

42nd Workshop on High-Energy-Density Physics with laser and ion beams

Development in Nano Fusion

Csernai, L.P. [NAPLIFE}

Laszlo P. Csernai, for the
NAPLIFE Collaboration
Univ. of Bergen, Norway

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 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 →

NAPLIFE Collaboration – Participants - ELKH, National Res. Lab.

Prof. Dr. Peter J. Lévai, Prof. Dr. Laszlo P. Csernai, Prof. Dr. Norbert Kroó, Prof. Dr. Tamás S. Biró, Dr. Márk Aladi, Dr. Roman Holomb, Dr. Miklós Kedves, Dr. Archana Kumari, Dr. István Papp, Dr. Péter Petrik, Dr. Péter Rácz, Dr. Béla Ráczkevi, Dr. István Rigó, Dr. Miklós Veres, Anett Szeledi, Ágnes Nagyné Szokol; Prof. Gábor Galbács, Dr. Balázs Bánhelyi, Dr. Mária Csete, Dr. Attila Czirják, Olivér Antal Fekete, Péter Földi, Emese Tóth, András Szenes, Dávid Vass; Prof. Dr. Attila Bonyár, Dr. Judit Kámán, Alexandra Borók; Zsolt Fogarassy, Kolos Molnár, Dr. Péter Dombi Dr. Melinda Szalóki, Laura Juhász; Prof. Dr. Horst Stoecker, Dr. Leonid Satarov, Dr. Anton Motornenko; Prof. Dr. Larissa Bravina, Dr. Evgeny E. Zabrodin; Prof. Dr. Rolf K. Eckhoff, Ádám Takács; Prof. Dr. Igor N. Mishustin, Prof. Dr. Daniel D. Strottman, Dr. Csaba Tóth, Prof. Dr. Dénes Molnár, Shereen Zangana

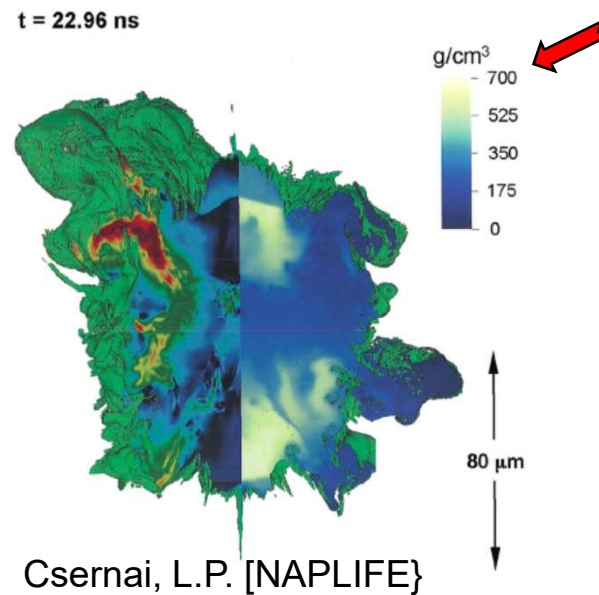
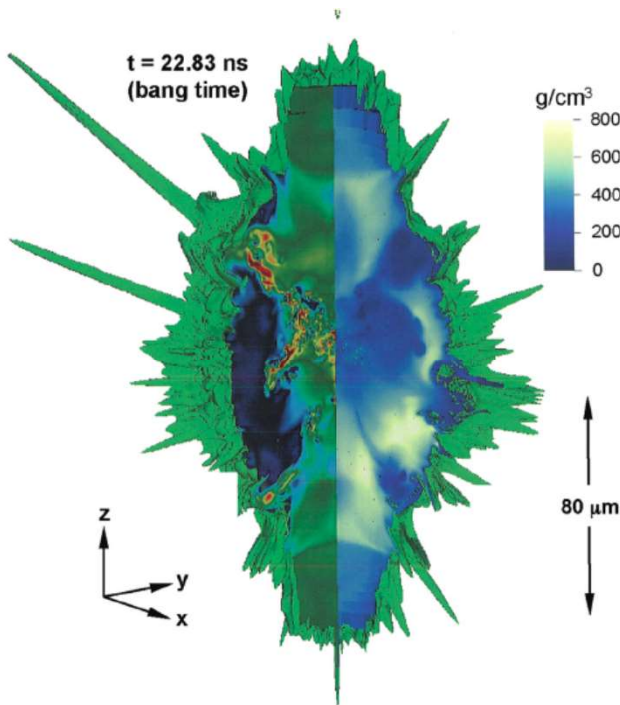
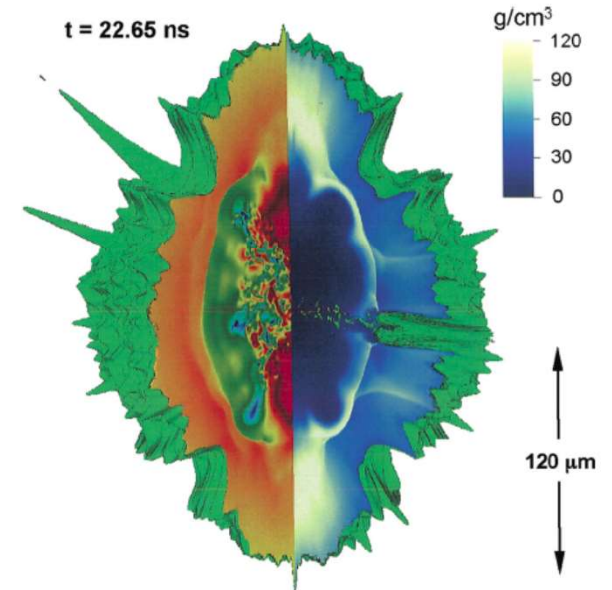
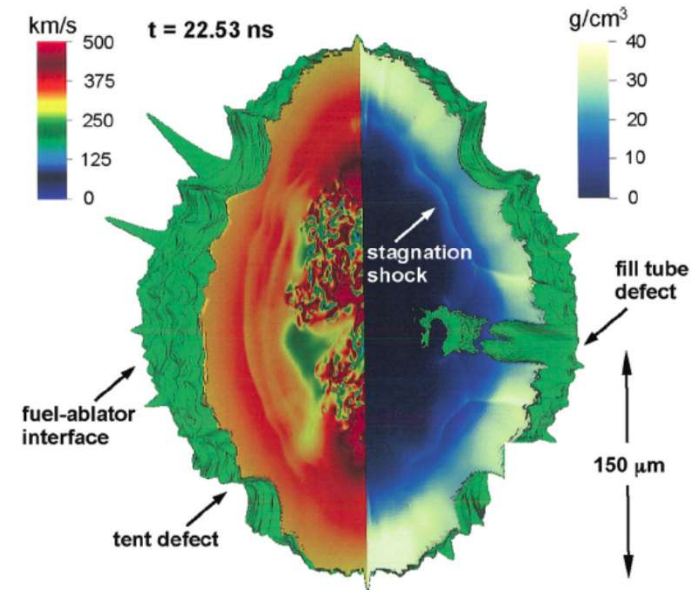
Rayleigh-Taylor Instability

[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

022703-10 Clark et al.

Phys. Plasmas 22, 022703 (2015)

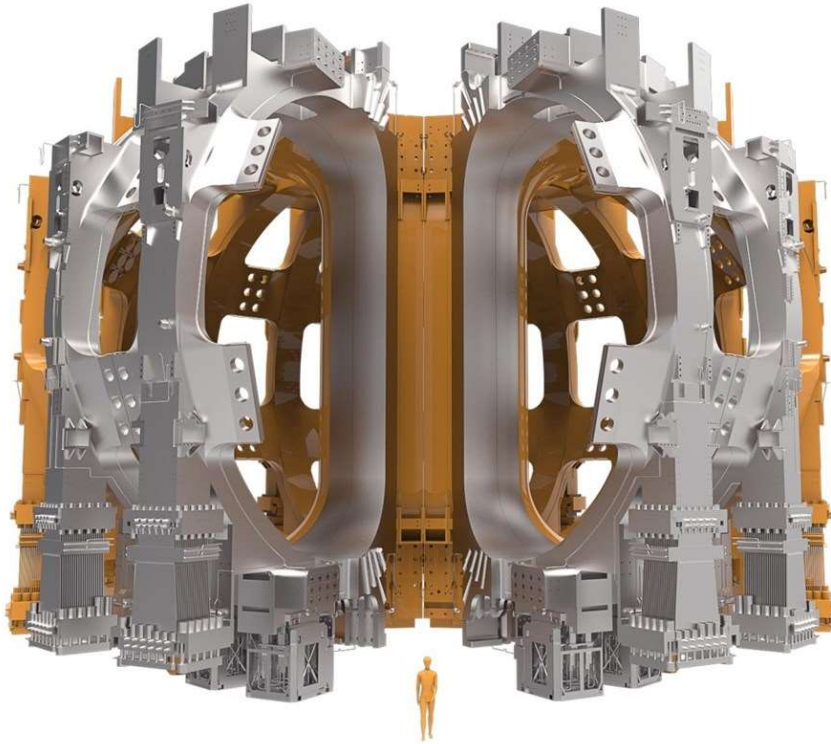


~adiabatic
 compression
 → 80 μm
 & heating

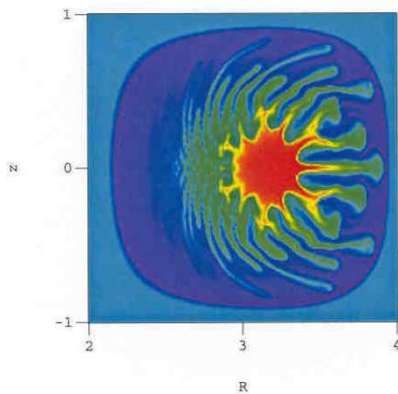
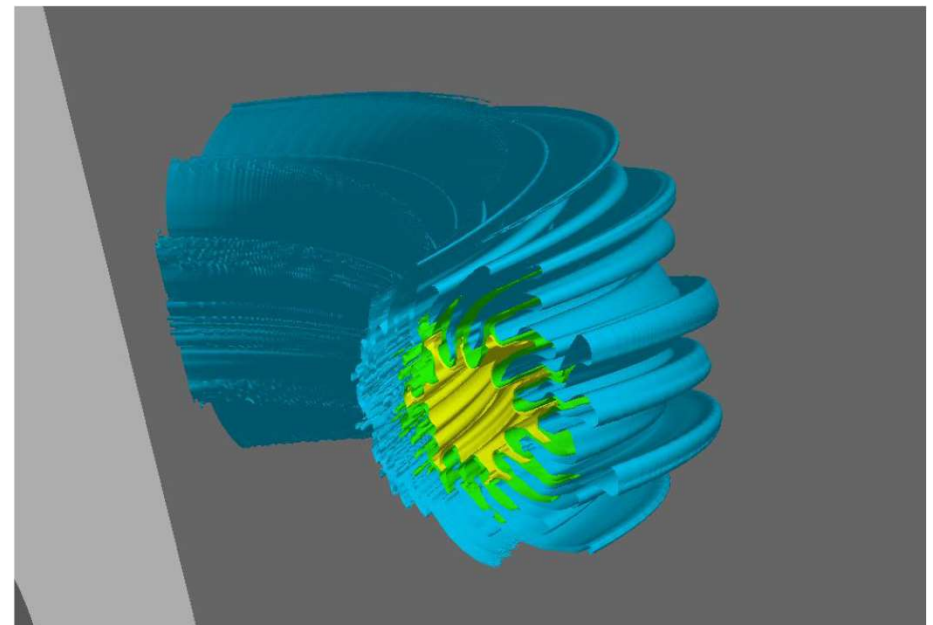
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ITER torus

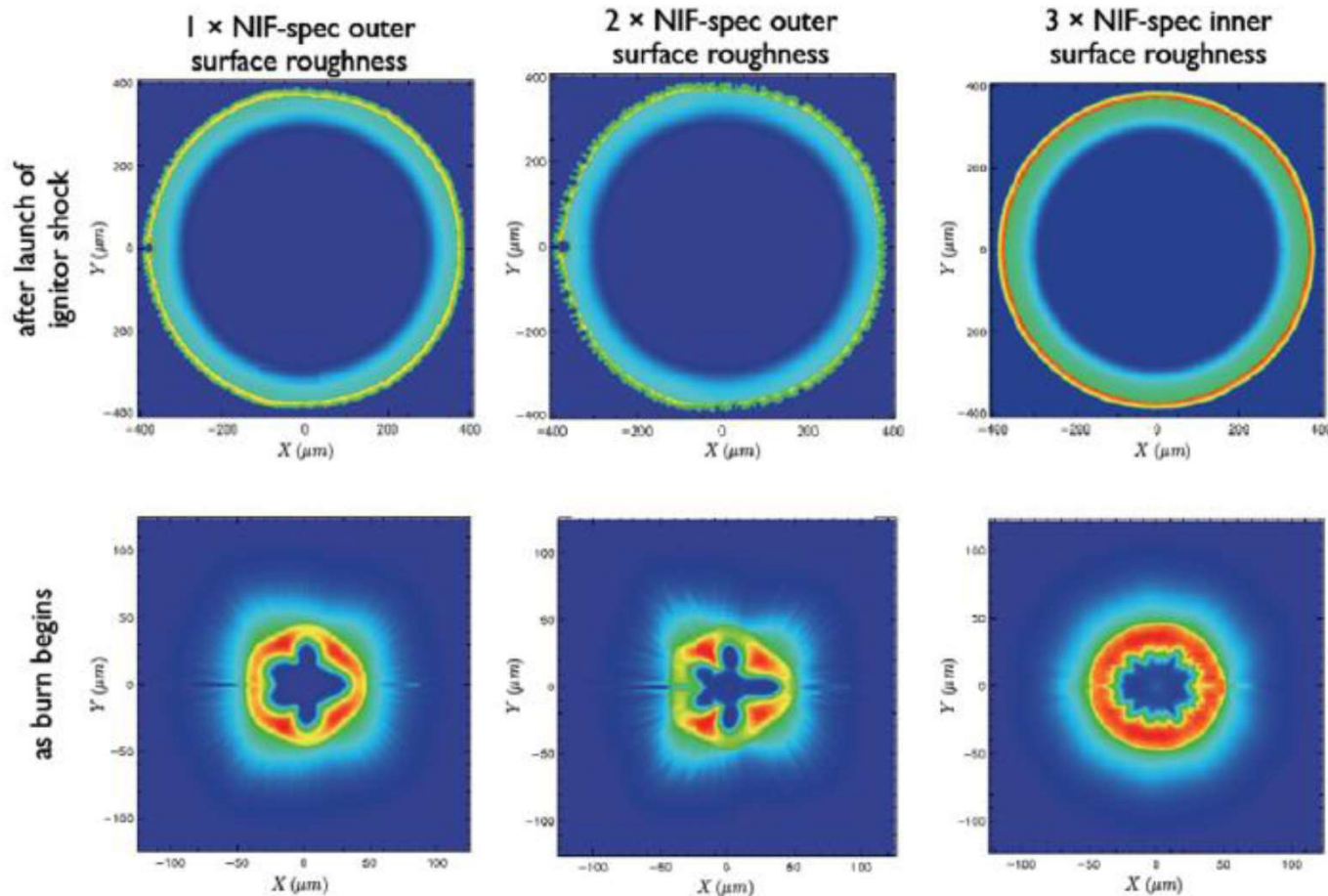
Under construction
Torus: 6x10x18m, $V=830 \text{ m}^3$,
 $Q=10$, planned
500MW\8min, plan
2008-2018 ??? >



RT instability



NIF – RT instability



The target is compressed to density $\sim 700 \text{ g/cm}^3$.

