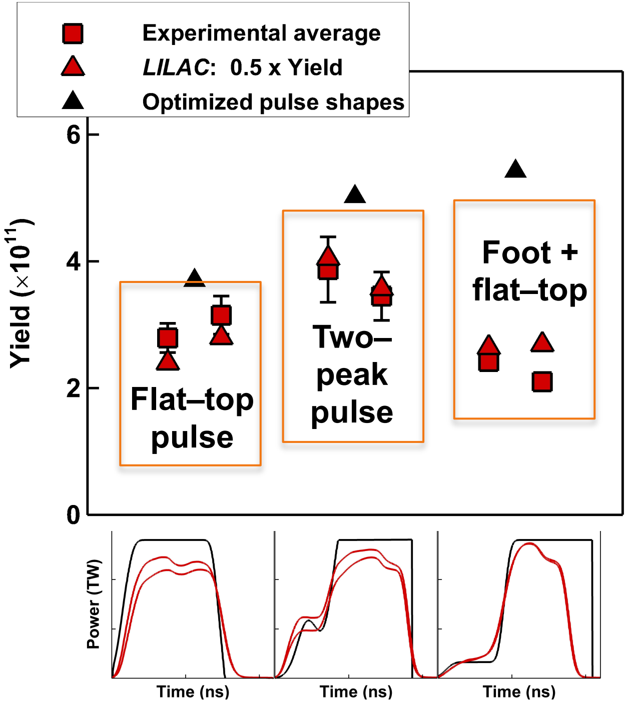
Optimization of OMEGA Exploding-Pusher Performance Using Shaped Pulses



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Novel shaped pulses demonstrate the ability to affect performance in OMEGA exploding-pusher implosions

- **Optimized shaped pulses were used in exploding-pusher experiments on OMEGA: one pulse with a tailored rise and the other with a foot pulse**
- **The optimized pulses are predicted to generate improved yield by means of improved timing, greater coupling, and multiple shocks**
- **The trends in the experimental yields are matched by simulations, which predict over a 30% increase with the actual optimized pulses**

Collaborators

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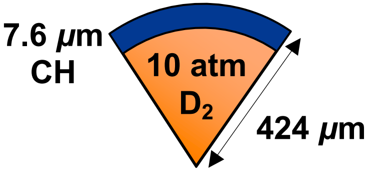
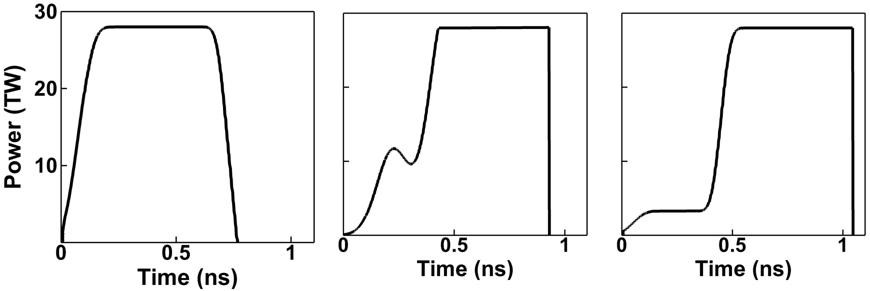
Laboratory for Laser Energetics**

OMEGA exploding-pusher (XP) implosions were performed using shaped laser pulses

- **A baseline flattop pulse was compared to two pulse shapes optimized with *Telios****
- **The fill density of 1.7 mg/cm^3 means Kn=λ_{ii}/R_{HS} ~ 0.15**
- **All designs have (free-fall yield) ~ 0.3× (total yield)**
  - **The free-fall yield provides a lower-bound yield estimate when the shell is disrupted by hydrodynamic instability**

	Baseline flattop	Two peak	Foot + flattop
V_{imp} (km/s)	703	723	738
R_{HS} (μm)	38	36	35
CR	11.1	11.8	12.1
Free-fall yield, Y_{FF} (×10^{11})	2.3	3.1	3.4
Total yield, Y_{TOT}	8.4	10.5	11.2
Y_{FF}/Y_{TOT} (×10^{11})	28%	30%	30%





Motivation: XPs provide an imprint-insensitive platform for testing LDD modeling.

