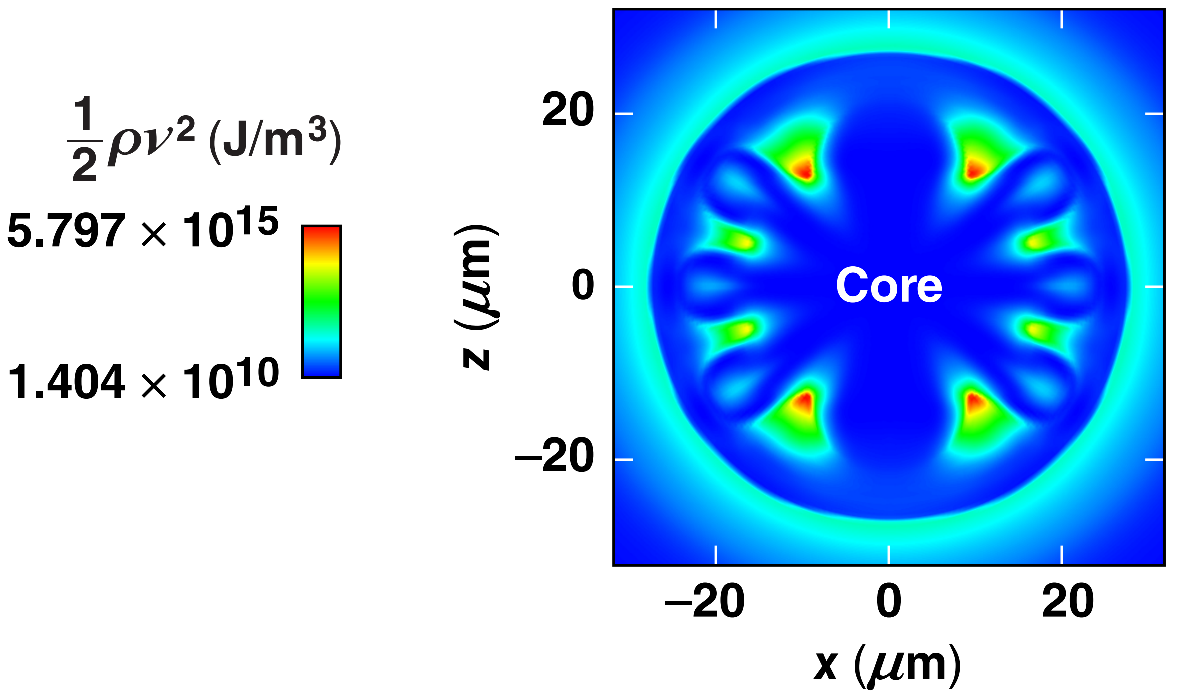
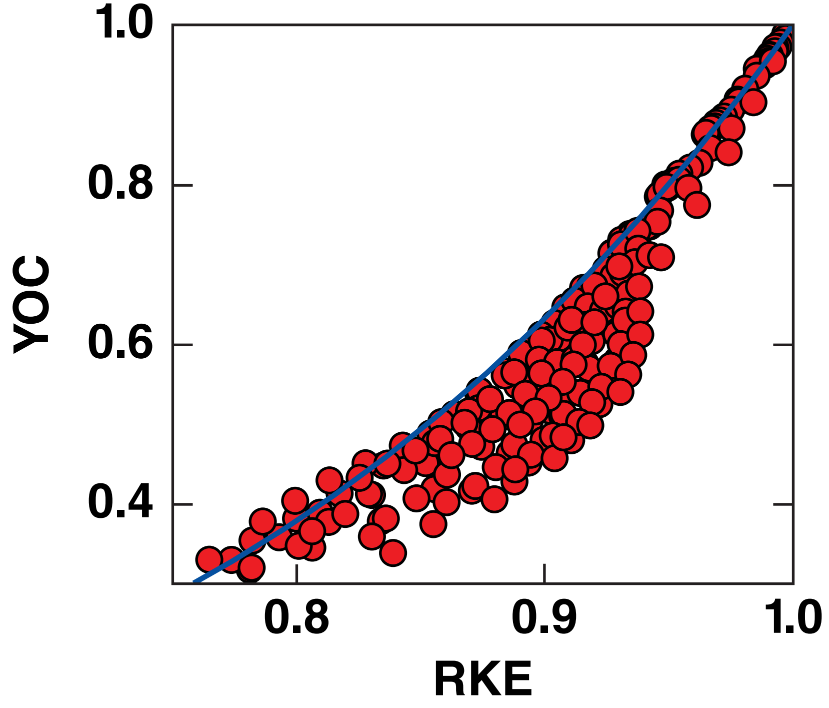
Three-Dimensional Studies of the Effect of Residual Kinetic Energy on Yield Degradation

