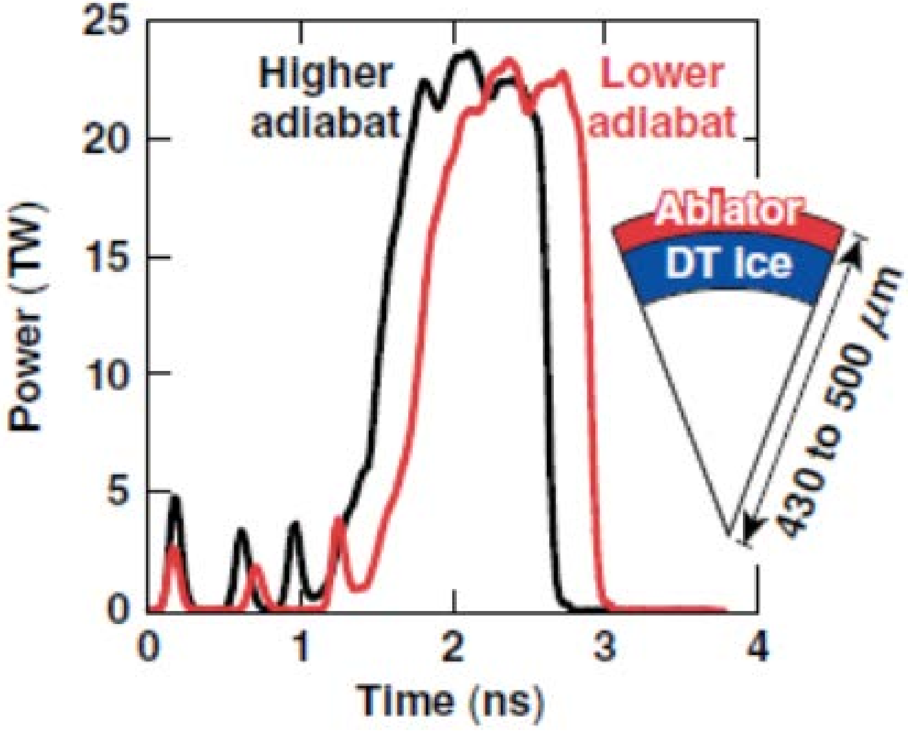
Review of LDD observations/knowledge-gaps/hypotheses



J. P. Knauer
University of Rochester
Laboratory for Laser Energetics

4th NISP workshop
DoE Leidos Facility
Washington, DC
13-14 September 2016

Comparison of simulation data to experimental data is the cornerstone of the LDD program

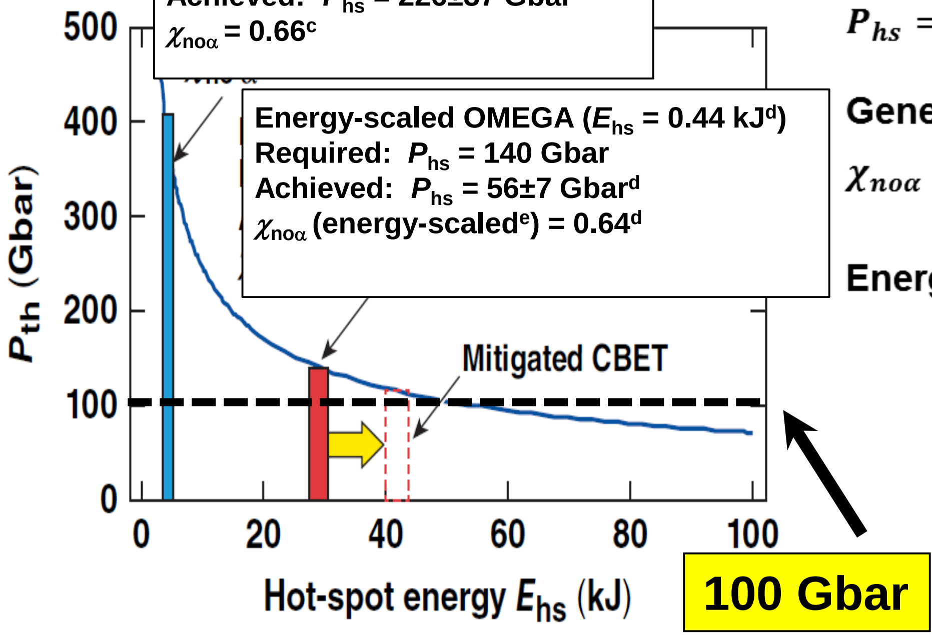
- LDD implosion performance is degraded with increased convergence
  - $P_{experiment}/P_{1D}$ decreases
  - Ion temperature measurement variation increases
- Implosions with lower adiabats show lower performance
- Comparisons of 2D and 3D simulation data with experimental data have led to 4 hypotheses of the performance of LDD implosions
  - Errors in 1D simulations
  - Long-wavelength non-uniformities in high-adiabat implosions
  - Effect of stalk and glue resulting in mix
  - Effect of laser imprint for low-adiabat implosions

More driver energy is coupled to the target reducing the requirements for convergence and pressures in LDD

UR LLE

Current high-foot indirect drive[a]
Required: P_{hs} = 350 to 400 Gbar
Achieved: P_{hs} = 226±37 Gbar[b]
$\chi_{no\alpha}$ = 0.66[c]

Energy-scaled OMEGA (E_{hs} = 0.44 kJ[d])
Required: P_{hs} = 140 Gbar
Achieved: P_{hs} = 56±7 Gbar[d]
$\chi_{no\alpha}$ (energy-scaled[e]) = 0.64[d]



Pressure threshold for ignition:[d]

$$P_{hs} = 250\ \text{Gbar}/\sqrt{E_{hs}/10\ \text{kJ}}$$

Generalized Lawson criterion:[c]

$$\chi_{no\alpha} = P\tau/P\tau_{ign} = (\rho R_{no\alpha})^{0.61}\left(0.12Y_{no\alpha}^{16}/M_{DT}^{stag}\right)^{0.34}$$

Energy scaling:[c,e] $\left(E_{laser}^{NIF}/E_{laser}^{OMEGA}\right)^{0.35}$

Direct-drive ignition: CR[†] > 22 and P_{hs} > 120 Gbar.
X-ray-drive ignition: CR = 30 to 40 and P_{hs} > 350 Gbar.

