Inertial Fusion Physics

Ryan McClarren - University of Notre Dame
ICTP - IAE School on AI for Nuclear, Plasma, and Fusion Science
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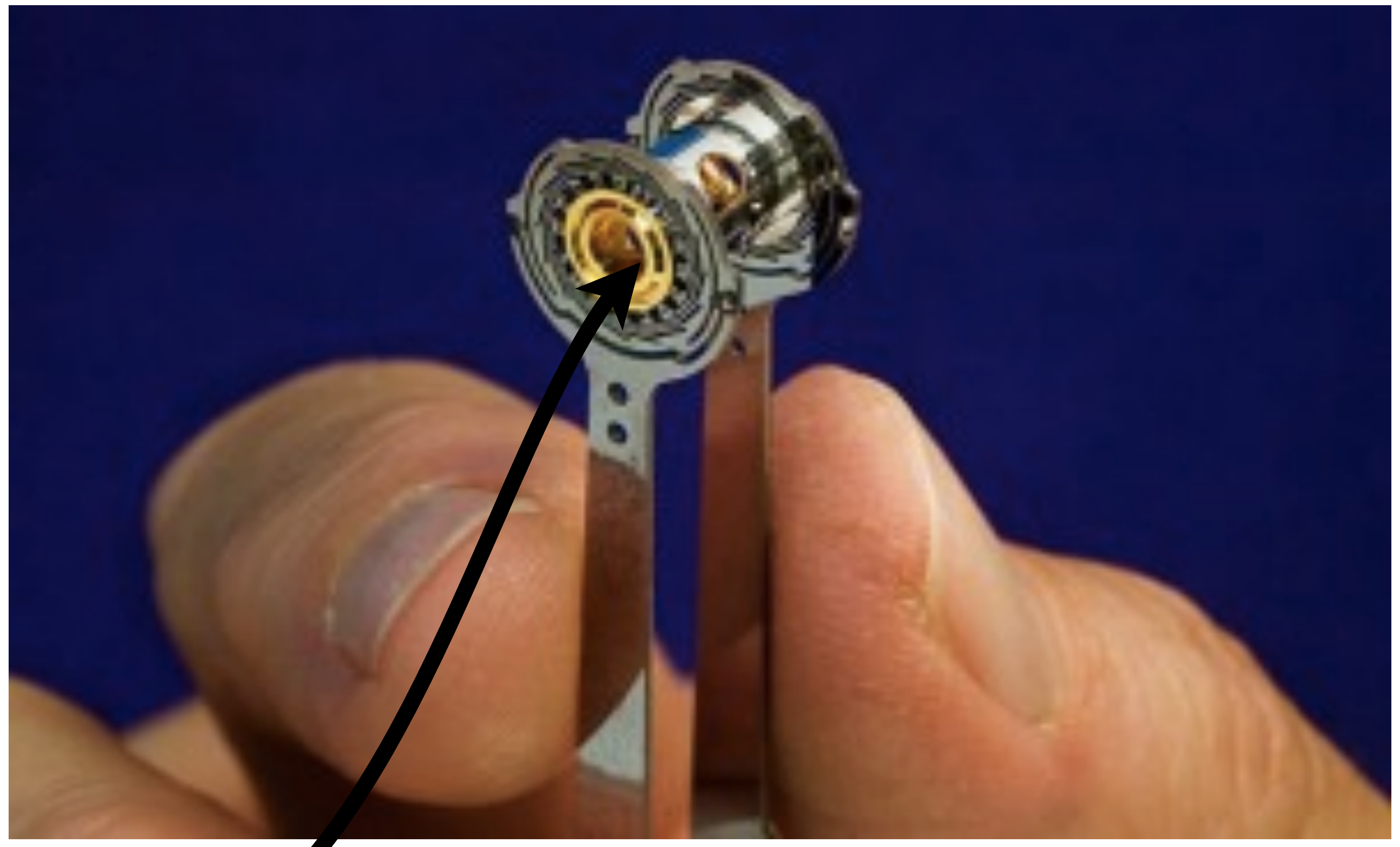
Inertial Confinement fusion attempts to create a sustained, controlled nuclear fusion reaction in the laboratory.

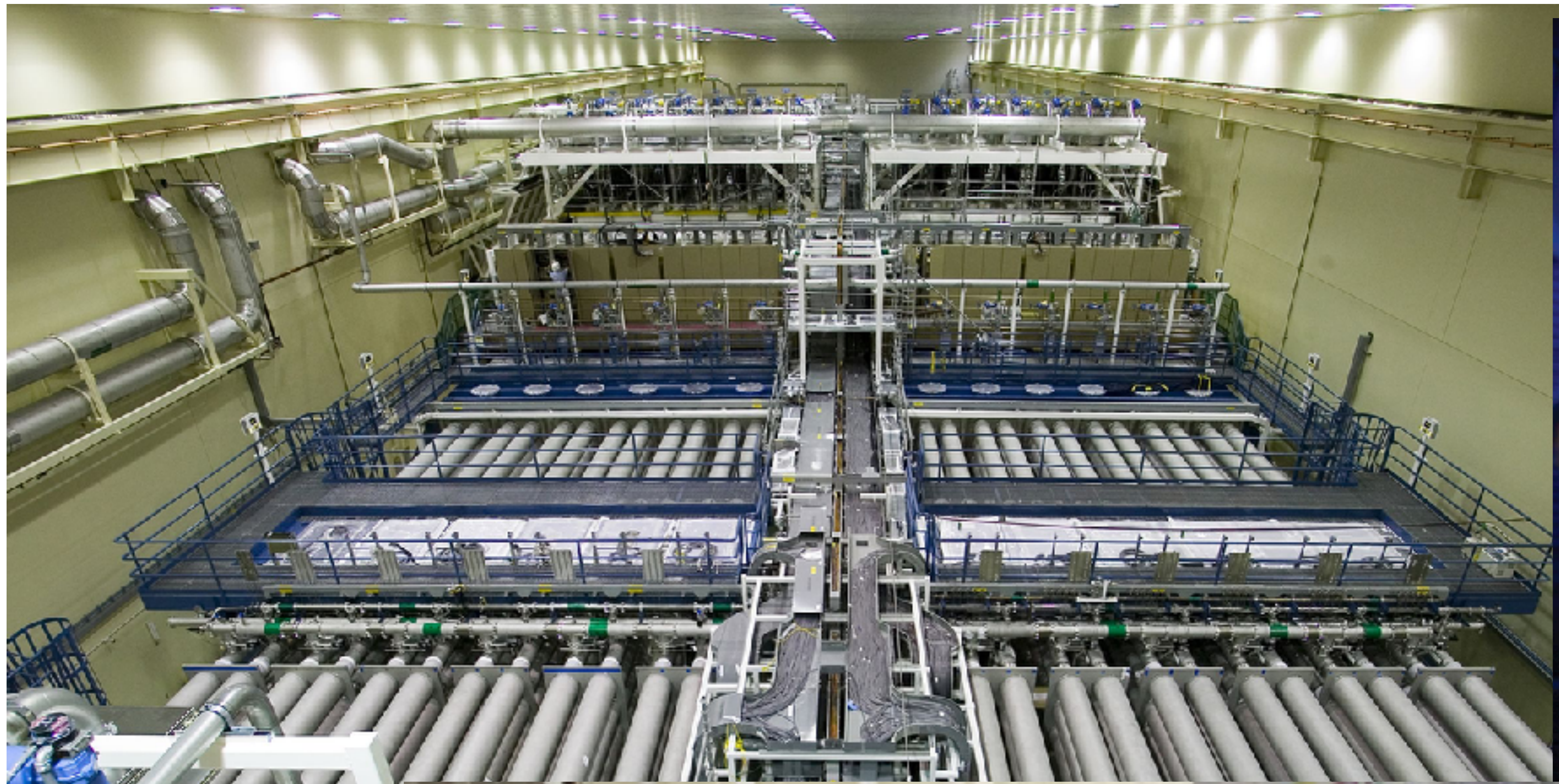
- What can we do if we take the energy (~2MJ) from a laser this size

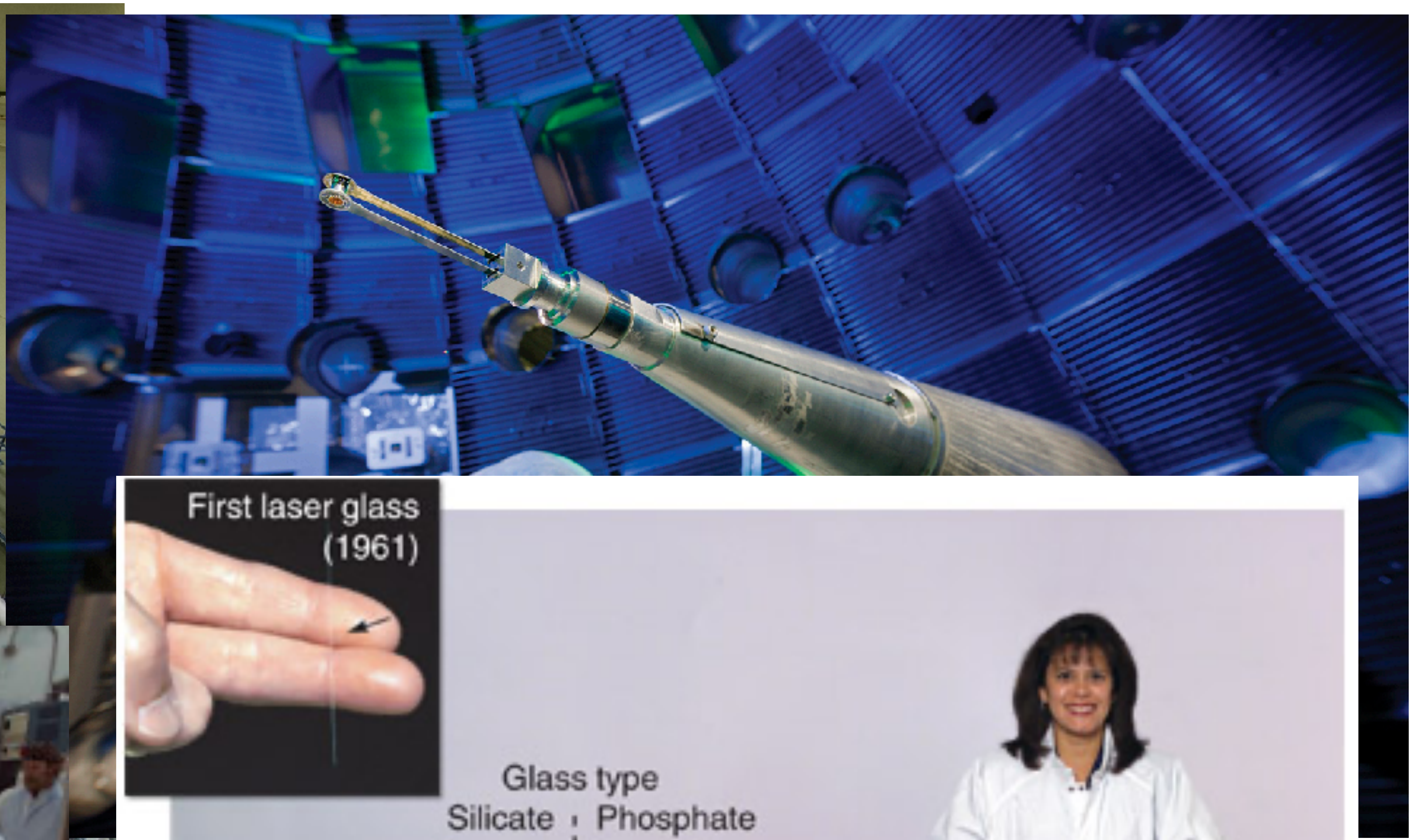


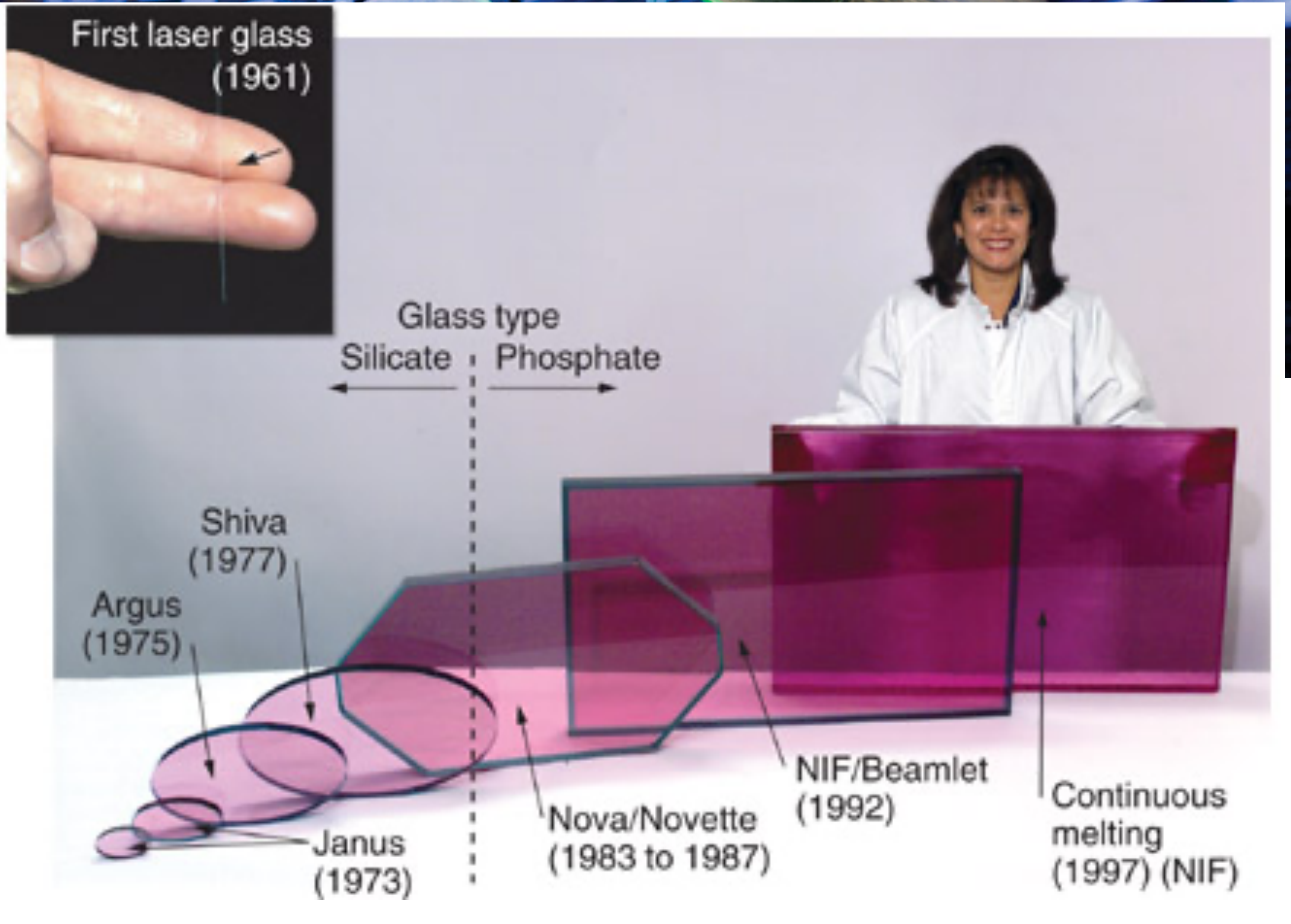
And focus it here in 20 ns.

