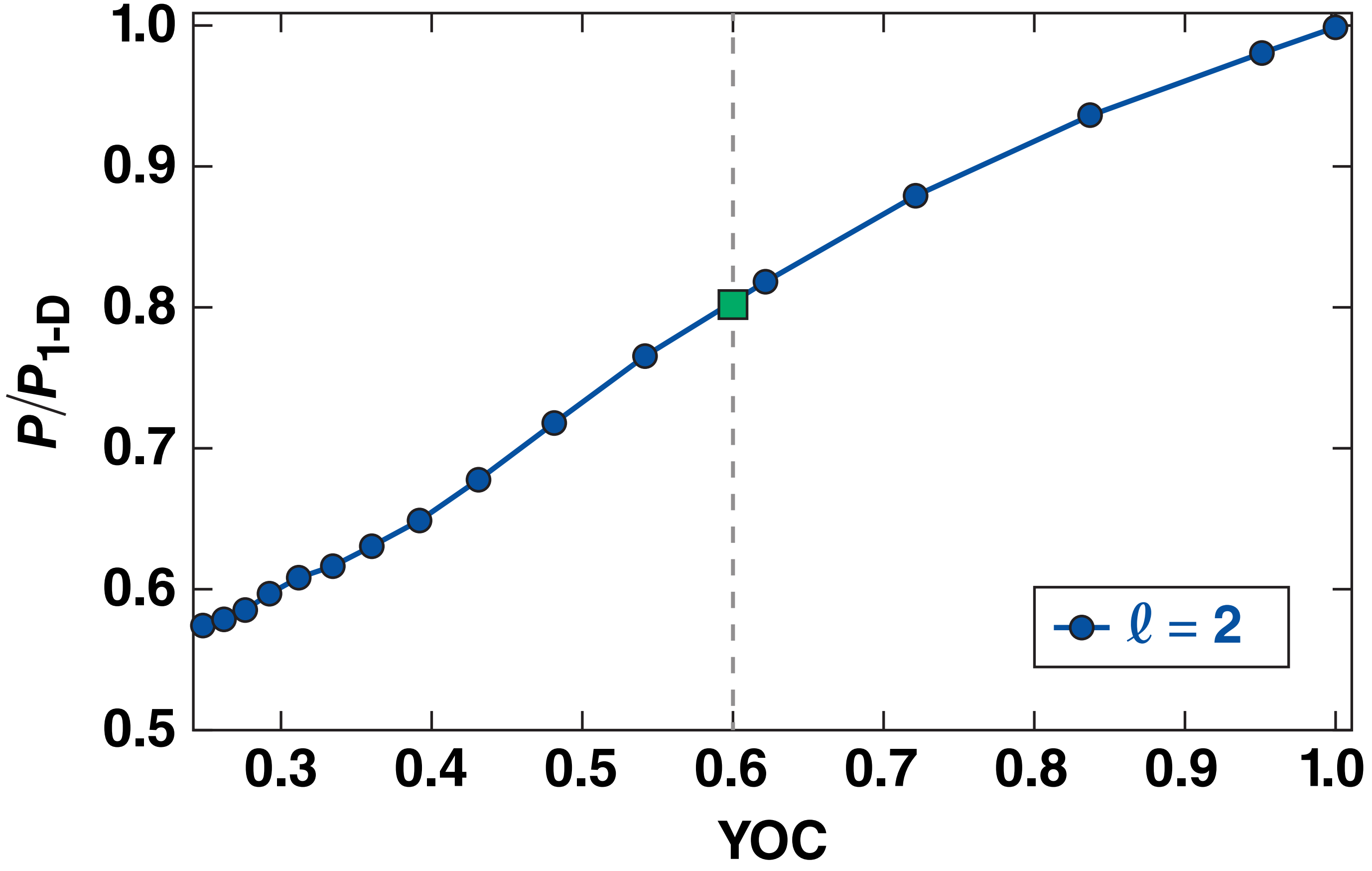
While intermediate-ℓ modes exhibit yield degradation caused primarily by a drop in volume, low-ℓ modes show no reduction in volume



$$\text{YOC} \simeq \left(\frac{P}{P_{1\text{-D}}}\right)^2 \left(\frac{V}{V_{1\text{-D}}}\right) \left(\frac{T}{T_{1\text{-D}}}\right)^{1.7} \left(\frac{\tau}{\tau_{1\text{-D}}}\right)$$