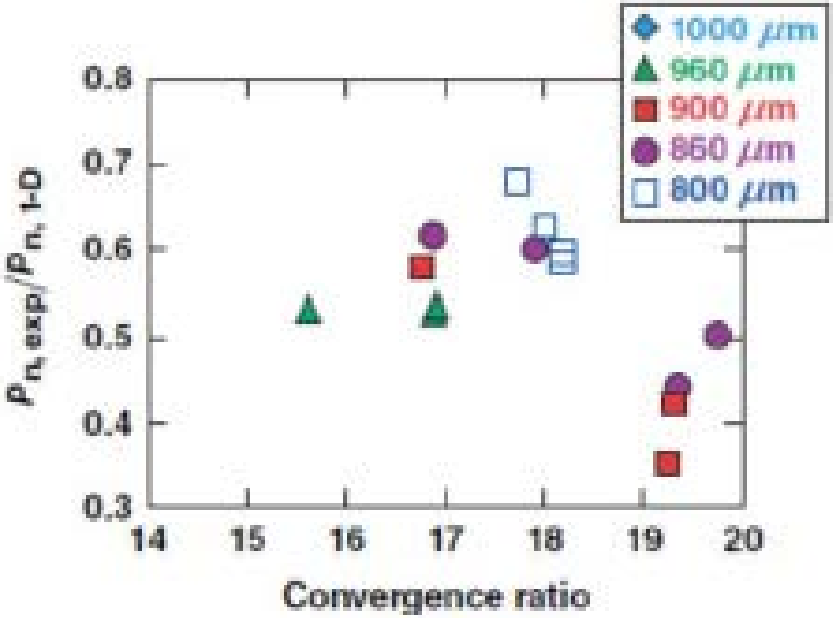
[a]O. A. Hurricane *et al.*, Nature 506, 343 (2014)
[b]T. Döppner *et al.*, Phys. Rev. Lett. 115, 055001 (2015)
[c]R. Betti *et al.*, Phys. Rev. Lett. 114, 255003 (2015); A. Bose *et al.*, PRE (in press)
[d]S. P. Regan, V. N. Goncharov *et al.*, PRL (in press)
[e]R. Nora *et al.*, Phys. Plasmas 21, 056316 (2014)

Implosion performance is reduced with increasing convergence

$$Yield \approx \int_{\Delta t_{burn}} dt \int_{V_{hs}} n_D n_T \langle \sigma v \rangle dV$$

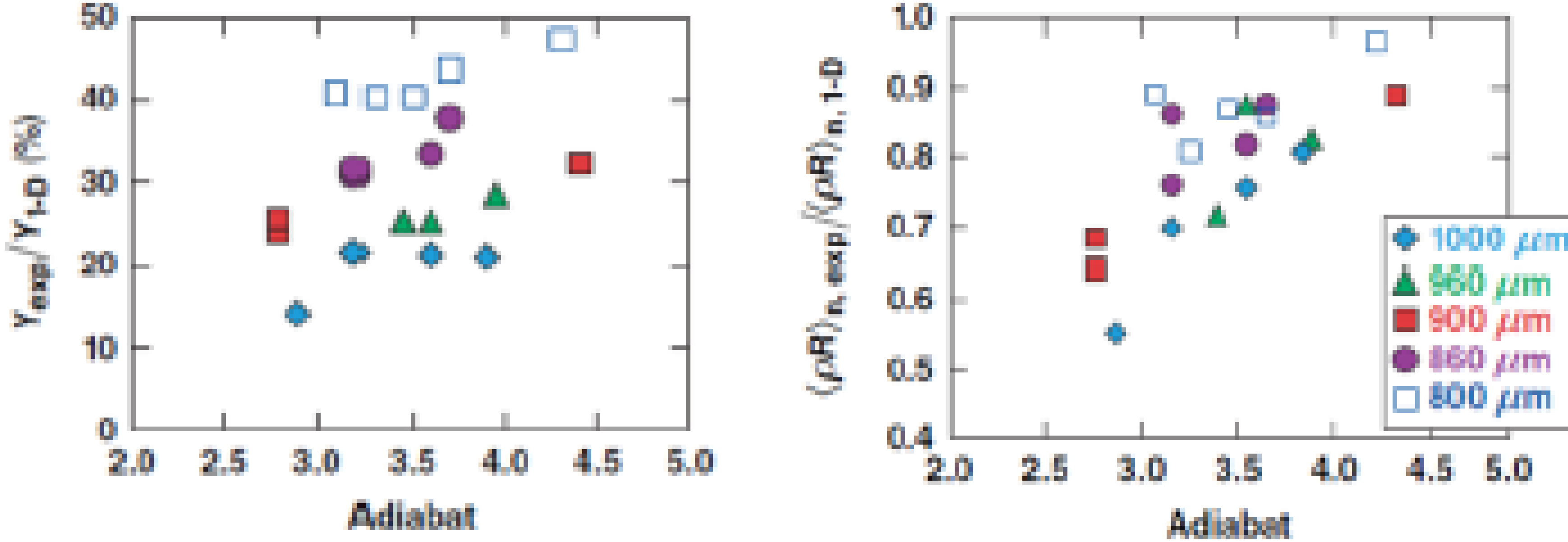
$$Yield \sim \underbrace{n_D n_T T_i^2}_{P_{HS}^2} \underbrace{\left(\int_{V_{hs}} \frac{\langle \sigma v \rangle}{T_i^2} dV \right)}_{\text{Depends on } T_i \text{ and } V_{hs}} \underbrace{\Delta t_{burn}}_{\text{Measured burn width}},$$

$$P_{HS} = \frac{Yield}{\sqrt{\dfrac{\int \langle \sigma v \rangle dV_{HS}}{T^2} \Delta t_{burn}}}$$



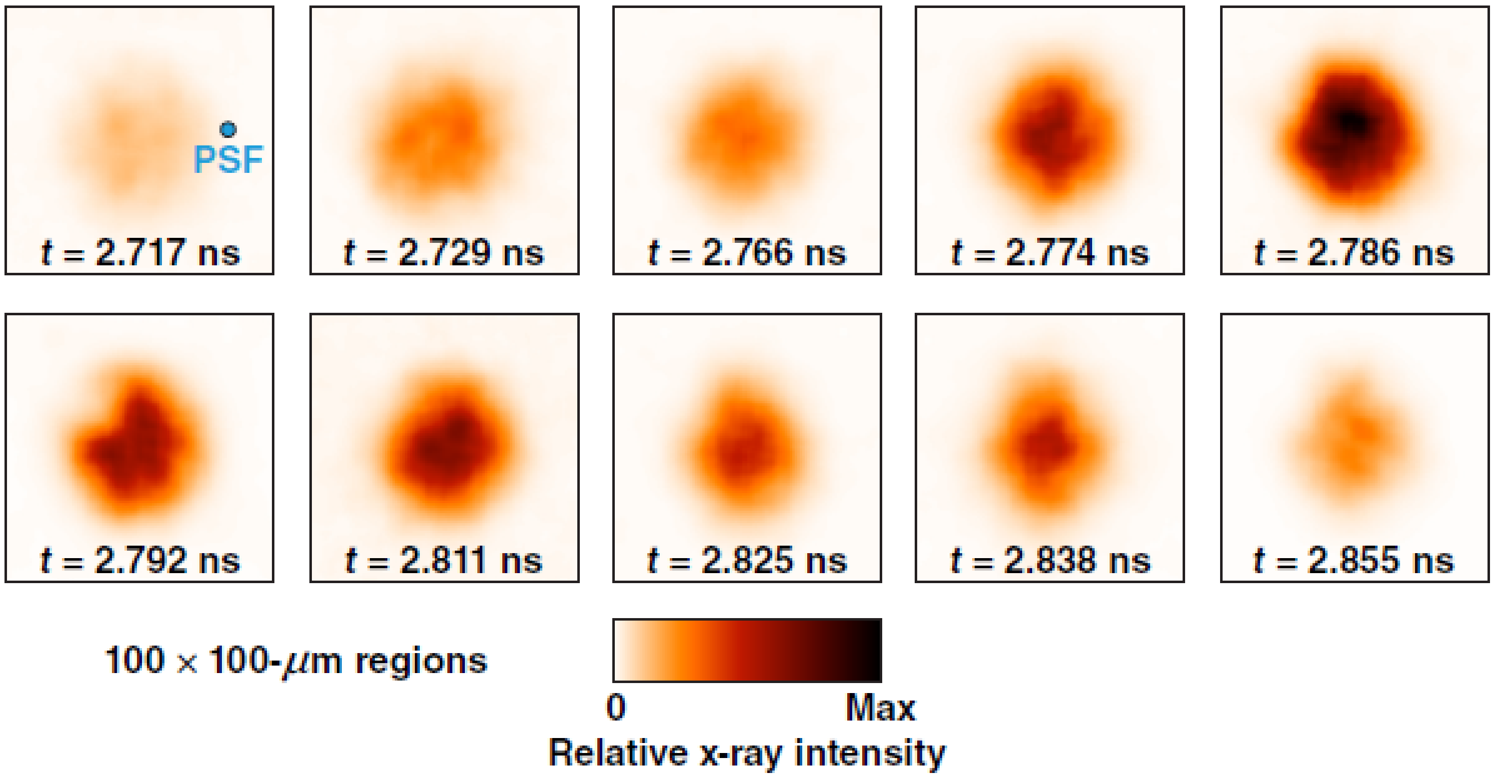
Highest pressures are obtained when the capsule radius matches the beam radius corresponding to 95% energy enclosed contour at 800 μm.

