Radiation dominated implosion with plasmonic nano-shells

Laszlo P. Csernai,
Univ. of Bergen, Norway
Wuhan Univ. of Technology, China
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Laser and Particle Beams

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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

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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

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.

Burning of Quark Gluon Plasma in Relativistic, Radiation Dominated Systems according to Relativistic Fluid Dynamics
-
Applications to Pellet Fusion

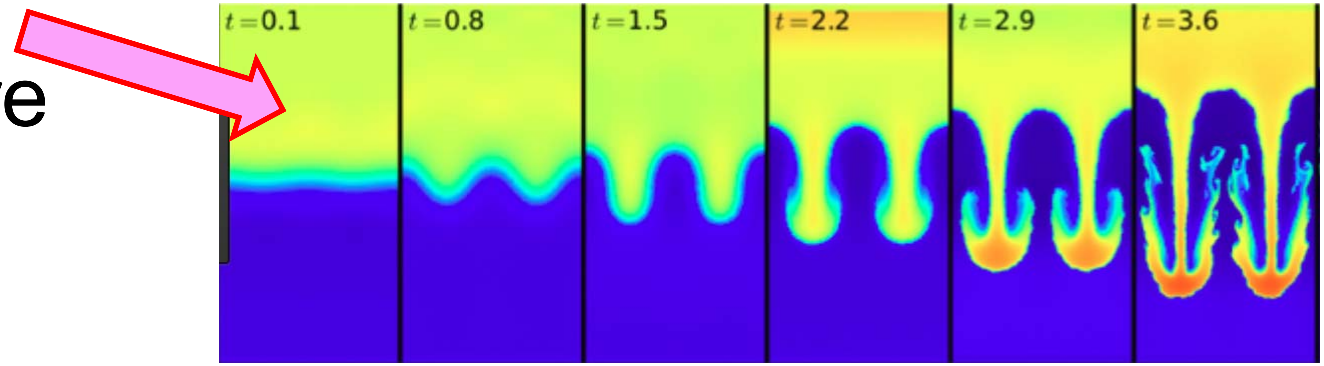
Classical Fluid Dynamics (CFD) does assumes that all dynamical processes, including shocks and detonations, are having speeds which are slower than the speed of light, c. (Note, however: Einstein's GR: Synchronizing watches)

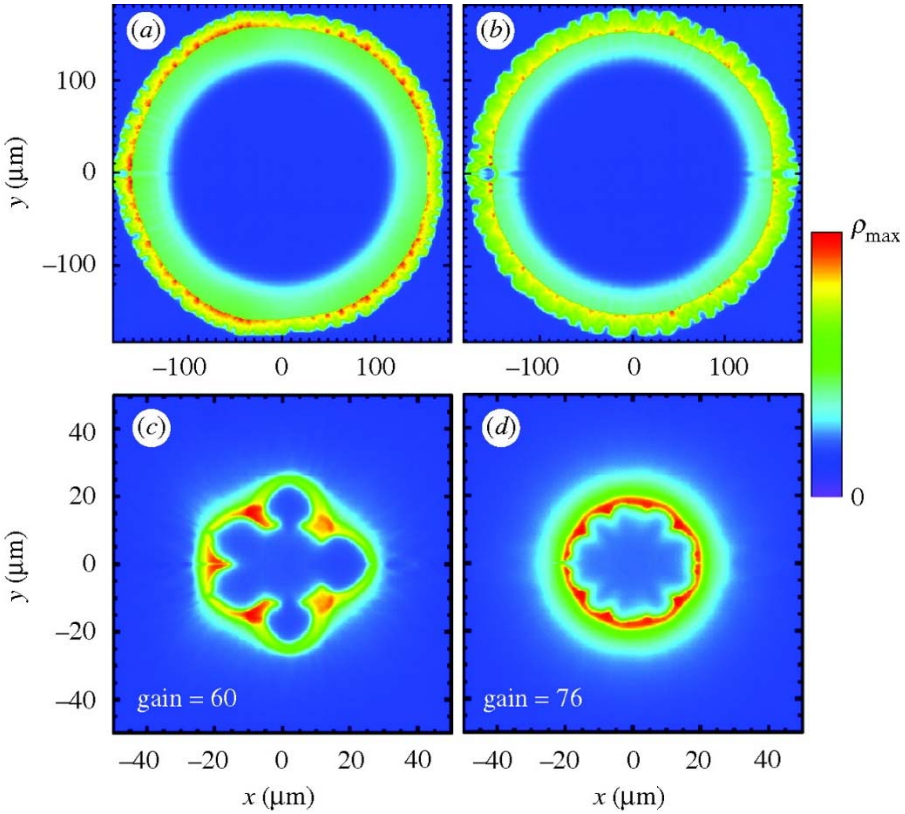
Engineering books keep this assumption even today!

In ICF research the mechanical Rayleigh – Taylor instability is the major obstacle to reach ignition in the whole volume of the target fuel.

Rayleigh – Taylor Instability

High pressure

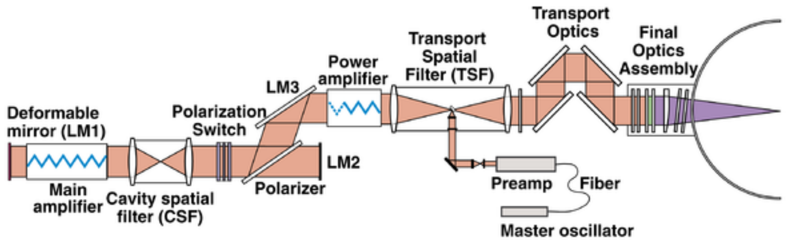




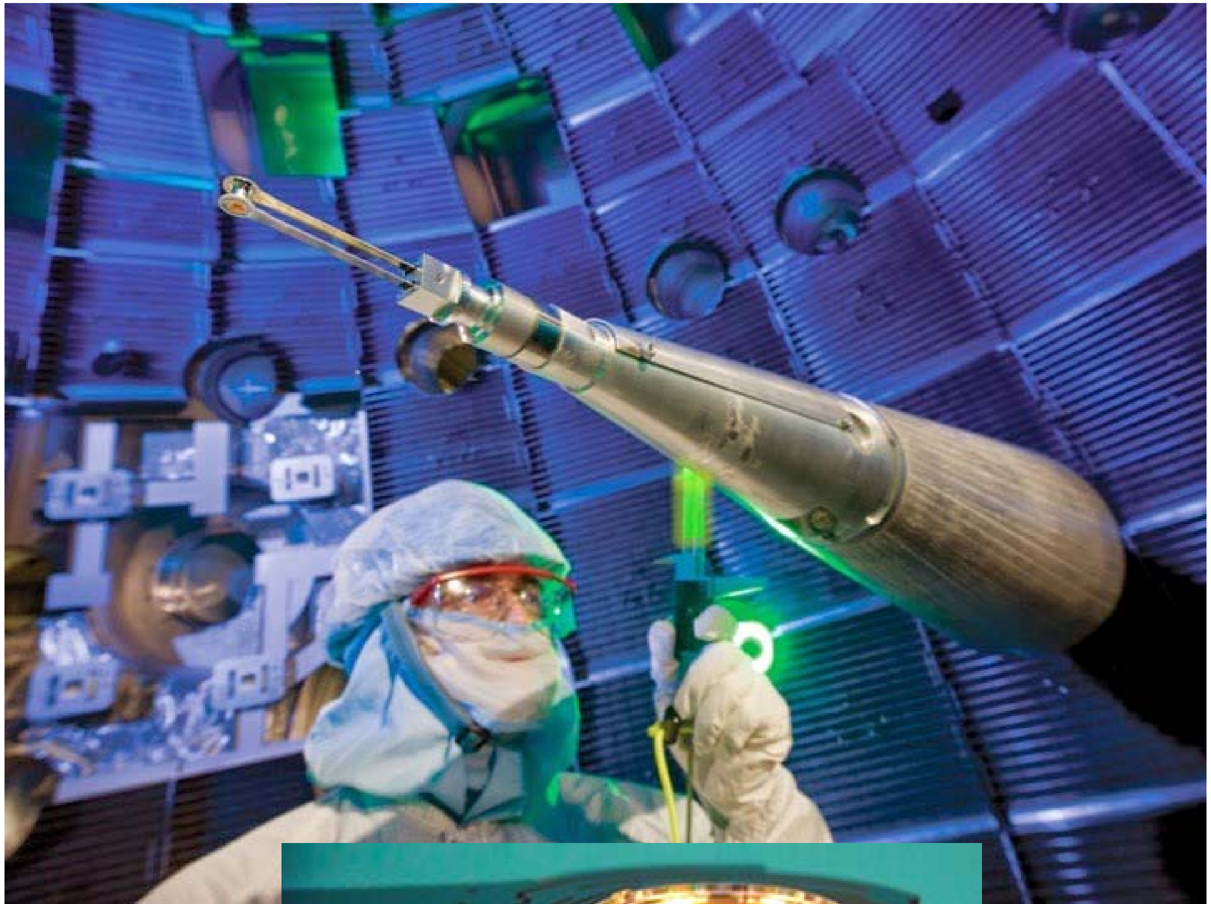
Spherical compression [LLNL]

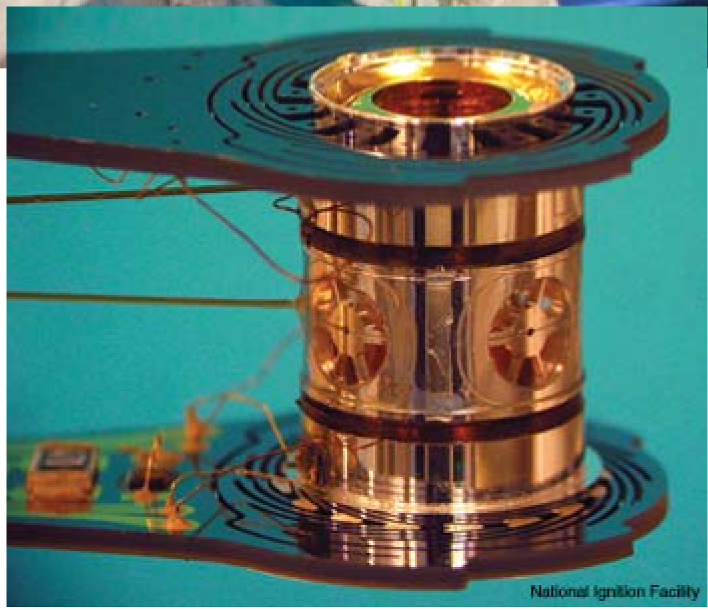
The ICF research

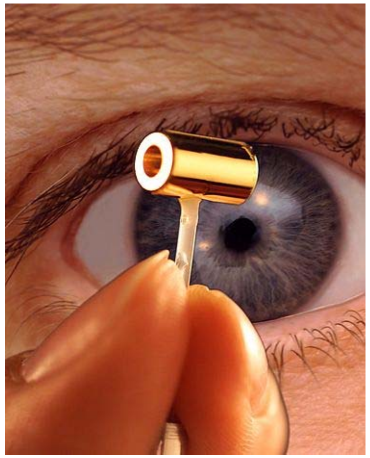
192 Lasers at NIF, 422MJ, 1/day, 25ns



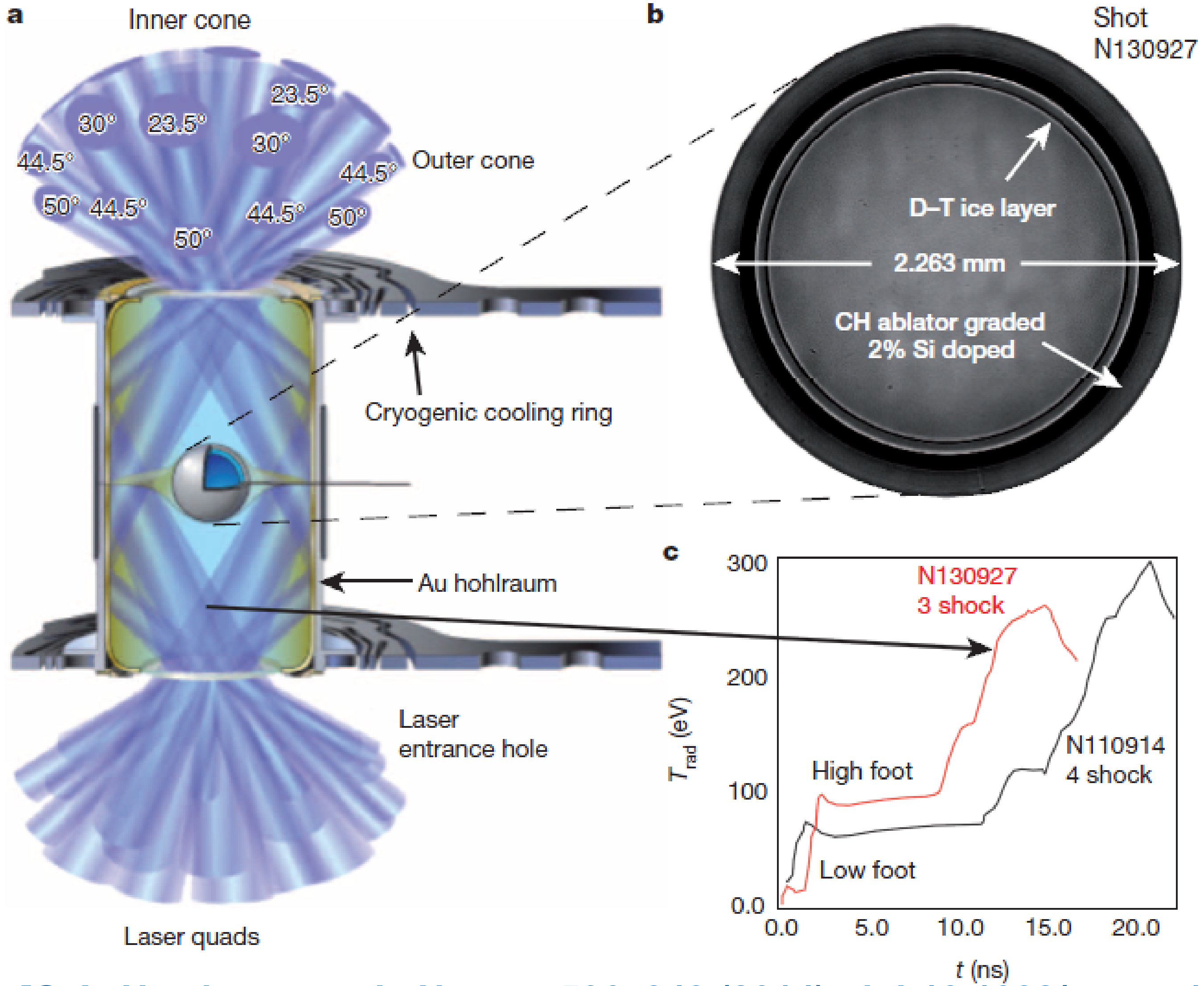
The Au hohlraum at NIF




National Ignition Facility



Indirectly Driven, ICF target for NIF



Time profile of the laser beam:

