Introduction to Inertial Confinement Fusion (ICF)

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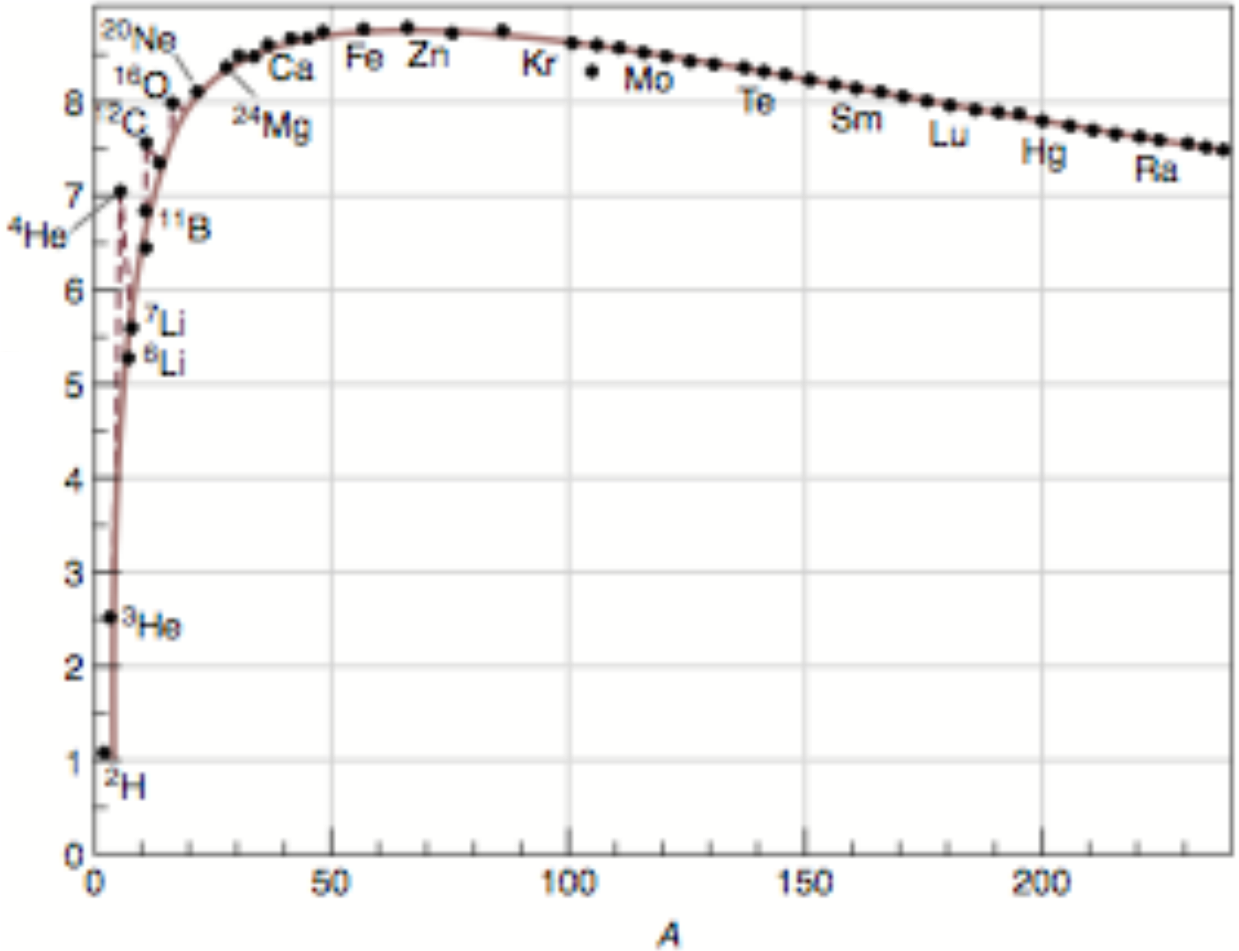
The voyage of nuclear fusion has started about 60 years ago (Sacharov, Teller, ...) and despite many progress has mainly provided disillusions...

50 years ago the laser was invented, opening the field of "Inertial Fusion" (Basov, Nuckolls, ...)

Today we are probably close to the demonstration of ignition, the scientific feasibility of fusion, which will conclude the first part of this travel.

Weizsaker semiempirical mass formula

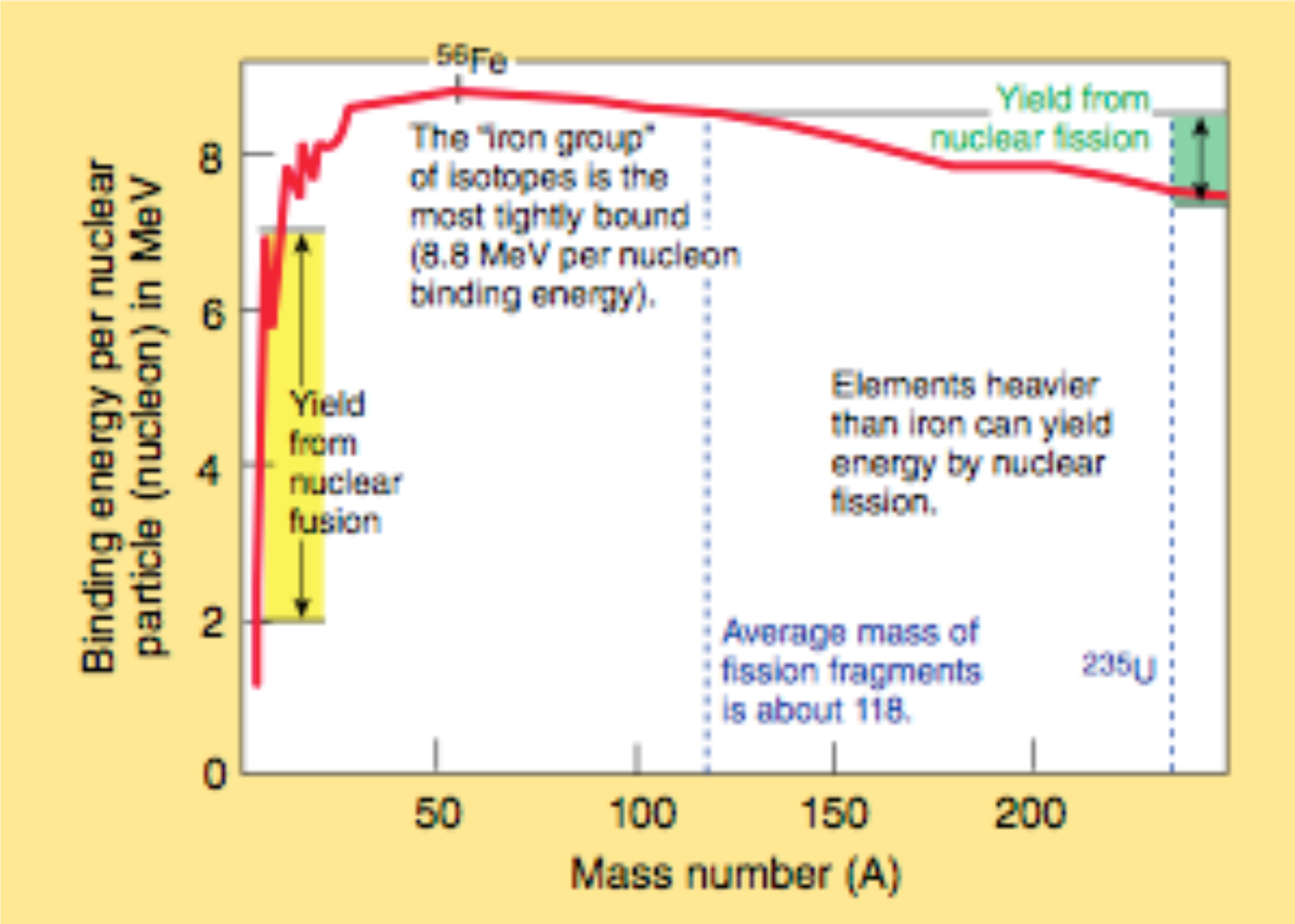


$$B_Z^A = \Delta m_Z^A c^2/A$$

Fig. 11-10 The binding energy per nucleon versus atomic mass number *A*. The solid curve represents the Weizsäcker semiempirical binding-energy formula, Equation 11-12.

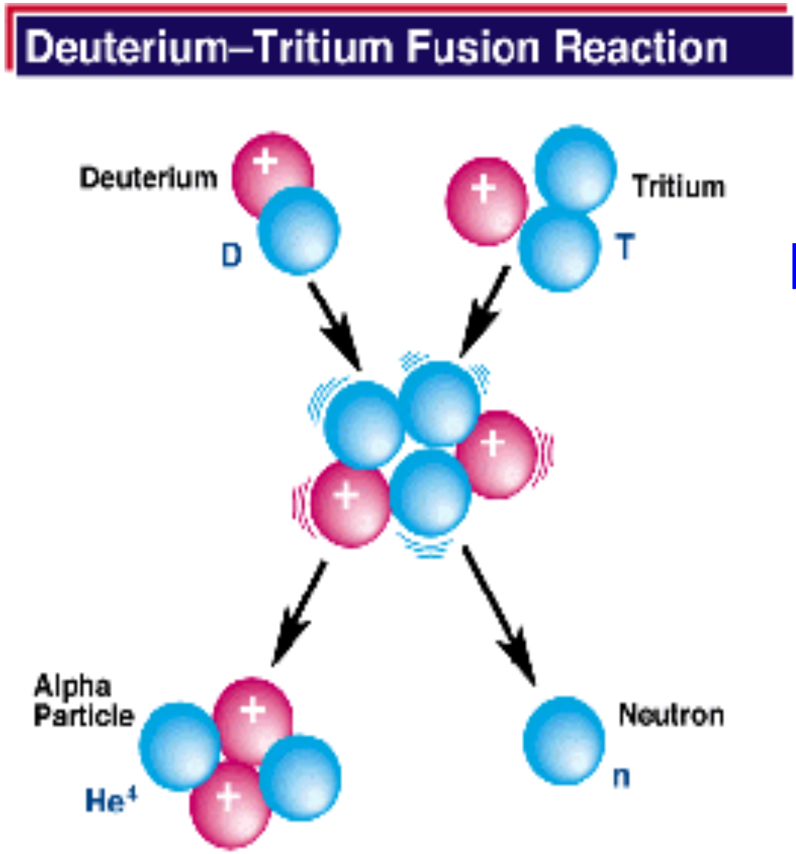
$$\Delta m_Z^A = Z m_p + (A - Z) m_n - m_Z^A.$$

Weizsaker semiempirical mass formula



$E=mc^2$

Thermonuclear Fusion:

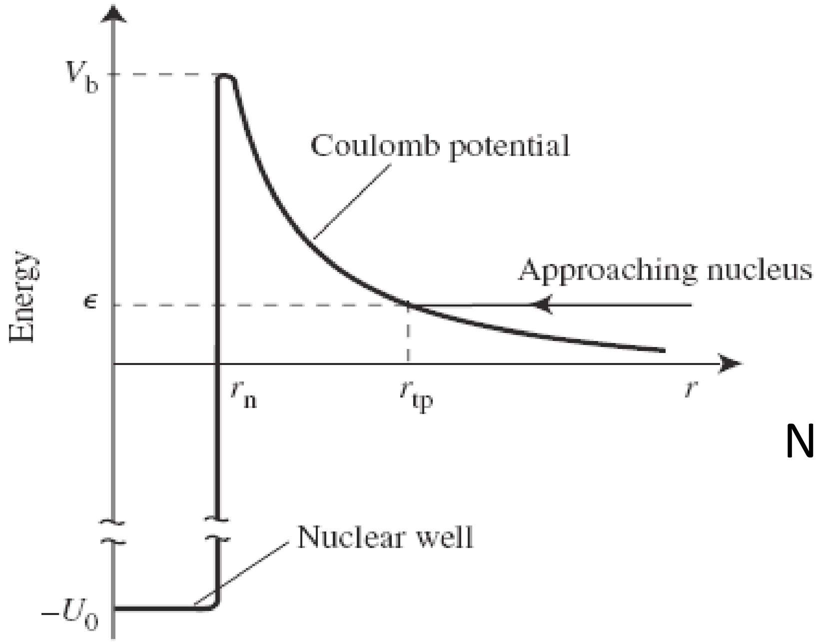


D + T → He^4 + n + 17,6 MeV

1/5 (17.6 MeV) = 3.5 MeV
for the α particle

4/5 (17.6 MeV) = 14.1 MeV
for the neutron

Coulomb repulsion:



- $$V_{Coulomb} \cong \frac{Z_1 Z_2 e^2}{4\pi\varepsilon_0 (R_1 + R_2)}$$

Nuclear radius depends on *A* as

- $$R_i \cong 1.4\ 10^{-15} A_i^{1/3}$$

The energy threshold ≈ 400 KeV, i.e. T≈ 4.6 10^9 K (1 eV = 11400 K). For comparison T≈ 1.6 10^7 K at sun core.

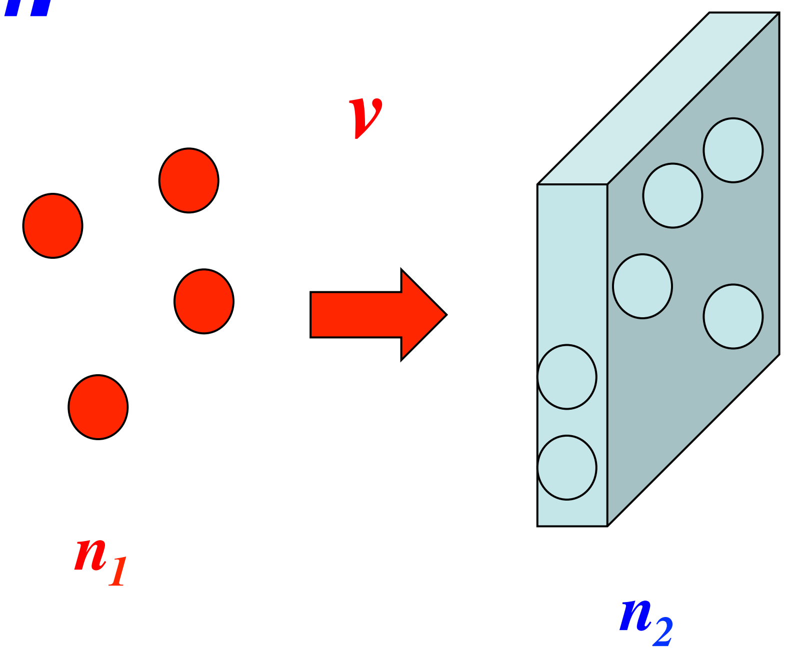
➔ Tunnel effect

Reaction probability and cross section:

$$\frac{dn}{dt} = \sigma(v)v\, n_1 n_2$$

n_1, n_2 densities of particles of species 1 and 2 (#/cm^3)

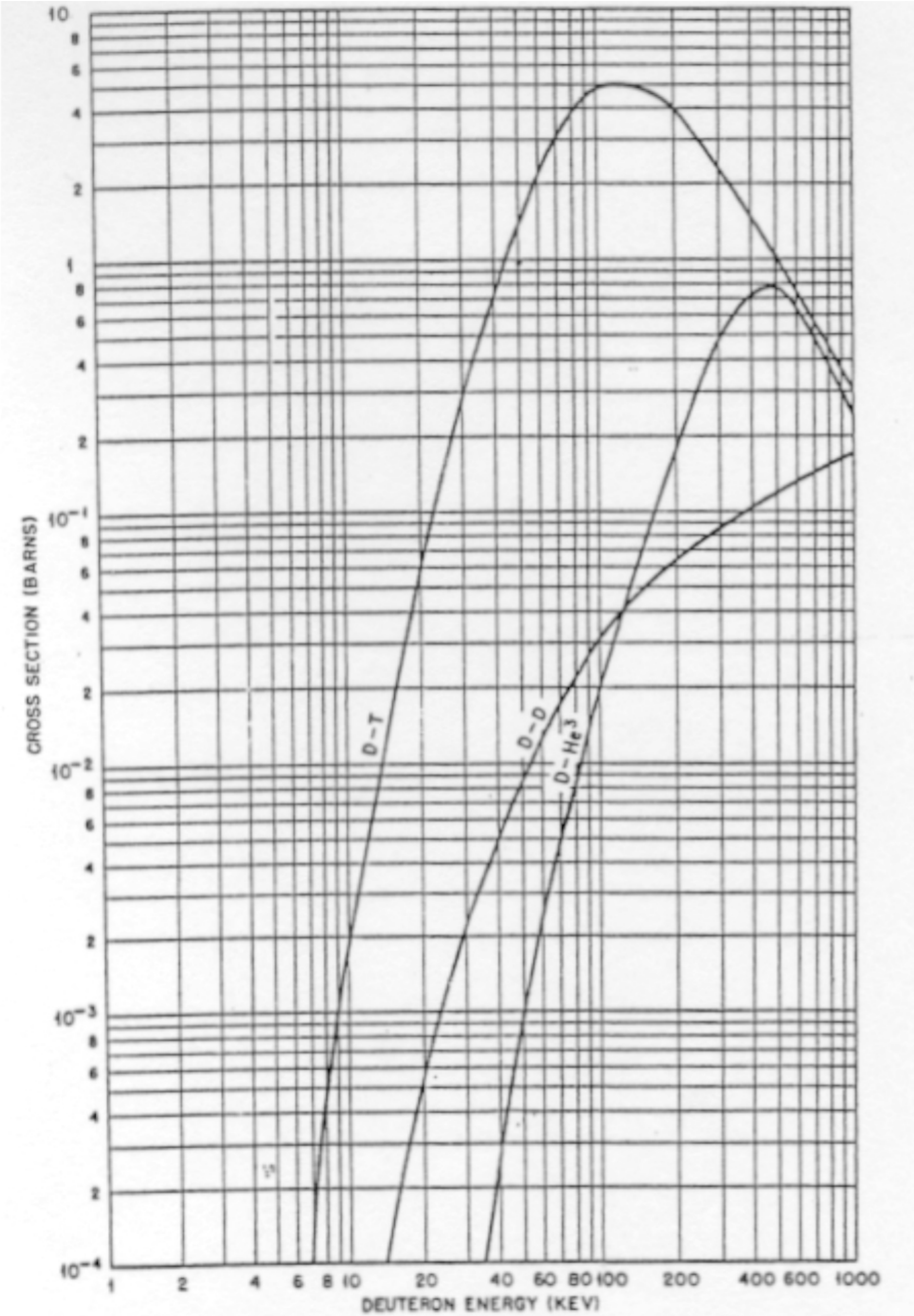
dn/dt number of reaction per unit volume and unit time



$n_1 v$ = #/cm^{2}sec = flux of incident particles

σ has the units of surface (cm^2)

$n_1 \sigma$ = total "covered" surface per unit volume.



Cross sections for D-T, D-D (total), and D-He³ reactions.

