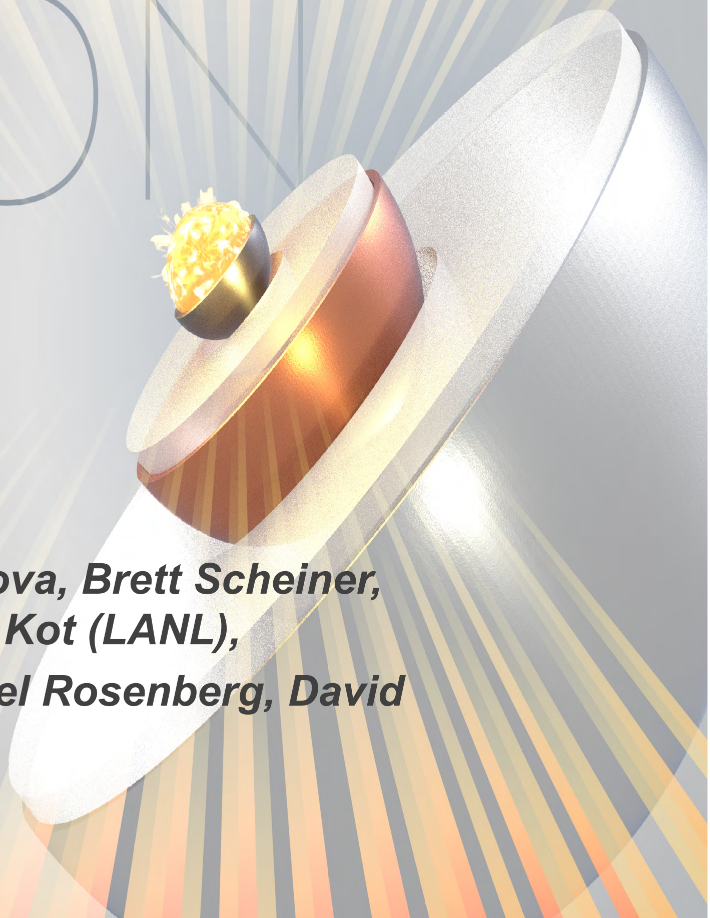
LA-UR-19-23624

Physics-driven target requirements for the Revolver direct-drive triple-shell ignition concept

Target Fabrication Workshop

April 25th, 2019



***Mark J. Schmitt**, Kim Molvig, Natalia Krasheninnikova, Brett Scheiner, Derek Schmidt, Scott Hsu, Carl Wilde, Lynn Kot (LANL),*

Dana Edgell, Fred Marshall, Patrick McKenty, Michael Rosenberg, David Turnbull (LLE),

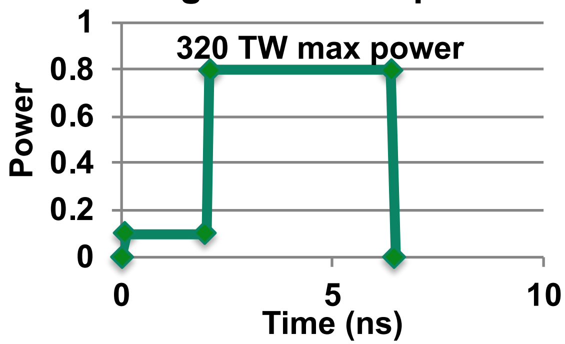
Matthias Hohenberger (LLNL)

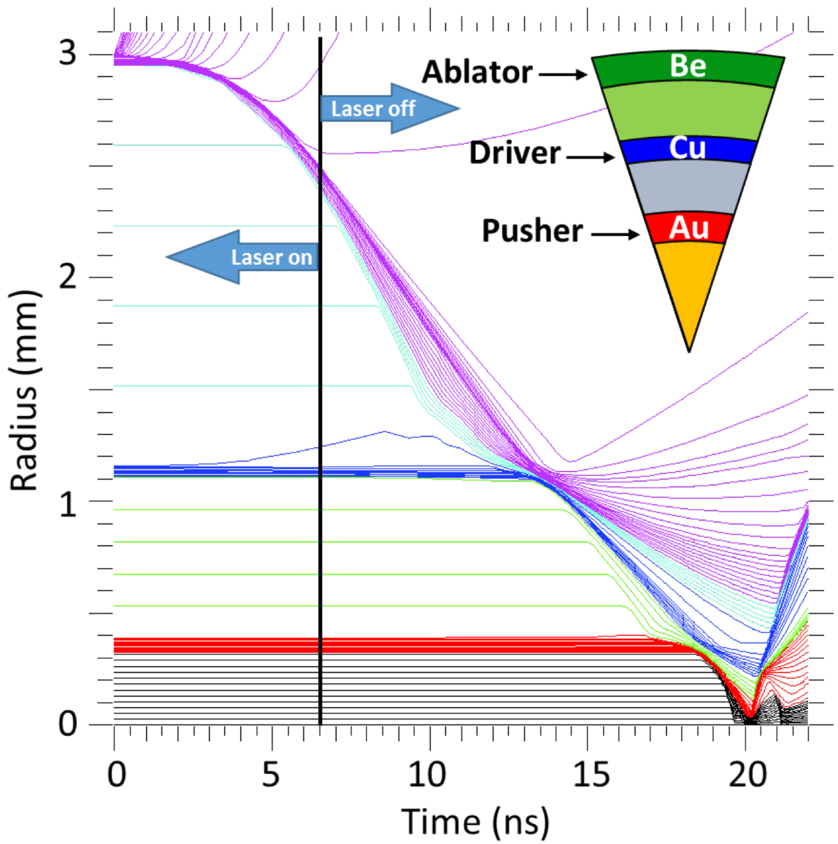
and Haibo Huang (GA)

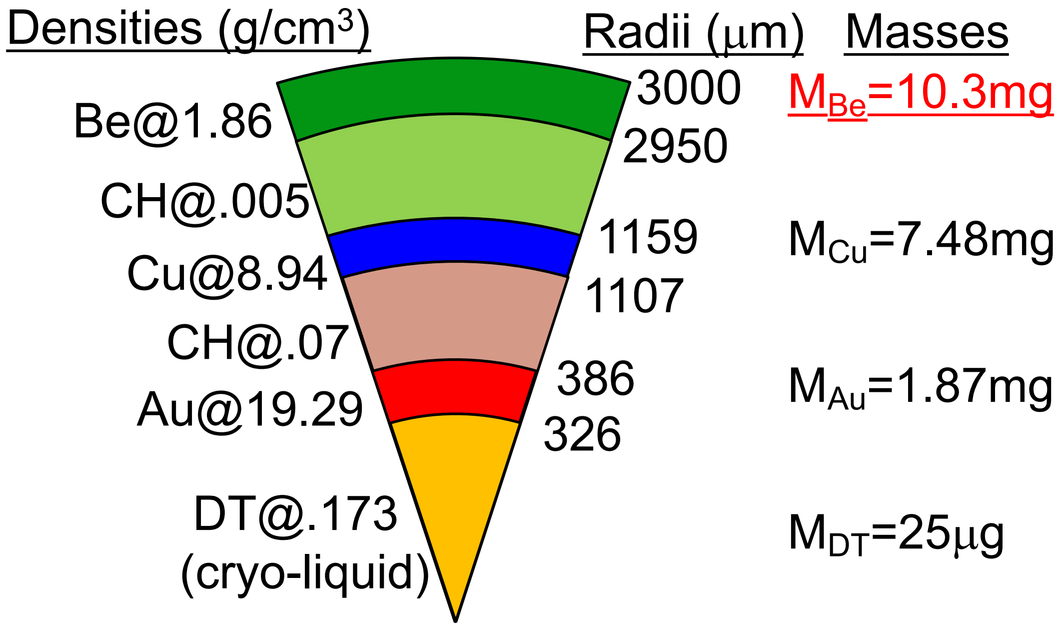
The Revolver concept for ignition on NIF: Directly-driven triple-shell target design*

- **Efficient conversion of laser-to-pressure**
- **Liquid DT converged only by a factor of 9**
- **Fuel compressed in 1.7 ns for 4.5 MJ yield**

1.68 MJ ignition drive pulse shape







- **30 Mbar ablation pressure (6 mm Ø) ➔ 400 Gbar in fuel (80 μm Ø) at ignition**

**Kim Molvig, Mark J. Schmitt, Albright, Dodd, Hoffman, McCall, and Ramsey, Phys. Rev. Lett. 116, 255003 (2016)*

Triple-shell direct-drive targets require unique fabrication capabilities for experimental validation of performance

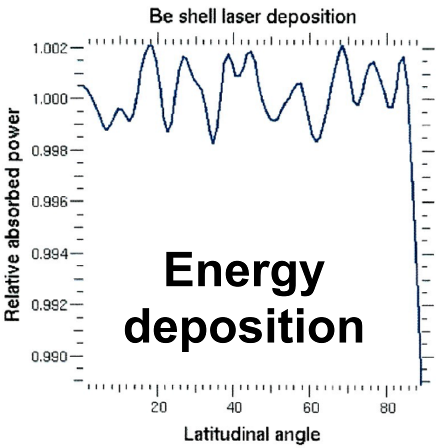
Fabrication & Experimental Path:

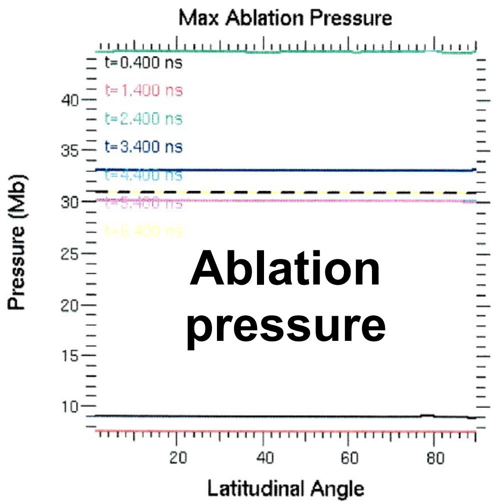
Systematically address each physics issue through theory-guided simulations followed by investigatory fabrication and experiments

- Symmetric direct-drive ablation-driven hydro-efficiency at low laser intensity with small beam-to-capsule ratios on large Be outer shells
- Kinetic energy transfer between colliding spherical shells
- Rayleigh-Taylor instability growth / suppression on all six shell surfaces
- Low-density support inside 100 mm^3 volume between outer shells
- Minimizing the effect of shell joints (laser or collision driven)
- Developing a method for cryogenic sealing of fuel filled high-Z capsules
- Fabrication and drive laser tolerances

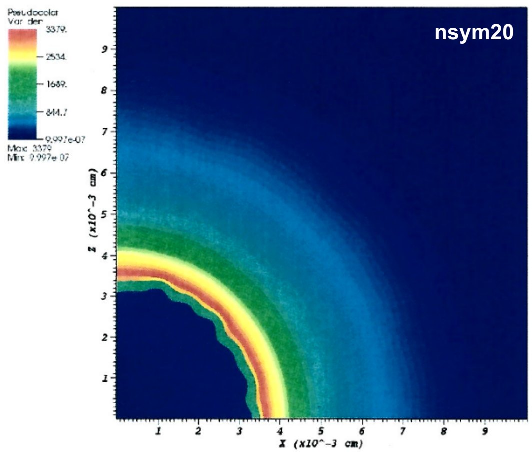
Start with symmetric drive using many (192) small laser beams before delving into polar drive optimization

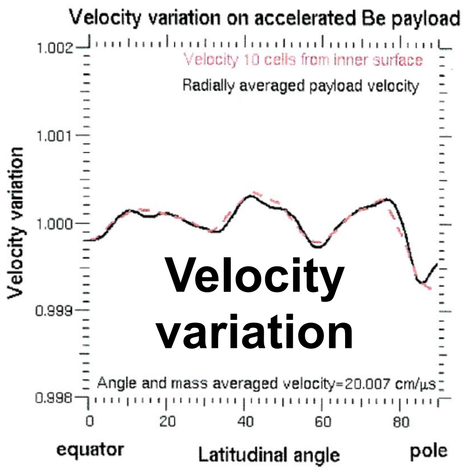
- **We now have an analytic model to perform the 3D uniformity for an arbitrary beam/cone geometry (192 beam, 5 cone used here)**