TC12191

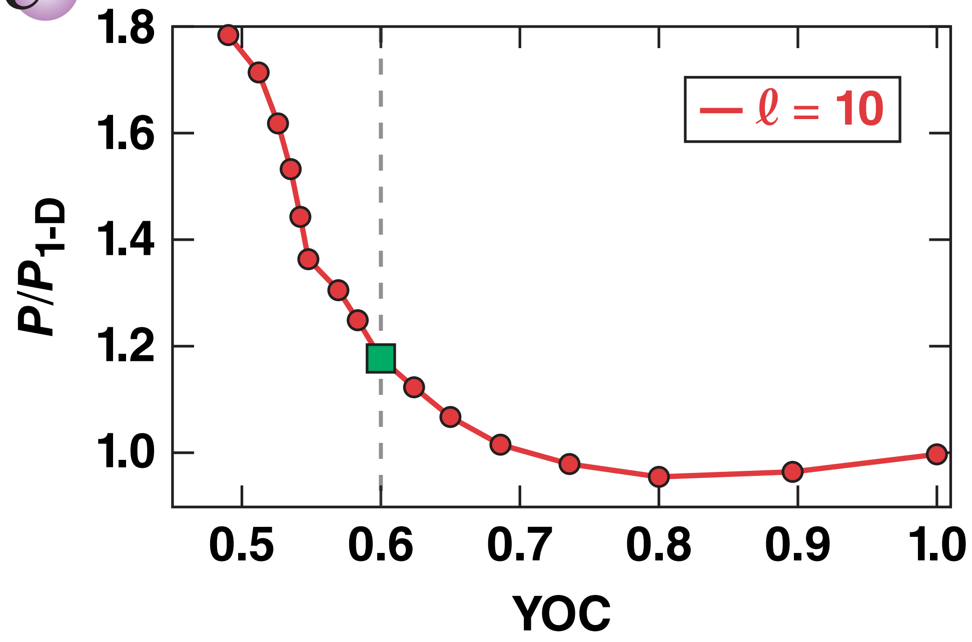
Yield degradation from low-ℓ modes result from a significant reduction in pressure compared to the 1-D value

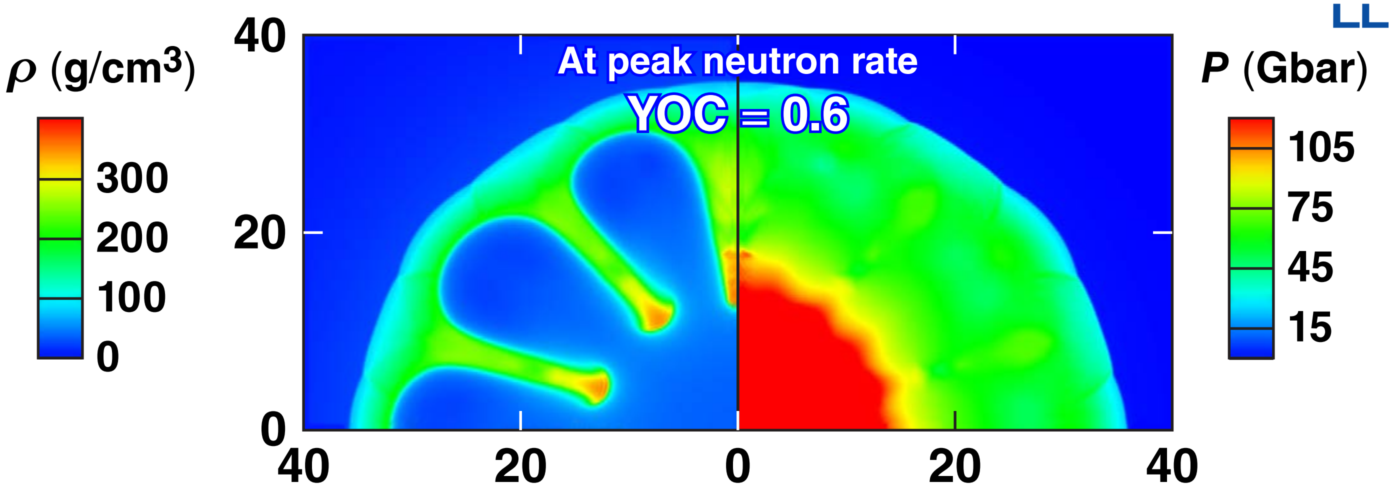


$$\text{YOC} \simeq \boxed{\left(\frac{P}{P_{1\text{-D}}}\right)^2} \left(\frac{V}{V_{1\text{-D}}}\right) \left(\frac{T}{T_{1\text{-D}}}\right)^{1.7} \left(\frac{\tau}{\tau_{1\text{-D}}}\right)$$

