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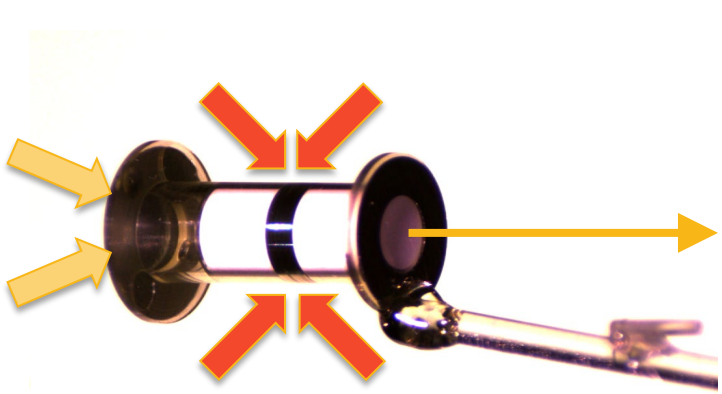
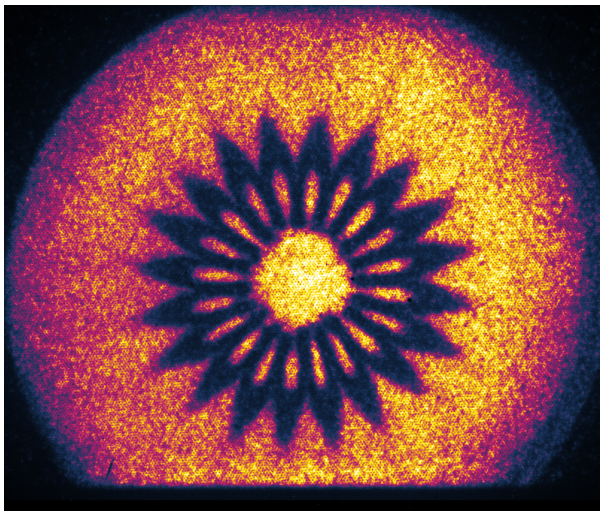
The Cylindrical Implosion Platform: Recent Results and Next Steps





ICF Update

J. P. Sauppe
for the
Cylindrical Implosion Team

Los Alamos NATIONAL LABORATORY EST. 1943

June 1, 2020

NNSA National Nuclear Security Administration
Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

The cylindrical implosion platform is only possible as a result of the hard work of many individuals across multiple institutions.

Los Alamos National Laboratory

John Kline
Kirk Flippo
Krista Stalsberg
Josh Sauppe
Sasikumar Palaniyappan
Ben Tobias
Steve Batha
Paul Bradley
Eric Loomis
Chris Long
Chris Biwer
Harry Robey
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Derek Schmidt
Thomas Day
Chris Wilson
Chris Hamilton
Brian Patterson
Lindsey Kuettner
Lynne Goodwin
Raymond Gonzales
Theresa Quintana

Grant Meadors
Rebecca Roycroft
} Postdocs

Codie Fiedler-Kawaguchi
William Gammel
} Postbacs/graduate students

Lawrence Livermore National Laboratory

Alex Zylstra
Nino Landen

Ben-Gurion University of the Negev and Nuclear Research Center of the Negev

Dov Shvarts
Elad Malka

Virginia Polytechnic Institute and State University

Bhuvana Srinivasan

And the great operations teams at the University of Rochester's Laboratory for Laser Energetics OMEGA laser facility and the National Ignition Facility at LLNL!

Outline

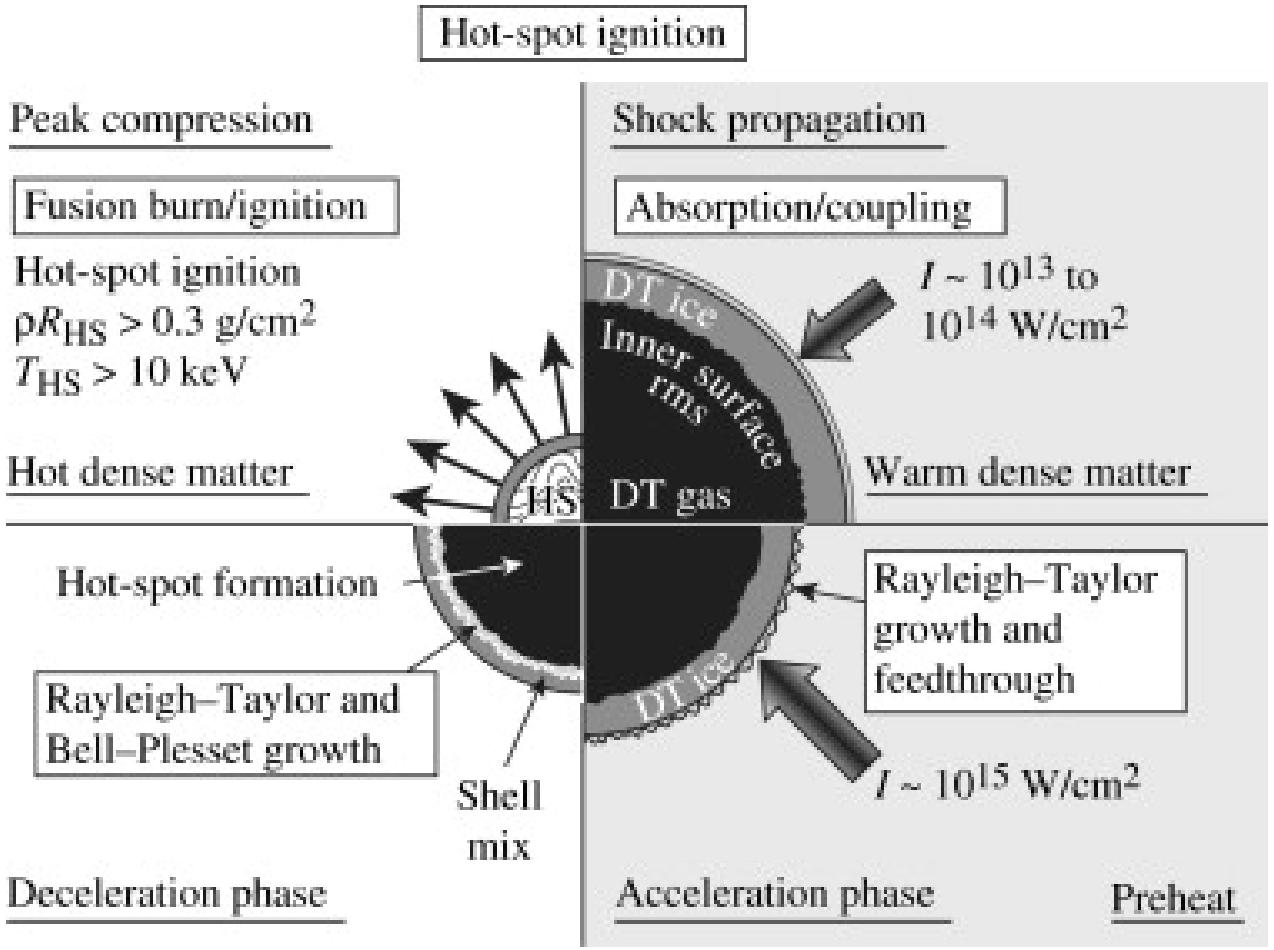
- Motivation
- Platform Introduction
- Scale-Invariant Instability Growth Experiments
- Recent Results at Higher Convergence
- Next Steps

Motivation

Inertial confinement fusion (ICF) implosions are designed to compress and heat DT gas and achieve ignition in the laboratory.

Final Convergence Ratio: CR=20—35

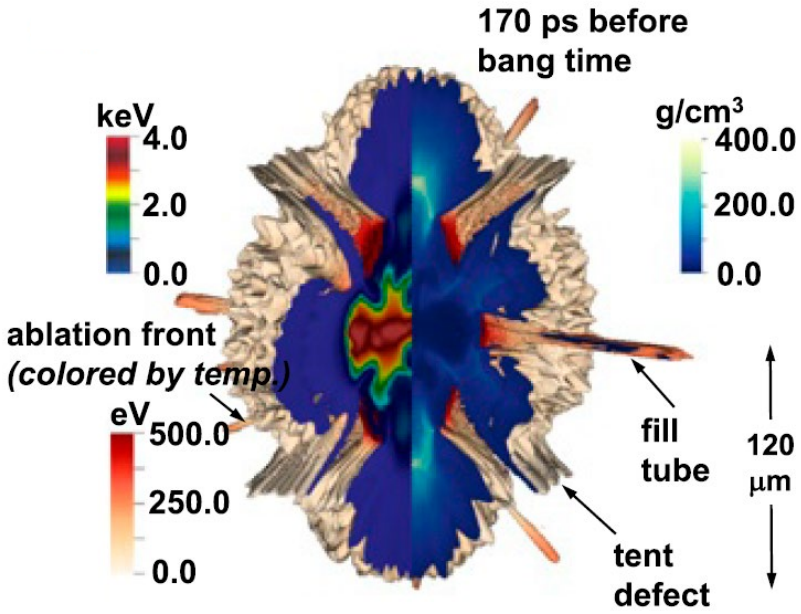
(CR=initial radius /final radius)



Regan et al. *High Eng. Dens. Phys.* **5.4** (2009)

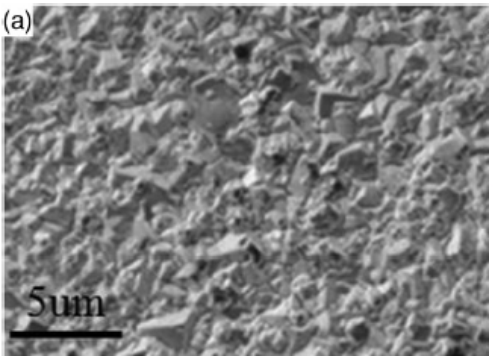
Hydrodynamic instability growth is believed to be a key factor limiting the performance of ICF implosions.

D. S. Clark et al.
Phys. Plasmas **23**,
056302 (2016)



- High resolution 3D *HYDRA* simulations of ICF implosions reveal they are plagued by hydrodynamic instability growth
- Instabilities limit compression and heating

There are many seeds for instability growth in an ICF implosion.



H. Huang et al.
Fusion Sci. Tech.
70, 377 (2016)

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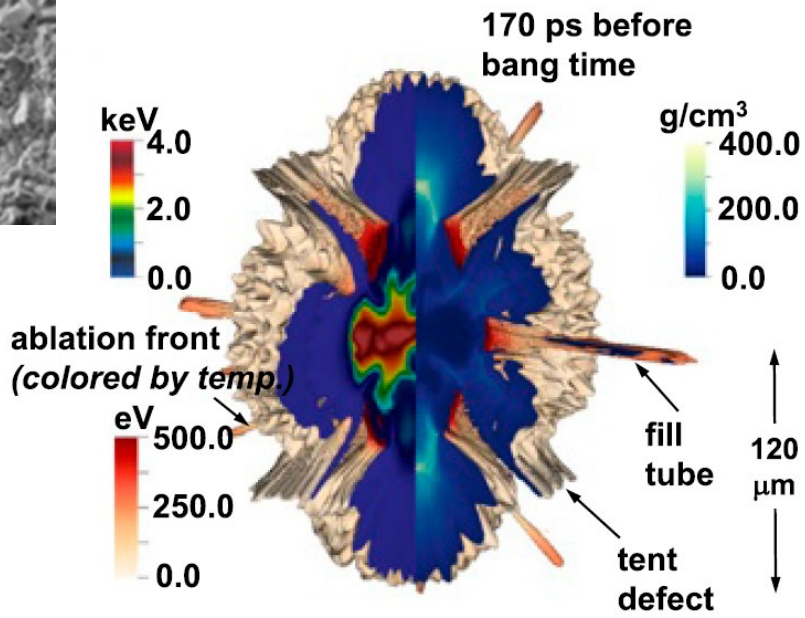
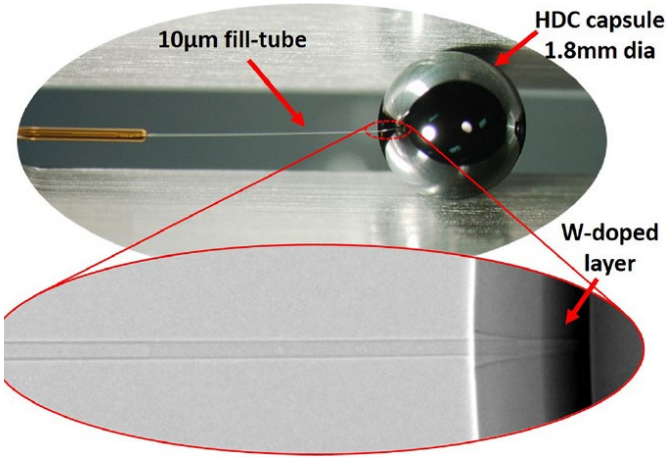
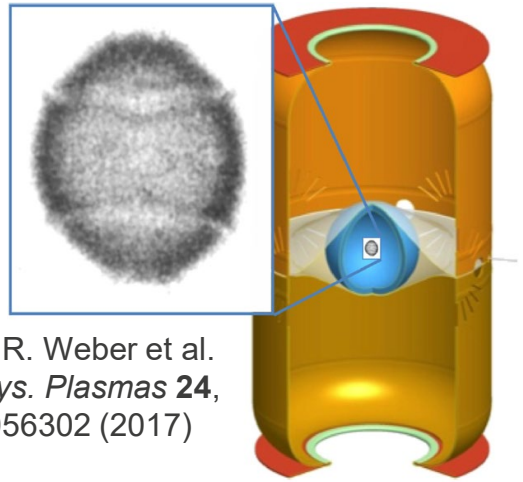


A. G. MacPhee et al.
Phys. Plasmas **25**,
082702 (2018)





C. R. Weber et al.
Phys. Plasmas **24**,
056302 (2017)

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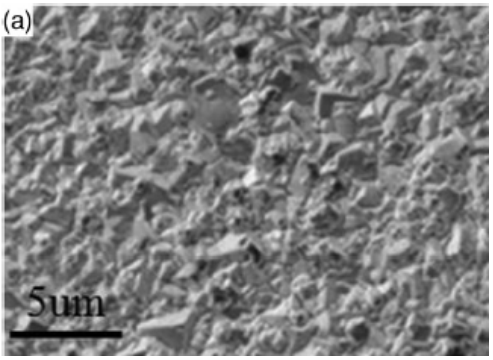

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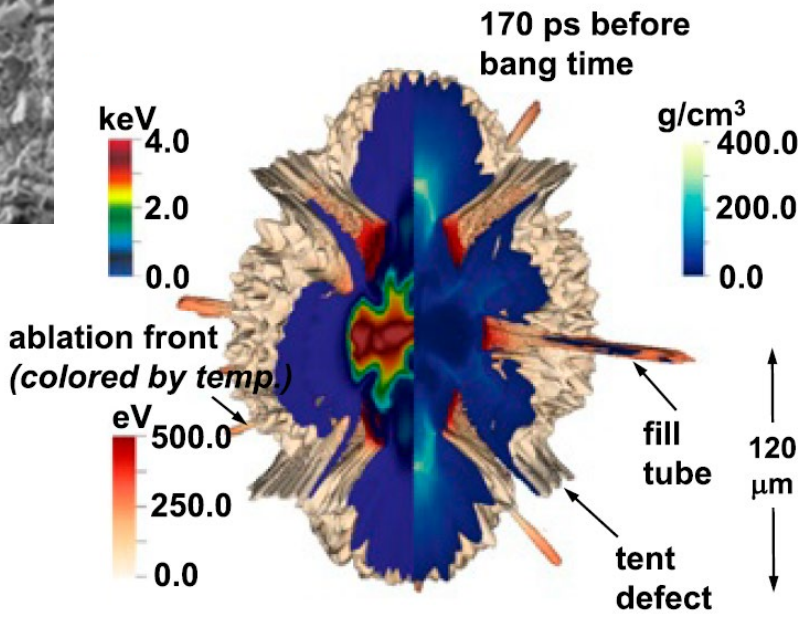
056302 (2016)



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Phys. Plasmas **25**,
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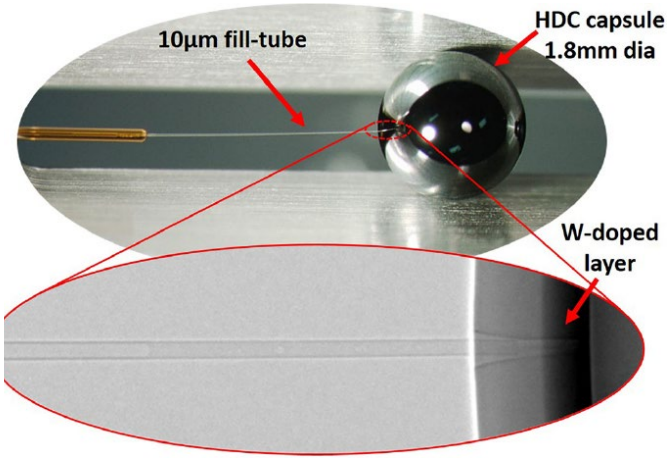

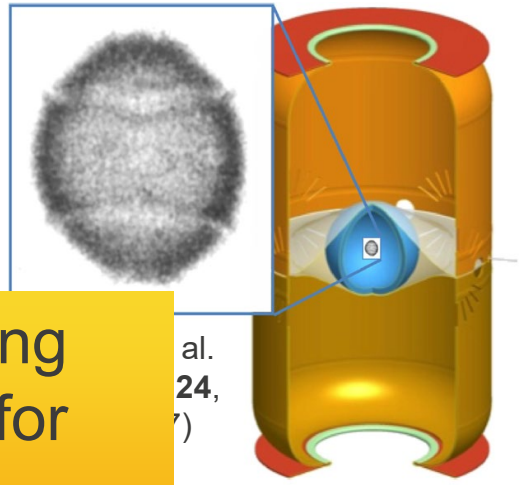

- High resolution 3D *HYDRA* simulations of ICF implosions reveal they are plagued by hydrodynamic
- Instabilities lim

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24,
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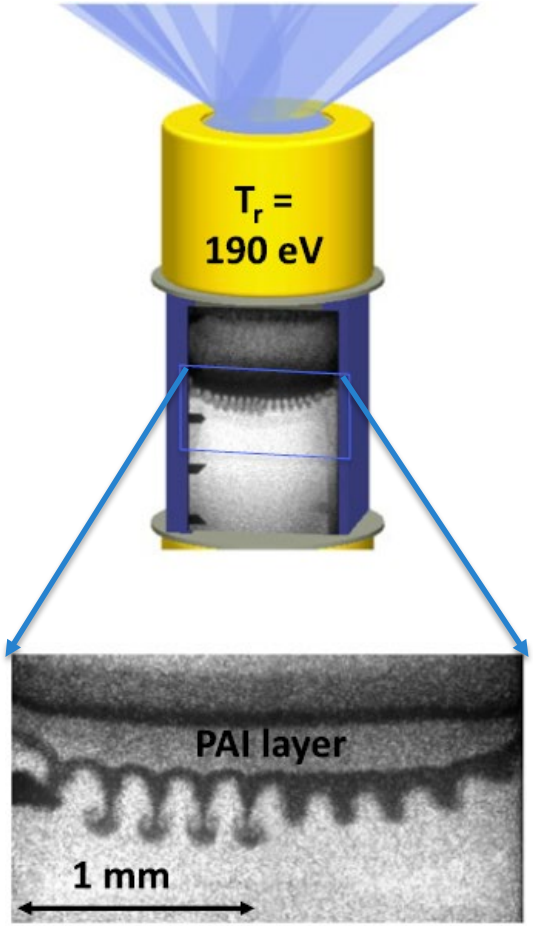
Understanding and mitigating instability growth is crucial for improving performance

Hydrodynamic instabilities have been extensively studied in planar geometry, but convergence modifies growth considerably.