The absolute DT yield and experimental ρR decrease with increasing α

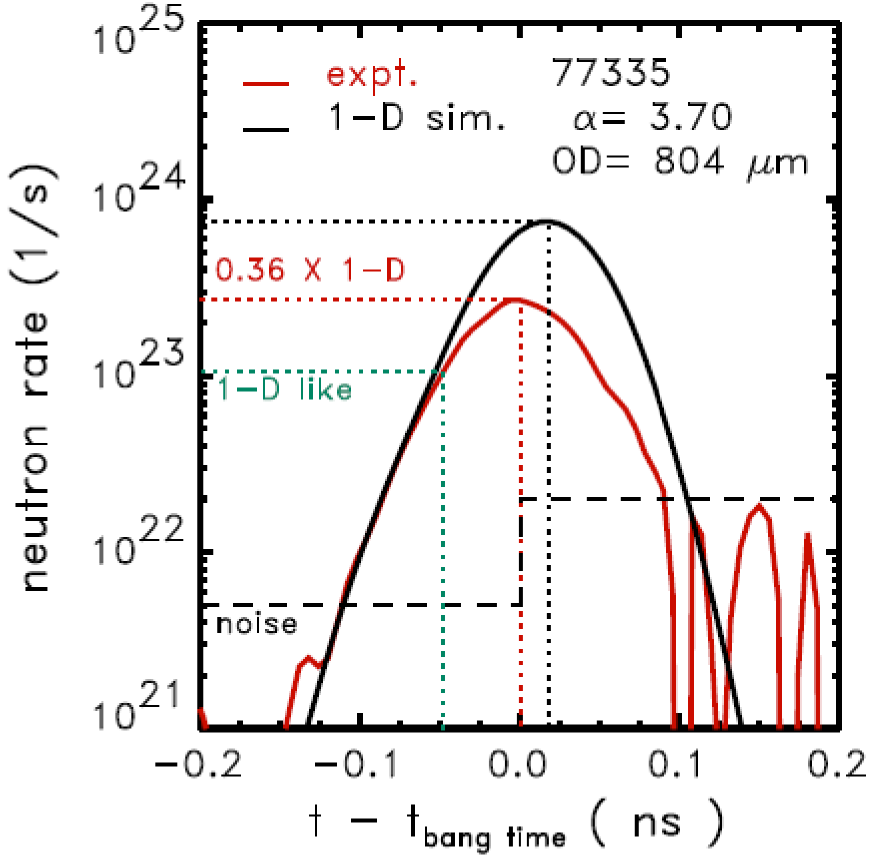


Adiabat (defined as pressure/Fermi pressure) = α

R_{HS} at stagnation is inferred from the 4-8 keV x-ray image recorded with the 16-channel KB microscope

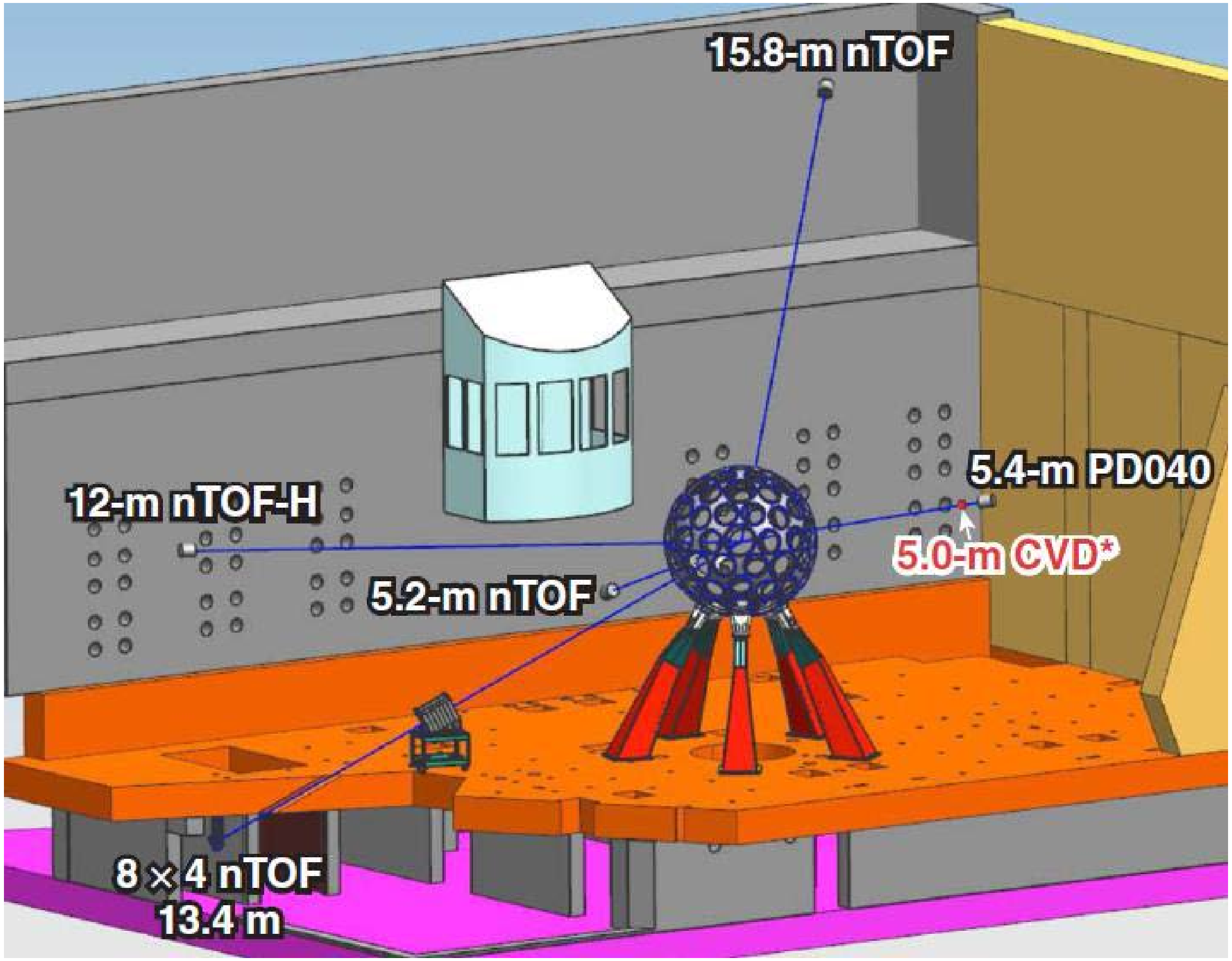


Burn width is determined by fitting the measured neutron rate with a Gaussian function

