Wigner 121
Scientific Symposium

Wigner Research Centre for Physics
Institute for Particle and Nuclear Physics
Nanoplasmonic Laser Fusion Laboratory
Laser Group

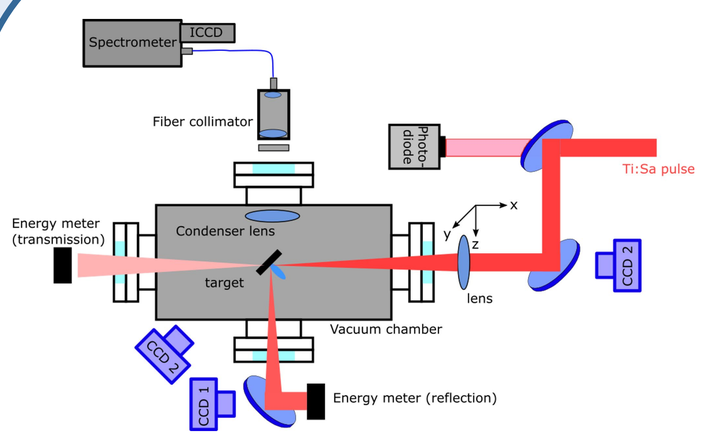
Introduction

In the framework of the **Nanoplasmonic Laser Fusion** project, we are carrying out theoretical and experimental investigations to explore the resonant nanoplasmonic effect at high laser intensities, as well as apply these processes for inducing nuclear interactions.

The **experimental studies** are based on the irradiation of different nanostructured targets by the focused beam of a femtosecond Ti-sapphire laser (Coherent Hidra). The laser pulses have a maximum energy of 30 mJ and minimum pulse duration of 40 fs, and so the maximum achievable focused laser intensity is about 10^{18} W/cm^2. The interaction processes and products are investigated by measuring the reflection and transmission energies, as well as using Laser Induced Breakdown Spectroscopy (LIBS) and Mass Spectrometry (MS) synchronously with the laser exposures. Polymer targets (e.g. urethane dimethacrylate, UDMA) in pure forms as well as doped with different concentrations of Au nanorods are studied. In addition, deuterated polymers are also analyzed in order to calibrate the measurement systems for the detection of deuterium content potentially created in the processes. We are also experimenting with targets containing boron with Au nanoparticles in order to induce proton-boron fusion reactions with enhanced efficiency. High energy ions (including alpha particles) are detected by CR-39 probes located around the laser exposure spot.

Kinetic modeling part of the nanorods: we estimate the **nanoantenna lifetime** in a **dynamical kinetic** model and describe how electrons are leaving the nanoantenna's surface [1,2]. Classical methods neglect **electron-electron interactions**. Particle simulations on the other hand use the electron number density, n_e, to randomly distribute electronlike marker particles on the metal surface, using similar velocity Verlet type finite difference time domain solving method. We compare the results in vacuum and UDMA and we will also show protons affected by the collectively moving electrons in the close proximity of the nanorods.

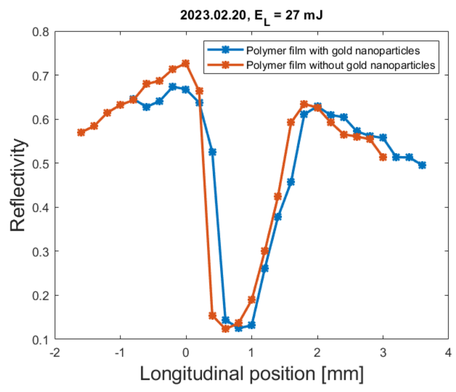
Reflection and LIBS measurements



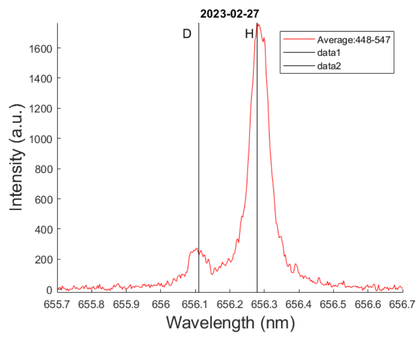
Experimental arrangement of the reflection as well as LIBS measurements.

The purpose of the reflection measurement is to find the threshold of the plasma mirror effect and to determine the energy absorbed by the target. The target was aligned at 45 degrees and reflection at right angles was measured in vacuum.

For the LIBS measurements, 2 mbar Ar buffer gas was introduced and the target surface was perpendicular to the laser beam. An LTB DEMON high resolution spectrometer was used for the analysis of the plasma light.

