Numerical simulations of nanostructured plasmas

Luca Fedeli

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The group at Politecnico di Milano
The group at Politecnico di Milano

Matteo Passoni
Associate professor

Luca Fedeli
Post-doc

Lorenzo Cialfi
PhD student

Arianna Formenti
PhD student

Material science/targetry team

Valeria Russo
Researcher

David Dellasega
Post-doc

Alessandro Maffini
Post-doc

Andrea Pazzaglia
PhD student

Margherita Zavelani Rossi
Associate professor

Numerical team

ENSURE

ERC
The group at Politecnico di Milano

Research interests

Laser-driven ion acceleration

Applications of laser-driven ions in material science

Secondary sources (e.g. laser-driven neutron sources)

Advanced targets for laser-plasma experiments (near-critical foams)
Nanostructured plasmas
Ultra-intense, ultra-short, ultra-high contrast lasers

Ultra-short (10s fs), ultra-intense (up to $\sim 10^{22}$ W/cm$^2$) laser systems

Ti:sapphire-based: $\lambda \sim 800$ nm

Very high temporal contrast, even $10^{10}$ @ps timescale
Nanostructured plasmas
Nanostructured plasmas

If we irradiate a solid, nanostructured, target with these lasers, the structures might survive.

In some cases this is incidental.

In other cases it is desirable.
If we irradiate a solid, nanostructured, target with these lasers, **the structures might survive**

In some cases this is **incidental**

In other cases it is **desirable**
Nanostructured near-critical density plasmas

Why bother with low density porous materials?

Essentially because we care about laser-interaction with near-critical plasmas
Near-critical plasmas

\[ n \ll n_c / \langle \gamma \rangle \]

\[ n \sim n_c / \langle \gamma \rangle \]

\[ n \gg n_c / \langle \gamma \rangle \]

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

\[ \langle \gamma \rangle = \sqrt{1 + a_0^2 / 2} \]

\[ a_0 = \frac{e E_0}{m_e \omega c} \]

Synchrotron emission

Collisionless shocks

Laser-driven ion acceleration
Near-critical plasmas

We don't really have many strategies to explore that density range

$1 \, n_c \text{ means few mg/cm}^3$ !

High-density gas-jets

Pre-heating

Low-density porous materials
Near-critical plasmas

We don't really have many strategies to explore that density range!

$1 \ n_c$ means few mg/cm$^3$!
Near-critical plasmas

Low-density carbon foam

Tunable density, down to $\sim 1n_c$ (fully ionized)

Zani et al. Carbon 56 (2013)
Near-critical plasmas

- Can be attached onto a solid foil: Proven.
  - Thickness range: ~4-60 μm

- Abrupt density change (but still low density): Proven.
  - But, better control is needed

- Density gradient: Proven.
  - But, challenging to control
Near-critical plasmas

- Can be attached onto a solid foil
- Abrupt density change (but still low density)
- Density gradient

A lot of “freedom” in target design (e.g. density tailored for Magnetic Vortex acceleration, Collisionless Shocks generation...).
Experiments with foam-attached targets
Experiments with foam-attached targets

In 2014/2015 we performed experiments with foam-attached targets

Gwangju PW-class laser facility

Aim: enhancing laser-driven ion acceleration with better laser-target coupling

I. Prencipe et al., PPCF 58 (2016)
M. Passoni et al., PRAB 19(2016)
Experiments with foam-attached targets

Up to $5 \times 10^{20}$ W/cm$^2$
30 fs, 30° pulse incidence
C-, P-, S- polarization
Thomson Parabole to look at ion spectra

Targets made of $0.75 \ \mu m$ Al + 0-36 $\mu m$ Carb. foam ($\sim 1 \ n_c$)

I. Prencipe et al., PPCF 58 (2016)
M. Passoni et al., PRAB 19(2016)
Experiments with foam-attached targets

Optimal foam thickness

I. Prencipe et al., PPCF 58 (2016)
M. Passoni et al., PRAB 19(2016)
Experiments with foam-attached targets

With foam no effects of pulse polarization

I. Prencipe et al., PPCF 58 (2016)
M. Passoni et al., PRAB 19(2016)
How do we simulate these plasmas?
How do we simulate these plasmas?