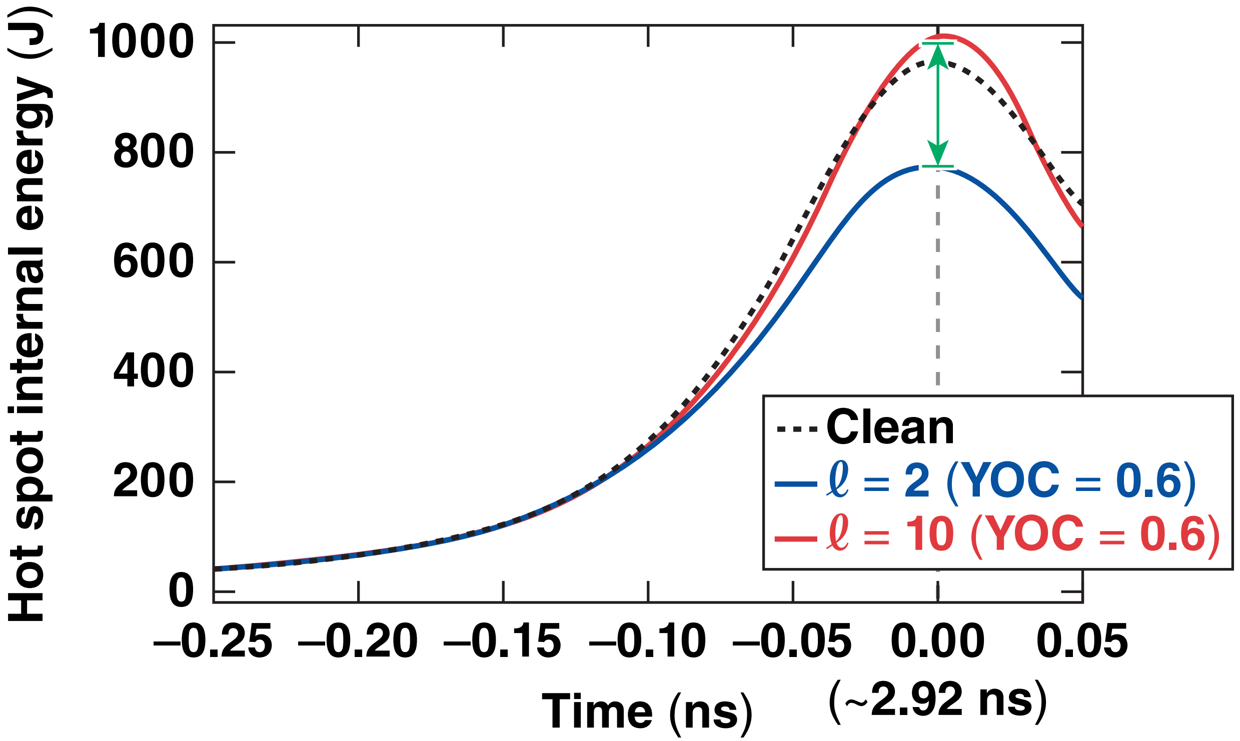
TC12192

Rayleigh–Taylor spike convergence results in an increase in the central pressure for intermediate-ℓ modes even when the YOC decreases: secondary piston



