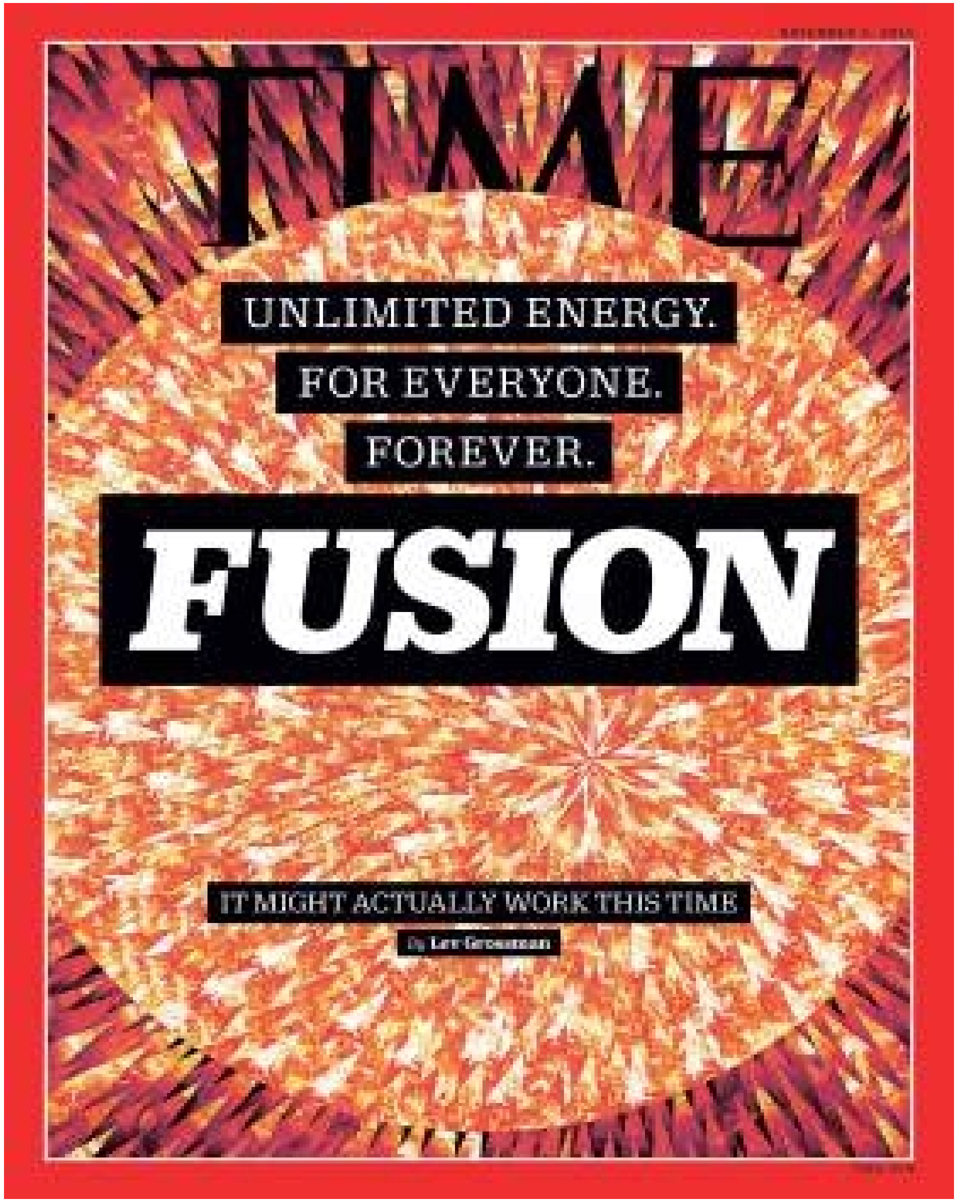
Basics of Inertial Fusion

Speaker:

Andrea Macchi
(CNR/INO, Pisa &
Dipartimento di Fisica,
Università di Pisa)

Event:
Lezione introduttiva al ciclo "Fusione Nucleare: Introduzione e Prospettive" Dipartimento di Fisica Enrico Fermi, Università di Pisa, 15/04/2024

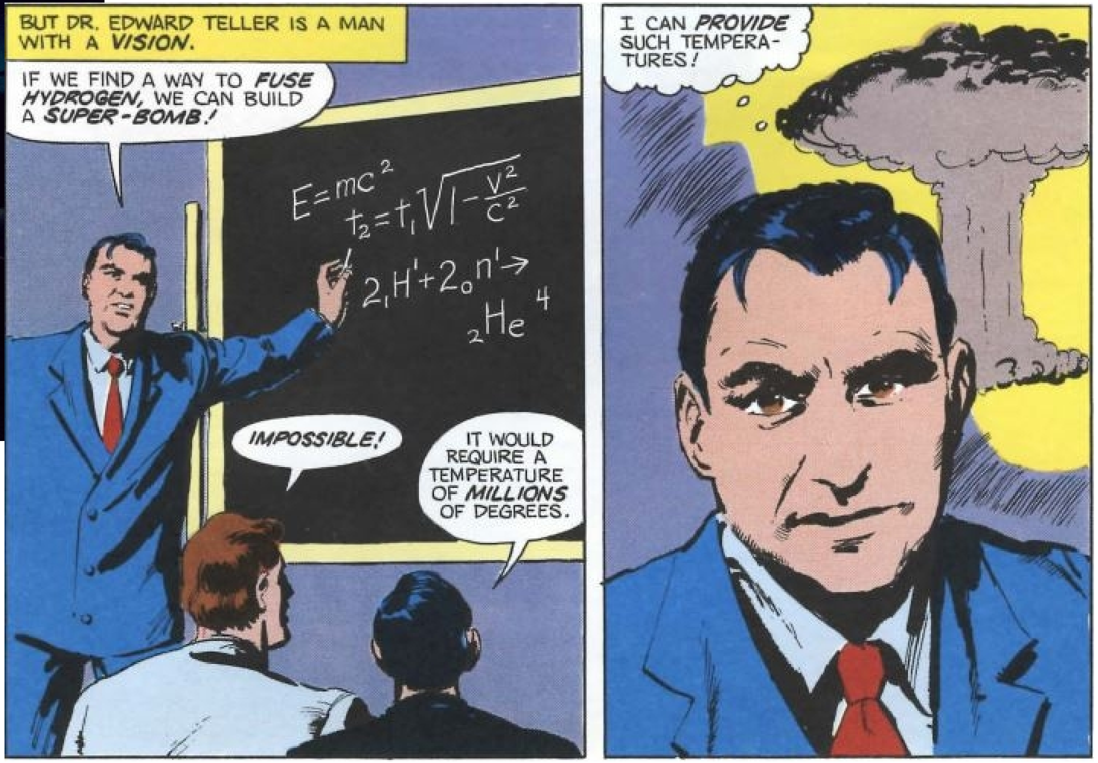
Is Fusion Coming?



"IT MIGHT ACTUALLY WORK THIS TIME"
TIME, October 2015

It Worked! In an Uncontrolled Way ...

Test “Ivy Mike” (1952) of H-bomb (H for "hydrogen”) design by E. Teller & S.Ulam (classified)



Fusion is driven by a primary "standard" fission-based atomic bomb

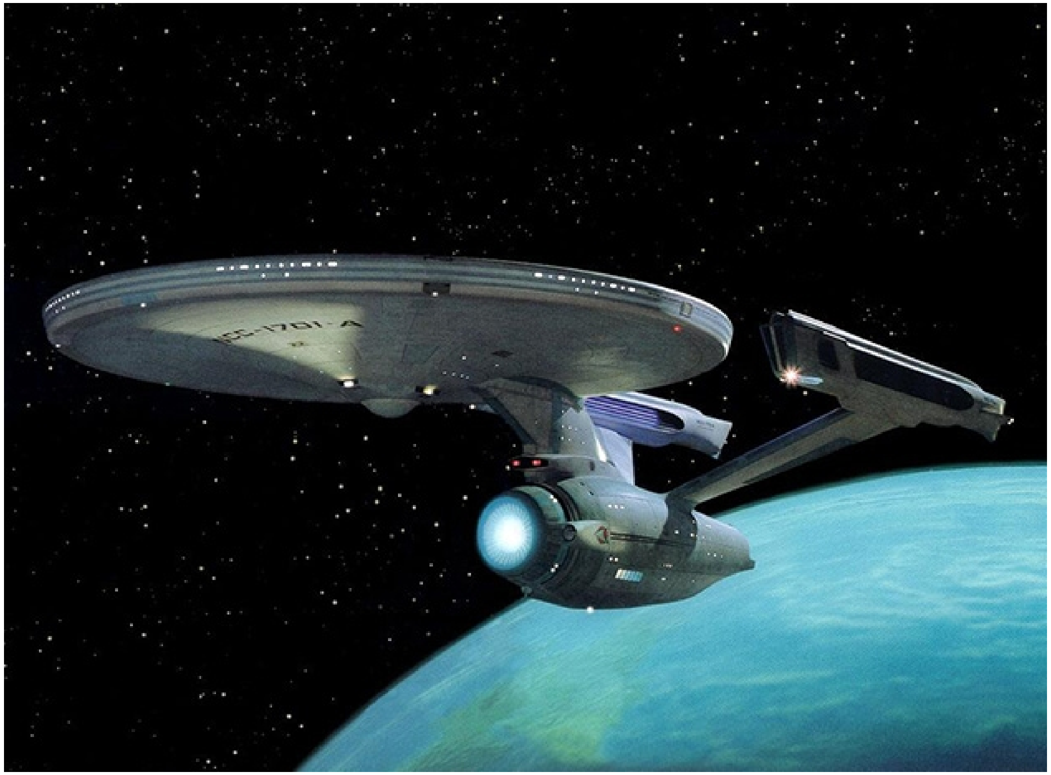
(*Spoiler*: research on fusion for energy production has no risk of nuclear ploriferation – besides being safer than nuclear fission – *but there is a military interest in inertial fusion*)

… but Controlling It Remains Difficult

The fusion experiment
of Dr Octopus
in "Spiderman 2" (2004)
©Marvel, Columbia Pictures

Strip: Amazing Spider-Man, #44
©Marvel comics

So, When It Will Be Possible?



From:

Memory Alpha / Beta, the wiki for Star Trek

(http://memory-alpha.wikia.com)

“For a number of years, humans were unable to create a sustained fusion reaction. As a result, humans used nuclear fission quite extensively during the 20th and 21st centuries. Humans were later able to create a sustained artificial fusion reaction, leading to the replacement of the older fission reactors. Fusion reactors became an everyday part of life in the United Federation of Planets. (...) On space vessels, nuclear fusion reactors provided power for general use, as well as for a ship's impulse drive. By the 24th century, fusion reactors had become small enough that many homes had their own fusion reactors to provide power for their occupants.”

