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Article

Nanofusion: Plasmons Help to Accelerate Protons

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Abstract

We report about laser fusion research with nanotechnology improved targets embedded in special polymers. Results of the last three years are reviewed here on laser matter interaction craters, laser infrared breakdown spectroscopy and Raman spectroscopy results, and a selected Thomson parabola image showing protons accelerated up to 300 keV energy. Such experiments are worth to be pursued further in order to reach nuclear fusion conditions that will be sufficient for net energy production.

Keywords: nuclear fusion; laser inertial fusion; proton acceleration; plasmon

1. Introduction

Energy is precious and counts as a fundamentum of all civilizations. The incoming future energy, which would be plenty for affordable price, is the nuclear fusion. It is the most economical energy per amount of fuel, for the most fashioned and tested deuteron - triton reaction less than a gramm contains the energy of one and a half kg fission material (uranium) and the same amount on energy than twenty tons of coal. It is based on the fusion of light elements, as a rule leading to several MeV energy release per reaction, in form of fusion products. Some of the possible reaction channels pose the remarkable property that no neutrons are produced, these are the aneutronic fusion reactions. Most prominently the reaction of protons with the ^{11}B boron isotope, resulting in three alpha particles with the kinetic energy in the range of 3 – 4 MeV each. Alpha particles can be stopped by a thin paper sheet, while the beta radiation of energetic electrons by metal foil. Even the gamma radiation of several hundred keV to MeV photons can be shielded by plumb walls. Only the energetic neutrons of over 10 MeV, as those stemming from the D+T reaction, cannot be stopped. They contribute to the contamination of reaction zone and its wall, therefore the idea of doping that wall with Lithium to catch as many neutrons as possible. However, for safe civil use aneutronic fusion reactions must be and will be preferred.

The approaches to fusion are numerous. The most known, i.e. "classical" ones are i) the equilibrium thermonuclear fusion under high pressure and temperature with magnetic field confinement (e.g. the international Thermonuclear Experimental Reactor, ITER) [1,2], and ii) the laser inertial fusion, compressing the fuel by synchronized laser beams (e.g. the National Ignition Facility, NIF) [3]. The latter made the first claim of producing more fusion energy than that of reaching the target in 2022 [4–6]. The private sector also shows an increasing interest in fusion research [7]. Alternative technologies of realizing or helping to ignite the fusion reactions are also numerous. Ideas of strong magnetic fields, coupling directly out the fusion energy via magnetic field [8], or helping fusion by very strong magnetic fields in cavities in order to increase the pressure in the fusion fuel [9] are just two examples of them. Our approach is using the plasmon effect, observed in low energy laser experiments, in order to concentrate the laser pulse energy in a smaller region, increasing hence the energy density there. That led us to name it Nanoplasmonic Laser Ignited Fusion Experiment, short NAPLIFE.

2. Materials and Methods

According to the above outlined strategy we have organized a unique research network within the framework of the Hungarian National Laboratories program, run by NKFIH [10], consisting of groups concentrating on four tasks: i) theoretical modelling and simulation of the laser matter interaction,

plasmon formation and electron and proton acceleration, [11–18] ii) target design and fabrication with nanoparticles [19–21], iii) laser irradiation with femtosecond laser pulses in the 1 - 30 mJ regime [22], and finally iv) spectroscopic activity for detecting the processes and their remnants in and outside of the target [23–26]. A flow diagram describing the interactions between these research tasks is drawn in Fig.1. The drawing was made by Judit Kámán [27].