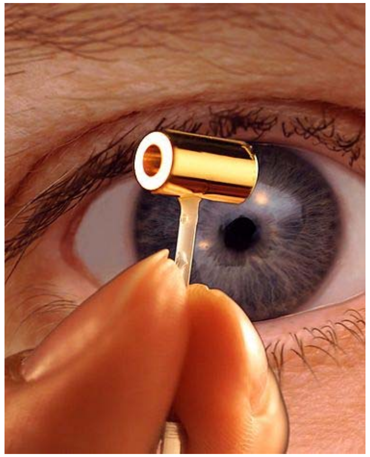
Initial pre-compression of ~ **10 ns**,
→ Stable compression

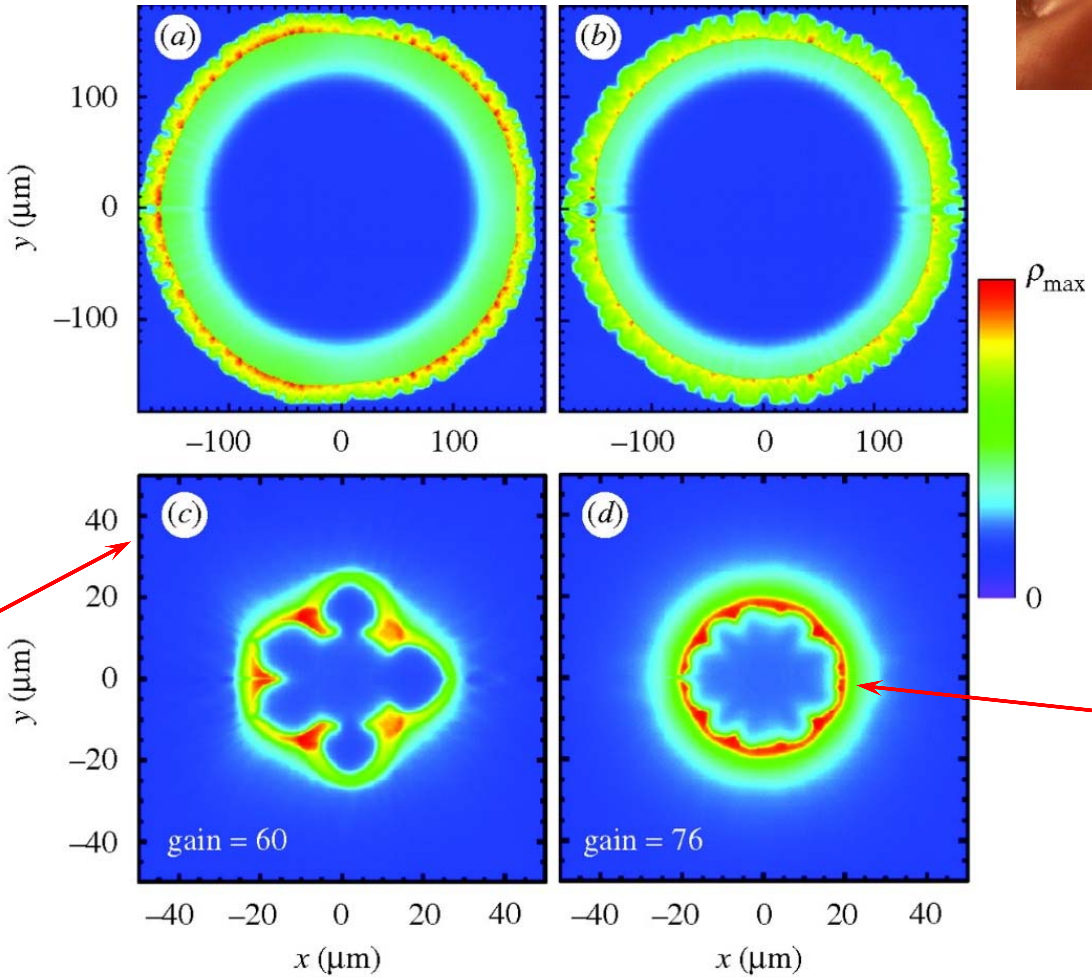
→ Then final "shocks" of ~ **15 ns** to ignite

[O.A. Hurricane et al., Nature, 506, 343 (2014), doi:10.1038/nature13008]

- The hohlraum

  The reconstructed size & shape of ignited source
  (~ 30x)