B. A. Remington et al.
Proc. Nat. Acad. Sci.
116.37, 18233 (2019)



- The classical Rayleigh-Taylor instability[1,2] occurs when a light fluid is accelerated into a heavy fluid

$$a(t) = a(0)\exp\left[\sqrt{A_T \ddot{R} k}\ t\right]$$

Amplitude

Atwood Number:
$$A_T = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

Acceleration

Wavenumber

- Convergence modifies this through Bell-Plesset[3,4] effects. In cylindrical geometry[5]:

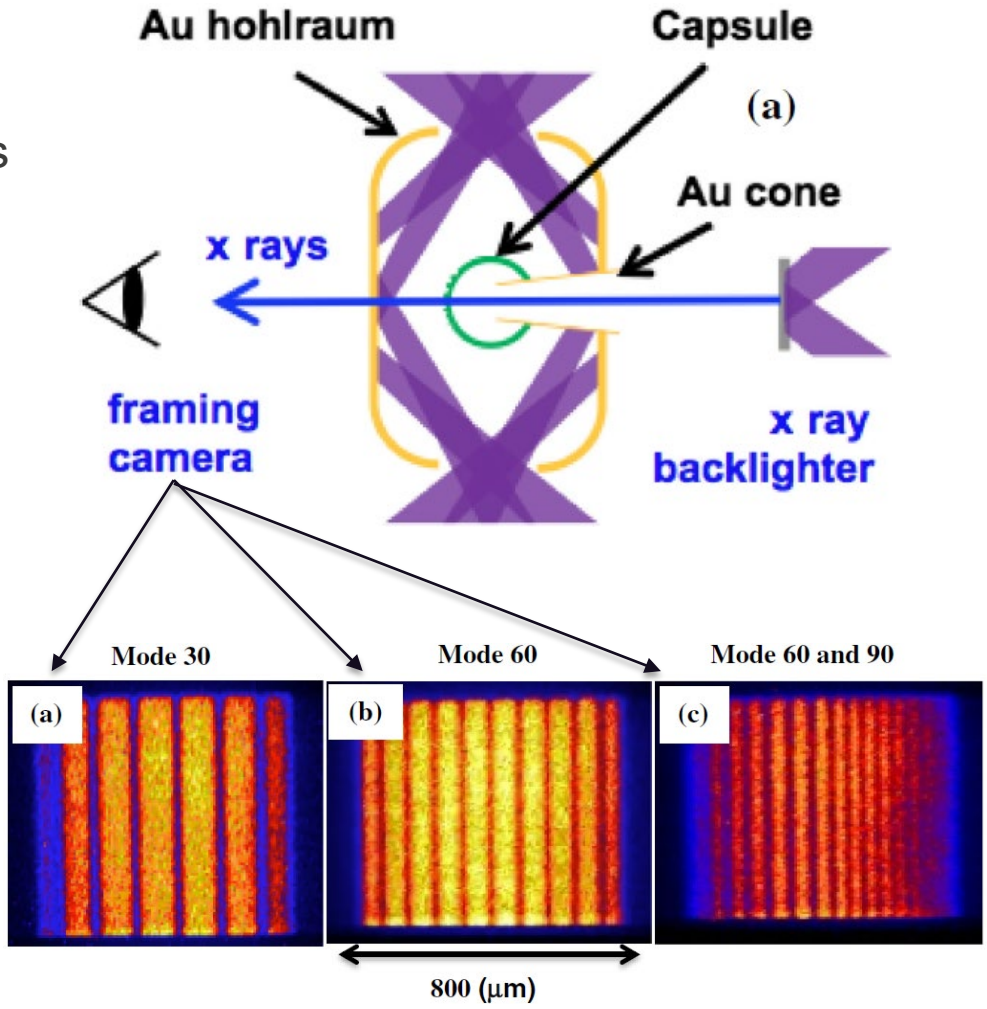
$$\left(-\gamma_\rho + \frac{d}{dt}\right)\frac{d}{dt}(a_m \rho R) = \gamma_0^2 (a_m \rho R)$$

1. Lord Rayleigh, *Proc. London Math. Soc.* s1-14 (1882) 170-177.
2. G. I. Taylor, *Proc. R. Soc. London,* Ser. A 201 (1950) 192-196.
3. G. I. Bell, *Los Alamos Tech. Rep.* LA-1321 (1951).
4. M. S. Plesset, *J. Appl. Phys.* **25** (1) (1954) 96-98.
5. R. Epstein, *Phys. Plasmas* **11.11** (2004) 5114.

Spherical geometry provides a direct surrogate to ICF implosions, but diagnostic access is challenging and convergence is often limited.

- Hydro-growth radiography (HGR) platform directly measures variations in optical depth
  - Models are needed to differentiate between density and length variations in the images
  - Limited to low convergence CR<3—4

V. A. Smalyuk et al. *Phys. Rev. Lett.* **112**, 185003 (2014)



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- Enhanced self-emission techniques can be used to infer growth indirectly at higher convergence

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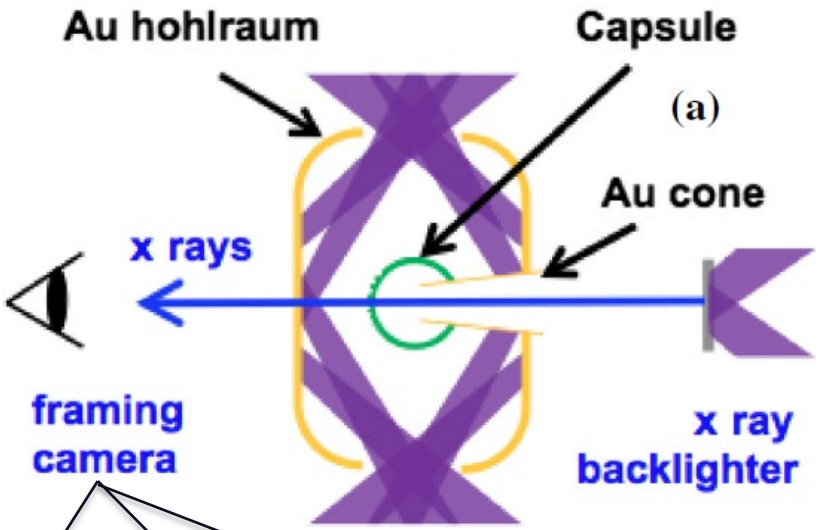
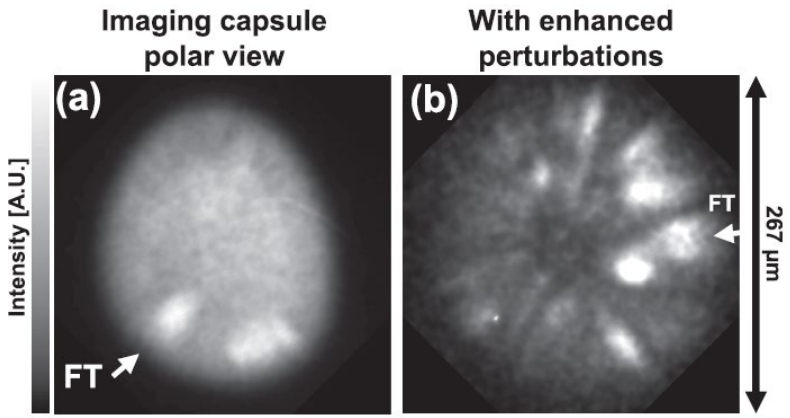
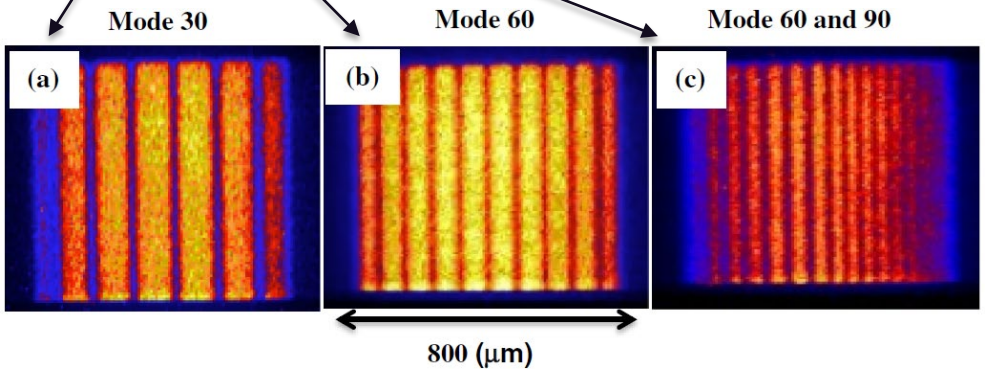




L. A. Pickworth et al. *Phys. Plasmas* **25.5**, 054502 (2018)



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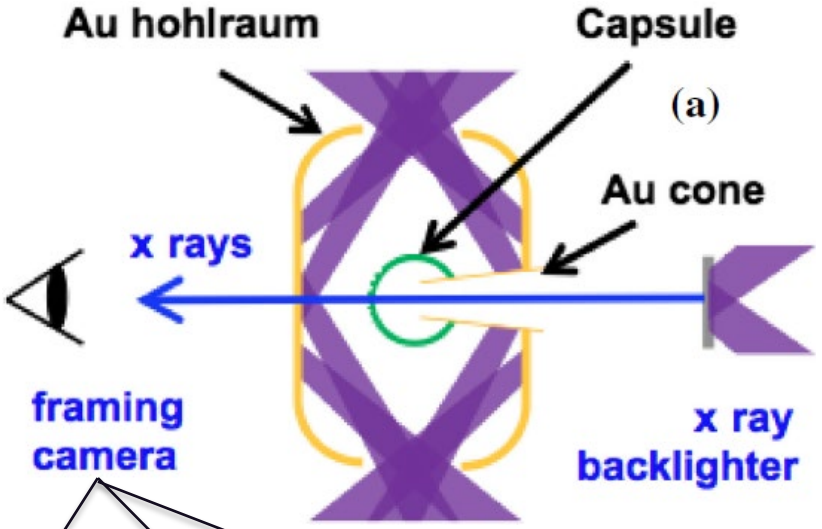
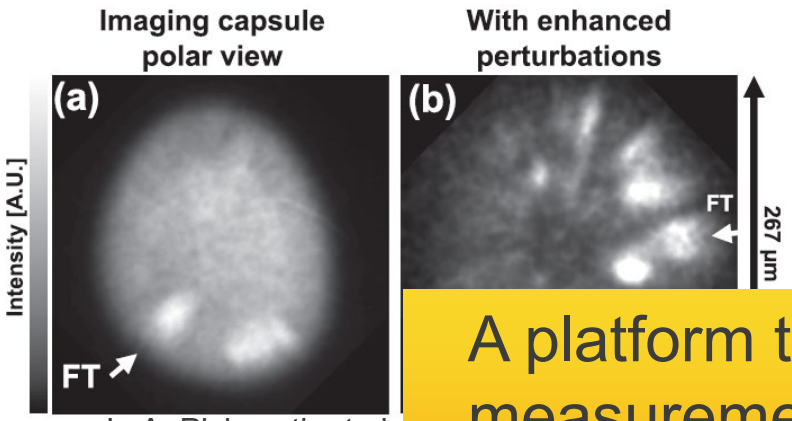
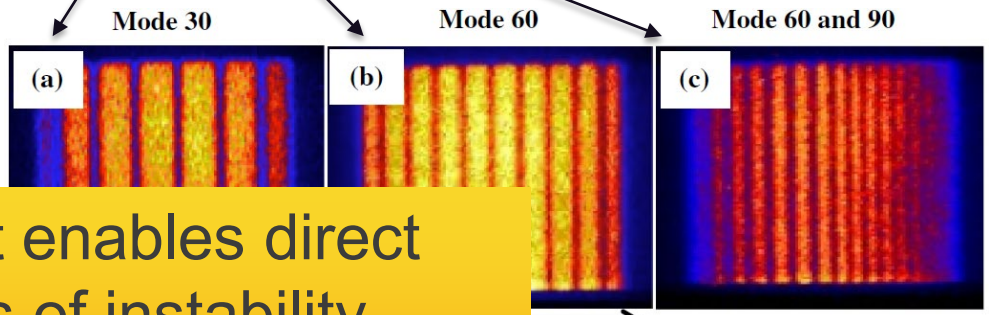






L. A. Pickworth et al. **25.5**, 054502

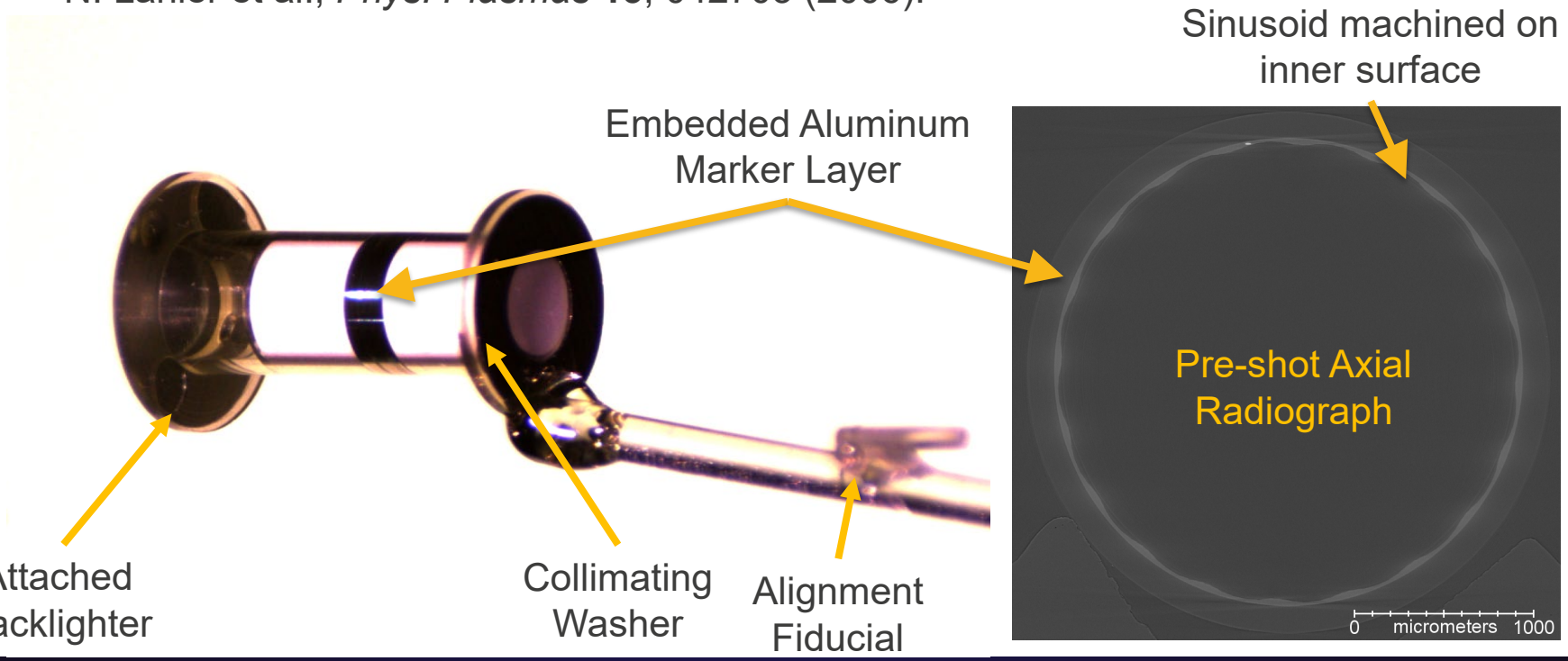
A platform that enables direct measurements of instability growth is very desirable

The Cylindrical Implosion Platform

Cylindrical implosions retain the effects of convergence while allowing direct diagnostic access to the unstable interface.

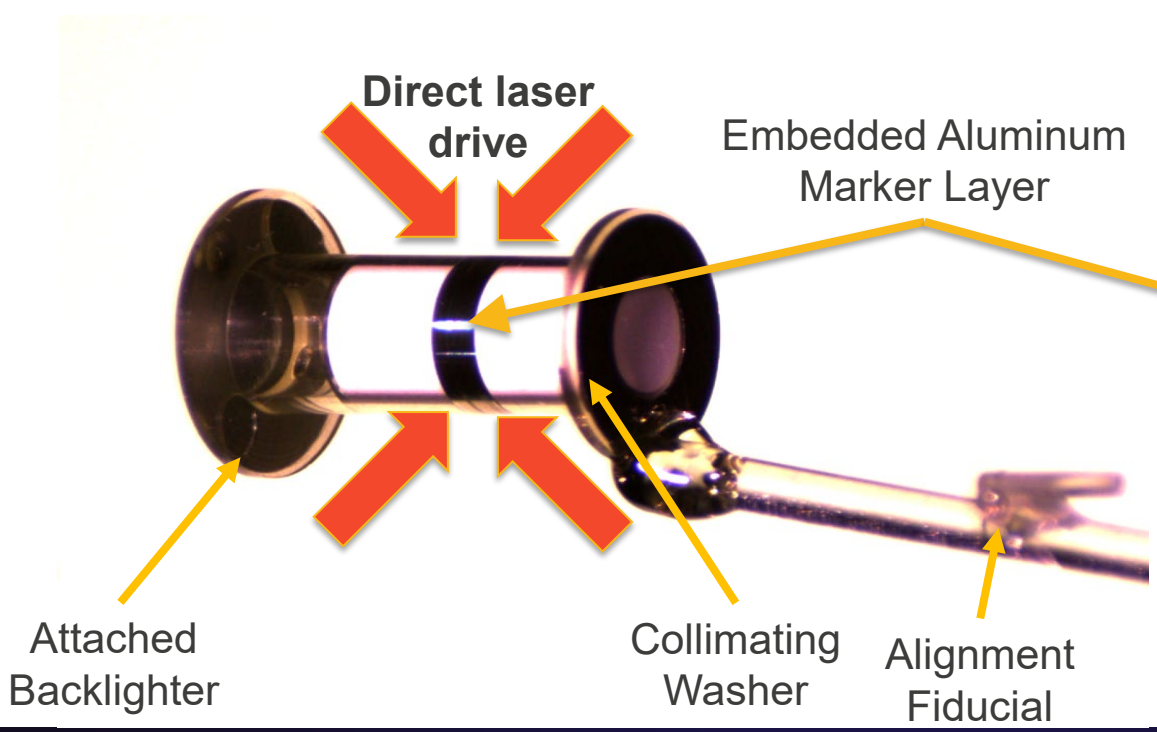
- Cylindrical implosions have been used for many years to study physics in convergent geometry

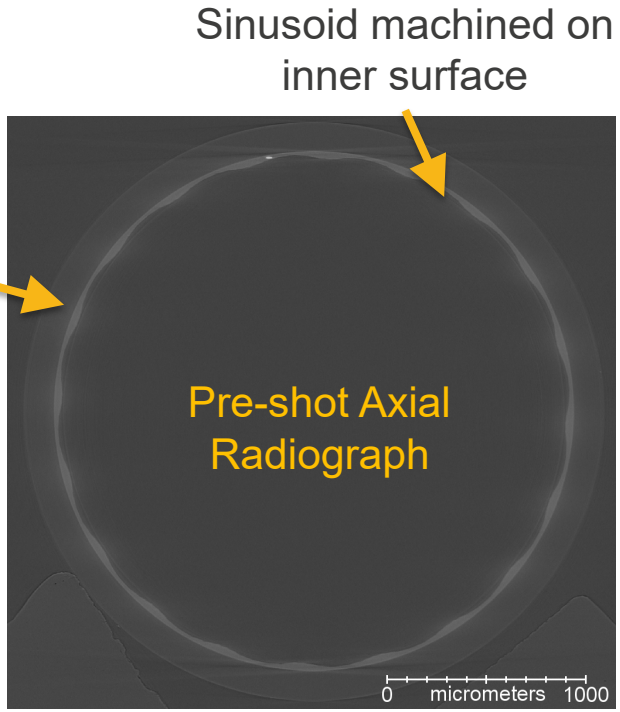
W. W. Hsing and N. M. Hoffman, *Phys. Rev. Lett*. **78**, 3876 (1997).
D. L. Tubbs et al., *Phys. Plasmas* **6**, 2095 (1999).
C. W. Barnes et al., *Phys. Plasmas* **9**, 4431 (2002).
J. R. Fincke et al., *Phys. Rev. Lett.* **93**, 115003 (2004).
N. Lanier et al., *Phys. Plasmas* **13**, 042703 (2006).



Cylindrical implosions retain the effects of convergence while allowing direct diagnostic access to the unstable interface.