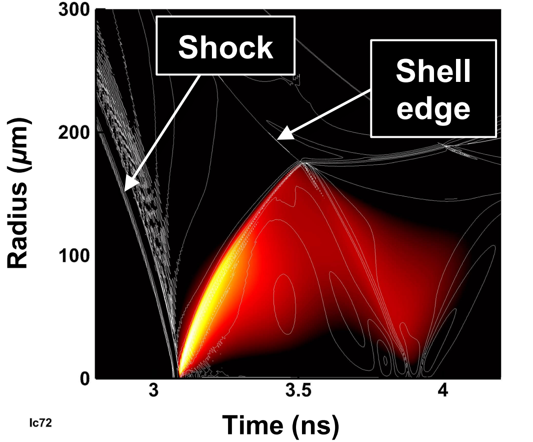
CR: convergence ratio; R_{HS}: hot-spot radius; V_{imp}: peak shell implosion speed; LDD: laser direct drive

*J. Delettrez, T. J. B., Collins and C. Ye, Phys Plasmas 26, 062705 (2019).

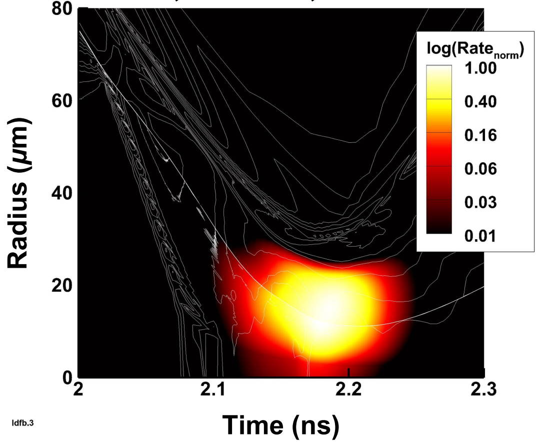
In exploding pushers, the yield follows the shock

- In a typical cryogenic implosion, yield is generated as the shell compresses the hot spot

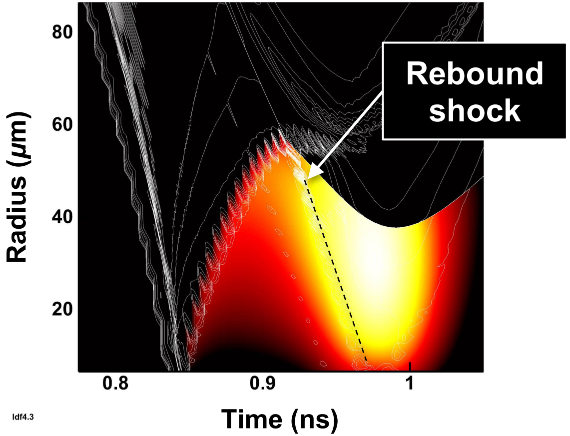
Shot 57229*: R_0=800 μm
Kn ~ 0.03, CR ~ 5, YOC ~ 100%

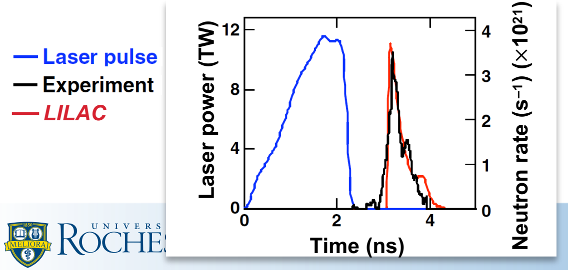


Cryo Shot 90288: R_0=430 μm
Kn ≪ 1, CR ~ 16, YOC ~ 40%



XP, flat-top pulse: R_0=430 μm
Kn ~ 0.15, CR ~ 12, YOC ~ 50%





Color contours: normalized log(fusion rate)
Contour lines: $|L_p|^{-1}$ (μm^{-1})

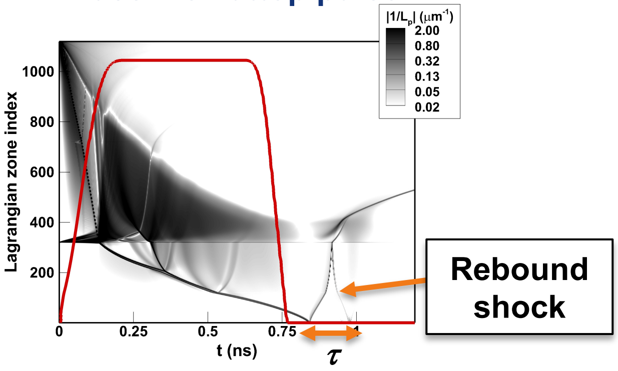
*A. Shvydky, APS (2010).
YOC: yield over clean