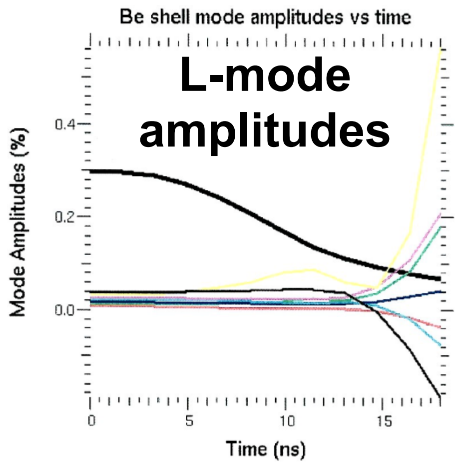




Density at peak burn





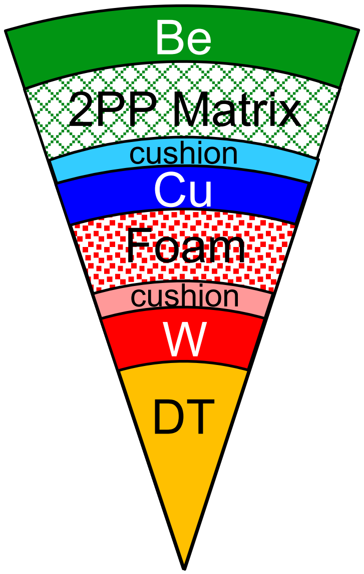


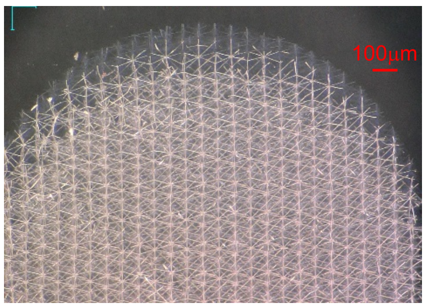
- **Many beams/per cone needed to keep m-modes small**
- **Gaussian spots minimize high mode asymmetries**
- **Beam-geometry modes must be designed out or damped**

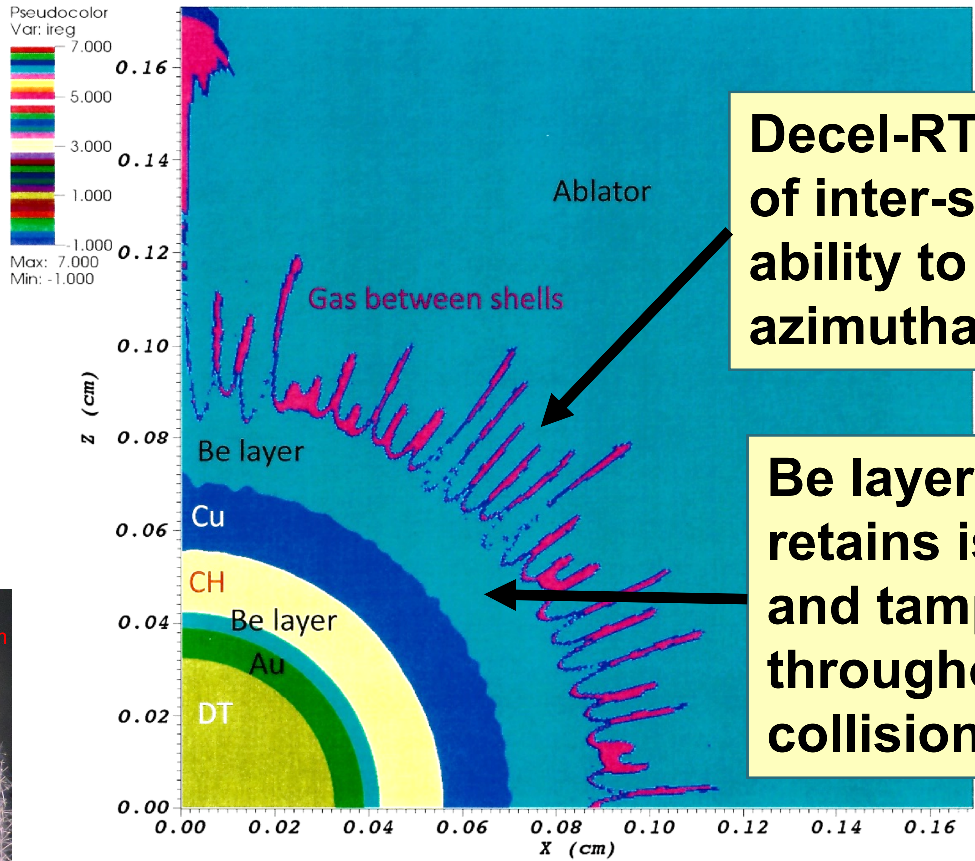
Los Alamos
NATIONAL LABORATORY

As experience with multiple shell collisions grows, the design continues to evolve...

- **Inter-shell material is modulated by RT of outer shell**







Decel-RT causes loss of inter-shell material's ability to provide azimuthal cushioning

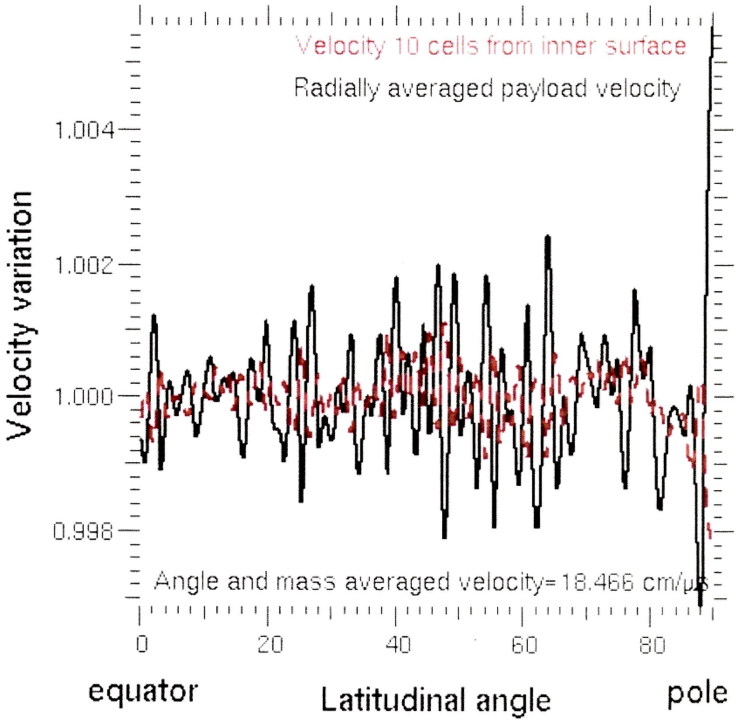
Be layer on Cu shell retains is cushioning and tamping capacity throughout the shell collision

- **The low-density material between the outer two shells cannot produce the needed smoothing for mode damping**
- **Solid density low-Z cushions are needed on interior shells**

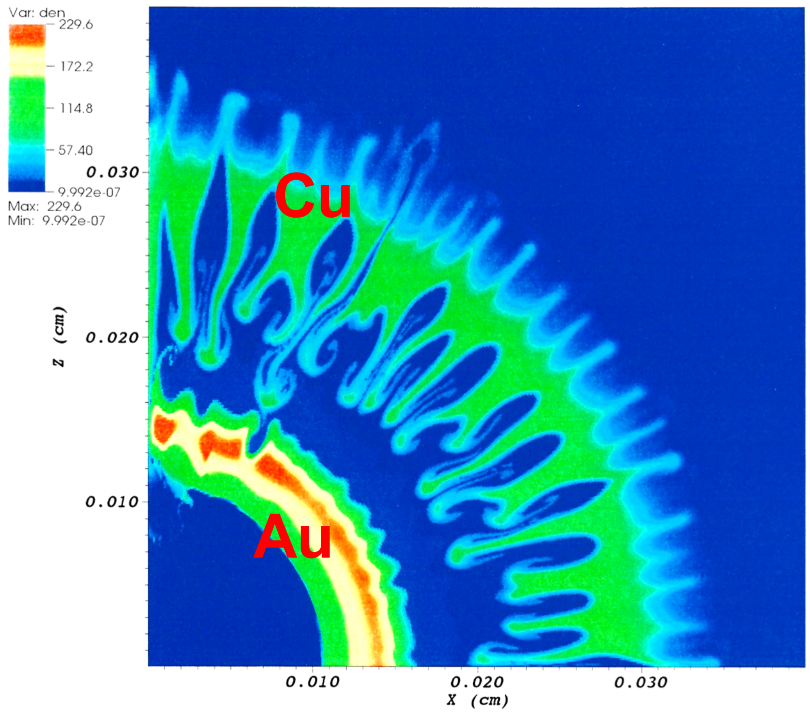
Shell imprint is correlated with residual velocity modulation on the ablator after laser turn off

- **Be laser imprint seen in RT pattern upon Cu shell deceleration**

Velocity modulation on Be shell



Cu & Au shell densities at Cu shell stagnation

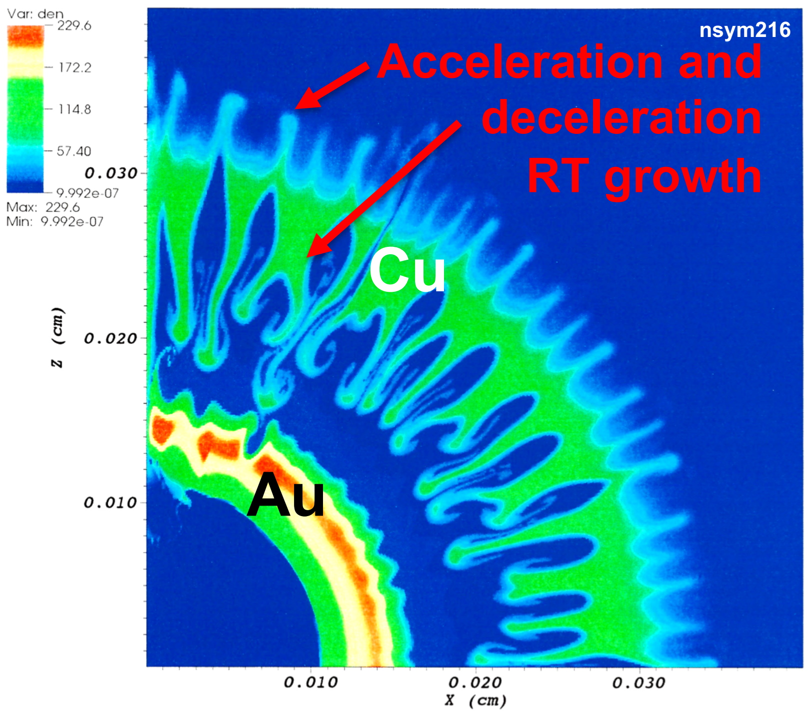


- **Imprint spectrum is dependent on residual laser beam overlap non-uniformities, ray statistics and smoothing from shell cushion layers**

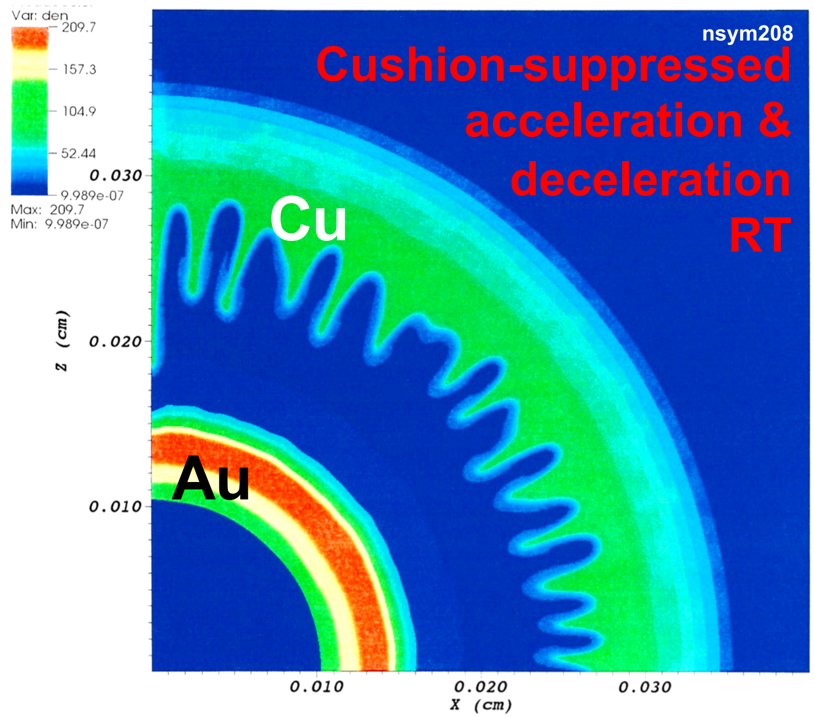
A low-Z cushion layer on the Cu shell damps higher spatial mode growth during Cu/Au collision