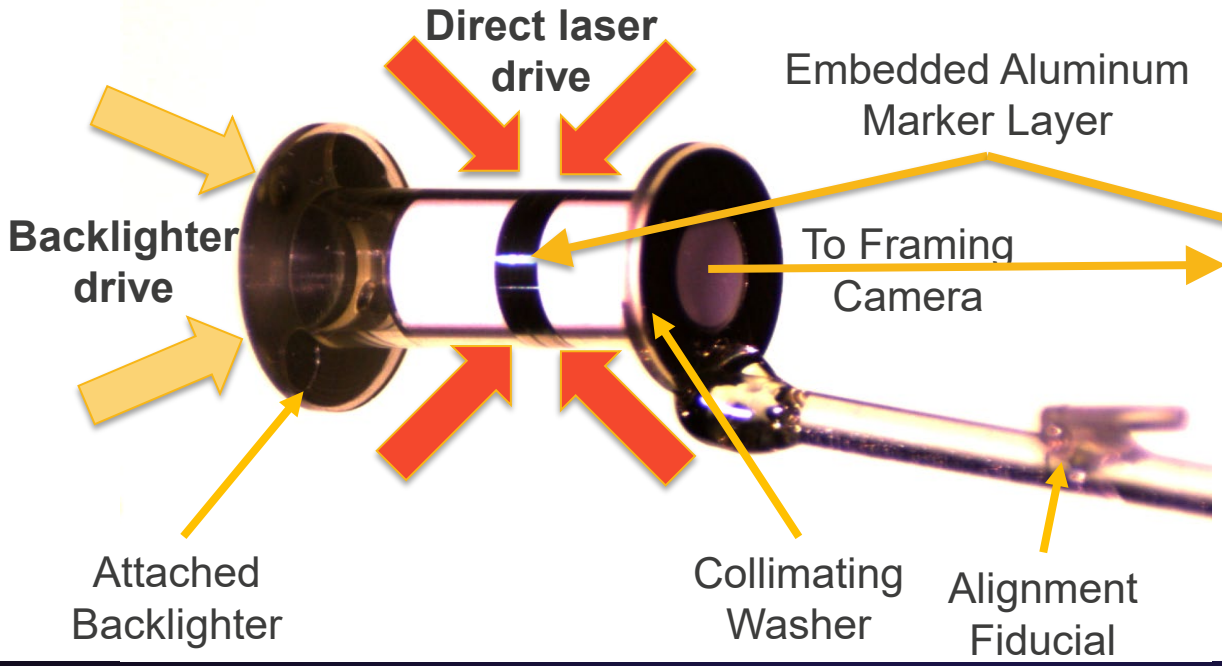
- Cylindrical implosions have been used for many years to study physics in convergent geometry
- Plastic ablator overcoating the marker is directly driven with laser light
- Instability growth occurs due to a combination of RT and BP effects

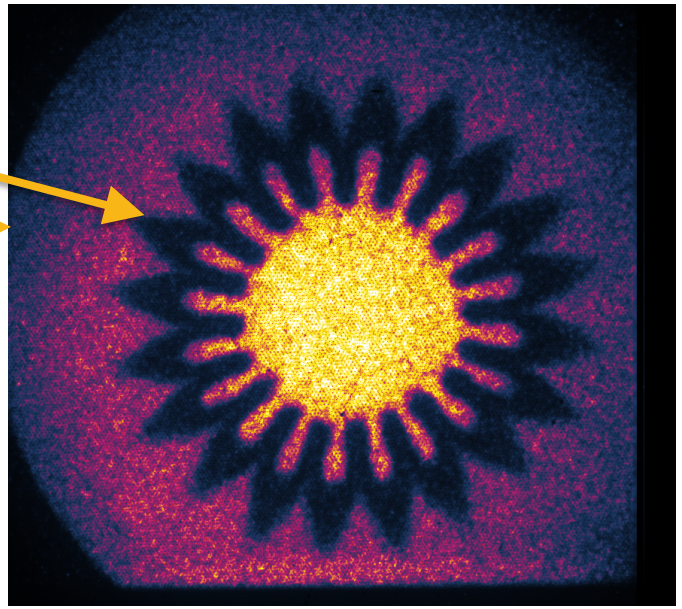




Cylindrical implosions retain the effects of convergence while allowing direct diagnostic access to the unstable interface.

- Cylindrical implosions have been used for many years to study physics in convergent geometry
- Plastic ablator overcoating the marker is directly driven with laser light
- Instability growth occurs due to a combination of RT and BP effects
- Diagnostic x-rays from a backlighter are preferentially absorbed in the marker, allowing direct measurements of the converging interface





LANL is pursuing a systematic approach to developing high CR cylindrical implosions on the National Ignition Facility (NIF).

- High convergence is a necessary but not sufficient condition for surrogacy to ICF implosions

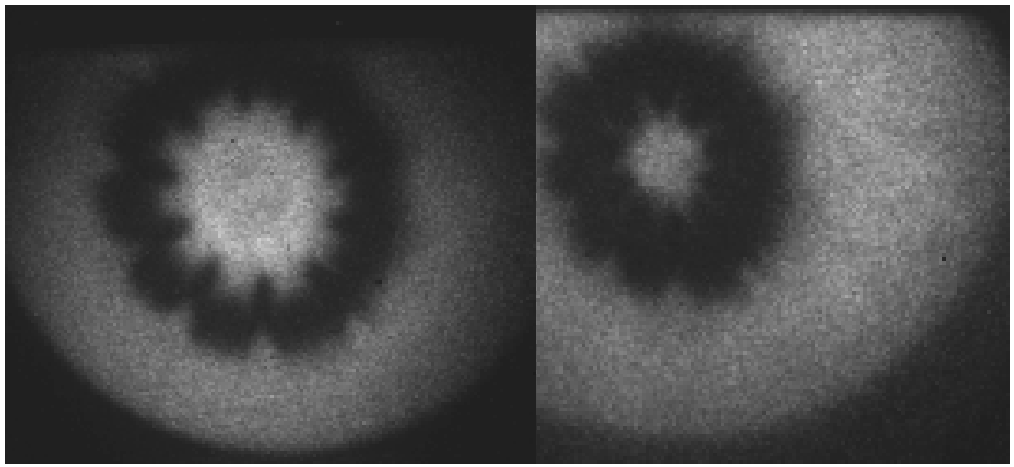
LANL is pursuing a systematic approach to developing high CR cylindrical implosions on the National Ignition Facility (NIF).

- Limitations at OMEGA necessitate high CR implosions be pursued at the NIF
- NIF energies allow for large initial target sizes while maintaining final viewing sizes (CRs) diagnosable at current resolution limits

CR~2
CR~5
CR~10
CR~15

OMEGA Scale-1 Cylinders
- Reboot platform

OMEGA 86832



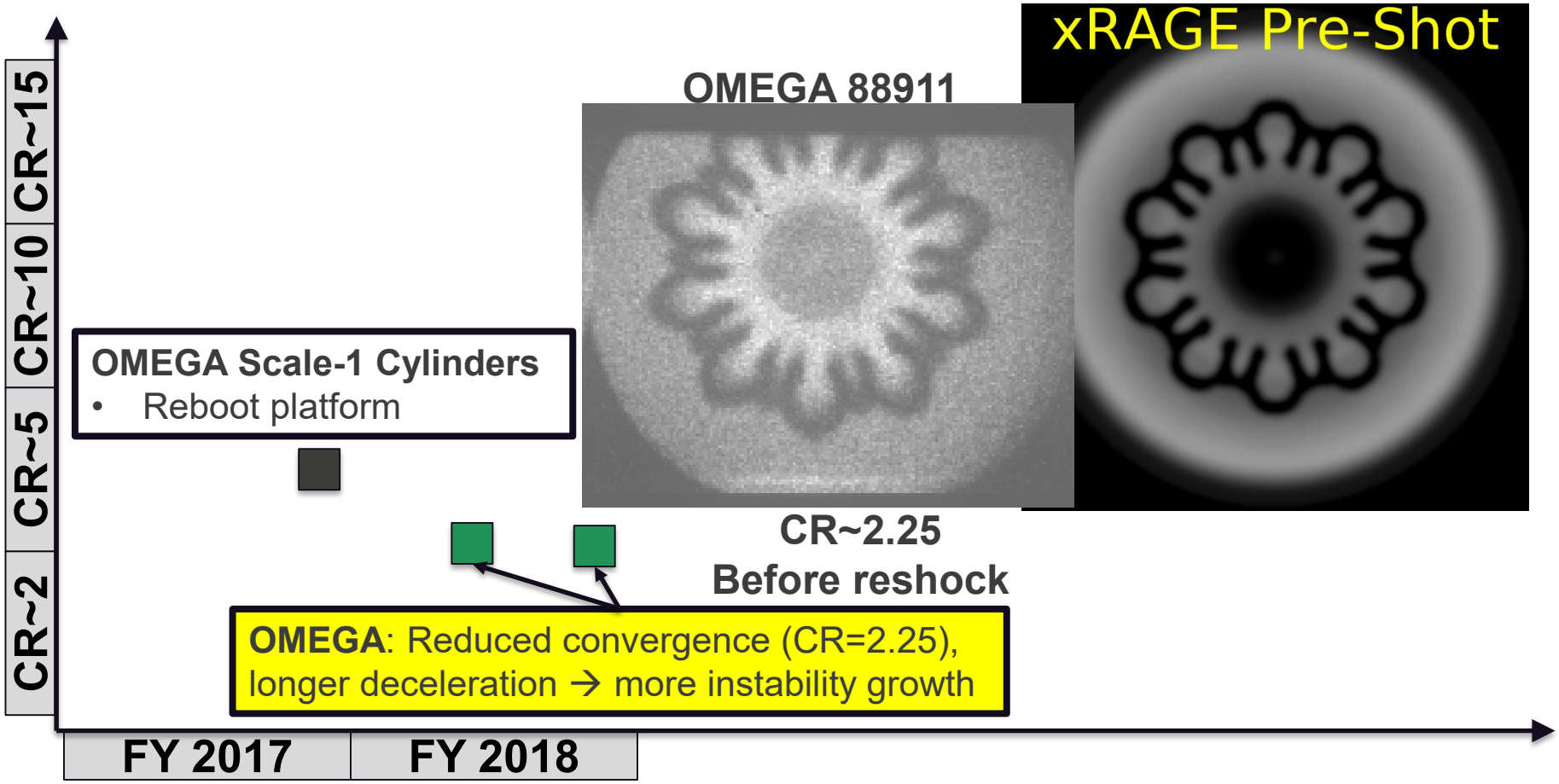
CR~4
Before reshock

CR~4.5
After reshock

FY 2017

LANL is pursuing a systematic approach to developing high CR cylindrical implosions on the National Ignition Facility (NIF).

- OMEGA experiments at lower convergence are incredibly useful for gaining better understanding of details of laser-driven cylindrical implosions



LANL is pursuing a systematic approach to developing high CR cylindrical implosions on the National Ignition Facility (NIF).

- First NIF cylinder experiments aimed at demonstrating a simple concept of scale-invariant instability growth

First NIF Scale-3 Cylinders (Feb. 2019)
- Verified laser drive for 3X larger cylinder
- Confirmed hydrodynamic scale-invariance
- Publications:

1. J. P. Sauppe et al. *Phys. Rev. Lett.* **124**, 185003 (2020)
2. S. Palaniyappan et al. *Phys. Plasmas* **27**, 042708 (2020)
3. J. P. Sauppe et al. *High Eng. Dens. Phys.* **36**, 100831 (2020)

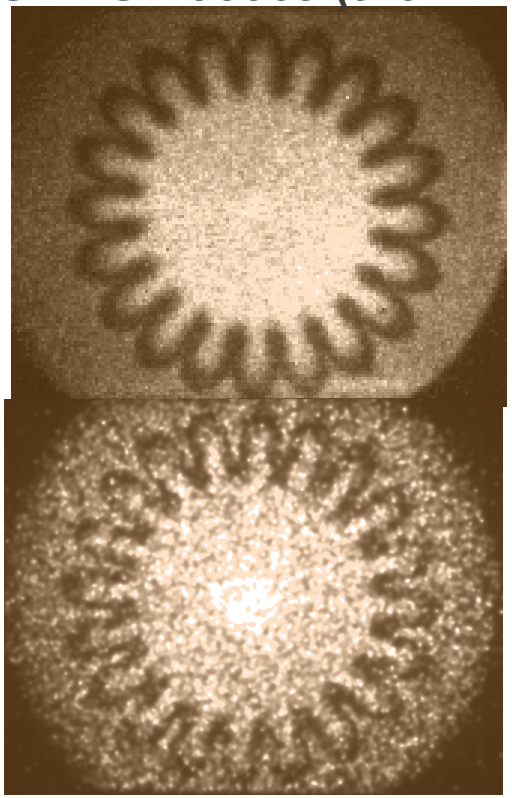
OMEGA Scale-1 Cylinders
- Reboot platform

OMEGA: Reduced convergence (CR=2.25), longer deceleration → more instability growth

CR~2 | CR~5 | CR~10 | CR~15

FY 2017 | FY 2018 | FY 2019

OMEGA 93069 (t~6.2 ns)



NIF N190212-003 (t~18.6 ns)

LANL is pursuing a systematic approach to developing high CR cylindrical implosions on the National Ignition Facility (NIF).

- Second NIF experiments pushed to higher CR and improved image quality

First NIF Scale-3 Cylinders (Feb. 2019)
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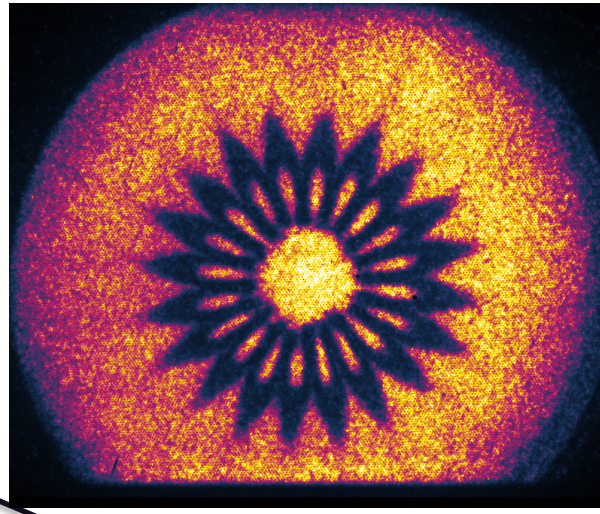
OMEGA Scale-1 Cylinders
- Reboot platform

OMEGA: Reduced convergence (CR=2.25), longer deceleration → more instability growth

Second NIF Scale-3 Cylinders
- Pushed to higher convergence
- Greatly improved image quality

N200213-001

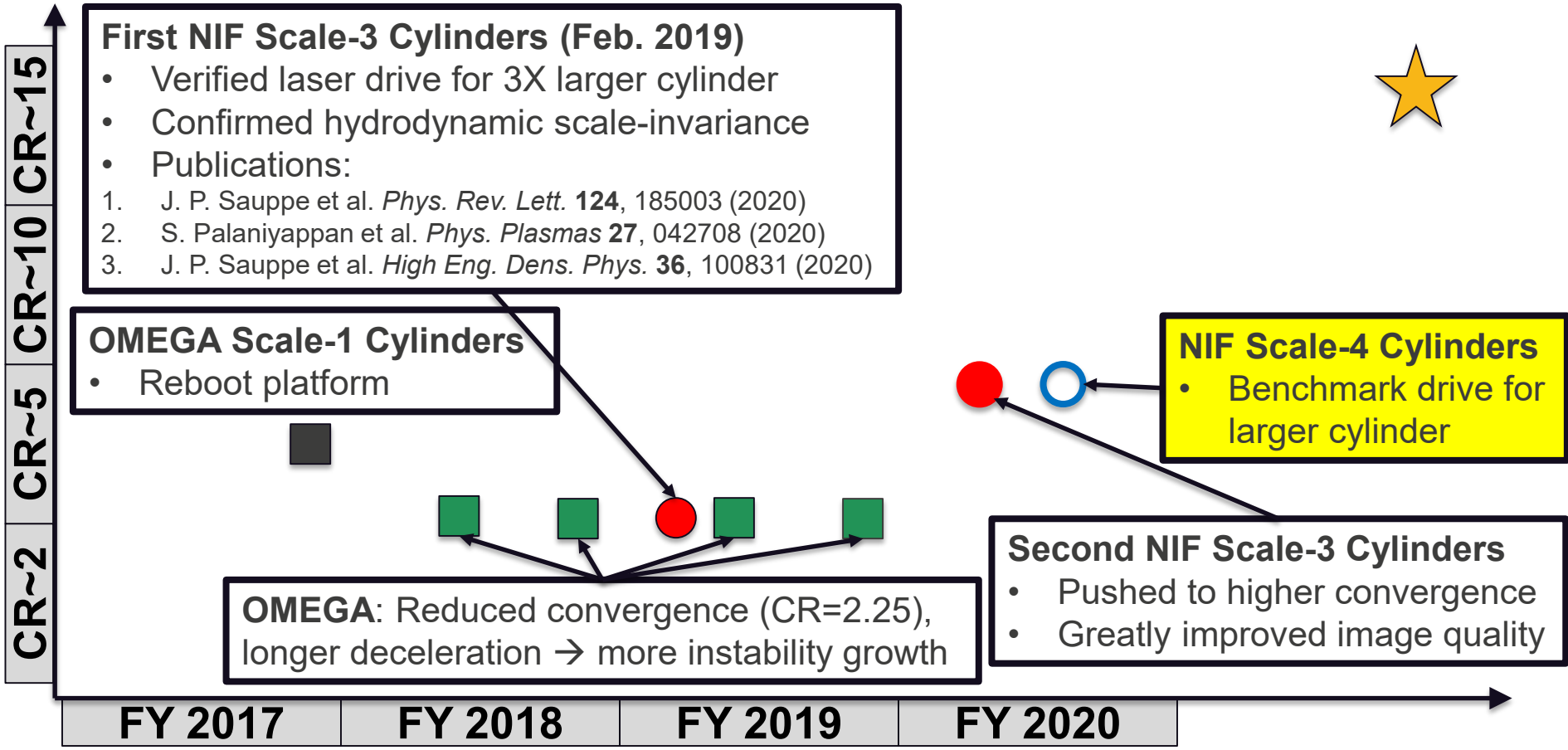


CR~2 | CR~5 | CR~10 | CR~15

FY 2017 | FY 2018 | FY 2019 | FY 2020

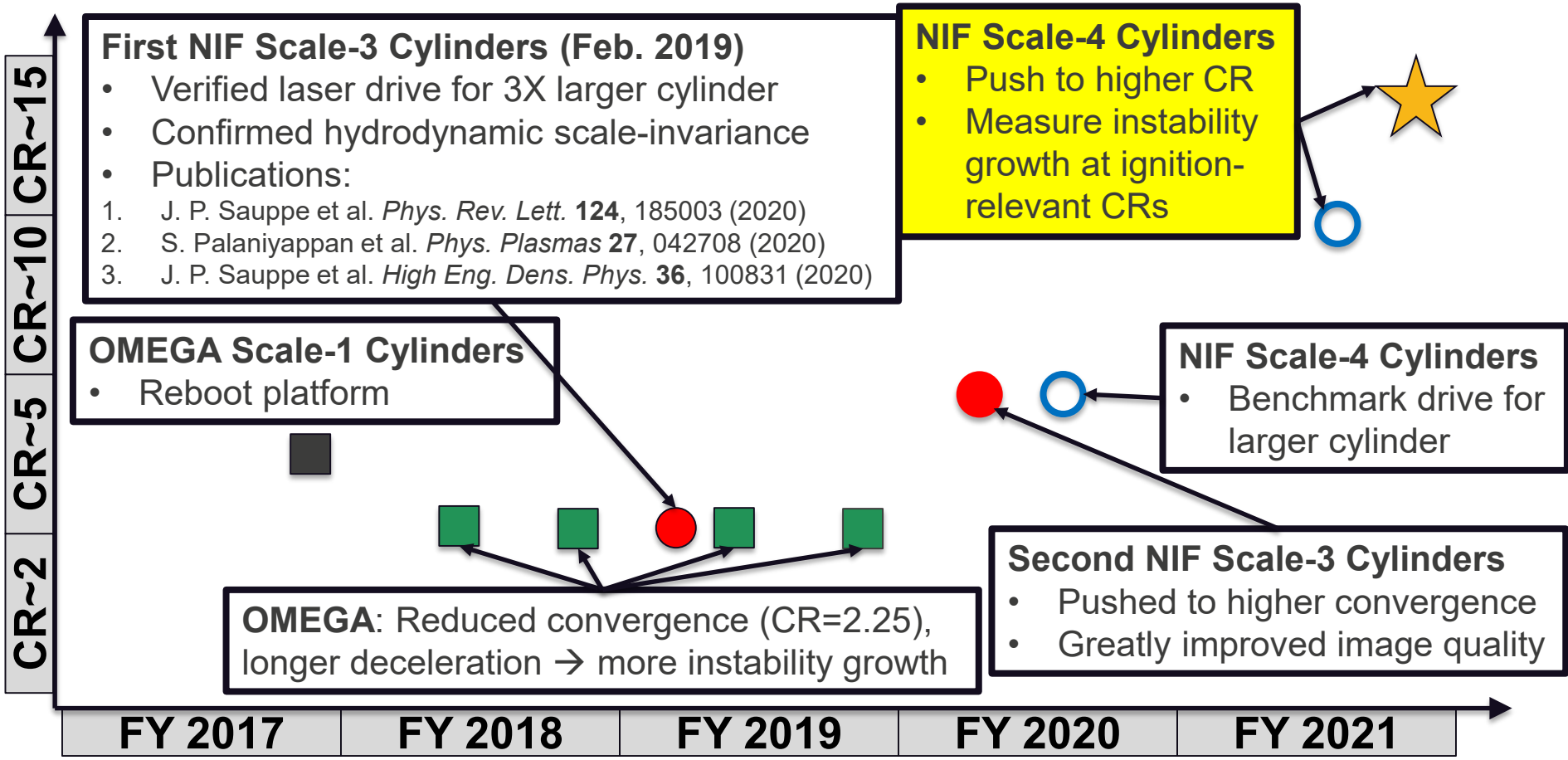
LANL is pursuing a systematic approach to developing high CR cylindrical implosions on the National Ignition Facility (NIF).

