Reaching 30% Energy Coupling Efficiency For Al and HDC Capsules Using Rugby Hohlraums at NIF

Y. Ping, P. Amendt, K. Baker, V. A. Smalyuk, H. Chen, S. Khan, E. P. Hartouni, D. Ho, O. Jones, O. N. Landen, N. Lemos, J. Lindl, A. Nikroo, M. Rubery, D. Schlossberg, M. Stadermann, D. Strozzi, R. Tipton, B. Woodworth (LLNL)

K. Meaney, Y. Kim, E. Loomis, E. Merritt, D. Montgomery (LANL)

N. Kabadi, B. Lahmann, J. Frenje, R. Petrasso (MIT)

FEC 2020, May 2021

LLNL-PRES-790265

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Great progress has been made in indirect-drive ICF, however the energy coupling is still very inefficient

Laser Energy ~ 1.9 MJ

X-ray Energy ~ 1.6 MJ

>80% energy is lost !

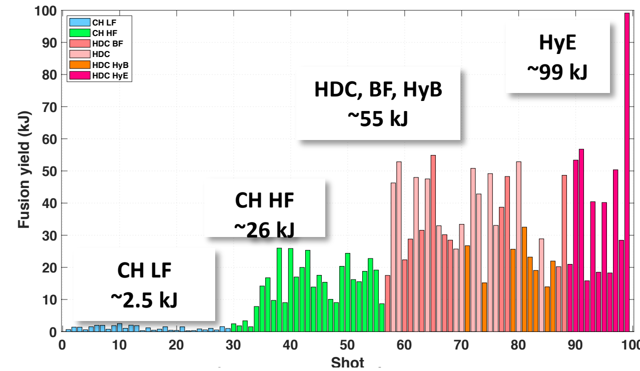
Energy to capsule ~150-270 kJ*
Set adiabat

Shell kinetic energy ~ 8-21 kJ*

Hot spot ~ 5-15 kJ*

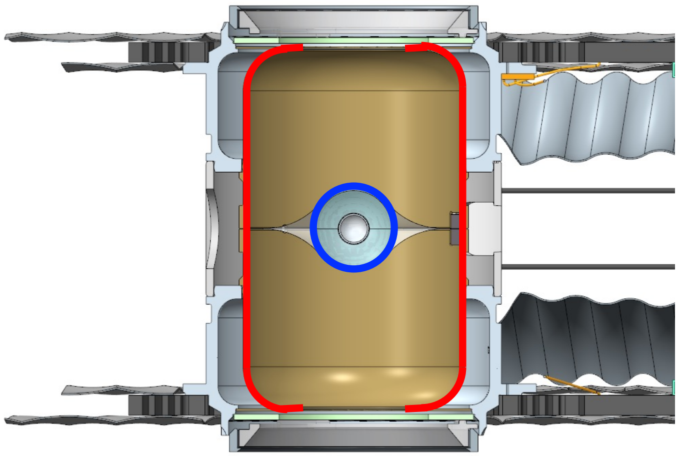
Burn propagation

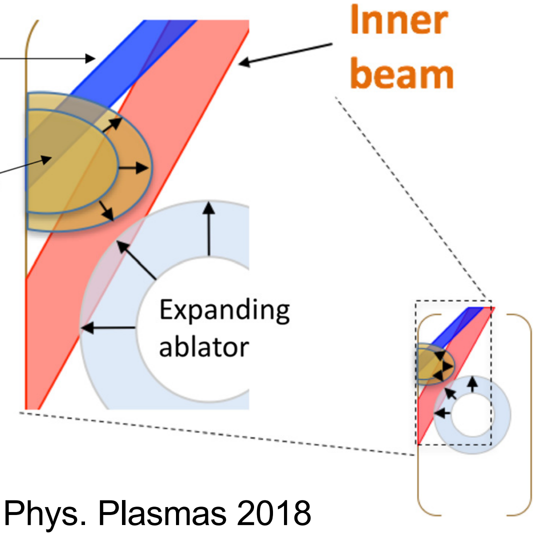
- * **CH ablators**: Hurricane *et al*. Nature 2014; Nature phys. 2016
- * **HDC ablators**: Le Pape *et al*. PRL 2018
- \+ ~270 kJ HybridE at 1.9 MJ, Zylstra *et al*. (2019)



A. Kritcher, DPP2020 invited talk

What constrains the energy coupling in a cylinder-shaped hohlraum is mainly simple geometry

