Plasma Physics

TU Dresden

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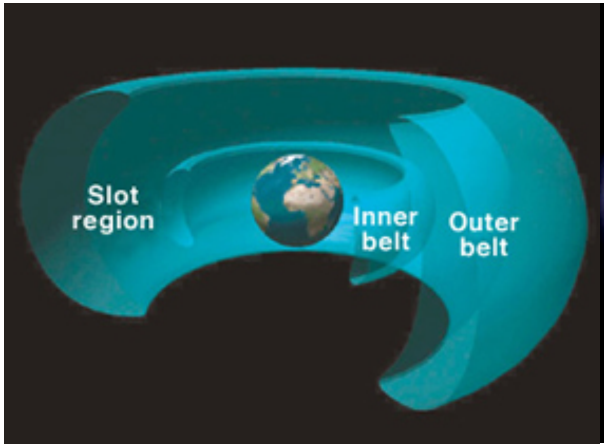
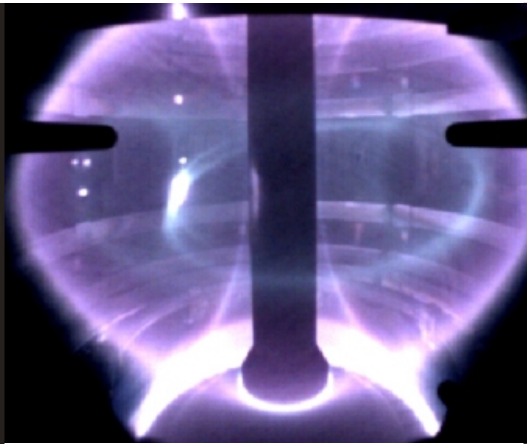
TECHNISCHE UNIVERSITÄT DRESDEN

Lecture 9: Laser plasmas & ICF



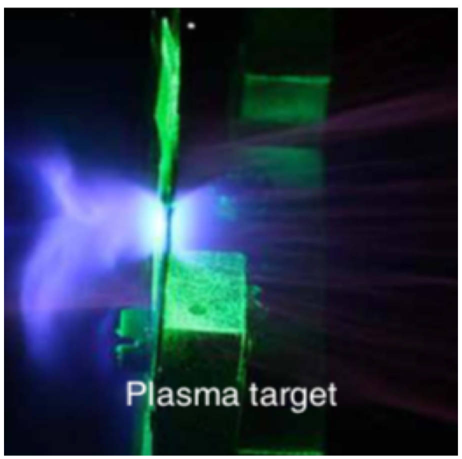


Plasma Physics: lecture 9

- Inverse Bremsstrahlung
- Laser Ablation
- The Lawson criterion revisited
- Inertial Confinement Fusion (ICF)
- Different technological approaches to ICF
- Big laser ZOO

The critical surface

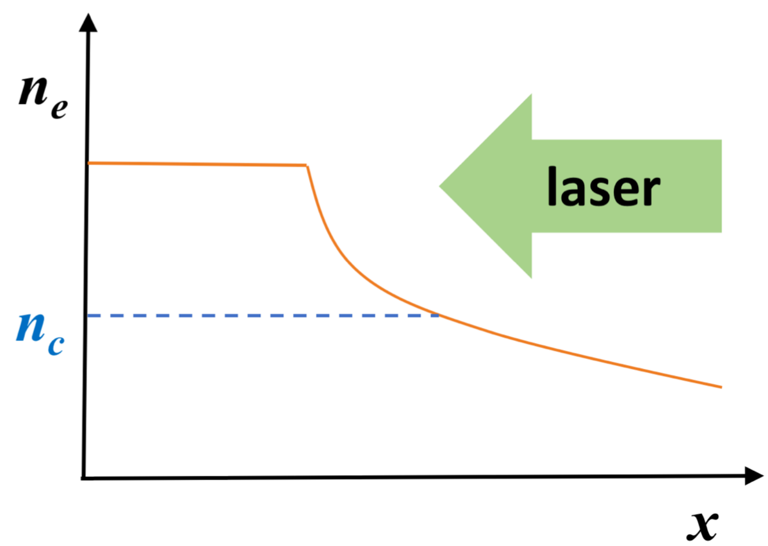
- When a laser hits a solid target, the surface is heated, and a plasma is formed.
- This plasma expands into the vacuum, and its density drops.



The critical surface

- In lecture 3 we derived the relationships for the propagation of electromagnetic radiation in plasma.
- We have derived the refractive index in plasma:

$$\mu = \sqrt{\varepsilon(\omega)} = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$



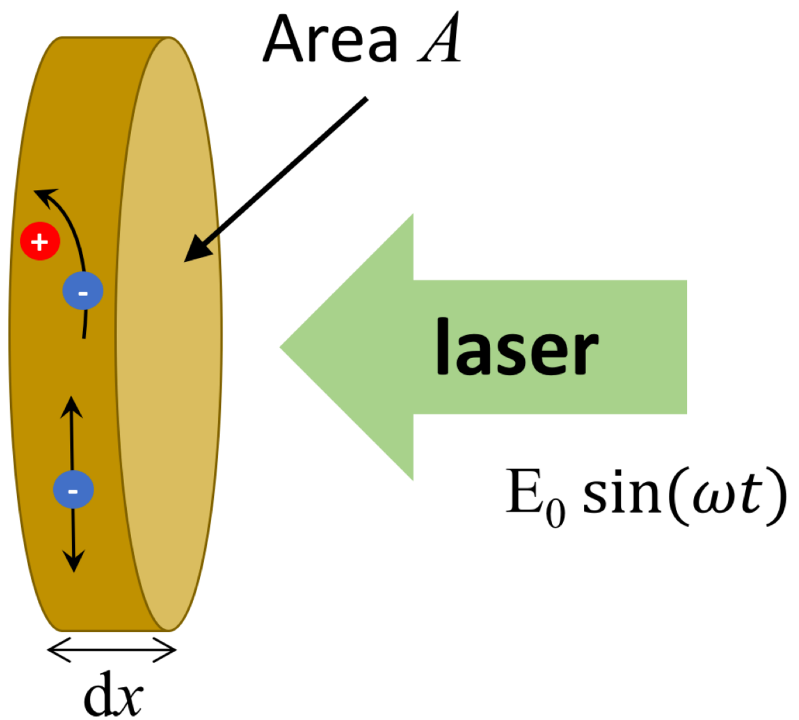
- And the critical density:

$$n_c = \frac{\omega^2 \varepsilon_0 m}{e^2}$$

- Laser light is absorbed at lower densities and reflected at the critical density n_c.

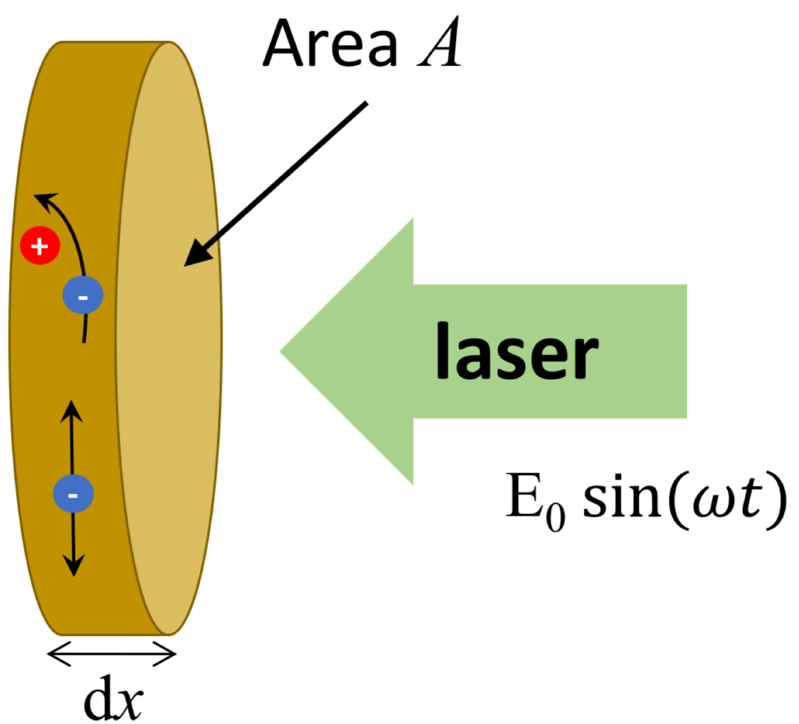
Inverse Bremsstrahlung

- The incident laser light (oscillating EM field) causes the electrons to oscillate.
- In the absence of collisions, these electrons re-radiate at the original laser frequency, so no energy is lost from the light.



Inverse Bremsstrahlung

- However, the electrons also have some random thermal velocity, and in reality they collide with ions. Thus the oscillatory energy is converted to thermal energy.
- We will estimate the absorption coefficient.

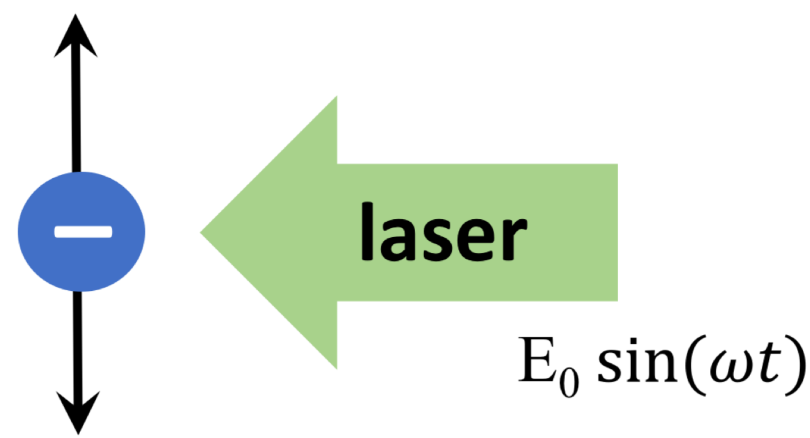


Oscillatory energy

- Incident laser with frequency ω, intensity I and peak electric field E_0:
- Equation of motion for electron:

$$m\ddot{x} = -eE_0 \sin(\omega t)$$

$$\dot{x} = \frac{eE_0}{\omega m} \cos(\omega t)$$



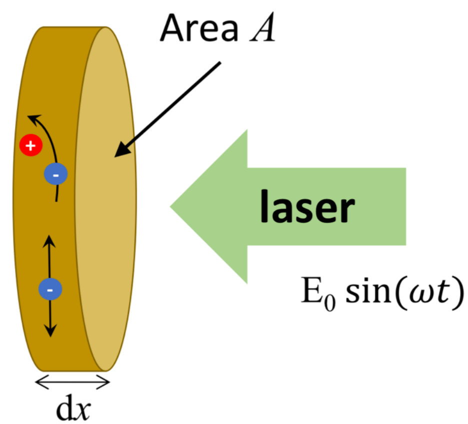
- Time averaged kinetic energy:

$$\boxed{\overline{\frac{1}{2} m\dot{x}^2} = \frac{e^2 E_0^2}{4m\omega^2}}$$

Total oscillatory energy

- For electron density n_e in a given volume, the total oscillatory energy:

$$U_e = n_e \left(\frac{e^2 E_0^2}{4 m \omega^2} \right) A \mathrm{d}x$$



$$U_{\mathrm{L}} = I A t$$

- The collision time between ions and electrons is τ_{ei} and fraction of the oscillatory energy that is converted to thermal energy to be $\approx t/\tau_{ei}$