The optimized pulses produce higher yield through multiple mechanisms

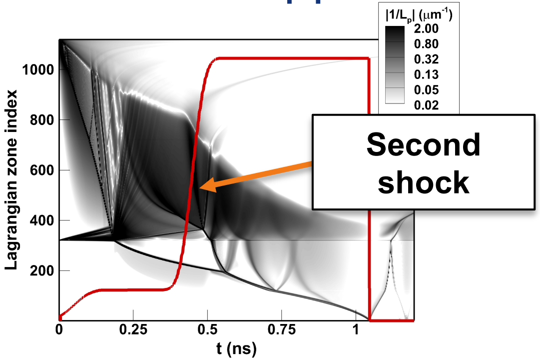
- The XP yield scales as $Y \sim n_i^2 \langle \sigma v \rangle \tau$, where τ is the shock transit time across the hot spot*
- The two-peak shock has a delayed rise to full power, which separates the shock and shell, increasing τ[1]
- The foot + flattop pulse generates a second distinct shock leading to a stronger primary shock
- Both optimized pulses remove the coasting phase
- The optimized pulses produce a higher shell density, which generates a stronger rebound shock and increased post-shock n_i, T_i, and $\langle \sigma v \rangle$

[1]See J. A. Marozas et al., LDD Tutorial, JT02.00001

Baseline flattop pulse



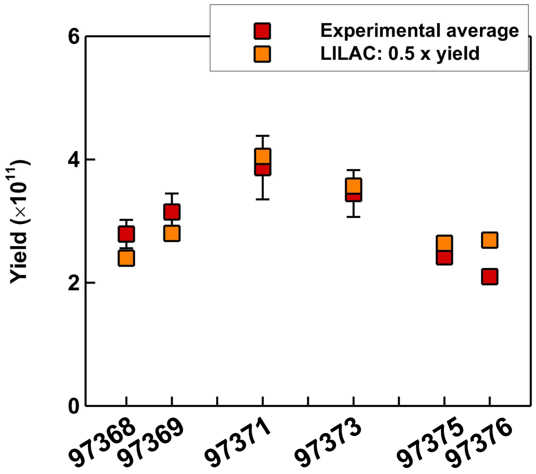
Foot + flattop pulse

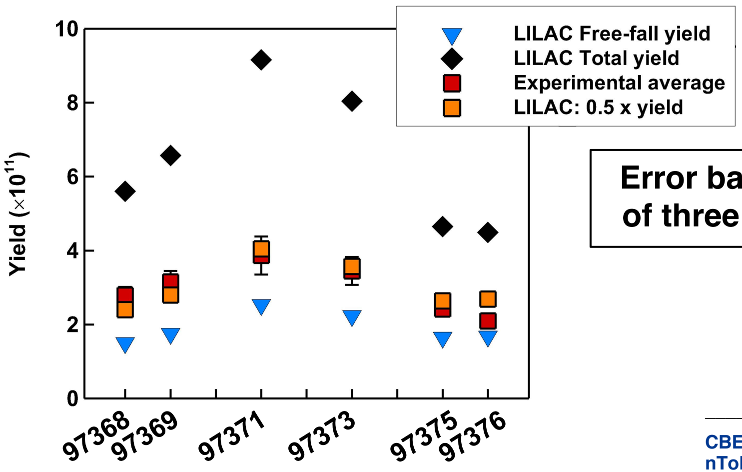


*For 5–10 keV, $\langle \sigma v \rangle \sim aT+bT^2$, equal parts linear and quadratic

The *LILAC* yield follows the experimental trend

- All six post-shot simulations model CBET and use a single flux limiter to match all the experimental bang times
- A multiple of the *LILAC* yield, YOC ~ 50%, reproduces well the experimental trend in yield
- If yield reduction is due to shell breakup and reduced ρR, this would indicate comparable shell instability among all the shots



