FOCUSED ENERGY

Laser-driven Inertial Fusion: status and perspectives after the achievement of ignition

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The New York Times

December 13, 2022

Scientists Achieve Nuclear Fusion Breakthrough With Blast of 192 Lasers

The advancement by Lawrence Livermore National Laboratory researchers will be built on to further develop fusion energy research.

https://www.nytimes.com/2022/12/13/science/nuclear-fusion-energy-breakthrough.html

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THE TIMES OF INDIA

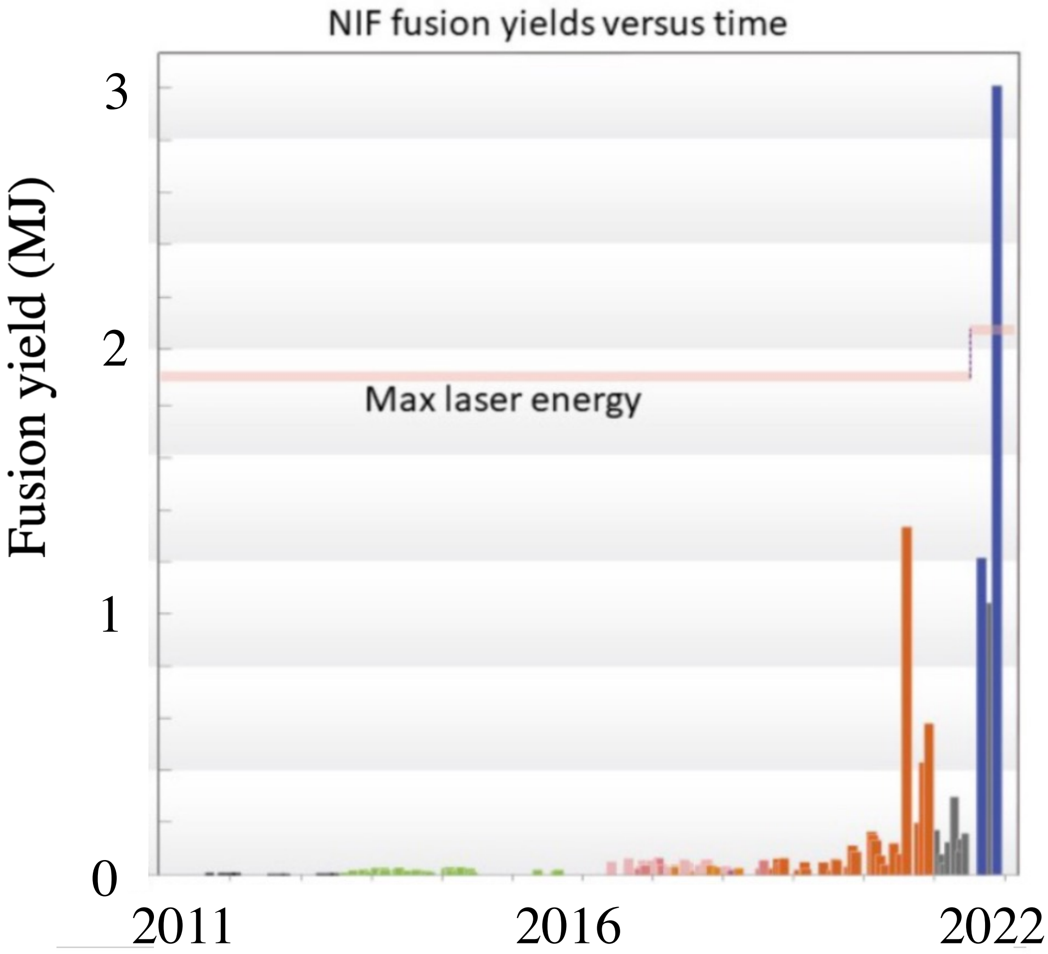
December 13, 2022

Here comes the Sun: Breakthrough in nuclear fusion

https://timesofindia.indiatimes.com/world/rest-of-world/here-comes-the-sun-breakthrough-in-nuclear-fusion/articleshow/96180155.cms

Aug. 8, 2021: Fusion yield = 1.3 MJ
Dec. 5, 2022: Fusion yield = 3.1 MJ
July 29, 2023: Fusion yield = 3.8 MJ

	Up to 2020	**2021**	**2022**
Target gain	< 0.07	0.7	1.5
Peak T	4.5 keV	9 keV	12 keV
Fuel burn-up	0.2%	2%	4%

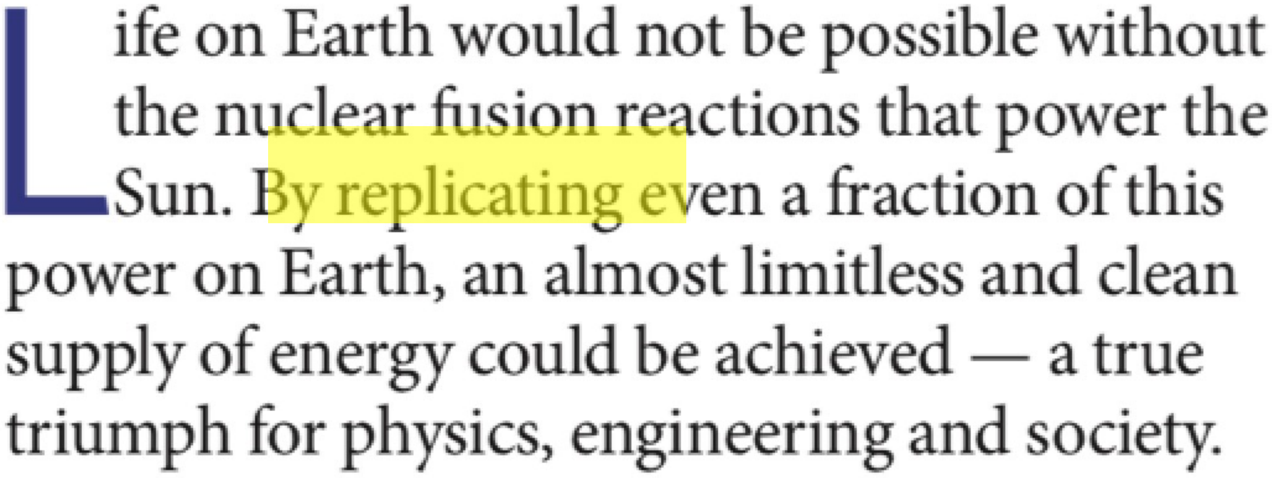


From:
Inertial Fusion Energy – Report of the Fusion Energy Sciences Basic Research Needs Workshop – draft Jan. 17, 2023

Summary

Laser-driven inertial fusion

- Principles
- Main issues
- Ignition experiments
- Alternative schemes (Fast- and Shock-ignition)
- Towards inertial fusion energy
- Perspective and conclusions



Life on Earth would not be possible without the nuclear fusion reactions that power the Sun. By replicating even a fraction of this power on Earth, an almost limitless and clean supply of energy could be achieved — a true triumph for physics, engineering and society.

B. Verbeck and A. Taroni, *Nature Phys*. **12**, May 2016

Actually, achieving fusion on Earth is not just "replicating" the Sun

	Sun	**Laboratory/Reactor**
fuel	hydrogen	deuterium-tritium
temperature	≤ 1.5 x 10^7 K	≥ 10 x 10^7 K
confinement	gravitational	magnetic (MCF) inertial (ICF) combined (MagLIF)
	opaque	transparent
pressure	**250 Gbar**	**400 – 500 Gbar in ICF**

Confinement. An option:
Inertial confinement fusion (ICF)

- **Fusion reactions**
  - **from a target containing a few mg of DT fuel**
  - **compressed to very high density ($\rho > 1000$ times solid density)**
  - **and heated to very high temperature**

- No external confinement => **fuel *confined by its own inertia***

  (mass) confinement time $\tau = R/c_s$,

  c_s: sound speed;
  R: linear dimension of the compressed fuel

- Explosive, **pulsed process**
  - Energy has to be provided cyclically by a suitable **driver**
  - The **fuel mass must be limited to about 10 mg**,
    in order to contain the explosion
    (1 mg of DT releases 340 MJ, equivalent to 85 kg of TNT)

ρR: ICF confinement parameter
Φ: burn efficiency

- ICF is pulsed.
- The fuel must remain confined for a time longer than the burn time
- reaction time: $\tau_{\text{reaz}} \approx \dfrac{1}{n < \sigma v >}$, $n = \rho/m_i$: ion number density
  ρ: mass density
- confinement time: $\tau_{\text{conf}} \approx \dfrac{R}{c_s}$, $c_s = 2.7 \times 10^7 \sqrt{T(\text{keV})}$ cm/s (sound speed)
- $\tau_{\text{conf}} > \tau_{\text{reaz}} \quad ==> \quad \rho R \geq \dfrac{c_s m_i}{< \sigma v >}$

at $T = 20 - 40$ keV, rhs depends weakly on T

$==> \rho \text{R} > 1.2 \text{ g/cm}^2$

- It can be shown that the fraction of burned fuel is, approximately, $\Phi = \rho R / (\rho R + 7 \text{ g/cm}^2)$, and in practice the confinement requirement is

$$\boldsymbol{\rho R > (2 - 3) \text{ g/cm}^2}$$

The essential physical ingredients of ICF:
Compression
Hot spot ignition

(homogeneous sphere of DT, radius R, density ρ)

- COMPRESSION:

  $\Phi > 30\%$ ==> $\rho R > 3$ g/cm^2

  mass $m = (4\pi/3)\rho R^3 <$ few mg ==>

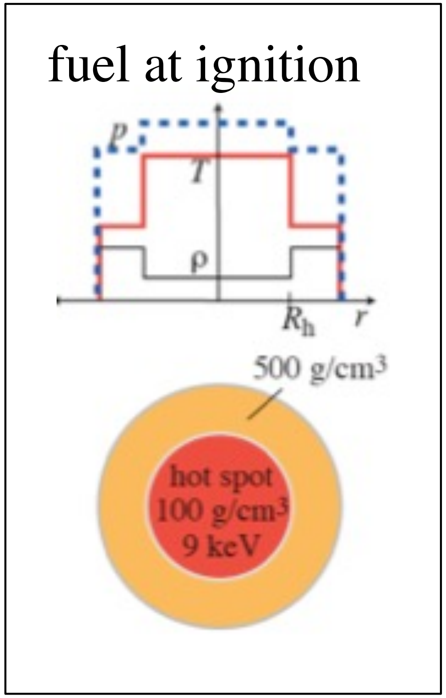
$$\rho > \frac{300}{\sqrt{m(\mathrm{mg})}} \ \mathrm{g/cm^3}$$

- HOT SPOT IGNITION

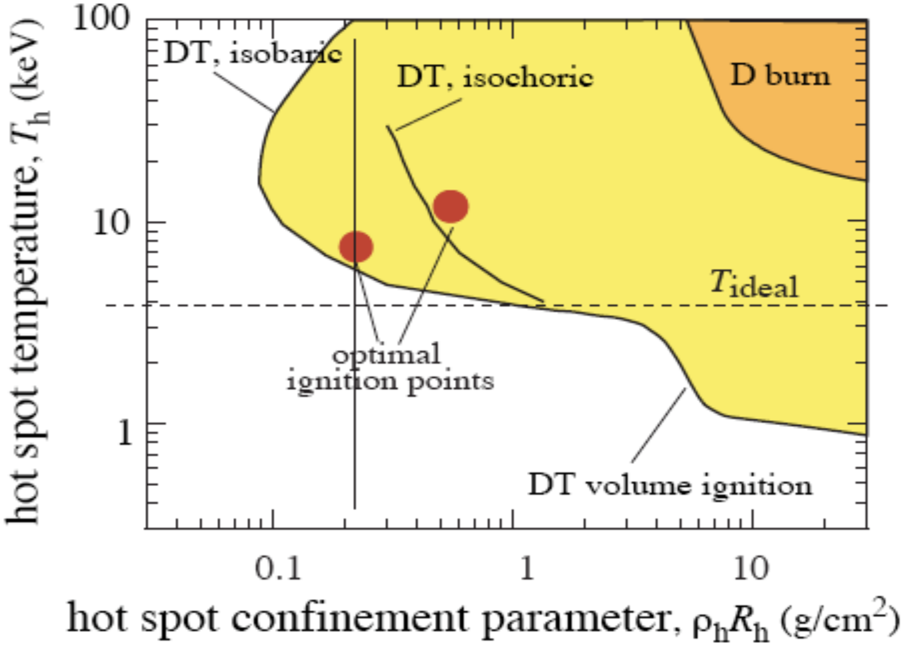
  do not heat the whole fuel to 5 keV;

  heat to 5 – 10 keV the smallest amount of fuel capable of self heating and triggering a burn wave

Hot spot ignition condition: Lawson-like ρR *vs* T criterion



$T_h > 7$ keV; $\rho_h R_h > 0.25$ g/cm^2



Ignition: once the hot spot is generated, competition between

- heating (α-particles)
- and cooling (electrons, bremsstrahlung, mechanical work)

The ignition condition is
essentially a condition on the hot spot pressure

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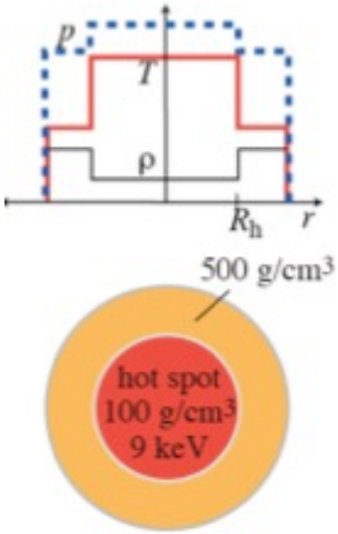
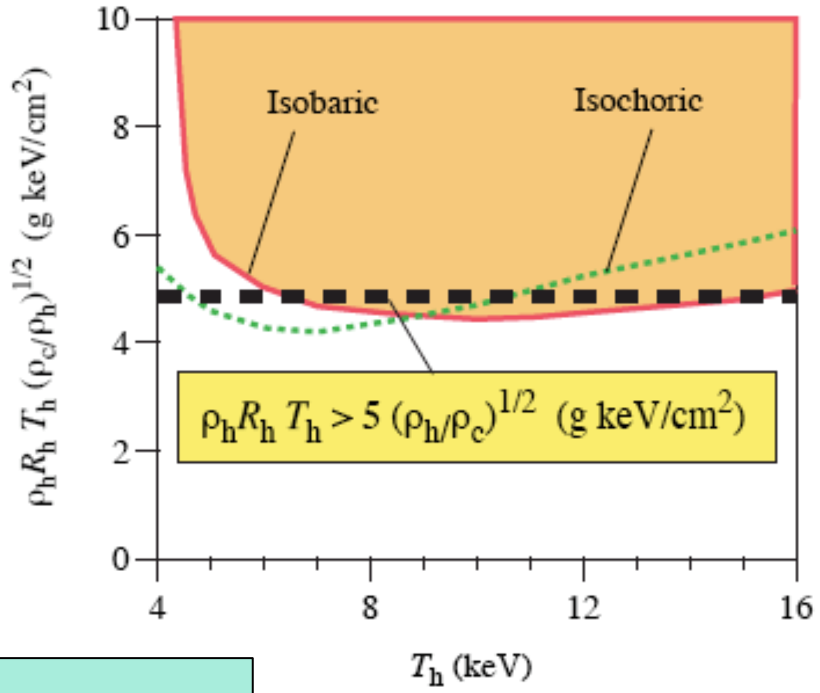
fuel at ignition



$\rho RT = PR$ criterion



pressure for ignition:

[assuming $\rho_c/\rho_h = 5 - 7$]

$$p \ (\text{Gbar}) > \frac{500}{\left(\dfrac{R_h}{30\ \mu\text{m}}\right)}$$

S. Atzeni *et al*., NJP (2013);
J. Lindl *et al*., NF (2014)
P. Patel, PoP (2020)

300–500 Gbar required ≈ pressure at the centre of the Sun

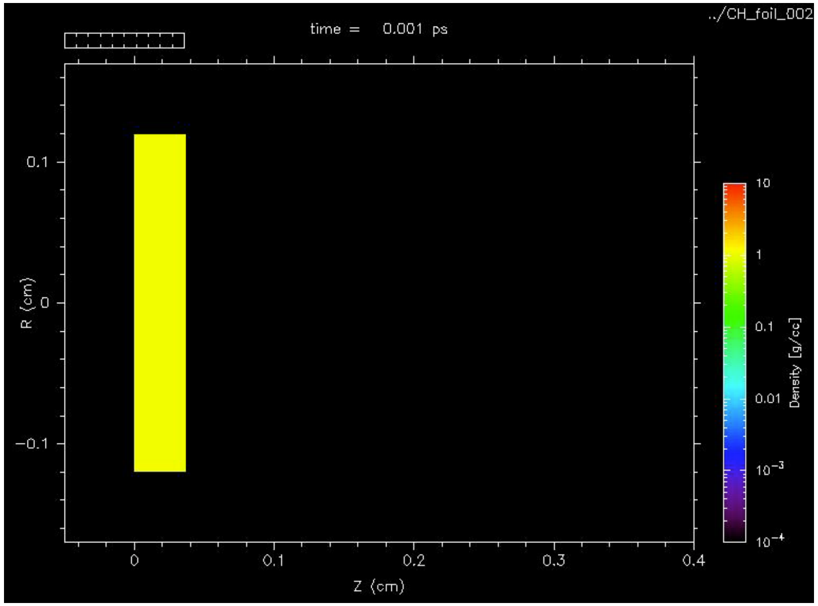
How to generate 500 Gbar?