- Larger cylinders are being considered for future NIF shots
- Larger initial size allows higher CR at same final viewing radius



LANL is pursuing a systematic approach to developing high CR cylindrical implosions on the National Ignition Facility (NIF).

- We hope to achieve ignition relevant CR~10-15 towards the end of FY21



Demonstrating Scale-Invariant Instability Growth between OMEGA and NIF Cylindrical Implosions

Hydrodynamic scaling is motivated by the fact that the Euler equations are invariant under certain transformations.

- The Euler equations are invariant to the transformation[1,2]

$$\vec{x} \rightarrow \lambda\vec{x}, \qquad t \rightarrow \lambda t$$

- If seeds for instability are also scaled, then growth is scale-invariant[3,4]

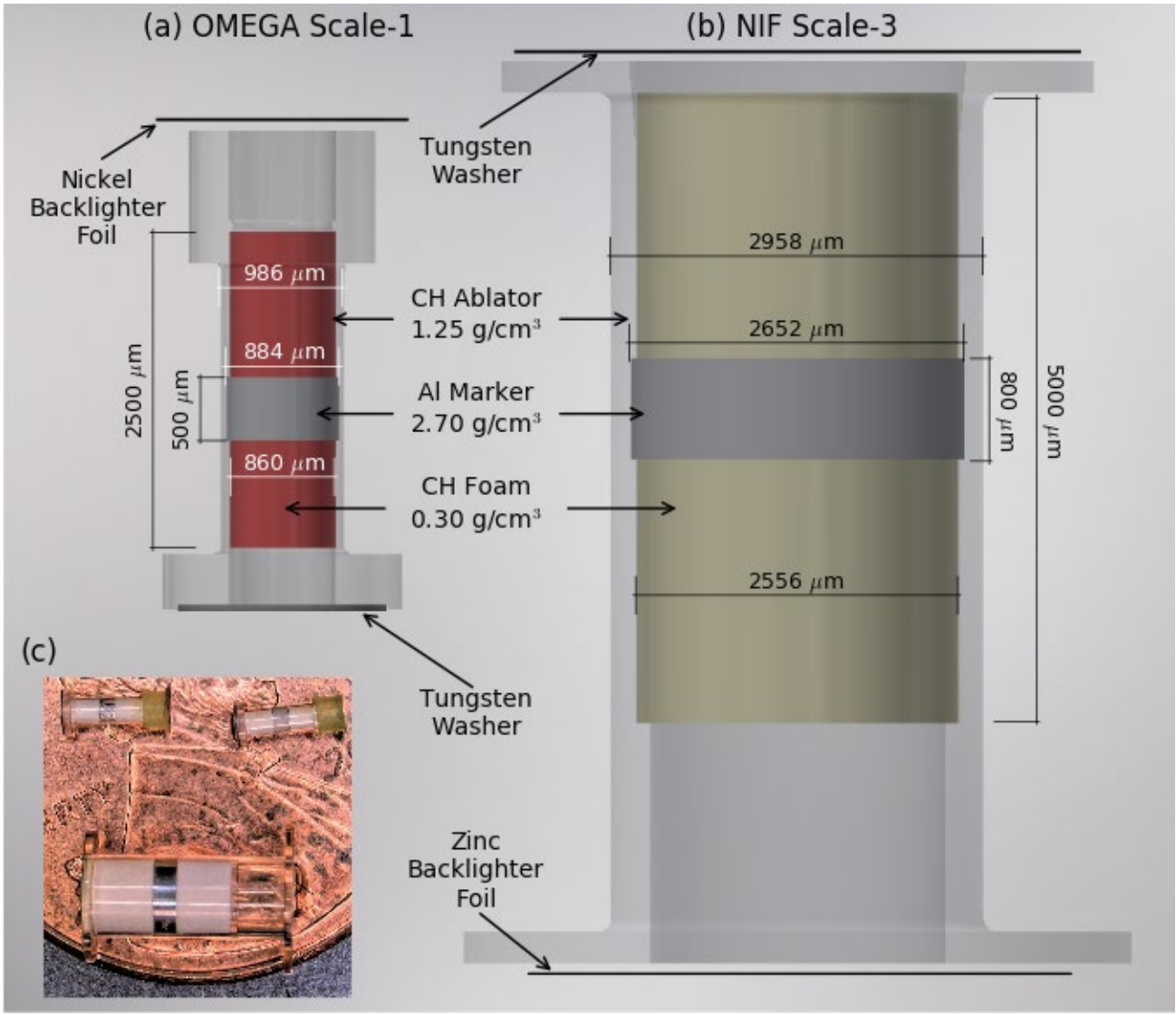
- However, many aspects of ICF/HED experiments do NOT scale:
  - Thermal conduction (and ablative stabilization)
  - Radiation transport
  - Laser plasma instabilities
- In addition, there are differences in laser facility settings:
  - Beam spots and phase plates used
  - Number of beams and their pointing

The short, impulsive drive used here relaxes these non-scaling constraints

1. Zel'dovich & Raizer, *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena* (NY Acad. Press 1966).
2. D. Ryutov et al., *Astrophys. J.* **518**, 821 (1999).
3. R. Nora et al., *Phys. Plasmas* **21,** 056316 (2014).
4. D. Casey et al., *Phys. Plasmas* **25**, 056308 (2018).

The NIF target is scaled up by a factor of $\lambda = 3$ in radial dimension from the OMEGA target, and laser drive is also extended in time.

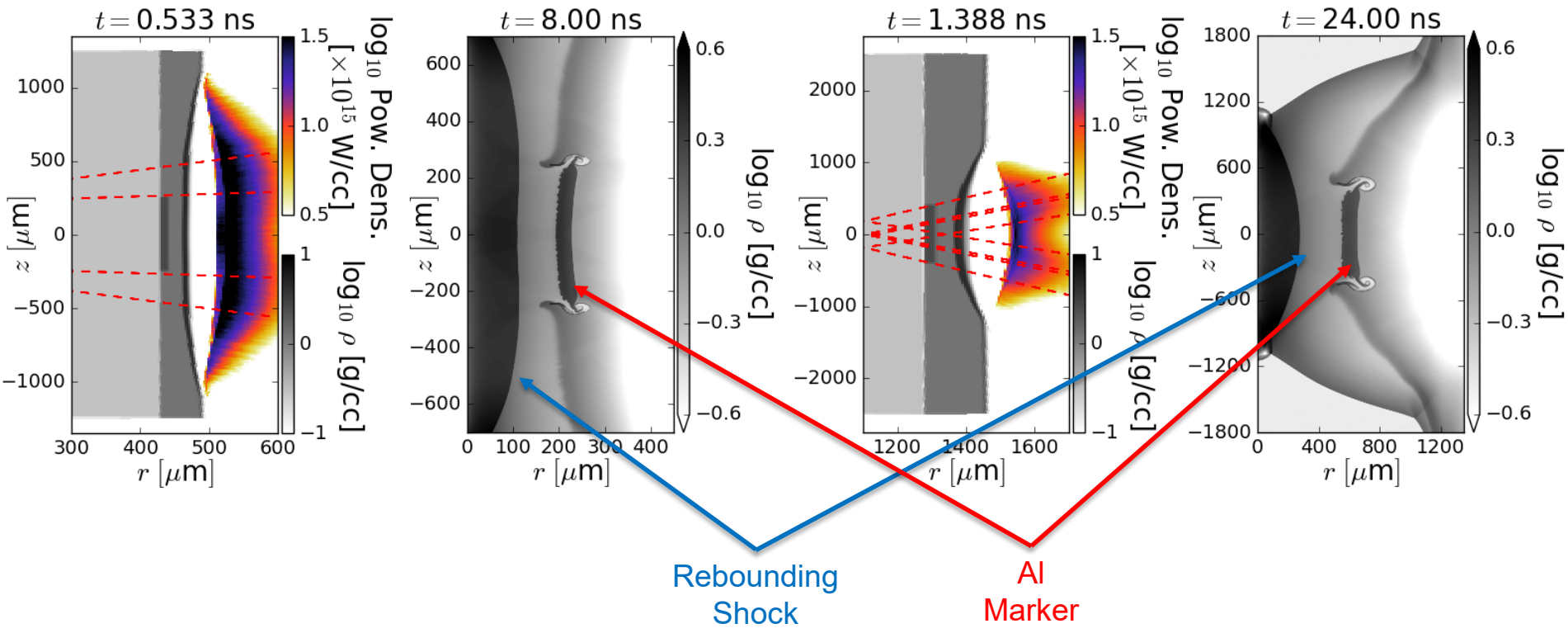
- Before pushing to high CR, a hydrodynamically scaled implosion was designed for the NIF
- Design is based on OMEGA experiments studying deceleration Rayleigh-Taylor instability at low convergence (CR~2.25)
- Radial size increased by 3X for the NIF, but axial length was not scaled



xRAGE[1,2] simulations are used to predict the laser beam pointings and powers that drive an axially uniform implosion of the marker.

OMEGA Scale-1 Implosion

NIF Scale-3 Implosion



1. M. Gittings et al., *Comp. Sci. Disc.* **1**, 015005 (2008).
2. B. M. Haines et al., *Phys. Plasmas* **24**, 052701 (2017).

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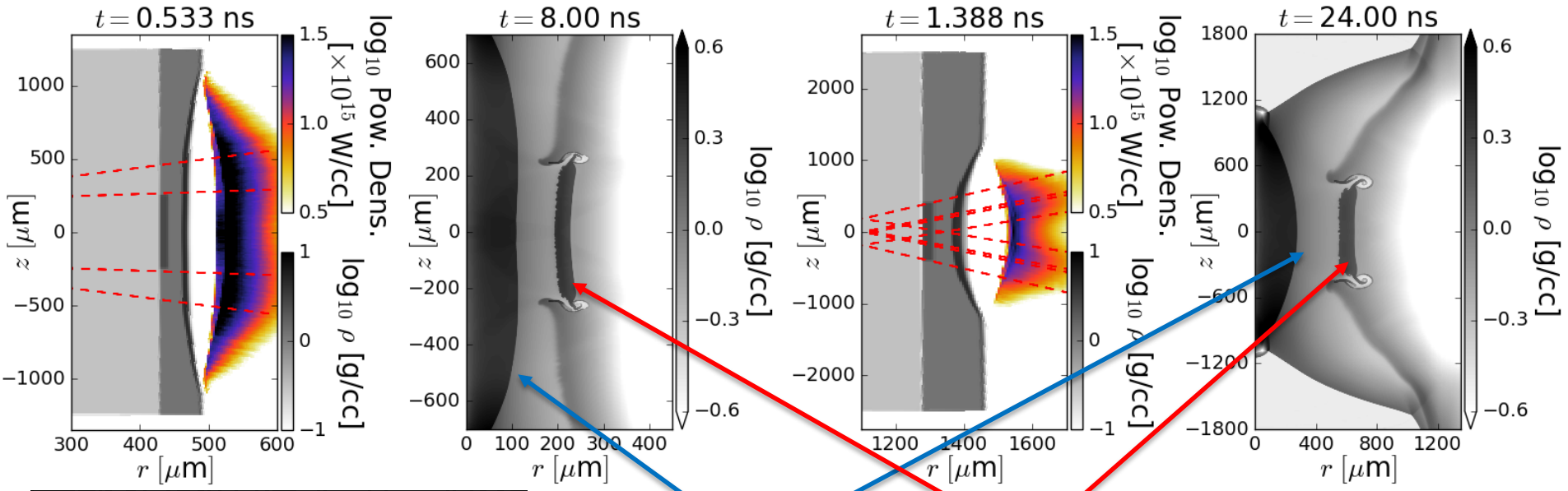
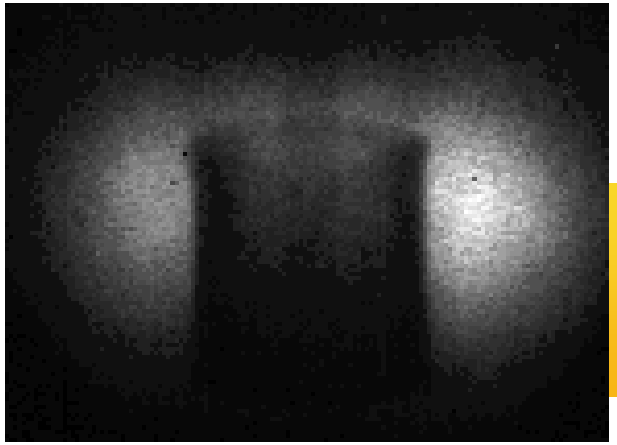
OMEGA Scale-1 Implosion

NIF Scale-3 Implosion





Rebounding Shock

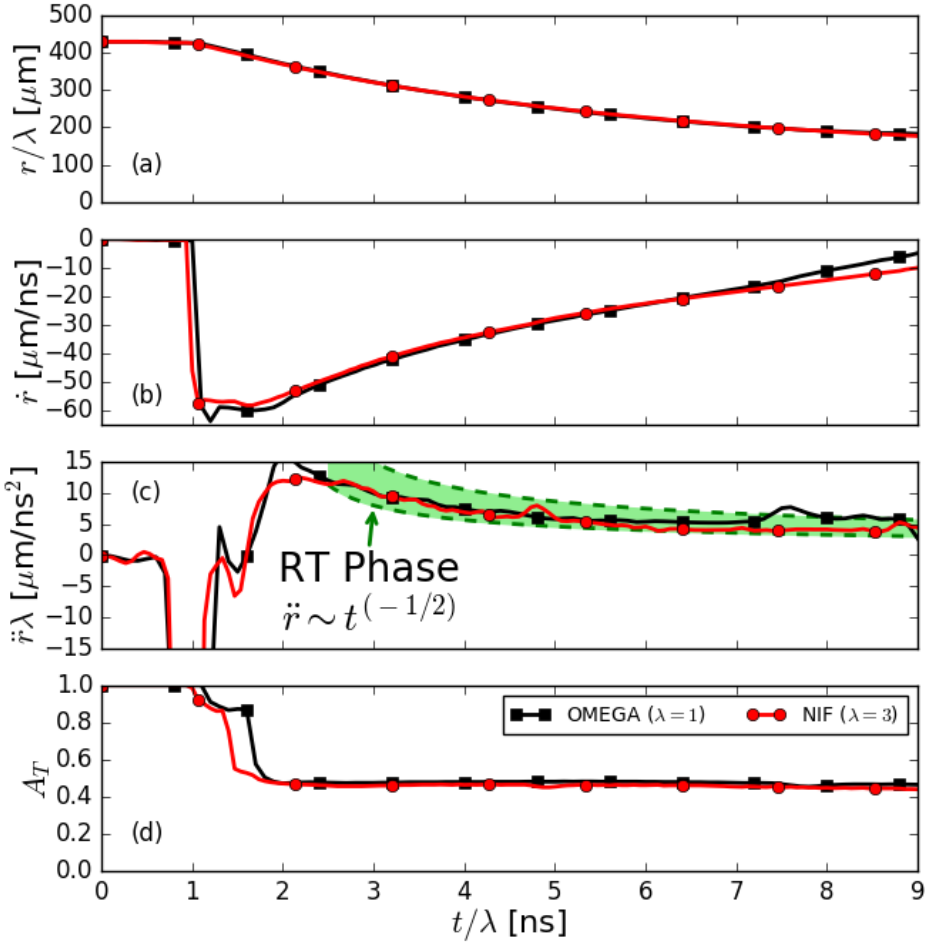
Al Marker

Transverse radiograph shows very small bowing of marker layer for OMEGA target (plans underway for NIF transverse views)

5005 (2008).

2. B. M. Haines et al., *Phys. Plasmas* **24**, 052701 (2017).

The hydrodynamic trajectories are scale-invariant between the OMEGA and NIF cylindrical implosion designs.



- Hydrodynamic variables recast in a scale-invariant form:

