Production of optimized multi-layer targets for enhanced laser driven ion acceleration

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Laser-driven Ion Sources

Laser → Target → Ions
Laser-driven Ion Sources

10s TW Class Lasers
- Compactness
- Stability
- High repetition rate

Applications in material science (e.g. Ion Beam Analysis, neutron generation and radioisotope production)
Laser-driven Ion Sources

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- Liquid targets
- Cryogenics jets
- Solid targets

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Target
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Applications in material science (e.g. Ion Beam Analysis)

TNSA
The target is the key!

- $I > 10^{19}$ W/cm$^2$
- Thickness $\sim 100$ s nm – some um
- $\downarrow t \rightarrow$ higher energies


Enhanced Target Normal Sheath Acceleration (TNSA)

- Hotter relativistic e-
- More ions at higher energies

The target is the key!

M. Passoni et al. Phys Rev Acc Beams 19.6 (2016)
Enhanced Target Normal Sheath Acceleration (TNSA)

Standard substrates...

- Rolling -> local thickness uncertainty (± 30 %)
- Limited number of thicknesses
- Deformation while attaching

Affecting hole by hole reproducibility!
Direct deposition of the target on the holder!

Many possible improvements on target!

- Tuning thicknesses (um – nm)
- Thickness uniformity (light tight)
- Multilayer film & Multielemental composition
- Film growth on frame → no attaching problems
Direct deposition of the target on the holder!

Deposition of near critical carbon foam via PLD

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- Tuning thicknesses (um – nm)
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Step-by-step target fabrication

Holes filling

Solidification

Substrate deposition

Ti / Ti+

Dissolution

Foam deposition (PLD)

C clusters

Activity in collaboration with SourceLAB

Francesco Mirani
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See Andrea Pazzaglia presentation

Main topic of this talk!
Magnetron Sputtering

- Physical Vapour Deposition (PVD)
- **Magnetic field** to concentrate the plasma on sputtering target.

- Well established **industrial technique**.
- Many target materials & substrates.
- Different types of **power sources**.
Magnetron Sputtering

Direct Current (DC) Magnetron Sputtering
- Mean power density $\sim 1$ W/cm$^2$
- Ionized fraction $\sim 1\%$
- Columnar growth:

High Power Impulse Magnetron Sputtering (HiPIMS)
- Peak power density $\sim 10^3$ W/cm$^2$
- Ionized fraction $> 50\%$
- Compact morphology:

- Uniform deposition on large surfaces.
- Film thickness from few nm up to several µm.
- Tunability of density, morphology and mechanical properties.

Holes filling

Filling material requirements:

- High solubility value
- Fast solidification
- Heat resistance
- Low viscosity in solution

best compromise

Solidification:

- ~ 1 hours in vacuum
- ~ 3 hours on heating plate (90 °C)

Reveal the presence of air bubbles

Accelerate the crystallization process
Substrate Production & Characterization

Selected material: Ti

- Good mechanical & thermal properties
- Good corrosion resistance
Substrate Production & Characterization

Selected material: Ti
- Good mechanical & thermal properties
- Good corrosion resistance

Sucrose Structural integrity

Compactness of the film
\[ \rho \approx 0.60 \rho_{\text{bulk}} \]

Fast failure after removal of sucrose!
Substrate Production & Characterization

Selected material:  
- Good mechanical & thermal properties
- Good corrosion resistance

HiPIMS  Sucrose Structural integrity  → Presence of a strong stress state

Wafer curvature measurement

Combine DC & HiPIMS deposition techniques in a bi-layer structure!

- DC: 50 – 75 % of the thickness
- HiPIMS: 25 -50 % of the thickness

Sucrose Structural integrity

Compactness of the film

\[ \rho \approx 0.80 \rho_{\text{bulk}} \]

Success after sucrose removal!

Substrates production between 300 - 400 nm thickness ± 5 % uncertainty
Combine DC & HiPIMS deposition techniques in a multi-layer structure!

<table>
<thead>
<tr>
<th>DC</th>
<th>HiPIMS</th>
<th>DC</th>
<th>HiPIMS</th>
</tr>
</thead>
</table>

DC: 60 – 90 % of the thickness
HiPIMS: 10 - 40 % of the thickness

- **Stresses**
- **Density**
  \[ \rho \approx 0.85 \rho_{\text{bulk}} \]

Success after sucrose removal!

Substrate production between 600 - 1000 nm thickness \( \pm 5 \%\) uncertainty
Effect of the % of HiPIMS

- **Stresses**
  - Increase of the HiPIMS fraction → beneficial effect on properties!
  - ↑ % HiPIMS → Reduce the stress state

- **Density**
  - ↑ % HiPIMS → Densification

Total film thickness = 600 nm
Outcomes

Reliable strategy to produce targets for laser-driven ion acceleration

- Thicknesses ranging from 300 nm up to 1 μm
- Uncertainty on the thickness lower than ± 5 %
- Compact morphology with high density values (up to 90 % of the bulk)

Possible improvements?