- **High mode features eliminated by Be cushions restore near-1-D yields**

<u>No cushion on Cu</u>
(“mix” region ~80 um thick)



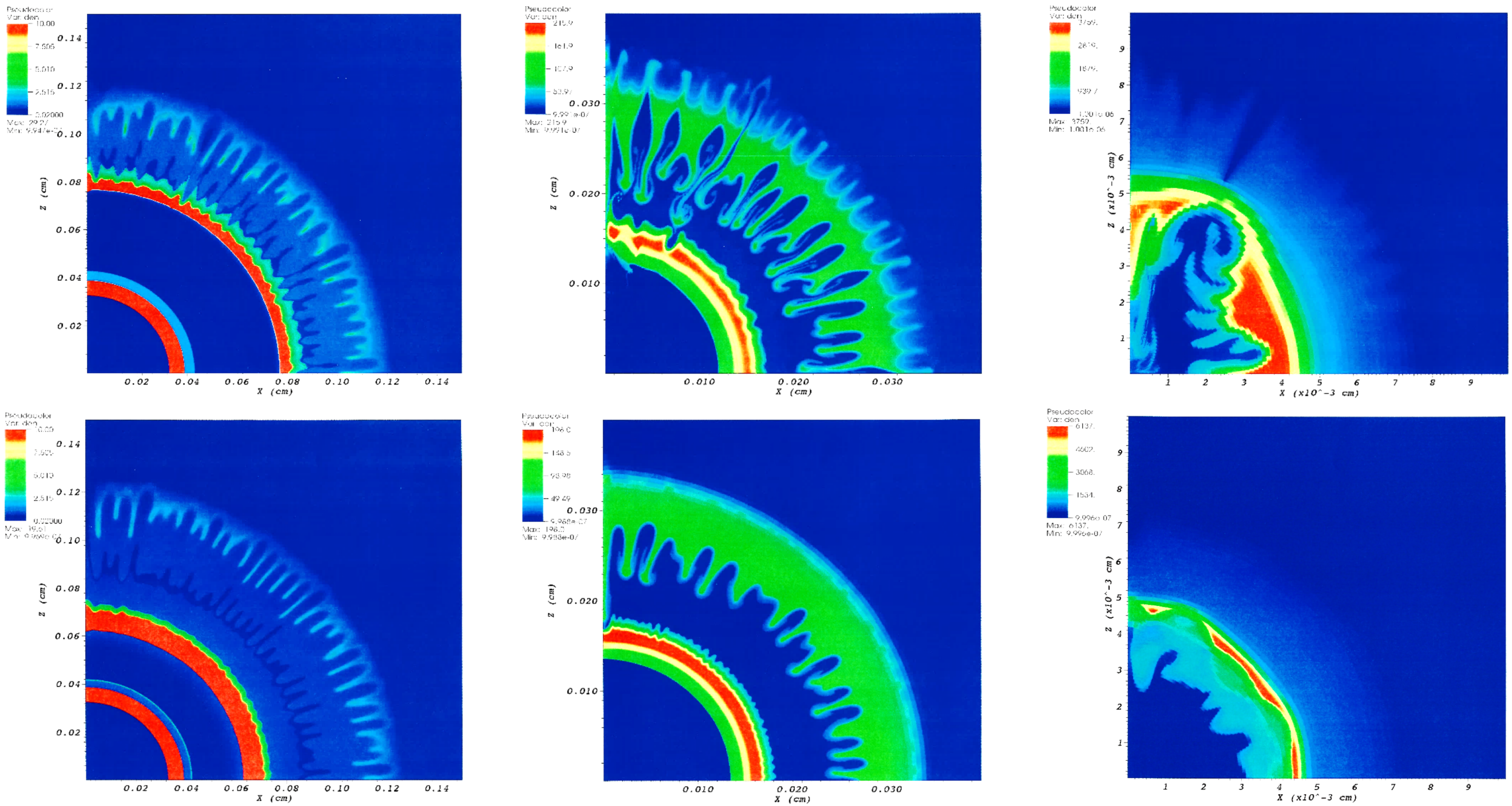
<u>50 um Be on Cu</u>
(“mix” region ~40 um thick)



- **Mix region width is exceeding the 1D fully-developed-turbulence mix width by a factor of 2 – 4 for deceleration of the Cu shell**

High Res 0.25º simulations show the smoothing and tamping effects of cushion layers on the implosion

- **Mode filtering of cushions from shell to shell is obvious**

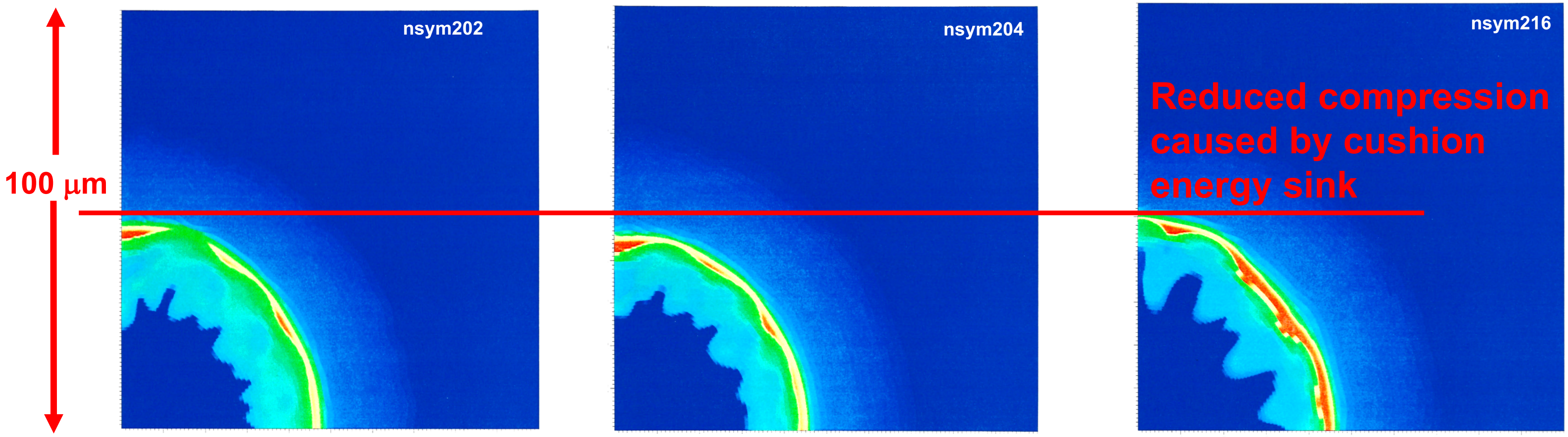


- **Be cushions provide low-pass spatial mode filtering**

Revolver design efforts continue to show the utility of 3 shells for symmetric implosions

- **High-resolution 192 beam simulations demonstrate that high modes are damped by shell collisions maintaining near 1-D yields.**
- **Density images at peak burn shown below**

1^{0} resolution | **0.5^{0} resolution** | **0.25^{0} resolution**



No cushions
4.4MJ yield
(same as 1D)

40 um Au cushion
4.4MJ yield

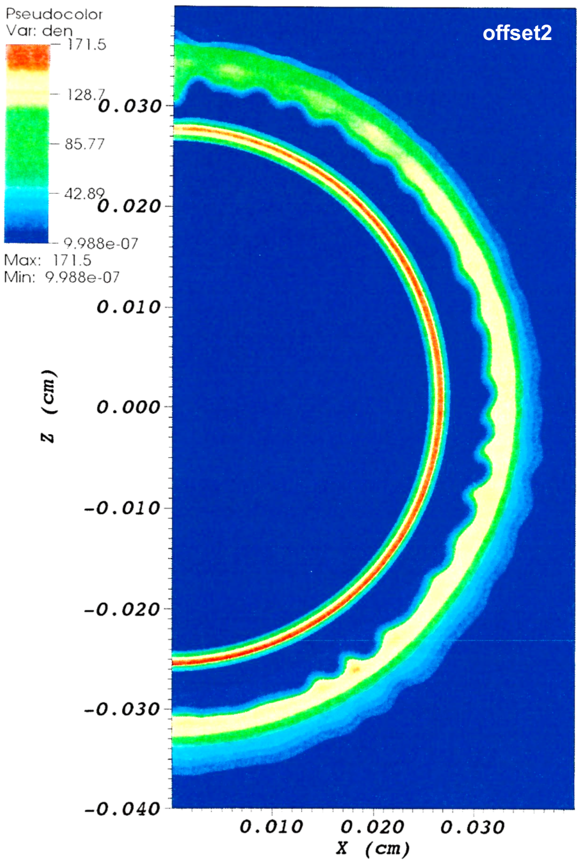
40um Au and 50um* Be Cushions
3.7 MJ yield
(un-optimized)

** Thickness yet to be optimized*

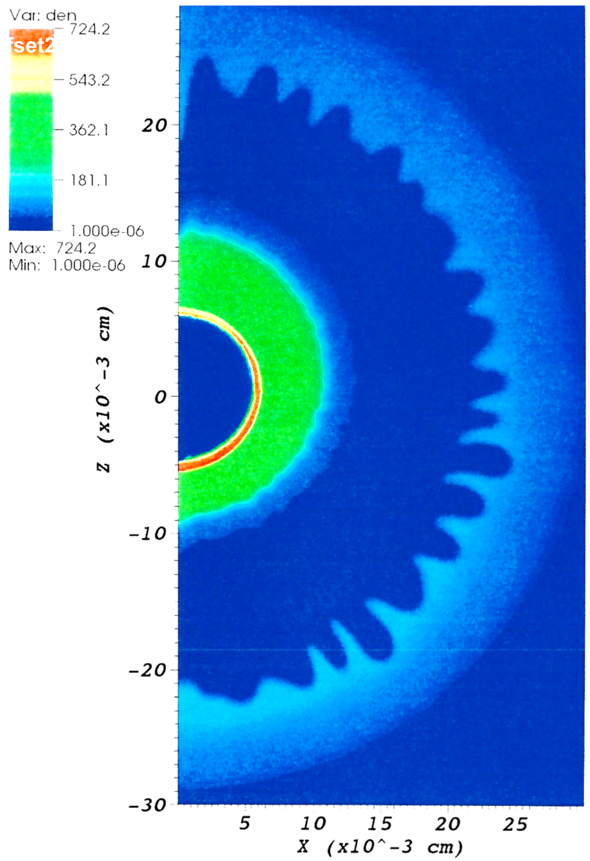
Inner shell misalignment of 25um produces > 3.4 MJ (crashes before burn finishes)

