Numerical simulations of Laser-Plasma interaction with nanostructured plasmas

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ENSURE

Ongoing collaborations with:

Milano

HZDR
OSAKA UNIVERSITY
SourceLAB
Queen's University Belfast

ERC ERC-PoC: INTER
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Valeria Russo
Researcher

4 Post-docs
D. Dellasega
A. Maffini
L. Fedeli
L. Cialfi

2 PhD students
A. Formenti
A. Pazzaglia

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

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Our numerical tools

https://github.com/ALaDyn/piccante

MARCONI (12\textsuperscript{th} in TOP500 as of Nov 2016)
CINECA Cluster, Intel Xeon Phi 7250 68C
1.4GHz, Intel Omni-Path (241,000 cores)
Linpack Performance: 6.2 PetaFlops
Nanostructured near-critical plasmas
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
- High angular momentum electron bunches
...
...but they are challenging from a “targetry” point of view!

How do we fill the gap?
- Pre-heating
- Very low-density nanostructured materials

High density gas-jets

Cryogenic hydrogen

Solids

\[ \frac{n_e}{n_c} \ (\lambda \sim 800\text{nm}) \]
...but they are challenging from a “targetry” point of view!

How do we fill the gap?

- Pre-heating
- Very low-density nanostructured materials

- Aerogels
- Nanotube arrays
- PLD Foams

High density gas-jets

Cryogenic hydrogen

Solids

\[ \frac{n_e}{n_c} \sim 800 \text{nm} \]
An example of a “foam-attached” target

Target conceived for a collision-less shock experiment

D. Dellasega  A. Maffini
An example of a “foam-attached” target
Foam has a porous, complex nanostructure

We’ve used these targets for some experimental activities...

2014/2015

PULSER laser at GIST (Gwangju, South Korea)
$I \sim 5 \times 10^{20} \text{ W/cm}^2$, $T_{\text{FWHM}} \sim 30$ fs

I. Prencipe et al. PPCF 58 (2016)
M. Passoni et al. PRAB 19 (2016)
And we still have several ongoing experimental activities involving foam-attached targets

May 2017: ion acceleration, electron heating, foam homogenization, reflected light...

2017/2018: ion acceleration, collision-less shocks

2017/2018: pulsed neutron generation

2017/2018: compact ion and neutron sources
How do we simulate these targets?
Idealized modeling vs “realistic” modeling
Idealized modeling
Idealized modeling

Laser propagation in uniform and nanostructured near-critical plasmas
L. Fedeli, A. Formenti, C. E. Bottani & M. Passoni EPJD
Topical Issue on “Relativistic Laser Plasma Interactions” (accepted) 2017

Electron heating in foam-attached targets
Idealized modeling

Laser propagation in uniform and nanostructured near-critical plasmas
L. Fedeli, A. Formenti, C. E. Bottani & M. Passoni
EPJD Topical Issue on “Relativistic Laser Plasma Interactions” (accepted) 2017
We studied three very idealized plasma models: **uniform** plasmas, **nanostructured** plasmas, and **“mixed”** plasmas. The study involved a 2D numerical simulation campaign.
In a wide range of laser intensities and average densities

Uniform plasma

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

Nanostructured plasma

\[ \bar{n} = \frac{n_e/n_c}{\sqrt{1+a_0^2/2}} \]
Main differences appear for partitioning of absorbed energy...

\[
\begin{align*}
\text{a}_0 = 1, & \quad n_0/n_c = 1 \quad \rightarrow \quad \bar{n} \approx 0.8 \\
\text{a}_0 = 5, & \quad n_0/n_c = 3 \quad \rightarrow \quad \bar{n} \approx 0.3 \\
\text{a}_0 = 15, & \quad n_0/n_c = 9 \quad \rightarrow \quad \bar{n} \approx 0.09
\end{align*}
\]
...and for the tail of electron energy spectra

For electron energy spectra we restrict ourselves to this diagonal (highest transparency)
...and for the tail of electron energy spectra

\[ a_0 = 15, n_0/n_c = 1 \]

\[ a_0 = 45, n_0/n_c = 3 \]

\[ a_0 = 135, n_0/n_c = 9 \]
A very similar approach was followed to simulated electron heating in near-critical foam-attached targets

Electron heating in foam-attached targets
A very similar approach was followed to simulated electron heating in near-critical foam-attached targets
Why foam-attached targets?
Why near-critical foam-attached targets?

Enhanced coupling in the near-critical layer

Higher laser absorption, higher electron temperature, enhanced ion acceleration...
Setup of the physical scenario

**Laser:** p-polarized, $a_0 = 1\text{-}15$, 30° incidence,

2D PIC simulations

**Simple flat target**
80 $n_c$, 0.5 $\mu$m

**Unif. foam target**
80 $n_c$, 0.5 $\mu$m +
1 $n_c$, 10 $\mu$m

**Nanost. foam target**
80 $n_c$, 0.5 $\mu$m +
balls $r=10$ nm, $n_e=100$ $n_c$
avg.1 $n_c$, 10 $\mu$m
Uniform foam vs nanostructured foam
Uniform foam vs nanostructured foam
Uniform foam vs nanostructured foam
Uniform foam vs nanostructured foam
Uniform foam vs nanostructured foam
Uniform foam vs nanostructured foam
Uniform foam vs nanostructured foam

$t = 0.64$

![Diagram showing comparison between uniform foam and nanostructured foam at time $t = 0.64$.](image)
Uniform foam vs nanostructured foam
Uniform foam vs nanostructured foam
Results: $T_{\text{unif}} > T_{\text{nano}} > T_{\text{flat}}$

For foam-attached targets we exclude the escaping fast-electron population.
Benchmark with experimental results

- Electron temperature model
- TNSA ion acceleration model

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

*quasi-static
Passoni-Lontano model
Benchmark with experimental results

- Electron temperature model
- 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
“Realistic” modeling

More realistic models
M. Passoni et al. PRAB 19 (2016)
I. Prencipe et al. PPCF 58 (2016)
A. Formenti PhD thesis (2017-?)
“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
“Realistic” modeling based on DLA

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Differences in the simulated ion spectra

![Graph showing differences in simulated ion spectra with energy scales and logarithmic axes. The graph illustrates the variation in dN/dE (arb. units) across different conditions: no foam, homogeneous foam, and nanostructured foam.]
What’s next on this topic?
Simulated diagnostics for realistic configurations

“A. Formenti”

“hollow foam”

“hill foam”

UNIFORM FOAM

HOLE FOAM

HILL FOAM

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Simulations of the reflected light

Flat target

Uniform foam

DLA foam
An improved realistic foam model

Real foam

Improved model

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

A. Pazzaglia
An improved realistic foam model

Real foam

Improved model

A model more closely based on the physics of Pulsed Laser Deposition
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A. Pazzaglia
Coupling of PIC spectra with Geant4

Electrons and ions

Secondary target

SourceLAB

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Conclusions
Conclusions

Nanostructured foams are one of the few ways to obtain a controlled near critical plasma.

With very high pulse contrast nanostructure might survive → simulations to understand what happens.

In numerical simulations the nanostructure is found to affect experimental observables.
Thank you for your attention!
More info on our website

www.ensure.polimi.it
Backup slides
which can have consequences on radiative losses
If we turn on radiation reaction...
What we’ve learned

Simple perturbations of the density can affect the interaction

Nanostructure leads to higher energy into ion population and lower $e^-$ energy distribution tails

For higher $a_0$: nanostructure affects radiative losses
What we’ve learned

Foam attached targets leads to higher electron temperature than simple flat targets

Nanostructure affects the interaction