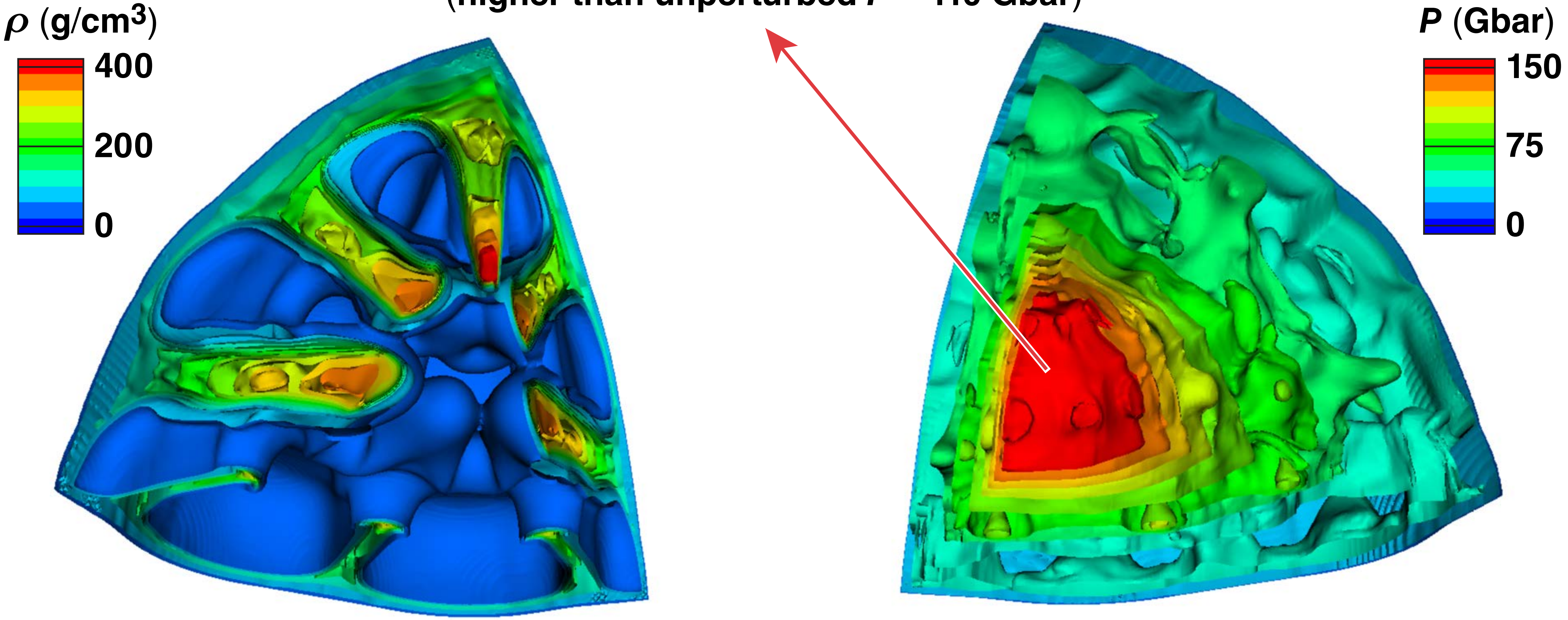


- Residual shell kinetic energy for low mode ~200 J
- Secondary conversion of shell kinetic energy to hot-spot internal energy for intermediate mode ~200 J



TC12193

Three-dimensional simulations with single mode ($\ell = 10$, $m = 10$) confirm the "secondary-piston" effect



Central region with $P \sim 150$ Gbar
(higher than unperturbed $P \sim 110$ Gbar)

