Improving Performance and Understanding of Direct-Drive Inertial Fusion Implosions Using Statistical Modeling of Experimental Data

Shot 100956 produced 2.2x10^{14} DT fusion reactions

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Summary

OMEGA direct-drive DT-layered implosions have achieved neutron yields up to 3.1e14, and could be optimized to produce 4e14 (> 1.1kJ of fusion energy)

- High fusion yields (3.1e14) on OMEGA have been demonstrated by increasing velocity to achieve high ion temperatures and by raising adiabats to maintain stability

- Laser absorption has been enhanced by using Si-doped CH ablators and using the multipulse driver (MPD)

- Yields up to 4e14 (fusion energy ≈ shell kinetic energy) are predicted when using shorter fill ages and more MPD pulse shape control

Collaborators

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The mapping model* is a useful design tool to uncover trends in the experimental database, identify degradation mechanisms and predict implosion performace

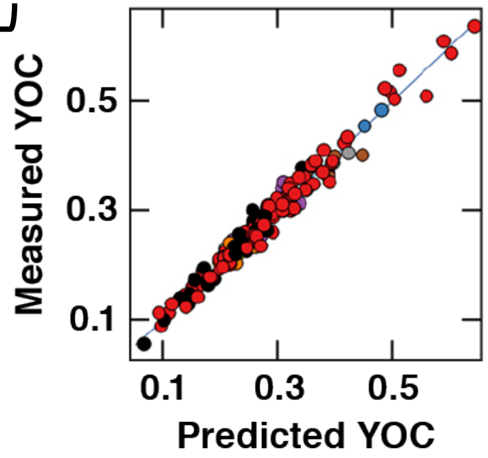
$$\text{Yield}_{\text{exp}} \approx \text{Yield}_{\text{sim}}^{1-\text{D}}\,\text{YOC}_{\text{hydro}}(\alpha_{\text{sim}},\ \text{IFAR}_{\text{sim}},\ \text{CR}_{\text{sim}})\ \text{YOC}_{\text{He}^3}\ \text{YOC}_{\ell=1}\,\text{YOC}_{\text{beam}}$$

$\text{YOC}_{\text{hydro}}$ = degradation from hydrodynamic instabilities

$\text{YOC}_{\ell=1}$ = degradation from target offset and laser mispointing

YOC_{beam} = degradation from finite beam size

YOC_{He^3} = degradation from tritium decay, ^{3}He build up, β particle damage to ice layer



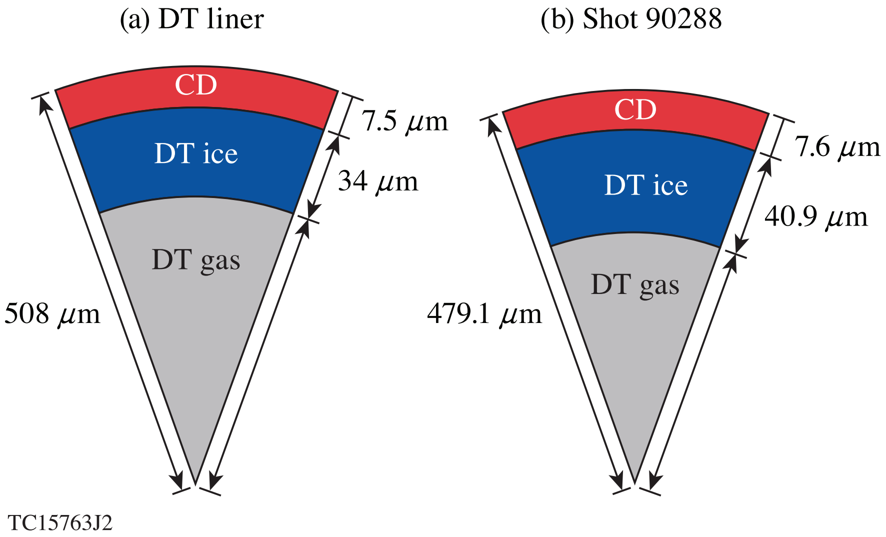
$$\text{Yield}_{\text{exp}} \approx \text{Yield}_{\text{sim}}^{1-\text{D}}\,\text{YOC}_{\text{hydro}}(\alpha_{\text{sim}},\ \text{IFAR}_{\text{sim}},\ \text{CR}_{\text{sim}})\ \text{YOC}_{\text{beam}}$$