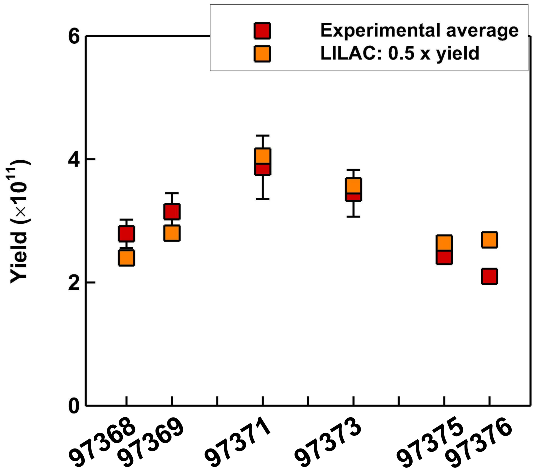


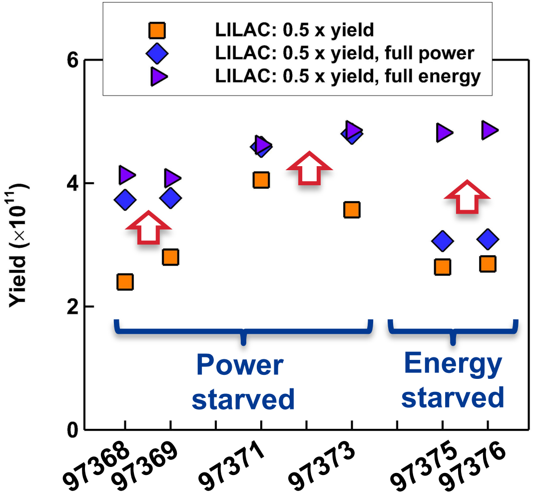
Error bars given by rms of three nToF detectors

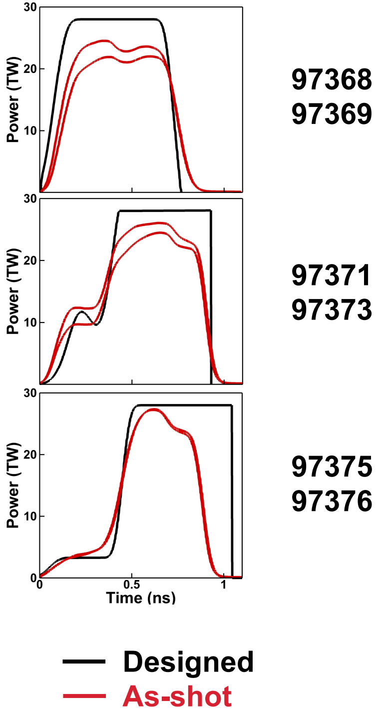
CBET: cross-beam energy transfer
nToF: neutron time-of-flight detector

The experimental pulses qualitatively reproduce elements of the optimized pulses

- The energy and power were below the design values by as much as 25% and 20%, respectively
- *LILAC* simulations indicate the performance is restored when these deficits are removed

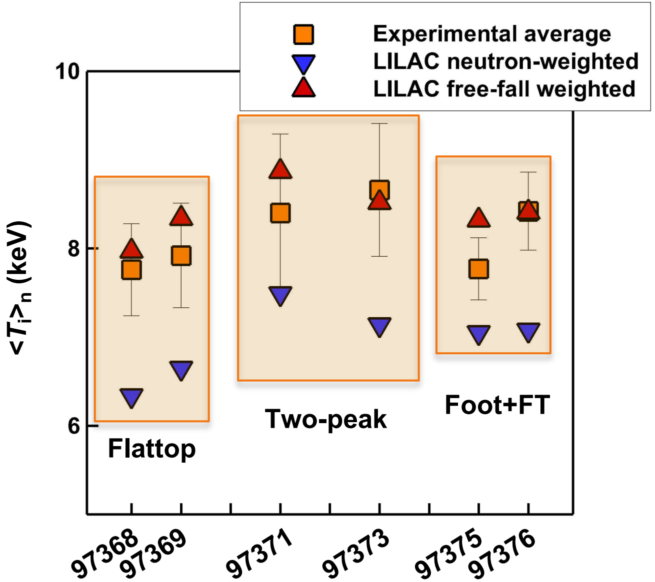


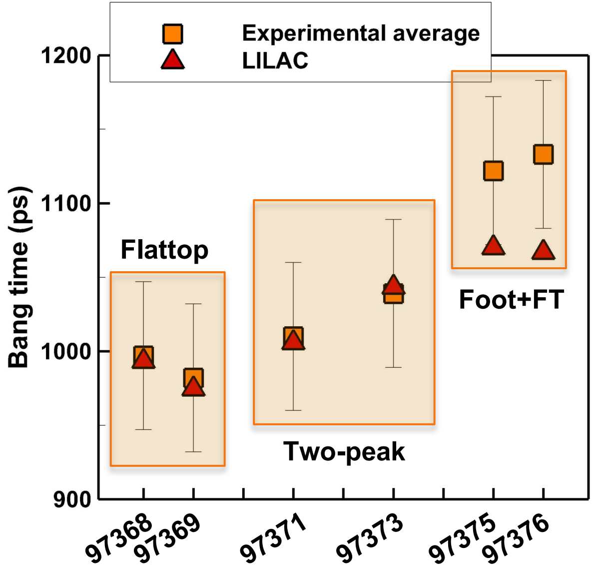




The experimental burn-weighted ion temperatures are comparable to the freefall-weighted ion temperatures