Kinetic energy density for single-mode $\ell = 12$, $m = 6$



$\text{YOC}^{\text{model}} = (1 - \text{RKE})^{4.4}$



K. M. Woo
University of Rochester
Laboratory for Laser Energetics

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Summary

A hot-spot model indicates that the yield degradation caused by low- and mid-mode nonuniformities is a strong function of the residual kinetic energy

- A synthetic single-mode database ranging from low mode ($\ell = 1$) to mid mode ($\ell = 12$) was built using the 3-D hydrocode *DEC3D** applied to the deceleration phase of inertial confinement fusion (ICF) implosions
- It is shown that the yield-over-clean (YOC) is strongly correlated to residual kinetic energy (RKE) at bang time
- The simulation results are also confirmed by a simple analytical hot-spot model

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*K. M. Woo *et al.*, "Three-Dimensional Studies of the Effect of Residual Kinetic Energy on Yield Degradation," to be submitted to Physics of Plasmas.

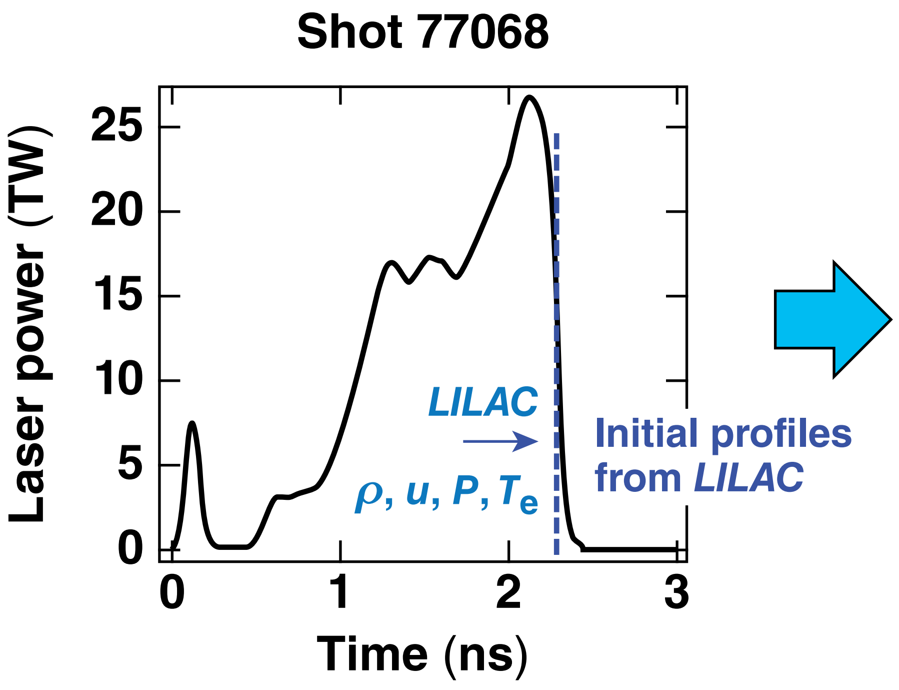
Collaborators

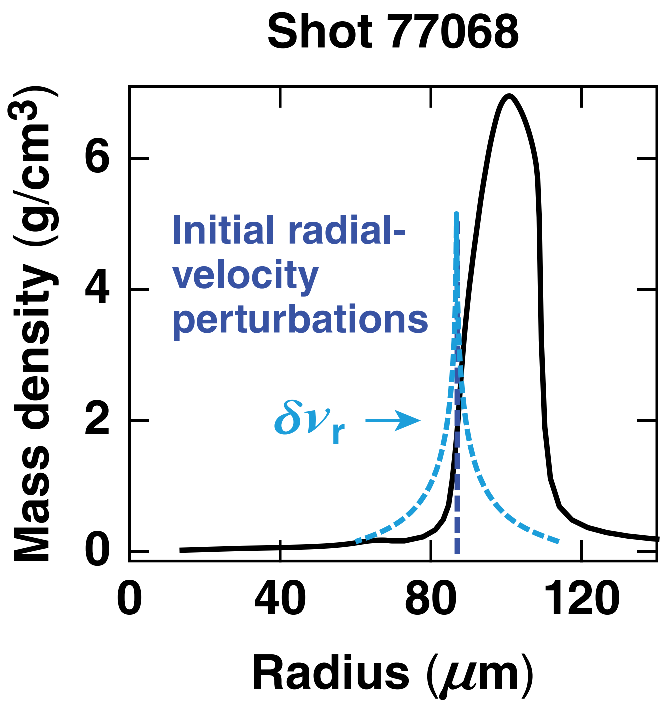
R. Betti, A Bose, D. Patel, and V. Gopalaswamy

University of Rochester
Laboratory for Laser Energetics

A synthetic single-mode database was built using *DEC3D* to study yield degradation caused by Rayleigh–Taylor instabilities (RTI) in the deceleration phase

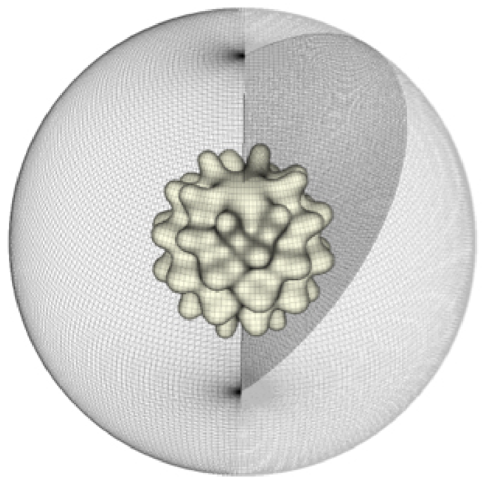
Simulation method





$\delta v_r = \Delta v / v_0$ is chosen appropriately to degrade the yield

3-D radiation–hydrodynamic deceleration-phase code *DEC3D*



1-keV T_e contour surface for single-mode $\ell = 12$, $m = 6$ at stagnation

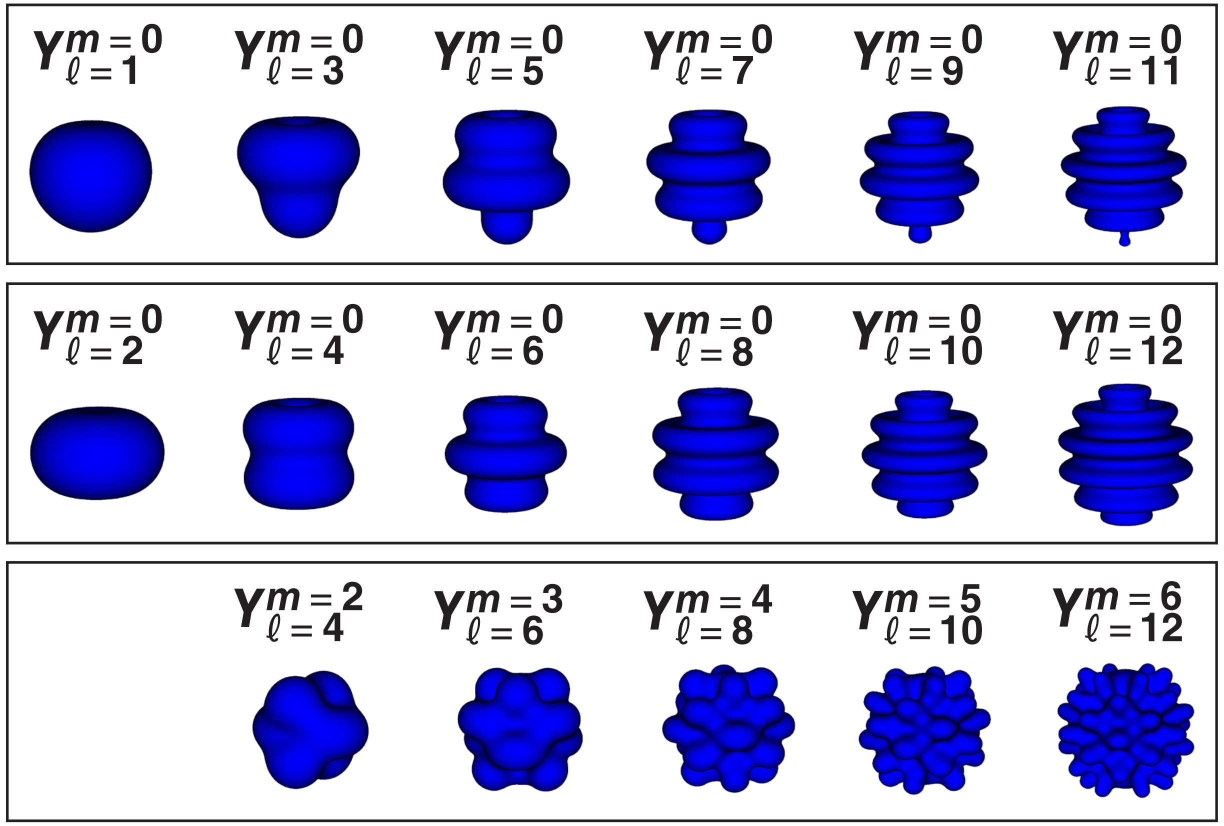
The synthetic database includes 3-D simulations using different velocity perturbations with spherical-harmonic single modes from $\ell = 1$ to $\ell = 12$