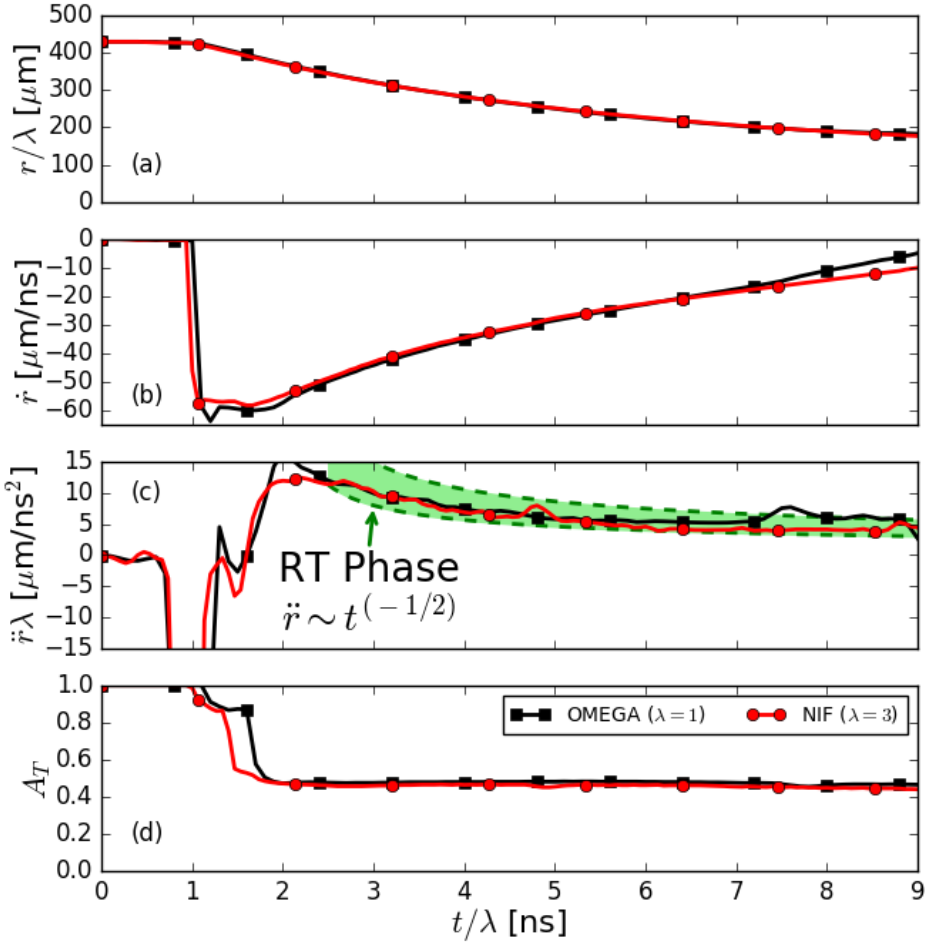
$$r = \lambda \hat{r}$$

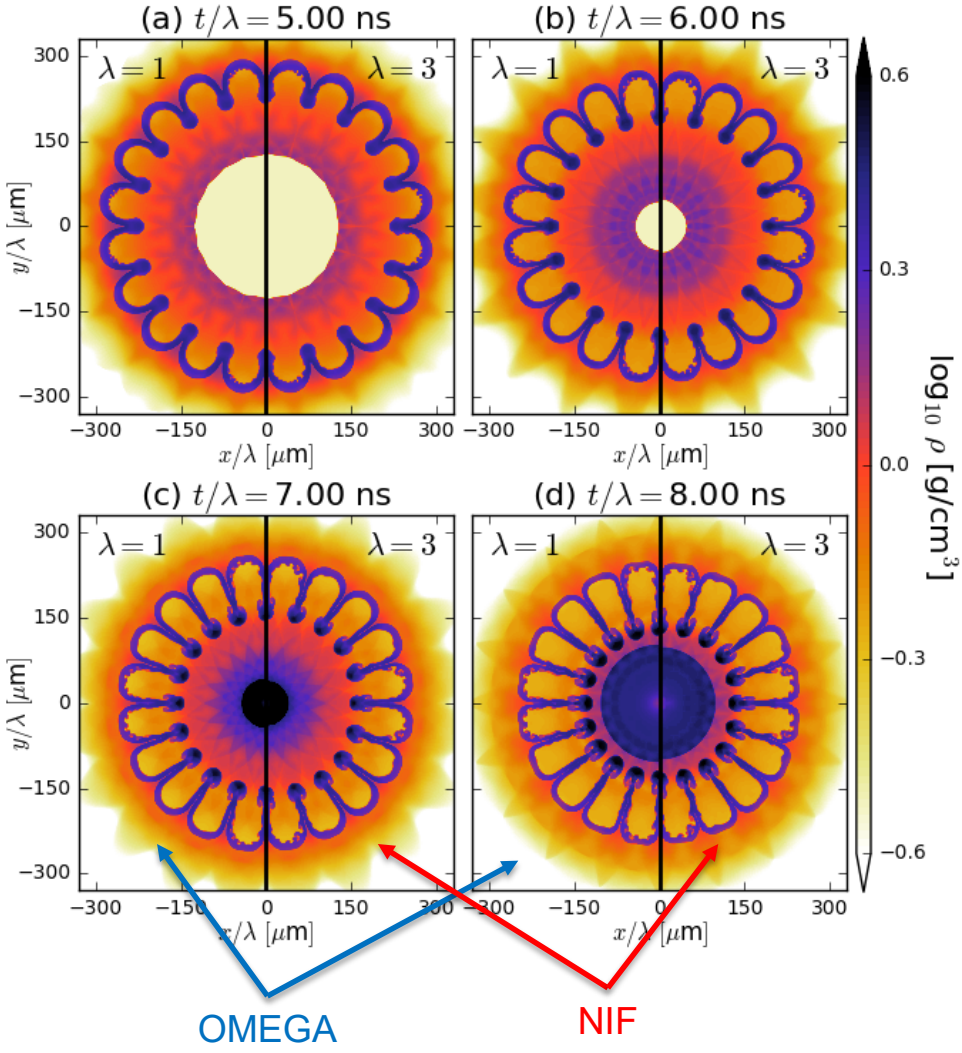
$$t = \lambda \hat{t}$$

$$\dot{r} = \frac{d(\lambda \hat{r})}{d(\lambda \hat{t})} = \hat{\dot{r}}$$

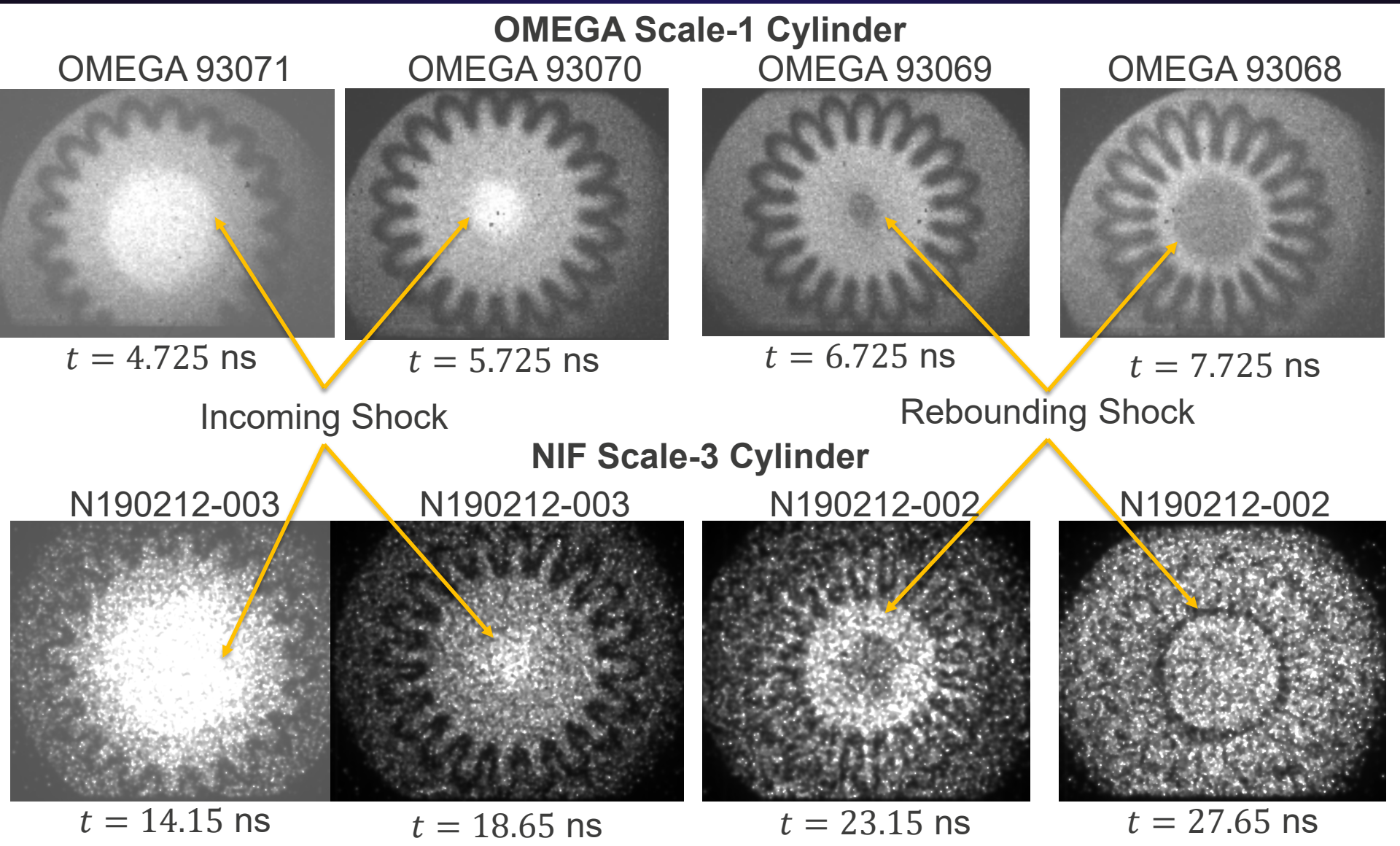
$$\ddot{r} = \frac{d^2(\lambda \hat{r})}{d(\lambda \hat{t})^2} = \frac{1}{\lambda} \hat{\ddot{r}}$$

The xRAGE simulations predict scale-invariant instability growth well into the nonlinear phase for a single-mode *m*=20 perturbation.

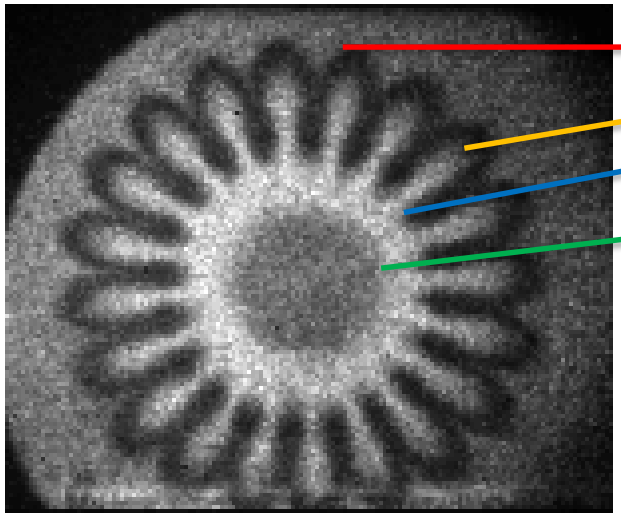




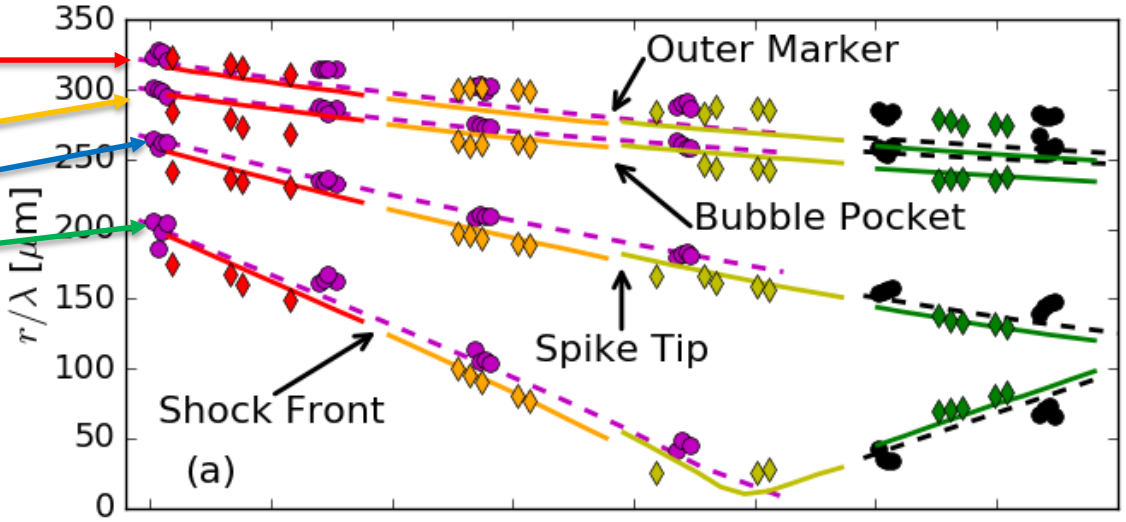
Experimental radiographs from the cylindrical implosions demonstrate scale-invariant instability growth between facilities.

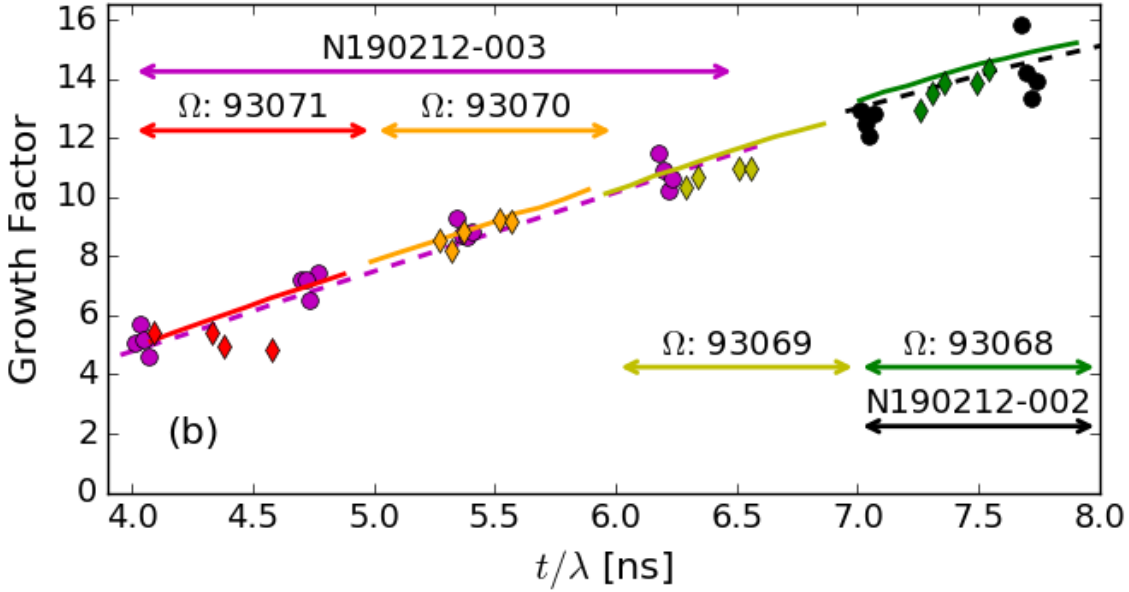


Growth factors of 14 are observed at late time ($t/\lambda = 7.7$ ns) for both sets of cylindrical implosion experiments.



OMEGA 93068

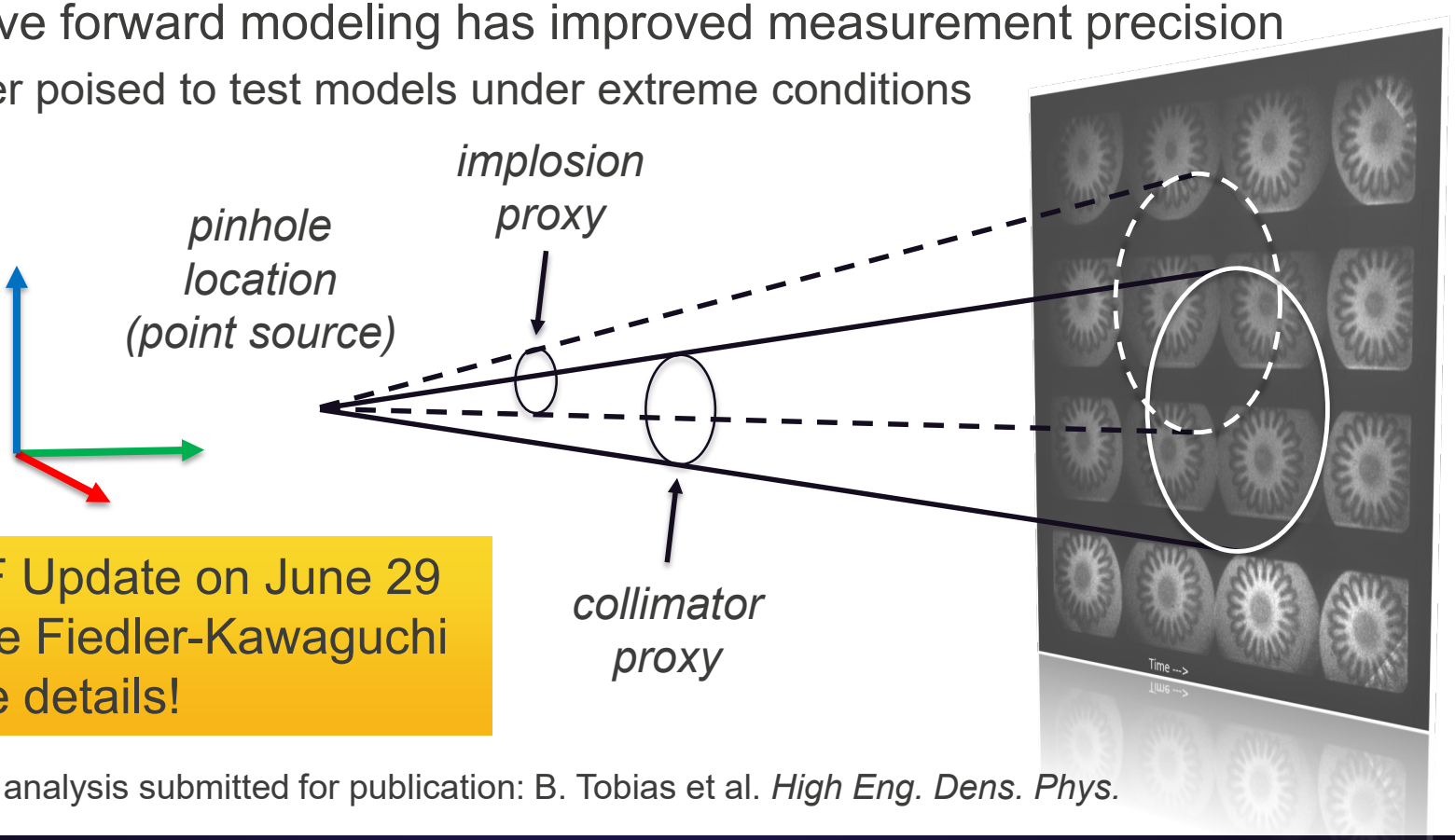




- Each shot is simulated separately using as-built dimensions and as-fired laser energy
- Common tuning parameters used for all simulations, only laser power multiplier differs between OMEGA and NIF

Accurate analysis of OMEGA data using the Bayes Inference Engine is contributing to our ability to tightly constrain models.

- The Bayes Inference Engine forward models the imploding cylinder and fits features collectively with regularization
  - Parallax and magnification are inferred in BIE
- Iterative forward modeling has improved measurement precision
  - Better poised to test models under extreme conditions



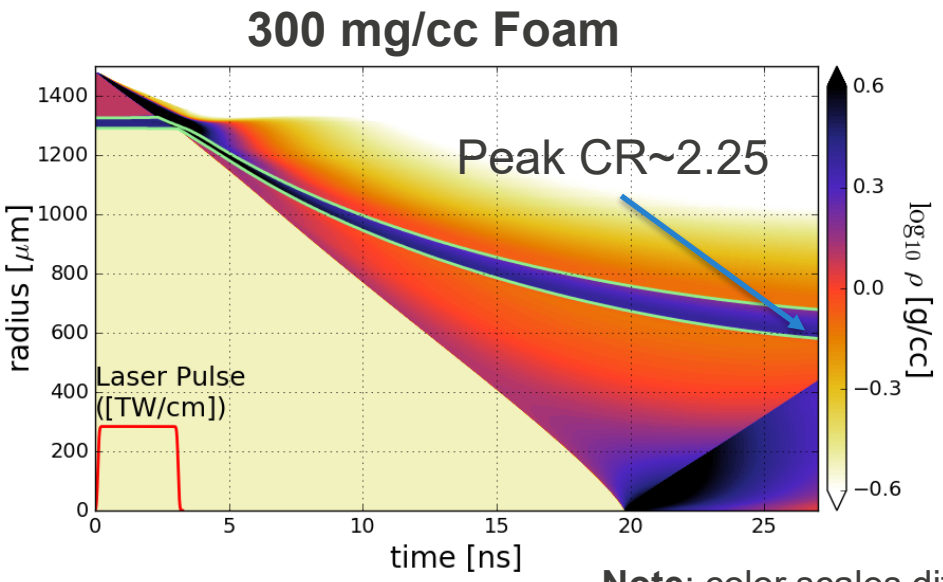
See ICF Update on June 29 by Codie Fiedler-Kawaguchi for more details!

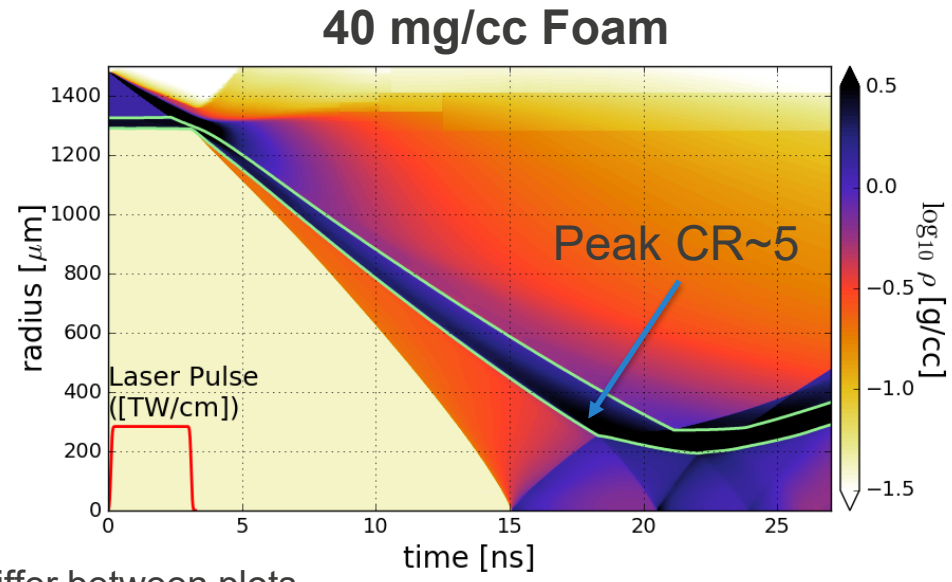
Details of BIE analysis submitted for publication: B. Tobias et al. *High Eng. Dens. Phys.*

Recent NIF Results at CR=5

The second Disc. Sci. cylinders shot day at NIF (Feb. 2020) increased convergence by lowering the central foam density.

- Laser power and beam pointings were kept fixed
- Target construction was identical except for foam density





Note: color scales differ between plots

- Higher CR is achieved with lower foam density
- The shock speed in the foam also increases, resulting in the rebound shock hitting the marker earlier in time → Tradeoffs in design space

A linear theory of instability growth, including compressibility and Bell-Plesset effects of convergence, is used to highlight differences.

$$\left(-\gamma_\rho + \frac{d}{dt}\right)\frac{d}{dt}(a_m \rho R) = \gamma_0^2 (a_m \rho R)$$

R. Epstein, *Phys. Plasmas* **11.11** (2004) 5114.

$$\gamma_0 = \sqrt{\frac{A_T m \ddot{r}}{r}}$$

classical

$$\gamma_R = \frac{1}{R}\frac{dR}{dt}$$

convergence

$$\gamma_\rho = \frac{1}{\rho}\frac{d\rho}{dt}$$

compressible

Preliminary estimates indicate that Bell-Plesset plays a larger role for the lower density foam targets that achieve a higher CR.