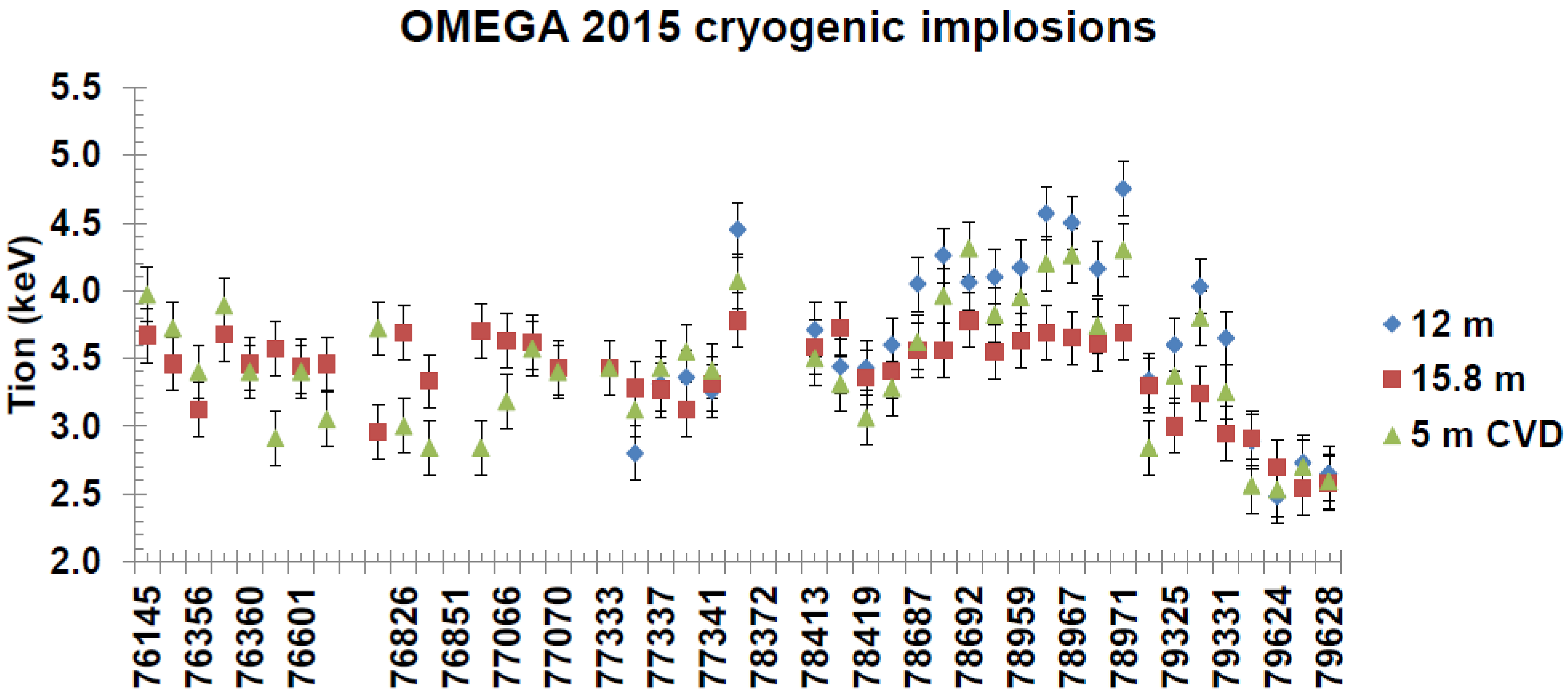


Current interpretation of Burn rate data is that the Yield is truncated befor peak compression

Ion temperature measurements are made along several lines-of-sight

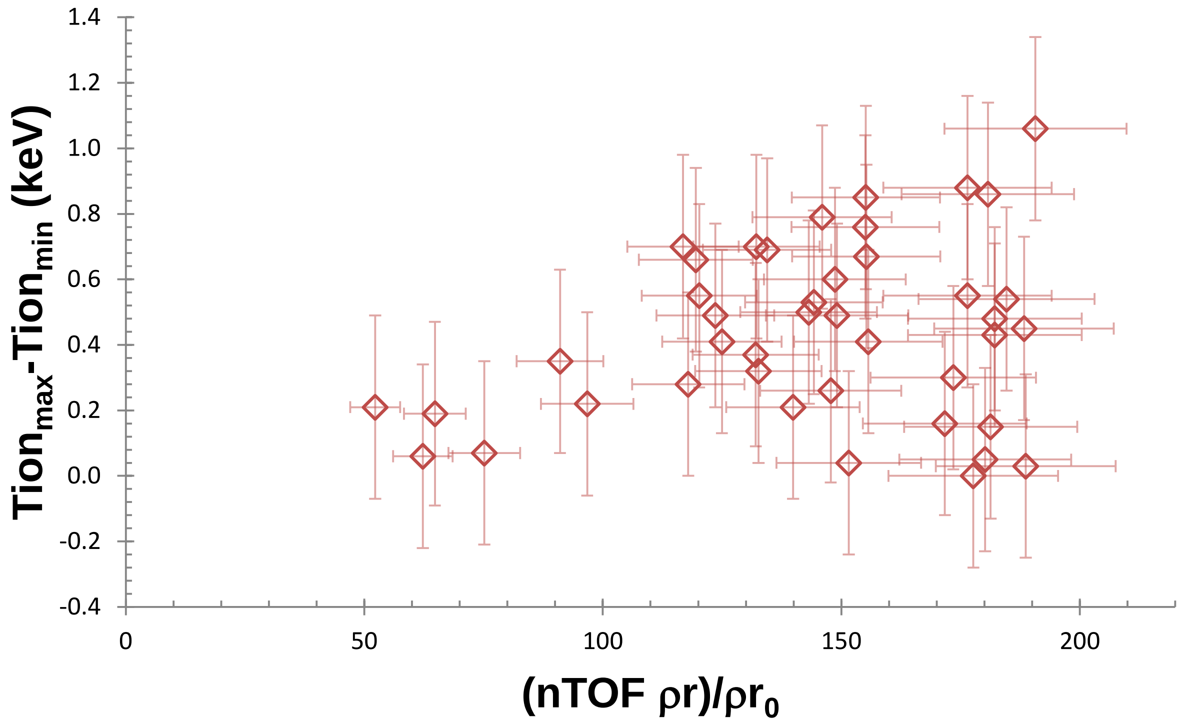


Large variations in the ion temperature measurements are observed by the nToF detectors