Image credits: atomicinsights.com and wired.com

1 MJ ~ 1 stick of dynamite
20 ns is about 10,000 times faster than it takes that dynamite to detonate.

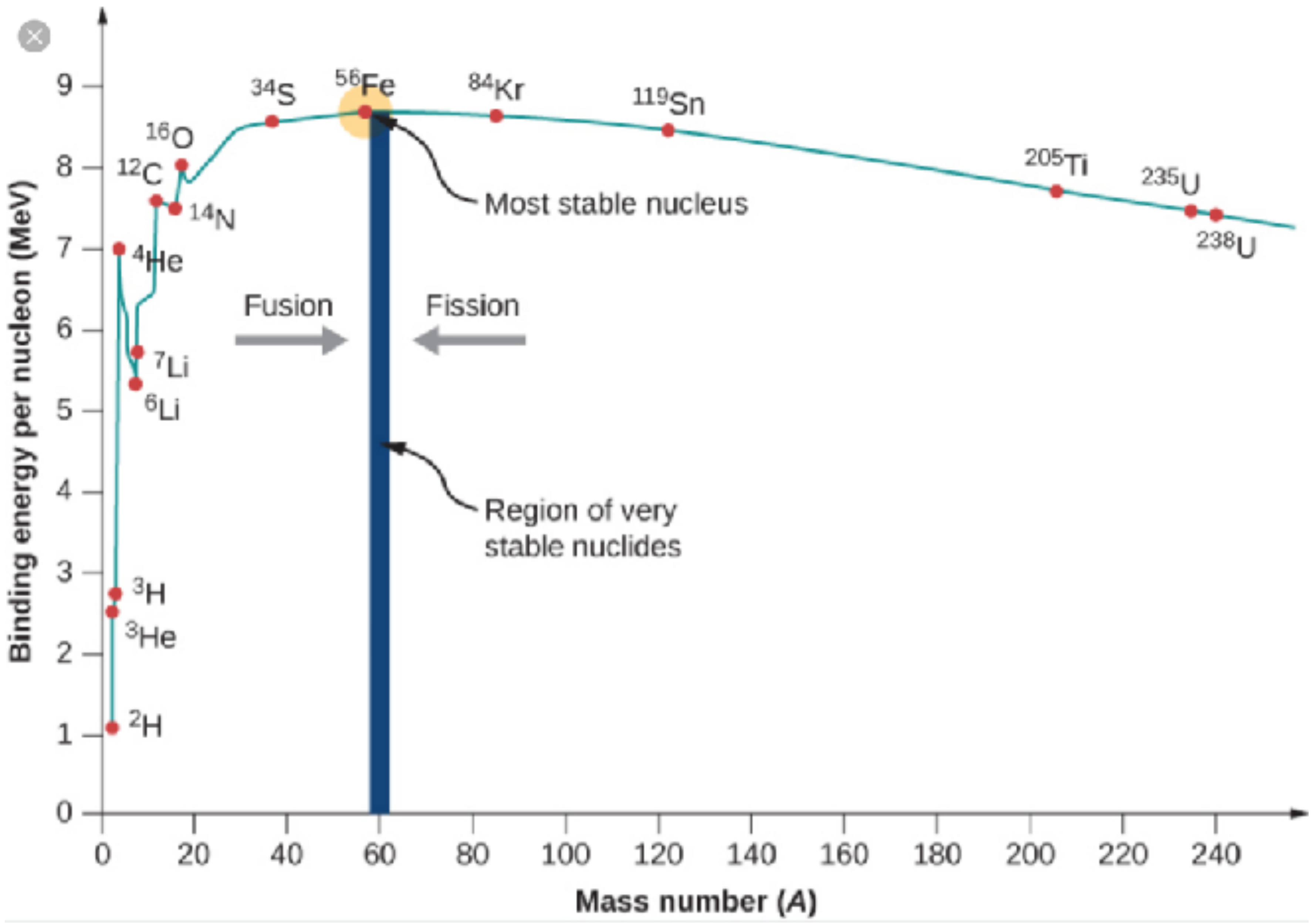


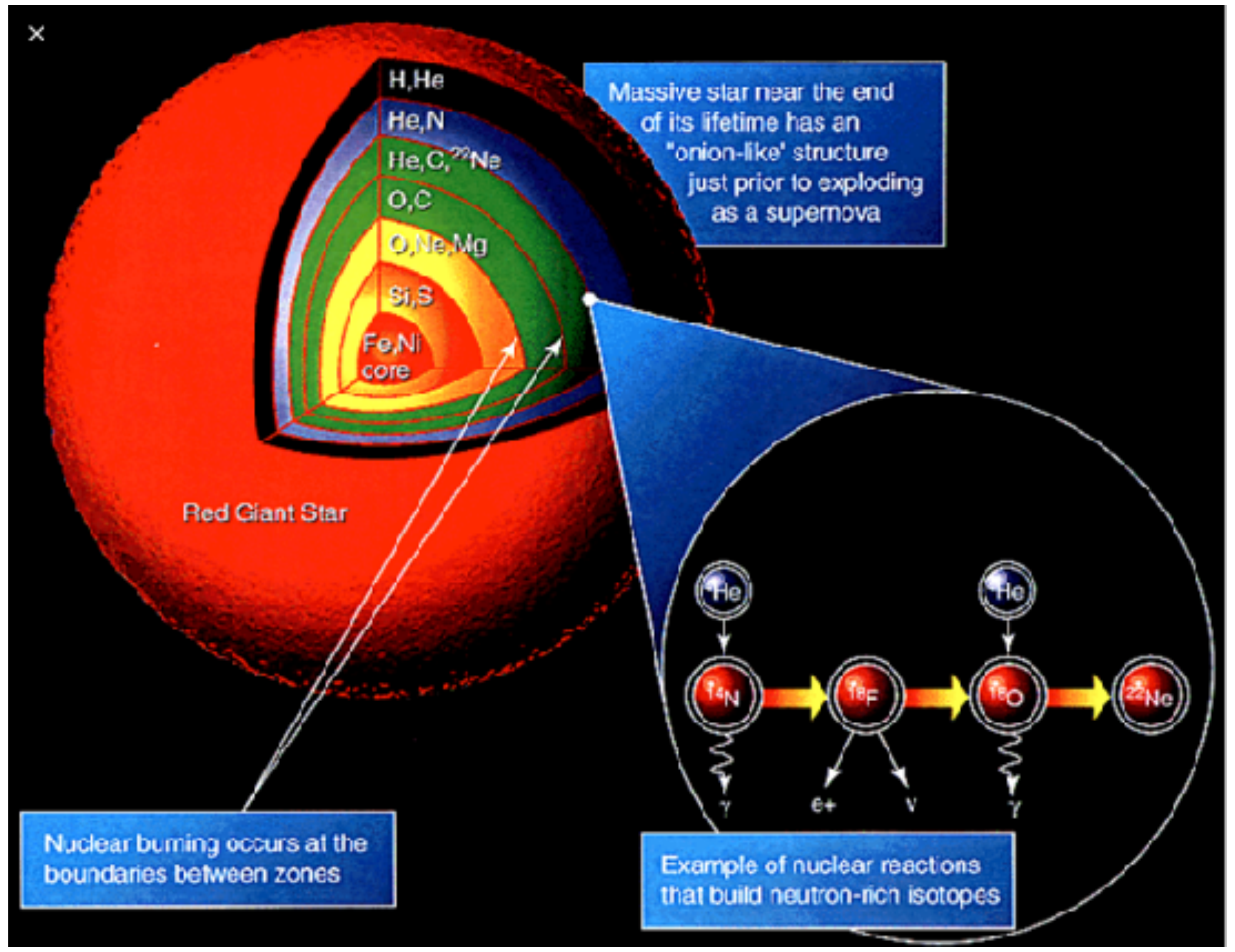



First laser glass
(1961)
Glass type
Silicate
Phosphate
Shiva
(1977)
Argus
(1975)
Janus
(1973)
Nova/Novette
(1983 to 1987)
NIF/Beamlet
(1992)
Continuous
melting
(1997) (NIF)

Exothermic Fusion Reactions

- Combining light nuclei goes up the binding energy per nucleon curve
  - This implies that if I fuse hydrogen isotopes together I can release a lot of energy
    - Even more on a per nucleon basis than fission
  - Notice that helium-4 (an alpha particle) has an anomalously high binding energy per nucleon
- Iron-56 is a special point: once you get beyond this energy is required to make larger nuclei. These endothermic reactions cause stars to die.
  - Once the the star cannot make fusion energy it begins to collapse on itself.
  - Most of the very heavy elements are formed in supernovae explosions
- The probability for fusion between simple hydrogen (^1H), is too small for non-stellar fusion.
  - We have to use the deuterium (^2D) and tritium (^3H) isotopes of hydrogen.
    - ^2D exists naturally on earth in 1/6500 hydrogen nuclei. There is 10^{14} tons of deuterium in the ocean.
    - ^3T is rare and radioactive, but it can be readily produced, as we will see.

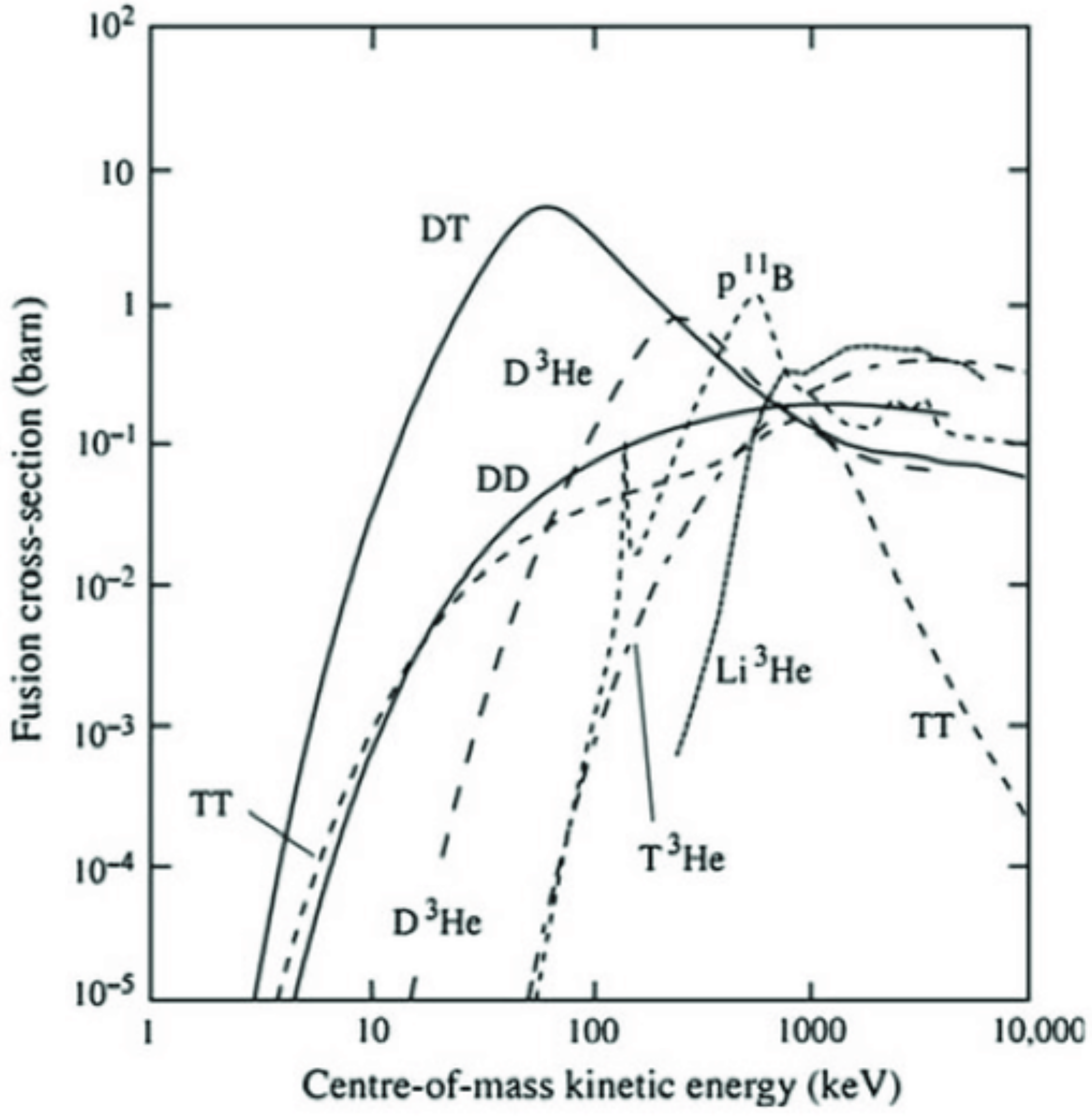




Conditions for Nuclear Fusion

- It has already been discussed that nuclear fusion is the joining of two nuclei to form a heavier nucleus (and other products).
  - The reaction that occurs most readily is between deuterium (^{2}H) and tritium (^{3}H).
  - This reaction also produces over 17.5 MeV, most of it carried by a 14.1 MeV neutron.
- The energy scale here is quite large, 1 keV = 1.1605 x 10^7 K.
- Nuclei at these temperatures are far too hot for any vessel to contain the plasma.
  - Magnetic confinement fusion uses magnetic fields to hold the plasma in place.
- In this lecture I will talk about a different approach to assemble the fuel into the correct configuration for fusion to occur.

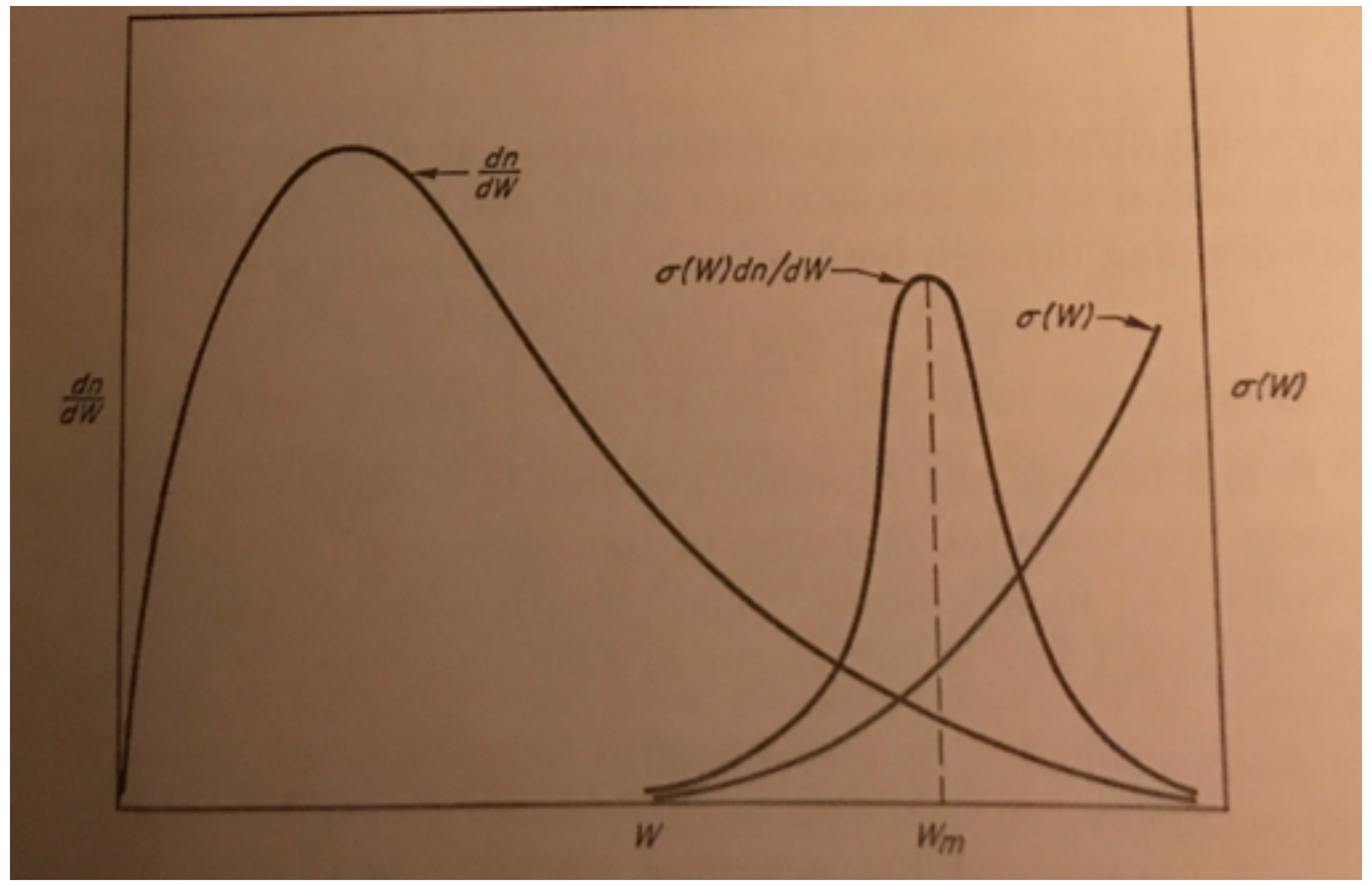
	Thermonuclear Fusion Reaction	**Probability**	**Q MeV**
1	${}^2_1D+{}^2_1D \rightarrow {}^3He + n$	50%	3.269
2	${}^2_1D+{}^2_1D \rightarrow {}^3_1T + p$	50%	4.033
3	${}^2_1D + {}^3_1T \rightarrow {}^4He + n$	100%	17.589
4	${}^2_1D + 3He \rightarrow {}^4He + p$	100%	18.353
5	${}^3_1T + {}^3_1T \rightarrow {}^4He + 2n$	100%	11.332



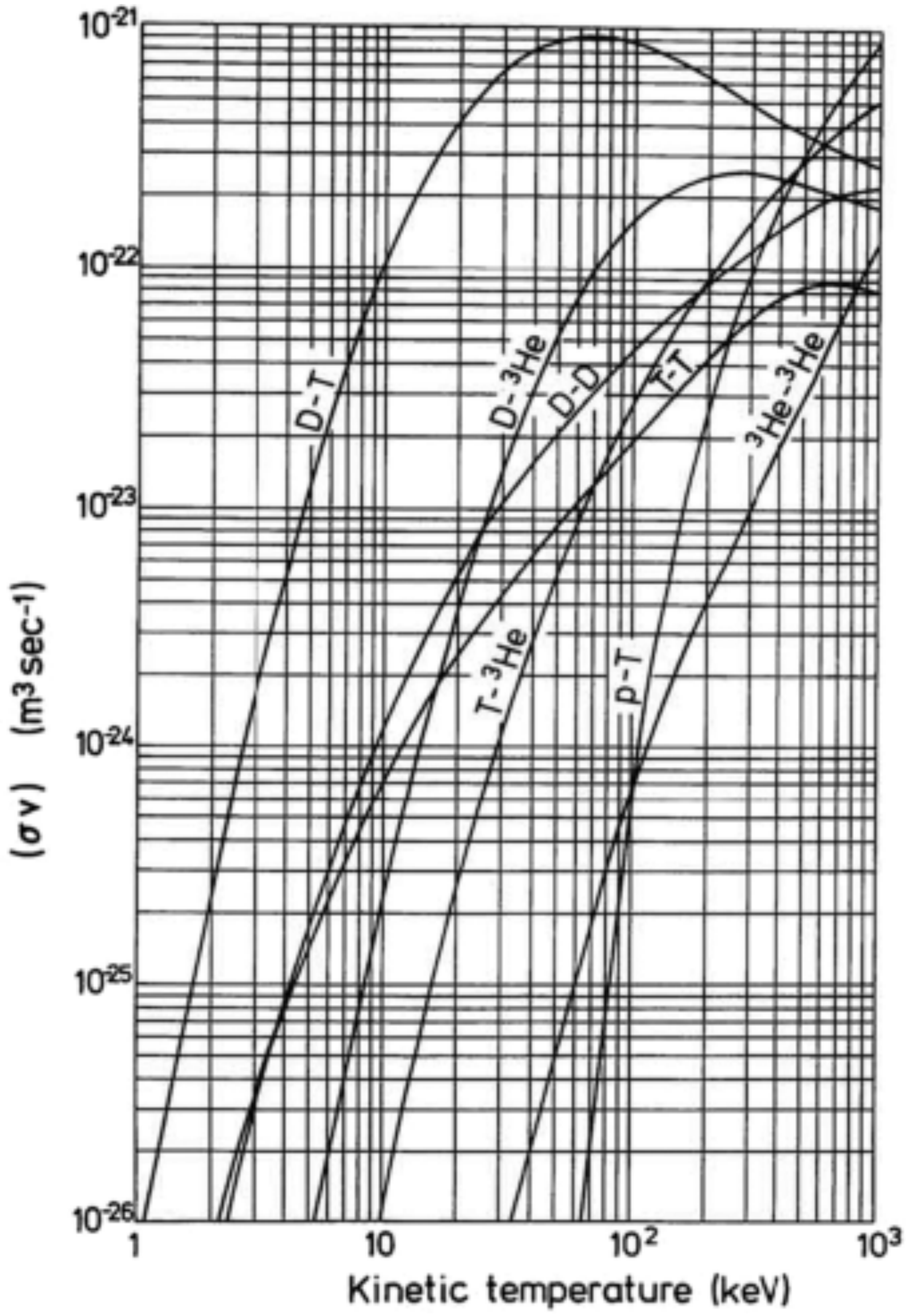
[1] Atzeni, Stefano, and Jürgen Meyer-ter-Vehn. The physics of inertial fusion: beam plasma interaction, hydrodynamics, hot dense matter. Vol. 125. OUP Oxford, 2004.