$\propto V_{imp}{}^{6}$ $\qquad \propto \left(\dfrac{\alpha}{IFAR}\right)^{1.3}\dfrac{1}{CR}$ $\qquad \propto \left(\dfrac{R_{beam}}{R_{target}}\right)^{3}$

Assuming short DT fills and appropriate offsets, fusion yields can be enhanced by increasing implosion velocity and improving both stability and illumination uniformity

* V. Gopalaswamy *et al.*, Nature 565, 581 (2019).
** A. Lees et al.,Phys. Rev. Lett. (2021)
YOC: Yield over clean
IFAR: In-flight aspect ratio
CR: Convergence ratio

Thin-ice DT liner targets generate high yields by simultaneously boosting implosion velocity and adiabat



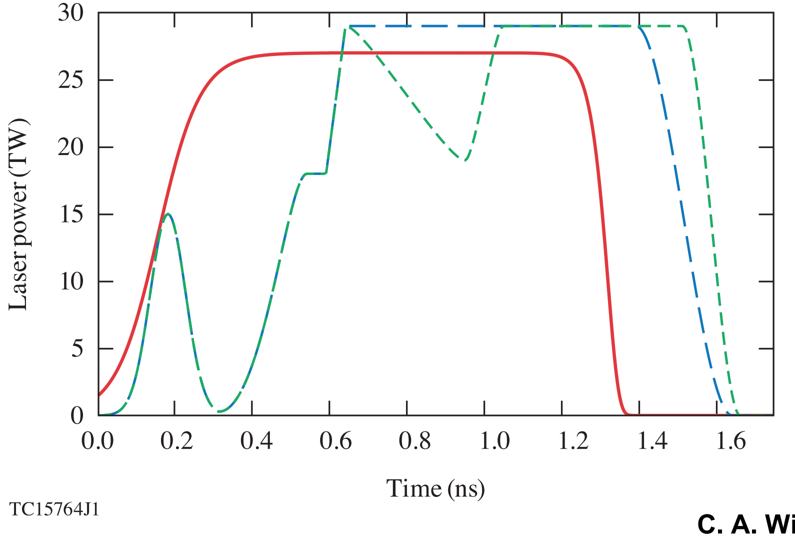
$$V_{imp} \propto \sqrt{\frac{P_a}{\rho_0}\left(\frac{R_0}{\Delta_0}\right)}$$

- By increasing $^*R_0/\Delta_0$, targets can be imploded faster without increasing laser intensity
- Implosion velocities ~650 km/s can be achieved with ~30 kJ of laser energy

DT liners are bigger, thinner than nominal high-performance targets like 90288

MPD leads to effective "zooming"

$$R_{95}^{picket} = 419\ \mu m$$
$$R_{95}^{drive} = 375\ \mu m$$

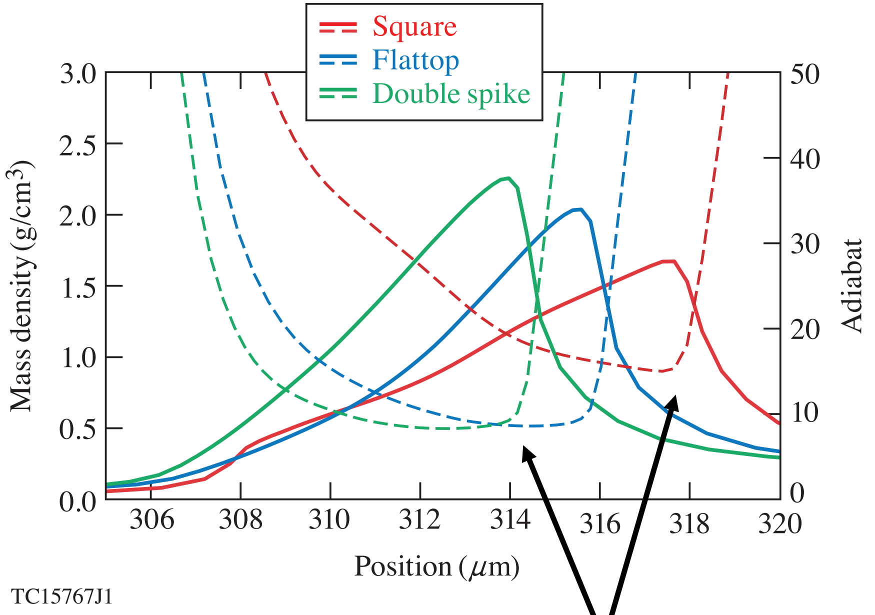


Square pulse
Flattop pulse
Double spike pulse

C. A. Williams et al, submitted Phys. Plasmas 2021

High-adiabat ablation fronts provide sufficient stabilization to survive the acceleration phase Rayleigh-Taylor instability (RTI) of ultrafast implosions