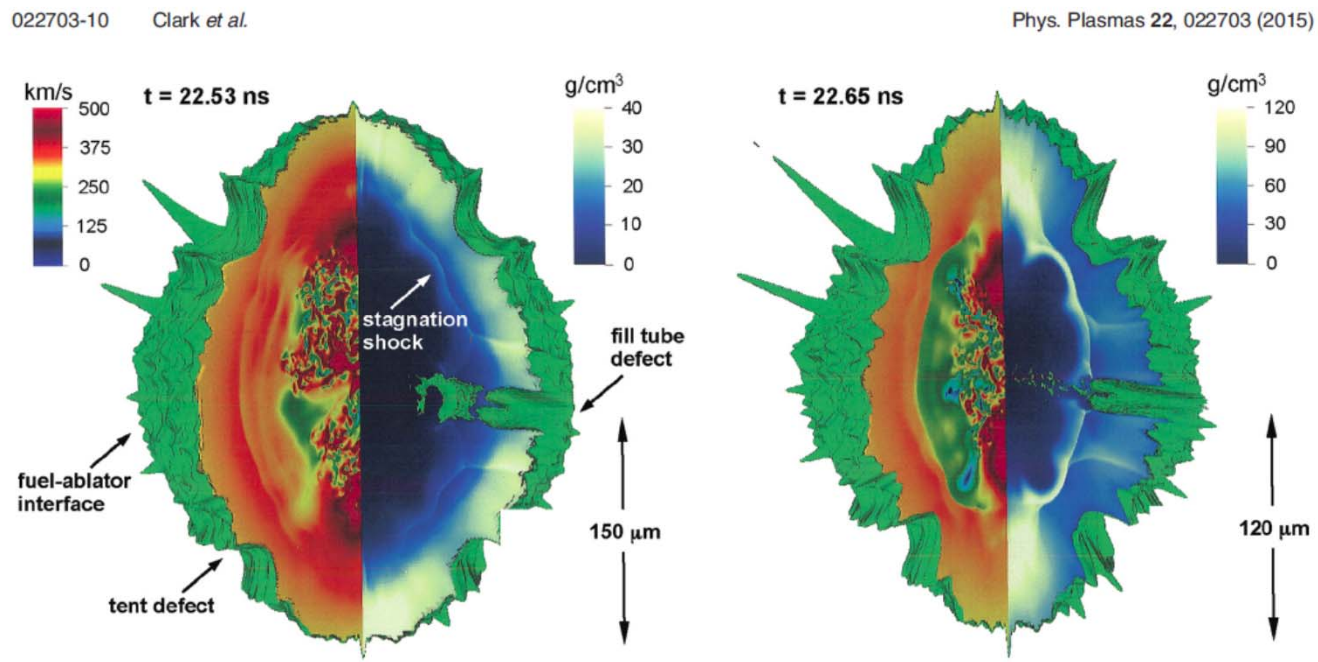


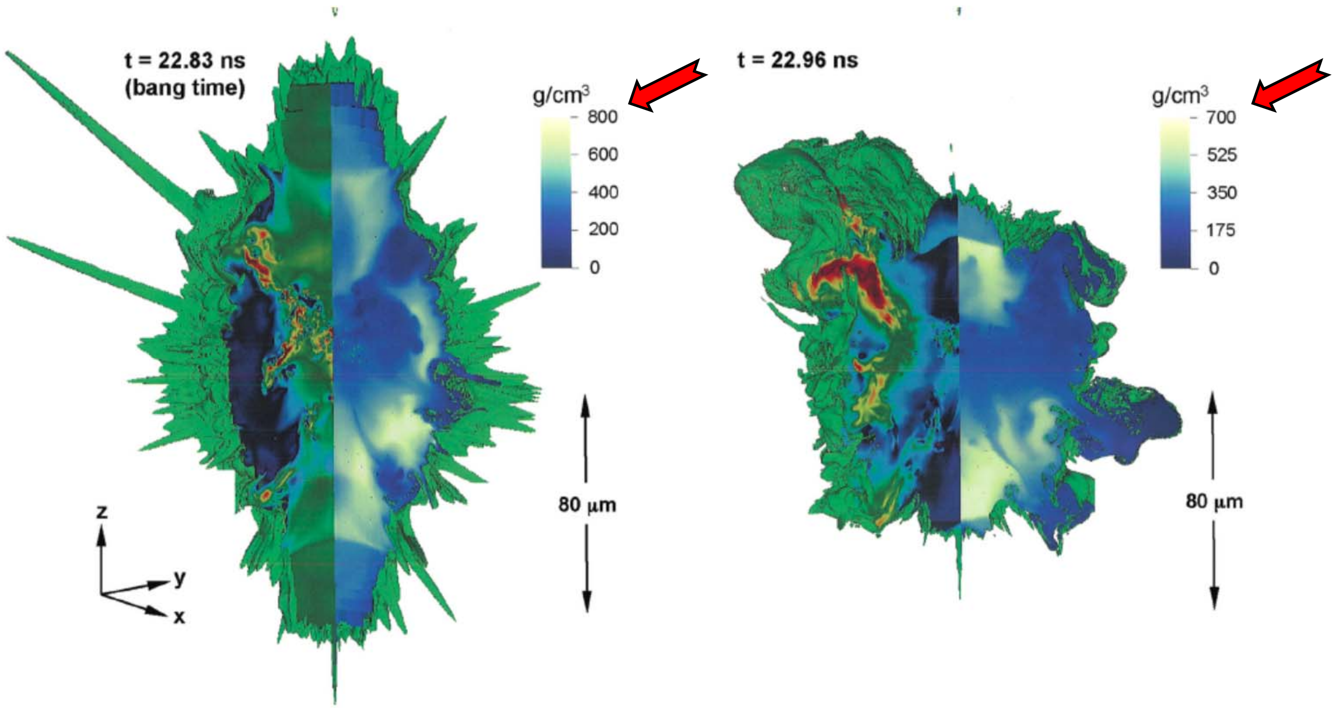
Max. compression

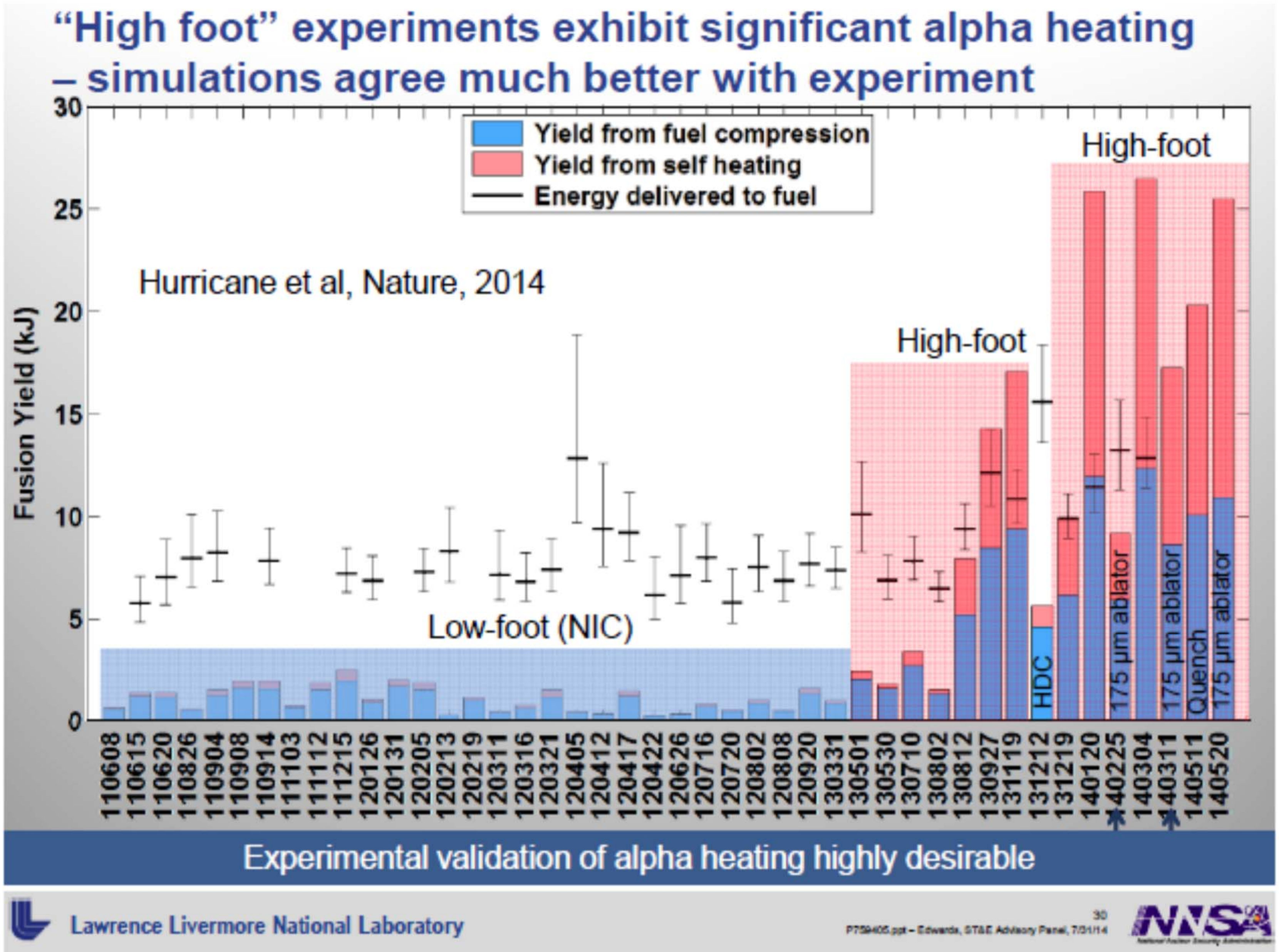
Re - expansion

[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







Phys. Rev. Lett. 120, 245003 – 14 June 2018:= **Q' > 2**

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

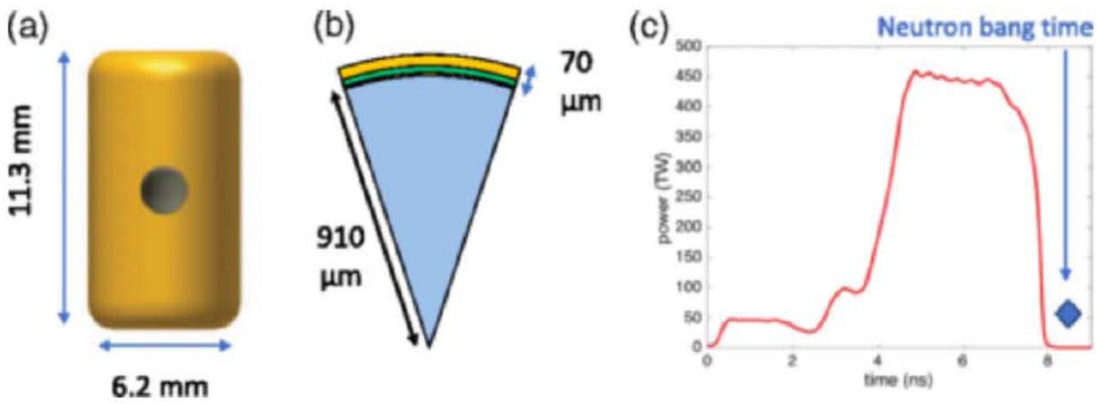


Figure 1

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

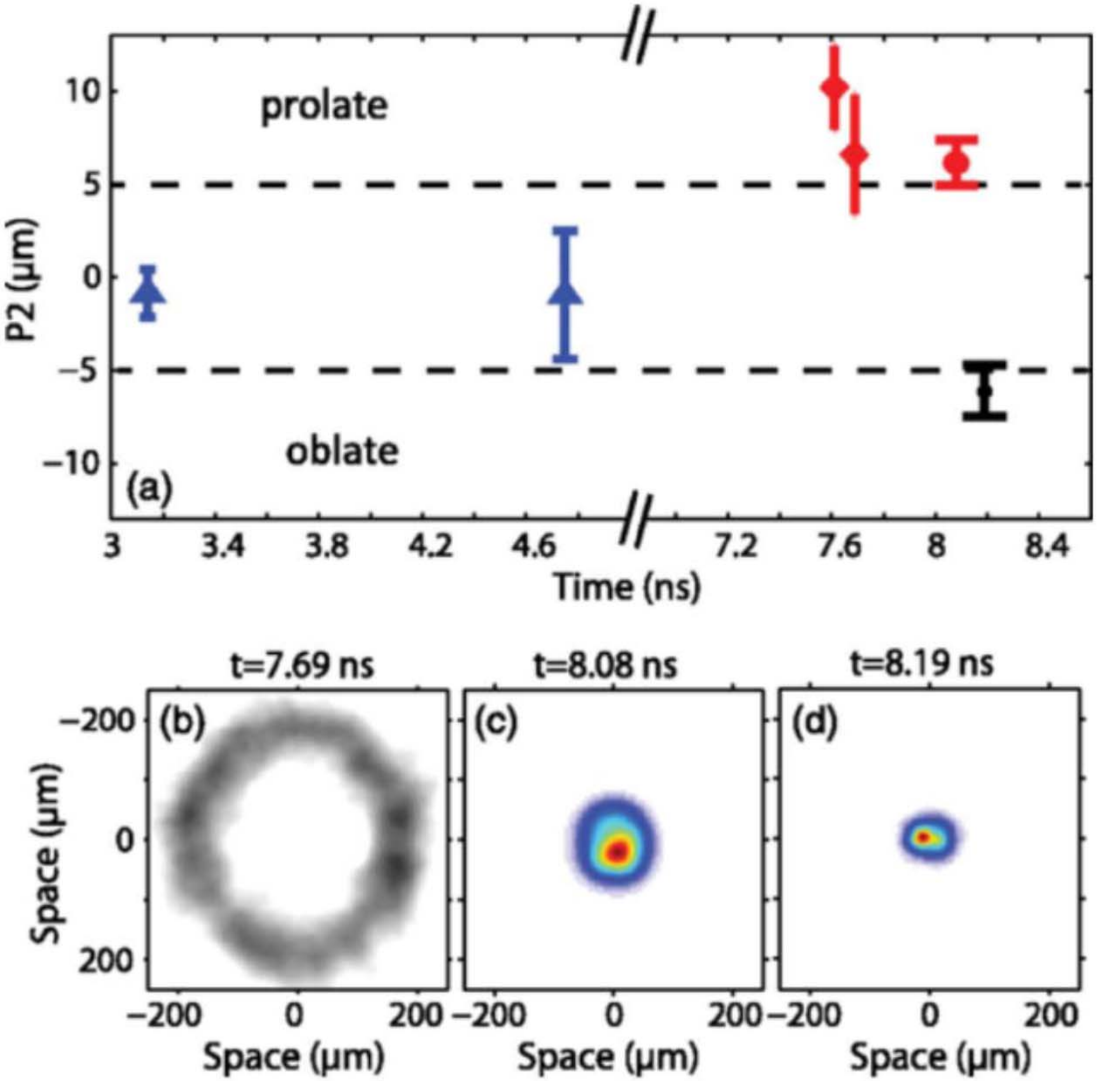


Figure 2

(a) History of the implosion symmetry for the doped HDC capsule measured at increasing convergence and time using a succession of experimental techniques. Blue points are keyhole data, red points are 2DconA data, black point is the DT cryogenic platform. The definition of $P2$ in microns as a measure of deviation from round is described in the text.
(b) equatorial x-ray radiograph of the shell, (c) equatorial x-ray image of the hot spot at bang time (convergence 17) (d), equatorial x-ray image of the hot spot at bang time (convergence 25).

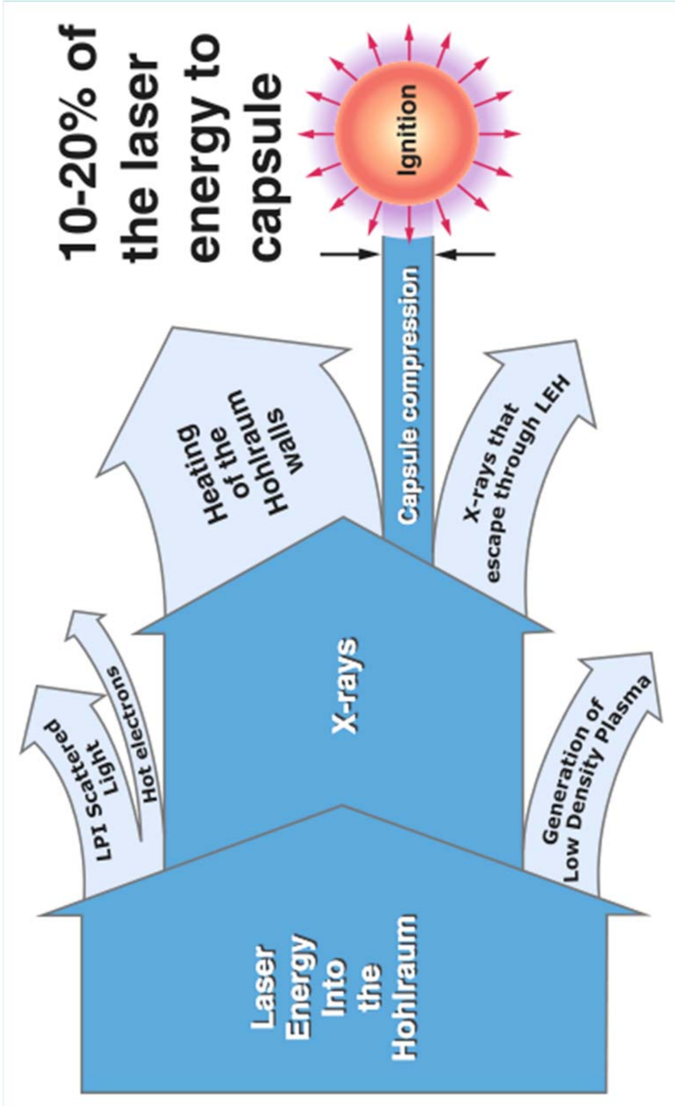
Notice: The ignition peak is now in the centre of the compressed target pellet!

Approximate energy efficiency of diff. process steps of NIF:

Input energy of the laser (xenon lamps are powered by a capacitor bank)	422 MJ
Laser Infrared output (amplified IR light of the laser)	3.6 MJ
Laser UV output (about 50% is left after conversion to UV)	1.8 MJ
Laser energy absorbed by the hohlraum (theoretical prediction: about 85% is left after the X-ray conversion in the hohlraum)	<1.5 MJ
Laser energy absorbed by the outer layers of the DT target pellet (theoretical prediction: about 15% of the X-rays are absorbed by the outer layers of the target)	<220 kJ
Actual energy absorbed by the DT target pellet (based on report that more energy for this shot was released than UV-energy that is absorbed in the DT-target).	<14 kJ

Energy out

Energy released by fusion reactions (fraction 3.3×10^{-5} of input energy of the laser)	**14 kJ**	~14 kJ



2014:= 0.003318% !

2018:= fusion energy of 54 kJ.

Burning of Quark Gluon Plasma in Relativistic, Radiation Dominated Systems according to Relativistic Fluid Dynamics
-
Applications to Pellet Fusion

Classical Fluid Dynamics (CFD) does assumes that all dynamical processes, including shocks and detonations, are having speeds slower than the speed of light, c.

Initial Relativistic FD (RFD) maintained this assumption based on the requirement of causality [A.Taub, 1948].→ Engineering books keep this assumption even today!

Relativistic Heavy Ion Physics proved the opposite!