- 25 um offset of the 386 um outer radius gold shell = 6.5% axial offset

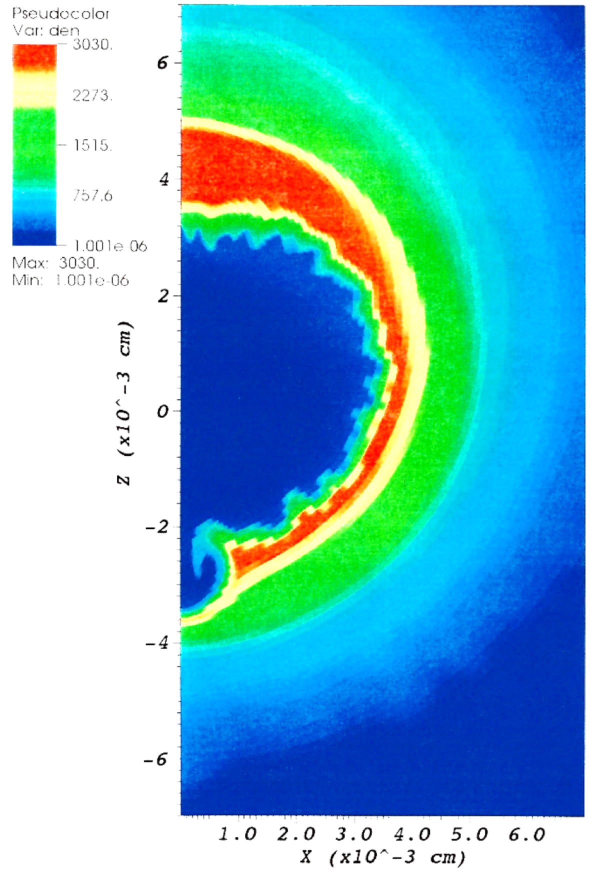
Cu striking offset Au
19.23 ns



Offset Au imploding
20.22 ns

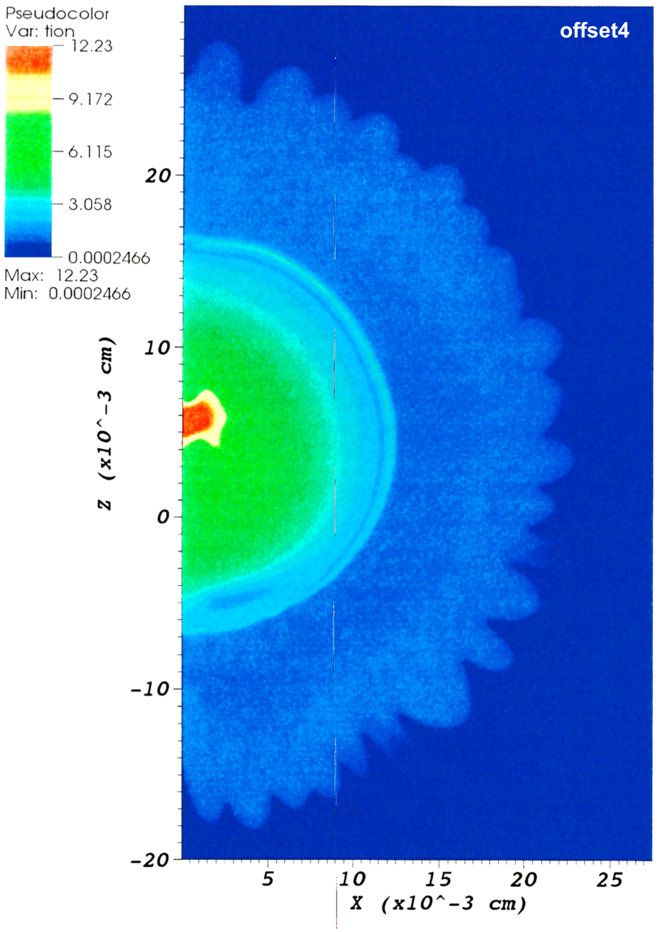


Au @ peak burn
20.39 ns

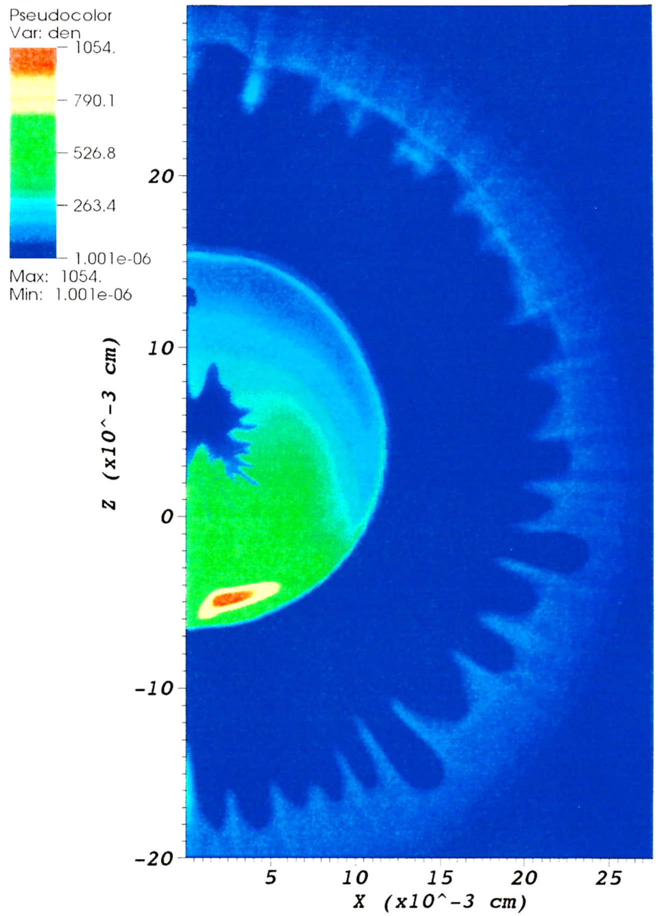


Complete target misalignment from laser centroid (TCC) of 20 um produces 4.2 MJ / 4.4 MJ yield

Ion Temperature



Density



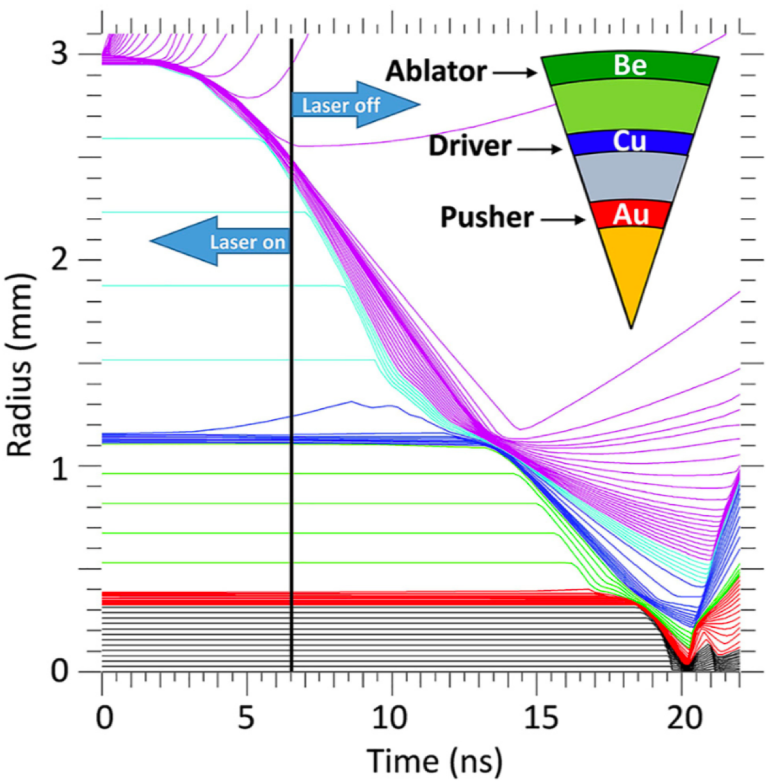
Plots at peak burn

0.5º resolution

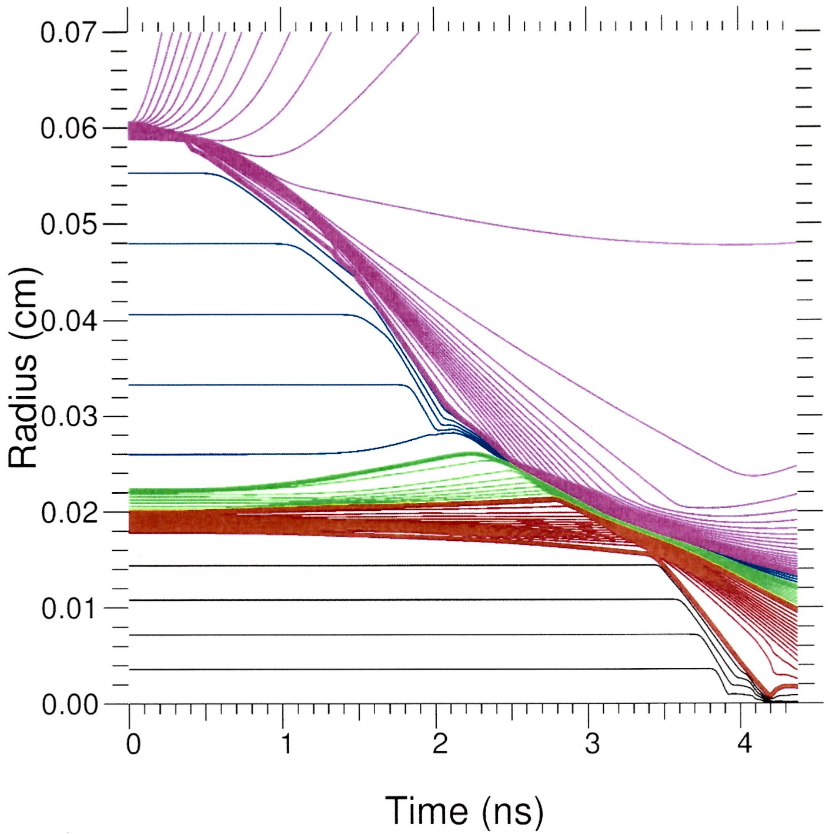
- **No cushions on inner shells for this simulation**

Triple-shell Revolver concept is being validated using scale experiments on Omega and NIF

Ignition Target



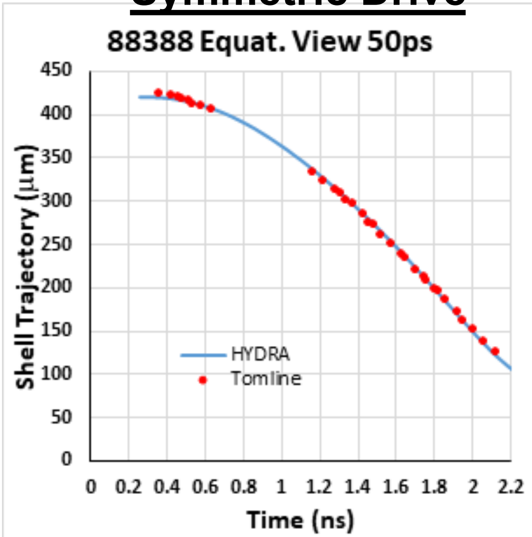
Omega-scaled outer 2 shells

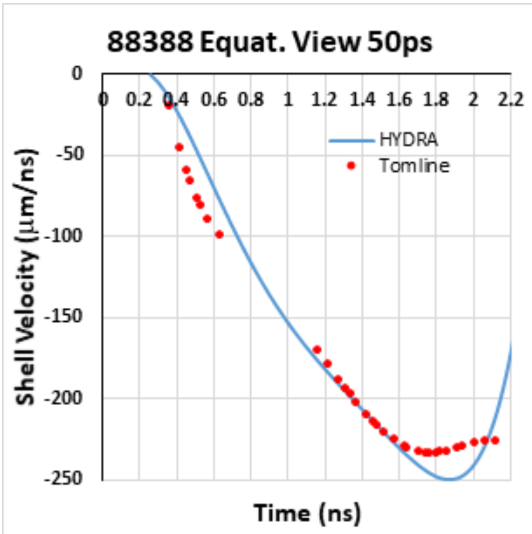


Revolver ablator-shell-only experiments on Omega validated beryllium ablator velocity at low intensity with small beam/capsule ratio

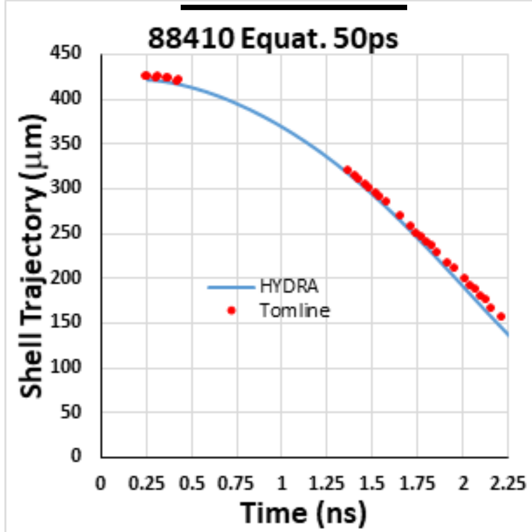
- **Excellent agreement in shell trajectory and velocity without any multipliers (0.06 flux limiter) for both symmetric and polar direct drive.**
- **Hydra only models blow-by, so platform has very small laser energy loss due to scatter and CBET (<5%).**
- **Verified code's predictability of ablation pressure of beryllium and lack of significant LPI at low laser intensity (2.5×10^{14}) using small laser beam to capsule diameter ratios.**