Initial velocity perturbation

A shape function to spread out the perturbation over space

$$\nu_r^{3\text{-D}}(r,\theta,\varphi,t_0) = \nu_r^{1\text{-D}}(r,t_0) + \underbrace{\frac{\Delta\nu}{\nu_0} f(r) Y_\ell^m(\theta,\varphi)}_{\delta\nu_r}$$

1-keV T_e contour surface at stagnation



- PPM* Riemann solver
- *HYPRE* thermal diffusion
- Resolution = 128 × 128 × 256 ($r \times \theta \times \phi$ zones)

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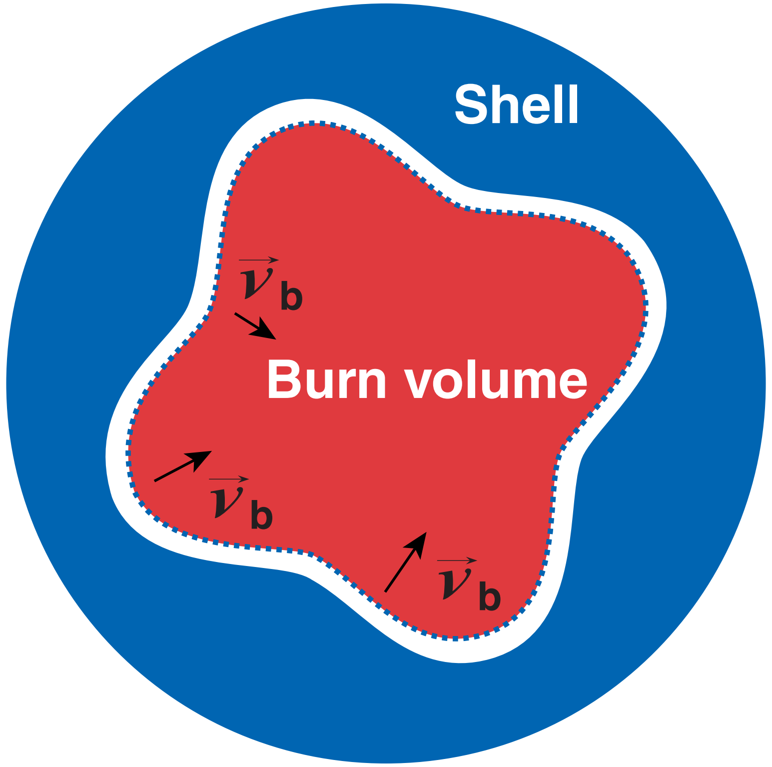
*PPM: piecewise parabolic method