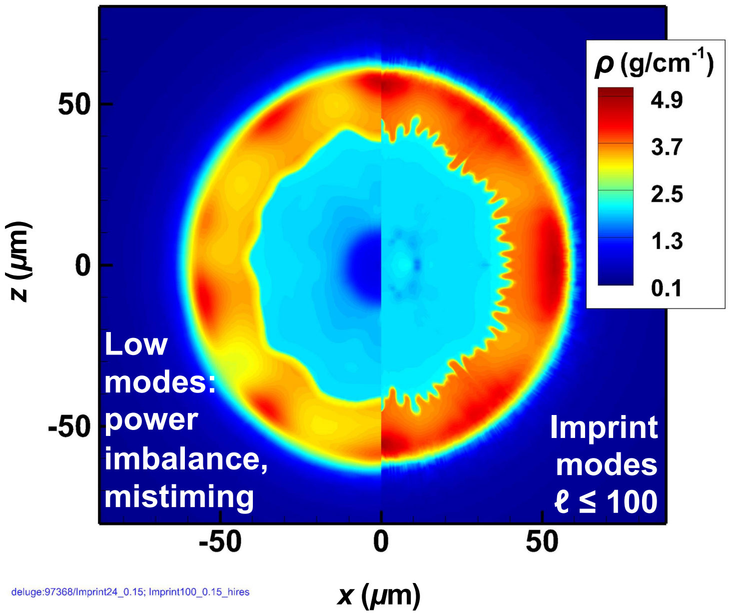
- **The bang times agree well except for the foot + flattop pulse, in which post-shot simulations underpredict the bang time by ~100 ps**





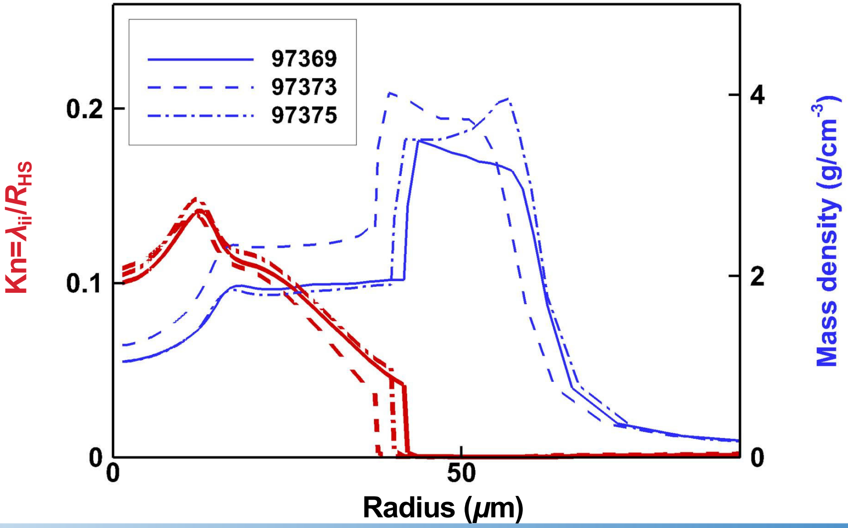
Two-dimensional *DRACO* simulations show little performance degradation due to hydrodynamic instability

- **XPs have large adiabat and shock-induced yield, reducing sensitivity to hydrodynamic instability**