Density & adiabat profiles at 2/3 convergence



$\alpha \approx 15$ **for square pulse and** $\alpha \approx 8$ **for shaped pulse DT liners**

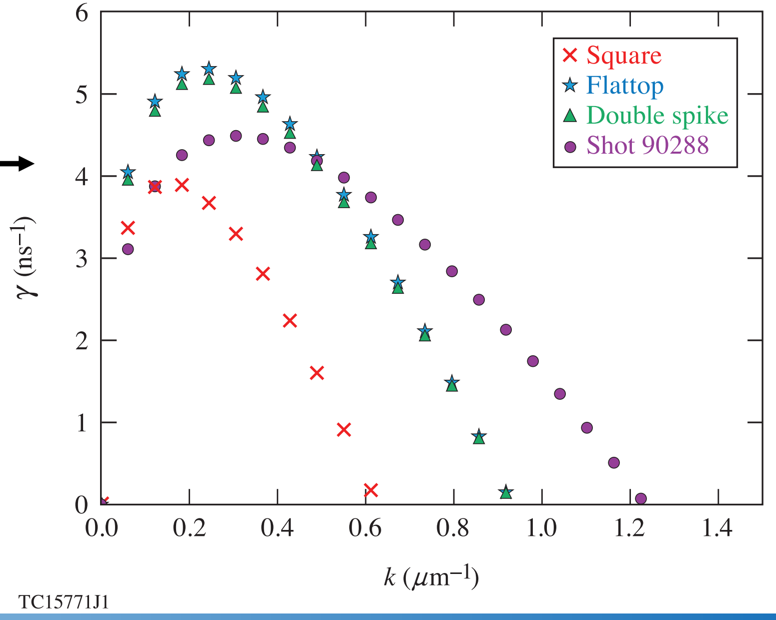
$$^{*}\gamma_{DT} = 0.9\sqrt{kg} - 2.7kV_a$$

Square pulse: g ≈ 450 μm/ns^2 & V_a≈ 9.3 μm/ns

Shaped pulses: g ≈ 550 μm/ns^2 & V_a≈ 8.2 μm/ns

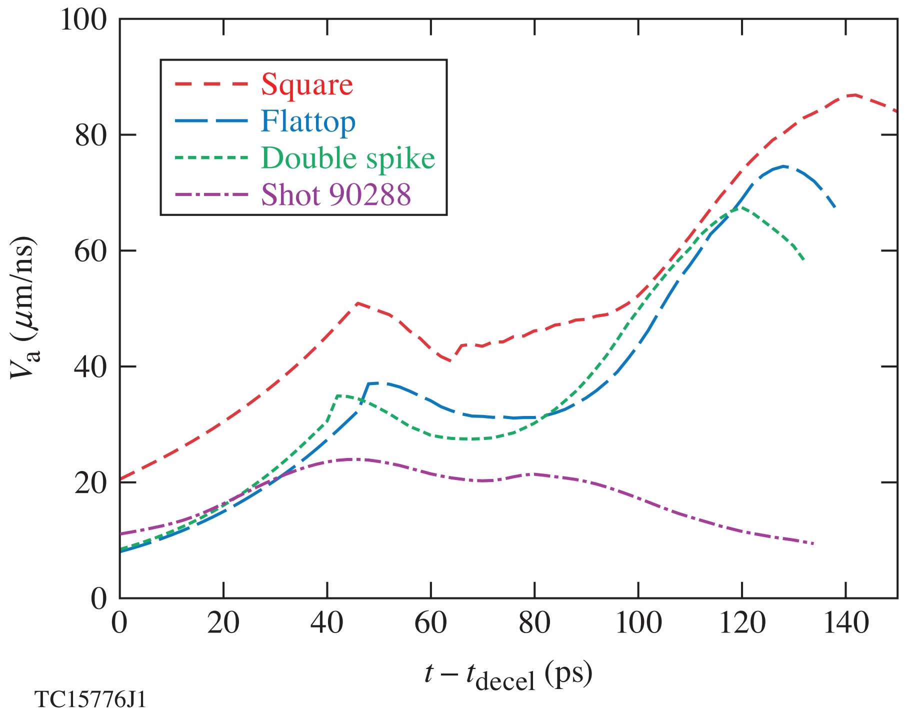
RT growth rate vs. wavenumber during acceleration phase

