Hot-Spot Mix in Ignition-Scale Implosions at the National Ignition Facility (NIF)

Space (μm)

Ge Kα

Ge Heα + satellite

(Ge in shell is photopumped by hot-spot x-ray continuum)

Photon energy (keV)

9.75

11.1

Ignition target (Rev. 5)

Fill tube 10 μm SiO₂

Hole 5 μm

Ge doping at. #%
0.0%
0.5%
1.0%
0.5%
0.0%

Ablator 190 μm

Ge-doped CH

Ice 68 μm

DT (THD) ice

DT (THD) gas

R = 1.1 mm

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Summary

Hot-spot mix in NIF ignition-scale implosions is diagnosed with Ge K-shell spectroscopy

- Hydrodynamic instabilities are predicted to mix CH and Ge ablator mass deep into the hot spot at ignition time (hot-spot mix)*
- The hot-spot mix mass was estimated from the Ge K-shell line brightness using a detailed atomic physics model
- Predictions of a simple mix model are consistent with the experimental results

The inferred amount of hot-spot mix mass for NIF ignition-scale implosions is comparable to or below the 75-ng requirement.**

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N. Izumi et al., CO8.00013.
R. Epstein et al., CO8.00014.
B. A. Hammel et al., GP9.00114.
K. J. Peterson et al., PO6.00006.
M. A. Barrios et al., PO6.00009.
NIC mix working group collaboration

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\textsuperscript{2}Lawrence Livermore National Laboratory
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\textsuperscript{4}Los Alamos National Laboratory
\textsuperscript{5}University of Nevada
\textsuperscript{6}Also Departments of Mechanical Engineering and Physics & Astronomy, University of Rochester
\textsuperscript{7}General Atomics
\textsuperscript{8}Sandia National Laboratories
The NIF Rev. 5 ignition capsule has a Ge dopant in the ablator to minimize x-ray preheat of the shell closest to the DT ice.

**Ignition target (Rev. 5)**

- Ablator 190 \(\mu\)m
- Ice 68 \(\mu\)m
- Fill tube 10 \(\mu\)m SiO\(_2\)
- Hole 5 \(\mu\)m

**Symcap target**

- Ablator 190 \(\mu\)m
- Ice 68 \(\mu\)m
- Fill tube 10 \(\mu\)m SiO\(_2\)
- Hole 5 \(\mu\)m

- CH
- Ge-doped CH
- DT (THD) ice
- DT (THD) gas

- Ge doping at. %:
  - 0.0%
  - 0.5%
  - 1.0%
  - 0.5%
  - 0.0%

- Outer ablator
- 17 \(\mu\)m CH (no Ge)
- (5 + 12 \(\mu\)m replaces DT)
- “Surrogate fuel layer”
- He + D\(_2\) gas

- Ge doping at. %:
  - 0.0%
  - 0.5%
  - 1.0%
  - 0.5%
  - 0.0%

- \(R = 1.1\) mm

Hot-spot mix mass is diagnosed in DT, THD, and symcap NIF ignition-scale implosions.

*D. S. Clark et al., Phys. Plasmas 17, 052703 (2010).*
Hydrodynamic instabilities are predicted to mix Ge and CH ablator mass deep into the hot spot at ignition time.

- High $\ell$-mode (50 to 200) surface perturbations
- If the seeds are large enough, they can drive jets of ablator into the hot spot
- Simulations indicate the hot-spot mix mass is from the 1% Ge-doped layer of CH ablator
- Simulations set surface-finish requirements to keep hot-spot mix <75 ng**

Ge dopant in the ablator provides a spectroscopic signature of hot-spot mix.

B. A. Hammel et al., GP9.00114.

A time-integrated x-ray spectrometer with 1-D spatial resolution was fielded on the NIF specifically to look for Ge emission caused by mix.

Absolute photometric calibration of HSXRS (9.75 to 13.1 keV) relates Ge K-shell emission-line brightness to the hot-spot mix mass.