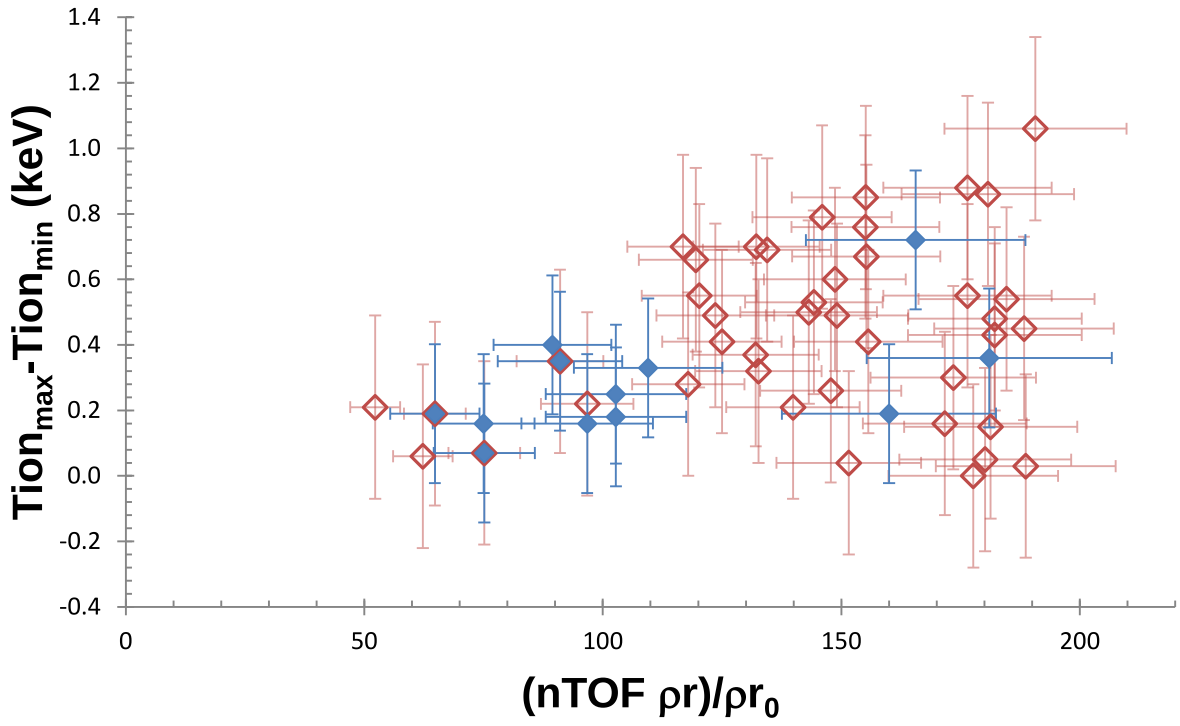
Difference between $Tion_{max}$ and $Tion_{min}$ is the largest for high convergence implosions

OMEGA 2015 cryogenic implosions



Difference between $Tion_{max}$ and $Tion_{min}$ is the largest for high convergence implosions

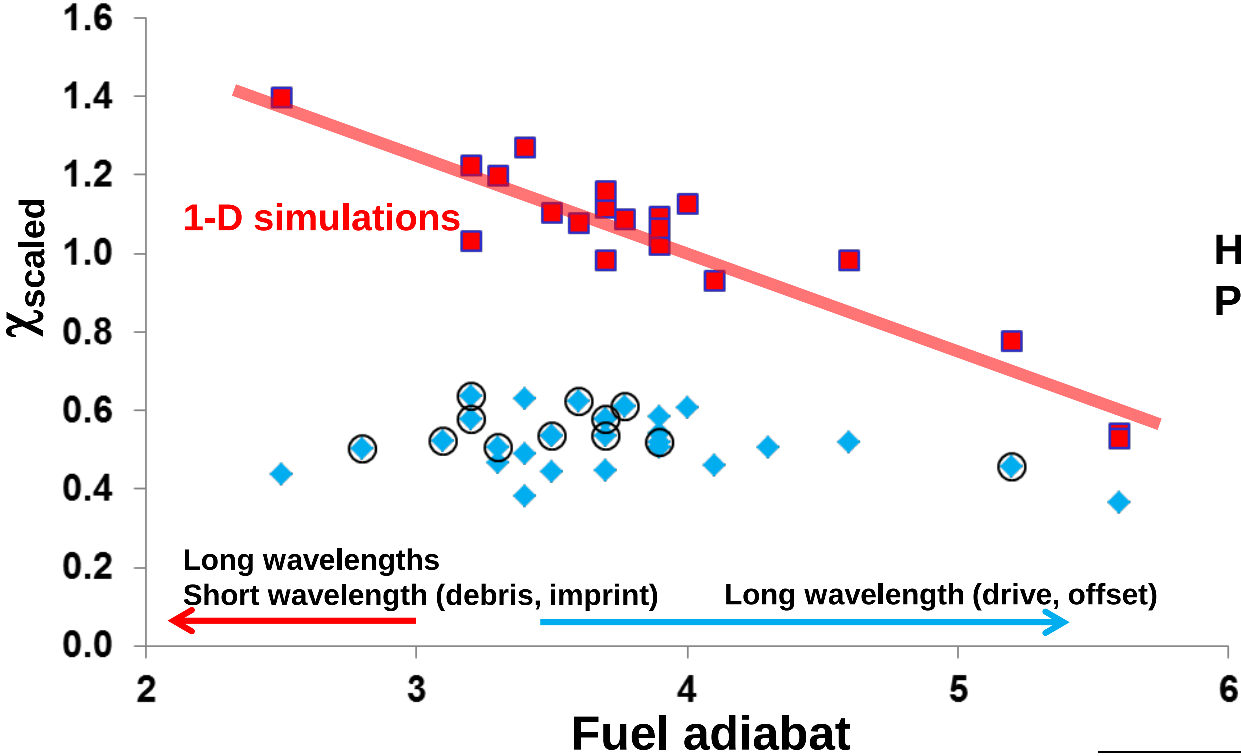
OMEGA 2015 and 2016 cryogenic implosions



Direct drive implosions on OMEGA have reached a hot-spot pressure of 56 Gbar but are degraded from 1D performance

Generalized Lawson criterion[1]

$$\chi_{scaled} = P\tau/P\tau_{ign} = (\rho R_{no\alpha})^{0.61}\left(0.12Y_{no\alpha}^{16}/M_{DT}^{stag}\right)^{0.34}\left(E_{laser}^{NIF}/E_{laser}^{OMEGA}\right)^{0.35}$$



Highest hot spot pressure
P_{hs} = 56±7 Gbar

○ Shot with inferred P_{hs}>50 Gbar [2]

[1]R. Betti *et al.*, Phys. Rev. Lett. 114, 255003 (2015); A. Bose *et al.*, PRE (in press)
[2] S. Regan et al., Phys. Rev. Lett. (2016)

