Proton Core Imaging Spectroscopy on OMEGA Implosions

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Abstract

Multiple pinhole cameras are being used to image the burn regions in implosions of both thin (~2 µm-glass) and thick (~20 µm-CH) shell capsules on OMEGA. Because the pinholes are generally much larger than the burn region, information about the proton source (i.e. size, shape, and symmetry) can be extracted from the "penumbra" of the resulting images. Capsules with D³He and DD fills have been studied with Proton Core Imaging Spectroscopy (PCIS). For thin-shell capsules, experimental differences in the burn regions between DD and D³He reactions will be explored, contrasted, and compared to 1-D calculations. Particularly intriguing is the situation for thick shell implosions. At first shock coalescence, the escaping charged particles sample a relatively small ρR. At bang time (a few hundred ps after shock coalescence), however, only the energetic 14.7-MeV protons escape, since they sample a much larger ρR (~70 mg/cm²). Comparisons of the shock and compression burn regions will be made.

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• **Proton core imaging spectroscopy (PCIS)** gives information about radial burn profiles of DD and D$^3$He reactions.

• PCIS provides radial burn profiles of DD and D$^3$He protons from D$^3$He implosions of thin and thick shell capsules at shock and bang time.

• For **thin (~2\(\mu\)m) shell capsules**, a temperature profile is inferred by comparing burn profiles of DD protons (3 MeV) and D$^3$He protons (14.7 MeV).

• For **thick (~20\(\mu\)m) shell capsules**, compare DD proton burn profile at shock time with D$^3$He burn profile at bang time.
PCIS simultaneously images protons from DD and D\textsuperscript{3}He reactions

D + D $\rightarrow$ T[1.01 MeV] + p[3.02 MeV]

D + \textsuperscript{3}He $\rightarrow$ $\alpha$[3.6 MeV] + p[14.7 MeV]

\textbf{Bang time}

D\textsuperscript{3}He(18 atm) SiO\textsubscript{2}[2 $\mu$m]
PCIS images proton emissions on to CR-39 plastic

- Capsule diameter: ~1000 μm
- Pinhole diameter: 300-2000 μm
- Pinhole plate thickness: 500 μm
- Target to Pinhole distance: 3-33 cm
- Pinhole to CR-39 distance: 33 cm

Tracks/cm²
Filters are placed in front of the CR-39 to adjust which particles will be detected.

Filter thickness is set so that “Bert” is sensitive to DD protons and “Ernie” is sensitive to $D^3He$ protons.
The penumbra of the image contains information about the burn profile

\[ \text{D}^3\text{He Proton tracks / cm}^2 \]

in the plane of the CR-39

( Shot 25599: \text{D}_2(6) \text{ }^3\text{He}(12) \text{ }\text{CH}[20] )
Finding the radial burn profile (part 1)

Step 1: Calculate the number of proton tracks per unit area $N$ as a function of radius in the image plane.

Step 2: Calculate $dN/dr$. 

![Graphs showing the radial burn profile]
Finding the radial burn profile (part 2)

Step 3: Use analytic inversion formula with system geometry to get radial profile of the proton emissivity in the capsule. (In this case, dN/dR is fit by a gaussian.)
Analytic inversions for two simple source functions*

\[ M \equiv \frac{R_d}{R_p} = \text{magnification} \]

\[ r_s = \frac{r_f}{M}, \quad a_s = 4M^3 \left( \frac{R_d}{r_f} \right)^2 A_f \]

*Exact only in the limit where pinhole diameter >> source diameter, but with very little error (< 5%) for the finite pinholes used here.
Comparison between burn profiles from uniform and gaussian source functions

Shot 27808: D₂(6) ³He(12) CH[20]

uniform source

dN/dR/cm²

D³He Protons/µm³

1/e ~ 40 µm

gaussian source

Radius (cm)

Radius (µm)
Test of pinhole center-finding algorithm

Shot 26081: D$_2$(6) $^3$He(12) SiO$_2$[1.9]

<table>
<thead>
<tr>
<th>Width of Penumbra (µm)</th>
<th>1000</th>
<th>900</th>
<th>800</th>
<th>700</th>
<th>600</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta x$ from Algorithm-Calculated Center (µm)</td>
<td>-1000</td>
<td>-500</td>
<td>0</td>
<td>500</td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>

Width calculated by default = 624.6 µm
Minimum width = 616.2 µm
(found with center displaced by dx = 100 µm, dy = -10 µm)

Error in the default values ~ 1.4%.
Summing pinhole images (shot 27808)

Pinhole images

1 pinhole

2 pinholes

3 pinholes

4 pinholes

N(R)/cm per R(cm) [x10^4]

dN/dR (cm^-3) per R(cm) [x10^6]

Radius (cm)
DD and D$^3$He protons are imaged for implosions of thin glass shell capsules at bang time

\[ \text{D} + \text{D} \rightarrow \text{T}[1.01 \text{ MeV}] + \text{p}[3.02 \text{ MeV}] \]

\[ \text{D} + ^3\text{He} \rightarrow ^\alpha[3.6 \text{ MeV}] + \text{p}[14.7 \text{ MeV}] \]

D$^3$He(18 atm) SiO$_2$[2 \mu m]
Burn profiles of DD and D$^3$He protons from a thin (1.8 $\mu$m) glass shell D$^3$He implosion

Shot 27456: D$_2$(6) $^3$He(12) SiO$_2$[1.8]

The 1/e points are at radii 60 and 110 $\mu$m
Temperature $T_i(r)$ can be inferred from the DD and $D^3He$ proton burn profiles.

