Precision measurements of stopping power at the NIF

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Cold Models
C at 2.2 g/cc, 300 K

Plasma Models
C at 8.5 g/cc, 4 eV

<\frac{dE}{dx}> [MeV cm^2/g]

15 MeV p through 175 mg/cm^2 of C

Measurement uncertainty

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NIF/JLF User group meeting, Livermore
Feb 1-3, 2016
LLNL-PRES-683262.
The NIF proton radiography platform is ready

- All components of the NIF proton radiography platform are ready:
  - A bright \(10^{10}\) protons, compact (35-80 \(\mu\)m diam), monoenergetic (4% \(\Delta E/E\)), isotropic source of 15 MeV and 3 MeV protons
  - PRAD diagnostic with 9×9 cm detector area at 39 cm from TCC
  - First demonstration coming up in mid-February
Monoenergetic proton radiography

Proton source → 3 and 15 MeV protons → Subject plasma → Proton detector
Phenomena investigated with monoenergetic proton radiography at OMEGA include:

- Laser-foil interactions
- Magnetic reconnection
- Magnetic flux compression
- RT instability
- Weibel instability
- ICF capsule implosions
- ICF hohlraums
- Charged-particle stopping

Proton source

Subject plasma

Proton detector

3 and 15 MeV protons

Fast-ignition capsule

Laser-foil plasma bubble

ICF hohlraum

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Monoenergetic proton source has been demonstrated*

**Setup:** 38 kJ, 6-quad direct drive of $D^3He$-filled, SiO$_2$ exploding pusher.

**Main Results:**
- Proton yield = $9.2 \times 10^9$
- $<E_p> = 14.981 \pm 0.036$ MeV
- $E_{rms} < 0.06$ MeV (consistent with no energy variation along different lines of sight)
- Source size = $79 \pm 19 \mu$m FWHM diam

A smaller capsule trades off yield for resolution

<table>
<thead>
<tr>
<th>Shot number</th>
<th>N151214-001</th>
<th>N151214-002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capsule diameter</td>
<td>440 µm</td>
<td>860 µm</td>
</tr>
<tr>
<td>Gas fill</td>
<td>18 atm D³He</td>
<td>18 atm D³He</td>
</tr>
<tr>
<td>N quads</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>E_{laser}</td>
<td>46.8 kJ</td>
<td>47.3 kJ</td>
</tr>
<tr>
<td>15 MeV proton yield</td>
<td>2.4×10⁹</td>
<td>1.3×10¹⁰</td>
</tr>
<tr>
<td>3 MeV proton yield</td>
<td>2.4×10⁹</td>
<td>3.4×10¹⁰</td>
</tr>
<tr>
<td>Source size</td>
<td>47 µm</td>
<td>75 µm</td>
</tr>
</tbody>
</table>

Using a “half-size” capsule reduces the 15 MeV yield by 5x, and the source size by ~1.5x
New PRAD diagnostic for proton radiography

- Mountable on DIM(0,0) and DIM(90,78)
- Compatible with WRFs and pTOF (but not mptof)
- Minimum detector standoff: 39 cm from TCC
- Active area is 9×9 cm square
  - 2 layers of CR-39 (protons)
  - 1 layer of BAS-MS IP (xrays)
Precision measurements of stopping power in WDM will use a variant of the proton radiography platform

- All components of the NIF proton radiography platform are ready:
  - A bright ($10^{10}$ protons), compact (35-80 μm diam), monoenergetic (4% $\Delta E/E$), isotropic source of 15 MeV and 3 MeV protons
  - PRAD diagnostic with 9×9 cm detector area at 39 cm from TCC
  - First demonstration coming up in mid-February

- Precise (~1%) measurement of charged-particle stopping power in warm dense matter will be demonstrated with a variant of the platform
  - 15 MeV $D^3He$ protons will be launched through a thick (175 mg/cm$^2$) slab of shock-compressed matter ($\Gamma_e = 0.6$, $\theta = 0.03$)
  - $\sim6\pm0.05$ MeV downshift will be measured with WRF spectrometers
  - A dedicated VISAR shot has characterized the sample $\rho$-$T$ state to high precision, and demonstrated uniformity better than 6%
We will measure source spectrum, cold matter and warm-dense matter downshifts on a single shot.

Cold $\Delta E$ \hspace{2cm} DIM(0,0) \hspace{2cm} Warm $\Delta E$

175 mg/cm² slab (500 μm HDC)

Protons arrive at same time as shock breaks out the back

8 mm

15 MeV protons

D³He backlighter

source $E_0$

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Stopping power models differ by much more than the anticipated measurement uncertainty.

<table>
<thead>
<tr>
<th>Stopping method</th>
<th>$&lt;E&gt;$ (MeV)</th>
<th>$&lt;E&gt; - E_{\text{SRIM}}$ (MeV)</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRIM</td>
<td>8.80</td>
<td></td>
<td>SRIM cold graphite stopping [300 K, 2.2 g/cc]</td>
</tr>
<tr>
<td>ICRU</td>
<td>8.89</td>
<td>0.09</td>
<td>ICRU cold amorphous carbon stopping [300 K, 2.2 g/cc]</td>
</tr>
<tr>
<td>Zimmerman</td>
<td>8.86</td>
<td>0.06</td>
<td>Zimmerman’s parametrization</td>
</tr>
<tr>
<td>AA-LDA</td>
<td>9.07</td>
<td>0.27</td>
<td>AA calc, with integration over density of linear response formula</td>
</tr>
<tr>
<td>AA-Bethe</td>
<td>9.41</td>
<td>0.62</td>
<td>Kohn-Sham AA calc plugged into Bethe limit</td>
</tr>
</tbody>
</table>

