Proton Acceleration with a Table-Top TW Laser

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3\textsuperscript{rd} ELIMED Workshop
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The PLA collaboration

Collaborators (since 2012):

- Proton Laser Applications S.L. (PLA, private company located close to Barcelona): Development of high-power laser systems.
- Institute for Instrumentation in Molecular Imaging (I3M, Valencia): Targets, particle detectors.
- Spanish Pulsed Laser Centre (CLPU, Salamanca).

Entire system built from scratch:

- Table-top laser developed by PLA. Strong private contribution.
- Detectors built and calibrated by I3M.
- Experiments performed at PLA installations.
PLA laser system

Table-top Ti:Sapphire laser:
- Diode pumping (Nd:YAG) for high rate (10-100 Hz)
- Multi-pass amp. stages (1.5 → 30 → 265 mJ)
- 2 saturable absorbers for enhanced contrast.
### Laser parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Series 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 2015</td>
<td></td>
</tr>
<tr>
<td>Pulse energy before comp.</td>
<td>150 mJ</td>
</tr>
<tr>
<td>Pulse energy on target</td>
<td>93 mJ</td>
</tr>
<tr>
<td>Pulse duration (FWHM)</td>
<td>43 fs</td>
</tr>
<tr>
<td>Peak power</td>
<td>2 TW</td>
</tr>
<tr>
<td>Focal spot (FWHM, μm²)</td>
<td>$5.0 \times 9.0$</td>
</tr>
<tr>
<td>Peak intensity $\left(10^{18} \text{ W}/\text{cm}^2\right)$</td>
<td>3.7</td>
</tr>
<tr>
<td>Contrast over ASE</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Pump rate</td>
<td>100 Hz</td>
</tr>
</tbody>
</table>
## Laser parameters

<table>
<thead>
<tr>
<th></th>
<th>Series 1</th>
<th>Series 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nov 2015</td>
<td>Jul 2016</td>
</tr>
<tr>
<td>Pulse energy before comp.</td>
<td>150 mJ</td>
<td>265 mJ</td>
</tr>
<tr>
<td>Pulse energy on target</td>
<td>93 mJ</td>
<td>165 mJ</td>
</tr>
<tr>
<td>Pulse duration (FWHM)</td>
<td>43 fs</td>
<td>55 fs</td>
</tr>
<tr>
<td>Peak power</td>
<td>2 TW</td>
<td>3 TW</td>
</tr>
<tr>
<td>Focal spot (FWHM, µm²)</td>
<td>5.0 × 9.0</td>
<td>5.0 × 11.5</td>
</tr>
<tr>
<td>Peak intensity (10^{18} W/cm²)</td>
<td>3.7</td>
<td>4.2</td>
</tr>
<tr>
<td>Contrast over ASE</td>
<td>10⁵</td>
<td>10⁸</td>
</tr>
<tr>
<td>Pump rate</td>
<td>100 Hz</td>
<td>10 Hz</td>
</tr>
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Experimental setup downstream to PLA laser:
Target and focus diagnostics

Interaction chamber \((10^{-2} \text{ mbar})\):

- Support for 24 foil targets
Target and focus diagnostics

Interaction chamber ($10^{-2}$ mbar):
- Support for 24 foil targets
- Al target foils (0.65-25 µm)
- Mylar foils (2-13 µm)
- Au foils (0.1-2 µm)
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- Position control with He:Ne laser
Particle detectors

CR-39 plates, 1 cm$^2$ (Radosys, Budapest):
- Relation $E_p$ - track diameter calibrated on 3 MV tandem accelerator (Centro Nacional de Aceleradores, CNA, Seville)
- Up to 1 MeV, unique relation
- For higher energies, thin Al absorbers
- Etching in 6.25N NaOH, 90°C, 4 hours
- Automatic readout (Radosys PT10 microscope)
- Self-developed track recognition software for image analysis
- Placed 100 cm behind the target.

![Graph showing the relation between $E_p$ [MeV] and $D$ [pixel]](image1)

![Image showing the etched CR-39 plates](image2)
Particle detectors

Time-of-flight detector:
- Based on fast plastic scintillator
- Dynamic range adjustable with optical filters
- Calibrated with pulsed proton beam as function of beam current (CNA)
- 227 cm behind target.
Results from Series 1 (93 mJ, LC)

Al target foils, 2-25 µm; CR-39 at 100 cm target distance:

- 4 µm
- 7 µm
- 10 µm
- 12.5 µm
- 18 µm
- 25 µm
Results from Series 1 (93 mJ, LC)

- Max. proton energy at 2 TW: $\sim 650$ keV
- Max. proton number: $\sim 10^6$/msr
- No eff. acceleration with 2-4 $\mu$m Al
- Much lower energies and particle numbers with Mylar foils

Spectra approximated by:

$$N_p = \frac{N_0}{E_p} \cdot e^{-E_p/E_0} \left(1 + e^{(E_p - E_{\text{max}})/\Delta E}\right) + N_{\text{bg}}.$$
Results from Series 2 (165 mJ, HC)

- Proton energies calculated from TOF
- Spectral distributions approximated by same analytic function as CR-39
- Similar results from CR-39 covered with Al absorbers ($\Delta E_{\text{max}} = 100$ keV).
Results from Series 2 (165 mJ, HC)

As compared to Series 1:

- Best results from thin Al/Au foils (< 2 µm)
- Protons from Mylar foils
- Effect of increased contrast seems more important than beam energy.
First experimental steps accomplished:

- Stable operation of PLA laser at 10-100 Hz
- Focussing and target diagnostics
- Clear proton signals demonstrated
- Proton spectra measured from several foil targets.

Results consistent with other experiments at low pulse energies.

![Graph showing laser pulse energy vs. max. proton energy and contrast.](image)
Status and perspectives

Next steps:

- Modified target design based on Si wafers for
  - Mass production
  - High rate capability
  - Limited target area
  - Controlled CH layer

(R. Zaffino, Centro Nacional de Microelectrónica, Barcelona).

- Laser upgrade for increased pulse energy:
  - 500 mJ before comp., 10 Hz with larger crystals
  - 100 Hz require additional cooling
  - 1 J with 3rd multi-pass amp.?

- Detector upgrade: TPS with fast readout.
- Accelerate C ions.
Status and perspectives

Possible applications: **Versatile tools for research**

- Radioisotope production (esp. $^{11}\text{C}$): requires 10-16 MeV $p$ at 100 Hz for preclinical studies (small animal models):
  - Use $^{11}\text{C}$ to label any organic molecule without structural change.
  - Labels at different sites to study details of metabolization.
  - Mol. biology, pharmaceutical research, models of pathologies, etc.

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**MS et al., IEEE NSS-MIC Conf. Record (2015)**

G. Antoni, B. Längström (2005)
Status and perspectives

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- **Biol. effects of high-LET radiation:** C ions, $< 40$ MeV$/u$, 1-10 Hz

**Activity after prolonged irradiation**

![Graph showing activity after prolonged irradiation](image)

G. Antoni, B. Längström (2005)

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  - Mol. biology, pharmaceutical research, models of pathologies, etc.
- Biol. effects of high-LET radiation: C ions, < 40 MeV/u, 1-10 Hz
- Ion therapy of superficial lesions (⇒ Poster by P. Mur).

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