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Communication

With Nanoplasmonics towards Fusion

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Abstract: A status report is presented about the Nanoplasmonic Laser Induced Fusion Experiment (NAPLIFE). The goal is to investigate and verify plasmonically enhanced phenomena on the surfaces of nanoantennas embedded in a polymer target at laser intensities up to a few times 10^{16} W/cm^2 and pulse durations of 40–120 fs. The first results on enhanced crater formation for Au-doped polymer targets are shown, and SERS signals typical for CD_2 and ND bound vibrations are cited. Trials to detect D/H ratio by means of LIBS measurments are reported. Plasmonics has the potential to work at these intensities, enhancing the energy and deuterium production, due to thus far unknown mechanisms.

Keywords: fusion; plasmonics; nanotechnology; energy production

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1. Laser Fusion Ignition Improvement by Nanoantennas

Taming nuclear fusion is a long-term dream [1]. Since the 1950s, several approaches have been developed towards this goal. To date, the most characteristic experiments belong to two groups of approaches: (i) magnetic confinement fusion (MCF) techniques and (ii) laser inertial heating and compression (ICF). The former approach has developed different techniques for producing the magnetic field which confines the hot plasma, such as tokamak and stellarator, while the latter uses more and more powerful lasers to increase the compression and to reach the ignition temperature necessary for starting elementary fusion reactions in thermal equilibrium. ITER in Cadarash, France is building the largest tokamak ever seen, and NIF in Los Alamos, Nevada collects the energy of 192 huge lasers onto a miniscule target (hohlraum). In both cases, magnetic confinement or inertial compressed fusion, there are plasma instabilities to fight.

The third type of approach, which generally do not aim for thermal equilibrium, have been discredited over the years by the "cold" fusion fallacy which presented high claims but provided no evidence. Yet, some fusion as a by-product of mechanical manipulations, such as sonoluminescence or cracking of metals enriched with hydrogen, have been reported in the passing decades. Generally, the chemical type of spectral or other evidence hunted down the presence of deuterium (atoms, not nuclei) in such cases. The real goal is to reach

tamed fusion, even as nanofusion in a controllable quantity is preferred for slow but rich energy production.

Nanoplasmonics is one of the efficient means of squeezing electromagnetic energy into nanosized volumes. It may result in hotspots around nanoparticles with high electron density, and thus high electromagnetic fields with characteristic lifetimes in the few times ten femtosecond range. The near field of these localized plasmons has a screening effect around positively charged particles (e.g., protons) and the momentum of the correlated motion of the plasmonic electrons may be transferred to these positively charged particles, resulting in their acceleration to high momentum and energy. These positive effects may play significant role in increasing the probability of fusion of these positive (e.g., proton, deuterium, boron, etc.) ions.

Our Nanoplasmonic Laser-Induced Fusion Experiment (NAPLIFE) investigates the extent to which nanotechnology may improve the laser beam targets in order to come closer to fusion ignition conditions at a lower input energy than is provided by the direct methods applied in big facilities. In this way, we hope to assist with the effects from plasmonics, from the collective motion of electrons illuminated by intense and ultrashort, well-contrasted laser pulses. After the first few years of this project, carried out with modest means, we report our initial experiences of the enhancement of laser energy absorption due to nanoplasmonic effects, stemming from doping metal (Au) nanoantennas in a transparent polymer target [2–7].

We prepare 20–160 micrometer-thick targets made of UDMA-TEGDMA copolymer, a material used in dentistry as tooth filler [2]. Our choice was motivated by the fact that while nanometals are easy to mix under a fluid, for laser shootings and transportation, a solid carrier is advantageous. The UDMA-TEGDMA can be solidified using UV light treatment after mixing. Au nanorods have been implemented into the polymer with carefully chosen size resonant to the laser wavelength of 795 nm. Furthermore, after finding the first signals for the presence of deuterium in the target remainder in molecular vibration spectra after shooting at it, for comparison and background measurements, we also use deuterized targets. This is achieved by admixing another, shorter molecule, the MMA, where all eight H atoms can be replaced by D atoms. In this way, up to 31 per cent D/H ratio can be achieved in the total copolymer molecule of the target. The width of the target is larger (160 μm), permitting us to study the crater sizes remaining after single shots, while it shall be smaller when planning multilayer targets in successive experiments.

