Advances in superintense laser interaction with nanostructured foams

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Aims and outline of the talk

- Introduction to superintense laser-matter interaction
- Superintense laser-driven ion acceleration
- The ENSURE and INTER projects @ POLIMI
- Laser-ion acceleration with multi-layer, nanostructured foam-based targets
- Concluding remarks
Superintense laser-matter interaction

New physics available by progress in laser technology

- Quantum Chromodynamics (strong force)
- Non-linear Quantum Electrodynamics
- Vacuum polarization
- Ultra-relativistic optics
- Relativistic optics
- Bound electrons

- High Harmonic Generation
- Laser damage
- Chirped Pulse Amplification
- Mode locking
- Q-switching

- Pulse energy
- Particle energy

(1) CUOS: Center for Ultrafast Optical Science (University Michigan)
(2) Apollon Laser, Centre Interdisciplinaire Lumière Extrême (France)
(3) Extreme Light Infrastructure (EU)
https://eli-laser.eu/
Important laser quantities

Typical laser parameters with Chirped Pulse Amplification (since ‘80s)

Laser wavelength (μm): \( \approx 1 \) (Nd-Yag), 0.8 (Ti-Sa), \( \approx 10 \) (CO\(_2\))

Energy (per pulse): \( 10^{-1} - 10^3 \) J

Pulse duration: \( \approx 10 - 10^3 \) fs \( \quad \) (at \( \lambda = 1 \) μm, \( \tau = c/\lambda = 3.3 \) fs)

Power: \( \approx 100 \) TW - few PW \( \quad \) (PW lines now available)

Spot size at focus: down to diffraction limit \( \rightarrow \) typically \( \varnothing < 10 \) μm

Intensity (power per unit area): \( 10^{18} \) W/cm\(^2\) up to \( 10^{22} \) W/cm\(^2\)

From huge facilities......

Nova laser, LLNL, 1984

... to table-top systems!

Commercial TW class laser, 2010s
The strength of laser fields: Laser field vs. “relativistic” field

\[
\frac{m_e \omega c}{e} \approx \frac{3.2 \times 10^{10}}{\lambda (\mu m)} \frac{V}{cm} \Rightarrow I \approx \frac{1.4 \times 10^{18}}{\lambda^2 (\mu m)} \frac{W}{cm^2}
\]

Relativistic electron momenta \((p \sim mc)\) in one laser cycle

Laser-driven ion acceleration

A non conventional way to accelerate heavy charged particle beams

Target:
μm-thick foils

Fast ions:
multi-MeV, collimated

electron cloud

Laser pulse:

\[ \varepsilon_p \approx 1-100 \text{ J} \]
\[ \tau_p \approx 10-10^3 \text{ fs} \]
\[ P_p \approx 10^{12} - 10^{15} \text{ W} \]
\[ I_p > 10^{20} \text{ W/cm}^2 \]

A. Macchi, M. Borghesi, M. Passoni, Rev. Mod. Phys., 85 751 (2013)
Conventional ion accelerators:

High-energy particle beams crucial for:

- Medicine: radiotherapy, nuclear diagnostics, ...
- Material engineering: ion beam analysis, implantation
- Nuclear engineering: Inertial Confinement Fusion, ...
- Basic science: particle & high energy physics, ...

Laser-driven ion accelerator:

**Appealing potential:**
- Compactness
- Cost effectiveness
- Flexibility

**Critical issues:**
- Gain control of the process
- Increase efficiency/performance
- Limitation and cost of lasers

Novel targets can be the key!

The ENSURE project @ Politecnico di Milano

**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
The ENSURE team @ Politecnico di Milano

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ENSURE
ERC-PoC: INTER

Ongoing collaborations with:

HZDR
OSAKA UNIVERSITY
Queen's University Belfast
Source LAB
The ENSURE team @ Politecnico di Milano

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2 Master’s students
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**Enhanced Target Normal Sheath Acceleration**

Conventional Target

- Laser Pulse
- Accelerated Ions
- Fast Electrons
- Solid Foil
- Surface interaction mechanisms
- **Target Normal Sheath Acceleration (TNSA)**

Multi-layer near critical Target

- Laser Pulse
- Accelerated Ions
- Fast Electrons
- Solid Foil + Low Density Layer
- Volume & Surface Interaction Mechanisms
- **Enhanced TNSA**
  - Higher laser energy absorption
  - Enhanced fast electron production
  - Enhanced number and maximum energy
  - of accelerated ions

Laser interaction with near-critical plasmas is interesting for several applications...