A Dense Hot Problem

In order to efficiently produce energy from fusion the DT mixture must be:

- hot enough to let nuclei go through the “electric” barrier
- dense enough to have high probability of fusing encounters
- lasting long enough to keep above conditions

Conditions depend on density n, temperature T, time τ

“Lawson criterion” for energy multiplication:

$$n\ \tau > \mathrm{f}(T)$$

minimum of $\mathrm{f}(T) \approx 10^{14}\ \mathrm{cm}^{-3}\ \mathrm{s}$ at $T \approx 10^{8}\ \mathrm{K} \approx 10\ \mathrm{keV}$

(alternate “triple product” form: $n\ \tau\ T > 10^{28}\ \mathrm{cm}^{-3}\ \mathrm{s\ K}$)

WARNING: these are rough order-of-magnitude numbers

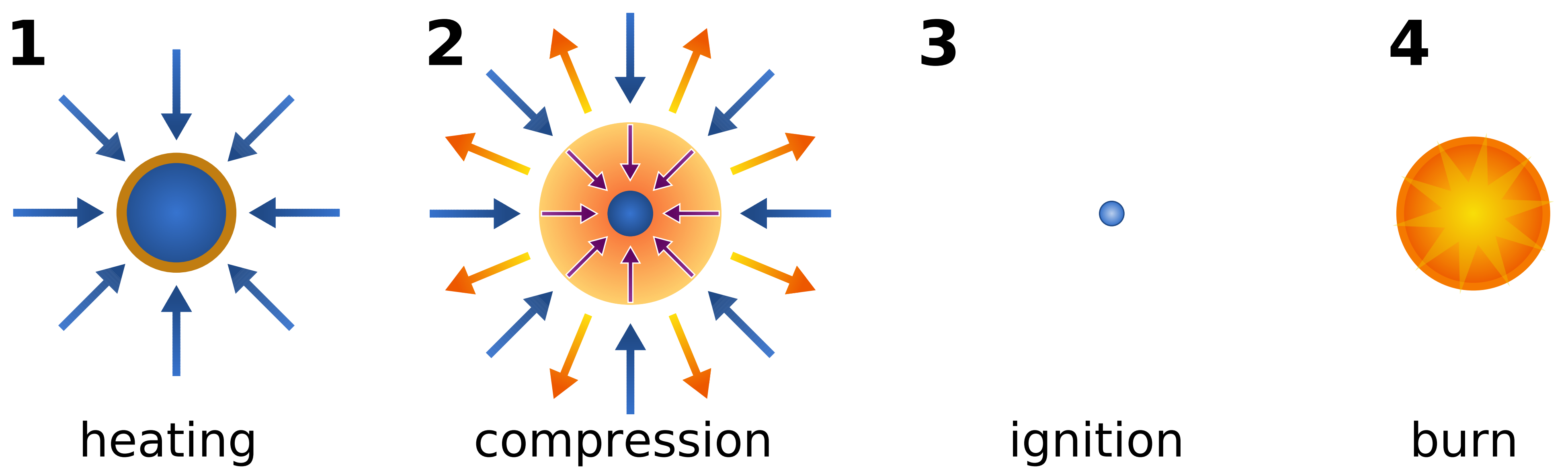
Inertial (Confinement) Fusion Concept

Two confinement options are suitable on Earth:

- **Magnetic Confinement** ($n \approx 10^{14}$ cm^{-3} , $\tau \approx 1$ s)

- **Inertial Confinement** ($n > 10^{23}$ cm^{-3} , $\tau < 10^{-9}$ s) - **ICF**

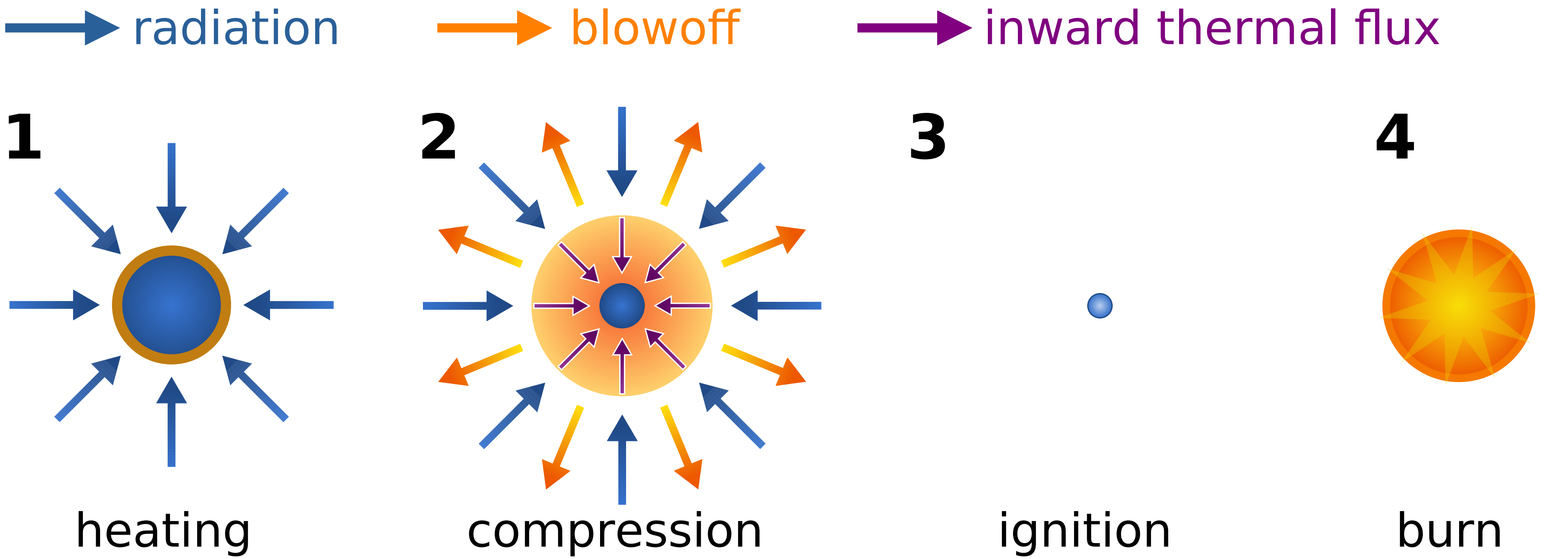
a D-T pellet is compressed above solid-density values and "confined" by inertia (no "active" confinement at all)



Benjamin D. Esham, Public domain, Wikimedia Commons
https://commons.wikimedia.org/wiki/File:Inertial_confinement_fusion.svg

Inertial (Confinement) Fusion Concept

1) Radiation beams heat the surface of the target forming a surrounding plasma envelope.
2) Fuel is compressed by the rocket-like blowoff of the hot plasma
3) The fuel core reaches 20 times the density of lead and ignites at 100,000,000 ˚C.
4) Thermonuclear burn spreads through the compressed fuel,



Benjamin D. Esham, Public domain, Wikimedia Commons
https://commons.wikimedia.org/wiki/File:Inertial_confinement_fusion.svg

Energy Constraints & the Hot Spot

The released energy must be limited to few GJ for safety:
no more than ~ tens of mg of DT at each shot can be burnt

Exploitation of energy production requires $G>100$
(with >1 HZ repetition rate)
but usually $G\sim 10$ for uniform burn of the fuel

Way out: ignite only the central region (hot spot) and then let burn propagate to the rest of the fuel

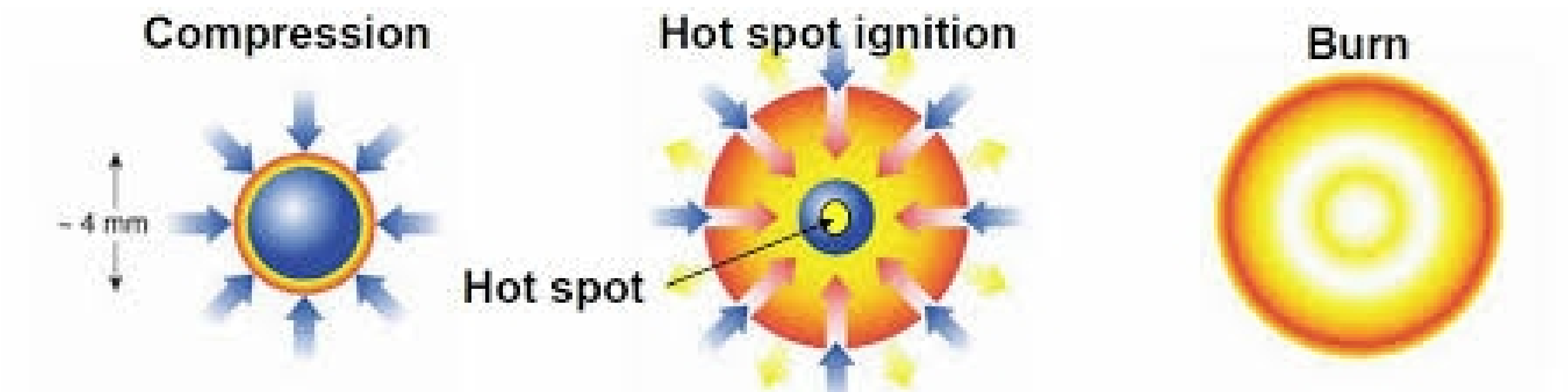


Image credit: R.Betti (Univ. Rochester & Princeton Plasma Physics Laboratory)

Energy Multiplication Condition

$E_{\rm fus}$: energy relased from fusion

$E_{\rm th}$: thermal energy $\qquad$ $E_{\rm dr}$: driver energy

$G \equiv \dfrac{E_{\rm fus}}{E_{\rm dr}}$ gain $\qquad$ $\eta \equiv \dfrac{E_{\rm th}}{E_{\rm dr}}$ efficiency

V: fuel density $\qquad$ $n_{\rm D} = n_{\rm T} = n/2 = n_e/2$

$\overline{\sigma_{\rm DT} v}$: number of reactions per unit time

(average of $\sigma_{\rm DT}(v)v$ over velocity distribution)

ε=17.6 MeV fusion energy per D-T pair

$$E_{\rm fus} = \frac{n^2}{4}\tau\varepsilon\overline{\sigma_{\rm DT} v}V \qquad E_{\rm th} = 2n\left(\frac{3}{2}T\right)V$$

$$n\tau = \frac{12T}{\varepsilon\overline{\sigma_{\rm DT} v}}\left(\frac{G}{\eta}\right)$$

Fuel Rarefaction and Optimal Temperature

$$c_s = \left(\frac{3T}{m_{\rm DT}}\right)^{1/2} : \text{ sound velocity}$$

R: fuel radius ($V = 4\pi R^3/3$)

$$\tau \approx \frac{R}{c_s}: \text{ fuel rarefaction time} \qquad \tau = \frac{12T}{n\varepsilon\overline{\sigma_{\rm DT}v}}\left(\frac{G}{\eta}\right)$$

$$E_{\rm th} = 2nT\left(\frac{4\pi}{3}R^3\right) \propto nT^{5/2}\tau^3$$

$$E_{\rm dr} = \frac{1}{\eta}E_{\rm th} \propto \frac{G^3}{\eta^4 n^2}\frac{T^{11/2}}{\overline{\sigma_{\rm DT}v}}$$

$$\min(E_{\rm dr}) \approx 1.6\times10^6\ \mathrm{J}\left(\frac{G^3}{\eta^4}\right)\left(\frac{n_{\rm sol}}{n}\right)^2 \quad @ \quad T \approx 10\ \mathrm{keV}$$

$$(n_{\rm sol} = 4.5\times10^{22}\ \mathrm{cm^{-3}})$$

$$\longrightarrow \quad n\tau \approx (6\times10^{13}\ \mathrm{cm^{-3}s})\left(\frac{G}{\eta}\right)$$