- Oscillatory energy gained in time t is equivalent to change in laser field energy:

$$\mathrm{d}U_e = \mathrm{d}U_{\mathrm{L}} = -\frac{t}{\tau_{\mathrm{ei}}} n_e \left(\frac{e^2 E_0^2}{4 m \omega^2} \right) A \mathrm{d}x$$

Absorption coefficient

- The absorption coefficient κ is defined such that for light of intensity I :

$$I = I_0 \exp(-\kappa x)$$

$$\mathrm{d}I = -\kappa I_0 \exp(-\kappa x)\mathrm{d}x$$

- Thus:

$$\begin{aligned}
\kappa &= -\frac{1}{I}\frac{\mathrm{d}I}{\mathrm{d}x} \\
&= -\frac{1}{U_\mathrm{L}}\frac{\mathrm{d}U_\mathrm{L}}{\mathrm{d}x} \\
&= \frac{1}{IAt}\frac{t}{\tau_\mathrm{ei}} n_e \left(\frac{e^2 E_0^2}{4m\omega^2}\right) A \\
&= \frac{1}{I}\frac{1}{\tau_\mathrm{ei}} n_e \left(\frac{e^2 E_0^2}{4m\omega^2}\right)
\end{aligned}$$

Absorption coefficient

- The electric field of the laser E_0, is related to the intensity I via the Poynting vector:

$$I = N = \frac{1}{2}\sqrt{\varepsilon_{\mathrm{r}}}\varepsilon_0 E_0^2 c$$

- By substituting for intensity:

$$\kappa = \frac{1}{2\tau_{\mathrm{ei}}}\left(\frac{n_e e^2}{\varepsilon_0 m\omega^2}\right)\frac{1}{c\sqrt{\varepsilon_{\mathrm{r}}}}$$

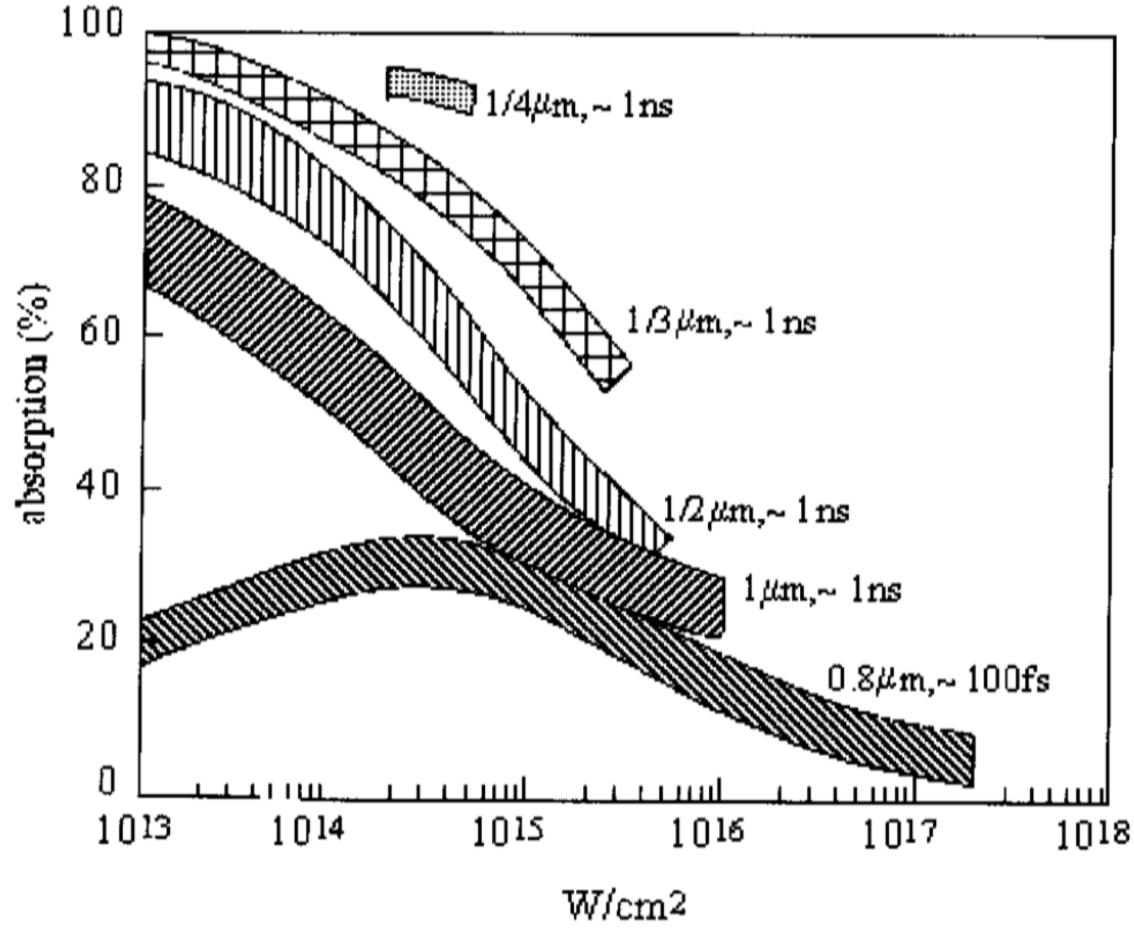
- Substituting for plasma frequency:

$$\boxed{\kappa = \frac{1}{2c\tau_{\mathrm{ei}}}\left(\frac{\omega_{\mathrm{p}}^2}{\omega^2}\right)\left(1 - \frac{\omega_{\mathrm{p}}^2}{\omega^2}\right)^{-1/2}}$$

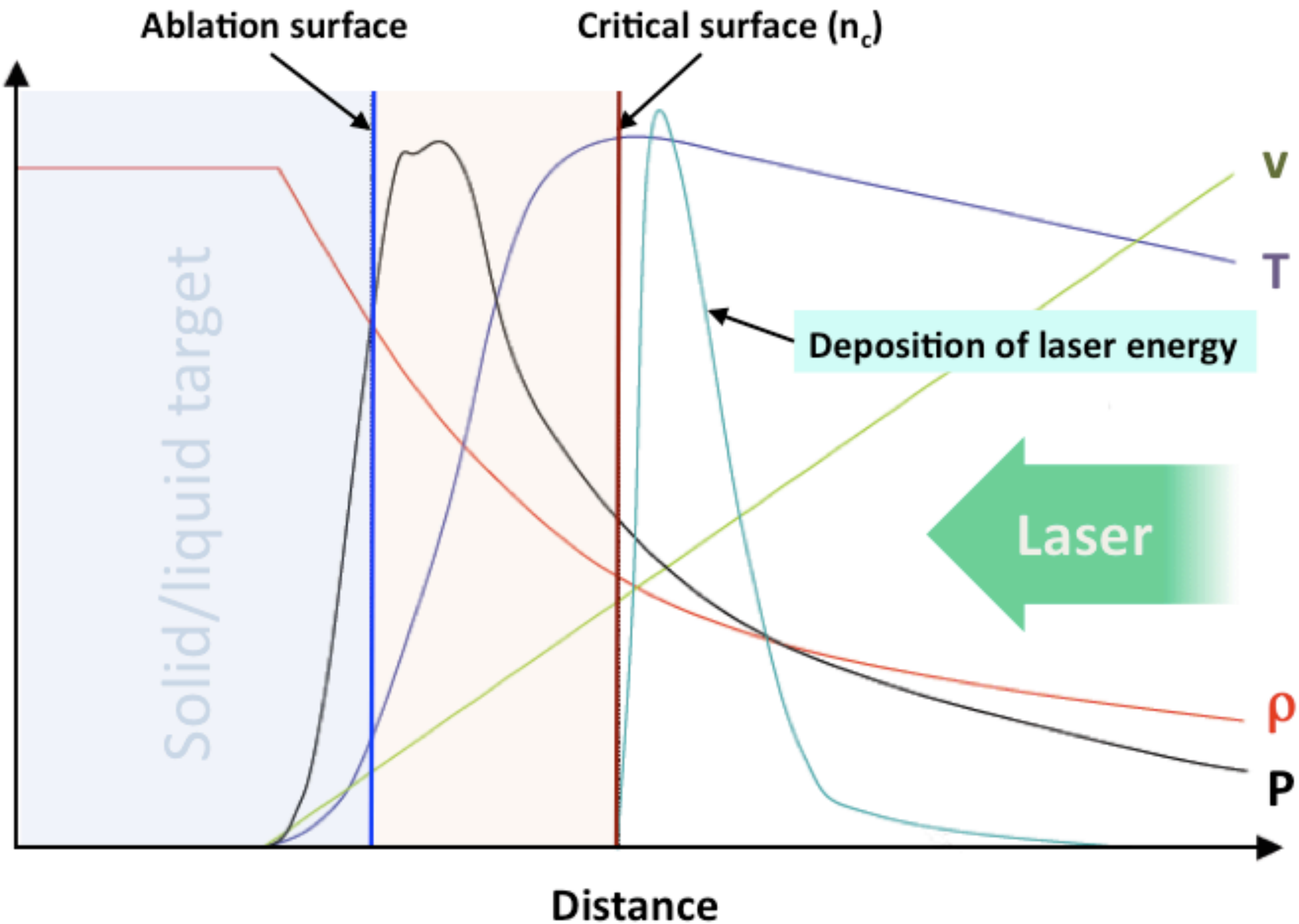
Absorption coefficient

- Thermalisation of the laser-induced oscillatory energy by electron-ion collisions that gives rise to the absorption mechanism, referred to as “inverse Bremsstrahlung”.
- We expect denser plasmas to absorb more efficiently.
- Shorter wavelength can propagate to higher density, thus should be better absorbed.
- At high irradiances, the plasma has higher temperature during the pulse, and thus the absorption drops.
- Note: a more rigorous method to derive the absorption coefficient would provide a factor of 2 grater value for κ, but the general approach is correct.

