Nanoplasmonic laser fusion

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Zimányi School,
Budapest, 5-9 Dec. 2022.

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How to remedy the problems of present Laser Fusion trials of NIF@Livermore & OMEGA@Rochester

Two ideas are combined by L.P. Csernai, N. Kroo, I. Papp:

[Patent # P1700278/3] (2017)

Problems:

- Rayleigh-Taylor (RT) instability
- Slow propagation of burning from central hot-spot

Solution:

- **Heat the system uniformly by radiation with RFD (1)**
- **Achieve uniform heating by Nano-Technology (2)**

[L.P. Csernai, N. Kroo, I. Papp, *Laser and Particle Beams*, LPB, 36(2), (2018) 171-178. .
https://doi.org/10.1017/S0263034618000149]

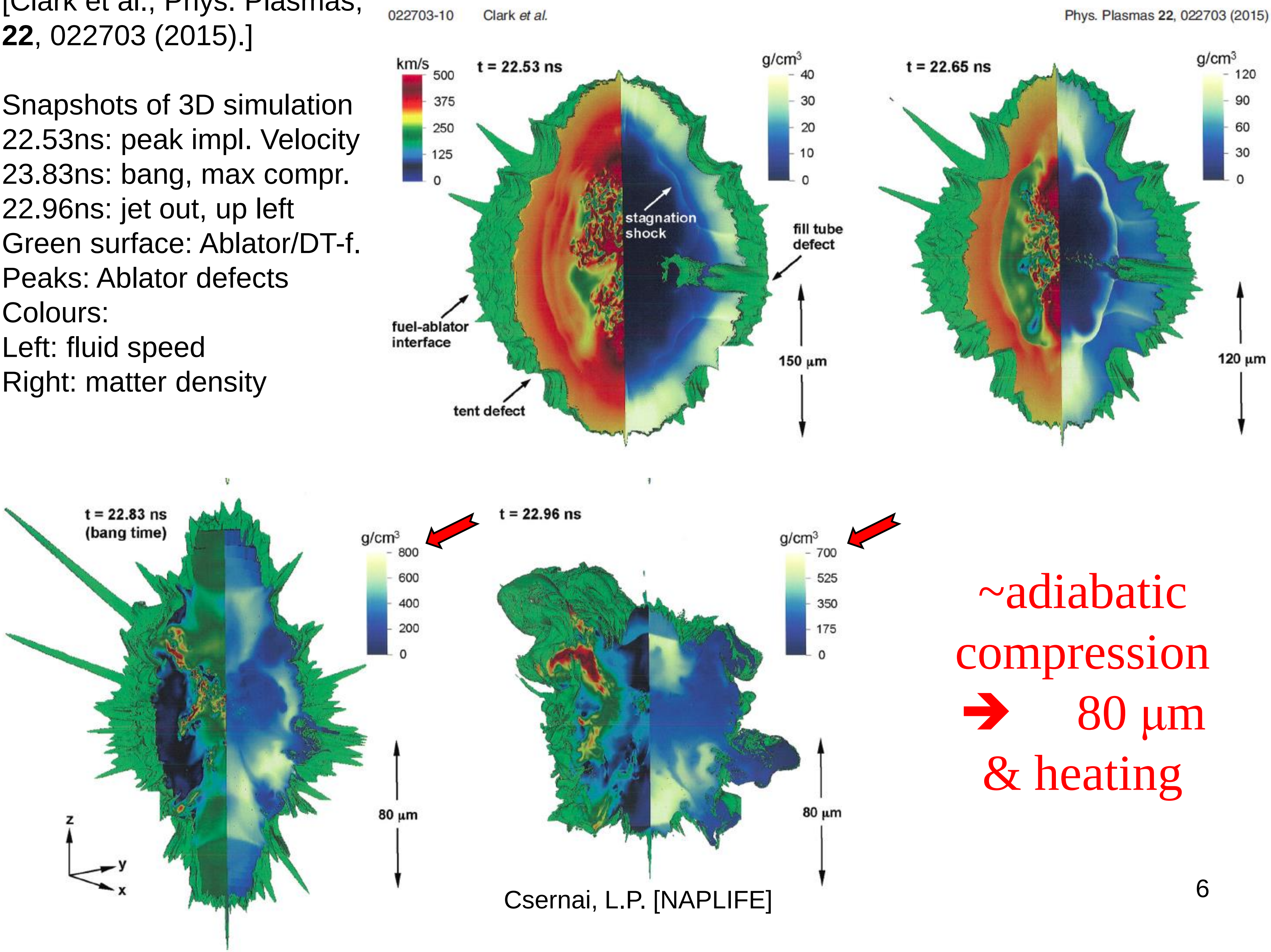
But let us go back in history →

Kőszeg, September 14**, 2019** - Int. Workshop on Collectivity
First meeting on the NAPLIFE project (12 people)

Rayleigh-Taylor Instability

[Clark et al., Phys. Plasmas, **22**, 022703 (2015).]

Snapshots of 3D simulation
22.53ns: peak impl. Velocity
23.83ns: bang, max compr.
22.96ns: jet out, up left
Green surface: Ablator/DT-f.
Peaks: Ablator defects
Colours:
Left: fluid speed
Right: matter density

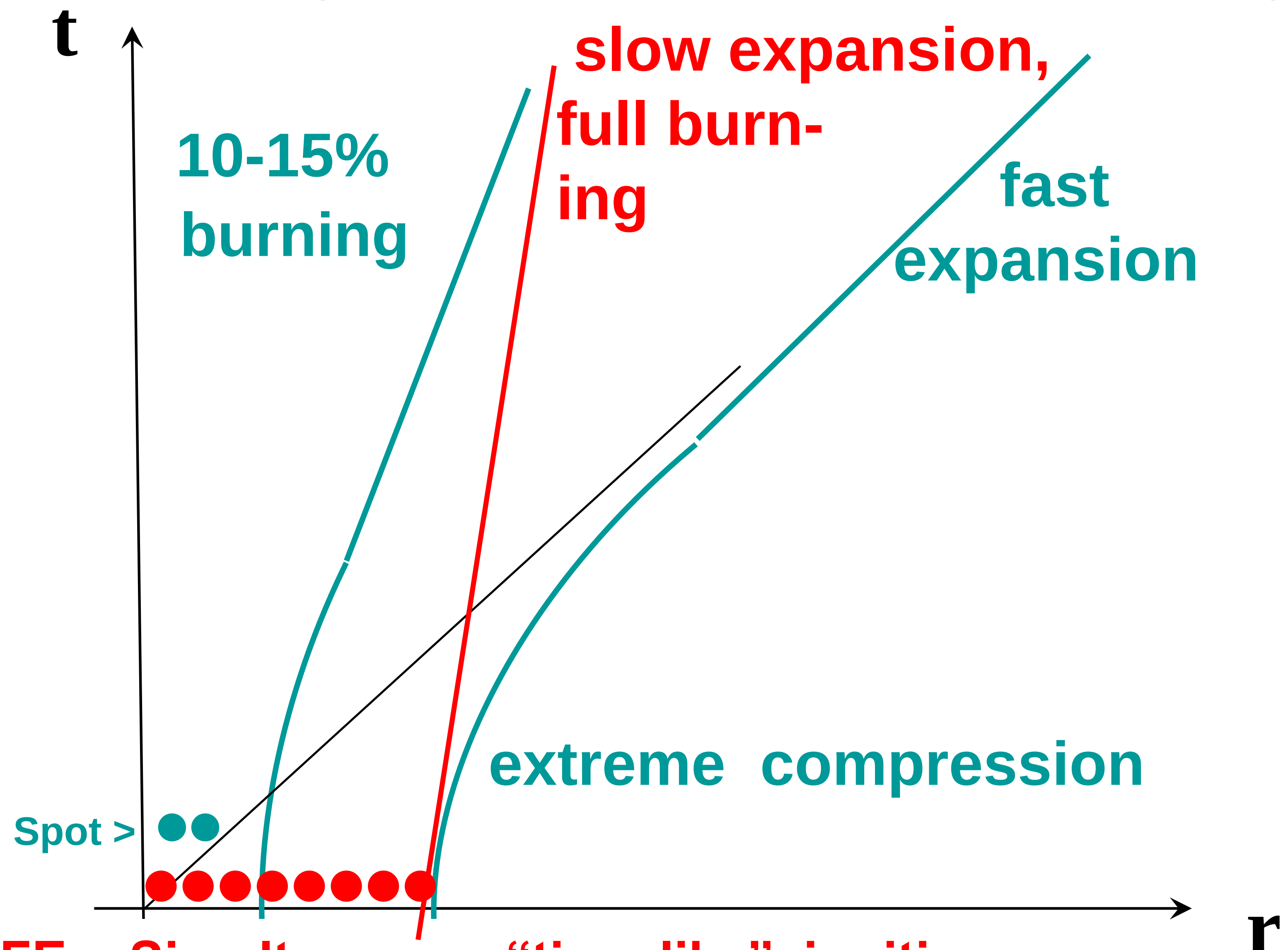


~adiabatic compression ➔ 80 μm & heating

Csernai, L.P. [NAPLIFE]

Slow propagation of burning

Spot ignition, fast expansion - slow burning



NAPLIFE: Simultaneous, “time-like” ignition

Csernai, L.P. [NAPLIFE]

How can we prevent it
Idea - #1

[A.H. Taub (1948)]

PHYSICAL REVIEW VOLUME 74, NUMBER 3 AUGUST 1, 1948

Relativistic Rankine-Hugoniot Equations

A. H. TAUB
*University of Illinois, Urbana, Illinois and Institute for Advanced Study, Princeton University, Princeton, New Jersey**

Next we suppose that the three-dimensional volume is a shell of thickness ϵ enclosing a surface of discontinuity $\sum$ whose three-dimensional normal vector is Λ_i. If we choose our coordinate system so that the discontinuity is at rest, then since

$$\lambda_\alpha \lambda^\alpha = 1, \quad \sum_{i=1}^{3} \Lambda_i^2 = 1,$$

we have

$$\lambda_i = \Lambda_i \quad \text{and} \quad \lambda_4 = 0.$$

Hence Eqs. (7.1) and (7.2) become, as ϵ goes to zero,

$$[\rho^0 u^i \Lambda_i] = 0, \tag{7.3}$$

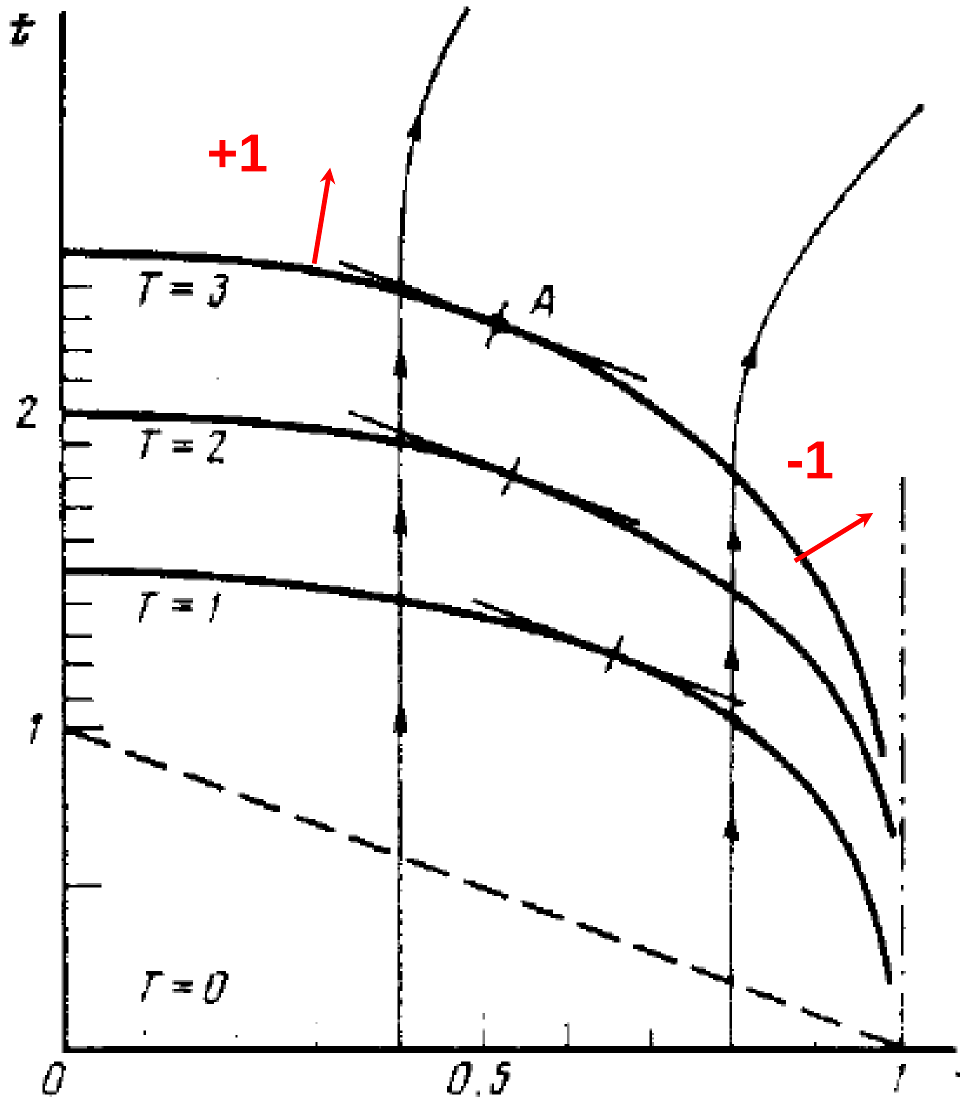
$$[T^{\alpha i} \Lambda_i] = 0, \tag{7.4}$$

where

$$[f] = f_+ - f_-$$

Taub assumed that (physically) only slow space-like shocks or discontinuities may occur (with space-like normal, λ_4=0).

This was then taken as standard, since then (e.g. LL 1954-)



[L. P. Csernai, Zh. Eksp. Teor. Fiz. 92, 379-386 (**1987**) & Sov. Phys. JETP 65, 216-220 (1987)]

corrected the work of [**A. Taub**, Phys. Rev. 74, 328 (**1948**)]

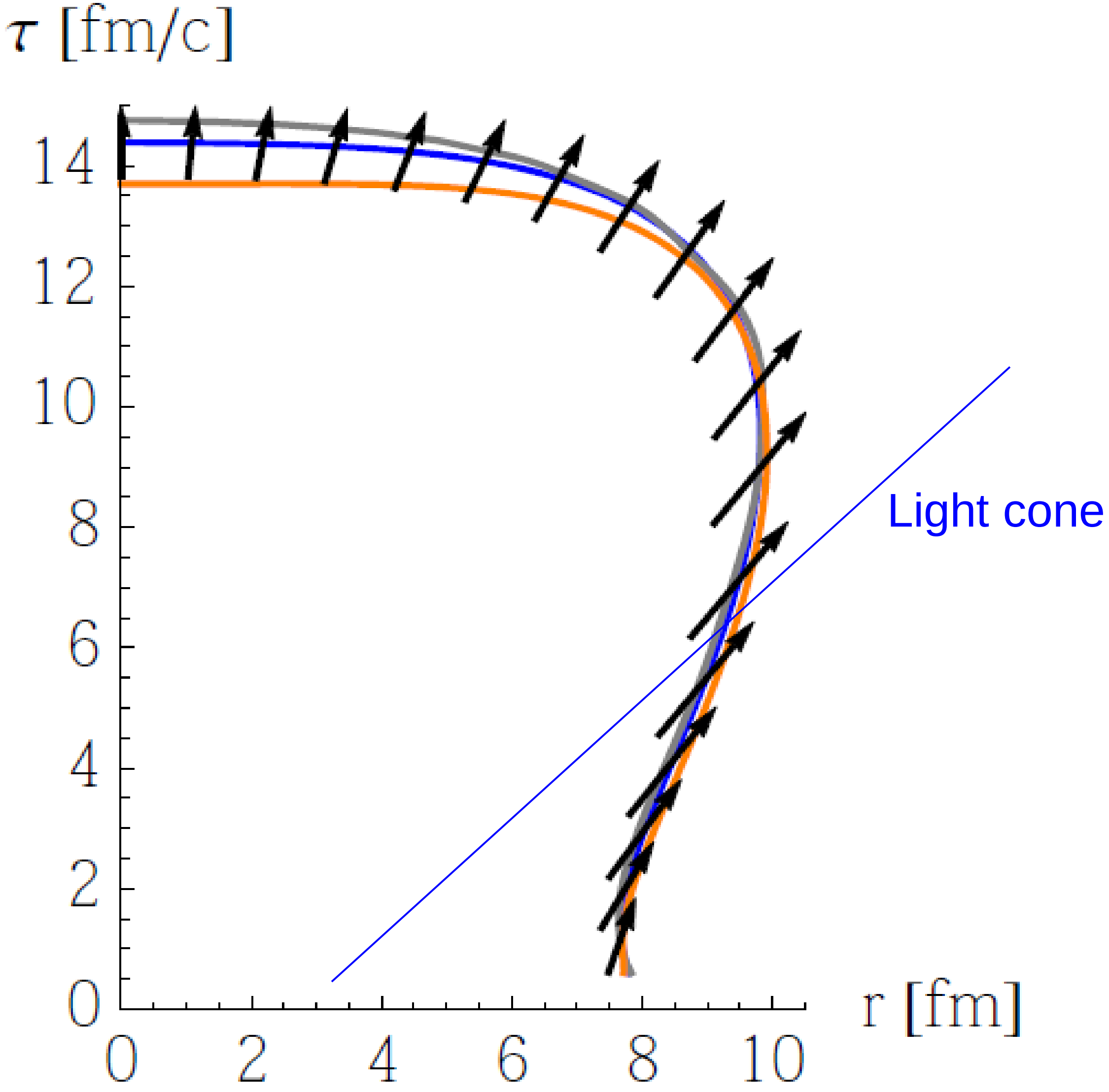
$$\lambda_\alpha \lambda^\alpha = \pm 1$$