But, although an ablator layer is used, only $\sim 10\%$ -of the target is ignited.

Elsewhere the surface protruded as “potato from the potato press”:
RT- instability.

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 Σ whose three-dimensional normal vector is Λ_i . If we choose our coordinate system so that the discontinuity is at rest, then since

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

we have

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

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

$$[\rho^0 u^i \Lambda_i] = 0, \quad (7.3)$$

$$[T^{\alpha i} \Lambda_i] = 0, \quad (7.4)$$

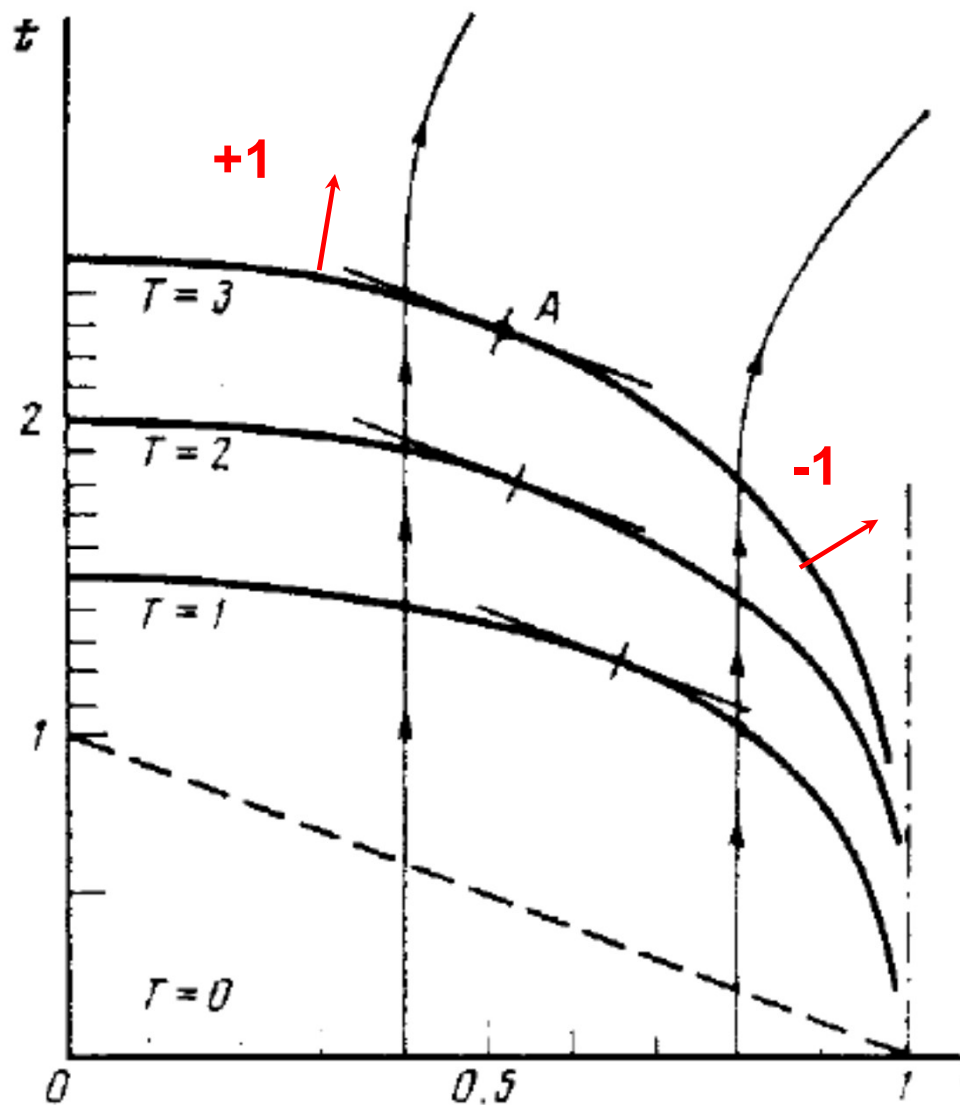
where

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

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Taub assumed that (physically) only slow space-like shocks or discontinuities may occur (with space-like normal, $\lambda_4=0$).

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)]

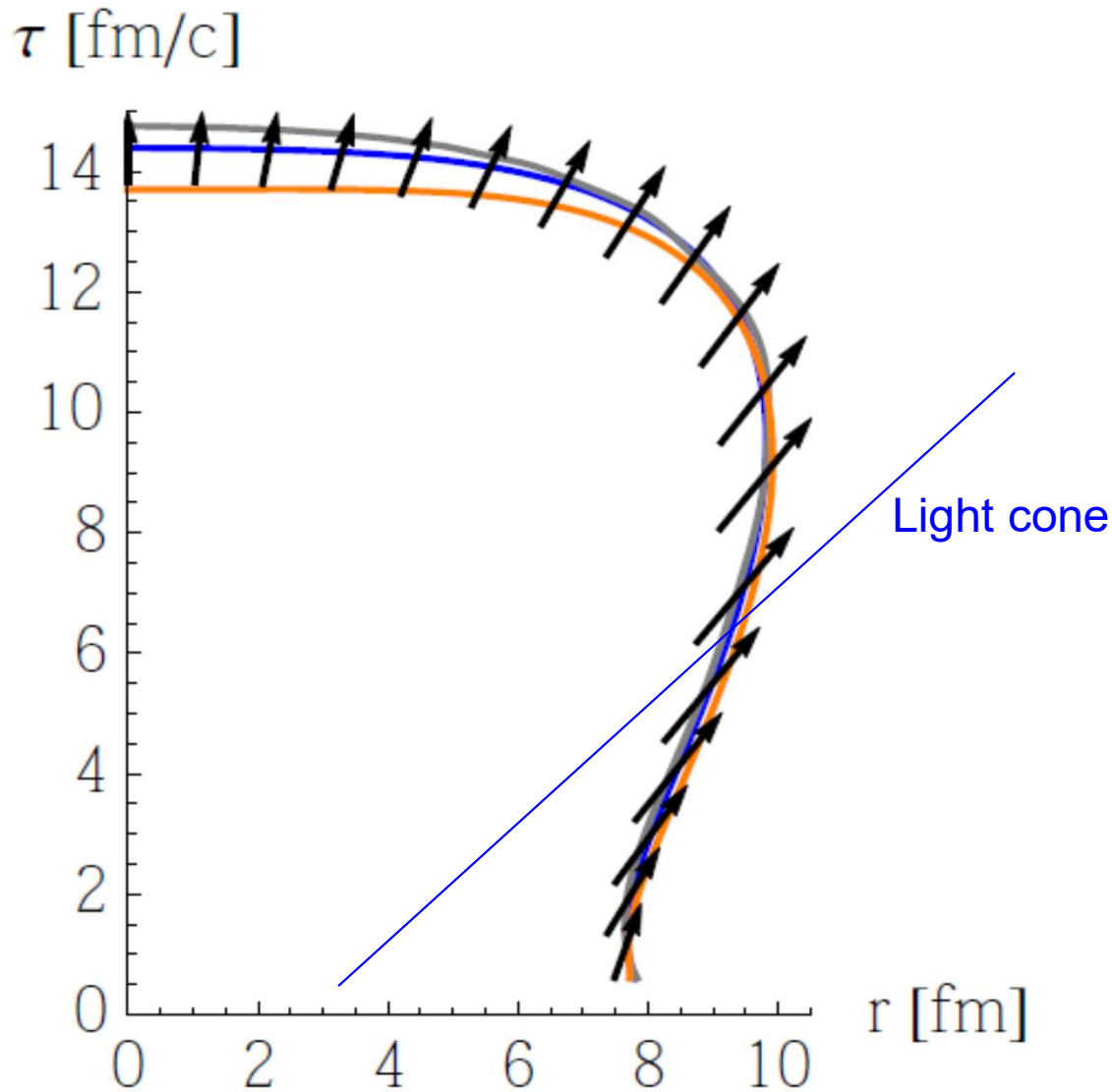
corrected the work of [A. Taub, Phys. Rev. 74, 328 (1948)]

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

Л. П. Чернаи

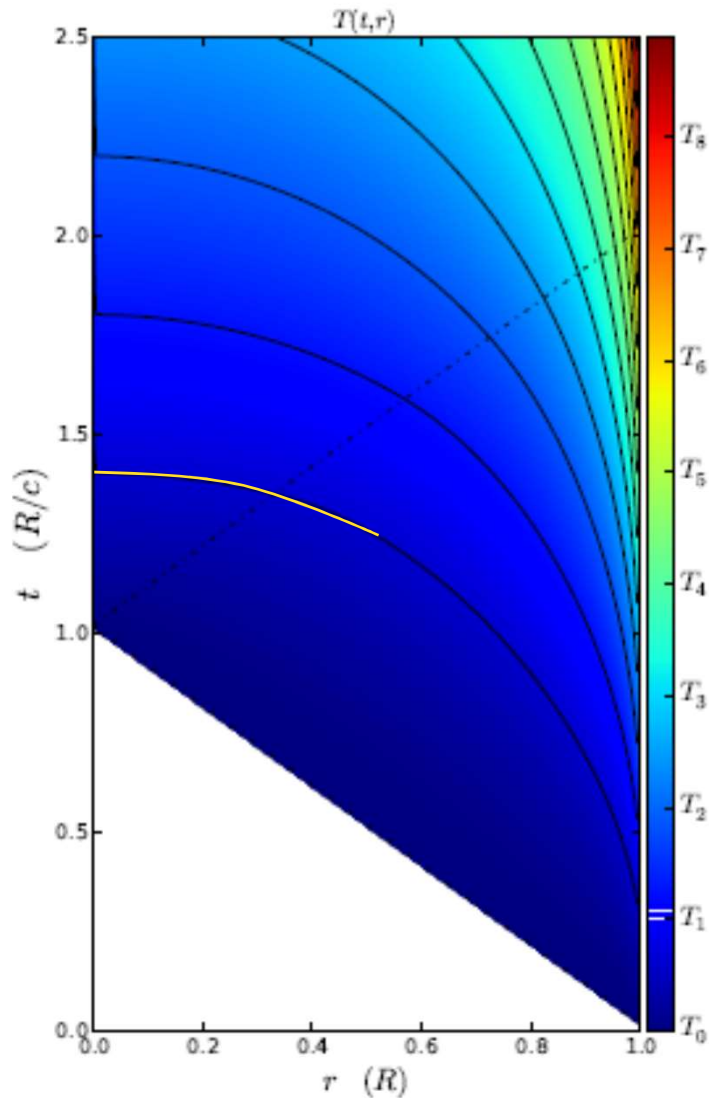
ДЕТОНАЦИЯ НА ВРЕМЕНИПОДОБНОМ ФРОНТЕ
ДЛЯ РЕЛЯТИВИСТСКИХ СИСТЕМ

Сборник трудов Института теоретической и экспериментальной физики



@ CERN in High energy heavy ion collisions

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



Fusion reaction:

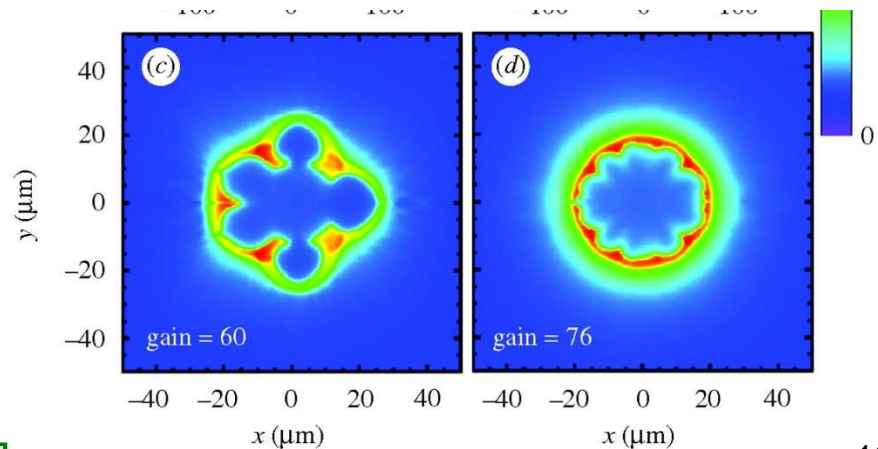


Constant absorptivity,
Spherical irradiation

Ignition temperature = $T_1 \rightarrow$

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

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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Key words:

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

Author for correspondence:

L.P. Csernai, Department of Physics and Technology, University of Bergen, Bergen, Norway. E-mail: Laszlo.Csernai@uib.no