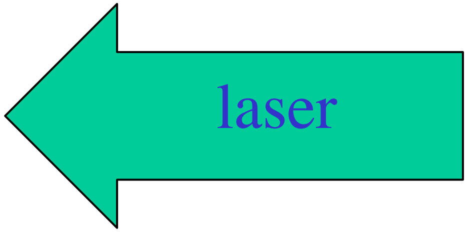
- Laser-driven or X-ray driven ablation (100 Mbar),
  => rocket

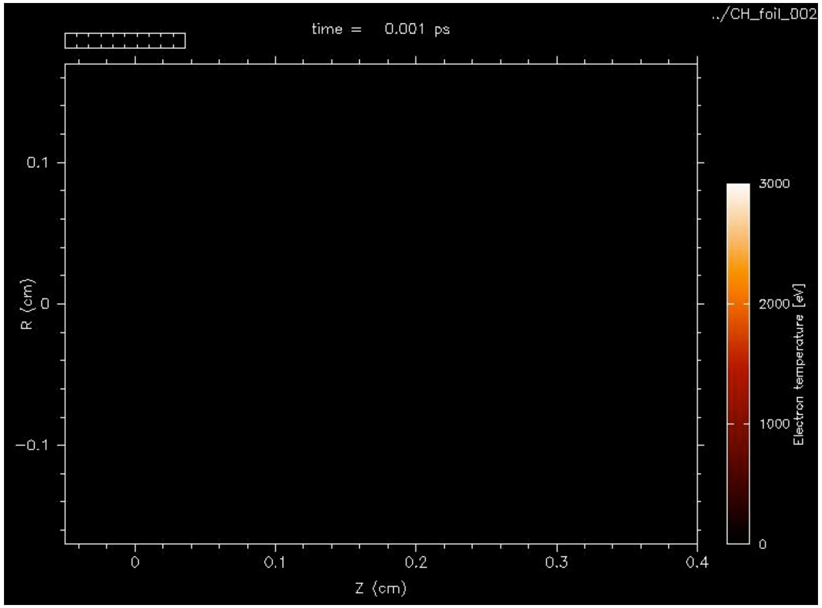
- spherical rocket

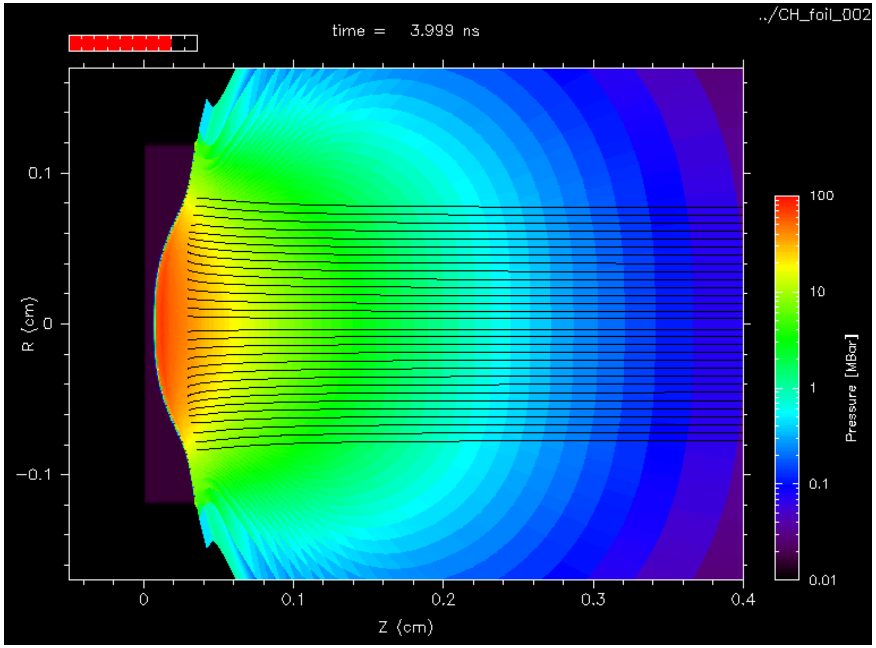
- multiplication x few 1000’s by geometrical convergence

Laser pulse on a solid: : pressure up to 100 Mbar









(In the relevant interaction regine)

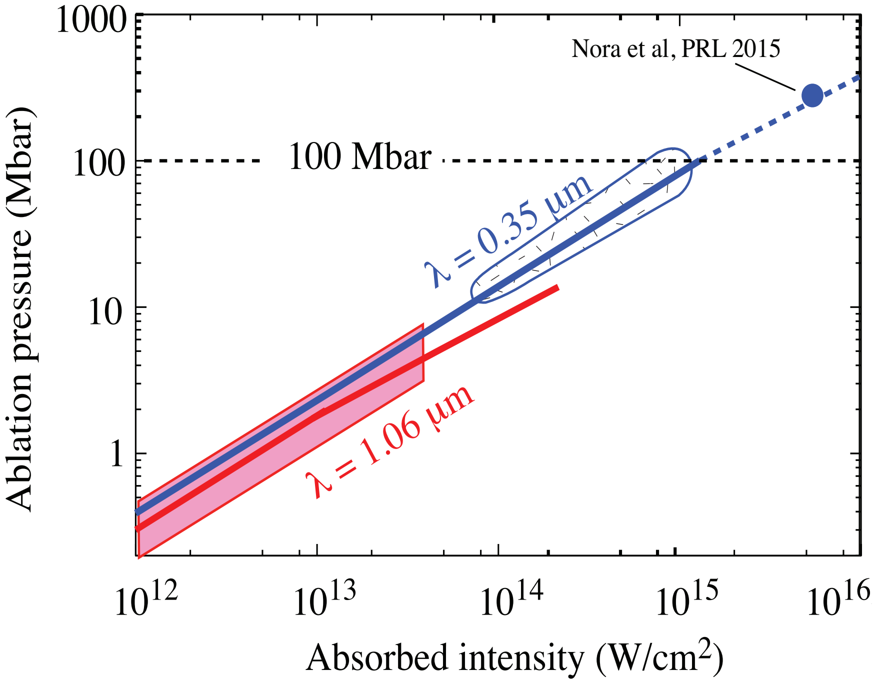
Laser light is **absorbed collisionally** (or by Inverse Bremsstrahlung) (*):
electrons, accelerated by the laser electric field, collide with ions and other electrons, so that energy is transferred from the electromagnetic field to the plasma.

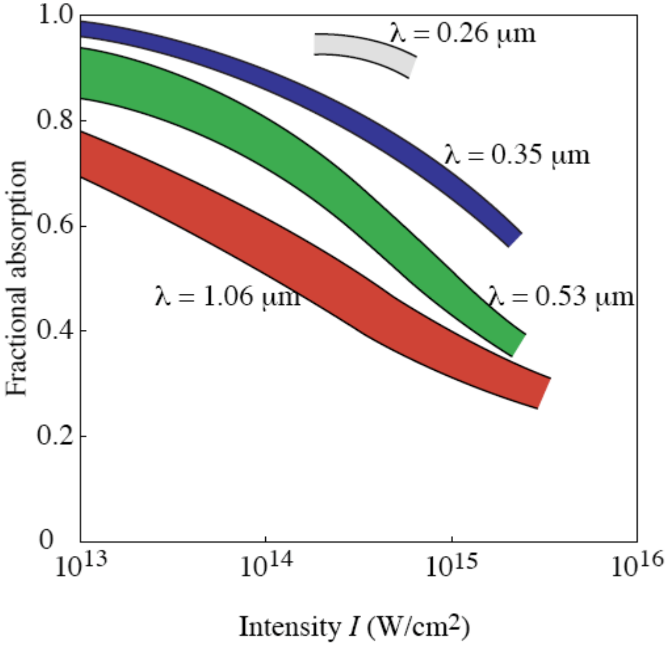
The laser **heated plasma is ablated and expands**

The pressure exerted on the non-ablated material is the **kinetic pressure of the hot plasma**, **not the radiation pressure of laser light.**

(*) See, e.g. Kruer, 'The Physics of Laser Plasma Interactions', Addison-Wesley (1988);
Atzeni & Meyer-ter-Vehn, 'The Physics of Inertial Fusion', OUP (2004), Ch. 11.1
P. Michel, 'Introduction to laser-plasma interactions', Springer (2023)

Laser drive can generate pressure of 100 Mbar

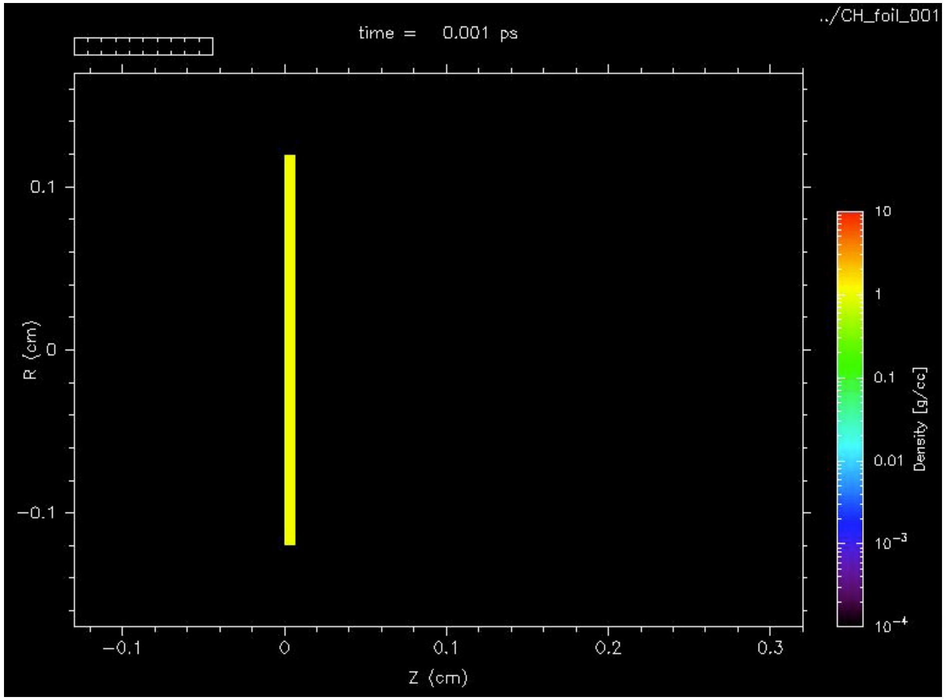


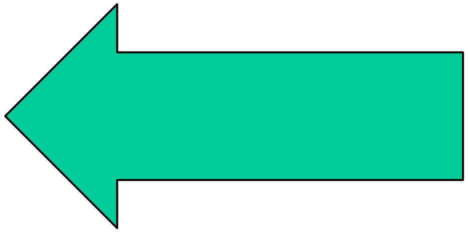

Garban-Labaune et al, PRL (1982)

Green or, better, uv light required for efficient absorption

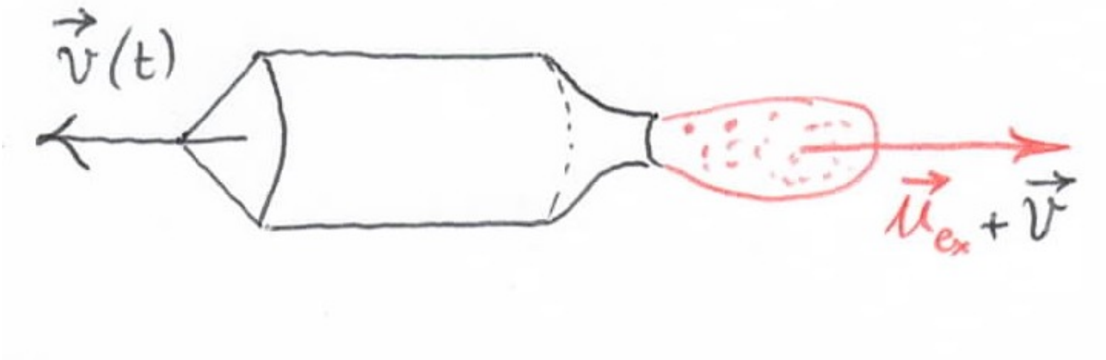
> 100 Mbar also obtained with thermal X-rays (with T = 300 eV)
[see e.g. Lindl, Phys. Plasmas (1995)]

Laser-driven rocket





laser

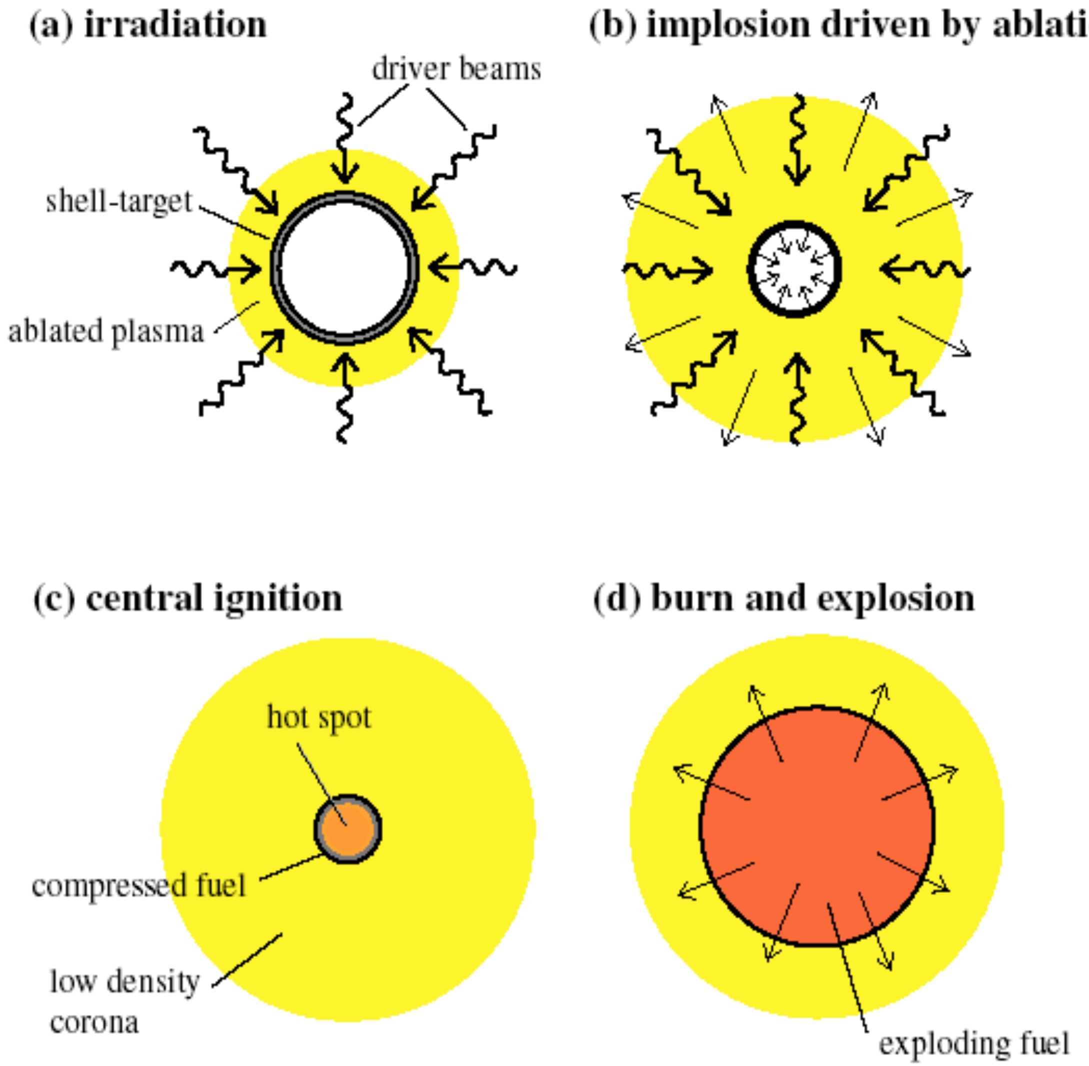


$$\mathbf{v}(t) = -\mathbf{u}_{ex} \ln \frac{m_0}{m(t)}$$

400 km/s “easily” achievable; efficiency is quite low (5–15%)

ICF by a laser-driven imploding spherical rocket:

Imploding fuel kinetic energy converted into internal energy and concentrated in the centre of the fuel



implosion velocity for ignition:

$u_{\text{imp}} > 300 - 400$ km/s

depending of the fuel mass:

$u_{\text{imp}} \propto m^{-1/8}$

(see, e.g., S. Atzeni and J. Meyer-ter-Vehn, The Physics of Inertial Fusion, Oxford University Press, 2004)

Next viewgraphs (and movies), from 1-D and 2-D simulations (DUED code)

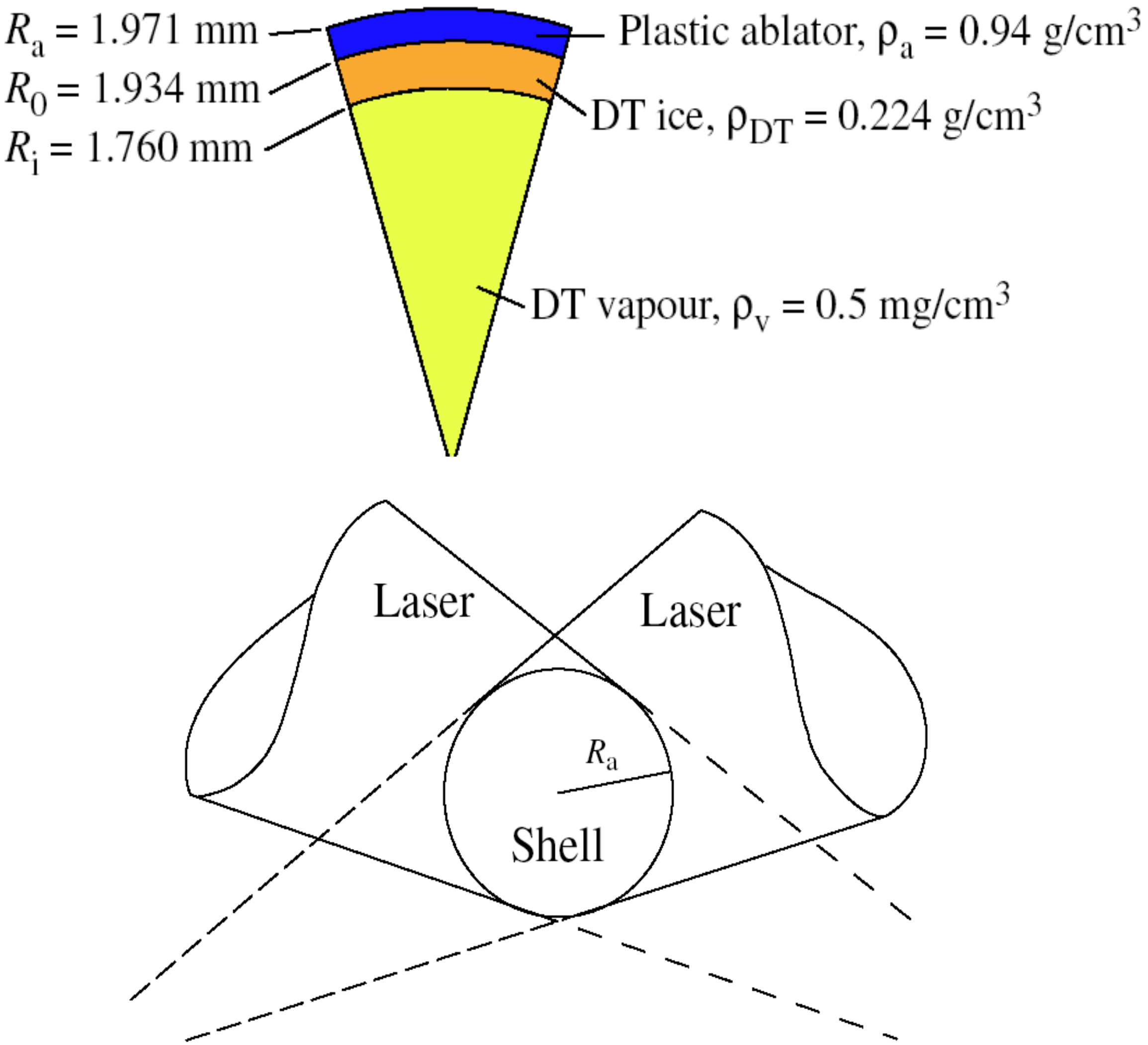
Simulation of a standard direct-drive target