Л. П. Чернаи

ДЕТОНАЦИЯ НА ВРЕМЕНИПОДОБНОМ ФРОНТЕ ДЛЯ РЕЛЯТИВИСТСКИХ СИСТЕМ

Журнал экспериментальной и теоретической физики

1987



@ CERN in High energy heavy ion collisions

[Stefan Floerchinger, and Urs Achim Wiedemann, Phys. Rev. C 89, 034914 (2014)]

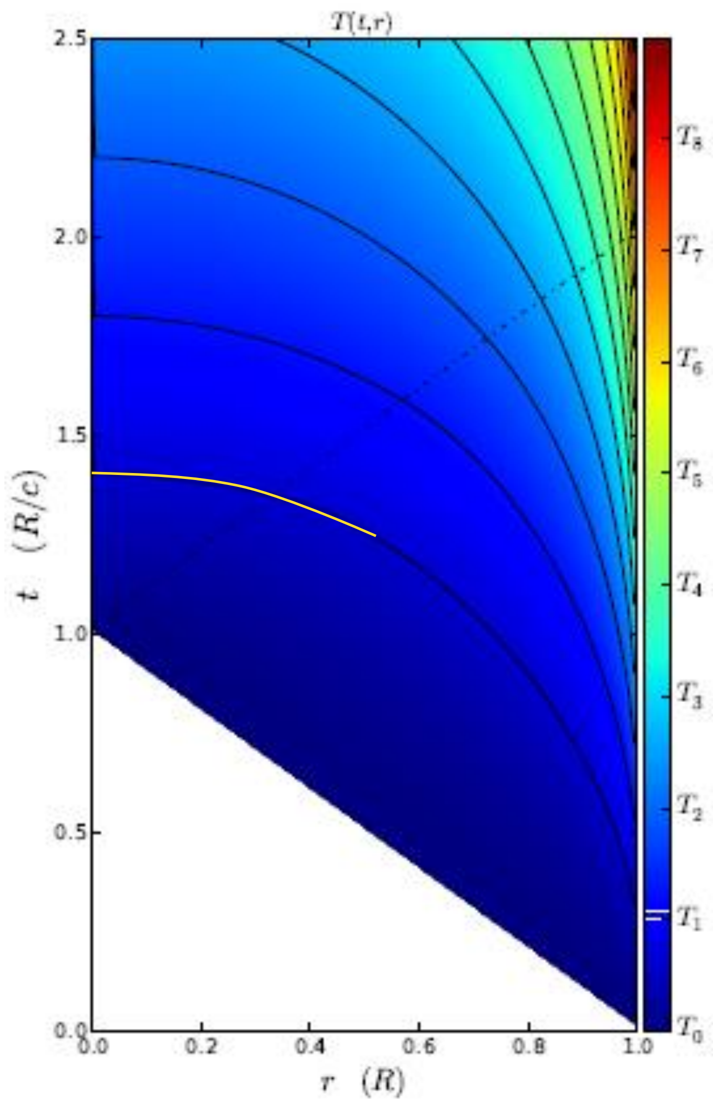
Fusion reaction:

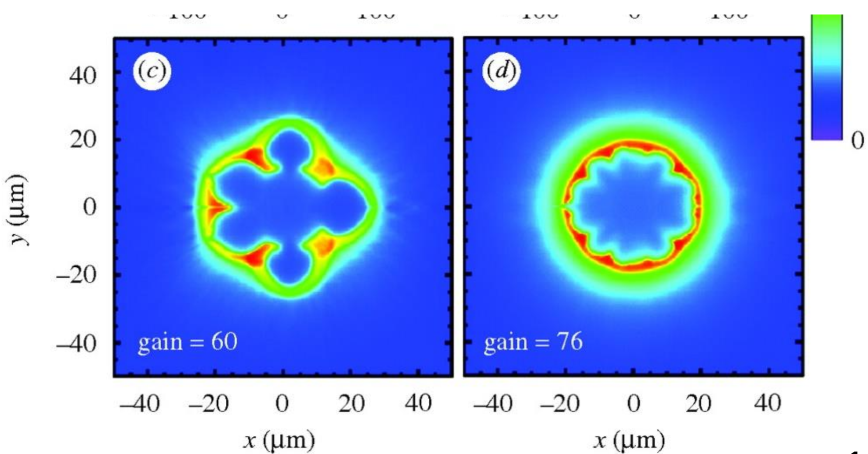
D + T ➔ n(14.1 MeV) + 4He (3.5 MeV)

Constant absorptivity,
Spherical irradiation
Ignition temperature = T1 ➔

Simultaneous, volume ignition up to 0.5 R (i.e. **12%** of the volume).

Not too good, but better than:





[L.P. Csernai & D.D. Strottman,
Laser and Particle Beams 33, 279 (2015).]

How can we realize it
Idea - #2

LPB, 36(2), (2018) 171-178.

Laser and Particle Beams

cambridge.org/lpb

Radiation dominated implosion with nano-plasmonics

L.P. Csernai[1], N. Kroo[2,3] and I. Papp[4]

[1]Department of Physics and Technology, University of Bergen, Bergen, Norway; [2]Hungarian Academy of Sciences, Budapest, Hungary; [3]Wigner Research Centre for Physics, Budapest, Hungary and [4]Department of Physics, Babes-Bolyai University, Cluj, Romania

Research Article

Cite this article: Csernai LP, Kroo N, Papp I (2018). Radiation dominated implosion with nano-plasmonics. *Laser and Particle Beams* 1–8. https://doi.org/10.1017/S0263034618000149

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Accepted: 3 April 2018

Key words:
Inertial confinement fusion; nano-shells; relativistic fluid dynamics; time-like detonation

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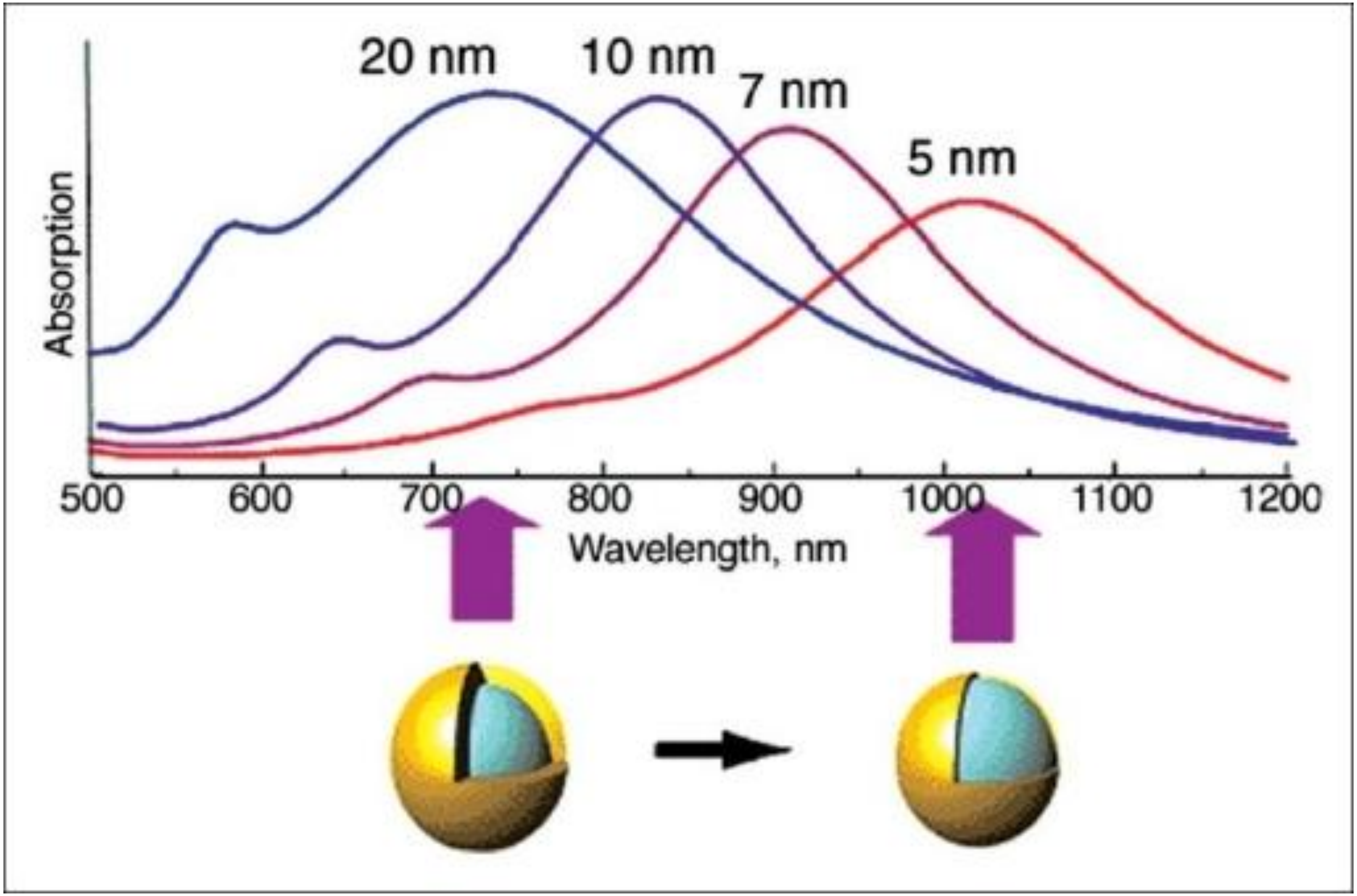
Abstract

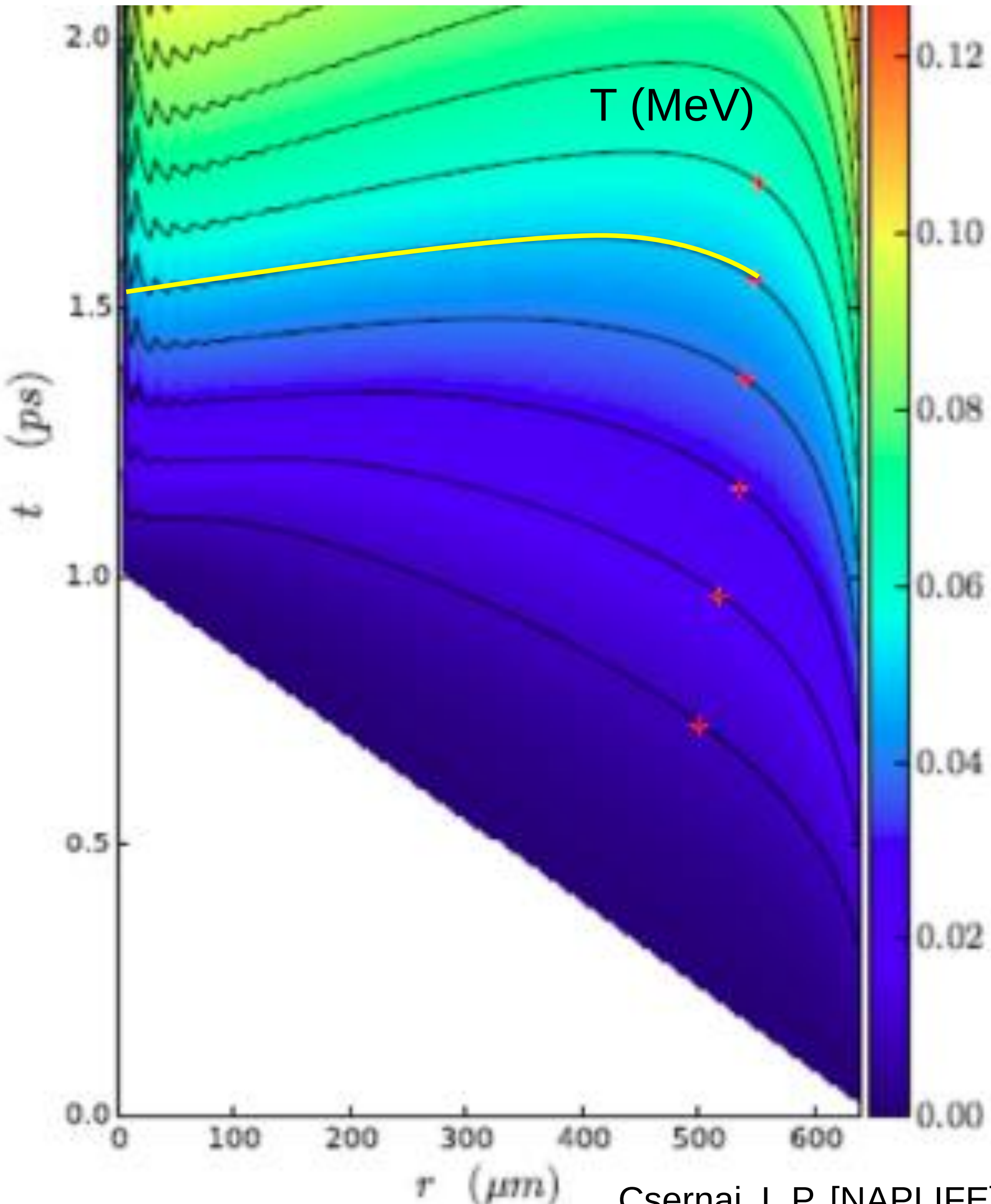
Inertial Confinement Fusion is a promising option to provide massive, clean, and affordable energy for mankind in the future. The present status of research and development is hindered by hydrodynamical instabilities occurring at the intense compression of the target fuel by energetic laser beams. A recent patent combines advances in two fields: Detonations in relativistic fluid dynamics (RFD) and radiative energy deposition by plasmonic nano-shells. The initial compression of the target pellet can be decreased, not to reach the Rayleigh–Taylor or other instabilities, and rapid volume ignition can be achieved by a final and more energetic laser pulse, which can be as short as the penetration time of the light across the pellet. The reflectivity of the target can be made negligible as in the present direct drive and indirect drive experiments, and the absorptivity can be increased by one or two orders of magnitude by plasmonic nano-shells embedded in the target fuel. Thus, higher ignition temperature and radiation dominated dynamics can be achieved with the limited initial compression. Here, we propose that a short final light pulse can heat the target so that most of the interior will reach the ignition temperature simultaneously based on the results of RFD. This makes the development of any kind of instability impossible, which would prevent complete ignition of the target.

… and 35th Hirschegg Int. Workshop on High Energy Density Physics, Jan. 25-30, **2015**

Golden Nano-Shells – Resonant Light Absorption



Csernai, L.P. [NAPLIFE]



Csernai, L.P. [NAPLIFE]

The absorption coefficient is **linearly** changing with the radius: In the center,

r = 0, α_K = 30 cm^{-1} while at the outside

edge α_K = 8 cm^{-1}.

The temperature is measured in units of T_1 = 272 keV, and T_n = n T_1.