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

Radiation dominated implosion with nano-plasmonics

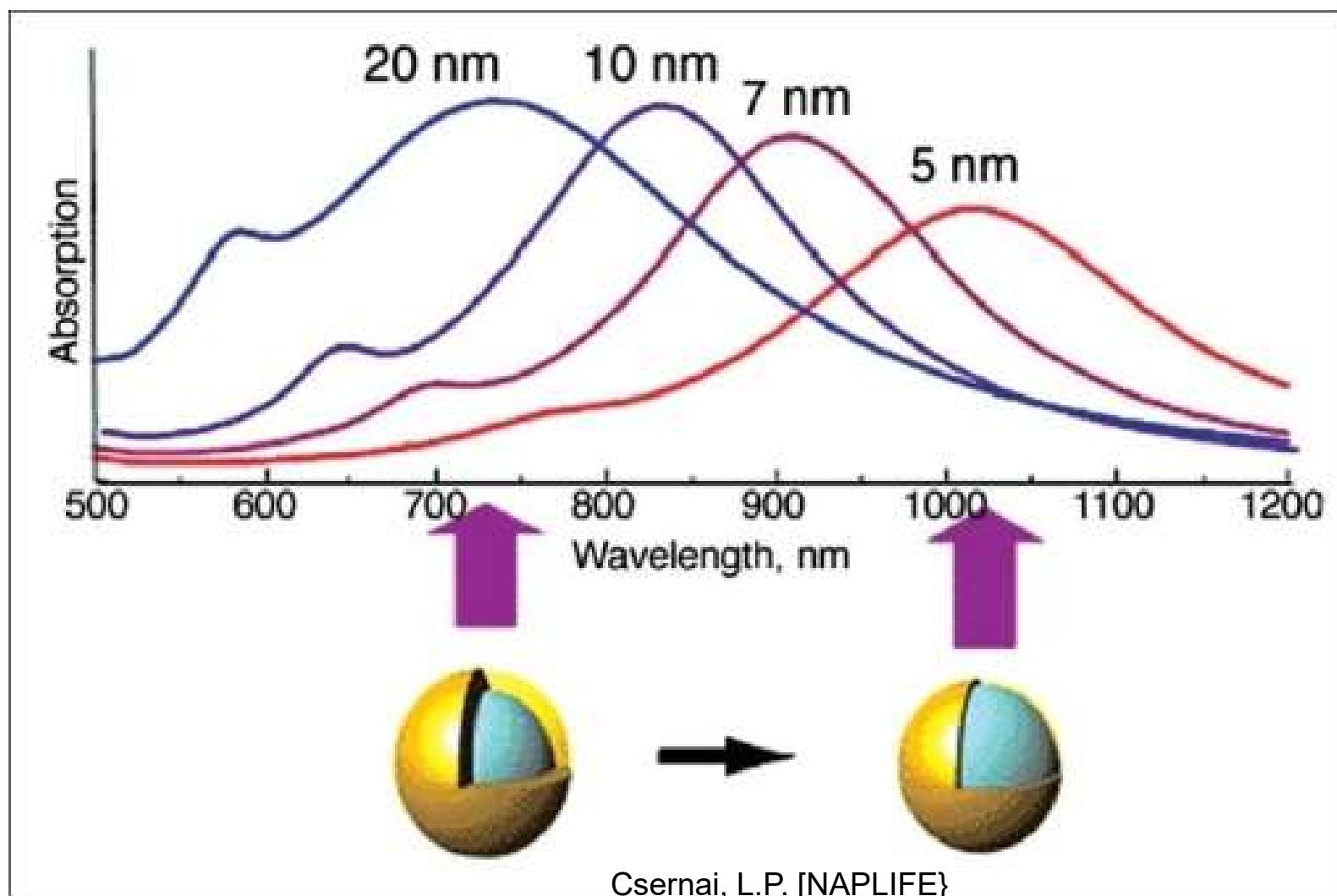
L.P. Csernai¹, N. Kroo^{2,3} and I. Papp⁴

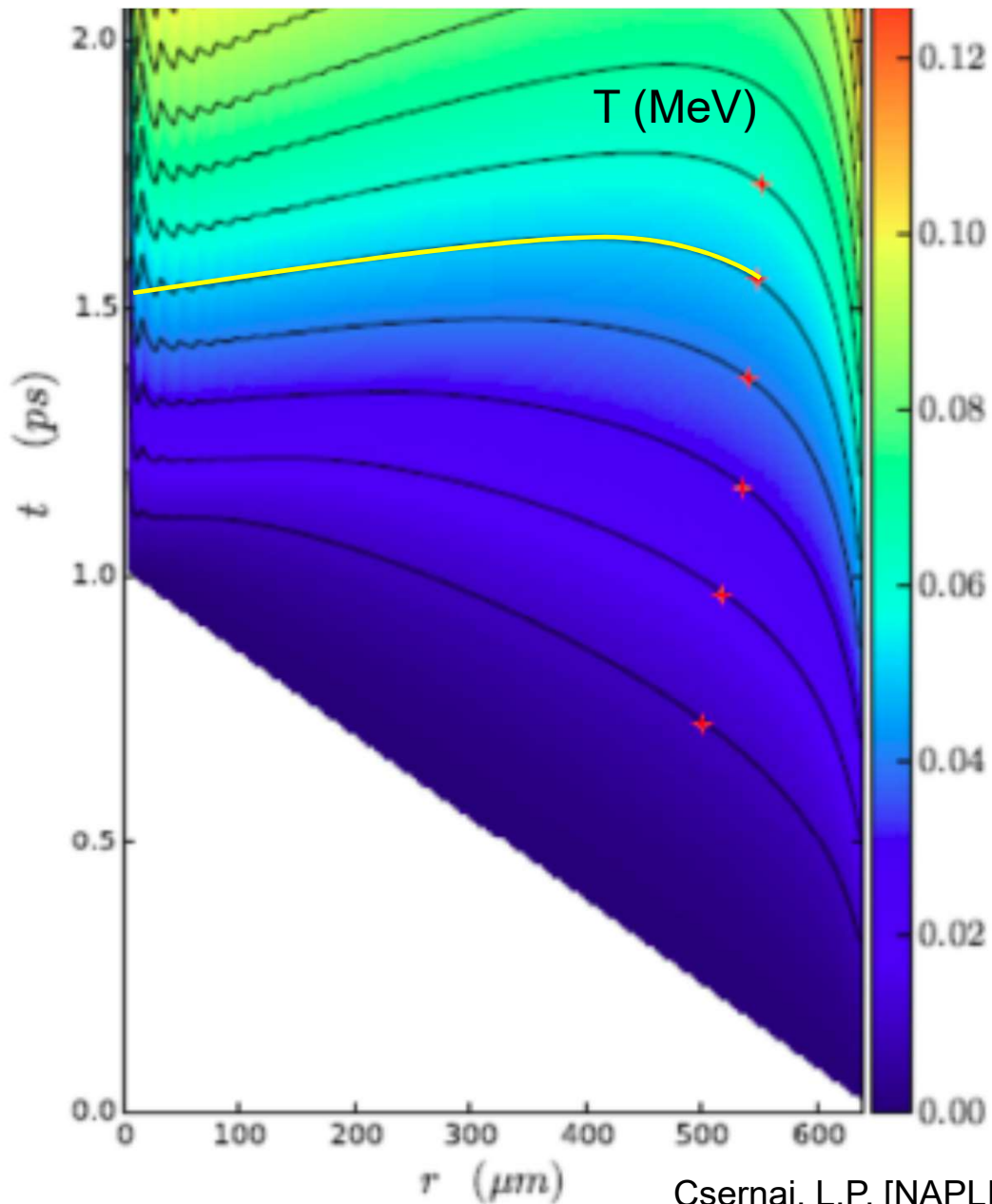
¹Department of Physics and Technology, University of Bergen, Bergen, Norway; ²Hungarian Academy of Sciences, Budapest, Hungary; ³Wigner Research Centre for Physics, Budapest, Hungary and ⁴Department of Physics, Babes-Bolyai University, Cluj, Romania

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.

Golden Nano-Shells – Resonant Light Absorption





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The absorption coefficient is **linearly** changing with the radius: In the center, $r = 0$, $\alpha_K = 30 \text{ cm}^{-1}$ while at the outside edge $\alpha_K = 8 \text{ cm}^{-1}$.

The temperature is measured in units of $T_1 = 272 \text{ keV}$, 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, ...

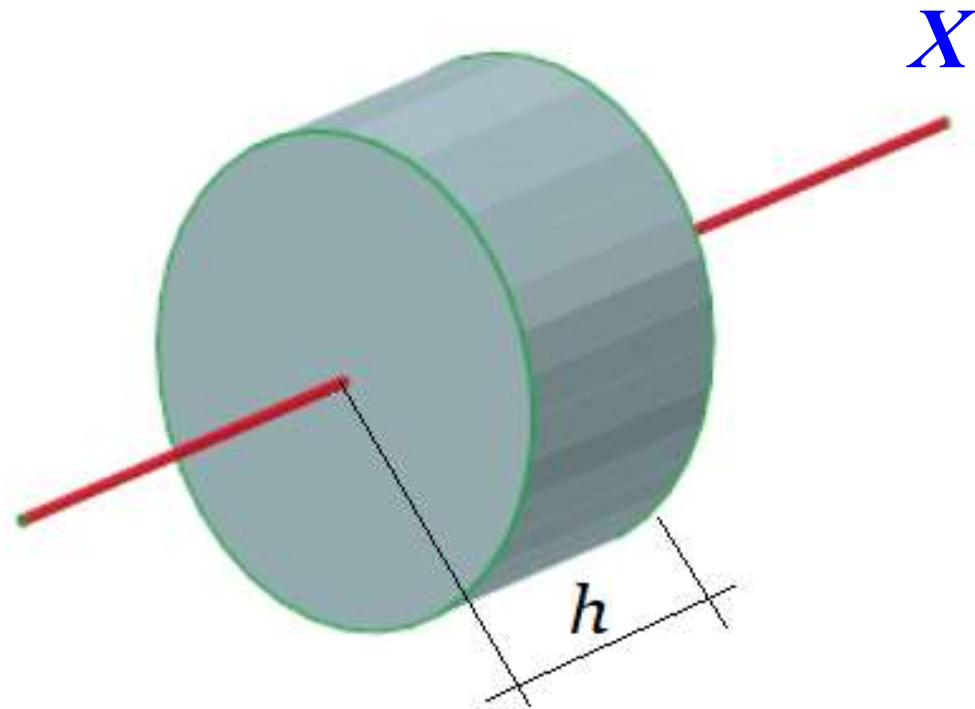


Figure 1: (color online) The target still should be compact to minimize the surface effects. The irradiation is performed along the x -axis from both sides towards the target. The laser beam should be uniform hitting the whole face of the coin shaped target.

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

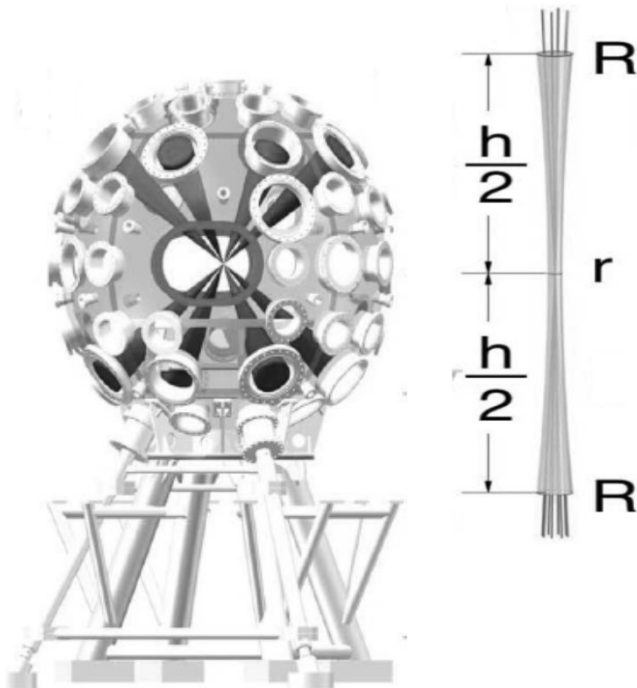
Experimental test of similar configuration @ ShenGuang-II Up, Shanghai :

Nuclear probes of an out-of-equilibrium plasma at the highest compression
Phys. Lett. A 383 (2019) 2285-2289.

G. Zhang^{a,b,*}, M. Huang^c, **A. Bonasera^{d,e,*}**, Y.G. Ma^{f,b,i,*}, B.F. Shen^{g,h,*}, H.W. Wang^{a,b},
 W.P. Wang^g, J.C. Xu^g, G.T. Fan^{a,b}, H.J. Fu^b, H. Xue^b, H. Zheng^j, L.X. Liu^{a,b}, S. Zhang^c,
 W.J. Li^b, X.G. Cao^{a,b}, X.G. Deng^b, X.Y. Li^b, Y.C. Liu^b, Y. Yu^g, Y. Zhang^b, C.B. Fu^k,
 X.P. Zhang^k

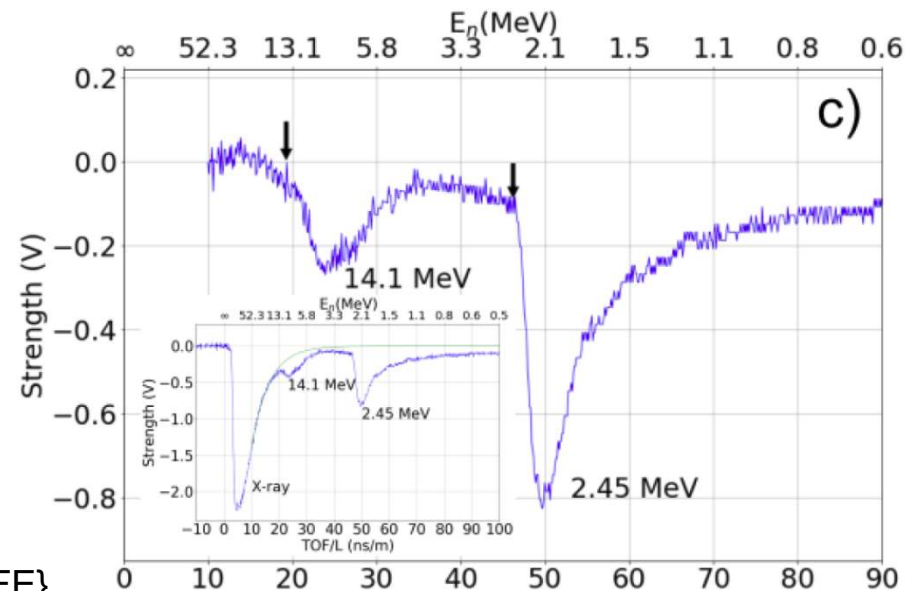
4 (up) + 4(down) lasers
 Target thickness, h ($3.6\mu\text{m}$ - 1mm)
 & radius, R , (150 - $400\mu\text{m}$) were
 varied.