Density

At peak neutron rate

Pressure

TC12204

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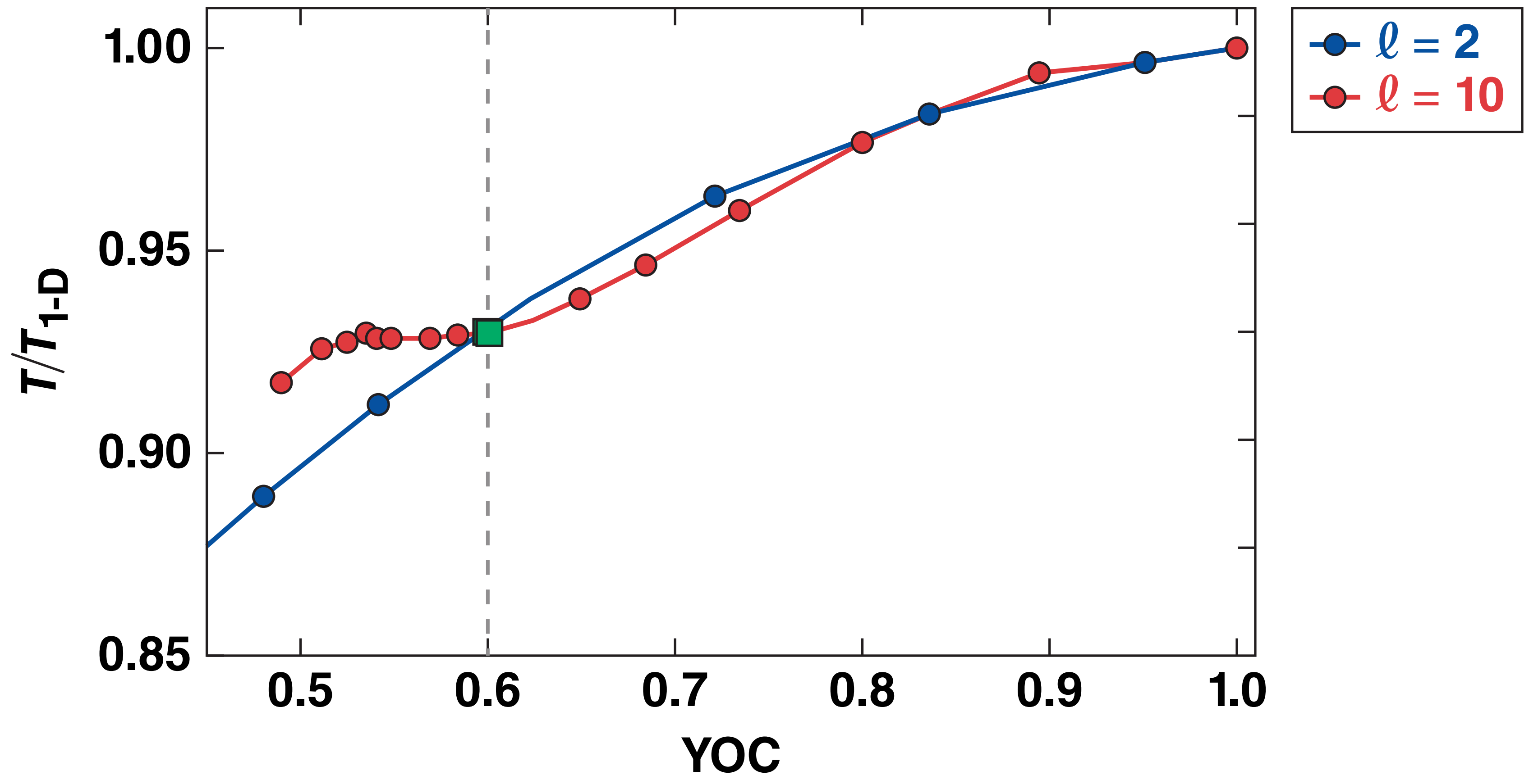