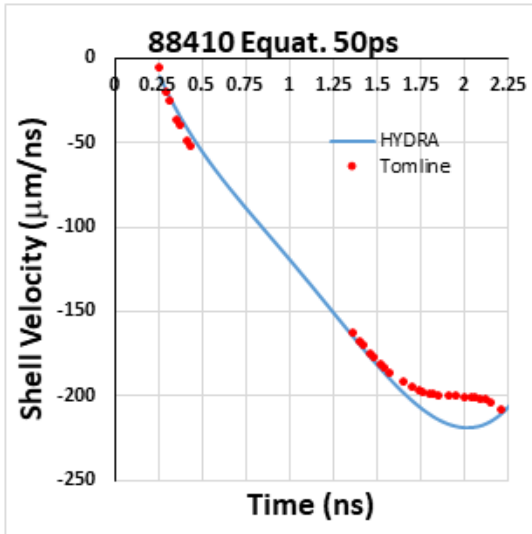
Symmetric Drive





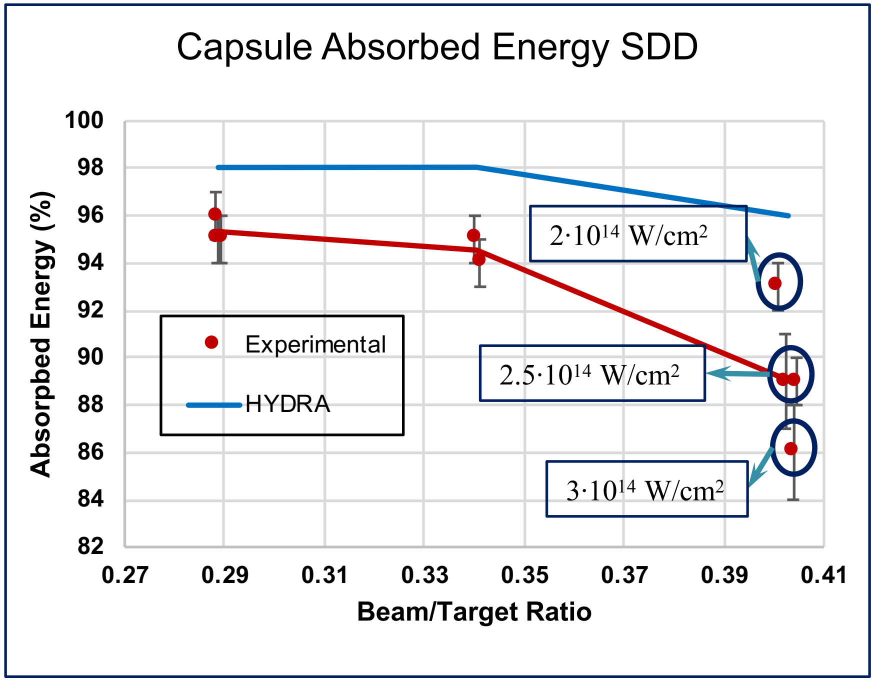
Polar Drive

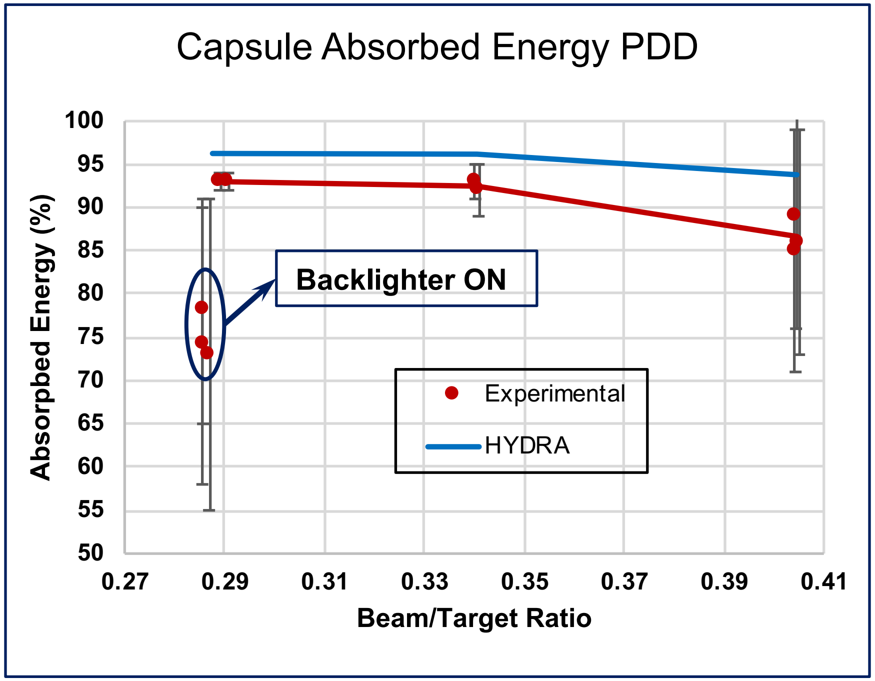




Simulations and data post-processing by Natalia Krasheninnikova, Tomline Michel and Fred Marshall.

Revolver 18AB demonstrated increasingly high laser absorption for decreasingly low beam/target ratios



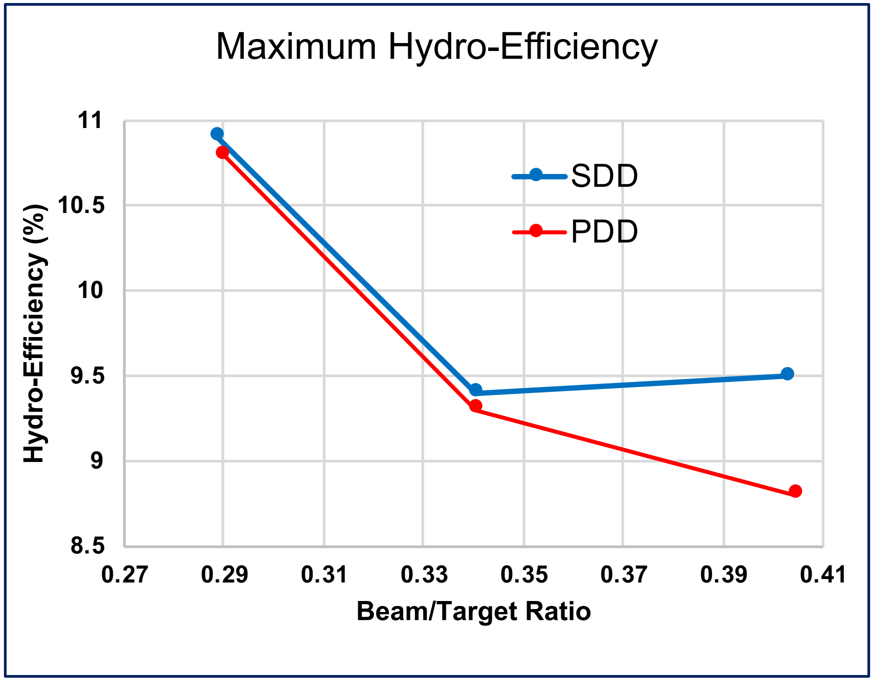


- **Smaller beam-to-target increases capsule absorption.**
- **Lower intensity on target increases absorption (most likely through decreased CBET).**
- **PDD decreases absorption by about 2-3%.**
- **Backlighter contaminates scatter diagnostics.**
- **Typical absorption above 90% for NIF-type target with small beams!**

Simulations and data post-processing by Natalia Krasheninnikova (LANL) and Dana Edgell (LLE).

Velocity inferred Revolver 18AB experimental hydro-efficiency is consistent with ignition design requirements

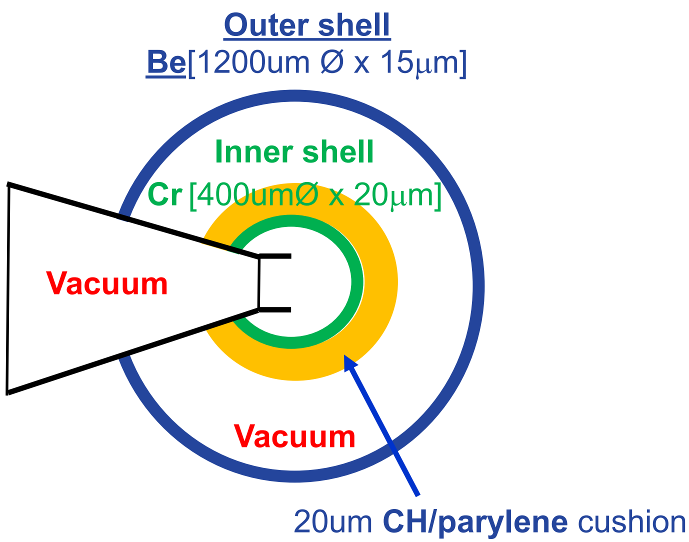
- **Robust burn target design needs Hydro-efficiency ~10%.**
- **Maximum hydro-efficiency for scaled Omega experiments (based on location of the peak pressure in the shell) is above 8.5%.**
- **Symmetry increases hydro-efficiency.**
- **Overall hydro-efficiency is 8.8% for NIF-type target!**



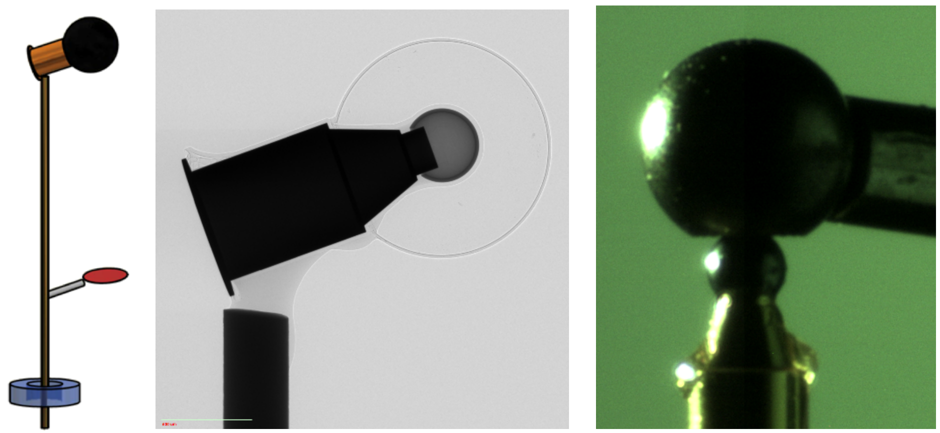
Simulations by Natalia Krasheninnikova (LANL).

Two-shell-on-cone platform shot on Omega in January 2019 to demonstrate collision energy transfer

Omega 2-shell assembly
(backlighter not shown)



Demonstrated Omega 2-shell assembly



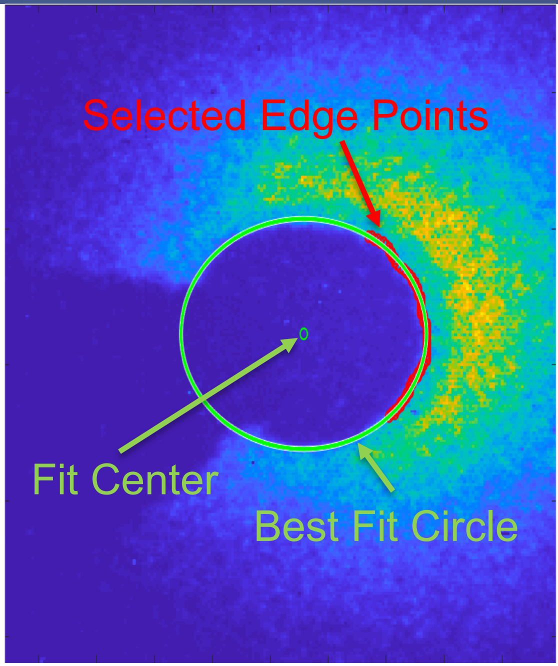
No hemi joints needed for these tests. Two backlighters were used for redundancy.

Primary target variations/goals:

- **<u>Simple outer shell of Be</u> : Ablator shell intensity same as NIF ignition design**
- **<u>Vacuum with a cushion</u>: (1) Measure velocity and shape of inner shell after collision and attempt to measure inner shell inner surface velocity using 2 new diagnostic techniques**

Target fabrication images by Derek Schmidt's Team (LANL) assembled using GA parts via Haibo Huang's team (GA).

