Diagnostics for Laser Driven Sources
CUOS High-Field Science Group

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Recent Collaborators:
LOA, UCLA/IST, Queens U. Belfast,
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Advantages of Laser Wakefield Accelerators

• Compact (Table Top) Size
  • High-acceleration gradient (up to 100 GeV/m)
    • \( \sim \)GeV electrons from cm-scale plasma
  • Small source size (down to \( \sim \)1 \( \mu \)m)

• Optically Synchronized
  • Easily allows for \( \sim \) fs accuracy
  • Jitter limited to mechanical stability of optics (no electronic jitter)

• Inherently Short Pulse
  • Driver is an ultrashort laser pulse (typically 100 fs or less, as \( c\tau_L < \omega_{pe} \))
  • Acceleration structure ("Plasma Bubble") can further reduce duration/emittance
    • Can achieve sub-fs duration using controlled injection [2]!

CUOS laser systems

Hercules
10J, 30fs, 800nm
2 × 10^{22} \text{ Wcm}^{-2}

4 channels of Nd:glass pump laser

T-cubed
10J, 400fs, 1.053\mu m
5 × 10^{19} \text{ Wcm}^{-2}

\lambda^3 (500Hz)
12mJ, 30fs, 800nm
5 × 10^{18} \text{ Wcm}^{-2}

Omega EP
<1000J, 1-10ps, 1.053\mu m
1 × 10^{19} \text{ Wcm}^{-2}

Titan
<300J, 1-10ps,
1.053\mu m
5 × 10^{19} \text{ Wcm}^{-2}

Gemini
2x15J, 30 fs, 800nm
\sim 10^{21} \text{ Wcm}^{-2}
Ion Measurements
Radiation Pressure Acceleration

High Intensity Laser

Target

Accelerated Ions

Experimental Setup for RPA

From Compressor

Plasma Mirror Chamber

To Beam Quality Diagnostics
X-ray diode

F/1 OAP

QWP

Experimental Chamber

Scint.&PMT

ES

DM

TP
Proton Acceleration From Thin Foils

Thickness Trends

Proton max energies converge for thin targets

![Graph showing thickness trends with max proton energy vs. thickness, comparing linear and circular trajectories.](image)
Neutron Measurements
Pitcher-catcher configuration

- Bulk and pitcher/catcher geometries used.
- Nuclear reactions selected based on target and catcher material.
- Deuterated surface contaminant layer was introduced with deuterated ice layers.

<table>
<thead>
<tr>
<th>Nuclear Reaction</th>
<th>Target</th>
<th>Catcher</th>
<th>Q Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{2}{1} d + \frac{2}{1} d \rightarrow \frac{3}{2} He + \frac{1}{0} n$</td>
<td>1.5(±0.5) mm CD</td>
<td>None</td>
<td>3.27 MeV</td>
</tr>
<tr>
<td>$\frac{1}{1} p + \frac{7}{3} Li \rightarrow \frac{7}{4} Be + \frac{1}{0} n$</td>
<td>100 nm (C$_2$H$_4$)$_n$</td>
<td>LiF</td>
<td>−1.64 MeV</td>
</tr>
<tr>
<td>$\frac{2}{1} d + \frac{7}{3} Li \rightarrow \frac{8}{4} Be + \frac{1}{0} n$</td>
<td>3 μm Mylar with (C$_8$D$_8$)$_n$ Paint</td>
<td>LiF</td>
<td>15.03 MeV</td>
</tr>
<tr>
<td>$\frac{2}{1} d + \frac{7}{3} Li \rightarrow \frac{8}{4} Be + \frac{1}{0} n$</td>
<td>800 nm Al with D$_2$O Ice</td>
<td>LiF</td>
<td>15.03 MeV</td>
</tr>
</tbody>
</table>
D-Li (Ice)
800 nm Al with frozen D$_2$O

- Cooling the target (-150°C) with liquid nitrogen and spraying heavy water into the chamber forms a layer of D$_2$O on the target surface.