Simultaneous, volume ignition is up to 0.9 R, so **73% of the fuel target!**

How can we realize it simpler and with less expense

Thick coin like flat target & Two beams only

Thickness of the target is: h ...

h depends on pulse energy, ignition energy, target mass, …

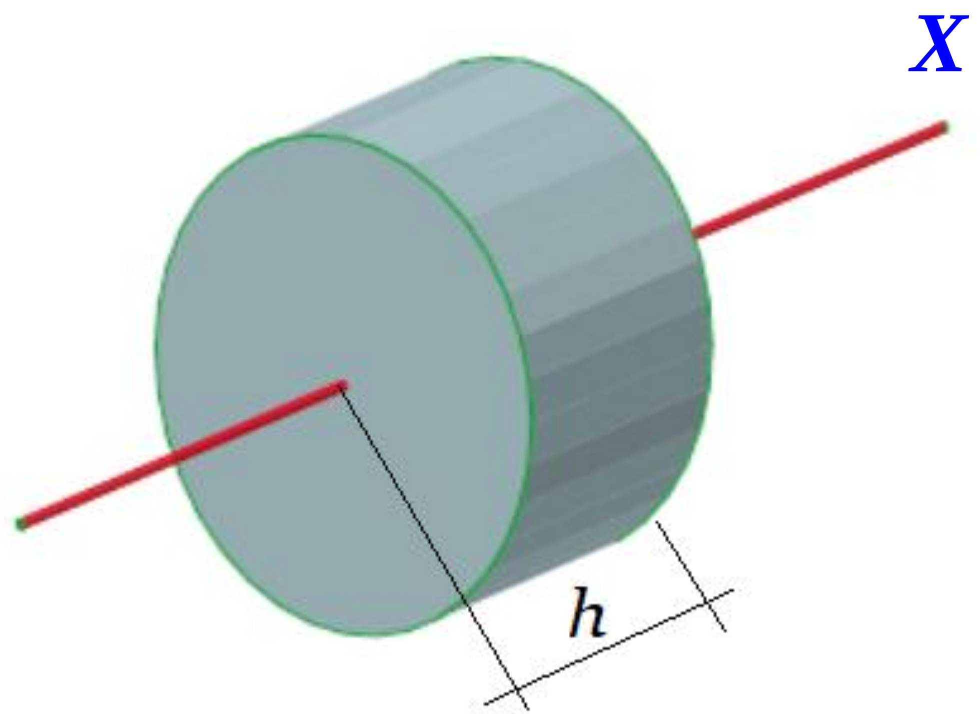
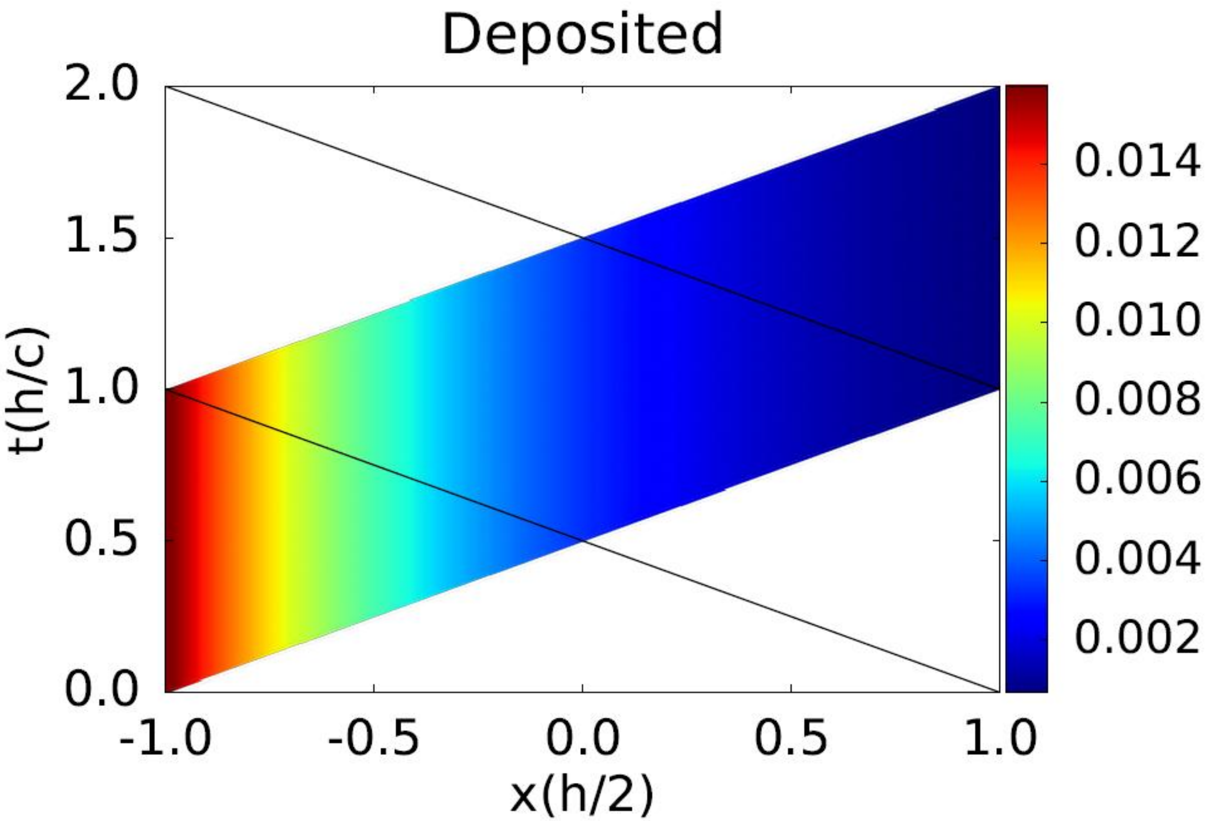


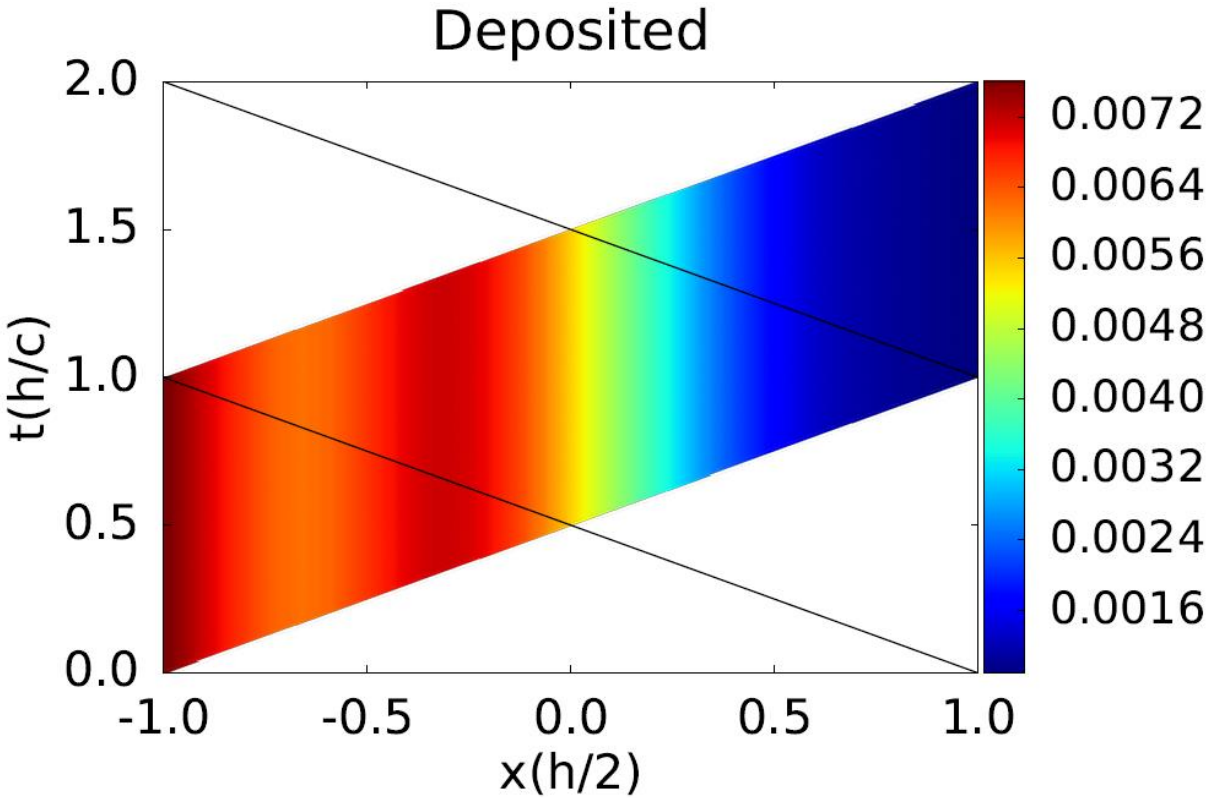
Figure 1: (color online) The target still should be compact to minimize the surface effects. The irradiation is performed along the x−axis from both sides towards the target. The laser beam should be uniform hitting the whole face of the coin shaped target.

[Csernai et al., (**NAPLIFE** Collaboration) *Phys. of Wave Phenomena,* **28** (3), 187-199 **(2020).**]



Without nano antennas

The deposited energy from laser irradiation from one side only. The absorption is constant, this leads to an exponentially decreasing energy deposition, and only a negligibly small energy reaches the opposite end of the target.



With nano antennas

The absorptivity is increased towards the center, due to the implanted nano antennas.

The deposited energy from laser irradiation from one side only. The absorption is modified by nano antennas so that the absorptivity is increasing towards the middle, so that the deposited energy is constant up to the middle. Then the absorptivity is decreasing, but hardly any energy is left in the irradiation front. Thus again only a negligibly small energy reaches the opposite end of the target.

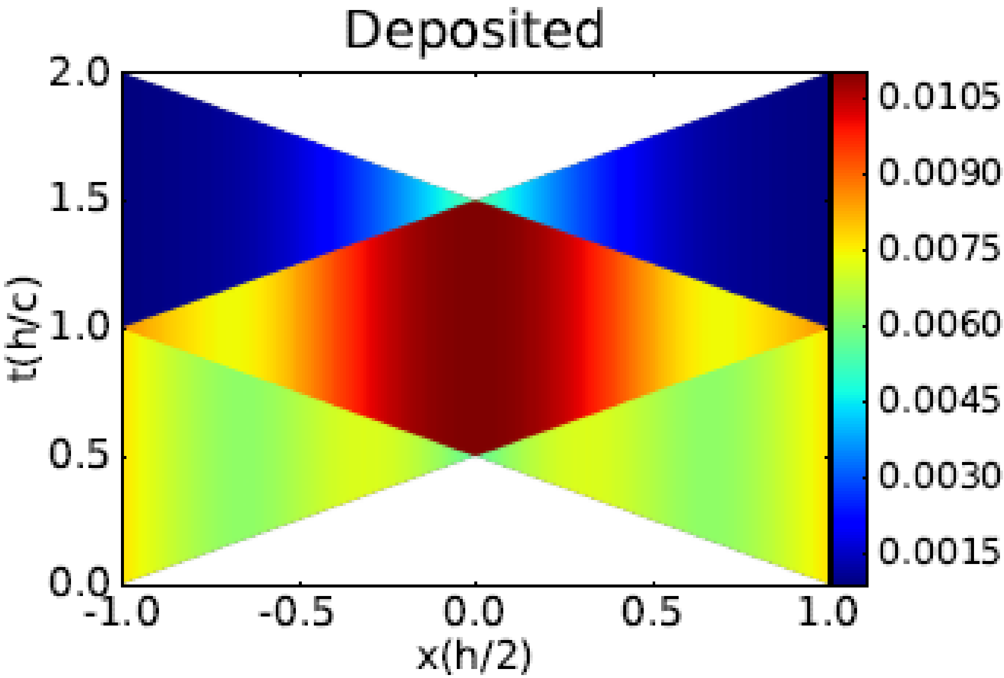


Figure 2: (color online) Deposited energy per unit time in the space-time across the depth, h, of the flat target. The time is measured in units of (h/c), where c is the speed of light in the material of the target. The irradiation lasts for a period of $\Delta t = h/c$ the time needed to cross the target. The irradiated energy during this time period is Q from one side, so it is $2Q$ from both sides together.
The color code indicates the deposited energy per unit time and unit cross section (a.u.). The deposited length is $\Delta x = c\Delta t$. Note! The absorptivity in this case $\alpha\kappa \neq$ const. For more details please see Appendix B.

With nano antennas

Irradiation from both sides.

Ignition energy is: Q_i/m
e.g. for DT target: $Q_i/m = 27$ kJ/g
➔ if we have $Q = 100$ J, then we can have a target mass:
$m_{DT} = Q / Q_i$ g = 3.703 mg.

Then with m_{DT} and ρ_{DT} given we get the DT-target's volume, V_{DT} and $h_{DT} = 2.67$ mm .

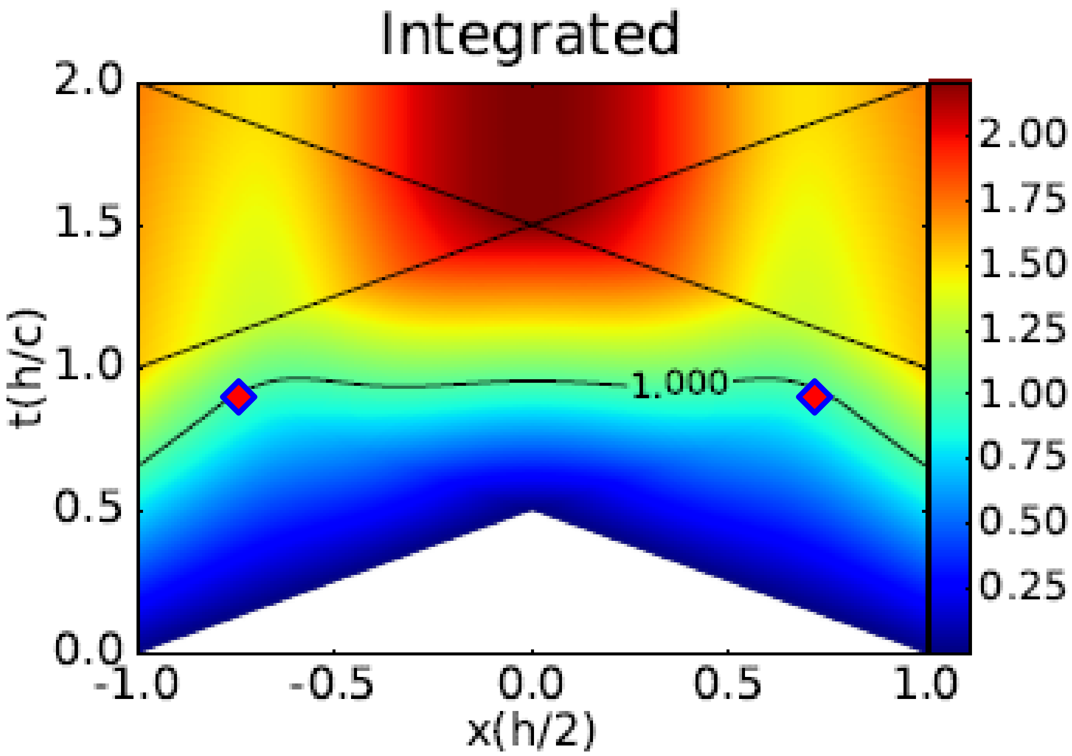


Figure 3: (color online) Integrated energy up to a given time in the space-time across the depth, h, of the flat target. The color code indicates the temperature, T, reached in a given space-time point, in units of the critical temperature, (T_c). The contour line $T = 1$, indicates the critical temperature, T_c where the phase transition or the ignition in the target is reached. This contour line is almost at a constant time, indicating simultaneous whole volume transition or ignition. The irradiated energy, Q is chosen so that, $1Q$ irradiation will achieve the critical temperature.

