Investigation of near-critical foam targets for laser-driven ion acceleration

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Acknowledgments

Nanolab @ Politecnico di Milano
- Advanced targets for laser driven ion sources
- Target fab, PIC, experiments
- Beamline application: material science

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Laser-particle acceleration group
- DRACO 150 TW/1 PW (Ti:Sapphire, 30 fs)
- Beamline application: cancer therapy (soon in vivo)

HZDR High Energy Density group
- HI/HE lasers @ European XFEL
- fs probing of laser-driven plasmas on the few nm scale by Small Angle X-Ray Scattering

Access to the characterization capabilities of the Institute of Ion Beam Physics and Material Research
Motivation and introduction

Target Normal Sheath Acceleration (TNSA)

Laser
Ti:Sapphire ~ 30 fs
100 TW-1PW
I ~ $2 \times 10^{16} - 4.5 \times 10^{20}$ Wcm$^{-2}$
Potentially 1-10 Hz

quasi-static space-charge field of ~ TV/m (Debye sheath)

Ions
- 10s MeV/nucleon
- $10^{11} - 10^{13}$ particles/pulse
- ps pulse duration at the source
- exponential spectra

A. Macchi et al., Rev. Mod. Phys., 85 751 (2013)
Motivation and introduction

Enhanced laser absorption in near-critical layer

Low-density layer
- Increased absorption and hot electron generation

Solid foil
- TNSA mechanism

2D PIC simulations
- Density ~ $n_c$
- Thickness ~ 10 µm

Mass density ~ 5.7 mg/cm$^3$ for C$^{6+}$, $\lambda$=800 nm
(graphite density $\approx$ 2 g/cm$^3$)

ns Pulsed Laser Deposition (PLD) in background gas

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

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

- **PLD Target**
  - Pyrolitic graphite

- **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

Target production

ns Pulsed Laser Deposition (PLD) in background gas

Low pressure
High kinetic energy
Atom-by-atom deposition

High pressure
Low kinetic energy
Cluster formation

Vacuum

Ar 30 Pa

Ar 150 Pa

ns Pulsed Laser Deposition (PLD) in background gas

Density gradient
Obtained by linear increase of background pressure (100 Pa to 700 Pa)

Ar, λ = 532 nm, E = 150 mJ, Substrate-Target distance = 4.5 cm
Target production

Diffusion limited cluster-cluster aggregation model for foam deposition
Diffusion limited cluster-cluster aggregation model for foam deposition
Target characterization

Morphology and nanostructure

Scanning Electron Microscopy

Raman Spectroscopy

He Ion Microscopy @ IBC-HZDR

Scanning Transmission Electron Microscopy
Target characterization

**Thickness**

Cross Section Scanning Electron Microscopy

*Diffusion limited cluster-cluster aggregation model*

Film thickness ~ 4 µm – 80 µm
Target characterization

Density and composition

Quarz Crystal Microbalance vs Energy Dispersive X-Ray Spectroscopy

Ion Beam Analysis (NRA and ERDA) @ IBC-HZDR

- Density benchmark
  $\rho_{IBA} \approx 13 \text{ mg cm}^{-3}$ vs $\rho_{EDS} \approx 12 \text{ mg cm}^{-3}$
- Composition
  - C $\approx 92$ at.%
  - H $\approx 6.3 \pm 2$ at.%
  - N $< 0.4$ ($\approx 0.2$) at.%
  - O $\approx 1.3$ at.%
Target development

Damage in neighbouring targets @ DRACO 150 TW
Target development

Damage in neighbouring targets @ DRACO 150 TW
3 Experimental campaigns

Ti:Sapphire lasers, ~30 fs, $\lambda=800$ nm, $I \sim 10^{16}$-4.5 $10^{20}$ W/cm$^2$

- **UHI100-CEA Saclay, France (2012)**
- **CoReLs-GIST 1 PW, South Korea (2014-15)**
- **DRACO 150 TW, HZDR, Germany (2017)**

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**PROOF OF CONCEPT**

- M. Passoni *et al.*, Plasma Phys. Control. Fusion, **56** 045001 (2014)

**PARAMETRIC SCANS**

**ADDITIONAL DIAGNOSTICS**
### Results

**Enhanced TNSA (cut-off energy, ion number)**

- FOR optimal foam properties
- Reduced dependence on substrate thickness

![Graphs showing experimental results](image-url)
Results

Effect of foam nanostructure

- Reduced dependence on polarization

![Graph showing the effect of foam nanostructure on proton energy and intensity.](image)

**Maximum proton energy (MeV)**

- **Intensity on target** ($10^{20}$ W/cm$^2$)

**Graph Legend**
- Al, p pol.
- Al, s pol.
- Al, c pol.
- Foam, c pol.
- Foam, p pol.
- Foam, s pol.

![3D Particle In Cell Simulations](image)
Summary

- **Target production**
  - C foam coating by ns Pulsed Laser Deposition
  - 4-80 µm, down to 7 mg/cm³

- **Target characterization**
  - SEM, EDS, QCM, STEM, Raman @ Politecnico di Milano
  - He microscopy, ERDA, NRA @ HZDR

- **Study of target damage @ DRACO, HZDR**

- **Experimental results**
  - TNSA enhancement and foam optimization
  - Role of nanostructure (3D PIC simulations)
Acknowledgments

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Thank you for your attention.
### Key features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Bandwidth (\Delta E/E)</strong></td>
<td>(10^{-3}) (natural FEL source) and (10^{-4}) (standard monochromator, seeding); (10^{-5}) (high-resolution monochromator)</td>
</tr>
<tr>
<td><strong>Photon energy range</strong></td>
<td>(3–5) keV**, <strong>5–20 keV, 20–25 keV</strong></td>
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<td><strong>Polarization</strong></td>
<td>Linear (horizontal)</td>
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<td></td>
<td>Circular (future option)</td>
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<tr>
<td><strong>Pulse duration</strong></td>
<td>(2–100) fs FWHM</td>
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<tr>
<td><strong>Beam size</strong></td>
<td>Sub-(\mu)m to (&gt;100) (\mu)m (provided by various compound refractive lens stages) &lt;br&gt; (&gt;)(mm) unfocused</td>
</tr>
<tr>
<td><strong>Special optics</strong></td>
<td>Split and delay line (<strong>BMF contribution</strong>)</td>
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<tr>
<td></td>
<td>High-resolution monochromator</td>
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<tr>
<td><strong>Optical lasers</strong></td>
<td>High-energy (100 J-class) long pulse (&gt;ns) laser (<strong>HIBEF contribution</strong>) &lt;br&gt; High-intensity (100 TW-class) short pulse (~30 fs) laser (<strong>HIBEF contribution</strong>) &lt;br&gt; Pump–probe (mJ to 100 mJ class) short pulse (~15 fs – 1 ps) laser</td>
</tr>
</tbody>
</table>

*10 bandwidth only for a few selected photon energies

**Limited in terms of focusing capability, available photon number of sample, quantum efficiency of detectors
Areal density evaluation

Energy Dispersive X-Ray Spectroscopy (EDS)

Two approaches for areal density calculation:

\[
\frac{I_{\text{film}}}{I_{\text{ref,film}}} = f(\rho z)
\]

\[
\frac{I_{\text{sub}}}{I_{\text{ref,sub}}} = g(\rho z)
\]

Coating method

Substrate method

Conventionally:
Thickmess measurement for compact films with known density


Density measurement of nanostructured films in a wide density range