Self-Heating Condition

$$\frac{\mathrm{d}E_{\mathrm{th}}}{\mathrm{d}t} = W_\alpha - W_{\mathrm{exp}} - W_{\mathrm{con}} - W_{\mathrm{rad}}$$

$$W_\alpha = \frac{n^2}{4}\overline{\sigma_{\mathrm{DT}}v} f_\alpha \varepsilon_\alpha \quad \alpha - \text{heating } (f_\alpha < 1\,,\, \varepsilon_\alpha = 3.52\ \mathrm{MeV})$$

$$W_{\mathrm{exp}} \propto \mathbf{u}\cdot\mathbf{\nabla}P \propto \frac{c_{\mathrm{s}}\rho T}{\bar{m}R} \quad \text{expansion (non} - \text{isobaric fuel)}$$

$$W_{\mathrm{con}} \propto \mathbf{\nabla}(\kappa_e \mathbf{\nabla}T) \propto \frac{T^{7/2}}{R^2} \quad \text{conduction}$$

$$W_{\mathrm{rad}} \propto \rho^2 T^{1/2} \quad \text{radiation (Bremsstrahlung)}$$

$$\frac{\mathrm{d}E_{\mathrm{th}}}{\mathrm{d}t} = 0$$

$$\longrightarrow \quad \text{relation between } \rho R \text{ and } T$$

$$\rho R \approx 0.2 - 0.4\ \mathrm{g\ cm}^{-2}$$

$$T \approx 5 - 10\ \mathrm{KeV}$$

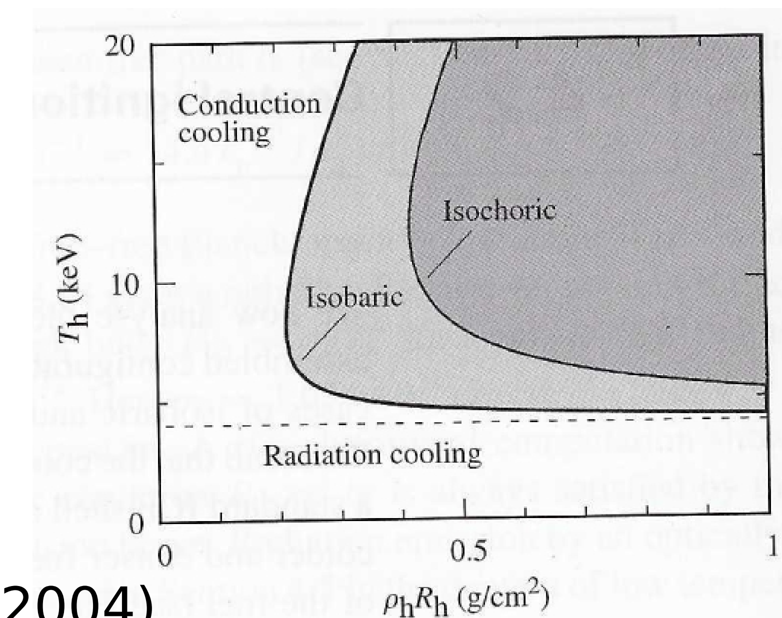


fig. from S.Atzeni, J.Meyer-ter-Vehn,
The Physics of Inertial Fusion (Oxford Science, 2004)

Fuel Burn

$$\frac{\mathrm{d}N_{\mathrm{fus}}}{\mathrm{d}t} = \overline{\sigma_{\mathrm{DT}} v} n_{\mathrm{D}} n_{\mathrm{T}} V(t): \text{ reaction rate}$$

$$V(t) = \tfrac{4\pi}{3}(R - c_{\mathrm{s}} t)^3 \text{ rarefaction}$$

$$N_{\mathrm{fus}} = \int_0^{R/c_{\mathrm{s}}} \frac{\mathrm{d}N_{\mathrm{fus}}}{\mathrm{d}t}\mathrm{d}t = \overline{\sigma_{\mathrm{DT}} v}\frac{n^2}{4}\frac{\pi R^4}{3c_{\mathrm{s}}} \equiv \frac{\rho R}{H_{\mathrm{B}}} N_{\mathrm{DT}}$$

$$H_{\mathrm{B}} \equiv \frac{8 c_s \bar{m}}{\overline{\sigma_{\mathrm{DT}} v}} \simeq 7 \text{ g cm}^{-2}$$

generalization for fuel depletion effects: $\dfrac{N_{\mathrm{fus}}}{N_{\mathrm{DT}}} \approx \dfrac{\rho R}{H_{\mathrm{B}} + \rho R}$

$$\frac{N_{\mathrm{fus}}}{N_{\mathrm{DT}}} = 30\% \quad \longrightarrow \rho R = 3 \text{ g cm}^{-2}$$

For 1 mg of DT releasing 100 MJ

$$\rho = 300 \text{ g cm}^{-3} = 1500 \rho_{\mathrm{S}}$$

Laser Heating and Ablation

Energy flux balance $AI_\mathrm{L} = f n_e v_e T_e$

($A < 1$ absorption , $f < 1$ “flux limiter”)

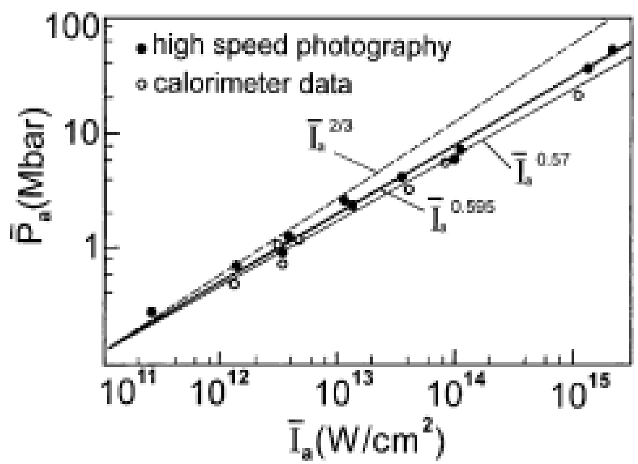
at cut-off density $n_c = n_e\big|_{\omega_\mathrm{L}=\omega_p} = \dfrac{m_e \omega_\mathrm{L}^2}{4\pi e^2}$

$$\varepsilon(\omega) = 1 - \frac{n_e}{n_c(\omega)} \qquad n_c = \frac{10^{21}\ \mathrm{cm}^{-3}}{(\lambda_\mathrm{L}/1\ \mu\mathrm{m})^2}$$

Temperature $T_e \approx I_\mathrm{L}^{2/3} n_c^{-2/3} m_e^{1/3}$

Ablation pressure $P_a = \rho c_\mathrm{s}^2 \approx I_\mathrm{L}^{2/3} n_c^{1/3} m_e^{1/3}$

At $I_\mathrm{L} \approx 10^{14}\ \mathrm{W\ cm}^{-2} \left(= \dfrac{10^6\ \mathrm{J}}{10^{-8}\mathrm{s}\ 1\ \mathrm{cm}^2} \right)$



$T_e \approx 300\ \mathrm{eV} \qquad P_a \approx 10\ \mathrm{Mbar}$

fig. from P.Mulser, S.Hain, F.Cornolti,
Nucl. Inst. Meth. Phys. Res. A **415** (1998) 165

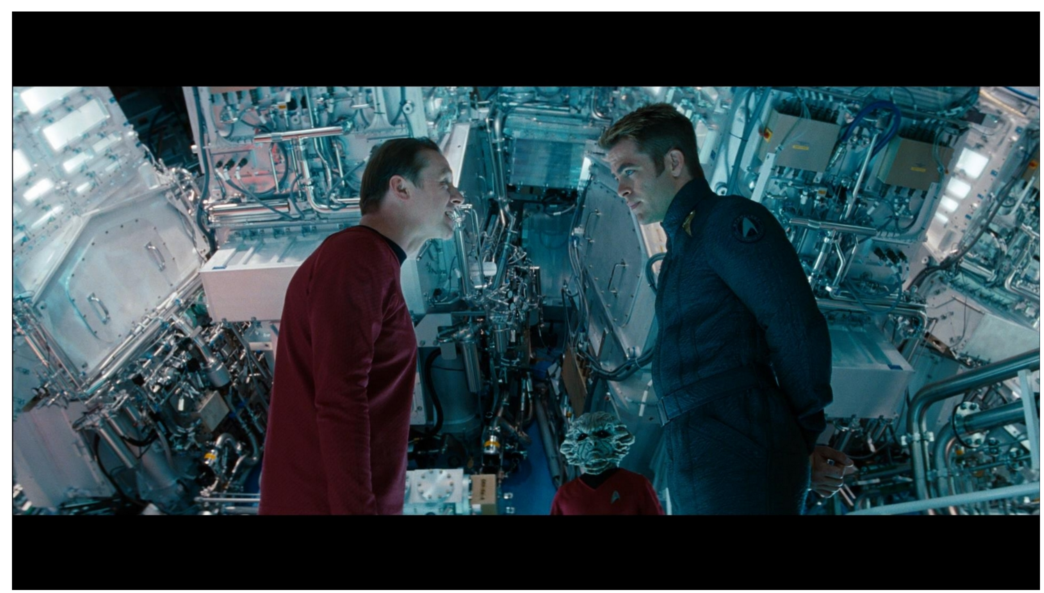
Laser Fusion: NIF

The National Ignition Facility (NIF): 192 beams focused on a DT capsule delivering up to 2 MJ at 500 TW power in few ns

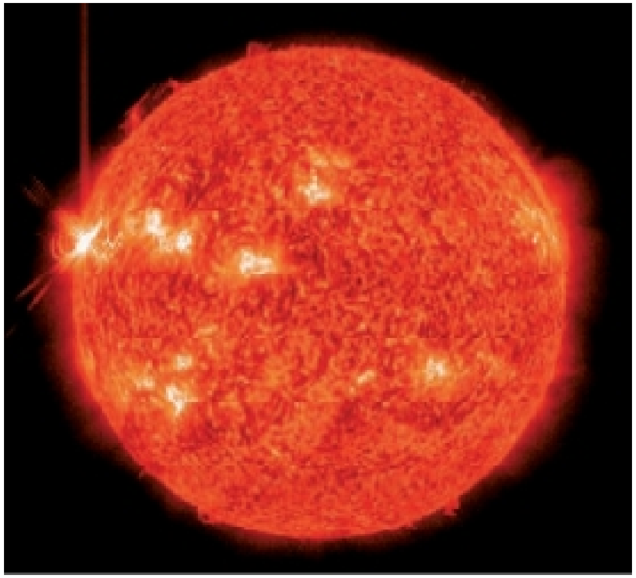
Construction cost: ~1 billion $
Operation: 1 shot/day
(~1 million $/shot)

2013: backdrop for
"Star Trek: into Darkness"

"Twin" laser in France
(Laser MegaJoule)