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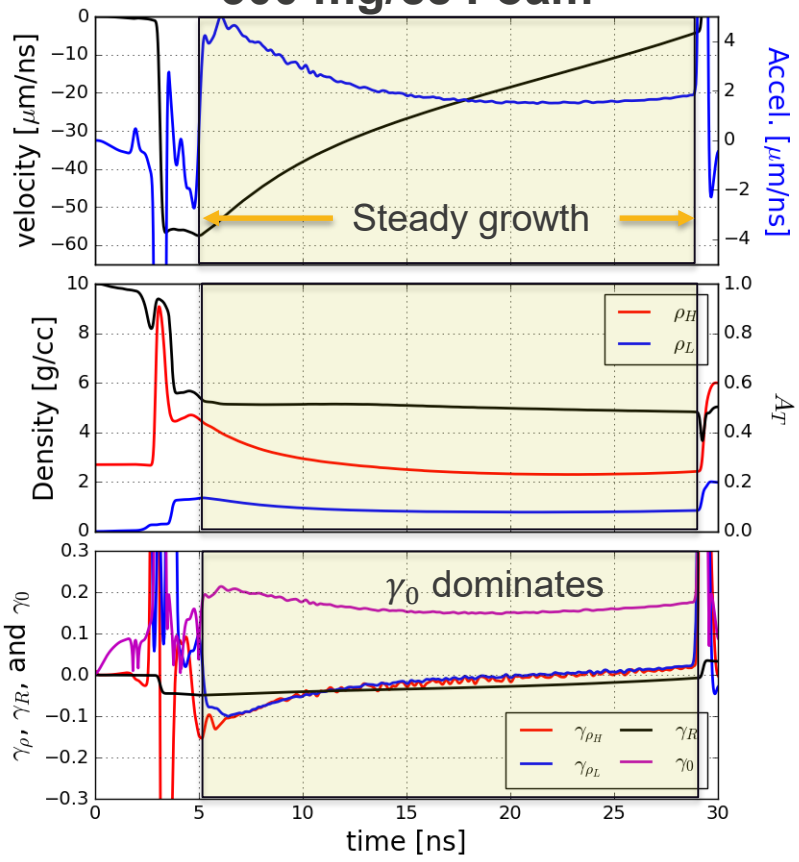
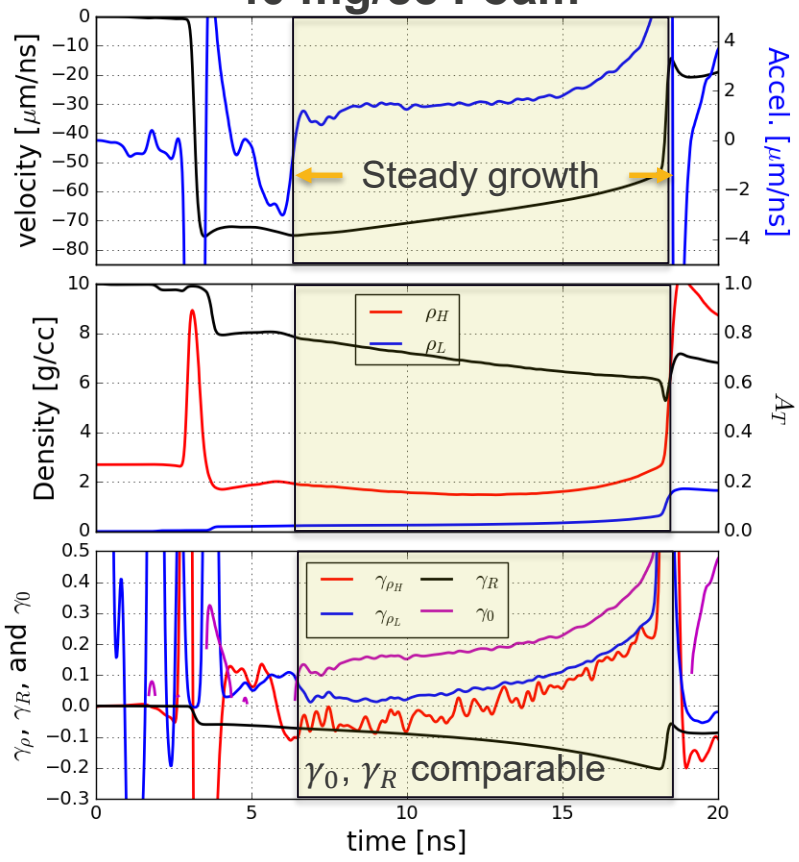
compressible

300 mg/cc Foam



40 mg/cc Foam



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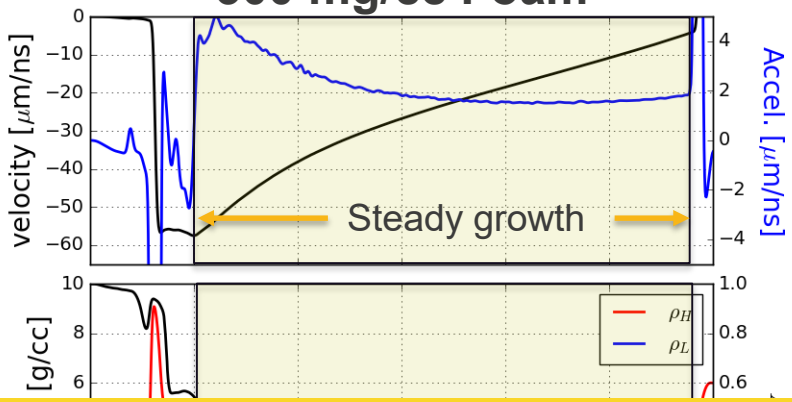
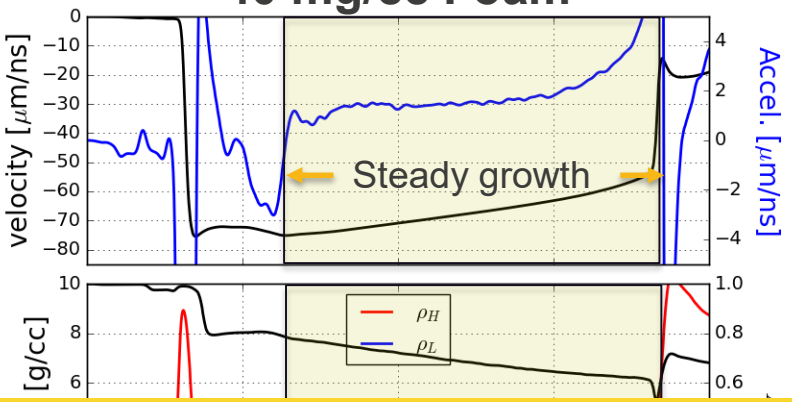
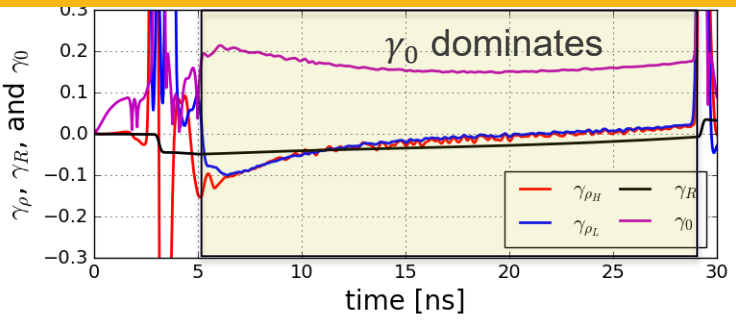
300 mg/cc Foam

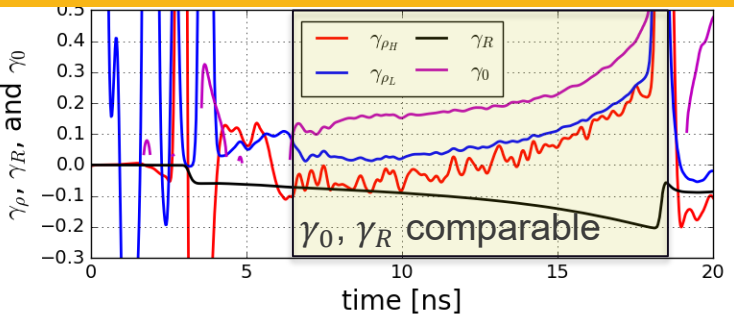


40 mg/cc Foam



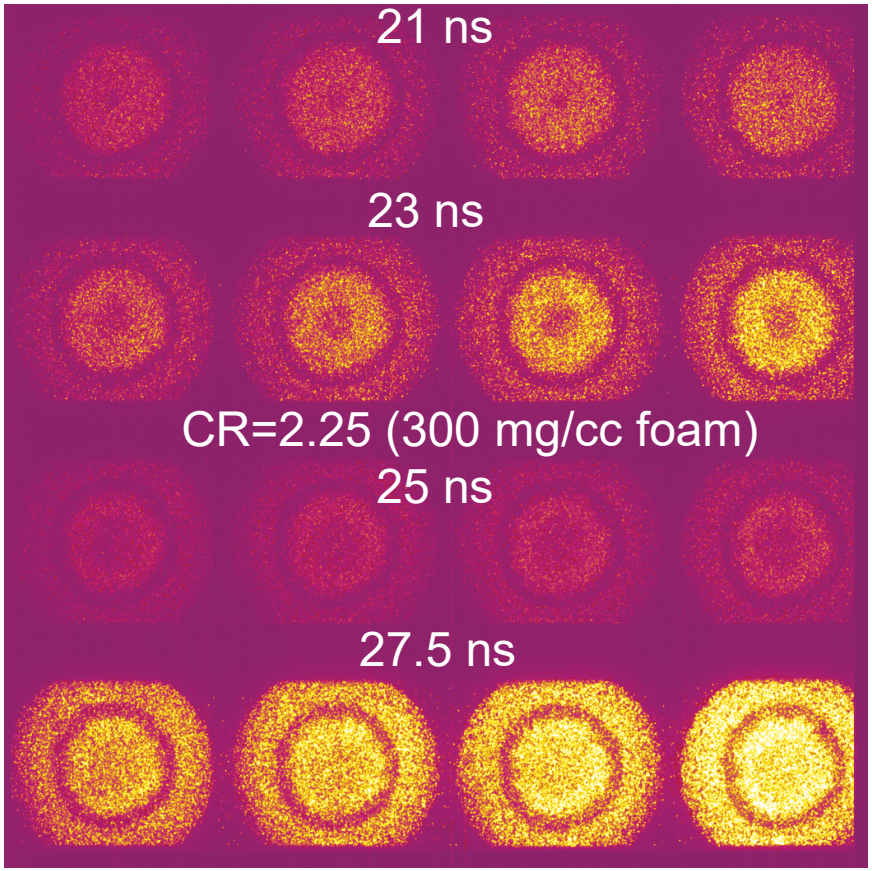
These differences will be investigated in greater detail this summer with returning graduate student Will Gammel (XCP-6, Univ. Arizona)





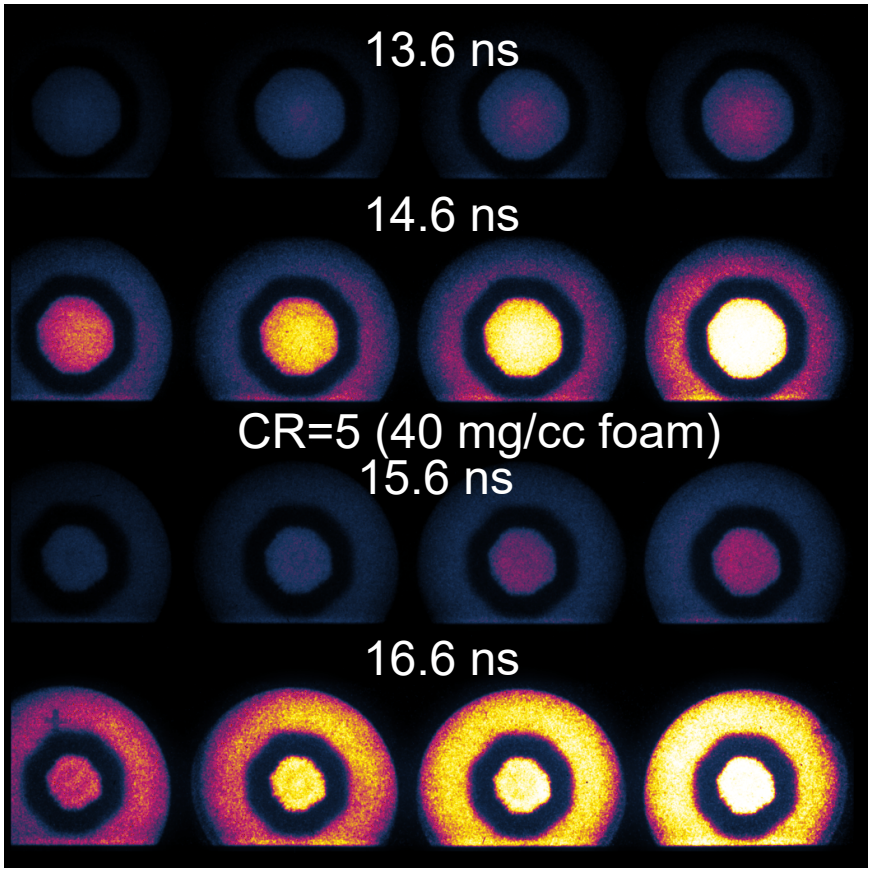
Significant changes were made to the diagnostic setup to improve images for our second Disc. Sci. shot day at higher convergence.

N190212-001



Very poor signal-to-noise in first shot day

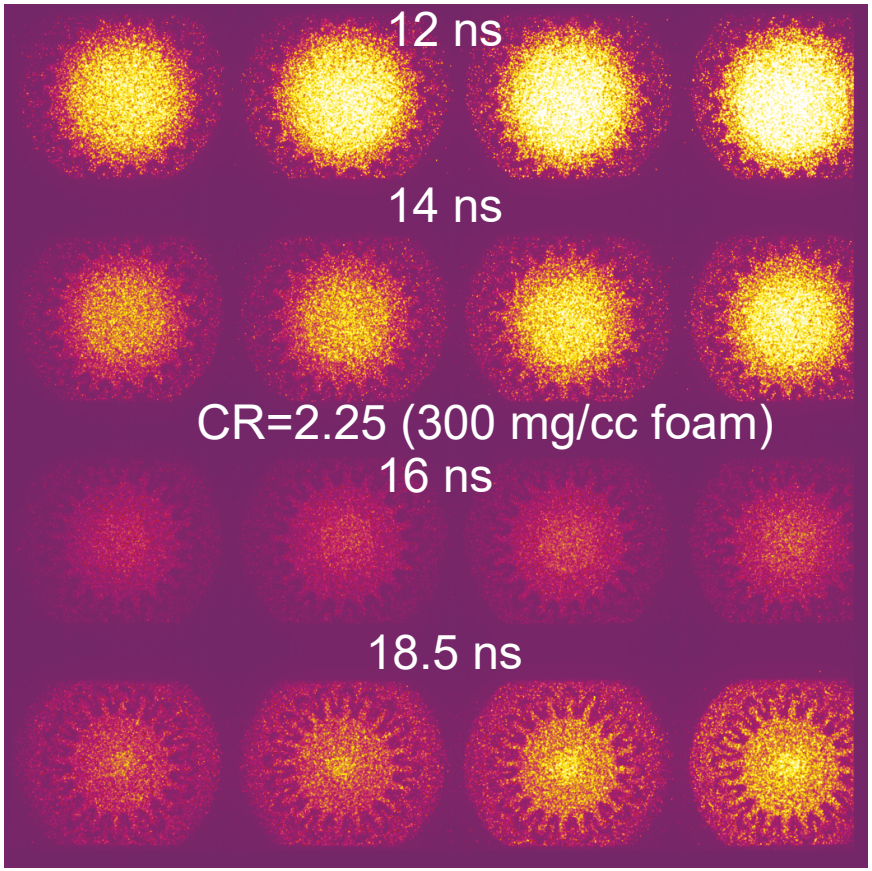
N200212-002



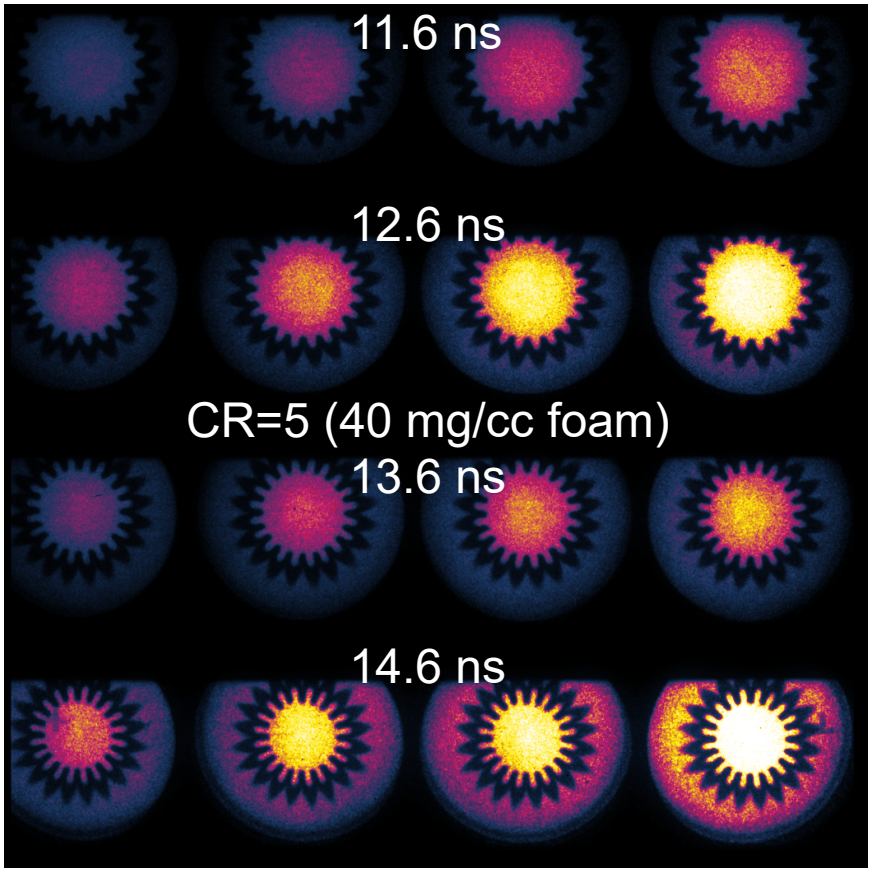
The m=8 feature is due to the laser drive (this was not apparent in first shot day)

Previous early time data for perturbed targets were reasonable, but signal is considerably improved in the most recent shot day.