Supersnout containing the hot-spot x-ray spectrometer (HSXRS)

$E_{UV} = 1$ to $1.3$ MJ

Cryogenic hohlraum

Fill tube

Supersnout on the NIF

Supersnout in polar dim 10 cm from NIF target chamber center

Target positioner

Supersnout in lab
1-D spectral imaging provides clear evidence of Ge-doped material mixing with the hot spot.

The Ge He\(_{\alpha}\) emission is emitted from the mix mass and Ge K\(_{\alpha}\) emission is from the cold, dense shell.
The absolutely calibrated x-ray spectrum is spatially integrated and the x-ray continuum is modeled

- The Ge He$\alpha$ and satellite emission lines are analyzed to infer the mix mass
- The Ge K edge and Ge K$\alpha$ are analyzed to infer compressed-shell conditions

R. Epstein et al., CO8.00014.
The absolutely calibrated x-ray spectrum is spatially integrated and the x-ray continuum is modeled.
X rays above the Ge K-edge photopump the Ge-doped ablator, producing Ge K$_\alpha$ emission

$I_0 \sim e^{-\hbar \nu / kT}$

Fluorescing Ge-doped ablator

Hot-spot-emitting x-ray continuum

\[
\int I_{K\alpha} \, dh\nu = \Delta I_{K\text{edge}} \, kT \, \omega_{K\alpha} \, F(\tau_K, \tau_L, kT)
\]

Ge K$_\alpha$ brightness can be used to diagnose shell areal density.

R. Epstein et al., CO8.00014.
The mix mass is modeled as multiple spheres of ablator mass with uniform plasma conditions and areal density.

Mix-mass assumptions:
1. uniform plasma conditions with $10 \text{ Gbar} < P < 50 \text{ Gbar}$ lasting 250 ps (x-ray burnwidth)
2. CH doped with 1% atomic Ge
3. transmission of compressed shell for Ge He$_\alpha$ + satellite spectrum is 30% (lower limit)

Identical, independent spheres have the same single values of $n_e$, $T_e$, $\rho R_{\text{CHGe}}$, and $\rho R_{\text{Ge}}$. 
Bright spots* in x-ray imploded core images are consistent with heterogeneous mixing of ablator material into the hot spot.

Fourier-analyzed, gated, broadband implosion images taken along hohlraum axis around peak compression**

Bright spots persist in time.


**M. A. Barrios et al., PO6.00009.
A detailed atomic physics model is used to estimate the amount of mix mass from the Ge K-shell line brightness

- $T, \rho$ – dependent emissivity model* gives the total emission per Ge mass within the He$_\alpha$ + satellite feature
- Spectral fit includes self-absorption–coupled level kinetics, which gives an estimate of $\rho R_{\text{Ge}}$
- The Ne through H-like species are represented with detailed-configuration accounting (DCA)
  - all single excitations through $n = 10$
  - all double excitations through $n = 3$
  - important resonance-line-emitting configurations are split
- The Stark-broadened Ge line shapes were calculated using the MERL** code

Measured spectra are compared with modeled spectra for 7068 combinations of $n_e$, $T_e$, and $\rho R_{\text{Ge}}$.

The calculated spectral line shapes are sensitive to variations in the electron temperature.

\[ n_e = 1 \times 10^{25} \text{ cm}^{-3}, \ \rho R_{\text{Ge}} = 0.165 \text{ mg/cm}^2 \]

\[ T_e = 2.0 \text{ keV} \]

\[ T_e = 2.5 \text{ keV} \]

- HSXRS response function has been applied

Spectral feature contains Ge B-like to Ge He-like charge states.
The calculated spectral line shapes are sensitive to variations in the electron density.