Size Matters

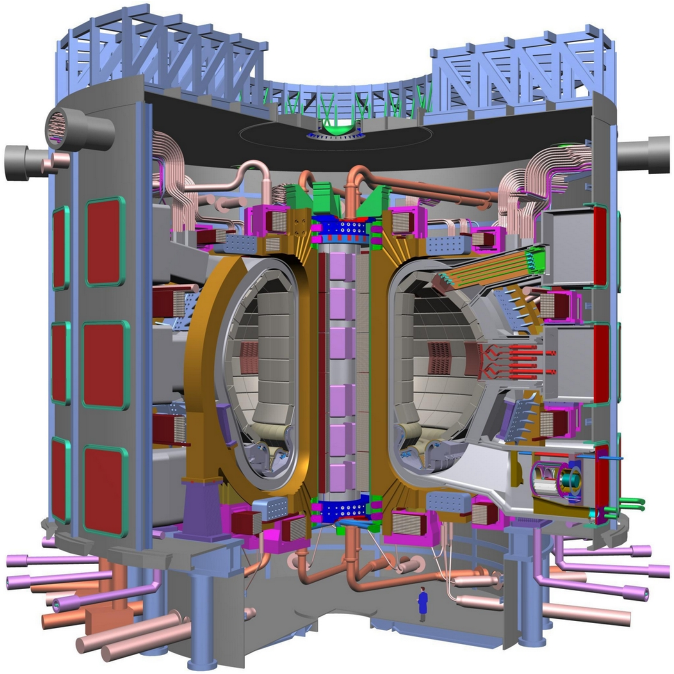


Stars have the big advantage of large mass and radius:

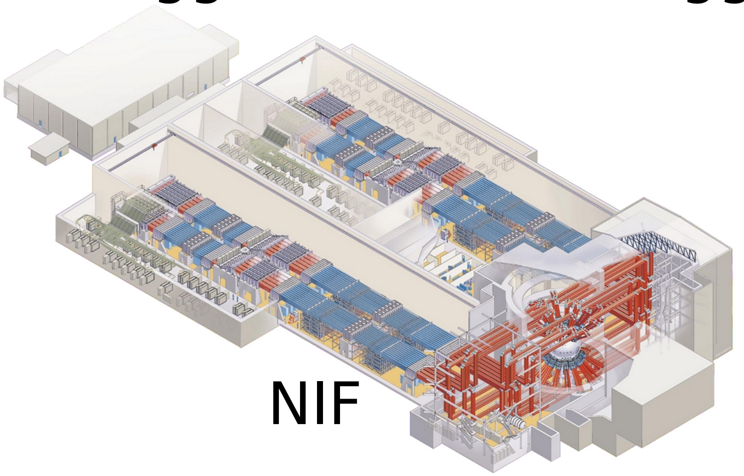
- burning plasma is confined by gravity (the star will collapse when fuel is over)

- radiation from the hot plasma is re-absorbed: cooling occurs only via the surface

While these conditions cannot be reached on Earth, to chase fusion man has created the largest machines of their kind
(biggest tokamak, biggest laser)



ITER



NIF

Plasma Instabilities

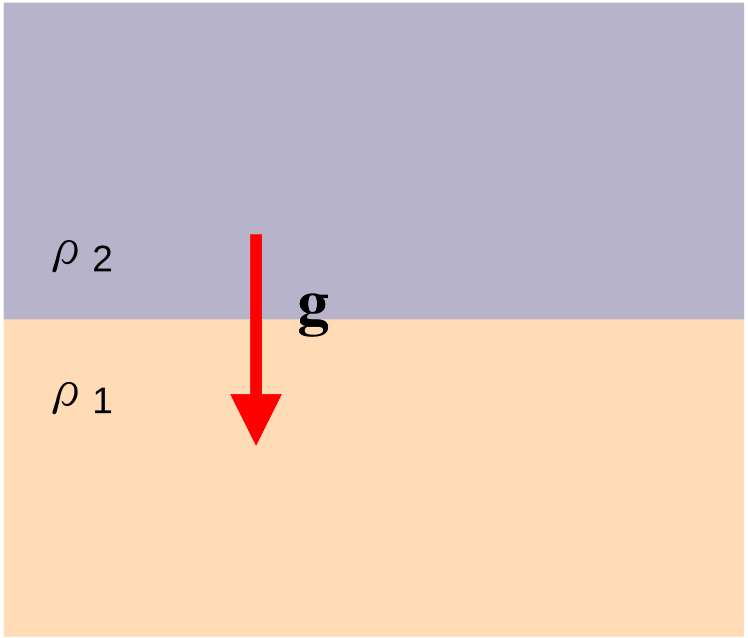
List of plasma instabilities [edit]

- Buneman instability,[3]
  - Farley–Buneman instability,[4][5]
  - Jeans–Buneman instability,[6][7]
  - Relativistic Buneman instability,[8]
- Cherenkov instability,[9]
- Coalescence instability,[10]
  - Non-linear coalescence instability
- Chute instability,
- Collapse instability,
- Cyclotron instabilities, including:
  - Alfven cyclotron instability
  - Cyclotron maser instability,[11]
  - Electron cyclotron instability
  - Electrostatic ion cyclotron Instability
  - Ion cyclotron instability
  - Magnetoacoustic cyclotron instability
  - Proton cyclotron instability
  - Non-resonant beam-type cyclotron instability
  - Relativistic ion cyclotron instability
  - Whistler cyclotron instability
- Diocotron instability,[12] (similar to the Kelvin-Helmholtz fluid instability).
- Disruptive instability (in tokamaks)[13]
- Double emission instability,
  - Edge-localized modes,[14][15]
  - Explosive instability (or Ballooning instability),[16]
- Double plasma resonance instability,[17]
- Drift instability[18] (a.k.a. drift-wave instability,[19] or universal instability[20])
  - Lower hybrid (drift) instability (in the Critical ionization velocity mechanism)
  - Magnetic drift instability,[21]
  - Slow Drift Instability
- Electrothermal instability
- Fan instability,[22]
- Firehose instability (a.k.a. hose instability), not to be confused with the similarly named Firehose instability in galactic dynamics
- Fish instability,
- Free electron maser instability,
- Gyrotron instability,
- Helical (Helix) instability,
- Jeans instability,[23][24]
- Magnetic buoyancy instability
  - Interchange instability (a.k.a. flute instability),[25]
  - Parker instability[26] (a.k.a. undular instability or magnetic Rayleigh–Taylor instability)
  - Mixed instability (a.k.a. quasi-interchange instability)
- Magnetorotational instability (in accretion disks)
- Magnetothermal instability (Laser-plasmas),[27]
- Modulational instability
- Non-Abelian instability,
- Pair instability (in supernovae)
- Peratt instability (stacked toroids)
- Pinch instability (a.k.a. Bennett pinch instability),[28][29]
  - Sausage instability (m=0)
  - Kink instability (m=1)
    - Helical kink instability (a.k.a. helical instability)
- Rayleigh–Taylor instability (RTI, a.k.a. gravitational instability)
- Rotating instability,[30]
- Tearing mode instability (or resistive tearing instability[31])
- Two-stream instability (a.k.a. beam-plasma instability, counter-streaming instability)
  - Beam acoustic instability
  - Bump-on-tail instability
  - Ion beam instability
  - Weak beam instability
- Weibel instability
  - Chromo–Weibel instability (i.e. non-abelian instability)
  - Filamentation instability (a.k.a. beam-Weibel instability),[32]

en.wikipedia.org/wiki/Plasma_stability#List_of_plasma_instabilities

"Is plasma involved? It won't work" (E. Teller)

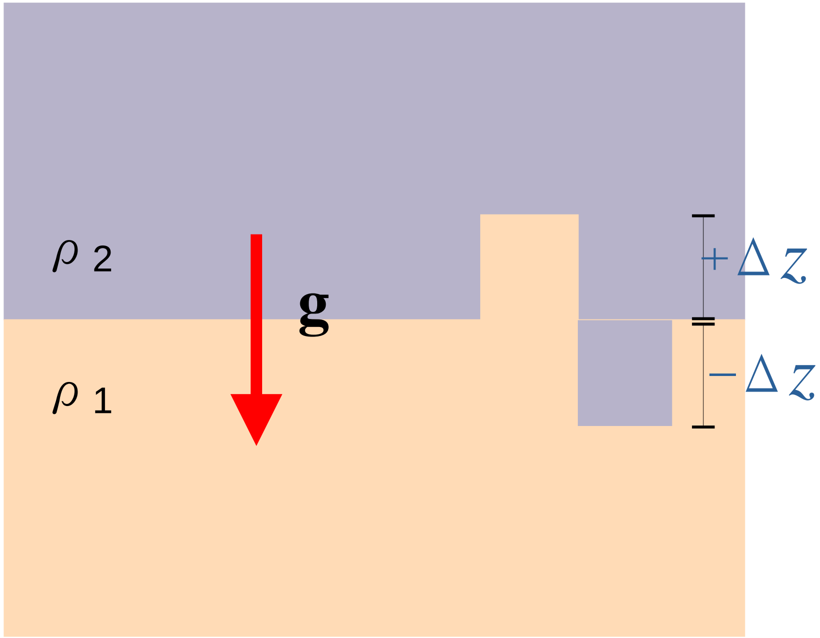
Rayleigh-Taylor Instability



Heavy fluid (2) over light fluid (1) in a gravity field $\mathbf{g}$

$$\rho_2 > \rho_1$$

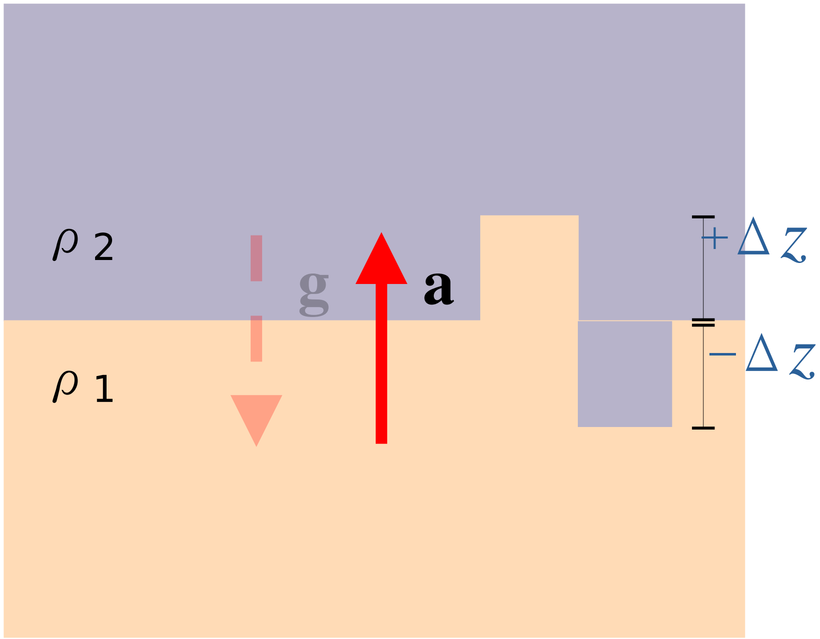
Rayleigh-Taylor Instability



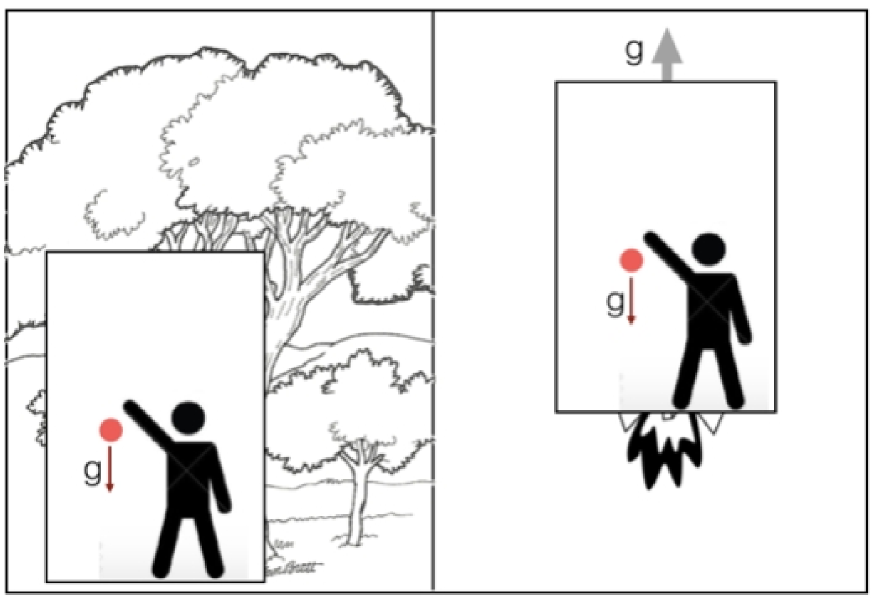
Heavy fluid (2) over light fluid (1) in a gravity field $\mathbf{g}$
The "exchange" of two fluid elements decreases the energy of the system, which is unstable