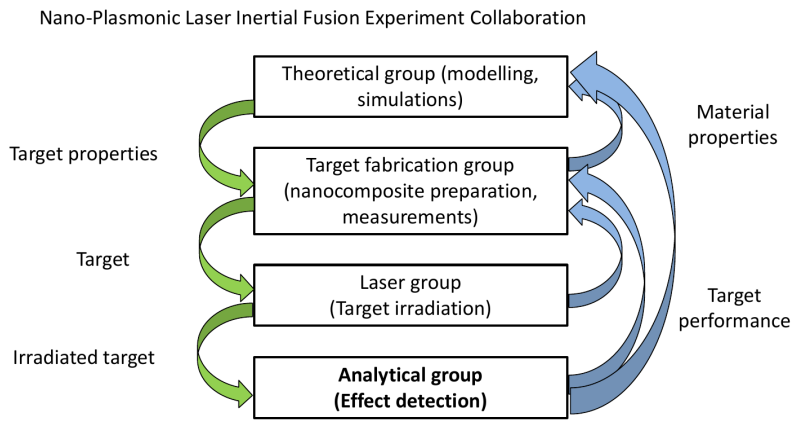


Figure 1. Relations between subgroups in the NAPLIFE project (Kámán 2023).

We use in particular gold nanorods of resonant size to the given laser beam with 795 nm wavelength, also varying the pulse duration and total energy. In this way we make an intensity scan. At the Hydra laser at the Hun-Rem Wigner Physics Research Center for Physics (Wigner RCP) we have achieved pulse intensities in the range of $5 \times 10^{15} \text{ W/cm}^2$ — $2 \times 10^{17} \text{ W/cm}^2$ and at the SYLOS laser at the ELI-ALPS, Szeged, in the range of $5 \times 10^{17} \text{ W/cm}^2$ — $5 \times 10^{18} \text{ W/cm}^2$ (cf. Fig.4). The mentioned nanorods are embedded in an UDMA-TEGDMA copolymer, also used in dentistry, because it can be made solid by UV light irradiation. Then thin films can be prepared, transported and irradiated by laser beams repeatedly. The gold nanorods in the resulted solid target film should not coagulate, this sets an upper limit on the achievable density and due to that on the generated plasmonic effect. A microscope photo of a selected target piece with randomly placed and randomly oriented Au nanorods are presented in the left part of Fig.2, due to the courtesy of Attila Bonyár [28]. The right half shows a newly fabricated target with regularly placed and parallel oriented nanorods. The importance of the nanorod orientation will be demonstrated in the next section by inspecting ion distribution and energies via the so called Thomson parabola pictures. The respective magnification factors - as it can be seen - differ. The nanorods have the same size in both cases.

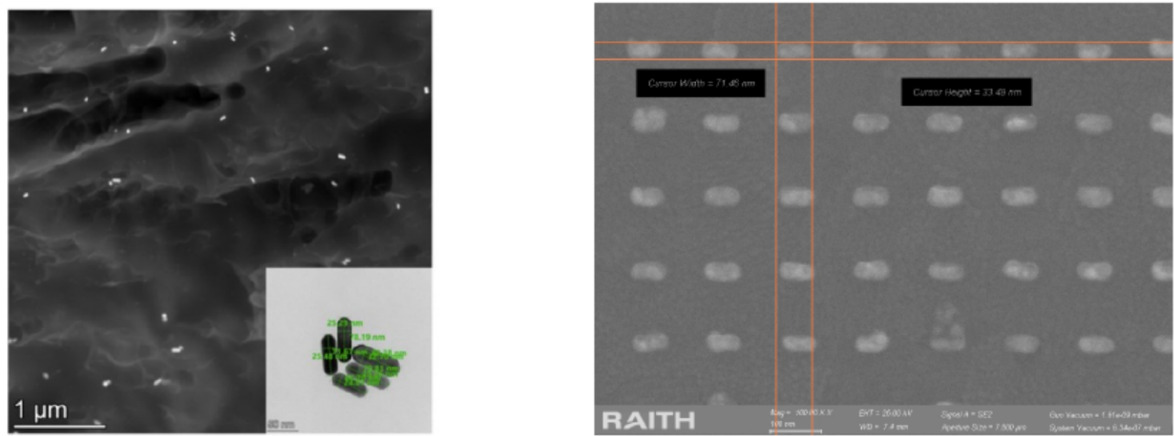


Figure 2. Photo of UDMA-TEGDMA embedded randomly placed and random oriented Au nanorods (Bonyár 2023) compared with regularly placed and oriented ones (Csernai, Márton 2024).