Total pulse energy 1.2kJ (2ns) for 8 beams.
 Shortest (250ps) pulses \rightarrow 100s MeV ions $>$
 non-thermal distr. = directed ion acceleration



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Typical fusion neutron energies were measured
 & used to extract the target density.



Experimental test of similar configuration @ ShenGuang-II Up, Shanghai :

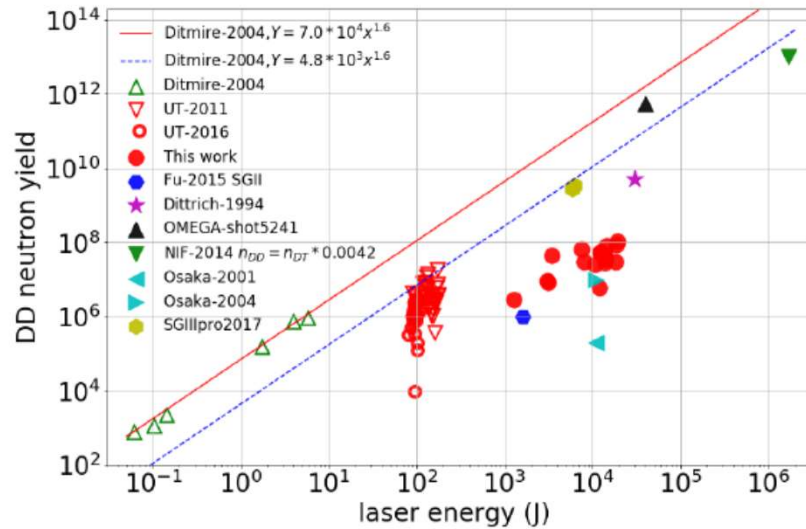


Figure 3: (color online) Fusion yield as function of laser energy. Different experimental results Ditmire-2004[40], UT-2011[20], UT-2016[19], Fu-2015 SGII[45], Dittrich-1994[49], NIF-2014[48], Osaka-2001[46], Osaka-2004[47], OMEGA-shot5241[41] and SGIIpro2017[42] are indicated in the inset.

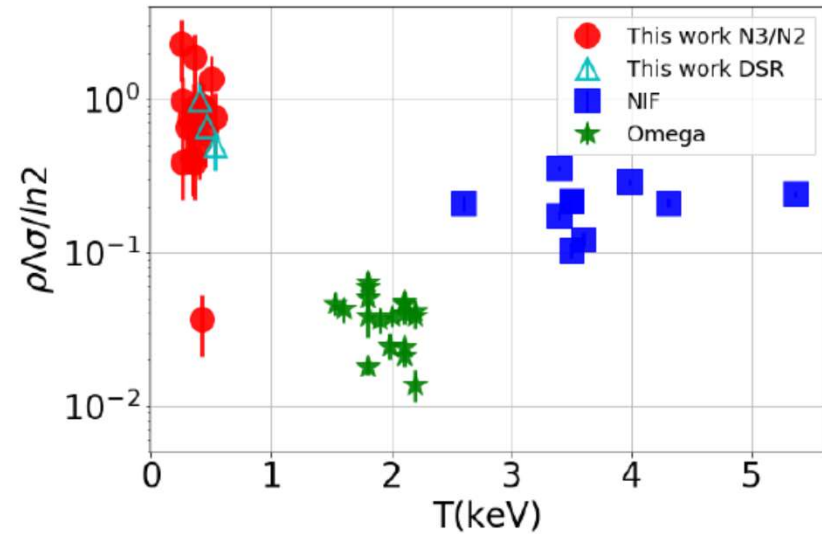
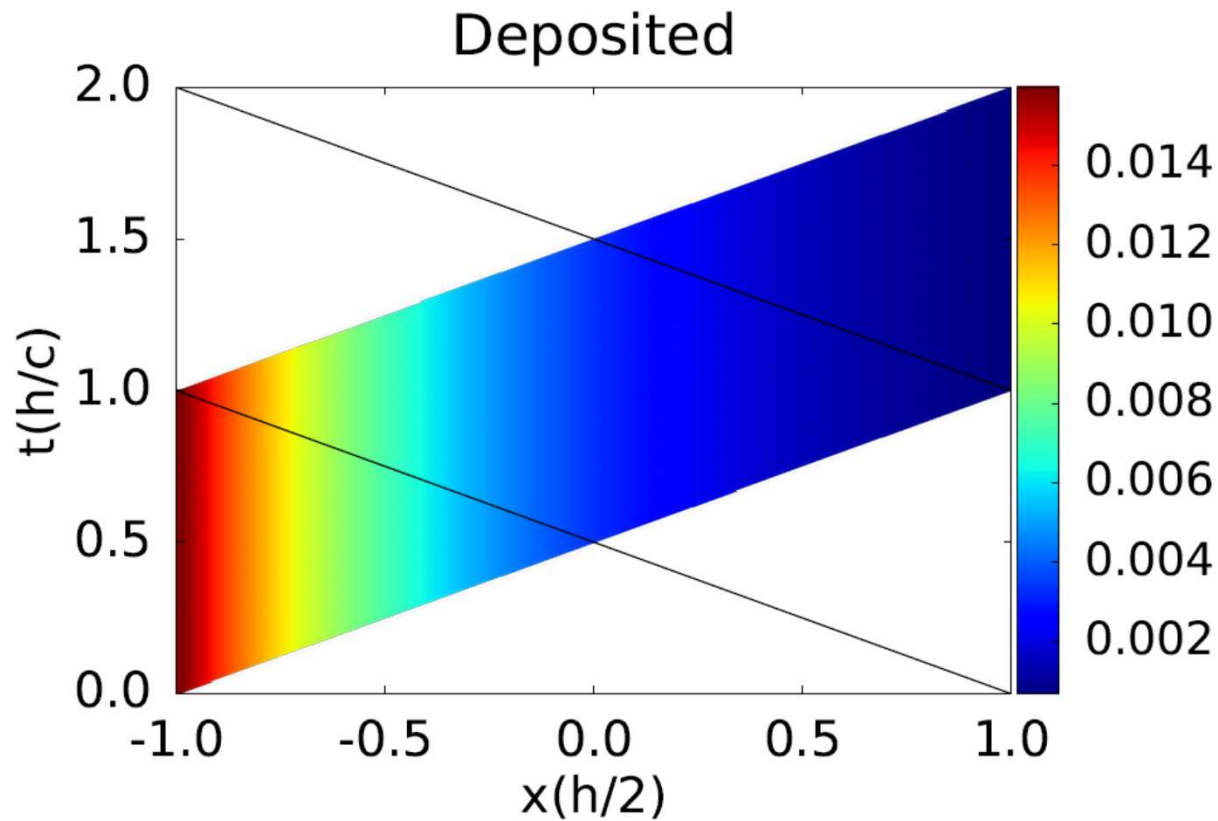


Figure 4: (color online) $\Lambda \rho \sigma / \ln 2$ obtained from eq.(4) vs T from eq.(1). Omega and NIF data are derived from the experiments[25], using the Down Scatter Ratio[23, 21]. Our results using the DSR method (N_4/N_3) are given by the open triangle symbols in good agreement with the N_3/N_2 ratios.

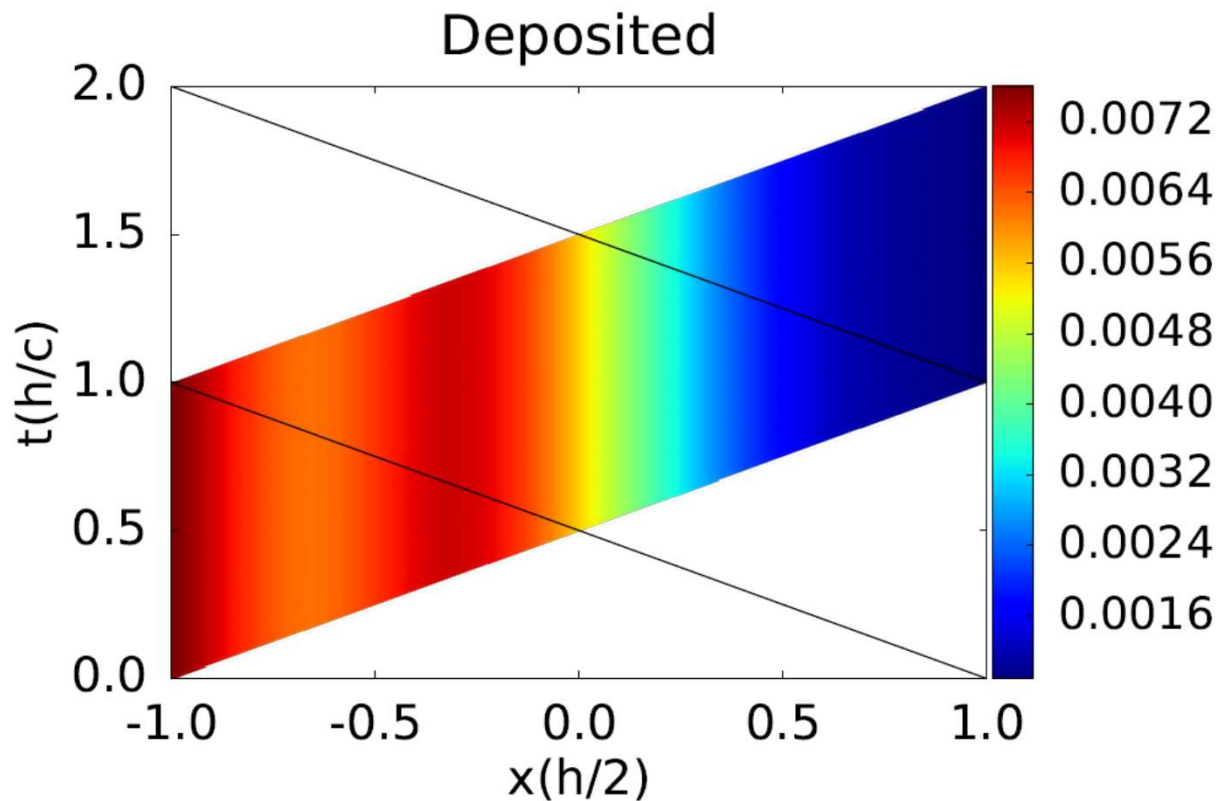
Stimulated by these considerations we decided not to fight non-equilibrium effects but rather enhance them, i.e. study plasmas highly compressed and completely out of equilibrium. A scheme for a colliding

However,
- no simultaneous ignition, and
- no nano-antennas up to now !



**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.

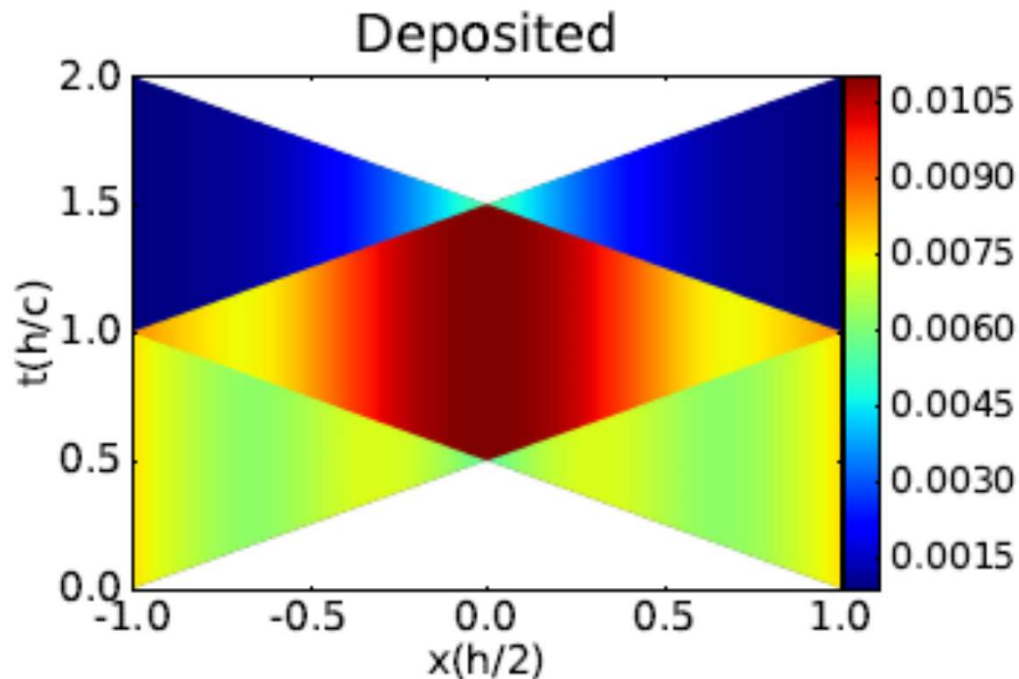


With nano antennas

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.

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With nano antennas

Irradiation from both sides.

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

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

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 $\alpha_K \neq \text{const}$. For more details please see Appendix B.