Csernai, L.P. [NAPLIFE]

With nano antennas

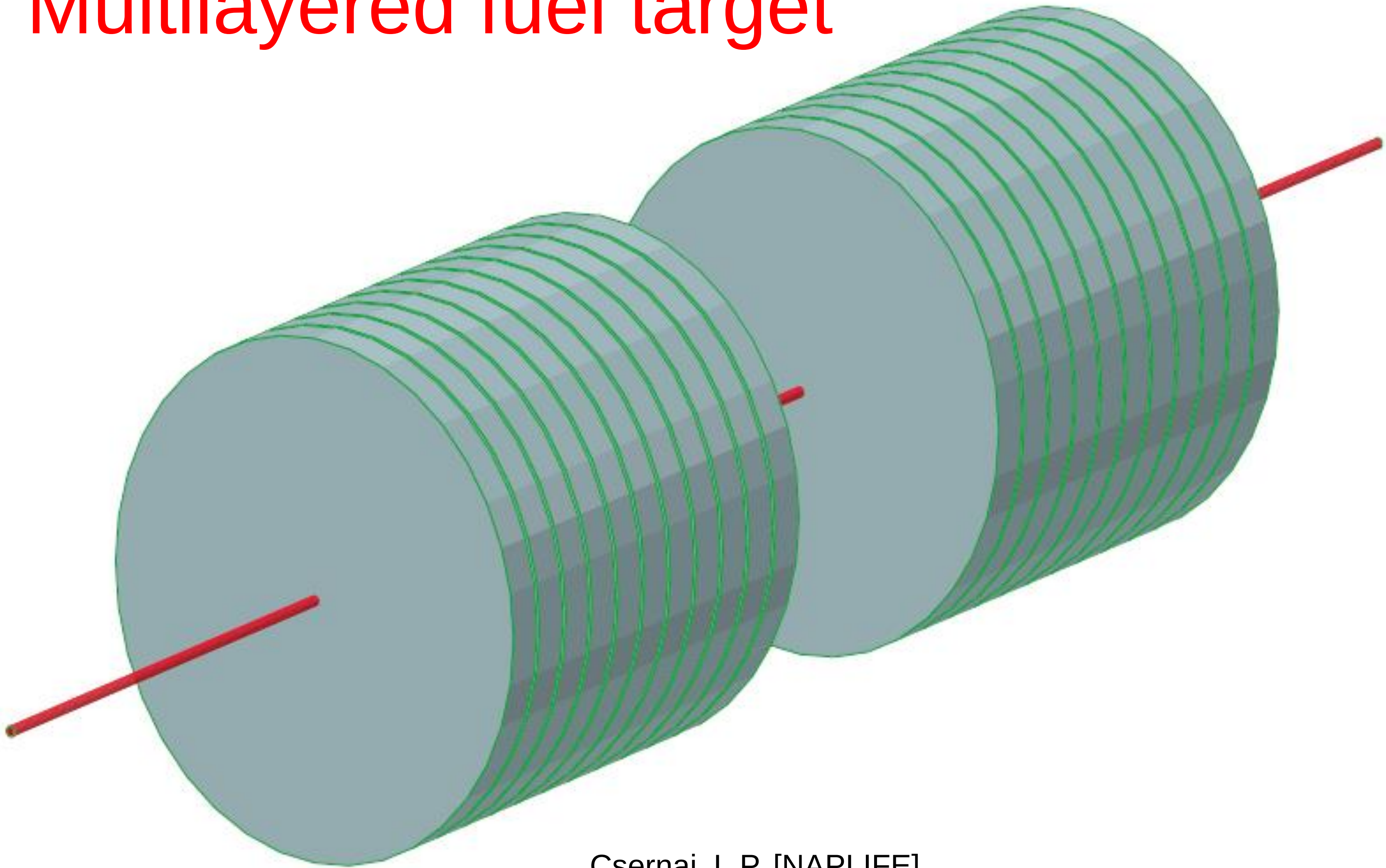
Ignition is reached at contour line $Q = 1$.

[Csernai et al., (**NAPLIFE** Collaboration) *Phys. of Wave Phenomena,* **28** (3), 187-199 **(2020).**]

Simultaneous ignition in the whole target volume ➔ Short Pulse: ELI - ALPS

New theory since July 14, 2021

Multilayered fuel target



Laser Wake Field Collider

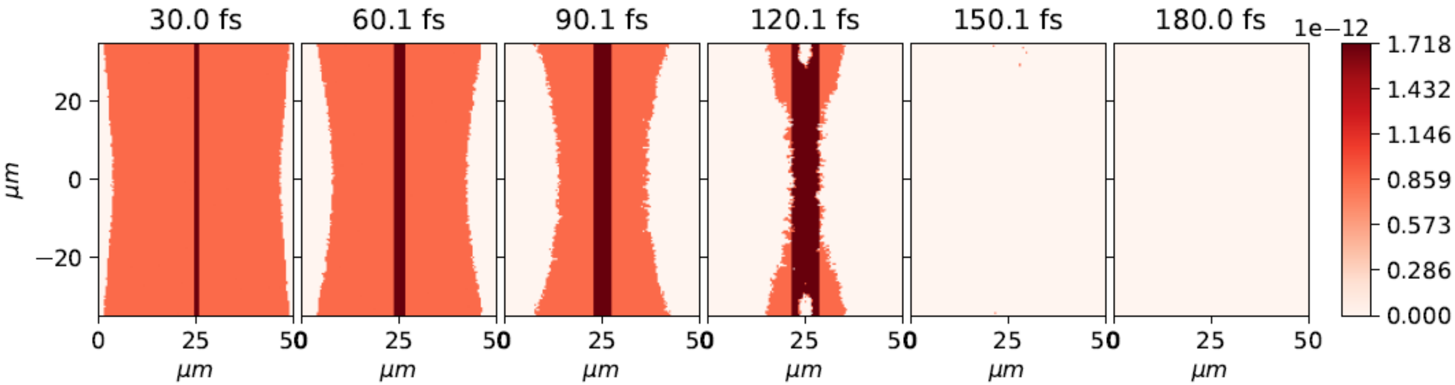
∃ Pre-compression/acceleration, before ignition

Ion (e.g. p) Energy $E_p \approx 50$ MeV (or more)

Initial beam densities assumed: $n_H \approx \gamma\, n_0 = 2{\cdot}10^{-19}/cm^3$ and $2{\cdot}10^{-21}/cm^3$

$\approx n_{liquid\text{-}H}$, $\approx n_{NIF}/1000$ (/wo precompression!)

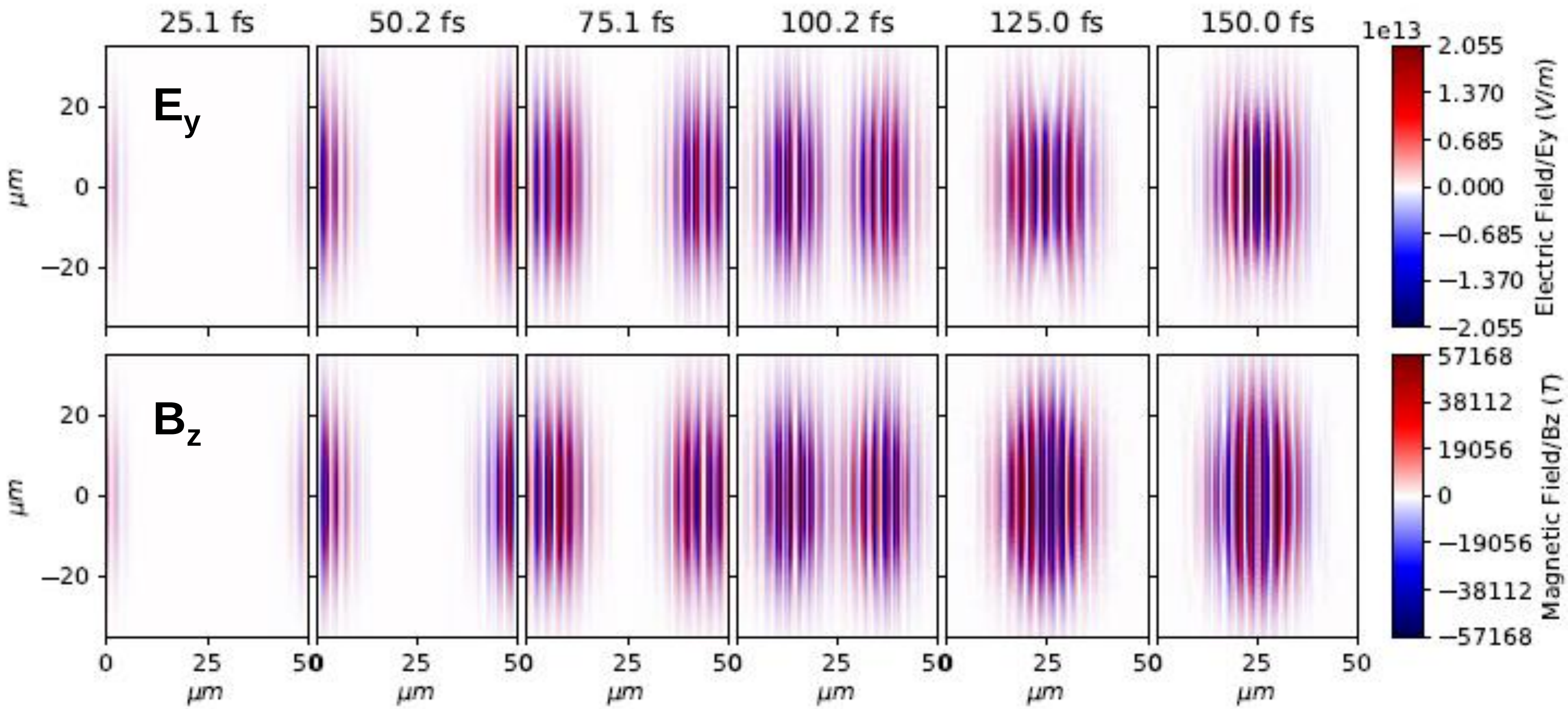
Target density after interpenetration: $n_t \geq 2\, n_H$



The ionization of the H atoms at ignition in a Laser Wake Field (LWF) wave due to the irradiation from both the +/- *x* directions

[Papp, I., et al., NAPLIFE, Phys. Lett. A 396, 12724 (2021).]

Laser Wake Field Collider



The electric field, E_y (top) and magnetic field, B_z (bottom) in a Laser Wake Field (LWF) wave formed by irradiation from the $\pm$x- direction. The rest number density of the H target is $n_H = 2.13 \; 10^{25}/m^3 = 2.13 \; 10^{19}/cm^3$. The laser beam wavelength is $\lambda = 1\mu m$. The LWF wavelength is about 20 λ. **Pulse energy is 19.6 J**.

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PRX ENERGY

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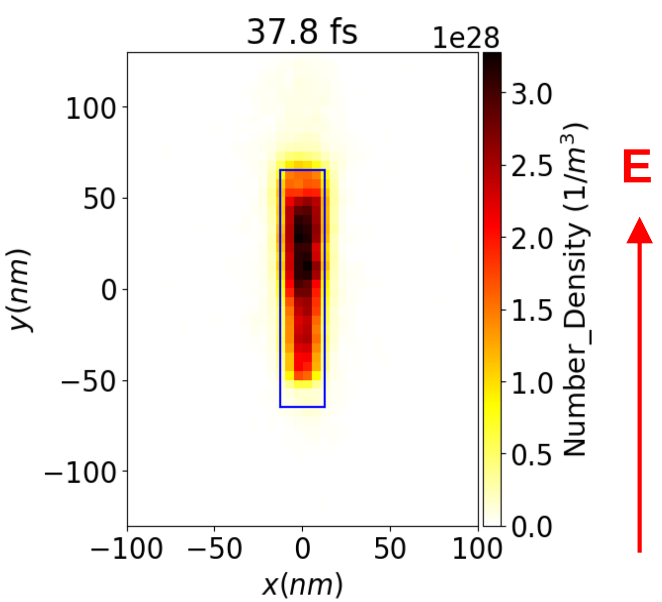
New theory since July 14, 2021

Kinetic Model Evaluation of the Resilience of Plasmonic Nanoantennas for Laser-Induced Fusion

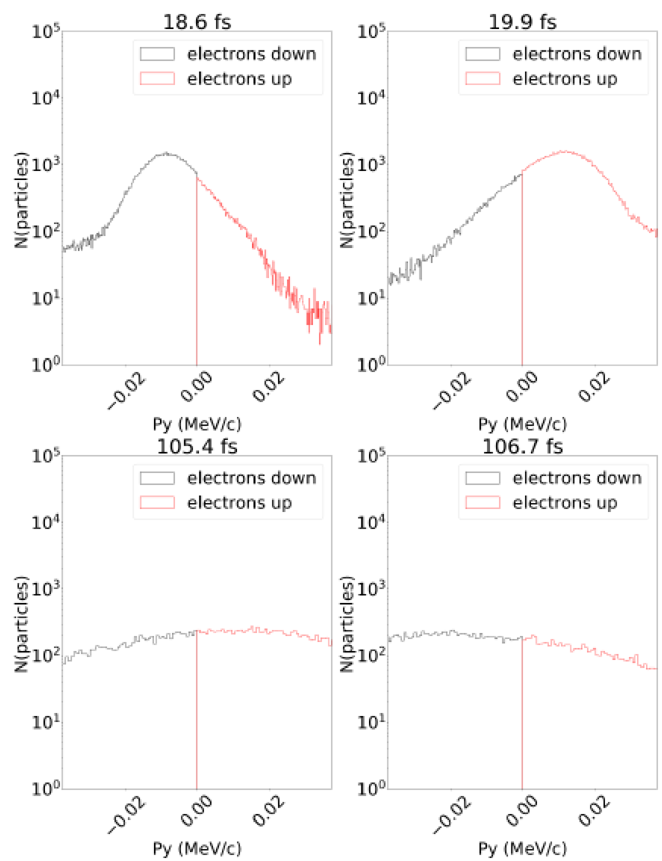
István Papp, Larissa Bravina, Mária Csete, Archana Kumari, Igor N. Mishustin, Dénes Molnár, Anton Motornenko, Péter Rácz, Leonid M. Satarov, Horst Stöcker, Daniel D. Strottman, András Szenes, Dávid Vass, Tamás S. Biró, László P. Csernai, and Norbert Kroó (NAPLIFE Collaboration)

PRX Energy 1, 023001 – Published 7 July 2022

Nanorod antenna proprties



ρ_e for 25x130 nm antennas, in vacuum. EPOCH

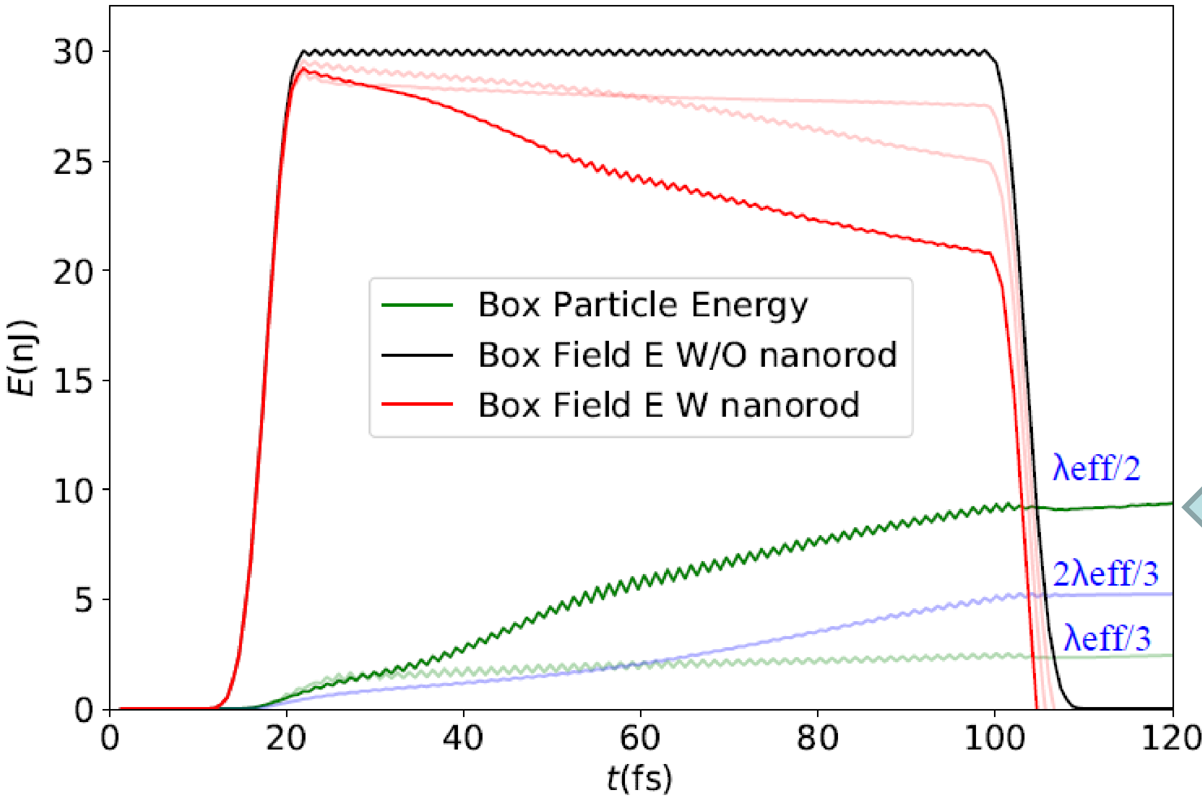


25x130 nm antennas, resonant for λ=795 nm

Laser Intensity:
$I = 4{\cdot}10^{15}\,W/cm^2$

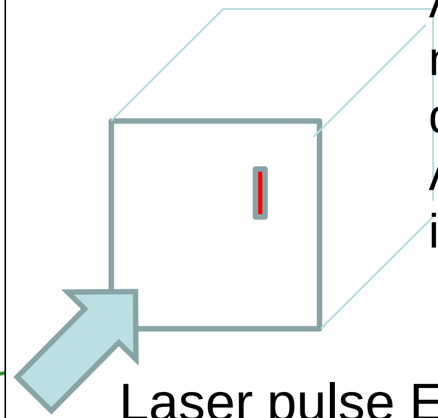
[I. Papp's talk of ICNFP2022]