Absorption coefficient



Laser ablation model



Laser ablation model

- Laser energy is deposited up to critical surface.
- Region outside critical surface is known as the corona, and is approximately isothermal.
- Laser energy flows down the temperature gradient to the target. Material is ablated away at the ablation surface.
- Pressure increases towards the ablation surface, as temperature is dropping, the density increases.
- As the plasma expands away from the target, the velocity increases (mass flow approximately constant).

Laser ablation model

- Assuming a steady-state situation, the mass flow at the ablation and critical surfaces must be constant:

$$\rho_{\mathrm{a}} u_{\mathrm{a}} = \rho_{\mathrm{c}} u_{\mathrm{c}}$$

- The momentum flux is also constant:

$$P_{\mathrm{a}} + \rho_{\mathrm{a}} u_{\mathrm{a}}^2 = P_{\mathrm{c}} + \rho_{\mathrm{c}} u_{\mathrm{c}}^2$$

- Plasma expansion looks like isenthalphic throttling process. We need to account for the kinetic energy flow in the plasma as well as the heat flow W between critical and ablation surfaces:

Enthalpy: H = U + PV

$$\frac{1}{2}\rho_{\mathrm{a}} u_{\mathrm{a}}^3 + H_{\mathrm{a}}\rho_{\mathrm{a}} u_{\mathrm{a}} + W = \frac{1}{2}\rho_{\mathrm{c}} u_{\mathrm{c}}^3 + H_{\mathrm{c}}\rho_{\mathrm{c}} u_{\mathrm{c}}$$

Laser ablation model assumptions

- For simplicity we assume the ideal gas equation of state, thus enthalpy is given by: *Normal ratio of heat capacities (=5/3)*

$$H = \left(\frac{\gamma}{\gamma - 1}\right)\frac{P}{\rho}$$

- Plasma at ablation surface is denser: $\rho_{\mathrm{a}} \gg \rho_{\mathrm{c}}$
- Assume that the thermal flux W is dominant:

$$W \gg \frac{1}{2}\rho_{\mathrm{a}} u_{\mathrm{a}}^3 + H_{\mathrm{a}}\rho_{\mathrm{a}} u_{\mathrm{a}}$$

- Assume plasma flow velocity at the critical surface is Mach ~ 1, i.e. sound velocity:

$$u_{\mathrm{c}} = \left(\frac{\gamma P_{\mathrm{c}}}{\rho_{\mathrm{c}}}\right)^{1/2}$$

Laser ablation model

- We can now construct the ablation model:

$$W = \frac{1}{2}\rho_c u_c^3 + H_c \rho_c u_c$$

- Substituting the previous expressions:

$$W = \frac{\rho_c}{2}\left(\frac{\gamma P_c}{\rho_c}\right)^{3/2} + \left(\frac{\gamma}{\gamma - 1}\right) P_c \left(\frac{\gamma P_c}{\rho_c}\right)^{1/2}$$

$$W = \frac{1}{\sqrt{\rho_c}} P_c^{3/2} \sqrt{\gamma}\left(\frac{\gamma}{2} + \frac{\gamma}{\gamma - 1}\right)$$

- For $\gamma = 5/3$, rearrange: $P_c \approx 4\rho_c^{1/3} W^{2/3}$

predicted pressure at the critical surface

Laser ablation model

- At the ablation surface the velocity tends to zero, and thus:

$$P_{\mathrm{a}} = P_{\mathrm{c}} + \rho_{\mathrm{c}} u_{\mathrm{c}}^2$$

- Substitute for u_c:

$$P_{\mathrm{a}} = (1+\gamma) P_{\mathrm{c}} = \frac{8}{3} P_{\mathrm{c}}$$

- Therefore the ablation pressure:

$$P_{\mathrm{a}} \approx \frac{32}{3} \rho_{\mathrm{c}}^{1/3} W^{2/3}$$

- There is a critical density for a specific laser wavelength:

$$\omega^2 = \frac{n_{\mathrm{c}} e^2}{\varepsilon_0 m_e}$$

Laser ablation model

- Assume fully ionised atoms of mass $M = 2Zm_p$ (nuclei with roughly equal numbers of protons and neutrons):

$$\rho_c = 2n_c m_p = 2m_p\left(\frac{\varepsilon_0 m_e \omega^2}{e^2}\right)$$

- Substitute into the expression for P_a:

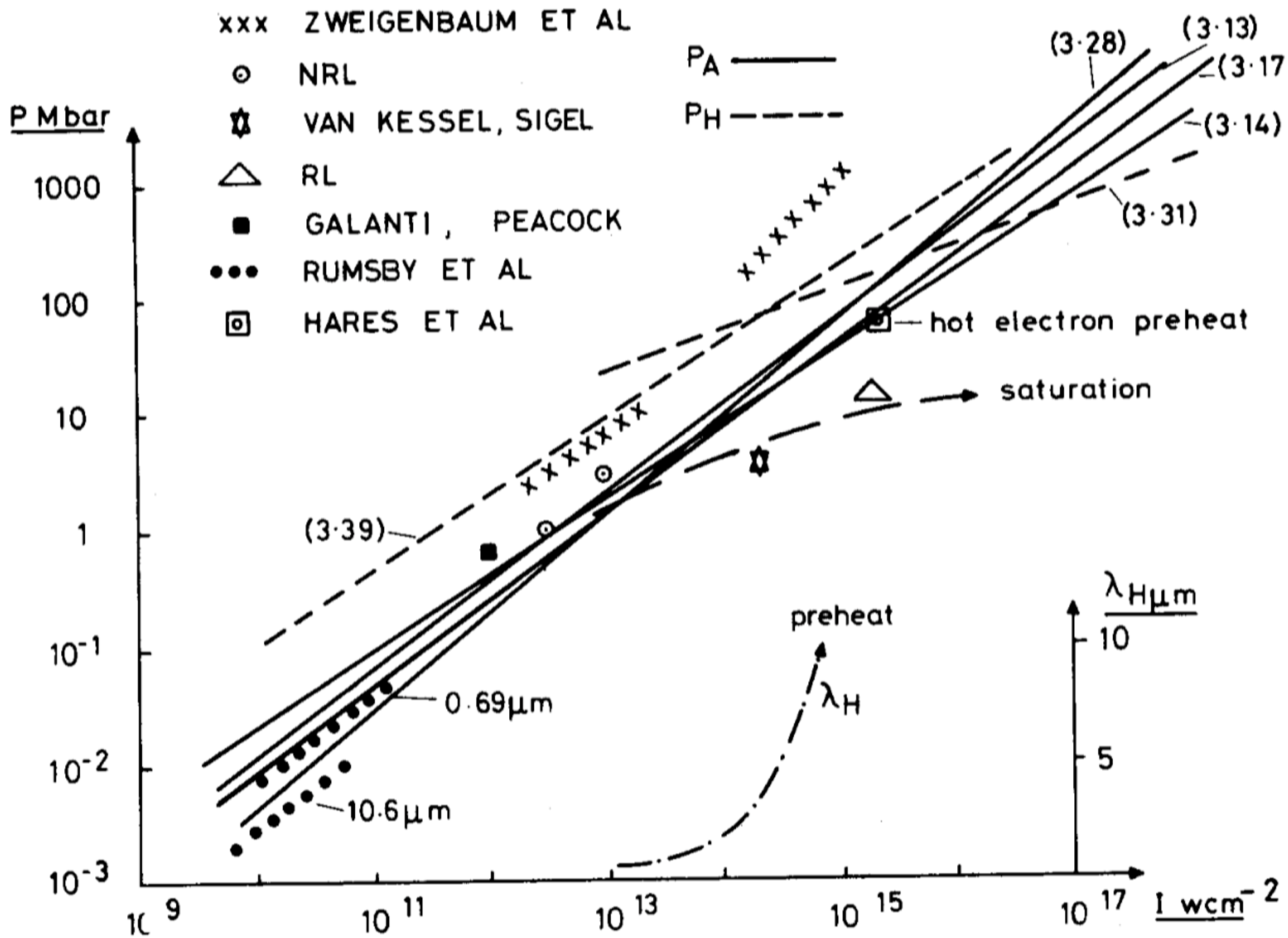
Laser intensity in W/cm²

$$\boxed{P_\mathrm{a} \approx \frac{32}{3}\left(\frac{2\varepsilon_0 m_e m_p \omega^2}{e^2}\right)^{1/3} W^{2/3}}$$

- For laser intensity in W/cm² we have:

$$P_a \approx 2.8\times10^{-9}\times W^{2/3}\ \text{Mbar}$$

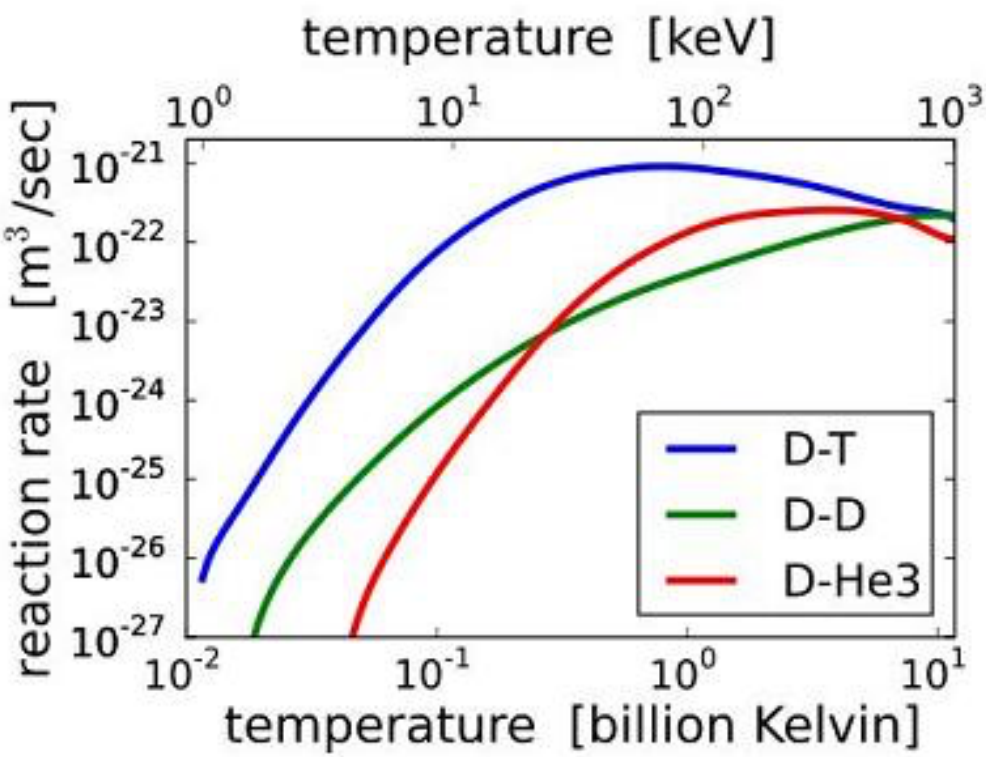
Laser ablation model

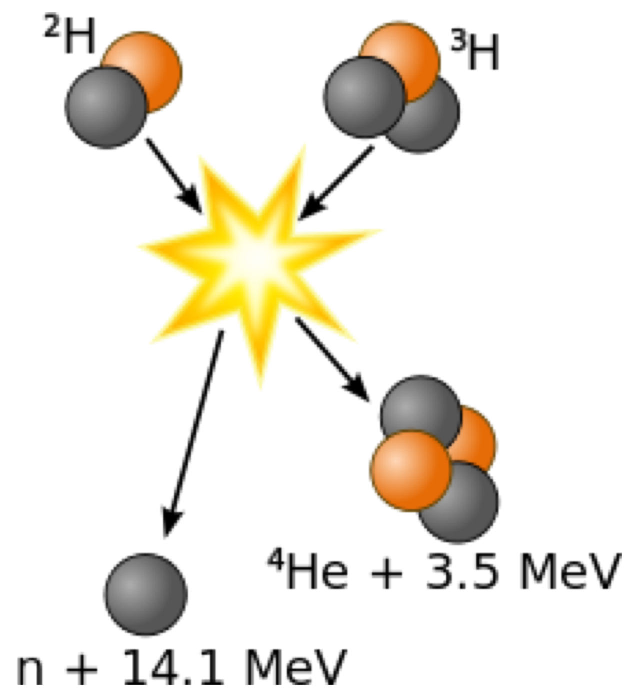


Thermonuclear fusion

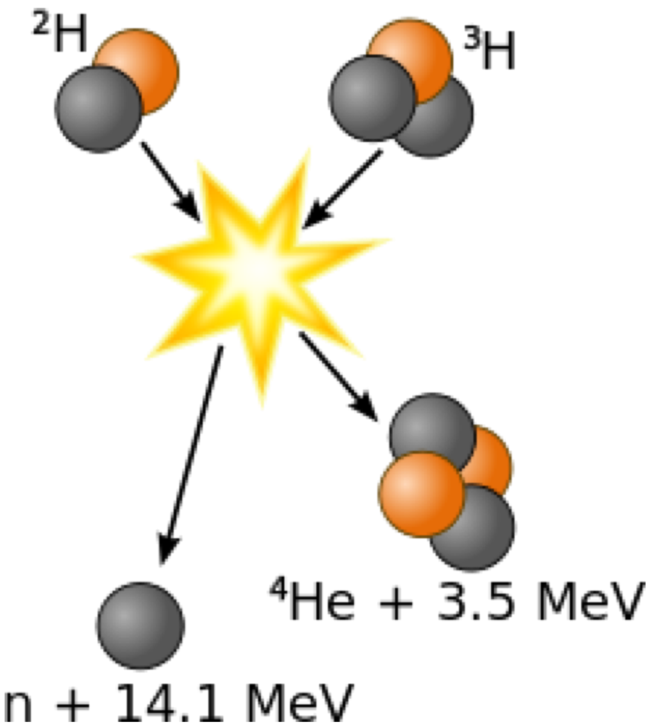
- D-T reaction rate is ~ 10^{-22} m^3s^{-1} at a temperature of 10 keV.

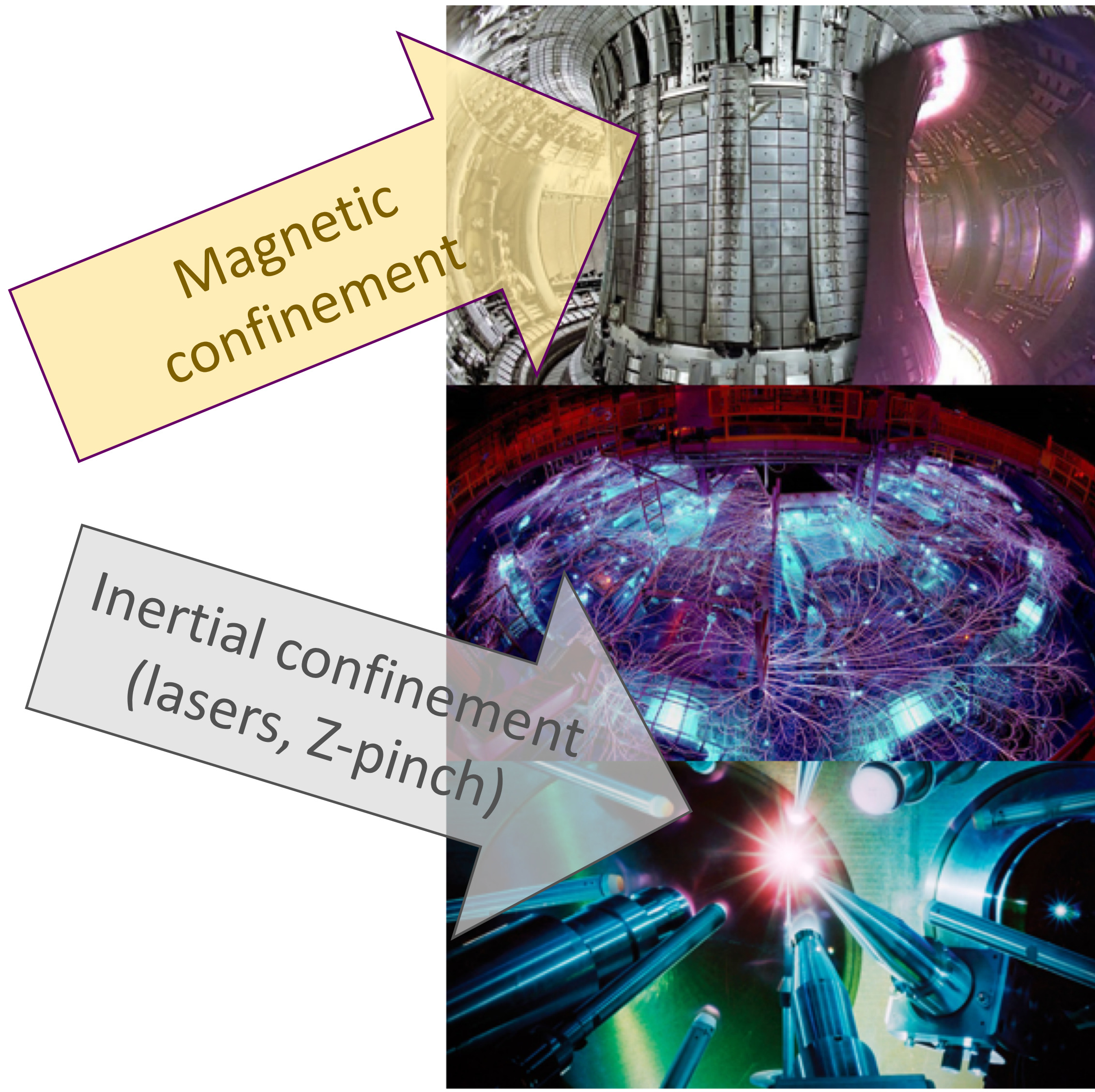
$$D + T \Rightarrow \alpha(3.5\text{MeV}) + n(14.1)\text{MeV}$$





Approaches to fusion research





The Lawson criterion

- For D-T fusion energy gain, the energy out must exceed the energy in. The energy out per volume is given by:

Energy per reaction

$$E_f = n_D n_T \sigma W \tau = \frac{n^2 \sigma W \tau}{4}$$

Assuming: $n_D = n_T = \frac{n}{2}$

Reaction rate *Plasma confinement time*

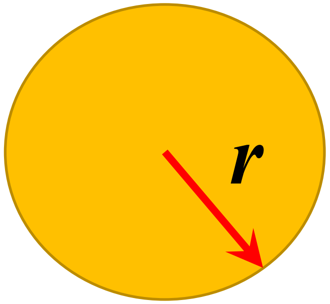
- This must exceed the energy required to heat the plasma to the temperature required for fusion:

$$E_t = 2 \times \frac{3}{2} n k_B T$$

- Thus:

$$\frac{n^2 \sigma W \tau}{4} > 3 n k_B T$$

The Lawson criterion



- We define the Lawson criterion:

$$\boxed{n\tau > \frac{12k_B T}{\sigma W}}$$

- For a $T = 10$ keV, $\sigma \sim 10^{-22}$ m^{3}s^{-1}, $W \sim 17$ MeV:

$$n\tau > \frac{12\times10^4}{10^{-22}\times17\times10^6} \sim 10^{20}\ \mathrm{sm}^{-3}$$

- Plasma of radius r and temperature T is confined by its own inertial for a time of order its initial radius divided by the sound speed.

$$\tau \approx \frac{r}{4C_s}$$

The Lawson criterion

- Derive the Lawson criterion for ICF:

$$\boxed{n\tau = \frac{\rho r}{4 C_{\mathrm{s}} M} > 10^{20} \quad \mathrm{s\ m^{-3}}}$$

- Where the sound speed is:

$$\boxed{C_s = \sqrt{\frac{k_B T}{M_{ion}}}}$$

- If we use the mass of a deuterium atom and $T \sim 10$ keV:

$$\rho r > 0.6 \text{ g/cm}^2$$

How much laser energy is needed?

- Combining:

$$\frac{n^2 \sigma W \tau}{4} > 3k_B T \quad \text{and} \quad \tau \approx \frac{r}{4C_s}$$

- We get: $$\frac{n^2 \sigma W r}{16C_s} > 3nk_B T$$

- Thus radius needed to satisfy the Lawson criterion:

$$r = \frac{48k_B T C_s}{n\sigma W}$$

How much laser energy is needed?