Thermonuclear Reactions

- From the perspective of chemical reaction, a thermal reaction uses the random, thermal motion of atoms to drive the reaction process.
- The idea is the same in thermonuclear reactions, we use the nuclei's motion and energy to drive reactions.
- In this case we must overcome the Coulomb barrier between the nuclei that repels their positive charges.
- To get the effective reaction rates, we integrate the product of the cross-section, σ, at a given particle energy multiplied by the Maxwellian at the ion temperature (dn/dW in the figure).
- The resulting integral is the reactivity, $\langle \sigma v \rangle$. We can multiply the reactivity by the number density, n_i, of each reactant to get the reaction rate.
    - $R_{\mathrm{DT}} = n_D n_T \langle \sigma v \rangle_{\mathrm{DT}}$, where the subscripts denote deuterium or tritium.
    - $R_{\mathrm{DD}} = \frac{1}{2} n_D^2 \langle \sigma v \rangle_{\mathrm{DD}}$, the half comes from that each nuclei cannot react with itself.
- If we average the cross-section of this reaction (bottom right) over the thermal distribution of energies in a plasma,
    - We see in the bottom left figure that DT fusion has the highest reactivity at lower temperatures.

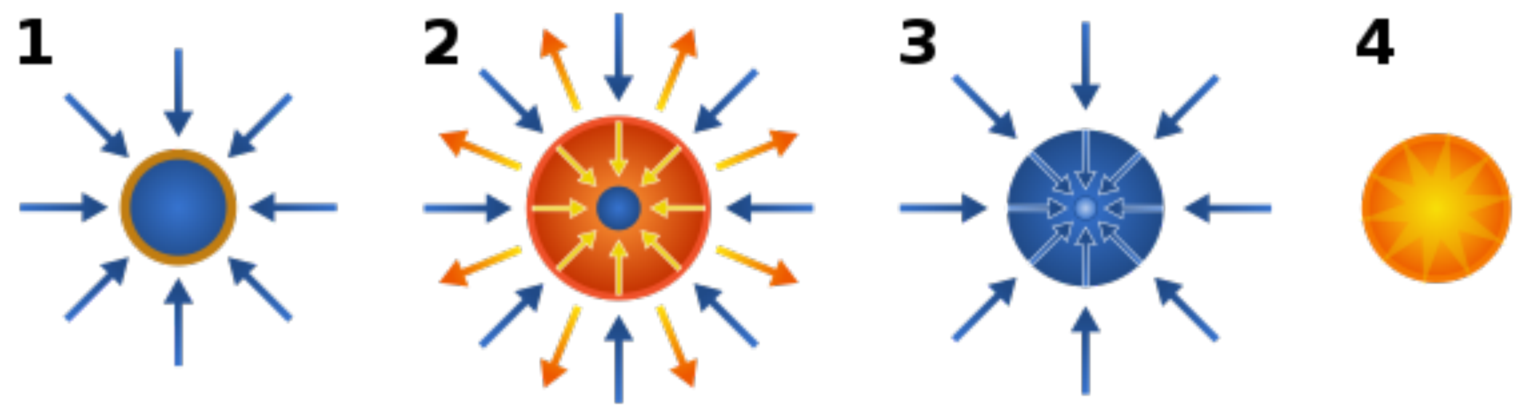


Glasstone & Loveberg

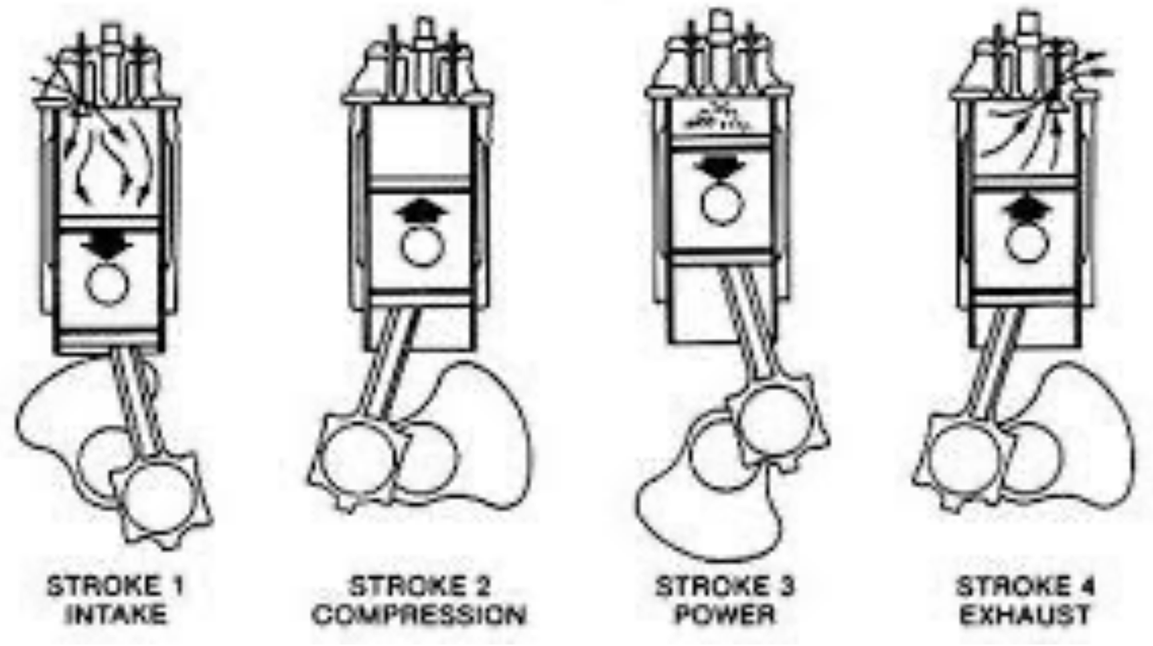


Inertial “Confinement” is not really confinement at all.

- What we mean by inertial confinement is keeping the fuel together for a long enough period of time for fusion to occur.
- There is no external means of confinement—unlike magnetic confinement where the magnetic field holds the plasma in place.
- We assemble the fuel into a small spherical volume and mass inertia keeps it together for roughly the time it takes for a sound wave to travel from the surface to the center.
  - After this amount of time the mass and density will go down (the density, it turns out is more important).
- Confinement times in IFE are *short*: less than a nanosecond often. Two consequences come from this
  - The fuel needs to be compressed to thousands of times its solid density.
  - The production of energy is a pulsed process whereby small amounts of fuel are “burned” and the energy is released in a sequence of micro-explosions.



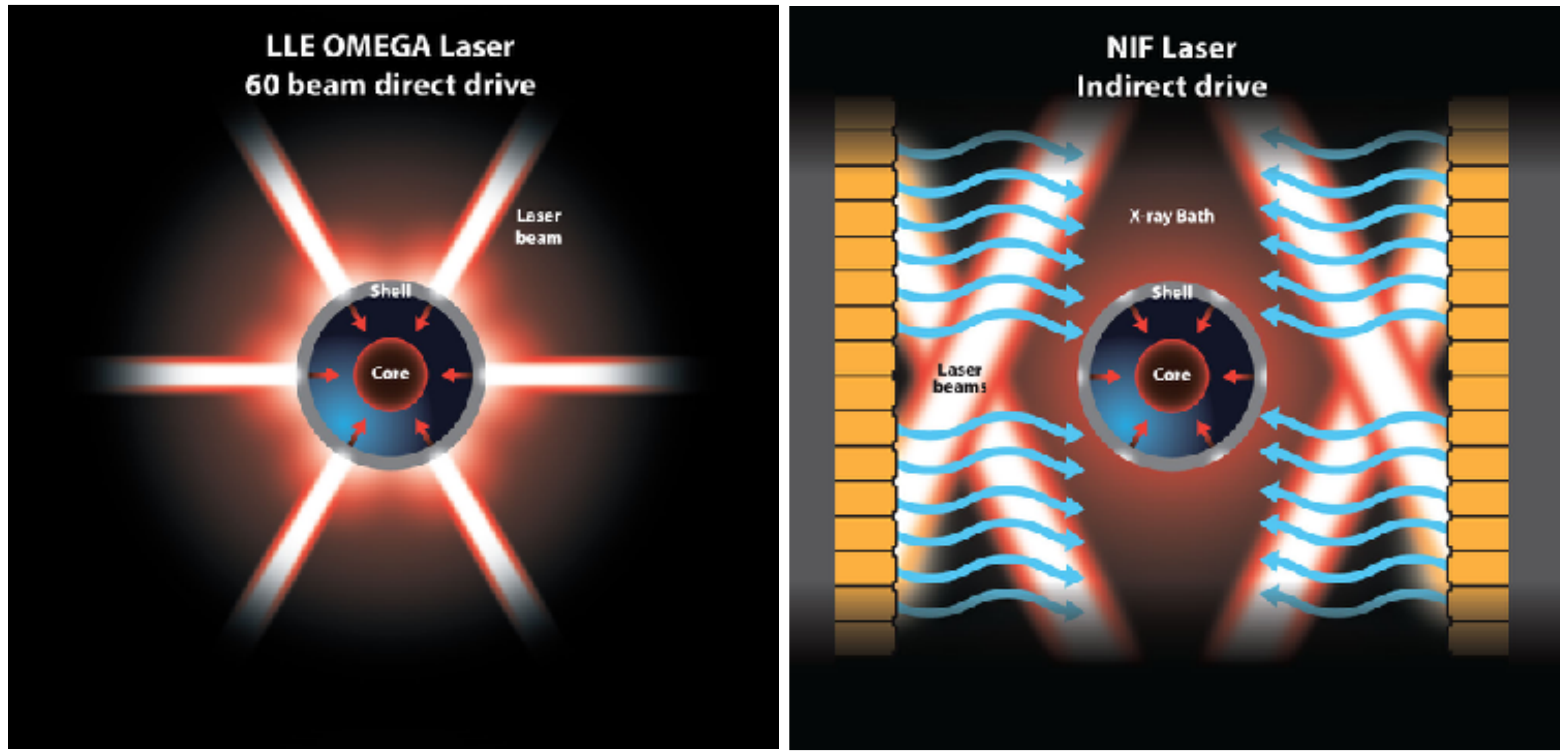
Wikimedia



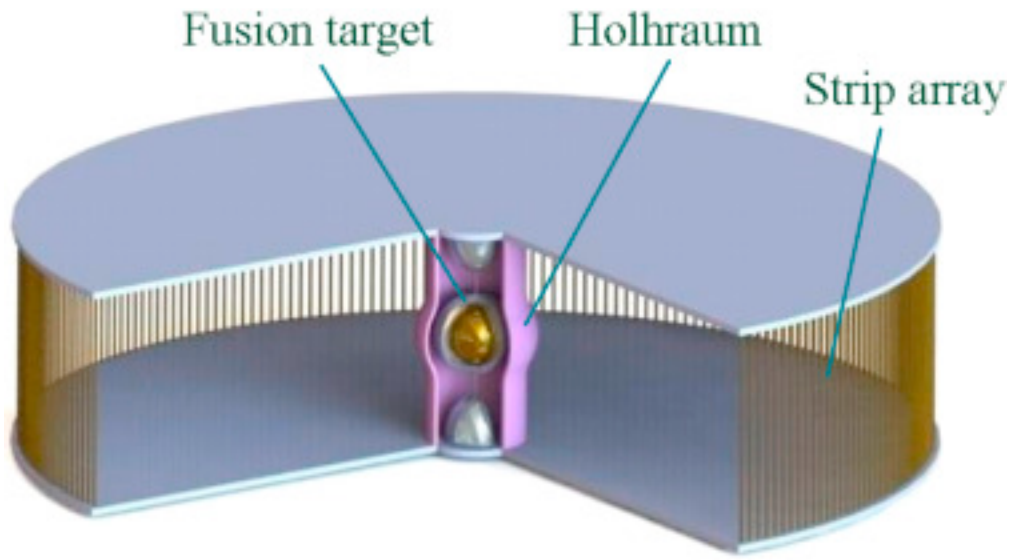
epa.gov

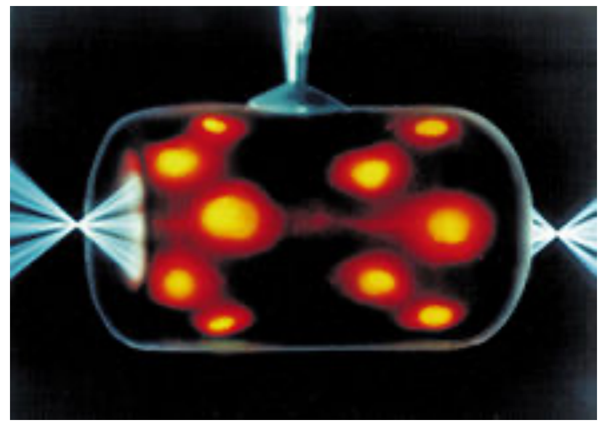
The Flavors of Inertial Fusion

- There are several variations on the idea in inertial confinement fusion of taking a solid fuel target and imploding it to high density and temperature.
- Direct Drive / Indirect Drive
  - Direct drive fusion drives the implosion by focusing energy directly on the target.
    - This energy could be lasers, ion beams, etc.
  - Indirect drive converts the energy source into x-rays that surround the target and drive the implosion.
    - This is often done using a metal tube called a hohlraum (or radiation cavity).
  - There are pros and cons to each approach.
    - It is difficult to create a spherical implosion using direct drive.
    - However, energy is lost in the conversion of laser/beam energy to x-rays.

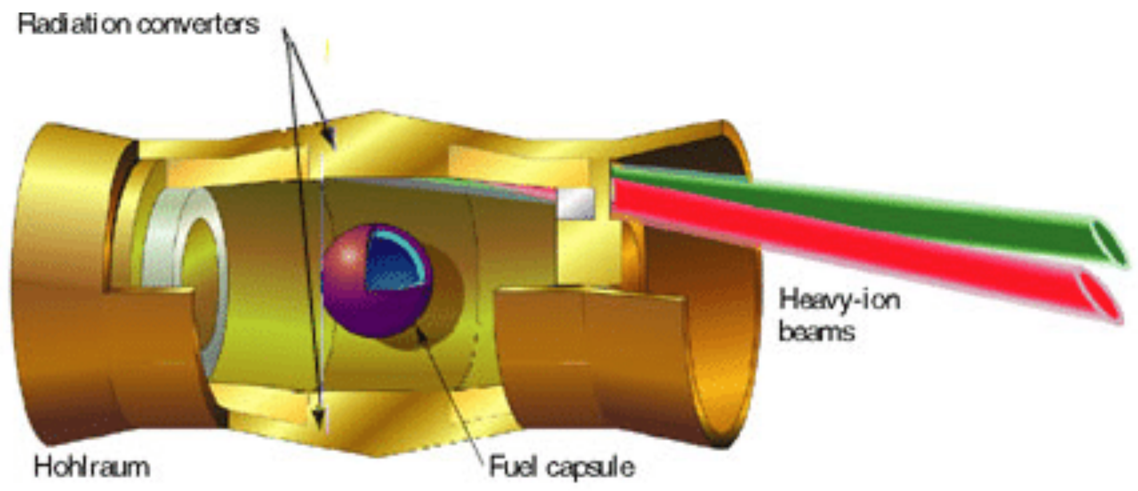


physics.org





J.M. Qi, Z. Wang, Y.Y. Chu, Z.H. Li,, 2016,

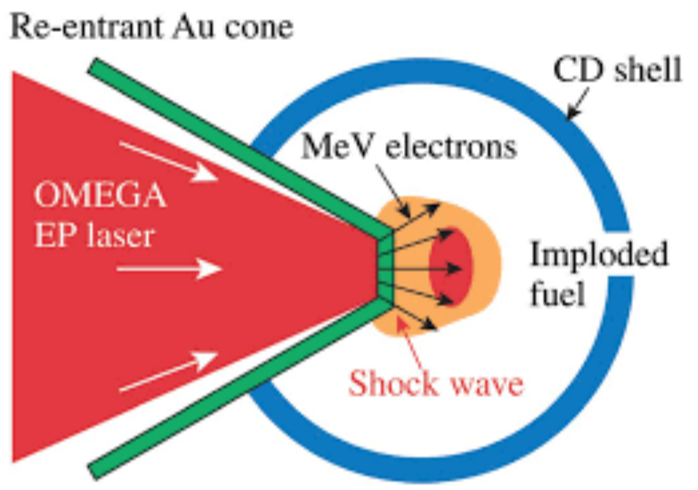


https://www.researchgate.net/publication/281184570_Ion_energy_loss_at_maximum_stopping_power_in_a_laser-generated_plasma/figures?lo=1