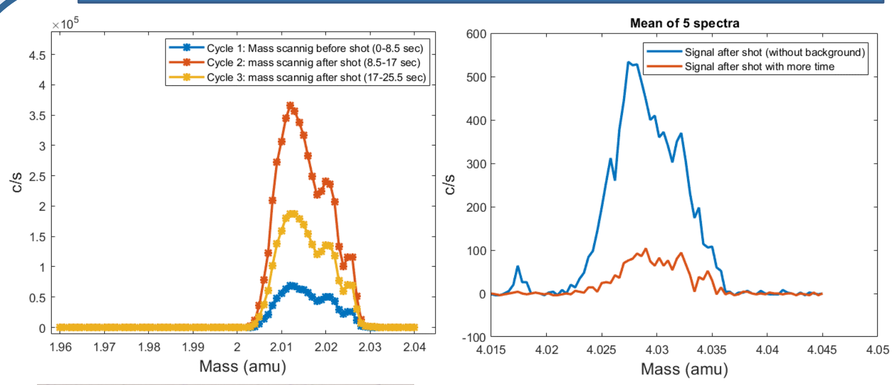


Plasma reflectivity as a function of the focus position of the laser beam (i.e., the intensity). At tight focusing the reflectivity decreases and higher energy can penetrate the medium.

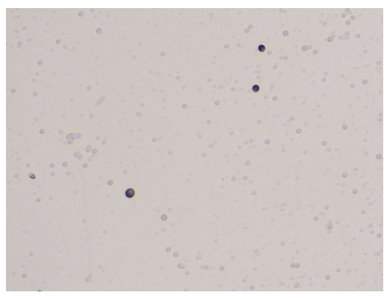


LIBS spectrum (average of 100 shots) obtained with a deuterated polymer sample. The high resolution of the spectrometer allows the distinction between the deuterium and protium isotopes of the hydrogen content.

MS and CR-39 analysis



A high resolution quadrupole mass spectrometer was applied for the analysis of the produts created by the laser irradiation. In the figures mass spectra of H_2 and D_2 molecules after a laser shot to a deuterated polymer target in the vacuum chamber can be seen.



Microscope image of an etched CR-39 trace detector plate mounted behind an Al foil filter in the vicinity of a target during high intensity laser shots. The UDMA target contained BN and was also doped with Au nanorods. The large black dots are the traces of alpha particles. The smaller dots originate from other ions (maybe protons).

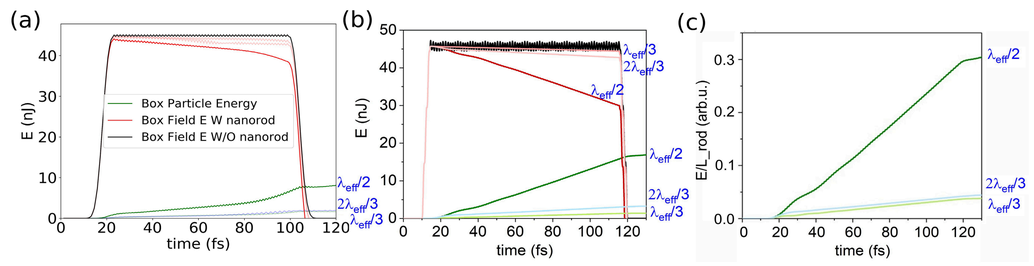
Kinetic Model

The conduction band electrons in metals behave as strongly coupled plasmas. The effect allows smaller than wavelength antennas with effective wavelengths. For golden nanorods of 25 nm diameter in UDMA-TEGDMA copolymer this gives an effective wavelength $\lambda_{eff}/2$ = 85 nm. The propagation velocity of light inside the medium is reduced to $c_s/\sqrt{\varepsilon_s}$, where $\varepsilon_s = n^2$.

$$\frac{\lambda_{eff}}{2R\pi} = 13.74 - 0.12\,[\varepsilon_\infty + \varepsilon_s 141.04]/\varepsilon_s - \frac{2}{p} + \frac{\lambda}{\lambda_p} 0.12\ \sqrt{\varepsilon_\infty + \varepsilon_s 141.04}/\varepsilon_s$$

We used the EPOCH's built in Villasenor and Buneman current deposition scheme

$$\vec{p}_{n+1} = \overrightarrow{p_n} + q\Delta t\left(\vec{E}_{n+1/2}(\vec{x}_{n+1/2}) + \vec{v}_{n+1/2} \times \vec{B}_{n+1/2}(\vec{x}_{n+1/2})\right)$$