3. Results

Our main results are manifold. First of all we are experimenting with and have developed a purposeful target fabrication procedure by using commercially available nanorod packages and embedding them into the above mentioned particular copolymer. Spectroscopic and microscopic control is done before transport and usage. We compare gold nanoparticle embedded samples with resonant size, off-resonant size and pure polymer targets. Recently, in 2025, we have obtained nanorods embedded in an arranged lattice pattern, too [20,21].

Second we irradiate with femtosecond laser pulses, changing the pulse duration between 12 and 160 fs. The corresponding intensity is inversely proportional to these durations. Shootings have been made at the Hun-REN Wigner Research Centre for Physics (Wigner RCP) in Budapest and at the ELI-ALPS in Szeged, the latter at user campaigns of several days. Beyond the duration the pulse's total energy has been also changed, going up to 30 mJ in a single pulse. The target films were fixed in a framework and the laser focus width of 10 - 20 microns was moving in position.

Third on- and offline spectroscopy was applied in order to study the effect of each shot, comparing the resonant nanorod targets with the other types. We study the craters by shape and size, which are due to the laser-matter interaction. While the crater depth features a monotonic increase by the laser pulse intensity all over the experimental range cf. Fig.3, the gold nanorod doped samples show a significant increase in the crater volume starting around the threshold intensity of $2 \times 10^{17} \text{ W/cm}^2$ cf. Fig.4. ELI-ALPS SYLOS measurements at higher intensities rather show a saturation effect in the crater volumes. Here one should note that the contrast is much higher at the ELI-ALPS instrumentation, so later these measurements will have to be repeated with and improved contrast of the Wigner RCP's Hydra laser.

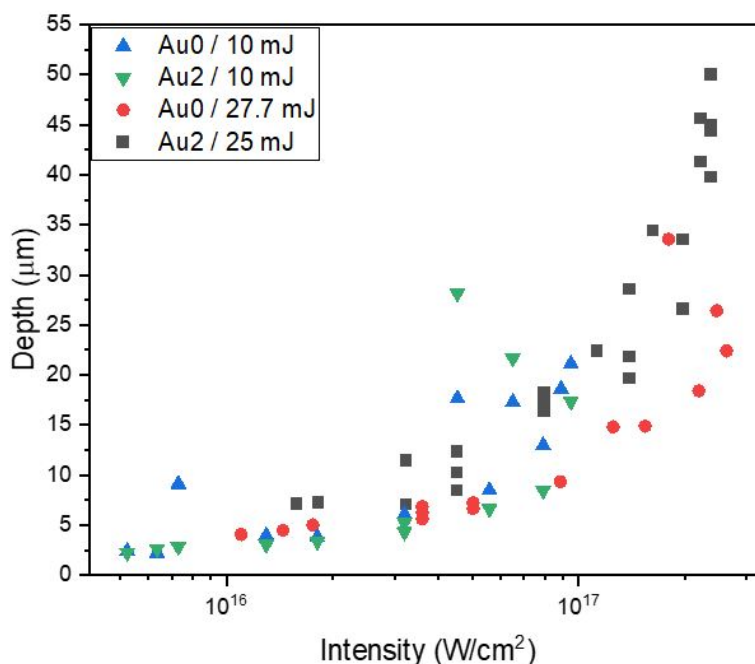


Figure 3. Damage crater depth vs laser pulse intensity (Szokol 2025).

