Complete characterization of the energy spectra of laser-accelerated protons for the production of radioisotopes used in medical imaging


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Outline

• Ultraintense laser-driven proton acceleration.

• The Laser Laboratory for Acceleration and Applications (L2A2):
  - Experimental set-up.
  - Measurements and results.

• Results analysis: scaling laws and estimations.

• Radioisotope production estimates.

• Conclusions.
Proton acceleration - Overview

- Ultraintense lasers:
  - High power and intensity (>\(10^{15}\) W/cm\(^2\)).
  - Low energies by pulse (mJ – 100 J).
  - Ultrashort pulses (ps, fs).
  - Focal spot sizes (∼\(\mu m\)).

- Multiple mechanisms involved:
  - Plasma generation on target surface.
  - Laser-plasma interaction: generation of electron bunch.
  - Target Normal Sheath Acceleration (TNSA): generation of proton/ion beam.
Proton acceleration - Overview

- Laser-plasma interaction: electron beam (~ MeV).
- Target Normal Sheath Acceleration (TNSA): proton beam.
  - Intense electric fields of ~TV/m.
  - Light ion acceleration (d, C,...).

Schematic representation of the process. Image: M.Roth et al. (2016).

Tipical energy spectrum of laser-driven protons.
Radioisotope production - PET

- Radioisotope production for PET (Positron Emission Tomography) imaging:
  - (p;n), (p;α), (d;n), etc. reactions for protons/ions up to 20 MeV.
  - Low-Z materials.

- Advantages over conventional accelerators:
  - Cheaper and more compact.
  - Localized production over general production.
  - Radioisotopes with shorter half-lifes.

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>Half life</th>
<th>Common production reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}$C</td>
<td>~20 min</td>
<td>$^{11}$B(p;n)$^{11}$C, $^{10}$B(d;n)$^{11}$C, $^{14}$N(p;α)$^{11}$C</td>
</tr>
<tr>
<td>$^{13}$N</td>
<td>~10 min</td>
<td>$^{12}$C(d;n)$^{13}$N, $^{16}$O(p;α)$^{13}$N</td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>~2 min</td>
<td>$^{14}$N(d;n)$^{15}$O</td>
</tr>
<tr>
<td>$^{18}$F</td>
<td>~110 min</td>
<td>$^{18}$O(p;n)$^{18}$F</td>
</tr>
</tbody>
</table>
The Laser Laboratory for Acceleration and Applications (L2A2)

- L2A2 laser parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>$\sim 10^{19}$ W/cm$^2$</td>
</tr>
<tr>
<td>Wavelength</td>
<td>800 nm</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>35 - 50 fs</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>1.2 J</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
</tr>
</tbody>
</table>

Picture and schematic view of the L2A2 facility.
The Laser Laboratory for Acceleration and Applications (L2A2)

Experimental set-up at L2A2.
Detection and diagnostic tools

- Thomson parabola: ion discrimination ($p$, $C^+$, $C^{+2}$, etc.).

*Detection set-up at L2A2. Scintillator detector: M. Seimetz (i3M).*
Experimental measurements

- Maxwell-Boltzmann like spectrum.
- Sharp cut-off energy.

\[ \frac{dN}{dE} = \frac{N_0}{\sqrt{2 Z K_B T_e E}} e^{-\frac{2E}{Z K_B T_e}} \]

- \( N_0 \): particle number.
- \( T_e \): distribution temperature.
- \( E_{\text{max}} \): cut-off energy.

Raw TOF signal and proton spectrum measured at L2A2.
Experimental measurements

- Multishot (10 Hz) operation.
- High stability (~13%) in cutoff energy and temperature.
- First laser-induced proton acceleration at 10 Hz.

Raw TOF signals (multishot).

Reconstructed proton spectra.

Maximum proton energies and temperatures.
Proton spectra estimates

- Estimations based on scaling laws.
- Laser optimized parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser energy</td>
<td>1.2 J</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>35 fs</td>
</tr>
<tr>
<td>Focal spot radius</td>
<td>2 μm</td>
</tr>
<tr>
<td>Intensity</td>
<td>$2 \cdot 10^{20}$ W/cm$^2$</td>
</tr>
<tr>
<td>Target thickness</td>
<td>2 μm</td>
</tr>
</tbody>
</table>
Proton spectra review

- Laser pulse durations below 60 fs.
- Laser pulse energies up to 2.6 J.
- Solid targets (Al, Cu, polymide,...).
- TNSA mechanism.

\[
\frac{dN}{dE} = \frac{N_0}{\sqrt{2} Z K_B T_e E} e^{-\sqrt{\frac{2E}{Z K_B T_e}}}
\]

Published proton spectra reviewed.
Proton spectra review

- Proton maximum energy scaling.

- Three target thickness ranges:
  - $< 1 \, \mu m$.
  - $1 - 6 \, \mu m$.
  - $\geq 6 \, \mu m$.

\[ a_0 = 0.85 \sqrt{\frac{I_L \cdot \lambda_L^2}{10^{18} \, \text{W} \, \text{cm}^{-2} \, \mu \text{m}^2}} \]

\[ \frac{dN}{dE} = \frac{N_0}{\sqrt{2 \, Z \, K_B T_e \, E}} \cdot e^{-\sqrt{\frac{2 \, E}{Z \, K_B T_e}}} \]

Proton cut-off energies of the experimental spectra reviewed in this work.
Radioisotope production estimates

Calculated spectra and cross sections of radioisotope production reactions, for protons (left) and deuterons (right).

Proton & deuteron spectra:
\[ E_{\text{max}} = 5.48 \text{ MeV} \]
\[ N_0 \sim 10^{12} - 10^{13} \text{ MeV}^{-1} \]

Higher than some radioisotope production cross section thresholds!
Radioisotope production estimates

• Radioisotope activities after 1h of irradiation at 10 Hz:

<table>
<thead>
<tr>
<th>Production reaction</th>
<th>Activity [MBq]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}$B(p;n)$^{11}$C</td>
<td>29.5</td>
</tr>
<tr>
<td>$^{10}$B(d;n)$^{11}$C</td>
<td>16.1</td>
</tr>
<tr>
<td>$^{14}$N(p;α)$^{11}$C</td>
<td>0.02</td>
</tr>
<tr>
<td>$^{14}$N(d;n)$^{15}$O</td>
<td>0.69</td>
</tr>
</tbody>
</table>

• Required doses for PET imaging:
  - Preclinical: 10 – 30 MBq.
  - Clinical: 200 MBq – Gbq. (achievable at ~100 Hz)

Production of $^{11}$C versus irradiation time at 10 Hz via $^{11}$B(p;n)$^{11}$C reaction.
Conclusions

- 10 Hz repetition rate laser-plasma proton accelerator for radioisotope production at L2A2.

- Proton energies up to 2 MeV at present.

- Improvements required in order to increase proton energies.

- Estimated ~MBq activities for radioisotope production in future experiments.
Thank you for your attention!