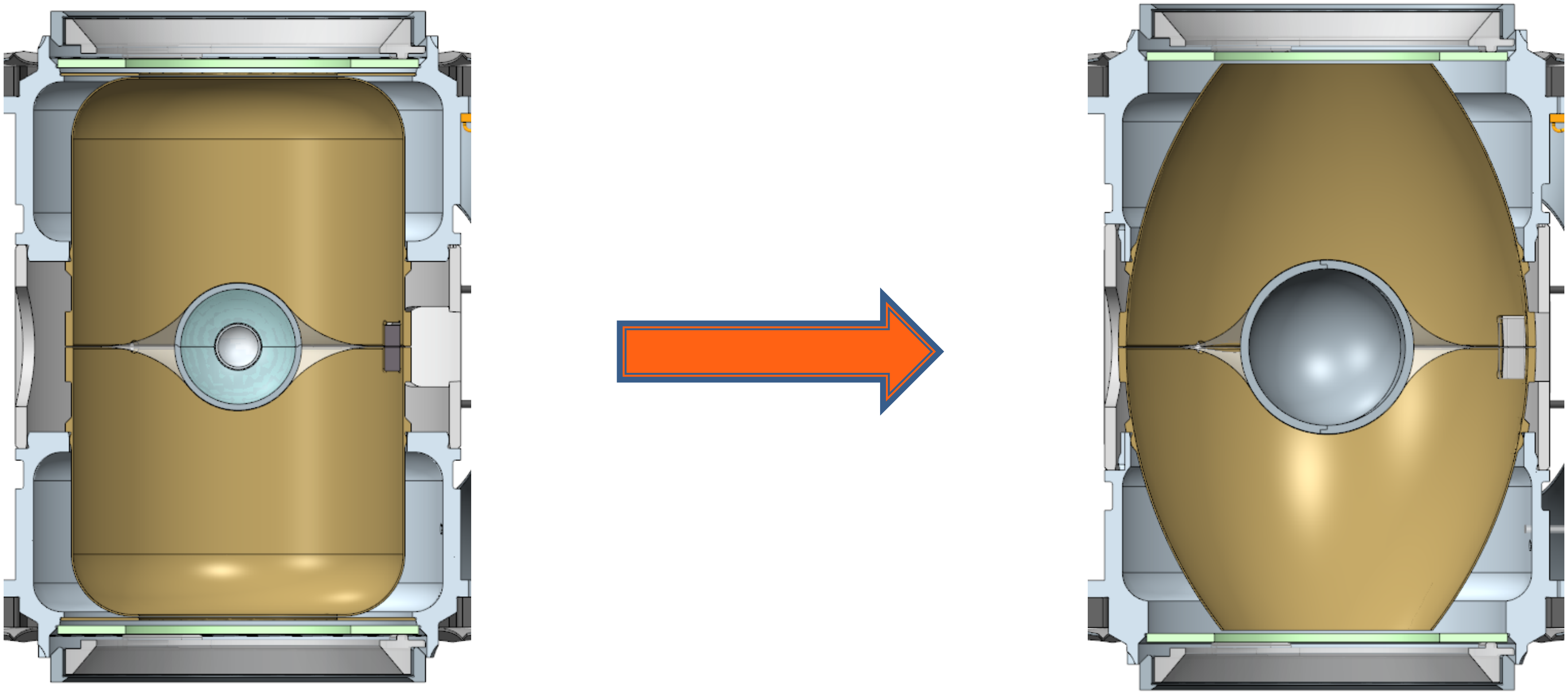




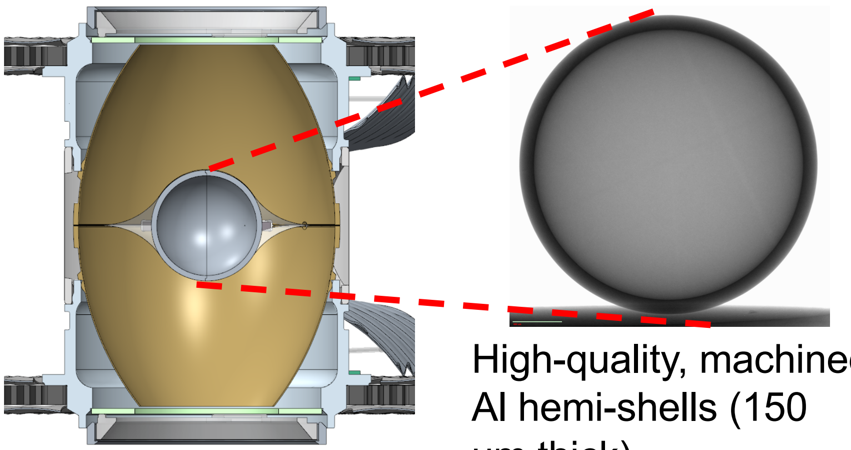
Callahan *et al*. Phys. Plasmas 2018

- The absorbed energy by the capsule is set by surface area ratio of hohlraum and capsule.
- Too large a capsule will lead to interference with laser beam propagation, and asymmetric implosion.
  - Recent shots using Iraum or $\Delta\lambda$ between inner and outer beams show promising shape-tuning.