$D + D \rightarrow T + H^1 + 4{,}03$ MeV

$D + D \rightarrow He^3 + n + 3{,}27$ MeV

$D + He^3 \rightarrow He^4 + H^1 + 18{,}3$ MeV

$D + T \rightarrow He^4 + n + 17{,}6$ MeV

D-T fusion reaction has a larger probability and peaks at lower energy

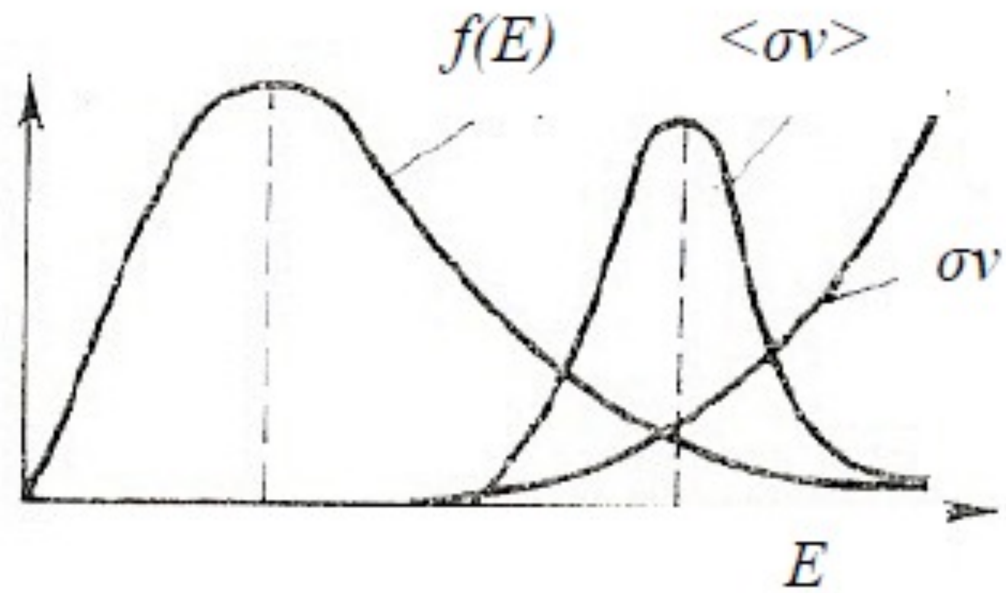
Reaction rate:

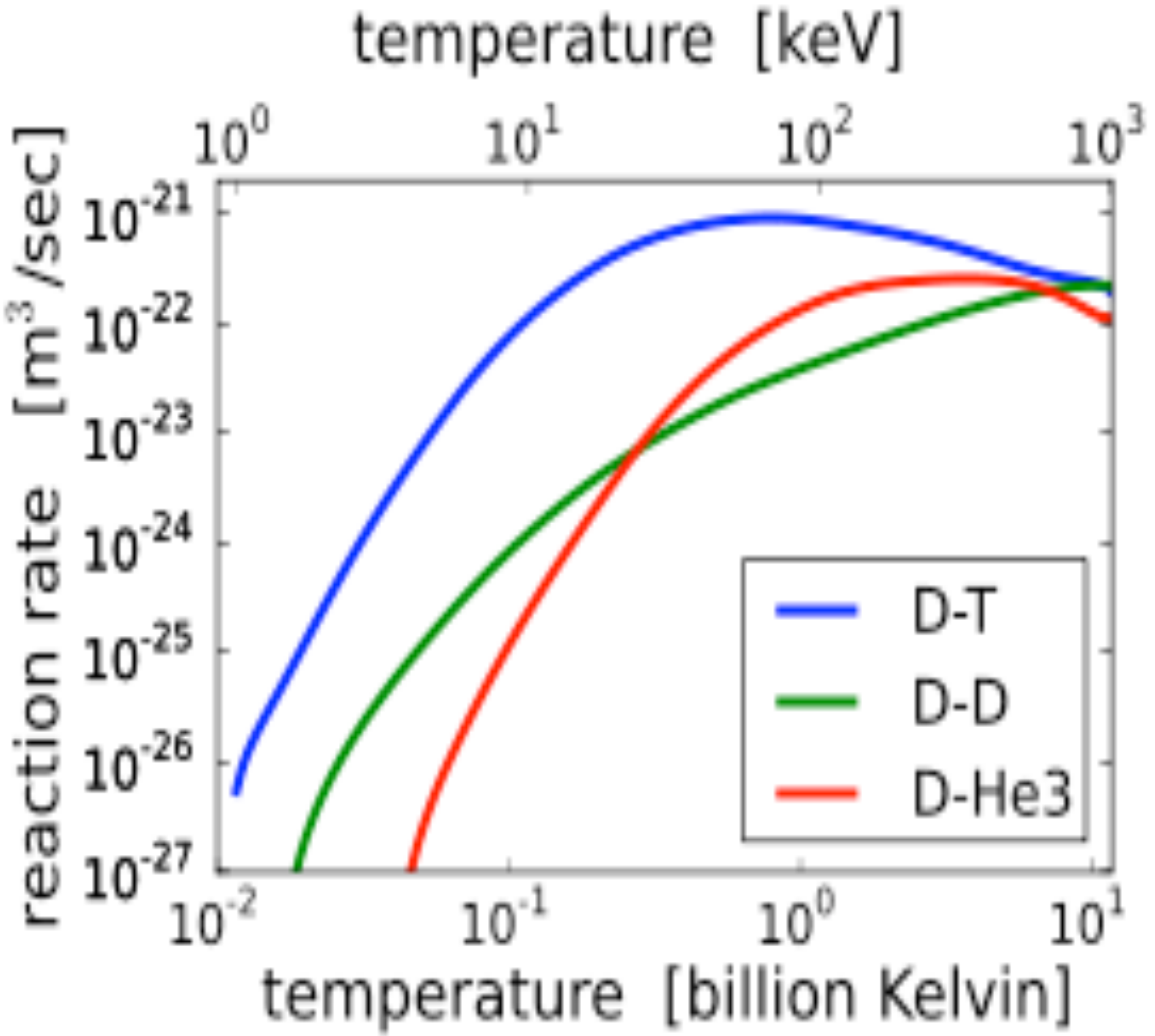
In a plasma we must average the cross section over the distribution of velocities

$$f_M(v) = (2\pi)^{-3/2} \exp(-m_r v^2/2T)$$

$$\langle \sigma v \rangle = 4\pi \int_0^\infty v^3 \sigma(v)\, f_M(v)\, dv.$$

At low temperature the main contribution to fusion reactions comes from ions in the distribution tail





Fusion needs high temperatures (T> 5 keV)

10^9 K ≈ 10^5 eV =100 keV

Reaction rate:

DT reaction

$$\langle \sigma_{DT} v \rangle \simeq 9.1 \times 10^{-16} \exp\left(-0.572 \left|\ln(T_{\mathrm{keV}}/64.2)\right|^{2.13}\right) \mathrm{cm}^3/\mathrm{s}.$$

3-100 keV

$$\langle \sigma_{DT} v \rangle \simeq C_{DT}^{b} T^3 = 1.1 \times 10^{-19} T_{\mathrm{keV}}^3 \, \mathrm{cm}^3/\mathrm{s}.$$

3-8 keV

$$\langle \sigma_{DT} v \rangle \simeq C_{DT} T^2 = 1.1 \times 10^{-18} T_{\mathrm{keV}}^2 \, \mathrm{cm}^3/\mathrm{s}.$$

8-20 keV

DD reaction

$$\langle \sigma_{DDn} v \rangle \simeq 2.7 \times 10^{-14} T_{\mathrm{keV}}^{-2/3} \exp\left(-19.8 T_{\mathrm{keV}}^{-1/3}\right) \mathrm{cm}^3/\mathrm{s}.$$

3-50 keV

Plasma conditions for fusion: confinament time

Confinament time: $$\tau = \frac{W}{P_{losses}}$$

W = internal energy per unit volume (J/m^3)

P_{losses} = dissipated power per unit volume (this is mainly radiation losses due to bremsstrahlung).

τ = the time over which the system is able to keep its energy)

$$W = \frac{3}{2}\left((n_e + n_i)kT\right) = 3n_e T(eV)$$

Rate of energy production

$$P_{fusion} = n_D n_T \langle \sigma v \rangle E_\alpha = 4n_e^2 \langle \sigma v \rangle E_\alpha$$

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LAWSON'S CRITERIUM

$$P_{fusion} > P_{losses} \qquad \Rightarrow \frac{1}{4} n_e^2 \langle \sigma v \rangle E_\alpha > 3 n_e T / \tau$$

$$\Rightarrow n_e \tau > 12T / \langle \sigma v \rangle E_\alpha \equiv L$$

$<\sigma v>$ depends on T.

[$E_\alpha = 3.5$ MeV]

$$L \equiv 12T / \langle \sigma v \rangle E_\alpha$$

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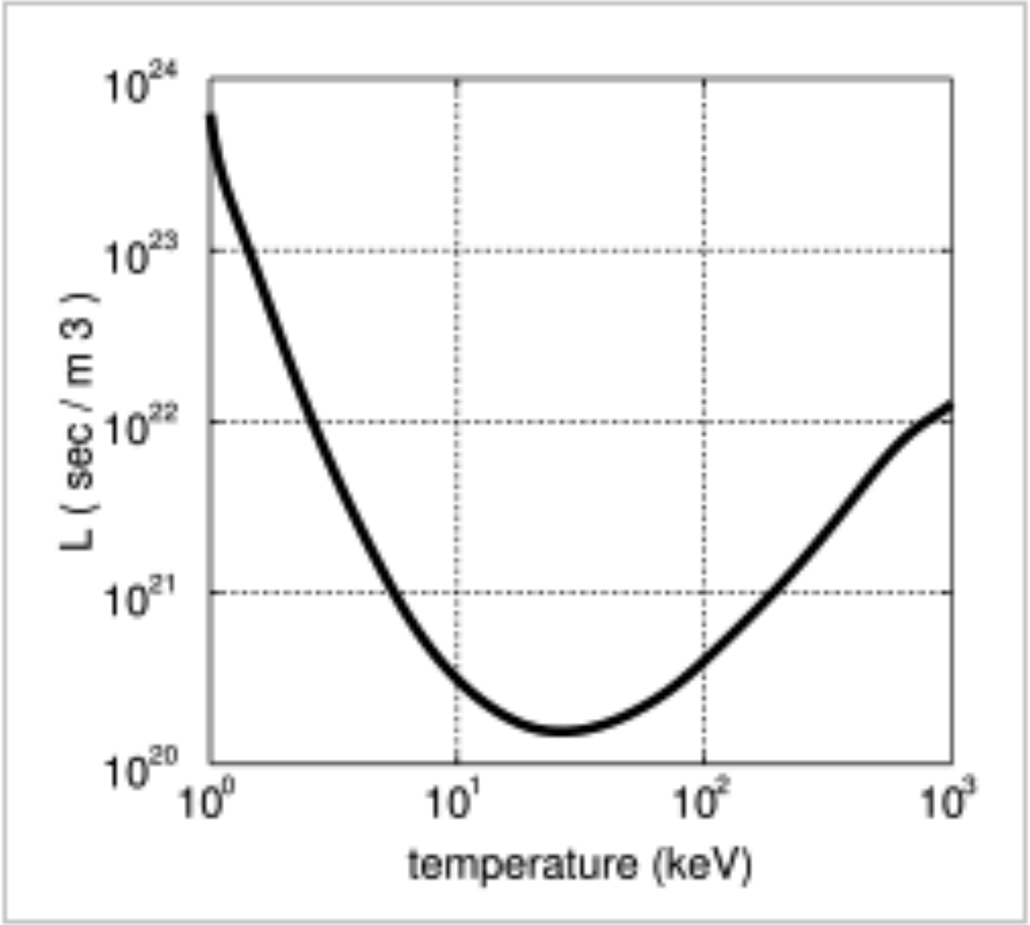


Is function of T and has a minimum at ≈ 25 keV ($2.9 10^8$ K)

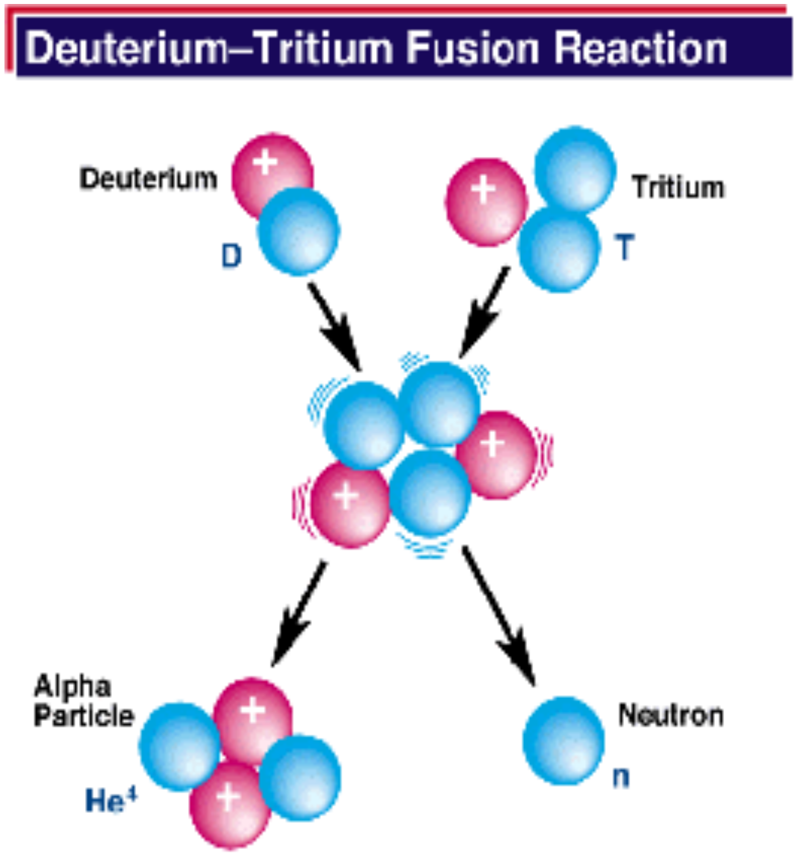
for $D + T \rightarrow {}^4He + n$

The deuterium-tritium L function (minimum $n_e\tau_E$ needed to satisfy the Lawson criterion) minimizes near the temperature 25 keV (300 million kelvins).

For D-T at T = 25 KeV, **Lawson's criterium** is :

$$n_e \tau > 1.5 \cdot 10^{14} \text{ s/cm}^3$$

Thermonuclear Fusion:



- **Need to have high temperatures to overcome Coloumb repulsion**

  $T_{min} \approx$ 5 - 10 keV

- **Need to have many fusion reactions to allow for energy gain, i.e. large number of particles and/or long confinement time.**
  Lawson's criterium

  $n_e \tau \approx 1.5\ 10^{14}$ s cm^{-3}

"Triple product" $n_e\tau T$ $\geq$ 8 1014 s cm^{-3} keV

Creating conditions for fusion:

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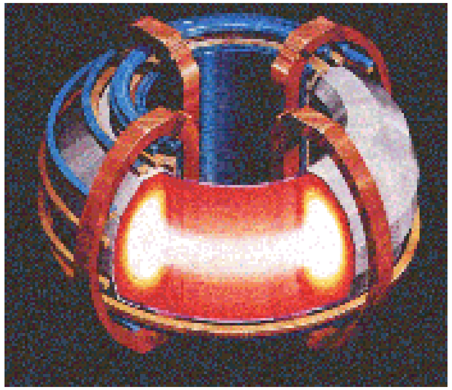
Gravitational Confinement

Heating Mechanisms:
* Compression (gravity)
* Fusion Reactions (such as the p-p chain)

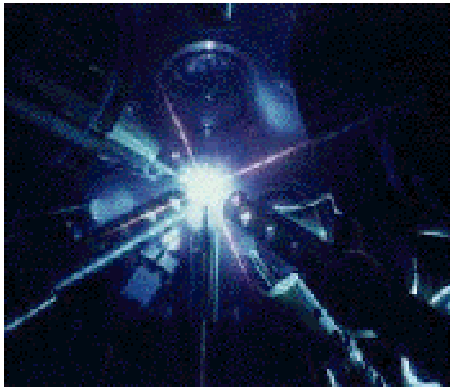
Magnetic Confinement

* Electromagnetic Waves
* Ohmic Heating (by electric currents)
* Neutral Particle Beams (atomic hydrogen)
* Fusion Reactions (D+T)



Inertial Confinement

* Compression (implosion driven by laser, or by X-rays from laser, or by ion beams)
* Fusion Reactions (primarily D+T)



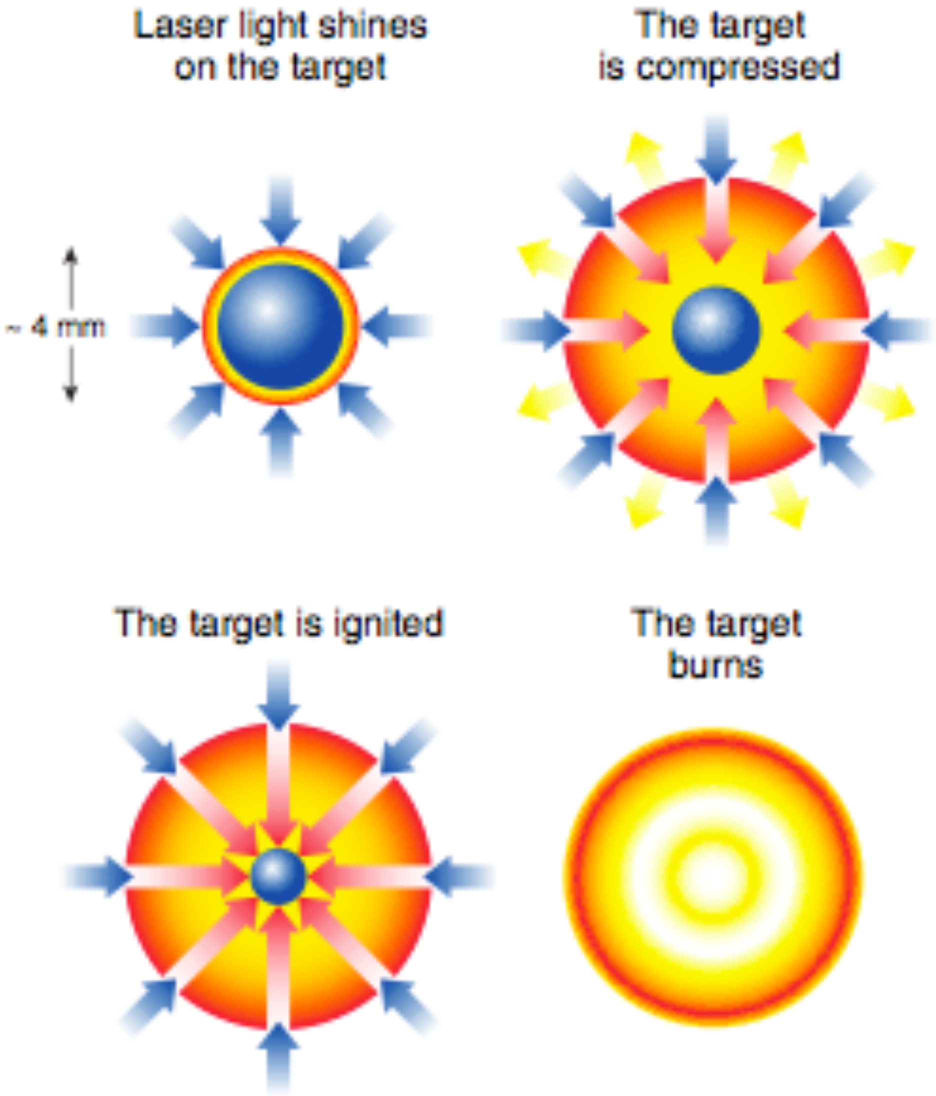
Creating conditions for fusion:

The secondary system (H-bomb) is ignited by the explosion of a "conventional" nuclear bomb

For controlled nuclear fusion:

- Need to ignite small mass of fuel
- Need to ignite with different tools!