Why bother with near-critical plasmas?

Several interesting applications:

- Enhanced ion acceleration
- Laboratory astrophysics
- $\gamma$-ray sources
- Inertial confinement fusion
- Electron acceleration
...
...from near critical plasma to low density materials

High density gas-jets

Cryogenic hydrogen

Solids

n_e/n_c
(λ~800nm)

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

- Aerogels
- Nanotube arrays
- Foams

1Willingale et al. PRL 96 (2006)
3Zani et al. Carbon 56 (2013)
Idealized modeling vs “realistic” modeling

uniform plasmas

“mixed” plasmas

nanostructured plasmas
Idealized modeling

Laser propagation in uniform and nanostructured near-critical plasmas
L. Fedeli, A. Formenti, C. E. Bottani & M. Passoni

Electron heating in foam-attached targets

https://github.com/ALaDyn/piccante
Wide range of laser intensities and average densities

Uniform plasma

\[-n = \frac{n_e / n_c}{\sqrt{1 + a_0^2 / 2}}\]
Wide range of laser intensities and average densities

Nanostructured plasma

\[-n = \frac{n_e / n_c}{\sqrt{1 + a_0^2 / 2}}\]
Main differences appear for partitioning of absorbed energy...
...and for the tail of electron energy spectra

\[ a_0 = 15, \frac{n_0}{n_c} = 1 \quad a_0 = 45, \frac{n_0}{n_c} = 3 \quad a_0 = 135, \frac{n_0}{n_c} = 9 \]
A very similar approach was followed to simulated electron heating in near-critical foam-attached targets

e\textsuperscript{-} temperature from PIC sim.  
TNSA ion acceleration model

Benchmark with exp.

I. Prencipe et al. PPCF 58 (2016)
M. Passoni et al. PRAB 19 (2016)

\* quasi-static Passoni-Lontano model
"Realistic" modeling based on DLA

Diffusion Limited Aggregation (DLA)
A simple and very well studied model to reproduce structures resulting from aggregation phenomena.

Witten & Sander, PRL 47, 1981
Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

\[ T = 08 \text{ tp} \]
Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

$T = 12 \, tp$
Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

\[ T = 16 \text{ tp} \]
Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

$T = 20\ tp$
Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

\[ T = 24 \text{ tp} \]
Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

\[ T = 28 \text{ tp} \]
Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

$T = 32$ tp
Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

$T = 36 \, \text{tp}$
Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

$T = 40 \text{ tp}$
“Realistic” modeling based on DLA

Differences in the simulated ion spectra!

I. Prencipe et al. PPCF 58 (2016)
M. Passoni et al. PRAB 19 (2016)
An improved realistic foam model

A model more closely based on the physics of Pulsed Laser Deposition...

Improved model

Real foam!
Development of advanced targets

NanoLab@POLIMI facilities and infrastructures:

Two ns-Pulsed laser deposition (PLD) systems
Thermal treatment systems

SEM, STM, AFM microscopy
Raman & Brillouin spectroscopy

Pulsed Laser Deposition (PLD) of nanostructured targets

Carbon "foams"

Density ~ mg/cm$^3$ (between gas and solid!)
New techniques to improve capability in advanced target production:

- femtosecond PLD
- HiPIMS

HiPIMS

femtosecond PLD

Yesterday (2016)

Tomorrow (within 2017)

Experimental: new labs @ POLIMI!

HiPIMS

Ep=5 mJ
\( t=100 \text{ fs} \)
\( I=10^{15} \text{ W/cm}^2 \)
Next steps: fs-PLD under development

Coherent “Astrella”
- Tabletop laser
- $\tau < 100$ fs
- $E_p > 5$ mJ

➢ Femto-machining and laser processing
➢ Femtosecond PLD
  - inherent production of NPs
  - New frontiers in foam production?
ns PLD in a background gas

Laser Beam \( \lambda = 266, 532, 1064 \text{ nm} \)
7ns, 0.1-2 J, 10 Hz
fluence: 0.1 - 20 J/cm\(^2\)
Intensity: \(10^7 - 2 \times 10^9\) W/cm\(^2\)

Background Gas
- Inert (He, Ar..)
- Reactive (O\(_2\))

Rotating substrate
- almost any substrate
- thickness down to 100 nm

Gas pressure
Laser fluence
Foam property control

Nano-scale
- Crystalline structure
- Composition

Micro-scale
- Average density
- Morphology
- ....