Resilience of Nanorod Antenna with EPOCH/PIC



Calculation Box (CB): 530x530x795 nm

λ = 795 nm



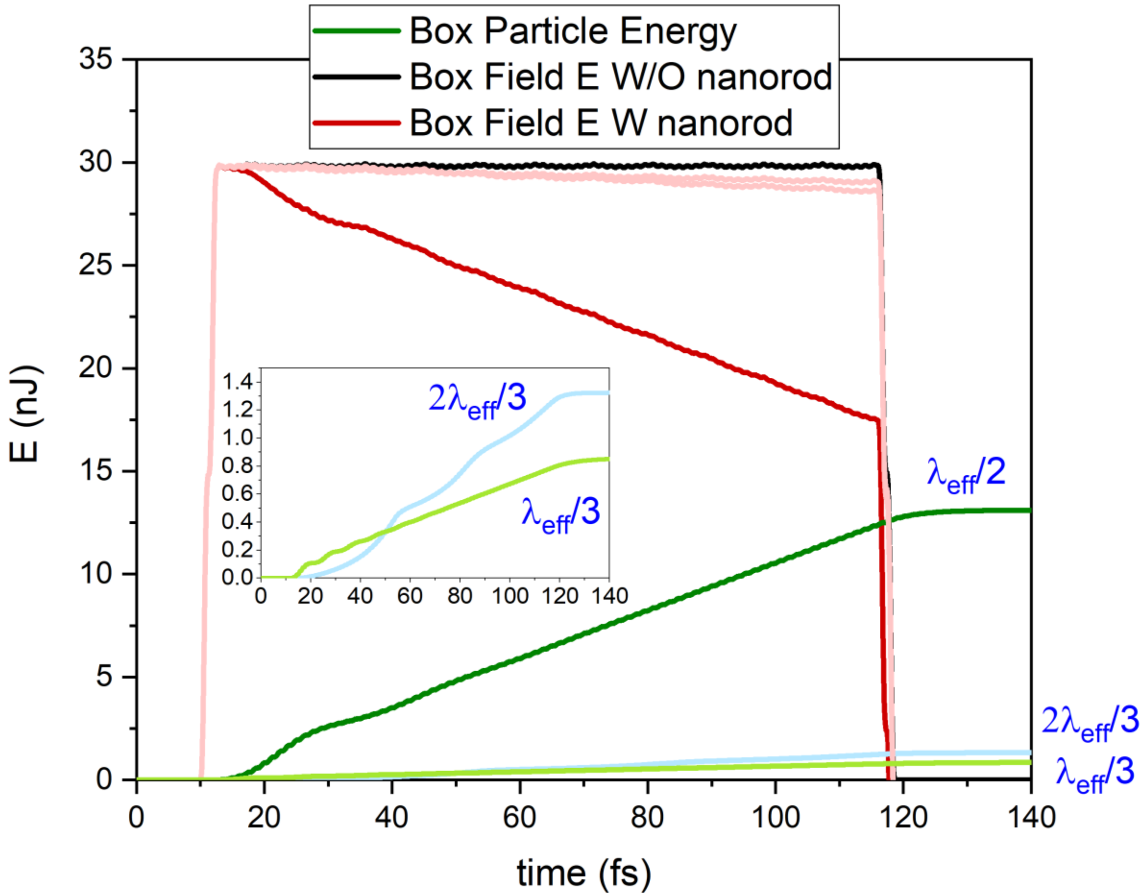
λ_{eff}=260nm nano-ant. dipole length Λ_{eff} /2=130nm i.e.,130x25nm

Laser pulse E_P=30mJ in CB, T_P=106 s ≈ 40λ/c

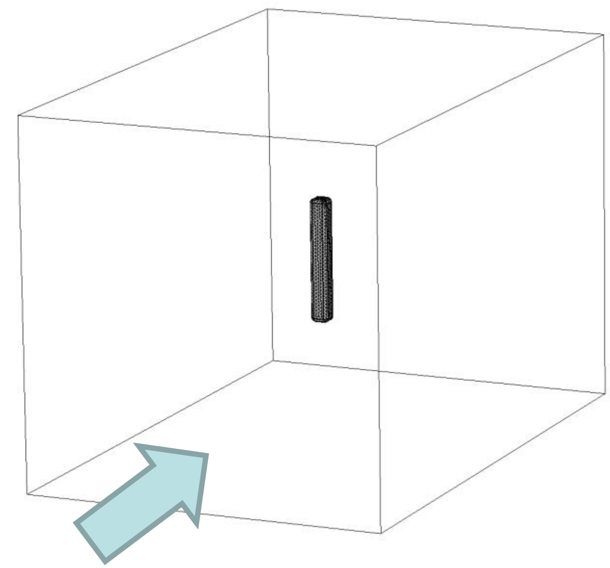
The nanorod antenna has a light absorption cross section, which is nearly 28.5 times bigger than its geometrical cross section

[I. Papp et al. (NAPLIFE Coll.) ***PRX Energy***, **1**, 023001 (2022)], and *[I.Papp's talk ICNFP2022]*

Resilience of Nanorod Antenna with COMSOL



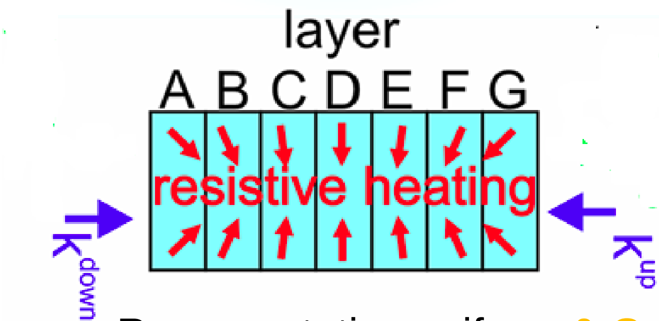
FEM computations with the same model parameters



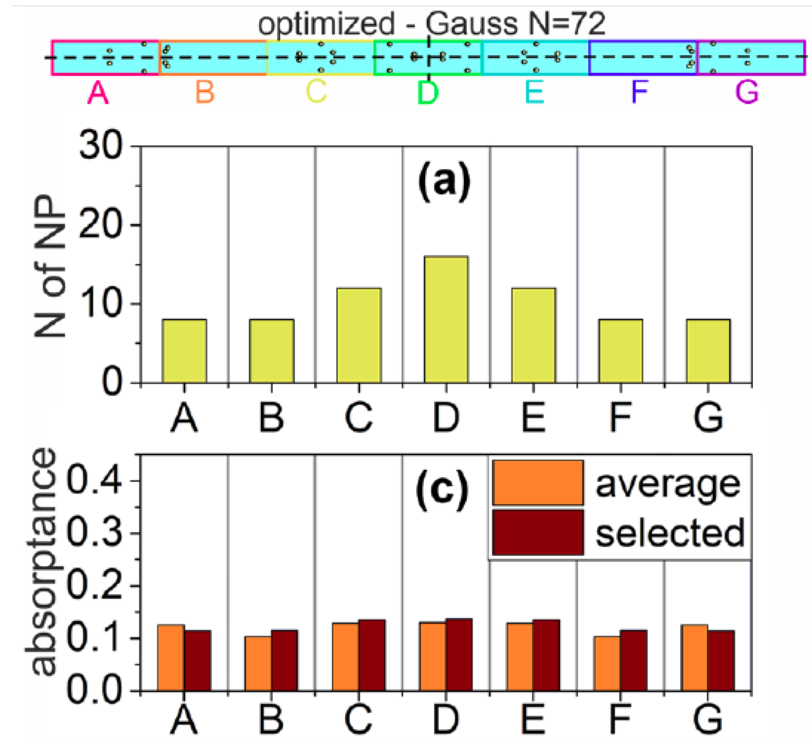
[M. Csete et al. NAPLIFE 2022]

Good qualitative agreement between FEM and EPOCH/PIC methods
Quantitative difference:
the hydrodynamic model of the electron plasma (FEM) predicts a sharper resonance than the kinetic model (EPOCH/PIC)

Layered target with variable light absorption



Representative uniform & Gaussian number density distributions of (d) 70 oriented nanorods, in a 1 × 1 × 21 µm3 supercell of UDMA polymer target, with random location distribution.



Plasmonics (2022) 17:775–787
https://doi.org/10.1007/s11468-021-01571-x

Comparative Study on the Uniform Energy Deposition Achievable via Optimized Plasmonic Nanoresonator Distributions

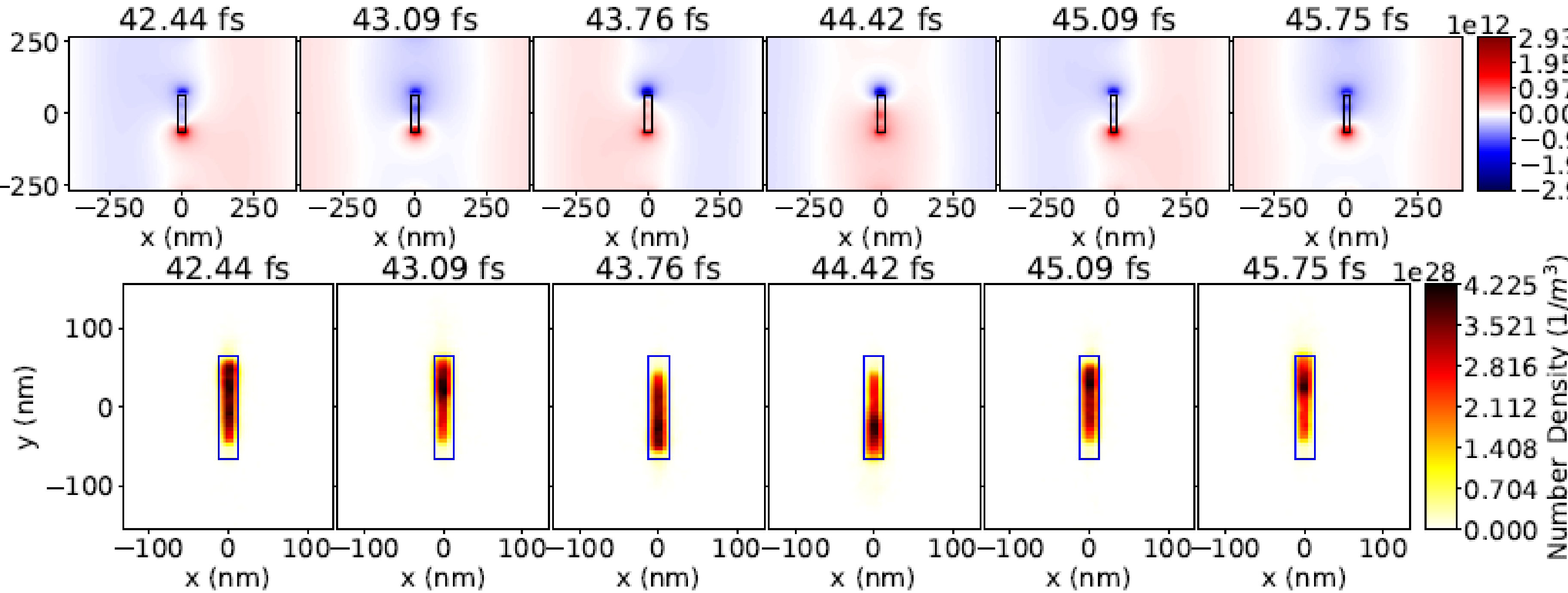
Mária Csete[1] · András Szenes[1] · Emese Tóth[1] · Dávid Vass[1] · Olivér Fekete[1] · Balázs Bánhelyi[2] · István Papp[3,4] · Tamás Bíró[3] · László P. Csernai[3,4,5] · Norbert Kroó[3,6]

[M. Csete, A. Szenes, E. Tóth, D. Vass, O. Fekete, B. Bánhelyi, T. S. Bíró, L. P. Csernai, N. Kroó: *„Comparative study on the uniform energy deposition achievable via optimized plasmonic nanoresonator distributions*“, Plasmonics (2022), 17: 775-787; https://doi.org/10.1007/s11468-021-01571-x.]

Kinetic Modelling of the Nanorod

in polymer UDMA

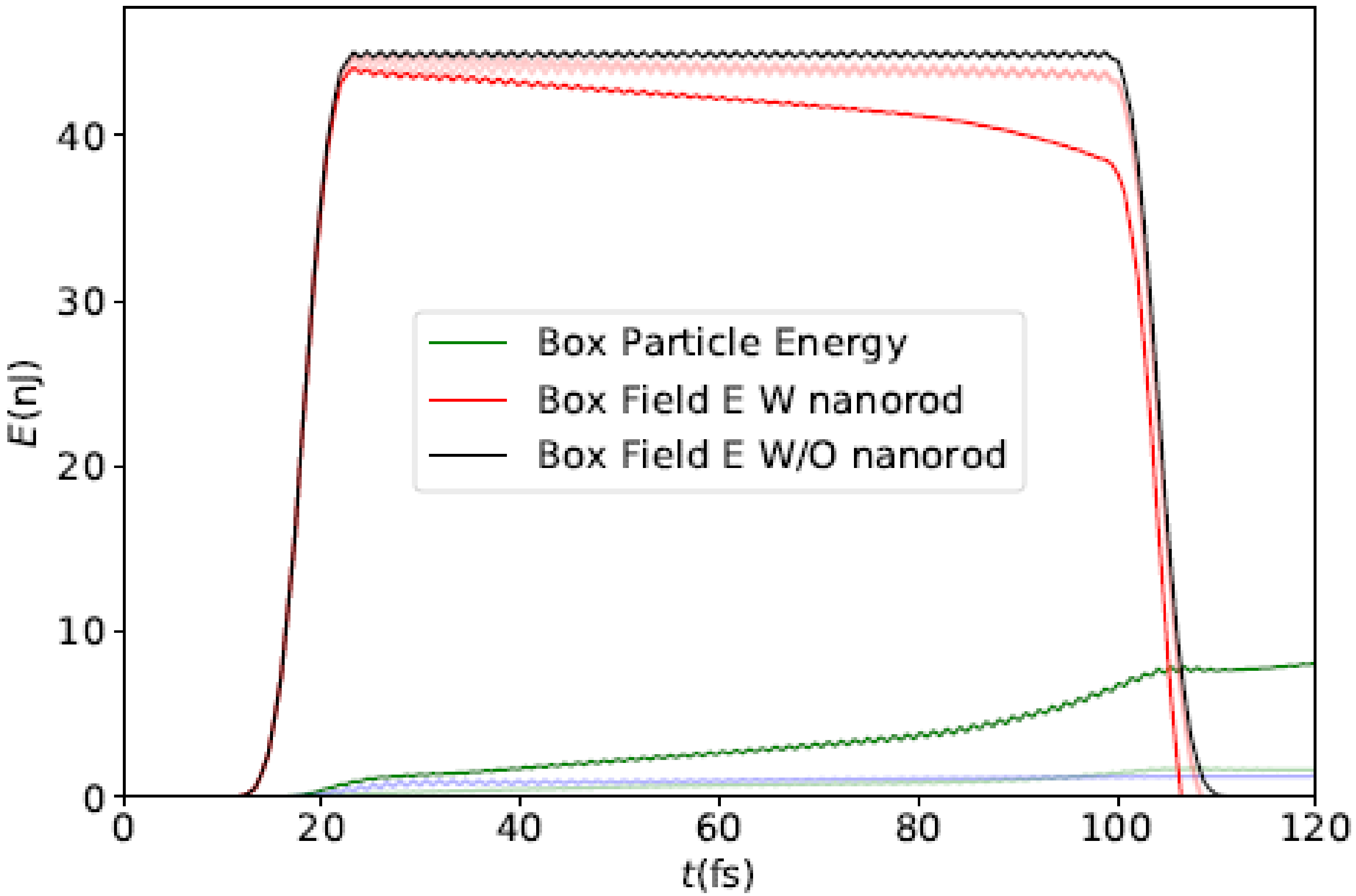
[I.Papp's talk ICNFP2022]



- Evolution of the E field's y component from 42.4 till 45.7 fs, around a nanorod of 25x130 nm.
- The direction of the E field at the two ends of the nanorod does not change.