Irradiated by a laser pulse, with wavelength of 0.25 μm
total energy of 1.6 MJ

Achieves energy gain about 60
It can be improved to achieve gain higher than 100

Ref: S. Atzeni and J. Meyer-ter-Vehn:
The Physics of Inertial Fusion, Oxford (2004, 2009)

Hollow shell target,
irradiated by a large number of overlapping beams



Target (hollow shell)

- Fuel mass: few mg
- Radius: 1 – 3 mm
- Fuel radius / thickness = 10

Laser driver pulse

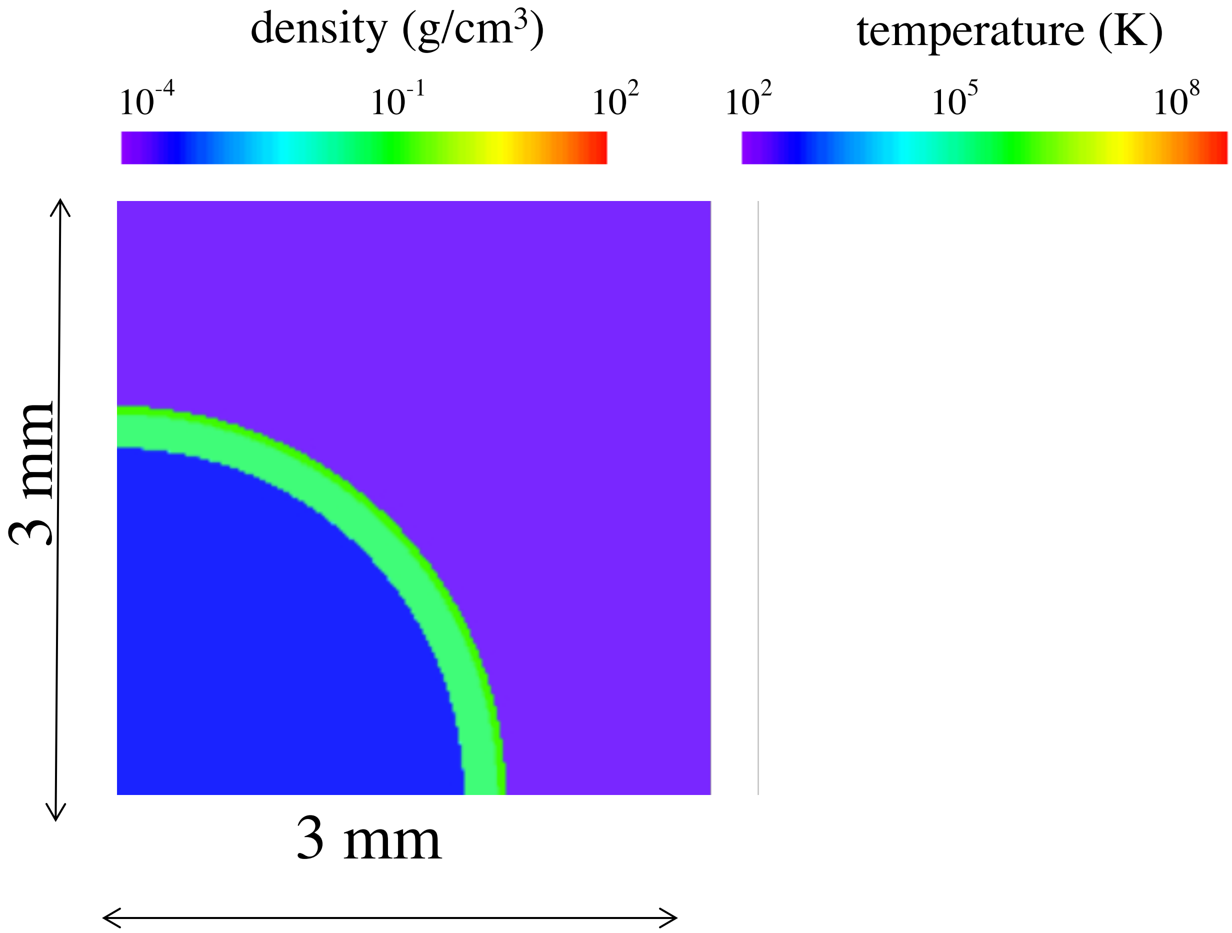
- Energy: 1 – 5 MJ
- Duration: 10 – 20 ns
- Peak power: 300 – 500 TW
- Peak intensity: 10^{15} W/cm^2
- Wavelength: (1/4) – (1/3) μm

Compressed fuel

- Density: 200 – 1000 g/cm^3
- Low average entropy, but hot-spot with T = 10 keV

Irradiation, implosion, compression, ignition & burn

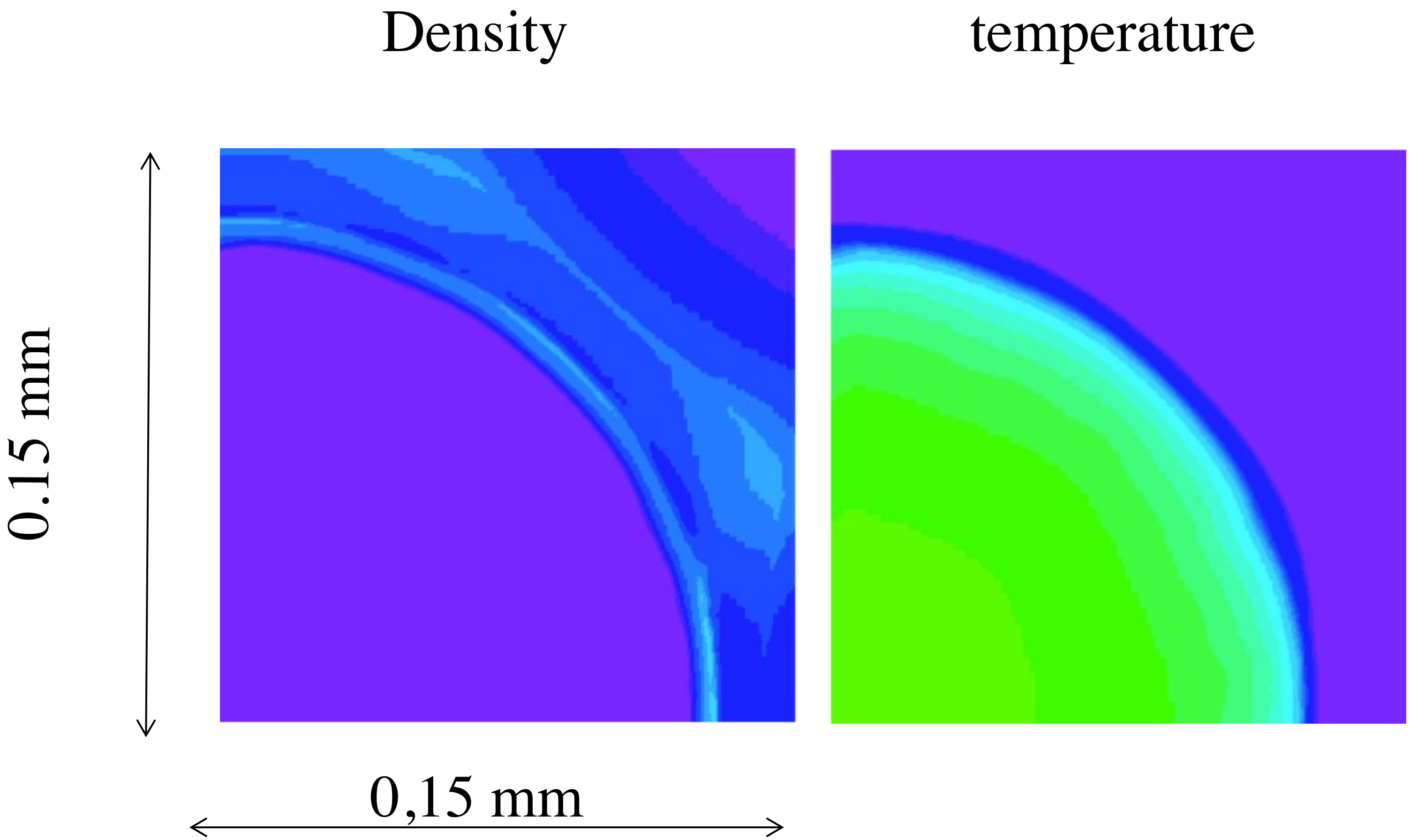
(shell with 1.67 mg of DT fuel, irradiated by 1.6 MJ pulse, see later)



simulated interval = 25 ns

S. Atzeni, 1992

Zoom (in space and time): final compression, ignition, burn and explosion



simulated time $= 0.5$ ns

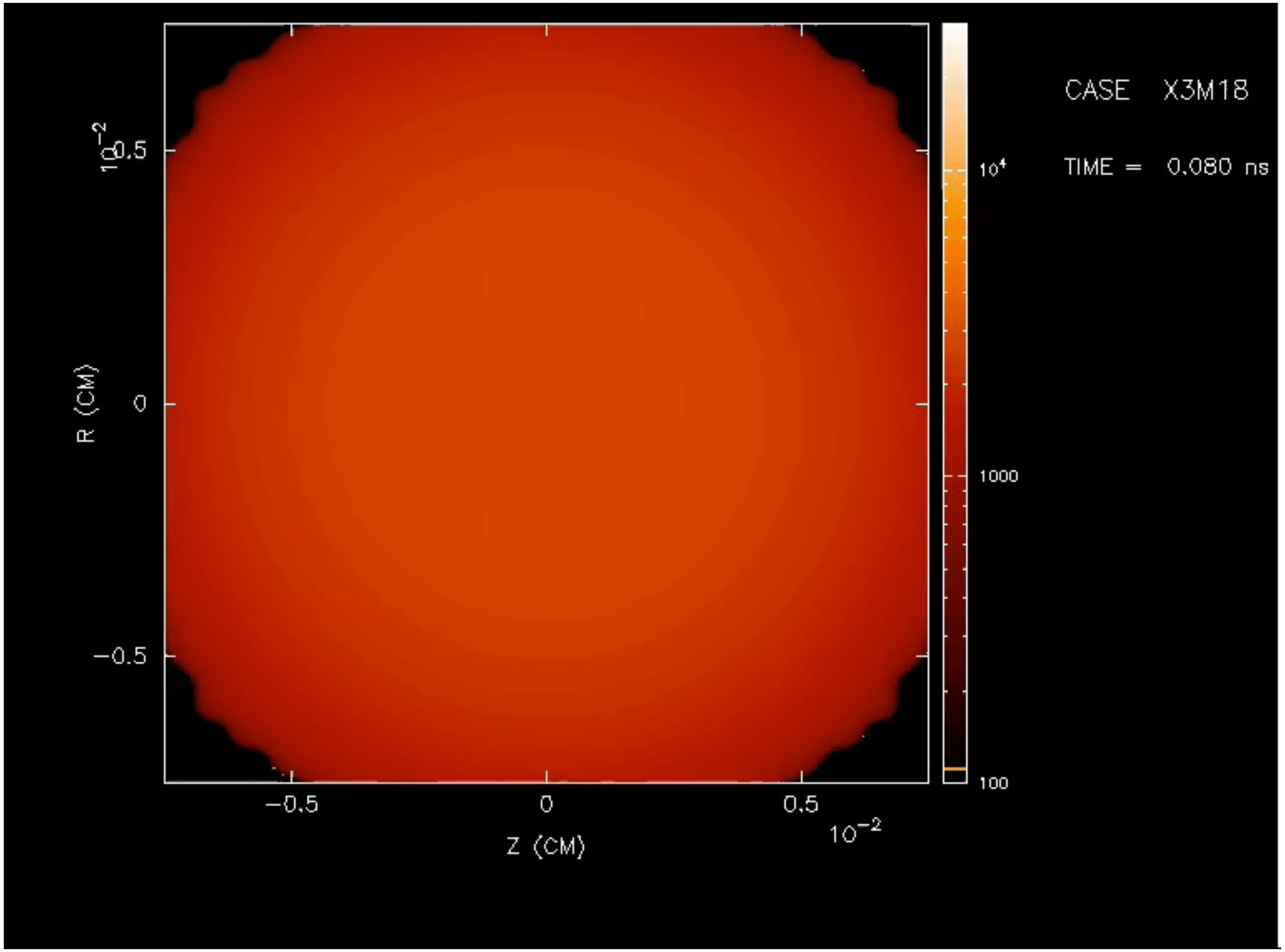
S. Atzeni, 1992

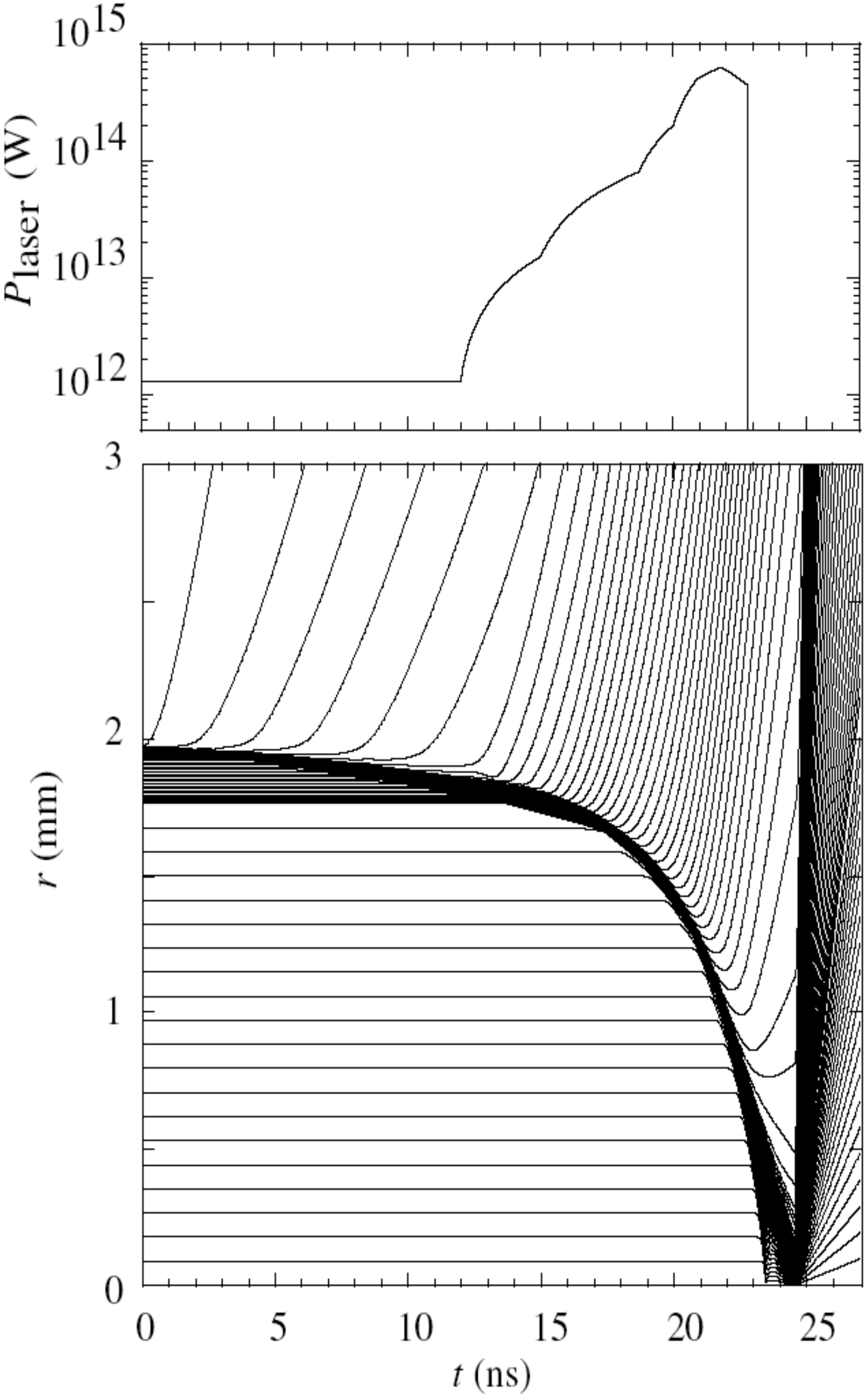
Rayleigh-Taylor instability hinders hot spot formation and ignition

(multimode perturbation with rms amplitude at the end of the coasting stage = 1.5 μm)

Ion temperature (eV) map evolution

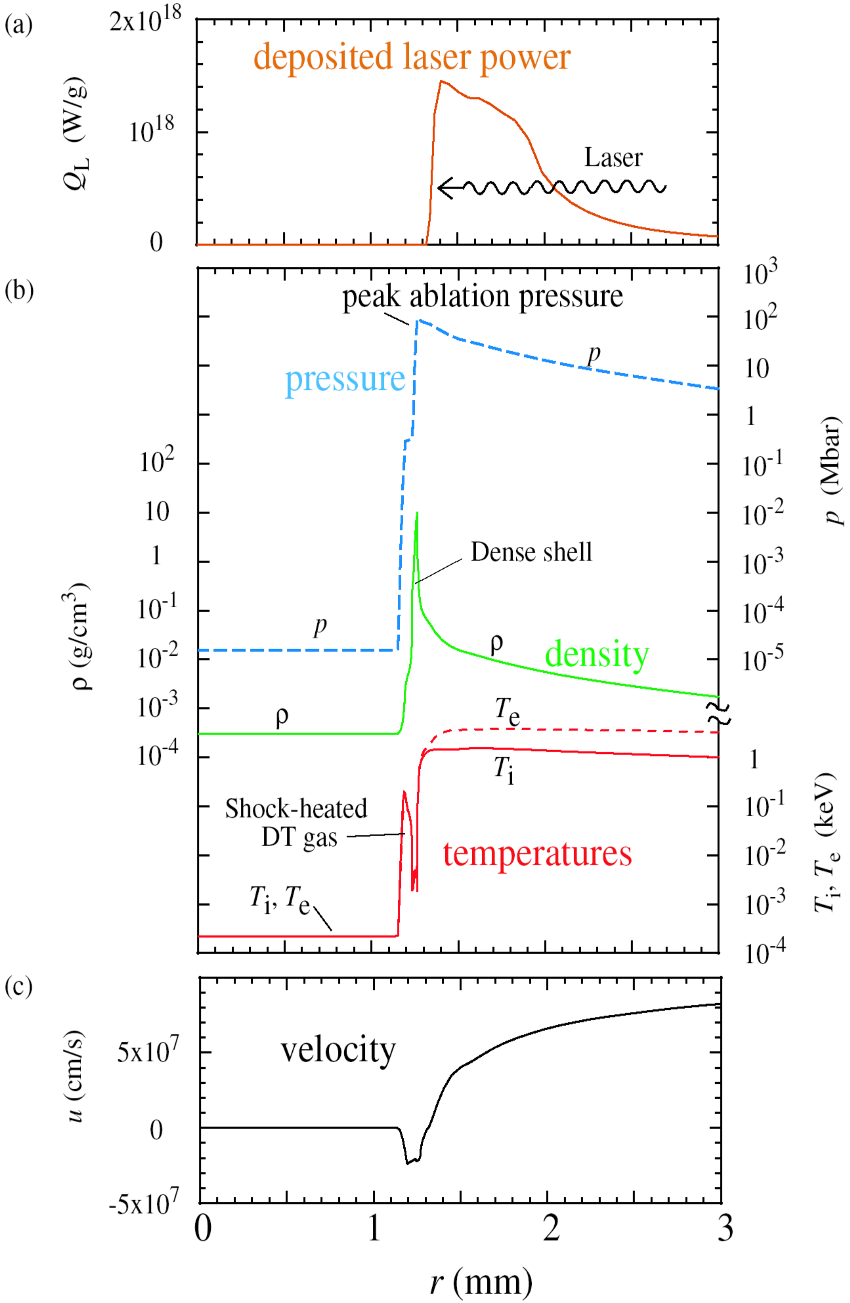
S. Atzeni and A. Schiavi, 2004





Laser power vs time

1-D
“Flow chart”