Field solver:

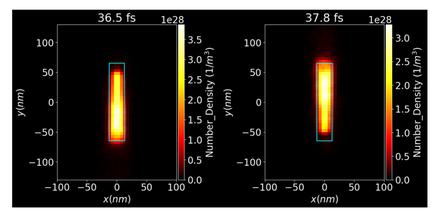
$$\varepsilon(\omega) = 1 - \frac{{\omega_p}^2}{(\omega^2 + i\Gamma\omega)}$$

Where ω_p is the plasma frequency:
γ is the damping factor or collision frequency:
and τ is the average time between collisions.

$$\frac{\partial \vec{E}}{\partial t} = \frac{1}{\mu_0 \varepsilon_0}\nabla \times \vec{B} - \frac{\vec{J}}{\varepsilon_0}, \qquad \frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$$

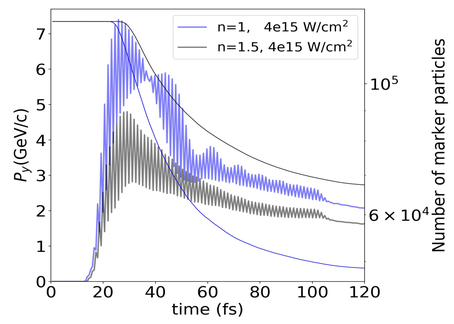
Particle simulation: $\frac{d}{dt}(\gamma\vec{v}) = \frac{q}{m}\left(\gamma\vec{E} + \gamma\vec{v} \times \vec{B}\right)$

Optical response of the gold nanorod with different numerical methods and lengths, L = $\lambda_{eff}/2$, $\lambda_{eff}/3$ and $2\lambda_{eff}/3$. (a) PIC, (b) FEM and (c) FEM with normalized values to unit antenna length.

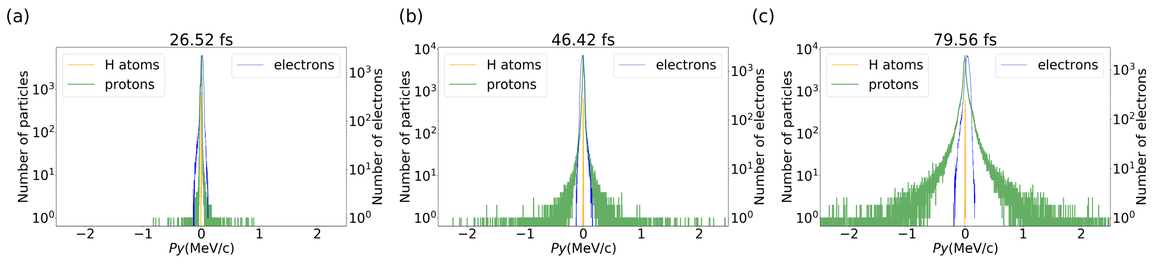


Results of the kinetic simulations

Conclusions of the kinetic **simulations**:
- The model is in good agreement with currently available widely accepted methods
- Quantitative differences mainly come at different resonant lengths
- The model is less idealized than before
- Ionization in the medium is now included, nuclear reactions are on the way
- Target pre-compression in the next step can be estimated



Time dependence of the **total** polarity directed momentum of the conducting electrons in the nanorod (left). Time dependence of the conducting electrons remaining in the nanoantenna (right).



Here we show the momentum distribution of particles at different times

Publications of the group

[1] *Kinetic model evaluation of the resilience of plasmonic nanoantennas for laser-induced fusion*, Papp I, Bravina L, Csete M, Kumari A, et al.. PRX Energy, 1, 023001 (2022).
[2] *Kinetic model of resonant nanoantennas in polymer for laser induced fusion*, I. Papp, L. Bravina, M. Csete, et al. (NAPLIFE Collaboration), Frontiers in Physics, 11, 1116023 (2023).
[3] *Laser induced proton acceleration by resonant nano-rod antenna for* fusion, I. Papp, L. Bravina, M. Csete, et al. (NAPLIFE Collaboration), arXiv:2306.13445 (2023).
[4] *Crater formation and deuterium production in laser irradiation of polymers with implanted nano-antennas*, L.P. Csernai, I.N. Mishustin, L.M. Satarov et al. (NAPLIFE Collaboration), Phys. Rev. E 108, 025205 (2023).
[5] *With Nanoplasmonics towards Fusion*, T. S. Biró, N. Kroó, L. P. Csernai et al., Universe, 9, 233 (2023).

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