$$\Delta U \propto (\rho_1 - \rho_2) g \Delta z < 0$$

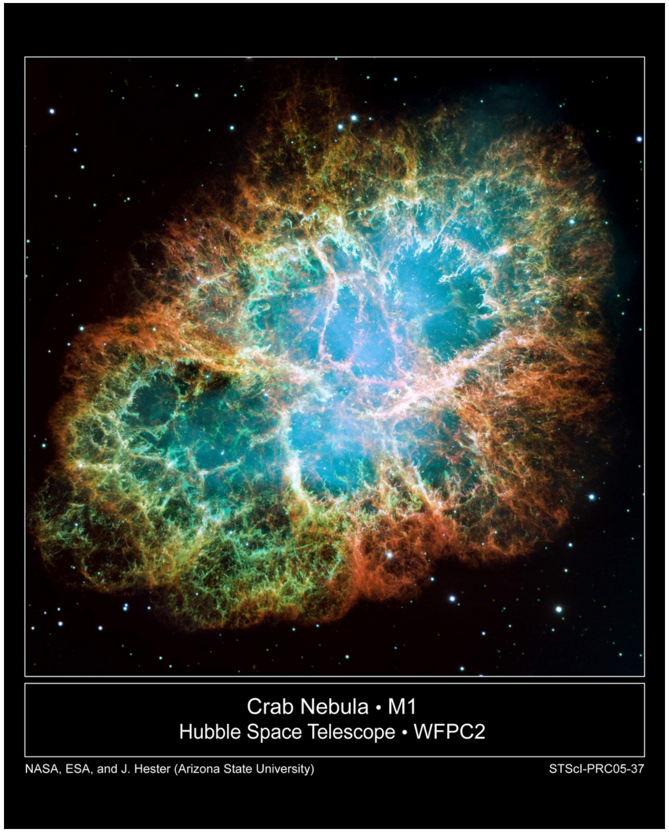
Rayleigh-Taylor Instability



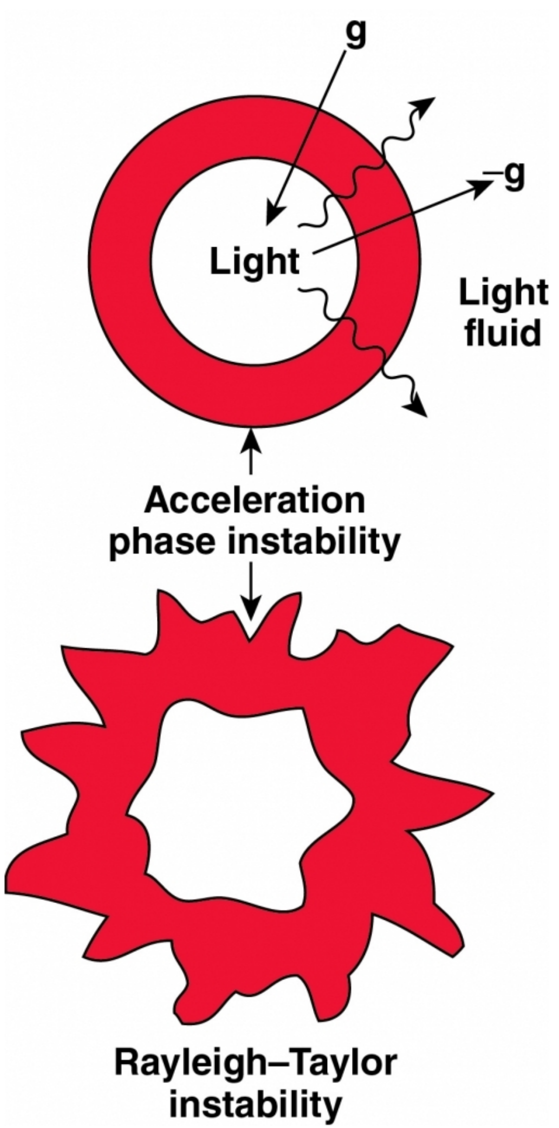
Because of the "Principle of Equivalence" the instability gwos also if there is an acceleration field $\mathbf{a}$ from the light fluid (1) towards the heavy fluid (2)

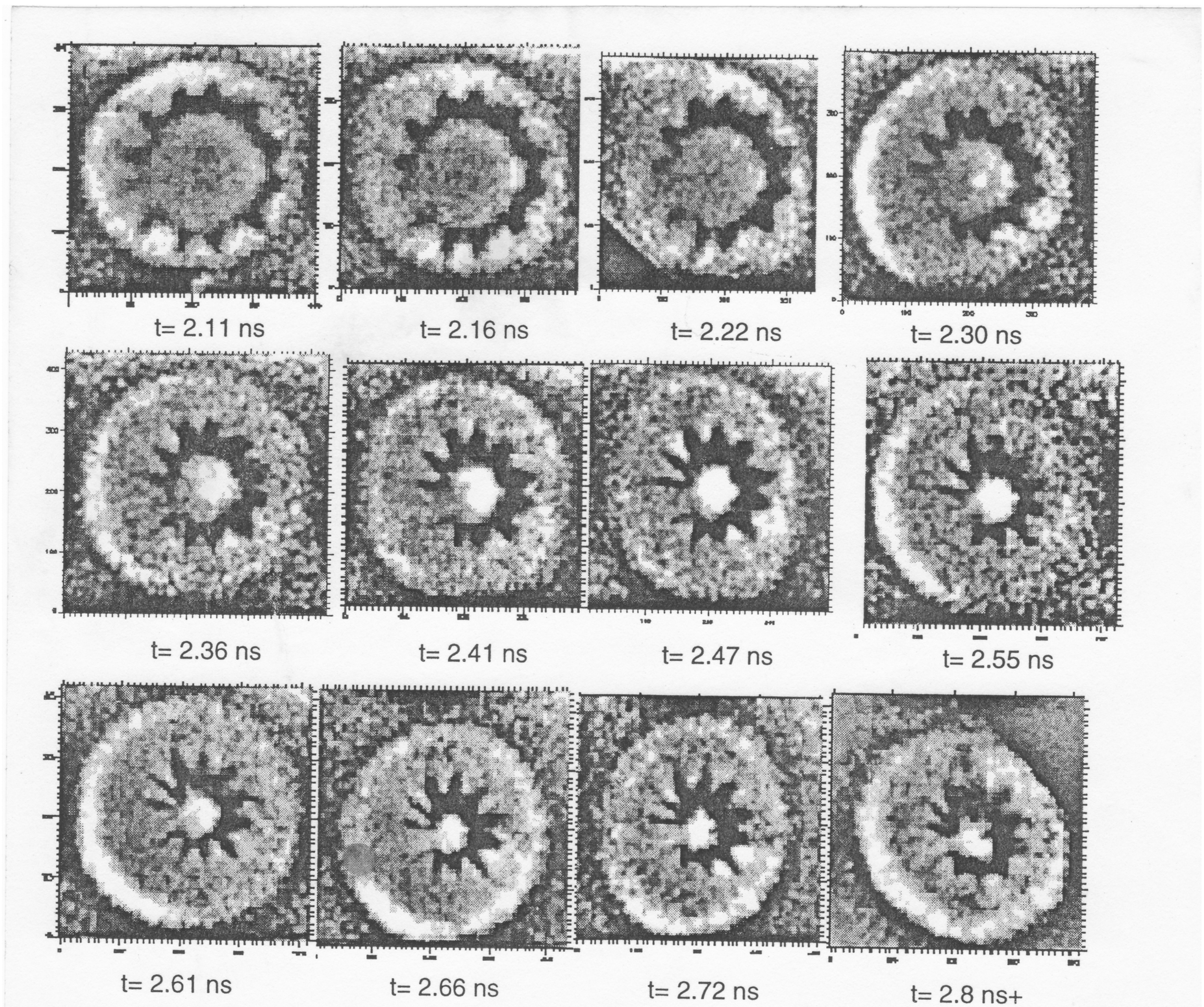


Francesca Ricci, "La Relatività Generale", www.matematicamente.it



RTI in ICF

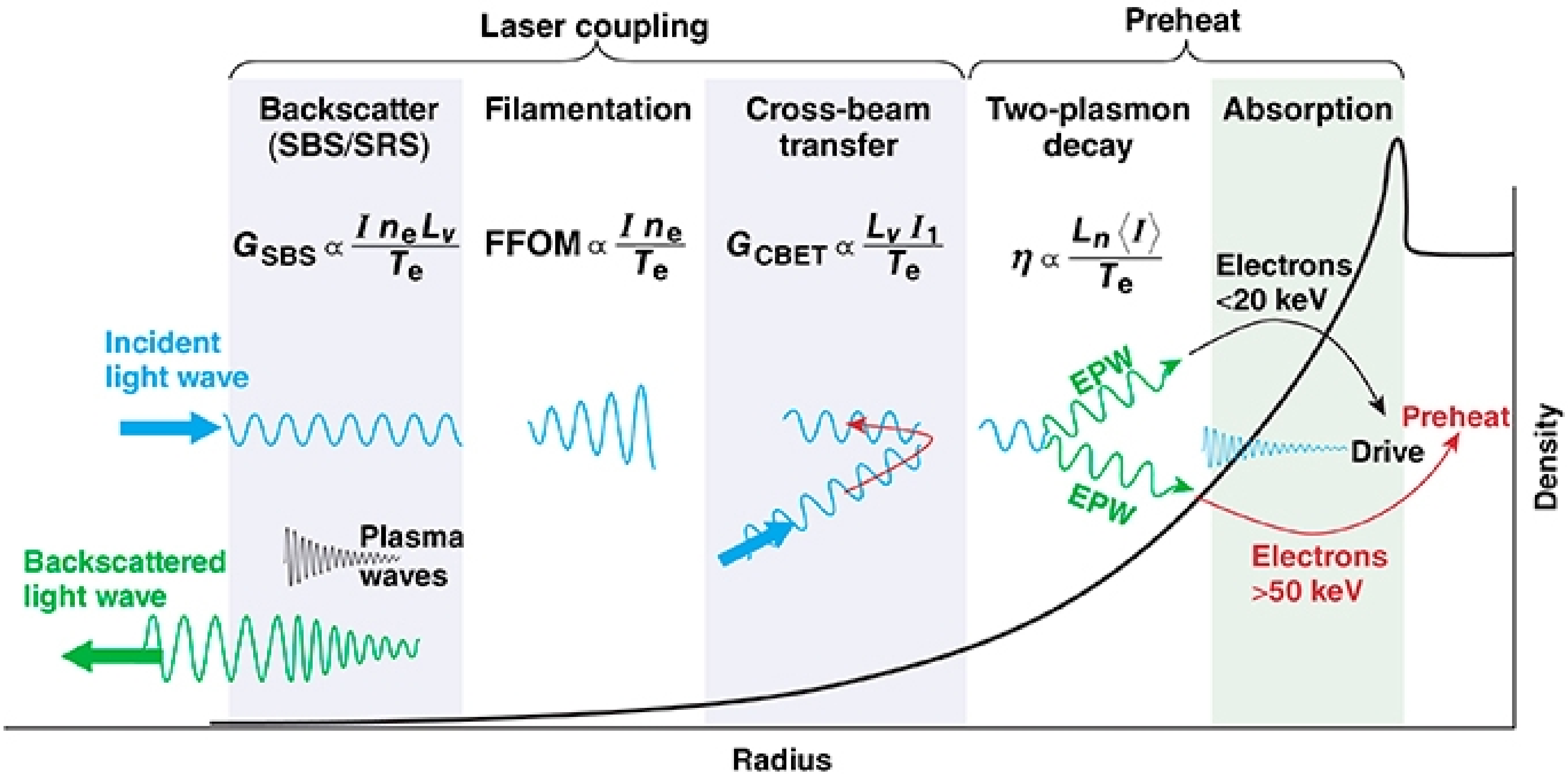




Cylindrical implosion at NOVA laser facility showing the Rayleigh-Taylor Instability

