Nanoplasmonic Laser Fusion

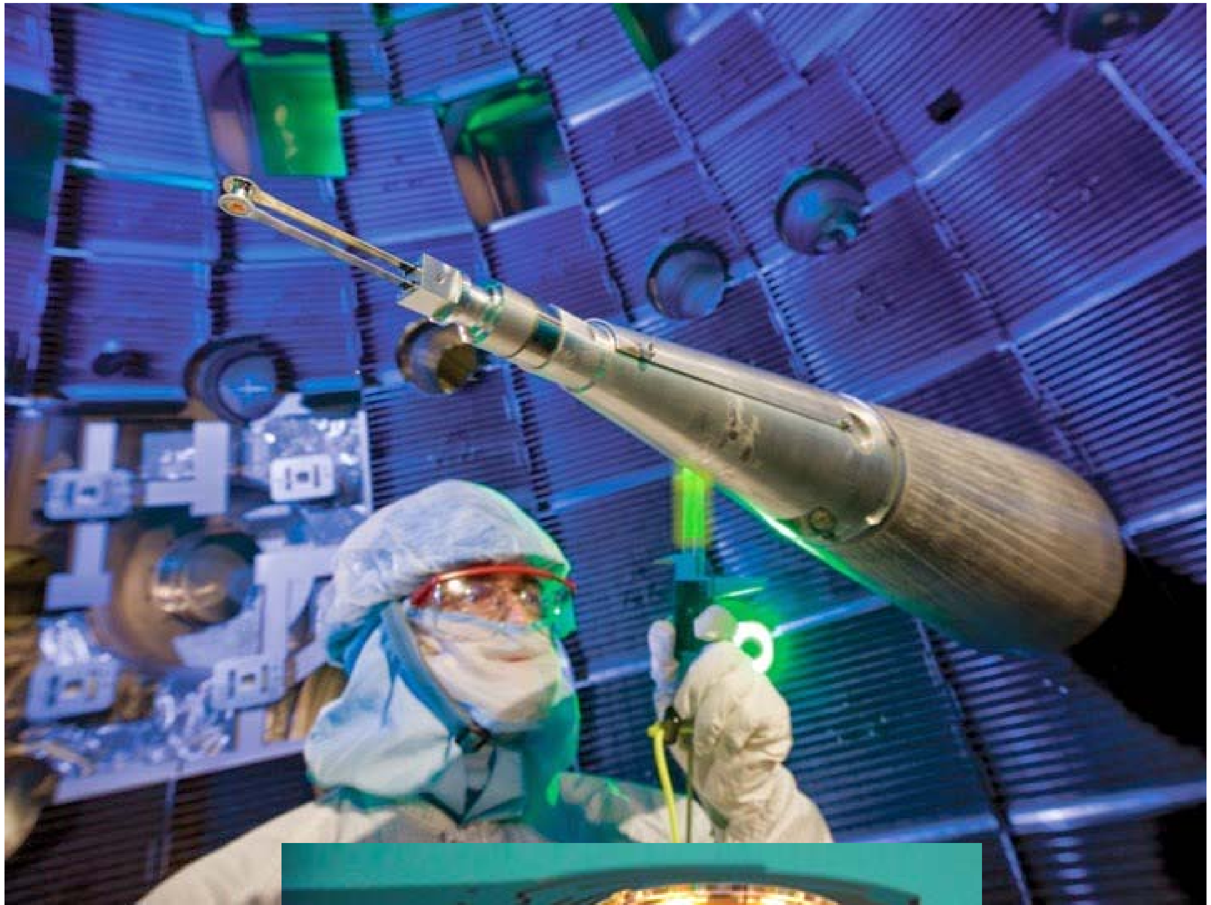
Laszlo P. Csernai, for the
NAPLIFE Collaboration
Univ. of Bergen, Norway
ICNFP - 2020,
Kolymbari, Crete, Sept. 11, 2020

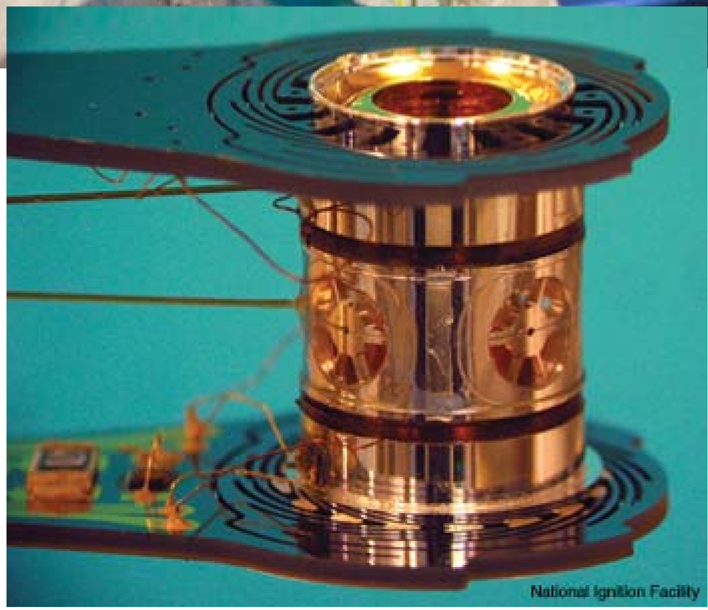
Nano-Plasmonic Laser Inetial Fusion Experiment (NAPLIFE) Collaboration

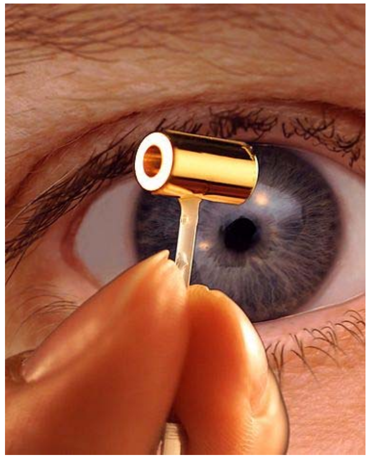
Márk Aladi, Attila Bonyár, Alexandra Borok, Larissa Bravina, Maria Csete, Péter Dombi, Miklós Kedves, Péter Lévai, Igor N. Mishustin, Dénes Molnár, Anton Motornenko, István Papp, Péter Petrik, Péter Rácz, Béla Ráczkevi, Leonid M. Satarov, Horst Stöcker Daniel D. Strottman, Melinda Szalóki, András Szenes, Csaba Tóth, Dávid Vass, Miklós Veres, Tamás S. Biró, László P. Csernai , Norbert Kroó

* L.P. Csernai, M. Csete, I.N. Mishustin, A. Motornenko, I. Papp, L.M. Satarov, H. Stöcker & N. Kroo, Radiation Dominated Implosion with Flat Target, *Physics of Wave Phenomena*, **28** (3) 187-199 (2020), (arXiv:1903.10896v3).
* L.P. Csernai, N. Kroo, & I. Papp, Radiation-Dominated Implosion with Nano-Plasmonics, *Laser and Particle Beams* **36,** 171 (2018), (arXiv:1710.10954)
* I. Papp, L. Bravina, M. Csete, I.N. Mishustin, D. Molnár, A. Motornenko, L.M. Satarov, H. Stöcker, D.D. Strottman, A. Szenes, D. Vass, T.S. Biró, L.P. Csernai, N. Kroó, Laser Wake Field Collider, *t.b.p*. (arXiv: 2009.00000)
* L.P. Csernai, N. Kroó, I. Papp, D.D. Strottman, Nano-plasmonic Laser Fusion, *Laser and Particle Beams, i.p.* (arXiv:2008.09847)

Indirectly Driven,
ICF target for NIF
at LLNL







PHYSICAL REVIEW LETTERS **120,** 245003 (2018)

S. Le Pape et al., (LLNL - NIF)

Fusion Energy Output Greater than the Kinetic Energy of an Imploding Shell at the National Ignition Facility

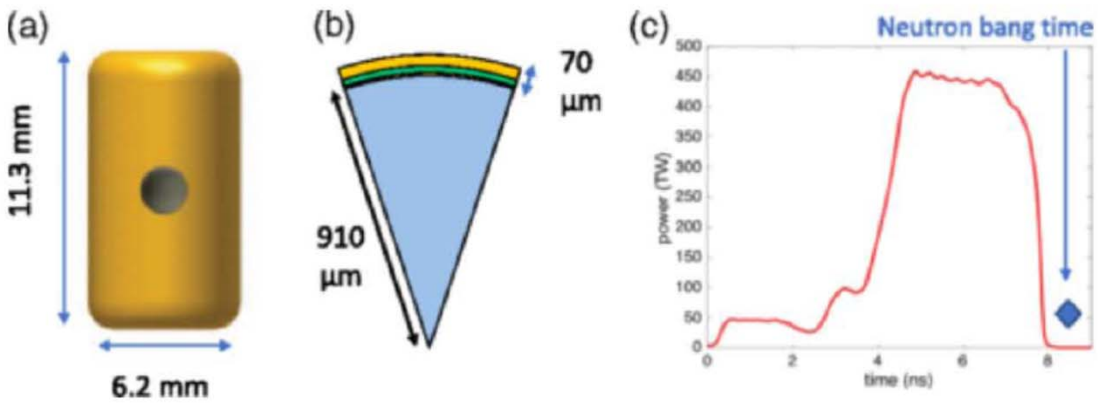


Figure 1

Target and laser specifications for shots N170601 and N170827. (a) 6.20 mm scale hohlraum (b) 70 μm thick HDC capsule used in the 6.20 mm scale hohlraum, green layer denotes the doped layer. This figure illustrates the doped layer of the HDC capsule. The doped HDC layer is 20 microns thick doped with 0.3% atomic percent of tungsten to shield the fuel from suprathermal x rays. This shielding is designed to reduce decompression of the inner capsule region and fuel and to improve the stability of the fuel-capsule interface. (c) Laser pulse.

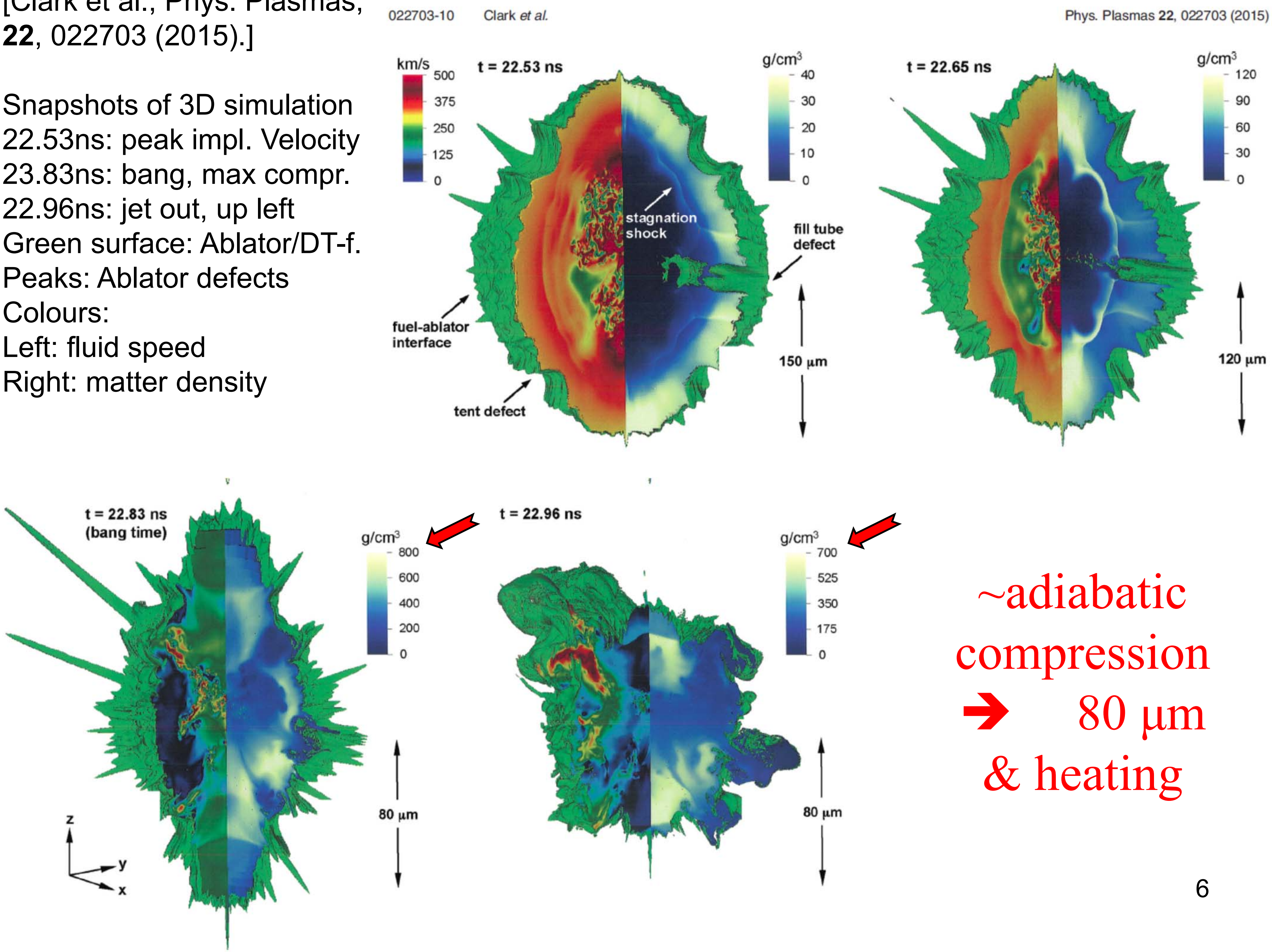
Depleted
Uranium

Notice: The last energetic part of the pulse is less than **4ns**!
(It was ~ 15ns earlier.)