- The fusion energy released per unit volume E_f in a D-T reaction can be written as:

Energy per unit volume

$$E_\mathrm{f} = \frac{n^2 \sigma W r}{16 C_\mathrm{s}} \approx E_\mathrm{t} = 3 n k_\mathrm{B} T$$

- Therefore total energy U required to heat a sphere of radius r to fusion conditions is:

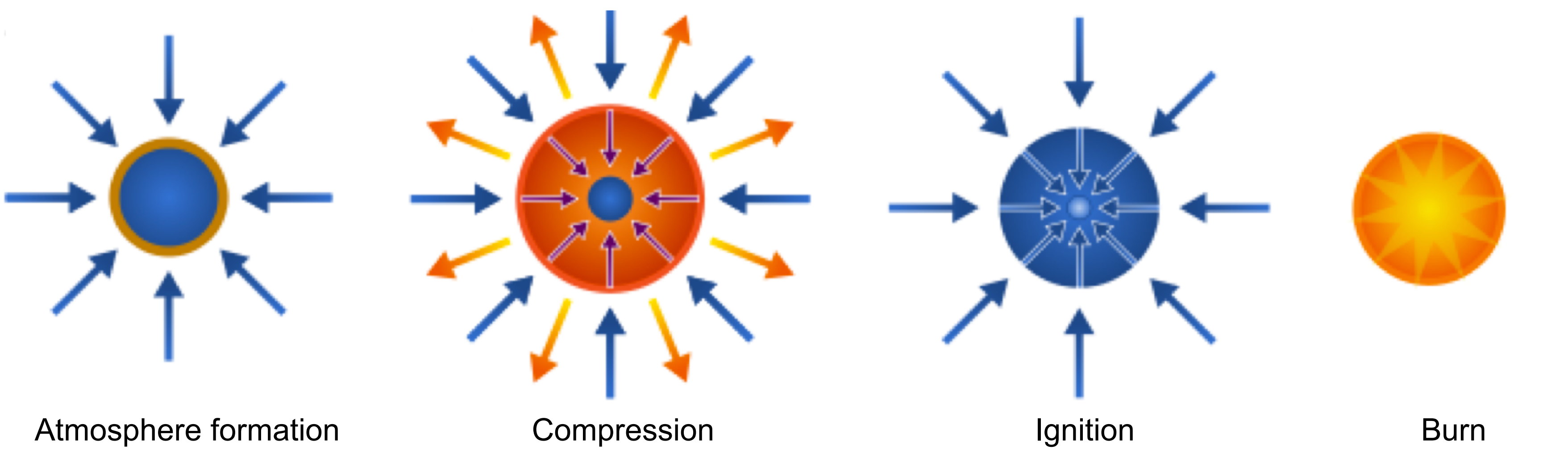
$$U = \frac{4\pi r^3}{3} E_f = 4\pi \left(\frac{48 k_B T C_s}{n \sigma W} \right)^3 n k_B T$$

- At 10 keV this is:

$$U \approx 4 \times 10^{68} \frac{1}{n^2} \ \mathrm{J}$$

Inertial confinement fusion (ICF)

- The idea of laser fusion is to compress a small frozen (solid) hollow D-T pellet into a very high density up to 1000 g/cm^3 $\approx 10^{26}$ cm^{-3} and heat it to extreme temperatures reaching 10 keV (10^7 K) using laser ablation.
- There are several approaches to laser fusion, next slides.
- An alternative approach to ICF is using Z-pinches (discussed in the previous lecture).



Compression requirements

- If we could compress the D-T by, say a factor of 100, the heating laser would only need to contain $\sim$ 100 kJ, (detailed calculations show we need a factor of ten more). However, to produce such high densities a large pressure is required. Assuming electrons are degenerate in the compressed plasma: Fermi energy

$$P_{\mathrm{F}} = \frac{2}{5} n E_{\mathrm{F}} = \frac{2}{5} \frac{\hbar^2 n}{2m} \left(3\pi^2 n\right)^{2/3}$$

- For $n = 100\times6\times10^{29}$,we find $E_F \sim$ 550 eV, $P \sim 2\times10^4$ Mbar. Thus we need pressures of order 200 times typical ablation pressures (more detailed calculations show factors of ~ 50).

Pressure Amplification

- Spherical compression amplifies the pressure.
- Initial acceleration of the imploding shell gives:

$$F = P_{\mathrm{a}} 4\pi r_0^2 = \rho_0 4\pi r_0^2 \Delta r a$$

ρ_0= initial density

- Assuming constant acceleration, the final velocity is:

$$v^2 = 2as$$

s = distance travelled

- The final radius is small, so assume $s = r_0$ and estimate the final kinetic energy:

$$\begin{aligned} \frac{1}{2}mv^2 &= mas \\ &= m\frac{P_{\mathrm{a}}}{\rho_0 \Delta r} r_0 \\ &= V P_{\mathrm{a}} \left(\frac{r_0}{\Delta r}\right) \end{aligned}$$

Pressure Amplification

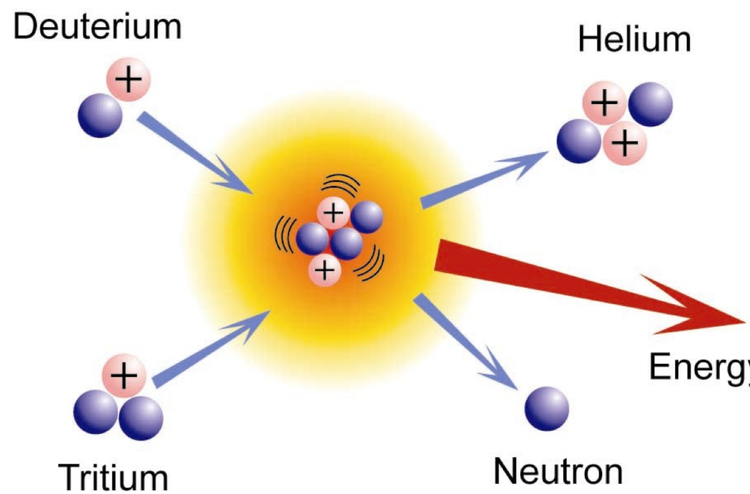
- As pressure is energy per unit volume, if this kinetic energy is converted into energy of compression adiabatically, then the stagnation pressure P_s is:

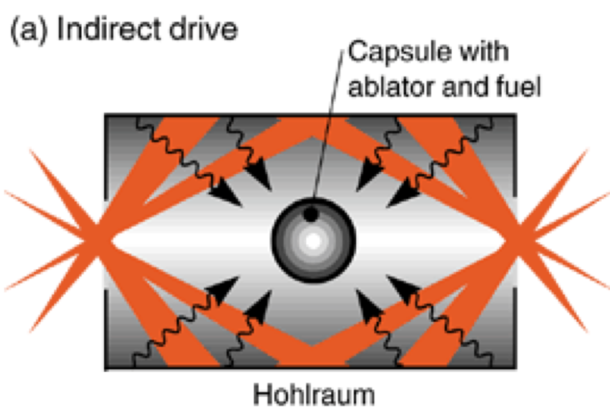
$$P_{\mathrm{s}} = \frac{1}{V}\frac{1}{2}mv^2 = P_a\left(\frac{r_0}{\Delta r}\right)$$

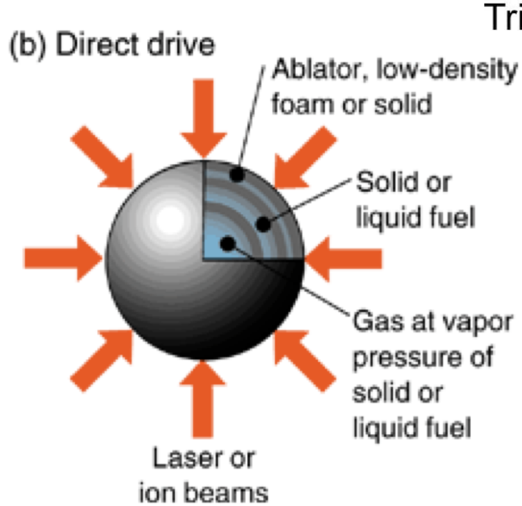
- In spherical compression, the ablation pressure is magnified by the aspect ratio.
- Note: these are just rough order of magnitude estimates. Further we must consider losses and the impact of plasma instabilities (to be discussed in the following lecture).

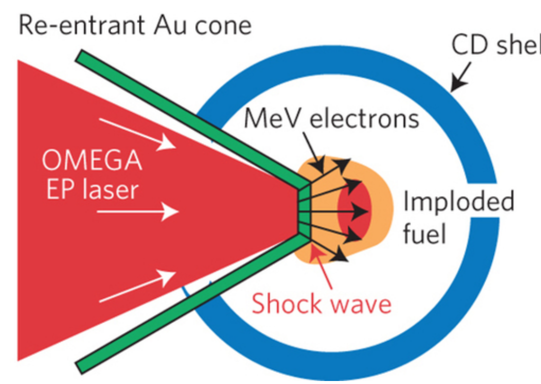
Approaches to laser ICF

- 60 – 200 laser beams reaching total power: 10^{12} W (TW)
- Reach high densities and temperatures
- 3 standard approaches:
  - Indirect drive
  - Direct drive
  - Fast ignition