Similar RT growth rates to nominal direct-drive implosions



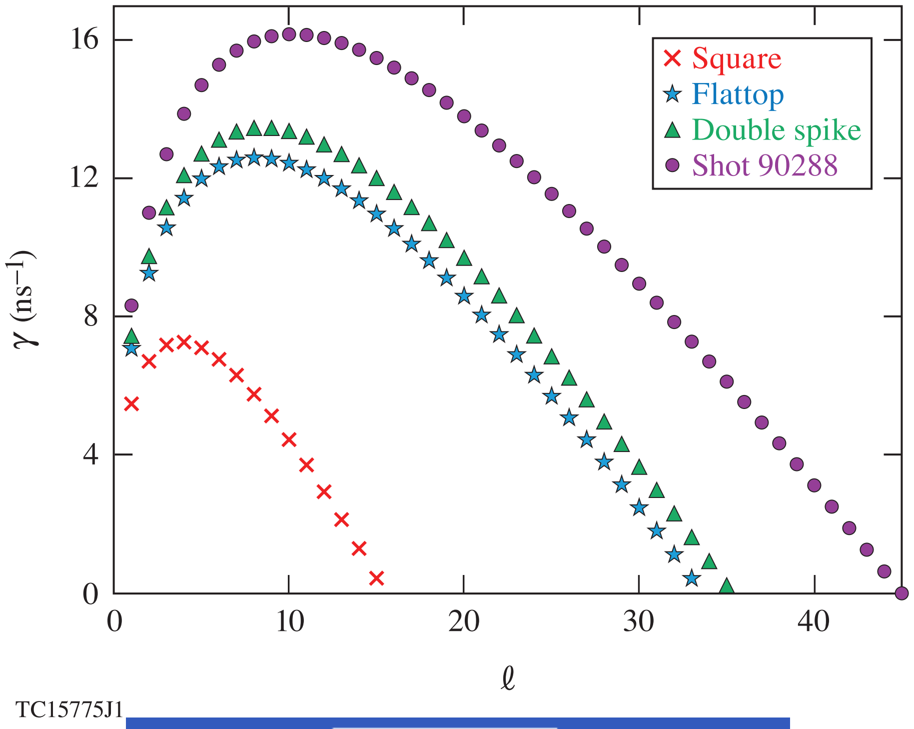
Low fuel convergence at stagnation and heightened hot-spot temperatures provide added stability during deceleration

Ablation velocity at hot-spot/shell interface



$$V_a \propto T_{hs}^{5/2} / \rho_{shell}$$

RT growth rates during deceleration

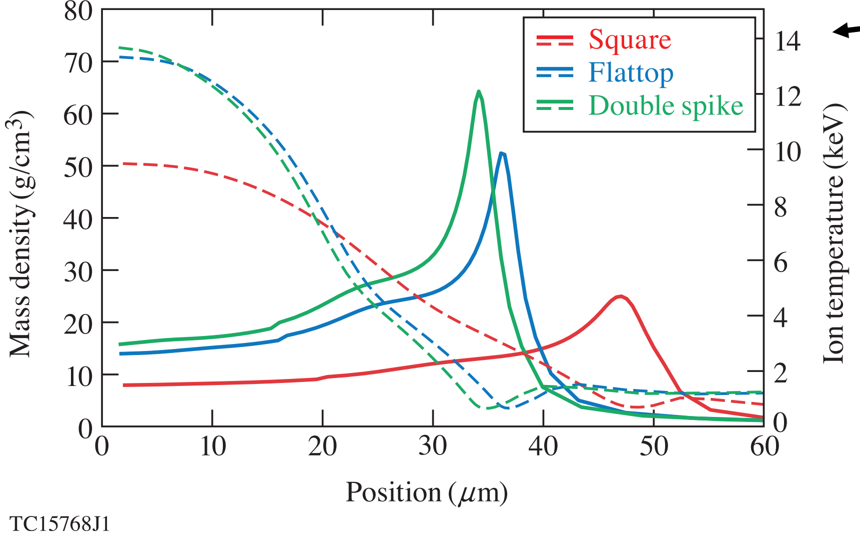


$$^{*}\gamma = 0.9\sqrt{\frac{k\langle g \rangle}{1 + k\langle L_{min} \rangle}} - 1.4k\langle V_a \rangle$$

