Ion acceleration at the Intense Laser Irradiation Laboratory: from exploration to exploitation

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SPIE Applying Laser-driven Particle Acceleration Workshop, Prague 02/04/2019
Introduction:
Laser Proton acceleration from exploration to exploitation

The Intense Laser Irradiation Laboratory laser system:
1) the 10 TW beam line
2) towards 200 TW beam line

On-going and foreseen exploitation activities:
1) PIXE with laser driven source
2) small batch radioisotopes production

Conclusions and Out-look
Proton laser-plasma acceleration Exploration


Macchi, Borghesi, Passoni Rev. Mod. Phys 85 (2013)

Hadron therapy facilities in operation worldwide, under construction and in the planning stage, at the end of 2016. From: January/February 2018 issue of CERN Courier.

Need a Break-through for laser-plasma based accelerator.

- **electron** laser-plasma acceleration in **user oriented facility** (e.g., EuPRAXIA project), and generation of X and gamma rays for **NDT**.
- **proton** acceleration application in Particle Induced X-ray Emission (**PIXE**) and radioisotope production.
The ILIL group is part of the Istituto Nazionale di Ottica and has been involved in laser-plasma acceleration in Italy since the beginning. With ELI-Italy contribution a new 200TW beam line is being constructed at ILIL in Pisa.

Laser plasma proton acceleration
The LILIA (laser induced light ions acceleration) experiment at LNF NIM B 331 (2014) 15–19, S. Agosteo et. al.

Laser wake-fied electron acceleartion
First Experimental Results from the Plasmon-X Project, Proceedings of the 51st Workshop of the CHANNELING 2008, p. 495, L. A. Gizzi,et.al.

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- Luca LABATE (CNR)*
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- Federica BAFFIGI (CNR), Ric TD
- Lorenzo FULGENTINI (CNR), Ric.
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- Danilo GIULIETTI (Univ. Pisa), Ass.*
- Antonella ROSSI (CNR) - Tech.
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- Davide TERZANI, PostDoc Student*(PI)

* Also at INFN
The laser system: 10 TW beam line

- Control room
- Laser front-end
- Power amplifier
- 10 TW Interaction
- up to 200 TW Interaction

Diagram showing the layout and components of the laser system, including the laser front-end, power amplifier, and 10 TW Interaction, with control room and up to 200 TW Interaction.
Proton acceleration with the 10 TW beam-line

10 TW Ti:Sa laser system, up to 450 mJ on target, $M^2 \sim 1.5$.
angle of incidence of 15°, f/4.5 Off-Axis Parabolic mirror (OAP),
spot size of 6.2 μm FWHM, giving a nominal intensity on target of about $2 \times 10^{19}$ W/cm$^2$.
Nanosecond temporal contrast better than $10^{10}$

Thomson Parabola
10 μm thick Al (left), 4 μm thick CH$_2$ foil coated with 100 nm Al (centre),
and 4 μm thick CD$_2$ foil coated with 100 nm Al (right)

200 TW beam-line

Tb: Sapphire oscillator

Booster amplifier

Öffner stretcher

Regenerative amplifier

LWFA TNSA

5-pass pre-amplifier

Compressor

4-pass amplifier

4-pass final amplifier

LWFA TNSA

Compressor

Nd: YAG

~30 mJ @ 10 Hz

~115 mJ @ 10 Hz

~1.8 J @ 10 Hz

~6 J @ 1 Hz

6 mJ @ 74 MHz

5 mJ @ 10 Hz

0.6 mJ @ 10 Hz

3.3 J @ 100 TW

4.5 J @ 1 Hz

12 J @ 1 Hz

6 mJ @ 10 Hz

30 mJ @ 10 Hz

700 mJ @ 1 Hz

700 mJ @ 1 Hz

700 mJ @ 1 Hz

12 J @ 1 Hz

12 TW

400 mJ

12 TW
100 TW beam-line: characterization

Laser diagnostic table

Spectrum

Pulse duration

Third-order auto-correlator
100 TW beam-line: Pilot experiments

Towards a Light-Ion Laser Acceleration Beamline (L3IA)

L3IA is a INFN funded project (CN5) to design and build a 14 MeV laser-driven proton beamline. The ion beam will be used as a test site for experiments in multidisciplinary applications. L3IA will be based on the ILIL laser installation currently undergoing a 250 TW upgrade.