- Extend the thickness range (from 100 nm to several μm).
- Improve the control of structural integrity.
- Exploit the co-deposition of several materials.
Next step...production of an integrated double layer target with ns & fs - PLD

See Andrea Pazzaglia presentation


Towards the applications

❖ Laser-driven Ion Beam Analysis

Towards the applications

- **Laser-driven Ion Beam Analysis**

  Recent experiment at CLPU with VEGA-2 laser!

Towards the applications

- **Laser-driven neutron sources**

- **Radioisotope production**
Acknowledgments
Thank you for your attention!
Near-critical targets for laser-driven acceleration

\[ I_{\text{laser}} = 10^{20} \text{ W/cm}^2 \rightarrow E_{\text{laser}} = 3 \times 10^{11} \text{ V/m} = 50 \times E_{\text{atomic}} \rightarrow \text{Full ionization} \rightarrow \text{Plasma!} \]

Plasma critical density:

\[ n_c = \frac{\pi m_e c^2}{e \lambda^2} \]

\[ n_c \approx 6 \text{ mg/cm}^3 \]

@ \( \lambda = 800 \text{ nm} \)

\[ n \approx n_c \text{ near critical plasma} \]

\[ n \approx n_c \text{ strong laser-plasma coupling} \]

\[ n << n_c \text{ underdense plasma} \]

Little laser absorption

\[ n >> n_c \text{ overdense plasma} \]

Most of laser is reflected

\[ \frac{n_e}{n_c} \]

mg/cm\(^3\)
Role of target properties (s-polarization, full power)

- **nearcritical foam thickness**: Al (0.75 µm) + foam (6.8 mg/cm³, 0-36 µm)

- **There is an optimum in near critical layer thickness**
- **Maximum proton energy enhanced** by a factor $\sim 1.7$
- **Number of proton enhanced** by a factor $\sim 7$

Ion acceleration @ PULSER (GIST)

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

**Role of pulse properties** Al (0.75 µm) + foam (6.8 mg/cm³, 8 µm)

- pulse **intensity**
- pulse **polarization**: s, p and circular polarization

Dependence on **polarization**:

- strong for Al foils
- reduced for foam targets

- foam vs Al: **volume vs** surface interaction?
- irregular foam surface: polarization **definition**?
- role of target **nanostructure**?
Ion acceleration @ DRACO 150 TW (preliminary data!)

**Laser parameters @ Draco (HZDR, Dresden)**
- Energy on target = 2 J
- Intensity = up to $5 \times 10^{20}$ W/cm$^2$
- Angle of incidence = 2°

**Foam PLD parameters**
- $F = 2.1$ J/cm$^2$
- $P = 1000$ Pa Ar
- $d_{ls} = 4.5$ cm
- Substrate = Al 1.5 µm
- Foam thickness = 4, 8, 12 µm

![Graph showing H$^+$ max. energy vs. laser power fraction (in collaboration with: I. Prencipe, T. Cowan, U. Schram et al.)](image1)

![Graph showing optimal foam thickness and No foam](image2)

![Graph showing # Particles vs. Energy (Al - shot #64 and Al + foam 4 um - shot #23)](image3)
Near-critical targets for laser-driven acceleration

\[ I_{\text{laser}} = 10^{20} \text{ W/cm}^2 \quad \Rightarrow \quad E_{\text{laser}} = 3 \times 10^{11} \text{ V/m} = 50 \times E_{\text{atomic}} \quad \Rightarrow \quad \text{Full ionization} \quad \Rightarrow \quad \text{Plasma!} \]

Plasma critical density:

\[ n_c = \frac{\pi m_e c^2}{e \lambda^2} \]

\[ n_c \approx 6 \text{ mg/cm}^3 \quad (\lambda=800 \text{ nm}) \]

\[ n \approx n_c \quad \text{near critical plasma} \]

\[ \text{strong laser-plasma coupling} \]

\[ n >> n_c \quad \text{overdense plasma} \]

most of laser is reflected

\[ n << n_c \quad \text{underdense plasma} \]

little laser absorption

\[ n_e/n_c \quad \text{mg/cm}^3 \]

\[ \begin{align*}
0.01 & \quad \text{Gas-jets} \\
0.06 & \quad 0.6 \\
1 & \quad 6 \\
10 & \quad 60 \\
100 & \quad 600 \\
\end{align*} \]

\[ \text{C foams: one of the (few) options} \]

\[ \text{Solids} \]
Presence of the bias: XRD analysis

- HiPIMS
  - Oriented growth;
  - Transition: $\text{phase } \alpha \rightarrow \text{phase } \omega$?

- DC (only $\alpha$ phase)

Maud:
**Laser-driven Particle Induced X-ray Emission (PIXE)**

- **PIXE:**
  
  - Particle Accelerator → Ion beam
  
  - MeV energy, low current

- **Laser-driven PIXE:**
  
  - **Unconventional features** of ion beam
    - (broad spectrum, tunable energy, ns bunch duration)
  
  - **Cheaper, portable** PIXE setup

- **Commercial codes not ok for laser PIXE**
  
  - Ad-hoc code developed

- **2) X-ray spectra**
  
  - Dedicated **software** to process x-ray data

- **3) Sample composition**
  
  - Concentration [%]
    - real
    - retrieved

  - Elements: Ca, Fe, Cu, Zn, Sn, Pb

  - Lead White, Varnish

  - Areal density [mg/cm²]