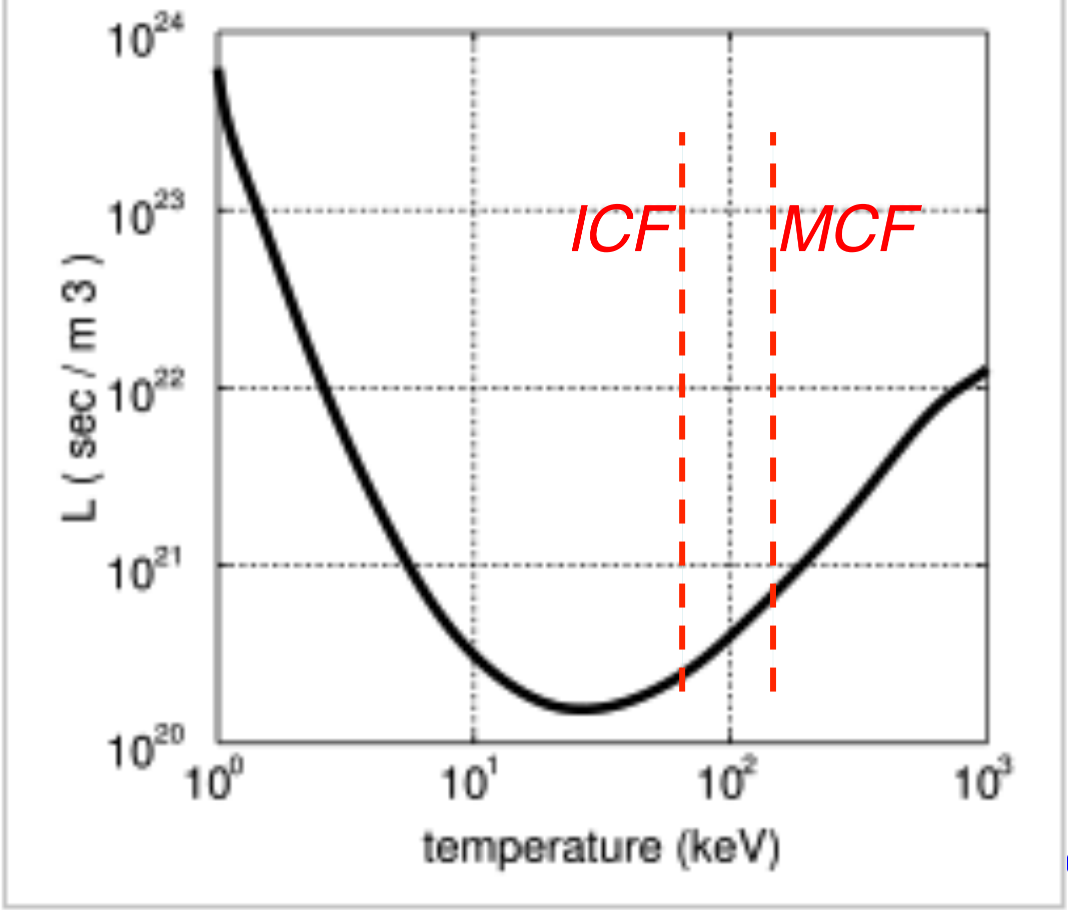
Principio del Confinamento Inerziale



Lawson’s criterium for inertial fusion

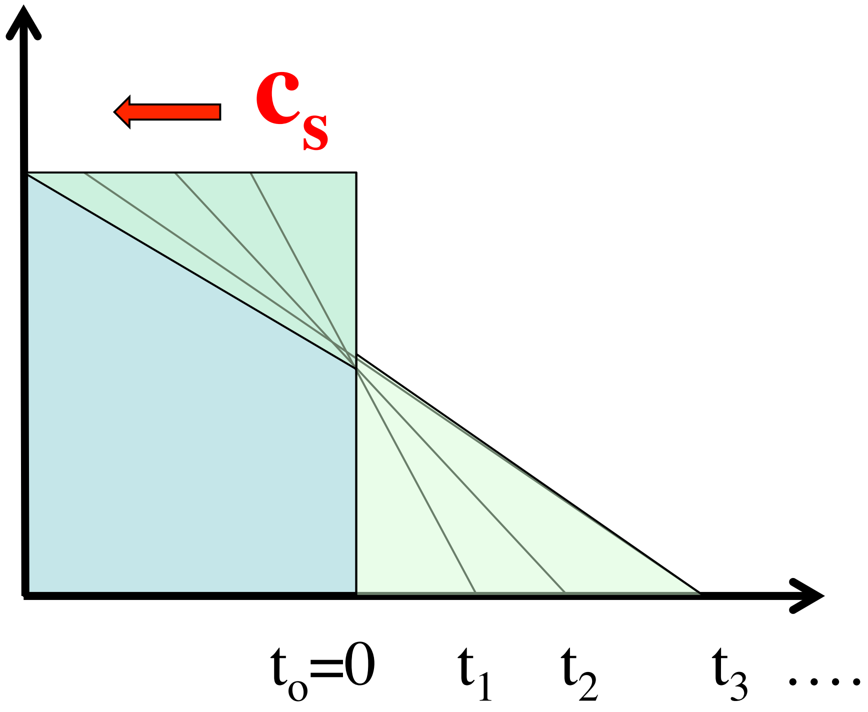
In ICFwe cannot reach 25 keV. Then

$n_e \tau \approx 6\ 10^{14}$ s cm^{-3}



Isothermal expansion of a gas

Rarefaction (expansion) wave
Self-similar model



$$n(x) = n_o \exp(-x/L)$$

$$L = c_s \ t$$

$$c_s = \left(\gamma ZkT/m\right)^{1/2}$$

Lawson's criterium for inertial fusion

$n_e \tau \approx 6\ 10^{14}$ s cm^{-3}

Disassembly time determined by the fuels inertia

$$\tau < R / c_s \qquad \Rightarrow \quad \text{we take } \tau = R / 4c_s$$

ion sound velocity in a plasma

$$c_s = \left(\gamma Z k T_e / m_i\right)^{1/2} = 9.8 \quad 10^5 \left(\gamma Z \ T_e(eV) / \mu\right)^{1/2} cm / s$$

$$\approx 7 \quad 10^7 \quad cm / s \quad (\text{for } \ \text{T} = 10 \text{ keV})$$

Notice:

in magnetic fusion the time τ expresses the *confinement of energy*

In inertial fusion it refers to the *confinement of mass*

Lawson's criterium for inertial fusion

$n_e \tau \approx 6\ 10^{14}$ s cm^{-3}

Disassembly time determined by the fuels inertia

$$\tau = R/4c_s \qquad c_s \approx 7 \quad 10^7 \quad cm/s \quad (\text{for} \quad \mathrm{T} = 10\ \text{keV})$$

$$n_e = n_i = 2 \times \frac{\rho(\text{g/cc})}{2.5}\ 6.022 \quad 10^{23} cm^{-3} = 4.8\rho \quad 10^{23} cm^{-3}$$

$$n_e \tau = 1.5 \quad 10^{14} = \left(4.8\rho \quad 10^{23}\right)\left(R/4 \times 7.6 \quad 10^7\right)$$

For typical ICF conditions

$$\Rightarrow \rho R = 1.5 \ \ 10^{14} \times 4 \times 7\ 10^7 / 4.8 \quad 10^{23} \approx 0.3 \text{ g/cm}^2$$

Maximum released energy

$$\mathcal{E}_{\text{fus}} = \varepsilon_{DT} N_f = \frac{M_f}{2m_i} \Phi_B \varepsilon_{DT} = 3.4 \times 10^5 \Phi_B M_f$$

Φ_B "burned fraction" of the fuel

M_f mass of fuel (in g)

$\mathcal{E}_{\text{fus}}$ fusion energy

ε_{DT} energy released in one reaction (17.6 MeV)

A few mg of DT are sufficient to produce an energy of several 100 MJ

To satisfy Lawson's criterion ($\rho R > 0.3$ g/cm^2) at the density of solid D-T (ρ_{sol} = 0.25 g/cm^3) would require R = 1 cm. This implies a large explosion.

Burning fraction in ICF

We need to calculate the "burned fraction" of the fuel

$$R(t) = R_f - c_s t \qquad t_{\max} = R_f / c_s$$

$$N_{tot} = \frac{1}{2} n_i V_f \qquad n_D = n_T = n_i / 2 \qquad V_f = \frac{4\pi}{3} R_f^3$$

$$N_f = n_D n_T \langle \sigma \mathrm{v} \rangle \int_0^{t_{\max}} \frac{4\pi}{3} \left(R_f - c_s t \right)^3 dt =$$

$$= \frac{4\pi}{3} n_D n_T \langle \sigma \mathrm{v} \rangle \left[-\frac{1}{4 c_s} \left(R_f - c_s t \right)^4 \right]_0^{t_{\max}} = \frac{\pi}{3} n_D n_T \langle \sigma \mathrm{v} \rangle \frac{R_f^4}{c_s}$$

$R(t) = R_f - c_s t$ $\quad t=0$ $R=R_f$ $\quad t=t_{max}$ $R=0$

Burning fraction in ICF

$$N_{ion} = \rho_f V_f / m_i = n_i V_f$$ total number of ions

$$N_{tot} = N_{ion} / 2$$ maximum number of reactions

$$N_f = \frac{\pi}{3} n_D n_T \langle \sigma \mathrm{v} \rangle \frac{R_f^4}{c_s} = \frac{1}{4m_i} \left[\left(\frac{4\pi}{3} R_f^3 \right) m_i n_i \right] \langle \sigma \mathrm{v} \rangle n_i \frac{R_f}{4c_s}$$

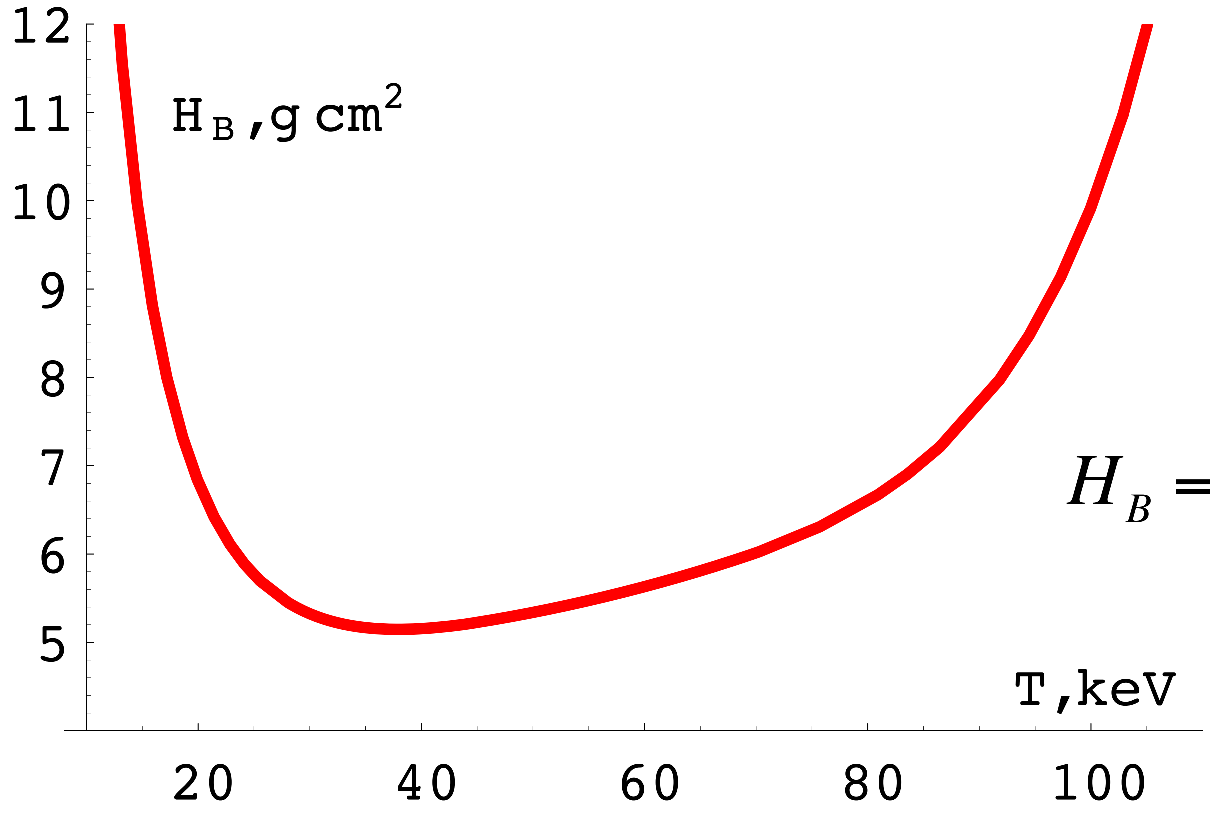
$$= \frac{1}{4m_i} \left[\rho_f V_f \right] \langle \sigma \mathrm{v} \rangle n_i \frac{R_f}{4c_s} = \langle \sigma \mathrm{v} \rangle N_{ion} \frac{R_f}{16c_s} = \langle \sigma \mathrm{v} \rangle N_{tot} \frac{R_f}{8c_s}$$

$$\Phi_B = \frac{N_f}{N_{tot}} = n_i \langle \sigma \mathrm{v} \rangle \frac{R_f}{8c_s} = n_i m_i \langle \sigma \mathrm{v} \rangle \frac{R_f}{8c_s m_i} = \frac{\rho_f R_f}{H_B}$$

$$H_B = \frac{8 m_i c_s}{\langle \sigma \mathrm{v} \rangle}$$

Burning fraction in ICF

H_B "combustion parameter" for a DT plasma fuel



$$H_B = \frac{8 m_i c_s}{\langle \sigma v \rangle} \approx 6 \ \ g / cm^2$$

Burning fraction in ICF

The calculation didn't take into acount fuel consumption

$$n_f = n_{DO} - n_D$$

$$\frac{dn_f}{df} = -\frac{dn_D}{df} = n_D^2 \langle \sigma \mathrm{v} \rangle$$

$$H_B = \frac{8 m_i c_s}{\langle \sigma \mathrm{v} \rangle} \approx 6 \;\; g/cm^2$$

$$n_D(t) = \frac{n_{DO}}{1 + n_{DO} \langle \sigma \mathrm{v} \rangle t}$$

$$t_{\max} = R_f / 4 c_s$$

$$n_{DO} = n_i / 2 = \rho_f / 2 m_i$$

Burning fraction in ICF

$$n_D(t_{\max}) = \frac{n_{DO}}{1 + n_{DO}\langle\sigma \mathrm{v}\rangle\left(R_f / 4c_s\right)}$$

$$\Phi = \frac{n_{DO} - n_D(t_{\max})}{n_{DO}} = 1 - \frac{n_D(t_{\max})}{n_{DO}} = 1 - \frac{1}{1 + n_{DO}\langle\sigma \mathrm{v}\rangle\left(R_f / 4c_s\right)}$$

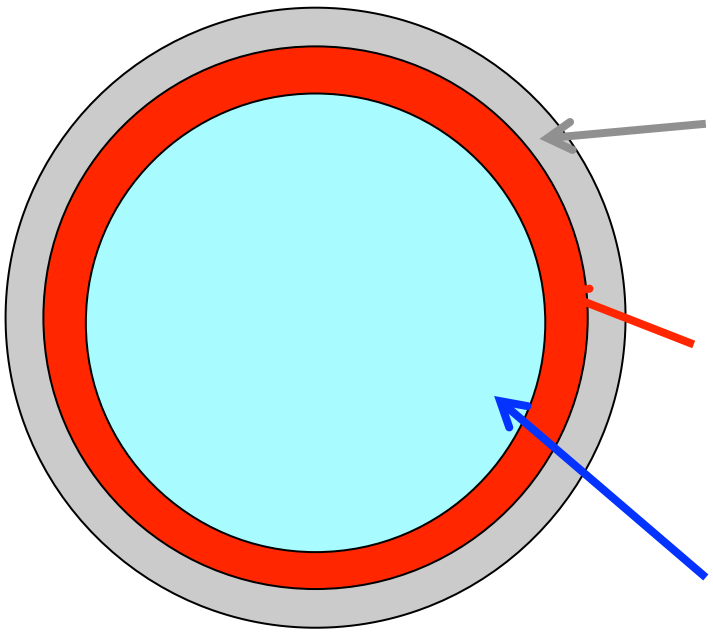
$$= 1 - \frac{1}{1_i + \left(\rho / 2m_i\right)\langle\sigma \mathrm{v}\rangle\left(R_f / 4c_s\right)} = 1 - \frac{1}{1 + \rho R_f / H_B}$$

$$= \frac{\left(1 + \rho R_f / H_B\right) - 1}{1 + \rho R_f / H_B} = \frac{\rho R_f / H_B}{1 + \rho R_f / H_B} = \frac{\rho R_f}{H_B + \rho R_f} \approx \frac{\rho R_f}{\rho R_f + 6}$$

Conventionally we take ρR ≈3 g/cm² that is 33% burned fuel

$$H_B = \frac{8 m_i c_s}{\langle\sigma \mathrm{v}\rangle}$$

ICF typical targets



“Ablator”
(plastics, SiO_2, Be, Diamond)

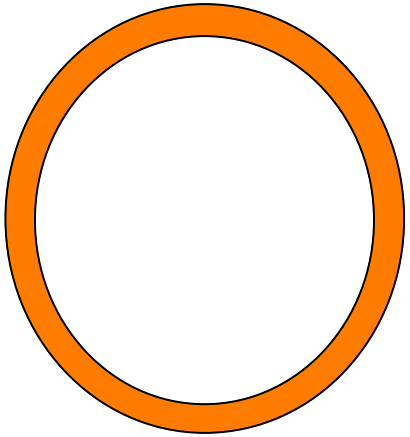
DT ice ($\rho = 0.25$ g/cm^3)
“Fuel” “Sgell”

DT gas

External radius ≈ mm

DT mass ≈ mg

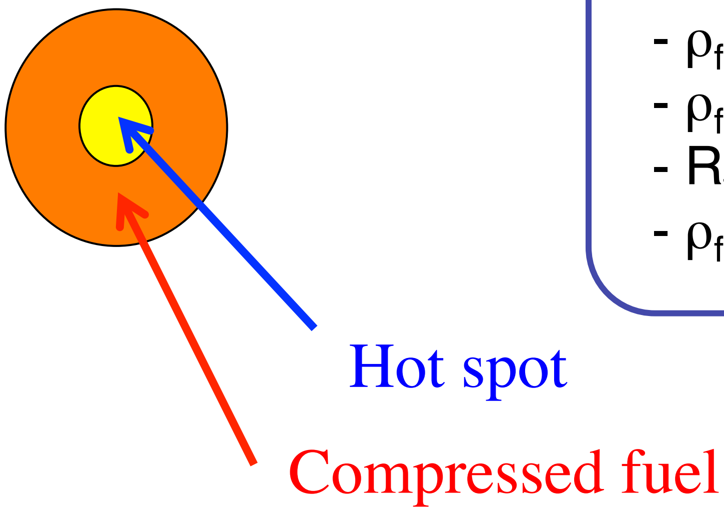
ICF typical targets



INITIAL CONDITIONS

CRYOGENIC SHELL

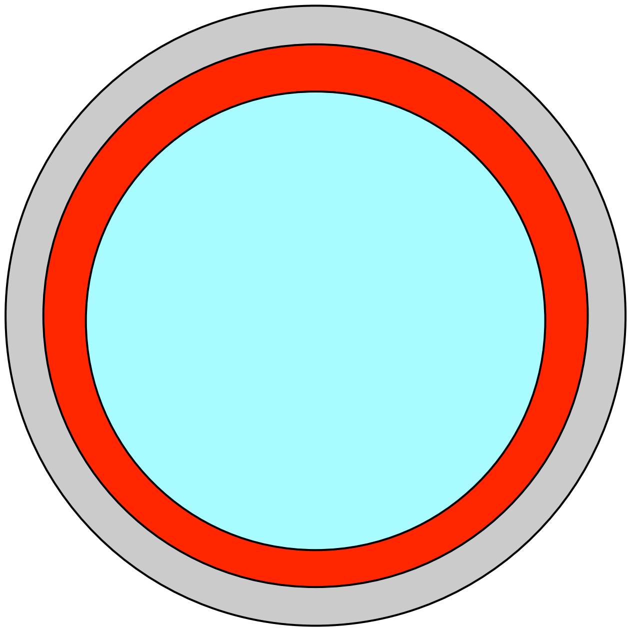
- $R_{in} \approx$ 2 mm, $R_{in} / \Delta r \approx 60$ ($\Delta r \approx 33\ \mu m$)
- $V \approx 4 \pi R_{in}^2 \Delta r \approx 1.6\ \ 10^{-3}\ cm^3$
- $\rho_{in} \approx 2.5 \times\ 0.2$ g/ cm^3, $M \approx 0.85$ mg