[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,

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

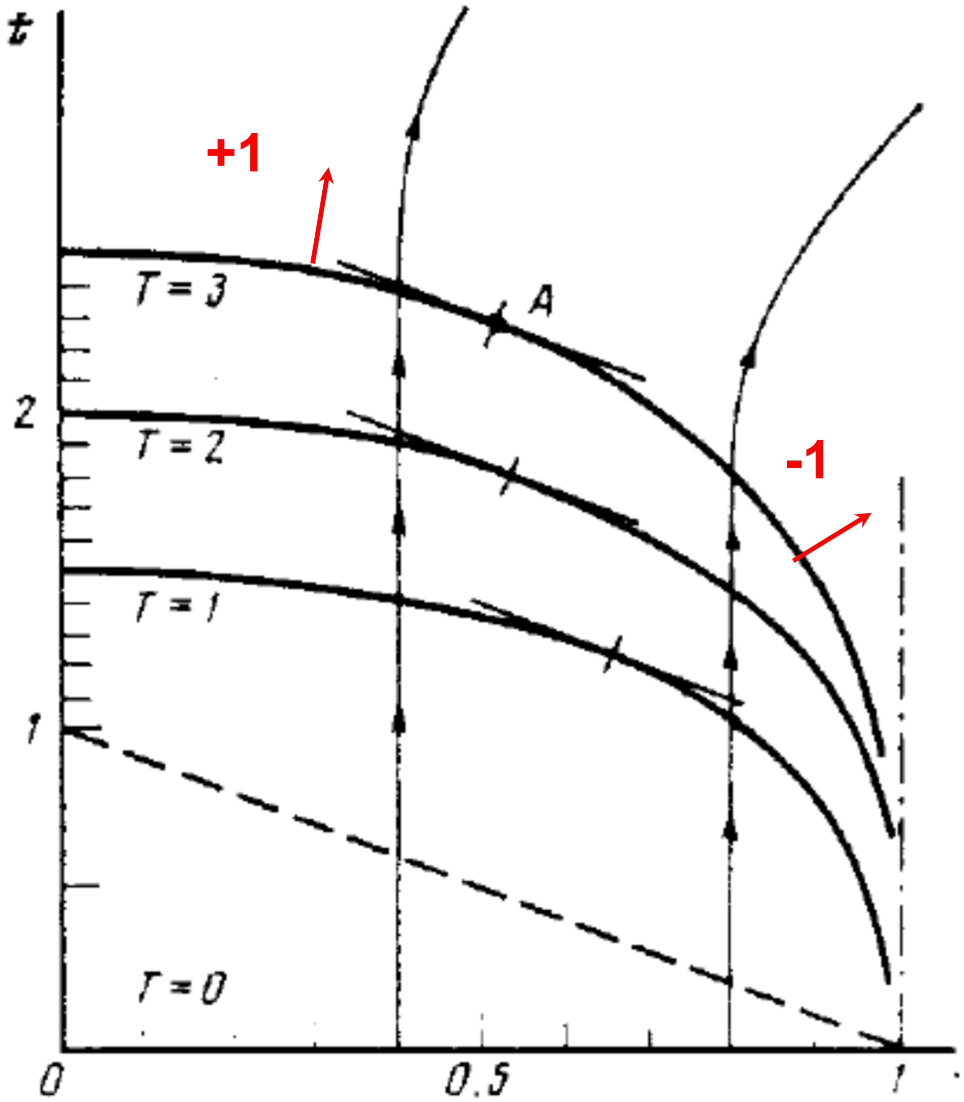
$$[T^{\alpha i} \Lambda_i] = 0, \tag{7.4}$$

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**)]

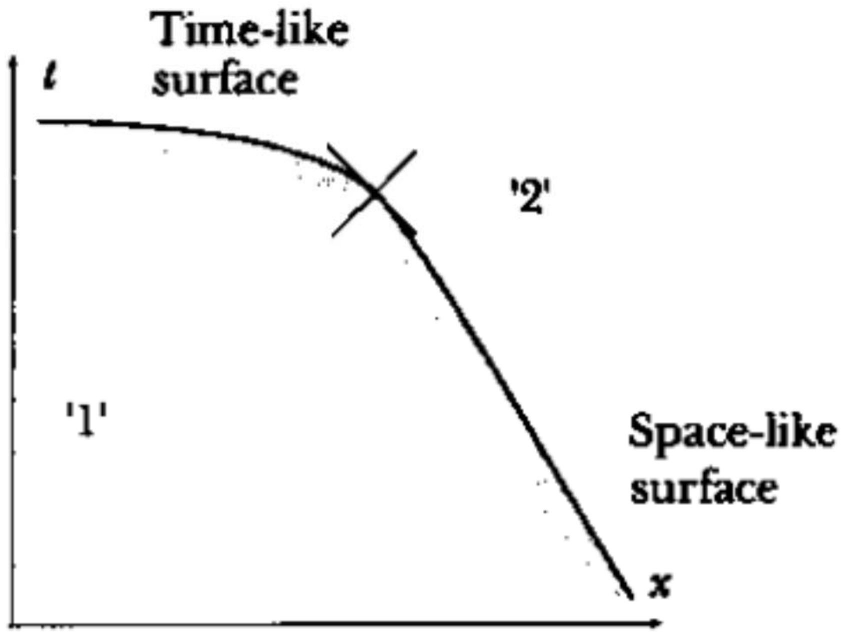
$$\lambda_\alpha \lambda^\alpha = \pm 1$$

Л. П. Чернаи

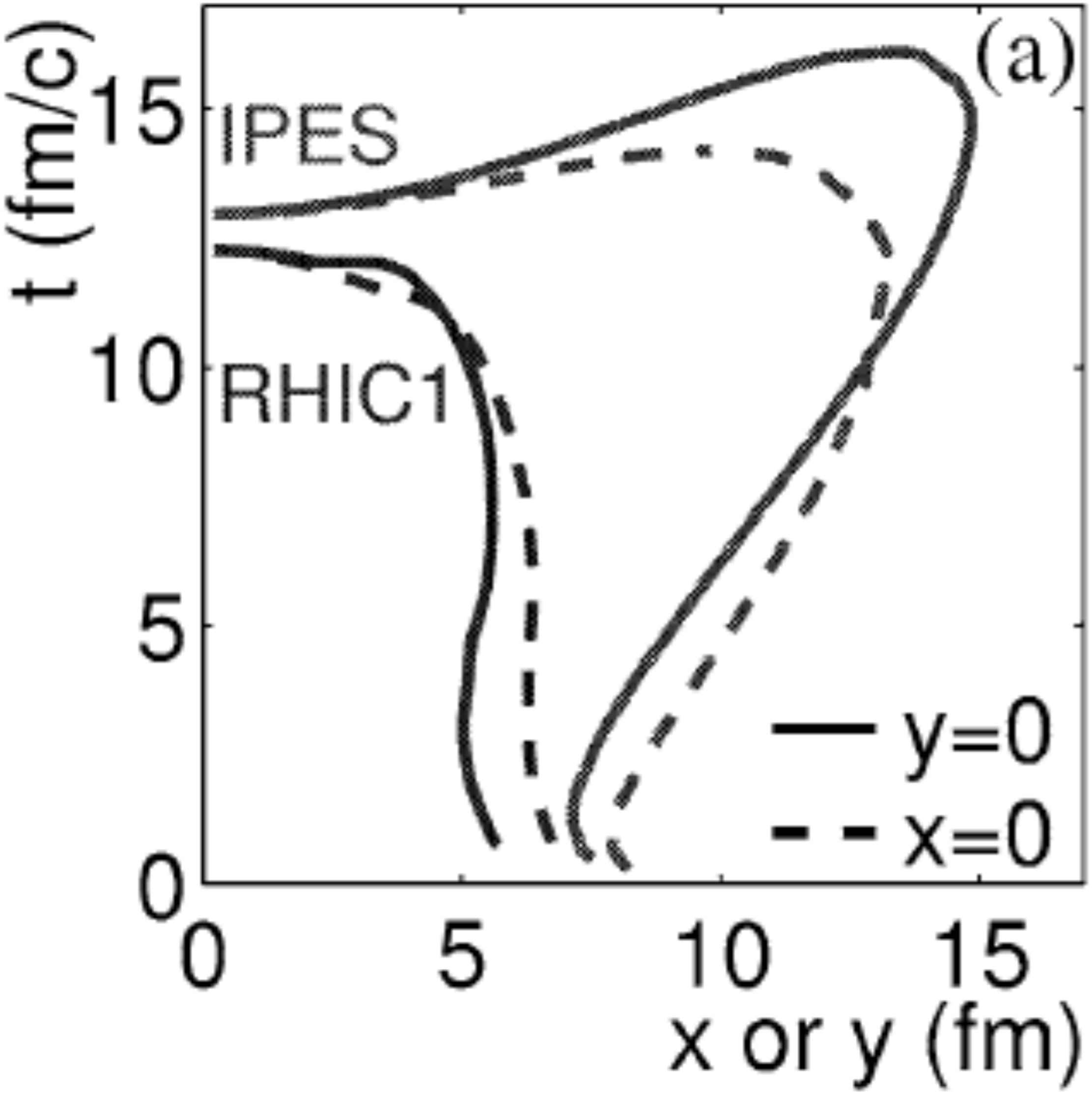
ДЕТОНАЦИЯ НА ВРЕМЕНИПОДОБНОМ ФРОНТЕ ДЛЯ РЕЛЯТИВИСТСКИХ СИСТЕМ

Журнал экспериментальной и теоретической физики

1987

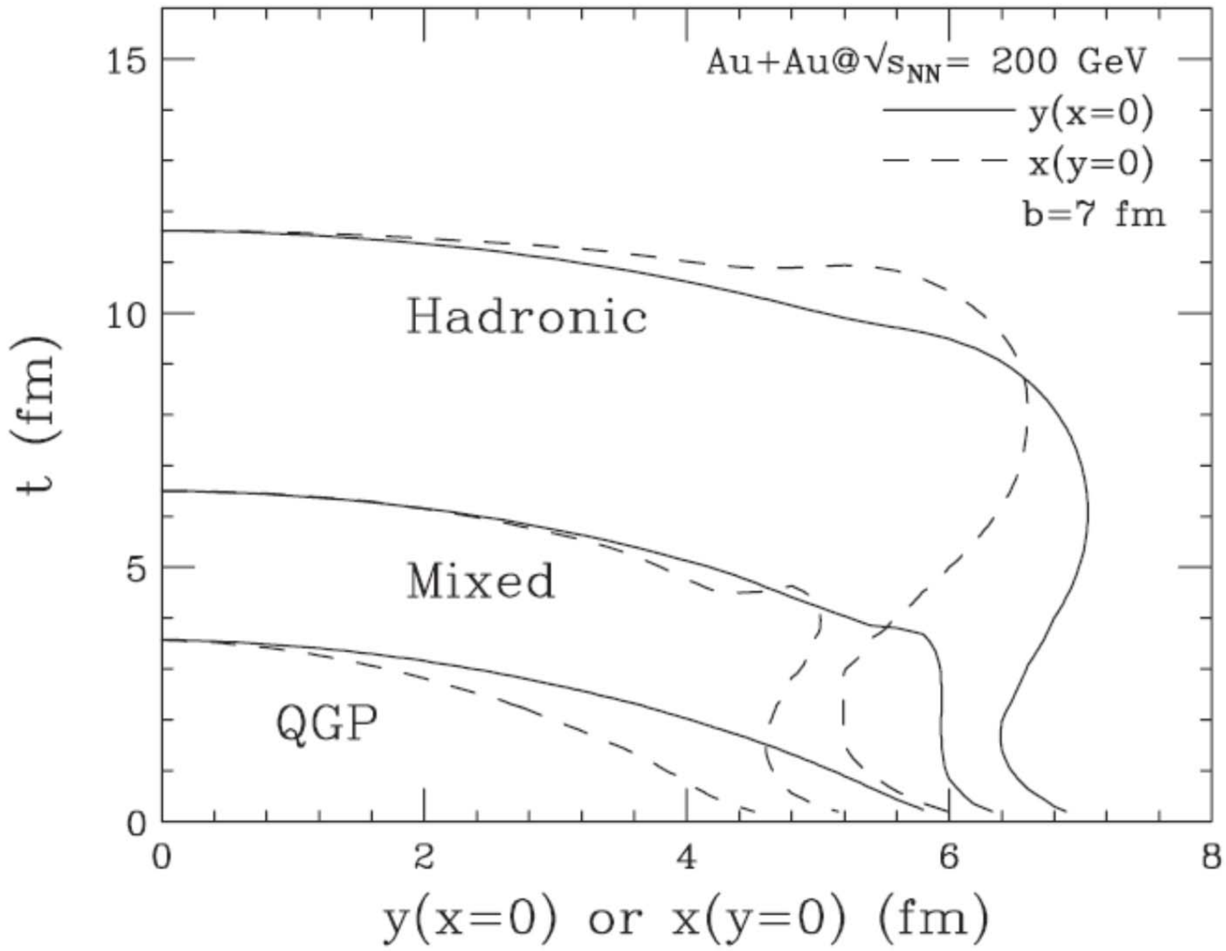


[L.P. Csernai:
Introduction to Relativistic Heavy Ion Collisions,
(**1994**, John Wiley & Sons, Cichester, England)]