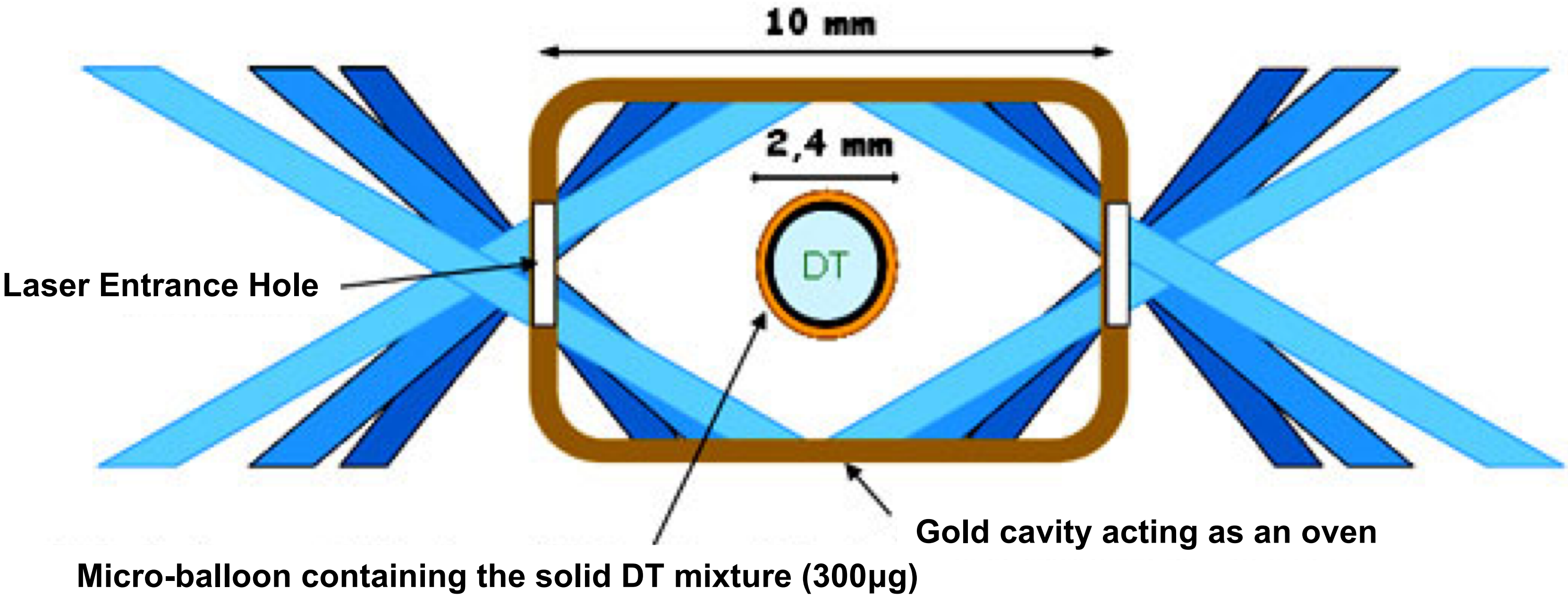


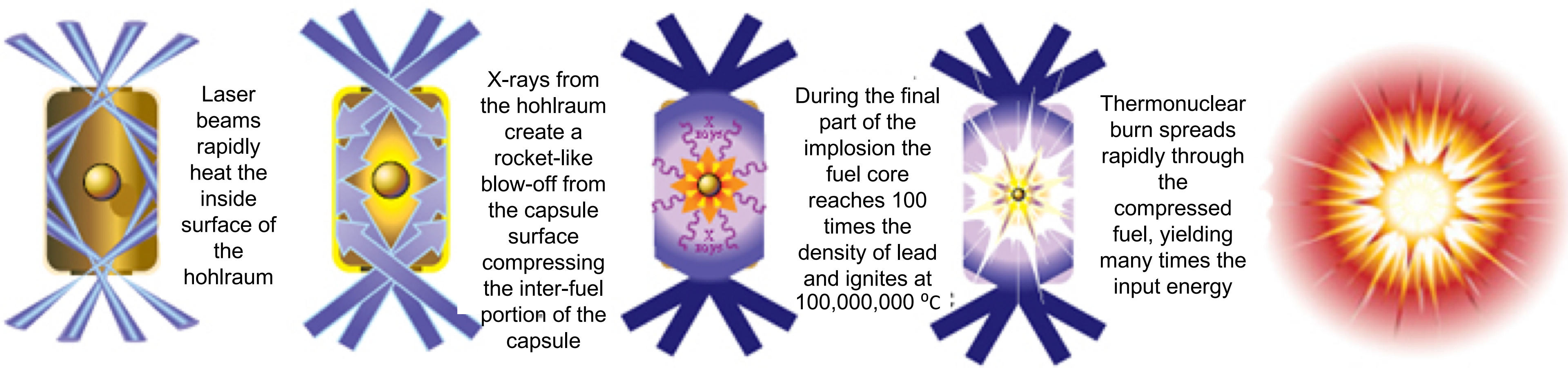




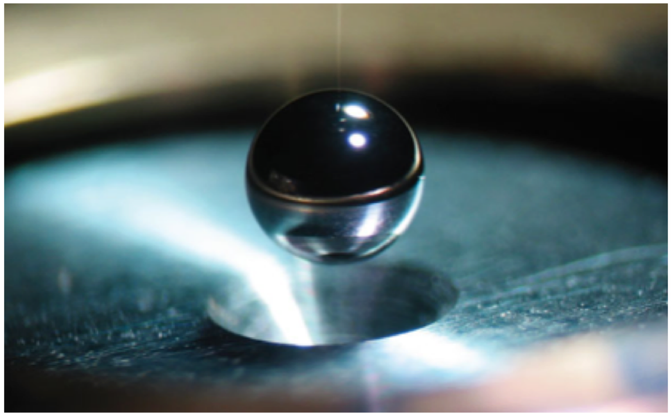


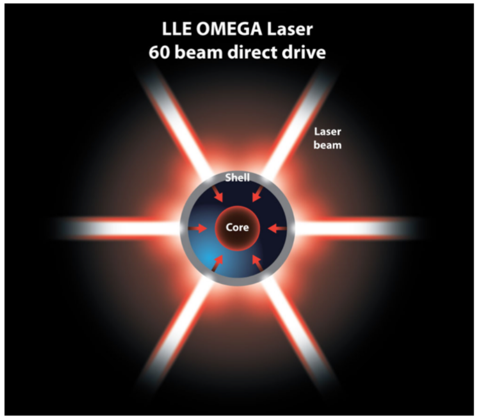
Indirect drive

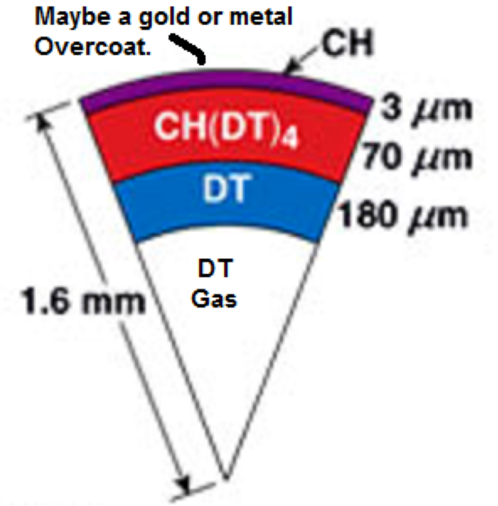




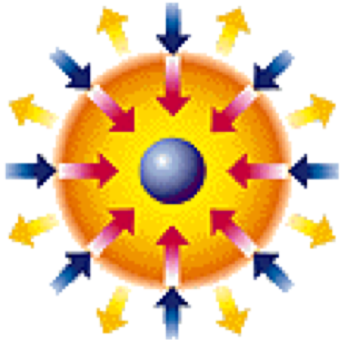
Direct drive



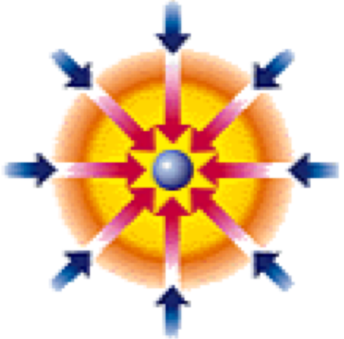




1) Atmosphere formation: Laser beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.



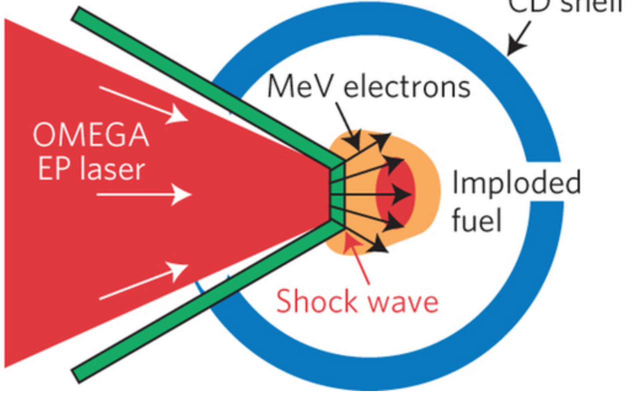
2) Compression: Fuel is compressed by the rocket-like blow-off of the hot surface material.

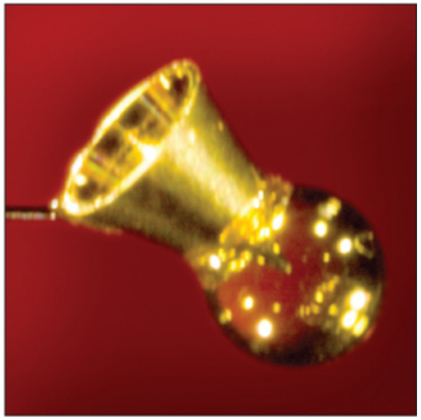


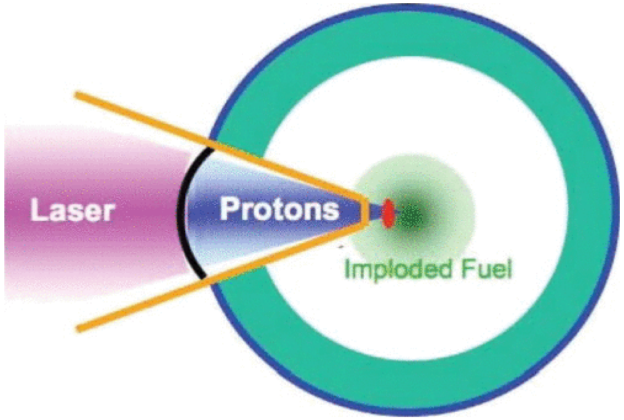
3) Ignition: During the final part of the laser pulse, the fuel core reaches 20 times the density of lead and ignites at 100,000,000 degrees Celsius.