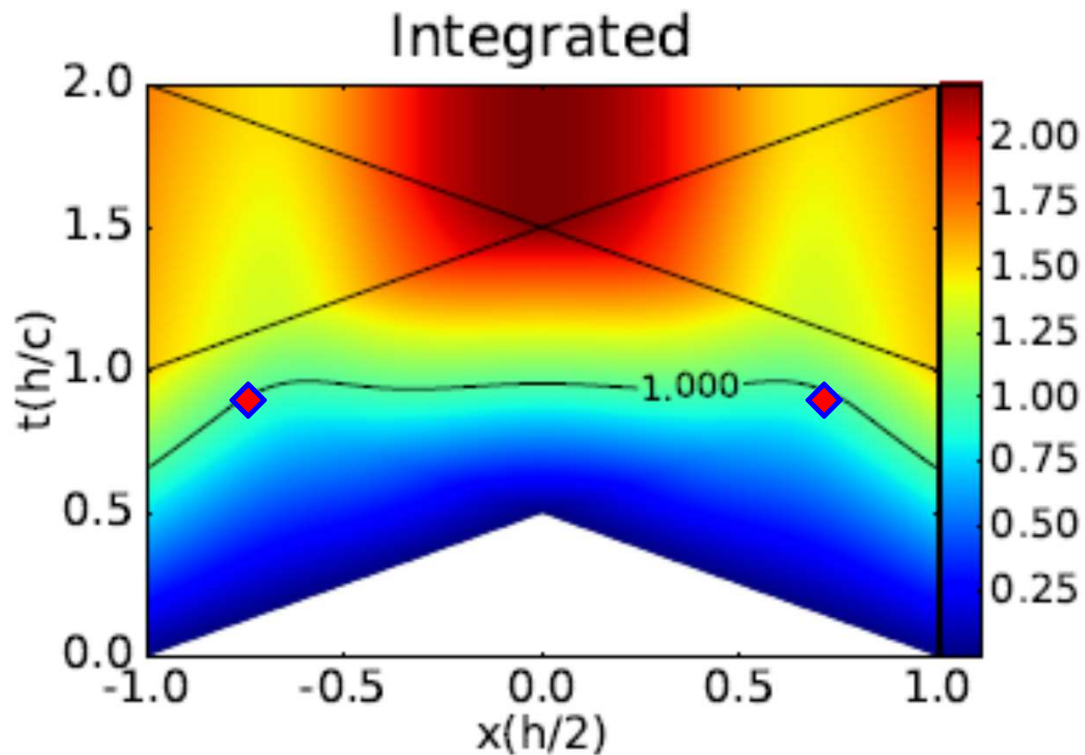


Figure 3: (color online) Integrated energy up to a given time in the space-time across the depth, h , of the flat target. The color code indicates the temperature, T , reached in a given space-time point, in units of the critical temperature, (T_c) . The contour line $T = 1$, indicates the critical temperature, 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.

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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

Validation tests at lower energies
idea #2 increased absorption via
nano-antennas

Wigner RCP, Budapest



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

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Target Modeling and Manufacturing

Target materials, absorptivity, implanted nanoantennas

Cyclic olefin copolymer (COC)

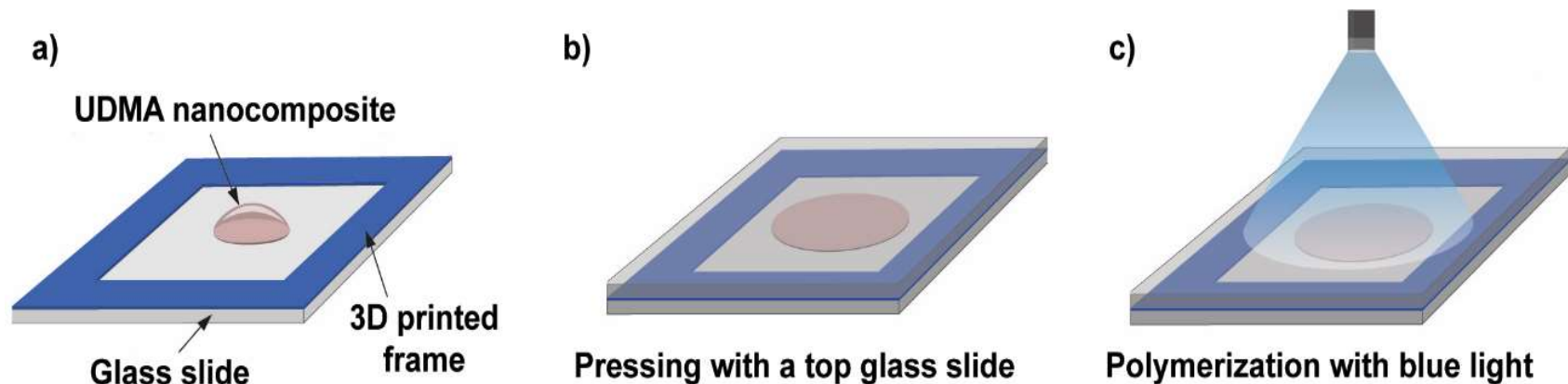
Urethane dimethacrylate (UDMA) - 75%

triethylene glycol dimethacrylate (TEGDMA) - 35%

Flat layered target

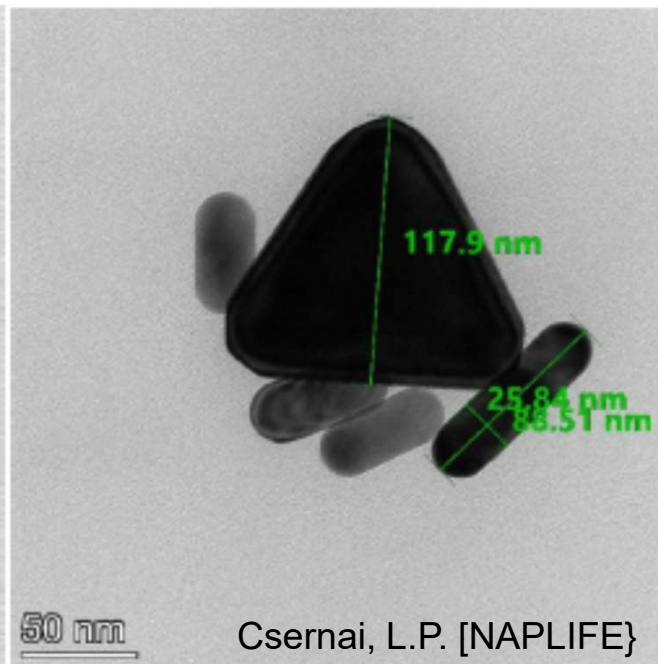
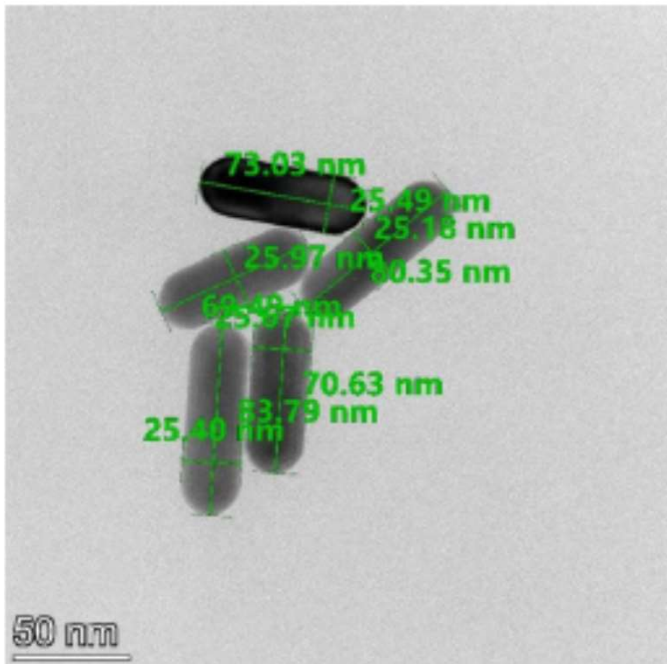
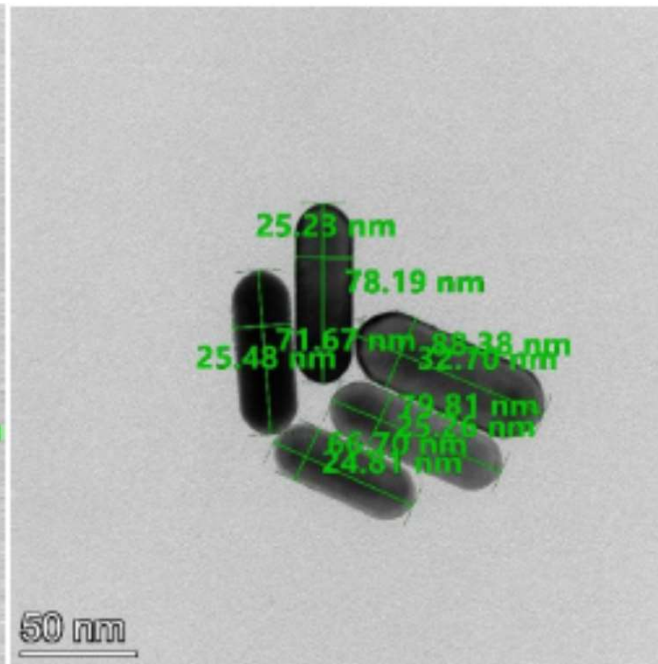
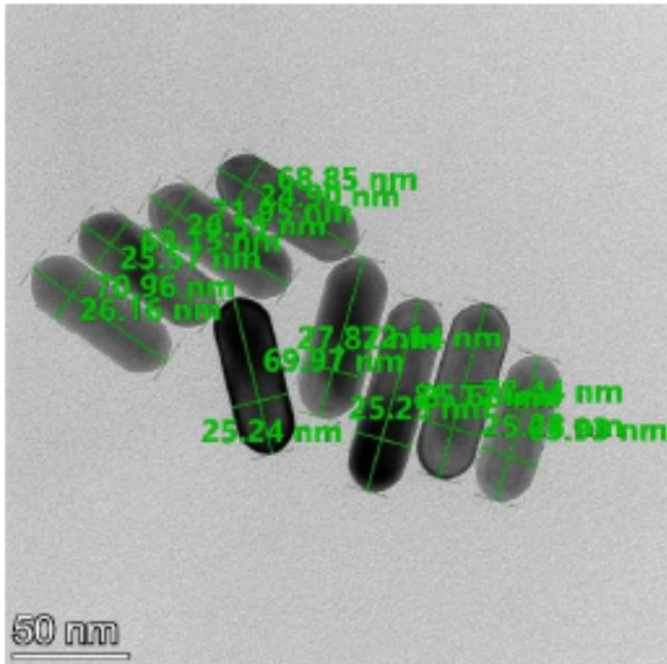
One layer thickness: 3 μm

Seven layers: 21 μm

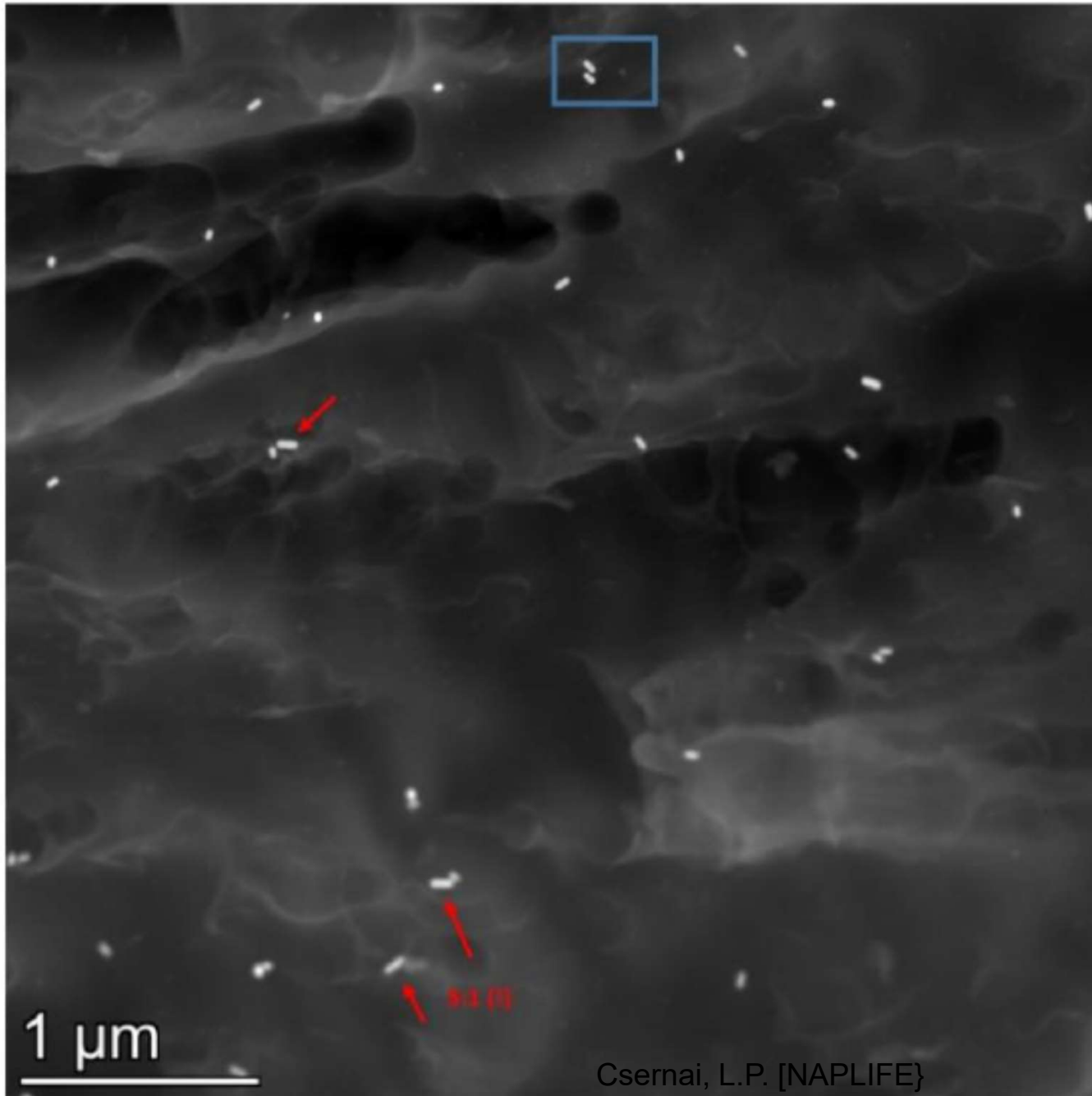


[A. Bonyar et al., In preparation]

Transmission
Electron-
microscopy
photos of
75x25 nm
gold nano-rod
antennas
**[A. Bonyar et
al.]**