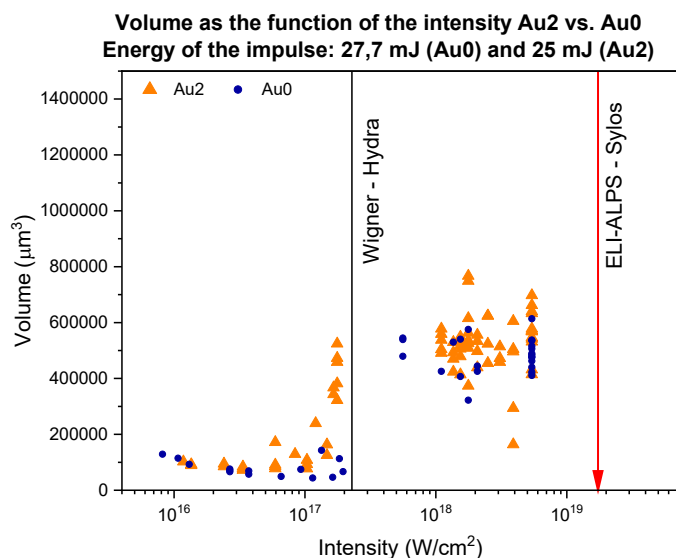


Figure 4. Damage crater volumes vs laser pulse intensity at the Wigner Hydra and at the ELI-ALPS SYLOS lasers (Szokol 2025).

The online spectroscopy was laser induced breakdown spectroscopy, LIBS, concentrating on the Balmer series of the H atom compared to that with the D atom. These should be signals of any possible deuteron production, and atomic reconstruction. For comparison artificially deuterium doped polymers were also investigated, up to 30% of D. Here our measurements are still somewhat inconclusive, although a deuterium production from a fraction of a percent up to a few per cent cannot be excluded. The natural abundance of deuterium is $1/6000 \approx 0,016\%$, so even this would be a significant finding [29]. We controlled these findings by applying mass spectroscopy after the shots from the vacuum chamber, selecting the atomic mass number range 1-4. Unfortunately only a tiny fraction of D could be detected, even from the deuterized samples, so this measurements must be technically improved in the future [23].

As important as the detection of fusion reaction products is the investigation of proton and heavier ion energies. It reveals information about chances of possible nuclear fusion reactions, not only counting the percentage of protons which overcome a threshold energy, but also gives us a leverage on selecting reaction channels. Then the future fusion technology would prefer less destructive processes than the lowest temperature and density DT reaction, according to the Lawson criterion [4]. Nowadays favorite channel is the $p + {}^{11}\text{B}$ reaction [30–33], with a near threshold resonance in the cross section at 162 MeV proton energy in the lab frame. Furthermore this reaction does not produce any neutron directly, only alpha particles in the 3–4 MeV energy range. This will improve the nuclear radiation safety situation enormously as well as the fusion device lifetime [34].

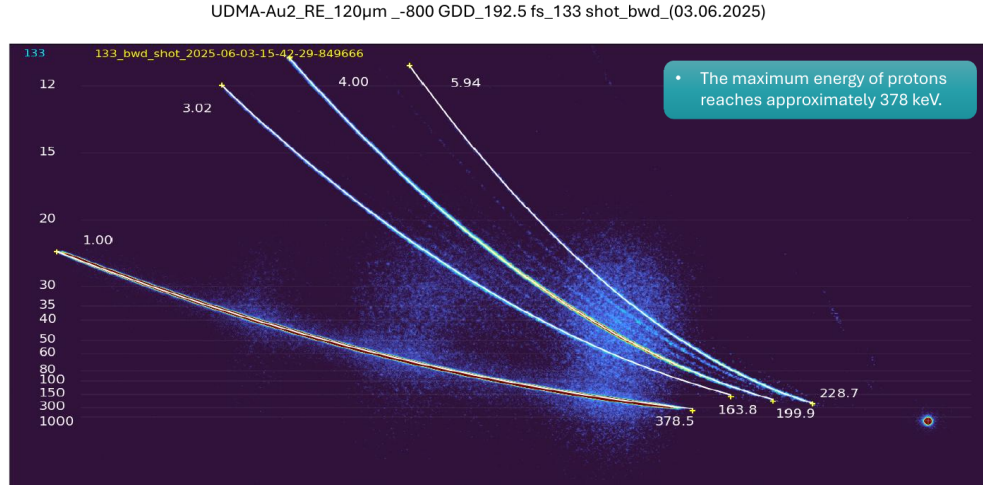


Figure 5. Thomson parabola image of high energy protons and light ions (Kedves, Aladi, Benabdelghani 2025). Maximal energies are up to several hundreds keV.