FINAL CONDITIONS

- $\rho_{fin} / \rho_{in} \approx 1000$
- $\rho_{fin} \approx 500$ g/ cm^3
- $R_{fin} \approx\ 74\ \mu m$
- $\rho_{fin} R_{fin} \approx 3.7$ g/ cm^2

Some orders of magnitude



If

$t_{laser} \approx t_{implosion} \approx 10$ ns

$I_L \approx 3\ 10^{14}$ W/cm^2

R≈2mm

Then

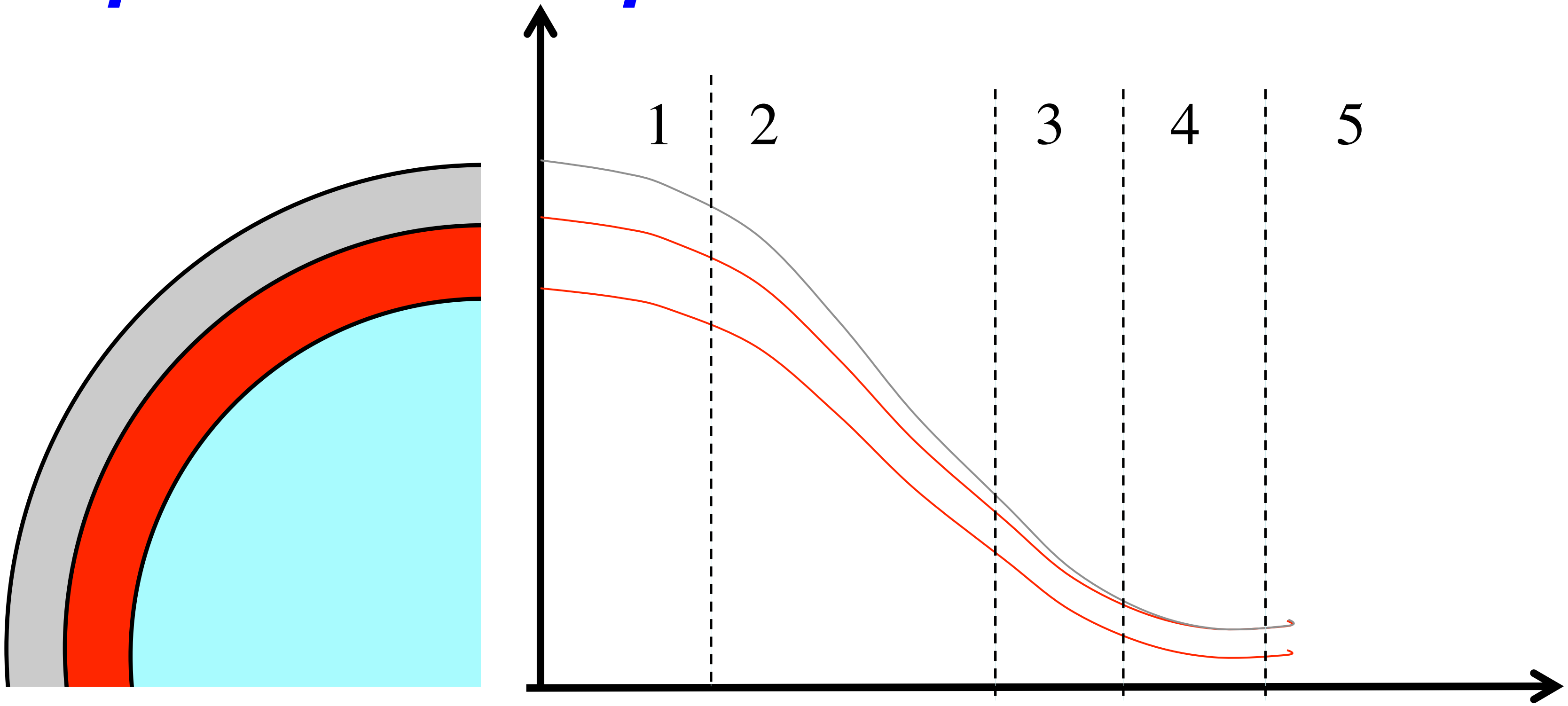
S=0.5 cm2

$E_{laser} = I_L t_{laser} S = 1.5$ MJ

$V_{implosion} = 2$ mm/10 ns

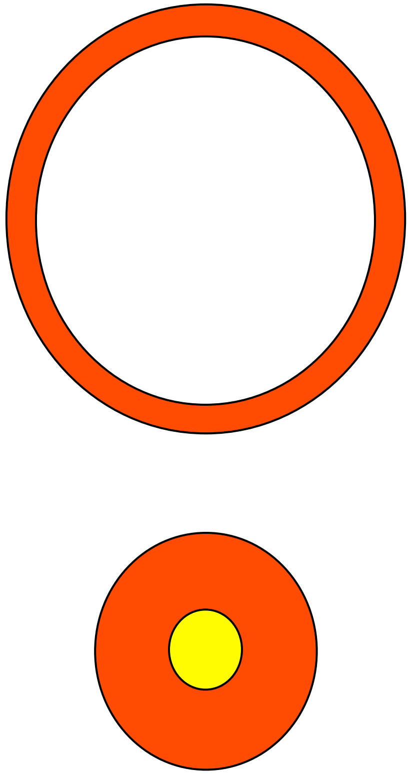
=200 μm/ns = 200 km/s

Space-time plot



1 ablation and acceleration
2 implosion (almost constant velocity)
3 deceleration
4 stagnation (creation of hot spot)
5 explosion

Why do we need a hot spot?



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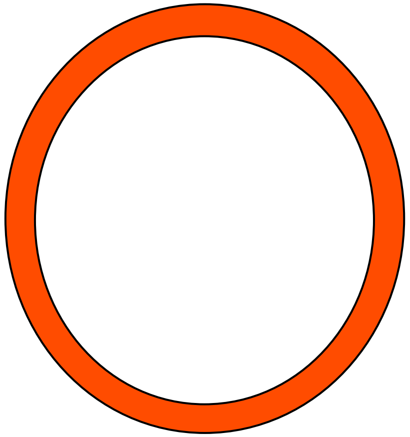
- $R_{fin} \approx 74\ \mu m$
- $\rho_{fin}\ R_{fin} \approx 3.7$ g/ cm^2

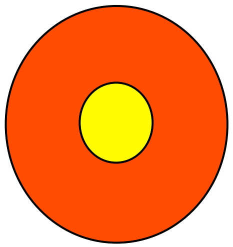
Total number of ions $N_{DT} \approx 2\ 10^{20}$

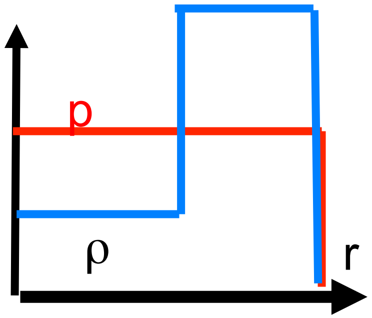
If $T_{fin} \approx 10$ keV, total thermal energy in fuel $E \approx 2\ (3/2\ N_{DT}\ T) \approx 1$ MJ !!

"Isobaric" approach to ICF



Stagnation is reached as the pressure of the internal fuel increases and gradually slows the shell down.
At stagnation $P_{shell} \approx P_{central\ spot}$



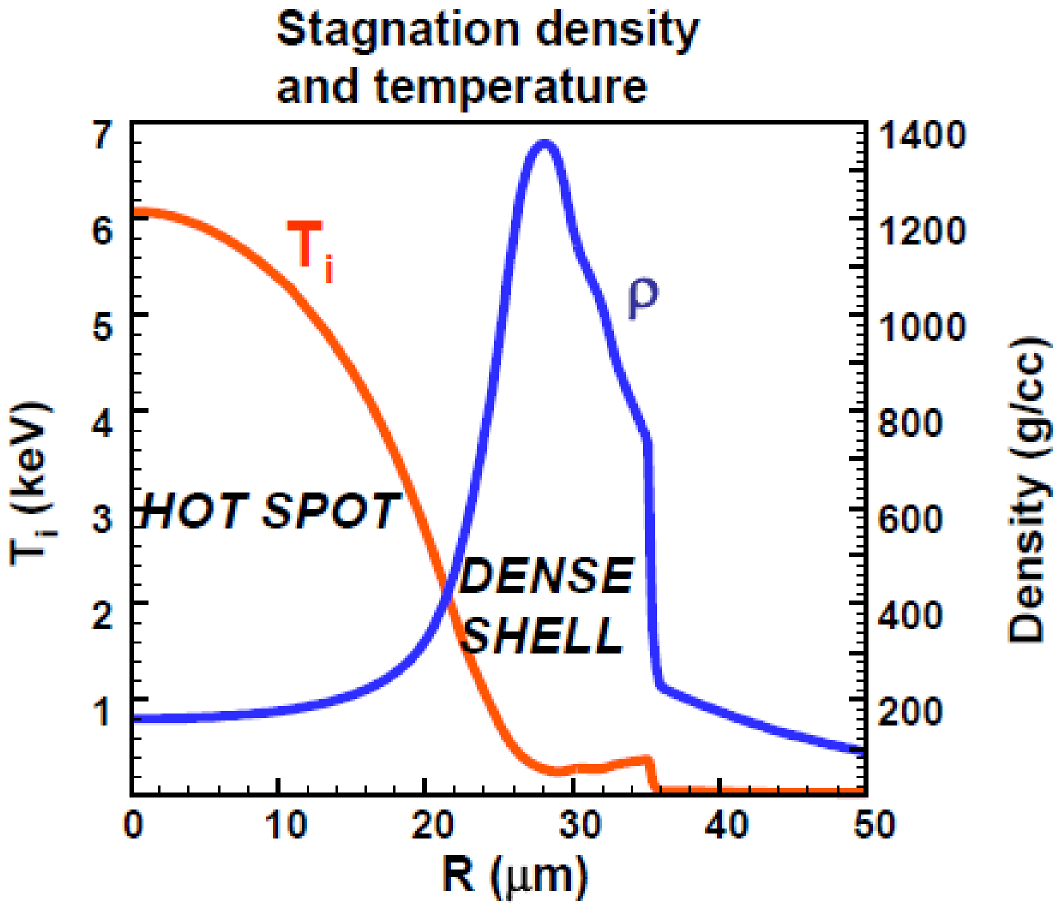


Kinetic Energy of (remaining) imploding shell is converted in:

- Compression of the fuel in the shell
- Heating of the central has

Produces an Isobaric fuel assembly
Conversion efficiency from laser ligth to kinetic energy of the shell is extremely low ≈ 5 %
Need for High Aspect ratio target and high implosion velocities
V ~400 km/s

NIF-like target (1 MJ)



$$n_e = n_i \; = 4.8\rho \quad 10^{23}\, cm^{-3}$$

$$P(Bar) = 1.8 \;\; 10^{-18} \quad n_{TOT}(cm^{-3})\; T_e(eV)$$

SHELL

-$\rho_{fin}\, R_{fin} \approx 10^3 \;\; g/\, cm^3 \times 40\, \mu m$
$= 4\; g/\, cm^2$

-$n_i \approx 5\; 10^{26}\, cm^{-3}$

HOT SPOT

-$\rho_{fin}\, R_{fin} \approx 130 \;\; g/\, cm^3 \times 22\, \mu m$
$= 0.3\; g/\, cm^2$

PRESSURE

-$P \approx 300$ GBar

Spherical geometry

Notice:

Ablation Pressure P $\approx$ 50 MBar

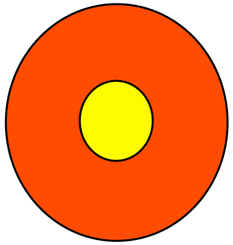
Pressure at stagnation P $\approx$ 50 Gbar

Amplification of a factor $\times$ 1000 due to convergence.

Spherical geometry is essential for ignition

Energy balance in the fuel

The compressed shell is a dense degenerate plasma



$$T_F = (3\pi^2 n)^{2/3}\hbar^2/2m,$$

$$T_F \simeq 14\,\rho^{2/3}\ \mathrm{eV},$$

$$p_F = \tfrac{2}{5} n_e T_F.$$

$$p_F = A_F \rho^{5/3} = 2.16\,\rho^{5/3}\mathrm{Mbar}.$$

"entropy parameter"

$$\alpha = p/p_F,$$

$$p=\alpha\, A_F\, \rho^{5/3}$$

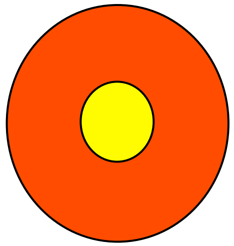
The hot spot is a hot classical plasma

Energy balance in the fuel

The compressed shell is a dense degenerate plasma

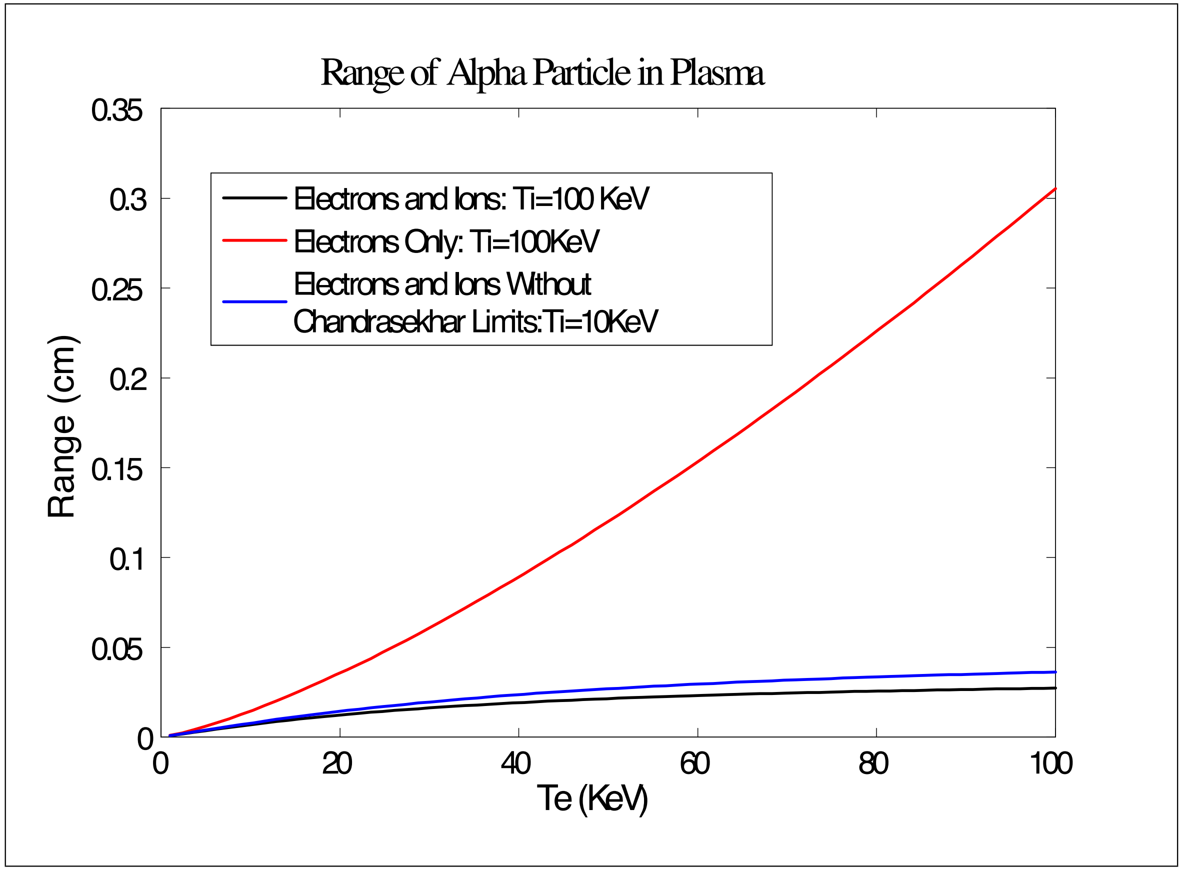
$$\mathcal{E}_{\mathrm{compr}} = \int_{V_f}^{V_0} p\, dV = \alpha M_f \int_{\rho_0}^{\rho_f} \frac{p_F}{\rho^2}\, d\rho \simeq \frac{3}{2}\alpha M_f A_F \rho_f^{2/3} = 0.35\, \alpha\, M_f \rho_f^{2/3}\, \mathrm{MJ}.$$

The hot spot is a hot classical plasma



$$\mathcal{E}_{\mathrm{chauf}} = \frac{3}{2}\,(n_e + n_D + n_T)\, T_h V_h = 3\, n_e T_h V_h = 110\, M_h T_{\mathrm{keV}}\, \mathrm{MJ}.$$

α particle range in ICF plasma



$$R_a = 0.107 \frac{T_e^{3/2}}{\rho \ln(\Lambda)} \, [cm]$$

Assuming 50/50 DT plasma (T_e in keV, ρ in g/cm^3). The plot of the range is shown in figure for ρ = 50 g/cm^3 and T_i= 100 keV

To get $R_a \approx 10\ \mu m$, one needs $\rho \approx 500$ g/cm^3

In this case α particles are confined within the plasma and contribute to its heating

Lessons from History ...

Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) Applications

JOHN NUCKOLLS, LOWELL WOOD, ALBERT THIESSEN & GEORGE ZIMMERMAN
University of California Lawrence Livermore Laboratory

Nature **239**, 139 - 142 (15 September **1972)**

Hydrogen may be compressed to more than 10,000 times liquid density by an implosion system energized by a high energy laser. This scheme makes possible efficient thermonuclear burn of small pellets of heavy hydrogen isotopes, and makes feasible fusion power reactors using practical lasers.