published 14 June 2018

[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

[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

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

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,

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

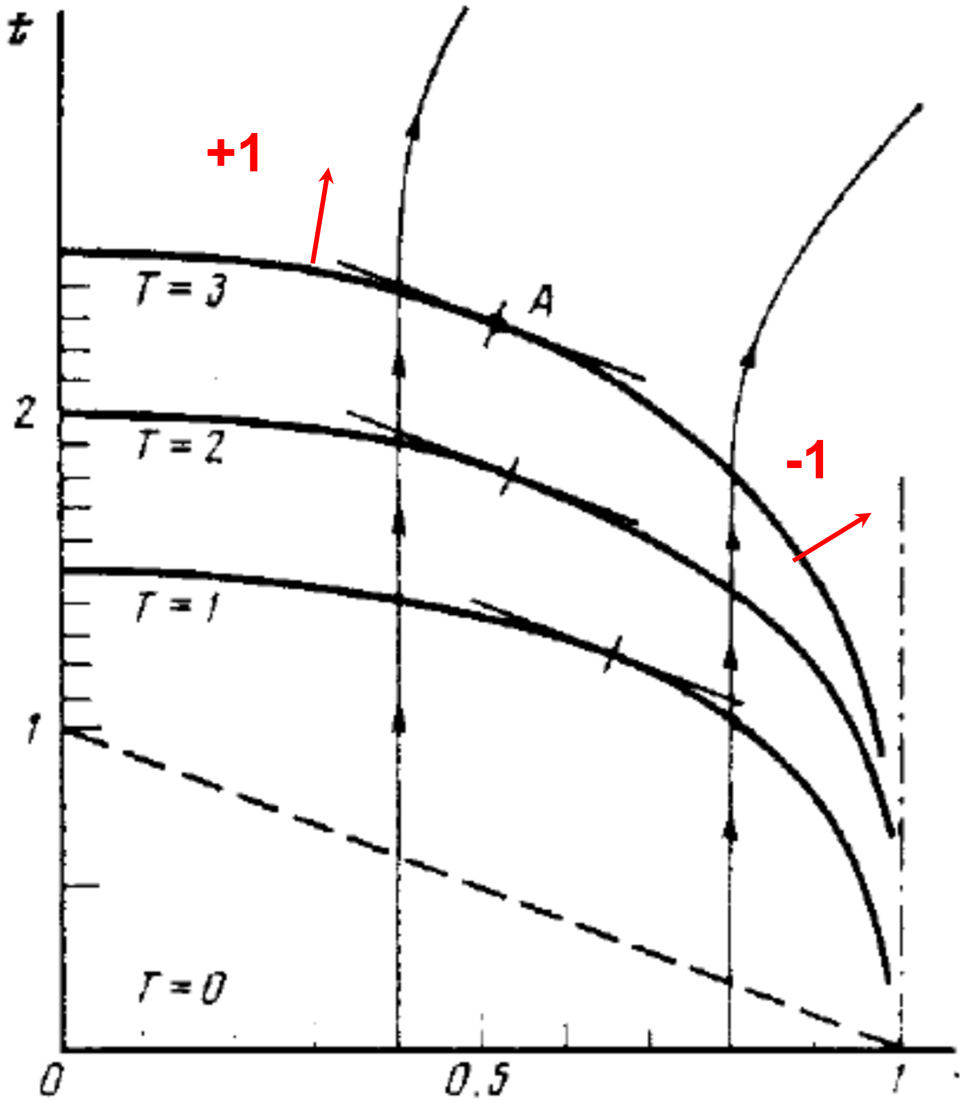
$$[T^{\alpha i}\Lambda_i]=0, \tag{7.4}$$

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**)]

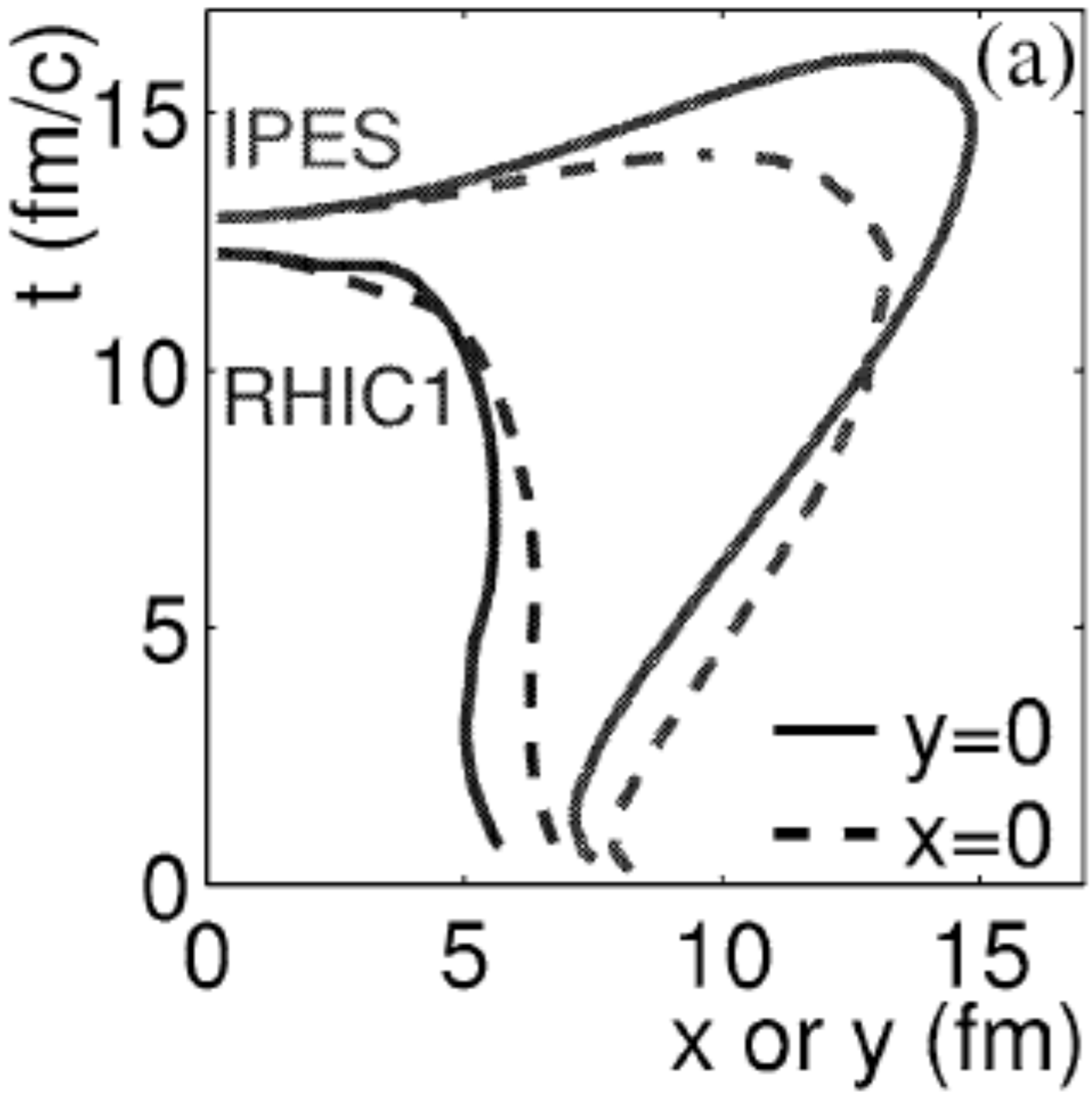
$$\lambda_\alpha \lambda^\alpha = \pm 1$$

Л. П. Чернаи

ДЕТОНАЦИЯ НА ВРЕМЕНИПОДОБНОМ ФРОНТЕ ДЛЯ РЕЛЯТИВИСТСКИХ СИСТЕМ

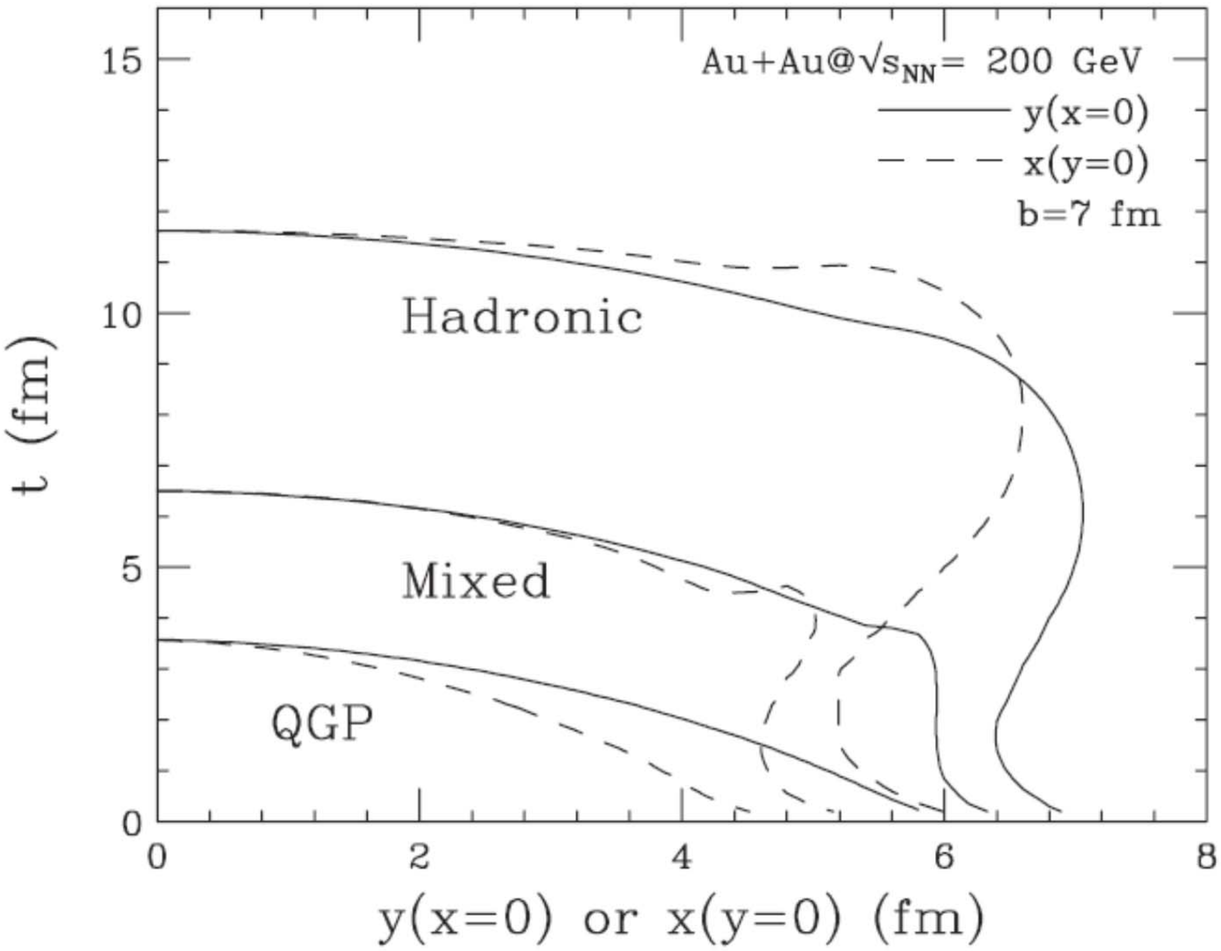
Журнал экспериментальной и теоретической физики