*K. M. Woo *et al.*, Bull. Am. Phys. Soc. 59, 354 (2014).

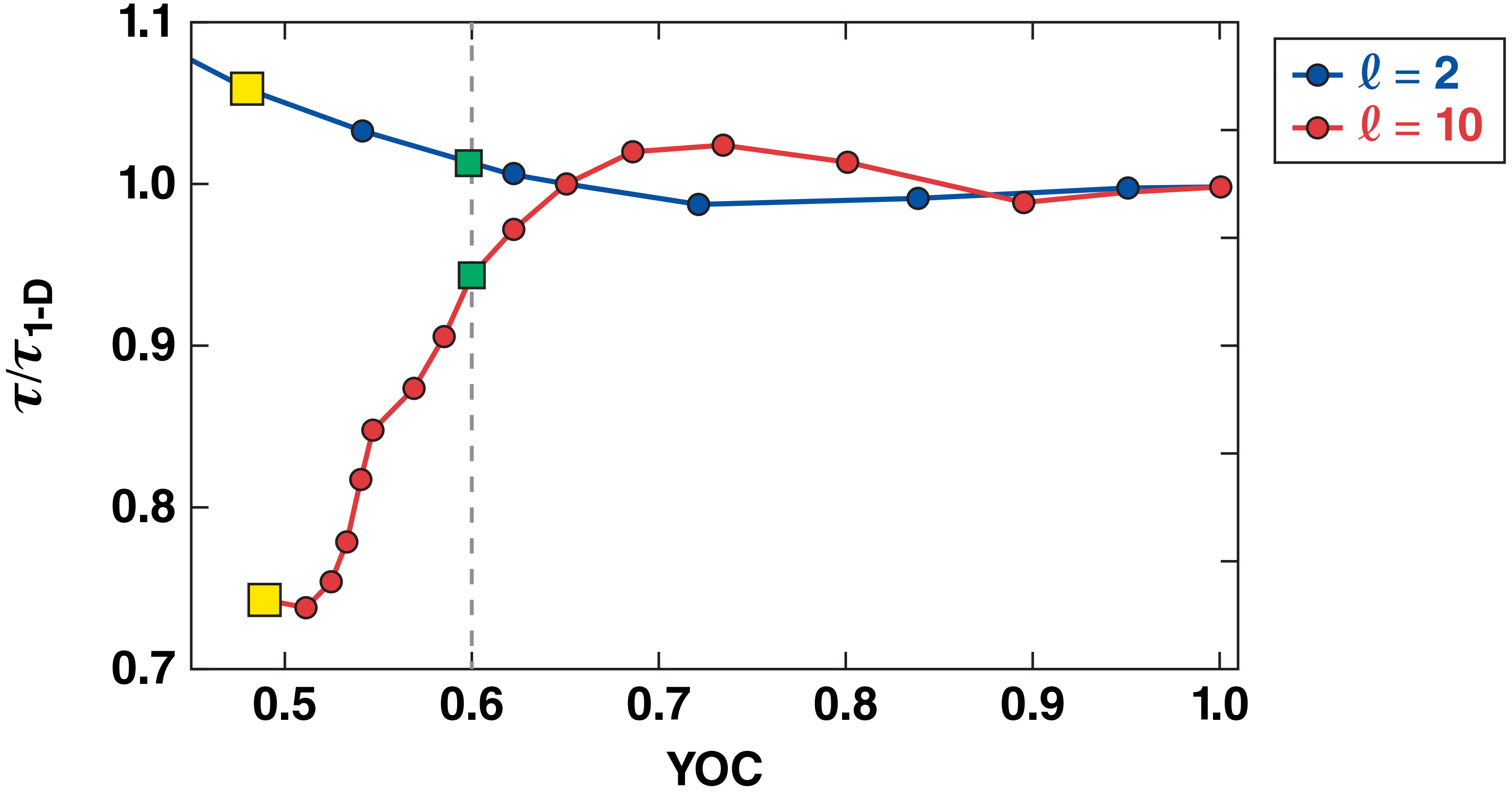
Ion temperatures are little affected by nonuniformities up to yield degradations of ~50%