$T_e = 2.0$ keV, $\rho R_{Ge} = 0.165$ mg/cm$^2$

$n_e = 1 \times 10^{24}$ cm$^{-3}$

$n_e = 1 \times 10^{25}$ cm$^{-3}$

- HSXRS response function has been applied

Spectral feature contains Ge B-like to Ge He-like charge states.
The calculated spectral line shapes are sensitive to variations in the Ge areal density

$n_e = 1 \times 10^{25} \text{ cm}^{-3}$, $T_e = 2.0 \text{ keV}$

$\rho R_{\text{Ge}} = 0.066 \text{ mg/cm}^2$

$\rho R_{\text{Ge}} = 0.330 \text{ mg/cm}^2$

- HSXRS response function has been applied

Spectral feature contains Ge B-like to Ge He-like charge states.
Hot-spot mix mass is determined from inferred $n_e$, $T_e$, and $\rho R_{\text{Ge}}$ and absolute brightness of Ge He\(\alpha\) and satellite spectrum.

Symcap: $n_e = 1.0 \times 10^{25} \text{ cm}^{-3}$
$T_e = 2.3 \text{ keV}$
$\rho R_{\text{Ge}} = 0.125 \text{ mg/cm}^2$
Mix mass = 29 ng

- Spectrum was corrected for shell attenuation
- Sphere diameter ~ $\mu$m and number of spheres ~$10^2$ to $10^4$

Mix-mass density: $n_e \rightarrow \rho_{\text{CHGe}}$ assuming $Z = 3.75$
Radius of sphere: $R = \rho R_{\text{CHGe}} / \rho_{\text{CHGe}}$
Mix-mass in sphere: $M_{\text{sphere}} = 4\pi R^3 \rho_{\text{CHGe}} / 3$
Total mix mass: $M_{\text{total}} = (\text{measured brightness} / \text{brightness per sphere}) M_{\text{sphere}}$
Similar analysis is performed for cryogenic layered DT and THD implosions

DT: $n_e = 0.8 (+0.2, -0.5) \times 10^{25} \text{ cm}^{-3}$
$T_e = 2.4 (+0.6, -0.3) \text{ keV}$
$\rho R_{\text{Ge}} = 0.075 (+0, -0) \text{ mg/cm}^2$
Mix mass = 17 ($-8, +36$) ng

- Spectrum was corrected for shell attenuation
- Sphere diameter $\sim \mu\text{m}$ and number of spheres $\sim 10^2$ to $10^4$

Mix-mass density: $n_e \rightarrow \rho_{\text{CHGe}}$ assuming $Z = 3.75$
Radius of sphere: $R = \rho R_{\text{CHGe}} / \rho_{\text{CHGe}}$
Mix mass in sphere: $M_{\text{sphere}} = 4\pi R^3 \rho_{\text{CHGe}} / 3$
Total mix mass: $M_{\text{total}} = (\text{measured brightness/brightness per sphere}) M_{\text{sphere}}$
Hot-spot mix mass inferred from x-ray spectroscopy is typically within the 75-ng allowance*

<table>
<thead>
<tr>
<th>Shot</th>
<th>CH Ge mix mass (ng)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N100929</td>
<td>74 (−48, +55)</td>
</tr>
<tr>
<td>N110121</td>
<td>67 (−47, +110)</td>
</tr>
<tr>
<td>N110201</td>
<td>15 (−12, +285)</td>
</tr>
<tr>
<td>N110212</td>
<td>20 (−17, +265)</td>
</tr>
<tr>
<td>N110603</td>
<td>18 (−14, +23)</td>
</tr>
<tr>
<td>N110608</td>
<td>63 (−44, +65)</td>
</tr>
<tr>
<td>N110615</td>
<td>15 (−10, +56)</td>
</tr>
<tr>
<td>N110620</td>
<td>17 (−8, +36)</td>
</tr>
<tr>
<td>N101004</td>
<td>14 (−7, +30)</td>
</tr>
<tr>
<td>N110208</td>
<td>29 (−10, +44)</td>
</tr>
<tr>
<td>N110211</td>
<td>20 (−8, 24)</td>
</tr>
<tr>
<td>N110612</td>
<td>79 (−39, 300)</td>
</tr>
</tbody>
</table>

There is a requirement for ignition, set from multidimensional radiation–hydrodynamic simulations, that the hot-spot mix mass be less than 75 ng.*

The mix mass is estimated with a model that combines linear analysis with detailed simulations of perturbation growth.