A simple 3-D hot-spot model is derived using energy conservation and an adiabatic condition, and neglecting the heat flux flowing into the cold bubbles

Three-dimensional hot-spot model



Neutron yield: $Y \simeq n^2 \langle \sigma v \rangle V \tau$

Yield-over-clean: $\mathrm{YOC} \simeq \left[\frac{n_{3\text{-D}}}{n_{1\text{-D}}}\right]^2 \left[\frac{T_{3\text{-D}}}{T_{1\text{-D}}}\right]^4 \left[\frac{V_{3\text{-D}}}{V_{1\text{-D}}}\right] \left[\frac{\tau_{3\text{-D}}}{\tau_{1\text{-D}}}\right]$

Adiabatic implosion:

$$P_{3\text{-D}} V_{3\text{-D}}^{5/3} = P_{1\text{-D}} V_{1\text{-D}}^{5/3}$$

$$\longrightarrow \quad \frac{P_{3\text{-D}}}{P_{1\text{-D}}} = \left(\frac{\mathrm{IE}_{3\text{-D}}}{\mathrm{IE}_{1\text{-D}}}\right)^{5/2} \quad \text{and} \quad \frac{V_{3\text{-D}}}{V_{1\text{-D}}} = \left(\frac{\mathrm{IE}_{3\text{-D}}}{\mathrm{IE}_{1\text{-D}}}\right)^{-3/2}$$

Energy conservation: $\mathrm{IE}_{\mathrm{HS}}^{\mathrm{stag}} = \mathrm{KE}_{\mathrm{tot}}^{\mathrm{max}} - \mathrm{KE}_{\mathrm{tot}}^{\mathrm{stag}} - \mathrm{IE}_{\mathrm{SH}}^{\mathrm{stag}}$

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Energy conservation and adiabatic condition are used to derive the YOC dependence in the residual kinetic energy