Hypothesis #1 for degraded performance: Errors in 1D simulations

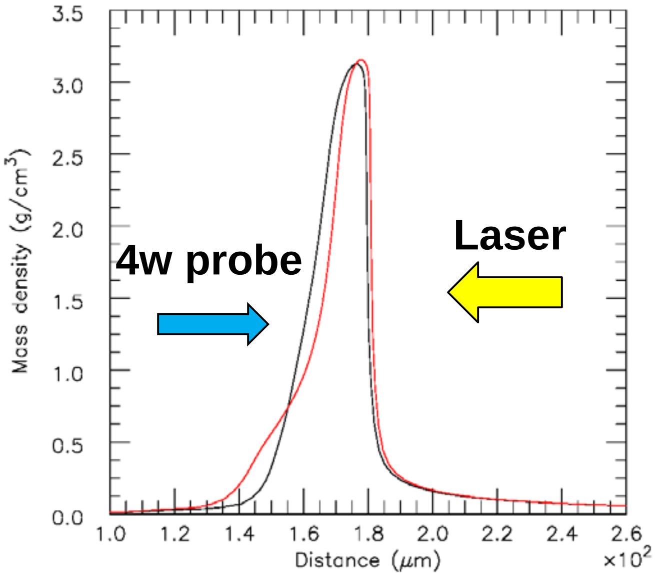
It is possible that with decreasing α, design errors can lead to significant deviations between simulation and experiment. It is speculated that these errors can include:

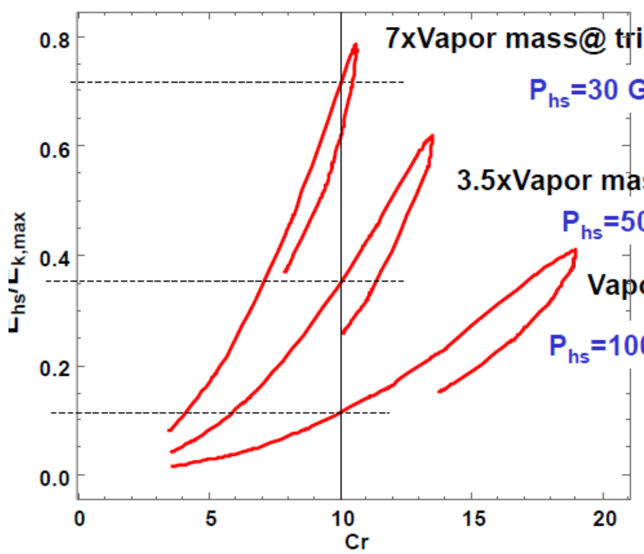
- **Mistimed shocks from pickets or shocks from the main pulse that are not modeled in simulation.**
- **Errors in opacity of DT or ablator in the weakly coupled regime (characteristic of the cold shell).**
- **Errors in heat conduction coefficients or other material properties in the DT or CH in the conduction zone (the region between the ablation surface and laser deposition region).**
- **Error in the inner-surface relaxation perhaps due to additional shocks, or low-level preheat that can potentially inject more material in the hot spot and reduce compression**

Too much mass in the hot-spot (vapor) prior to deceleration is simulated to be a failure mechanism for hot-spot formation

UR LLE

- Excessive shell relaxation (rarefaction) at inner fuel boundary (EOS, secondary shocks etc)
- Short-scale mix/jets mix cold DT and ablator into hot-spot





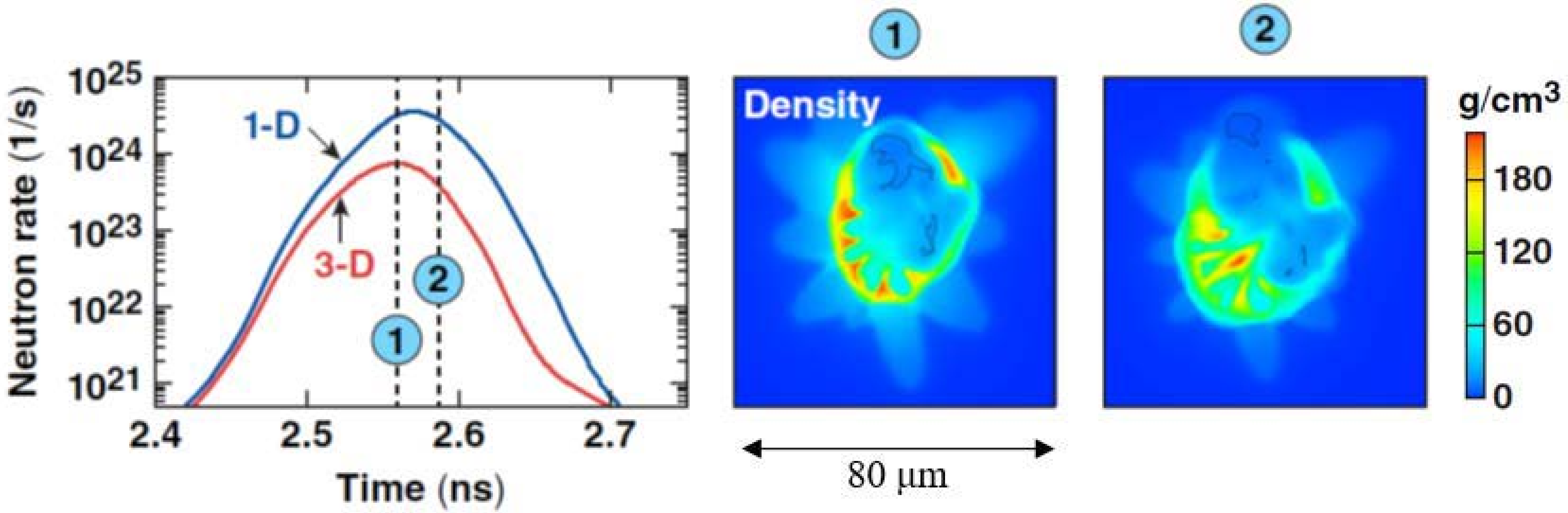
- Inferring inner surface profile using Thomson scattering is ongoing

Hypothesis #2 for degraded performance: Long-wavelength non-uniformities in high-adiabat implosions

Asymmetries are observed in the gated x-ray images of the hot spot. The cold shell asymmetry is unknown thus far. Based on the hot-spot measurements alone, it is unclear if the observed asymmetry leads to a reduction in performance. Long-wavelength asymmetries are suggested by the apparent Ti measurements, which indicate the presence of significant RKE at peak compression.

3D simulations with the ASTER code indicate that imbalances between beams (10 % power imbalance, 10 ps RMS beam mistiming, and 20 μm RMS beam miss-pointing) can potentially introduce long wavelength asymmetries. These non-uniformity seeds cause truncation of the burn relative to spherically symmetric simulations, and a bubble of hot gas that distort the cold shell , increase hot-spot volume, reduce DT neutron yield, and introduce ρR variations. The apparent Ti measured in different directions also vary significantly in these simulations, consistent with observations. It is thus hypothesized that long wavelength modes from beam imbalances can result in the observations characteristic of high-α implosions.