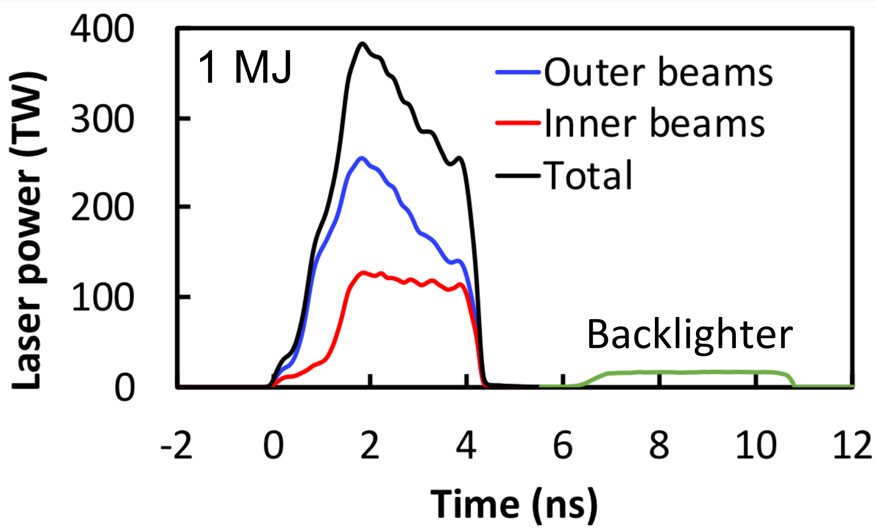
Since energy coupling is mainly set by geometry, why not also try a different shape of hohlraum?



A new design with 3mm diameter Al capsule in Au rugby hohlraum was implemented to study the coupling efficiency



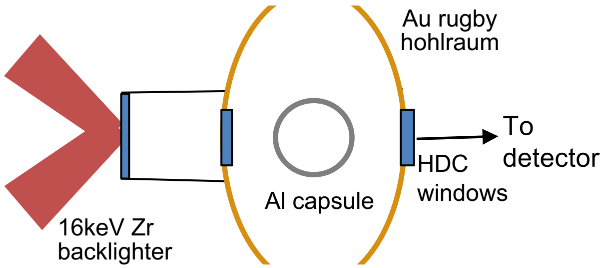
High-quality, machined Al hemi-shells (150 um thick)



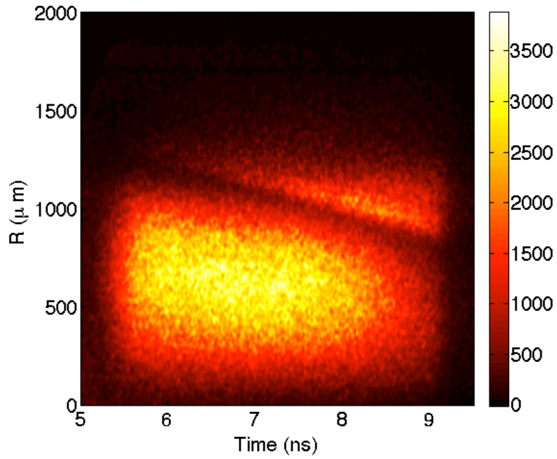
- Al capsule 3 mm OD, ~50% larger than typical ICF capsule (~2 mm)
- Low gas fill 0.3 mg/cc in hohlraum
- Reverse-ramp pulse shape for impulsive drive delivery for double-shell design
- This campaign started at 0.7x scale with 1 MJ, 5ns laser drive

Measured shell velocity and mass remaining confirmed that shell kinetic energy reaches ~34 kJ at 0.7x scale