In polymer UDMA

[I.Papp' et al., arXiv:2212.]

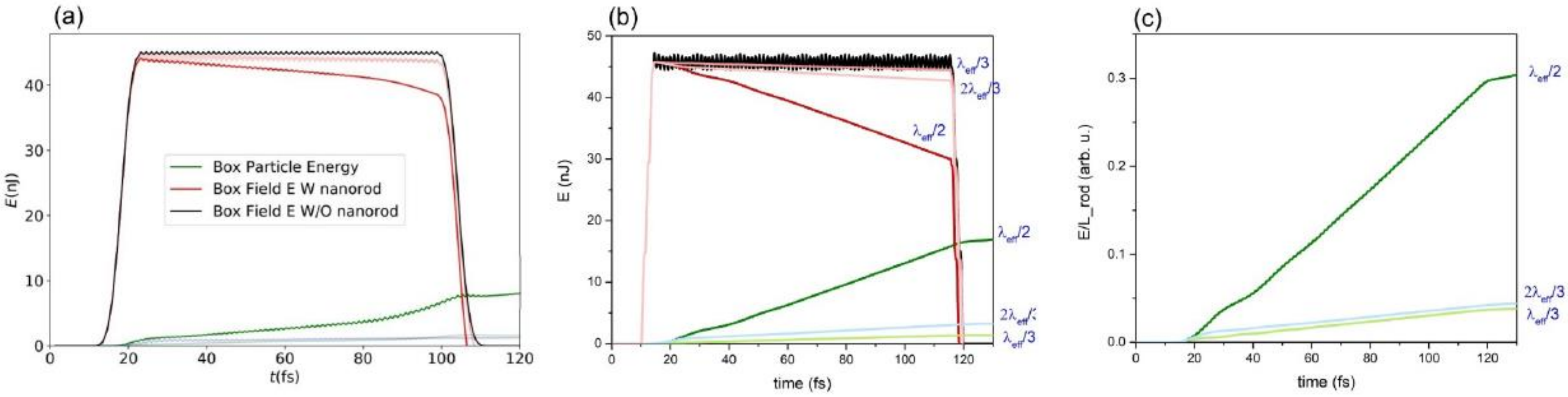


deposited energy in the nanorod (green line)

Energy development in Calculation Box and in Nano-rod antenna

In EPOCH PIC model and in COMSOL Multi-Phys. Model

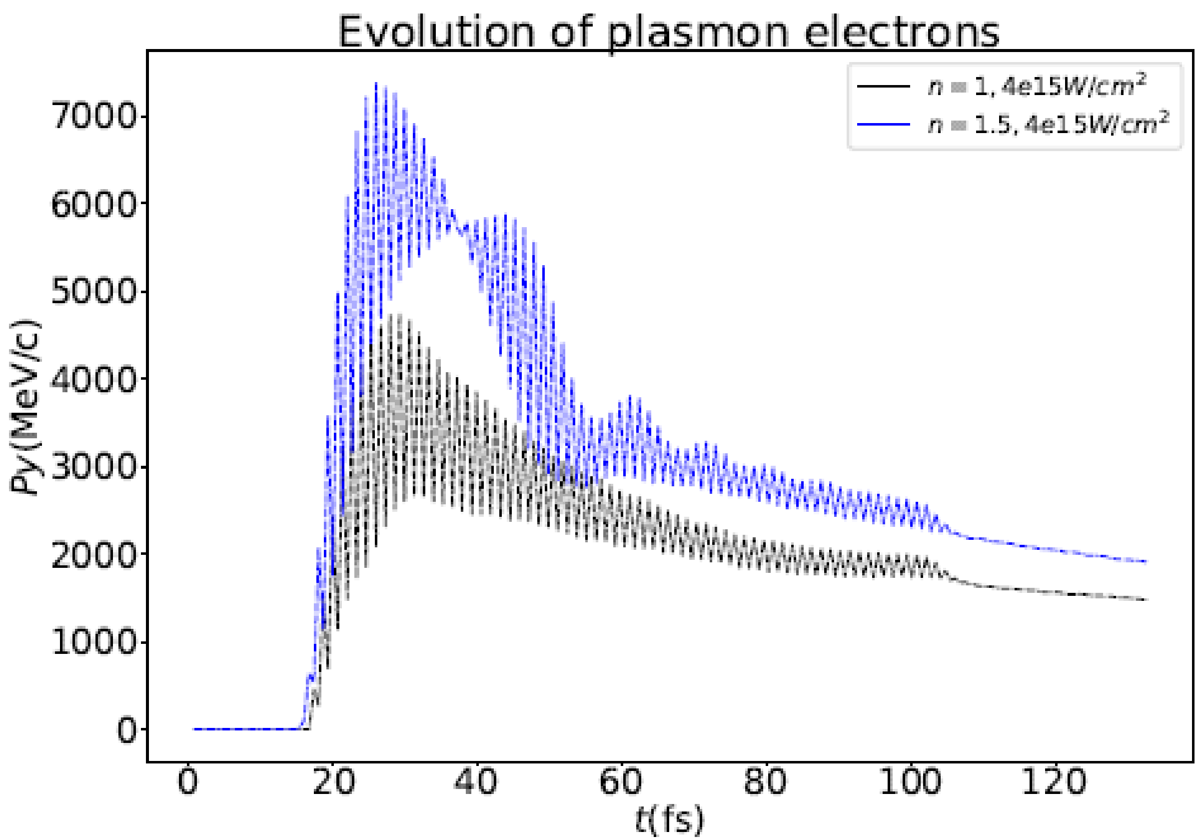
EPOCH (nJ) COMSOL (nJ) COMSOL E_L a.u.



Csernai, L.P. [NAPLIFE]

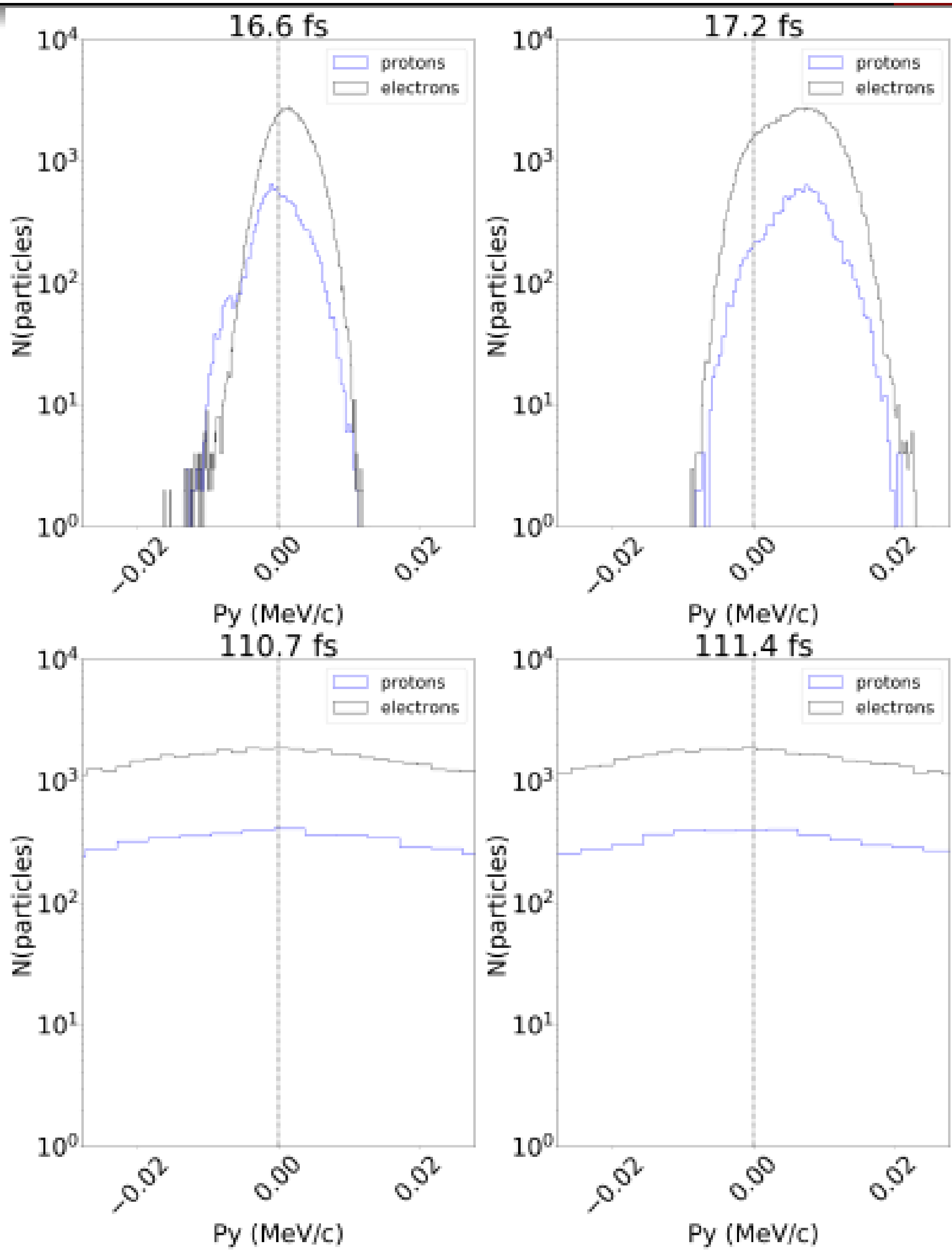
in vacuum & polymer UDMA

[I.Papp et al., arXiv : 2212



accumulated momentum of conduction electrons in **vacuum** (blue) and in **UDMA** (black) with their corresponding resonant length

In polymer UDMA



Protons surrounding the nanorod

[I.Papp et al., arXiv: 2212.]

Considerations for the simulation box:
$S_{CB} = 530 \times 530\text{nm}^2 = 2.81 \times 10^{-9}\text{cm}^2$ and length of $L_{CB} = 795\text{nm}$

beam crosses the box in $T = 795\text{nm}/c = 2.65\text{fs}$

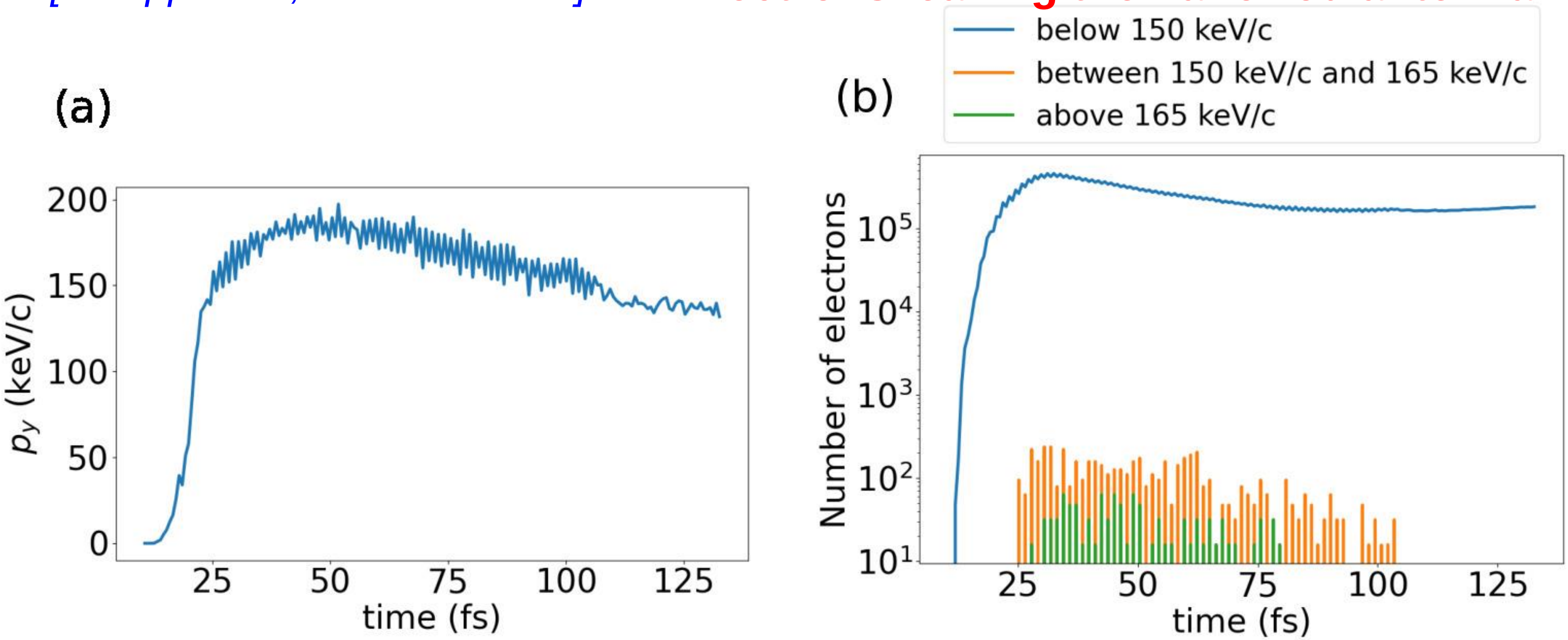
Nanorod size: 25 nm diameter with 85 nm length

Pulse length: $40 \times \lambda/c = 106$ fs
Intensity: 4×10^{15} W/cm^2

In polymer UDMA

[I.Papp et al., arXiv: 2212.]

Electrons leaving the nano-rod antenna



Resilience of Nanorod antennas are sufficient for regulate ignition time at ELI-ALPS energies!