To date we are analyzing thousands of shots with respect to proton acceleration. The protons and other light ions are observed by Thomson parabola detection, where parallel electric and magnetic fields cause a transverse deviation from the original current direction. According to this impacts are detected alongside parabolic lines, each line belonging to another mass over charge (m/q) ratio. Figure 5 presents such an image, where proton energies up to 370 keV show up. The image is shown due to the courtesy of Miklós Kedves and Márk Aladi, members of NAPLIFE [33].

Let us discuss here in detail why and how these parabolic tracks emerge. Charged particles fly through electric and magnetic fields, which deflect them from their original paths. Assuming realistically that they are emitted in direction z with a velocity much higher than the components gained in the fields orthogonal to this direction, i.e. $v_z \gg v_x, v_y$, we approximate the total kinetic energy as $E \approx mv_z^2/2$. The deviations in y (electric) and x (magnetic) direction are obtained by the Lorentz force accelerating in the fly-by time:

$$y = \frac{q}{m} \mathcal{E}_y \cdot \frac{\ell_1^2}{2v_z^2} = \frac{q}{E} C_1, \quad (1)$$

and

$$x = \frac{q}{m} v_z B_y \cdot \frac{\ell_2^2}{2v_z^2} = \frac{q}{\sqrt{mE}} C_2. \quad (2)$$

Here the electric and magnetic fields are orthogonal to the original flight direction, and extend along a length of ℓ_1 and ℓ_2 respectively. The reference point, $(x = 0, y = 0)$, is without any deviation. For charged particles that corresponds to infinite kinetic energy, $E = \infty$ or to zero charge, $q = 0$.

Comparing these two equations, the x and y direction positions can be related to each other:

$$y = \frac{m}{q} \frac{C_1}{C_2^2} \cdot x^2. \quad (3)$$

To each mass to charge ratio, m/q , belongs a separate parabola. The higher the initial kinetic energy the nearer the detected point to the $(0, 0)$ patch.

Summarizing the above calculation, the ions fly through electric and magnetic fields, which deflect them from their original directions. Assuming realistically that $v_z \gg v_x, v_y$, i.e. the ion beam directed velocity dominates up to the detection, one easily sees that the accelerations in the electric field direction and orthogonal to the magnetic field direction are connected to the dominant velocity component, v_z . The deviations are calculated from the accelerations and fly-by times, the latter being inversely proportional to the dominant velocity component. Hence the deviations depend on the specific charge, q/m , and on the velocity like $1/v_z^2$ (electric) and $1/v_z$ (magnetic), respectively. That

draws a parabola for each fixed m/q value. In atomic units this value is $m/q = 1$ for protons and only for them. Some higher values can be composed from higher charged heavier ions on various ways, e.g $m/q = 4$ can be for a three times ionized carbon atom or a four times ionized oxygen atom. They make up a common track.

Furthermore the Thomson parabola images can be converted to energy distributions. Since the vertical, y deviation is simply connected with the original kinetic energy, cf. eq.1, counting the hits on a given parabola as $N(y)dy$ in a short interval $[y, y + dy]$ one concludes on the original kinetic energy distribution by using a Jacobian:

$$f(E) \sim \frac{qC_1}{E^2} N\left(\frac{qC_1}{E}\right) \quad (4)$$

Figure 6 shows the energy distribution of protons and some heavier m/q ions for a selected Thomson parabola image obtained by Márk Aladi, Miklós Kedves and Iméne Benabdelghani.