1987

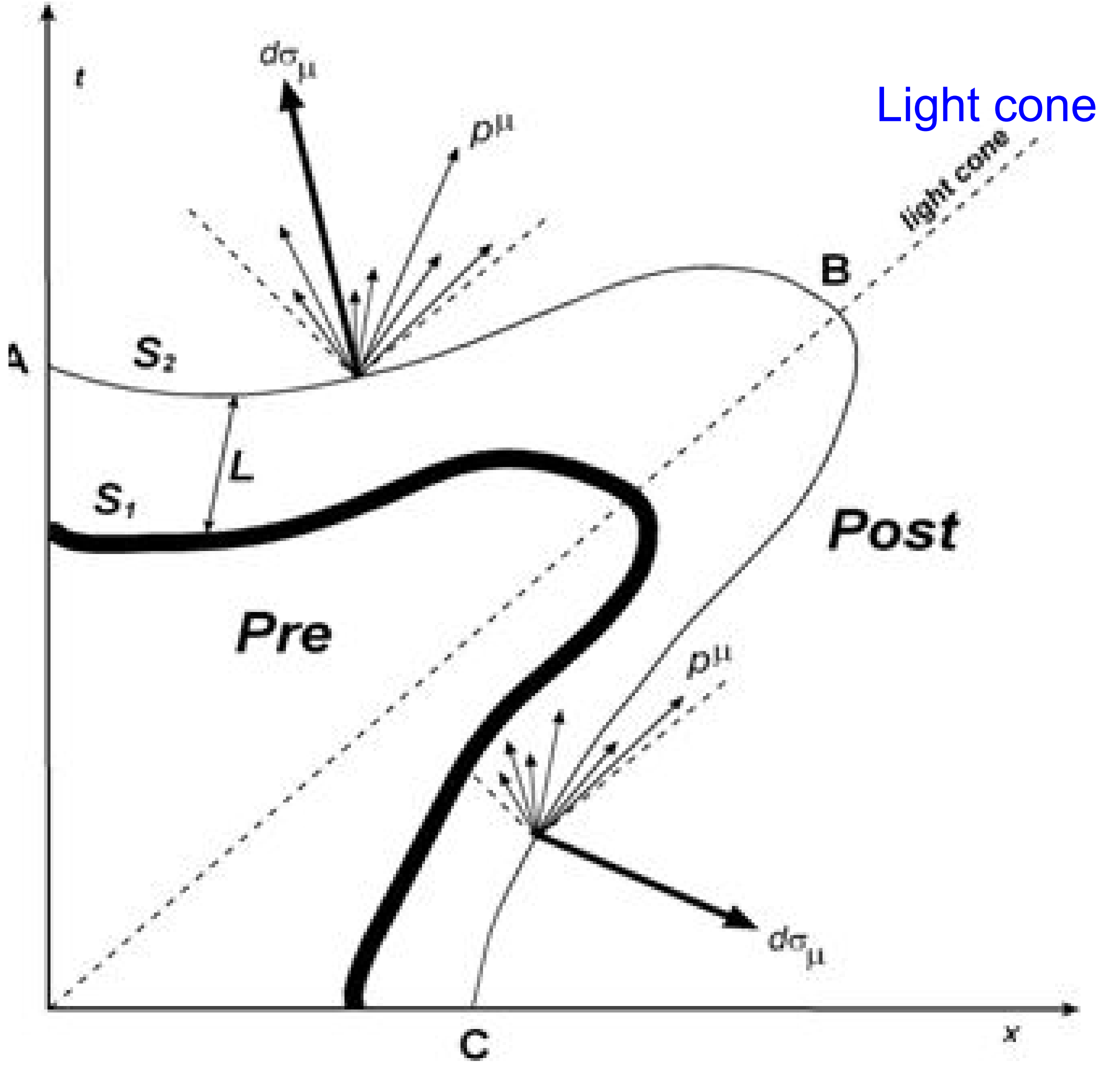


Discovery of QGP:
2000 CERN
2001 BNL

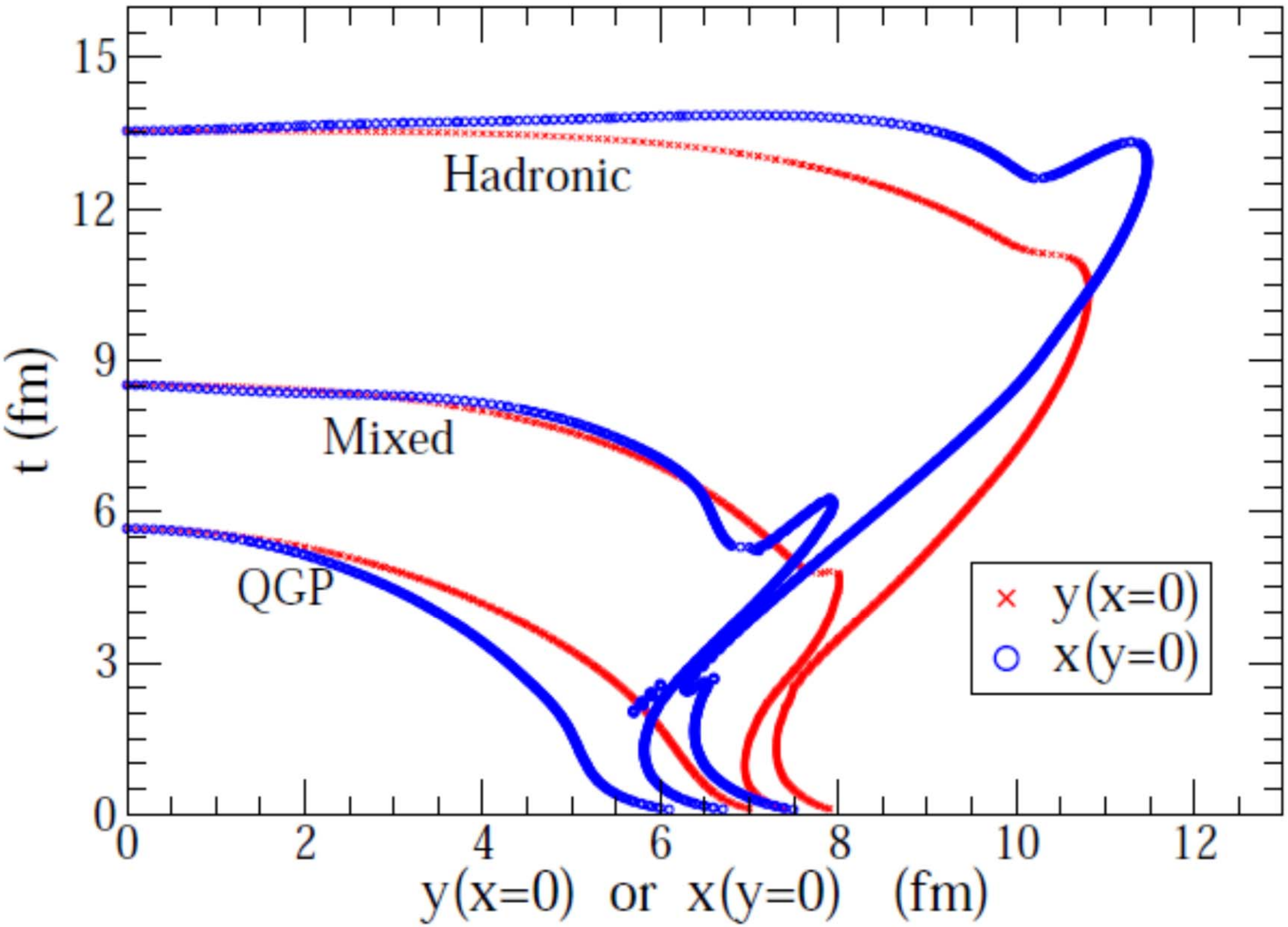
[U.W. Heinz and P.F. Kolb, Phys. Lett. B 542, 216 (2002)]



[R. Chatterjee, et al., Phys. Rev. Lett. 96, 202302 (2006)]



[E. Molnar, et al., J. Phys. G 34 (2007) 1901]



[E. Frodemann, et al., J.Phys. G 34, 2249-2254 (2007)]

