Interaction between superintense laser fields and nanostructured plasmas

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why a nanostructure in the first place?

$I \geq 10^{18} \frac{W}{cm^2}$

density profile with characteristic lengths on nm – sub-μm scale, i.e. ~ skin depth - wavelength
Nanostructured materials give access to a large parameters space

- wide range of regimes available
- high surface-to-volume ratio
- high degree of porosity
- high conversion efficiency of laser energy into plasma energy!
A huge variety of nanostructured materials is interesting for superintense laser-plasma interaction experiments.

- Nanowires
  - Ni
  - Co

- Carbon nanotubes
  - W. Ma et al. Nano Lett. 7.8 (2007)

- Cluster gas jets

- Gold foam

- Gratings

- Laser-induced structures
A huge variety of nanostructured materials has been employed in superintense laser-plasma experiments

ultrahigh-energy density matter

fast ignition for inertial confinement fusion

charged particle acceleration


high field plasmonic

flat target

grating target


photon sources

plasma optics
A key issue is to provide accurate modeling of both the laser and the nanostructured plasma in their interaction. From the theoretical standpoint, the nanostructure is often disregarded!
It is worth trying to include the nanostructure, even if it will soon be destroyed by the intense light.

**lifetime of the nanostructure: simple estimation**

- nanoparticle, as the brick of the nanostructure
- hypothesis: $a_0$ is high enough that all electrons are ejected from the nanoparticle
- characteristic velocity of a test ion

\[
\beta = \sqrt{\frac{2 \omega_{p,i} R}{c}} \sqrt{\frac{r - R}{r}} \sim 10 \mu m \text{ ps}^{-1}
\]

→ nanostructure washed away in ~ 100 fs

ion density @ 90 fs
We have studied laser-nanostructured plasma interaction with PIC simulations to assess the role of the nanostructure itself. 

**WHAT**
- study the role of the nanostructure

**HOW**
- insights on a wide range of regimes
- accurate description of the nanostructure

combined use of 2D and 3D simulations to explore the parameter space

**WHAT**
- morphology
- \( n_e/n_c \)
- \( a_0 \)
First, we explored a wide range of laser & plasma parameters with 2D PIC simulations.
Each diagonal has its own value of the “opacity parameter”

\[ \tilde{n} = \frac{n_0/n_c}{\sqrt{1 + a_0^2/2}} \]

the larger, the more opaque the plasma is to the laser

We simulated semi-infinite homogeneous plasma slabs

And also semi-infinite nanostructured plasma slabs

Here the nanostructure is simply a collection of **nanospheres randomly arranged in space**

nanospheres

\[ r_s \sim 40 \text{ nm} \]
\[ n_e \sim 90 \, n_c \]
\[ d_s \sim 13 \text{ nm} \]

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\[ \tilde{n} \approx 0.8 \]
\[ \tilde{n} \approx 0.3 \]
\[ \tilde{n} \approx 0.09 \]

We found out that in the **opaque diagonal** the nanostructure allows for a much higher laser absorption

**enhanced absorption mostly because ions absorb much more**

We found out that in the transparent diagonal the nanostructure damps the maximum electron energy.

indicators of a self-similar behavior even with a nanostructure

Then, we selected the most interesting cases to be simulated with 3D PIC


nanostructured vs. homogeneous

nanoparticles

$ r_s \sim 40 \text{ nm} $

$ n_e \sim 60 \ n_c $

$ d_s \sim 16 \text{ nm} $

**foam-like structure:** obtained with a cluster-cluster aggregation model (see poster for more details)
We found out that previous 2D simulations caught well the behavior of the irradiated nanostructure.

1. **opaque diagonal**
   - total absorption
   - nanostructured curve
   - homogeneous curve
   - $a_0 = 5$
   - $n_e = 3$

2. **transparent diagonal**
   - electron spectra
   - nanostructured curve
   - homogeneous curve
   - $a_0 = 45$
   - $n_e = 3$

Then, we selected the most interesting \((a_0, n_e)\) case to be simulated with 3D PIC using several different morphologies ordered nanowires vs. random nanowires most interesting because it’s the closest to the transparency threshold

We found out that the details of the nanostructure can deeply affect the energy and angular distributions for all nanostructures \( \sim 80\% \) of laser energy absorption.

Different absolute number of energetic electrons

If we assume the self-similarity, it would be 300 MeV for \( a_0 = 100, n_e = 60 n_c \)

Lastly, we studied the role of the nanostructure in double-layer targets for enhanced laser-driven ion acceleration. Nanostructures and homogeneous near-critical layers do not necessarily work the same way. More details in the poster.
Conclusions

NANOSTRUCTURE MATTERS!

- include it for a complete description
- not including it, leads to “wrong” results depending on the regime of interaction

Perspectives

What happens at extreme intensities?
→ Rafael Caprani, MSc Thesis in collaboration with LULI

How reliable and predictive?
→ compare with experiments

Applications?
→ radiation sources

Analytical modeling?
→ To be developed
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