Laser absorption ==>

ablation

high temperature plasma

very high pressure

(next lecture)

corona expands,

shocks launched in the shell

Back-of-the envelope parameter estimate

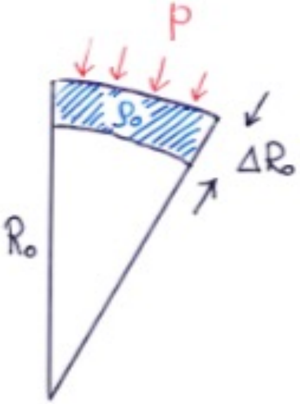
- specific energy = > implosion velocity
- implosion velocity & target size => driving pressure
- size and velocity => implosion time and pulse time
- target mass and specific energy => fuel energy
- coupling efficiency & fuel energy => driver energy
- driver energy, pulse time, target size => driver power and intensity

A key parameter is the shell aspect ratio (radius to thickness, $R_0/\Delta R_0$):
The larger the aspect ratio the lower power and intensity,
but more critical target stability and symmetry

Specific internal energy (compression* and thermal) at ignition = specific kinetic energy of the imploding fuel = $u_i^2/2$

=> implosion velocity u_{imp} = 300 - 350 km/s

Average pressure: assume constant pressure applied at thin hollow shell, as the radius shrinks by 50%:



=> $$(1/2)\, m_f\, u_{imp}^2 \approx \langle p\rangle\, (7/8)(4\pi/3)\, R_0^3$$

$$\langle p\rangle \approx (12/7)\, \rho_{DT}\, u_{imp}^2\, (\Delta R_0/R_0) \qquad (**)$$

Peak pressure $\approx 2.5 \langle p\rangle$

$\Rightarrow$ for $R_0/\Delta R_0 = 10$, peak pressure = 80-100 Mbar

100 Mbar = 10 TPa pressure required to implode at u_{imp} = 350 km/s

*) Partial degeneracy important

**) ρ_{DT} : density of solid DT

Back-of-the-envelope estimates of target parameters

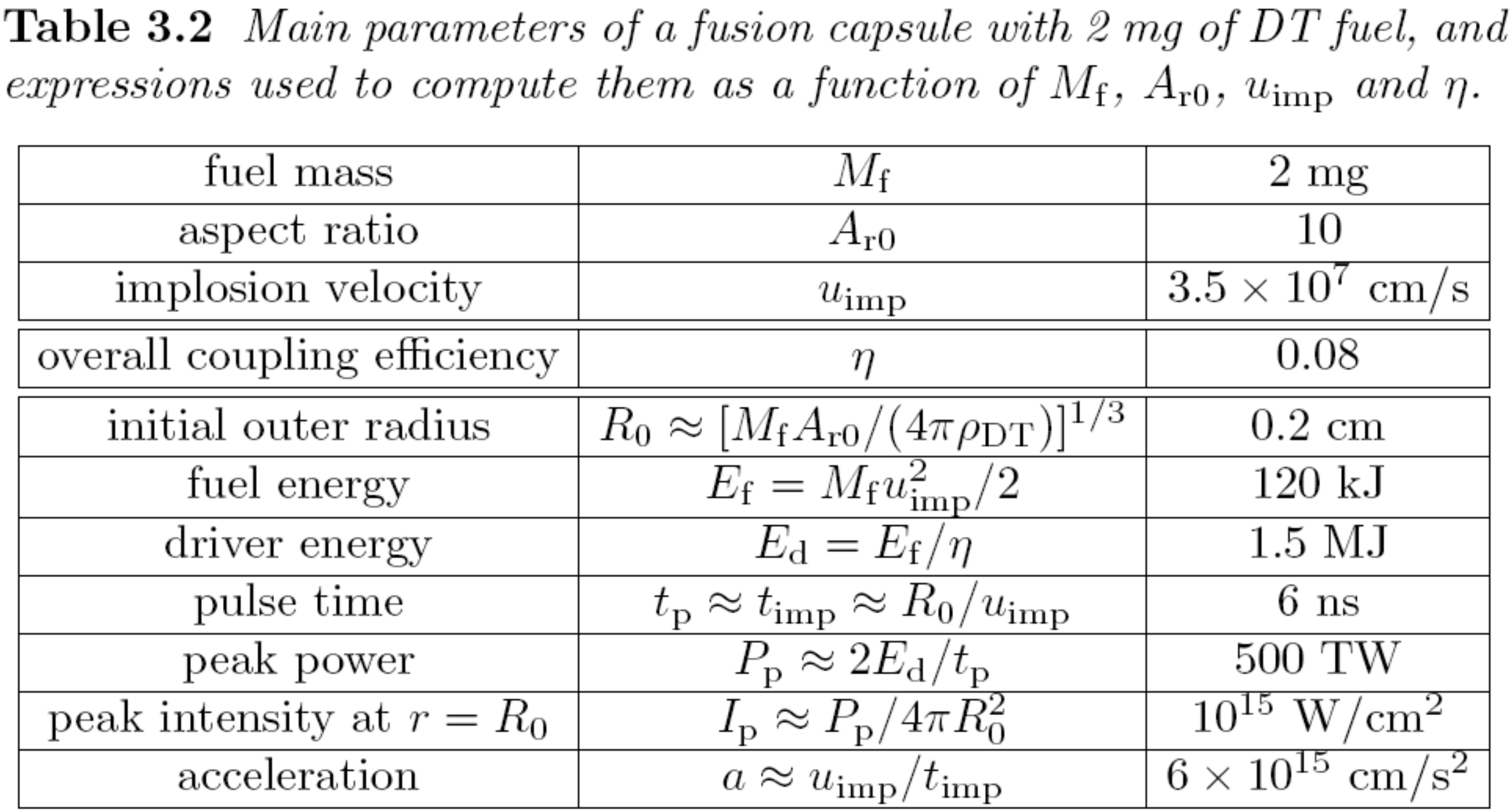


Table 3.2 *Main parameters of a fusion capsule with 2 mg of DT fuel, and expressions used to compute them as a function of* M_f, $A_{\mathrm{r}0}$, u_imp *and* η.

fuel mass	M_f	2 mg
aspect ratio	$A_{\mathrm{r}0}$	10
implosion velocity	u_imp	3.5×10^7 cm/s
overall coupling efficiency	η	0.08
initial outer radius	$R_0 \approx [M_\mathrm{f} A_{\mathrm{r}0}/(4\pi\rho_\mathrm{DT})]^{1/3}$	0.2 cm
fuel energy	$E_\mathrm{f} = M_\mathrm{f} u_\mathrm{imp}^2/2$	120 kJ
driver energy	$E_\mathrm{d} = E_\mathrm{f}/\eta$	1.5 MJ
pulse time	$t_\mathrm{p} \approx t_\mathrm{imp} \approx R_0/u_\mathrm{imp}$	6 ns
peak power	$P_\mathrm{p} \approx 2E_\mathrm{d}/t_\mathrm{p}$	500 TW
peak intensity at $r = R_0$	$I_\mathrm{p} \approx P_\mathrm{p}/4\pi R_0^2$	10^{15} W/cm^2
acceleration	$a \approx u_\mathrm{imp}/t_\mathrm{imp}$	6×10^{15} cm/s^2

ICF simulation codes include a lot of physics and must resolve “small” scales

DUED Code (*) model

- 2D **Lagrangian scheme + rezoning**
- 2 – temperatures (electrons, ions)
- non-local electron transport
- (flux-limited) multigroup radiation diffusion
- real matter equation of state
- collisional transport
- LTE or non-LTE opacities (MPQ’s SNOP code)
- laser-matter interaction: 3D ray tracing; inverse-bremsstrahlung absorption
- ion beam-matter interaction (binary collisions)
- thermonuclear fusion reactions
- non-thermal fusion reactions of fusion products [T(1 MeV) and ^{3}He (0.8 MeV)] and of D, T, and ^{3}He scattered by neutrons
- fuel burn-up (D,T,^{3}He)
- multigroup diffusion of charged fusion products of DD, DT, D^{3}He
- Montecarlo neutron transport: elastic scattering, (n,2n), ^{3}He(n,p)T, (n,γ)
- Montecarlo fast electron transport in dense matter
- diffusion of neutron-knocked ions (several energy groups each)

(*) S. Atzeni and coworkers (1985 –

Laboratory Inertial Confinement Fusion (ICF) essentials

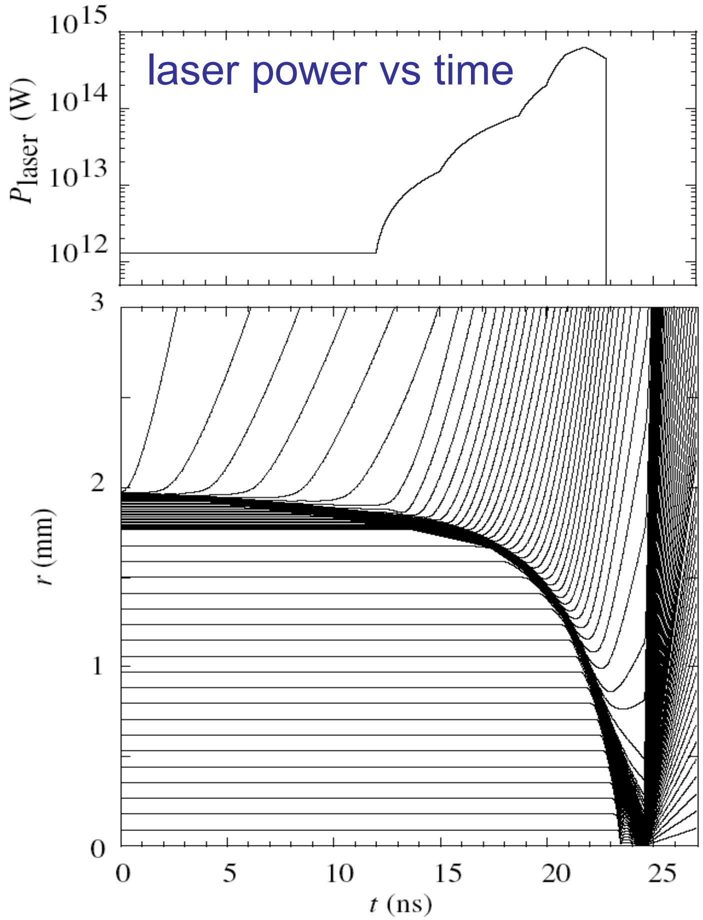
Four basic requirements

1. Implosion velocity u_{imp} of 300 – 400 km/s:
   100 Mbar pressure, efficient "rocket acceleration"
   => green, uv radiation or X-rays, $I = 10^{15}$ W/cm^2
2. Low-entropy compression (low "adiabat" $\alpha = p/p_{\mathrm{Fermi\text{-}degenerate}}$)
   => **accurate temporal pulse shaping**
3. Symmetric implosion => **uniform irradiation**
4. **Control of Rayleigh-Taylor instability (RTI):**
   conflicts with previous requirements:
   RTI growth increases with increasing u_{imp} and decreasing α

2nd issue: **compress efficiently**

do not heat before compressing =>

- no "preheating" by fast particles, hard X-rays
- tune the pulse, to reach high pressure "gradually"

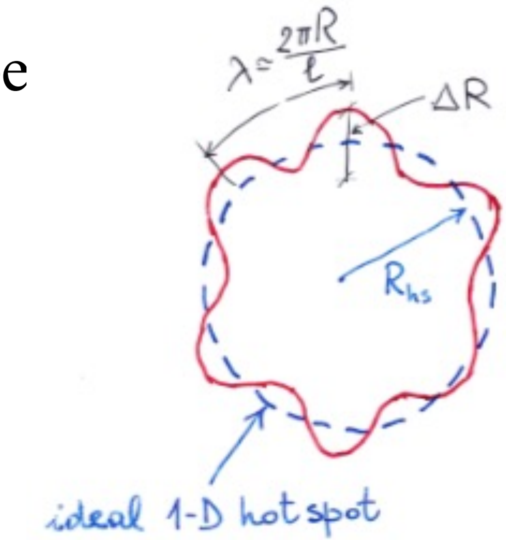


"Pulse shaping":

laser power
carefully tuned, to launch
a sequence of properly timed
shocks, that approximate
adiabatic compression

3^{rd} issue: implosion **symmetry:**

long scale shape of compressed fuel depe
on driving pressure non uniformity



$$\frac{\delta R}{R} = \frac{\delta u_{\text{imp}}}{u_{\text{imp}}} = \frac{\delta p}{p} \cong \frac{2}{3}\frac{\delta I}{I}$$

we want hot spot relative deformation $\delta R_h / R_h << 1$

but R_h is typically 1/30 of the initial radius R_0

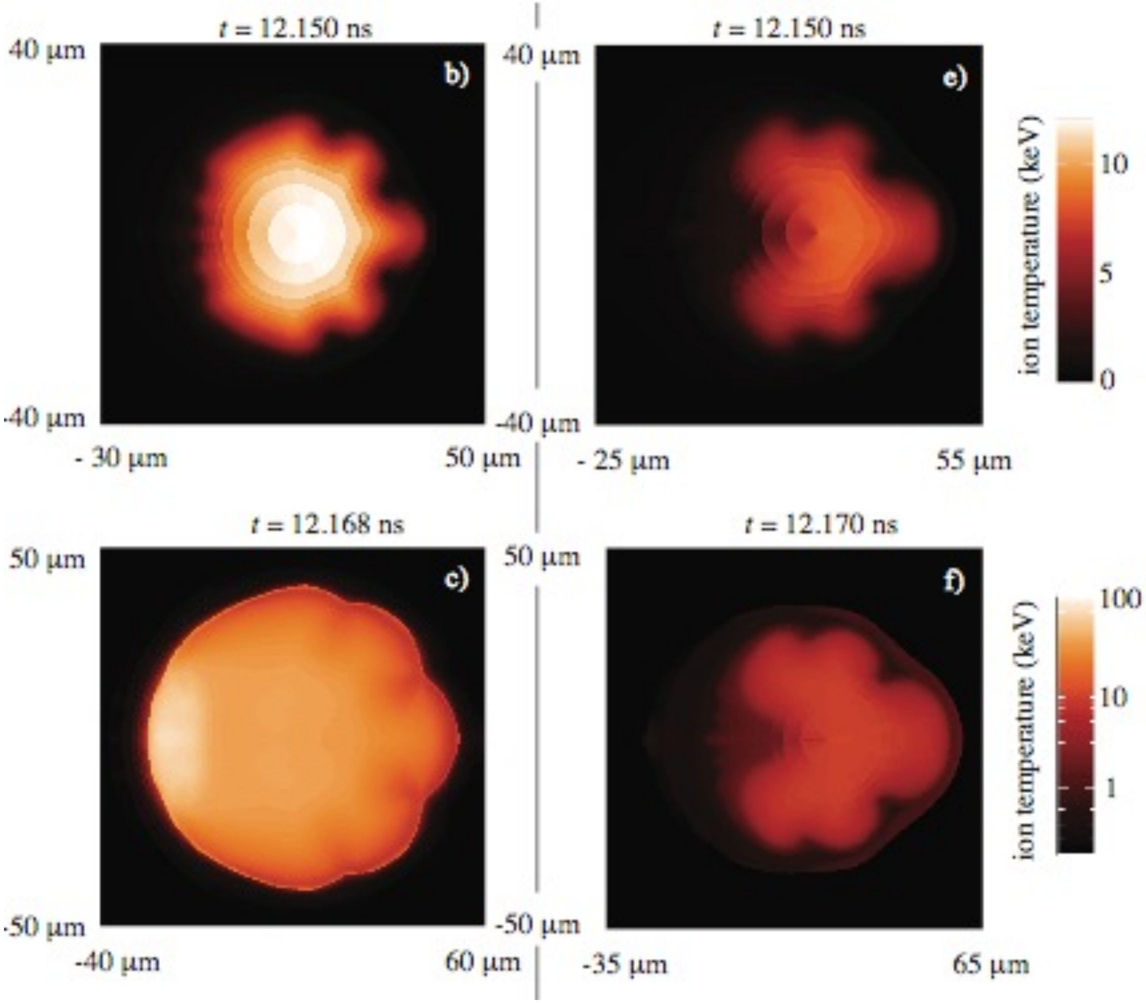
==> $\delta I/I << 1/20$; ==> we request $\delta I/I < 1\%$