Shell-on-cone target requires least squares fit of an arc of a circle to determine the capsule radius vs time



- Edge detection used to identify edge
- Portion of edge opposite to the cone is selected
- Circle is fit using the following least squares method:

When a=1, the circle in the plane can be expressed as

$$a\mathbf{x}^T\mathbf{x} + \mathbf{b}^T\mathbf{x} + c = 0.$$

With the selected data this specifies an overdetermined system

$$\begin{bmatrix} x_{11} & x_{12} & 1 \\ \vdots & \vdots & \vdots \\ x_{N1} & x_{N2} & 1 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ c \end{bmatrix} = \begin{bmatrix} -(x_{11}^2 + x_{12}^2) \\ \vdots \\ -(x_{N1}^2 + x_{N2}^2) \end{bmatrix}$$

The least squares method provides the coefficients and the radius is determined as

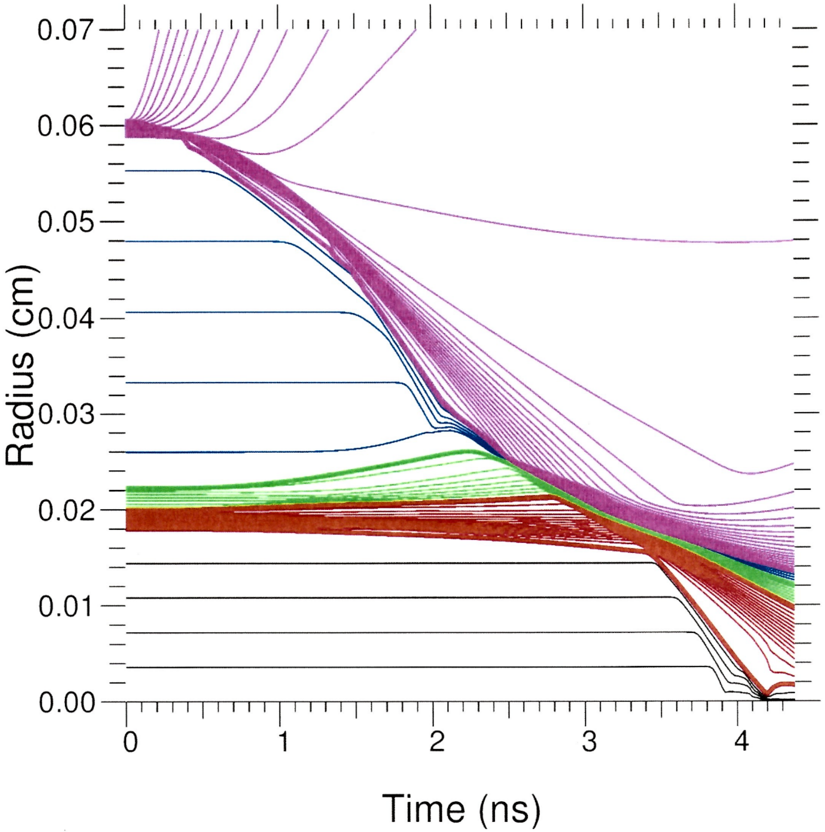
$$R = \sqrt{\frac{b_1^2 + b_2^2}{4} - c}.$$

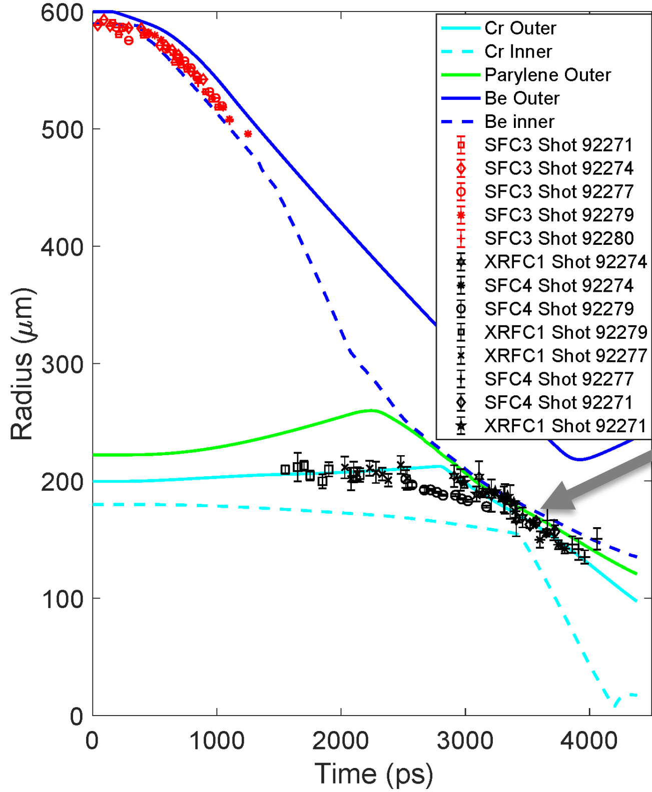
The fit covariance matrix and propagation of error produces error bars for R.

Data post-processing routine and analysis for cone platform by Brett Scheiner, XCP-6

Scaled 2-shell direct drive experiments in January on Omega validated the collision energy transfer with cushioning

Sub-scale Omega (Jan '19)





FY19 Omega radiograph data* of outer shell velocity (7.54±0.62 cm/μs) in excellent agreement with simulations (7.27 cm/μs)

Shots in August will attempt to measure the inner shell velocity

* 95% confidence is 1.96σ

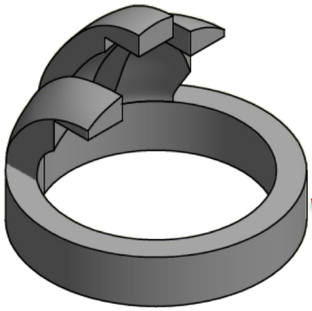
** Data post-processing by Brett Scheiner. Revolver19A collision energetics publication in preparation*

Los Alamos NATIONAL LABORATORY

Pioneering Fibers & Fingers for new diagnostic capabilities

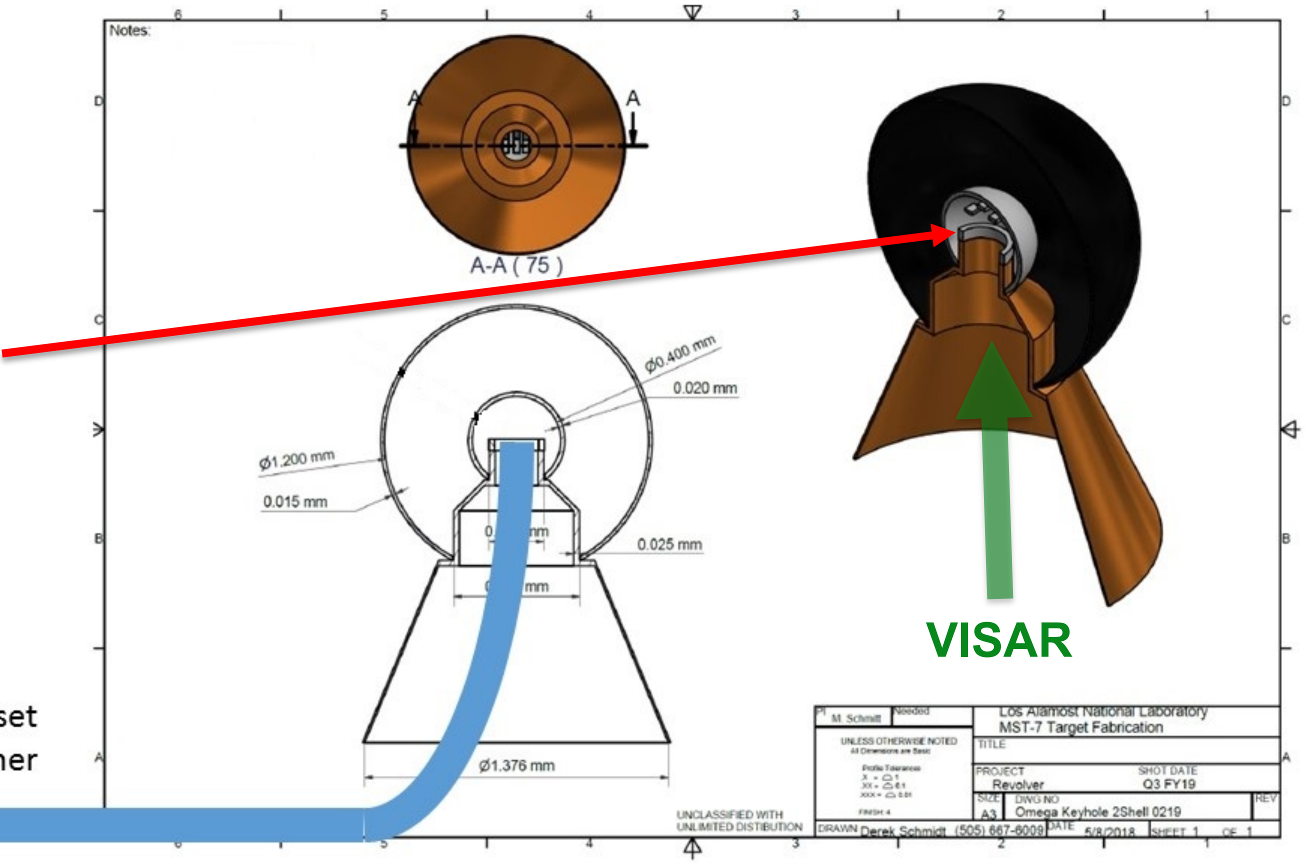
- **Measuring the inside shell velocity at high speeds (~200 km/sec) needed for validation of collision kinetic energy efficiency and surface evolution**

Fingers



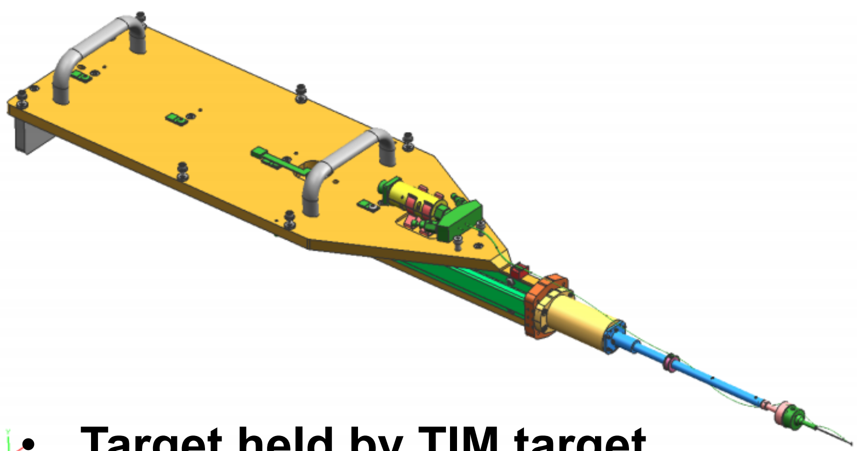
Fibers

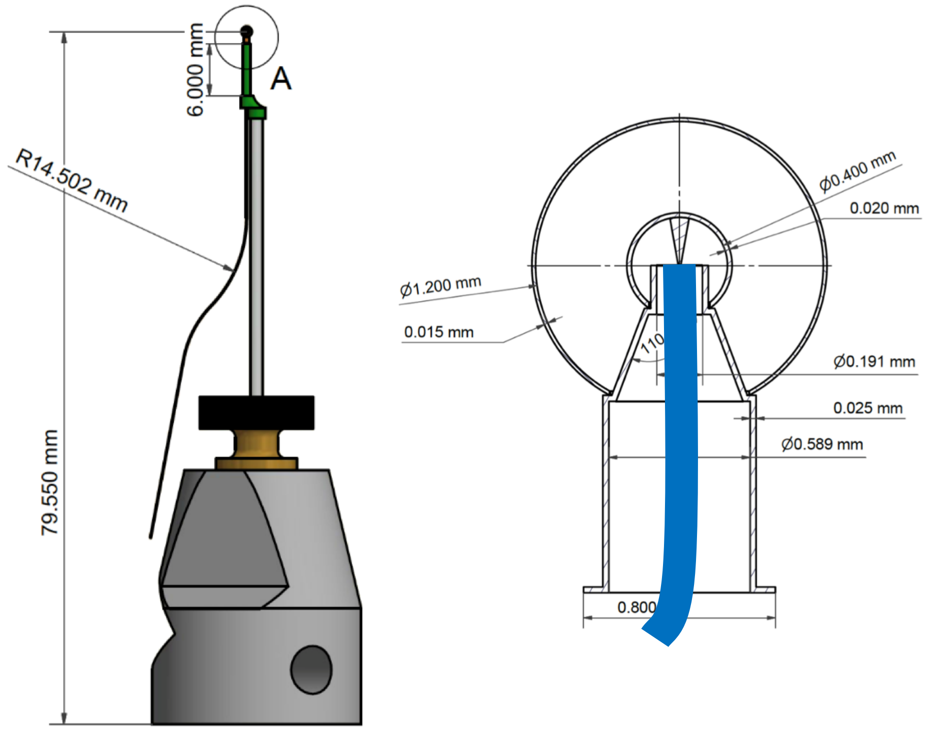
HSPDV fiber, flat polished or cleaved, set 200 microns from inner surface