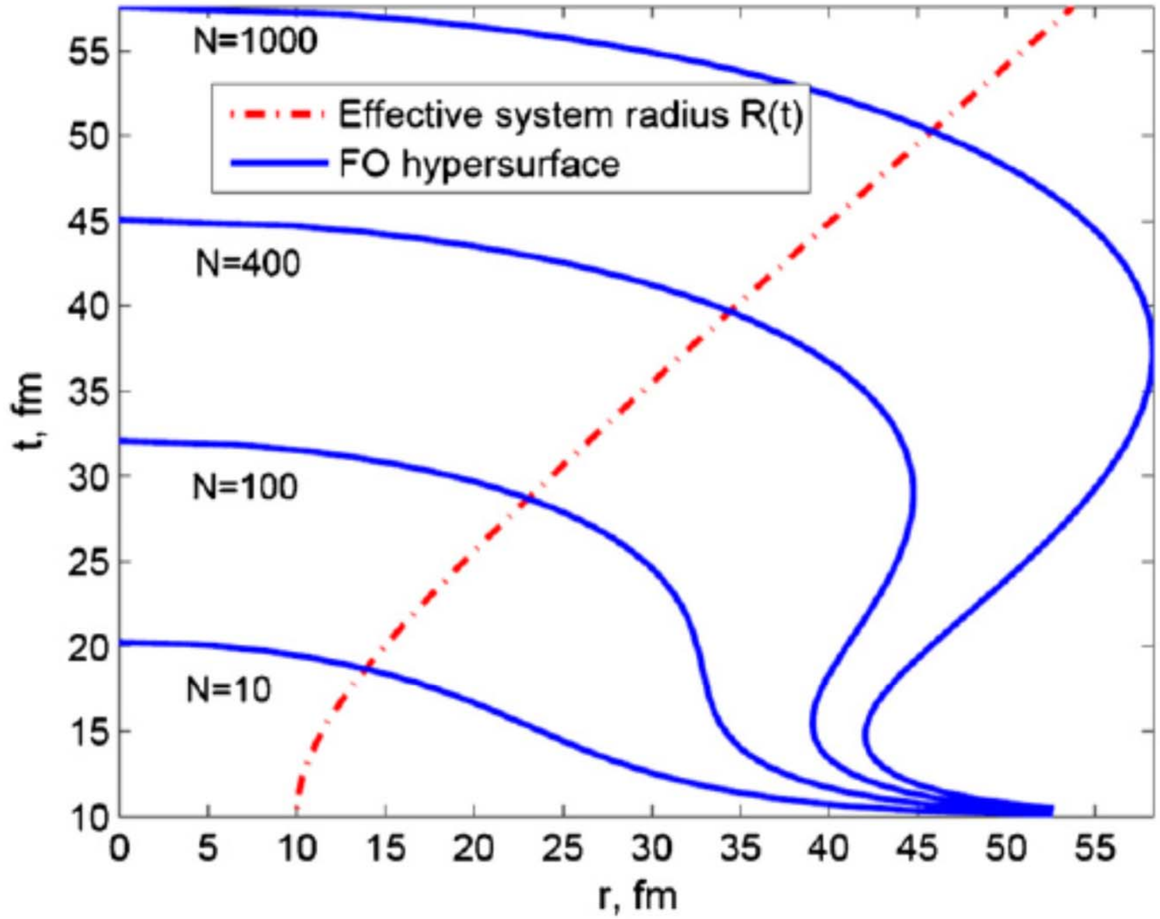
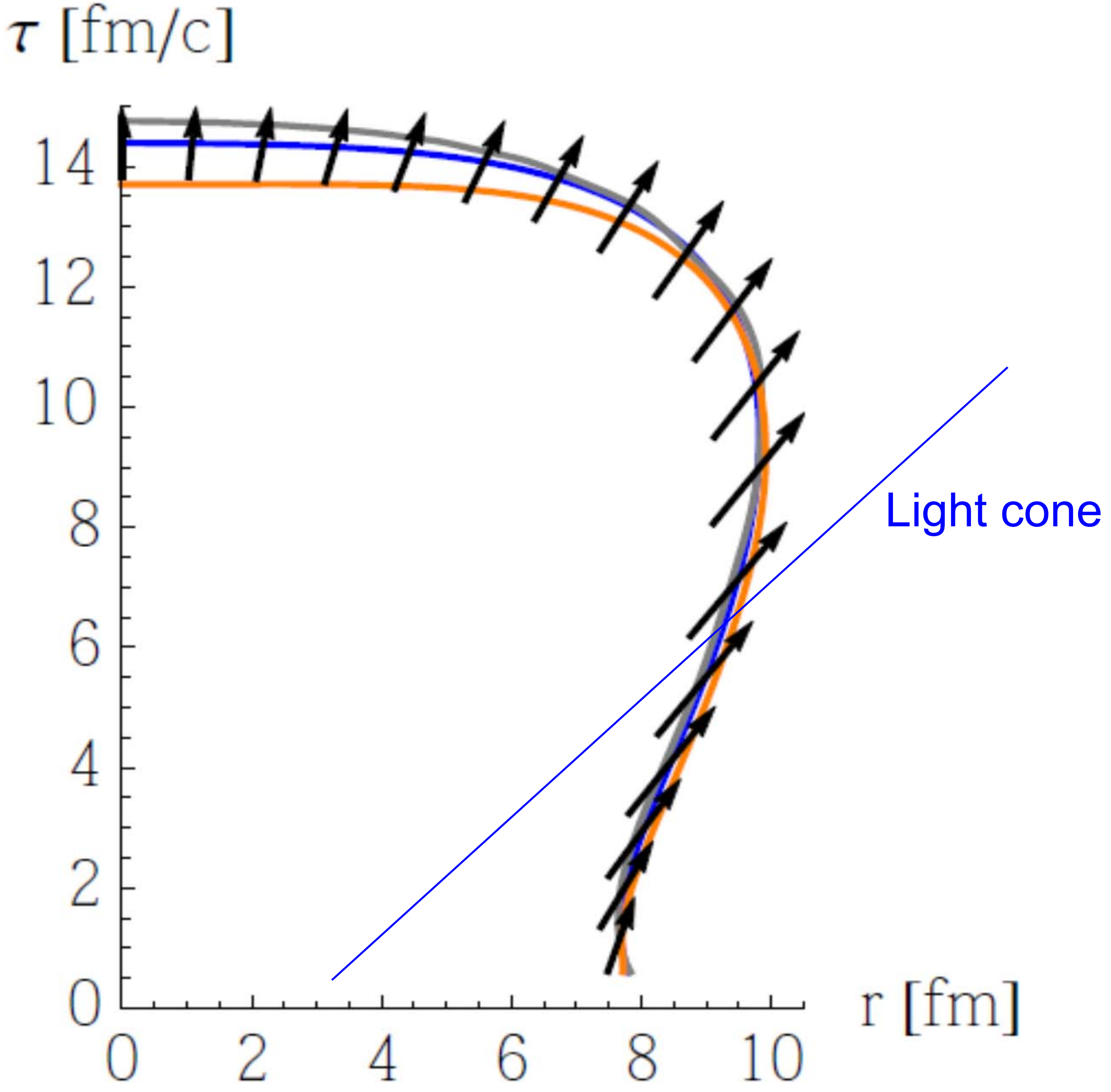
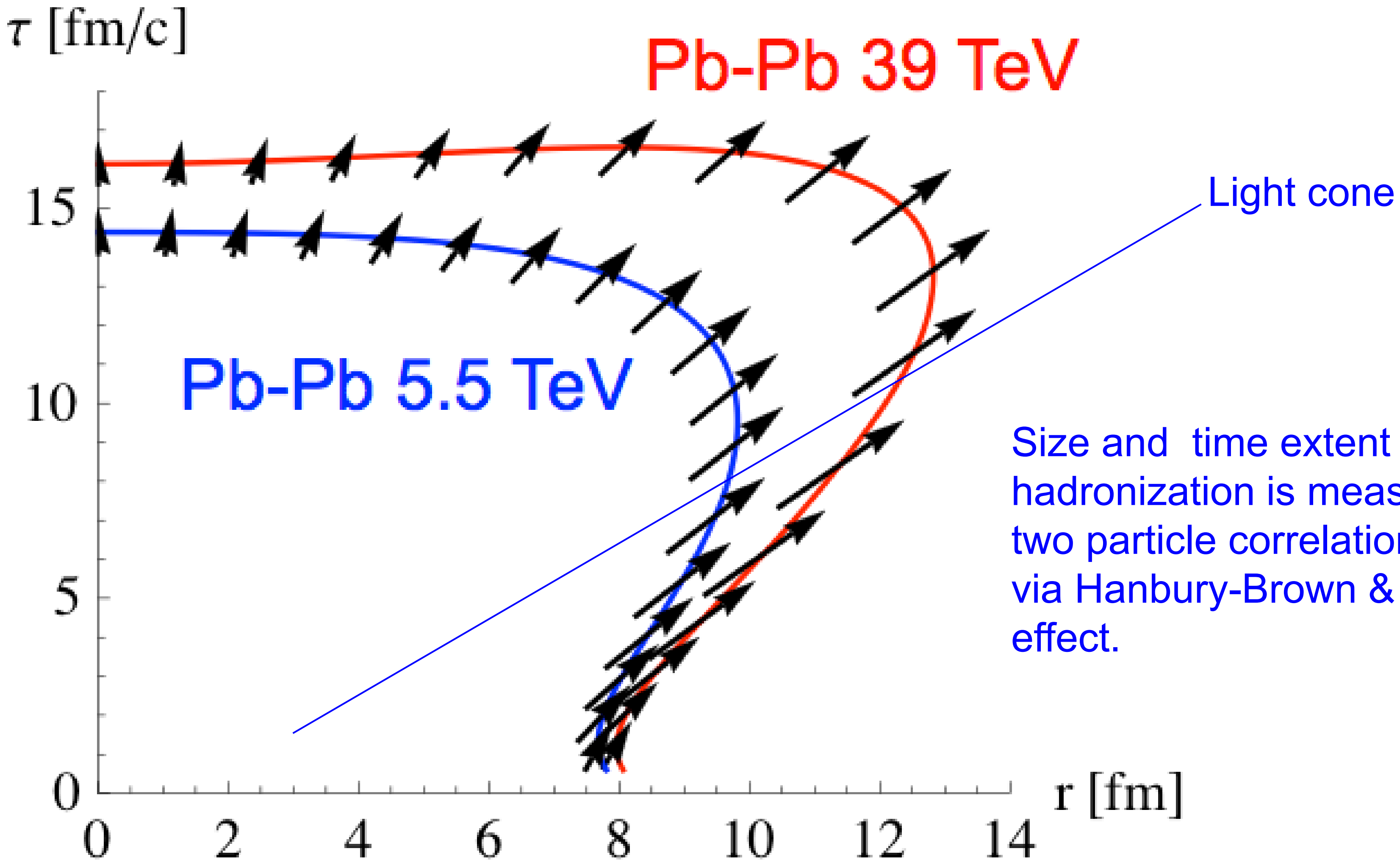


Figure 4. Freeze-out surfaces calculated from the Bondorf condition (see the text) for various particle numbers *N*.



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



Size and time extent of hadronization is measured by two particle correlations, via Hanbury-Brown & Twiss effect.

[N. Armesto, et al., Nucl.Phys. A931 (2014) 1163]

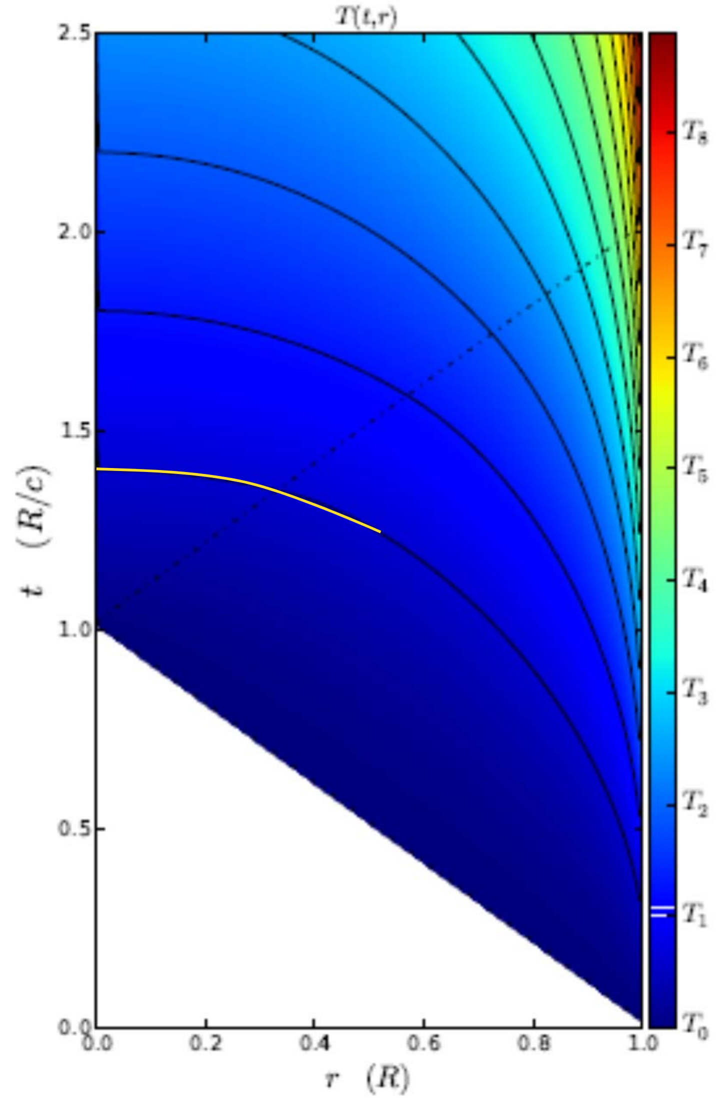
Applications to Pellet Fusion (I-st)

Relativistic Heavy Ion Physics proves that simultaneous ignition and burning is possible, both theoretically and experimentally (two particle corr.) !

Up to now all theoretical studies of Internal Confinement fusion are based on Classical Fluid Dynamics (CFD) [HYDRA, LASNEX]

Still the aim is to

- achieve Volume Ignition
- achieve Rapid Ignition
- but within CFD ?! →



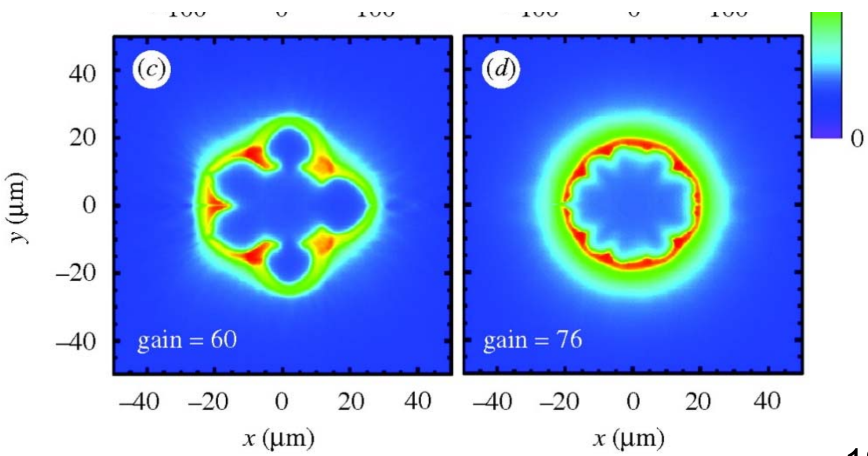
Fusion reaction:

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).]

Can we achieve larger volume ignition (II-nd)

Two ideas are combined by

L.P. Csernai, N. Kroo, I. Papp **[Patent # P1700278/3](*)**

(2017)

- **Heat the system uniformly by radiation with RFD**
- **Achieve uniform heating by Nano-Technology**

Uniform, **4π radiation** should heat the target to ignition within the light penetration time (i.e. ~ 10-20 ps). This follows from RFD!