3d ASTER simulations show low mode perturbations that rupture the cold-fuel shell



Low mode bubble has broken through the cold fuel shell

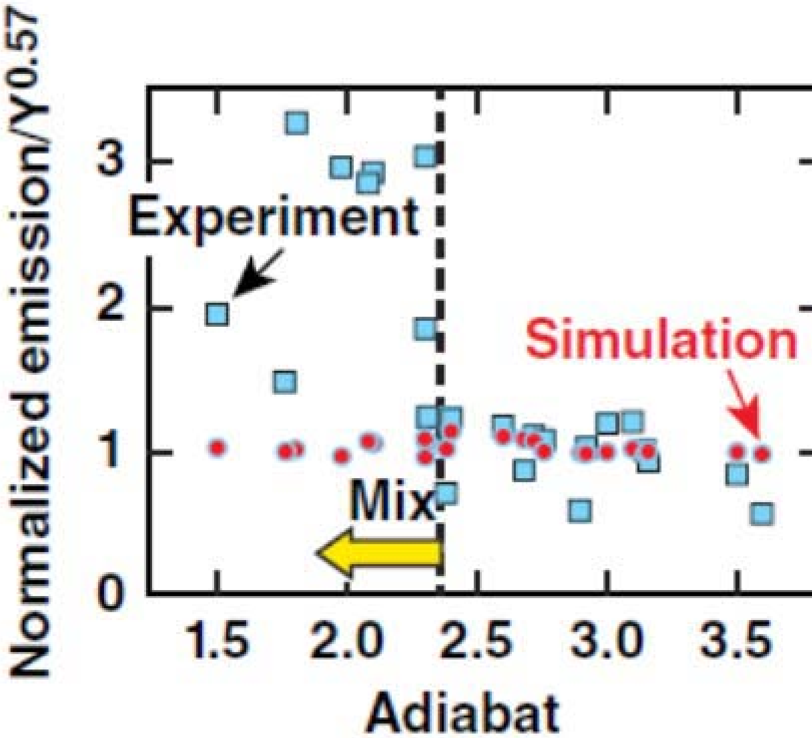
Hypotheses #3 for degraded performance: Effect of stalk and glue resulting in mix

Spherically symmetric simulations, which do not include the effect of ablator carbon in the hot spot, have shown that the ratio of the hot-spot emission to $Y_n^{0.57}$, where Y_n is the DT neutron yield, should be approximately one. Significantly higher values of this ratio would suggest materials other than D or T in the hot spot. Relatively thick-ablator-layer implosions (where the CH thickness $\gtrsim$ 8 μm) indicate increasing values of this ratio with decreasing α. The increased observed emission from the hot spot is highly suggestive of mix from the ablator. For thinner values of CH ablators, all the carbon is ablated and none remains to be injected into the hot spot.

3D ASTER simulations suggest that jets of cold material can be injected into the hot spot due to the stalk or the glue that attaches the stalk to the capsule. This may be responsible for the increasing mix observed in the experiments. When beam imbalance alone is included in the simulation (without a stalk), the perturbation from the stalk that launches a jet is not evident.

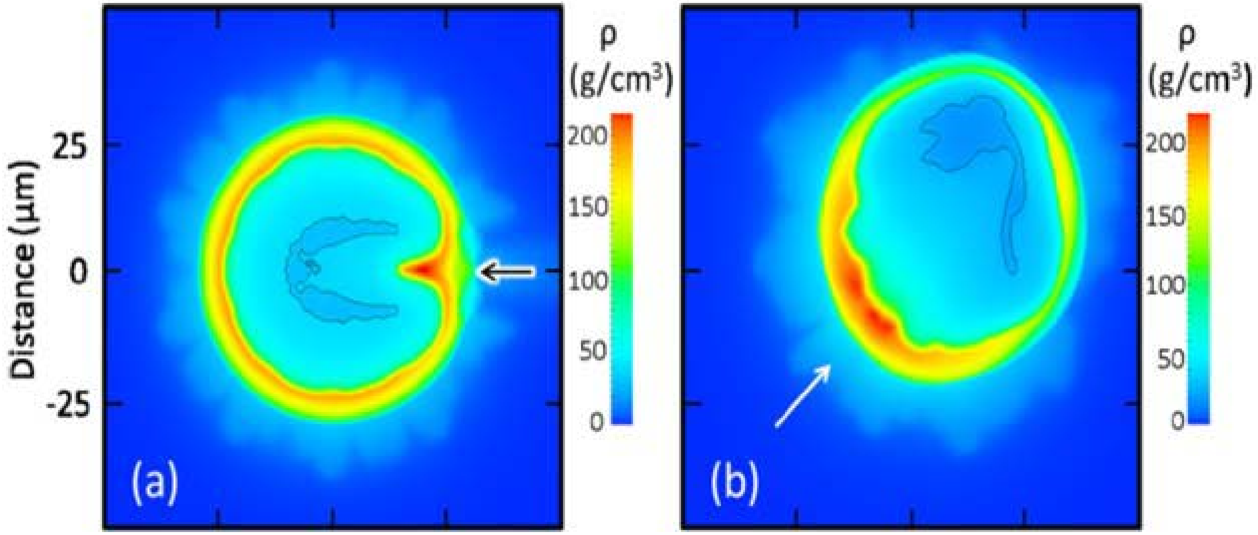
Target "engineering" features like a stalk can inject high-Z material into the hot spot

UR LLE



A clear signature of mix is seen for implosions with an α < 2.4

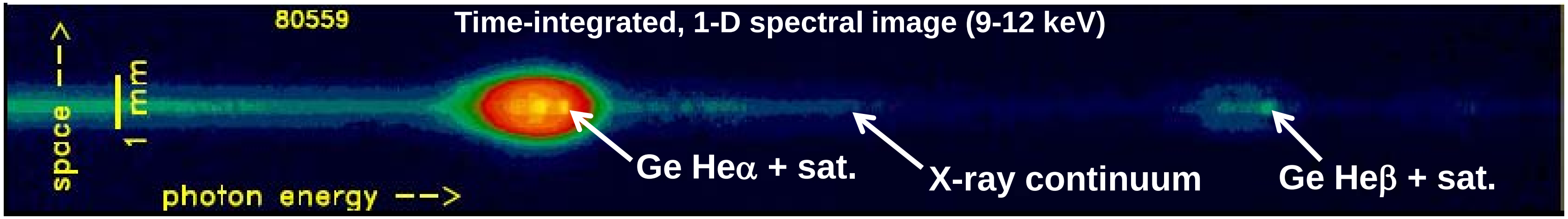
Jets of cold material either from the ablator or the shell may be responsible for the increasing mix