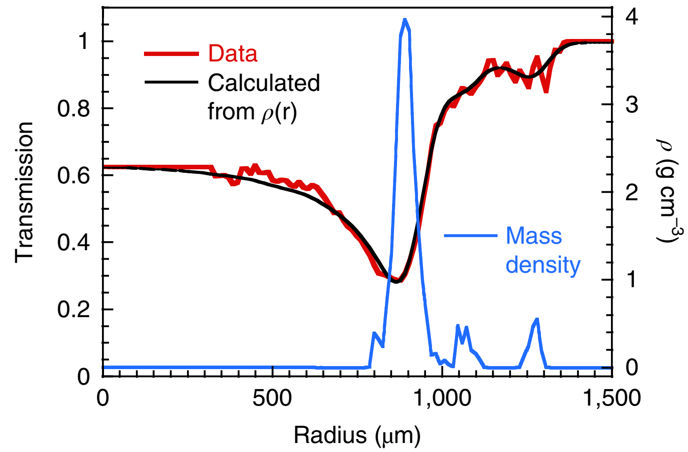
Experimental schematic



Streaked x-ray radiograph



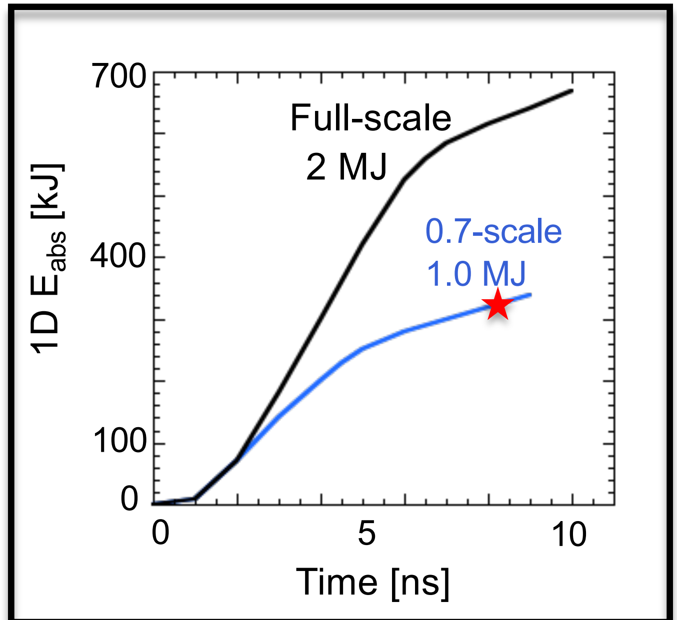
Reconstructed density profile



- Measured mass remaining 3.0 ± 0.2 mg at 8.4ns
- Measured velocity 151 ± 8 um/ns
- Shell kinetic energy 34 ± 4 kJ with 1.0 MJ drive
- Typical shell kinetic energy is 21 kJ with 1.9 MJ drive in cylinders (Le Pape *et al*. PRL 2018)

Good agreement with simulations indicates ~300 kJ coupled into capsule, or 30% of total laser energy

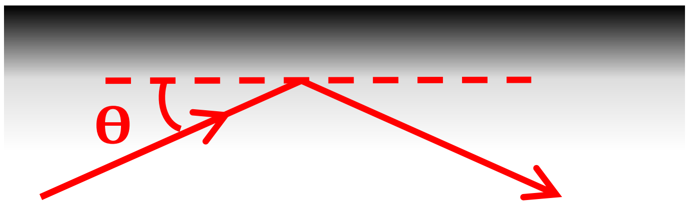
	Measured	Simulated
Peak Tr (eV)	248 ±3	248
At 8.4ns		
Shell velocity (μm/ns)	151 ±8	144
<R> (μm)	890 ±20	884
<ρR> (mg/cc)	3.3 ±0.7	4.3
Shell FWHM (μm)	89 ±14	100
Mass (mg)	3.0 ±0.2	3.67
Shell kinetic energy (kJ)	34 ±4	38
At 10.6ns		
<R> (μm)	550 ±20	538



Full scale design shows ~700 kJ coupling

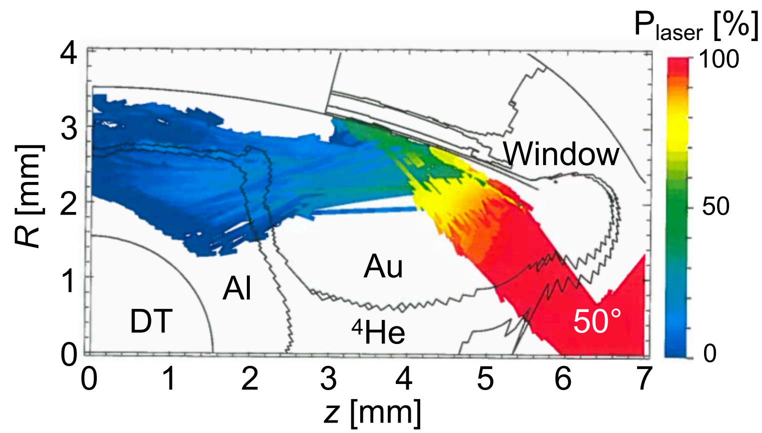
Ping, Smalyuk, Amendt, et al. Nature Phys. 2019

For these large capsules, symmetry tuning can be achieved by varying rugby shape due to angle-sensitivity of reflectivity