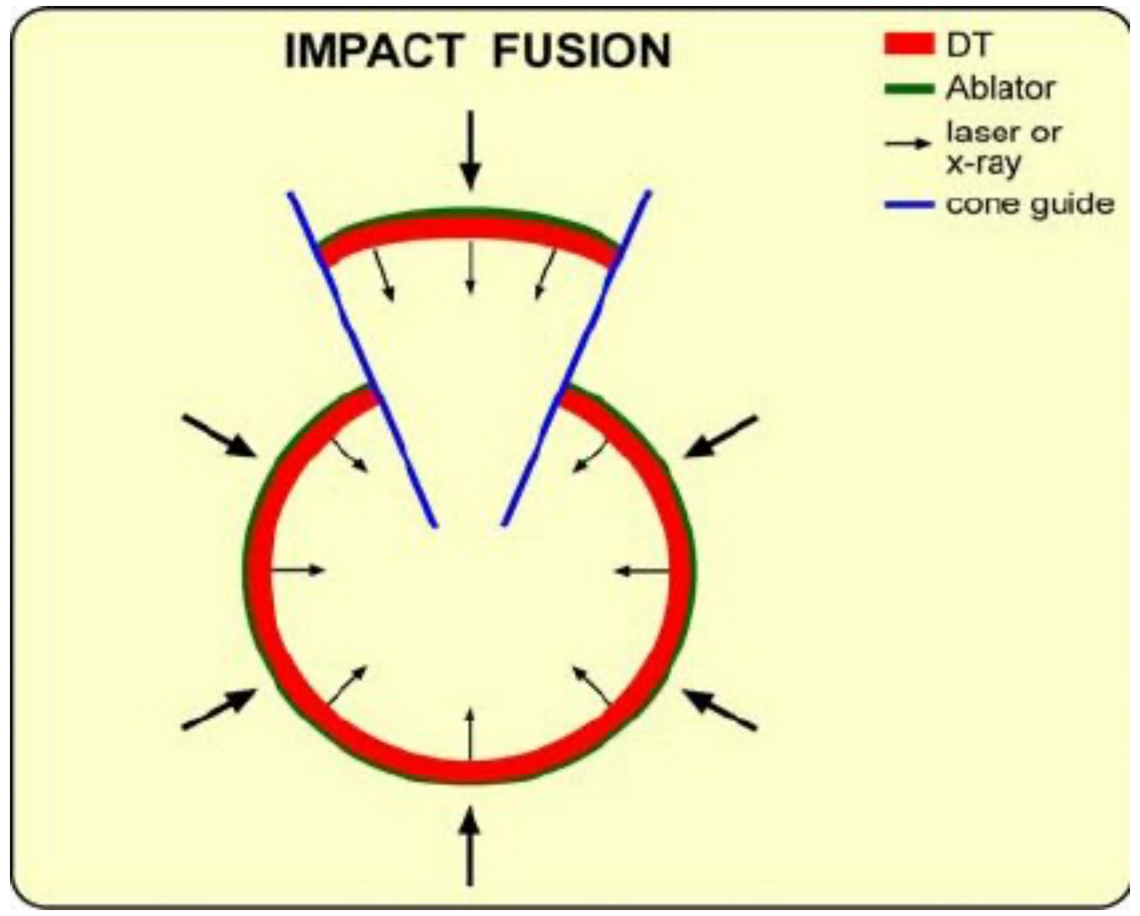

Capsule schematic
HDC (80 μm)
DT ice
(55–65 μm)
DT
vapour
1,000–1,050 μm
Radiation drive
Laser power
Hohlraum radiation
temperature
Power (TW)
Time (ns)
T_{rad} (eV)
Inner cone
Outer cone
23.5°
30°
44.5°
50°
Cryogenic cooling ring
6.4 mm
11.2 mm
Fuel fill tube
Hohlraum
3.64 mm
Laser entrance
hole
Laser quads
Implosion process
Bath of hohlraum
X-ray radiation
DT ice
DT vapour
Ablating shell
Compress
and heat
fuel
Time
Fusion burn

Fast ignition vs. Self-ignition

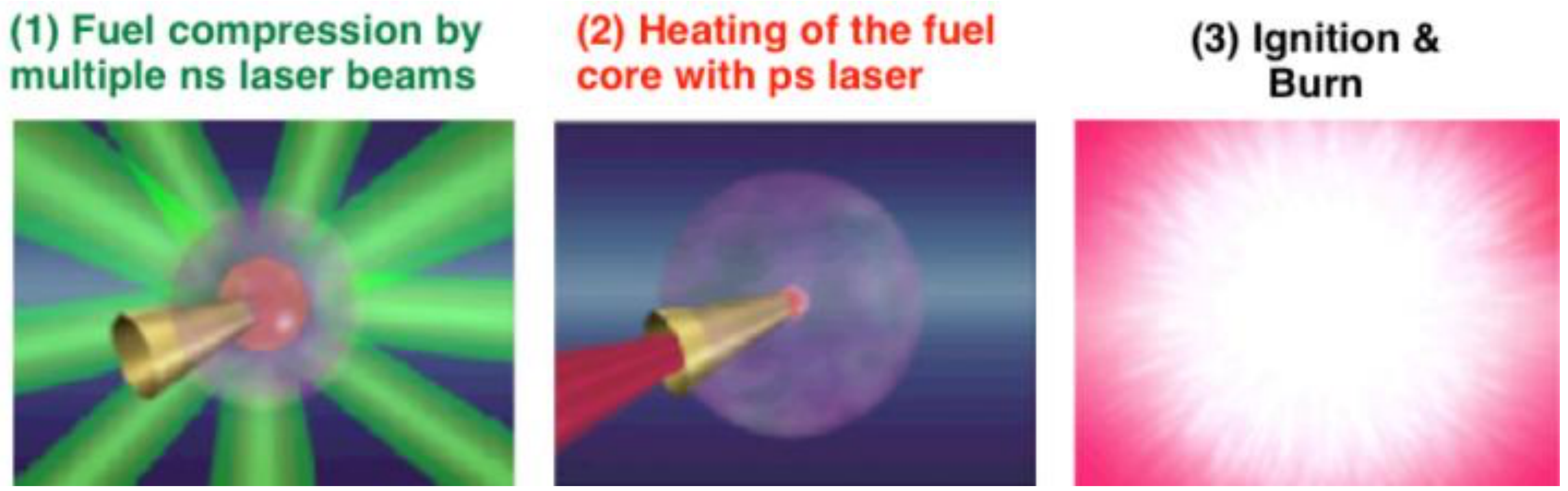
- There are also two classes of approaches to starting the fusion ignition.
- The standard approach is to compress the fuel to the right conditions and create a hot spot where fusion occurs.
    - The fusion energy is deposited in the fuel, and continues the fusion burn.
- The other approach is called fast ignition.
- In fast ignition the fuel is compressed, but then energy is added at the correct time and location to start ignition of the fuel.
    - This can be done by using an ion beam or using a laser to create a particle beam that penetrates the fuel to the correct location.
- You can think of these as being analogous to a gasoline engine vs. a diesel.
    - One needs the spark to initiate combustion, the other creates the conditions for combustion to occur spontaneously.
- The main benefit of fast ignition is that the implosion doesn't have to be as "perfect" to get ignition.



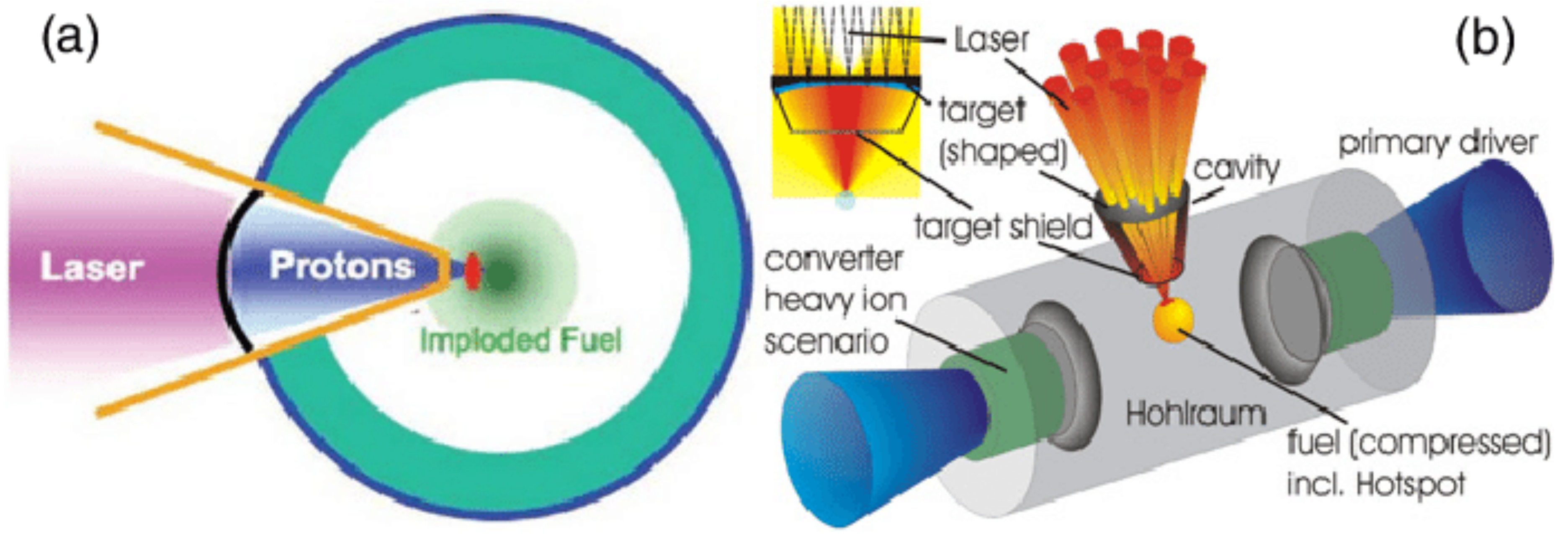
https://www.osti.gov/servlets/purl/1255527



https://www.researchgate.net/publication/238069986_Study_of_Inertial_Fusion_Energy_via_the_Equation_of_State/figures?lo=1



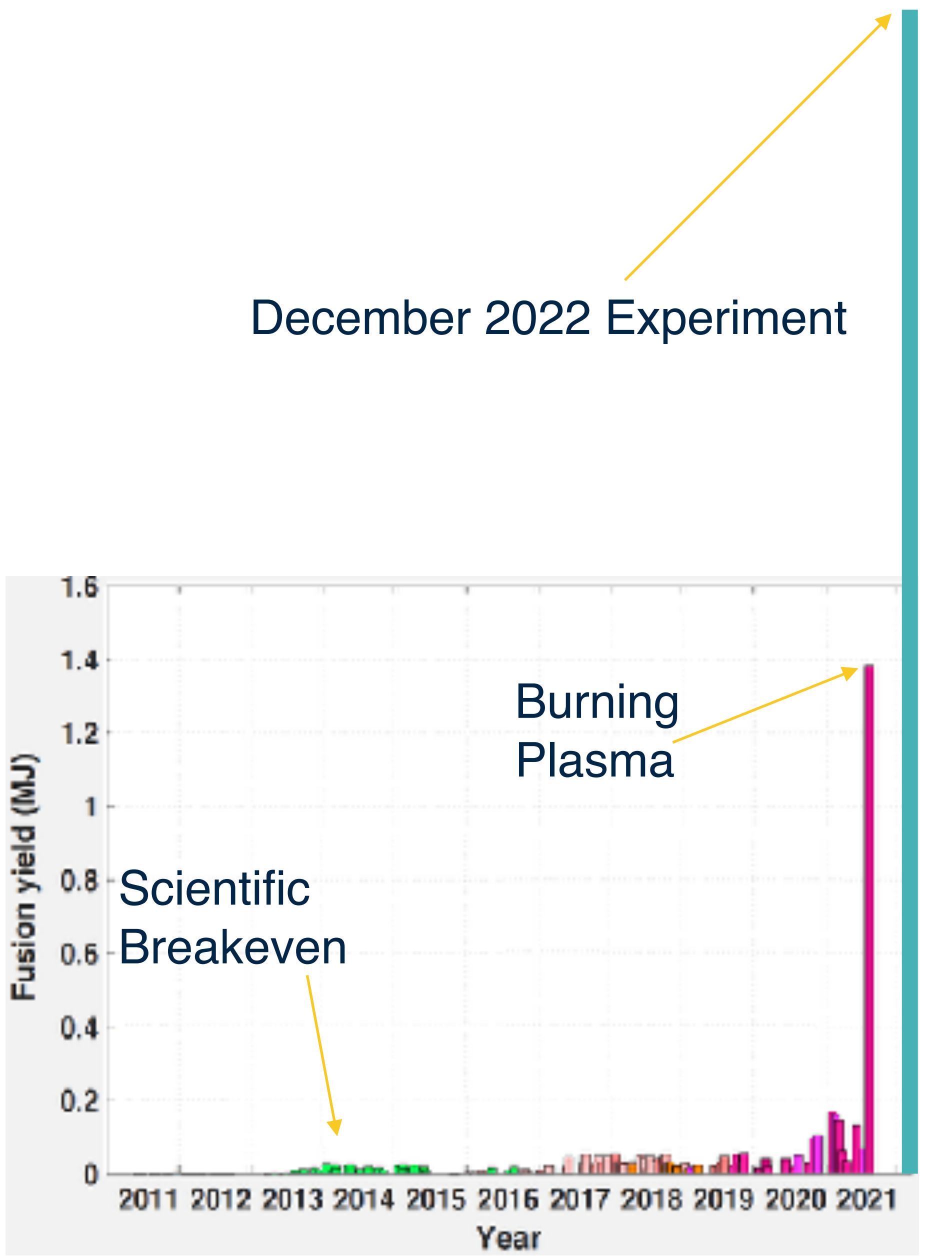
https://www.opli.net/opli_magazine/eo/2018/efficient-generation-of-high-density-plasma-enabled-by-high-magnetic-field-sept-news/



https://www.researchgate.net/publication/231043483_Progress_and_prospects_of_ion-driven_fast_ignition/figures?lo=1

Energy Gain has different forms for inertial fusion

- In the inertial fusion process, energy must be delivered to the fuel for each implosion. Call this energy E_d.
- The energy released by fusion in the target is E_{fus}. This is also sometimes called the fusion yield.
- The ratio of these is the Gain, $G = \frac{E_{fus}}{E_d}$. The recent experiment at Lawrence Livermore National Laboratory reported a gain over 1.5.
    - This uses the laser energy as E_d; the energy to charge the laser was actually larger.
- Other measures of gain have been developed over the years.
- "Scientific breakeven": producing more fusion energy than PdV work to compress the fuel.
- Burning plasma: crossing the ignition threshold and creating self-heating.
    - This also produced more energy than energy delivered to the capsule.
- For energy production, gains around 100 will be required.



Livermore National Laboratory, Wikimedia commons

Magnitude of implosion is a remarkable feat.

- High implosion velocity: 300 – 450 km/s
- Compression ratio
  - 20-40x in radius
  - Volume reduced by 30,000x
- Stagnation pressure ~400 Gbar
- Each NIF shot begins at 16 K and ends at 50 million K
- The conditions created in the experiment fall in the regime known as ***High Energy Density***

Image: Steve Obenschain

Areal Density and Ignition Conditions

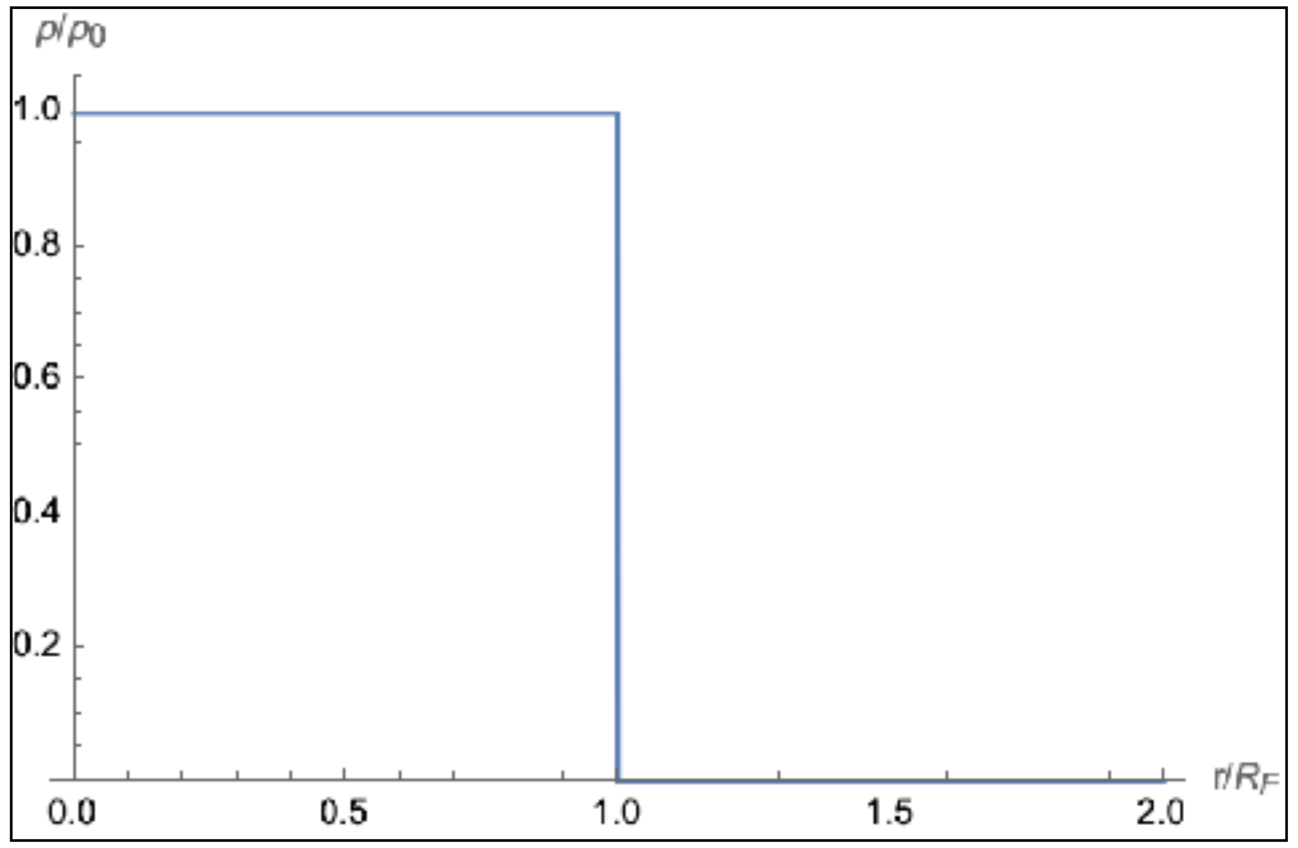
- Consider a sphere of plasma consisting of equal parts deuterium and tritium.
  - Assume it has a uniform mass density ρ and temperature T at time $t = 0$ with a free boundary at a radius R_{f}.
- From gas dynamics the sphere will expand in the form of a rarefaction wave. The front of the wave moves toward the center of the sphere at a the sound speed

$$c_s = \sqrt{2k_{\mathrm{B}}T/m_{\mathrm{f}}} \approx 2.810^7\sqrt{T}\ \ [\mathrm{cm/s}]$$

where T is in keV, k_{B} is the Boltzmann constant, and $m_{\mathrm{f}} \approx 2.5m_{\mathrm{p}}$ with m_{p} the mass of a proton.

