Near critical density, foam-based, multi-layered targets for laser-driven ion acceleration

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ERC-2014-CoG No.647554
ENSURE

Ongoing collaborations with:

Milano

HZDR

OSAKA UNIVERSITY

SourceLAB

Queen’s University Belfast

ERC-PoC: INTER
The ENSURE project

Laser-driven ion acceleration
Theoretical/numerical & experimental investigation

Materials science
Development of low-density foams & advanced targets for laser-plasma experiments

Applications in materials and nuclear science
Materials characterization (e.g. PIXE) with laser-driven ions
Secondary neutron sources for radiography and detection[

Fundamental physics and laboratory astrophysics
Laser interaction with (near-critical) nanostructured plasmas
Collisionless shock acceleration of ions
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Valeria Russo
Researcher

4 Post-docs
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2 PhD students
A. Formenti  A. Pazzaglia

3 Master’s students
F. Mirani  A. Tentori  M. Sala
People involved in experimental activities

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Enhanced Target Normal Sheath Acceleration

Conventional Target

- Laser Pulse
- Solid Foil
- Surface interaction mechanisms
- Accelerated Ions
- Fast Electrons

Target Normal Sheath Acceleration (TNSA)

Multi-layer near critical Target

- Laser Pulse
- Solid Foil + Low Density Layer
- Volume & Surface Interaction Mechanisms
- Accelerated Ions
- Fast Electrons

Enhanced TNSA

- Higher laser energy absorption
- Enhanced fast electron production
- Enhanced number and maximum energy
- of accelerated ions

Foam-attached targets for Enhanced-TNSA

2D PIC simulations (ALaDyn code)

- \( \lambda = 0.8 \mu m \)
- \( \tau_L = 25 \) fs
- \( a_0 = 10 \)
- \( I_L \approx 2 \times 10^{20} \) W/cm\(^2\)
- \( w_0 = 3 \mu m \)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Areal Density</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(^{6+})</td>
<td>1-8 (n_c)</td>
<td>1-12 (\mu m)</td>
</tr>
<tr>
<td>Al(^{9+})</td>
<td>80 (n_c)</td>
<td>0.5 (\mu m)</td>
</tr>
<tr>
<td>H(^+)</td>
<td>9 (n_c)</td>
<td>50 nm</td>
</tr>
</tbody>
</table>

Enhanced Maximum Proton Energy
For foam attached Targets

- density < 10 mg/cm\(^3\) (for \(\lambda \approx 1 \mu m\))
- thickness from 5 to 10s \(\mu m\)

...from near critical plasma to low density materials

High density gas-jets

0.1 1 10 100

Cryogenic hydrogen

Solids

Few options:
- Pre-heating
- Very low-density nanostructured materials with 1/500\textsuperscript{th} density of solids

\begin{itemize}
  \item Aerogels\textsuperscript{1}
  \item Nanotube arrays\textsuperscript{2}
  \item Foams\textsuperscript{3}
\end{itemize}

\begin{align*}
  \frac{n_e}{n_c} \\
  (\lambda \sim 800\text{nm})
\end{align*}

\textsuperscript{1}Willingale et al. PRL 96 (2006)
\textsuperscript{2}Bin et al. PRL 115 (2015)
\textsuperscript{3}Zani et al. Carbon 56 (2013)
**ns Pulsed Laser Deposition (PLD) in a background gas**

Nd:YAG laser
532 nm, 0.8 J cm\(^{-2}\), 7 ns, 10 Hz

**PLD Target**
e.g. pyrolytic graphite

**Background gas**
(film structure)
Ar-He, pressure up to 1000 Pa

**Substrate**
Thickness down to 10s nm
Diameter up to 5 cm
Rotation few rpm (film thickness profile)

**Target-substrate distance**
(film structure)
45-85 mm

**Process duration**
(film thickness)
5 – 60 min

ns Pulsed Laser Deposition (PLD) in a background gas

High kinetic energy
Atom-by-atom deposition

Process parameters (e.g. gas pressure)

Low kinetic energy
Cluster formation

200 μm
10 μm
1 μm
Nanoparticle formation by ns PLD in background gas

1. Adiabatic expansion
2. Shock wave formation
3. Nanoparticle synthesis
4. Nanostructured film formation

Not possible use a unique model for describing the whole process

Investigating the role of
- Pulse energy
- Ar pressure
- Target-substrate distance

To control
- energy of the species,
- deposition rate,
- coupling with expanding plasma
- expansion dynamics,
- diam. of nanoparticles,
- porosity of the film
Role of process parameters - pressure

Density (mg/cm³) vs. Pressure (Pa)

- E = 200 mJ
- d = 4.5 cm

Atkins: 4 µm

Nanoparticles: 4 µm

1 µm
Relatively easy to produce Carbon nanoparticles

Foam: PLD parameters

- $E=100 \text{ mJ}$
- $P=100 \text{ Pa Ar}$
- $d_{ts}=8.5 \text{ cm}$
- thickness = 12 $\mu$m

~ 10 nm
Not so easy to control the growth of the whole film!