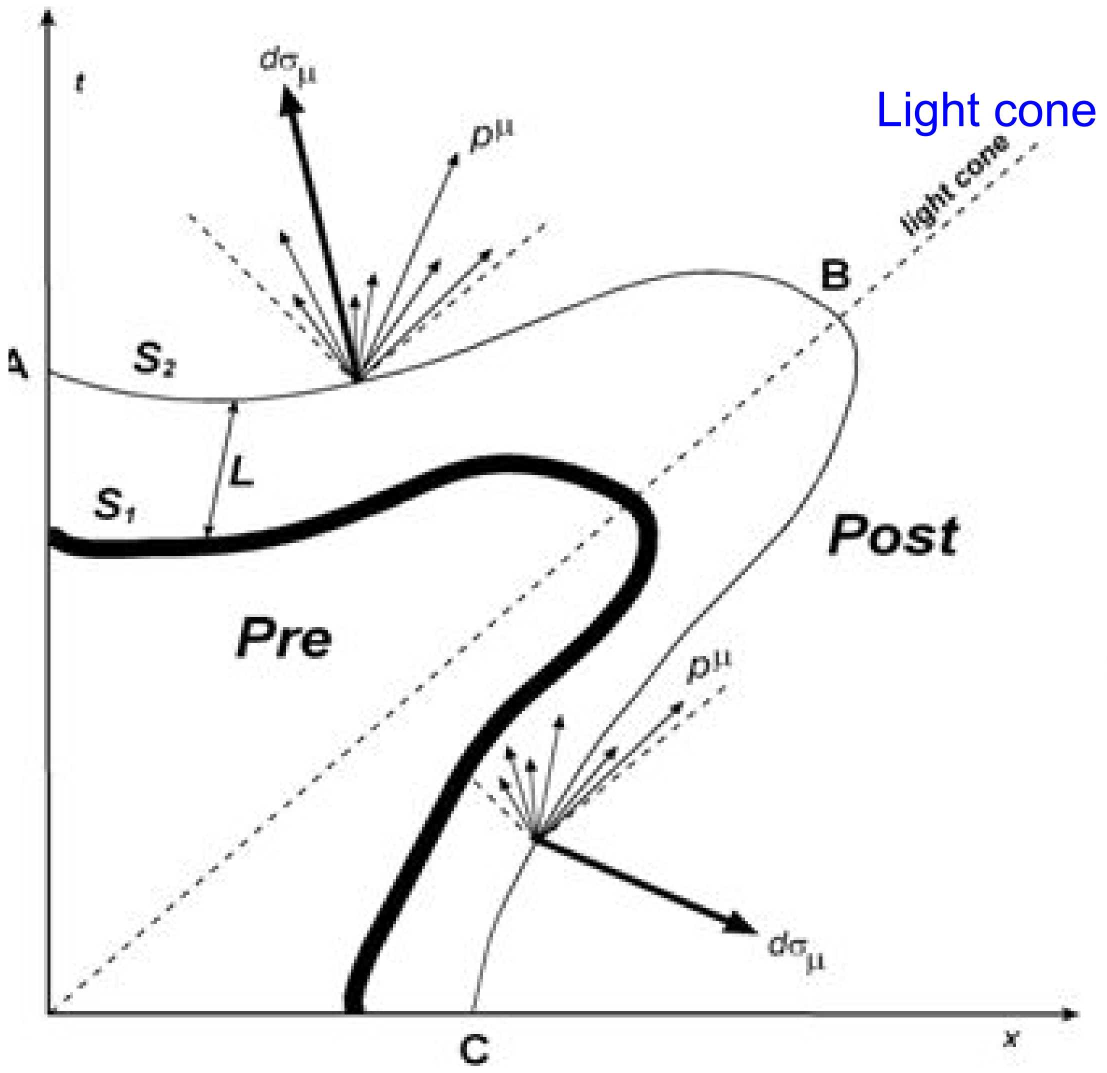


Discovery of QGP:
2000 CERN
2001 BNL

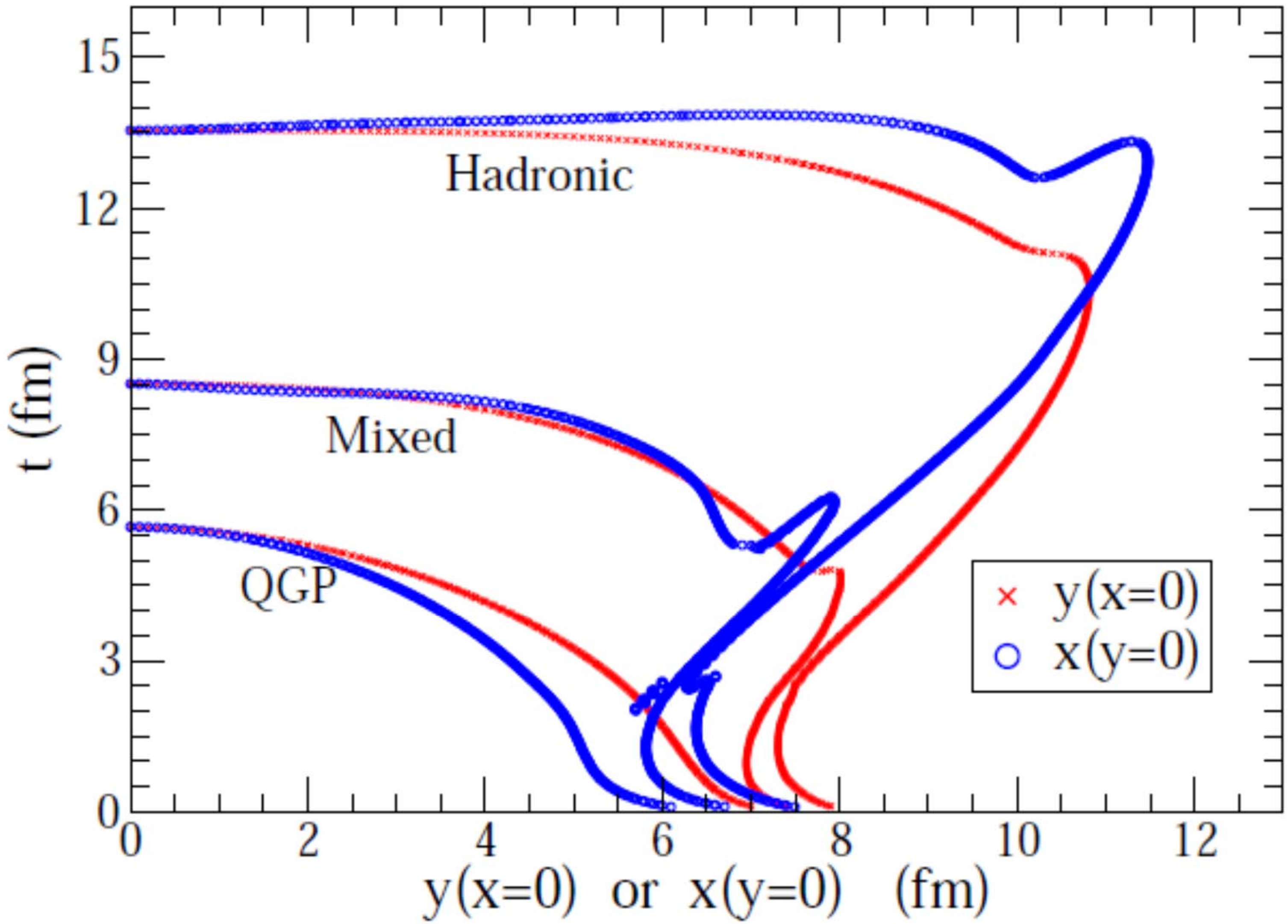
[U.W. Heinz and P.F. Kolb, Phys. Lett. B 542, 216 (2002)]



[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)]

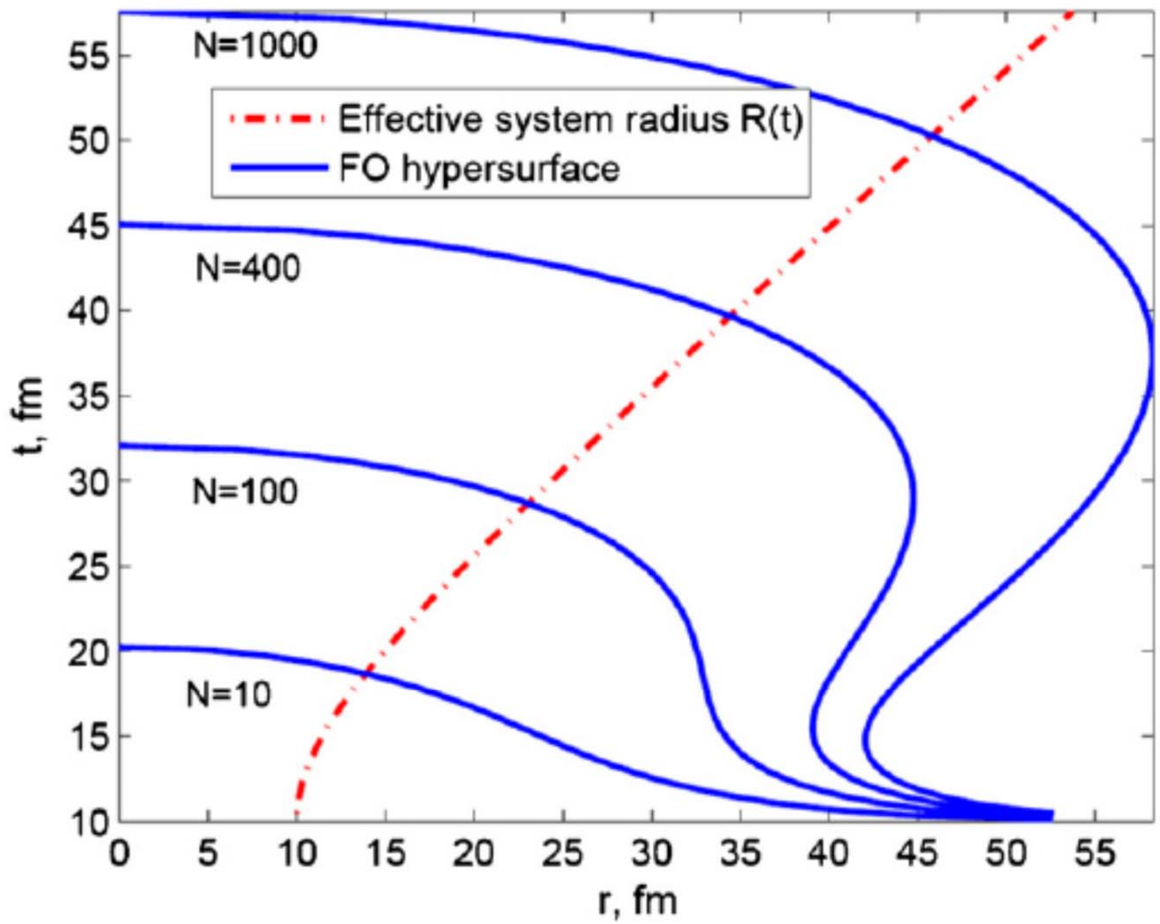
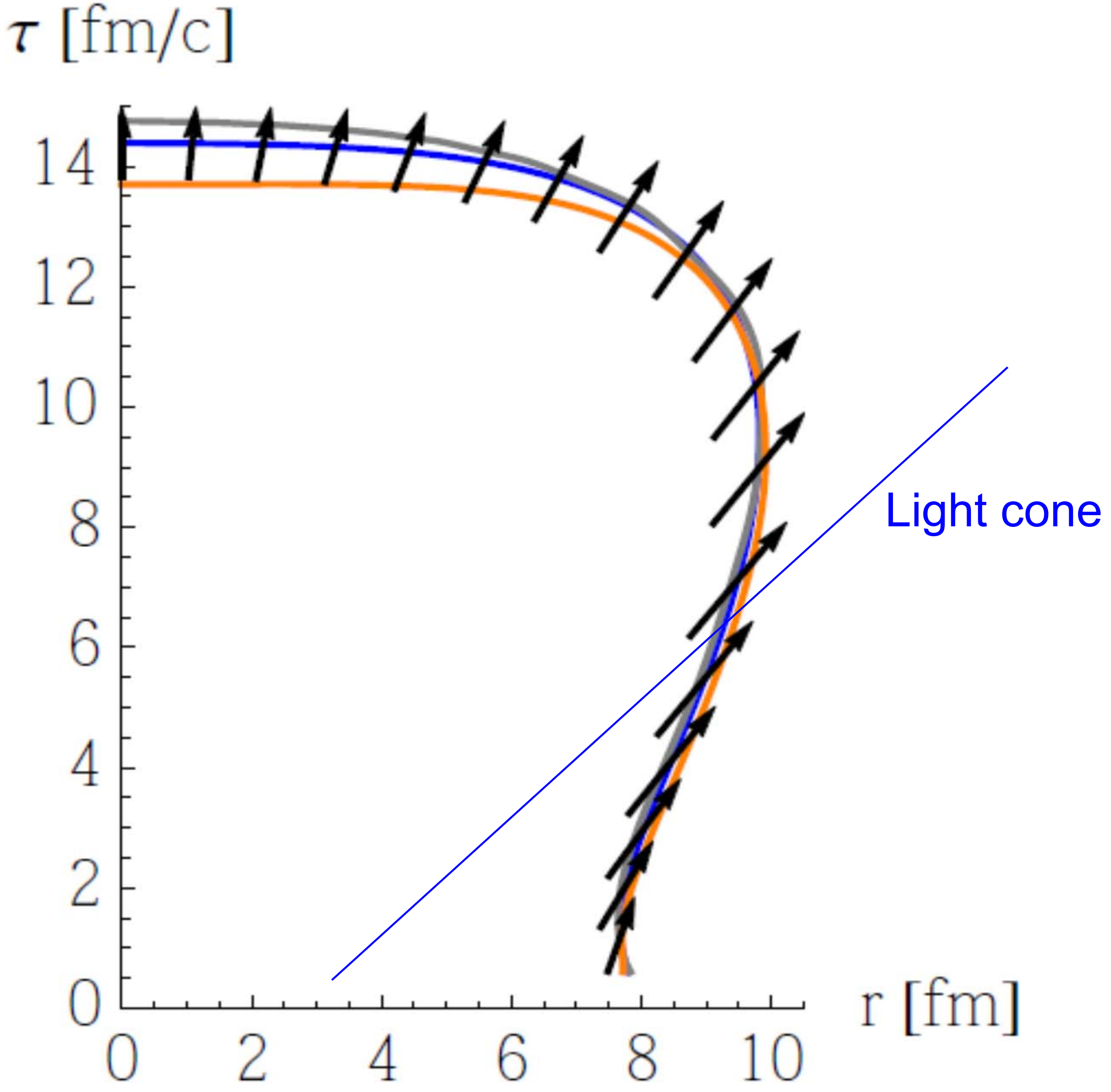
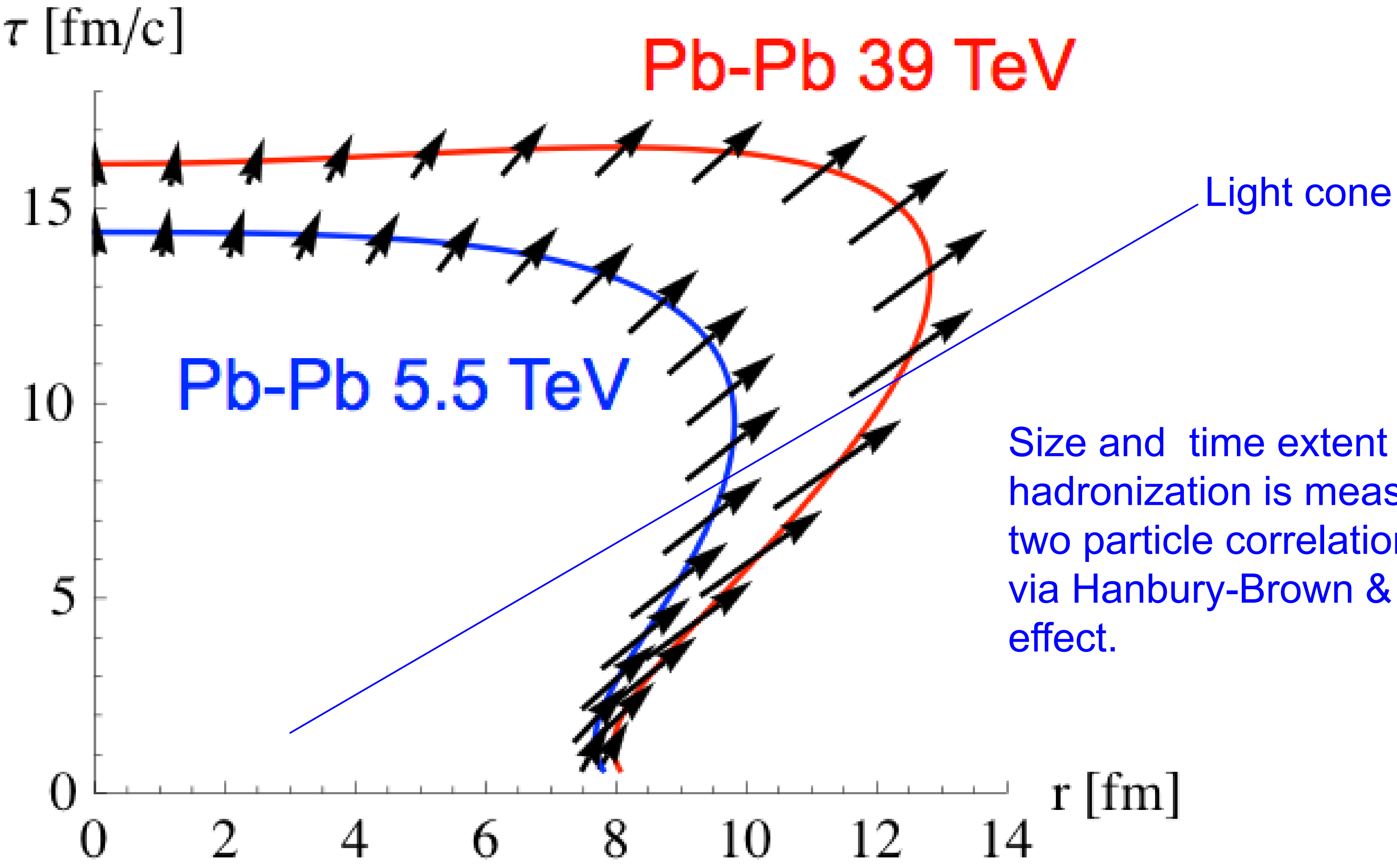