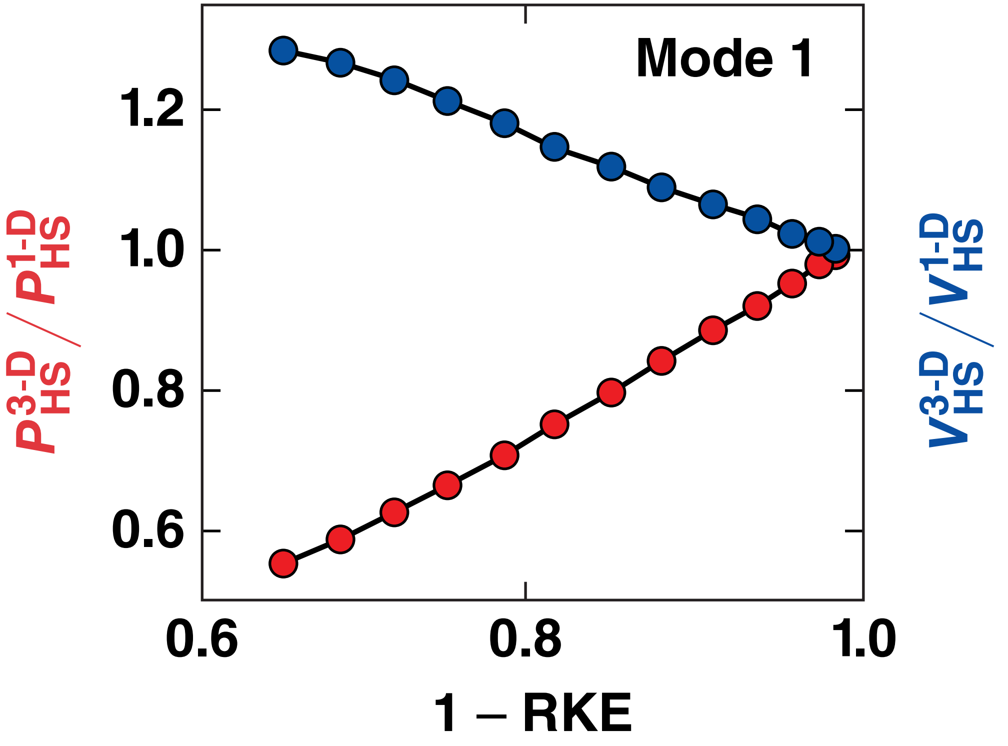
Definitions

$$\hat{Q} = Q_{\text{3-D}} \big/ Q_{\text{1-D}} \quad \text{and} \quad \text{RKE} = \frac{\text{KE}^{\text{3-D}}_{\text{shell}}\left(t^{\text{3-D}}_{\text{stag}}\right) - \text{KE}^{\text{1-D}}_{\text{shell}}\left(t^{\text{1-D}}_{\text{stag}}\right)}{\text{KE}^{\text{max}}_{\text{tot}}} \longrightarrow \frac{\text{IE}^{\text{3-D}}_{\text{HS}}}{\text{IE}^{\text{1-D}}_{\text{HS}}} \simeq 1 - \text{RKE}$$

$$\boxed{\hat{P} = (1 - \text{RKE})^{5/2}, \hat{V} = (1 - \text{RKE})^{-3/2}}$$

$$\text{YOC}^{\text{model}} = \overbrace{\hat{P}^{4}_{\text{HS}}\,\hat{V}^{3}_{\text{HS}}}\,\hat{M}^{-2}_{\text{HS}}\,\hat{\tau}_{\text{BW}} \approx (1 - \text{RKE})^{5.5}\,\hat{M}^{-2}_{\text{HS}}\,\hat{\tau}_{\text{BW}}$$

Using 1-D scaling for the mass ablation rate (next slide)



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For low modes, a 1-D scaling of the mass ablation rate is used to derive the 3-D hot-spot mass

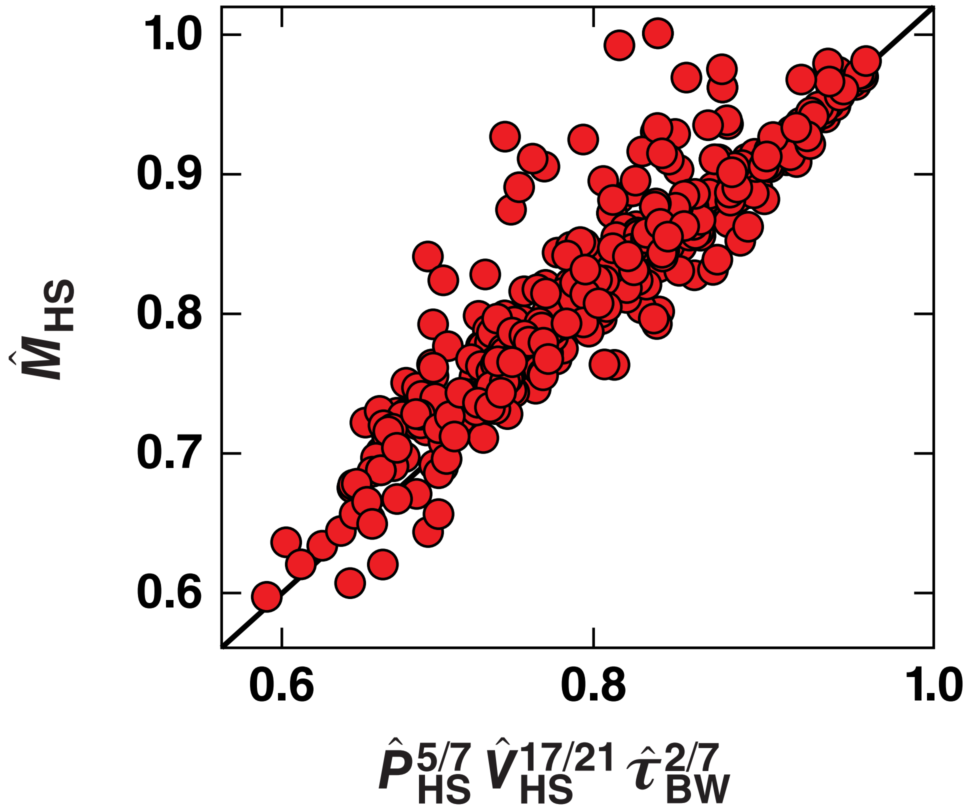
One-dimensional approximations for mass ablation rate* and hot-spot surface area