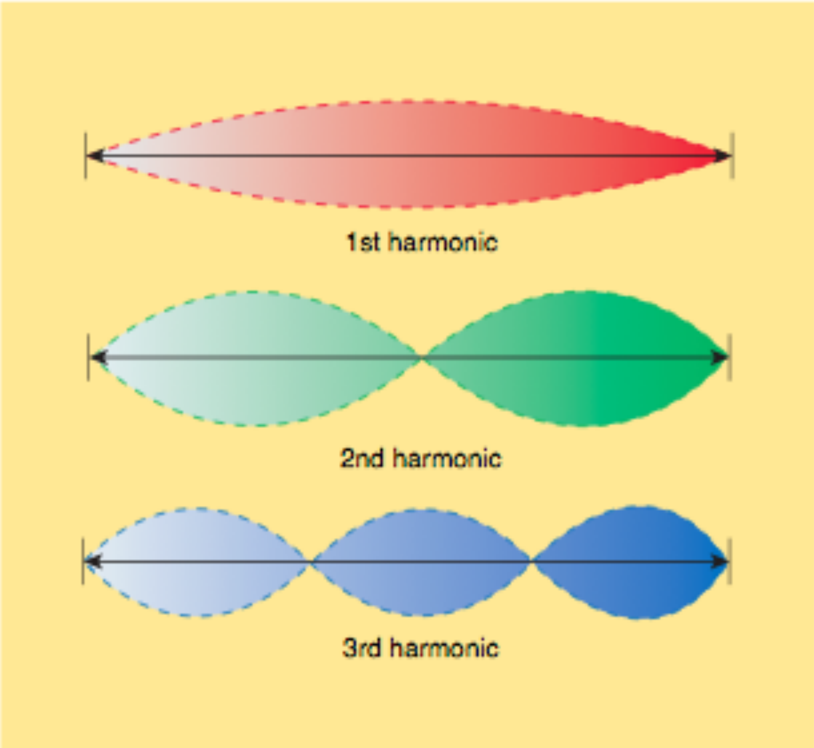
Early predictions for laser ignition were ~1kJ [Nuckolls]

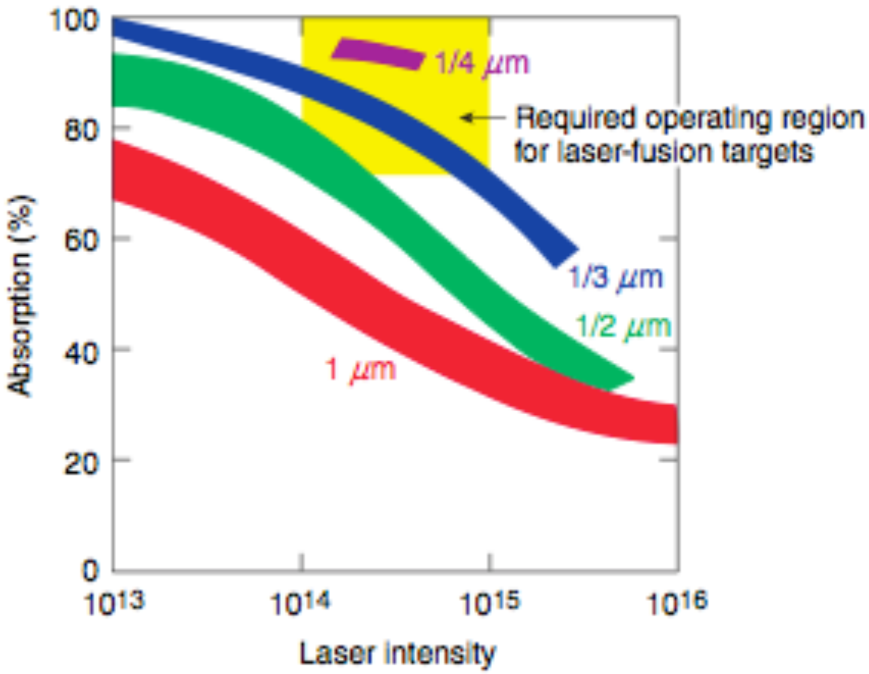
- **What was wrong?**
  - Very strong sensitivity to implosion velocity
  - Optimistic assessment of hydro instability growth
  - Assumption of high coupling efficiency at high laser irradiance

Note: estimates for high gain have remained ~ constant (at ~MJ), as much weaker dependence on implosion velocity

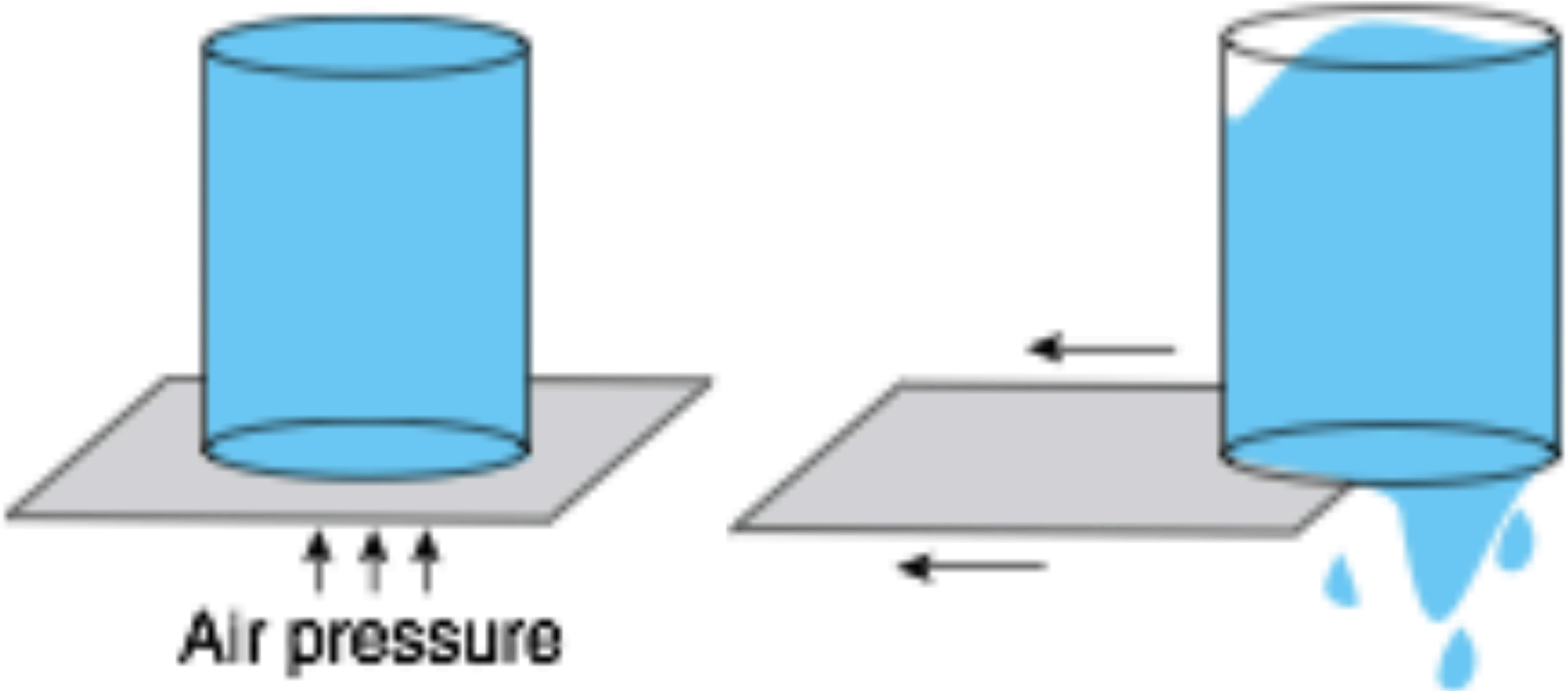
Absorption ruled out IR lasers

Laser Matter Interaction prohibits large intensities (low absorption, high preheating)

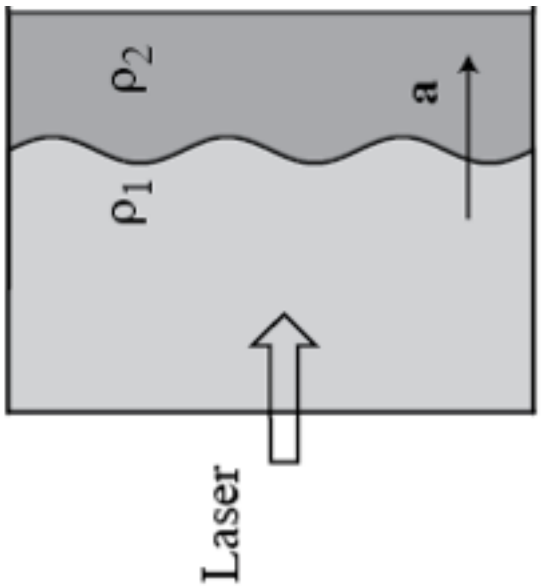




Rayleigh-Taylor Instability:



Rayleigh-Taylor Instability:



Use Fourier expansion (we write a sinusoidal perturbation).
Here $A(x,t) = A_O \cos(kx - \omega t)$

The equation of dynamics bring to write a dispersion relation $\varepsilon(\omega,t) = 0$

If ω is real stable behaviour (wave which is eventually damped and dies away)
If $\omega = i\gamma$ is imaginary then the perturbation grows like
$A(x,t) = A_O \cos(kx)\, e^{\gamma t}$

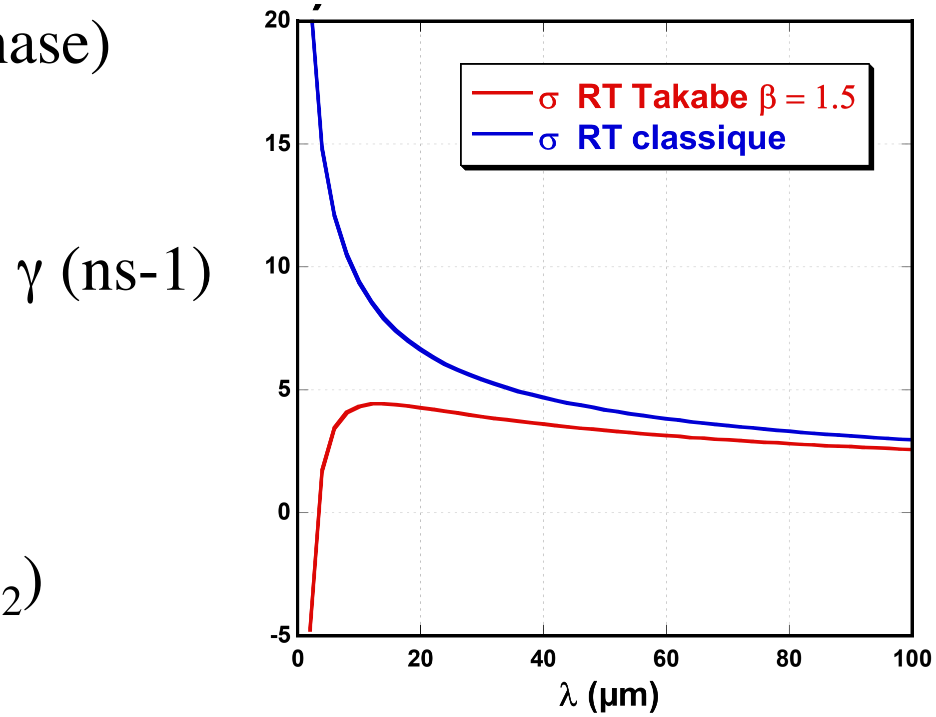
Rayleigh-Taylor Instability:

"Classical" growth rate (linear phase)

$$\gamma = \sqrt{Akg}$$

$$A = \sqrt{\frac{\rho_2 - \rho_1}{\rho_2 - \rho_1}}$$

Atwood number (instable if $\rho_1 < \rho_2$)

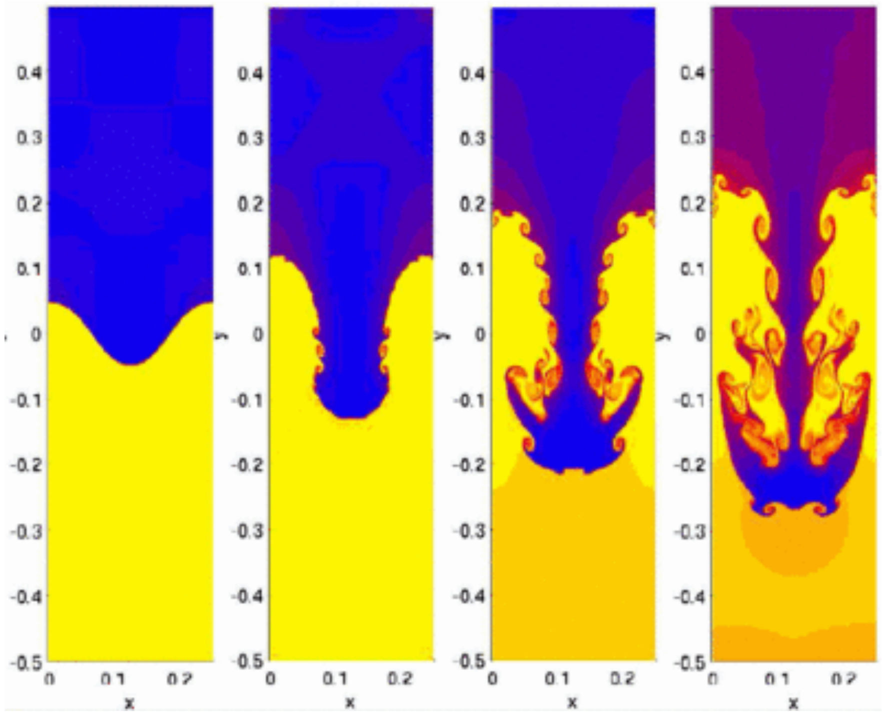


$$\gamma = \sqrt{\frac{Akg}{1 + kL}} - \beta k v_{abl}$$

Modified "Takabe" expression. L plasma density gradient

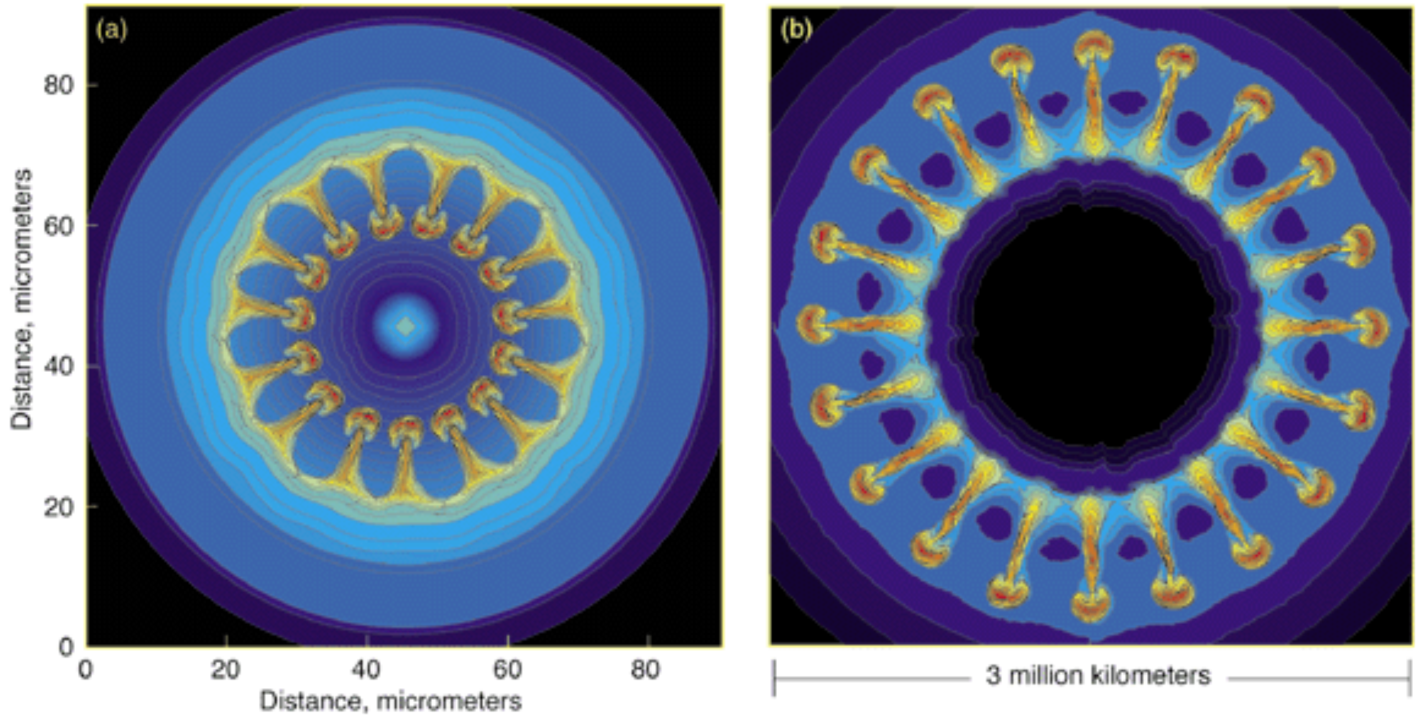
Rayleigh-Taylor Instability

- Major instability: heavy material pushes on low density one
- Will always occur since driver is never 100% symmetric
- The Rayleigh-Taylor instability always grows



➢**Energy must be delivered as sysmmetric as possible!**

Rayleigh-Taylor Instability – spherical implosions /



Striking similarities exist between hydrodynamic instabilities in (a) inertial confinement fusion capsule implosions and (b) core-collapse supernova explosions. [Image (a) is from Sakagami and Nishihara, *Physics of Fluids B* **2**, 2715 (1990); image (b) is from Hachisu et al., *Astrophysical Journal* **368**, L27 (1991).]

➢**Energy must be delivered as sysmmetric as possible!**

Good news:

Experiments with GEKKO XII laser, Institute of Laser Engineering, University of Osaka, Japan

- **Experimental demonstration of compression of DT up to 600 × solid density** (Azechi et al., Las. Part. Beams, 1991)

- **WE ARE ABLE TO OBTAIN DENSITIES DIRECTLY RELEVANT FOR ICF!**

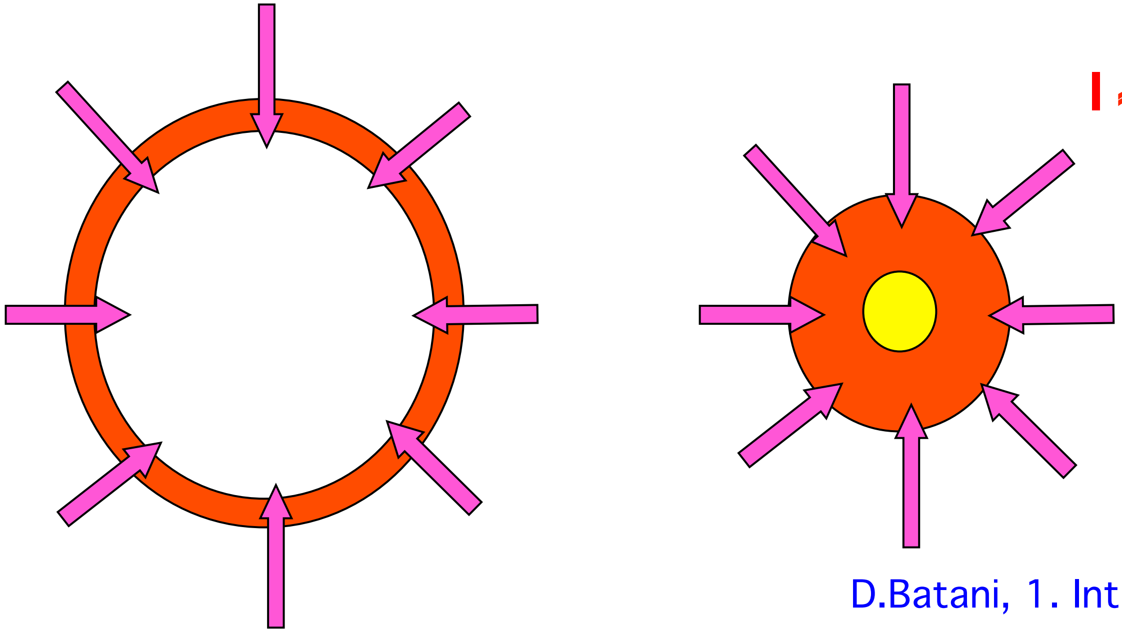
  However: number of neutrons much smaller than expected: The central hot spot was not generated

ICF: direct drive approach

Lawson's Criterium (buring criterum) for ignition (D-T): $\rho R > 3$ gcm^{-2} and $T \approx 5 - 10$ keV

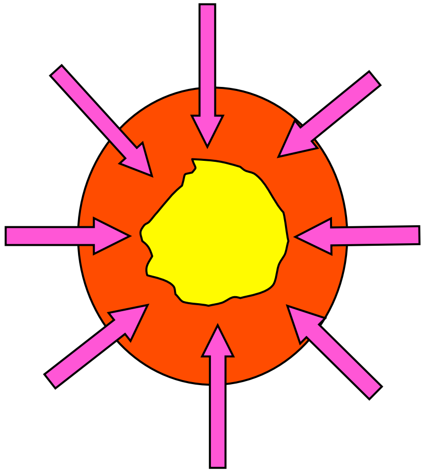
- synchronized laser pulses with spherical irradiation symmetry
- shock wave compression (up to 1000 × solid density)
- ignition from a central hot spark produced by shock coalescence
- isobaric approach

$I \approx 10^{14}$ W/cm^2 10 ns



Problems of classical scheme:

Non uniformities in laser irradiation or in target bring to:



- Mixing of fuel and wall, higher Z*, increased emission and cooling
- The central hot spot is not generated

$$\frac{\Delta R_{fin}}{R_{fin}} \approx \frac{\Delta v}{R_{fin}} t_{imp} \approx \frac{R_{in}}{R_{fin}} \frac{\Delta v}{v_{imp}} \approx \frac{R_{in}}{R_{fin}} \frac{\Delta I}{I}$$

Then:

$$\frac{\Delta R_{fin}}{R_{fin}} \approx 50\% \Rightarrow \frac{\Delta I}{I} \approx 1\%$$

How to relax uniformity constraints for ICF?