Ion viscosity is a more likely candidate for performance degradation

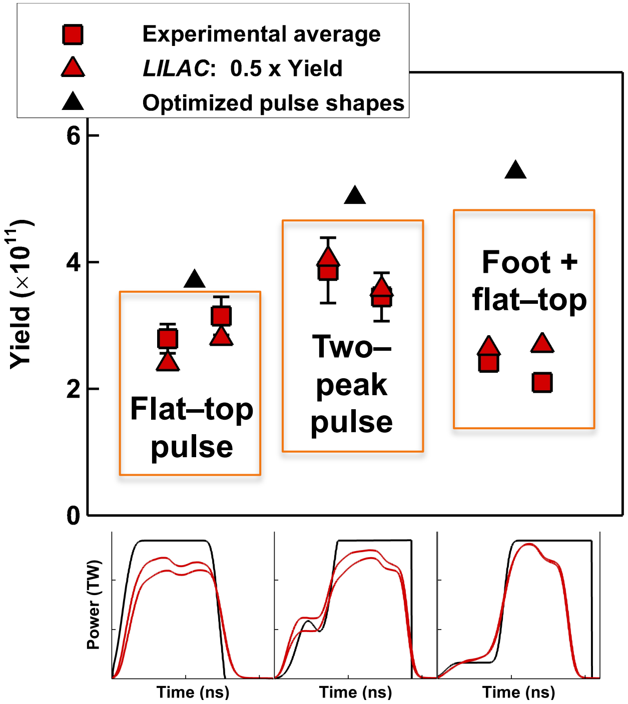
- Studies by Rosenberg *et al*. (2014)[1] and Atzeni *et al*. (2019)[2] have shown that Kn ~ 0.15 is intermediate between the fluid and kinetic regimes, and the observed YOC ~ 50% is typical for XPs in this range
- Ion viscosity in this regime reduces return-shock strength, lowering yield and T_i[2,3] and could account for the observed YOC ~ 50%



[1]M. J. Rosenberg *et al.*, PRL, 112, 185001 (2014).
[2]S. Atzeni *et al.*, 46th EPS Conf. on Plasma Phys. (2019).
[3]See also I. Igumenschev, BO09.00005, this conference.

A yield increase of over 30% is predicted for the optimized pulses relative to the flattop baseline pulse

- The requested pulse shapes were simulated using the same prescription used to model the experimental data
- The yields are uniformly higher than the experimental data because
  - all pulses use the same energy (18 kJ) and peak power (28 TW)
  - the pulses are optimally timed for the target radius



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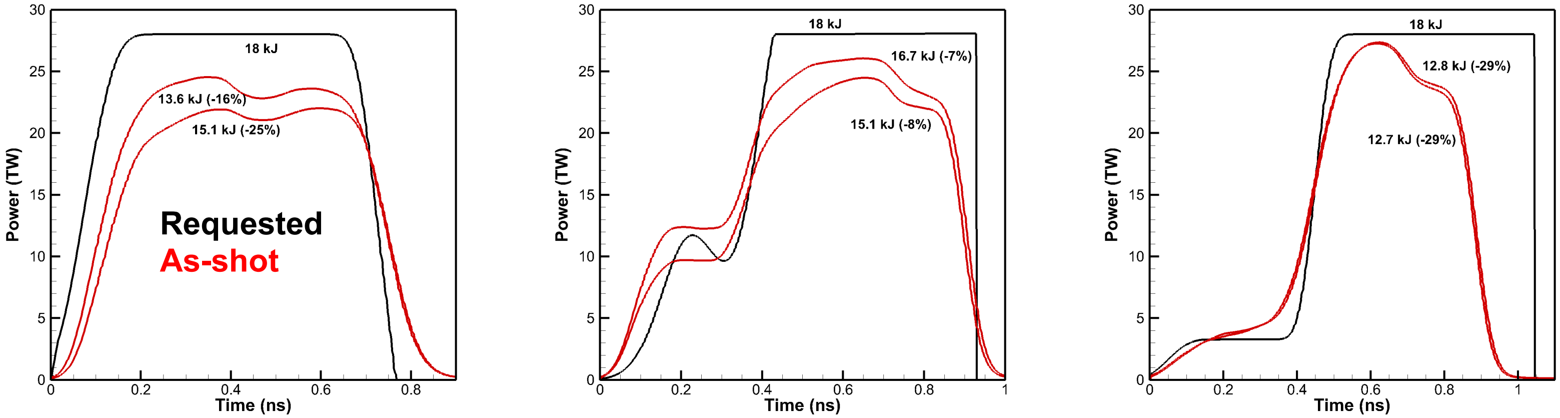
Related talks

- J. A. Marozas, LDD Tutorial, JT02.00001 (Tue PM)
- P. W. McKenty, NIF Contoured-shell XPs, GO09.00008 (Tue AM)
- I. Igumenshchev, Effects of ion viscosity in OMEGA cryo, BO09.00005 (Mon)