$$\frac{M_{\mathrm{HS}}}{\tau} \simeq \underbrace{\dot{m}_{\mathrm{abl}}}_{T_{\mathrm{HS}}^{5/2}/R} \overbrace{S_{\mathrm{HS}}}^{R^2} \sim T_{\mathrm{HS}}^{5/2} R \sim \left(P_{\mathrm{HS}} V_{\mathrm{HS}} / M_{\mathrm{HS}}\right)^{5/2} V_{\mathrm{HS}}^{1/3}$$

Scaling for 3-D hot-spot mass

$$\hat{M}_{\mathrm{HS}} = \hat{P}_{\mathrm{HS}}^{5/7} \hat{V}_{\mathrm{HS}}^{17/21} \hat{\tau}_{\mathrm{BW}}^{2/7} = (1-\mathrm{RKE})^{4/7} \hat{\tau}_{\mathrm{BW}}^{2/7}$$

$$\hat{M}_{\mathrm{HS}}^{\mathrm{model}} = \hat{P}_{\mathrm{HS}}^{5/7} \hat{V}_{\mathrm{HS}}^{17/21} \hat{\tau}_{\mathrm{BW}}^{2/7}$$



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* C. D. Zhou and R. Betti, Phys. Plasmas 15, 102707 (2008); 16, 079905(E) (2009).

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The YOC is a strong function of the residual kinetic energy

Yield degradation driven by pure hydrodynamics

$$\text{YOC} \approx (1 - \text{RKE})^{5.5}\, \hat{M}_{\text{HS}}^{-2}\, \hat{\tau}_{\text{BW}}$$

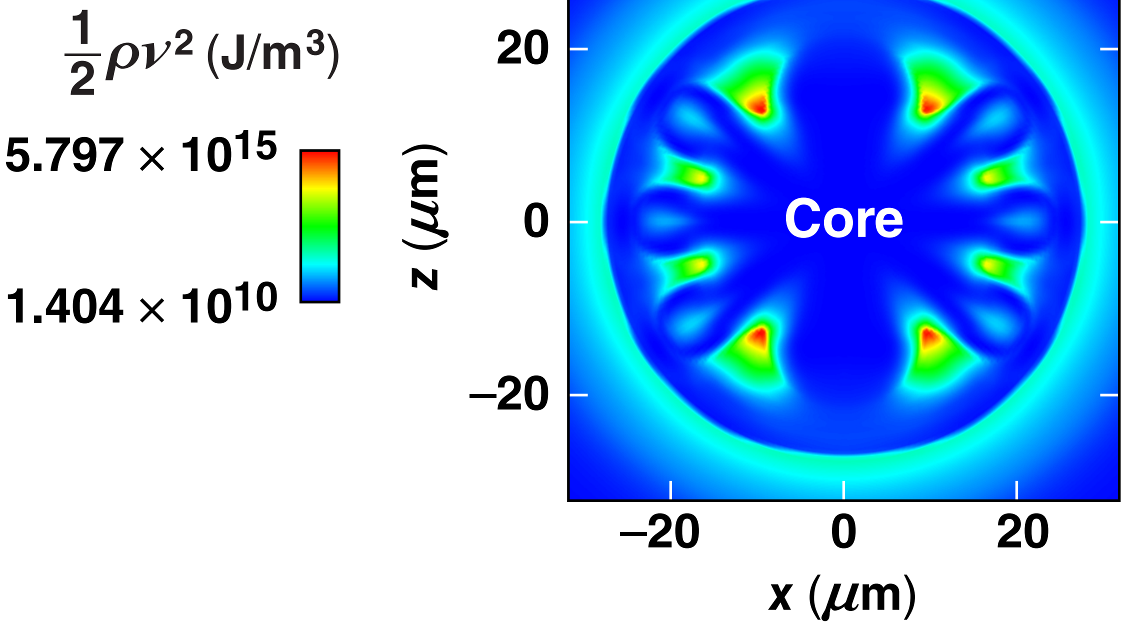
Yield degradation includes the mass ablation effect

$$\hat{M}_{\text{HS}} \approx (1 - \text{RKE})^{4/7}\, \hat{\tau}_{\text{BW}}^{2/7}$$

$$\text{YOC} \approx (1 - \text{RKE})^{4.4}\, \hat{\tau}_{\text{BW}}^{3/7} \approx (1 - \text{RKE})^{4.4}$$