Macro-scale
- Uniformity
- Thickness profile

PLD process parameters

Laser Wavelength
Laser Fluence
Gas pressure
Geometry
Deposition time
Building blocks: carbon nanoparticle

**Elementary constituents:**
10-20 nm nanoparticles

**C-C bonding:**
Nearly pure sp² odd-membered rings and few chain-like structures

**Crystalline structure:**
Topologically disordered domains, Size ~ 2nm

A. Zani *et al.*, Carbon, 56 358 (2013)
Observing the foam growth process....

10 shots

100 shots

1000 shots

5000 shots
Role of process parameters - pressure

\[ \lambda = 532 \text{ nm} \]
\[ F = 2.1 \text{ J/cm}^2 \]
\[ d_{T-S} = 4.5 \text{ cm} \]

\section*{atoms}

\section*{nanoparticles}
Tuning a single parameter may not be enough….

Same density = 1.5 \( n_c \)
Same thickness \( \approx 8 \) \( \mu m \)

- \( F = 1.1 \) J/cm\(^2\)
- \( P = 100 \) Pa Ar
- \( d_{ts} = 8.5 \) cm

- \( F = 1.4 \) J/cm\(^2\)
- \( P = 500 \) Pa Ar
- \( d_{ts} = 4.5 \) cm

Better uniformity & coverage!
Towards “thinner” foams…

Nominal thickness ≈ 4 µm

F = 1.4 J/cm²
P = 500 Pa Ar
\( d_{ts} = 4.5 \text{ cm} \)

F = 2.1 J/cm²
P = 1000 Pa Ar
\( d_{ts} = 4.5 \text{ cm} \)

1) Decreasing deposition time might not be enough!
2) Understanding foam growth vs process parameters is crucial
New multilayer target development

Double side deposition on a ultra-thin C layer (100 nm)
Interest: laser induced electrostatic shock generation

in collaboration with:
A. Morace
Ion acceleration with foam-based targets
Target preparation, experiments on laser facilities and simulations
Experiments on laser facilities

**Ion acceleration experiments:**
- Performed at **GIST** (Rep. of Korea) in 2015-2016
- Performed at **HZDR** (Germany) in 2017
- Performed at **ILE** (Osaka) in 2017

**Setup of an ion acceleration experiment:**

**Effects of advanced targets:**

![Graph showing Maximum proton energy (MeV) vs Intensity on target (10^20 W/cm^2)](image)
Foam: PLD parameters

- $E=130 \text{ mJ}$
- $P=500 \text{ Pa Ar}$
- $d_{ts}=4.5 \text{ cm}$
- thickness $= 8, 12, 18, 36 \text{ µm}$
- Substrate $= \text{Al 0.75 µm}$

Ion acceleration: laser parameters

- Energy on target $= 8 \text{ J}$
- Intensity $= 0.5 \times 10^{20} - 5 \times 10^{20} \text{ W/cm}^2$
- Angle of incidence $= 30^\circ$

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)
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
- $d_{ts} = 4.5$ cm
- Substrate = Al 1.5 µm
- Foam thickness = 4, 8, 12 µm

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**Graphs**

1. **Laser power fraction (%)** vs. **H$^+$ max. energy [MeV]**
   - 4 mm C foam on 1.5 mm Al
   - 1.5 mm Al, no foam

2. **Foam thickness [µm]** vs. **H$^+$ max. energy [MeV]**
   - Optimal foam thickness
   - No foam

3. **Energy [MeV]** vs. **Particles [1/(MeV*sr)]**
   - 4 µm C foam on 1.5 µm Al
   - 1.5 µm Al, no foam

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An example of application:

**Material characterization & processing with laser-driven ion beams**

- Ion beam analysis: RBS, NRA, PIXE,…
- Neutron imaging and radiography….
- Ion implantation
- Radiation damaging…

Laser-driven ion beams may *ensure* major advantages!

F. Mirani, Master thesis in Nuclear Engineering (2017)
Another example of application:

**Towards a portable neutron source**

2017/2018: pulsed neutron generation

2017/2018: compact ion and neutron sources for materials characterization
Conclusions

• **Nanostructured foams** are one of the few ways to obtain a controlled near-critical plasma

• Simulations to understand how this affects **laser-nanostructured plasma interaction**; nanostructure may affect experimental observables

• Production of **multilayers targets** composed of near critical carbon foam 4 um thick

• Promising results in **laser-ion acceleration experiments**

• Laser-ions can be interesting in **materials and nuclear sciences**
Thanks for your attention!