$$\text{YOC} \simeq \left(\frac{P}{P_{1\text{-D}}}\right)^2 \left(\frac{V}{V_{1\text{-D}}}\right) \left(\frac{T}{T_{1\text{-D}}}\right)^{1.7} \left(\frac{\tau}{\tau_{1\text{-D}}}\right)$$

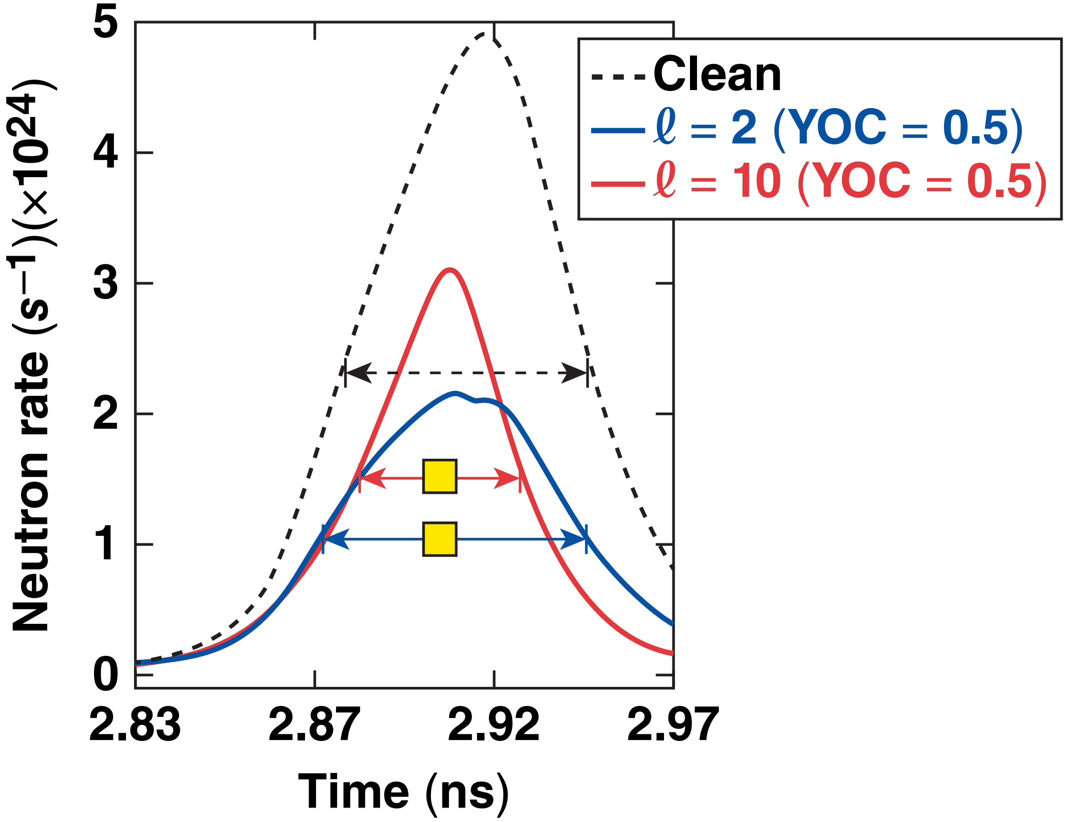
TC12194

Burnwidths are reduced only for intermediate-ℓ modes because of the secondary-piston effect



The burn widths are comparable for YOC > 0.6

High levels of single-mode asymmetry



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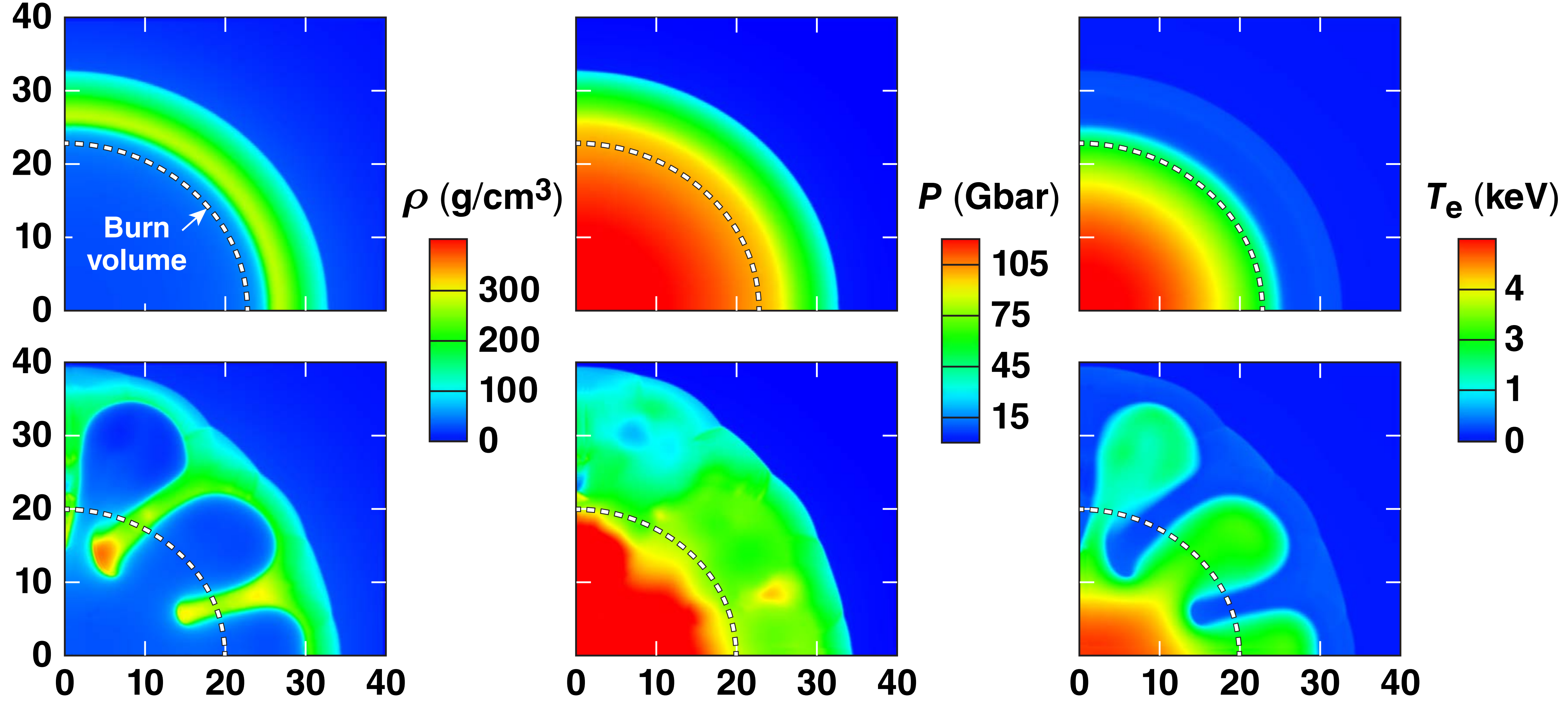
TC12195