It is difficult to obtain thin and homogeneous/reliable coatings!
Foam: PLD parameters

- $E=100$ mJ
- $P=100$ Pa Ar
- $d_{ts}=8.5$ cm
- thickness = 12 µm
- Substrate = Al 1.5 µm

Ion acceleration: laser parameters

- Energy on target = 1 J
- Intensity = $1.7 \times 10^{16} - 3.3 \times 10^{19}$ W/cm²
- Angle of incidence = 10°

Partial foam ionization ($C^{2+}/C^{4+}$): under-critical plasma

- Enhanced proton acceleration regime
- Foams are too thick
Improving uniformity at lower thickness

Foam: PLD parameters
- \( E = 100 \text{ mJ} \)
- \( P = 100 \text{ Pa Ar} \)
- \( d_{ts} = 8.5 \text{ cm} \)
- thickness = 8 µm

Foam: PLD parameters
- \( E = 130 \text{ mJ} \)
- \( P = 500 \text{ Pa Ar} \)
- \( d_{ts} = 4.5 \text{ cm} \)
- thickness = 8 µm

Improved reproducibility + lower thickness available
Acceleration experiment @ Pulser GIST

in collaboration with:
I. W. Choi, C. H. Nam et al.

Foam: PLD parameters
- E=130 mJ
- P=500 Pa Ar
- d_{ts}=4.5 cm
- thickness = 8, 12, 18, 36 µm
- Substrate = Al 0.75 µm

Ion acceleration: laser parameters
- Energy on target = 8 J
- Intensity = 0.5 \times 10^{20} - 5 \times 10^{20} \text{ W/cm}^2
- Angle of incidence = 30°

Higher ion energies using thinner foams
Acceleration experiment @ Pulser GIST

in collaboration with:
I. W. Choi, C. H. Nam et al.

Insensible respect to polarization (volume interaction)
Further improvement: foam thickness below 5 µm

Foam: PLD parameters

- $E=130$ mJ
- $P=500$ Pa Ar
- $d_{ts}=4.5$ cm
- thickness = 4 µm

Foam: PLD parameters

- $E=200$ mJ
- $P=1000$ Pa Ar
- $d_{ts}=4.5$ cm
- thickness = 4 µm

Increasing the energy of the impinging nanoparticles
Target development for experiments @ DRACO

Thin foam issues

Usual target holder
120 available shots

Damage in neighbouring targets

Careful engineering of target holder
- Ceramic
- 23 available shots x holder
- Rectangular holes

Caustics formation due to the shape of the hole

in collaboration with:
I. Prencipe, T. Cowan, U. Schram et al.
Acceleration experiments @ DRACO 150 TW (preliminary data)

Foam: PLD parameters
- E=200 mJ
- P=1000 Pa Ar
- d_{ts}=4.5 cm
- thickness = 4, 8, 12 µm
- Substrate = Al 1.5 µm

Ion acceleration: laser parameters
- Energy on target = 2 J
- Intensity = 5 \times 10^{20} \text{ W/cm}^2
- Angle of incidence = 2°

in collaboration with:
I. Prencipe, T. Cowan, U. Schram et al.
New multilayer target development

Double side deposition on a ultra-thin C layer (100 nm)
Interest: laser induced electrostatic shock generation
For further improvement: foam growth modelling

Diffusion limited cluster-cluster aggregation model
Nanoparticles aggregate before reaching the surface
For further improvement: foam growth modelling

Diffusion limited cluster-cluster aggregation model
Nanoparticles aggregate before reaching the surface
Density gradients

- \( E = 100 \, \text{mJ} \)
- \( P = 1000 \, \text{Pa Ar} \)
- \( d_{ts} = 5 \, \text{cm} \)

Gold foams

- \( E = 150 \, \text{mJ} \)
- \( P = \text{from 100 Pa to 700 Pa Ar} \)
- \( d_{ts} = 4.5 \, \text{cm} \)

- \( \approx 10 \, \text{mg/cm}^3 \)
- \( \approx 150 \, \text{mg/cm}^3 \)
**Conclusion**

- Production of multilayers targets composed of near critical carbon foam 4 um thick
- Promising results in laser ion acceleration experiments

**Near future developments**

- **Foam brittleness**: further improve the target holder to allow a higher density of shots using thin foam
- Production of targets with **density gradients & different composition** (e.g. C-H or C-D; high Z materials)
- Multi-layered targets exploiting capabilities also of **fs-pulsed laser deposition (foam)** and **High Power Impulse Magnetron Sputtering (substrate)**
- **Theoretical and numerical modelling** of foam formation and growth, to be used also for reliable PIC numerical analysis of the **laser-foam interaction physics** *(see L. Fedeli next talk)*
- Production of **prototype foam-based target systems** to be used in compact interaction chambers
- On site production of foam targets with a suitable PLD laser?
Thank you for your attention!
More info on our website

www.ensure.polimi.it