- The front of the wave is located at $R = R_{\mathrm{f}} - c_s t$ and the confinement time is found by setting $R = 0$ and solving for the time or $\tau_{\mathrm{conf}} = R_{\mathrm{f}}/c_{\mathrm{s}}$.
- The confinement time needs to be compared to the time for fusion to occur, $\tau_{\mathrm{fus}} = \left(\langle\sigma v\rangle n_0\right)^{-1}$, where $n_0 = \rho/m_{\mathrm{f}}$ is the ion number density.
- The ratio of the confinement time to the fusion time scale is $\tau_{\mathrm{conf}}/\tau_{\mathrm{fus}} = \langle\sigma v\rangle n_0 R_{\mathrm{f}}/c_s$. This equation can be rearranged to be

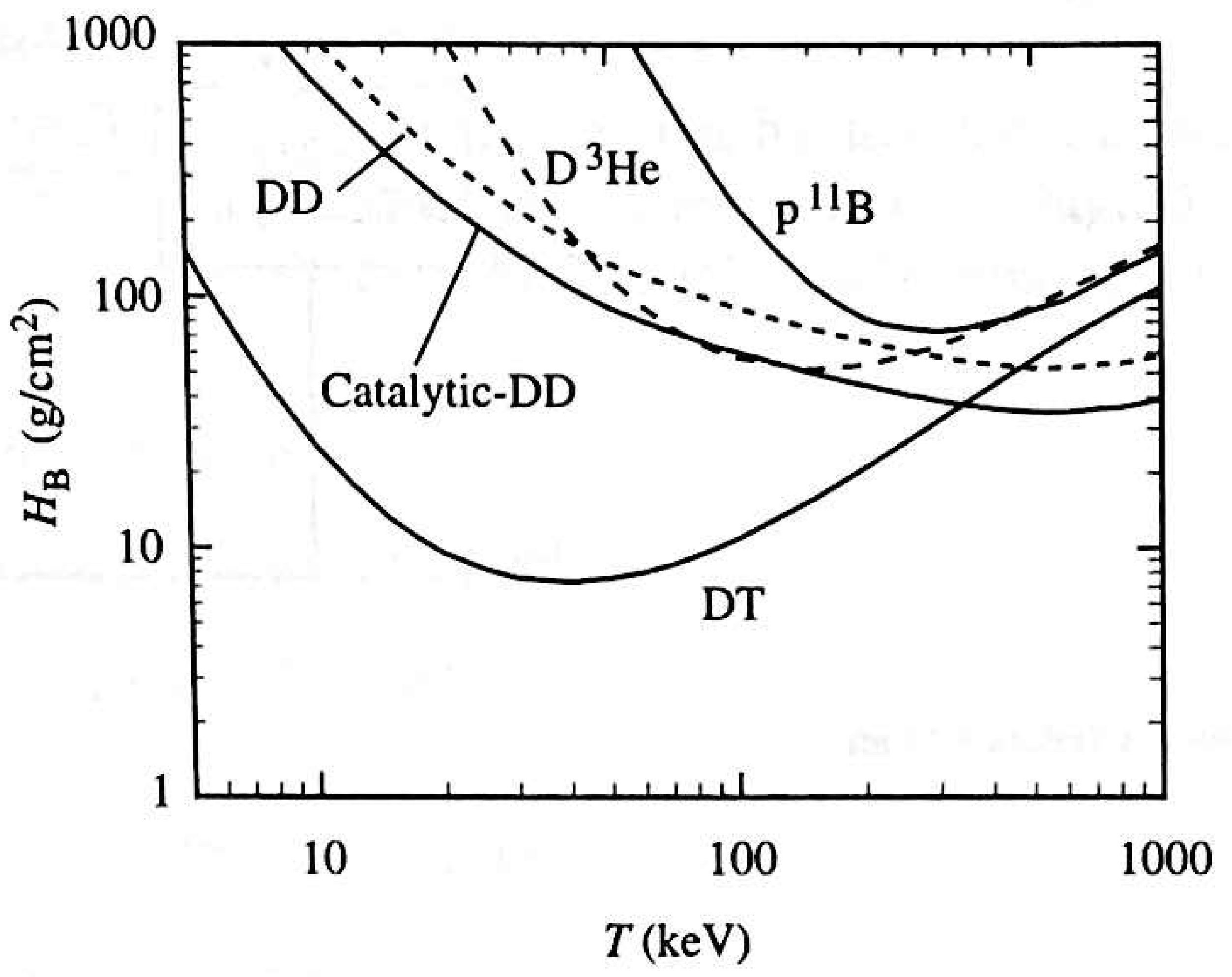
$$\frac{\tau_{\mathrm{conf}}}{\tau_{\mathrm{fus}}} = \left(\frac{\langle\sigma v\rangle}{m_{\mathrm{f}}c_s}\right)\rho R_{\mathrm{f}}\,.$$



Burn Efficiency and Burn Parameter

- The *burn efficiency,* $\Phi = N_{\rm fus}/N_{\rm DT}^{(0)}$, is the ratio of number of fusion reactions to the number of DT pairs initially present.
- Assuming, $\Phi \ll 1$, (low burn) the number of fusion reactions taking place in time dt is
$$dN_{\rm fus} = \langle \sigma v \rangle n_{\rm D} n_{\rm T} V(t) dt = \langle \sigma v \rangle \frac{\rho^2}{4m_{\rm f}^2} V(t) dt \, .$$
- The volume of the high density region is the volume that the rarefaction wave has not reached yet so $V(t)/V_0 = [R(t)/R_{\rm f}]^3 = (1 - c_s t/R_{\rm f})^3$.
- Integrating over the confinement time we get $\int_0^{\tau_{\rm conf}} dt\, V(t)/V_0 = R_{\rm f}/4c_s$, or that the effective confinement time is 1/4 $\tau_{\rm conf}$.
- The efficiency is then $\Phi = \frac{\langle \sigma v \rangle}{8 m_{\rm f} c_s} \rho R_{\rm f}$, where again we see the areal density appear.
- The burn parameter, $H_{\rm B} = 8 m_{\rm f} c_s / \langle \sigma v \rangle$, is inversely proportional to the efficiency.
- A more complex derivation for higher burn conditions gives

$$\Phi \approx \frac{\rho R_{\rm f}}{H_{\rm B} + \rho R_{\rm f}}$$



Requirements for an IFE Reactor

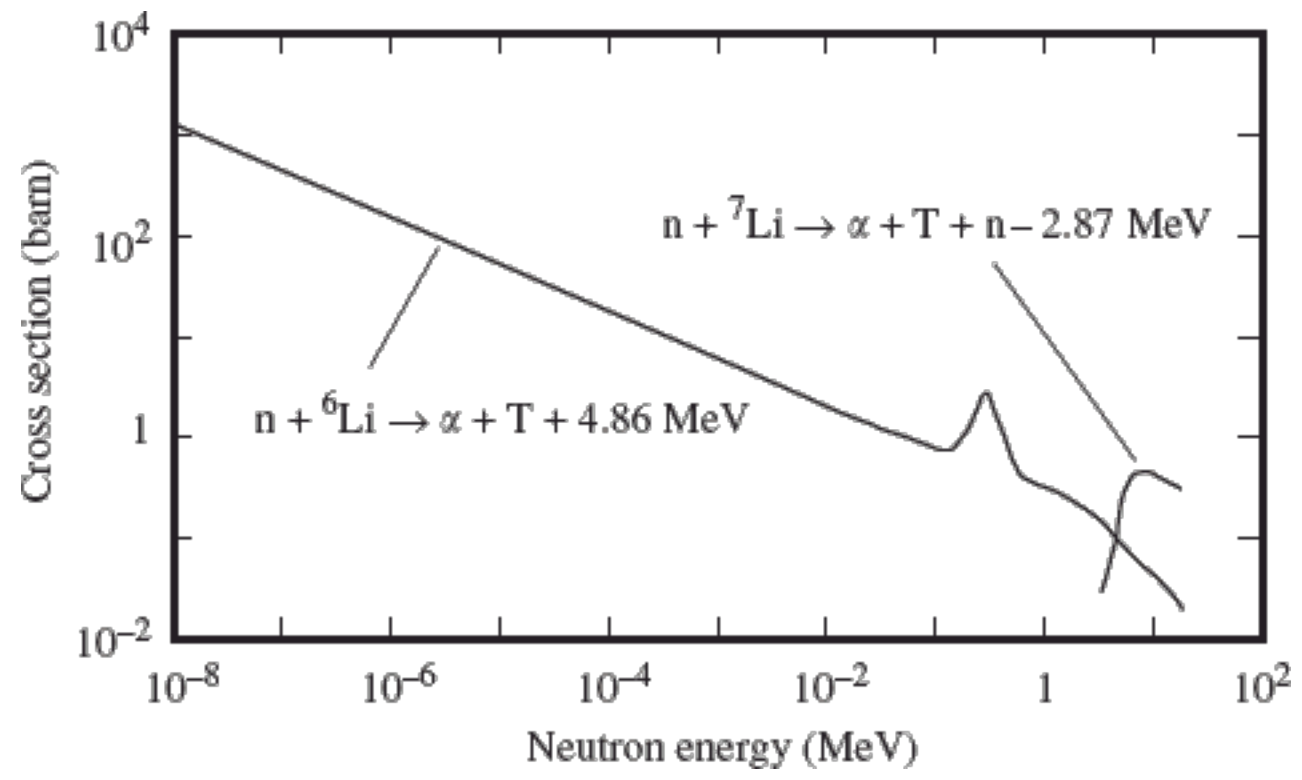
- In the fusion reaction we have defined the gain, G. Therefore, if we know the driver (i.e., laser, ion beam, etc.) energy, E_d, the fusion energy is GE_d. The gain could also include exothermic reactions between neutrons and the blanket.
- The driver itself needs energy and if the efficiency of the driver is η_d, then the total energy in is $E_\mathrm{d} = \eta_\mathrm{d} E_\mathrm{in}$.
- The total energy recovered from fusion is based on the thermal efficiency of energy conversion, $E_\mathrm{out} = \eta_\mathrm{th} G E_\mathrm{d} = \eta_\mathrm{th}\eta_\mathrm{d} G E_\mathrm{in}$
- For the next shot, we will need another E_in to initiate it, so only a fraction will be available to send to the electrical grid.
- Using some rough numbers, $\eta_\mathrm{th} \approx 40\,\%$, $\eta_d \approx 10 - 33\,\%$, and saying that $E_\mathrm{out} \approx 4E_\mathrm{in}$, we arrive at

$$G = 30 - 100$$

- This is our desired gain. There is a limit on the amount of fuel we can fuse in a single implosion.
  - The reactor vessel must contain the energy released via fusion without damage.
- The complete fusion of 1 mg of DT releases 337 MJ of energy. If the burn efficiency is 1/3, then ≈ 10 mg of fuel is appropriate.
  - 1 GJ is about the equivalent of 250 kg of high explosives, but the energy is carried by low-momentum particles and photons, rather than gas.

A medium is needed to capture the neutrons.

- As mentioned before, in the DT fusion reaction most of the energy is carried by the 14.1 MeV neutron.
- In most cases the neutron will leave the fuel and need to be captured.
- It has been proposed that a blanket around the reaction vessel containing lithium would have two benefits.
- Natural lithium contains two isotopes that both react with neutrons
  - $^{6}\mathrm{Li} + {}^{1}\mathrm{n} \rightarrow {}^{3}\mathrm{T} + {}^{4}\mathrm{He} + 4.86\,\mathrm{MeV}$
  - $^{7}\mathrm{Li} + {}^{1}\mathrm{n} \rightarrow {}^{3}\mathrm{T} + {}^{4}\mathrm{He} + {}^{1}\mathrm{n} - 2.87\,\mathrm{MeV}$
- Both reactions produce tritium, which does not occur naturally on earth. This process is called tritium breeding.
- Also, notice that one of the reactions produces energy while producing tritium.
- Only 4.85% of natural Li is ^{6}Li. The two isotopes are easy to separate.
- There have been proposals to have a flowing blanket with liquid lithium that would be the working fluid in a thermodynamic cycle.
- The blanket would be needed for inertial or magnetic fusion.



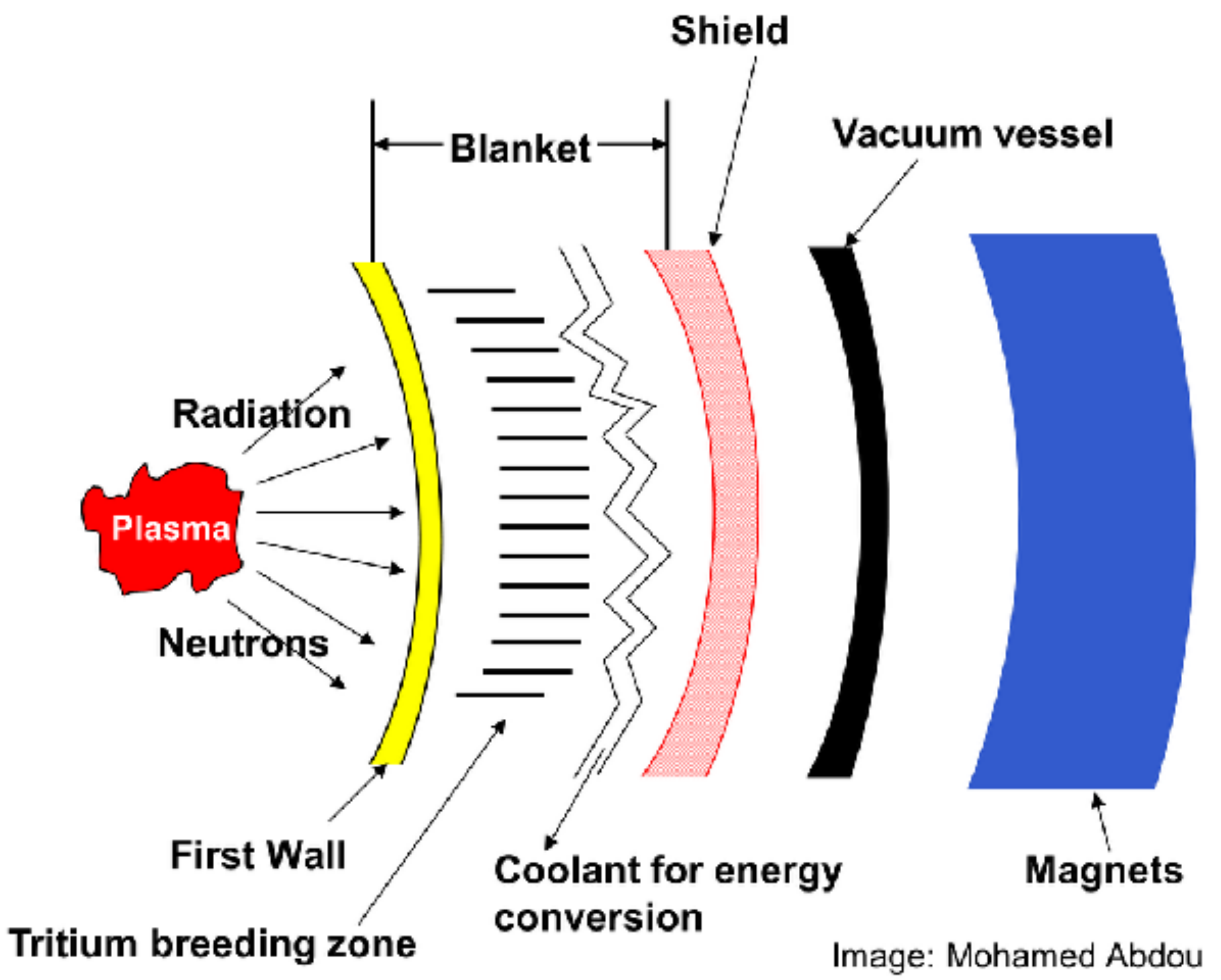
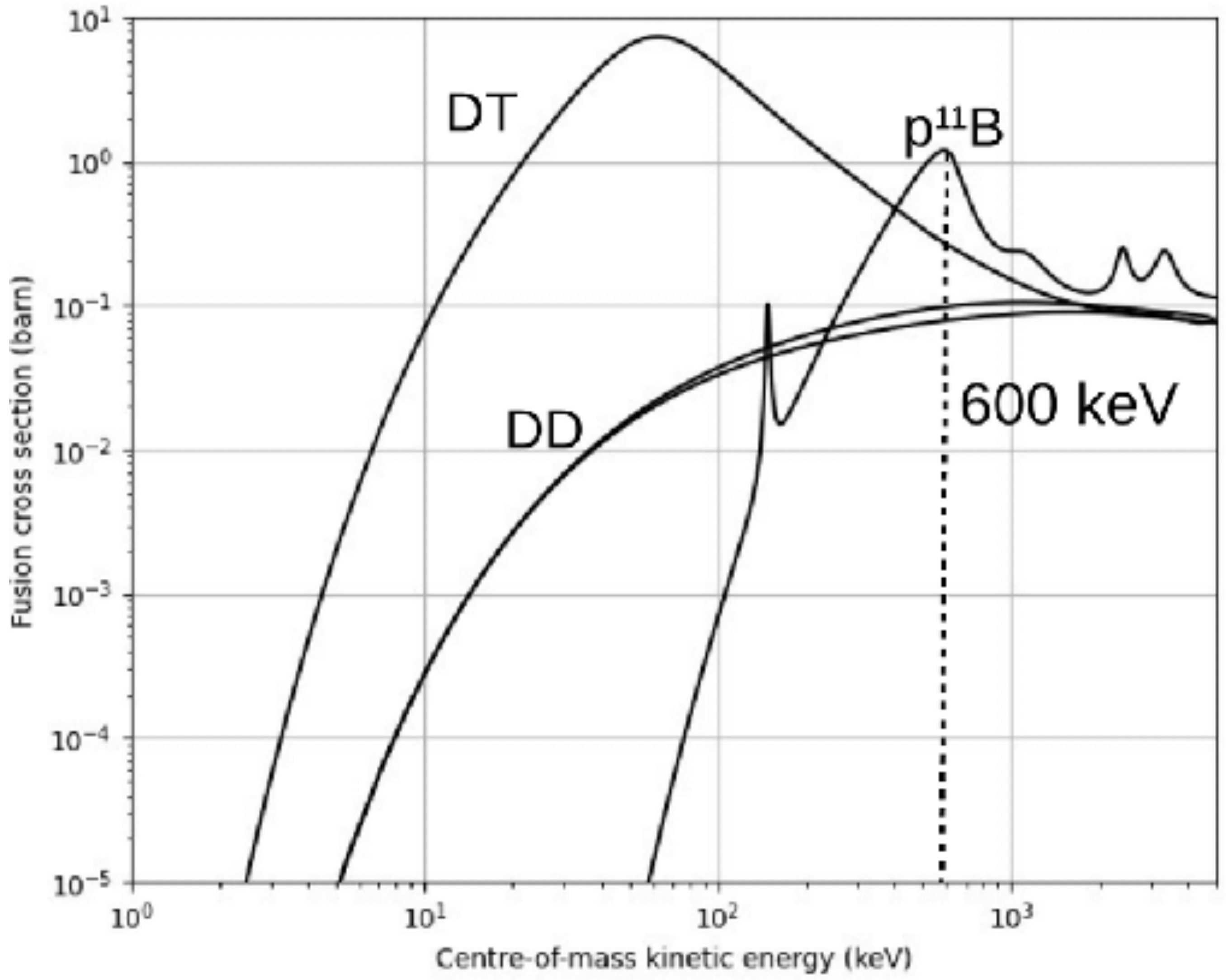