CELIA

- **USE INDIRECT DRIVE**

- **USE OPTICAL SMOOTHING**

- **USE OF "FOAM BUFFERED TARGETS"**

Willi et al., Phys. Rev.Lett.,1995

- **SEPARATE COMPRESSION AND IGNITION**

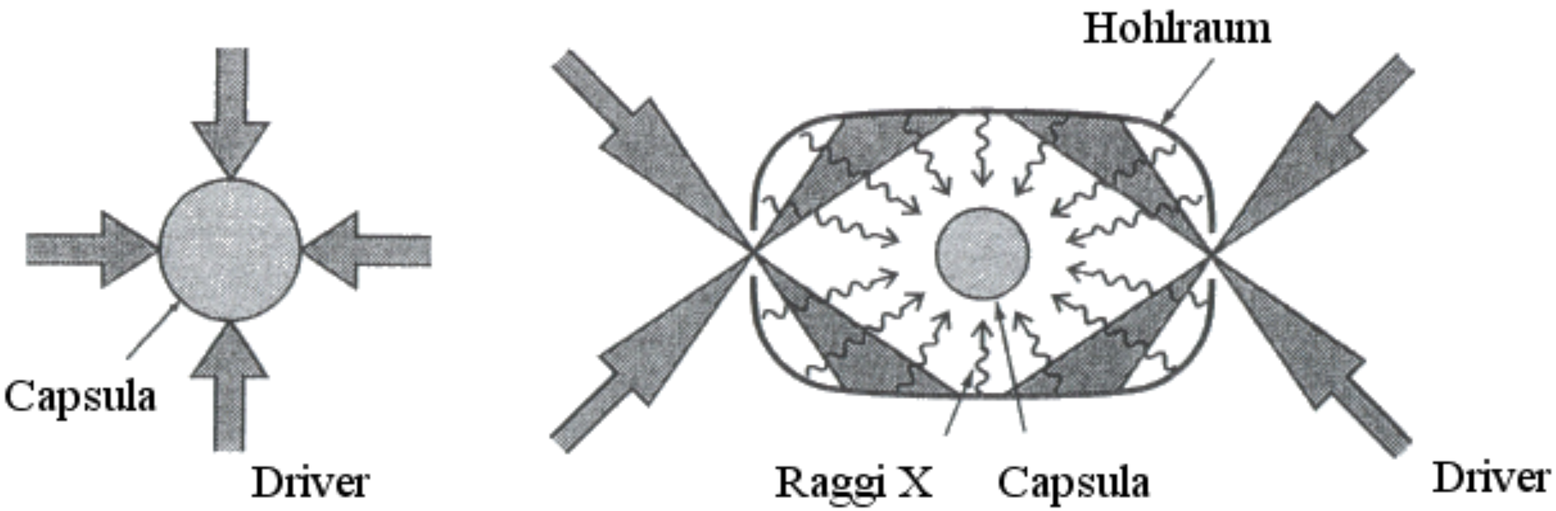
Fast Ignition

Tabak et al., Phys. Plasmas, 1994

Shock Ignition

R. Betti, et al. Phys. Rev. Lett., 2007

Inertial confinement: direct vs. indirect drive



a) Diretto

b) Indiretto

Direct: higher efficiency, more problems with uniformity

Indirect: better uniformity but reduction of efficiency

In both case you need MJ-class laser systems

Targets

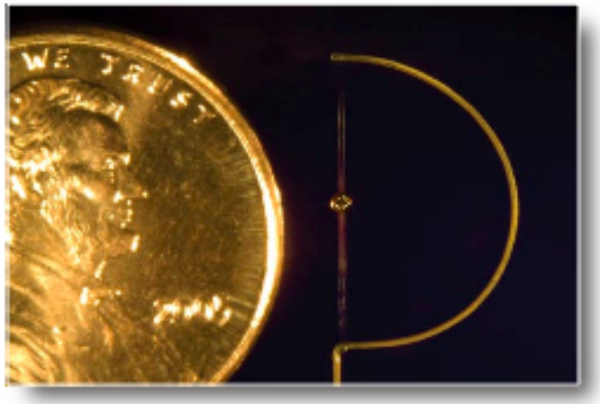


Figure 3.3: The laser-fusion targets used on OMEGA experiments are typically ~1 mm in diameter and are suspended by spider silks.

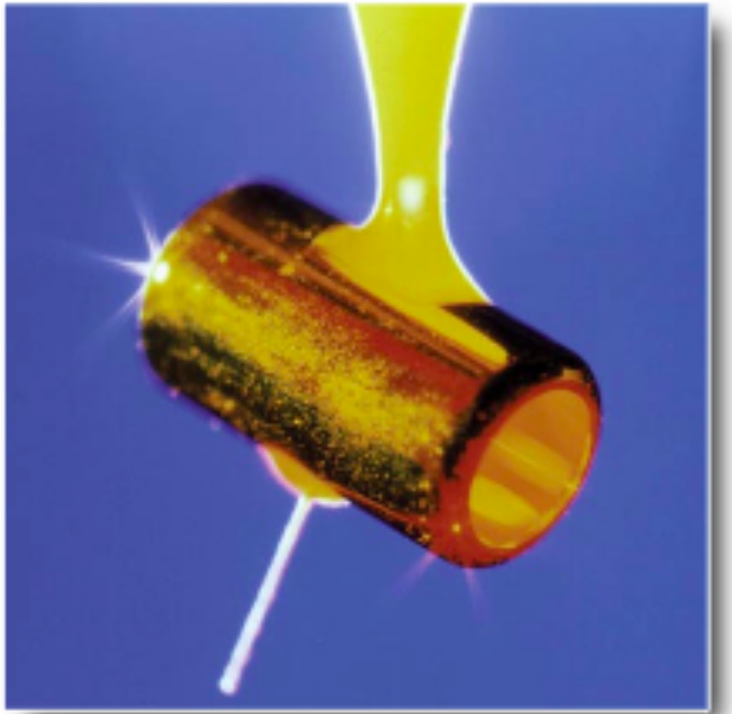
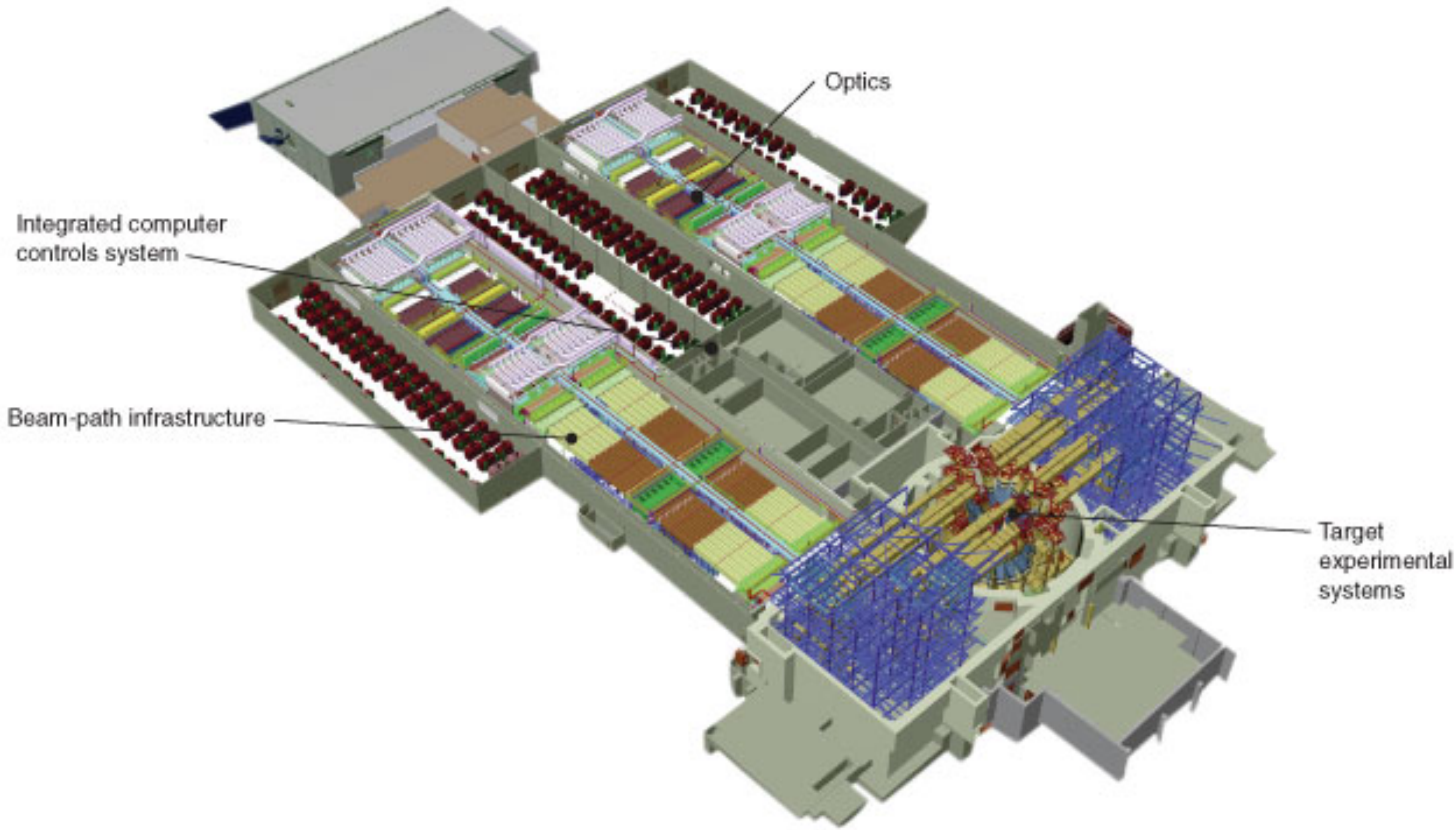
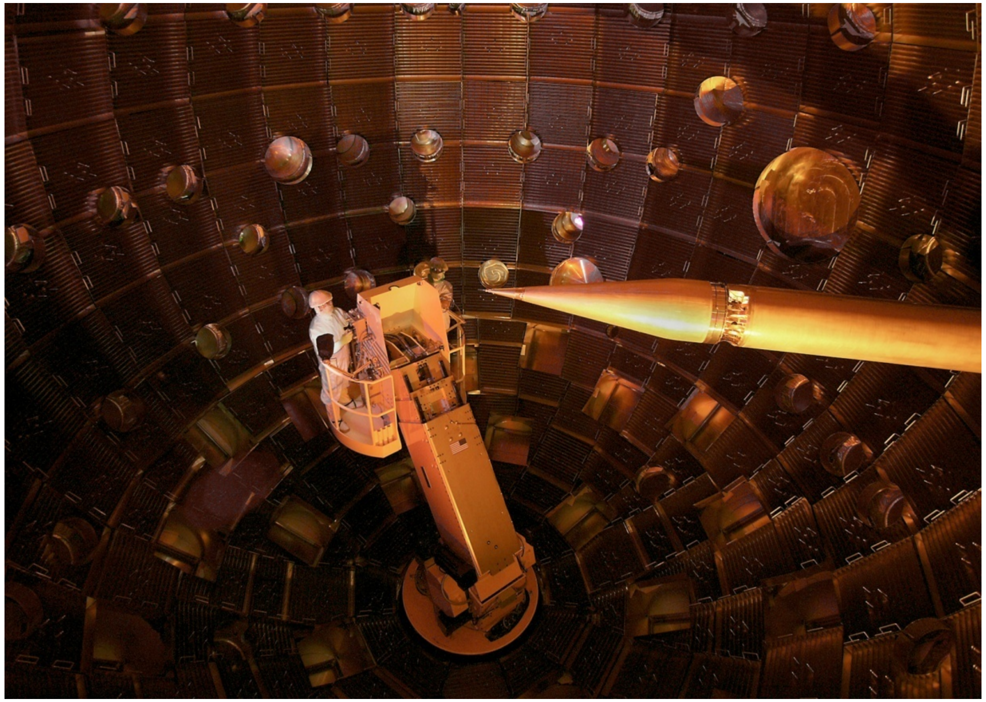


Figure 3.7: A typical indirect-drive target.

National Ignition Facility (NIF) - layout

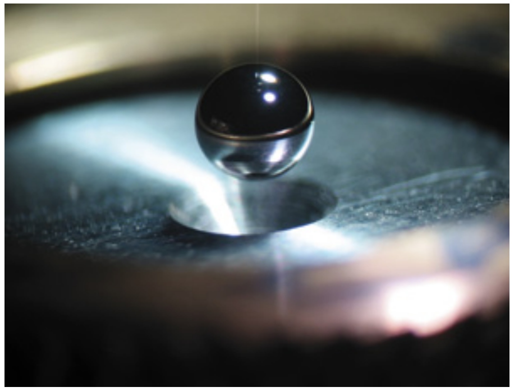


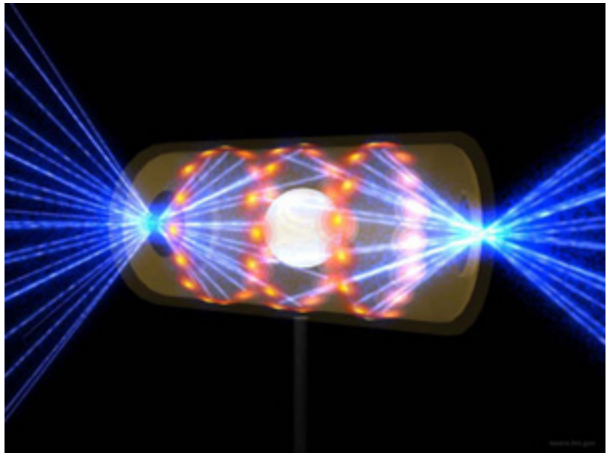
NIF



Indirect drive

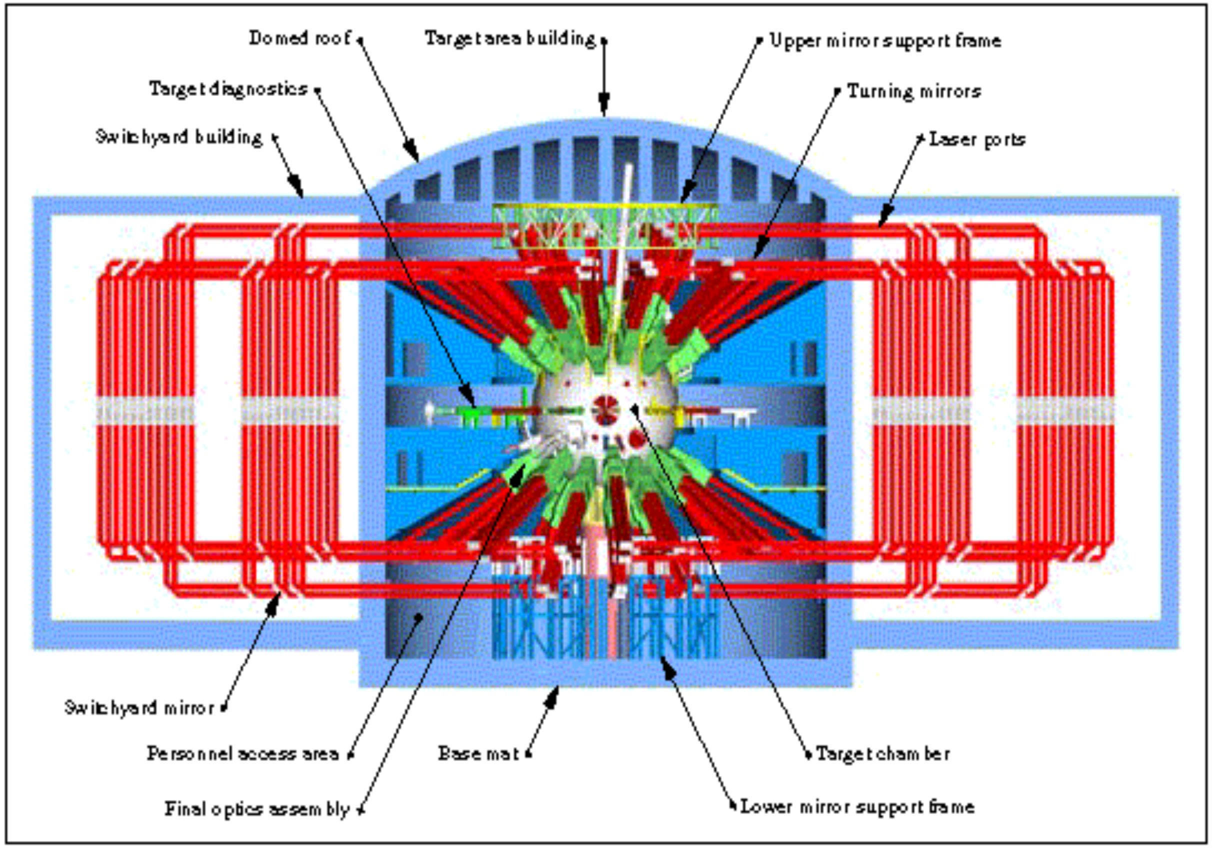
- Chamber
- Target holder
- Hohlraum
- Pellet





Lasers - NIF and Megajoule:

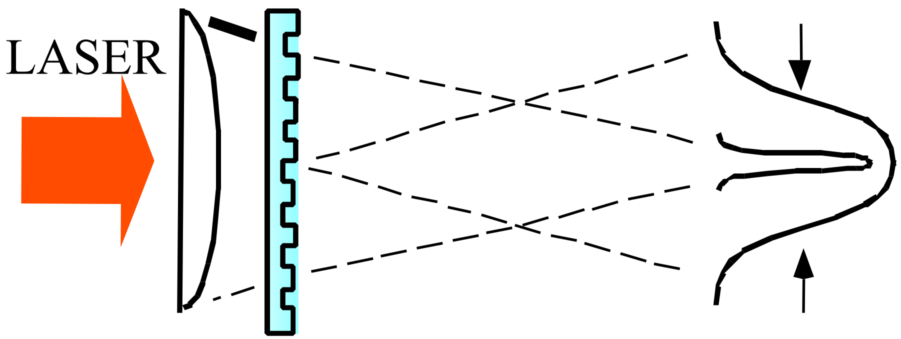
Controlled Thermonuclear Fusion



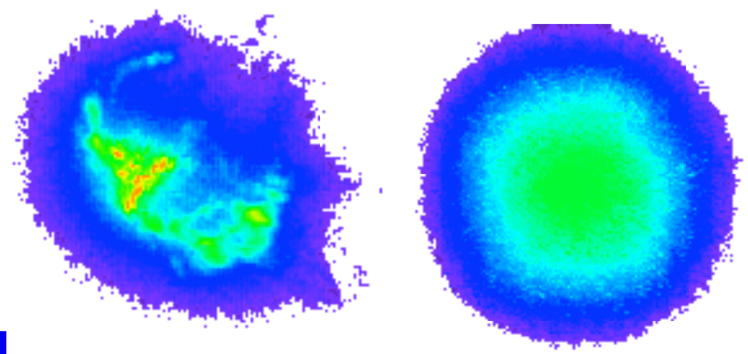
Nd:glass
2 MJ
10 ns
200 beams

Optical smoothing techniques:

Optical smoothing techniques (RPP, ISI, SSD..) introduced (80's, 90's) to produce "gaussian" beam profiles with small scale modulations



