Laser-Driven Targetry: The Road to Clinical Applications

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Laser Plasma Acceleration for Electrons and Protons


Laser Proton Acceleration at LLNL

Proton angular distribution
Proton spectrum


Laser proton acceleration: intensity vs energy

The therapeutic energy range
Initial goal
After upgrade
3D PIC Simulation
Double Target
63 MeV Quasi-Monochromatic
Particle in cell (PIC) simulation results (Ueshima 1999b) on ion and electron acceleration by laser irradiation on three thin targets. A laser intensity of $10^{21}$ W/cm$^2$ on the target surface is applied.

<table>
<thead>
<tr>
<th>Case</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy conversion</td>
<td>50%</td>
<td>24%</td>
</tr>
<tr>
<td>Ion</td>
<td>4%</td>
<td>8%</td>
</tr>
<tr>
<td>Electron</td>
<td>48%</td>
<td>16%</td>
</tr>
<tr>
<td>Peak energy H$^+$</td>
<td>200 MeV</td>
<td>400 MeV</td>
</tr>
<tr>
<td>Peak energy Al$^{10+}$</td>
<td>1 GeV</td>
<td>2 GeV</td>
</tr>
<tr>
<td>Peak energy electron</td>
<td>25 MeV</td>
<td>17 MeV</td>
</tr>
<tr>
<td>Average energy H$^+$</td>
<td>58 MeV</td>
<td>95 MeV</td>
</tr>
<tr>
<td>Average energy Al$^{10+}$</td>
<td>130 MeV</td>
<td>500 MeV</td>
</tr>
</tbody>
</table>

Theoretical Results

Proton and Electron Densities (t=100 fs)

E. Fourkal et al. Medical physics (2002)

Electrons and protons expand ballistically into vacuum

Energy and Angular Distribution

There is a large spread in energy and angular distribution.

Particle Selection and Beam Collimation
Particle Selection and Beam Collimation

Ma (2000)
Movable aperture to select protons of desired energy with sharp beam penumbra

Combined Dose Distribution

Energy and Dose Rate

Monoenergetic Laser-driven Ion Beams
Demonstration and modeling of monoenergetic carbon ions from shortpulse driven laser acceleration.

Experiment:
30 TW LANL Trident laser using 20 nm palladium targets.

Simulation:
Hybrid code BILBO (Backside Ion Lagrangian BlowOff), parameters set to match experiment.

Indications of a multi-parametric scaling law

Experiments with foil targets at intensity $10^{18} - 10^{20}$ W/cm² show that the ion energy depends on

- intensity (e.g., $I_{\text{max}} \propto I^{1/2}$)
- foil thickness
- material
- pulse contrast
- focal spot size
- laser polarization
- target geometry

model parameters
- dimensionless amplitude $a_{\text{mp}} = E_{\text{max}}/E_{\text{cutoff}}$
- effective plasma density, $n_{\text{e}}$
- effective plasma thickness $l_{\text{d}}$
- focal spot size $D$
- fixed (p-polarized)
- fixed (planar)

Future steps to improve results:
PIC-Simulation for POLARIS:
- E = 150 J, $\tau = 150$ fs, $d_{\text{fo}} = 50$ nm
- $d_{\text{fo}} = 5.5$ nm, $a_{\text{mp}} = 0.1$ nm
- ablation peak at $E = 775$ MeV with $DE/E \approx 1$
- initial proton number $\approx 10^9$
- Reduce spot size: better localization of fast within homogeneous field
- higher stability
- Increase laser power: for sufficient thin targets cutoff energy scales with $E_{\text{cutoff}} \propto 230$ MeV ($a_{\text{mp}}/1$PW)$^{1/2}$

Monoenergetic proton acceleration

Courtesy of R. Sauerbrey

Monoenergetic Proton Acceleration

Courtesy of S. Bulanov
Ion max. energy vs. laser energy and power

[Fig. 1] Timo Burkert et al., PRL 96, 105001, 2006

Multistage proton acceleration

Up to 100% increase in max. proton energy with multistage stages.

[Veltchev et al. 2007]

Treatment Optimization

Comparison of Isodose Distribution

7 field IMRT
7 field laser protons

[Fourkal et al. 2003]
Comparison of DVH

Bladder

Target

Rectum

Femur

Comparison of Isodose Distribution

7 field IMPT (mono-E)

7 field proton

Comparison of DVH

Target

Rectum

Bladder

Femur

Shielding for the Treatment Head
Secondary Sources for Shielding Considerations


Head Leakage Measurement

0.5cm steel, 10cm polyethylene, 3cm lead

Head Leakage Dose

Table 1. Dose equivalent per therapeutic absorbed dose (TEA), in mm of Pb/Cu around treatment head

<table>
<thead>
<tr>
<th>Detector</th>
<th>Proton Source</th>
<th>Electron beam</th>
<th>X-ray</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>9.7E-04</td>
<td>5.0E-05</td>
<td>1.0E-04</td>
<td>9.7E-04</td>
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<tr>
<td>C</td>
<td>9.2E-04</td>
<td>3.2E-06</td>
<td>6.0E-05</td>
<td>9.2E-04</td>
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<tr>
<td>D</td>
<td>3.7E-04</td>
<td>3.0E-05</td>
<td>1.6E-04</td>
<td>3.7E-04</td>
</tr>
<tr>
<td>E</td>
<td>2.3E-04</td>
<td>1.4E-05</td>
<td>1.0E-04</td>
<td>2.3E-04</td>
</tr>
<tr>
<td>F</td>
<td>4.1E-04</td>
<td>1.0E-05</td>
<td>4.0E-05</td>
<td>2.0E-04</td>
</tr>
<tr>
<td>A</td>
<td>6.1E-04</td>
<td>1.0E-05</td>
<td>3.0E-05</td>
<td>6.0E-04</td>
</tr>
<tr>
<td>C</td>
<td>1.6E-04</td>
<td>1.0E-05</td>
<td>1.0E-05</td>
<td>1.6E-04</td>
</tr>
</tbody>
</table>

Leakage dose < 0.1% of treatment dose

Shielding Issues for Laser-Accelerated Protons

Fan et al 2007 Med Phys Biol
System Design

The Cost of a Laser-Proton Unit

- The building/shielding – $0.5 million × N
- The high-power laser – $2-3 million
- The gantries - $1-2 million × N

The cost of a carbon unit will be slightly higher!

The Laser-Proton Facility

- Renovation completed in June 2005
- An off-campus facility for experimental studies
- Laser/target chamber/shielding installed/commissioned in Sept 2006
- Research laser-proton accelerator license granted by the State

The Building/Shielding – $0.5 million × N

The High-Power Laser – $2-3 million

The Gantries – $1-2 million × N
The FCCC Laser System

The Experimental Setup

The FCCC Laser-Proton Team

- Dr. Charlie Ma Program director
- Dr. Eugene Fourkal Physicist, target and PIC studies
- Dr. Jason Li Physicist, dosimetry and treatment planning
- Dr. Iavor Veltchev Physicist, laser physics research
- Dr. James Fan Physicist, shielding calculations, Monte Carlo
- Dr. Teh Lin Physicist, laser-proton acceleration
- Dr. Alain Guemnie Tafo RA, laser-proton acceleration experiments

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