High-speed photonic Doppler velocimetry (HSPDV) diagnostic capability enabled at LLE

- **HSPDV could potentially give time-resolved velocity of inner shell (like PDV in hydro-test program)**





- **Target held by TIM target positioner, and fiber runs down the TTP and out of the TIM via a custom vacuum feedthrough**

- **1550-nm single-mode fiber (Thorlabs 1550BHP), 9-µm core, 125-µm cladding**

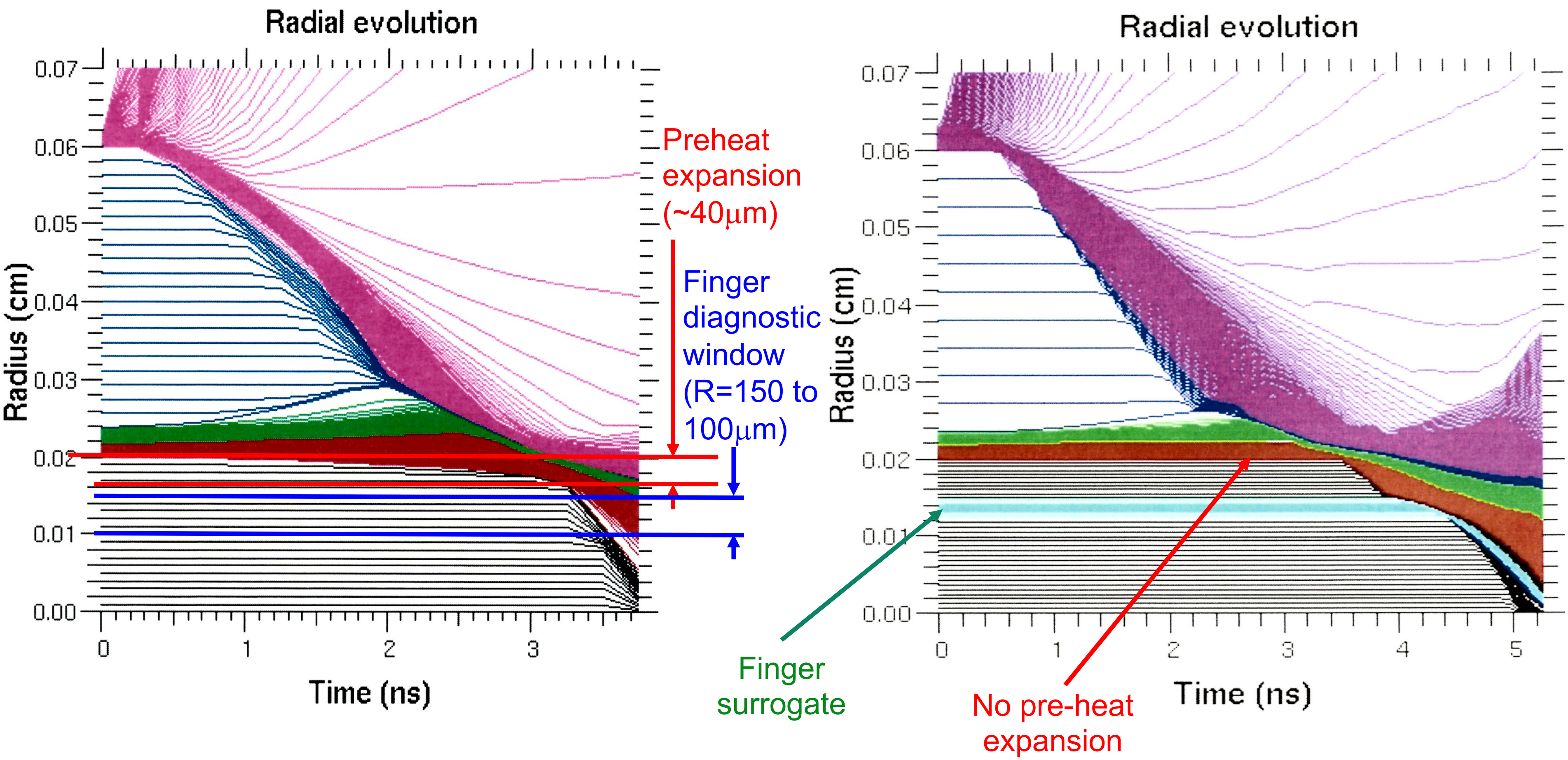
MSTS: Have HSPDV, will travel (Jason Mance & Team)

Mobile self-contained HSPDV equipment rack brought to Omega for shots

We are currently modifying the target design to optimize it for internal diagnostic measurements

Be/Ar outer shell & Cr inner shell (January 2019)

CH outer shell & Mo inner shell (August 2019)



Revolver continues to push forward on design optimization, physics validation and target fabrication

- Goals: – Validate drive symmetry and the use of cushioning to suppress instability growth, laser asymmetry and target manufacturing features

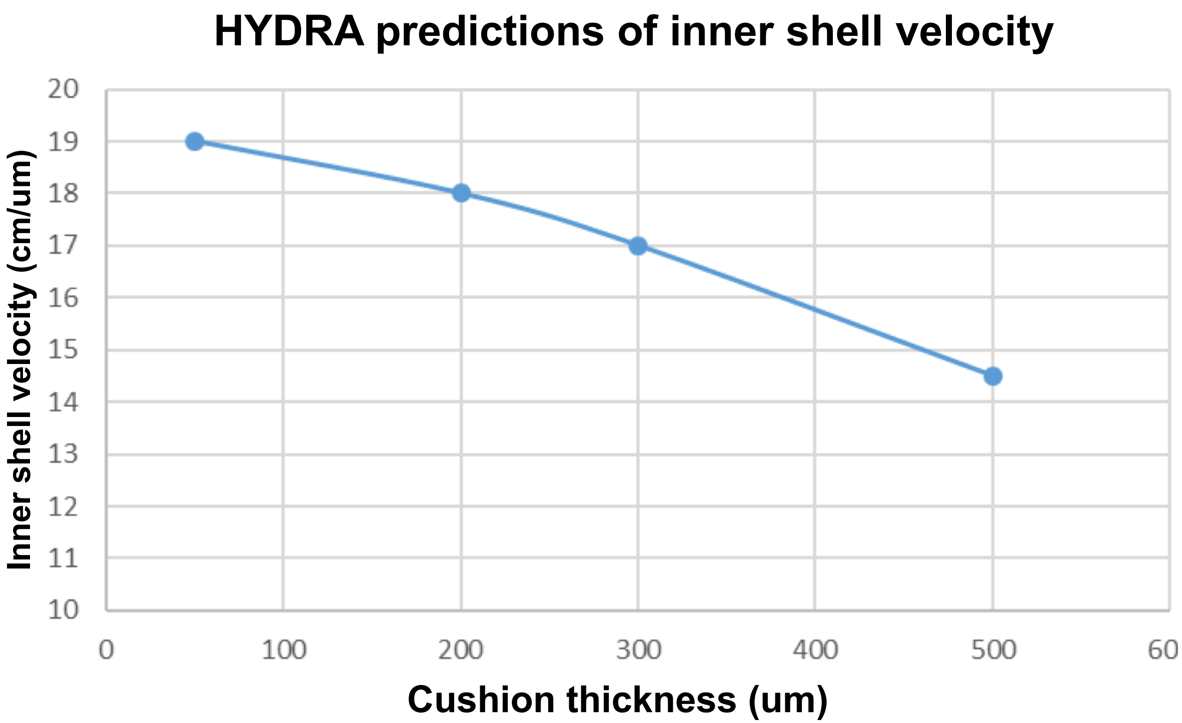
- Demonstrate NIF-scale hydro-efficiency and PDD implosion symmetry
- Demonstrate NIF-scale collision energy transfer efficiency to ≤10% (150kJ) level
- Demonstrate efficiency scaling versus the amount of shell cushioning
- Demonstrate mitigation/smoothing by cushion of laser/fabrication imprint

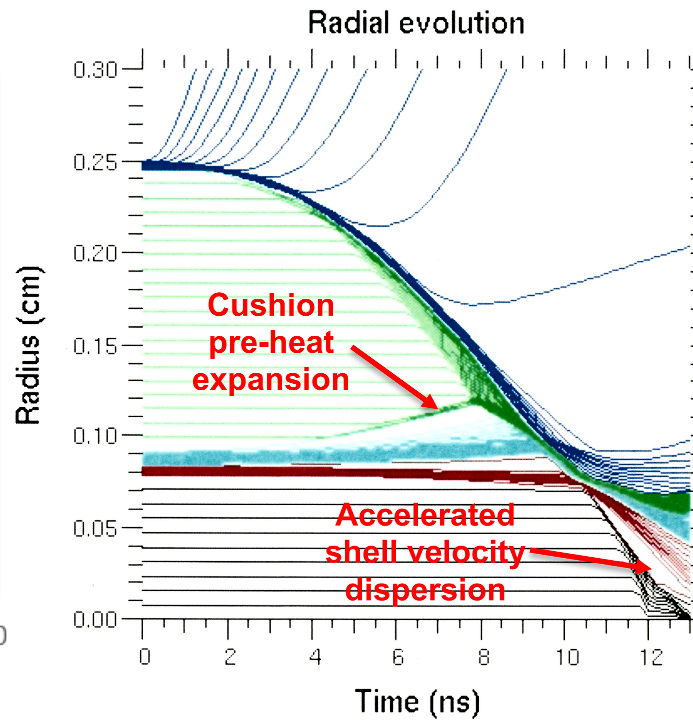
- Experimental & fabrication approach:

  - Measure ablator shell velocity and scattered light fraction at NIF scale
  - Measure post-collision velocities and symmetry of outer & inner surfaces of inner shell via x-ray backlighting at NIF scale
  - Fabricate two-shell targets with matrix structures, foams and hemispheres
  - Measure scaling of inner shell velocity with cushion thickness
  - Measure perturbation on inner shell from outer shell joints and structures
  - Begin to address DT liquid-filled metal shell fabrication concepts

Clear changes in inner shell velocity versus cushion thickness will be measured

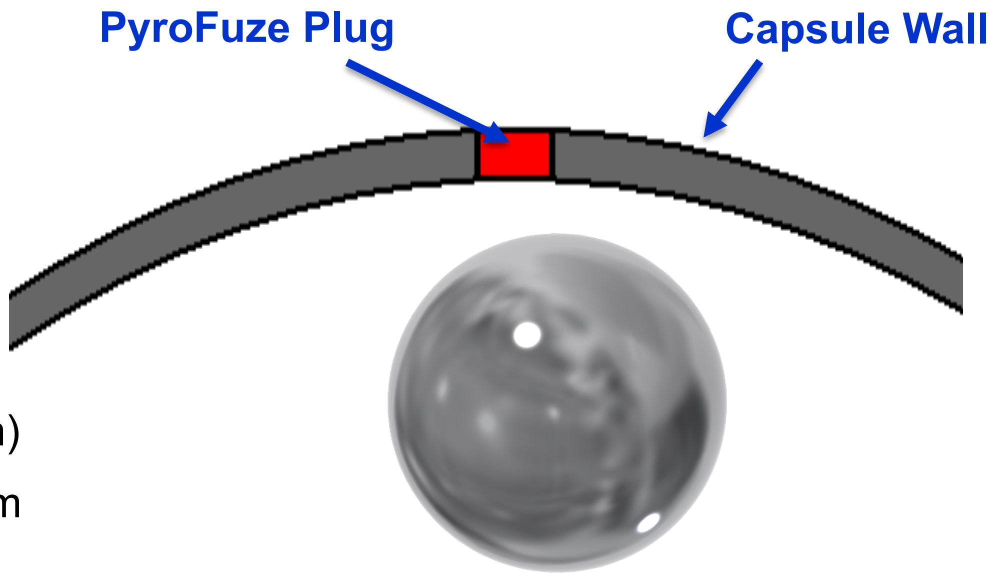
- Optimization is a trade-off between the amount of smoothing and the loss of inward kinetic energy needed to compress the DT fuel





- Experiments with cushion layers that provide discernable changes in velocity and mode smoothing for resolvable mode numbers are needed

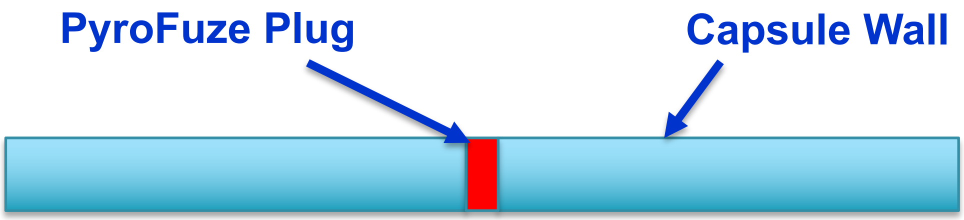
Development Concept: Eliminate the Fill Tube in the Inner Capsule



Fill Concept

- Insert Capsule into Deuterium or Tritium Fill Vessel
- Cryogenically liquefy gas and fill capsule
- Insert PyroFuze plug (Palladium/Aluminum)
- Electrical/Laser Initiate Plug (650ºC minimum)
- Exothermic reaction melts plug to quickly form and seal capsule wall
- Raise temperature of capsule to room temperature → Results in HIGH pressure fill in Inner capsule → Max pressure unknown??