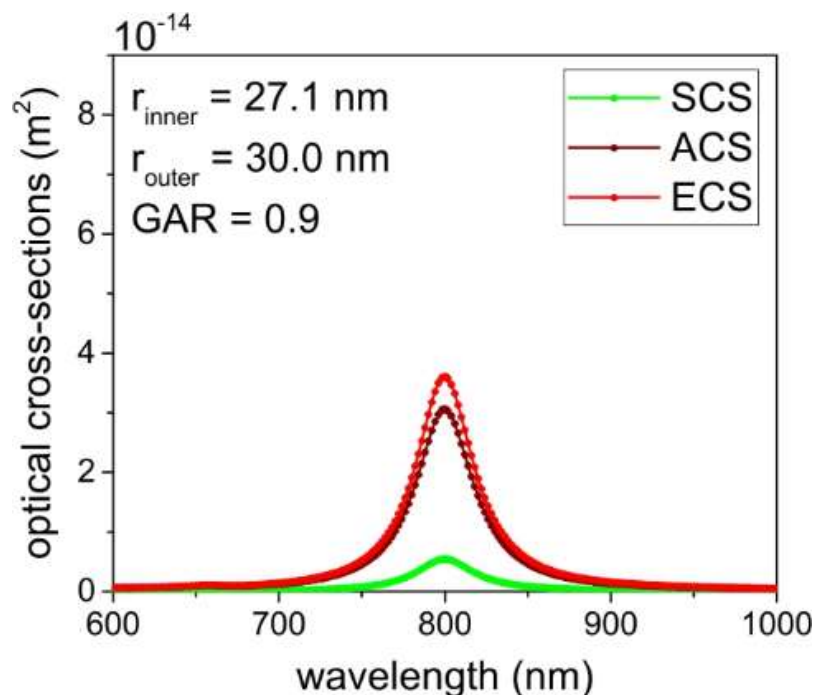
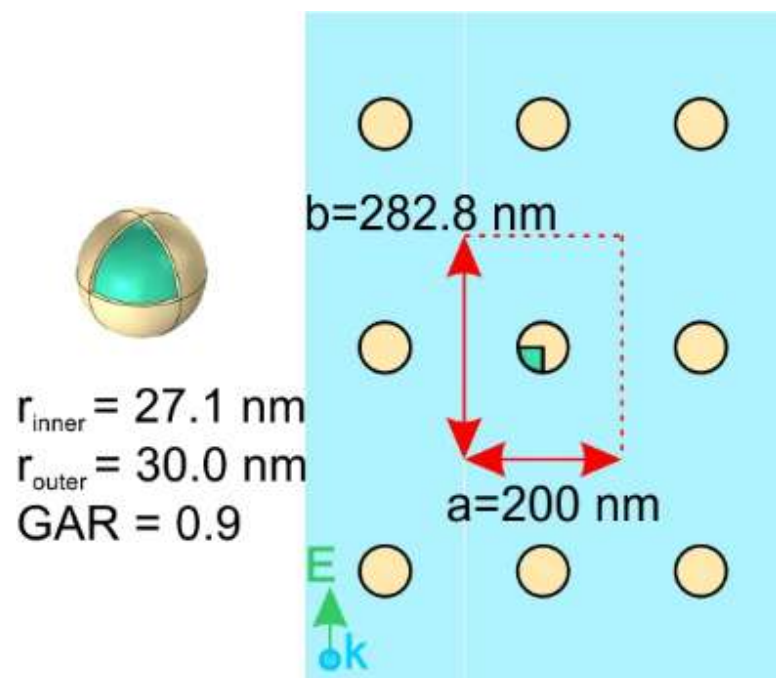
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TEM Photo of
~uniformly
implanted
nanorod
antennas in
UDMA target
polymer. The
density is
 $9-20 / \mu\text{m}^3$
[A. Bonyar et
al.]

Nano-particle absorption

The target absorptivity is increased via core-shell type plasmonic nano-shells. Calculations via solving the Maxwell equations, and evaluating the ohmic heating were performed using the COMSOL simulation package.



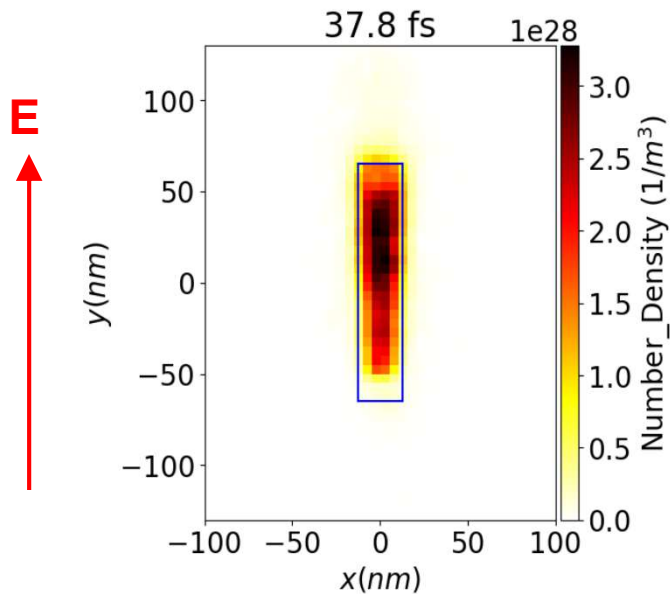
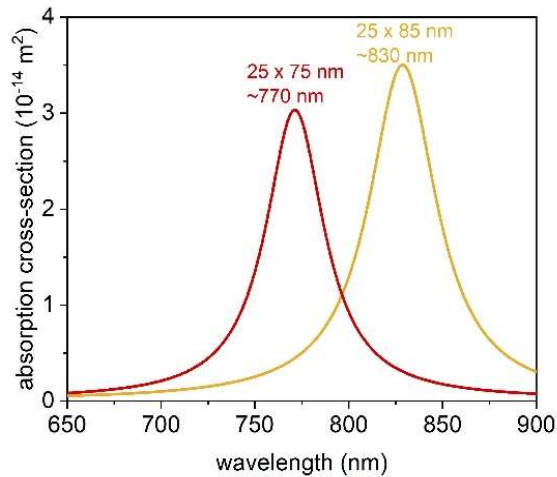
1 ps laser pulse length, $\lambda = 800 \text{ nm}$, One-sided & two-sided irradiation tested, 85-100 % absorption in the target length h . Nano-antenna shapes, layer configurations, layer distribution varied & analyzed.

[M. Csete, et al., U. Szeged, HU <https://doi.org/10.1007/s11468-021-01571-x>]

Nanorod antenna properties

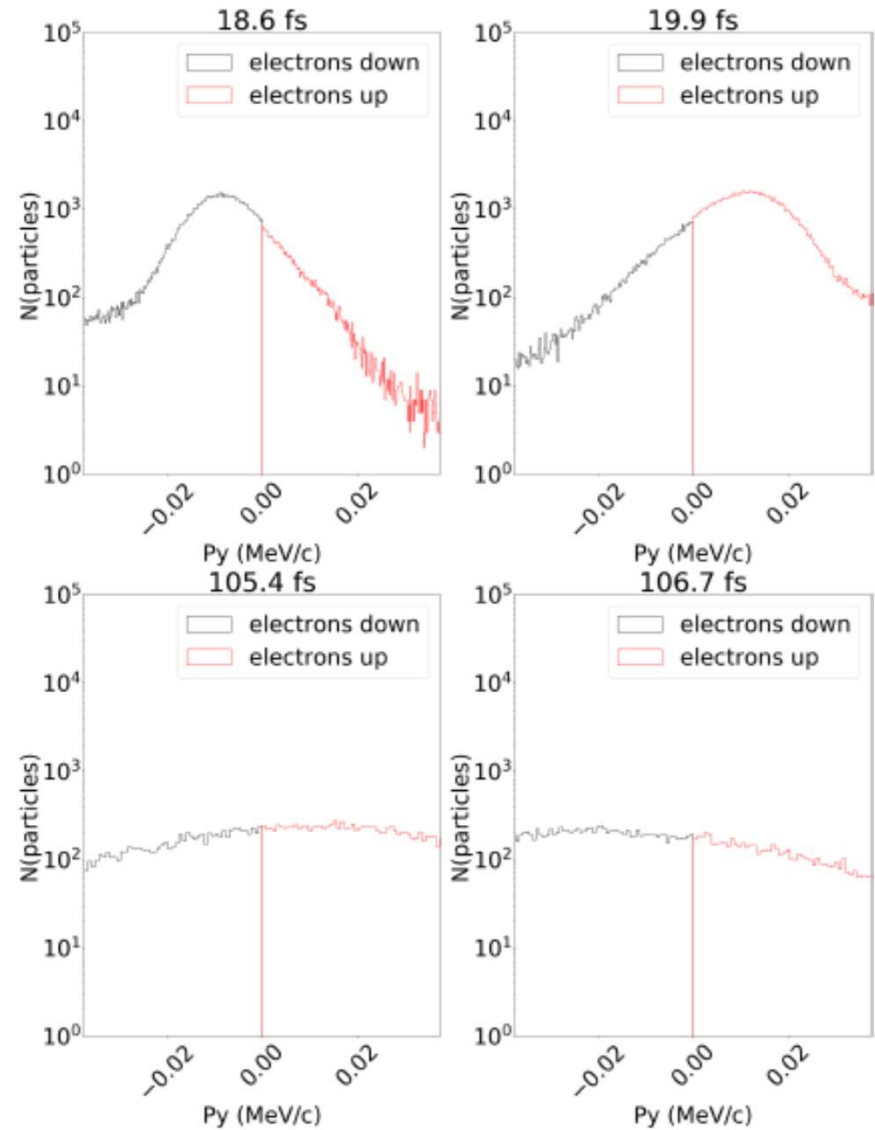
25x75 nm & 25x130 nm antennas, resonant for $\lambda=795$ nm, in UDMA.

[M. Csete et al. [NAPLIFE], in print.



ρ_e for 25x130 nm antennas, in vacuum. EPOCH modified
 [I. Papp et al. [NAPLIFE] in prep.
 See poster W11.

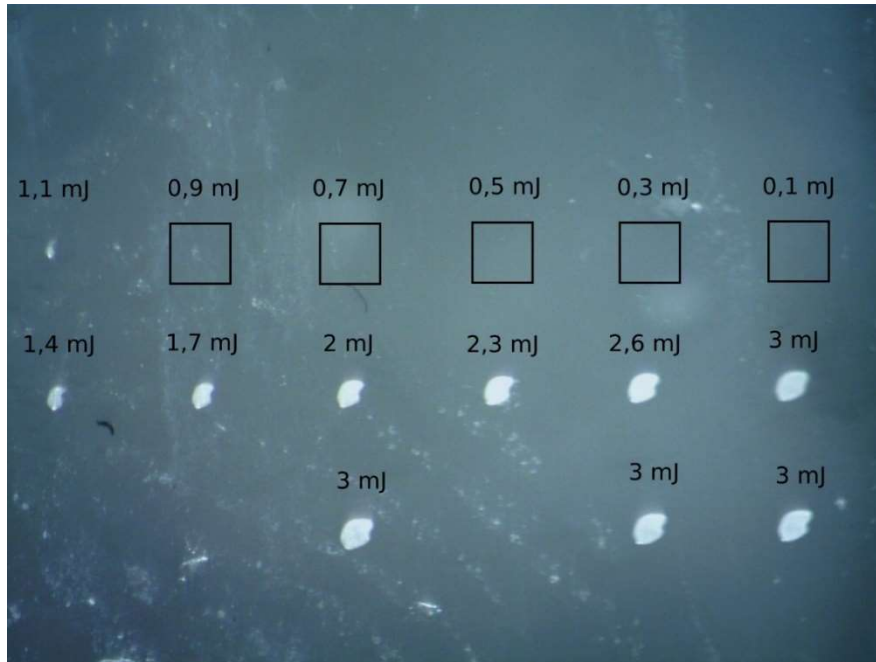
Resilience



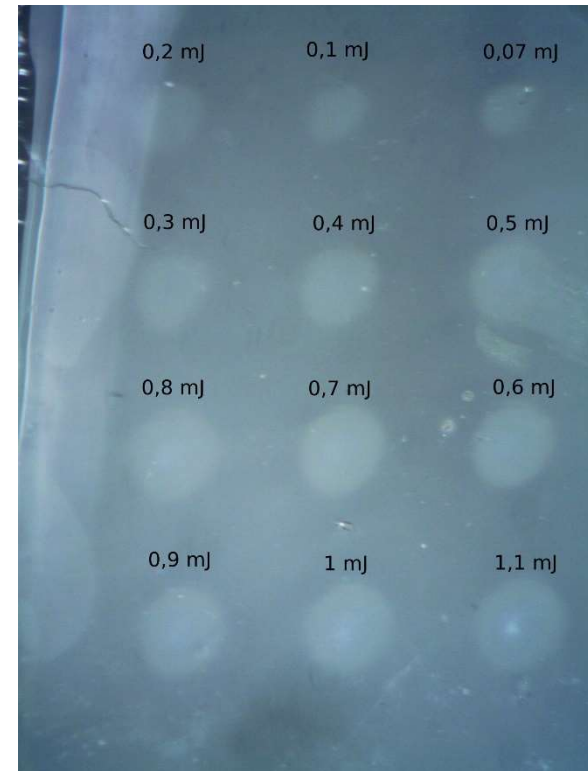
Effect of Short Pulse Laser Beams on target

[Bonyar, Kroo, et al.]