N190212-003



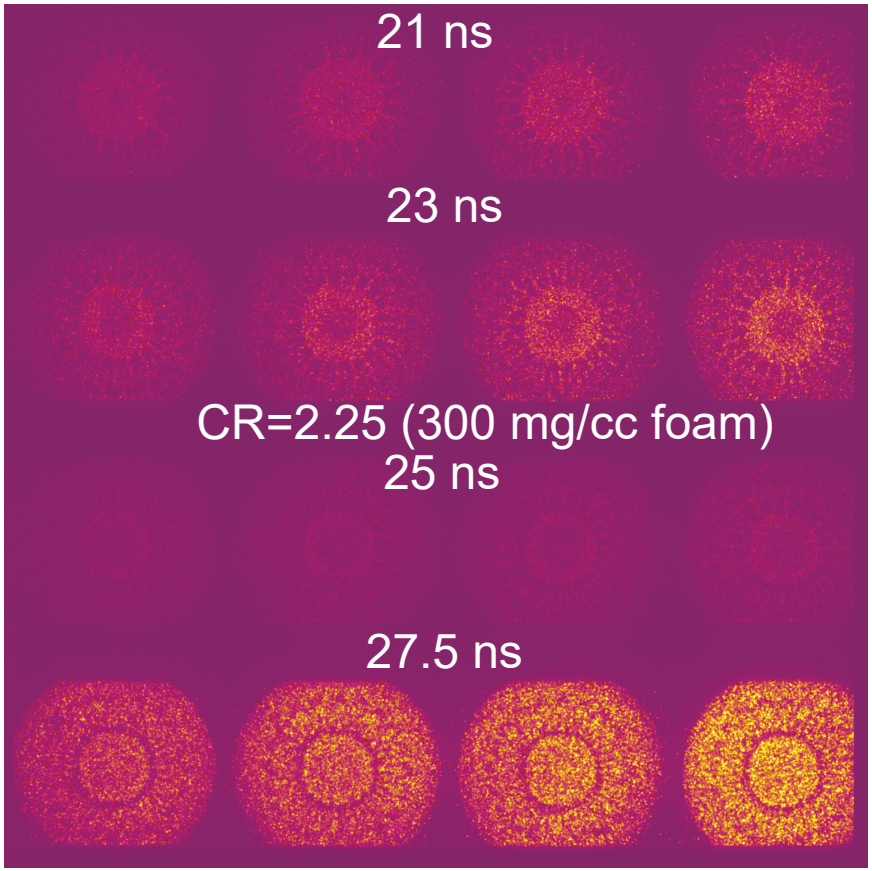
N200212-003



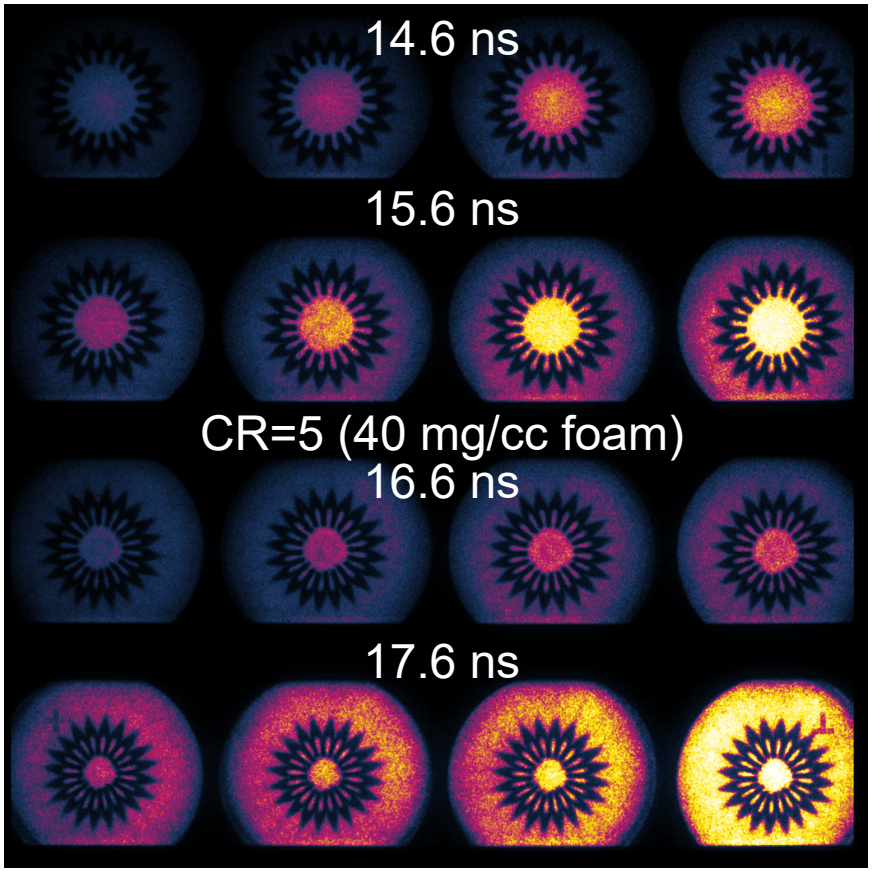
Note this is not a 1-to-1 comparison, due to differences in foam density

Diagnostic improvements provide clearly resolved bubble pockets and spike tips at late times in the implosion.

N190212-002



N200213-001

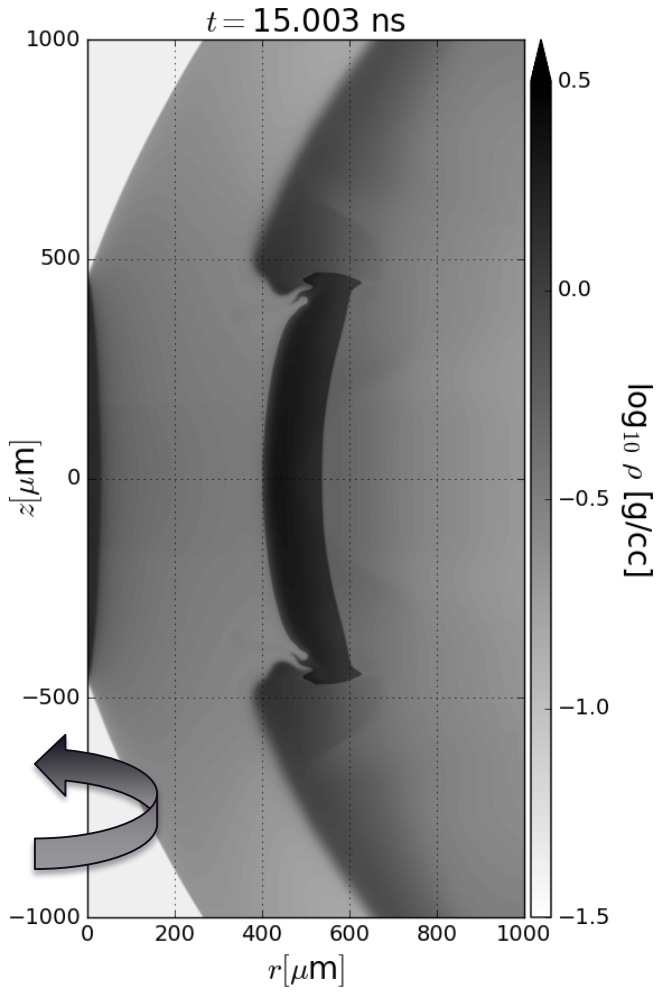


Diagnostic improvements thanks to Sasi Palaniyappan, Ben Tobias, and Kirk Flippo

Signal 7500 →15000 on strip 4

The xRAGE pre-shot computation of the smooth target shows modest marker bowing in the 2D $r-z$ geometry computation.

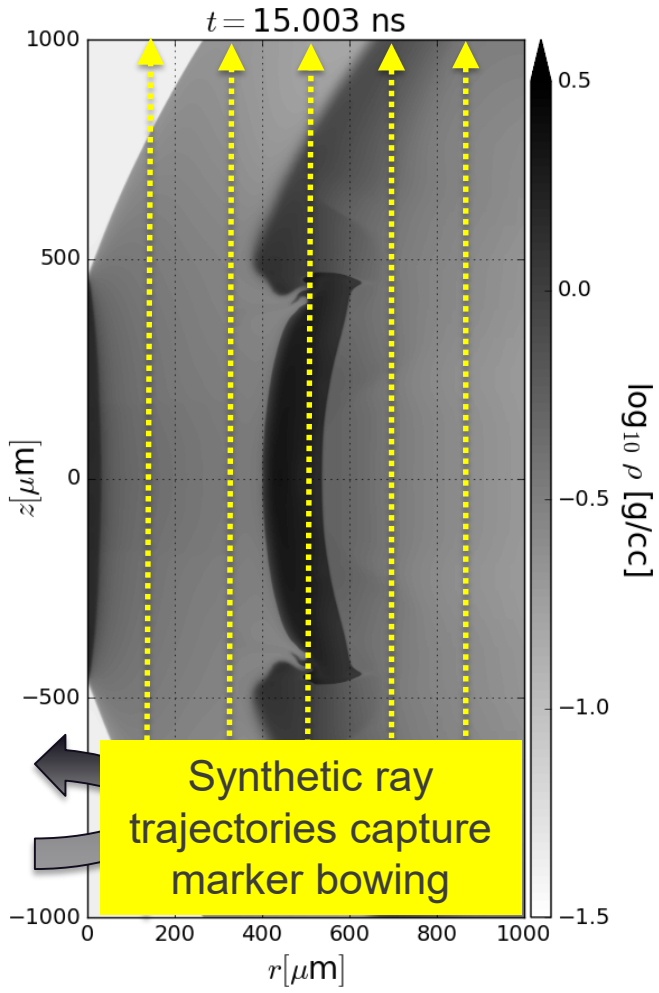
- Pre-shots use as-built target dimensions with nominal laser pulse

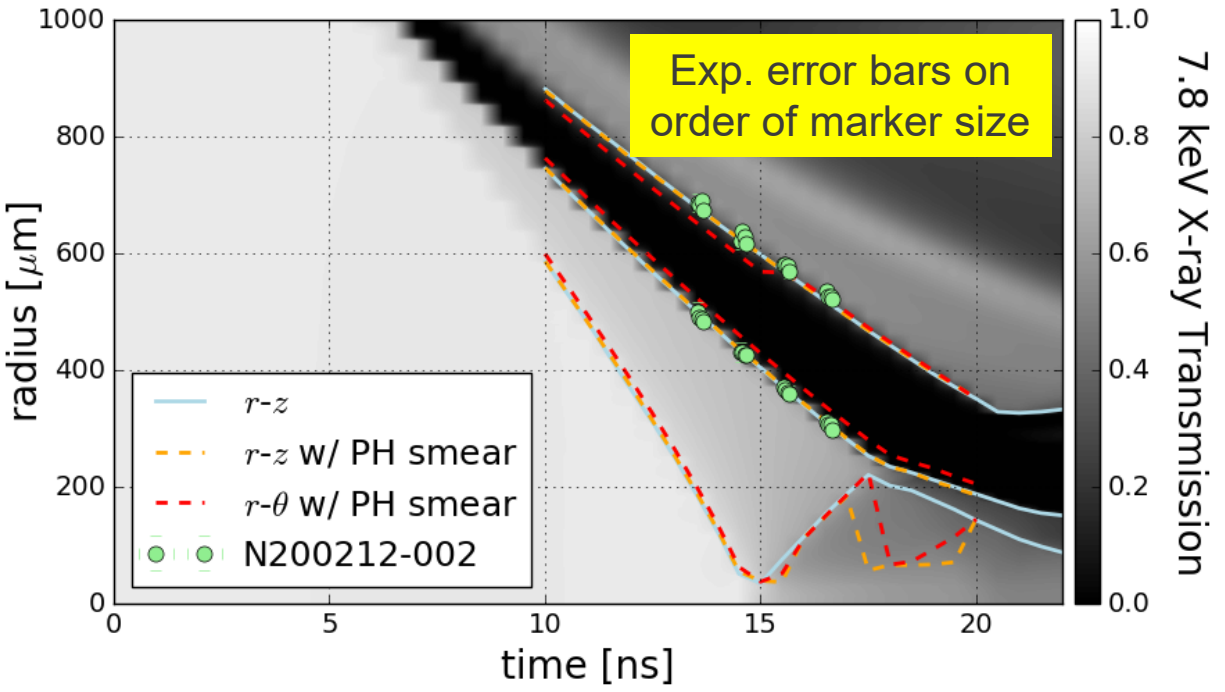


- The 2D $r-z$ geometry computation is sufficient to capture behavior of targets with no azimuthal asymmetry
  - Marker bowing and axial non-uniformity of shock front
- Note that the laser drive imprints an $m = 8$ asymmetry
  - 3D computations are required to capture both marker bowing and drive asymmetry
  - But 3D laser ray trace not yet available

The xRAGE pre-shot computation of the smooth target matches the experimental data very well.

- Synthetic radiographs produced by following rays down the cylinder axis for direct comparison to experimental data

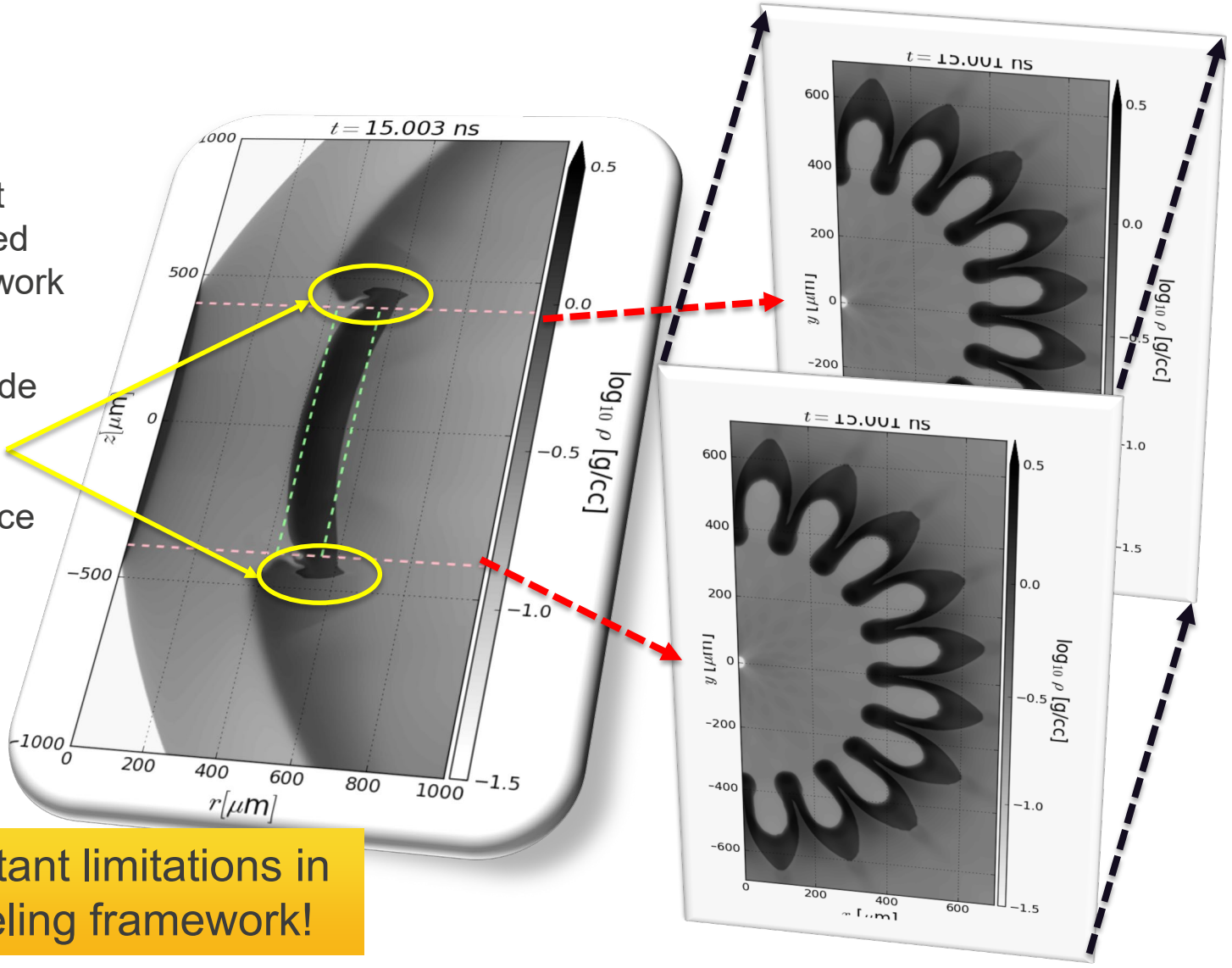




- Excellent agreement between xRAGE pre-shot simulation (calibrated based on previous shot day) and experiment

Perturbed target radiographs replace the central marker region with results from $r-\theta$ computation to capture azimuthal variation.

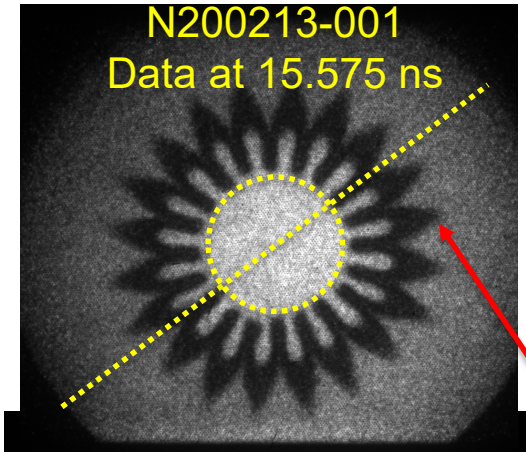
- Marker bowing is not captured for perturbed targets in this framework
- Excess marker outside of initial +/-400 μm region will push out apparent outer surface

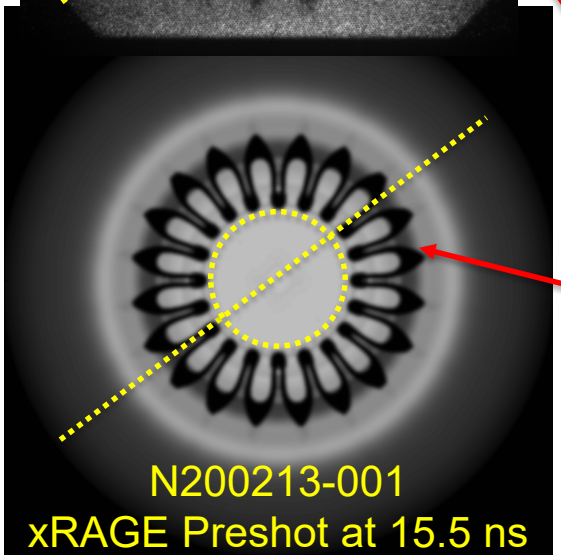


These are important limitations in the current modeling framework!

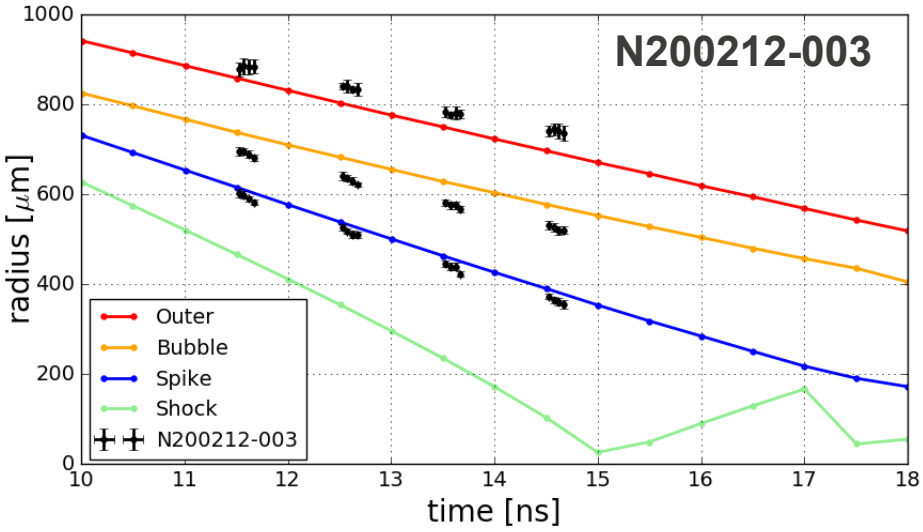
The pre-shot predictions capture perturbed target data reasonably well, despite the current limitations of the modeling framework.