(the larger the ignition margin, the larger tolerable $\delta I/I$

(eg, Atzeni, *Eurphys*. *Lett*. 1990)

symmetry: requires uniform illumination, as well as accurate target positioning

small mispositioning can lead to failure



10 µm displacement

Gain = 95% of 1D gain

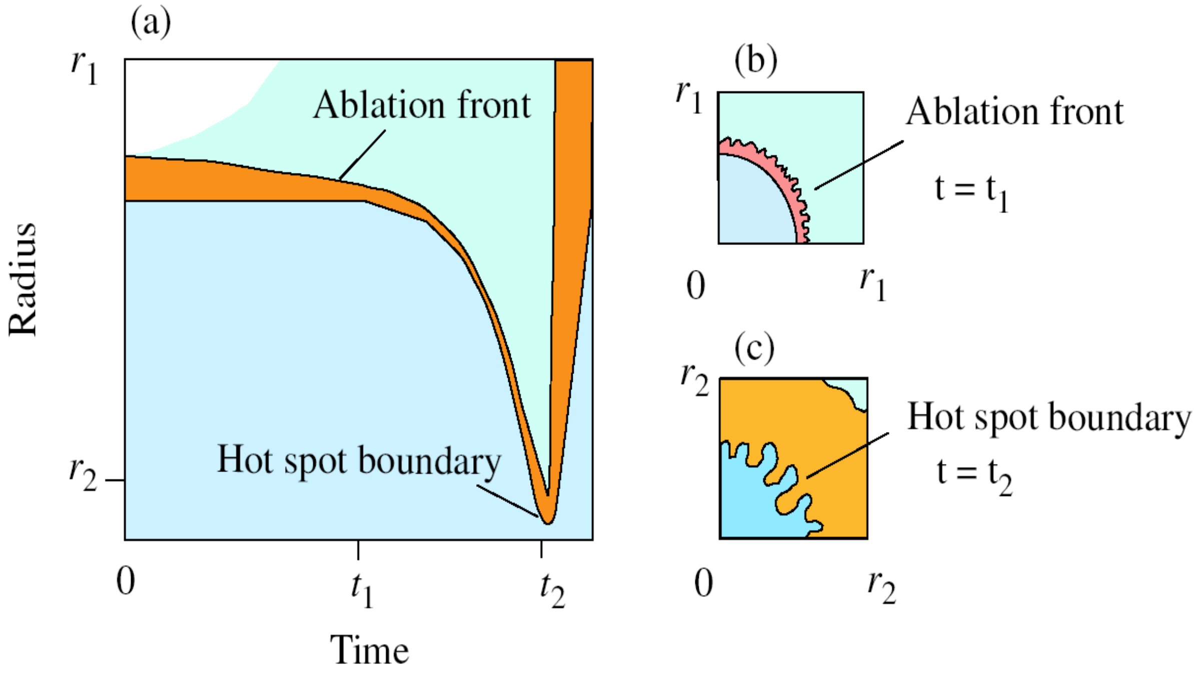
20 µm displacement

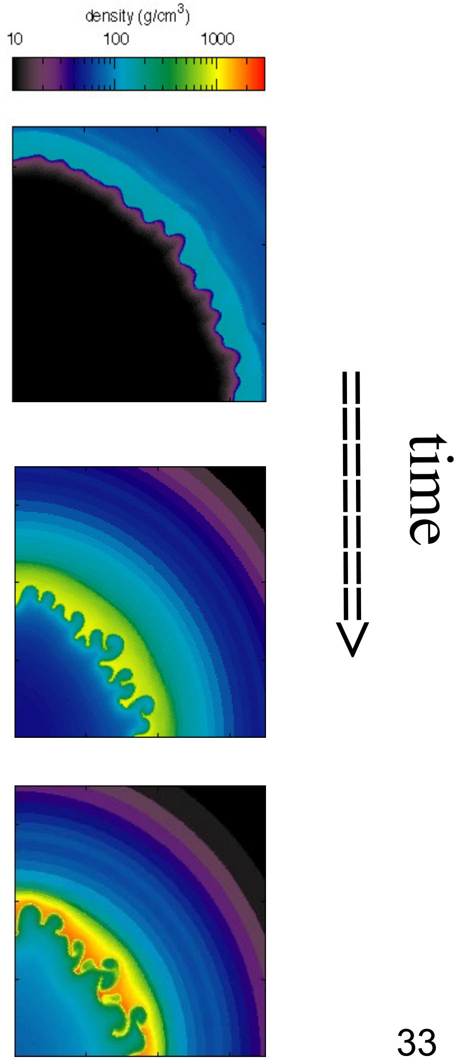
Gain = 1% of 1D gain

S. Atzeni, A. Schiavi, A. Marocchino, *Plasma Phys. Controll. Fusion* 2011

4th issue: **Rayleigh-Taylor instability**

unavoidable in inertial fusion





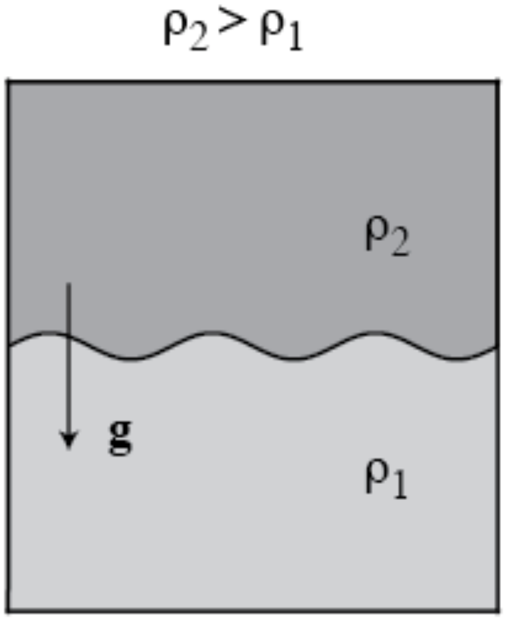
deceleration-phase instability at the hot spot boundary
(2D simulation)

Atzeni & Schiavi, PPCF 2004

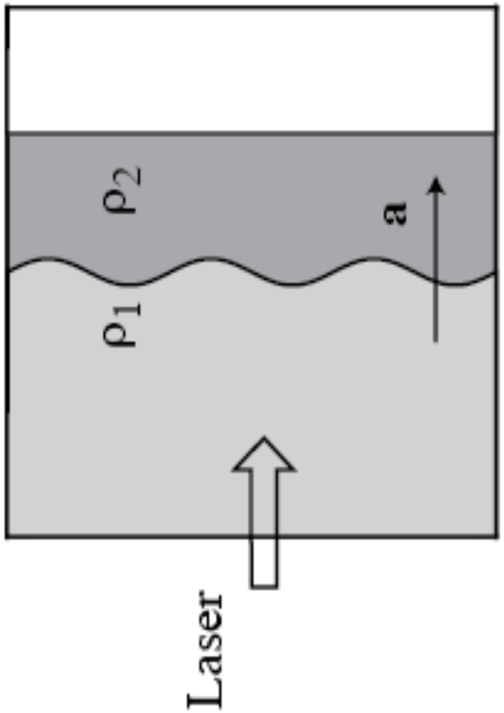
Rayleigh instability of superposed fluids

Taylor instability of accelerated fluid

Rayleigh instability of interface in hydrostatic equilibrium

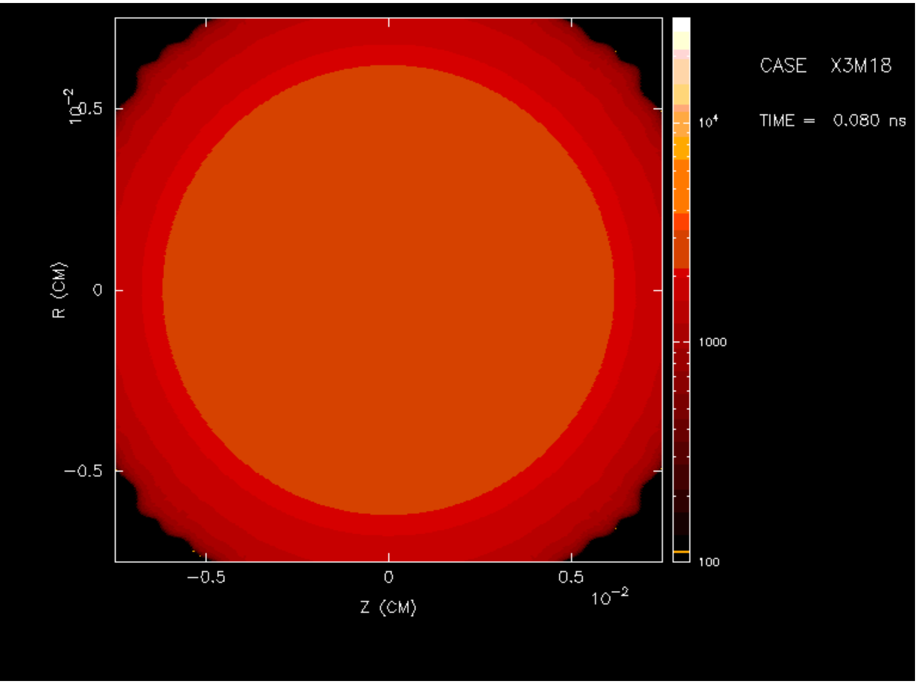


Taylor instability of accelerated interface; equivalent to Rayleigh instability if analysed in a frame moving with the interface



RTI hinders hot spot formation

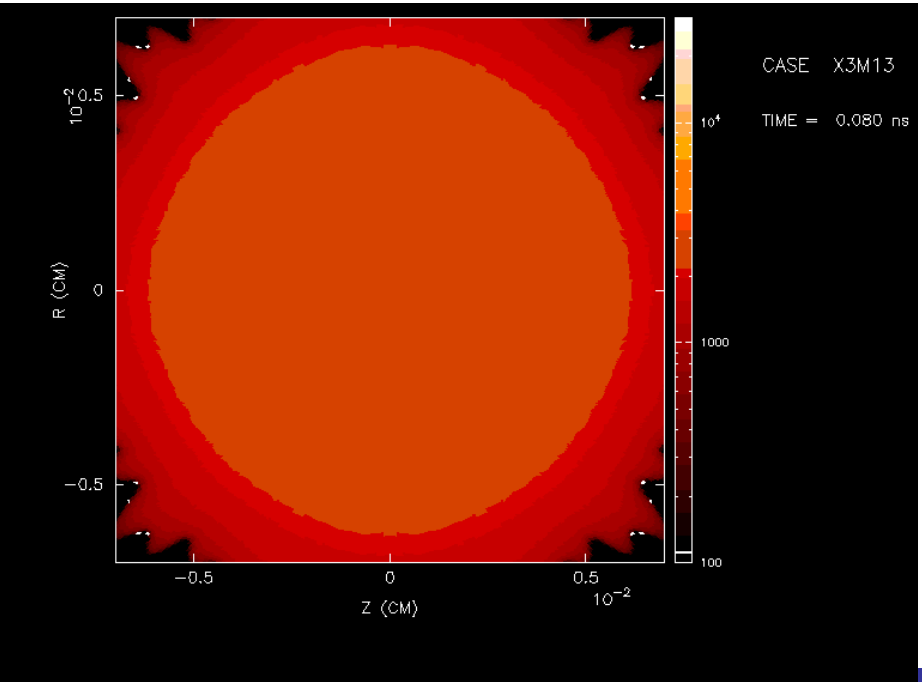
Here simulations assuming initial multimode spectrum on the inner surface of the shell



“moderate” initial amplitude (1.5 μm rms) at the end of the implosion coasting stage:

⇒ deformed hot spot;

⇒ ignition still occurs



“large” initial amplitude (6 μm rms):

⇒ hot spot NOT formed

Ion temperature (eV) map evolution

movies by S. Atzeni and A. Schiavi, 2004

A variety of inertial fusion schemes have been proposed

- drivers:
  - lasers
  - ion beams
  - pulsed power sources

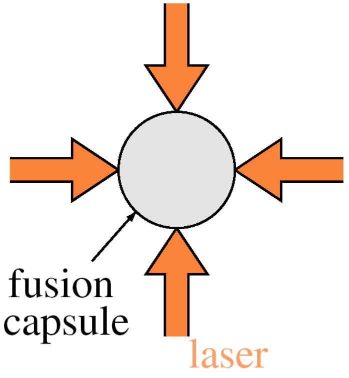
- compression-driving irradiation schemes:
  - direct
  - indirect

- ignition schemes:
  - conventional central ignition
  - fast ignition
  - shock ignition

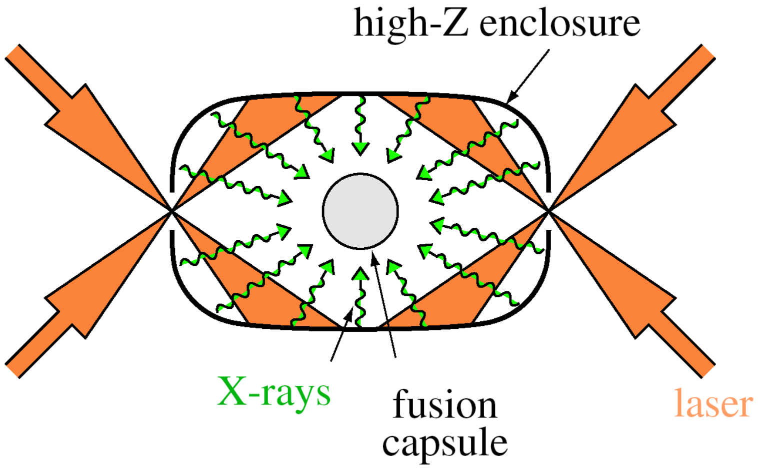
direct drive and indirect drive

In indirect drive, the fuel containing capsule is irradiated by thermal X-rays (200-300 eV), generated and confined in a cavity (a hohlraum).

a) direct-drive



b) indirect drive



Why indirect-drive ?

Pros:

- long scale irradiation uniformity weakly dependent on beam disposition
- smooth radiation field on short scales
- RTI less violent then in direct drive,

Con: lower coupling efficiency [& much more complex modelling] (laser => X-rays => capsule, with loss to generate the radiating plasma, loss from the hole, loss of X in the hohlraum wall)

Experiments at the NIF (National Ignition Facility) achieved ignition using indirect-drive (2021–23)

Testing ignition

$\approx$ 1995: experimental, theoretical, computational data base,
supporting design of ignition experiments (Lindl, PoP 1995)

Indirect drive: weaker RTI, low sensitivity to beam non-uniformities

Required laser pulse:
1.8 MJ – 500 TW; vuv (0.35 μm), accurate pulse shaping (**NIF laser**)

fuel mass $m_{\mathrm{DT}} = 0.17$ mg
implosion velocity $u = 370$ km/s; adiabat $\alpha = 1.5$

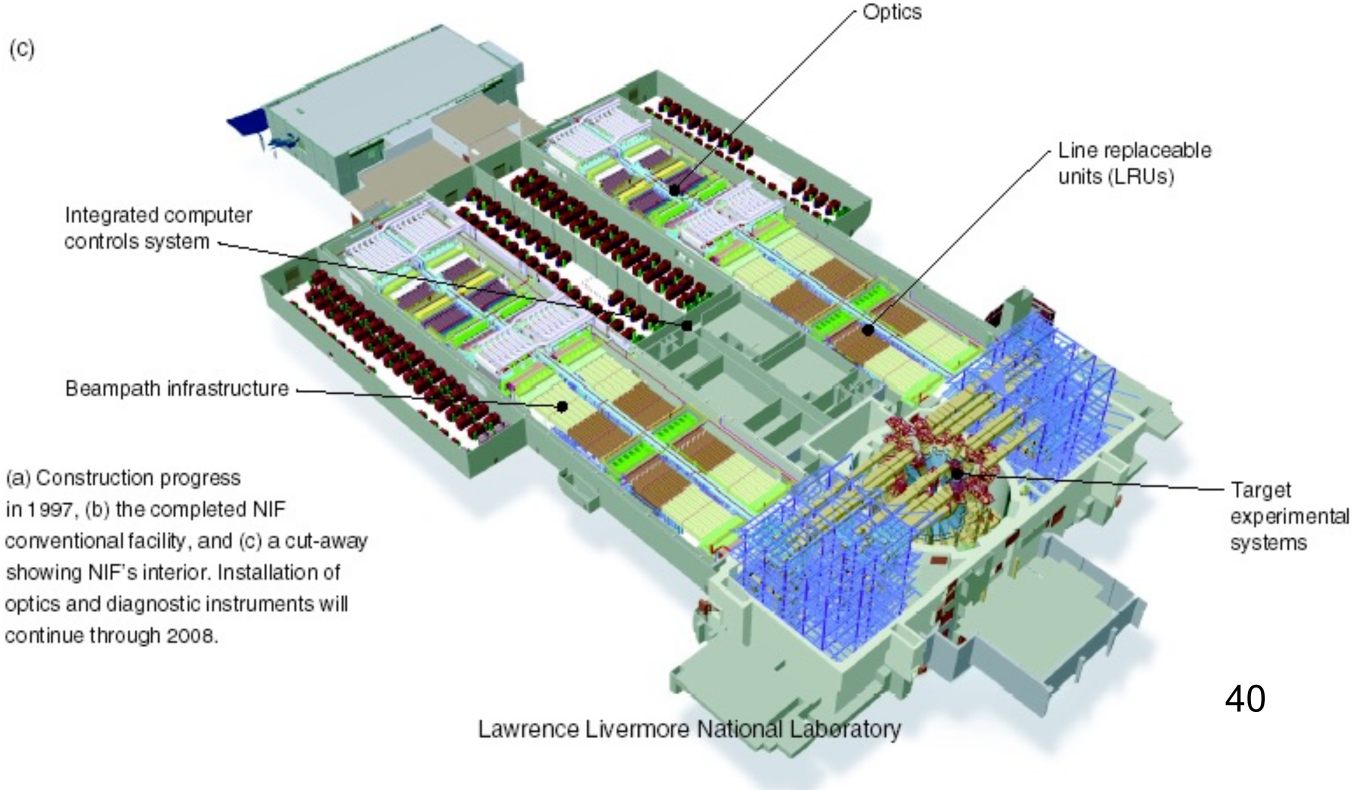
objective: $Y > 15$ MJ (gain $G \geq 10$)

fuel at ignition:
hot spot pressure > 350 Gbar; $\langle \rho R \rangle = 1.5\ \mathrm{g/cm^2}$;
peak density = $1000\ \mathrm{g/cm^3}$

NIF Laser

Frequency tripled
Nd:glass

E = 1.8 MJ (now 2.1)
λ = 351 nm
P_{peak} = 500 TW
192 beams



(a) Construction progress in 1997, (b) the completed NIF conventional facility, and (c) a cut-away showing NIF's interior. Installation of optics and diagnostic instruments will continue through 2008.

Lawrence Livermore National Laboratory

NIF hohlraum coupling & symmetry

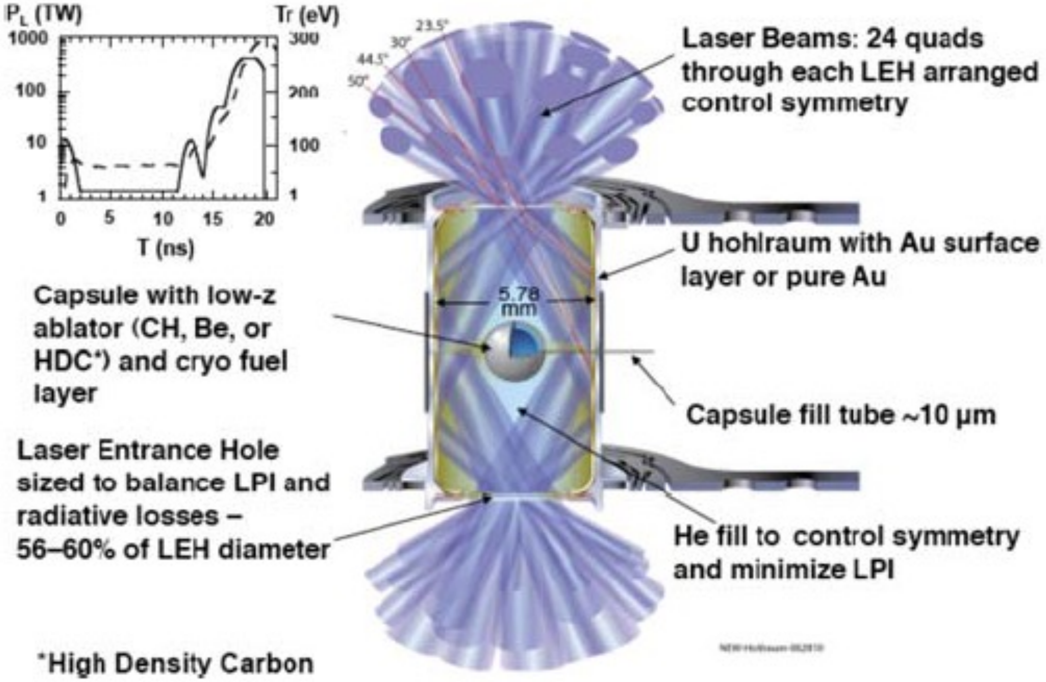


FIG. 2. Schematic of ignition target design, highlighting key features and options for hohlraum and capsule materials. Also indicated is the laser pulse shape showing the laser power in TW and the radiation temperature reached at that power versus time in ns.