Image: Mohamed Abdou

Neutron-free fusion

- The neutrons produced in DT fusion are a problem for two reasons,
    - They leave the plasma, taking their energy with them so that they cannot contribute to the heating of the plasma.
    - Neutron interactions with matter typically create radioactive products when absorbed by a nucleus.
- These neutrons will create short-lived radioactive products in the materials surrounding the fusion reactions.
- Even a reactor containing only deuterium to start will produce tritium and eventually neutrons.
- One reaction between a proton (^{1}H) and boron-11 creates no neutrons:
    - $^{1}\mathrm{H} + {}^{11}\mathrm{B} \rightarrow 3\left({}^{4}\mathrm{He}\right) + 8.6\,\mathrm{MeV}$
- ^{11}B is 80.35% of natural boron, and boron is 0.001 percent of the earth's crust.
- No radioactive reactants or products, and all the products are charged particles which would stay in the fuel, continuing to heat it.
- Unfortunately, the cross-section for this reaction is much smaller than DT fusion.



Fuel compression/temperature requirements

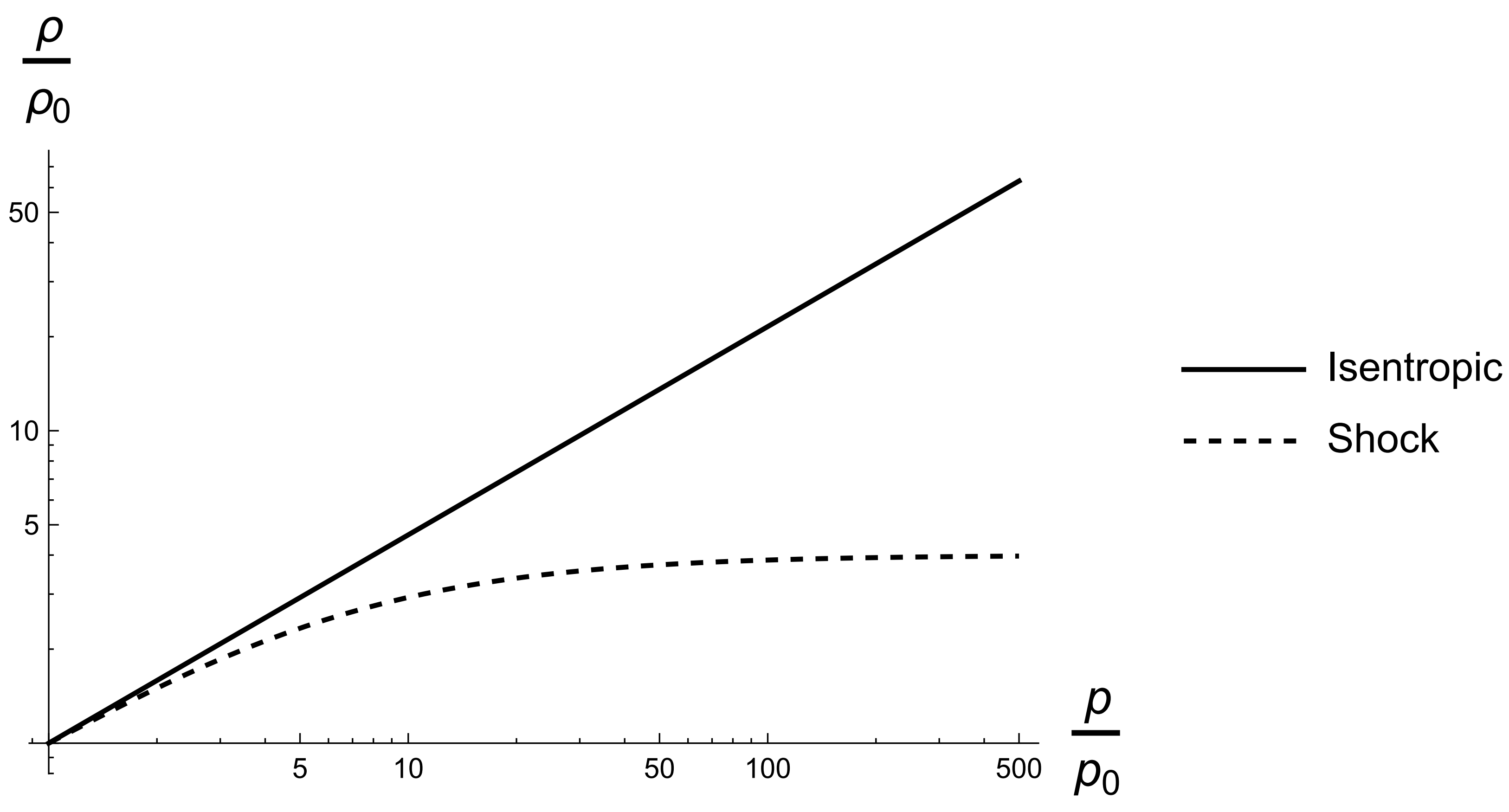
- The amount of fuel in an implosion will be small (tens of mg). The areal density, ρR, still controls the confinement time and burn efficiency.
- To get a 33% burn efficiency, Φ, we can use the previous equations to find that $\rho R_{\mathrm{f}} \approx 3\ \mathrm{g/cm^2}$.
- A spherical fuel volume has a mass of $M_{\mathrm{f}} = \dfrac{4\pi}{3}\rho R_{\mathrm{f}}^3$, which using the value for areal density we just found, gives $\rho \approx 300\ \mathrm{g/cm^3}$, for a 1 mg fuel mass.
- The density of (cryogenic) solid DT is $\rho_{\mathrm{DT}} = 0.225\mathrm{g/cm^3}$, so to get the desired value for ρR_{f} we need to compress the fuel by a factor of about 1500.
- We also know that the temperature of the fuel must be elevated to the keV range to allow fusion reactions to readily take place.
    - If the fuel is uniformly heated to 5 keV, the energy contained in the D-T pair that fuses is 30 keV on average and the energy released is 17.6 MeV. With a 30% burn efficiency and typical driver efficiencies, this will give us a gain of only around 20 as an upper bound.
- Rather than heat the fuel uniformly, we would rather only heat a small hot spot, and have the alpha particles produced in the fusion reaction heat the surrounding fuel.
- The properties of alpha particles require a much smaller value of $\rho R_{\mathrm{f}} = 0.2 - 0.5\ \mathrm{g/cm^2}$.

Compressing the fuel - fast and isentropically

- The fuel needs to be compressed quickly (remember our confinement time from before).
- Here we will show that it needs to be done isentropically (or nearly so).
- The internal energy of the fuel is governed by the first law of thermodynamics: $de = T\,ds - p\,dV$, where s is the specific entropy and $V = 1/\rho$ is the specific volume.
- If the compression is done isentropically, $ds = 0$, and we use a gamma-law equation of state, we have that

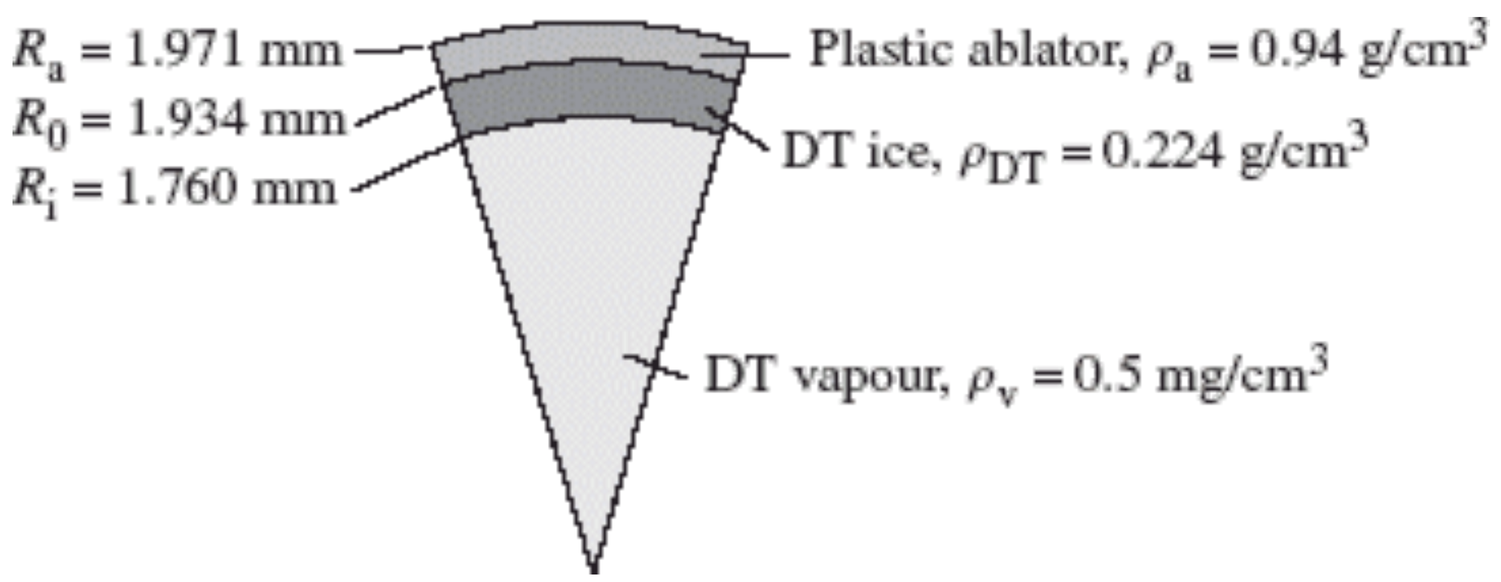
$$\frac{\rho}{\rho_0} = \left(\frac{p}{p_0}\right)^{\gamma-1}$$

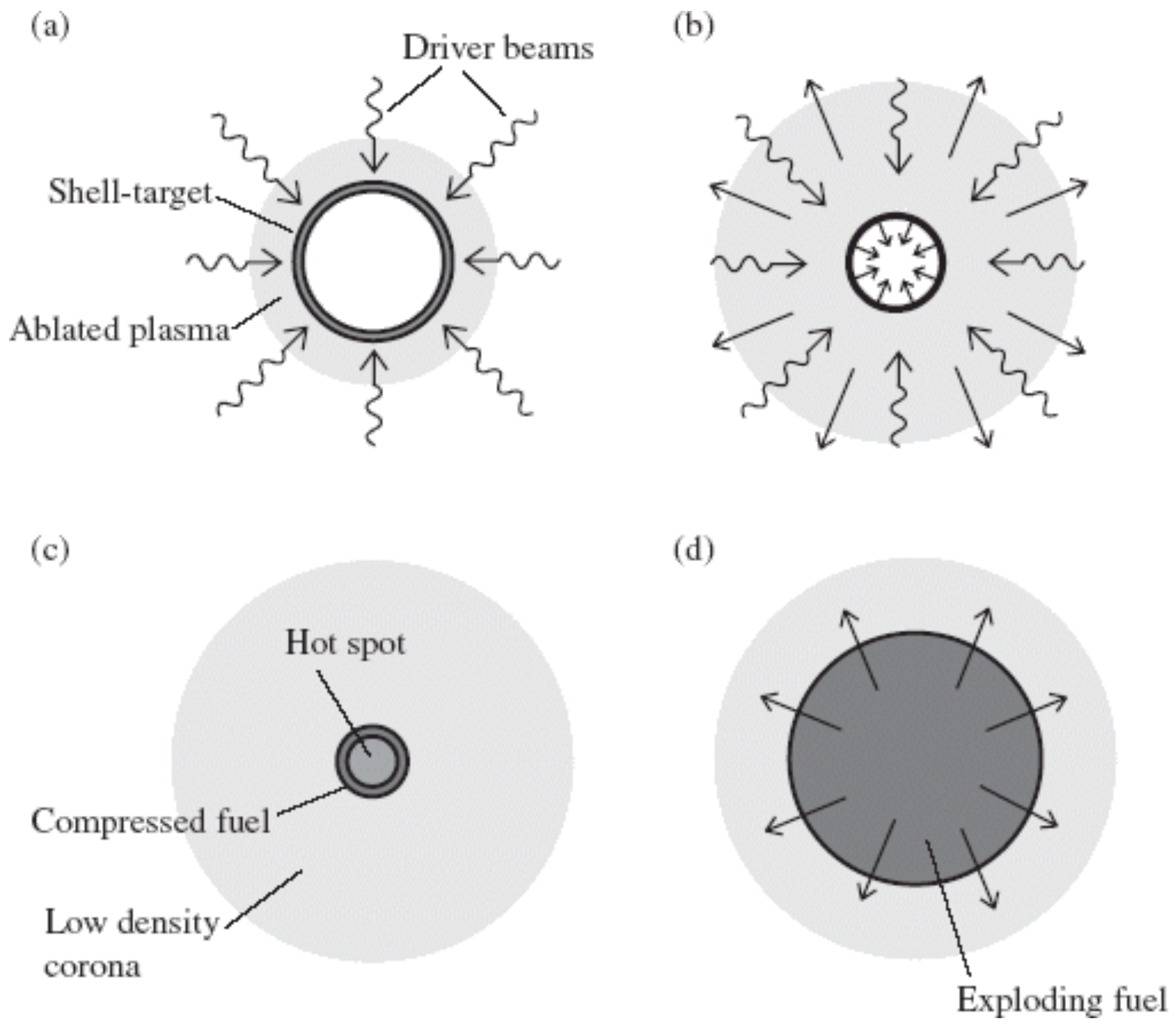
- For shock compression, the Rankine-Hugoniot relations give $\dfrac{\rho}{\rho_0} = \dfrac{\gamma + \frac{\gamma p}{p_0} + \frac{p}{p_0} - 1}{\gamma + \frac{(\gamma-1)p}{p_0} + 1}$.
    - As the pressure ratio increases, this limits to $\dfrac{\rho}{\rho_0} = (\gamma+1)/(\gamma-1)$.
    - For $\gamma = 5/3$, this limit is 4 and is shown at the graph.