**Particle-In-Cell codes**

\[ \partial_t f + \mathbf{v} \cdot \nabla_x f + q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \nabla_p f = 0 \]

Maxwell's equations

\[ f(x, p, t) \approx \sum_i S(x - x_i(t)) \delta(p - p_i(t)) \]

We need to simulate these **complex structures** in Particle-In-Cell (PIC) codes
How do we simulate these plasmas?

We've used and we'll use foam-attached targets in forthcoming experiments.

We need numerical support.

How do we model these structures?

Models

- Uniform plasmas
- Idealized model
- More realistic model
Instead of using a uniform plasma (as typically done in the literature), we can try to use a “random balls” model.

Simplified models

- Very crude model
- No μm-scale structure
- Spheres are not connected
Simplified models

- Few parameters to play with
- Ordered vs Disordered
- Radius and average distance
Simplified models

We can even mix a uniform plasma with a random balls plasma.

Might simulate partial pre-heating.
More realistic models
More realistic models

Diffusion limited aggregation model

Experiments with foam-attached targets
We used a realistic model to support our experimental activity on foam-attached targets.

I. Prencipe et al., PPCF 58 (2016)
M. Passoni et al., PRAB 19 (2016)
How do we simulate these plasmas?

Simulations with realistic foams allowed to reproduce essential features observed in the experiments.

I. Prencipe et al., PPCF 58 (2016)
M. Passoni et al., PRAB 19 (2016)
Some recent developments

Simulations done by A. Formenti

Synthetic RadioChromic Films for direct comparison with experimental results.

Also to understand the effect of foam inhomogeneities

Simulations done by A. Formenti
Some recent developments

Synthetic RadioChromic Films for direct comparison with experimental results.

Simulations done by A. Formenti
Simulations of nanostructured plasmas: some examples with simplified models
Simulations of nanostructured plasmas: some examples with simplified models

Laser propagation in near-critical foams

Enhanced electron heating with foam-attached targets
Laser propagation in near-critical plasmas
Laser propagation in near-critical plasmas
Laser propagation in near-critical plasmas

The numerical setup

P-polarized, gaussian
\[ a_0 = 45, \quad w = 5\lambda, \quad \tau_{\text{FWHM}} = 15\lambda/c \]

Uniform, \( n = 3 \ n_c \)
30 part.p.cell (for e⁻)

Box: 220\( \lambda \) x 60\( \lambda \)
Resolution: 30 pp\( \lambda \)
Laser propagation in near-critical plasmas

\[ t = 0 \text{ } \lambda/c \]

\[ y/\lambda \]

\[ x/\lambda \]

\[ e^- \text{ density} \]

30
Laser propagation in near-critical plasmas
Laser propagation in near-critical plasmas
Laser propagation in near-critical plasmas

![Graph showing laser propagation](image)
Laser propagation in near-critical plasmas
Laser propagation in near-critical plasmas
Laser propagation in near-critical plasmas
Laser propagation in near-critical plasmas
Laser propagation in near-critical plasmas

$t = 40 \lambda/c$

$e^{-}$ density

$x/\lambda$

$y/\lambda$

CINECA

piccante

Open Source PIC Code

POLITECNICO MILANO 1863
Laser propagation in near-critical plasmas
Laser propagation in near-critical plasmas

\[ t = 50 \lambda/c \]

\[ x/\lambda \]

\[ y/\lambda \]

\[ e^- \text{ density} \]

CINECA

piccante

Open Source PIC code

POLITECNICO MILANO 1863
Laser propagation in near-critical plasmas

D. J. Stark et al. PRL 116 (2016)
Laser propagation in near-critical plasmas

The numerical setup

P-polarized, gaussian
\( a_0 = 45, \ w = 5\lambda, \ \tau_{\text{FWHM}} = 15\lambda/c \)

Rnd. spheres, \( <n> = 3\ n_c \)
\( r = 0.178\ \lambda \), filling=0.1
270 part.p.cell (for e⁻)
Numerical simulations

I can mix the two plasmas, going from a fully uniform plasma to a fully disconnected random spheres - plasma

67% + 33% = 3 n_c on avg.
Numerical simulations
Numerical simulations

From “completely random spheres” to completely uniform
Numerical simulations

“Some” temperature difference here
Numerical simulations

Significant cut-off energy difference
Numerical simulations

This is observable if we look at the spectrum of synchrotron emission. Peak scales as $\sim \gamma^3 \omega_c$

According to the model, “uniform is probably better” for synchrotron emission

In principle we could see if the model makes any sense with a simple experiment

Pre-heating of the foam

Reduce the contrast
Electron heating in foam-attached targets
Electron heating in foam-attached targets
Electron-heating in foam-attached targets

A lot of existing literature! Interesting for several reasons: ion acceleration, electron/positron beams, electron transport...