Figure 4. Freeze-out surfaces calculated from the Bondorf condition (see the text) for various particle numbers *N*.



[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

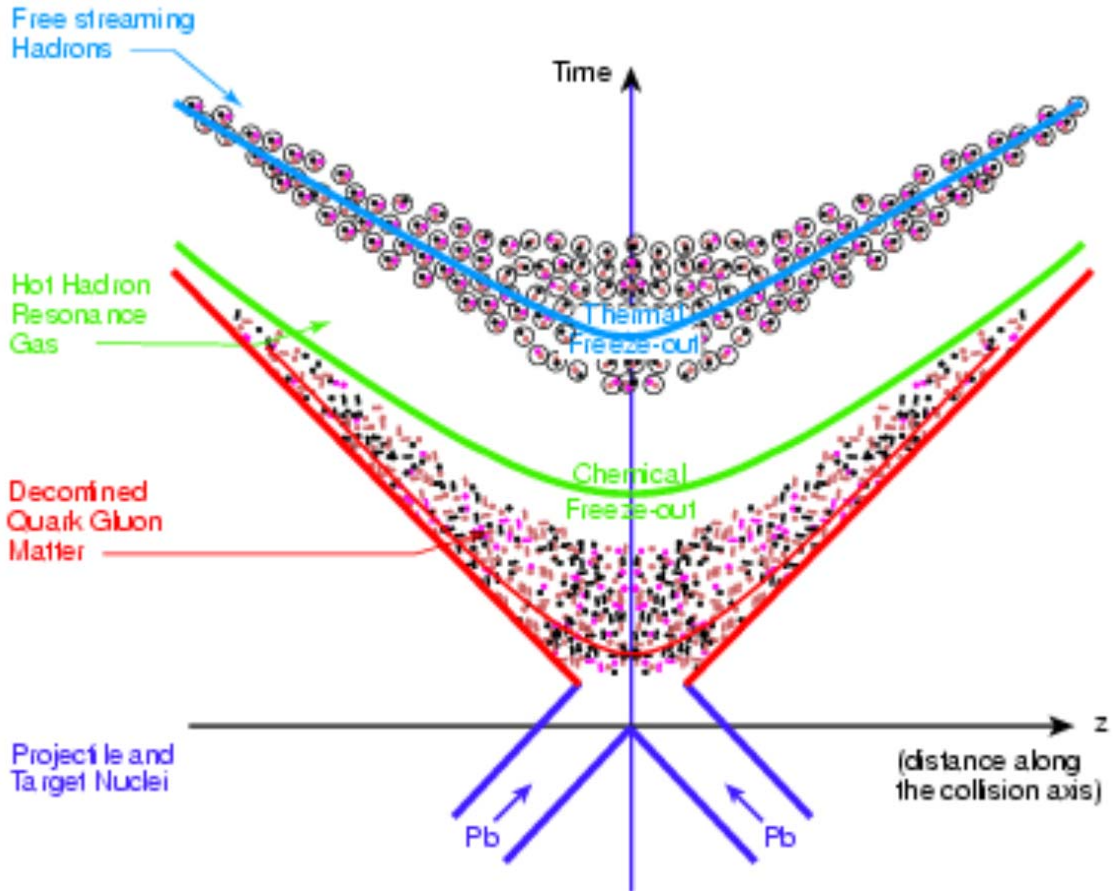
Up to now all theoretical studies of Internal Confinement fusion are based on Classical Fluid Dynamics (CFD) [HYDRA, LASNEX]

Still the aim is to

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

Relativistic Heavy Ion Physics proves that simultaneous ignition and burning is possible, both theoretically and experimentally!

This is not against causality, as the burning front is within the light cone of the initial state (i.e. the initial ST configuration).



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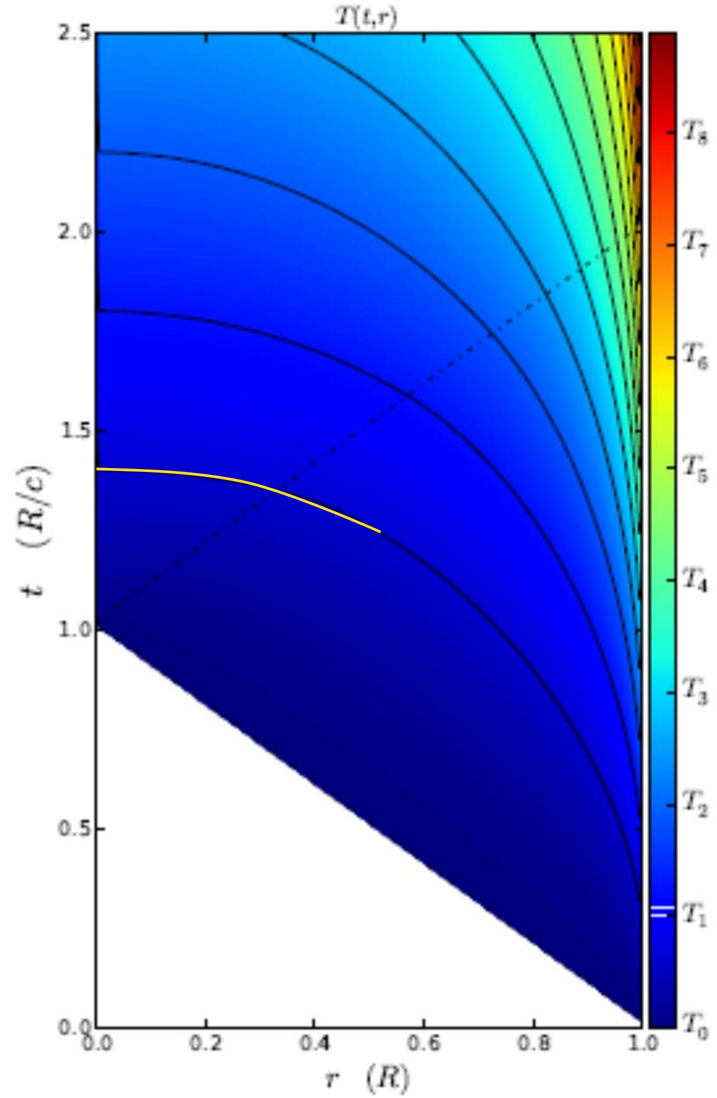


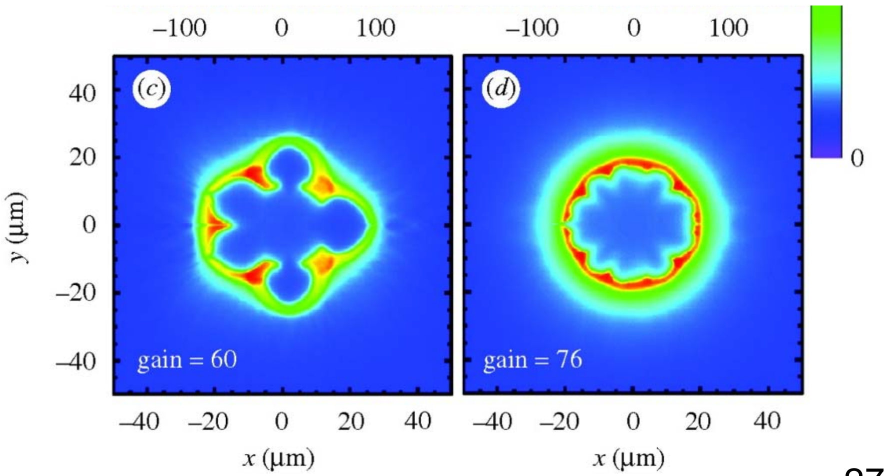
Fusion reaction:

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 better volume ignition, and how?

Two ideas are combined by
L.P. Csernai, N. Kroo, I. Papp **[Patent # P1700278/3](*)**

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

Mechanical compression and adiabatic heating should be reduced, because it is slow and leads to Rayleigh-Taylor instabilities. Similarly outside ablator surface should be reduced also.

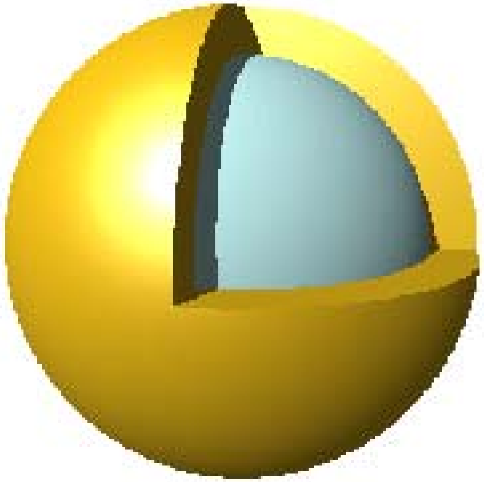
Uniform, 4π radiation should heat the target to ignition within the light penetration time (i.e. ~ 10-20 ps). This follows from RFD!

[L.P. Csernai, N. Kroo, I. Papp, *Laser and Particle Beams*,
. https://doi.org/10.1017/S0263034618000149]

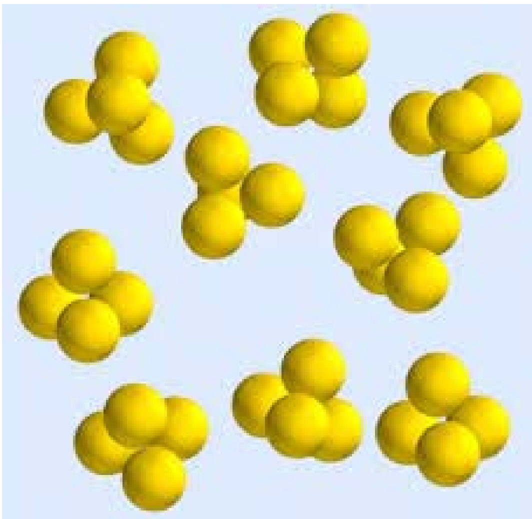
How can we achieve uniform heating?

- **Optimize the light absorptivity of the target by imbedding golden nano-shells of resonant size into the DT pellet.**
- **Nano-shells can increase light absorption by up to a factor of 30 or more.**

- Light heats up 1st the external surface of the pellet and for a longer time. To compensate for this we have to increase the absorptivity of the central domains of the pellet.
- We can optimize the absorptivity by imbedding nano-shells of increasing density towards the center of the pellet.
- This way we can achieve near uniform, simultaneous, volume ignition.