* R. Betti, M. Umansky, V. Lobatchev, V. Goncharov, and R. McCrory, Physics of Plasmas 8, 5257 (2001).

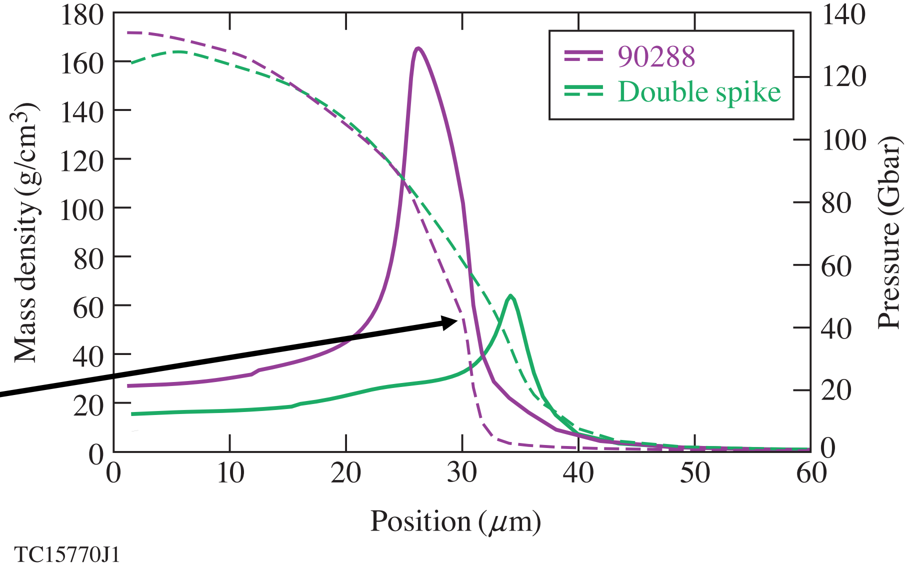
DT liners display unique properties, including hot-spot-dominated areal densities and higher compressive power than nominal implosions

Ion temperature & density profiles at bangtime



Average ion temperatures up to 8.7 keV

Similar stagnation pressures to those of high-convergence implosions



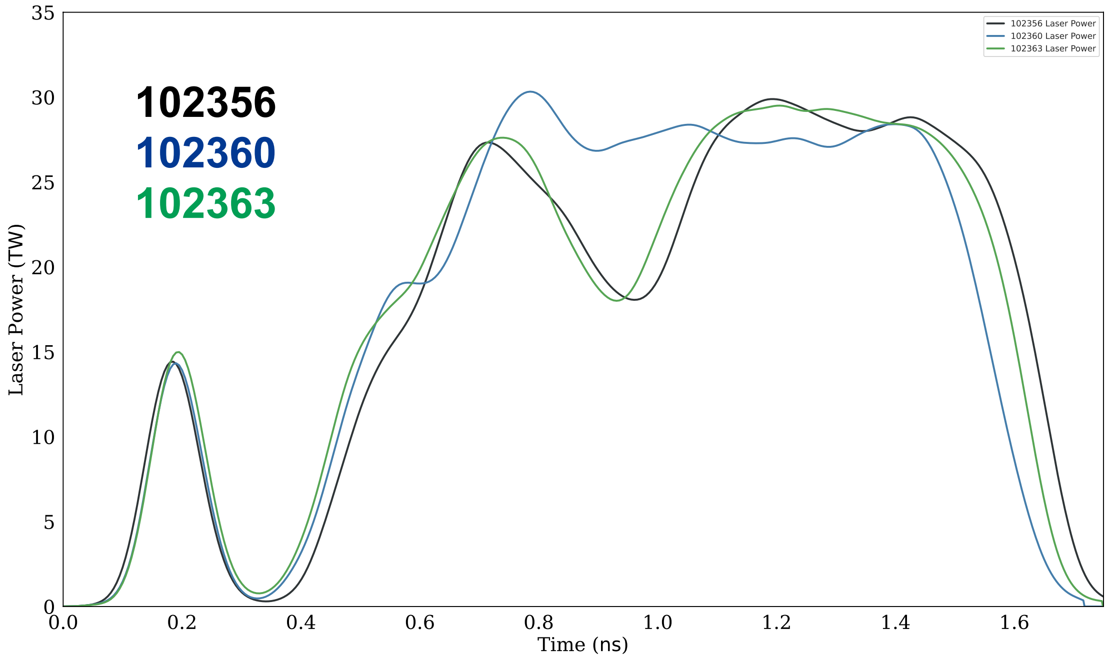
Typical ρR distribution is 40% hot-spot, 60% cold shell
DT liners are 60% hot-spot, 40% cold shell