However, several issues of existing models (Angular dependence, polarization dependence...) and no models for foam-attached targets

L. Cialfi, L. Fedeli, M. Passoni, accepted with minor revisions, PRE
Electron-heating in foam-attached targets

Not easy to find parametric scans for e⁻ temperature

But a lot of data on laser-driven ion acceleration

L. Cialfi, L. Fedeli, M. Passoni, accepted with minor revisions, PRE
Write a model for $T_e(a_0, \text{pol})$

**JxB heating**

$$T_e[MeV] = 0.511 \cdot C_1(\text{pol}) \cdot \left( \sqrt{1 + \frac{a_0^2}{2}} - 1 \right) + 0.511 \cdot C_2(\text{pol}) \cdot \left( \sqrt{1 + 2 a_0^2 \sin^2 \theta} - 1 \right) \cdot \tan \theta$$

**Vacuum heating**
Electron-heating in simple targets

Write a model for $T_e(a_0, \text{pol})$

**JxB heating**

**Vacuum heating**

$$T_e[\text{MeV}] = 0.511 \cdot C_1(\text{pol}) \cdot \left( \sqrt{1 + \frac{a_0^2}{2}} - 1 \right) + 0.511 \cdot C_2(\text{pol}) \cdot \left( \sqrt{1 + 2 a_0^2 \sin^2 \theta} - 1 \right) \cdot \tan \theta$$

2D/3D simulations to check model and fit parameters
Electron-heating in simple targets

Write a model for $T_e(a_0,\text{pol})$

$J \times B$ heating

$T_e[\text{MeV}] = 0.511 \cdot C_1(\text{pol}) \cdot \left(\sqrt{1 + \frac{a_0^2}{2}} - 1\right) + 0.511 \cdot C_2(\text{pol}) \cdot \left(\sqrt{1 + 2a_0^2 \sin^2 \theta} - 1\right) \cdot \tan \theta$

Vacuum heating

2D/3D simulations to check model and fit parameters

Plug $T_e$ into existing model for ion acceleration

$E_{\text{max}}(\text{ions}) = Z_i k_b T_e \left[ \phi' - 1 + \frac{\beta(\phi', \zeta)}{l(\phi', \zeta) e^{\phi + \zeta}} \right]$  

Electron-heating in simple targets

JxB heating

Vacuum heating

\[ T_e[\text{MeV}] = 0.511 \cdot C_1(\text{pol}) \cdot \left( \sqrt{1 + \frac{a_0^2}{2}} - 1 \right) + 0.511 \cdot C_2(\text{pol}) \cdot \left( \sqrt{1 + 2a_0^2\sin^2\theta} - 1 \right) \cdot \tan \theta \]

Benchmark with experiments

Exp. data
I. Prencipe et al.
PPCF 58 (2016)
M. Passoni et al.
PRAB (2016)
Electron-heating in near-critical plasmas

What about foam-attached targets?

L. Cialfi, L. Fedeli, M. Passoni, accepted with minor revisions, PRE

APL Robinson et al, PPCF 53 (2011)

Pulse erosion

$T_e \sim a_0^2$

Ponderomotive expulsion

$T_e \sim a_0$
Electron-heating in near-critical plasmas

What about foam-attached targets?

