A Cylindrical Implosion Platform to Study Hydrodynamic Instabilities in High Energy Density Regimes

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OMEGA shot 93069, \( t \approx 6.2 \text{ ns} \)

NIF N190212-003, \( t \approx 18.6 \text{ ns} \)

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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. HEDP 5.4 (2009)
Hydrodynamic instability growth is believed to be a key factor limiting performance of ICF implosions.

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- Instabilities limit compression and heating
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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. Understanding and mitigating instability growth is crucial for improving performance.
Hydrodynamic instabilities have been extensively studied in planar geometry, but convergence modifies growth considerably.

- The classical Rayleigh-Taylor instability\(^1,2\) occurs when a light fluid is accelerated into a heavy fluid

\[
A(t) = A(0) \exp \left( \sqrt{A_T \dot{R} k \ t} \right)
\]

Atwood Number:

\[
A_T = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}
\]

- Convergence modifies this through Bell-Plesset\(^3,4\) effects. In cylindrical geometry\(^5\):

\[
\left( -\gamma \rho + \frac{d}{dt} \right) \frac{d}{dt} (a_m \rho R) = \gamma_0^2 (a_m \rho R)
\]

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

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


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- Plastic ablator overcoating the marker is directly driven with laser light
- Instability growth occurs due to a combination of RT and BP effects
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- The desired initial mode spectrum is machined with high precision on the inner surface of an embedded aluminum marker layer.
- 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.
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**OMEGA**
- Reboot platform

**OMEGA**

- Reduced convergence (CR=2.5), longer deceleration \(\rightarrow\) more instability growth

**FY 2017**

**FY 2018**
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- Verified laser drive for 3X larger cylinder
- Confirmed hydrodynamic scale-invariance

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NIF N190212-003 at ~18.6 ns

OMEGA 93069 at ~6.2 ns
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**Second scale-3 NIF cylinders**
- Push to higher convergence
- Improve image quality

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Scale-4 NIF cylinder
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Scale-4 NIF cylinders
- Push to higher CR
- Measure instability growth at ignition-relevant CRs

Second scale-3 NIF cylinders
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FY 2017 | FY 2018 | FY 2019 | FY 2020 | FY 2021
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This talk will focus on hydrodynamic scaling of cylindrical implosions from OMEGA to NIF at low CR.
Hydrodynamic scaling is motivated by the fact that the Euler equations are invariant under certain transformations.

- The Euler equations are invariant to the transformation\(^1,2\)
  \[
  \vec{x} \rightarrow \lambda \vec{x}, \quad t \rightarrow \lambda t
  \]

- If initial seeds for the instability are also scaled, then hydrodynamic 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

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\textsuperscript{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

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

Transverse radiograph shows very small bowing of marker layer for OMEGA target

During the drive phase, the laser deposition region is well separated from the ablation front location for both scales.

- Ablation pressure is about 45 Mbar, with coronal temperatures ~1500 eV
- Radiation is beginning to preheat the aluminum marker, and the temperature at the leading edge is roughly 1 eV
Following shock breakout, the pressure and density gradients at the inner surface are misaligned, an RT unstable configuration.

- Shock strength is around 15 Mbar
- Shocked CH foam has density of 1.3 g/cm³, slightly more than 4-fold increase
- Aluminum temperature is 18—20 eV at this time with density 3.6 g/cm³
The marker continues to decompress as it converges, and the inner surface remains unstable during the deceleration.

- Shock strength increases as it approaches the cylinder axis
- Aluminum temperature has cooled to 12 eV and density is 2.1 g/cm³
The marker layer coasts in to a final CR~2.25, and the rebounding shock impacts it at 9 ns (OMEGA) or 28 ns (NIF).

- Shock strength jumps to 50 Mbar after it rebounds from the axis
- At OMEGA, imaging is limited to only 7.8 ns after the start of laser drive, so imaging reshock with this platform is not possible (but we can with NIF)
The hydrodynamic trajectories are scale-invariant between the OMEGA and NIF cylindrical implosion designs.

- Hydrodynamics equations recast in scale-invariant form:

\[ r = \lambda \hat{r} \]
\[ t = \lambda \hat{t} \]
\[ \dot{r} = \frac{d(\lambda \hat{r})}{d(\lambda \hat{t})} = \hat{r} \]
\[ \ddot{r} = \frac{d^2(\lambda \hat{r})}{d(\lambda \hat{t})^2} = \frac{1}{\lambda} \hat{r} \]
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.

**OMEGA Scale-1 Cylinder**

- OMEGA 93071
  - $t = 4.725$ ns
  - Incoming Shock

- OMEGA 93070
  - $t = 5.725$ ns

- OMEGA 93069
  - $t = 6.725$ ns

- OMEGA 93068
  - $t = 7.725$ ns
  - Rebounding Shock

**NIF Scale-3 Cylinder**

- N190212-003
  - $t = 14.15$ ns

- N190212-003
  - $t = 18.65$ ns

- N190212-002
  - $t = 23.15$ ns

- N190212-002
  - $t = 27.65$ ns
Growth factors of 14 are observed at late time \((t/\lambda = 7.7 \text{ ns})\) for both sets of cylindrical implosion experiments.

- Each shot is simulated separately using as-built dimensions and as-fired laser energy
- Common tuning parameters used for all simulations
LANL is pursuing a systematic approach to developing high CR cylindrical implosions on the National Ignition Facility (NIF).

- Scale-invariant hydrodynamic instability growth is observed in cylindrical implosions at OMEGA and NIF that varied in radial size by a factor of 3
  - Same tuning parameters used in design, despite the disparate scales

- xRAGE simulations consistently capture the dynamics of implosion
  - Even at low CR, discrepancies between simulation and data remain
  - Due to mix, preheat, or 3D effects? → Requires further investigation

- The NIF scale-3 cylindrical implosions will begin pushing to higher convergence (CR~5) in experiments scheduled for Feb. 12, 2020
  - Changes are planned to diagnostic setup that should greatly improve image quality on the next set of shots

- A NIF scale-4 cylindrical implosion is being designed for future experiments pushing to CR=10 and beyond