Random Phase Plate $\Phi \approx 0.9 \lambda f/d$

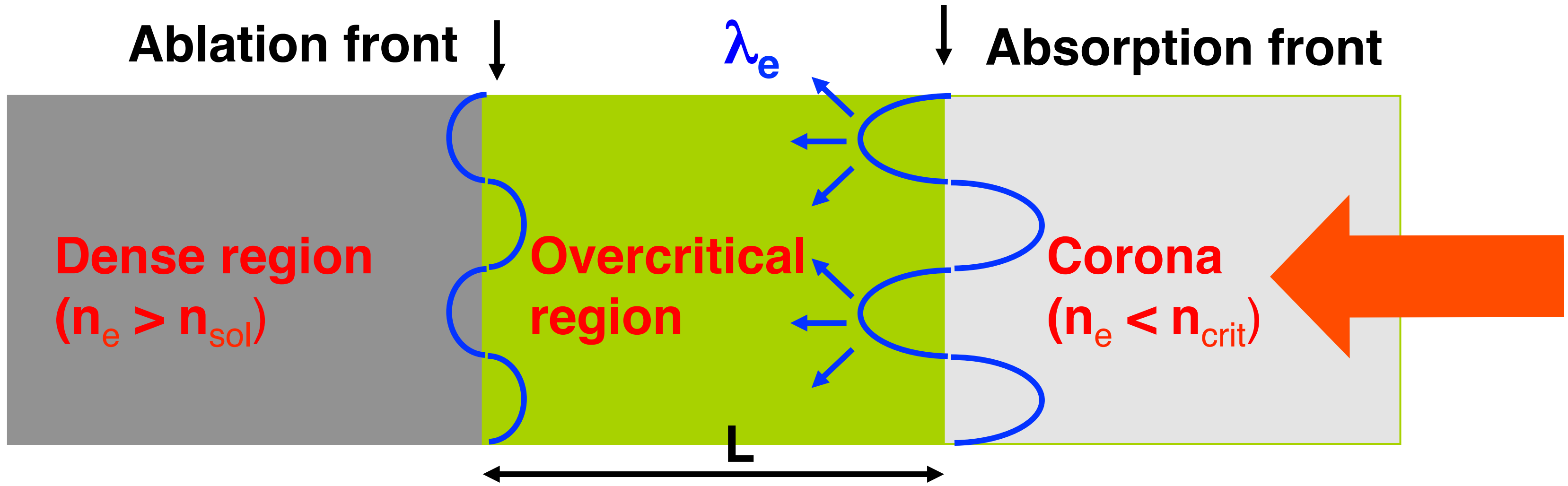


2D square elements with 0 or π dephasing *(Kato, PRL, 1984)*

Small scale modulations are rapidly washed out by thermal smoothing

Thermal smoothing:

Laser is absorbed at the absorption front but pressure is applied at the ablation front



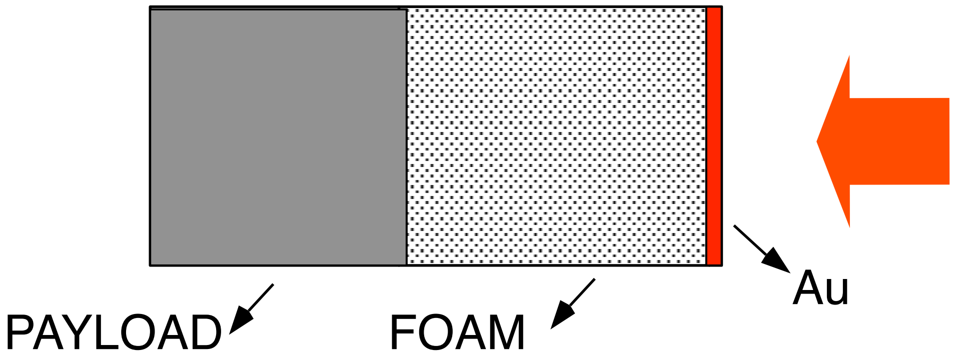
$$\Delta P / P \approx \Gamma \, \Delta I / I$$

Non-uniformities present at the laser absorption surface are reduced at the ablation surface by

$$\Gamma \approx \exp\left[- \alpha L \left(2\pi / \lambda_{perp}\right)\right]$$

L "stand-off distance"

Foam buffered targets:



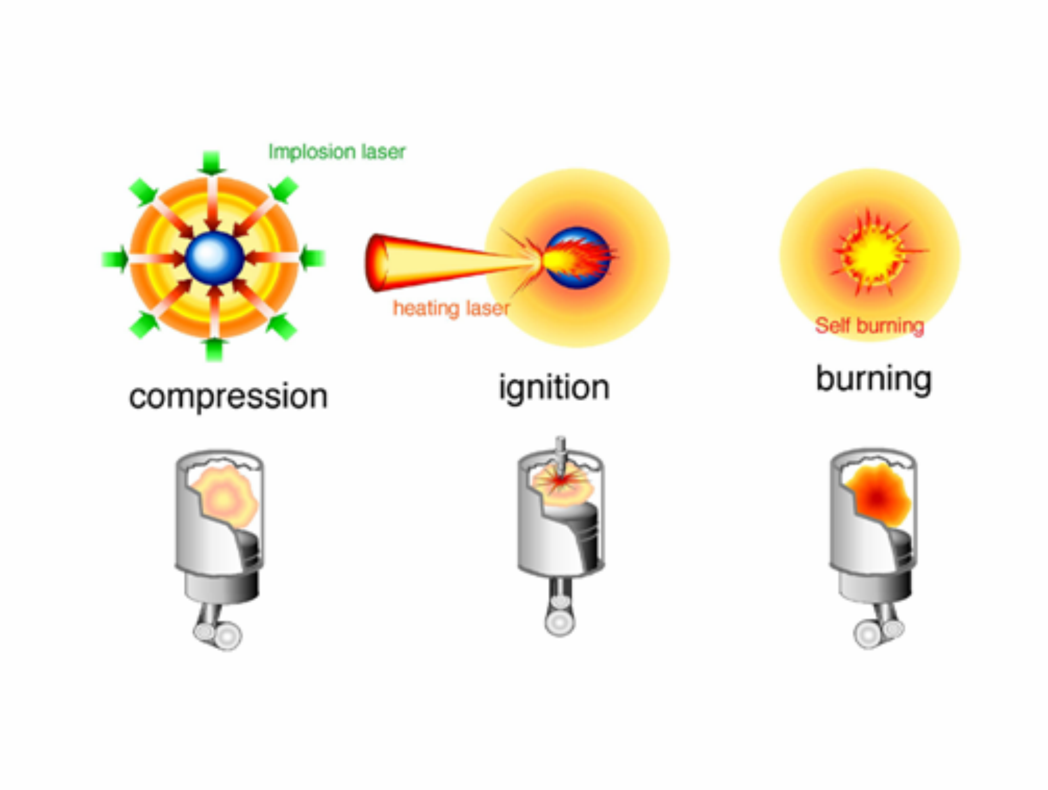
(Dunne et al., PRL 1995)

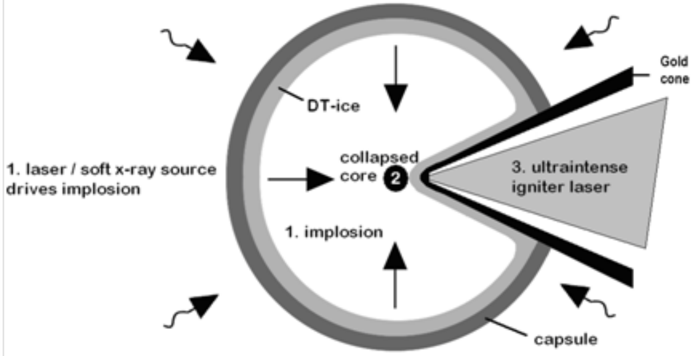
CREATE A SUPERCRITICAL AND SUFFICIENTLY WIDE PLASMA IN FRONT OF THE TARGET

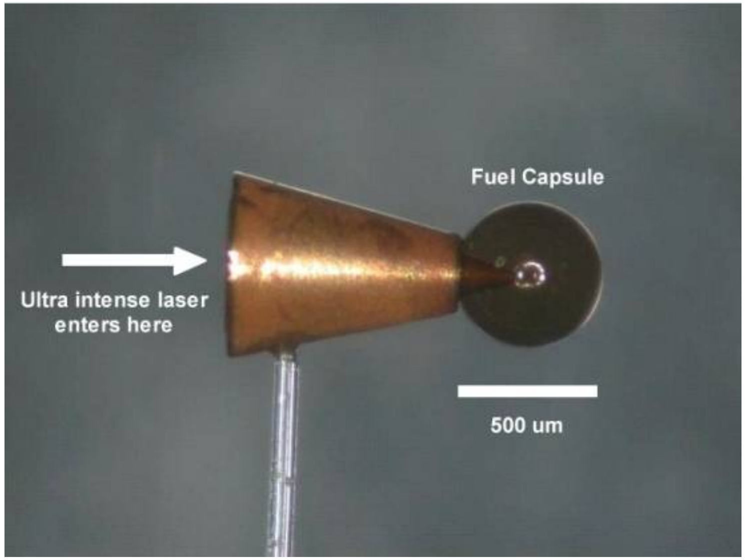
OPEN QUESTIONS:

- **Optimal parameters of foam and converter**
- **What λ_{perp}?**
- **Effects on hydrodynamics? Shock heating of DT?**

Inertial Fusion- Fast Ignition



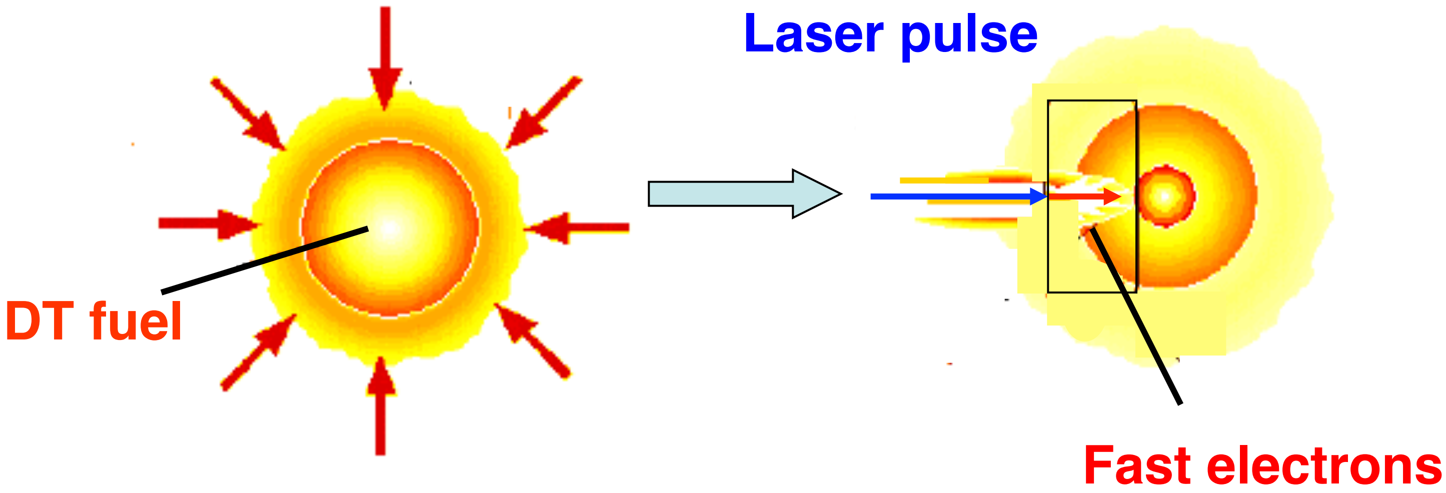




The concept of"fast ignition"

- 1: "normal" compression with ns laser beams (we are able to compress!)

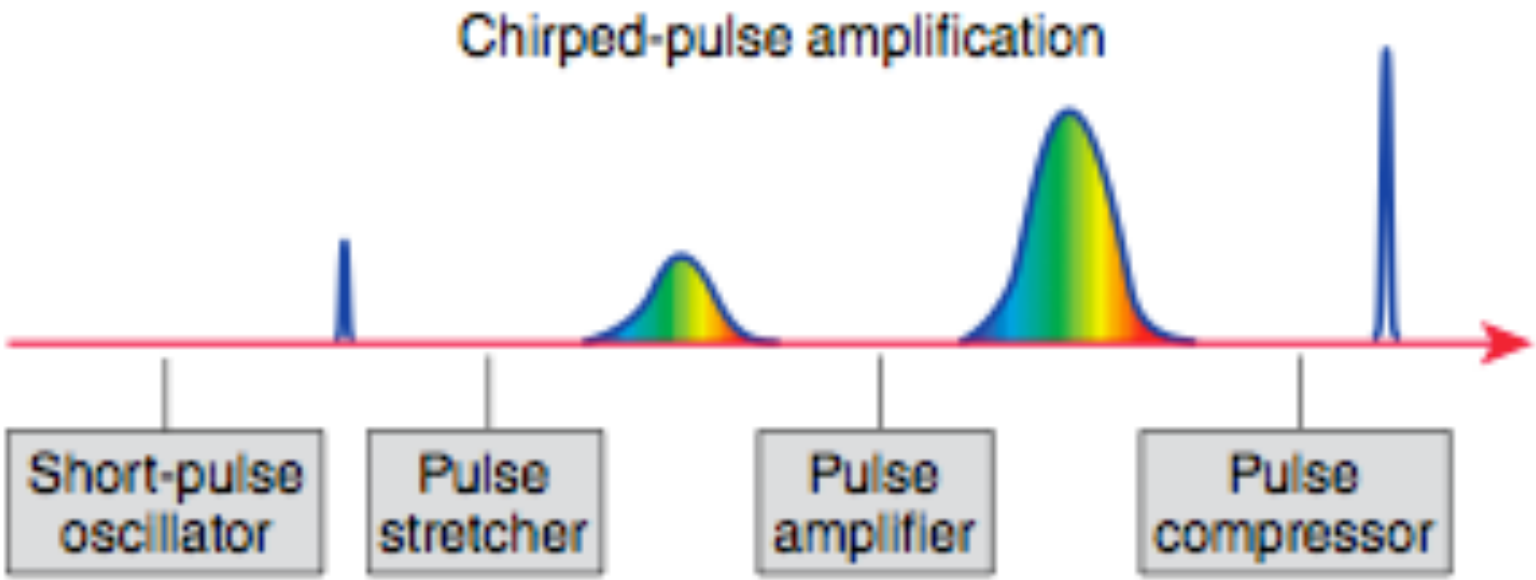
- 2: a CPA laser creates a beam of relativistic electrons (lateral hot spot)



- Typical parameters: $E \approx 10$ kJ, $\Delta t \approx 10$ ps, $R \approx 10\mu m$, $E_{fast} \approx 1$ MeV

High-intensity lasers (high energy – short pulse)

Laser-plasma interaction in the “relativistic regime”



Evolution of laser performance:

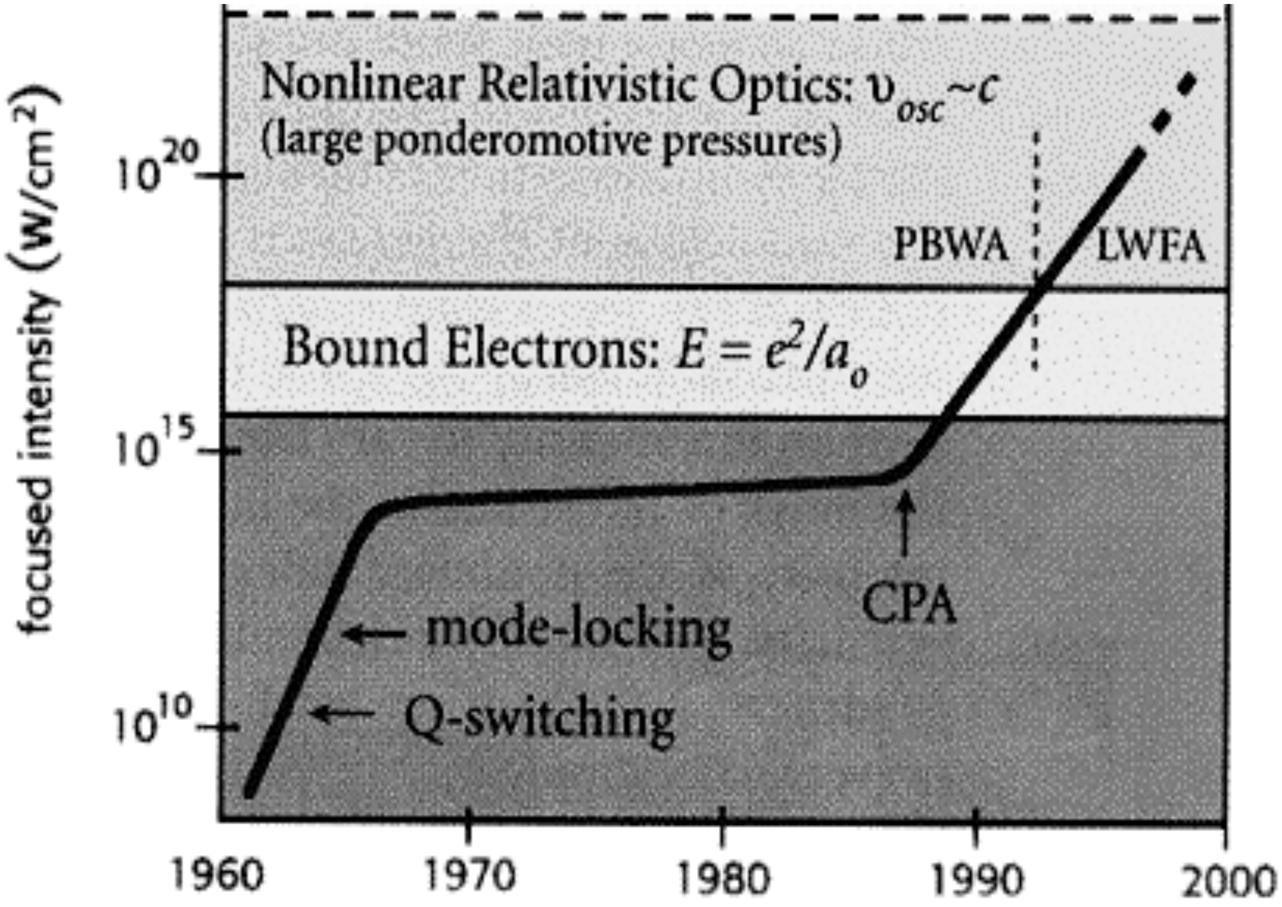
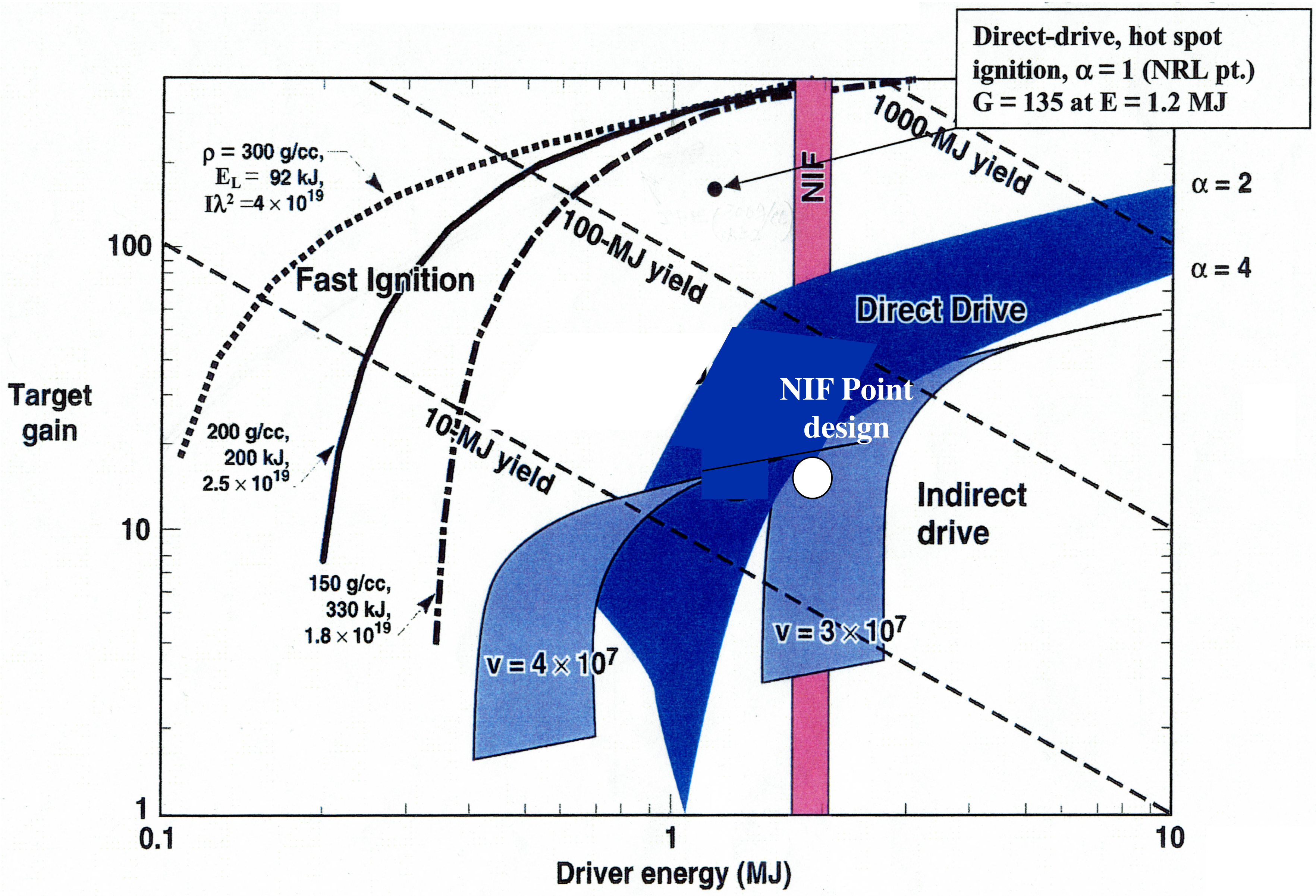