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

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]

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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

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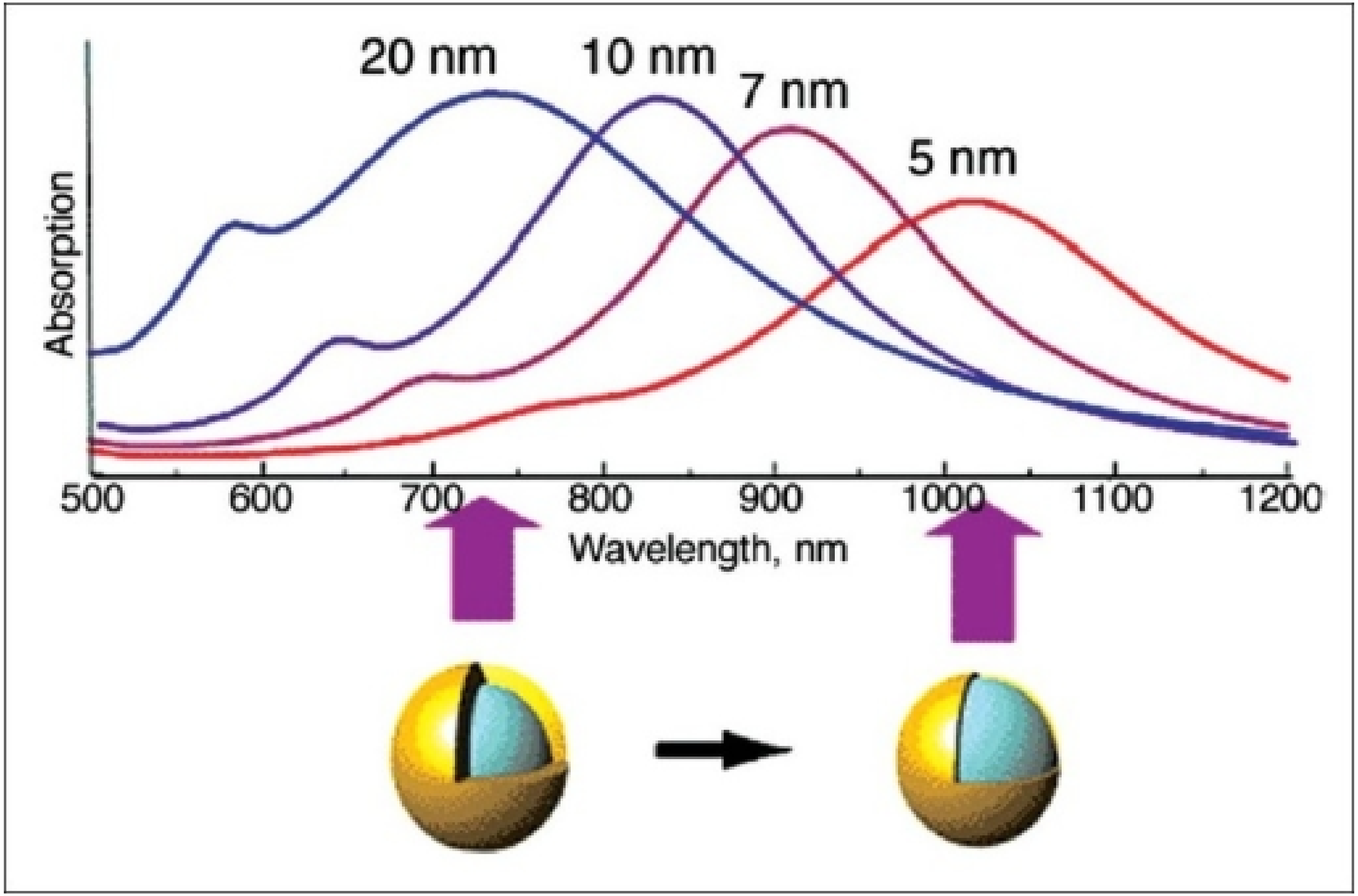
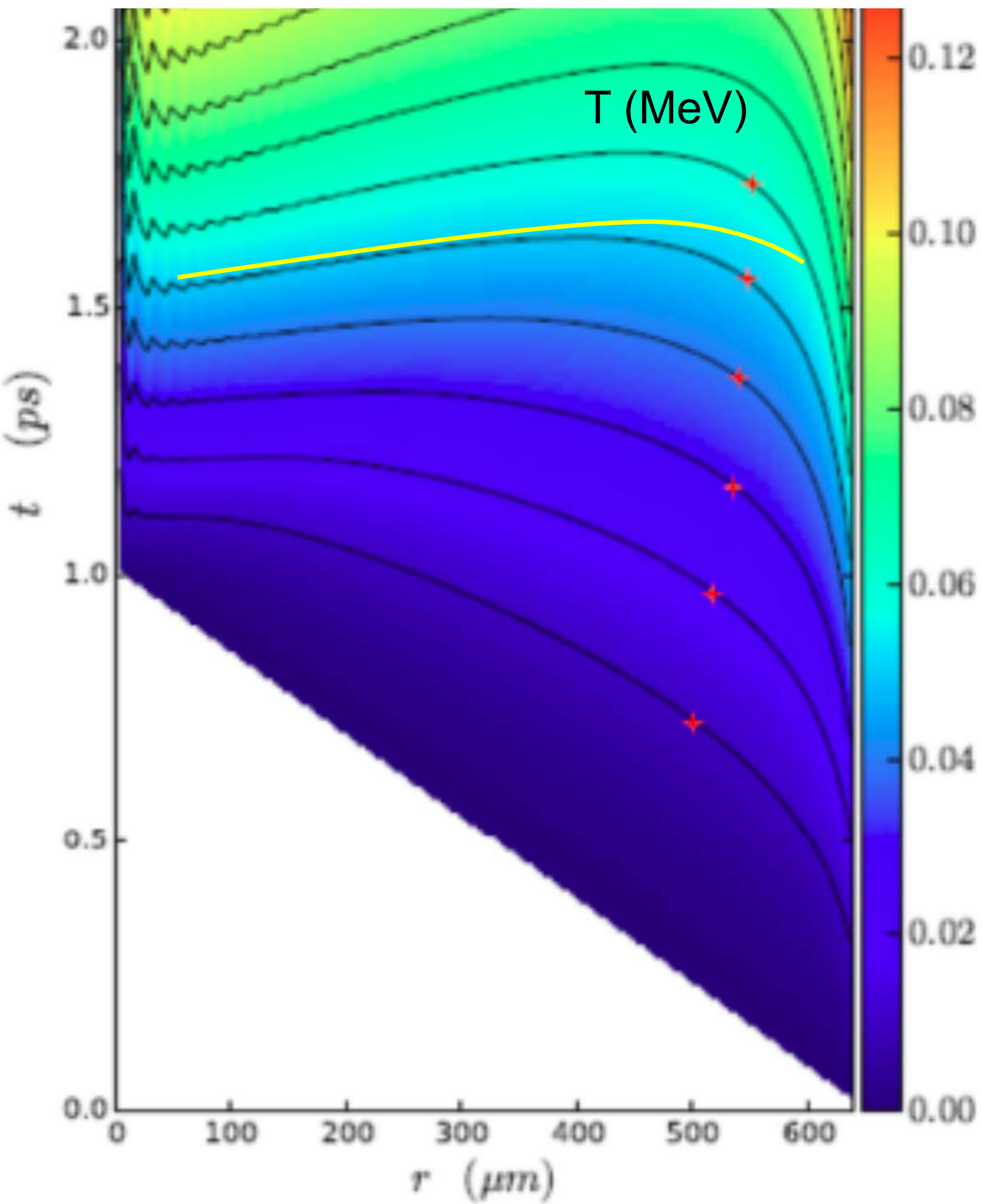
Abstract

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





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!**

Thick Coin like target - New Developments

L.P. Csernai, N. Kroo, I. Papp

X

Thickness of the target is: h

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

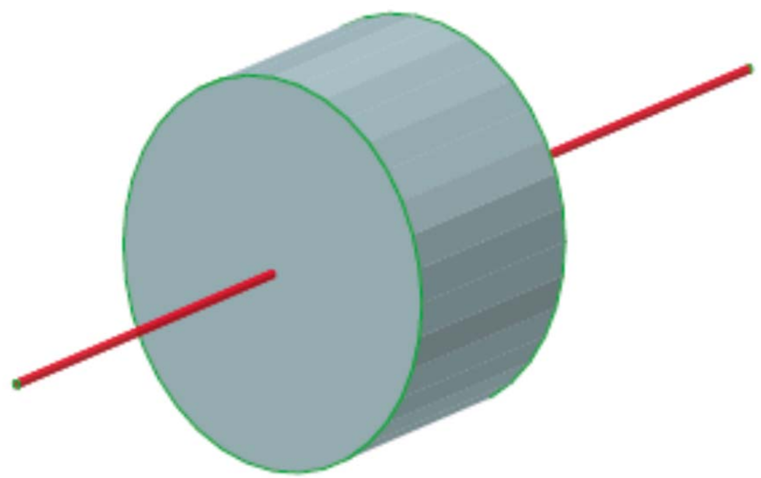
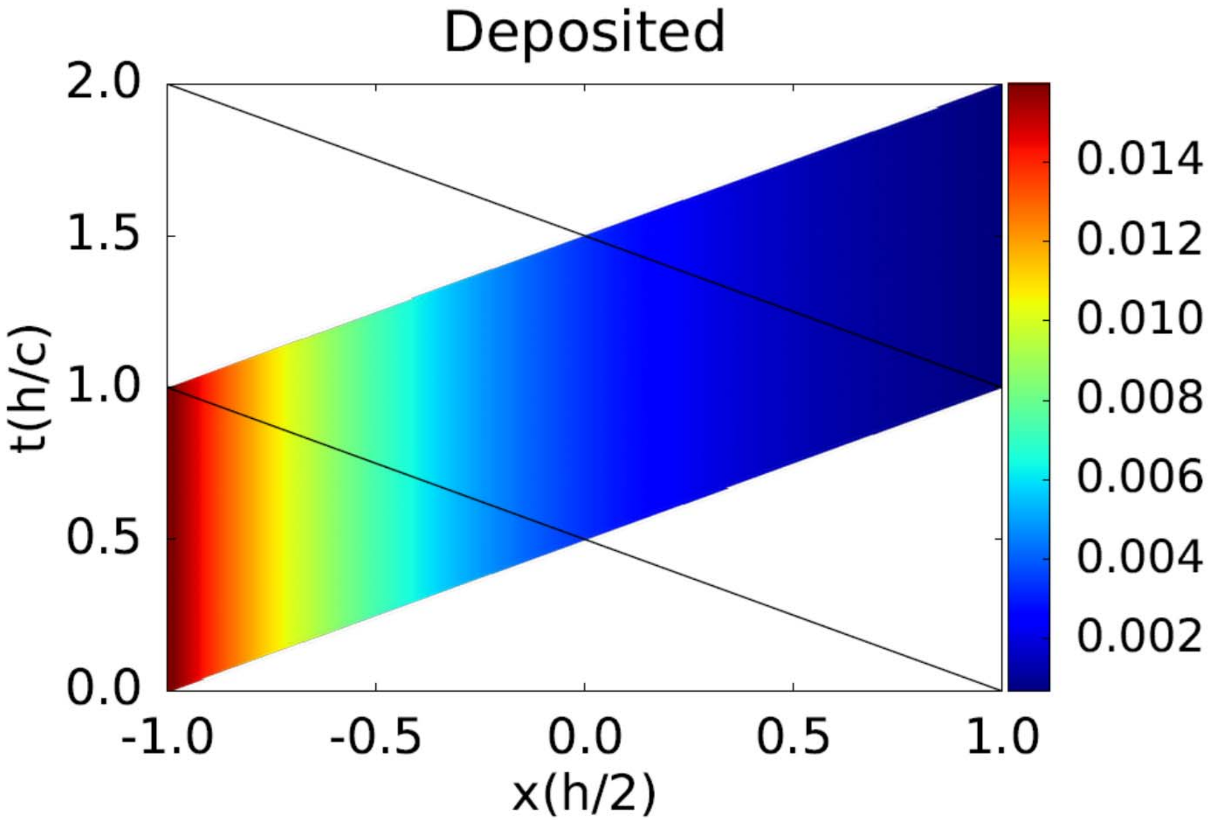


Figure 1: (color online) The target still should be compact to minimize the surface effects. The irradiation is performed along the $x-$axis from both sides towards the target. The laser beam should be uniform hitting the whole face of the coin shaped target.



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.

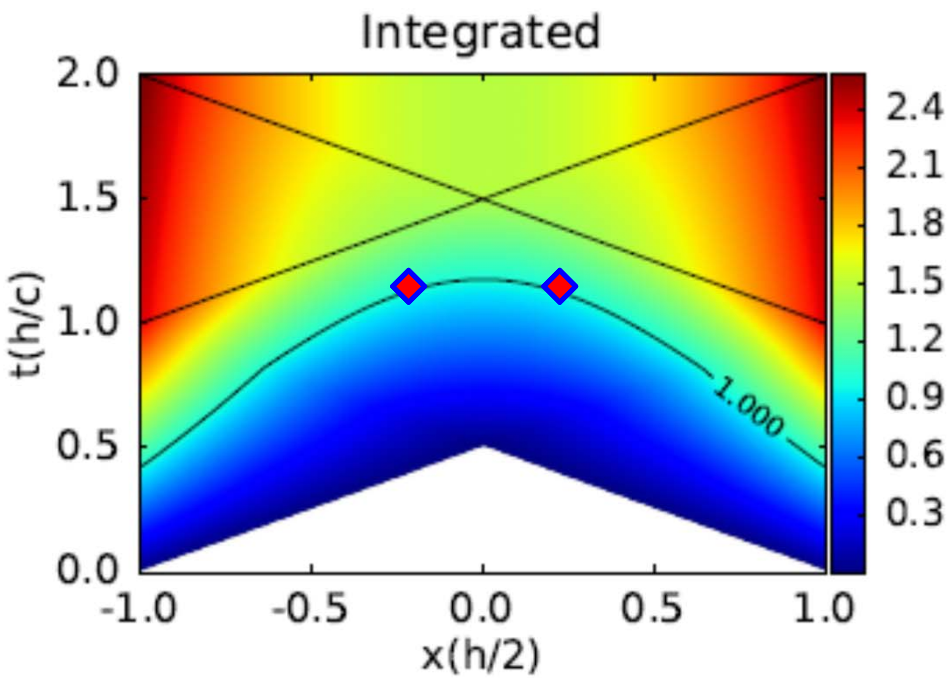


Figure 4: (color online) Integrated energy up to a given time in the space-time across the depth, h, of the flat target. The color code indicates the temperature, T, reached in a given space-time point, in units of the critical temperature, (T_c). The contour line $T = 1$, indicates the critical temperature, T_c, where the phase transition or the ignition in the target is reached. This contour line, compared to the one in Fig. 3, is never constant in time, indicating no simultaneous whole volume transition or ignition. The time-like (causally unconnected) part of the transition takes place only in the central $\sim$ 15% of the target volume. The two straight lines indicate the light-cones originating at the outside edges of the target at the ending of the irradiation pulse.