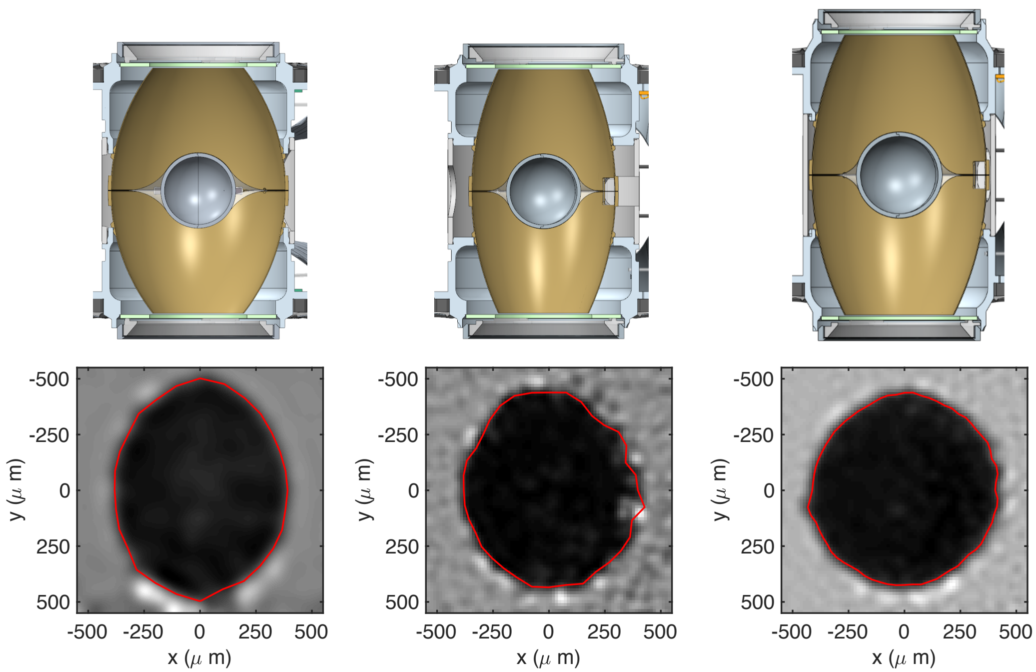
- Turning point at $n_e = n_c \, sin^2\theta$
- Inverse bremsstrahlung absorption $\propto n_e^2 \;\propto\; sin^4\theta$

Simulated laser energy deposition at a rugby wall

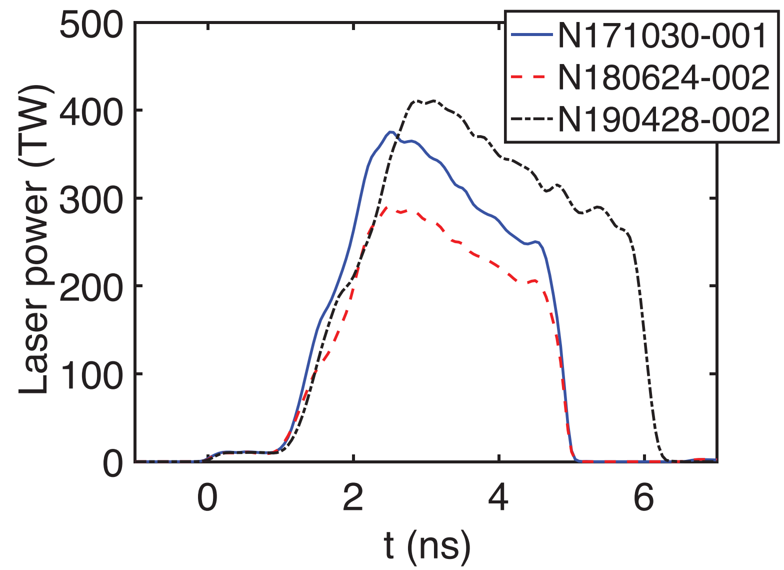


The reflectivity is very sensitive to incident angle, so that the wall angle is an effective knob to tune symmetry.

Symmetry tuning has been achieved experimentally by varying rugby shape



P2/P0 = 13% **P2/P0 = 8%** **P2/P0 = 1.6%**



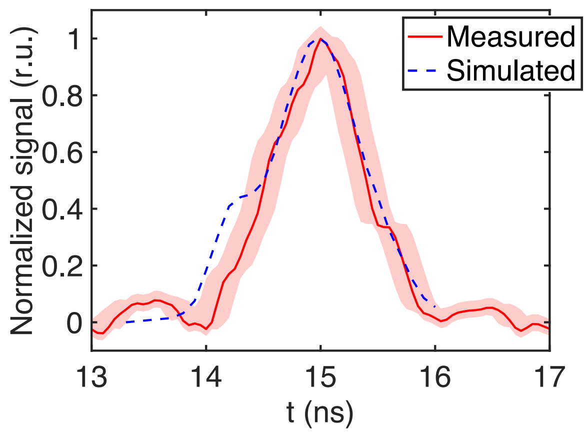
Ping, Smalyuk, Amendt, et al. Phys. Plasmas, 2020