Hsing & Hoffman, Phys. Rev. Lett. **78** (1997) 3876

Laser-Plasma Interactions & Instabilities



Raman or Brillouin backscattering reduces coupling, filamentation and cross-beam transfer affect irradiation uniformity, two plasmon decay generate plasma waves which in turn accelerate unwanted “hot” electrons, ...

www.lle.rochester.edu/education/research-areas/plasma-ultrafast-science-engineering/inertial-confinement-fusion/

Direct Vs Indirect Drive

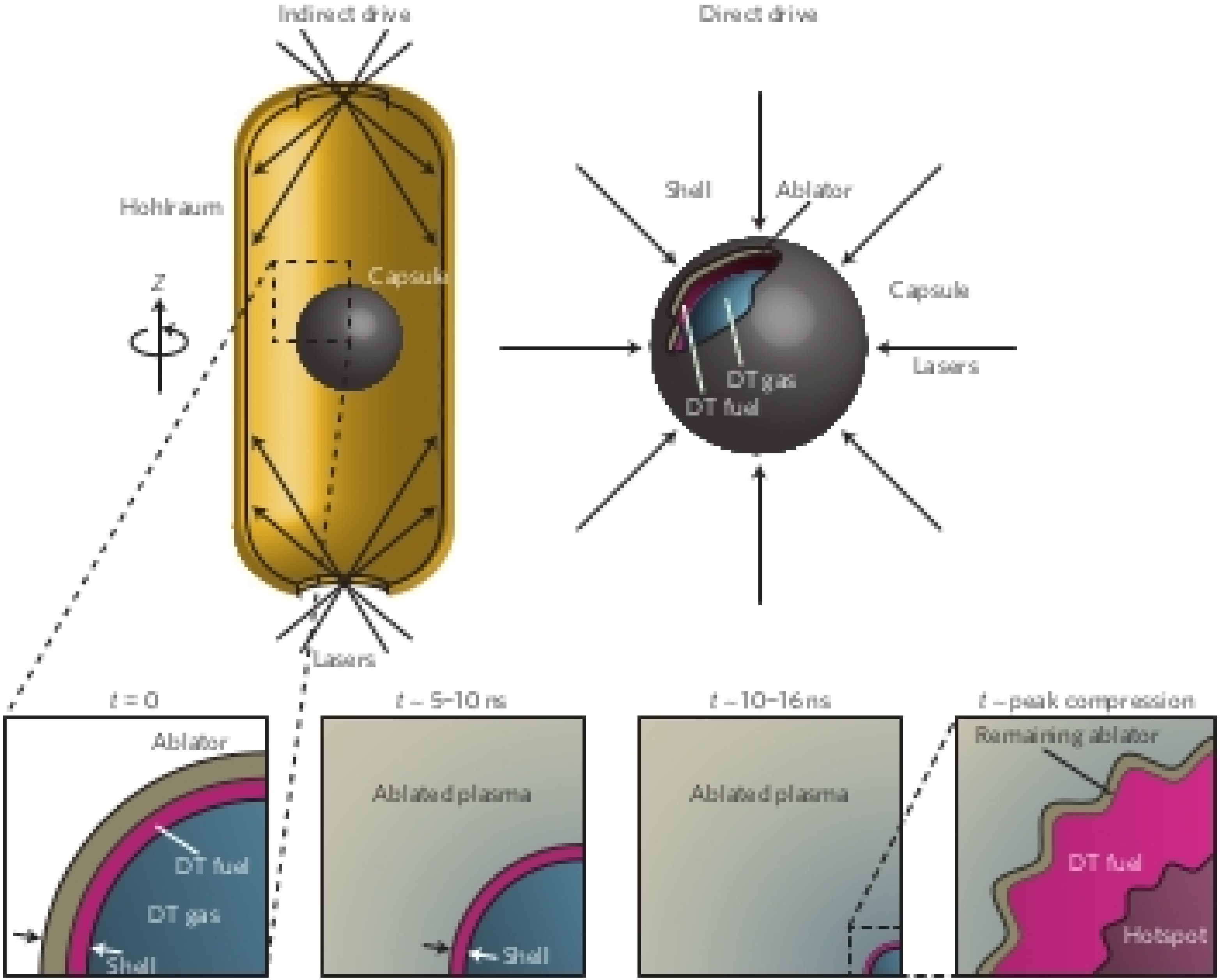


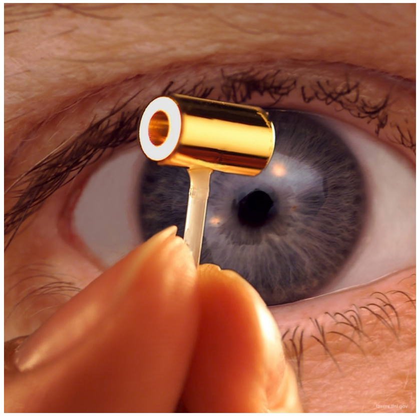
Figure from R.Betti & O.Hurricane, Nature Physics. **12** (2016) 435

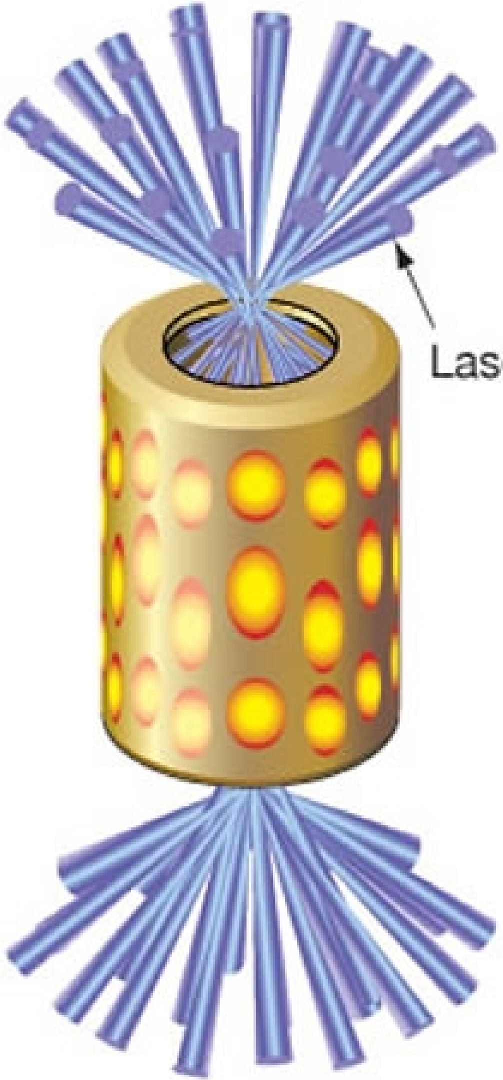
Pros & Cons of Indirect Drive

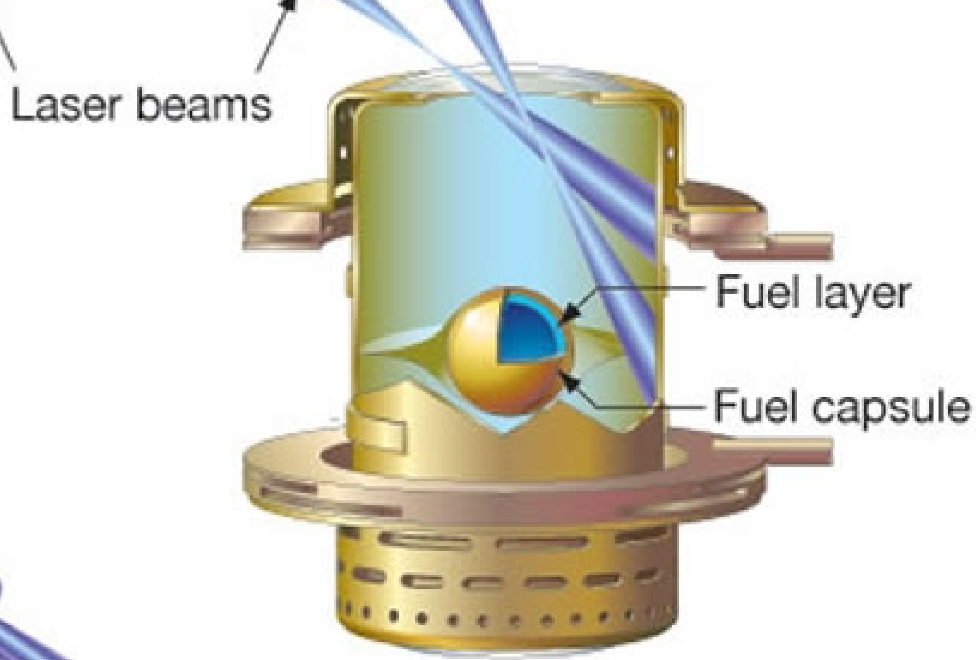
An X-ray "bath" is produced inside a gold cylinder (*Hohlraum*)

- isotropic radiation, more uniform heating
- penetration in deeper layers

- reduced laser-to-heating efficiency
- higher target complexity







Figures from lasers.llnl.gov/science/icf

2022: NIF Reaches Ignition*

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

Editors' Suggestion   Featured in Physics

Lawson Criterion for Ignition Exceeded in an Inertial Fusion Experiment

H. Abu-Shawareb *et al.*[*]
(Indirect Drive ICF Collaboration)

(Received 25 February 2022; revised 24 June 2022; accepted 6 July 2022; published 8 August 2022; corrected 16 August 2022)

For more than half a century, researchers around the world have been engaged in attempts to achieve fusion ignition as a proof of principle of various fusion concepts. Following the Lawson criterion, an ignited plasma is one where the fusion heating power is high enough to overcome all the physical processes that cool the fusion plasma, creating a positive thermodynamic feedback loop with rapidly increasing temperature. In inertially confined fusion, ignition is a state where the fusion plasma can begin "burn propagation" into surrounding cold fuel, enabling the possibility of high energy gain. While "scientific breakeven" (i.e., unity target gain) has not yet been achieved (here target gain is 0.72, 1.37 MJ of fusion for 1.92 MJ of laser energy), this Letter reports the first controlled fusion experiment, using laser indirect drive, on the National Ignition Facility to produce capsule gain (here 5.8) and reach ignition by nine different formulations of the Lawson criterion.