Neglect/slowly varying

Kinetic energy density for single-mode $\ell = 12$, $m = 6$



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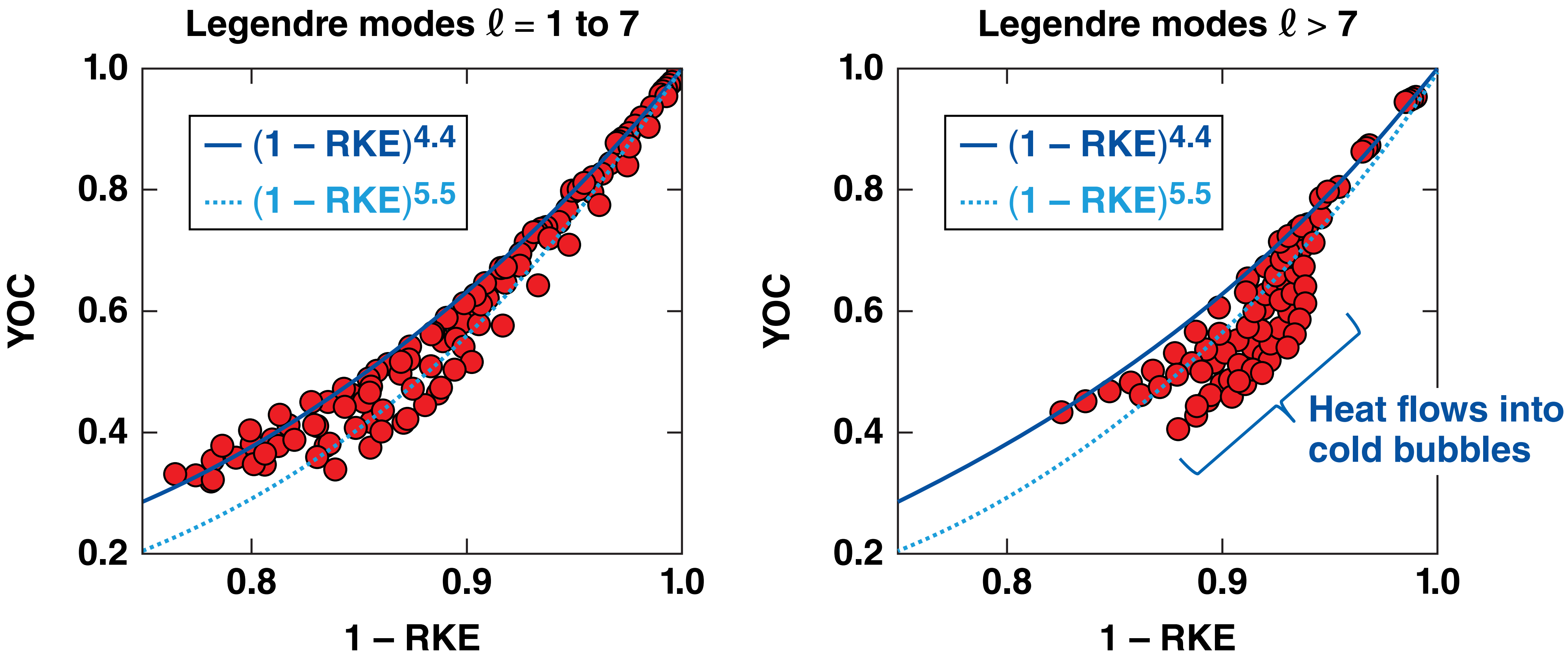
*A. L. Kritcher, *et al.*, Phys. Plasma, 21, 042708 (2014).

The RKE model provides a reasonable approximation for the YOC for low to mid modes and provides an upper bound for the YOC for mid modes



The results are consistent with 2-D *HYDRA* simulations by Kritcher *et al.**

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Summary/Conclusions

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