Good agreement on bang time, yield, in-flight capsule size, and velocity is consistent with ~450 kJ coupling at a 1.5 MJ drive

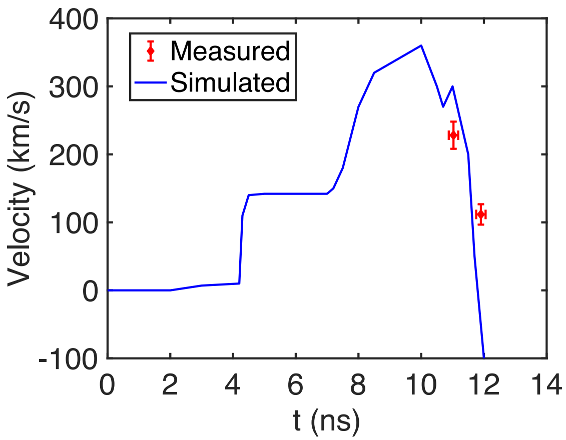
	Simulation*	N190122-002 0.9x scale
Laser MJ	1.5	1.558†
Gas fill	DT 7mg/cc	DT 7mg/cc
Yield	1e14 neutrons	8.11± 0.25 e13, ~ 78% YOC
Bang time	15.0 ns	15.10 ± 0.15 ns
P0 at 15ns	338 um	329 ± 14 um

* No drive mults, *FL*=0.04

Good agreement in measured and simulated bang time



Peak velocity reaches 350 km/s for 120um-thick Al capsule

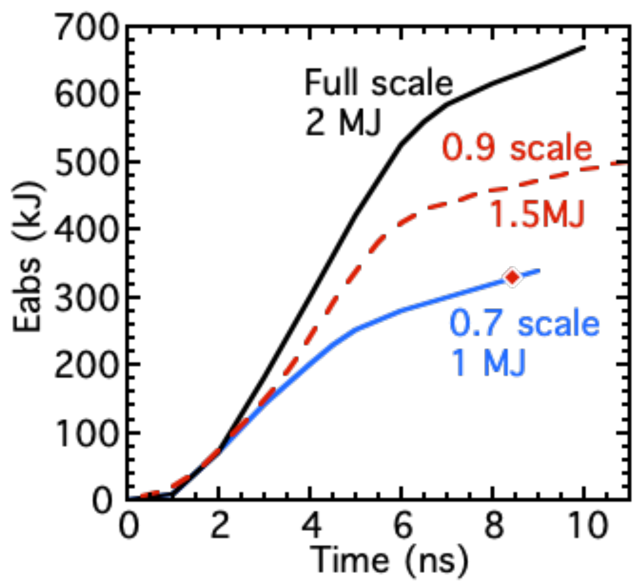


- These results were obtained for:
  3.0-3.4mm Al capsule in Au Rugby hohlraum; reverse-ramp pulse shape; up to 1.5 MJ laser drive

Ping, Smalyuk, Amendt, et al. Phys. Plasmas, 2020

Enhanced energy coupling is one step forward toward ignition

Energy absorbed by capsule vs time



Neutron yield scaling:

Pressure Velocity Scale

$$Y \sim p_{if}^{0.64} \frac{v_{imp}^{4.5}}{\alpha_{if}^{1.4}} S^{4.6} \delta (1 - RKE_{norm})^{3.8}$$

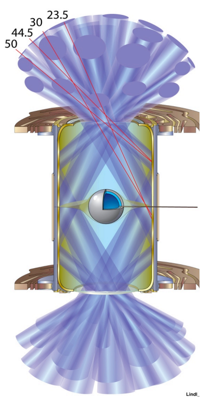
Adiabat Stability Symmetry

A. Kritcher, DPP2020 invited talk

- These results are encouraging, but there are a lot more to do to reach ignition.