The understanding can be extended to explain trends in results with multimode nonuniformities

OMEGA target at time of peak neutron rate

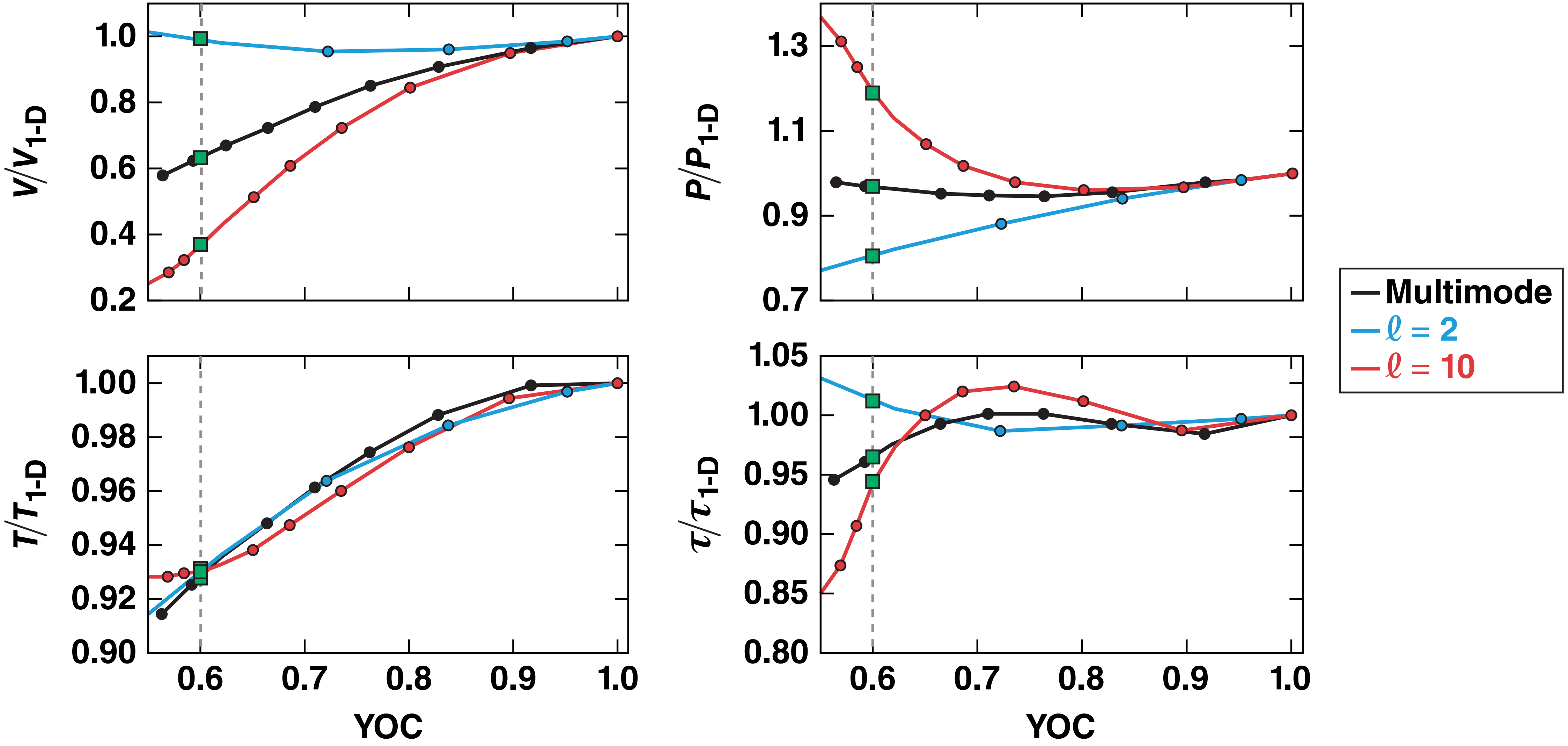


Clean

Multimode

With superposition of low modes and intermediate $\ell = 10$ mode

Multimode simulations can be explained by superposing the trends shown by low and intermediate modes



TC12198

Summary/Conclusions

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