- The lack of carbon and the absence of oxygen species above O$^{6+}$ leads to a pure deuteron signal on the Q/M = ½ TP parabola.
D-Li (Paint)

3 \( \mu \)m Mylar painted with Deuterated polystyrene paint

- Thompson Parabola overlaps \( \text{C}^6^+ \) and \( \text{D}^+ \) because they have the same \( \text{Q/M} \).
- CR-39 shows the presence of two distinct species in the trace.
Bubble Detector

- Sensitive to neutrons between 200 keV and 15 MeV
- 1 bubble per $10^3$ neutrons/cm$^2$
- Small and portable design allows them to be placed anywhere outside of the chamber allowing flux measurements in different directions.

Neutron Diagnostic Setup

BD-PND neutron bubble detectors

F/1 OAP

1. 275 cm
2. 330 cm
3. 950 cm

TOF

Neutron Signal

Catcher In

Catcher Out

Photon Flash

nToF Signal Voltage (V)

Time (ns)
Deuteron Acceleration

- The D-Li (Ice) technique improves both the energy and number of accelerated neutrons with a 1 \((\pm 0.5)x 10^{-5}\) conversion efficiency.

- It is important to note that this is the MCNP Q/M = \(\frac{1}{2}\) signal, so the D-Li (Paint) signal contains some carbon contaminants.

- The Simulation D-Li (Ice) trace was calculated using a PIC code which modeled the target scale length as \(\rho = A \times e^{-z/L_s}\).

- The simulated spectra was used for neutron simulations which are discussed later.
Deuteron Optimization

- Quantified the purity of the beam using the number and energy ratio of deuterons to protons above 0.5 MeV.
- The purity increased with shorter time delays.
- Redeposition of hydrogenous contaminants and sublimation reduce the purity for longer delays.
- D$_2$O was 99.8% pure yielding a theoretical maximum number ratio of 500.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Volume</th>
<th>Timing</th>
<th>Peak Number Ratio</th>
<th>Peak Energy Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>120° – 180° K</td>
<td>100 (±50) μl</td>
<td>350 ms</td>
<td>250 (±100)</td>
<td>620 (±250)</td>
</tr>
</tbody>
</table>
Neutron Generation

- Highest energy neutrons (16.8 MeV) were generated with the deuterated ice targets.
- The highest flux (2.3 X 10^7 n/sr) was seen with p-Li.
- The bulk d-d reaction showed little energy upshift which was consistent with low energy ions from bulk targets on HERCULES.
- p-Li spectrum showed the same exponential shape as the proton spectra, but not the d-Li.

<table>
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<tr>
<th>Nuclear Reaction</th>
<th>Target</th>
<th>Highest Measured Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{2}\text{D} + \frac{1}{2} \text{D} \rightarrow \frac{3}{2} \text{He} + \frac{1}{0} \text{n})</td>
<td>1.5(±0.5) mm CD</td>
<td>8.0 (±4.6)×10^5 n/sr</td>
</tr>
<tr>
<td>(\frac{1}{2}\text{p} + \frac{7}{3} \text{Li} \rightarrow \frac{4}{4} \text{Be} + \frac{1}{0} \text{n})</td>
<td>100 nm (C(_2)H(_4))(_n)</td>
<td>2.3 (±1.1)×10^7 n/sr</td>
</tr>
<tr>
<td>(^{2}\text{D} + \frac{7}{3} \text{Li} \rightarrow \frac{8}{4} \text{Be} + \frac{1}{0} \text{n})</td>
<td>3 μm Mylar with (C(_8)D(_8))(_n) Paint</td>
<td>1.3 (±0.6)×10^6 n/sr</td>
</tr>
<tr>
<td>(\frac{1}{2}\text{p} + \frac{7}{3} \text{Li} \rightarrow \frac{4}{4} \text{Be} + \frac{1}{0} \text{n})</td>
<td>800 nm Al with D(_2)O Ice</td>
<td>1.2 (±0.6)×10^6 n/sr</td>
</tr>
</tbody>
</table>