High energy coupling can enable single-shell volume-like ignition

Central hot spot energy flow



Laser Energy ~ 1.9 MJ

X-ray Energy ~ 1.6 MJ

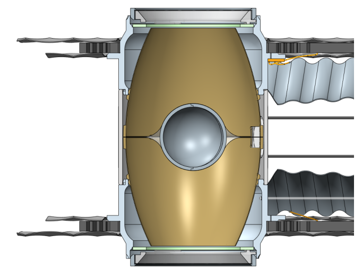
Energy to capsule ~150-270 kJ*
Set adiabat

Shell kinetic energy ~ 8-20 kJ*

Hot spot ~ 5-15 kJ*

Burn propagation

VOLUME IGNITION-like energy flow



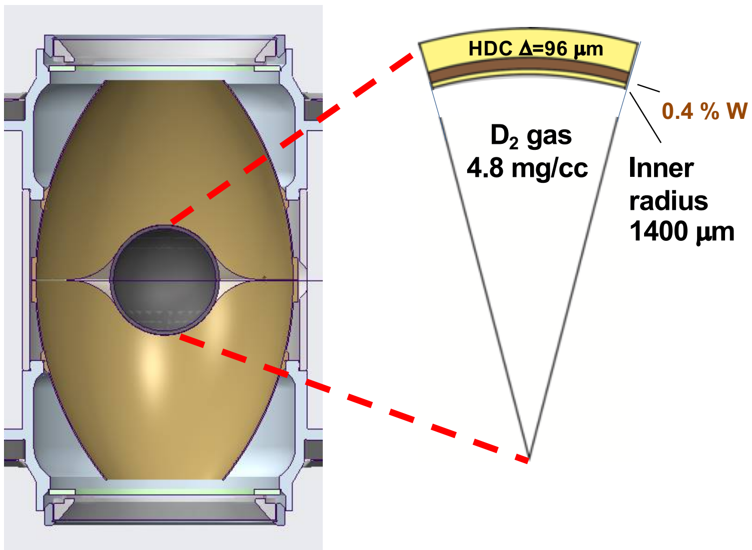
Energy to capsule ~450 kJ:
Sets high adiabat, lowers convergence, more stable

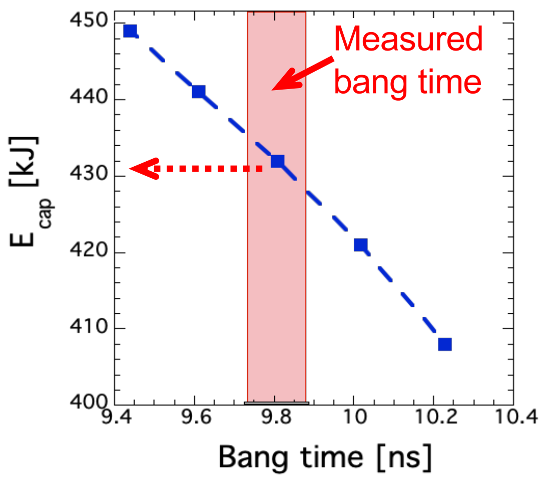
Shell kinetic energy ~ 50 kJ

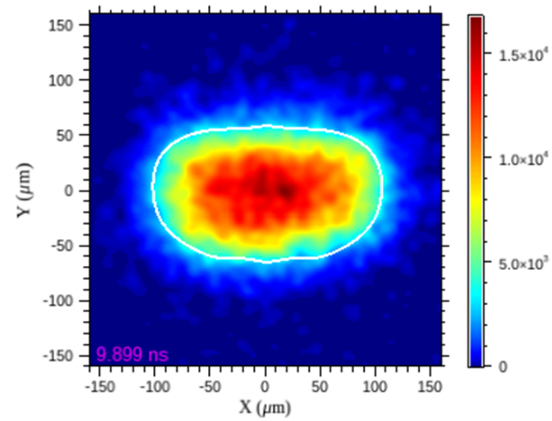
Entire fuel is hot spot: ~ 30 kJ,
More tolerant to defects, high α

Volume ignition?

A new series of NIF shots has started to test high-volume and -adiabat capsule (HVAC) design