Milano, INFN and UNI (Coord)
Pisa, INO-CNR and INFN (Coord)
Bologna, INFN and UNIBO
Firenze, INFN
Catania, INFN
Napoli, INFN and UNI

Light Ion Accelerating Line (L3IA): Test experiment at ILIL-PW, L.A. Gizzi et.al., 909, 2018, 160
Laser-plasma with nanostructured targets

Up to hundreds MG magnetic field behind thin substrate; collimated relativistic electron transport in MA currents

Enhancement of Kα emission from the substrate

Warm Dense Matter Plasmas with temperature of several keV at near solid density

Near complete absorption

Gbar pressure expected

Larger yield of hot electrons

Much hotter fast electrons

Possible application for proton acceleration

Cristoforetti et al., Scientific Reports, 7, 1479, 2017
Sarkar et al., APL Photonics, 2, 066105, 2017
TiO$_2$ nanochannels for proton acceleration

Produced by G. D’Arrigo

_Institute for Microelectronics and Microsystems (IMM-CNR)_

_Catania, Italy_

Target Thickness 14 microns, no bulk on the rear side
Pore Diameter ~100 nm, Porosity ~43%

Experiments and simulations in progress
LaserPIXE is a technology Transfer project, co-funded by UE, through Regione Toscana, and VCS S.r.l (Parma-Italy), a company expert in custom vacuum chambers and components. **Research Partners:** LABEC Laboratory (INFN-Florence), Institute of Clinical Physiology (CNR, Pisa).

**Goal:** design a prototype proton laser-plasma accelerator (up to ~3 MeV) to perform PIXE measurements.

The LABEC laboratory in Florence

PIXE measurements at LABEC of aerosol from air quality monitoring stations.

Courtesy of Massimo Chiari, INFN LABEC laboratory Florence
PIXE with laser-plasma based accelerators: production of > 3 MeV cut-off protons

- 10TW beam line;
- Off-the-shelf OAP: f/1, 90 degrees
- Laser-plasma acceleration targets: Al 10 micron, Ti 5 micron.
Start-to-end simulations from the proton source through the magnets up to the X-Ray detector are in progress using GEANT4 tool kit.

Radioisotope production

**Reaction:** \(^{18}\text{O} (p, n)^{18}\text{F}\)

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Cross section (mb)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>[IAEA 2001]</td>
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<tr>
<td>2.5</td>
<td>8.3</td>
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<tr>
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<tr>
<td>3.5</td>
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<tr>
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<tr>
<td>5.0</td>
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</table>

\(T_{1/2}(^{18}\text{F}) = 109.7 \text{ min} = 6582 \text{ s}\)

- **Laser driven radioisotope production**

Proton beams generated with high-intensity lasers:

Applications to medical isotope production,

*S. Fritzler et. al., Appl. Phys. Lett.83:3039, 2003*

- e.g. radioisotopes with shorter life time:
  - \(^{11}\text{C} (20 \text{ min}); \)\(^{13}\text{N} (10 \text{ min}).\)
Radioisotope production

The goal of this activity is to investigate the feasibility of the production of small batch of radioisotopes in combination with a micro-fluidic device.

SET-UP OUTLINE

<table>
<thead>
<tr>
<th>Initial Energy (MeV)</th>
<th>Final Energy (MeV)</th>
<th>Cross section (mb)</th>
<th>Stoppin Power In target (MeV g/cm²)</th>
</tr>
</thead>
<tbody>
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<td>6,0</td>
<td>5,7</td>
<td>248,5</td>
<td>63,0</td>
</tr>
</tbody>
</table>

Collaborators:
- Australian Nuclear Science and Technology Organisatio (ANSTO) – Radiochemistry team;
- Institute of Clinical Physiology, CNR;
- Institute of Nanotechnology, CNR.
Conclusions

- The new laser system and beam-lines at ILIL has been presented
- the use of nanostructured solid targets at ILIL has been discussed
- on-going research activity towards applications of laser driven ion accelerators has been presented

Out-look:

- After decades of intense exploration of laser driven acceleration the technology is mature enough to foreseen in the short term a break-through in non-biological applications
- the break-through will trigger interest and further advanced research needed for biological applications
Acknowledgments

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Thank You

for the attention