Without nanorods(30x)

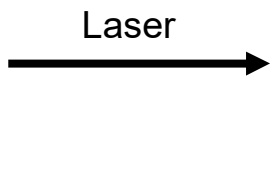


With nanorods (40x)



One pro mil nanorods

Thickness:
~30 μ to 40 μ



300 fs long laser pulses

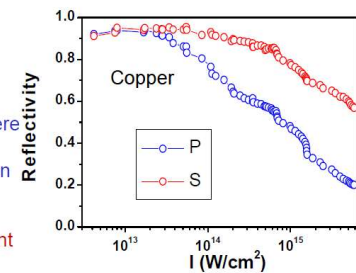
Focus: 85 μ diameter
Pulse length: 300fs
Max Intensity ~4.10¹⁴W/cm²

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$A = 1 - R$

$I < 3 \times 10^{13} \text{ W cm}^{-2}$, A is almost polarization independent & obeys Fresnel laws, as IB is dominant

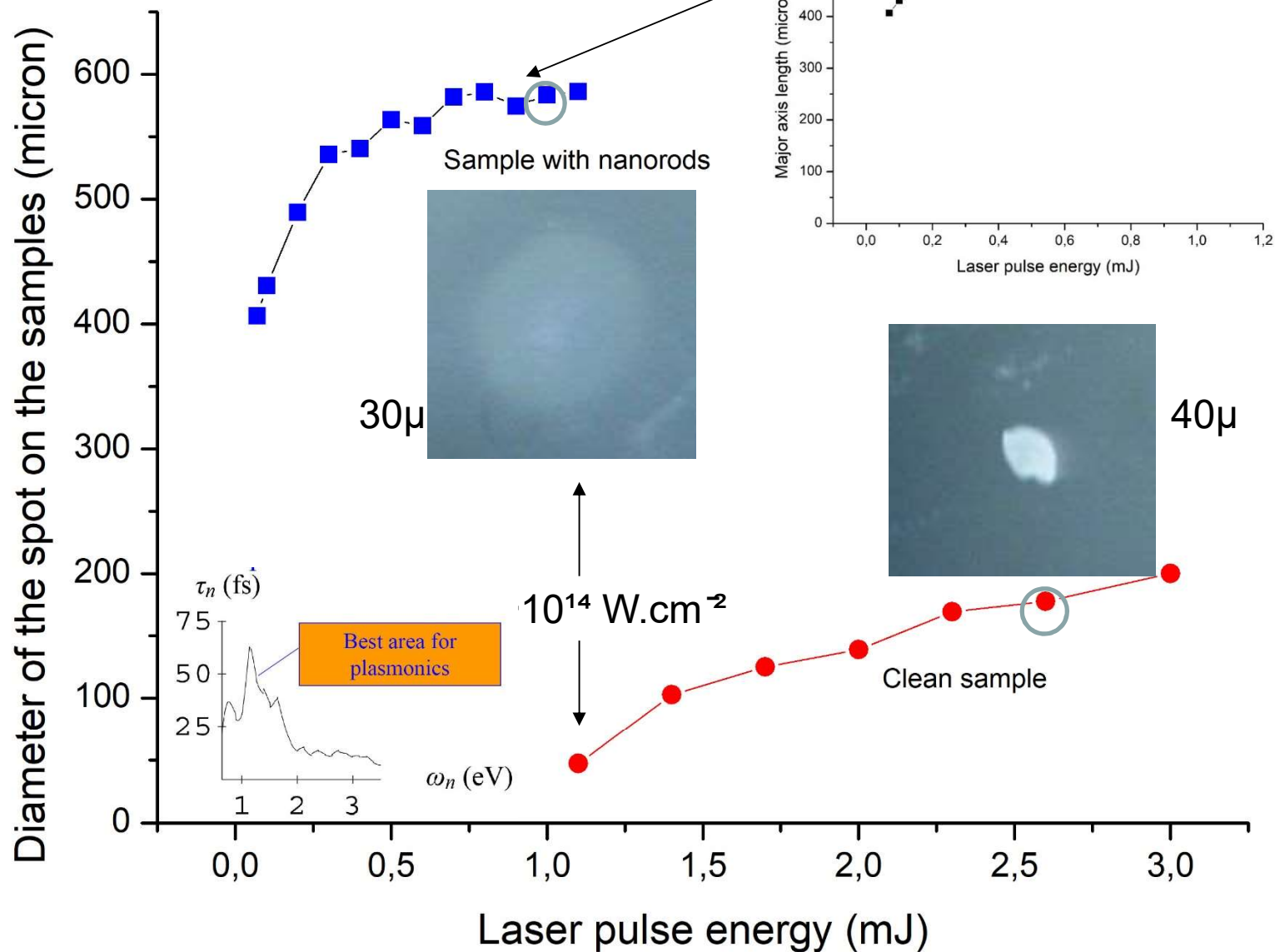
- at higher intensities, there is a clear polarization dependence of absorption
- the difference in absorption should account for extra absorption mechanisms, which are polarization dependent



R vs I at 45°

TIFR data

Laser pulse length: 300 fs
 Ti:Sa laser: $\lambda=800\text{nm}$, $\sim 1.55\text{eV}$



Large plasmonic gain

Laser pulse energy (mJ)

Csernai, L.P. [NAPLIFE]

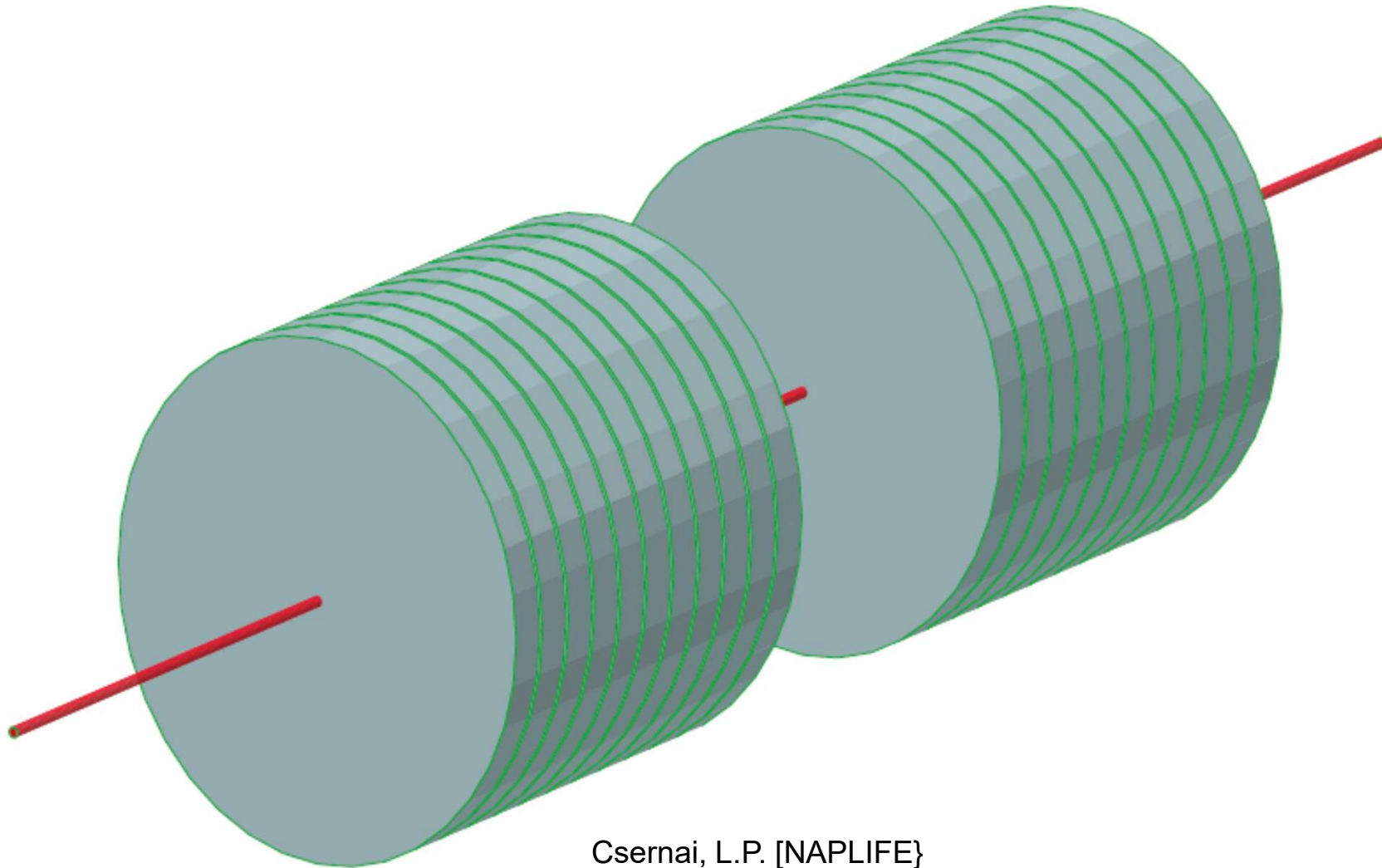
[Bonyar, Kroo, et al.]

Validation tests at lower energies
idea #1 Simultaneous (time-like)
transition (ignition)



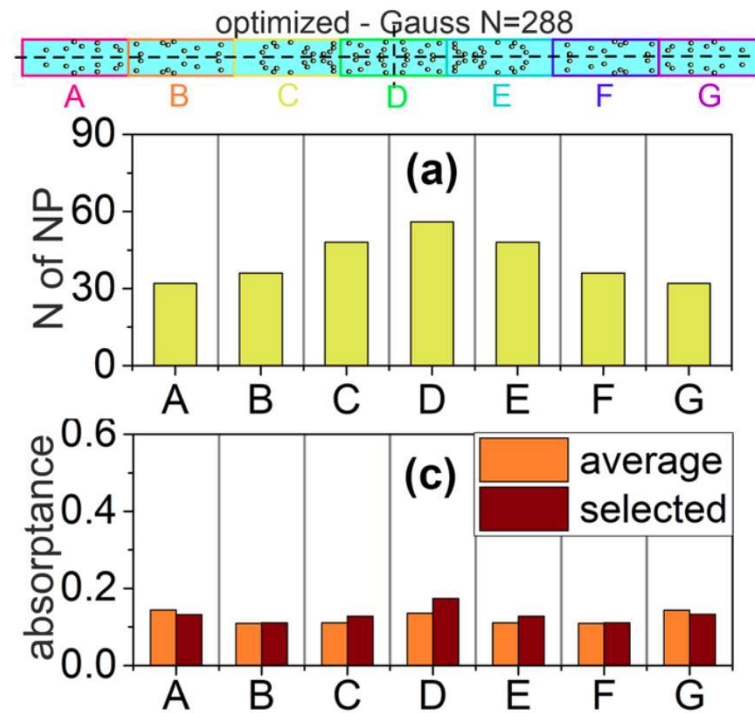
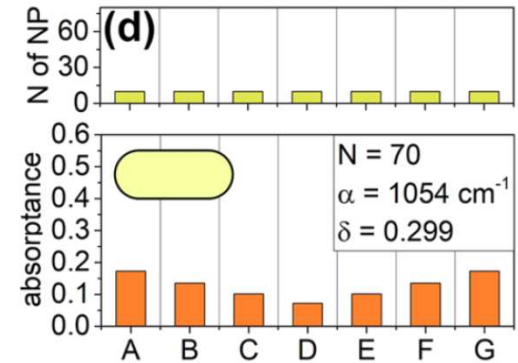
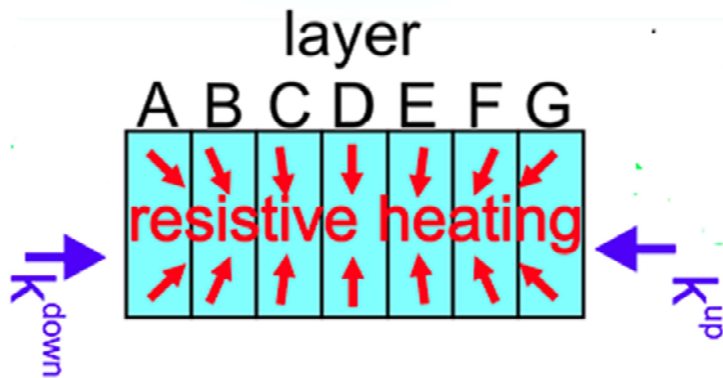
Two opposing beams

Multilayered fuel target



Layered target with variable light absorption

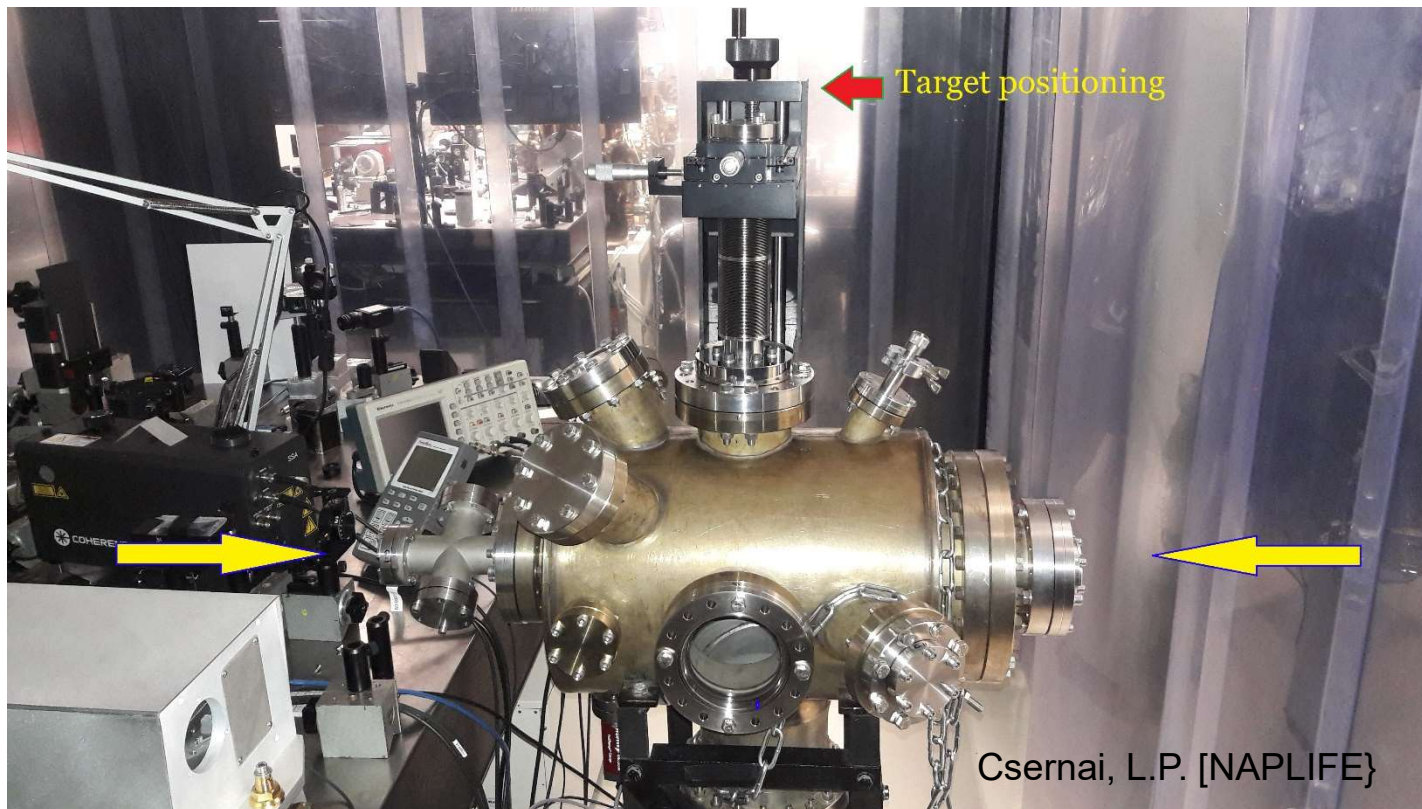
Representative uniform number density distributions of (d) 70 oriented nanorods, in a $1 \times 1 \times 21 \mu\text{m}^3$ supercell of UDMA polymer target, with random location distribution.