(courtesy of LLNL)

symmetry control:

- beam orientation
- beam pointing
- hohlraum aspect ratio
- hohlraum fill

beam coupling:
choice of materials

entropy control:
cryogenic fuel, pulse shaping, ablator doping to limit preheat

RTI limitation:
ultra-smooth capsule surface, choice of materials, …

National ignition campaign, NIC, (2010-12) demonstrated strong compression, but did not achieve ignition

	NIC baseline goal	achieved	best result prior to NIC
Confinement parameter ρR	1.5 g/cm^2	1.3 g/cm^2	0.2 g/cm^2
DT peak density	1000 g/cm^3	800 g/cm^3	200 g/cm^3
peak pressure	350 Gbar	130 Gbar	
implosion velocity with nominal NIC imploding mass	370 km/s	350 km/s	
laser energy	1.5 MJ	1.95 MJ	
peak laser power	450 TW	520 TW	

- implosion velocity smaller than expected (see later)
- pressure (much) smaller than expected

Note that NIF laser outperforms design specs

D. Hicks *et al*., *Phys*. *Plasmas* **19**, 122702 (2012);
N. B. Meezan *et al*., *Phys*. *Plasmas* **20**, 056311 (2013);
O. L. Landen *et al*., *Plasma Phys*. *Controll*. *Fusion* **54**, 124026 (2012)
J. D. Lindl *et al*., *Phys*. *Plasmas* **21**, 020501 (2014)

NIF baseline ignition experiments (NIC campaign) vs simulations

NIC campaign: **general qualitative agreement**, strong compression**, but**

Ignition is a strongly non linear process (a bifurcation); several simultaneous small discrepancies can have dramatic effects:

- 15% laser light backscattered from the hohlraum (vs few % expected), due to parametric instabilities (LPI: laser plasma instabilities)
- Implosion velocity 10% smaller than expected (for given absorbed energy)
- Low-mode asymmetries, turned out to be time dependent, and poorly controllable
- once the required implosion velocity was approached (by increasing laser power and/or reducing shell thickness) fuel contaminated as a consequence of instabilities

J. D. Lindl *et al*., *Phys*. *Plasmas* **21**, 020501 (2014)

outstanding (and unique) diagnostics essential for understanding the above results

e.g. neutron and X-ray images, with resolution of a few microns and a few ps

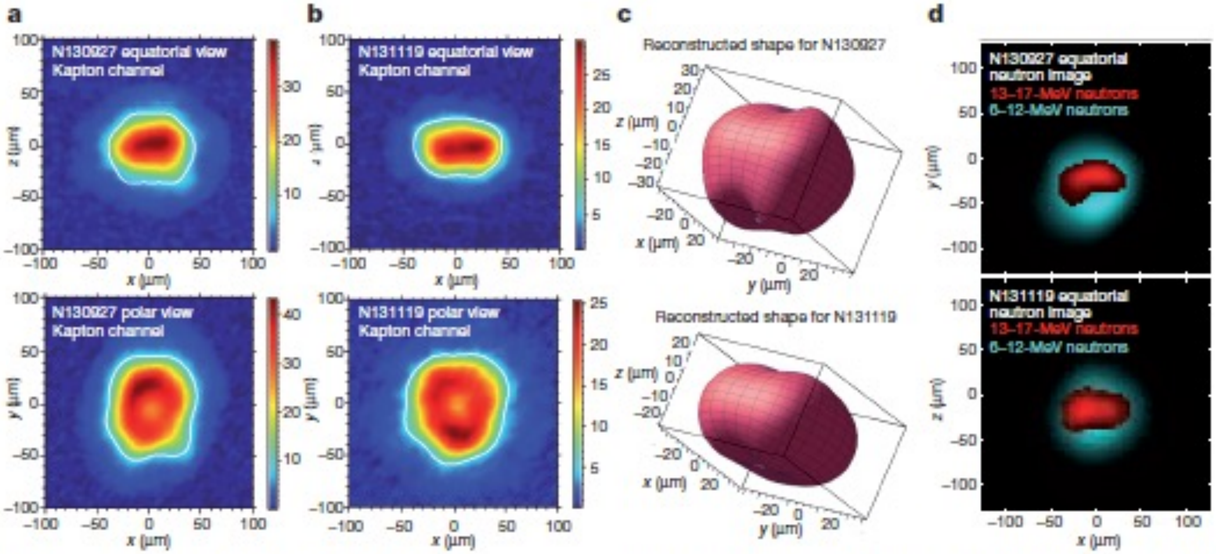


Figure 2 | X-ray and neutron images of the hotspot at bang-time. **a**, Equatorial (side-on) and polar (top-down) views of the hotspot shape for N130927. Kapton is the filter material in the imaging system that allows transmission of X-rays with energies of more than 6 keV. **b**, As in **a**, but for N131119. In these X-ray images, the contour shown in white is taken at the 17%-peak-brightness level (the colour scales show the brightness in arbitrary units) and is used to obtain a description of the shape in Legendre modes (equatorial view) and Fourier modes (polar view). **c**, Three-dimensional reconstructions of the hotspots. **d**, Superposition of direct (13–17 MeV) and down-scattered (6–12 MeV) neutron images from N130927 and N131119. (X-ray image analysis courtesy of N. Izumi, S. Khan, T. Ma and A. Pak of the NIF Shape Working Group; neutron image analysis courtesy of D. Fittinghoff, G. Grim, N. Guler and F. Merrill of the NIF Neutron Imaging System Working Group.)

O. Hurricane *et al*., Nature **506**, 343 (2014)

From the 2010-2012 NIC to the 2021-2022 MJ shots

- **increase foot power (*) and shorten laser pulse to reduce plasma formation =>** reduce LPI, reduce time-dependent asymmetry, reduce RTI growth

- **increase efficiency**: change hohlraum shape and material, make hohlraum smaller

- **reduce instability seeds =>** diamond instead of plastic, smaller fill tube, thinner tent, improve capsule surface quality, improve DT ice quality

(*) power of the initial part of the pulse. Makes the process faster, however increases the fuel entropy

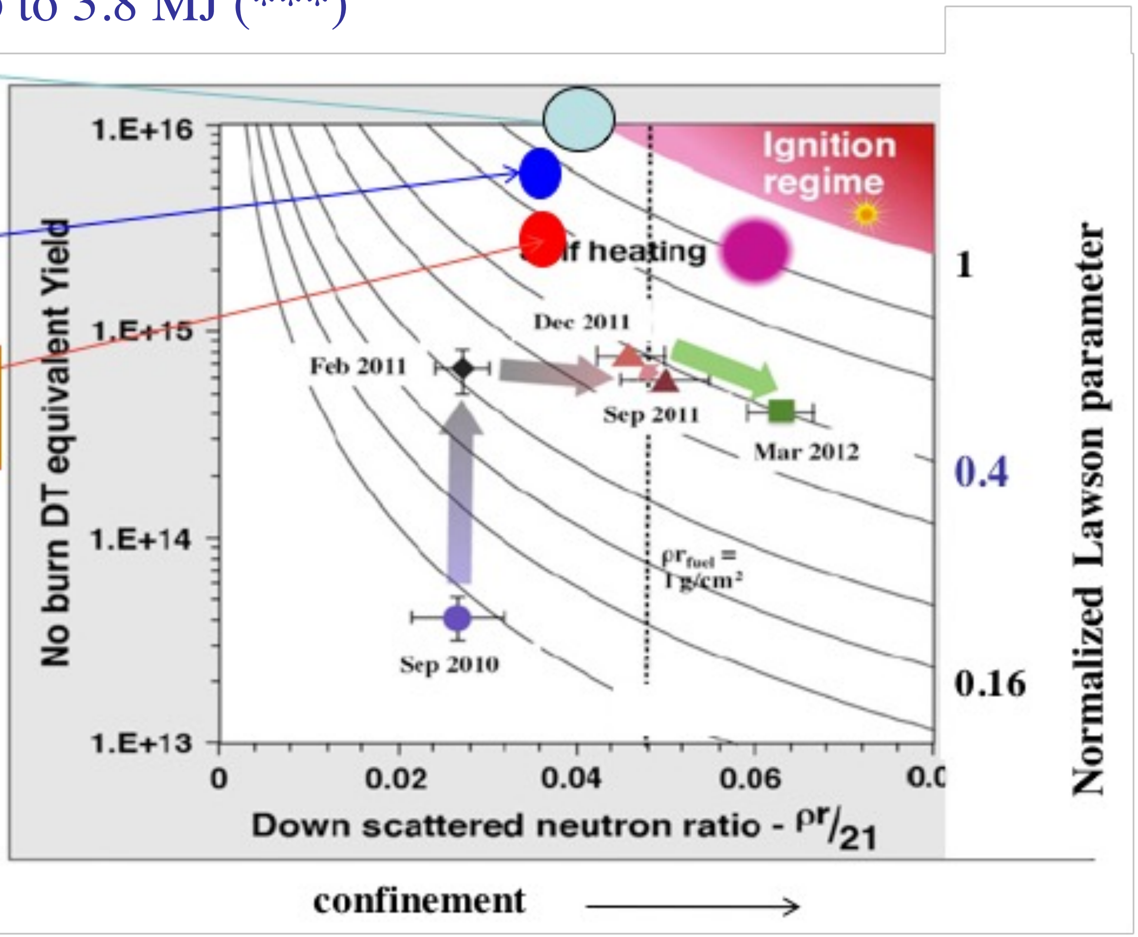
August 8, 2021: 1.3 MJ. Burn multiplication by self-heating > 20 (*,)**
hot spot p: 550 Gbar, hot spot T > 10 keV

2022, 2023: yield up to 3.8 MJ (***)

Aug. 8, 2021:
1.3 MJ

2015-2018:
55 kJ

Nov. 2013 –
Spring 2014: 27 kJ

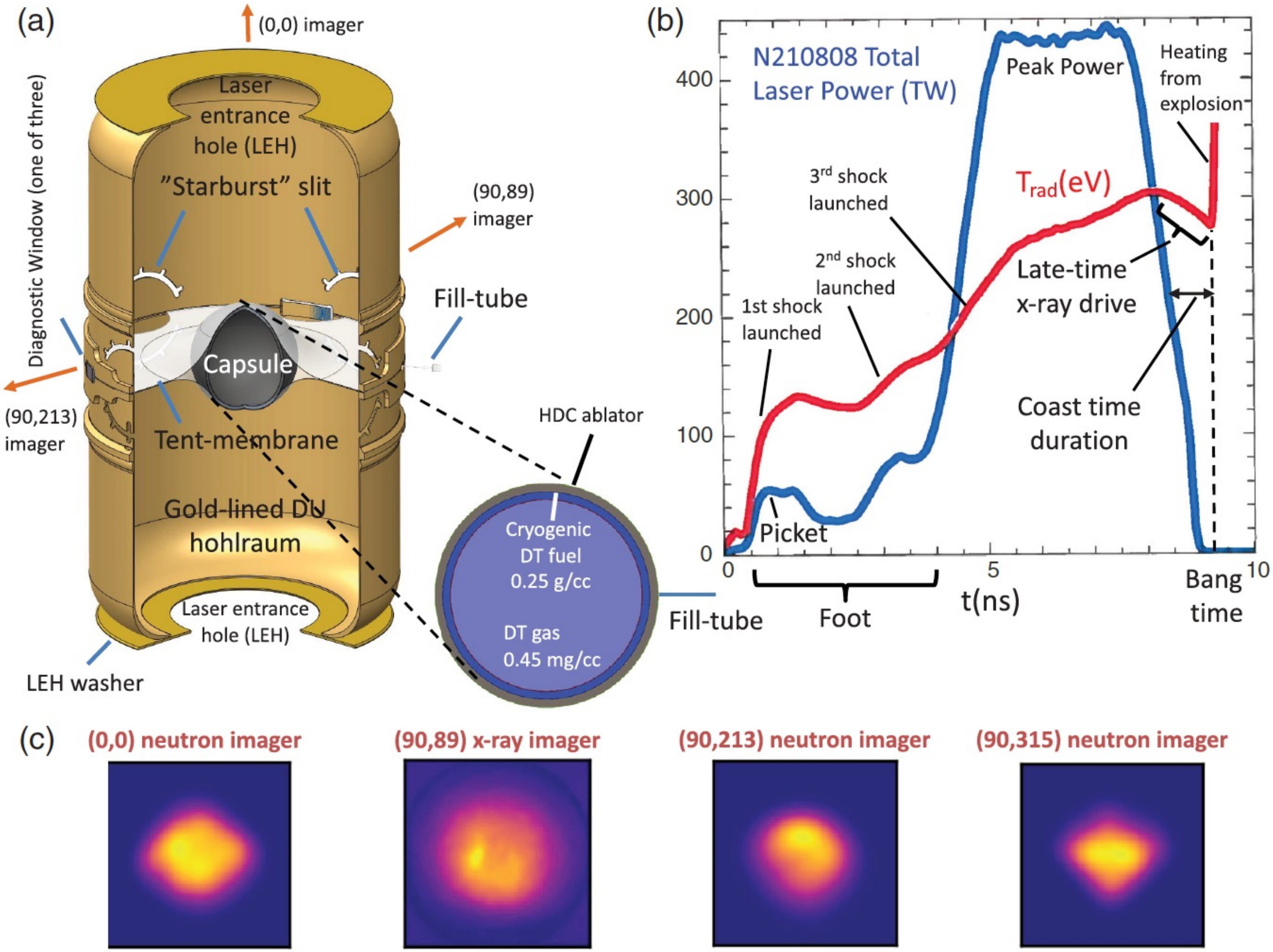


(*) hundreds of contributors:
campaign leaders
O. Hurricane & D. Callahan
A. Zylstra & A. Kritcher

(**) H. Abu Shwareb et al., *Phys. Rev. Lett.* **129**, 075001 (2022); A. L. Kritcher et al., *Phys. Rev.* **106**. 025201 (2022); A. B. Zylstra et al., *Phys. Rev. E* **106**. 025202 (2022)

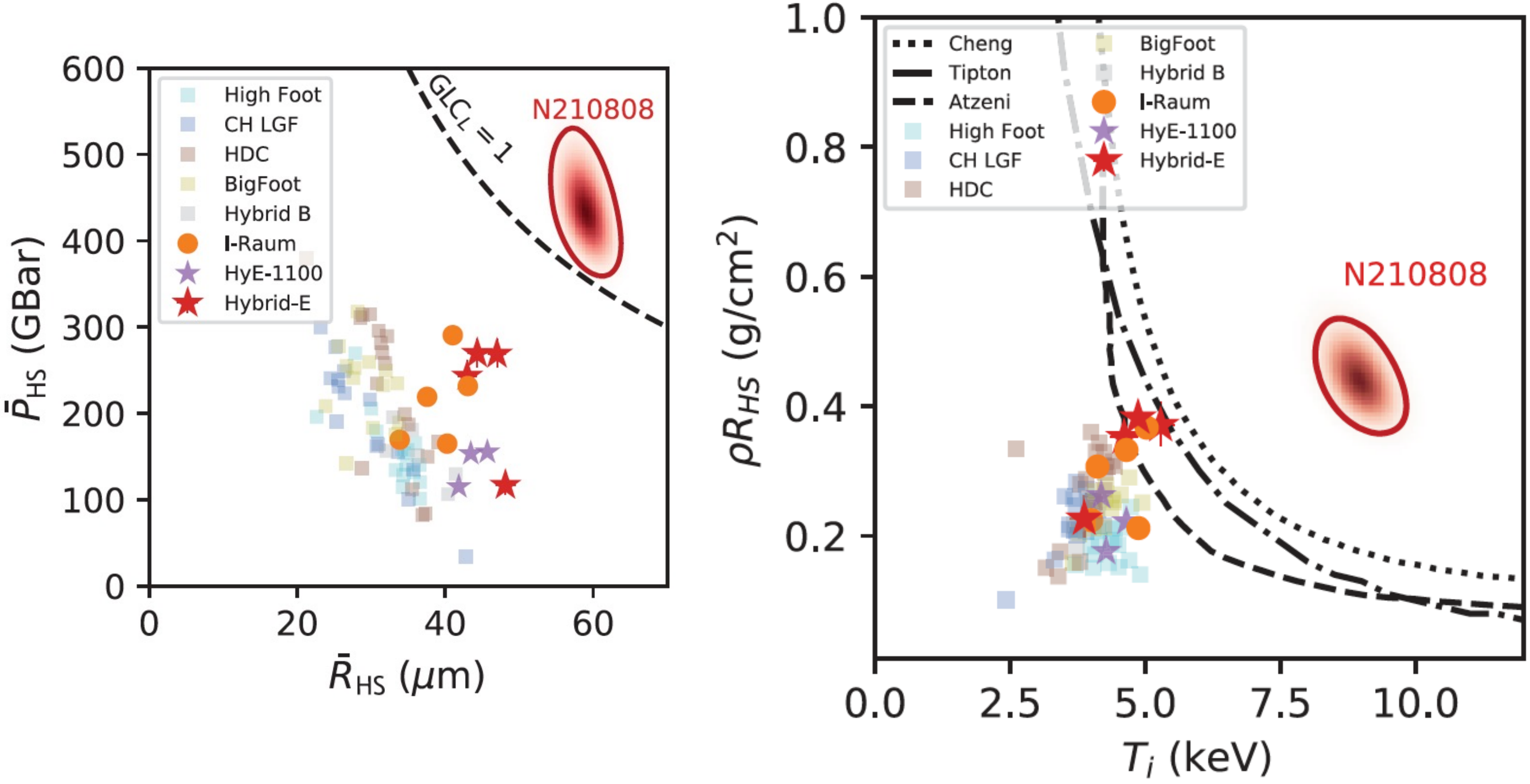
(***) H. Abu-Shawareb *et al*.,(The Indirect Drive ICF Collaboration), *Phys. Rev. Lett*. **132**, 065102 (2024)

PHYSICAL REVIEW LETTERS **129,** 075001 (2022)



H. Abu Shwareb et al., *Phys. Rev. Lett.* **129**, 075001 (2022)

PHYSICAL REVIEW LETTERS **129,** 075001 (2022)



H. Abu Shwareb et al., *Phys. Rev. Lett.* **129**, 075001 (2022)

How far from ignition? (a 2018 slide)

Yield in high foot experiments ~ 60 kJ, while ignition yield $Y > 1$ MJ

Really so far from ignition? Is yield the right metric?