Shot	Hot-spot ρR (mg/cm^2)	Shell ρR (mg/cm^2)
Square	37.4	25.2
Flattop	54.8	31.3
Double Spike	59.8	35.9
90288	77.8	100.9

Ultrahigh implosion velocities leads to high pressures with less mass than nominal high-performance implosions

Shots 102356, 102360 and 102363 were fielded on OMEGA on 11/2/2021 using two shaped pulses on CD and Si-doped targets

	7.2	0	33.0	
102363	2.3	5.6	33.1	1009.8

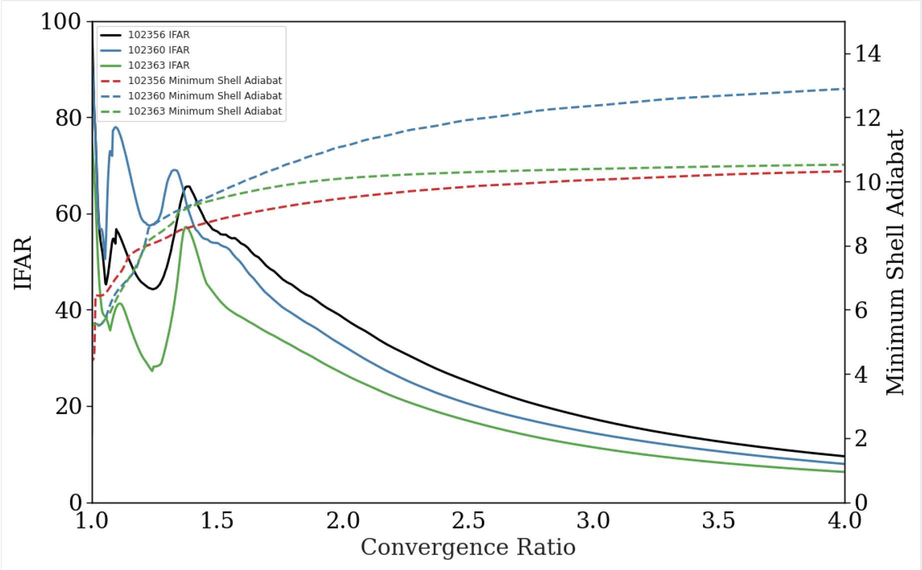


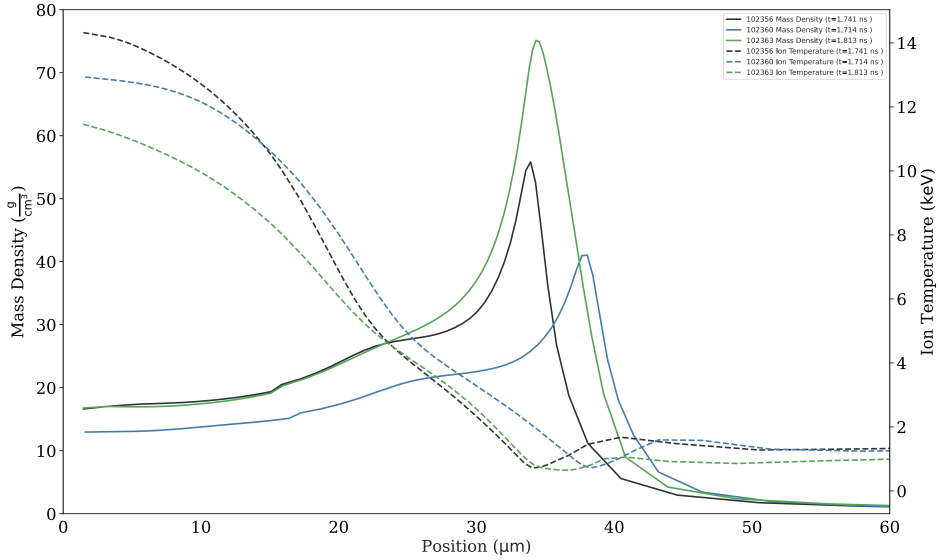
- **30.5 – 30.8 kJ delivered to target**
- **Pulse shape control more difficult than full-bandwidth SSD**
- **Difficulty constructing foot and steep ramp leads to shock mistiming and non-ideal adiabat gradient**