Initial Development Path



- Start with flat foils that have a 20um hole
- Insert PryoFuze under cryogenic temperatures in liquid hydrogen and seal
- Test the strength of W capsules (GA)

Target fabrication advances are needed to capitalize on the merits of the Revolver ignition concept

- Scaled single-shell targets on Omega have provided data consistent with high laser coupling efficiency (>90%) and high hydro-efficiency (~10%) at low drive intensity (2.5×10^{14} W/cm^2) without significant LPI generated
- Scaled double-shell targets on Omega have provided data consistent with predicted collision kinetic energy transfer efficiency between shells including a Rayleigh-Taylor cushion layer on the inner shell
- Sub-scale experiments and new diagnostics are being developed to test potential design issues
- Unique target fabrication issues are being addressed
- Experiments will continue on Omega and NIF this summer

Back up slides

Collaborating with Nevada DOE on using HSPDV diagnostic for ICF

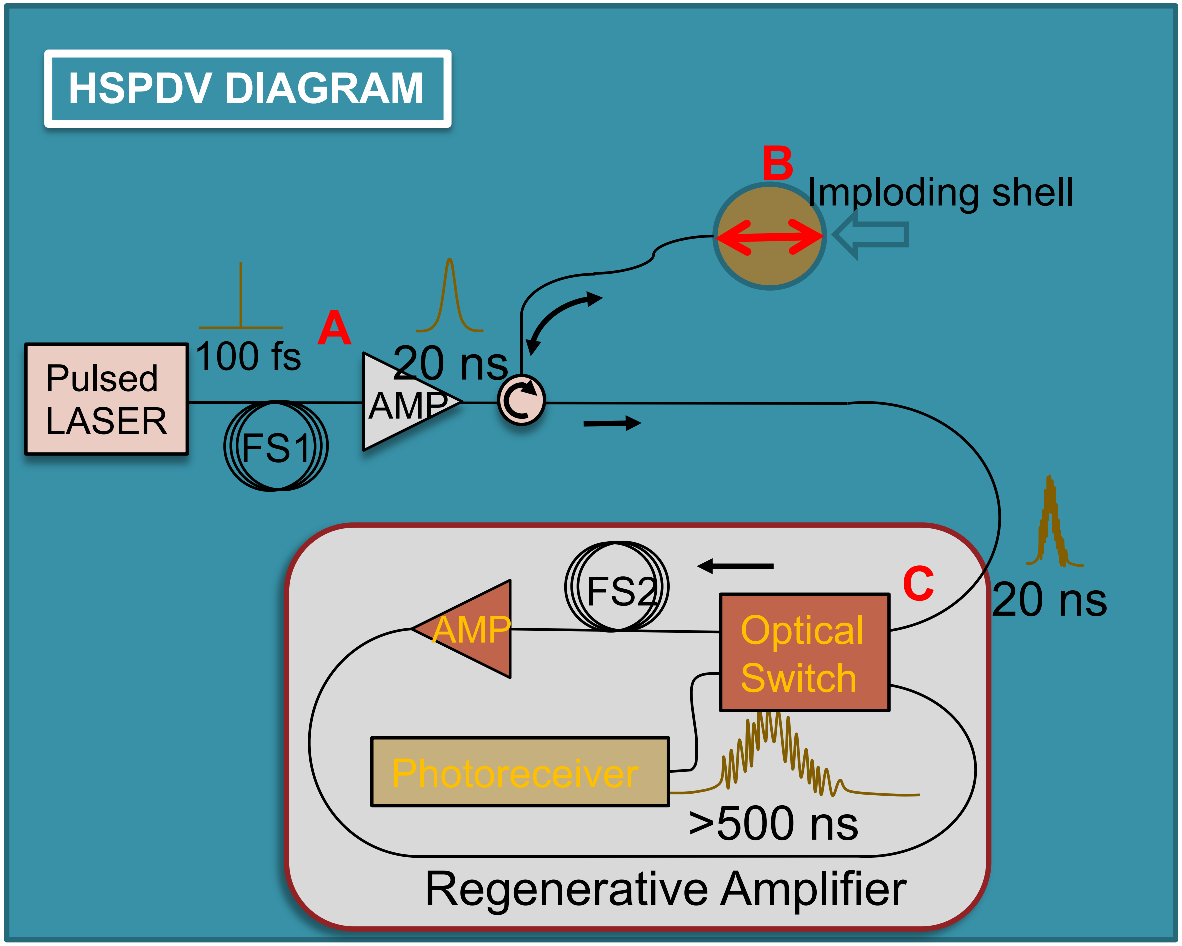
(A) Stretch fs laser pulse to ~20 ns

(B) Encode PDV signal onto laser pulse (200 km/s → 260 GHz beat frequency, 3.8 ps time resolution)

(C) Stretch signal in dispersive fiber to 260 ns → *beat frequency lowered to 20 GHz*

(D) Record beat frequency on scope and calculate velocity $v = f\lambda/2$ (f = beat frequency)

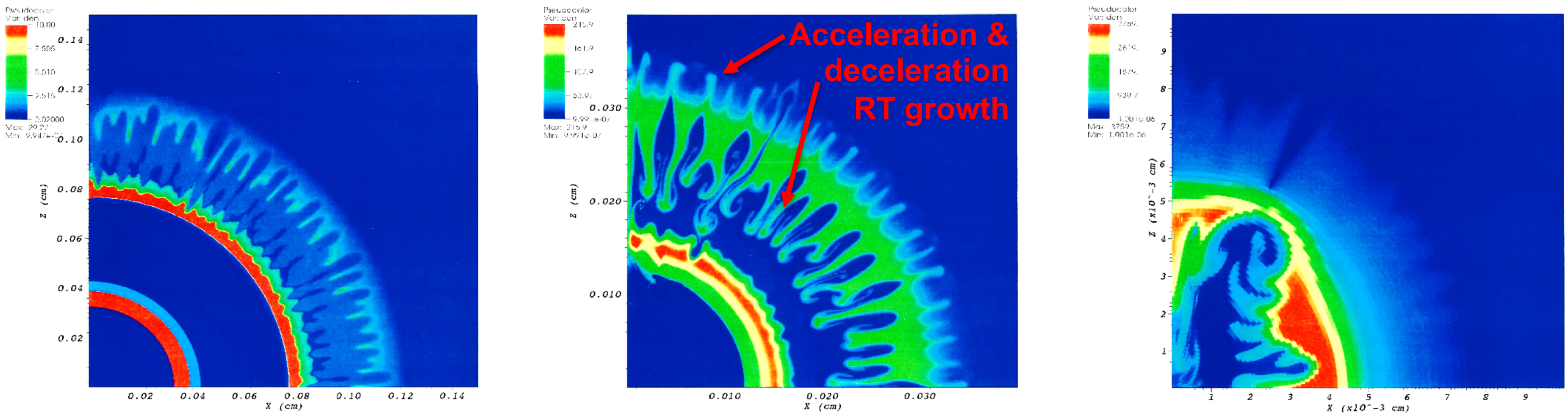
- Beat frequency occurs from mix between reflections off fiber face and shell
- Initial beat frequency gives distance from fiber to shell with ~1 μm accuracy
- If shell stays reflective, time record of velocity is recorded
- Even if reflectivity goes away, breakout time of shell and impact time on fiber are recorded to give average velocity



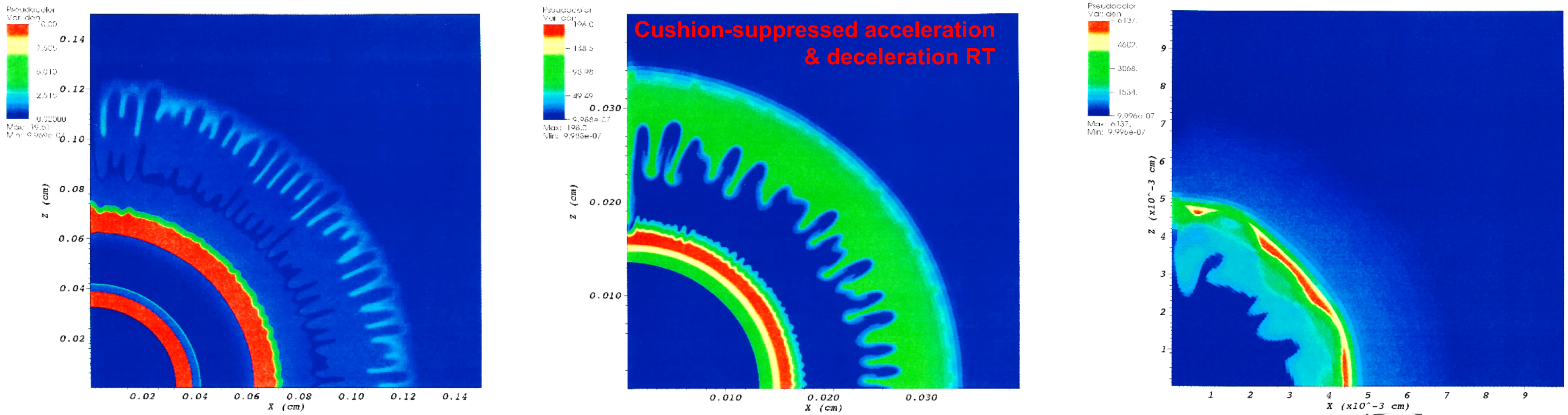
HSPDV diagnostic courtesy of Jason Mance, MSTS

Understanding the effects of cushion layers on inner shell imprint & asymmetry is crucial for designing DDMS targets

- **Mode growth from RT is clearly seen in DDMS designs**



- **Be/CH cushions provide crucial inter-shell spatial mode filtering**



Abstract

The Revolver concept employs several unique design and fabrication features to attempt to obtain ignition using the current National Ignition Facility (NIF) laser system. Direct laser drive of a large, thin 6 mm diameter x 50mm thick outer beryllium shell maximizes laser drive energy conversion to target inward kinetic energy at low intensity (3×10^{14} W/cm^2) while simultaneously minimizing any nonlinear drive non-uniformities and target coupling inefficiencies caused by laser-plasma instabilities. The relatively short laser drive time of 6.5 ns allows the energy to couple to the target before the plasma critical density radius shrinks significantly, thereby eliminating the need for laser zooming of the imploding target.
Shell asymmetry growth from the outer shell into the intermediate copper shell and finally into the inner tungsten shell is examined. Drive uniformity metrics are proposed for achieving multi-megajoule yields on the current NIF. Target design enhancements to mitigate drive non-uniformities are examined for their efficacy against both laser pointing errors and shot-to-shot laser beam power variations. A low density support material under the beryllium ablator shell is crucial for efficient acceleration and laser energy coupling to inward kinetic energy. Moreover, simulation of solid density Be or CH cushions on the exterior surfaces of the inner two concentric shells are shown to be crucial for suppressing the growth of asymmetries in the convergence of the liquid DT fuel. Unique fabrication requirements for the complete ignition target include the fabrication of thin hemispherical shells, a low-density (5 gm/cc) additively-manufactured support lattice between the outer two shells and a novel fabrication concept for fielding the liquid-DT-density-filled inner tungsten shell at room temperature. An overview of recent Omega target fabrication efforts and subsequent experiments using novel 2-shell-on-cone targets will be given. Experimental data showing excellent laser hydro-coupling efficiencies (>90%) to the outer shell and as-predicted kinetic energy transfer from the outer shell to the second shell will be presented. The plan for future fabrication efforts and experiments will be given.

Research in this presentation was supported by the Laboratory Directed Research and Development Program of Los Alamos National Laboratory under project number 20180051DR.

*Kim Molvig, Mark J. Schmitt, B. A. Albright, E. S. Dodd, N. M. Hoffman, G. McCall, and Ramsey, *Low fuel convergence path to direct-drive fusion ignition* Phys. Rev. Lett. 116, 255003 (2016)