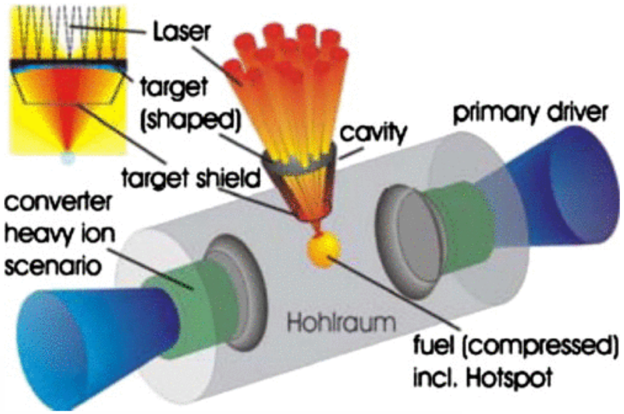
4) Burn: Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

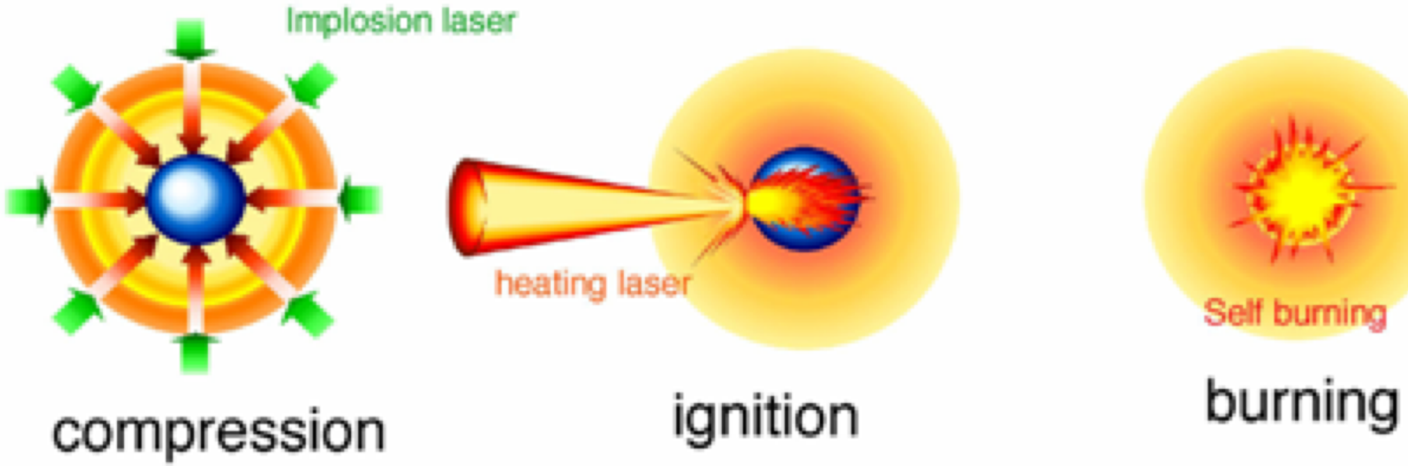
Fast ignition









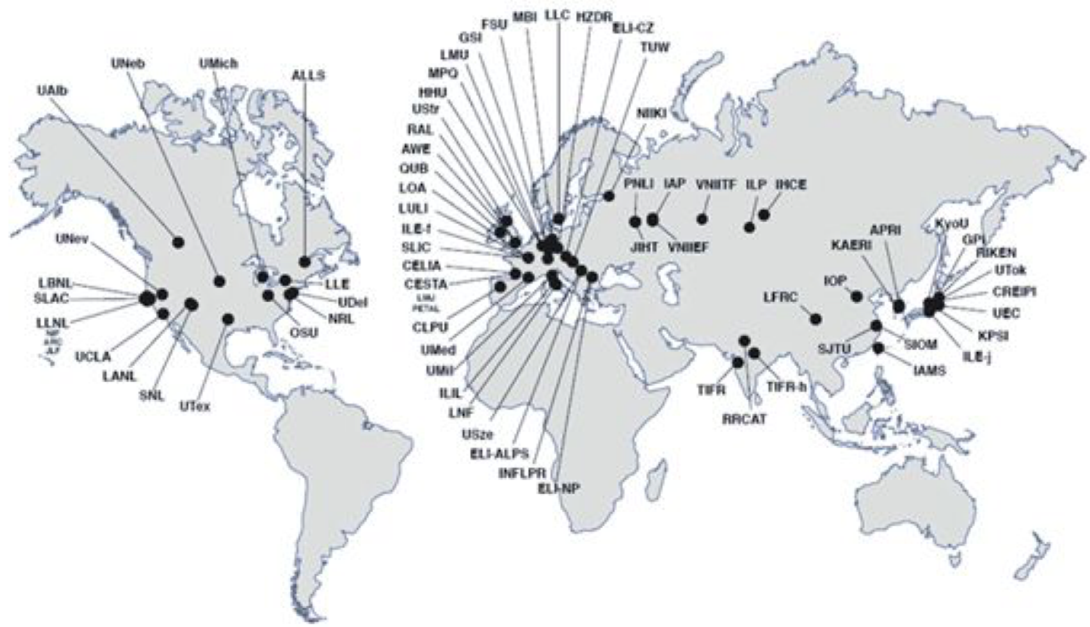


The worlds biggest lasers

Integrated initiative Laserlab-Europe

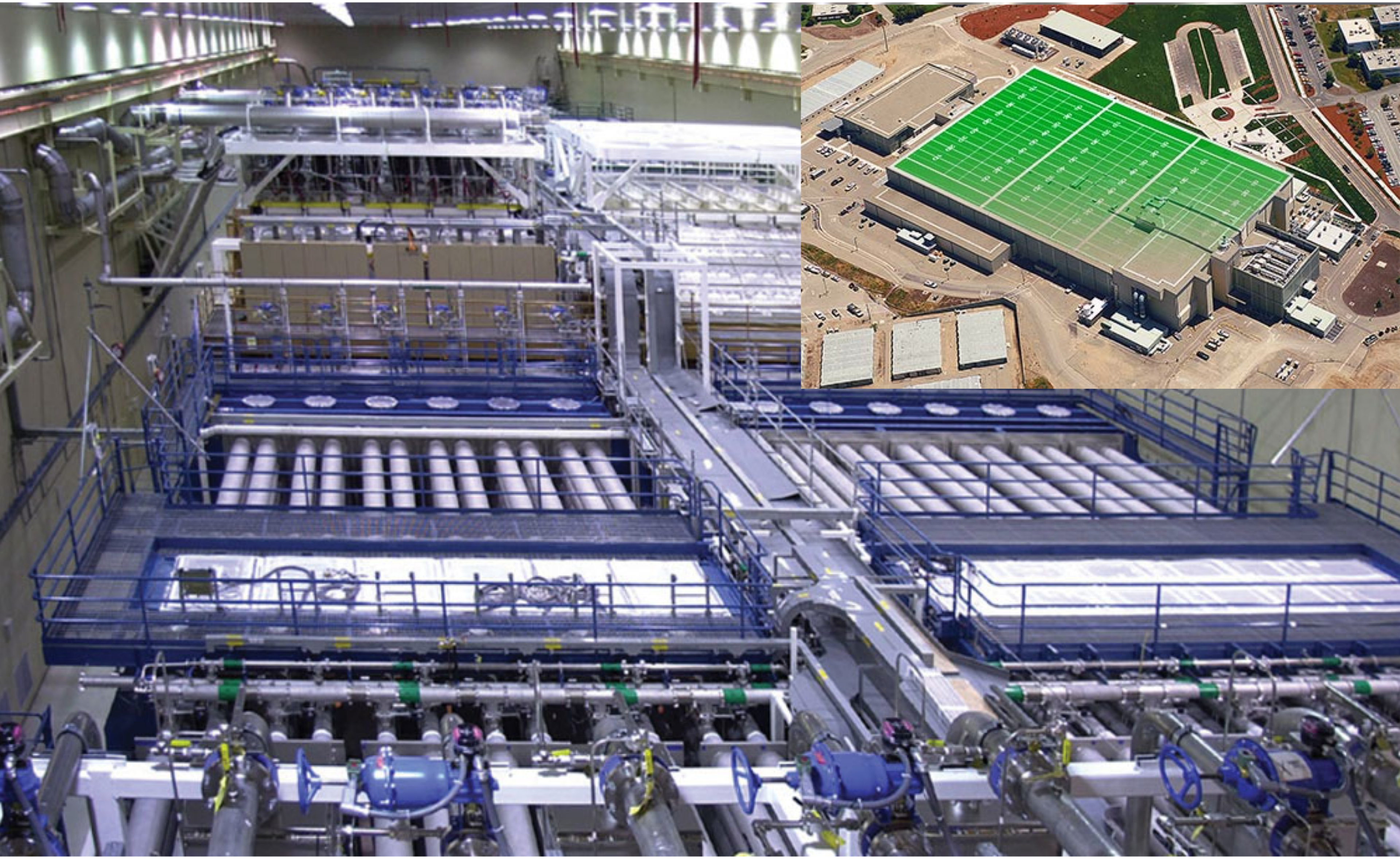
30 national laser facilities from 16 European countries