The theory behind hoping for an enhancement of energy density due to plasmonics requires extended computer simulations on the motion of electrons on the Au nanoantennas of resonant size and various shapes. Although in the experiment, we are using cylindrical shapes, other shapes and metals sometimes promise a higher value of near field enhancement [8]. Theoretically, near-field enhancement (NFE) factors in the order of 100 can be reached, meaning an energy density enhancement of 10^4 in near atomic layers, up to cca. 10–30 nm-s.

The classical approach to studying plasmonic effects on nanoparticles involves the use of the dielectric function of the free electron gas, which often neglects important phenomena such as electron–electron interactions and spill-out effects; these are typically included by fit parameters. However, alongside such classical methods, we also use kinetic models utilizing the particle-in-cell (PIC) method. In PIC simulations, marker particles are randomly distributed on the metal surface based on the electron number density, and these particles move in a continuous phase space, while densities and currents are computed in stationary mesh cells.

The PIC method has been shown to be an efficient tool for analyzing the electron dynamics and for modeling spill-out effects in plasmon simulations [9,10].

A kinetic model simulation [11–14] reveals collectively moving electrons and protons up to momenta in the 100 MeV range—such projectiles in principle may initiate a few nuclear reactions in the surrounding polymer atomic layers (cf. Figure 1) [15,16].

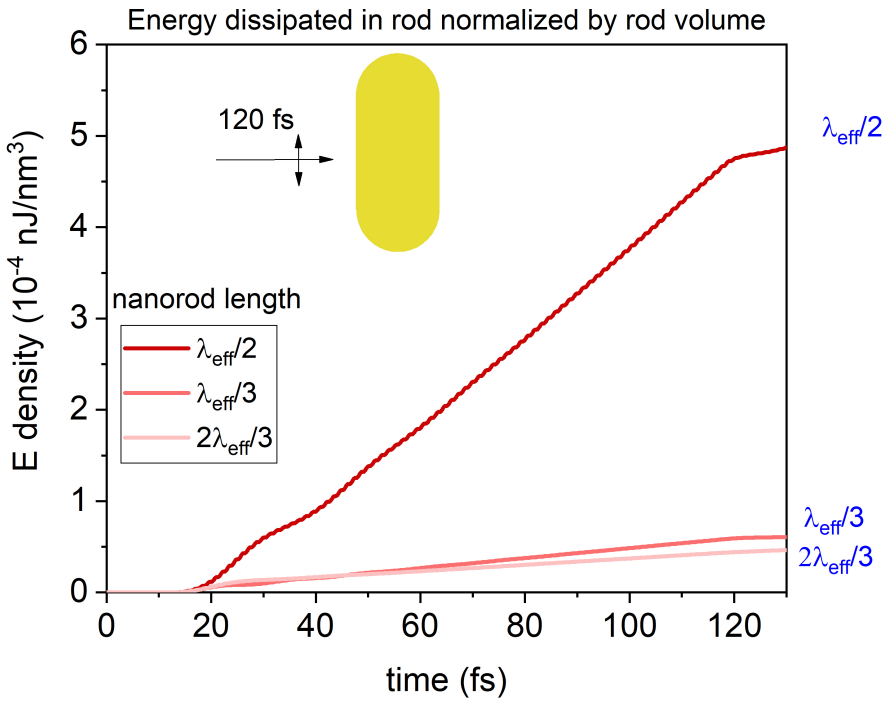

Figure 1. Result of a single nanoantenna simulation using a hydrodynamic (HDM) model implemented into FEM numerical codes. The importance of the in–medium resonant length is shown by the energy of accelerated electrons from the conducting band in the metal.