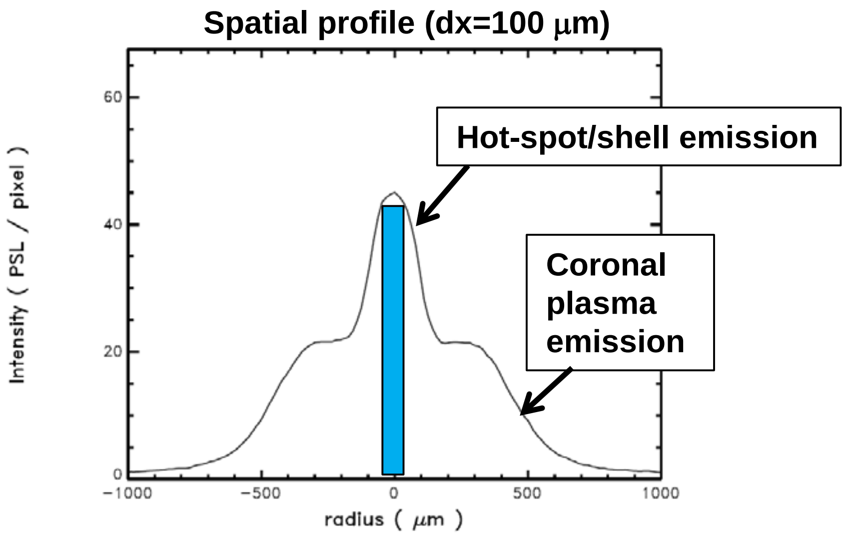


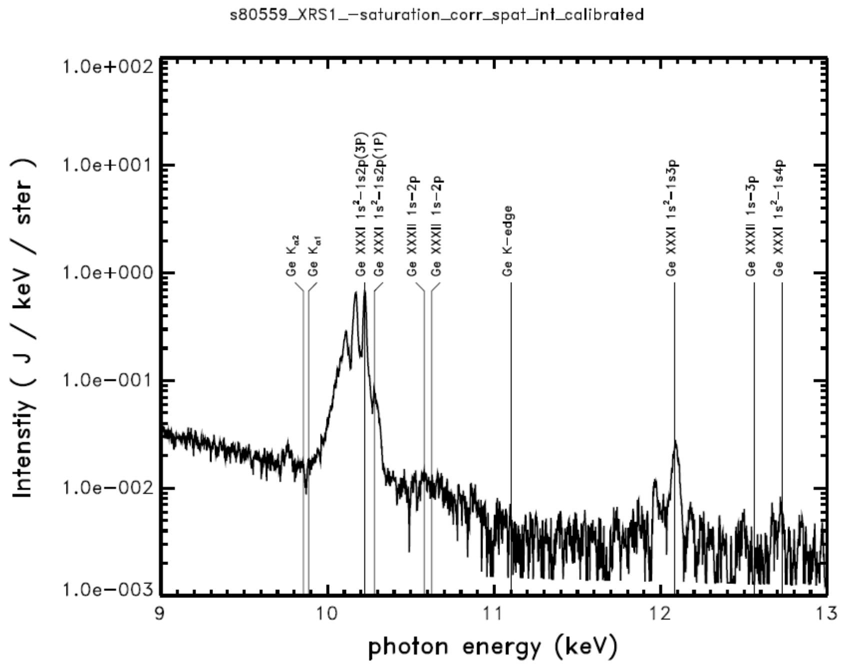
Material injected into hot spot from stalk

Material injected into hot spot from beam imbalance

Measured spatial profile indicates Ge K-shell emission is emitted from hot spot and compressed shell







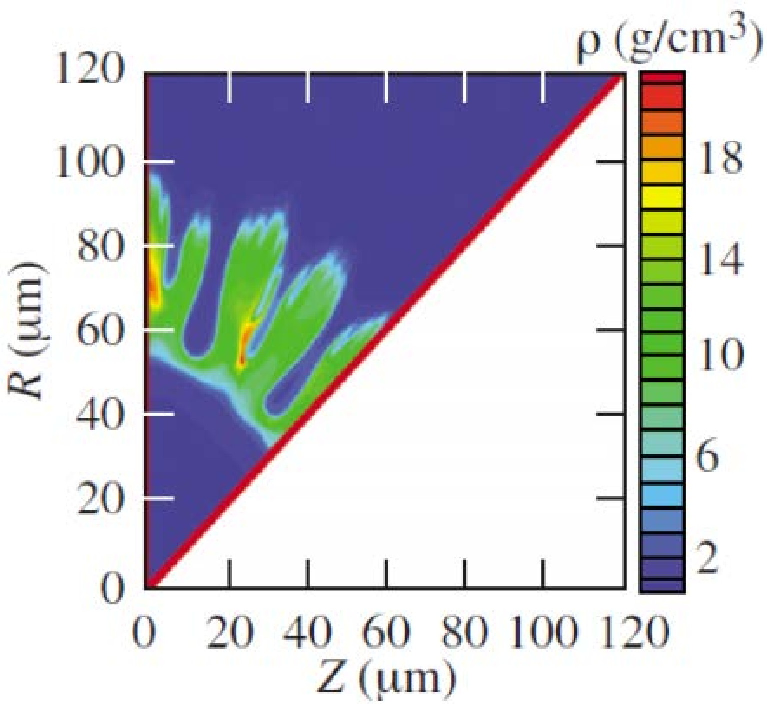
Mix mass can be inferred from Ge K-shell emission*

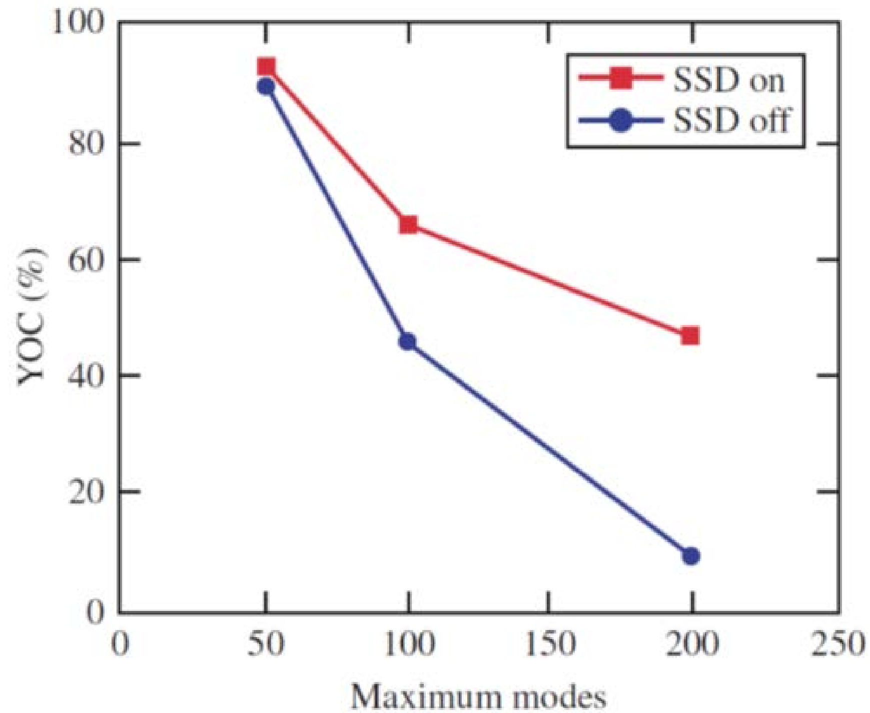
*Regan et al., PRL 111, 045001 (2013)

Hypotheses #4 for degraded performance: Effect of laser imprint for low-adiabat implosions

Laser imprint from single beam non-uniformity can potentially compromise the implosion performance. DRACO [3.13] simulations that include the effect of imprint and related short wavelength growth indicate that the average shell density in α = 2.5 implosions is reduced, resulting in an ineffective piston. These simulations also indicate a reduced DT neutron yield relative to the spherically symmetric simulation (Figure 11b), reduced ρR, increased hot-spot size, and reduced hot-spot pressure. It is surmised that the higher-α implosions ($\alpha \gtrsim 3.5$) are relatively sensitive to imprint while lower- α implosions are most likely affected by this mechanism.

2D DRACO simulations show high mode perturbations developing from laser imprint





An a = 2.5 implosion performance improves with SSD on

Comparison of simulation data to experimental data is the cornerstone of the LDD program

- LDD implosion performance is degraded with increased convergence
  - $P_{experiment}/P_{1D}$ decreases
  - Ion temperature measurement variation increases
- Implosions with lower adiabats show lower performance
- Comparisons of 2D and 3D simulation data with experimental data have led to 4 hypotheses of the performance of LDD implosions
  - Errors in 1D simulations
  - Long-wavelength non-uniformities in high-adiabat implosions
  - Effect of stalk and glue resulting in mix
  - Effect of laser imprint for low-adiabat implosions