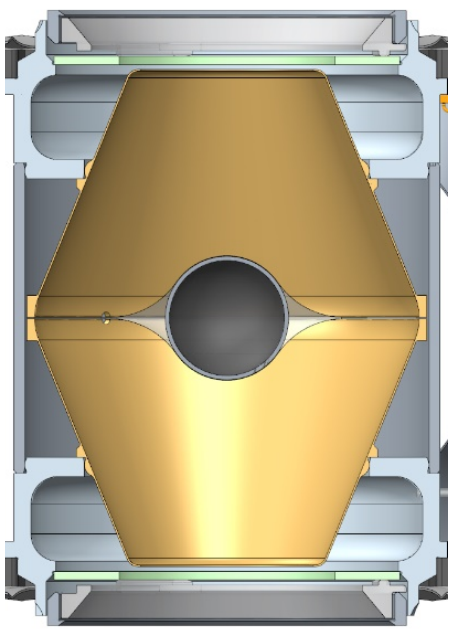




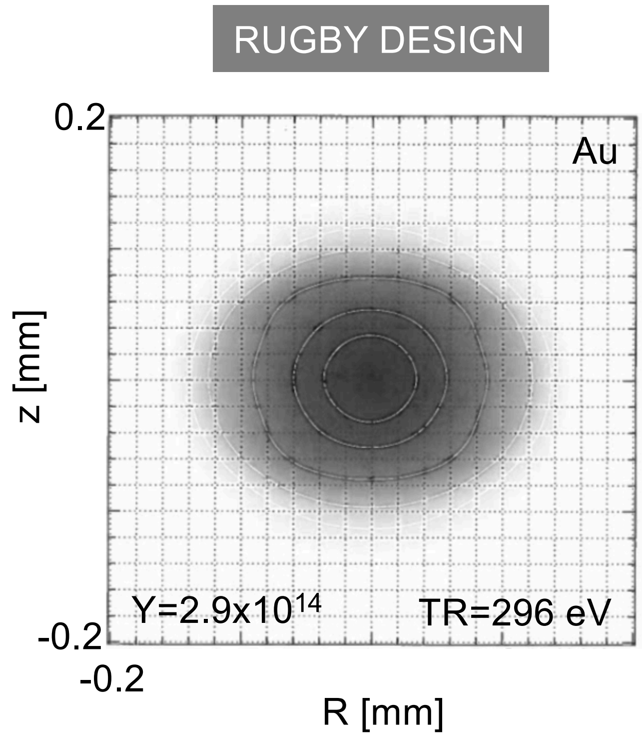


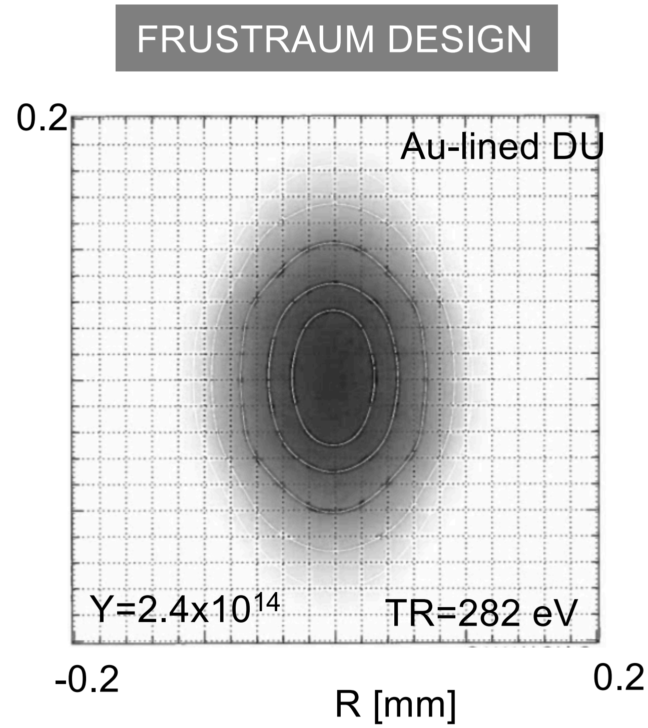
- 3mm HDC capsule with 2-shock 5ns laser drive.
- Energy coupling reached 430kJ, or 32% during walkup shots up to 1.4MJ.
- Hot spot was moderately oblate, P2/P0 = - 30%.
- Symmetry needs to be tuned by wall curvature or Δλ.

Substituting Frustraum for Rugby hohlraum shows transition to prolateness in gas-filled capsule simulations

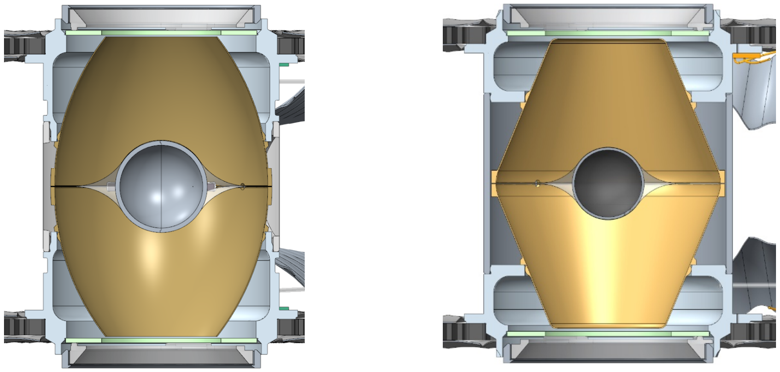


Amendt, et al. Phys. Plasmas, 2019





Summary: these results open up new opportunities toward ignition



Advanced hohlraums with larger capsules for higher yield

- ~3x energy coupling for hot spot ignition
- High coupling enables volume ignition
- Larger hot spot is more robust to defects and instabilities

Multiple-shell approach for ignition

- Lower ignition threshold
- Low radiation loss
- Low convergence requirement
- More tolerance on asymmetry
- Noncryogenic targets