Flux was 6 times higher in the forward direction.
Neutron Generation

- Highest energy neutrons, 16.8 (±0.3) MeV, were generated with the D-Li (Ice) technique.
- A higher flux of $3 \times 10^6$ was also seen with D-Li (Ice).
- The D-Li (Paint) spectra shows a dual peak spectra with bumps at 5 MeV and 12 MeV, while the D-Li (Ice) spectra is exponential.
- Monte Carlo simulations predict dual dump spectra.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Target and Catcher</th>
<th>Max Flux (n/sr)</th>
<th>Max $E_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-Li (Paint)</td>
<td>$3 \mu m$ Mylar with $(C_8D_8)_n$ Paint + LiF</td>
<td>$4.6 (\pm 2.2) \times 10^5$</td>
<td>$12.6 \pm 0.3$ MeV</td>
</tr>
<tr>
<td>D-Li (Ice)</td>
<td>$800$ nm Al with $D_2O$ Ice + LiF</td>
<td>$3 (\pm 1.4) \times 10^6$</td>
<td>$16.8 \pm 0.3$ MeV</td>
</tr>
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</table>
$\frac{1}{2}$ KHz Neutron Generation
Electron beam experiments
High repetition rate LWFA enables real-time control and optimization

Lambda-cubed
0.8 TW
35 fs
500 Hz

Continuous flow
High repetition rate: real-time beam optimization
(Coherent control of plasma dynamics)
High repetition rate: real-time beam optimization

- Adaptive optics system: optimize the deformable mirror using a genetic algorithm directly for the electron beam.

- Heuristic search for best mirror figure for optimal electron production.

Highest laser intensity ≠ best electron beams !!
Gas Cell targets: Made on 3D Printer

- Printed on 3D printer!
- Need high-resolution (Viper SLA)

Mounted 20mm Gas Cell

After 450 Shots Laser Damage/Ablated Solid Target

10mm Gas Cell

Variable length two stage gas cell

CFD modeling of gas flow (COMSOL)
Collimated, High-Energy Positron Measurements

Scaling with Z and d consistent with a two-step process (Bremsstrahlung + Bethe-Heitler)

- Overall positron yield: $3 \times 10^7$ e$^+$
- Overall lepton yield: $3 \times 10^8$ (secondary e$^-$/e$^+$)
- Positron density: $2 \times 10^{14}$ cm$^{-3}$
- Lepton density: $2 \times 10^{15}$ cm$^{-3}$
- Divergence: 3 mrad

G. Sarri et al. PRL 110 255002 (2013)
Neutral Electron-Positron Beams

- Max Positron density: $10^{16}$ cm$^{-3}$
  - comparable to the highest density of stable antimatter obtainable nowadays in the laboratory
  - directly comparable to predictions for astrophysical jets

- Neutral $e^+e^-$ plasma with $n = 3 \times 10^{15}$ cm$^{-3}$
Ultra-high brilliance multi-MeV $\gamma$-ray beam from non-linear Thomson scattering

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(γ,n) Activation as a β⁺ Source

NaI Scintillator

Si Target

Nal Scintillator

28Si → 27Si

28Si + γ → 28Si

27Al

+ n

e⁻ + 28Si → e⁺ + 28Si

MICHIGAN ENGINEERING
UNIVERSITY OF MICHIGAN
Activation of U238 and silicon as a gamma-beam diagnostic

Graphs showing the activation of different isotopes as a function of energy and time.

- Graph a) shows the cross-section (σ) for different isotopes (239Pu, 235U, 238U) as a function of energy (MeV).

- Graph b) shows the measured activity over time for high-purity silicon (>99.999%) with raw data and a 5 s moving average.

- Graphs below show the energy spectrum for specific isotopes:
  - 134I (847 keV) and 134I (884 keV).
  - 92Sr (1386 keV) and 138Cs (1436 keV).
Tools for solid and gas target studies as we approach the radiation dominant regime

- High intensity & high contrast sources: $\sim 10^{22} \text{W/cm}^2$ & $\sim 10^{-12}$
- Ion imaging & spectroscopy: 10-20 MeV to 30 nm thin
- Electron & positron divergence & spectroscopy:
- X-ray divergence & spectroscopy: Nuclear activation & Compton scattering: 6-18 MeV @ High Brilliance
Thank You

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