*whatever it means in ICF

2022: NIF Reaches Breakeven

PHYSICAL REVIEW LETTERS **132**, 065102 (2024)

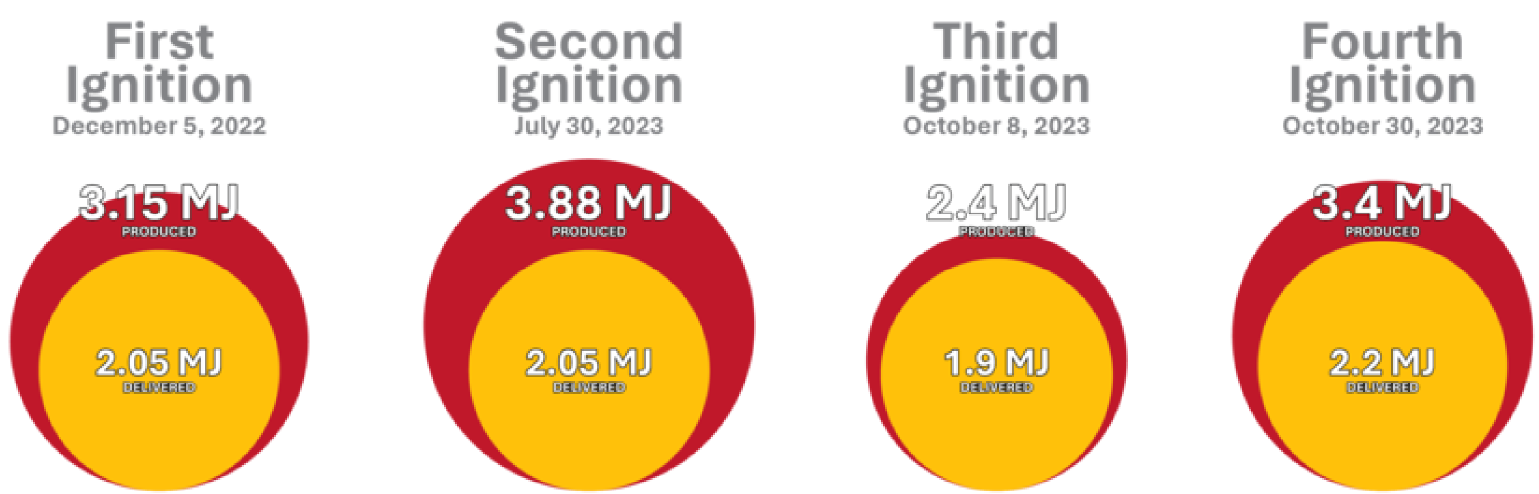
Editors' Suggestion   Featured in Physics

Achievement of Target Gain Larger than Unity in an Inertial Fusion Experiment

H. Abu-Shawareb *et al.*[*]
(The Indirect Drive ICF Collaboration)

(Received 27 October 2023; accepted 3 January 2024; published 5 February 2024)

On December 5, 2022, an indirect drive fusion implosion on the National Ignition Facility (NIF) achieved a target gain G_{target} of 1.5. This is the first laboratory demonstration of exceeding "scientific breakeven" (or $G_{\mathrm{target}} > 1$) where 2.05 MJ of 351 nm laser light produced 3.1 MJ of total fusion yield, a result which significantly exceeds the Lawson criterion for fusion ignition as reported in a previous NIF implosion [H. Abu-Shawareb *et al.* (Indirect Drive ICF Collaboration), Phys. Rev. Lett. **129**, 075001 (2022)]. This achievement is the culmination of more than five decades of research and gives proof that laboratory fusion, based on fundamental physics principles, is possible. This Letter reports on the target, laser, design, and experimental advancements that led to this result.



December 2022

Lawrence Livermore National Laboratory
@Livermore_Lab · **Segui**

BREAKING NEWS: @ENERGY and @NNSAnews today announced the achievement of #FusionIgnition at @lasers_llnl — a major scientific breakthrough decades in the making that will pave the way for advancements in national security and clean energy: llnl.gov/news/national-...

4:38 PM · 13 dic 2022

December 2022

Can Fusion Solve the Climate Crisis?

Scientists made a huge breakthrough on the road to emissions-free power. Here's what that means, and doesn't mean.

Forbes

BREAKING • INNOVATION

Here's How Nuclear Fusion Works—And Why It's A Big Deal For Scientists

The New York Times

SCIENCE

Fusion Industry Suddenly White-Hot After U.S. Lab Breakthrough

With commercialization years away, investors flock to technology's long-term clean-energy potential

ENERGY

What to know about DOE's fusion milestone

Experiments at a U.S. government lab may have provided "proof that the physics work." But future fusion reactors might turn to a different technology for replicating the energy that powers the sun.

THE WALL STREET JOURNAL.

REUTERS®

POLITICO

CNBC

U.S. to reveal scientific milestone on fusion energy

Scientists announce a fusion breakthrough with big implications for clean energy

CLEAN ENERGY

Nuclear fusion breakthrough: Scientists generate more power than used to create reaction

What to know about DOE's fusion 'breakthrough'

E&E NEWS | ENERGYWIRE

source: www.fusionindustryassociation.org

Glory on Linkedin ...

Andrea Macchi • You
Research Scientist, CNR/INO; -Lecturer...
1yr •

By reading this press release, we find that the result obtained at the National Ignition Facility (NIF) has yet to be confirmed: however, rumors of "2.5 megajoules in neutron energy from 2.1 megajoules of laser energy" have been circulating in the community since a few days. So this is a breakthrough, although not unexpected since NIF had already announced ignition a few months ago and the results were published after peer review in Physical Review Letters and other APS journals. At that time, however, there were doubts on the reproducibility of the process and a net gain of energy was not apparent. For non-specialists it is worth reminding that the gain is measured as the ratio of fusion energy over the laser energy on target: since the efficiency of the laser to convert electrical power into light is rather low, the "commercial" efficiency is rather low (presumably of the order of 1%). Future research will have to improve the laser efficiency and repetition rate (it is roughly estimated that more than a shot per second would be needed in a commercial power plant; at present NIF fires a shot per day, at the cost of one million dollars per shot) and the energy gain: it has been estimated that only a few per cent of the fuel has been burnt, and the aim in the long term is to have a 10000% gain or even more. These are formidable challenges for which no evident solution is apparent at present and which suggest that in the long term the Inertial Confinement Confusion (ICF) approach may be less suitable for sustainable energy

production than the Magnetic Confinement; the latter, however, is still far from ignition and net gain. In the mid term NIF and ICF experiments could help to test how to manage the neutron flux, i.e. converting neutron energy in heat and electricity and developing materials able to bear the high neutron flux. Ultimately the NIF result, upon confirmation, would be a milestone in fusion research but the road to clean fusion energy remains long and difficult. It is also worth reminding that NIF's mission includes stockpile stewardship (presumably it might allow nuclear tests in the laboratory avoiding surface ones) but its political and military impact is not clear at present.

Martijn Rasser • 2nd
CRO and Managing Director, Datenna
1yr •

Huge, huge, huge development in the quest for the ultimate energy source. **U.S. Department of Energy (DOE)** Secretary **Jennifer Granholm** and Under Secretary Jill Hruby will announce "a major scientific breakthrough" on Tuesday.

"US government scientists have made a breakthrough in the pursuit of limitless, zero-carbon power by achieving a net energy gain in a fusion reaction for the first time, according to three people with knowledge of preliminary results from a recent experiment.

Physicists have since the 1950s sought to harness the fusion reaction that powers the sun, but no group had been able to produce more energy from the reaction than it consumes — a milestone known

La svolta Usa sulla fusione nucleare

Share

By Vittoria Vimercati, Editor at LinkedIn News

Updated 1 year ago

Il Dipartimento di Energia degli Stati Uniti ha annunciato un risultato storico nella **fusione nucleare**: per la prima volta, gli scienziati americani hanno prodotto più energia da una fusione rispetto all'energia utilizzata per alimentare l'esperimento.

Il "guadagno netto di energia" è considerato una **pietra miliare** nel tentativo portato avanti da decenni di ottenere energia illimitata dalla fusione nucleare, la reazione che si verifica quando due o più atomi vengono fusi insieme.

Gli esperimenti, **che potrebbero cambiare il futuro dell'energia pulita**, sono stati condotti dal Lawrence Livermore National Laboratory.

Andrea Macchi • You
Research Scientist, CNR/INO; -Lecturer, Ph...
1yr • Edited •

[Sorry, Italian only] Qualche elemento in più per capire meglio (molto in breve). L'esperimento di cui si parla è stato realizzato presso la National Ignition Facility, dove si usa un mega-laser per far implodere una sferetta di Deuterio-

NIF and Stockpile Stewardship

“NIF is the only facility that can create the conditiions that are relevant to udnerstanding of moden nuclear weapons [...]

Understanding how materials used behave as they age under the extreme environments produced in a thermonuclear reaction is a key element of stockpile stewardship”