An example implosion

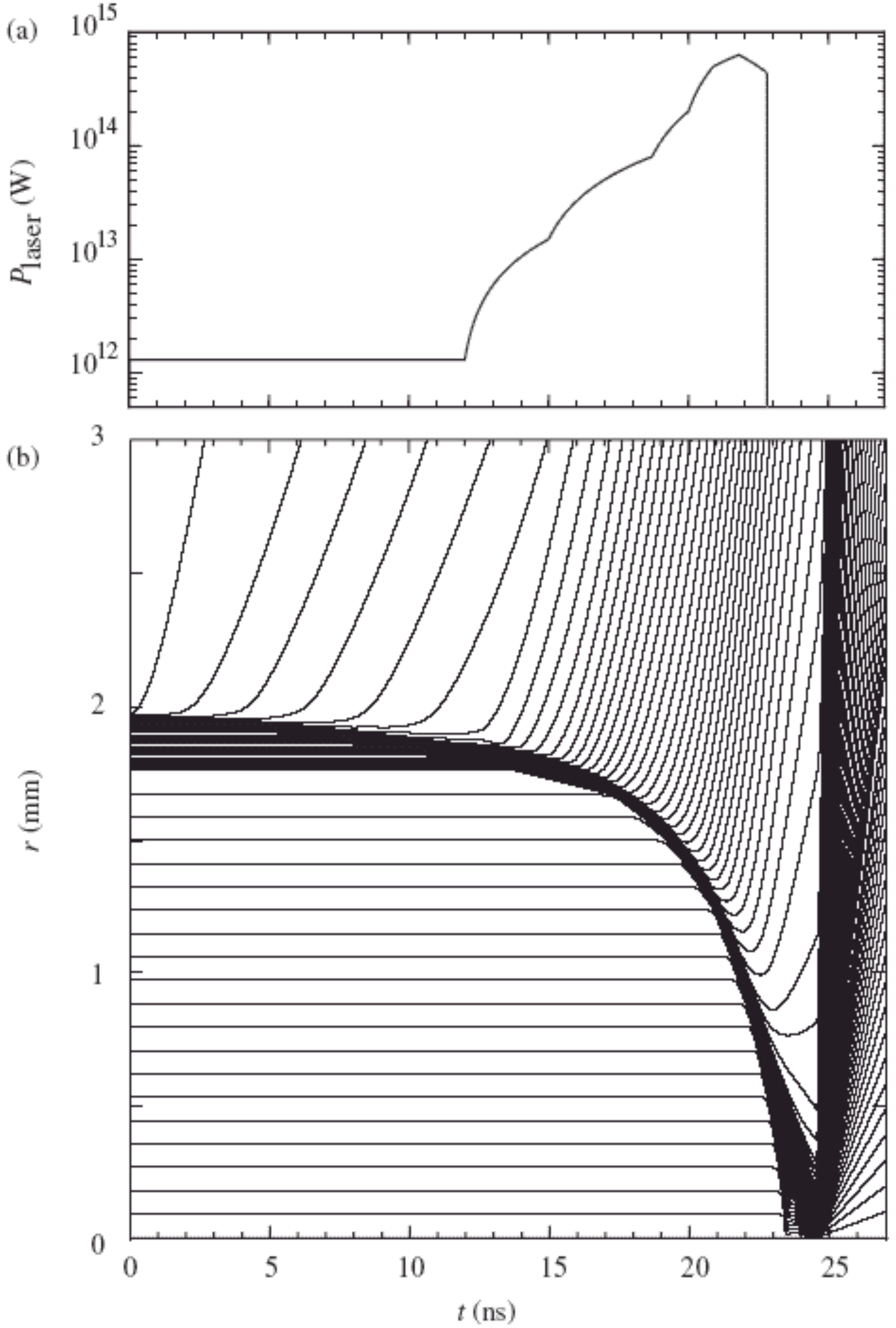
- We will now walk through a 1-D simulation of a characteristic implosion as detailed in [1].
- The "pie diagram" at right shows the composition of the fuel.
  - It is a sphere of plastic, with an inner layer of solid DT "ice".
  - A small amount of DT vapor is inside the solid shell.
  - The capsule is initially at 18 K (and we are going to take it to > 100 million K)
- One tactic to compressing the fuel is to shine laser light onto it.
- The pulse is shaped so that multiple shocks are launched and that they coalesce together at the appropriate moment.
- The implosion is started by the laser light vaporizing (or ablating) the surface of the fuel capsule.
- We will see four phases of the implosion:
  - (a) initial ablation, (b) compression, (c) hot spot creation, and (d) burn/expanding fuel





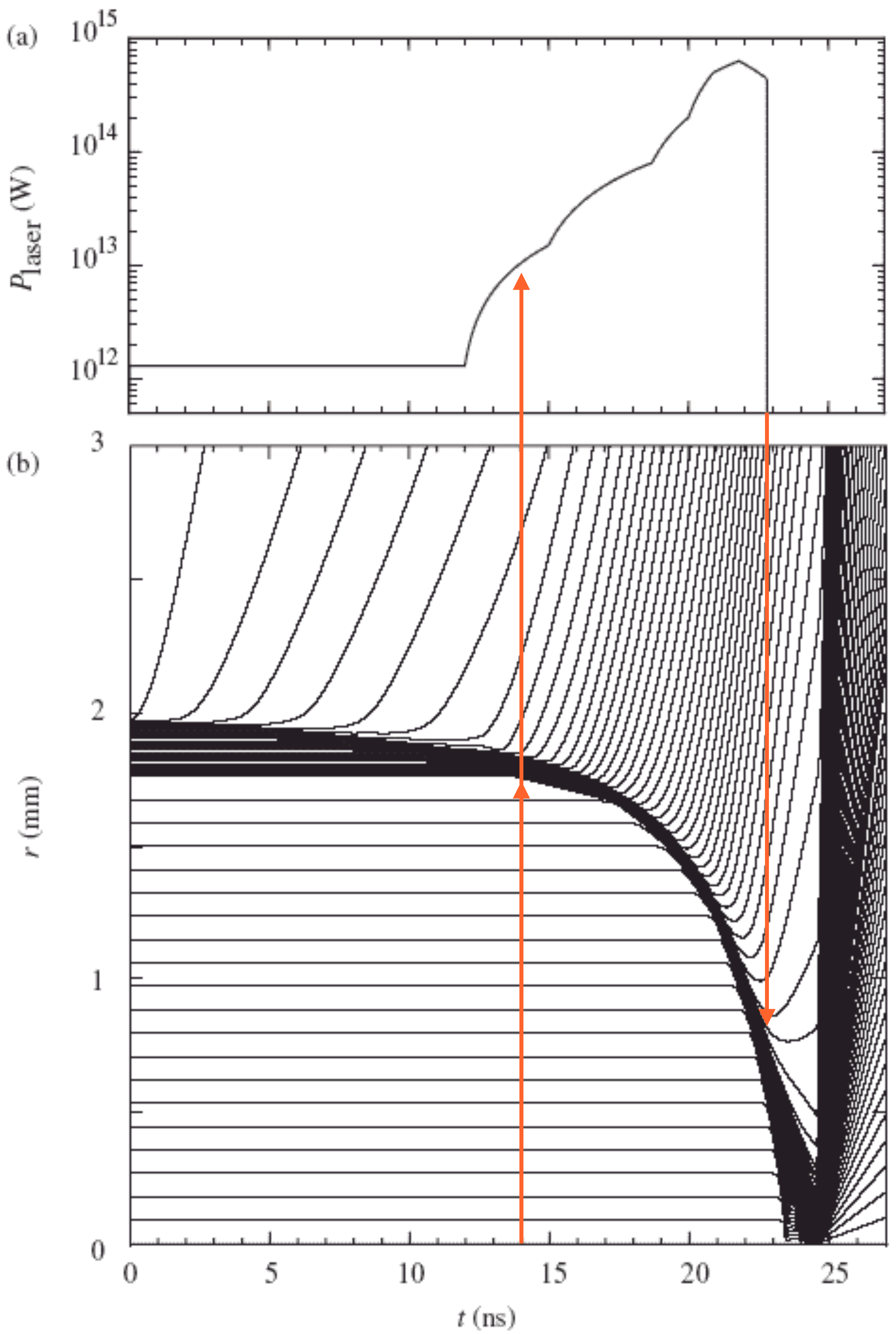
Irradiation and Implosion

- To conserve momentum, the non-vaporized surface of the capsule moves inward launching a shock wave. By adjusting the laser pulse shape, one can control the rate at which shocks are launched.
- The figure at right, from [1], shows this.
    - The top plot shows the laser power as a function of time. Notice the four regions of increasing power.
- The bottom part of the figure is known as an implosion diagram. Each division in r corresponds to a fixed mass of fuel.
    - The lines are close together at the surface of the full near 2 mm to resolve the ablation.
    - The rising lines indicate material being ablated.
    - Falling lines indicate material being compressed.



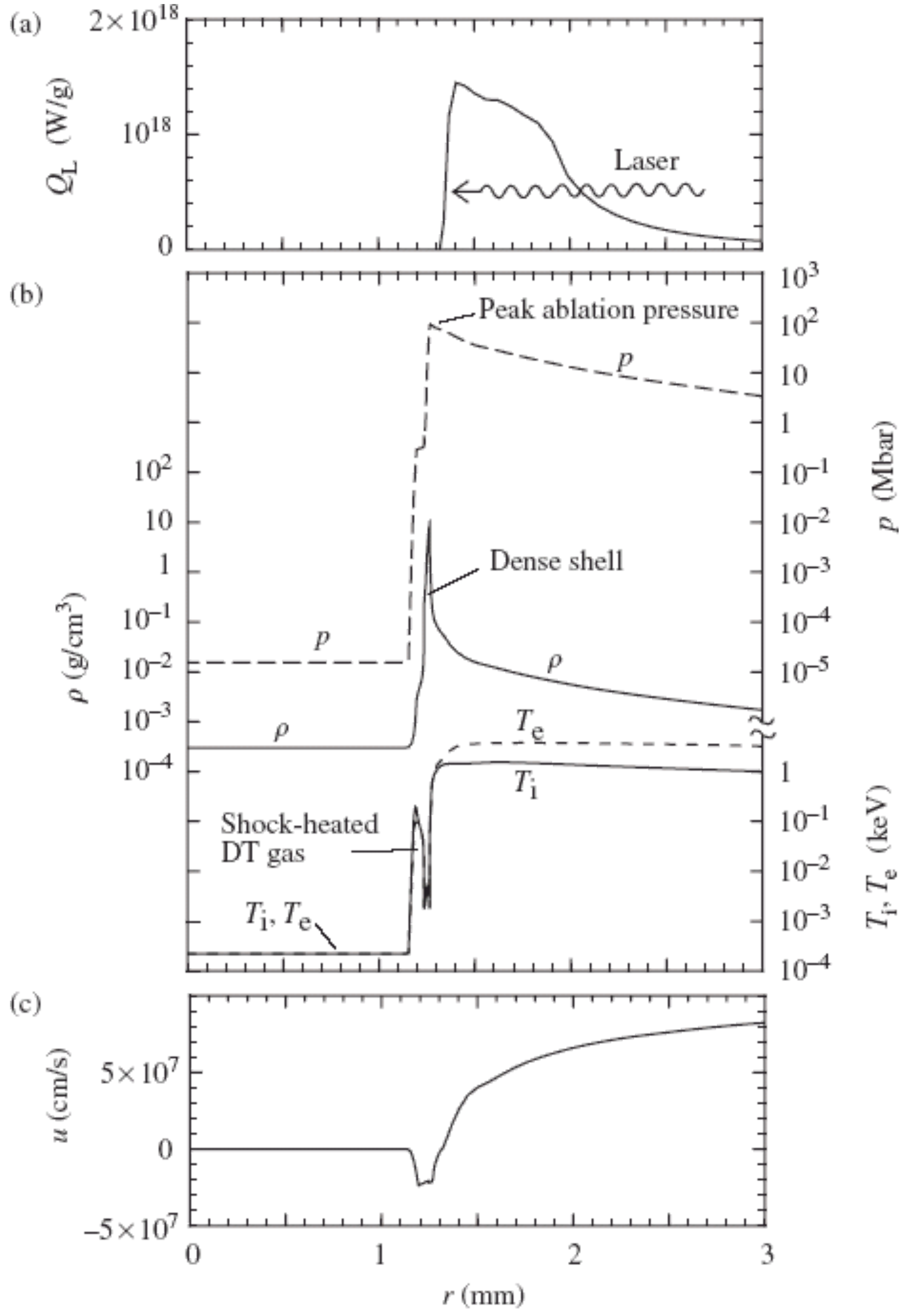
Irradiation and Implosion

- A shock with pressure 1 Mbar breaks through the inner surface of the fuel around 14 ns.
  - This is also around when the laser power is increased.
  - The high power leads to more ablation, as the increased slope of the rising lines indicates.
- Subsequent shocks now cause the entire outer shell to accelerate inward.
- At the peak laser power, the ablation pressure is about 130 Mbar.
- When the laser turns off, that capsule has absorbed about 1.3 MJ of energy and almost 90% of the outer layer of the capsule has been ablated.
- Also, at this time the capsule has about 1/2 the radius (1/8 the volume) of the original fuel.
  - The surface is coasting inwards at about 370 km/s



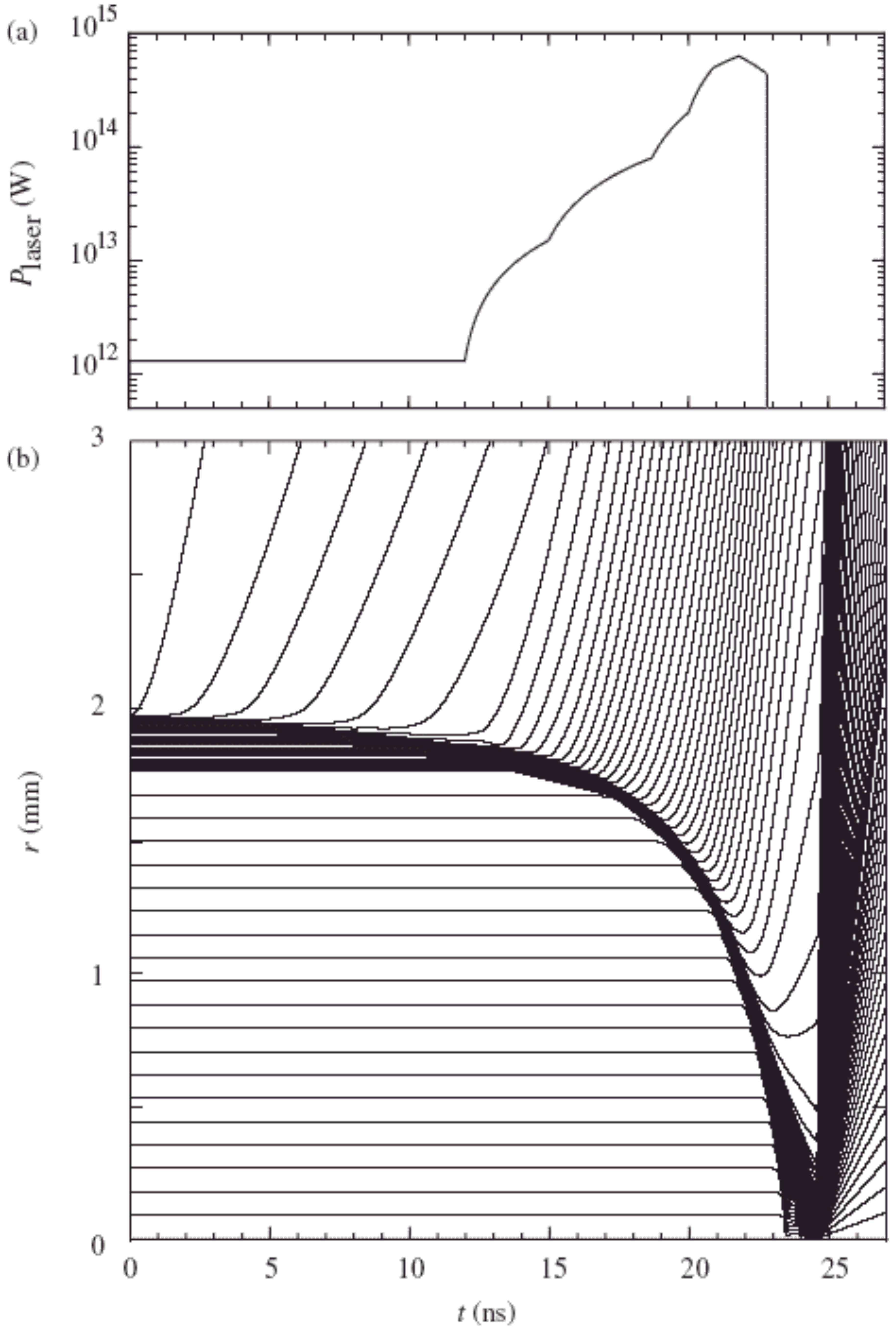
Implosion details

- The figure at right shows the state of the system at 21 ns.
- We see in (c) that there is fast expansion of the outer layers (positive velocity *u*).
  - The small region of negative velocity is the imploding front.
- In part (a) we see that the absorption of laser light, Q_L, is maximum at the peak density, but is also absorbed in the low density corona.
- This energy is primarily absorbed in the electrons, causing their temperature to be higher than that of the ions.
- Also, the shock traveling into the fuel has a temperature spike from shock heating, and a noticeable rise in the density.
- For the near term, the picture will have the implosion continuing, with the shock moving to the left.