Embedding nanoantennas into the fusion remedies another obstacle inherent in present nuclear fusion techniques. Both MCF and ICF methods are fighting the Rayleigh–Taylor instabilities when the target is compressed to achieve high nuclear reaction rates. This leads to more and to less compressed domains, and consequently, only the highly compressed domains ignite. Due to the rapid expansion arising from the high pressure, the less compressed domains do not reach ignition at all.

In ultra-relativistic heavy ion reactions, this problem does not occur, since the hadronization process takes place on a timelike oriented hypersurface that is simultaneously in the whole spatial volume. It is possible to achieve a similar situation in ICF fusion with *short* laser ignition pulses of picosecond or femtosecond lengths [17]. For this purpose, one has to regulate the energy deposition in the fusion target. The implanted nanoantennas, with an adequately designed density distribution, also help to reach this goal [8,18].

In the following section, we concentrate on the results of spectral investigations and their correlation within each other.

2. Results: Sers, Crater Sizes, Libs Spectra

The study of the effect of 40 fs laser pulses ranging in energy from 1 mJ to 30 mJ on the above-described target reveals a monotonic, almost linear dependence of crater diameters on the increasing pulse energy [19,20]. All measurements are compared at the best focusing, i.e., at maximal laser field intensity. For the optimal focusing case, down to a light beam hit diameter of about 20 µm, high enough intensities can be reached (up to 10^{17} W/cm^2). At the best focus position plus–minus 1 mm, the reflection drops dramatically from 70% down to around 10%. In this situation, the effects on the target are not disturbed by much light reflection on plasma mirrors. The craters are investigated sometimes days after the shootings, since the target material conserves them in a way similar to that of the old-fashioned gel-film detectors in nuclear experiments. Hundreds of craters have been studied by our research team using white light interferometry. As an example cf. Figure 2.

Additionally, soft spectral measurements on the treated targets were also conducted after the shootings. Most prominently, SERS (surface enhanced Raman scattering) performed by illumination with infrared lasers with low-energy (ns long) pulses was used to study molecular vibrations, which are typical in organic polymers. In particular, CH_2 and NH bonds were sought, with the aim of replacing them with CD_2 and ND groups. Certainly, a standard computer model also had to be used in the background to produce and calculate the wavelength of the corresponding lines in the SERS spectrum [21–23]. Here, we have found a wide enhancement of the intensity in the ranges characteristic for CD_2 and ND, in an integrated yield way beyond that which could have been counted for the natural deuterium ratio of $D/H \approx 1/6000$ cf. Ref. [19].

Laser-Induced Breakdown Spectroscopy (LIBS) is being employed more and more in the nuclear/fusion research field of late [24–29], due to the fact that it can sensitively detect not only heavy but also the lightest elements. It is microdestructive, can be applied remotely, and in a high-vacuum environment, it is able to provide isotopic resolution for all three hydrogen isotopes. All these features make this method appealing for laser-ignited fusion research conducted in a vacuum chamber, where the microplasma generated on the surface of the target can act as an emission source for LIBS-monitoring measurements. We are studying the emission intensities of the Balmer alpha line of protium (H) at 656.240 nm and deuterium (D) at 656.123 nm in the plasma plume. The wavelengths of these lines differ with 0.117 nanometer, but in a high-vacuum environment, the line widths are smaller than this; thus, they can be separated.

We are using LIBS to detect a possible excess D being formed from H via nuclear processes. Comparative monitoring experiments are being carried out on UDMA/TEGDMA co-polymer targets with and without gold nanorods added. For optimization and calibration purposes, we also prepare and use partially deuterized targets made from a mixture of UDMA and a fully deuterized methyl-methacrylate (MMA) monomer. By changing the mixing ratio of the monomers, a series of co-polymer targets with varying D content is fabricated.