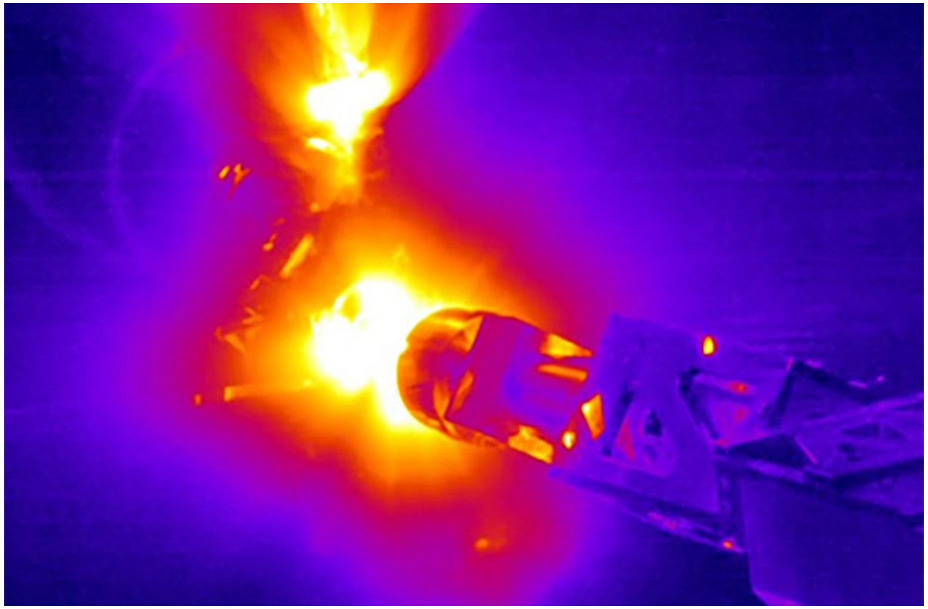
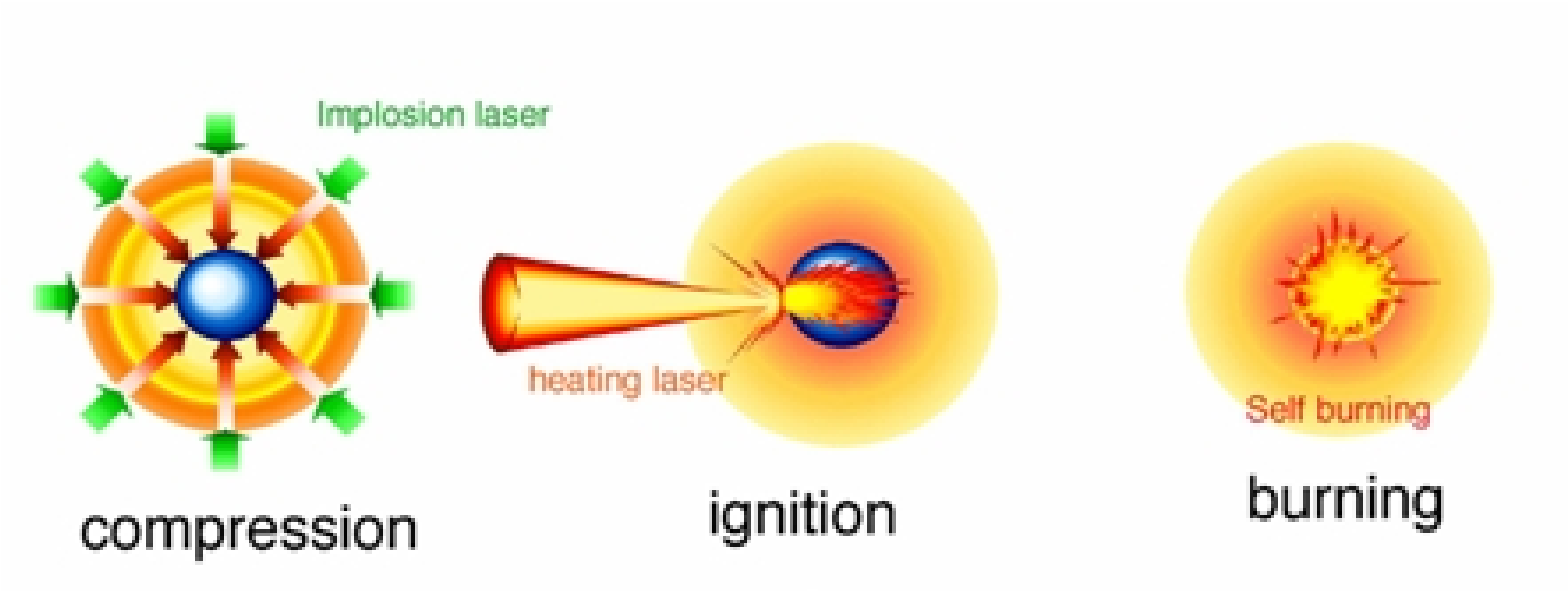


Image of a NIF experiment at the moment of peak implosion. This experiment was aimed at developing a high-pressure strength measurement capability for plutonium.

lasers.llnl.gov/science/nif-and-stockpile-stewardship
lasers.llnl.gov/science/stockpile-stewardship

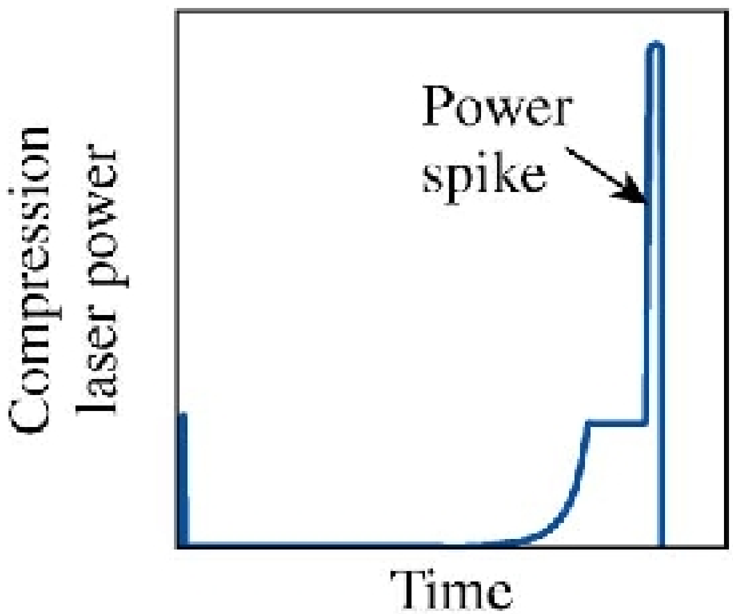
Alternate Approaches: Fast Ignition



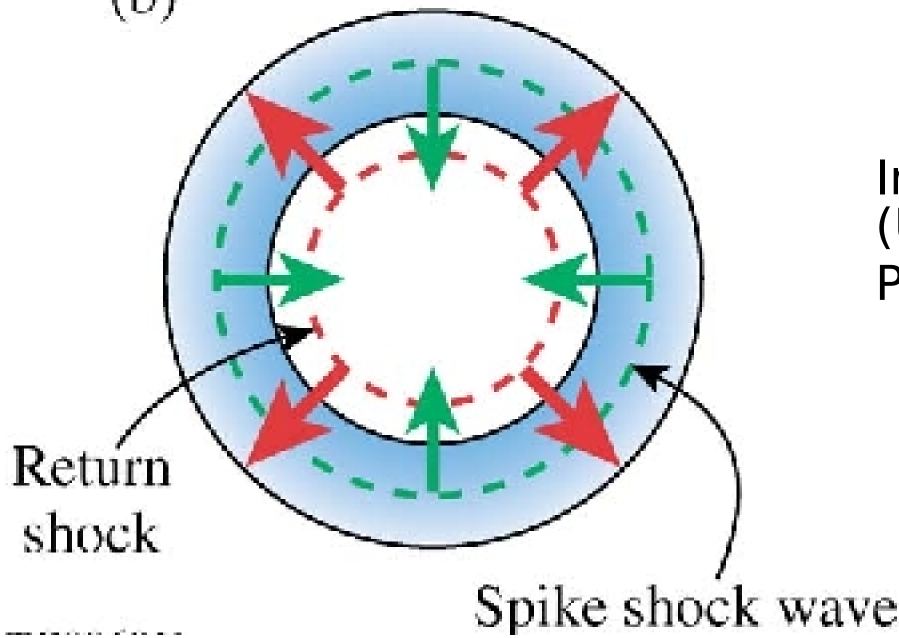
Compression is separated from ignition: a picosecond duration, petawatt power beam (either a laser pulse interaction directly with the fuel or a laser-driven proton beam externally generated) creates a “spark” to ignite the fuel and start burn in isochoric conditions

Image credit: Los Alamos National Laboratory
https://www.lanl.gov/projects/dense-plasma-theory/background/dense-laboratory-plasmas.php

Alternate Approaches: Shock Ignition



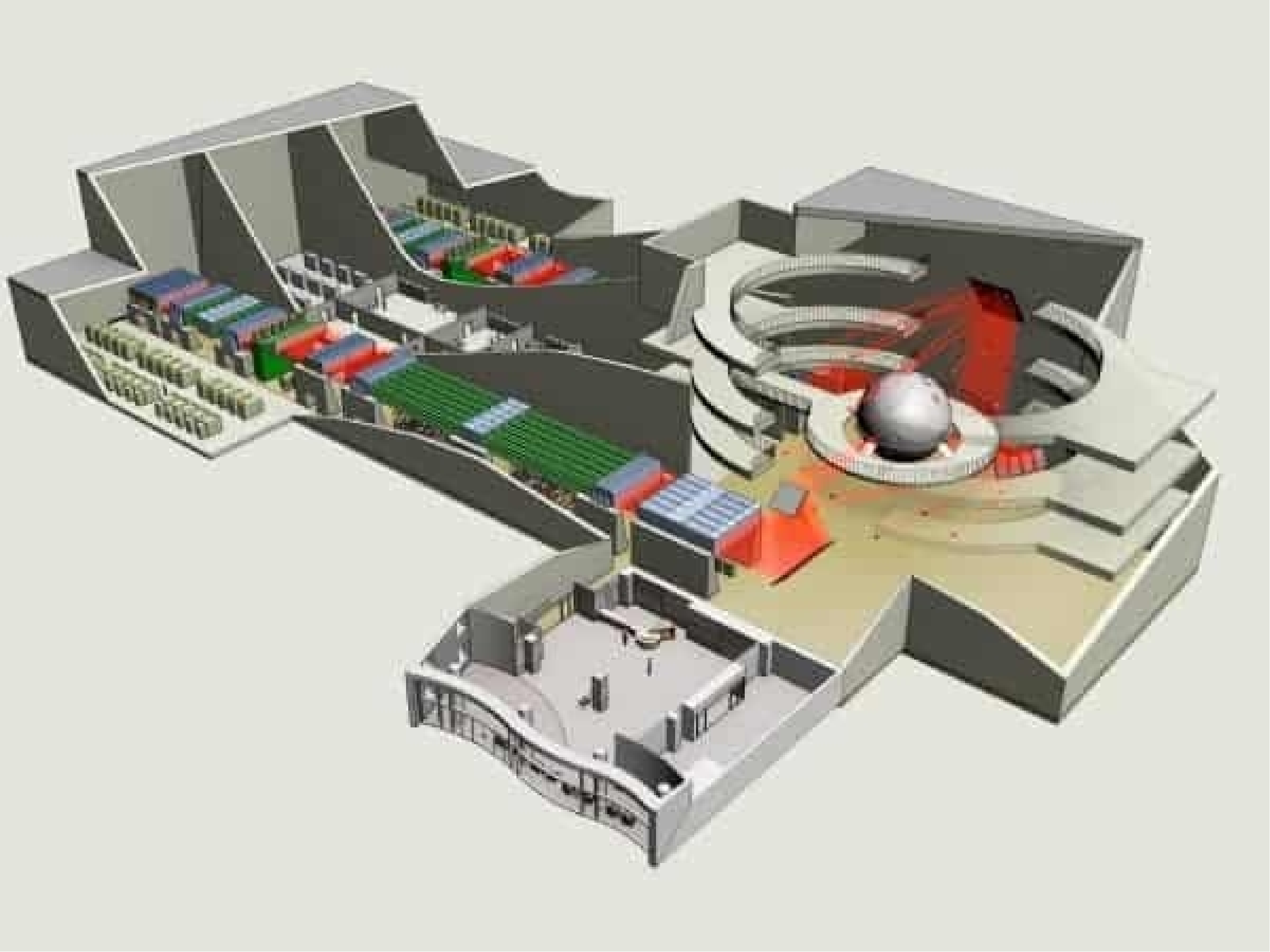
(b)



A laser pulse with a high power spike generates a strong converging shock wave which collides with the return shock; appropriate timing produces high compression in the central region (hot spot)

Image credit: R.Betti
(Univ. Rochester &
Princeton Plasma Physics Laboratory)

HIPER: an EU ICF Project



High Power Energy Research facilty: proposed in early 2000’s (as a fast/shock ignition facility), frozen in the late 2010’s, reboosted after 2022.

Open Challenges for ICF towards IFE

Specific:

- improve single implosion performance towards higher gain

- improve efficiency also thinking out of indirect drive (direct drive? shock ignition?)

- develop high power lasers with (much) higher efficiency and repetition rate

Common to magnetic fusion:

- develop the Tritium breeding (neutrons on Lithium blanket) cycle

- test materials in power plant conditions (synergy?)