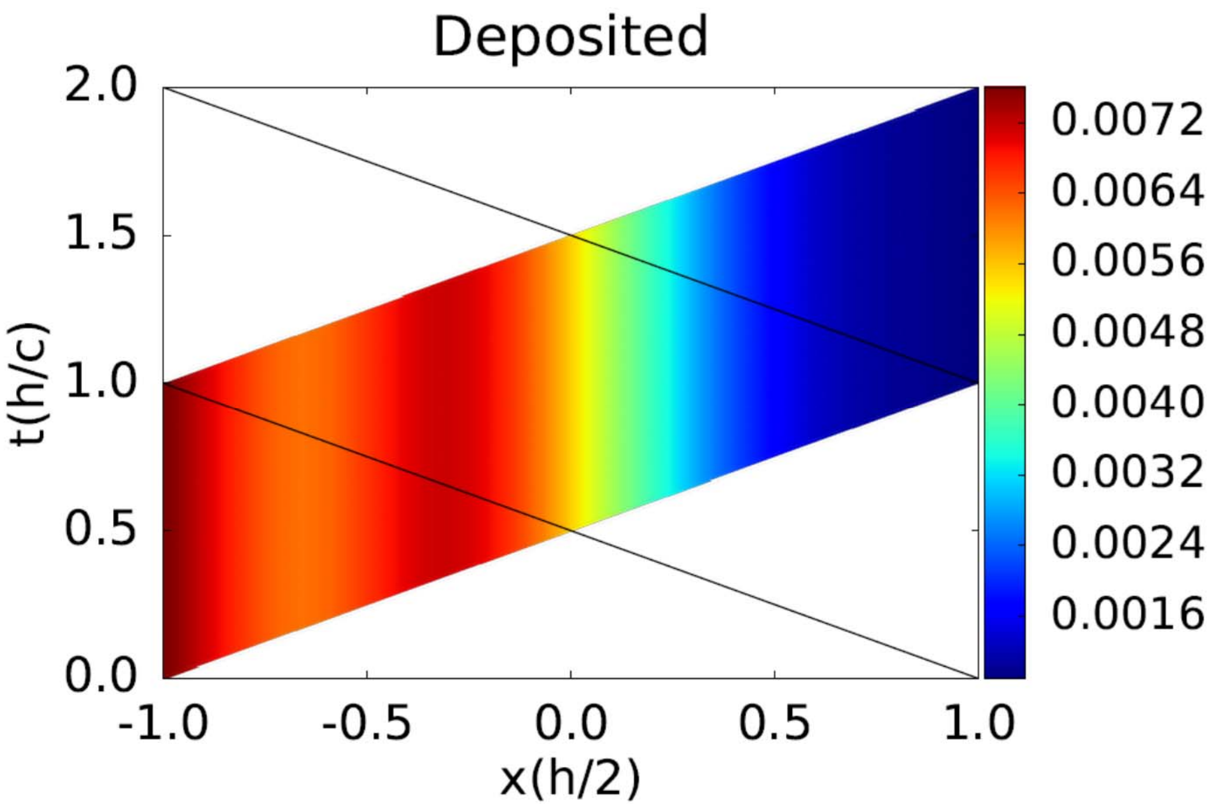
Without nano antennas

Irradiation from both sides.

Exponential decrease of deposited energy. Due to the already deposited energy, less energy reaches the middle ➔

The front and back surface is heated up but the middle is not!

Pulse length is: $t_P = h/c$



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.

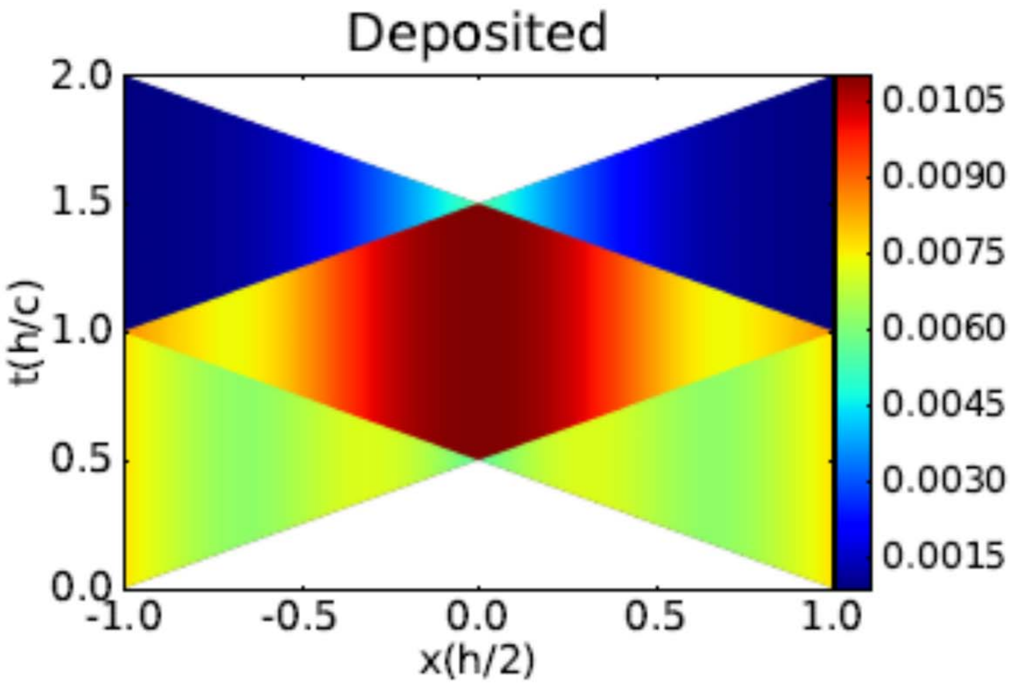


Figure 2: (color online) Deposited energy per unit time in the space-time across the depth, h, of the flat target. The time is measured in units of (h/c), where c is the speed of light in the material of the target. The irradiation lasts for a period of $\Delta t = h/c$ the time needed to cross the target. 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 $\alpha_K \neq$ 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 .

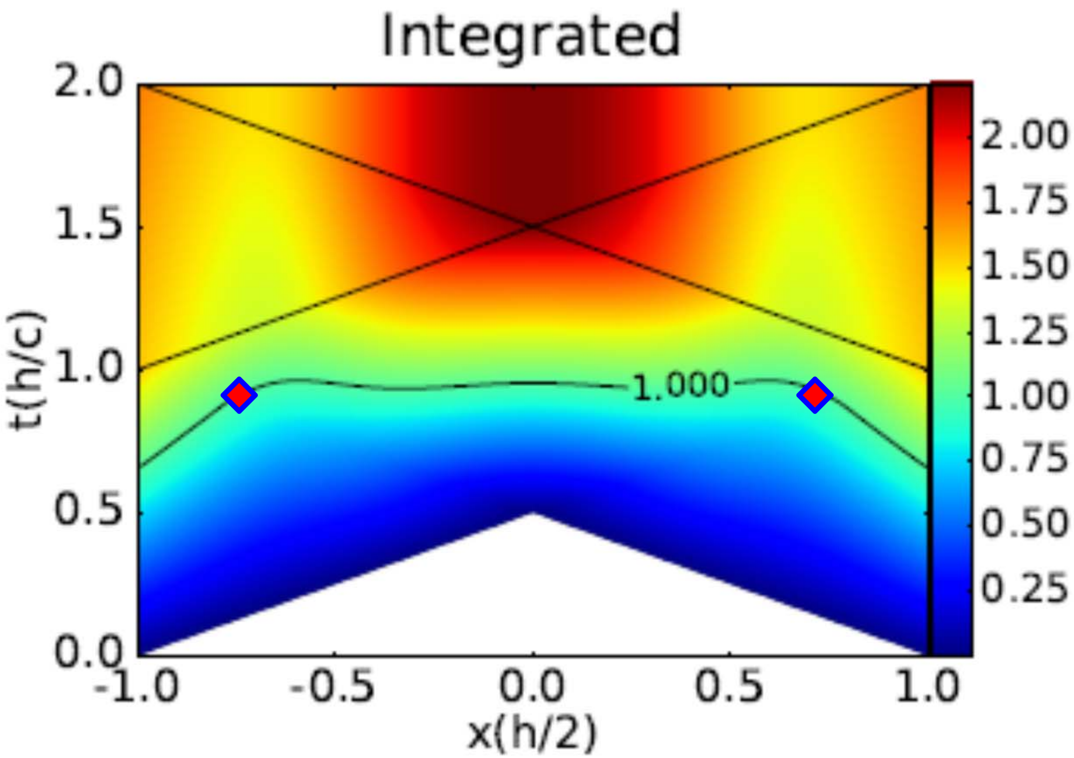


Figure 3: (color online) Integrated energy up to a given time in the space-time across the depth, h, of the flat target. The color code indicates the temperature, T, reached in a given space-time point, in units of the critical temperature, (T_c). The contour line $T = 1$, indicates the critical temperature,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

With nano antennas

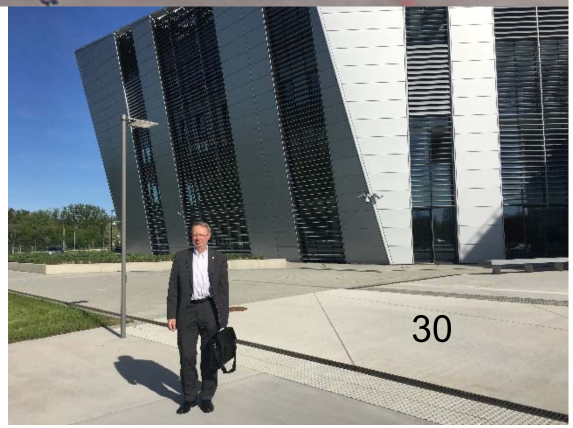
Ignition is reached at contour line $Q = 1$.

[L. P. Csernai, M. Csete, I. N. Mishustin, A. Motornenko, I. Papp, L. M. Satarov, H. Stöcker, N. Kroo, ***arXiv***:1903.10896, ***Submitted to MRE***]

European Laser Infrastructure – Szeged, HU

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

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



Test of principles with smaller pulse energy

1 Relativistic **time-like** (simultaneous) ignition
2 Using **nano antennas** to reach whole volume uniform ignition
3 Using **1D geometry**, with two beams from opposite direction

Let us take
a polilactic acid (PLA) target with T = 150 C **melting** temperature,
Melting energy: $Q_i/m = 28$ J/g
➔ a $P = 30$ mJ , 1 ps laser, this leads to $m_i = 0.32$ mg target

HAS Wigner RCP, Budapest

Márk Aladi, Miklós Kedves, Béla Ráczkevi,
Péter Lévai   et al.
Laser wake acceleration of protons for radiation therapy

Fusion plasma diagnostics, ITER, JET etc.

Péter Dombi, Péter Rácz, Norbert Kroo et al.