**Mix-mass model**

1. Transform capsule surface maps into $\ell$ space
2. Multiply by growth factors at peak velocity
3. Transform back to physical space
4. Find volume of ablator inside the hot spot
5. Multiply by density calibrated with detailed bump simulations (~10 g/cc)
6. The resulting mass is an estimate of what gets into the hot spot

Based on 2-D simulations, 20 ng of mix mass is added for the fill-tube jets.

The inferred amount of hot-spot mix for ignition-scale implosions is comparable to or below the 75-ng requirement.

Further efforts may be needed to control hot-spot mix:
1. Reduce capsule surface-mass perturbations
2. Reduce the growth factors of hydrodynamic instability
3. Change the ablator material (e.g., Cu-doped Be)
The inferred amount of hot-spot mix for ignition-scale implosions is comparable to or below the 75-ng requirement.

Further efforts may be needed to control hot-spot mix:
1. Reduce capsule surface-mass perturbations
2. Reduce the growth factors of hydrodynamic instability
3. Change the ablator material (e.g., Cu-doped Be)
The Ge dopant in the Rev. 5 ablator of the ignition target design has been replaced with a Si dopant*

Variants of this capsule doped with trace amounts of Ge and Cu will be used to diagnose hot-spot mix with x-ray spectroscopy.

*S. Glenzer, Bl3.00001.
*D. Callahan, Bl3.00002.
*D. Hicks, Bl3.00003.
*B. Spears, Bl3.00006.
Hot-spot mix will be examined with Cu and Ge ablator dopants in NIF ignition-scale implosions

Cu, Ge, Si-doped CH ablator

<table>
<thead>
<tr>
<th>Layer</th>
<th>Dopant (atm. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cu (0.1%)</td>
</tr>
<tr>
<td>2</td>
<td>Si (0.7%)</td>
</tr>
<tr>
<td></td>
<td>Ge (0.15%)</td>
</tr>
<tr>
<td>3</td>
<td>Si (1.7%)</td>
</tr>
<tr>
<td></td>
<td>Ge (0.15%)</td>
</tr>
<tr>
<td>4</td>
<td>Si (1%)</td>
</tr>
<tr>
<td>5</td>
<td>None</td>
</tr>
</tbody>
</table>

Supersnout II (5.75 to 16.5 keV)

- Gated x-ray detector
- Filter and image-plate detector
- Elliptical Bragg crystals
- Blast shield
- 12× (or 4×) gated and time-integrated broadband x-ray pinhole images

X-ray radiography of imposed surface perturbations will be studied in future experimental campaigns.*

*K. J. Peterson et al., PO6.00006.
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- The hot-spot mix mass was estimated from the Ge K-shell line brightness using a detailed atomic physics model

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R. Epstein et al., CO8.00014.
B. A. Hammel et al., GP9.00114.
K. J. Peterson et al., PO6.00006.
M. A. Barrios et al., PO6.00009.
The NIF ignition capsule has a Ge dopant in the ablator to minimize x-ray preheat of the shell closest to the DT ice.

Measured atomic fraction of Ge dopant in glow-discharge polymer (GDP = CH) shell

X-ray radiograph of symcap capsule

Ge dopant in the ablator provides a spectroscopic signature of hot-spot mix.
Hot-spot mix mass was diagnosed on four NIF symcap implosions