Shot 27456: $D_2(6)$ $^3He(12)$ SiO$_2[1.8]$
Yield averaged temperatures compared to results from other diagnostics

Shot 27456: $\text{D}_2(6)\ ^3\text{He}(12)\ SiO_2[1.8]$

<table>
<thead>
<tr>
<th>Diag.</th>
<th>$Y_{\text{D}_3\text{He}}$</th>
<th>$Y_{\text{DD}}$</th>
<th>$&lt;T_i&gt;_{\text{D}_3\text{He}}$</th>
<th>$&lt;T_i&gt;_{\text{DD}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCIS</td>
<td>$1.3 \times 10^{10}$</td>
<td>$4.2 \times 10^{10}$</td>
<td>$\sim 15$</td>
<td>$\sim 8$</td>
</tr>
<tr>
<td>WRF</td>
<td>$1.2 \times 10^{10}$</td>
<td>$-\times 10^{10}$</td>
<td>$14$</td>
<td>$-\times 10^{10}$</td>
</tr>
<tr>
<td>nTOF</td>
<td>$-\times 10^{10}$</td>
<td>$5.0 \times 10^{10}$</td>
<td>$-\times 10^{10}$</td>
<td>$\sim 10$</td>
</tr>
</tbody>
</table>

$<T_i> \sim 6-7\text{ keV}$ from the ratio of the total yields $Y_{\text{DD}}/Y_{\text{D}_3\text{He}}$ determined from PCIS
Results from a thin shell capsule implosion are compared to 1-D simulations.

Shot 27456: D₂(6) ³He(12) SiO₂[1.8]
DD and D$^3$He protons from thick shell implosions are imaged at shock and bang time, respectively

\[
\begin{align*}
D + D & \rightarrow T[1.01 \text{ MeV}] + p[3.02 \text{ MeV}] \\
D + ^3\text{He} & \rightarrow \alpha[3.6 \text{ MeV}] + p[14.7 \text{ MeV}]
\end{align*}
\]

\(\text{D}^3\text{He}(18 \text{ atm}) \text{ CH}[20 \text{ \(\mu\text{m}\)]} \)
Burn profiles of DD and D\(^3\)He protons from a thick (20\(\mu\)m) CH-shell D\(^3\)He implosion

Shot 27806: D\(_2\)(6) \(^3\)He(12) CH[20]

at shock time

at bang time

1/e ~ 100 \(\mu\)m

1/e ~ 45 \(\mu\)m
Burn profiles of DD and D³He protons from several thick shell capsule implosions

**DD Proton Burn Profiles**
(at shock time)

- 27806
- 27808
- 27810
- 27811,12

**D³He Proton Burn Profiles**
(at bang time)

- 27806
- 27808
- 27810
- 27811,12
Yield comparison of all thick shell profiles

<table>
<thead>
<tr>
<th>Shot #</th>
<th>Bert $Y_{DD}$ PCIS ($\times 10^8$)</th>
<th>1/e point</th>
<th>Ernie $Y_{D3He}$ PCIS ($\times 10^8$)</th>
<th>$Y_{D3He}$ WRF ($\times 10^8$)</th>
<th>1/e point</th>
</tr>
</thead>
<tbody>
<tr>
<td>27806</td>
<td>1.3</td>
<td>100</td>
<td>3.7</td>
<td>3.7</td>
<td>45</td>
</tr>
<tr>
<td>27808</td>
<td>0.9</td>
<td>110</td>
<td>2.7</td>
<td>2.2</td>
<td>40</td>
</tr>
<tr>
<td>27810</td>
<td>1.2</td>
<td>110</td>
<td>2.4</td>
<td>1.8</td>
<td>45</td>
</tr>
<tr>
<td>27811,12*</td>
<td>1.2</td>
<td>80</td>
<td>1.9</td>
<td>1.9</td>
<td>40</td>
</tr>
</tbody>
</table>

*PCIS summed over two shots.
Yields for this data are normalized.
Summary

• With Proton Core Imaging Spectroscopy (PCIS), the first burn profiles of DD and D³He reactions have been obtained of thin- and thick-shell implosions

• $T_i(r)$ and $n_i(r)$ profiles have been inferred for thin-shell implosions and compared to 1-D simulations

• Burn profiles of DD and D³He reactions at shock coalescence and at bang time have been measured for thick shell implosions.
Future Work

- Optimize PCIS instrumentation.
- Begin to build up a data base of images, and establish the range of PCIS applicability.
- Compare PCIS to x-ray and neutron images.
- Compare PCIS to 1-D and 2-D simulated images.
- Investigate asymmetries in burn region, and develop algorithms to treat asymmetries.
- Obtain orthogonal images.