OMEGA shots 102356, 102360 and 102363 produced yields ranging from 2.6 x 10^{14}, 2.7 x 10^{14} and 3.1 x 10^{14} , the highest yields to-date at LLE

*LILAC values given in brackets

Shot Number	Yield (10^{14})	Predicted Yield (10^{14})	V_{imp} (km/s)	Areal Density (mg/cm^2)
102356	2.60 [9.85]	2.80	[682]	[91.6]
102360	2.75 [8.24]	2.78	[662]	[79.7]
102363	3.12 [8.72]	3.10	[607]	[111.0]





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Extra Content

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High yields are predicted even in the free-fall model, which overestimates degradation

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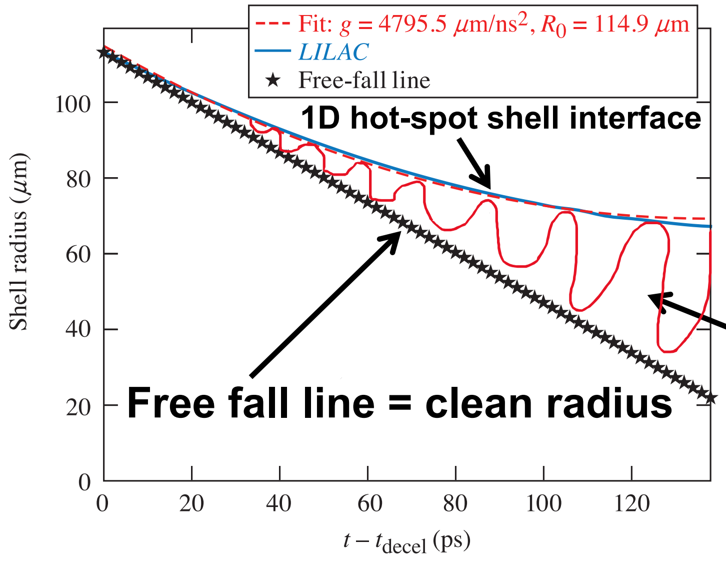
- Free-fall line model assumes the following:

1) RT growth is nonlinear from the onset of deceleration
2) RT spikes encounter no resistance when they ingress on hot-spot (free fall)
3) No fusion takes place within the RT spikes or bubbles (clean burn volume)



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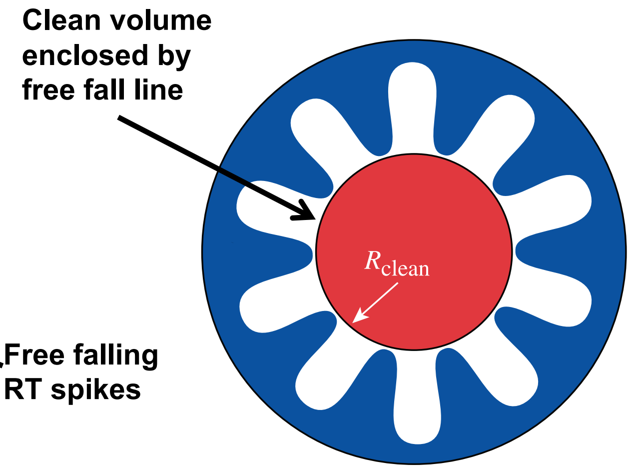

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$$Y_{free} = \int_0^\infty \dot{Y}(t)\left(\frac{R_{clean}(t)}{R_{1D}(t)}\right)^3 dt$$

Flattop – 2.46e14

Double-Spike – 2.64e14