A better metric(*): generalized Lawson parameter $\chi = (p\tau)/(p\tau)_{\text{ignition}}$ [τ: confinement t]

- Yield multiplication by self-heating M_y is a unique function of χ: $M_y = M_y(\chi)$
- In terms of measurable quantities: $\chi = \text{const}\ (\rho R)^{0.61} (Y/m_{DT})^{0.24}$

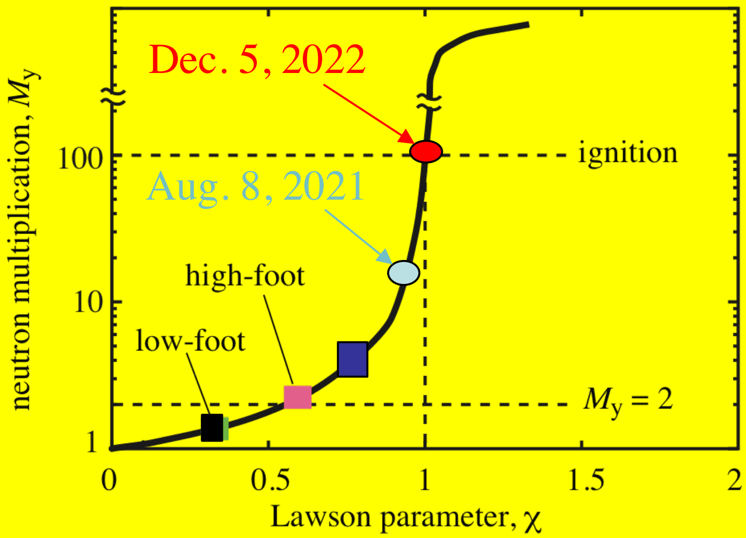
Low foot experiments: $\chi \le 0.3$ $(M_y \le 1.3)$

First High foot experiments: $\chi = 0.6$ $(M_y = 2)$

2018: $\chi = 0.65$ $(M_y = 3)$

For ignition: $\chi \geq 1$ $(M_y > 100)$:
progress by a factor ≈ 1.7 needed

SA, EPL **109**, 45001 (2015), adapted



(*) R. Betti et al., Phys. Plasmas 17, 058102 (2010)

How far from ignition?
How to increase Lawson parameter? (a 2018 slide)

What in terms of driver/target hydro parameters?

$\chi \approx \mathrm{ITF}^{0.4}$, with ITF the LLNL ignition threshold factor

[Spears *et al*, PoP 2012, Lindl *et al*., PoP 2014]

$\chi = \chi_{1D}$ x (corrections for deviations from1D)

$\chi_{1D} \approx \eta^{0.4}\, E^{0.4}\, u^{2.4}\, \alpha^{-0.6}$

In the high foot expt. (corrections ...) ≅ 1

=> χ_{1D} must grow by 1.7; all laser energy already used;

⇒ increase η

⇒ increase u

⇒ decrease α,
without degrading symmetry and stability

This is the rationale informing the strategy leading from the 2011 results to the ignition shot of Dec. 2022

NIF, July 29, 2023: 3.8 MJ, Gain = 1.8

Relevant to Inertial Fusion Energy?

- Yield increase x 5 possible at NIF (in indirect-drive)
- Coupling efficiency x 5 possible with direct-drive => 5 times larger fuel mass for the same laser energy => Yield x 15–20
- Gain increase x 2.0 with shock ignition or fast ignition [*]

==> $G = 1.8 \times 4 \times 15 \times 2.0 = 216$

[*] or very efficient d.d. schemes, as proposed by Goncharov, and by Bodner (white papers presented at DoE-OFE IFE workshop, Feb. 22–24, 2022)

Higher gain (than expected on NIF)?
Ignition at smaller laser energy ?
Simpler targets?

NIF-LMJ designed 15 years ago; since then

- laser progress:
  - smooth beams
  - ultraintense lasers
  - pulse shaping
- new ignition schemes (fast ignition, shock ignition)
- improved understanding of RTI

==>

- **New options for direct-drive**

and/or

- Alternate approaches to ignition

Direct-drive:

- more efficient than indirect-drive
- substantial progress in the past few years: see, e.g. C. A. Williams *et al*., *Demonstration of hot-spot fuel gain exceeding unity in direct-drive inertial confinement fusion implosions*, *Nature Phys*. (2024) https://doi.org/10.1038/s41567-023-02363-2 and the reviews by Craxton et al., PoP (2015) and by Betti and Hurricane (Nature Phys. 2016)]
- progress due to use of statistical modeling [Gopalaswamy, Betti, et al, Nature, 565, 581 (2019)]
- Much simpler spherical targets? [Goncharov et al, PRL (2020), Igumenshchev et al., PRL 2022]

However, still issues with RTI @ high implosion velocity

Instability risks grow with increasing implosion velocity

Can ignition be achieved
with “reduced” implosion velocity?

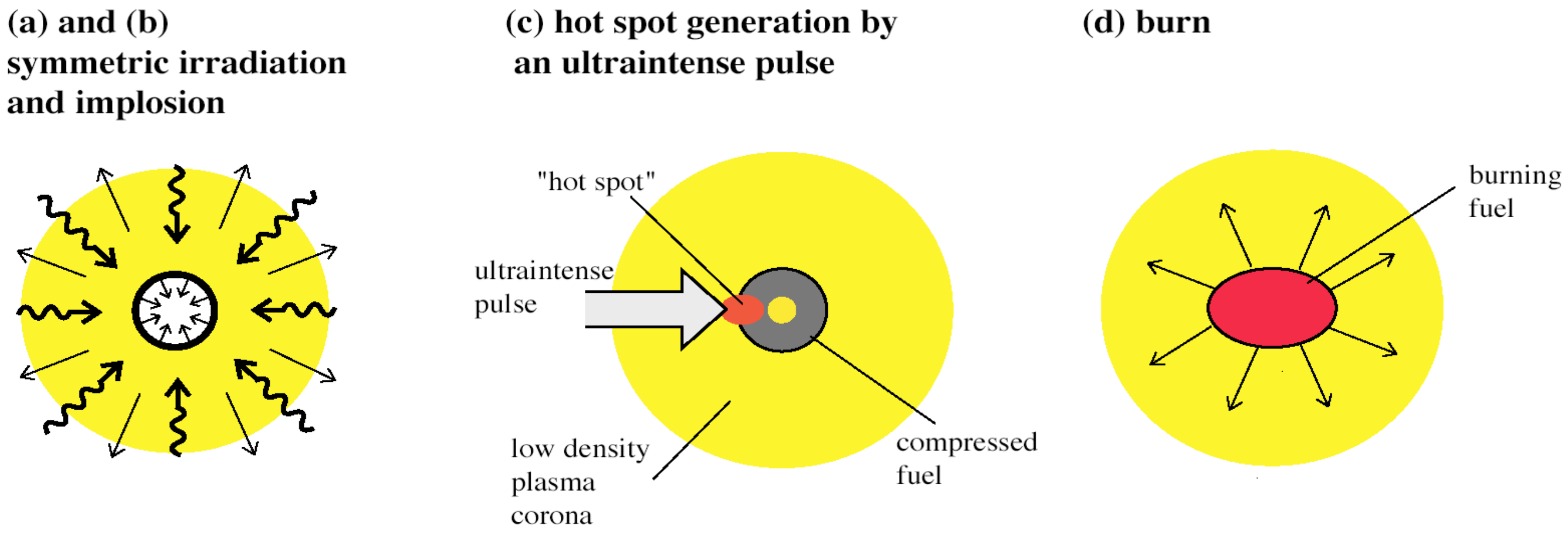
i.e. how can additional means increase
an “insufficient” hot spot pressure?

= = >

fast ignition

shock ignition

Fast ignition



(a) and (b) symmetric irradiation and implosion

(c) hot spot generation by an ultraintense pulse

(d) burn

To ignite a DT fuel precompressed to density of 300 g/cm^3: deliver 20 kJ in 20 ps on a 40 micron diameter spot

- Scheme: M. Tabak et al., Phys. Plasmas 1, 1626 (1994).
- Ignition requirements: S. Atzeni, Phys. Plasmas 6, 3316 (1999); S. Atzeni and M. Tabak, Plasma Phys. Controll. Fusion 47, B769 (2005)

Shock ignition (*)

the hot spot is generated by
a properly timed, laser-driven strong shock

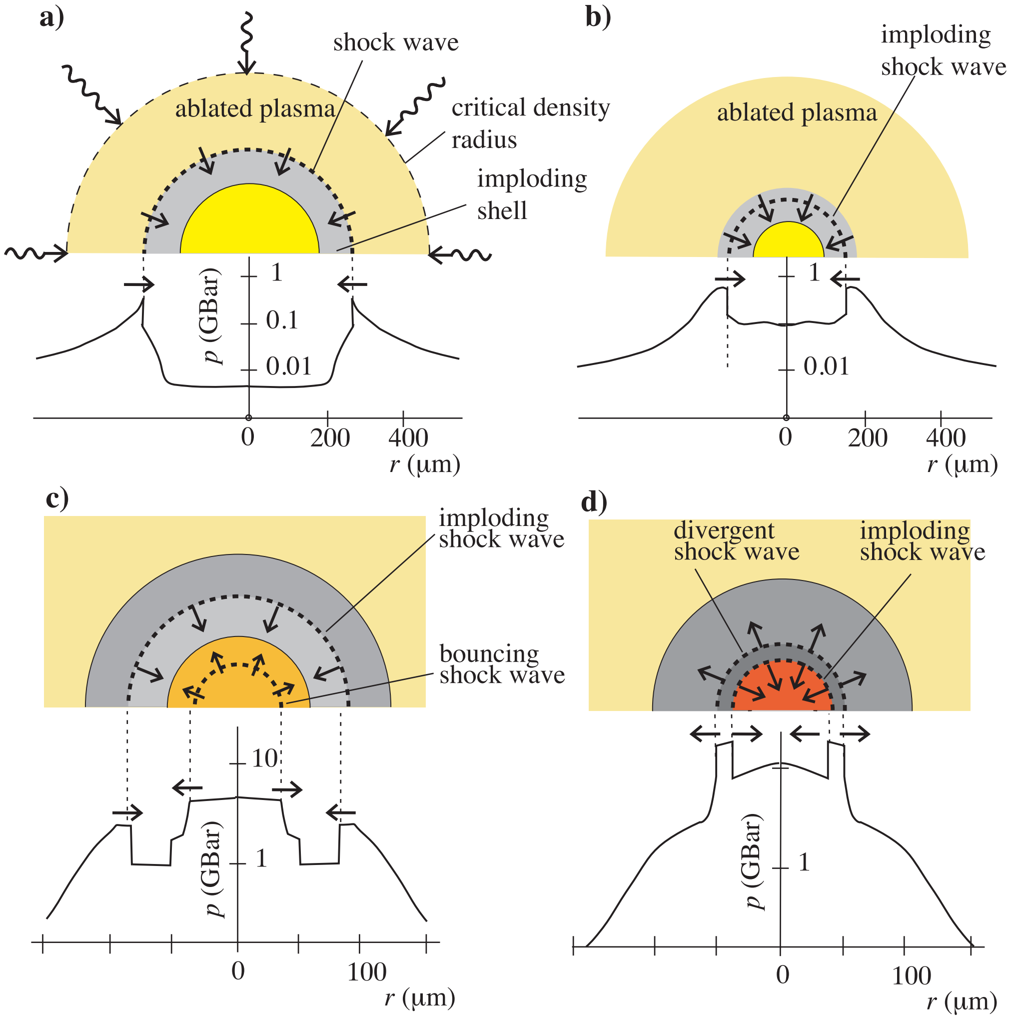
--- standard implosion (moderate velocity)

a) pulse generates imploding shock

b) imploding shock amplified as it converges

c) imploding shock pregresses, while shock bounces from center

d) the two shocks collide, and launch new shocks; the imploding shock heats the hot spot

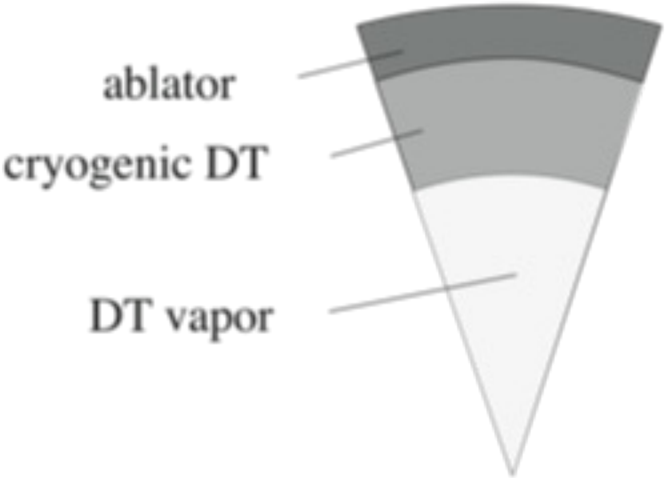


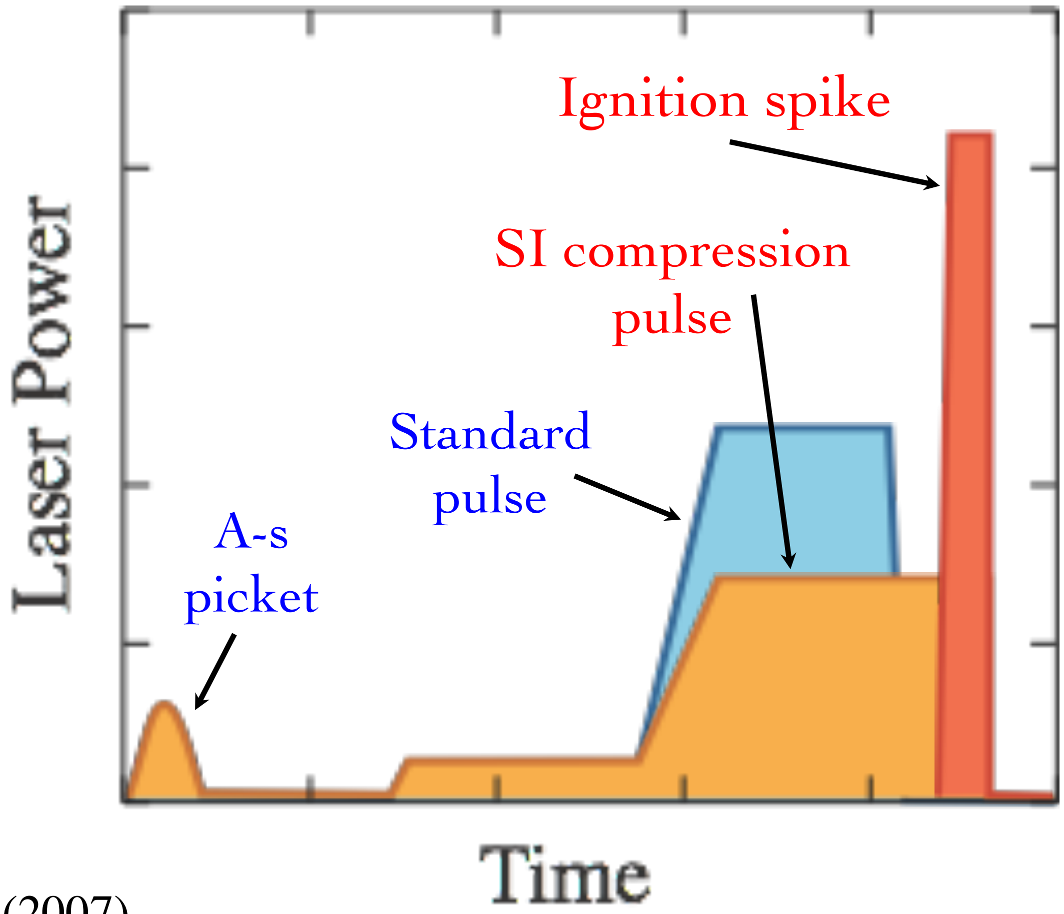
(*) R. Betti *et al.*, *Phys. Rev. Lett.*, 98, 155001 (2007).