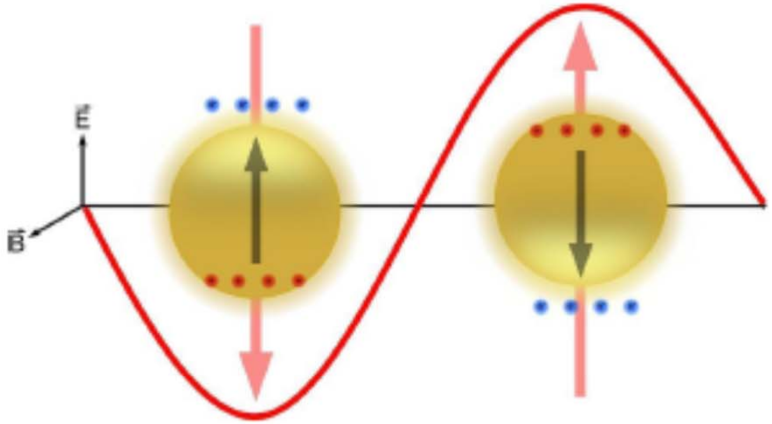
The *reflectivity* of the target can be made negligible, and the **absorptivity can be increased by one to two orders of magnitude** by the plasmonic nano-shells embedded in the target fuel.

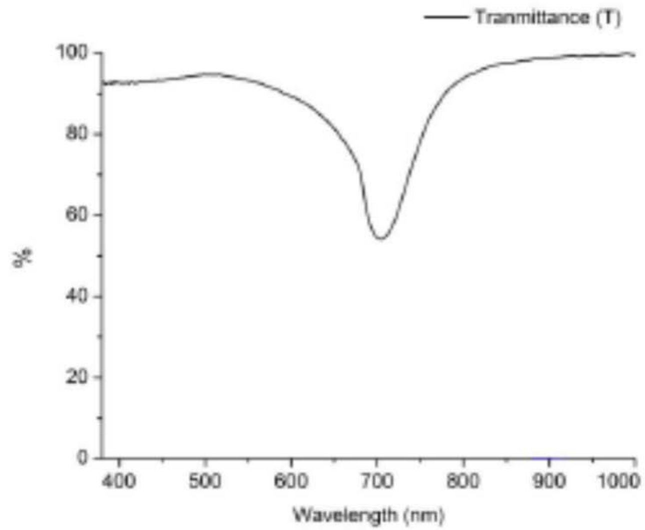


Thus higher ignition temperature can be achieved with no or modest compression. The **short light pulse** can heat the target so that most of the interior will reach the ignition temperature simultaneously.

This **prevents** the development of any kind of mechanical or pressure **instability**, which would prevent complete ignition of the target.

Metal nanoparticles (MNP) and their optical properties

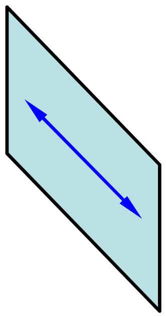




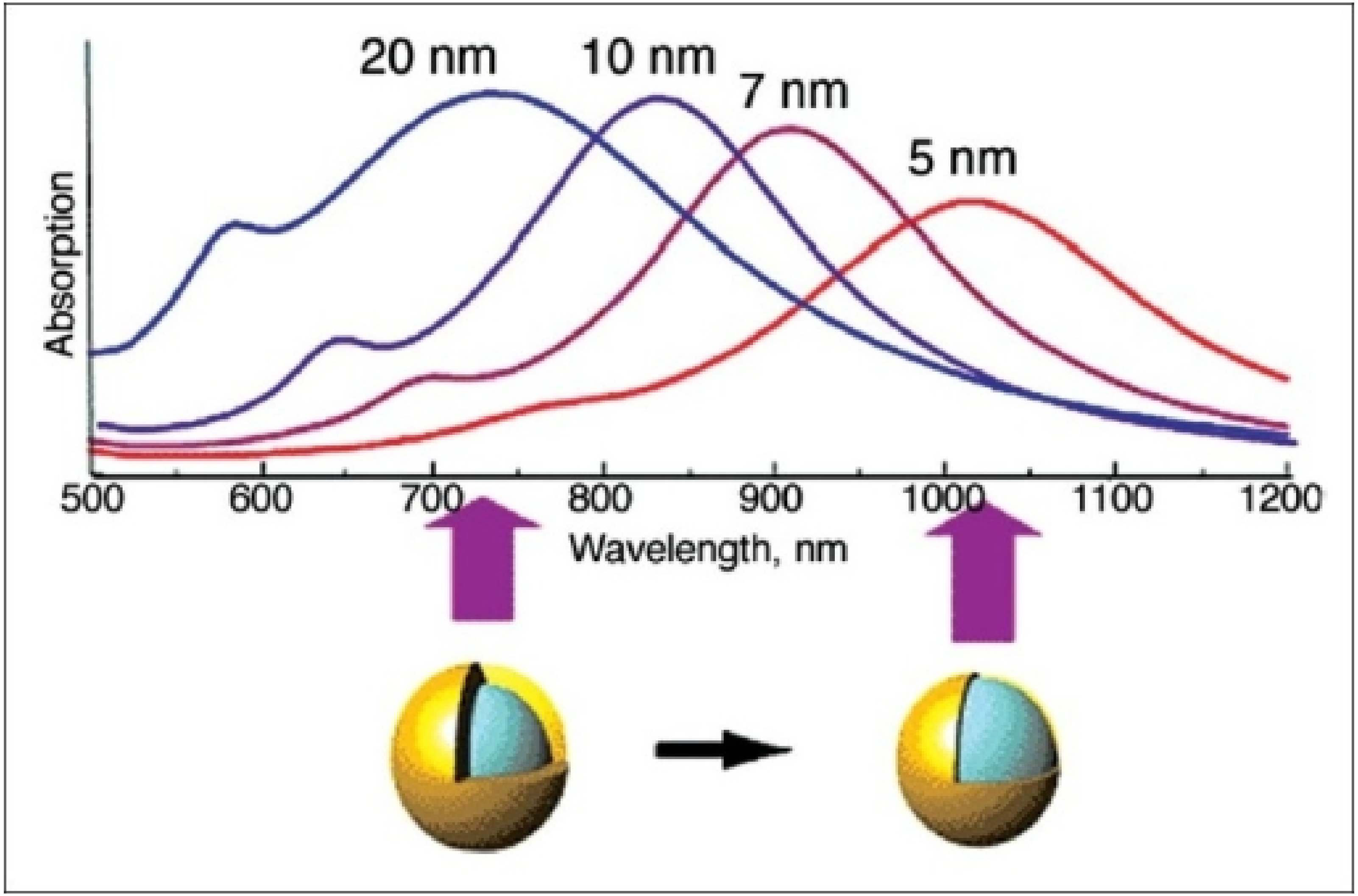
[Martin Greve, IFT Seminar, Fall (2017) for PV Solar panels]

Localized Surface Plasmon Resonance (LSPR)!

Omnidirectional TV antenna



Golden Nano-Shells – Resonant Light Absorption



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Radiation dominated implosion with nano-plasmonics

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

doi.org/10.1017/S0263034618000149

Variation of absorptivity by Nanotechnology

Doping INF pellets with golden nano-shells enables us to achieve the desired variable absorptivity (Tanabe, 2016).

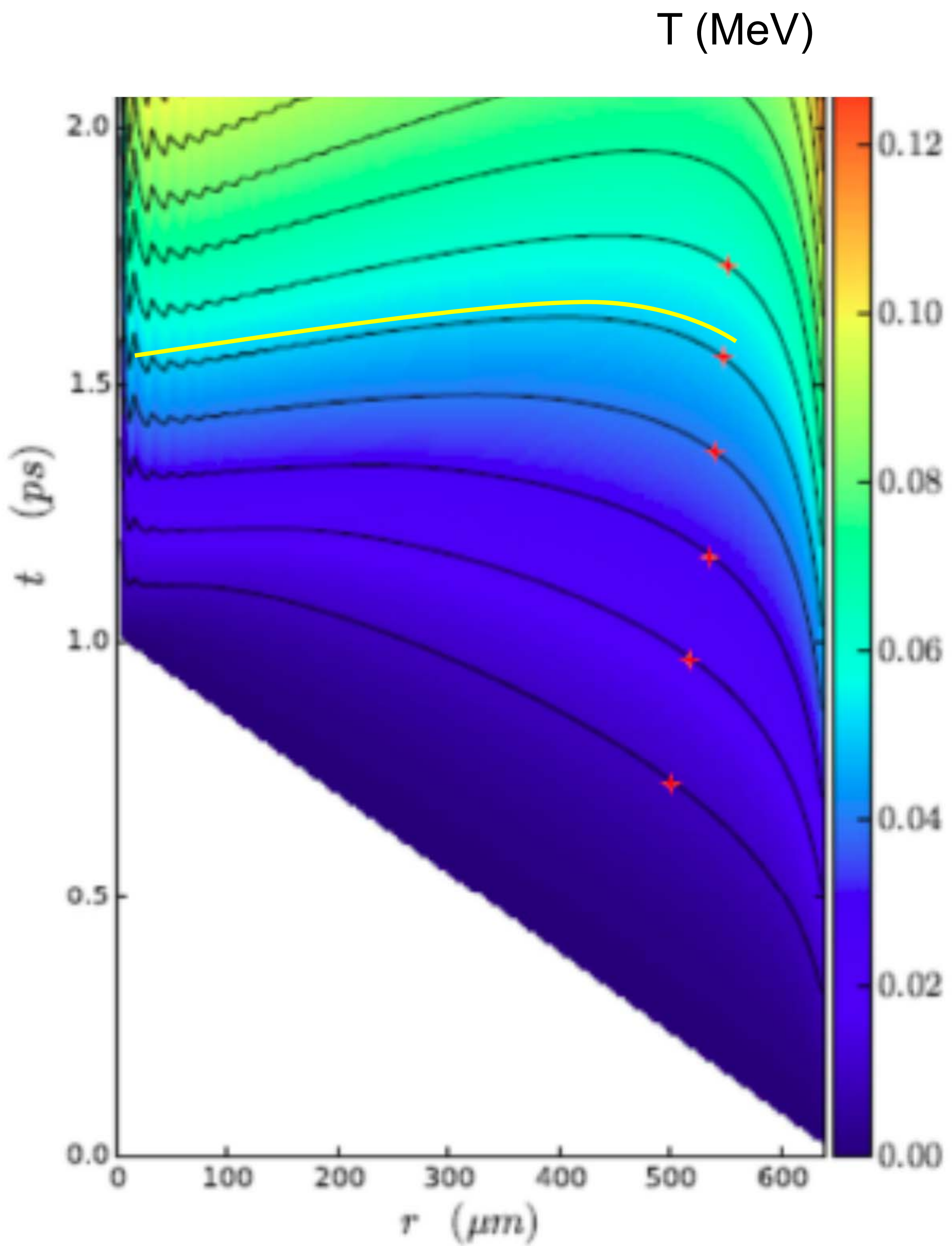
$$\alpha_k = \alpha_{k0} + \alpha_{ns} \, , \qquad (12)$$

where the absorptivity of nano-shells, α_{ns}, is

$$\alpha_{ns} = \rho G Q_{abs}. \qquad (13)$$

For a nano-shell of $R = 30$ nm the additional contribution would be $\rho G Q_{abs} = \rho Q_{abs}$ 0.283 cm^2. Consequently, for a typical nano-shell density (James *et al.*, 2007) of $\rho = 10^{11}/\text{cm}^3$ and a $Q_{abs} \approx 10$, we can reach an additional absorptivity of

$$\alpha_{ns} = 28.3 \, \text{cm}^{-1}. \qquad (14)$$



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}.

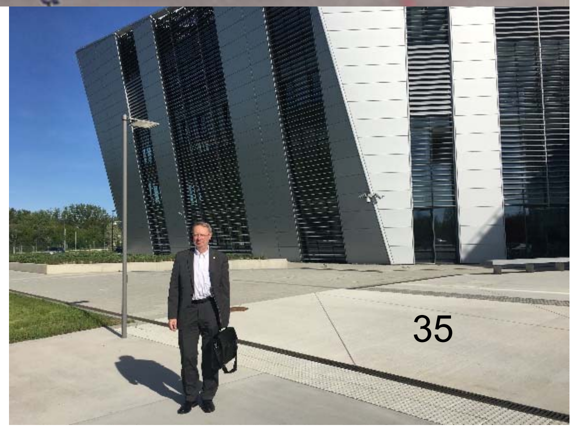
The temperature is measured in units of T_1 = 272 keV, and T_n = n T_1.

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

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**



HAS Wigner RCP, Budapest

Gagik P. Dzsotjan, József Bakos, Gábor Demeter, Dávid Dzsotjan, Miklós Kedves, Béla Ráczkevi, Zsuzsanna Sörlei, Péter Lévai

Laser wake acceleration of protons for radiation therapy

- proton beam energy is deposited at a location of a certain depth [Bragg peak]
- tumor treatment with minimal side damage (compared to other radiation therapies)
- target is low density (~ like water or more)
- Collaboration with Peking University, China

These features are similar to the needs of laser induced ICF with nano-plasmonics!
Deposition at a depth via the Bragg peak is an alternative way to get volume ignition

Gábor Veres, István B. Földes, Márk Aladi, Imre Ferenc Barna, Róbert Bolla, Zsolt Kovács, Mihály Pocsai, Dániel Dunai, Gábor Anda et al.

Fusion plasma diagnostics, ITER, JET etc.

Péter Dombi, Péter Rácz, Norbert Kroo et al.

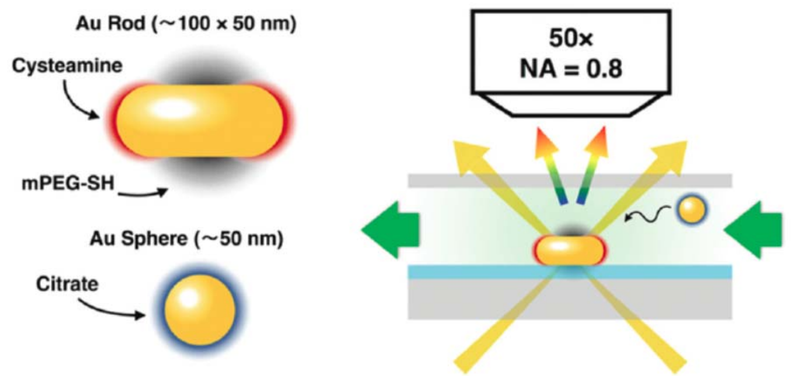
Laser induced nano-plasmonics

HAS Centre for Energy Research, Budapest
Inst. for Technical Physics and Materials Science

András Deák, S. Pothorsky, D. Zámbó, D. Szekrényes, Z. Hajnal, Béla Pácz et al.