<table>
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<tr>
<th>Shot</th>
<th>Mix $n_e$ ($\times 10^{25}$ cm$^{-3}$)</th>
<th>Mix $T_e$ (keV)</th>
<th>Mix $\rho R_{Ge}$ (mg/cm$^2$)</th>
<th>CH Ge mix mass (ng)</th>
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<tr>
<td>N101004</td>
<td>0.8 (+0.2, −0.5)</td>
<td>2.4 (+0.6, −0.3)</td>
<td>0.150 (−0, +0.25)</td>
<td>14 (−7, +30)</td>
</tr>
<tr>
<td>N110208</td>
<td>1.0 (+0, −0.5)</td>
<td>2.3 (+0.4, −0.3)</td>
<td>0.125 (+0.025, +0.1)</td>
<td>29 (−10, +44)</td>
</tr>
<tr>
<td>N110211</td>
<td>0.9 (+0.1, −0.4)</td>
<td>2.0 (+0.3, −0.2)</td>
<td>0.150 (−0, +0.125)</td>
<td>20 (−8, 24)</td>
</tr>
<tr>
<td>N110612</td>
<td>0.9 (+0.1, −0.5)</td>
<td>2.2 (+0.5, −0.5)</td>
<td>0.075 (+0.025, −0)</td>
<td>79 (−39, 300)</td>
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</table>

• Hot-spot mix-mass analysis assumes uniform plasma conditions with $10 \text{ Gbar} < P < 50 \text{ Gbar}$ lasting 250 ps, 1% atomic Ge dopant, and 30% shell transmission
Hot-spot mix mass was diagnosed on eight NIF cryogenic-DT or THD layered implosions

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<td>74 (–48, +55)</td>
</tr>
<tr>
<td>N110121</td>
<td>0.3 (+0.6, +0.1)</td>
<td>2.1 (+0.3, –0.5)</td>
<td>0.075 (+0, –0)</td>
<td>67 (–47, +110)</td>
</tr>
<tr>
<td>N110201</td>
<td>1.0 (+0, –0.4)</td>
<td>1.6 (+0.8, –0.5)</td>
<td>0.2 (–0.1, +0.15)</td>
<td>15 (–12, +285)</td>
</tr>
<tr>
<td>N110212</td>
<td>0.5 (+0.1, +0.1)</td>
<td>1.6 (+0.8, –0.5)</td>
<td>0.075 (–0, +0.15)</td>
<td>20 (–17, +265)</td>
</tr>
<tr>
<td>N110603</td>
<td>0.4 (+0.6, +0)</td>
<td>1.9 (+0.6, –0.3)</td>
<td>0.075 (+0.025, –0)</td>
<td>18 (–14, +23)</td>
</tr>
<tr>
<td>N110608</td>
<td>0.4 (+0.6, +0)</td>
<td>2.0 (+0.4, –0.3)</td>
<td>0.075 (+0, –0)</td>
<td>63 (–44, +65)</td>
</tr>
<tr>
<td>N110615</td>
<td>0.9 (+0, –0.5)</td>
<td>2.2 (+1.0, –0.5)</td>
<td>0.075 (+0, –0)</td>
<td>15 (–10, +56)</td>
</tr>
<tr>
<td>N110620</td>
<td>0.8 (+0.2, –0.5)</td>
<td>2.4 (+0.6, –0.3)</td>
<td>0.075 (+0, –0)</td>
<td>17 (–8, +36)</td>
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Sphere diameter ~ $\mu$m

Number of spheres ~ $10^2$ to $10^4$

- Hot-spot mix-mass analysis assumes uniform plasma conditions with 10 Gbar < $P$ < 50 Gbar lasting 250 ps, 1% atomic Ge dopant, and 30% shell transmission
The bright spots in the gated images could be evidence of ablator material jets in the hot spot.

Fourier analysis is used to filter envelope and bright spots from raw image.
The Ge K-edge contrast and cold Ge opacity are used to diagnose the areal density of Ge-doped ablators.

\[ \frac{\rho R(\text{CH Ge})}{\rho R(\text{Ge})} = \frac{\text{mass}(\text{CH Ge})}{\text{mass}(\text{Ge})} = \begin{cases} 18.9 \text{ for 0.5\% atomic fraction} \\ 9.9 \text{ for 1.0\% atomic fraction} \end{cases} \]