2D Particle-In-Cell simulations to obtain $T_e$

Investigation limited to one particular setup

L.Cialfi, L.Fedeli, M.Passoni, accepted with minor revisions, PRE
Electron-heating in near-critical plasmas

Two models for the foam

Homogeneous foam $n_e = n_c$

Rnd. Spheres $\langle n_e \rangle = n_c$
$r = 10 \text{nm}, n_e = 100 n_c$

L. Cialfi, L. Fedeli, M. Passoni, accepted with minor revisions, PRE
Electron-heating in near-critical plasmas

Simple linear fit: \[ T_e[MeV] = C_1 + C_2 a_0 \]
Electron-heating in near-critical plasmas

Same idea of flat targets

$T_e$ → Ion acceleration model → Estimation of $E_{max}$ → Benchmark

**Graph:**
- Vertical axis: Maximum proton energy (MeV)
- Horizontal axis: Intensity on target ($10^{20}$ W/cm$^2$)
- Curves:
  - Black: Experimental results
  - Red: Nanostructured foam
  - Blue: Homogeneous foam

L.Cialfi, L.Fedeli, M.Passoni, accepted with minor revisions, PRE
Nanostructured plasmas
If we irradiate a solid, nanostructured target with these lasers, the structures might survive.

In some cases this is incidental.

In other cases it is desirable.
Nanostructured plasmas

Wide topic, growing interest in the community.

L. Fedeli et al. PRL 116 (2016)
T. Ceccotti et al. PRL 111 (2013)
V. Kaymak et al. PRL 117 (2016)
S. Jiang et al. PRL 116 (2016)
K.Q. Pan et al. PoP 23 (2016)
Nanostructured plasmas

High Field Plasmonics
Electron acceleration with a relativistic surface plasmon

\[ \frac{\omega}{c} \sin (\theta) = \frac{\omega}{c} \sqrt{\frac{1 - \omega_p^2/\omega^2}{2 - \omega_p^2/\omega^2}} \pm n \frac{2\pi}{d} \]

L. Fedeli et al. PRL 116 (2016)

I \sim 5 \times 10^{19} \text{ W/cm}^2
Nanostructured plasmas

2D/3D PIC simulations confirmed the picture

And were able to reproduce exp. results

3D PIC Simulation

Exp. results
Other kinds of nanostructures plasmas

High Field Plasmonics
Enhanced high-order harmonic emission from irradiated grating targets

L. Fedeli et al. (to be submitted soon)
Other kinds of nanostructures plasmas

High Field Plasmonics
Enhanced high-order harmonic emission from irradiated grating targets

Exp. Resonance @ 30°

L.Fedeli et al. (to be submitted soon)

Dr A.Macchi

Dr A.Sgattoni
Conclusions

<table>
<thead>
<tr>
<th>Ultra-intense, ultra-short, ultra-high contrast lasers allow to study <strong>nanostructured plasmas</strong></th>
</tr>
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<tbody>
<tr>
<td>Sometimes this is <strong>desirable</strong> (e.g. for gratings), sometimes it is <strong>accidental</strong> (e.g. for foams).</td>
</tr>
<tr>
<td><strong>Nanostructure can strongly affect laser-plasma interaction</strong> and <strong>we need simulations</strong> to support and guide experimental activities</td>
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Since only recently ultra-short, ultra-high contrast lasers have become available, there are **many possible scenarios to study**.
Thank you for your attention!
How do we “build these structures”?

Which accurately describes many natural structures

Diffusion-limited aggregation

- Moving particle
- Fixed particle
- Substrate
Diffusion-limited aggregation

- Moving particle
- Fixed particle

Check if surrounding cells are free
Diffusion-limited aggregation

Moving particle

Fixed particle

Random movement on the grid
Diffusion-limited aggregation

- Moving particle
- Fixed particle

The particle moves
Diffusion-limited aggregation

- Moving particle
- Fixed particle

Check if surrounding cells are free
Diffusion-limited aggregation

Moving particle

Fixed particle

Random movement on the grid
Diffusion-limited aggregation

- Moving particle
- Fixed particle
Diffusion-limited aggregation

- Moving particle
- Fixed particle

Check if surrounding cells are free
Diffusion-limited aggregation

- **Moving particle**
- **Fixed particle**

Random movement on the grid
Diffusion-limited aggregation

- Moving particle
- Fixed particle
Diffusion-limited aggregation

The particle touches a filled cell. It stops there.
Diffusion-limited aggregation

- Moving particle
- Fixed particle

The particle touches a filled cell. It stops there
Diffusion-limited aggregation

- **Moving particle**
- **Fixed particle**

A new particle starts from the edge of the grid.