Laser induced nano-plasmonics

Validation tests:
Ti-Si Hidra L. 30mJ 10Hz 40fs

See Attila Bonyár's talk

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

Nuclear probes of an out-of-equilibrium plasma at the highest compression

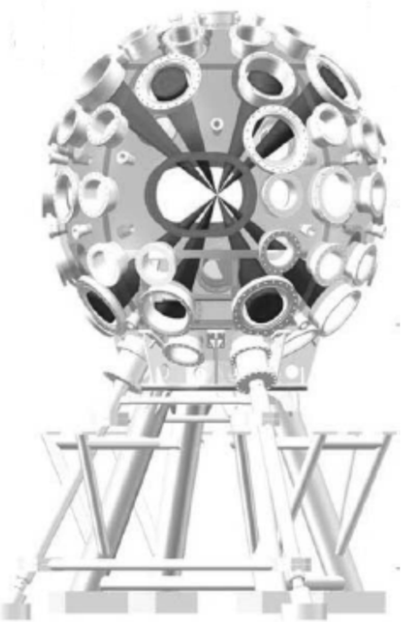
Phys. Lett. A 383 (2019) 2285-2289.

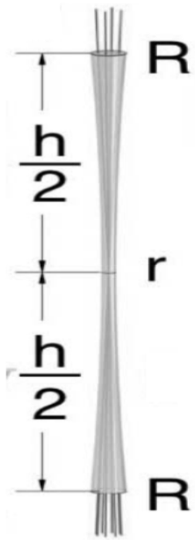
G. Zhang[a,b,*], M. Huang[c], A. Bonasera[d,e,*], Y.G. Ma[f,b,i,*], B.F. Shen[g,h,*], H.W. Wang[a,b], W.P. Wang[g], J.C. Xu[g], G.T. Fan[a,b], H.J. Fu[b], H. Xue[b], H. Zheng[j], L.X. Liu[a,b], S. Zhang[c], W.J. Li[b], X.G. Cao[a,b], X.G. Deng[b], X.Y. Li[b], Y.C. Liu[b], Y. Yu[g], Y. Zhang[b], C.B.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

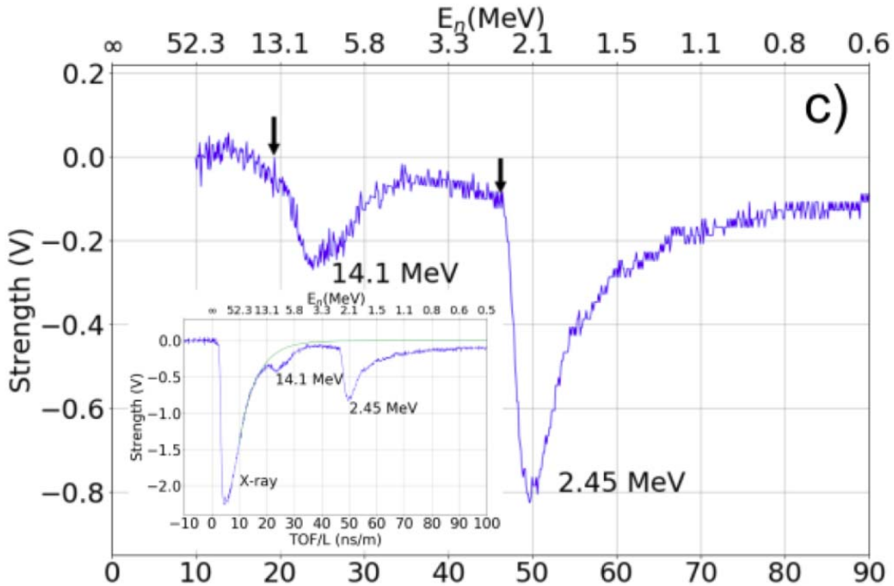
4 (up) + 4(down) lasers
Target thickness, h (3.6µm-1mm) & radius, R, (150-400µm) were varied.

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

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







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

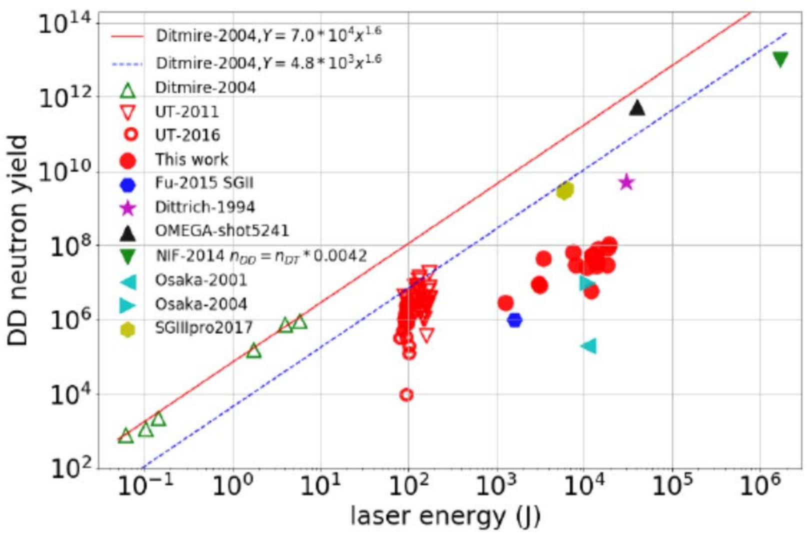


Figure 3: (color online) Fusion yield as function of laser energy. Different experimental results Ditmire-2004[40], UT-2011[20], UT-2016[19], Fu-2015 SGII[45], Dittrich-1994[49] , NIF-2014[48] , Osaka -2001[46], Osaka-2004[47], OMEGA-shot5241[41]and SGIIIpro2017[42] are indicated in the inset.

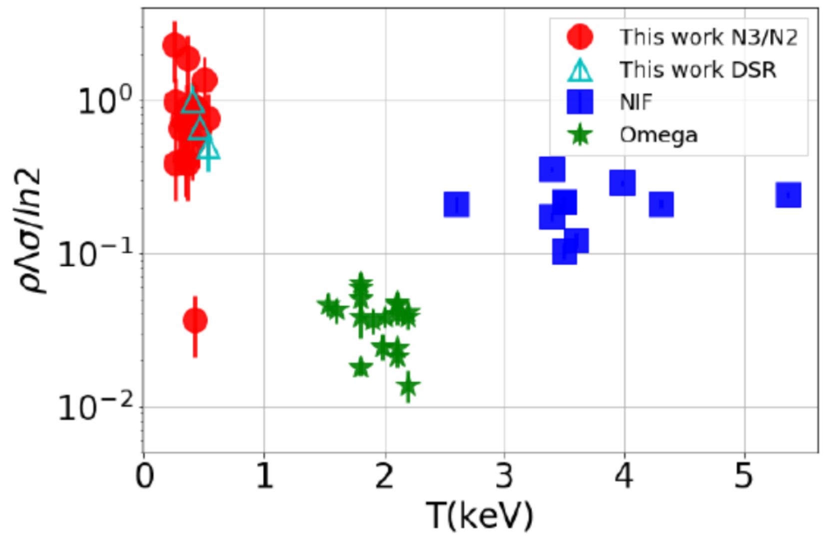
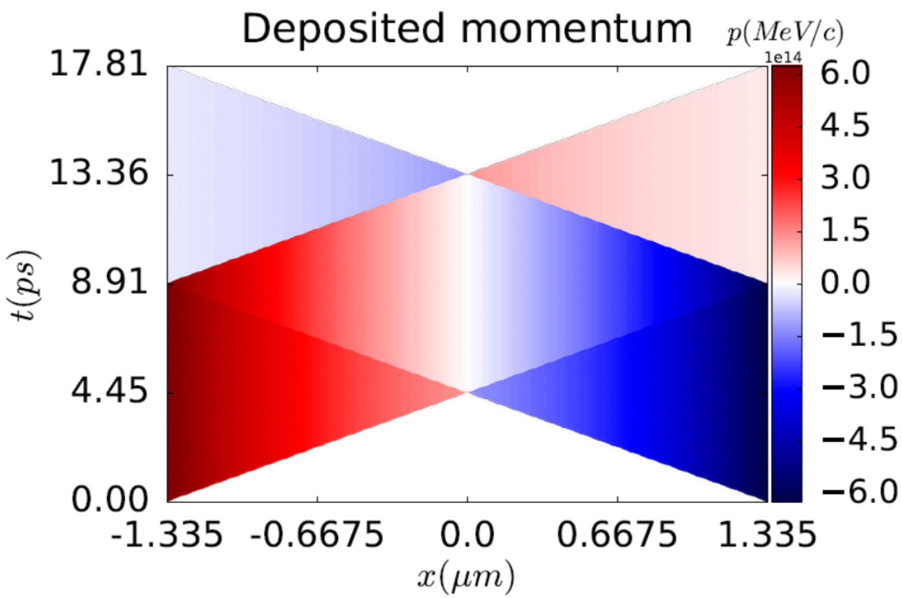


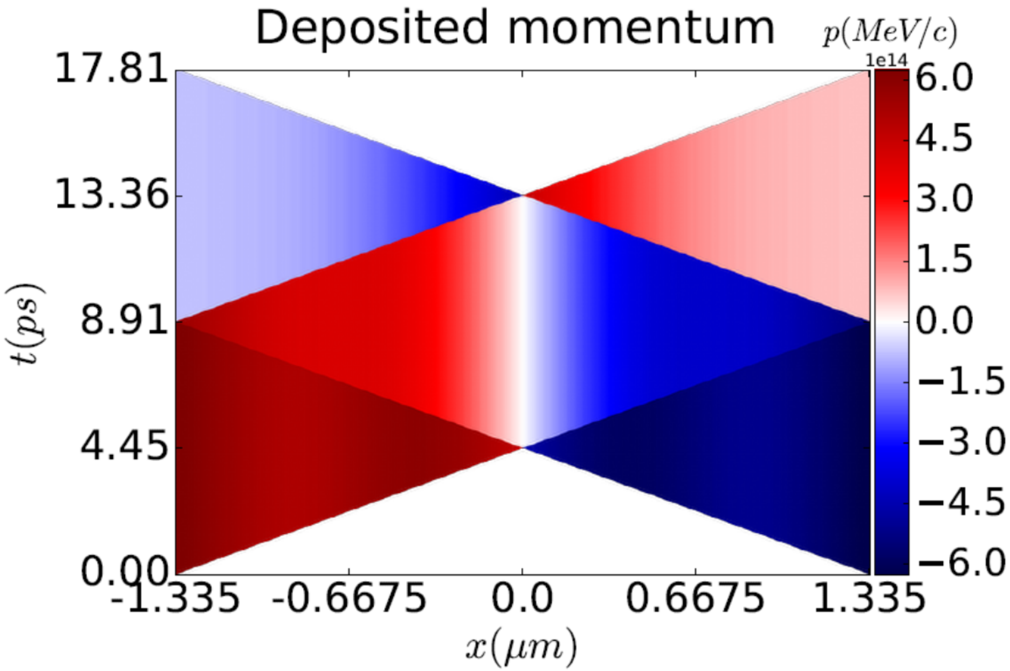
Figure 4: (color online) $\Lambda\rho\sigma/\ln 2$ obtained from eq.(4) vs T from eq.(1). Omega and NIF data are derived from the experiments[25], using the Down Scatter Ratio[23, 21]. Our results using the DSR method (N_4/N_3) are given by the open triangle symbols in good agreement with the N_3/N_2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