Additional slides

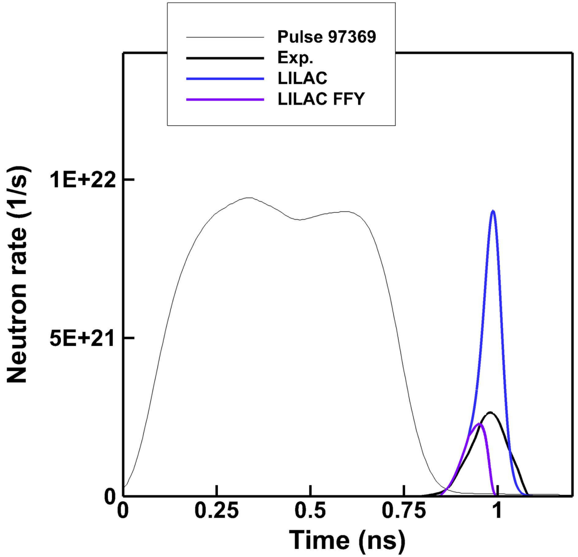
The experimental pulses qualitatively reproduce elements of the optimized pulses but fall short on power, energy and uniformity

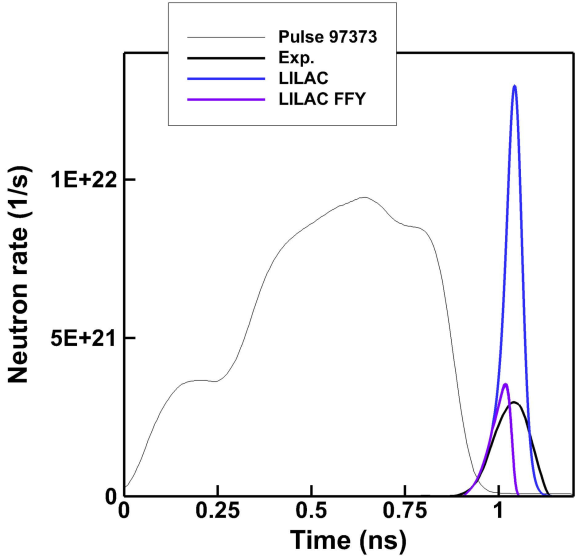
- The as-shot pulse energy was 8% to 25% below the requested 18 kJ and the peak drive power was low for all shots, 22-25 TW instead of the designed 28 TW
- The only pair of shots with equal energy (97369 and 97371) did not have equal peak power, confounding comparison
- Shaped pulses of duration ≤ 1 ns are unusual and challenging and growing pains were expected; OMEGA System Science has identified a path forward for future experiments