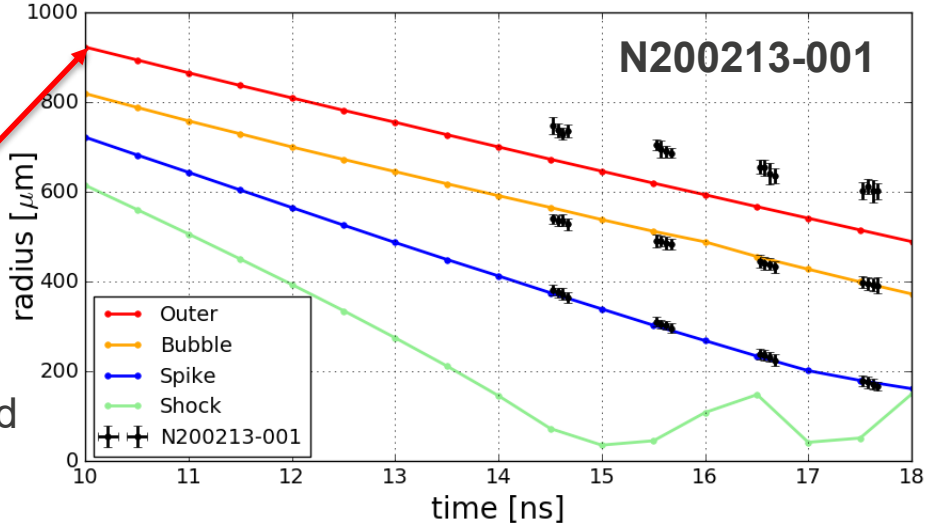
- Discrepancies are currently attributed to marker bowing, which is under investigation





Images scaled to approximately match washer diameter



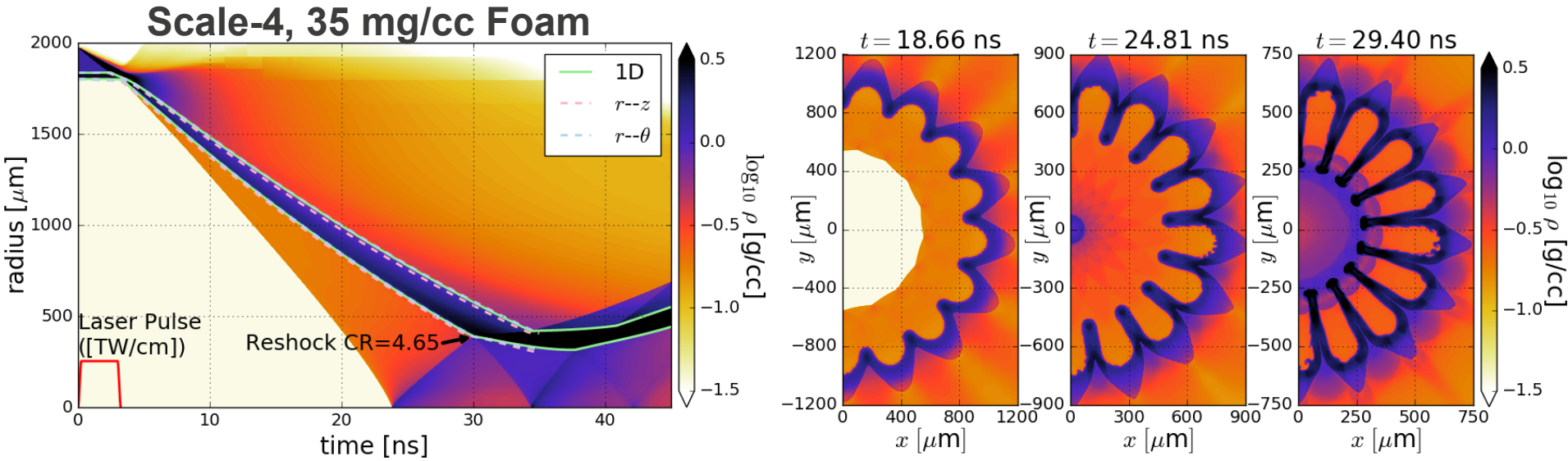


Differences in outer bubble position could be explained by marker bowing

Next Steps

The next cylinder shots (Fall 2020) will increase radial dimension to 4 mm outer diameter (scale-4 design) with a low density foam.

- Laser power is NOT increased (limits overall optics damage usage)
  - Lower intensity (4×10^{14} W/cm^2 compared to 6.5×10^{14} W/cm^2) on target might even result in less LPI/CBET and more effective coupling
- Beam pointings are shifted to drive axially uniform marker implosion
  - Some fine-tuning will be needed to mitigate m=8 from drive imprint

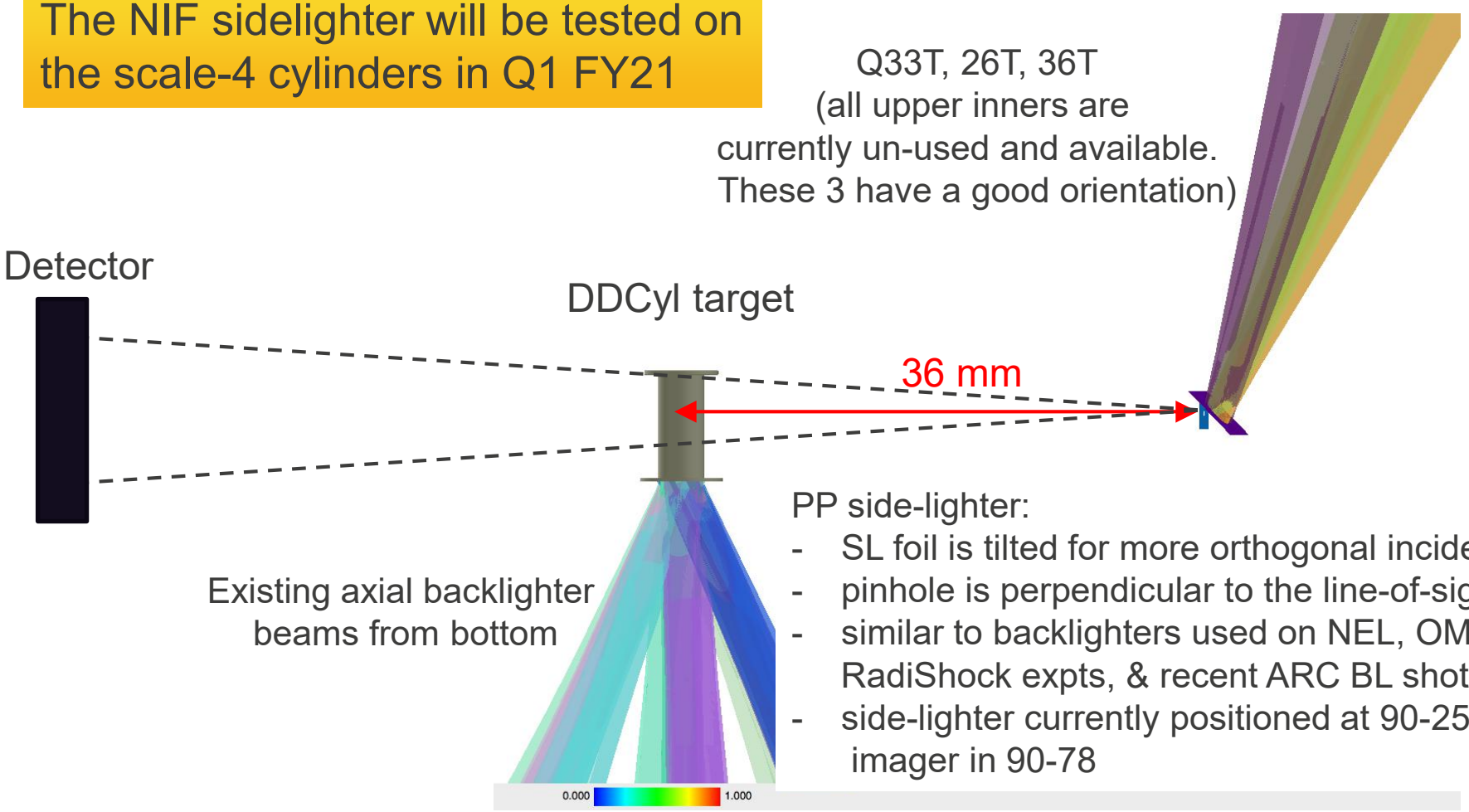


Larger cylinders are being pursued to keep the viewing area reasonable as we push to higher CR in future experiments

A point-projection backlighter could be a possibility for obtaining an orthogonal view of the DDCyl target.

The NIF sidelighter will be tested on the scale-4 cylinders in Q1 FY21

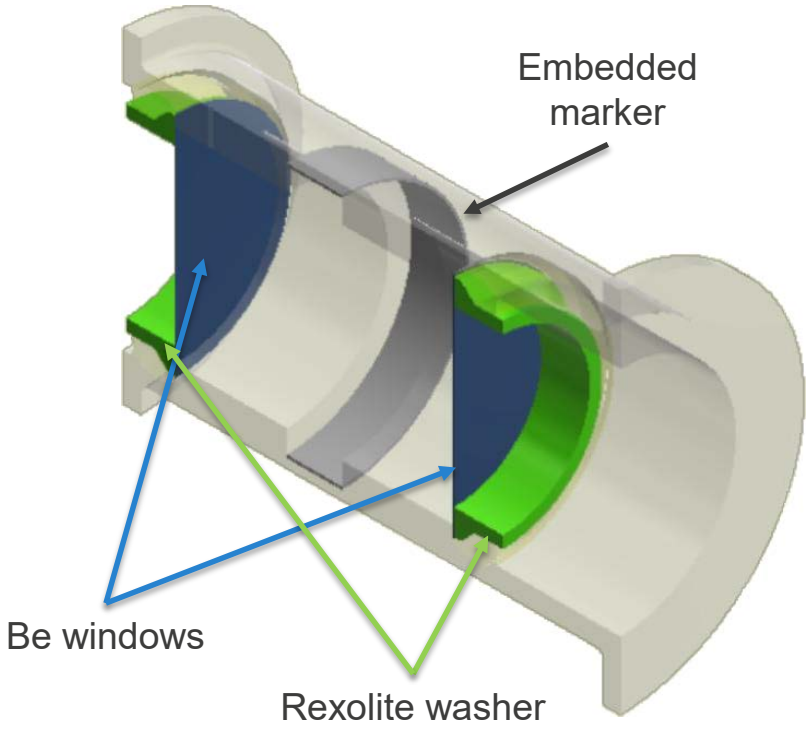
Q33T, 26T, 36T
(all upper inners are currently un-used and available. These 3 have a good orientation)



PP side-lighter:
- SL foil is tilted for more orthogonal incidence
- pinhole is perpendicular to the line-of-sight
- similar to backlighters used on NEL, OMEGA RadiShock expts, & recent ARC BL shots
- side-lighter currently positioned at 90-258 for imager in 90-78

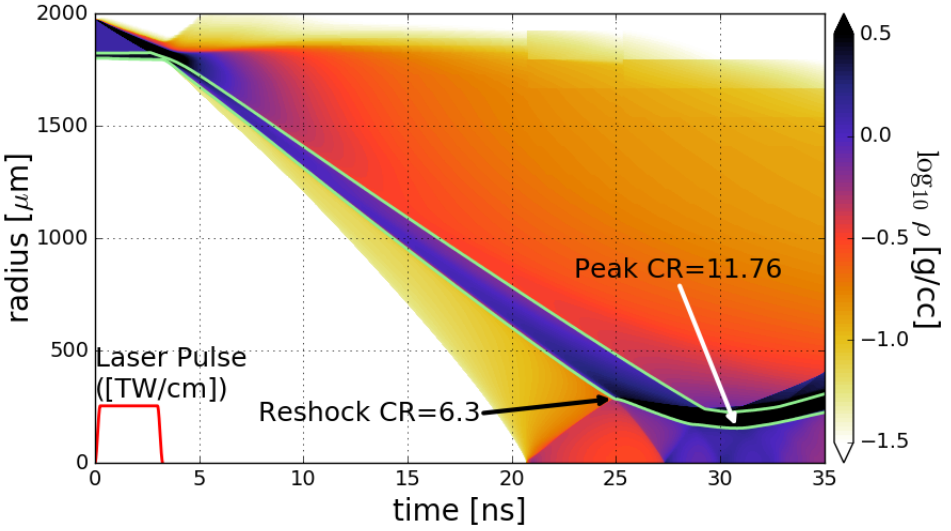
Slide courtesy H. Robey

Low density gas-filled (C_3D_8) cylinders increase convergence without requiring modifications to the laser drive.



Schematic by T. Day

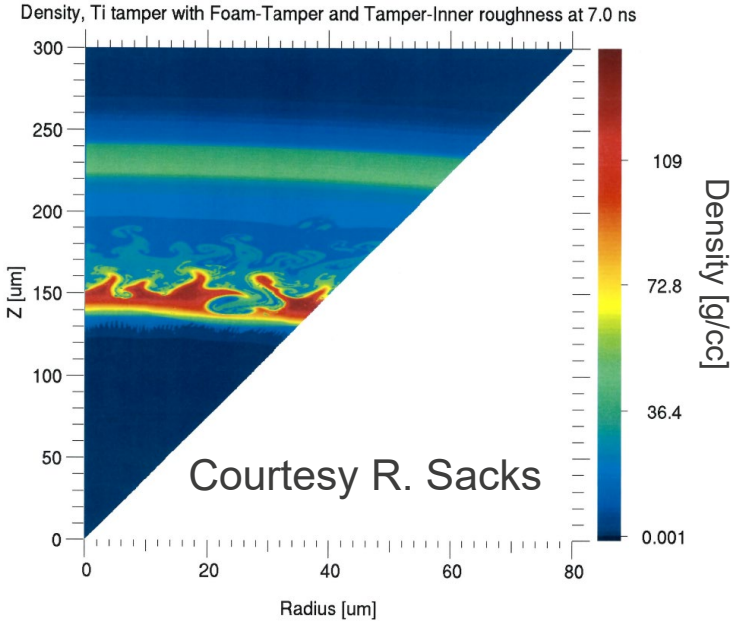
- Reshock occurs at CR~6, and peak convergence occurs at CR~12 with a 10 mg/cc fill



- 10 mg/cc fill of C_3D_8 at room temperature has a pressure of 4.5 atm
  - Engineering stresses manageable

Gas-filled cylinders will be tested for scale-1 cylinders at OMEGA in Q1 FY21, and scale-4 targets are planned for either Q3/Q4 FY21 or Q1/Q2 FY22 at the NIF.

Double cylinders are being designed to investigate proposed instability mitigation schemes for double shells beyond FY21.



- High-resolution wedge simulations in *HYDRA* indicate that the tamper/pusher interface in a double shell is very unstable
- Accurately assessing the efficacy of graded layers for stability is non-trivial in spheres

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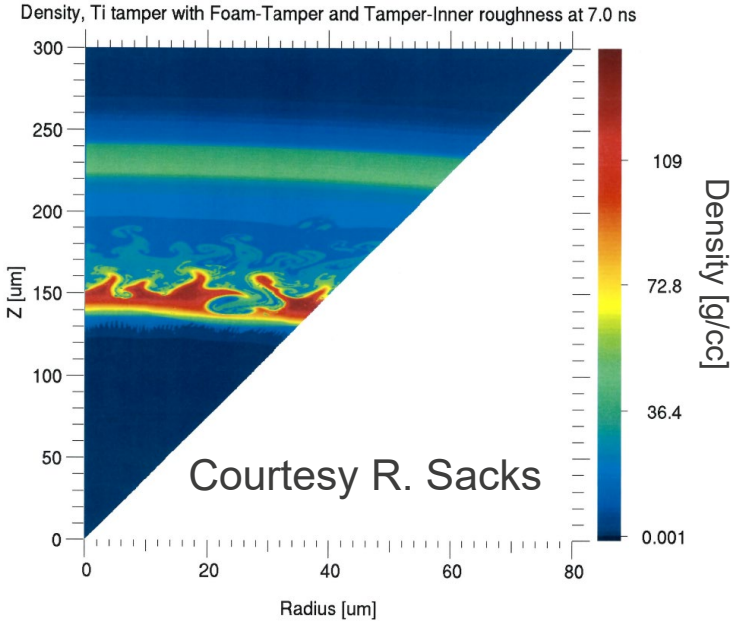

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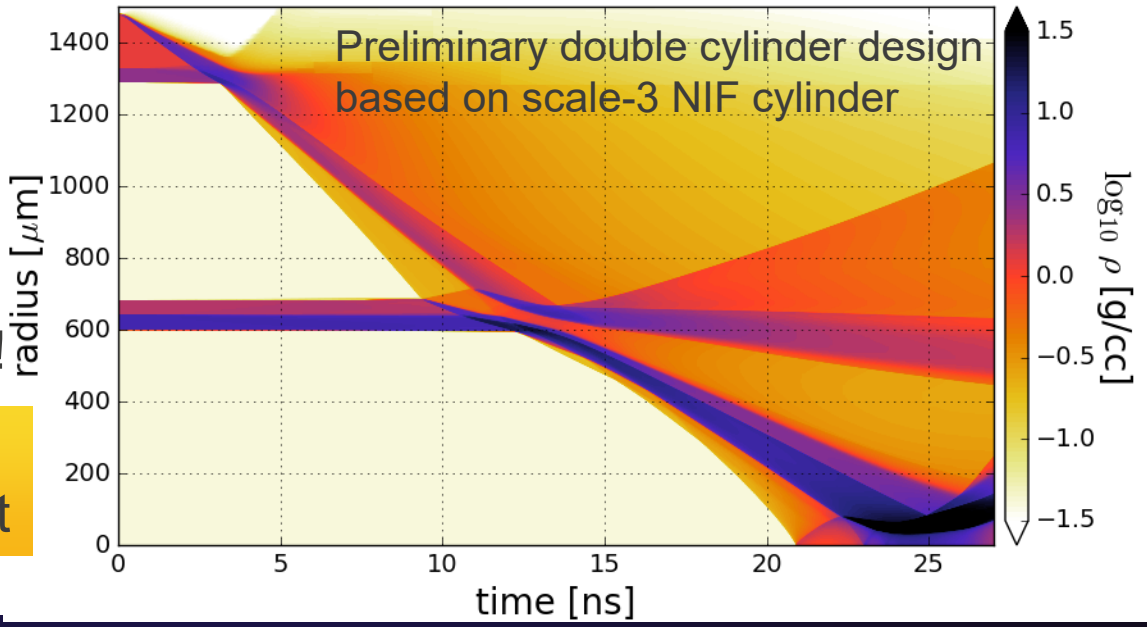
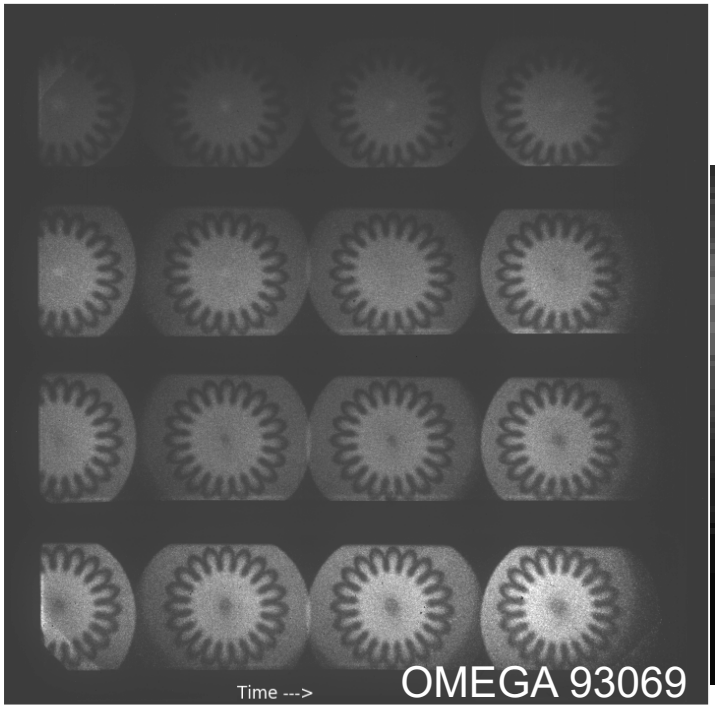


- Double cylinders can provide direct measures of instability growth and mitigation efficacy!

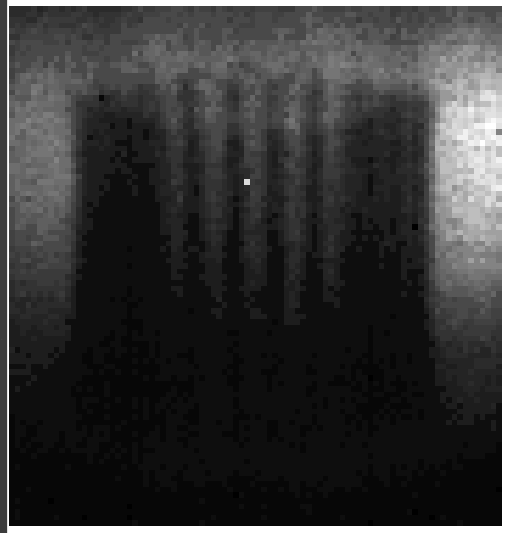
Designs being pursued with new postdoc Rebecca Roycroft

The high quality data obtained in these HED experiments will be used to help validate the 3D hydrodynamics in xRAGE.

- Both axial and transverse views can be used to constrain the simulations
- We are working closely with ASC V&V to run a 3D cylindrical implosion on Trinity that tests the 3D hydrodynamics in xRAGE against data



Mode structure visible in transverse radiograph



Chris Biwer will provide visualization support for the 3D results

Postdoc Grant Meadors will be leading V&V efforts to understand simulation sensitivities to target dimensions

Conclusions

- LANL has reinvested in a cylindrical implosion platform, enabling direct measurements of instability growth in convergent geometries
- Scale-invariant hydrodynamic instability growth is observed in cylindrical implosions at OMEGA and NIF that varied in radial size and implosion time-scale by a factor of 3 (CR=2.25)
- Greatly improved NIF data at CR=5 are currently being analyzed
- The cylindrical implosion platform is growing:
  - Larger scale-4 cylinders will be fielded at the NIF
  - Point-projection sidelighters for the NIF implosions
  - Gas-filled designs should increase CR>10
  - Double cylinders are being pursued for FY22 and beyond
  - Results will aid in V&V efforts for 3D hydrodynamics in xRAGE