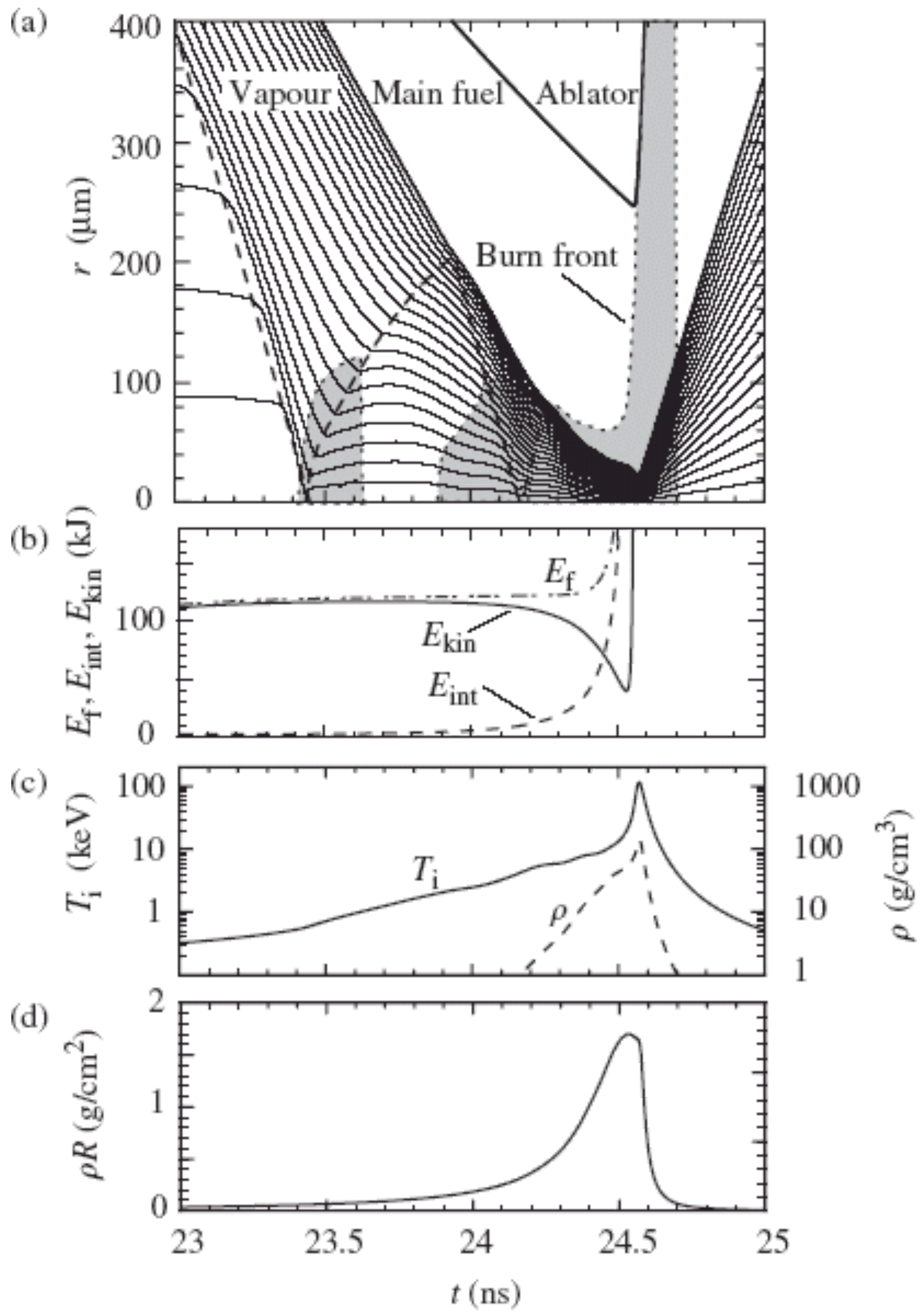
Stagnation, Burn, and Expansion

- At 24.5 ns, the shell hits the center and comes to rest.
  - The fuel pressure reaches 250 Gbar,
  - A hot spot with peak temperature about 10 keV and confinement parameter $\rho R \simeq 0.25$ g/cm^2 has formed in the center.
- The colder fuel surrounding the hot spot has been compressed to $\rho \simeq$ 400 g/cm^3 .
  - At stagnation, ignition occurs in the central hot spot.
- A burn wave moves outwards, igniting the whole fuel,
  - The fuel expands rapidly.
  - The fuel remains confined and burns efficiently for a time interval of about 50 ps.
  - About 19% of the fuel is burnt, and 105 MJ of fusion energy are released, corresponding to a target gain of G = 65.



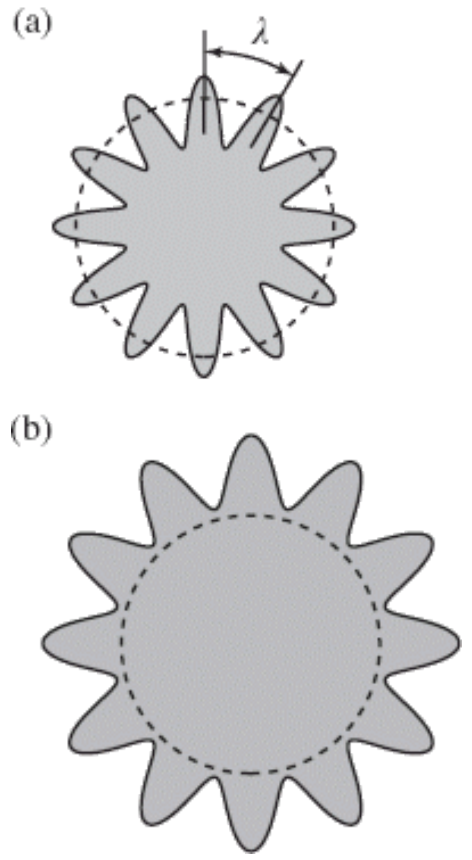
Details of the burn

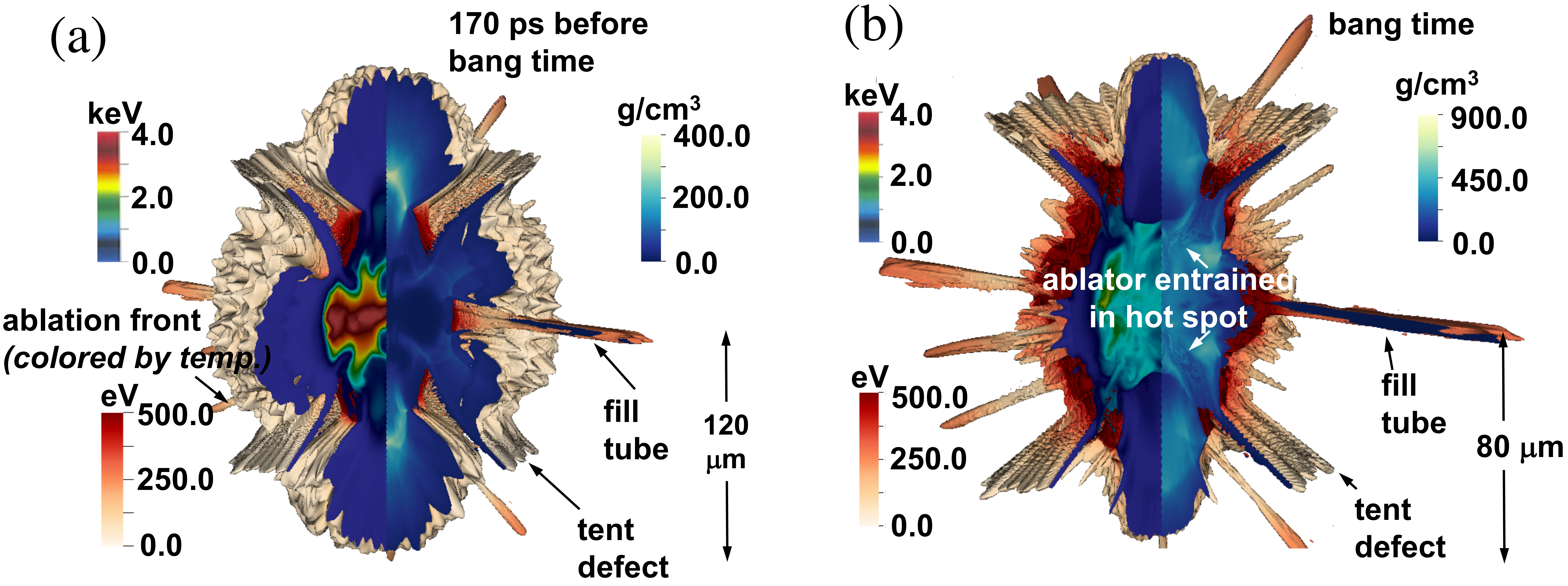
- If we zoom in on the time near the hot spot formation we notice several phenomenon.
- The shading on part (a) of the figure indicates regions where the ion temperature is greater than 4 keV, and fusion is taking place.
- Stagnation is indicated by the horizontal lines between 23.5 and 24 ns.
- The thick dashed lines in (a) are shocks. We can see the shock reaching the center just before 23.5 ns, reflecting out, and then reflecting off the outer surface of the capsule.
- When this shock returns toward the origin, the fuel is compressed to a very high areal density, and the kinetic energy of the material is converted to internal energy (see panel b).
- At about 24.5 ns we reach the maximum compression and just before the expansion we reach the minimum kinetic energy of the system.
    - This is the so-called “bang time” because from this point forward the kinetic energy rapidly increases as the fuel explodes outward.



It looks so easy, what’s the problem.

- There are two problems with the scenario we just talked through.
  - Stability/Symmetry
  - Delivering energy to the capsule
- The simulation we just walked through assumed that the energy is deposited in the capsule in a spherically symmetric way.
- If we are shining laser light on the target, this would assume that we can irradiate the target uniformly using a number of laser beams.
- Any asymmetry in the irradiation will lead to a non-uniform implosion.
- Long-wavelength perturbations could affect the hot spot size and cause the implosion to fissile.
  - In the figure, the dashed circle is the required hot spot size.
  - Depending on the perturbation wavelength, the effective hotspot size might be too small
- More problematic are Rayleigh-Taylor instabilities that can amplify small asymmetries.
  - The surface is inherently RT unstable because the dense surface is being accelerated by the ablating material.

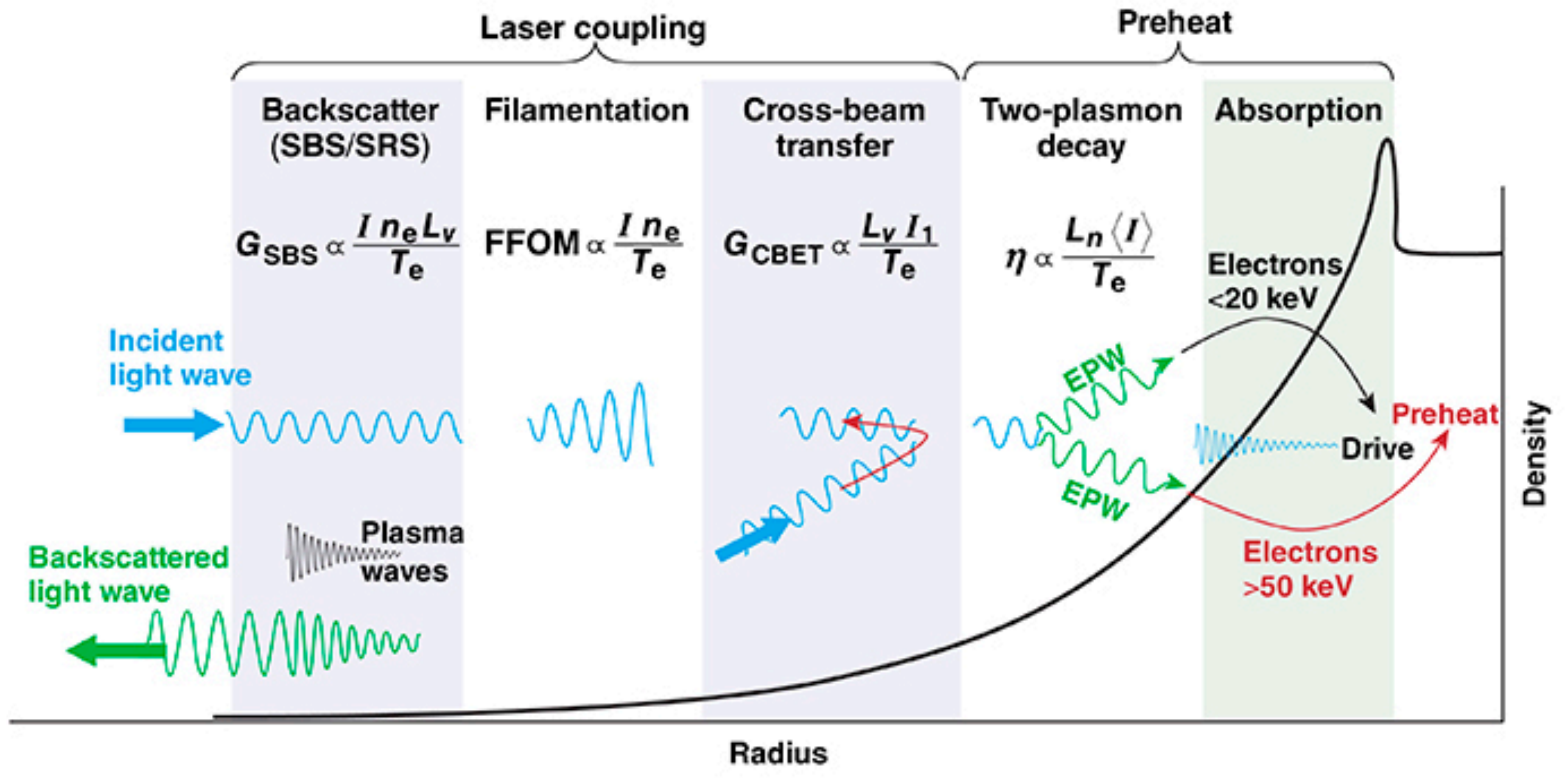




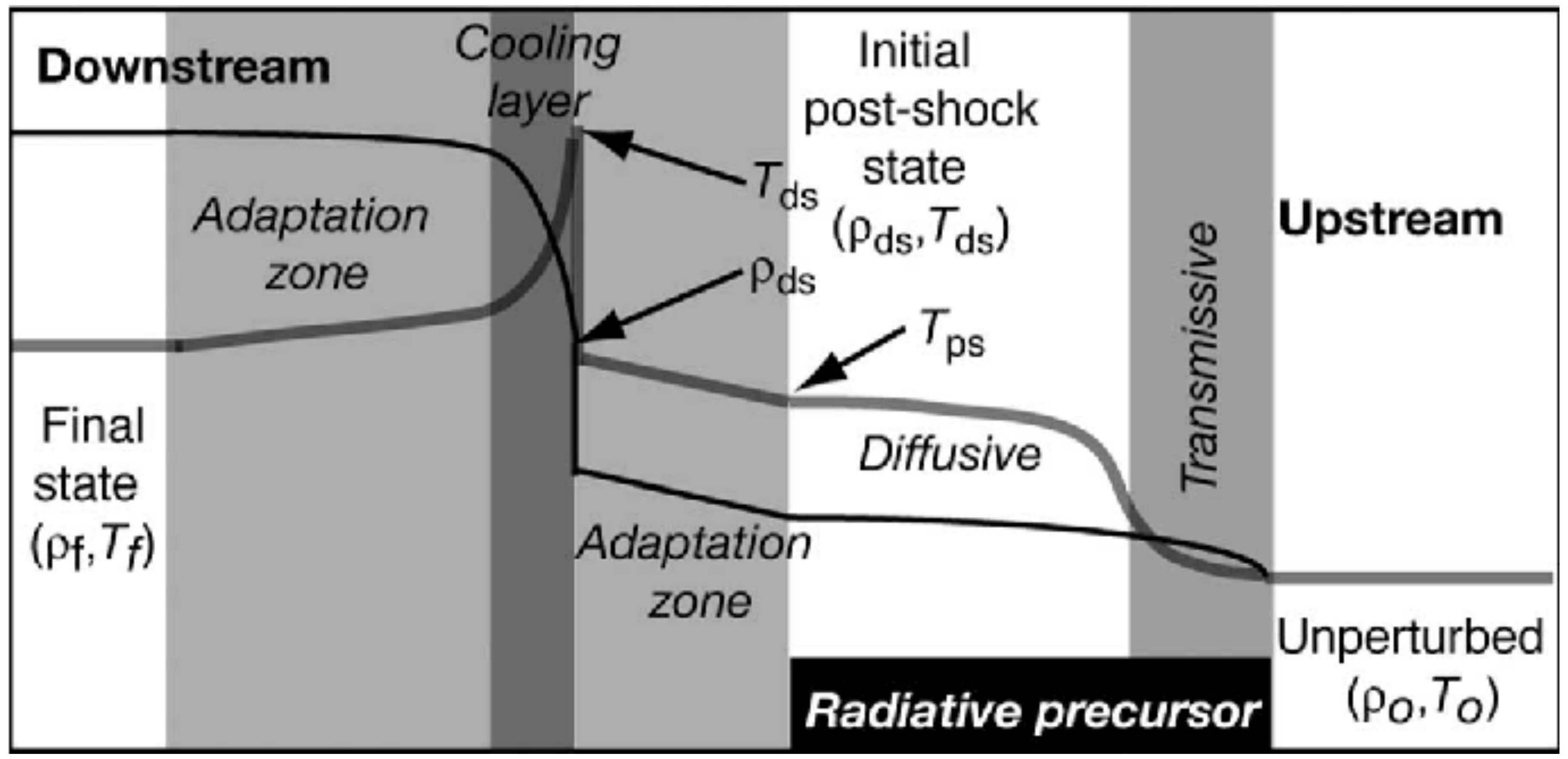
(a)
170 ps before
bang time
keV
4.0
2.0
0.0
g/cm3
400.0
200.0
0.0
ablation front
(colored by temp.)
eV
500.0
250.0
0.0
fill
tube
tent
defect
120
μm
(b)
bang time
keV
4.0
2.0
0.0
g/cm3
900.0
450.0
0.0
ablator entrained
in hot spot
eV
500.0
250.0
0.0
fill
tube
tent
defect
80 μm

We are really only scratching the surface here.

- The creation of fusion conditions involves a host of physical processes that must be understood.
- Laser-plasma interactions: how lasers interact with the target, whether direct or indirect drive, is crucial to understanding the fusion experiments.
  - Additionally, the target will be changing shape during laser irradiation due to ablation.
    - For direct drive this is especially important because the target will be shrinking.
    - In indirect drive, the ablated plasma can block the incoming laser light from reaching the hohlraum walls.
- The conversion of laser to x-ray energy in the holhraum and the effect of the laser spots on the evolution also have a complicated interaction.
- The hydrodynamics of the implosion and the heating of the hohlraum are both in the radiation-hydrodynamics regime.
  - This means that the thermal radiation produced by the material is comparable with the energy or energy fluxes of hydrodynamic motion.
  - The resulting dynamics of the system cannot be properly modeled without taking this radiation into account.
  - One consequence of this is that material upstream of a shock “knows” a shock is coming because the radiation travels in front of the shock, heating the upstream material.
  - This can allow compression to be larger than in non-radiating shocks.



https://www.lle.rochester.edu/index.php/education/research-areas/plasma-ultrafast-science-engineering/laser-plasma-interactions/



Drake, 2007