Deposited momentum

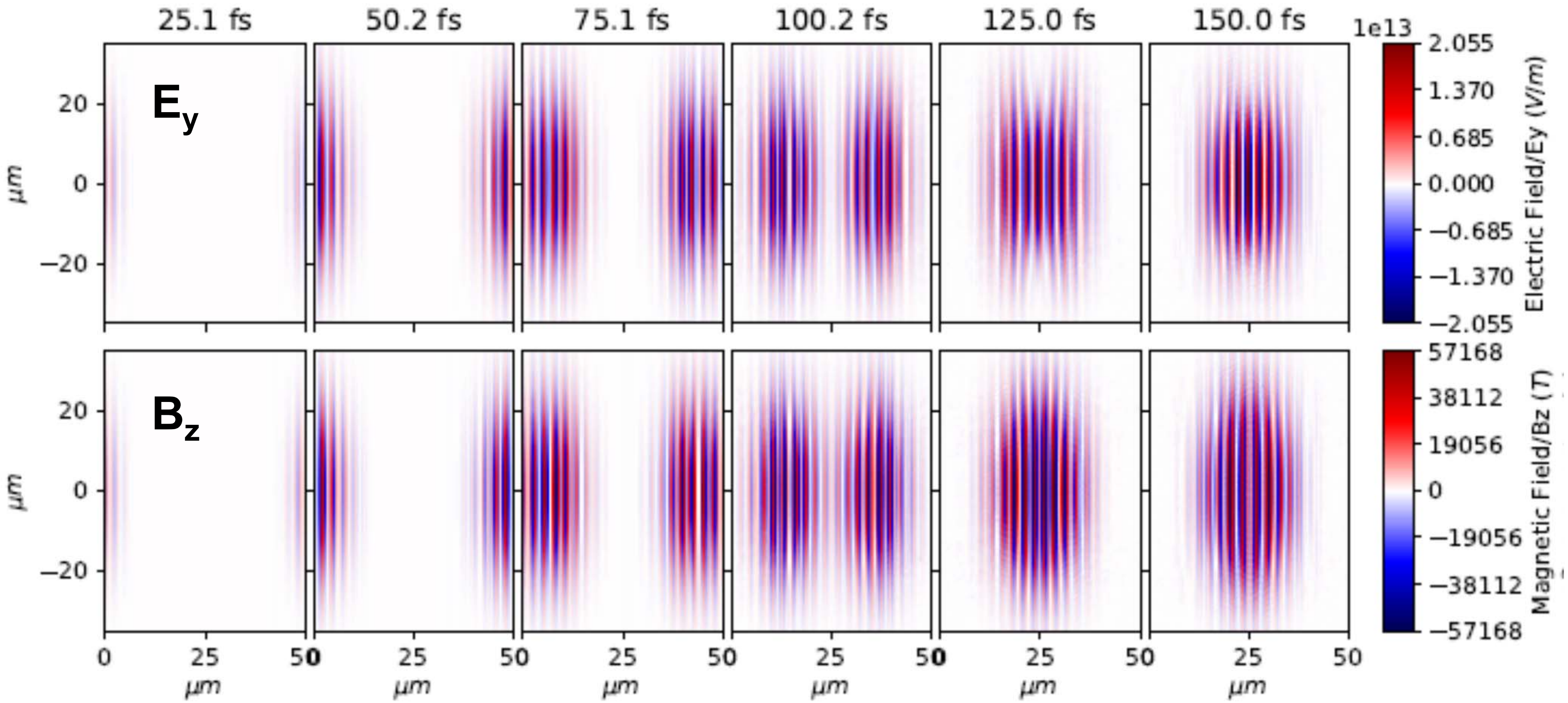


Leads to compression w/o external ablator surface
[Gyulassy, Csernai, NPA 1986]
→ **leads to QGP formation w/o RT instabilities**



Implanted **nano-antennas** increase further the compression !!

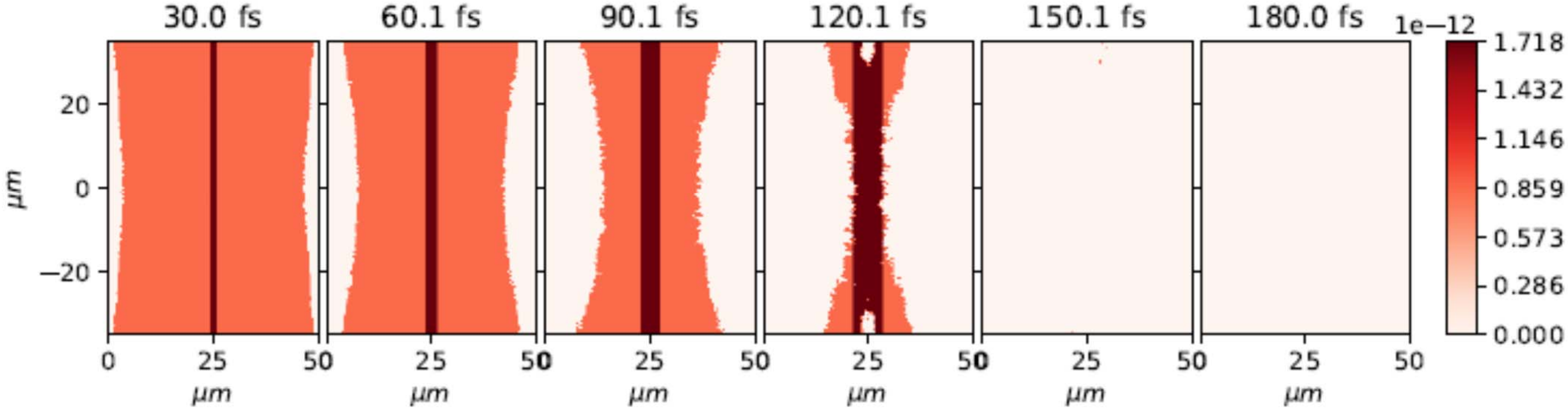
Laser Wake Field Collider



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**

[Papp, I., et al., NAPLIFE Collaboration, arXiv-2009.03686]

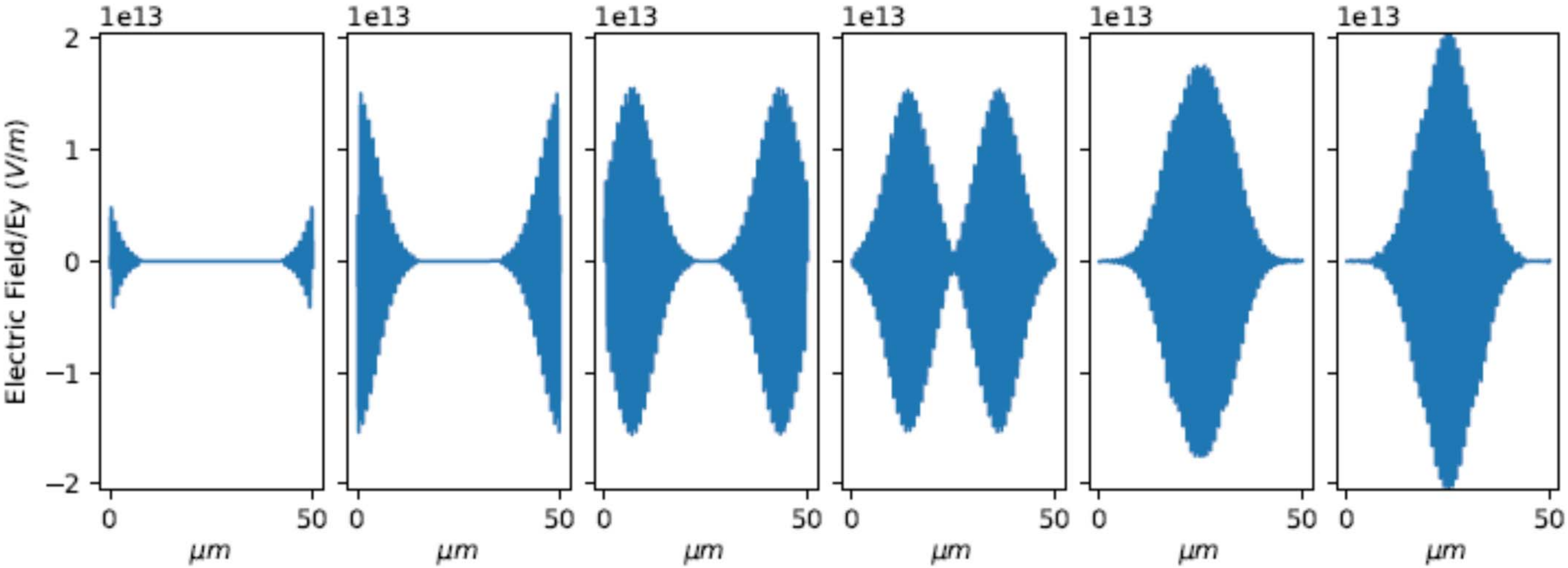
Ionization of the H target



The ionization of the **H atoms** in a Laser Wake Field (LWF) wave due to the irradiation from both the x- directions, on an initial target density of $n_H = 2.13 \times 10^{27}/m^3 = 2.13 \;\; 10^{21}/cm^3$. The energy of the H atoms in Joule [J] per marker particle is shown. The H atoms disappear as protons and electrons are created. Due to the initial momentum of the colliding H slabs, the target and projectile slabs interpenetrate each other and this leads to double energy density. Several time-steps are shown at 30 fs time difference.

[Papp, I., et al., NAPLIFE Collaboration, arXiv-2009.0368]

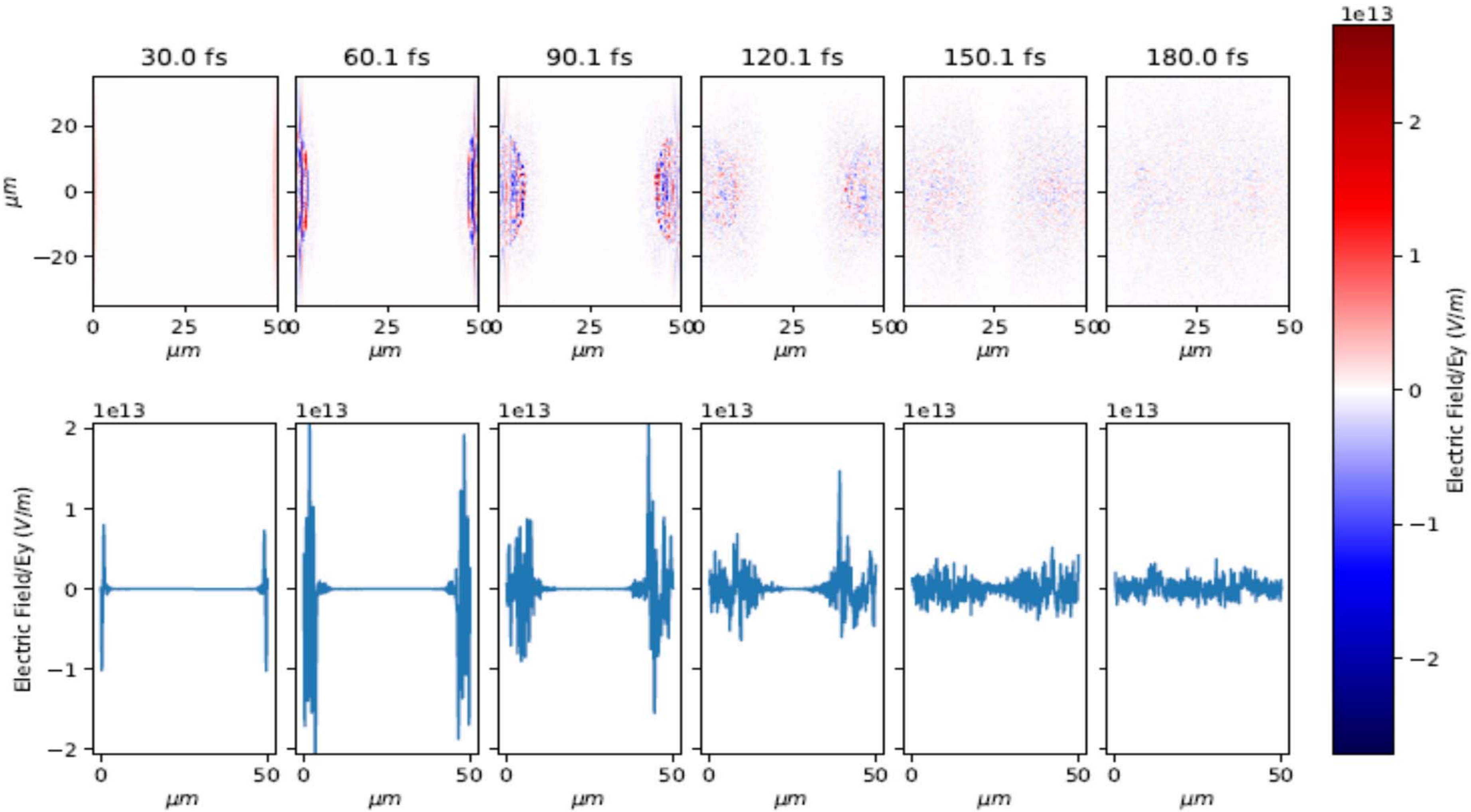
E_y in the middle of transverse plane



Electric Field, E_y in a Laser Wake Field (LWF) wave formed by irradiation from both the $\pm$x- directions. The field strengths are shown in the middle of the transverse, [y,z], plane along the x-axis. In the other, not shown, directions the fields are weaker by orders of magnitude. The initial target density is $n_H = 2.13 \times 10^{19}/cm^3$. Several time-steps are shown at 25, 50, 75, 100, 125 and 150 fs times.

[Papp, I., et al., NAPLIFE Collaboration, arXiv-2009.0368]

E_y in the middle of transverse plane



Same as the previous figure, with **larger initial target density**
$n_H = 2.13 \times 10^{21}/cm^3$. ~ **Liquid Hydrogen**

Thus, ultra-relativistic heavy ion physics lead to discovery Quark Gluon Plasma (QGP), but also to advances in **(i)** relativistic fluid dynamics (RFD).

With **(ii)** nano technology this may revolutionize in a simple, and **(iii)** affordable 1D geometry the technological development*) of ➔

Nanoplasmonic Laser Inertialconfinement Fusion Experiment (NAPLIFE)

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