New experiments since July 14, 2021

Validation tests at lower energies:
1.) Increased absorption via nano-antennas /Done
2.) Simultaneous transition on Twosided multilayer target

Wigner RCP, Budapest

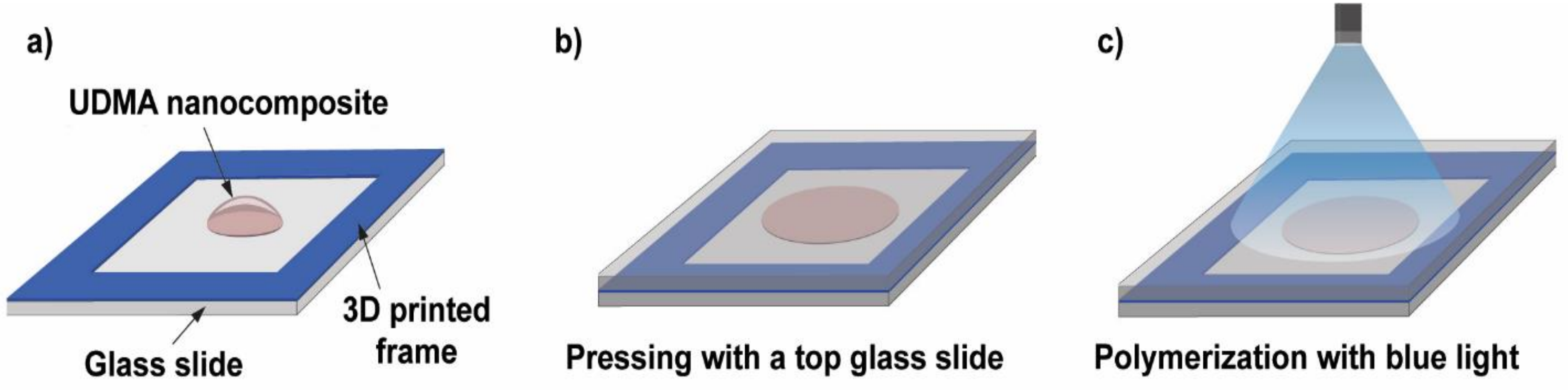
Ti:Sa Hidra Laser: 30mJ, 10Hz, 40fs **[P. Racz et al., Wigner RCP]**

Target Manufacturing

Target materials, absorptivity, implanted nanoantennas

Cyclic olefin copolymer (COC)
Urethane dimethacrylate (UDMA) - 75%
triethylene glycol dimethacrylate (TEGDMA) - 35%

Flat layered target
One layer thickness: 3 μm
Seven layers: 21 μm

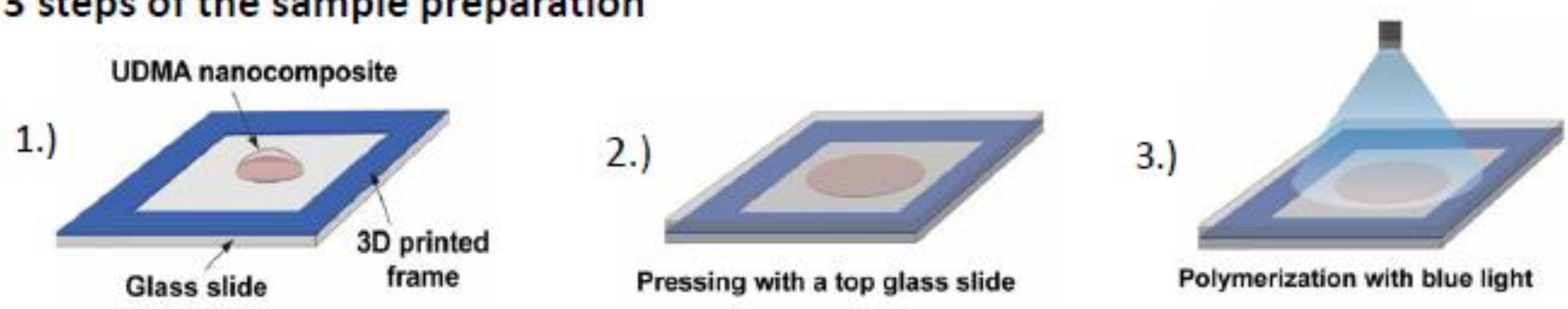


[A. Bonyár et al., Int. J. Mol. Sci. **23**, 13575 (2022).*]*

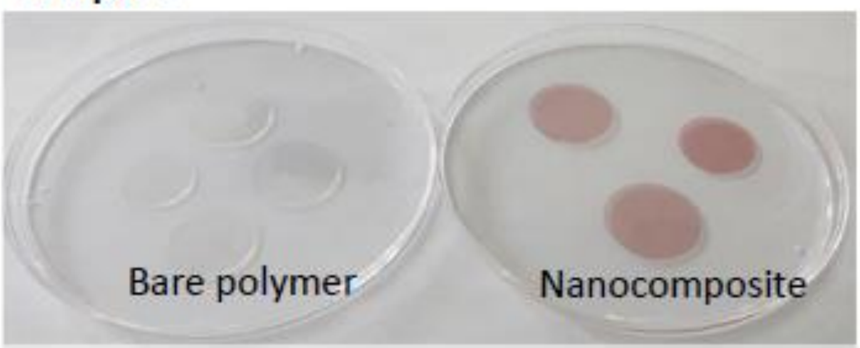
[A. Bonyár et al., Int. J. Mol. Sci. **23**, 13575 (2022).*]*

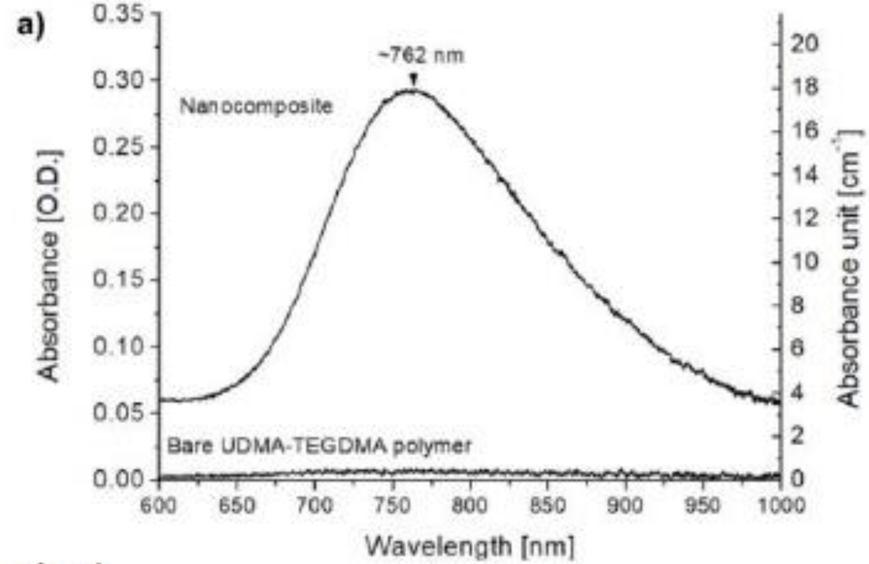
3. Fabrication methods – Sandwich Pressing

3 steps of the sample preparation



Images of the bare and the doped samples





<u>Challenges:</u>

- ➢ the viscosity needs to be controlled,
- ➢ layer uniformity needs to be controlled (pressing).

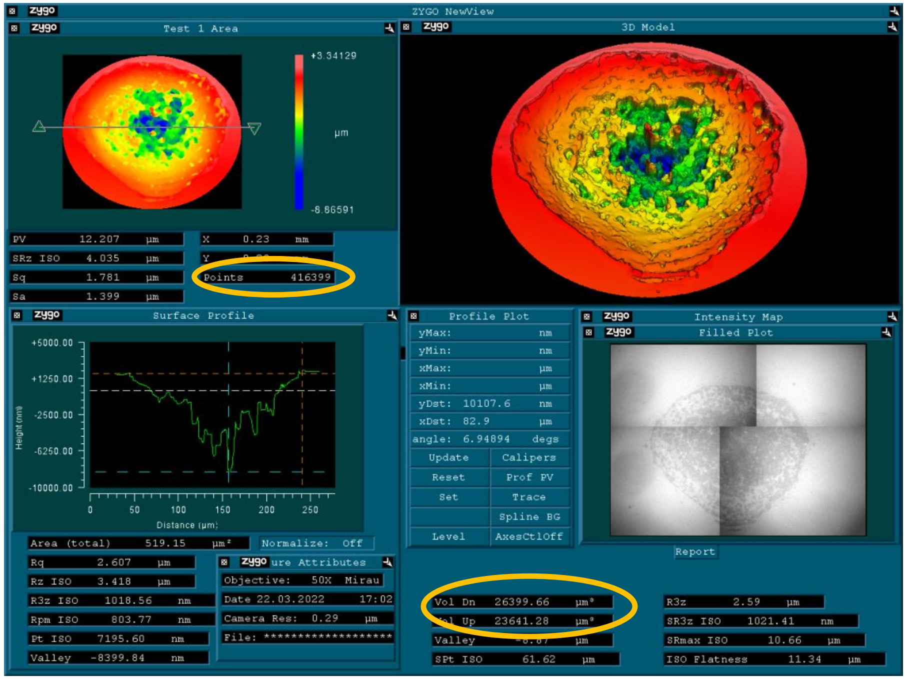
Validation tests →

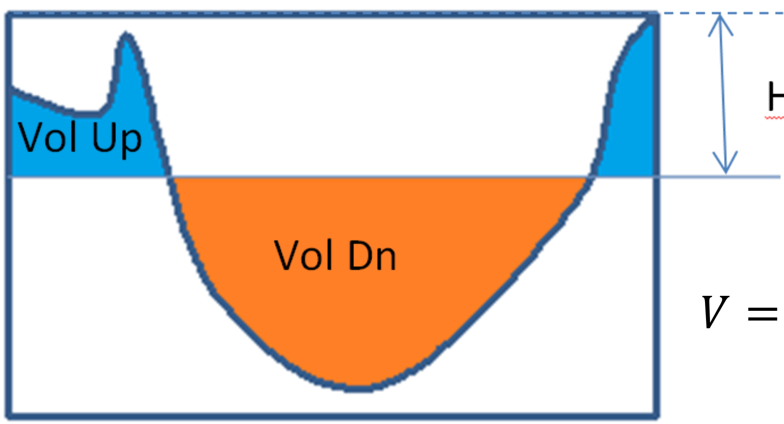
1.a)

*** Crater Volume**

Volume determination method

1. Setting of the reference plane
2. Mesuring of the H_{min} value on 4 different points, and averaging them
3. Recording the values VolUp, VolDn and the number of the points
4. Calculating the area of the pixels
5. Calculating the volume of the cylinder over the reference plane





H_{min}

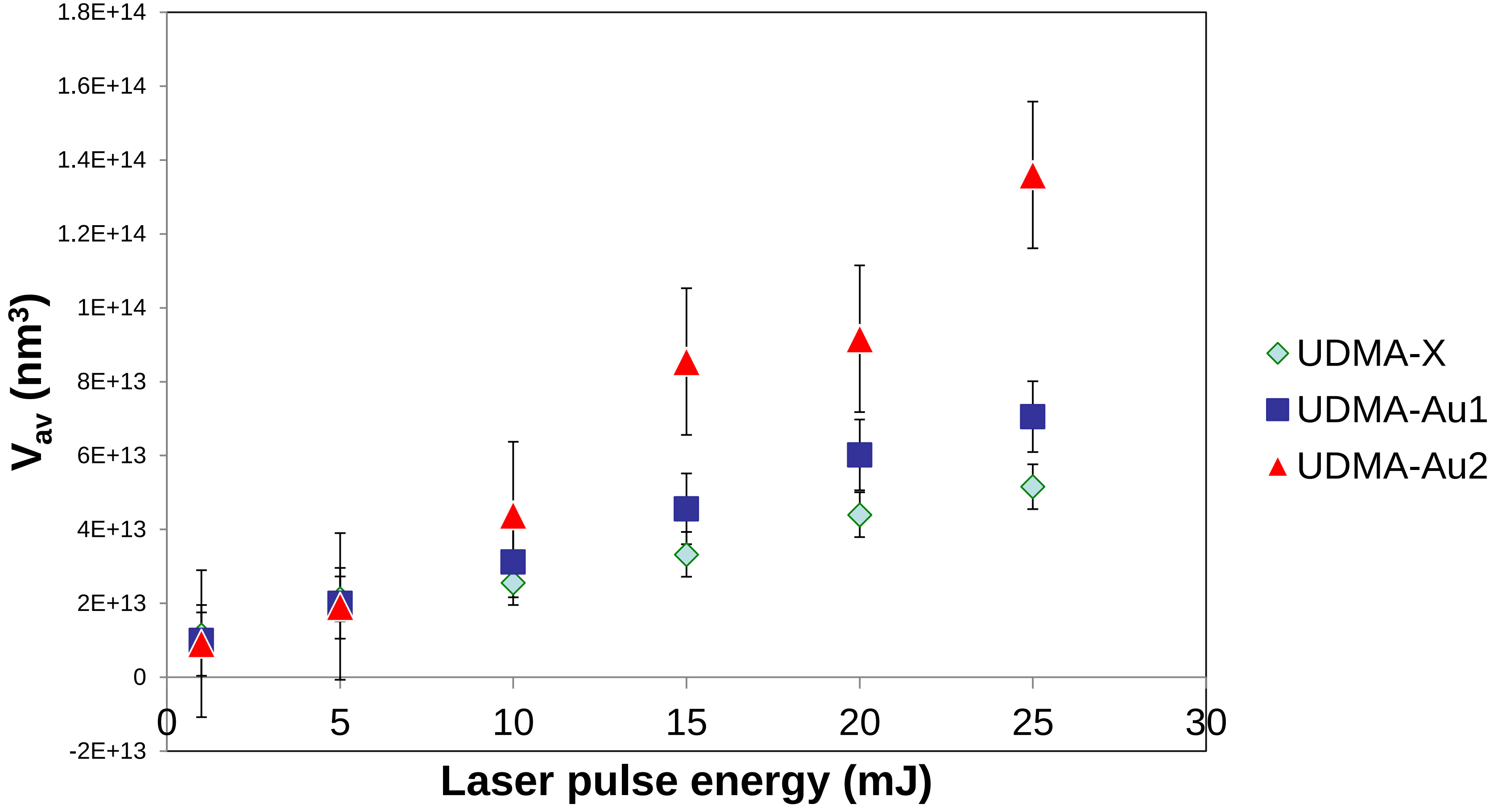
Reference plane

$$V = VolDn + T_{pixel} \cdot Points \cdot H_{min} - VolUp$$

[Ágnes Szokol & Judit Kámán, ICNFP 2022]

Crater volume

The analysis of the crater volumes – in 5 different points for every energy & target



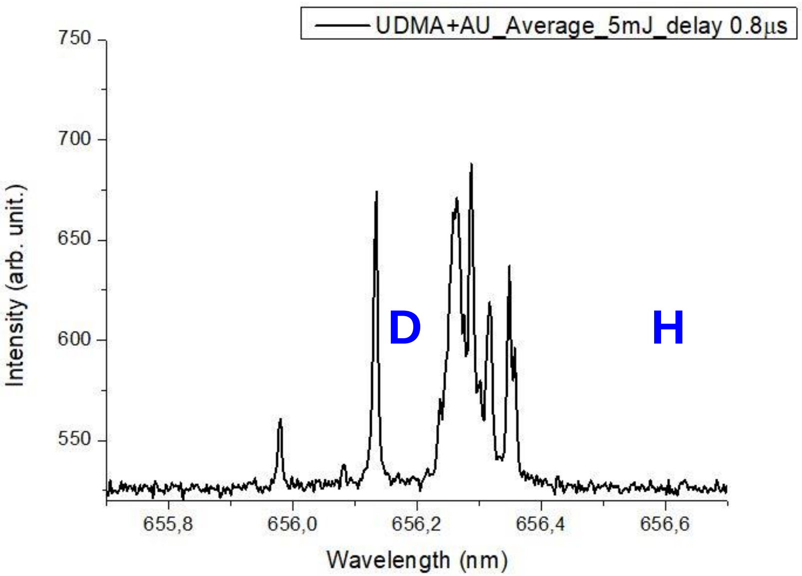
Csernai, L.P. [NAPLIFE]

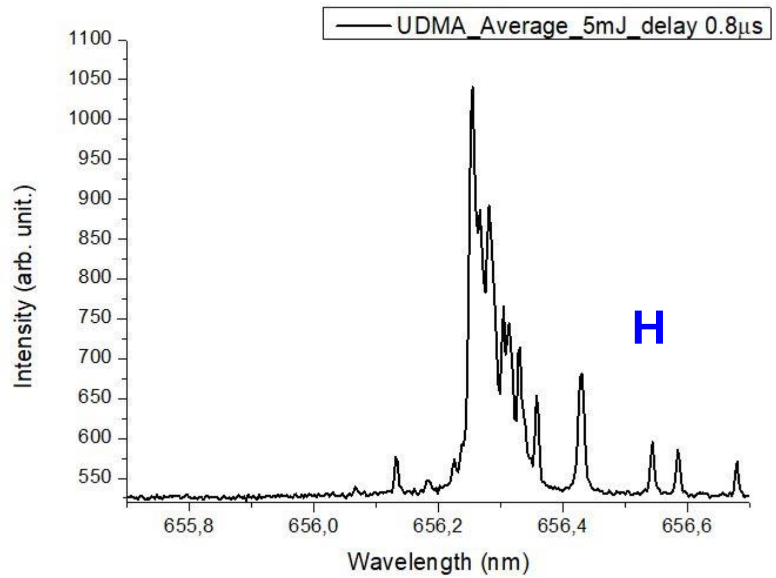
Validation tests →

1.b)

*** Deuterium production**

Deuterium production (PRELIMINARY ! ?)