Validation tests – Target manufacturing

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.]

Soon !



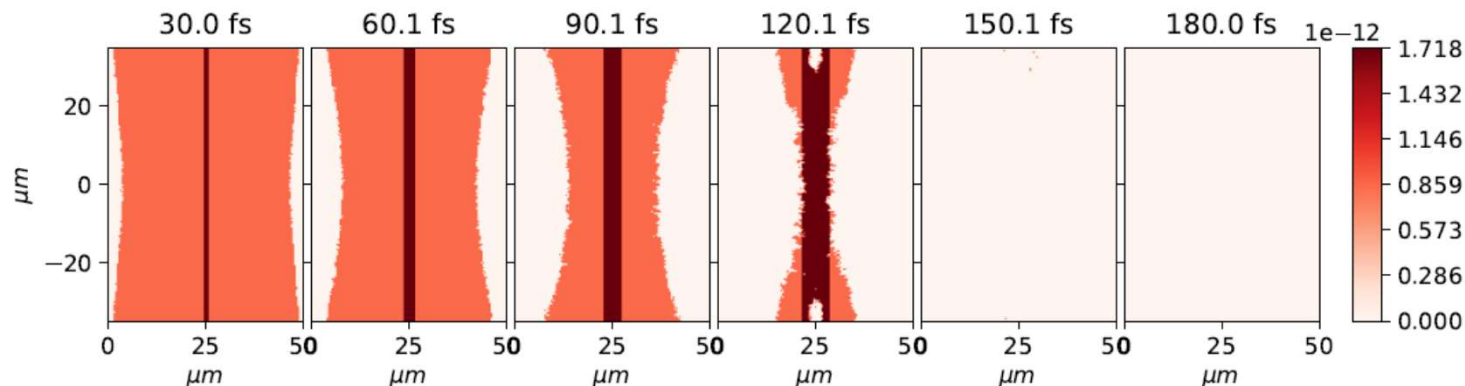
Laser Wake Field Collider

∃ Pre-compression/acceleration, before ignition

Ion (e.g. p) Energy $E_p \approx 100$ MeV (or more)

Initial beam densities assumed: $n_H \approx \gamma n_0 = 2 \cdot 10^{-19}/\text{cm}^3$ and $2 \cdot 10^{-21}/\text{cm}^3$
 $\approx n_{\text{liquid-H}}$, $\approx n_{\text{NIF}}/1000$ (/wo precompression!)

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

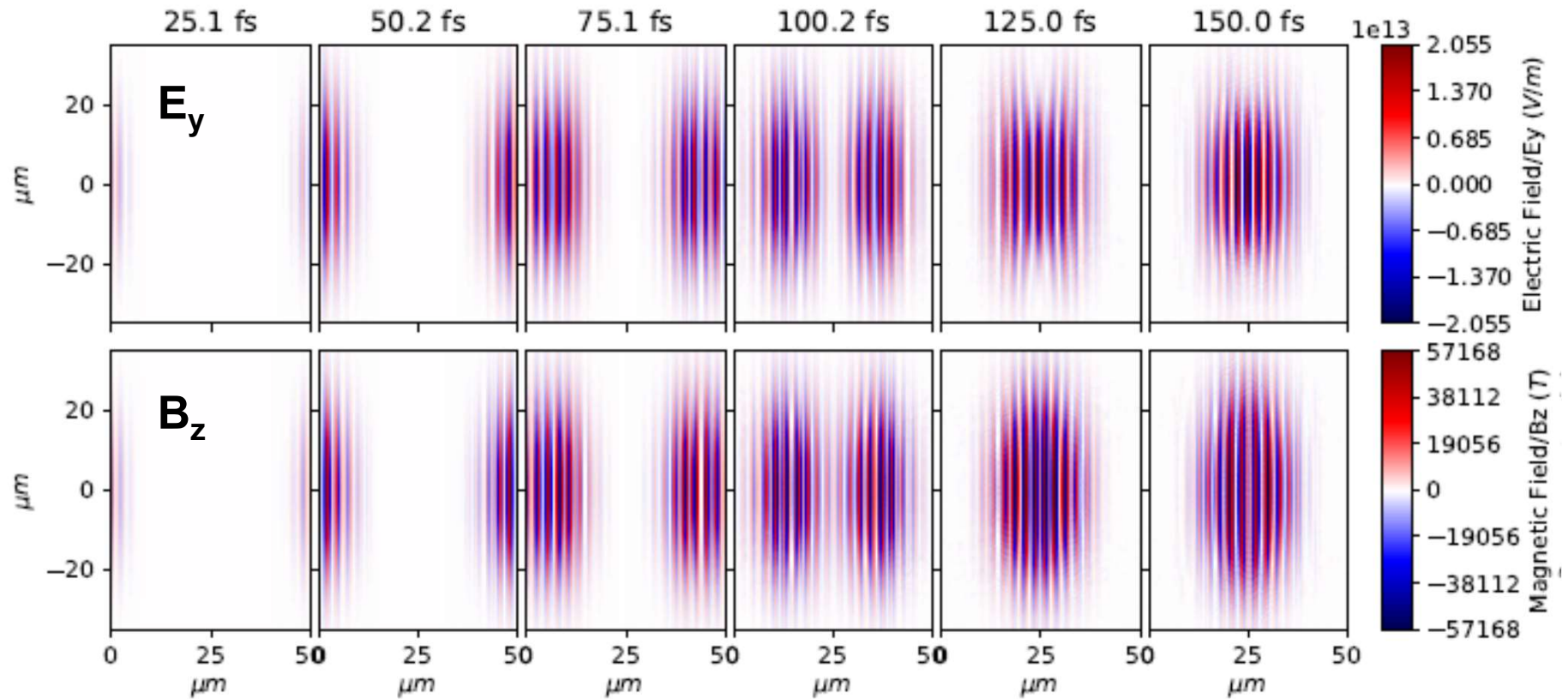


The ionization of the H atoms at ignition in a Laser Wake Field (LWF) wave due to the irradiation from both the +/- x directions

[Papp, I., et al., NAPLIFE, Phys. Lett. A 396, 12724 (2021).] See poster W11

Csernai, L.P. [NAPLIFE}

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 $n_H = 2.13 \cdot 10^{25}/\text{m}^3 = 2.13 \cdot 10^{19}/\text{cm}^3$. The laser beam wavelength is $\lambda = 1\mu\text{m}$. The LWF wavelength is about 20λ . **Pulse energy is 19.6 J.**

..

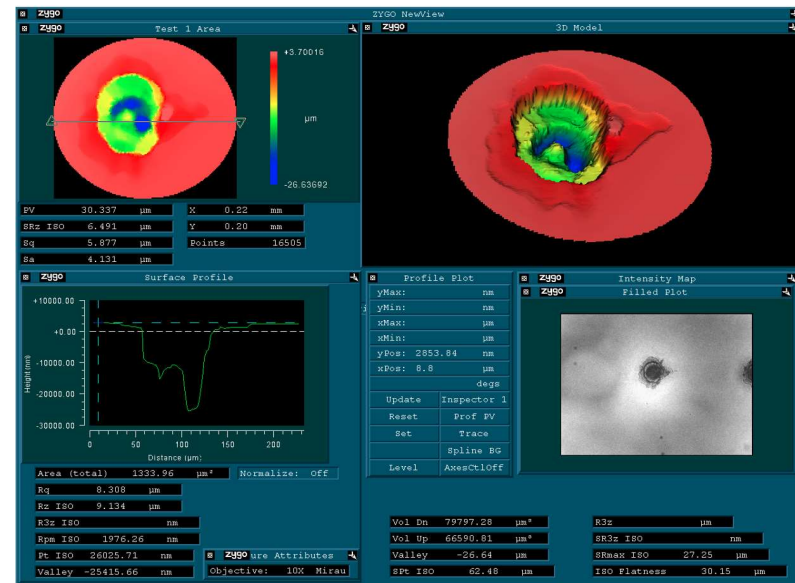
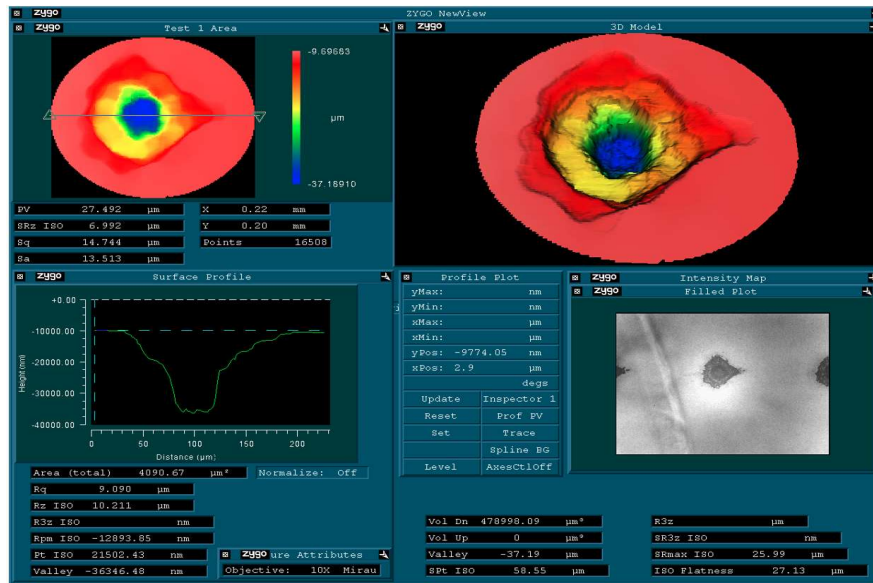
Validation tests →

Unexpected surprise:

**Laser Induced Fusion
with Nanoantennas**

Deuterium production with 795nm 40fs Ti:Sa laser 10^{16} - 10^{17} W/cm² intensity

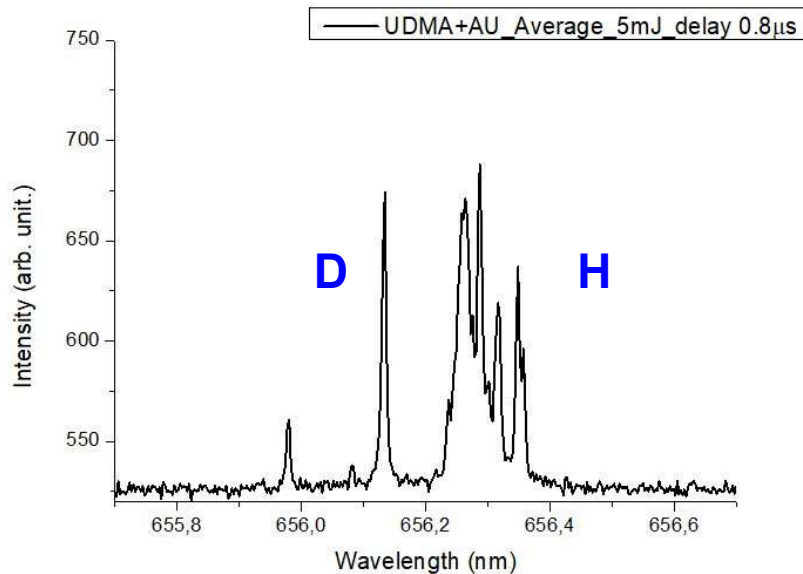
UDMA-TEGDMA target 20-100 μm thick, $\backslash\text{w}$ & $\backslash\text{wo}$ Au nanorods 25x85nm.
→ 5 mJ pulse → crater of 4.55 - $1.07 \cdot 10^{14}$ μm^3 $\backslash\text{w}$ & $\backslash\text{wo}$ Au $\sim 15/ \mu\text{m}^3$



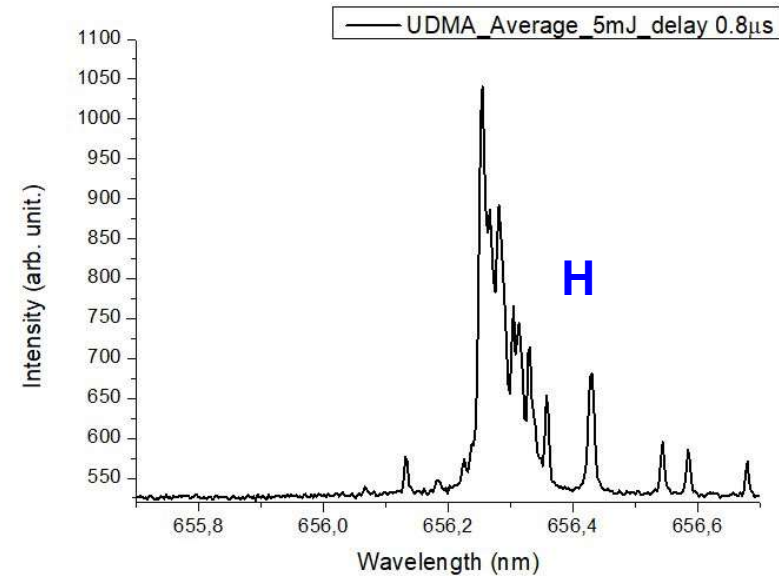
→ From the crater the emitted matter was analysed by Raman spectr. & Laser Induced Breakdown Spectroscopy (LIBS).

Deuterium production

(PRELIMINARY !)



5-12% **D** + 88-95% **H**
~ 10^{17} **D** / pulse (10Hz)



100% **H**
Lyman- α line

Two step process (average of 20 shots):



Electron capture may happen spontaneously in heavy nuclei,

here laser light and resonant nanorods act similarly, high e^- density

UDMA (470: H38, C23, O8, N2)

**High Energy, Short Pulse Laser,
unique
at
ELI – ALPS
Szeged**

A photograph of a man in a dark suit and white shirt standing on a paved plaza in front of a large, modern building with a distinctive, angular, metallic facade. The building's facade is composed of dark, perforated panels. The man is holding a black bag and is looking towards the camera. The sky is clear and blue. The text "European Laser Infrastructure ELI-ALPS Szeged, HU" is overlaid in large, bold, red letters on the right side of the image.

**European Laser
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ELI-ALPS
Szeged, HU**

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European Laser Infrastructure – Szeged, HU



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

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

Thanks for your attention