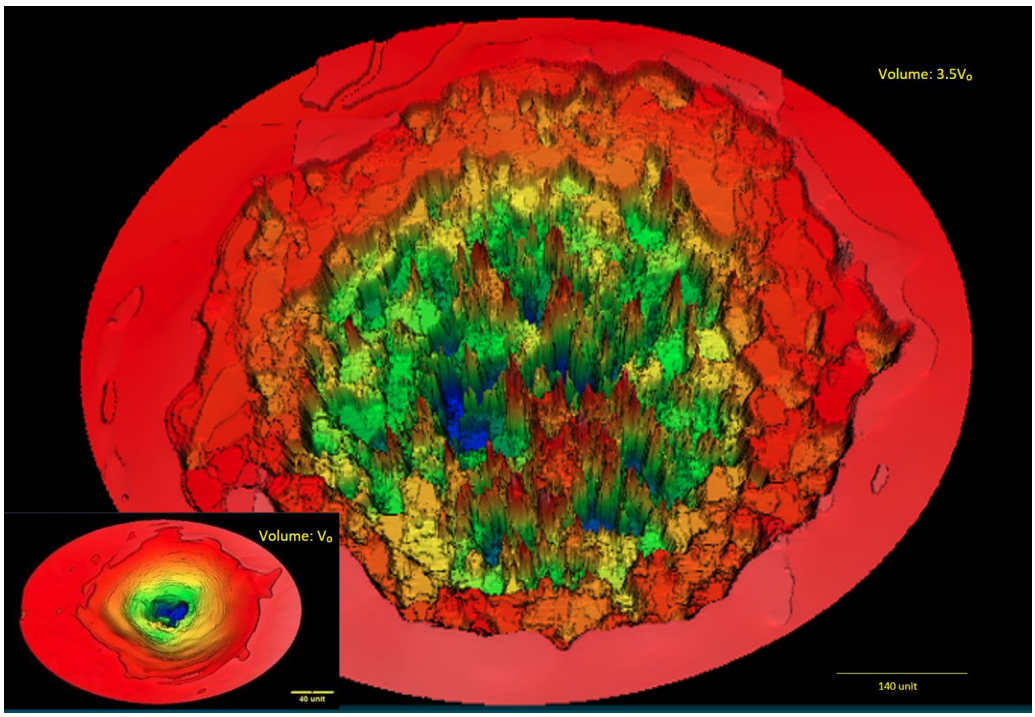

Figure 2. Comparison of crater sizes between undoped and Au-doped targets at the same laser pulse of 27 mJ energy. The pictures are made using white light interferometry and brought to their respective sizes to agree based on the real micrometer dimension of the horizontal line notations.

Complementary in situ high-resolution mass spectrometry measurements, aiming at the detection of low mass/charge ratio charged and chargeless products by controlling the ionization source, are also currently being performed during the laser irradiation of the targets. Since these measurements are still ongoing, we cannot report the final results here.

Preliminary experimental data show that the particular experimental conditions and requirements make the measurements difficult. A large number of repeated measurements are needed to obtain reliable spectra. Given the association of the laser intensity not only with the possible ignition of a few fusion reactions, but also with the LIBS emission signal generation, further increasing of the laser intensity (including better focusing of the beam and an improved contrast of the pulse with a preceding pedestal) would make this analysis even more sensitive.

3. Conclusions

In conclusion, we have presented the NAPLIFE collaboration and project with the goal of studying ultrashort laser pulse energy utilization based on their plasmonic effects in nanotechnologically manipulated polymer targets towards nuclear fusion ignition energies. The present preliminary experiments did show a drastic change in the energy absorption due to gold nanorod embedding into UDMA/TEGDMA copolymer, even at random orientation and low density. The crater sizes observed after laser shots by microscope techniques reveal a factor of 3–4-fold enhancement, while theoretical simulations of the near field enhancement (NFE) predict up to a factor of 100 in the field strength enhancement [8,20,30]. The first results from the kinetic modeling of electron and proton motion on and near to the nanoantennas are also presented [11]. Here, we find proton momenta up to the 100 MeV range; to overcome the Coulomb barrier in vacuum (without nanoparticle effects on the screening of it) one needs a factor of roughly 10 more.

Further studies are planned by varying the nanoparticle density, form and material, as well as trying different coatings, possibly delivering nuclear reactants with near-threshold resonances, such as boron and beryllium. Beyond our local activity, we plan to join experiments at facilities providing higher laser pulse energy and better contrast, e.g., at ELI-ALPS in Szeged, Hungary.

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