Shock ignition

vs

conventional direct-drive central ignition

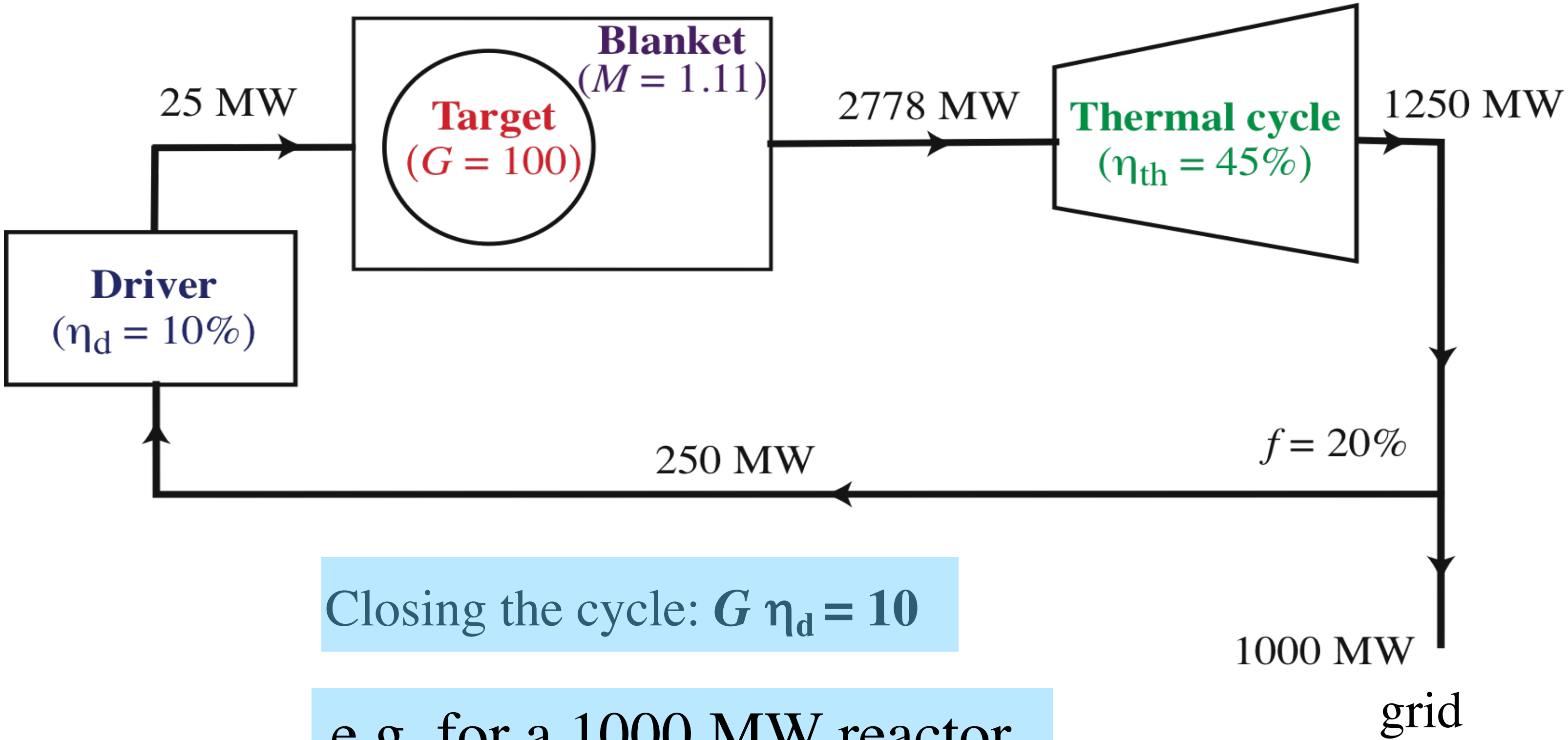




Concept: R. Betti *et al*, PRL 98, 155001 (2007)
Review: S. Atzeni *et al*., *Nucl. Fusion* **54**, 054008 (2014)

Towards Inertial Fusion Energy

Inertial fusion energy reactor cycle



Closing the cycle: $G\ \eta_d = 10$

e.g. for a 1000 MW reactor

$G = 100;$

$\eta_d = 10\%$

$E_d = 2.5$ MJ

$\nu_{driver} = 10$ Hz

Substantial progress required in

- target physics
- driver technology
- target technology

	For IFE	NIF	Required progress
Target gain	**100**	1.5	70
Driver efficiency	**10%**	0.7%	15
Driver rep. rate	**few Hz**	1/day	10^5–10^6

cost of target < 30% Cost Of Energy =>

cost of target < 40 cent $\times \left(\frac{Y_{\mathrm{fus}}}{250\ \mathrm{MJ}}\right)\left(\frac{COE}{5\ \mathrm{cent/kWh}}\right)\left(\frac{\eta_{\mathrm{th}}}{40\%}\right)$

Enormous progress required
Potential solutions do exist

More efficient targets proposed; can be(partially) tested on the NIF

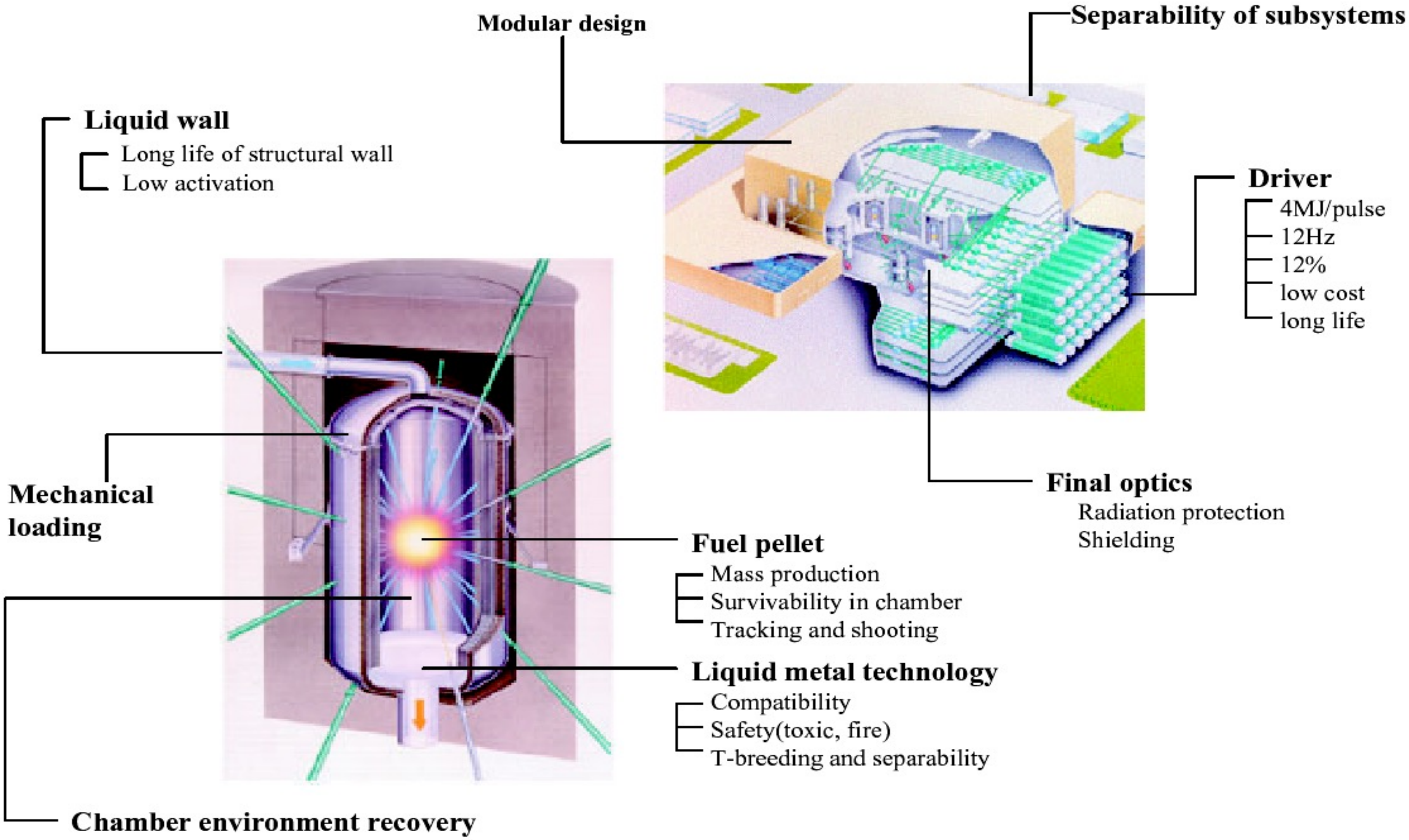
NIF is a 30 year old concept
> 10% efficient, Hz operating “small” lasers now exist. Must be scaled up.
Costs must be reduced (possible, with diode mass production)

Current targets are hand-made and complex. Simpler targets are conceivable.
Mass production is expected to decrease costs by many orders of magnitude
(cfr. semiconductors: 1947 first transistor vs billions of transistors on a chip)

Other areas requiring R&D

- Target injection and tracking
- Reaction chamber vacuum management
- Tritium breeding
- ...

Inertial fusion reactor conceptual design



Modular design

Separability of subsystems

Liquid wall
- Long life of structural wall
- Low activation

Driver
- 4MJ/pulse
- 12Hz
- 12%
- low cost
- long life

Mechanical loading

Final optics
- Radiation protection
- Shielding

Fuel pellet
- Mass production
- Survivability in chamber
- Tracking and shooting

Liquid metal technology
- Compatibility
- Safety(toxic, fire)
- T-breeding and separability

Chamber environment recovery

Fusion lasers potential applications

Large potential market for

Laser driven radiation sources for non-destructive diagnostics (structural analysis, counter-proliferation, homeland security)

Non-fusion scientific applications

- Laboratory astrophysics (magnetic turbul. [1], collisional and collisionless shocks [2], RTI in SNR)
- Thermonuclear reaction rates (e.g. He^3-He^3) [3]
- Materials at extreme pressures (e.g. super-ionic fluids [4])
- Particle acceleration (ions, electrons, positrons) [5]
- Femtosecond chemistry
- X-ray lasers

[1] G. Gregori et al, *Nature 481, 480 (*2012)
[2] C. Li et al., *Phys Rev Lett* 123, 055002 (2019)
[3] A. Zylstra et al., *Phys Rev Lett* 119, 222701 (2017)
[4] M. Millot et. al, *Nature Phys*. *14, 297 (*2018)
[5] M. Borghesi et al, Rev. Mod. Phys. 85, 751 (2013); E. Esarey et al, Rev. Mod. Phys. 81, 1229 (2009)

New initiatives in Europe?

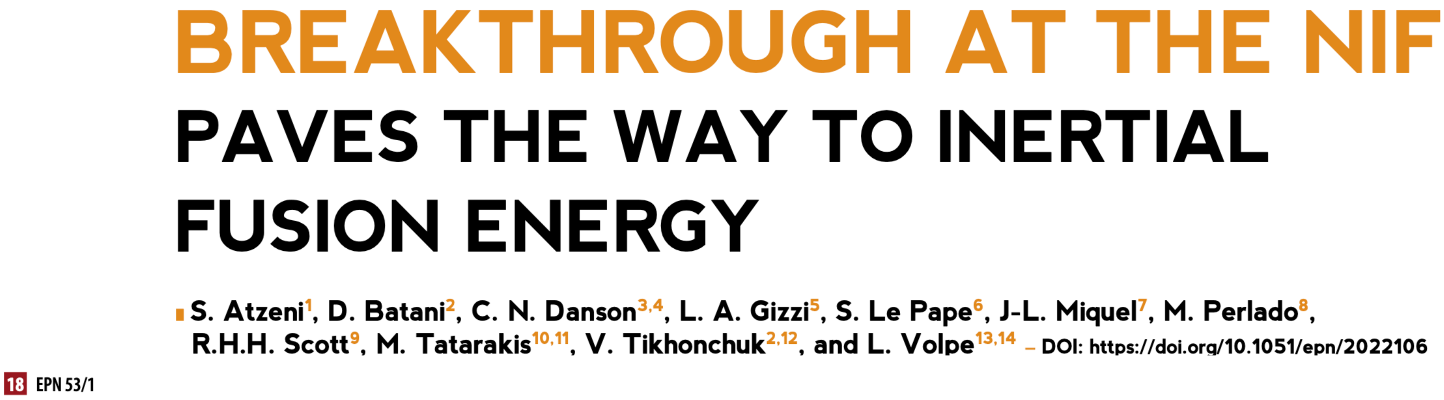
High Power Laser Science and Engineering, (2021), Vol. 9, e52, 4 pages.
doi: 10.1017/hpl.2021.41

HIGH POWER LASER
SCIENCE AND ENGINEERING

PERSPECTIVE

An evaluation of sustainability and societal impact of high-power laser and fusion technologies: a case for a new European research infrastructure

S. Atzeni[1], D. Batani[2], C. N. Danson[3,4], L. A. Gizzi[5], M. Perlado[6], M. Tatarakis[7,8], V. Tikhonchuk[2,9], and L. Volpe[10, 11]



BREAKTHROUGH AT THE NIF PAVES THE WAY TO INERTIAL FUSION ENERGY

S. Atzeni[1], D. Batani[2], C. N. Danson[3,4], L. A. Gizzi[5], S. Le Pape[6], J-L. Miquel[7], M. Perlado[8], R.H.H. Scott[9], M. Tatarakis[10,11], V. Tikhonchuk[2,12], and L. Volpe[13,14] – DOI: https://doi.org/10.1051/epn/2022106

18 EPN 53/1

HiPER

The continuation of HiPER- HiPER Plus

Proposal for a new "direct-drive" laser-fusion programme in the EU

A German-US company enters the game, too

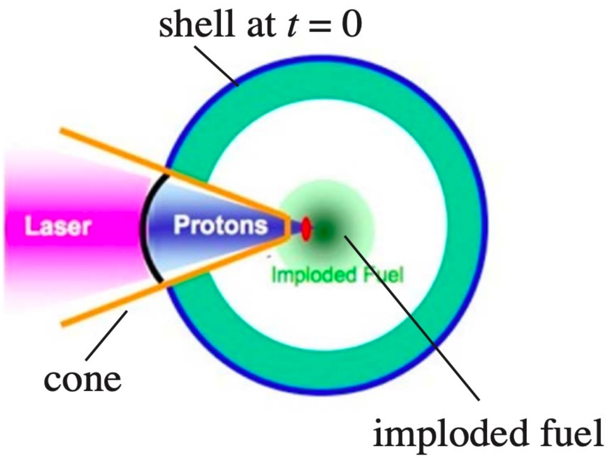
FOCUSED ENERGY

Focused Energy GmbH/Inc (Darmstadt/Austin)

Goal:

demonstrate IFE (i.e. build and operate a Pilot Plant), using

- Laser direct-drive, with
- Fast Ignition by a laser-produced proton beam (*) or shock ignition



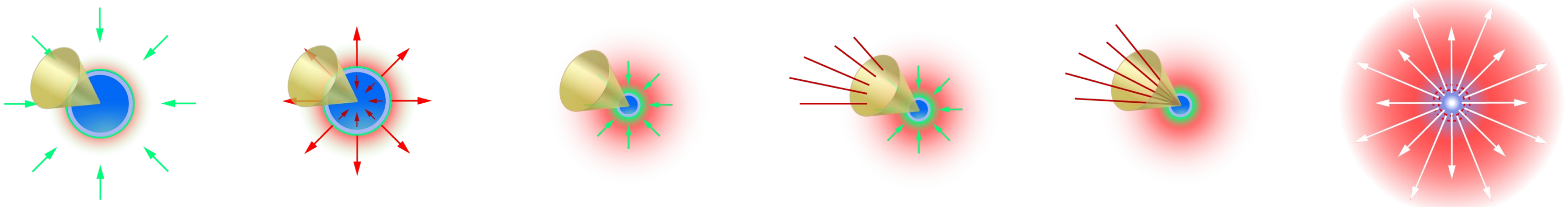
(*) concept: M. Roth et al, PRL 86, 436 (2001)
proton beam requirements: S. Atzeni et al, NF 42, L1 (2002)

Focused energy is performing a pre-conceptual design of a Pilot Fusion Power Plant, using laser direct-drive and proton Fast Ignition (*)

FOCUSED ENERGY

Requirements: Gain ≥ 100, high rep-rate

Efficiency: laser direct-drive
High gain: proton fast ignition, pFI (*)
Technology: ‘2 ω’ (527 nm) laser



1 Absorption and heat transport

2 Acceleration and rocket effect

3 Deceleration and compression

4 Laser-ion beam generation

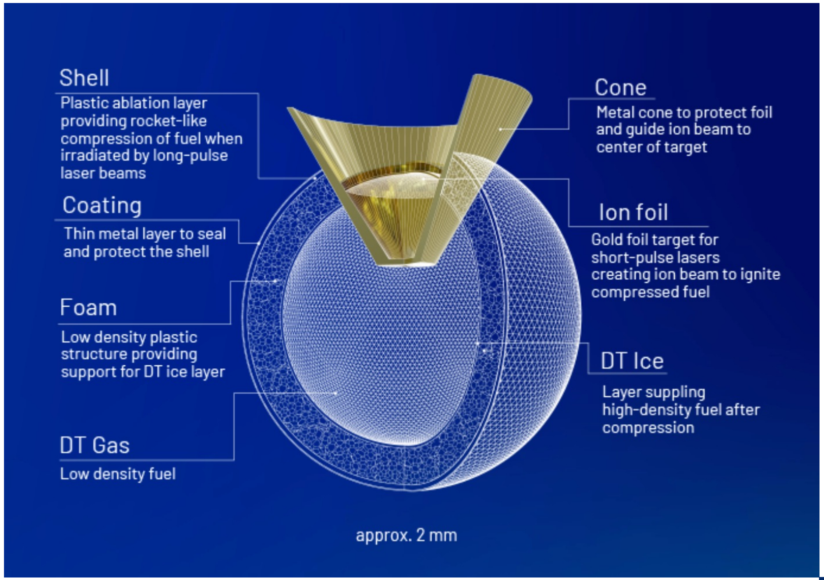
5 Ion beam heating of dense fuel

6 Ignition and fusion burn

Specific challenges: Efficiency of proton generation and transport
Cone-inserted target
Laser-plasma instabilities at 2ω

(*) also being evaluated: shock ignition ; 527 nm vs 351 nm laser drive.

Target and reactor concept



Shell
Plastic ablation layer providing rocket-like compression of fuel when irradiated by long-pulse laser beams

Coating
Thin metal layer to seal and protect the shell

Foam
Low density plastic structure providing support for DT ice layer

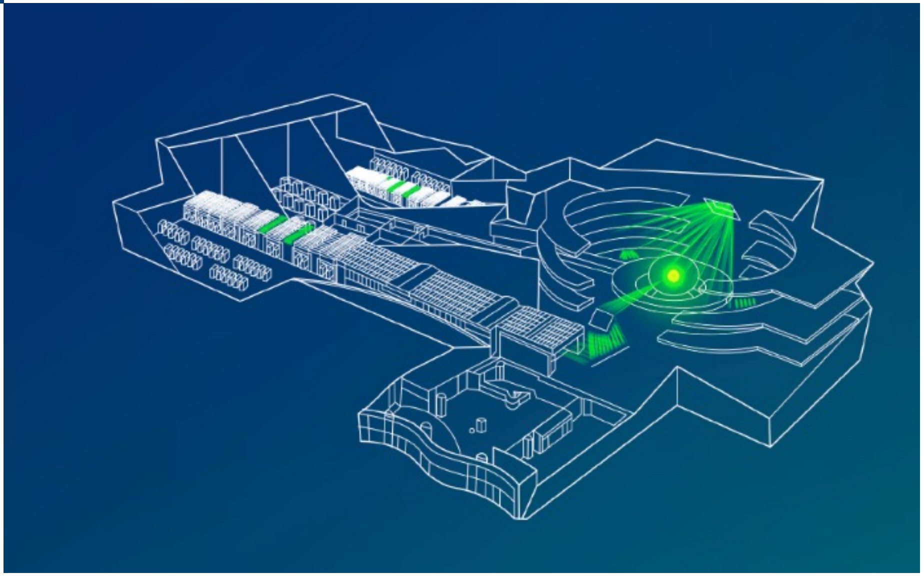
DT Gas
Low density fuel

Cone
Metal cone to protect foil and guide ion beam to center of target

Ion foil
Gold foil target for short-pulse lasers creating ion beam to ignite compressed fuel

DT Ice
Layer suppling high-density fuel after compression

approx. 2 mm



Final remarks

In the past 50 years:

- impressive progress in lasers
- impressive progress in physics understanding and modelling
- crucial role of diagnostics (often, laser-based: backlighters, proton imaging, ...)

- a number of ingenious schemes proposed
- synergy with other laser-driven physics, potential applications

Ignition achieved,
The path to reactor long, but conceivable

= => a lot of exciting opportunities (and demanding work)
for young scientists and engineers!

Thank you for your attention!