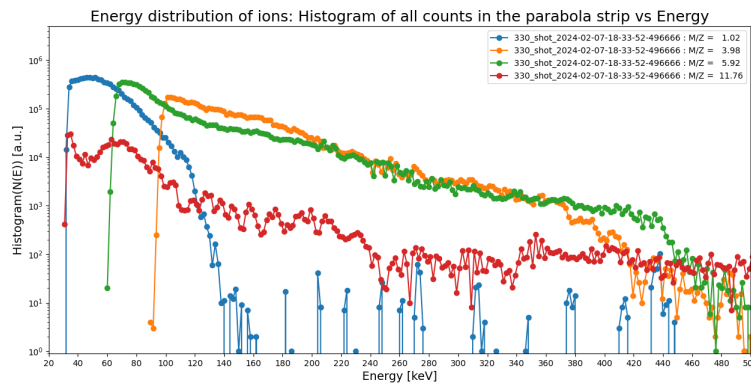


Figure 6. Proton and ion energy distributions from a Thomson parabola image (Kedves 2025).

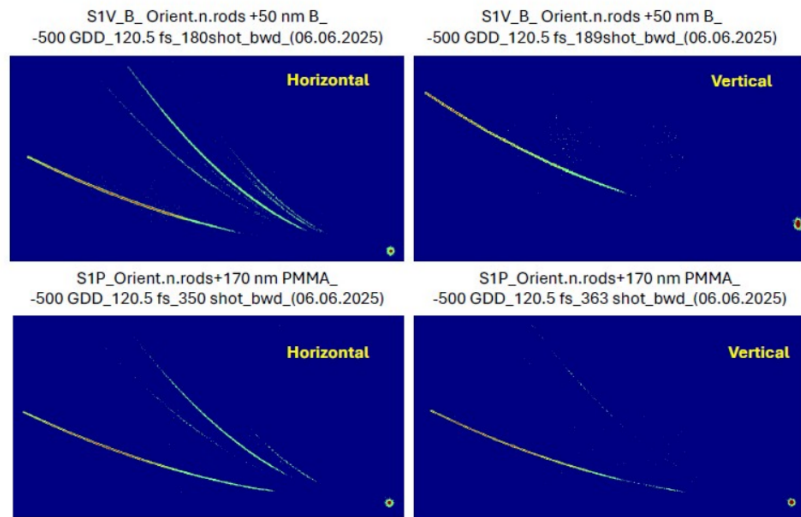


Figure 7. Laser pulse polarization dependence of the effects on oriented nanorod targets.

Finally let us note that the Thomson parabola images can also be analyzed with respect to the velocity distributions. Observe that

$$\frac{1}{v_z} = \frac{\mathcal{B}_y}{\mathcal{E}_y} \frac{\ell_2^2}{\ell_1^2} \frac{y}{x}. \quad (5)$$

Hence the distribution of $1/v_z$ values can in principle be obtained from these data. This quantity appears in the so called Gamow-Sommerfeld factor [35,36], when calculating the quantum tunneling probability under a Coulomb barrier.

4. Conclusions

We have inspected that some protons do reach energies relevant for nuclear fusion reactions. Not only in theoretical simulations, but also in experiments. The number of several hundred keV energy protons is minor in the moment, future developments will have to improve on it. On the other hand these were achieved by only 25 mJ laser pulses. This is the essence of the nanofusion concept.

In the future we plan to pursue further variations of target fabrication both with randomly and regularly arranged nanoparticles of resonant size, and as a control of non-resonant size. A variation of the fusion fuel embedded in the target or eventually used as a second sheet is also planned. In particular boronized targets should be investigated. While a number of nuclear reactions opens up above a given proton energy, we explicitly would like to concentrate on aneutronic channels, in order to save the laboratory environment and to keep our devices clean from induced radioactivity.

More details on the procedures and results outlined above shall be reported in further articles of this thematic issue, in particular in the contributed papers by Norbert Kroó, Miklós Kedves, Márk Aladi, Iméne Benabdelghani and Ágnes Nagyné Szokol.

We do believe that this research is part of efforts establishing a perspective for the civilian, non-invasive and mobile use of nuclear fusion in the future.

Author Contributions: This single author contribution summarizes and relies on the work of several researchers involved in the NAPLIFE project (<https://cernai.no/naplife>), T.S. Biró being the professional leader of it.

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Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

NAPLIFE Nanoplasmonic Laser Ignited Fusion Experiment

NKFIH Hungarian National Office for Research, Development and Innovation

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