5-12% **D + 88-95% H**

~ 10^{17} D / pulse (10Hz)

100% **H**

Balmer-α line

Two step weak process (average of 20 shots), UDMA (470: H38, C23, O8, N2)

p + e* → n + **ν** \ electron capture (-1.24 MeV)

n + p → d + **γ** \ neutron capture (+2.22 MeV)

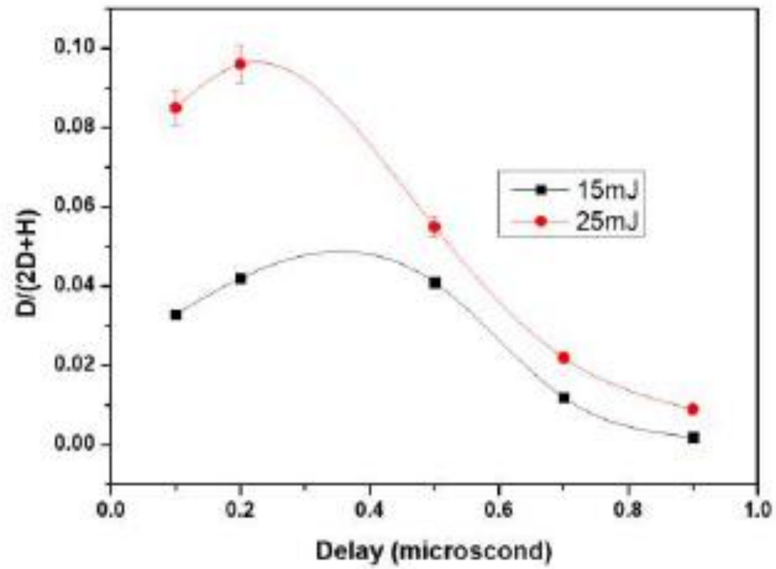
Electron capture may happen spontaneously in heavy nuclei,

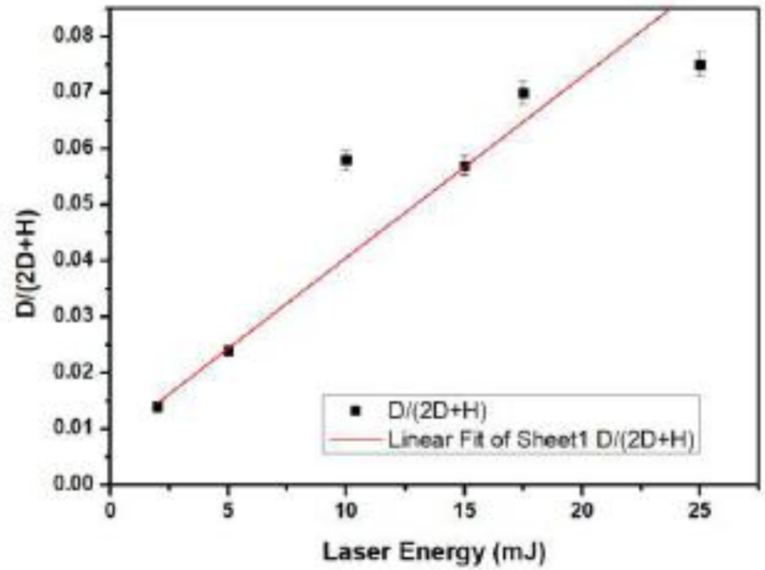
here laser light and resonant nanorods may act similarly at high e density.

Alternatively n transmutation from C-13 or other nuclei to H ➔ D.

[Archana Kumari & Miklos Veres's talk in ICNFP 2022]

Calculation of ratio; D/(2D+H)





At 17.5 mJ, D(A)=1.828, H(A)=8.32
D(A)/H(A)=0.21
D(A)/[2*D(A)+H(A)]=0.15
No. of H atoms=2.51*10^16
No. of atoms that were converted from H to D=3.765*10^15

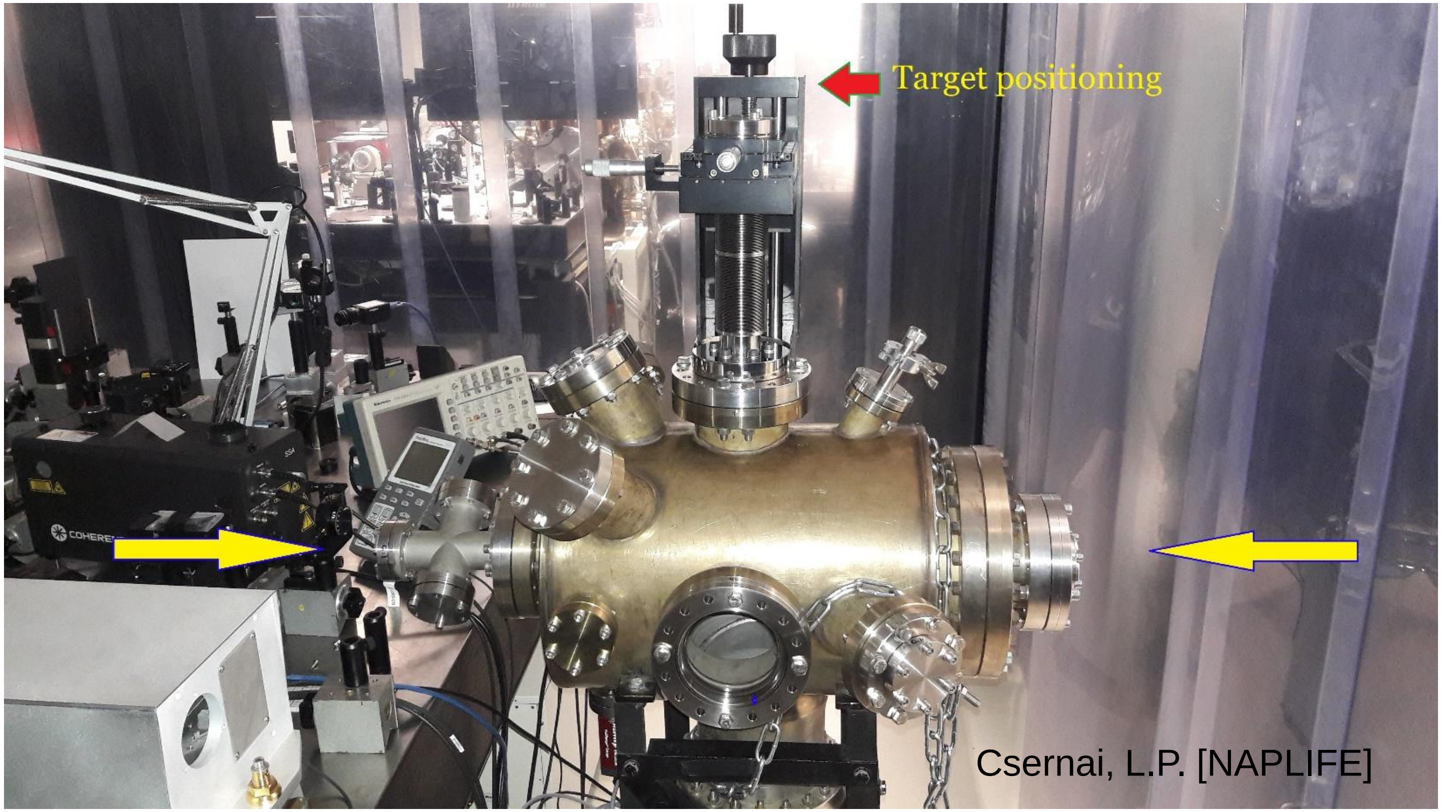
Validation tests at lower energies

2.)
Two opposing beams
simultaneous (time-like) transition

Validation tests – Two sided shot

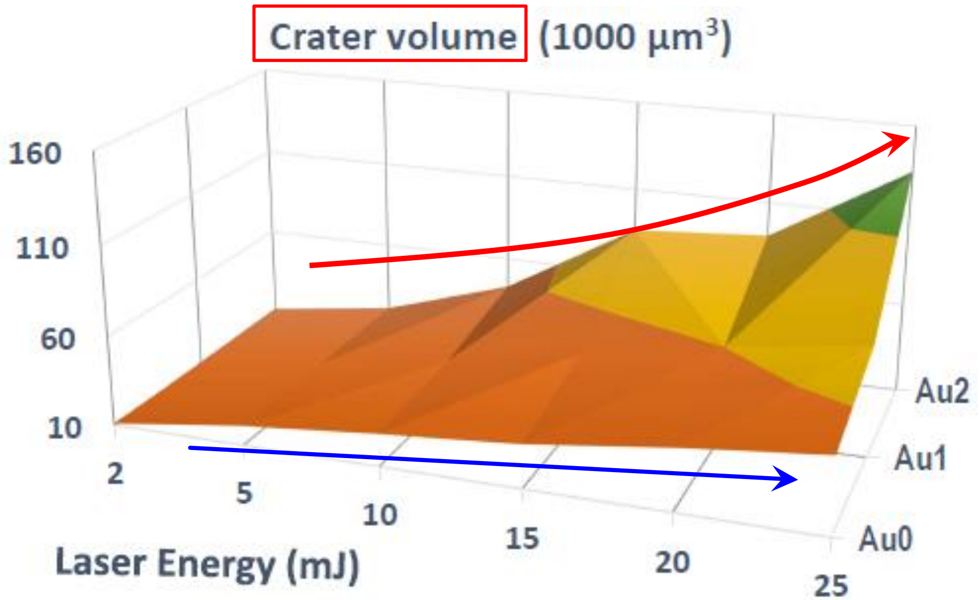
Two basic principles are tested on non-fusion material targets at low energies

- **Implanted with nano-antennas ➔ Amplified absorption** √
- **Multilayer targets ➔ Simultaneous Ignition (in progress)**



*[M. Csete,
A. Bonyár,
I. Papp,
P. Rácz,
et al.]*
In preparation

Theoretical analyzis of
Crater & Deuterium production



Crater Formation and Deuterium Production in
Laser Irradiation of Polymers with Implanted Nano-antennas

László P. Csernai[1,2,3], Igor N. Mishustin[3], Leonid M. Satarov[3], Horst Stöcker[3,7,8], Larissa Bravina[4], Mária Csete[5,6], Judit Kámán[1,5], Archana Kumari[1,5], Anton Motornenko[3], István Papp[1,5], Péter Rácz[1,5], Daniel D. Strottman[9], András Szenes[5,6], Ágnes Szokol[1,5], Dávid Vass[5,6], Miklós Veres[1,5], Tamás S. Biró[1,5], Norbert Kroó[1,5,10]
(NAPLIFE Collaboration)

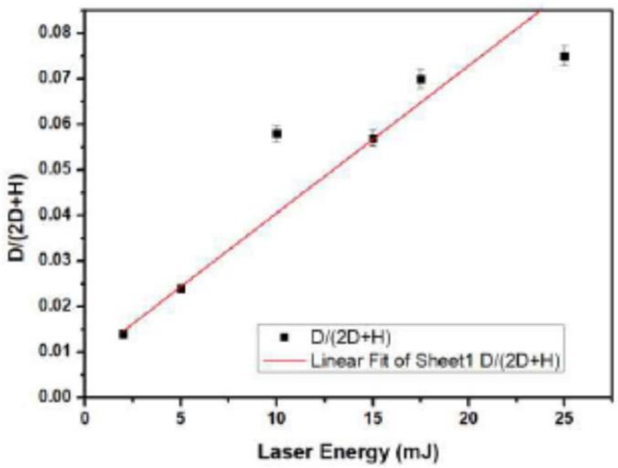
arXiv: 2211.14031 [physics-plasma-ph]

With nanorods V grows non-linearly. Increasing energy deposition. Several types of targets are considered: Au1 and Au2 with implanted nano-rod antennas, and Au0 without implantation. The mass concentrations of implanted particles in UDMA are 0.126% and 0.182% for targets Au1 and Au2, respectively.

With nanorods, Au2, deposited energy into the crater increases non-linearly (!?)

Origin of this extra energy (?)

Deuterium production



Deuterium atom production is observed both by LIBS and Mass spectrometry. Increases with laser pulse energy for Au1 target (Au0 &Au2 in progress). Two possibilities are analyzed:

a) electron capture $e+p+0.783\ MeV \rightarrow n+\nu$, & $p+n \rightarrow d+2.225\ MeV$ exotherm, but weak interaction . With Au1, Au2, high n_e , Collective effects (!?)

b) n transmutation e.g. on $p + {}^{13}C \rightarrow d + {}^{12}C$ or $p + {}^{12}C \rightarrow d + {}^{11}C$, these are exotherm, so ~ 5-15 MeV extra p energy is needed, that might be possible. However, the cross section is still too small for the observed 5-10% D/H ratio.

In this case the recombination $d \rightarrow D$ rate can exceed the $p \rightarrow H$ rate during the final expansion from irradiated hot-spot volume, V_{ir} to final crater volume, V_C This depends on the volume ratios, and may explain the observed rates!

[Csernai, Mishustin, Satarov, et al., (NAPLIFE Coll.) arXiv: 2211.14031 [physics-plasma-ph]]

Deuterium production

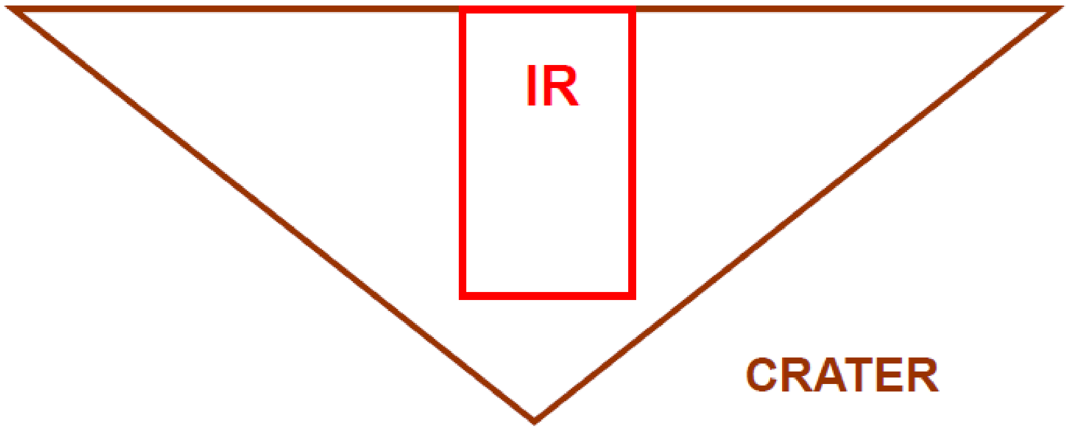


FIG. 4. (color online) Schematic cross section of the final crater (C) and the laser irradiation region (IR). The energy and momentum of the laser beam is initially absorbed in the IR.

Our D/H estimates depend strongly on the V_{ir} / V_C ratio. Not directly measurable.

Nuclear densities are not so much changed due to Au1 or Au2 implants so nuclear density catalyser effects are less probable.

[Csernai, Mishustin, Satarov, et al., (NAPLIFE Coll.) arXiv: 2211.14031 [physics-plasma-ph]]

High Energy, Short Pulse Laser,

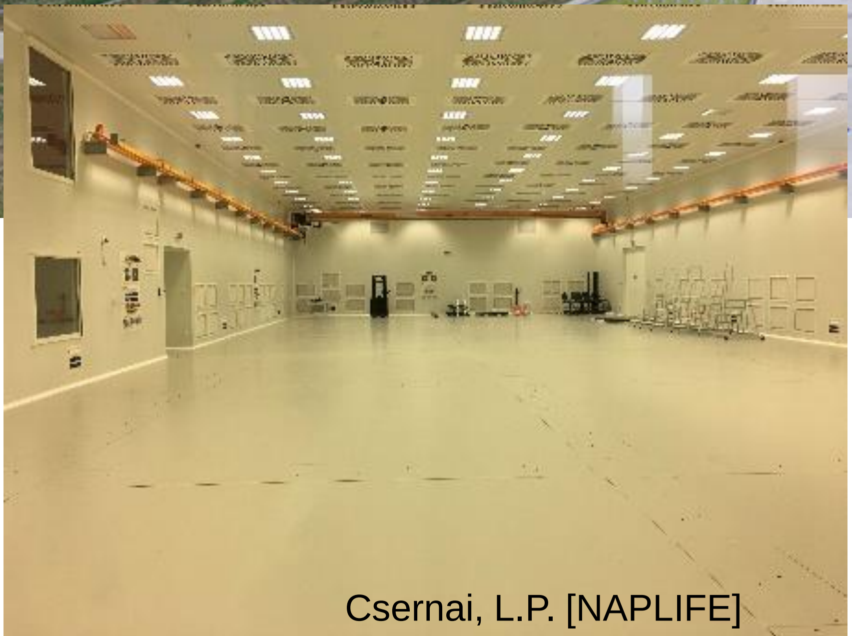
unique

at

ELI – ALPS

Szeged

European Laser Infrastructure – Szeged, HU



Csernai, L.P. [NAPLIFE]

ELI-ALPS Szeged:
EU Extr. Light Infrastructure
Attosec. Light Pulse Source

2PW High Field laser
10 Hz, <10fs, **20 J**

Thanks for your attention