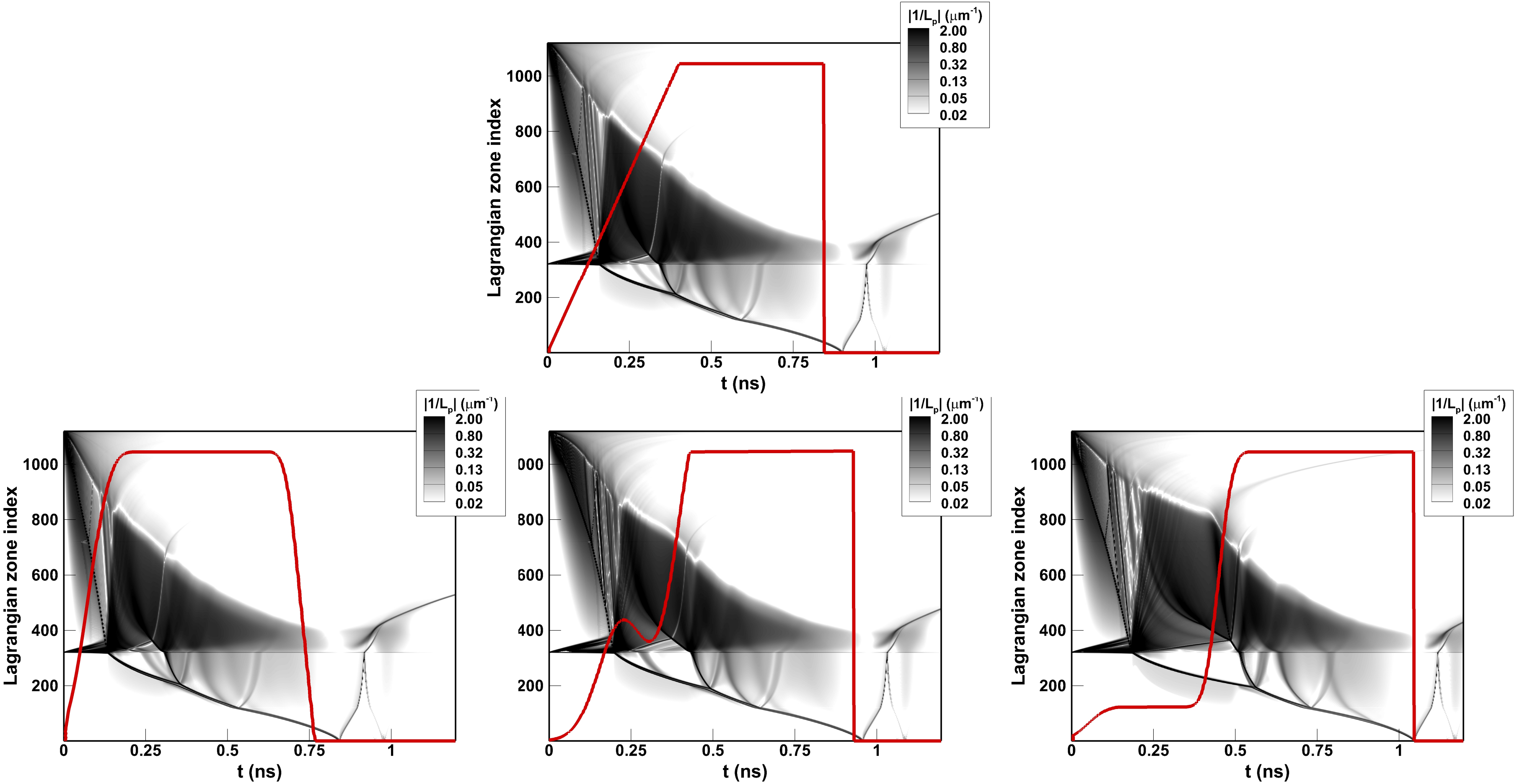


The LILAC free-fall yield follows the experimental trend

- **The experimental yields lie between the free-fall and total yield, with burn widths comparable to the LILAC burn widths, suggesting some contribution to the overall yield from compression of the hot spot by the shell**

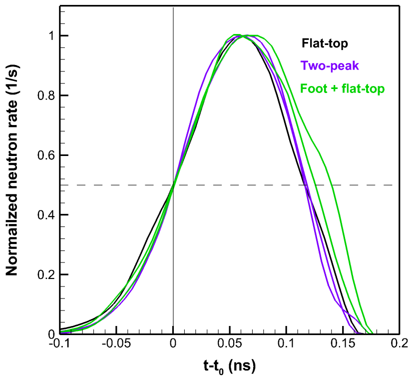


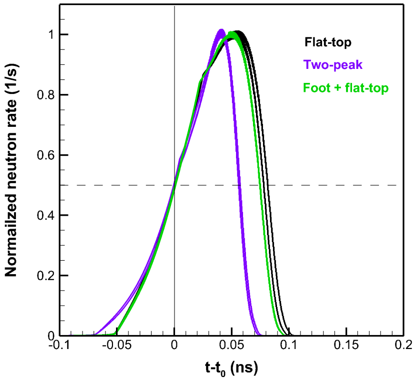



|1/L$_p$| (μm^{-1})
2.00
0.80
0.32
0.13
0.05
0.02
Lagrangian zone index
1000
800
600
400
200
0
0.25
0.5
0.75
1
t (ns)

The foot + flat-top pulse shows a small increase in the burn width

- **Burn widths are typically smaller in simulation than in experiment,**





	Experimental data					LILAC			
Shot	**5.4 m nTOF Yield**	**12 m nTOF yield**	**5.4 m Tion (keV)**	**12m Tion (keV)**	**Burn width (ps)**	**Vimp (km/s)**	**Peak HS press.**	**rho R**	**Burn width (ps)**
97368	2.48E+11	2.87E+11	7.06	8.31	124	644	9.6	20	
97369	2.75E+11	3.25E+11	7.17	7.98	123	662	10.2	20	
97371	3.16E+11	4.10E+11	7.15	9.04	121	706	14.9	21	
97373	2.93E+11	3.60E+11	7.61	9.05	121	691	14.1	22	
97375	2.26E+11	2.45E+11	7.29	8.12	138	671	10.3	19	
97376	1.95E+11	2.14E+11	7.83	8.52	134	674	10.6	20	

Tim Collins