15 MeV protons through 175 mg/cm² carbon (8.5 g/cc, 4 eV or 2.2 g/cc, 300 K)
**ΔE/Δx measurement can be made with ~1% uncertainty**

Mean stopping power of 15 MeV protons going through the compressed HDC slab

<table>
<thead>
<tr>
<th>parameter</th>
<th>nominal value and expected uncertainty</th>
<th>dE/dx uncertainty (%)</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔE</td>
<td>6.00 ± 0.05 MeV</td>
<td>0.8%</td>
<td>Energy downshift (50 keV WRF uncertainty)</td>
</tr>
<tr>
<td>ΔE_{Au}</td>
<td>0.14 ± 0.02 MeV</td>
<td>0.3%</td>
<td>Au layer adjustment to downshift</td>
</tr>
<tr>
<td>ΔE_{abl}</td>
<td>0.07 ± 0.03 MeV</td>
<td>0.4%</td>
<td>Ablated mass adjustment to downshift</td>
</tr>
<tr>
<td>ΔρL</td>
<td>175 ± 0.5 mg/cm²</td>
<td></td>
<td>Initial HDC areal density (= ρ₀Δx)</td>
</tr>
<tr>
<td>Δx</td>
<td>500 ± 0.2 μm</td>
<td>0.04%</td>
<td>Initial HDC slab thickness</td>
</tr>
<tr>
<td>ρ₀</td>
<td>3.50 ± 0.01 g/cc</td>
<td>0.3%</td>
<td>Initial HDC density</td>
</tr>
<tr>
<td>ΔE/ΔρL</td>
<td>33.1 ± 0.3 MeV cm²/g</td>
<td>1.0%</td>
<td>Mean stopping power through slab</td>
</tr>
</tbody>
</table>

(Notional values only: first measurement will be made in two weeks!)
But...

What is the state of the material?
A dedicated VISAR shot has characterized the slab state

24.4 km/s HDC shock Hugoniot state:
- $P = 10.5$ Mbar
- $\rho = 7.0$ g/cc ($\rho/\rho_0 = 2.0$)
- $T = 0.9$ eV
- $\Gamma = 0.63$ (coupling parameter)
- $\theta = 0.03$ (degeneracy parameter)

Transverse shock speed uniformity = 1.5%
Ok, so why start with shocked HDC?

- The shock Hugoniot is a reproducible, well-characterized locus of material states
  - Hugoniot passes through WDM regime
  - Wealth of experimental data along the Hugoniot
  - dE/dx measurement interpretation can be revised by future Hugoniot measurements

- HDC:
  - Is transparent (can track the shock through the sample with VISAR)
  - Has high shock velocity (shorter pulse is needed to launch steady shock through the whole sample)
dEdx measurement at NIF is degenerate, strongly coupled

Previous stopping power experiments
NIF shot #1: HDC shocked to ~11 Mbar

NIF offers a more-precise measurement of a better-characterized plasma than any previous experiment
The NIF proton radiography platform is ready, and will be used to precisely measure stopping power in WDM

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  - ~6±0.05 MeV downshift will be measured with WRF spectrometers
  - A dedicated VISAR shot has characterized the sample $\rho$-$T$ state to high precision, and demonstrated uniformity better than 6%
Backup slides
Preshot simulations predict uniform WDM state

In sample at time of proton arrival (18.7 ns):
- 14.7 Mbar (2% variance)
- 7.8 g/cc (1.4% variance)
- 2.5 eV (12% variance)

\[ \Gamma_e = 0.48, \theta = 0.13 \]

*Fe EOS used for Au calculation
Preshot expected longitudinal uniformity: 1.4% in density, 12% in temperature

- VISAR will measure shock velocity through entire transit with ~0.25% precision
  - Constrains average P, ρ, T Hugoniot conditions to better than 1%
- Reverberations will relax to the same P-u_p value as the final steady shock
- Stopping is dominated by uniform shocked sample
  - Ablated mass and Au layer are 2.9, 2.6% of initial total mass, respectively

Sample state:
- 14.7 Mbar (2% variance)
- 7.8 g/cc (1.4% variance)
- 2.5 eV (12% variance)
- Γ_e = 0.48, θ = 0.13

This variation has small effect on the stopping power compared to 1% measurement uncertainty
Transverse variations are expected to be <5%

- 8 upper inner quads (32 beams) are split and tiled over 2 mm
- Tiling gives expected 10% illumination uniformity over entire 2 mm area
  - Illumination uniformity <5% over proton spectrometer (WRF) FOV
- Uniformity of illumination will be measured with GXD
- Transverse uniformity of shock will be measured with VISAR
Timing uncertainty affects <1% of sample mass

- Timing uncertainty will be of order 100 ps
  - Shock breakout and proton bang time measured with VISAR and pTOF

- Thick (500 μm) sample reduces fractional importance of this timing uncertainty

200 ps early:
  shock has not compressed last 5.6 μm of sample (1%)

Nominal timing

200 ps late:
  Last ~1% has started to release

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Electromagnetic fields should not be a problem

- E fields decay rapidly ($\tau \sim 100$ ps) after laser turns off
  - Proton arrival 300 ps after laser turns off
- B fields located predominantly around perimeter, have no effect on energy
- We will measure strength and topology of fields in situ in a dedicated experiment to confirm they will not be an issue for $dE/dx$
Scattering and straggling effects have been evaluated with TRIM and are relatively small for these conditions.