Nano-particle assembly at the single particle level
- manufacturing of Au nano-shells and nano-rods
- imbedded in different concentrations in carriers
- polarized target constructions with nano-rods (for polarized laser irradiation)
- testing resonant light absorption

Nanoscale



Scheme 1 Schematics of the prepared nanoparticles (left) and the measurement arrangement (right). The patchy nanorods are first immobilized on ITO covered substrates, then the aqueous nanosphere solution is introduced and changes in the scattered spectrum upon binding detected.

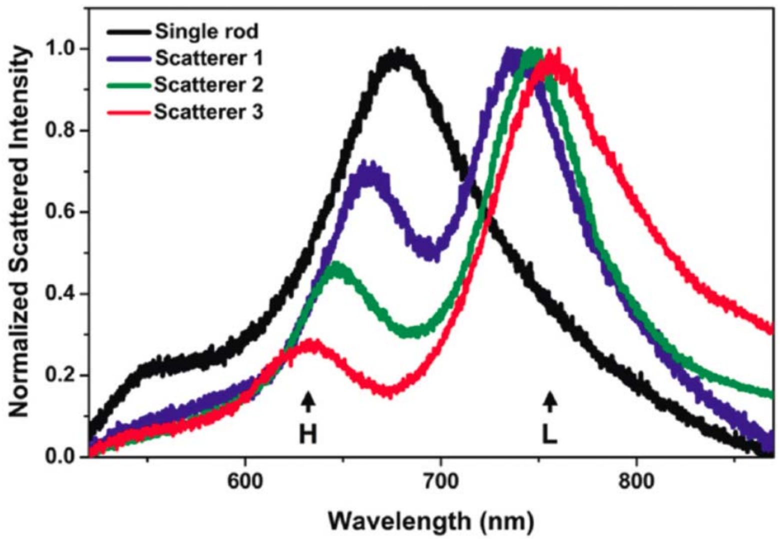


Fig. 1 Typical scattering spectra measured *in situ* in the liquid cell. The appearance of the high (*H*) and low (*L*) energy peaks surrounding the dip indicate the formation of a heterodimer. The spectrum of a single nanorod before the assembly is shown for reference.

[Detecting patchy nanoparticle assembly at the single-particle level, S.Pothorszky et al., Nanoscale 9(2017)10344]

Available resources:

	Pulse energy	Pulse frequency	Pulse length
LLNL NIF 192 laser 3D	2.15 MJ	1/day	~ 10-30 ns
ELI-APLS 2PW High field laser	20 J	10 Hz	< 10 fs
Wigner - Coherent Ti-Si Hidra L.	30 mJ (upto 100 mJ)	10 Hz	40 fs
Optimal for laser induced ICF with nano-plasmonics tests	?	1 Hz	1-10 ps !

Target size → required ignition pulse length for simultaneous (time-like) ignition

Target thickness 2L [m]		Max Pulse time 3L/c [s]	
2.00E-03	mm	1.00E-11	10 ps
2.00E-04	100 µm	1.00E-12	ps
2.00E-05	10 µm	1.00E-13	100 fs
2.00E-06	µm	1.00E-14	10 fs
2.00E-07	100 nm	1.00E-15	fs
2.00E-08	10 nm	1.00E-16	100 as
2.00E-09	nm	1.00E-17	10 as

Another Option to Reach Volume Ignition
Heavy-Ion Beams – FAIR & NICA

- Energy deposition by heavy ion beams – Bragg peak!
- Absorption depth can be tuned! ➔
- Beam bunch energy distribution could be achieved
- Present Bunch length is ~ 70 ns
- Bunch length of 10 ps may be reached [B. Sharkov]
- ➔ **Proposal(s), Patent(s), Laser wake acc. ?**

Time-like detonation in presence of magnetic field

Ritam Mallick* and Shailendra Singh
Indian Institute of Science Education and Research Bhopal, Bhopal, India
(Dated: August 6, 2018)

Today !

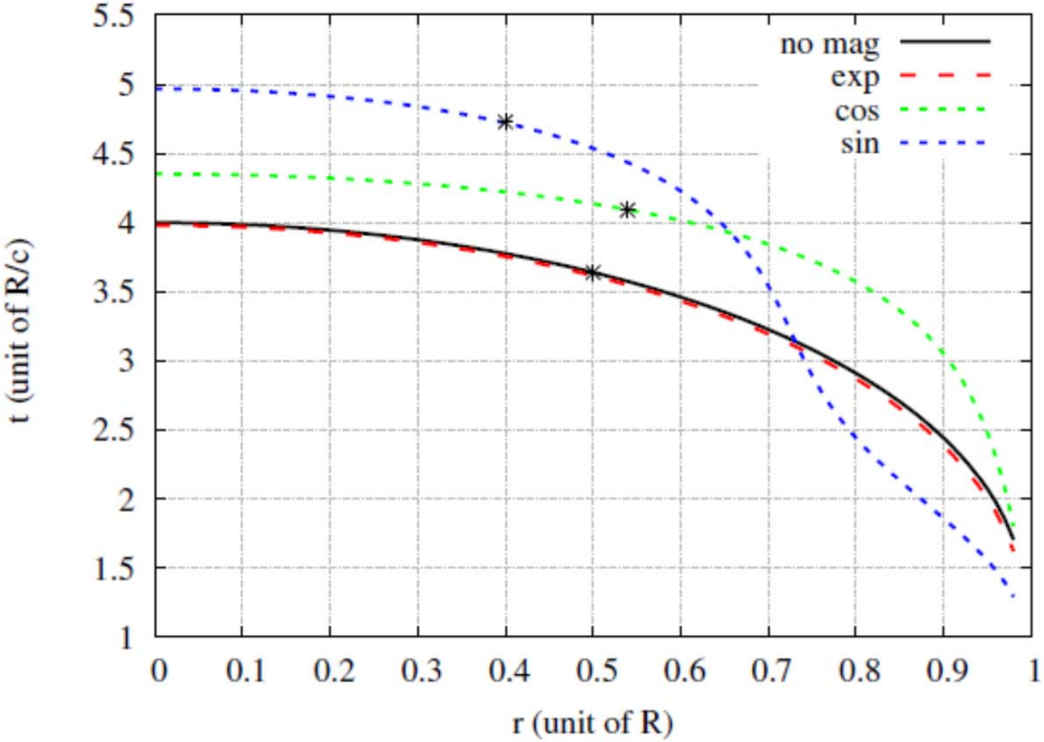


FIG. 1. Contour $T(r,t) = T_c$ for non magnetic and magnetic curves are drawn. The values of the normalized parameters are $K = 1 = \frac{4\pi CQ}{C_v}$, $\alpha = 1.0$ and $T = 3$ (in unit of $\frac{2\pi CQ}{C_v}$).

Thus, ultra-relativistic heavy ion physics did not only lead to fundamental discoveries, as the **EoS and transport** properties of Quark Gluon Plasma (QGP) **,**

but also to advances in relativistic fluid dynamics (RFD), which may revolutionize the technological development of **Inertial Confinement Fusion** research and other dynamical radiation dominated processes.

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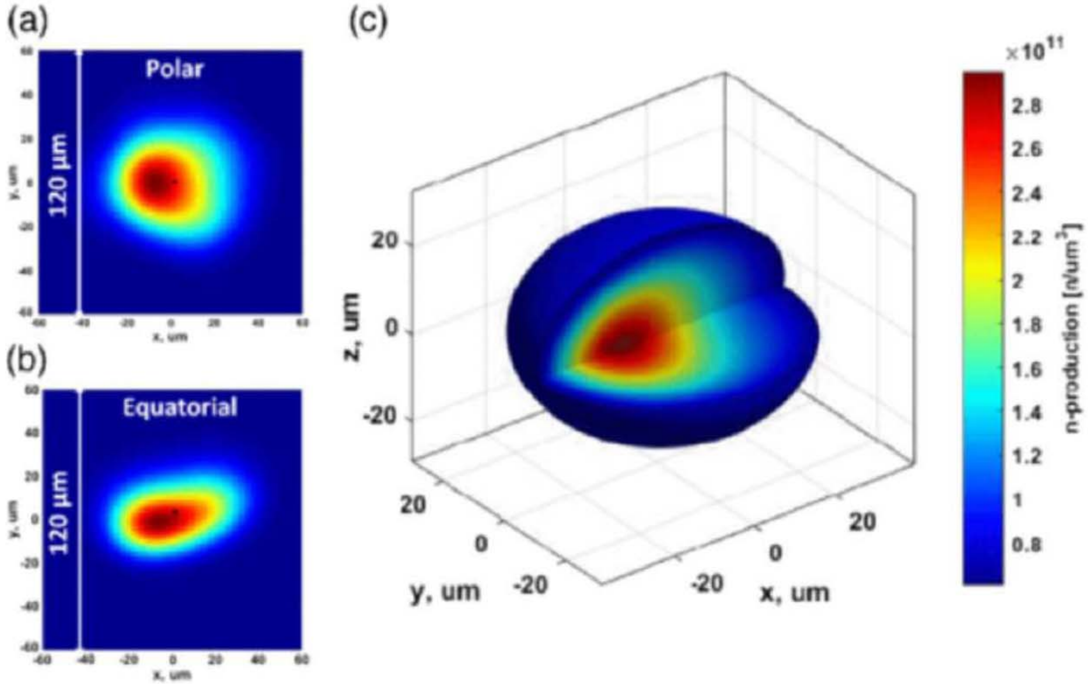

Figure 3

Shot N170601. (a) Polar neutron image. (b) Equatorial neutron image. (c) Three-dimensional reconstructed neutron volume of the hot spot.

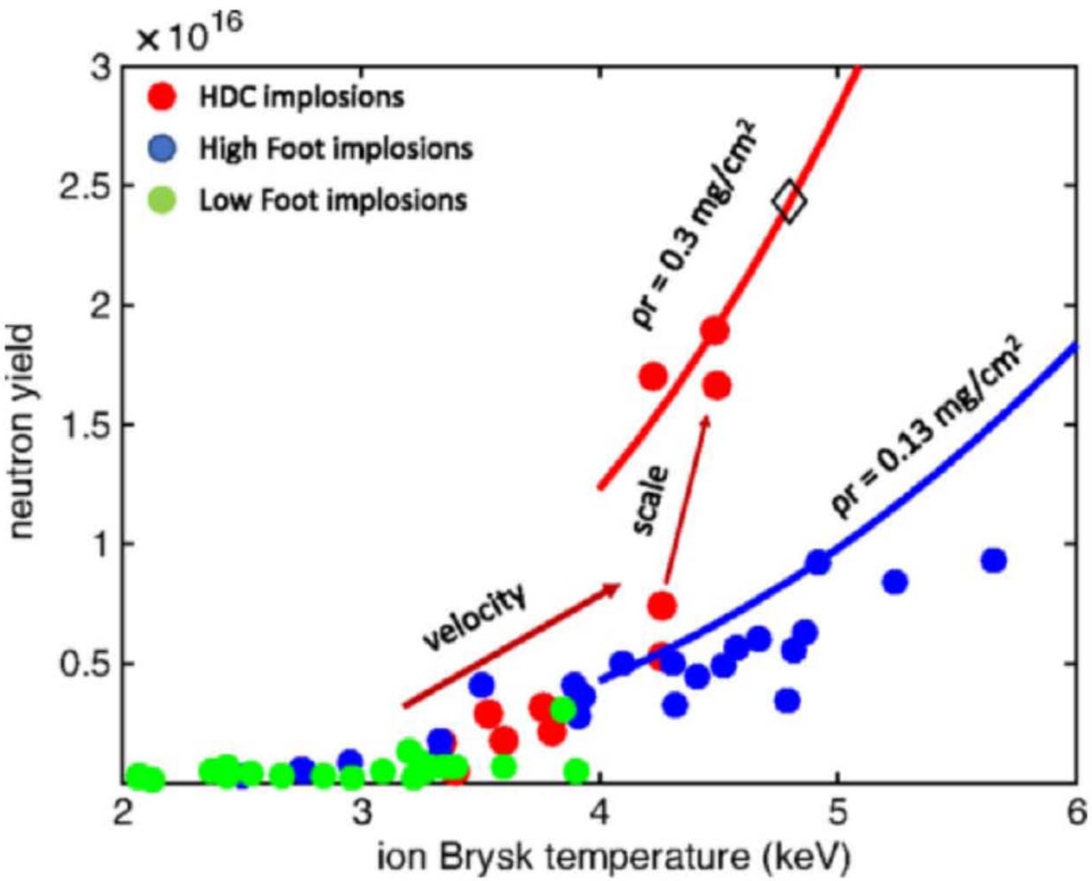

Figure 4

Total DT neutron yield as a function of ion temperature, red dots are doped HDC implosions, blue dots are high foot implosions, green dots are low foot implosions. The neutron yield is plotted against the lowest burn averaged DT ion temperature measured by NTOF detectors (Brysk temperature). For high foot implosions, the Brysk temperature is estimated to be up to a keV higher due to flows in the hot spot. Black diamond is the point where α deposited energy equals bremsstrahlung and conduction losses. Solid curves are a yield extrapolation with temperature using a constant ρr and adiabat.