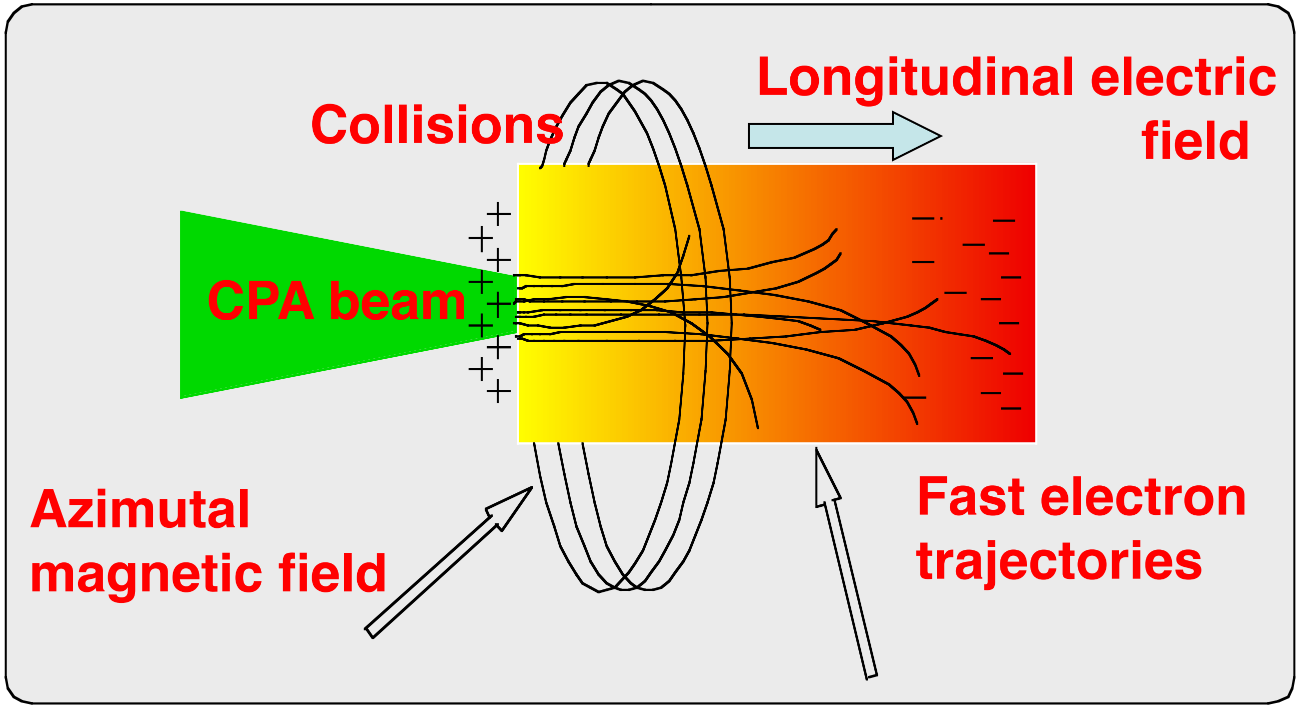
Figure 1. Laser intensity as a function of year, showing the impact of the CPA concept and the different thresholds of physical regimes. The sharp increase in intensity since the advent of CPA is comparable to the sharp increase after the invention of the laser in the 1960's.

Advantage of FI



Study of propagation:

Propagation of fast electrons in matter between n_c and 100 n_c over 200 - 300 μm is critical for the feasibility of fast ignition



- **Collisional Effects (Stopping Power)**
- **Electric field effects**
- **Magnetic fields effects**

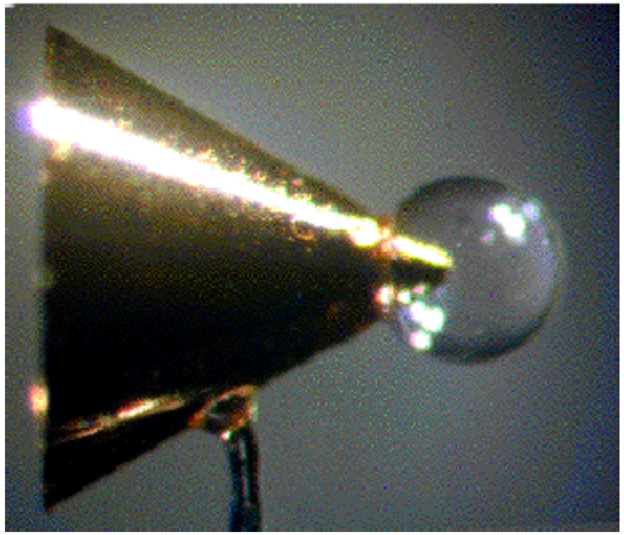
NEW PHYSICAL PROBLEM: VERY DIFFERENT FROM JUST BETHE-BLOCH

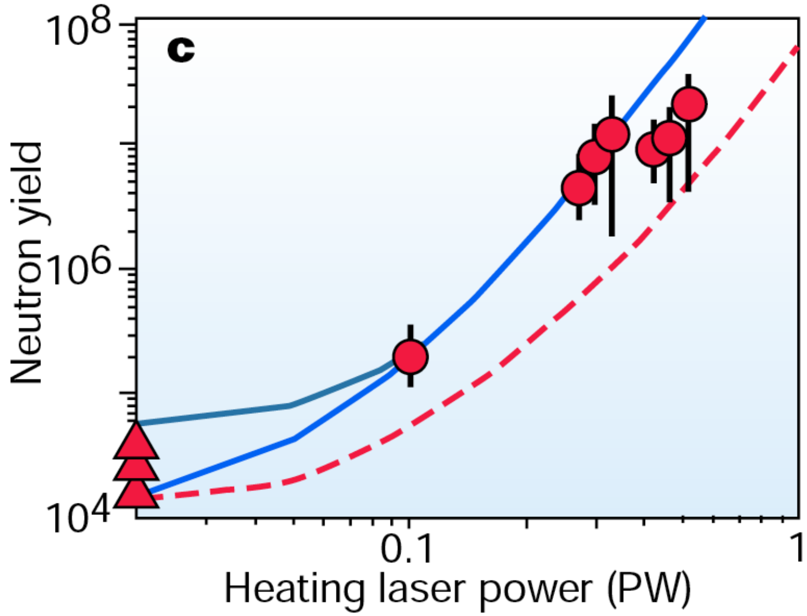
Use of cone targets

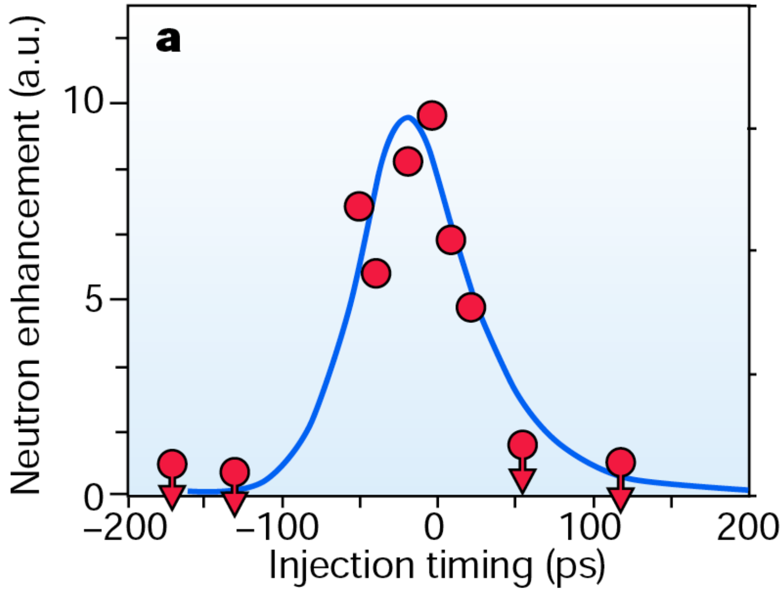
"Cone guided" targets were tested at the ILE in Osaka

- The laser can interact in regions at higher densities
- Increment in neutron yield from compressed fusion targets

R. Kodama et al., Nature 418, 933 (2002)







Physical issues

- Cones do not seem viable for future reactors (same problems of ID targets)
- The presence of the cone may prevent a sufficiently uniform compression and produce high-Z pollution
- How to control electron beam energy?
- Is there any tools to control electron beam divergence?

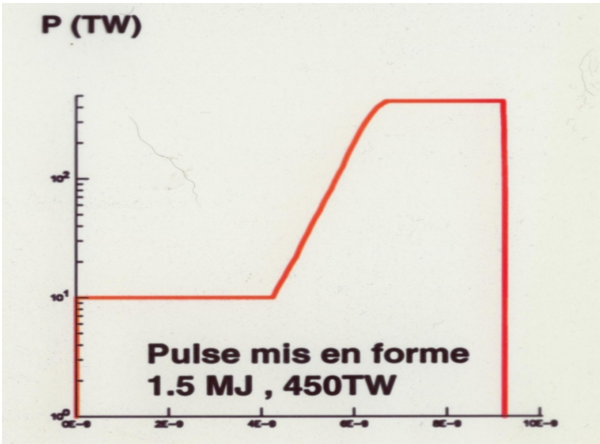
Although a very promising idea, FI is in a "premature" stage for what concerns technological developments (we need a 100 kJ - 10 ps laser beam)

[the main issue here is *scalability of collective effects*...]

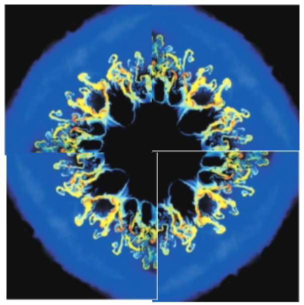
A final laser spike launches a converging shock

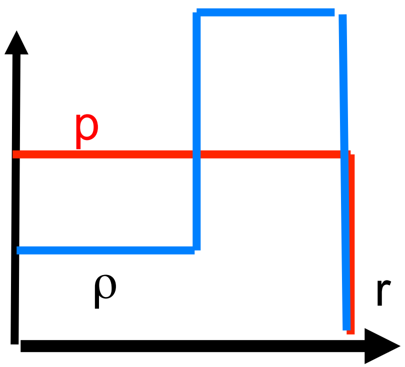
Conventionnal direct drive

450 TW, 1.5MJ pulse



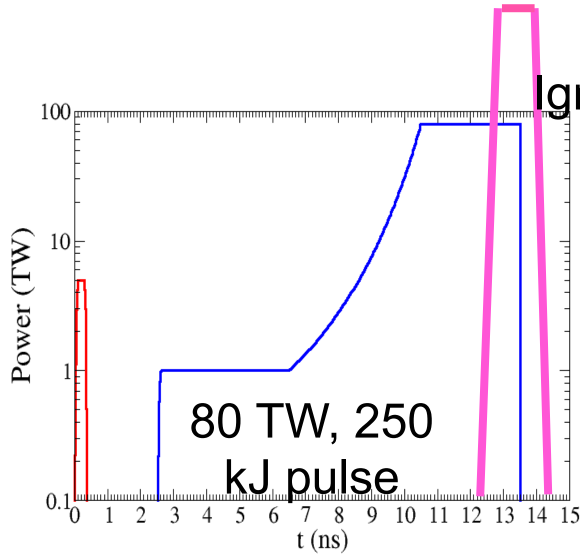
High Aspect ratio target
V ~400 km/s



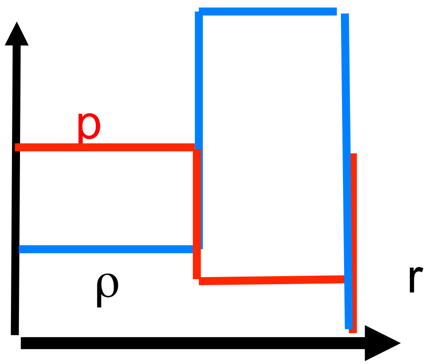


Produces an Isobaric fuel assembly

Low velocity drive



Low AR V~240 km/s

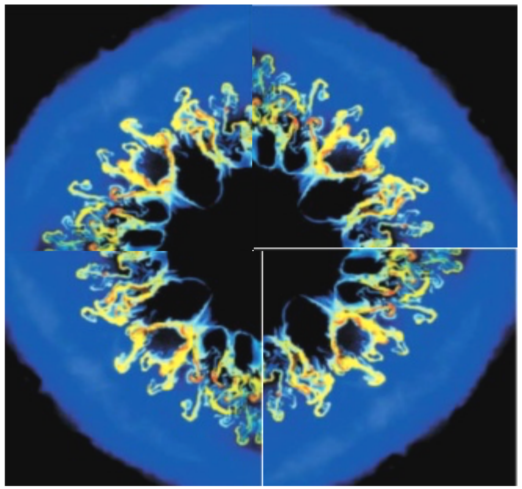


Fuel assembly is non isobaric

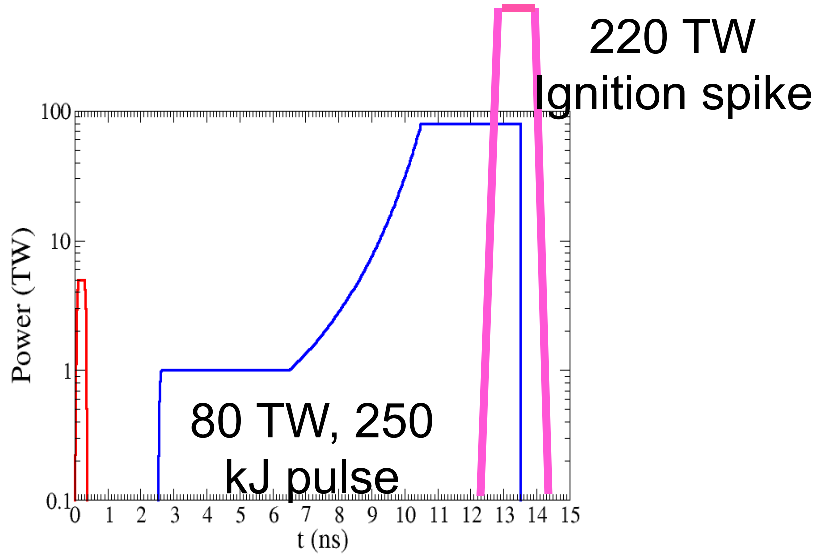
D.Batani, 1. Introduction to Fusion, 2016

Shock ignition is less sensitive to hydro instabilities

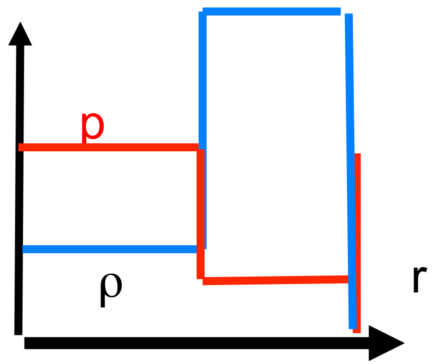
In SI, you do not create the hot spot with the “main” compression beam. Hence you do not need such highh implosion velocity. Hence you can implode a more massive thicker shell which does not break due to RT



Low velocity drive



Low AR V~240 km/s



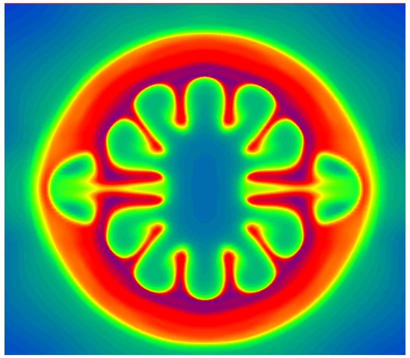
Fuel assembly is non isobaric

The Ignition shock mitigates RT growth at stagnation

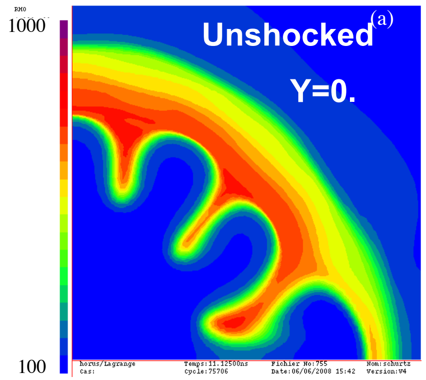
HiPER target at time of maximum ρR (1D)

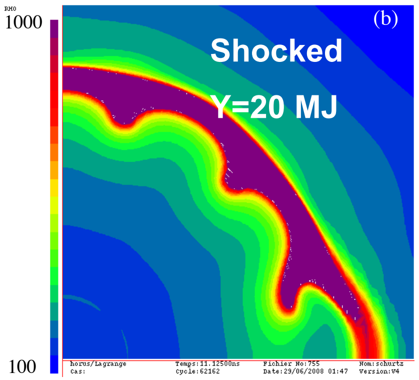
180 kJ

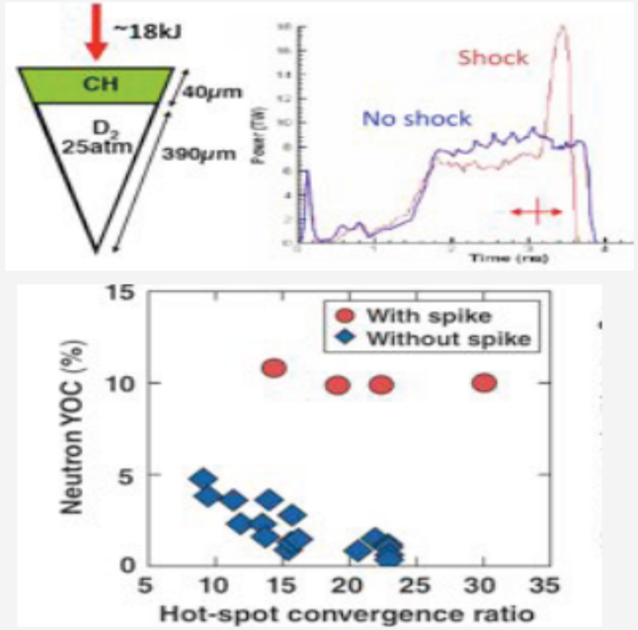
48 beams



HiPER target at ignition time







Is this experimental evidence of shock RT mitigation?

- OMEGA shock driven target
- D2 gas with CH shell
- Same total energy: shock, no shock

W. Theobald et al.