National high-power laser facilities world-wide

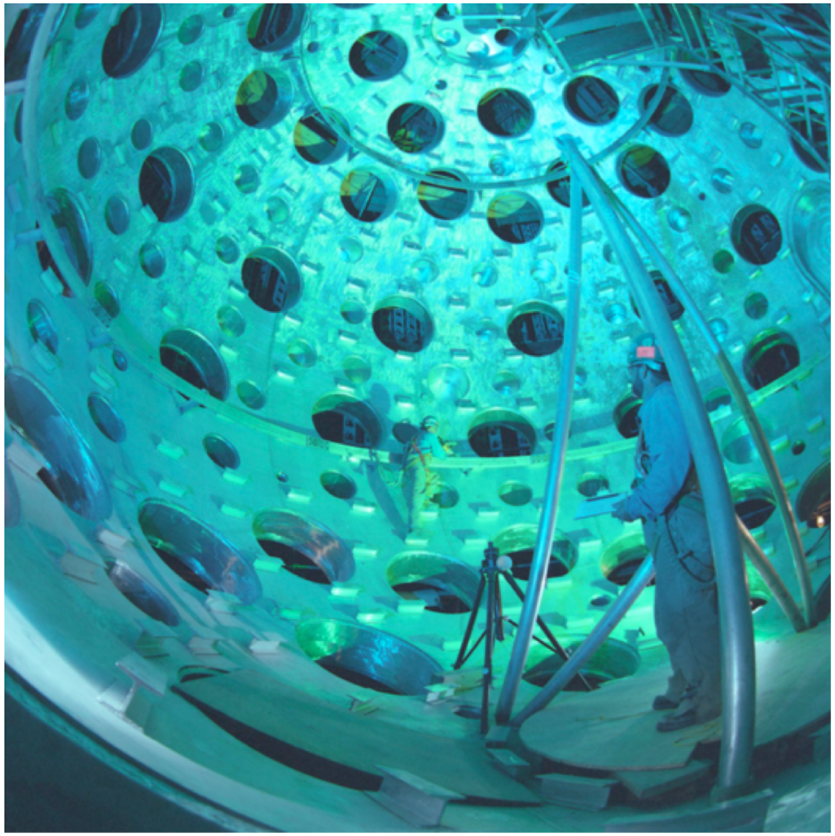


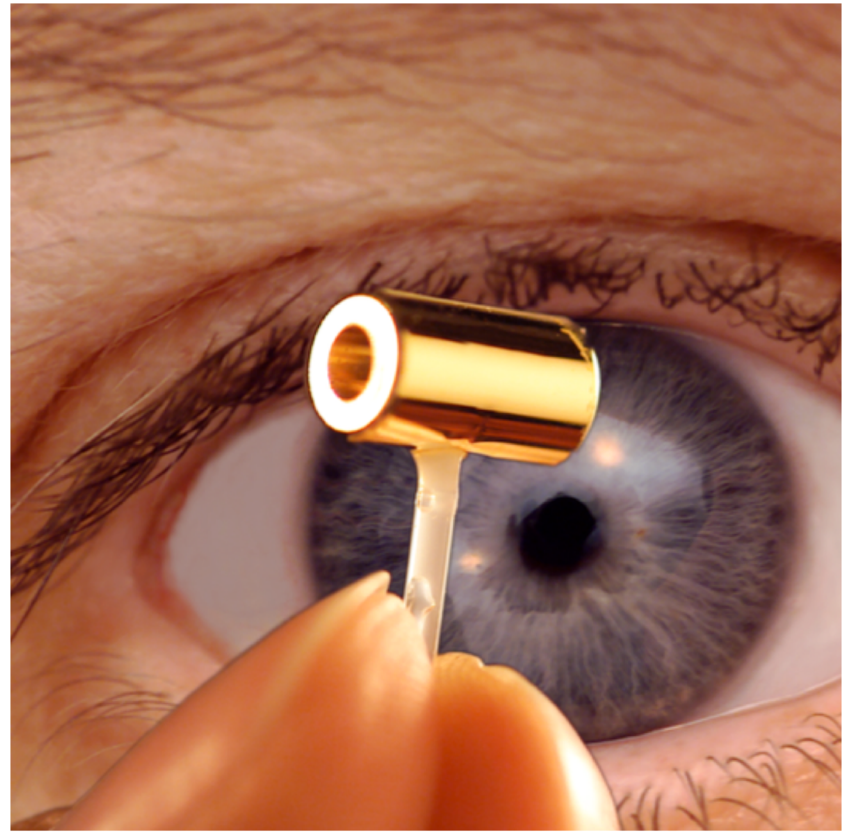
Ultra-high intensity laser systems worldwide in 2010 (ICUIL)

National Ignition Facility



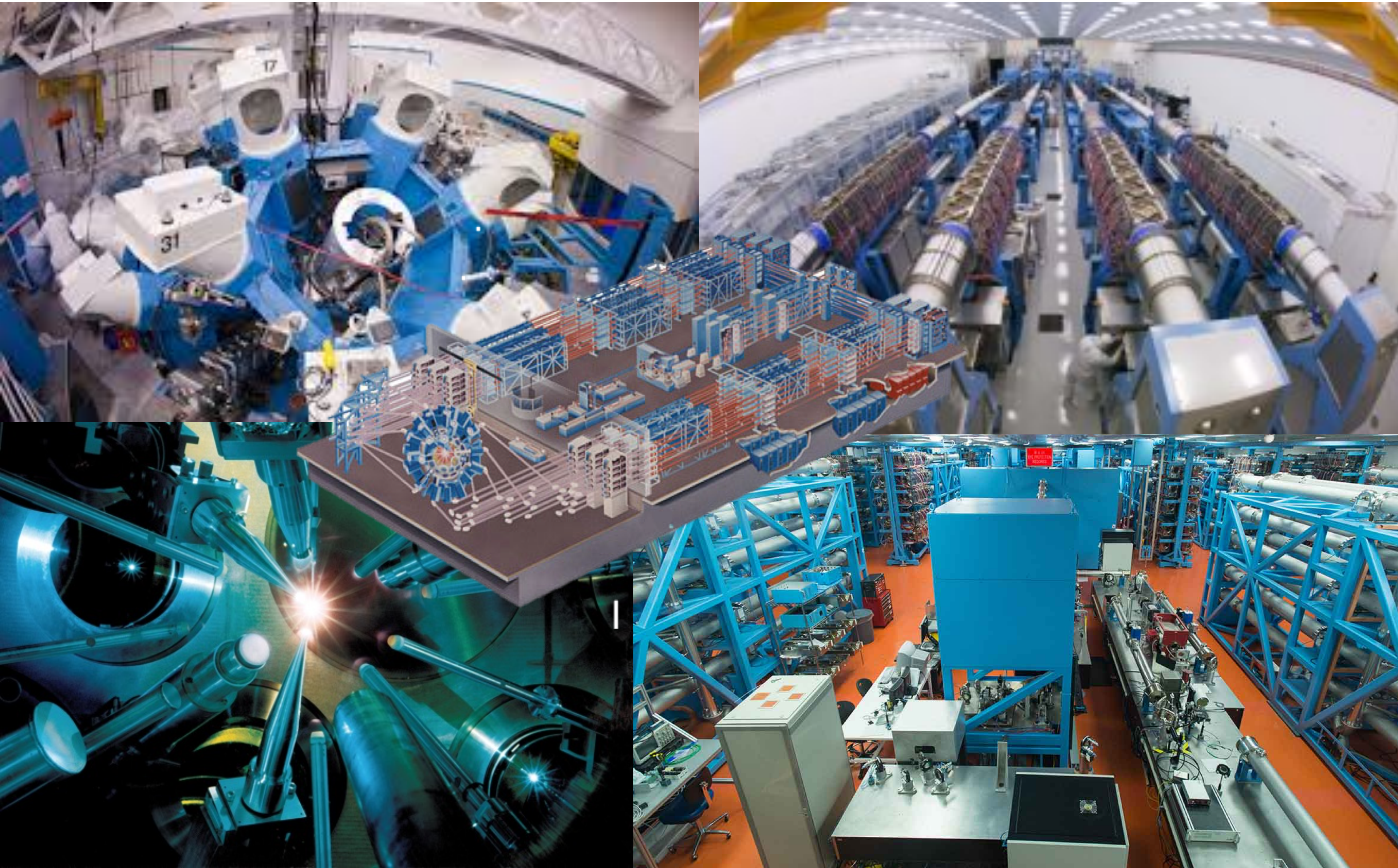
National Ignition Facility





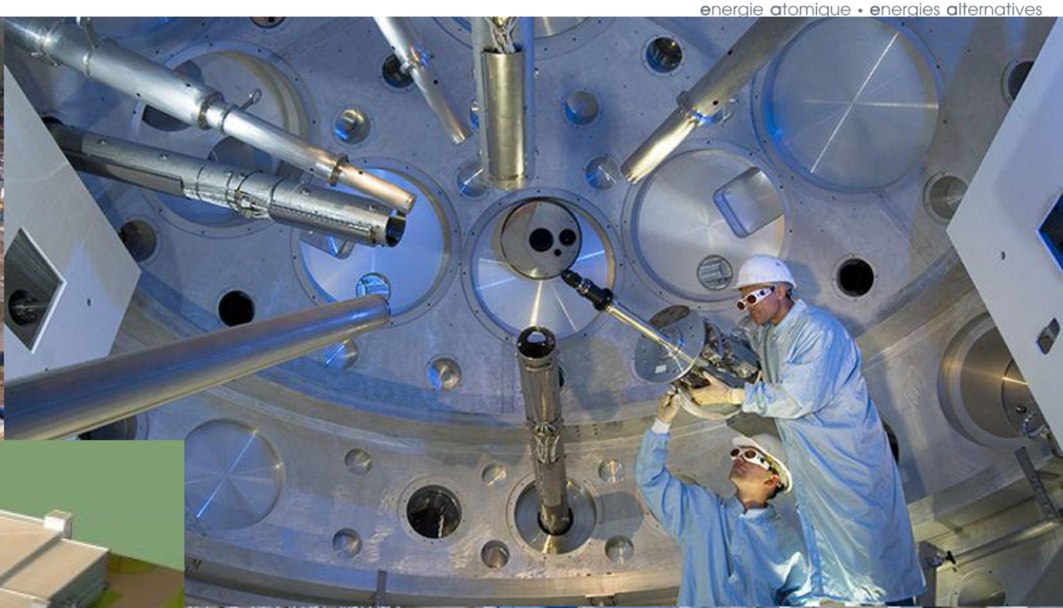
192 laser beams, each nearly a metre in diameter, are focussed with lenses through the holes in the chamber to spots in the centre only a few 100 microns.

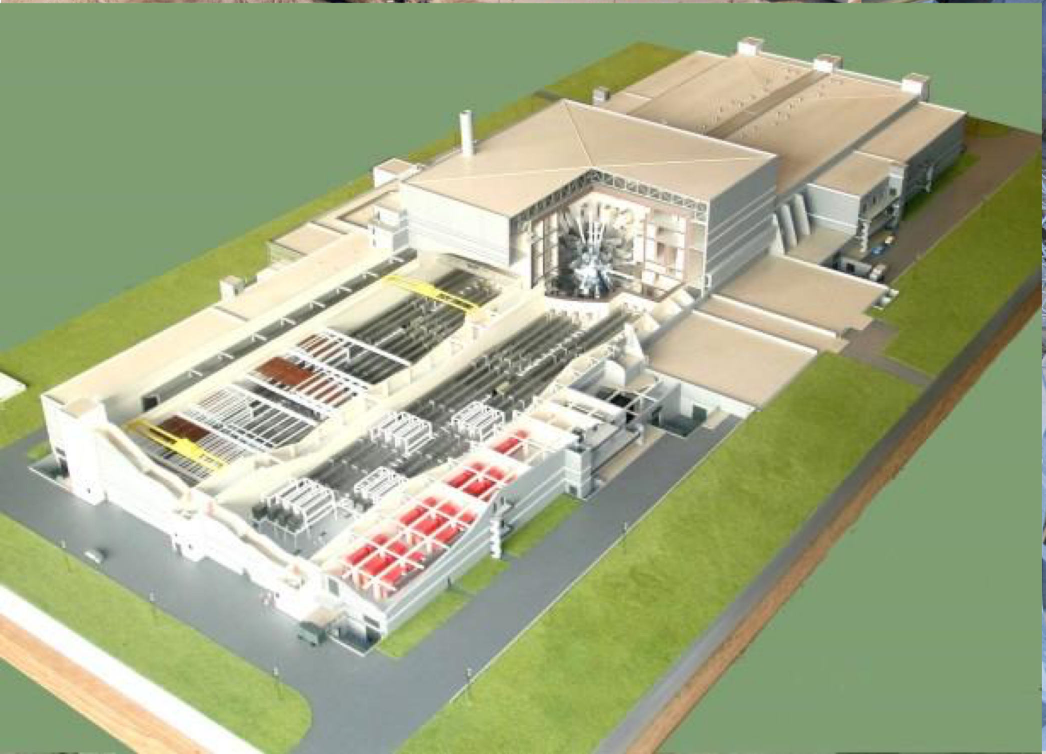
Omega laser facility



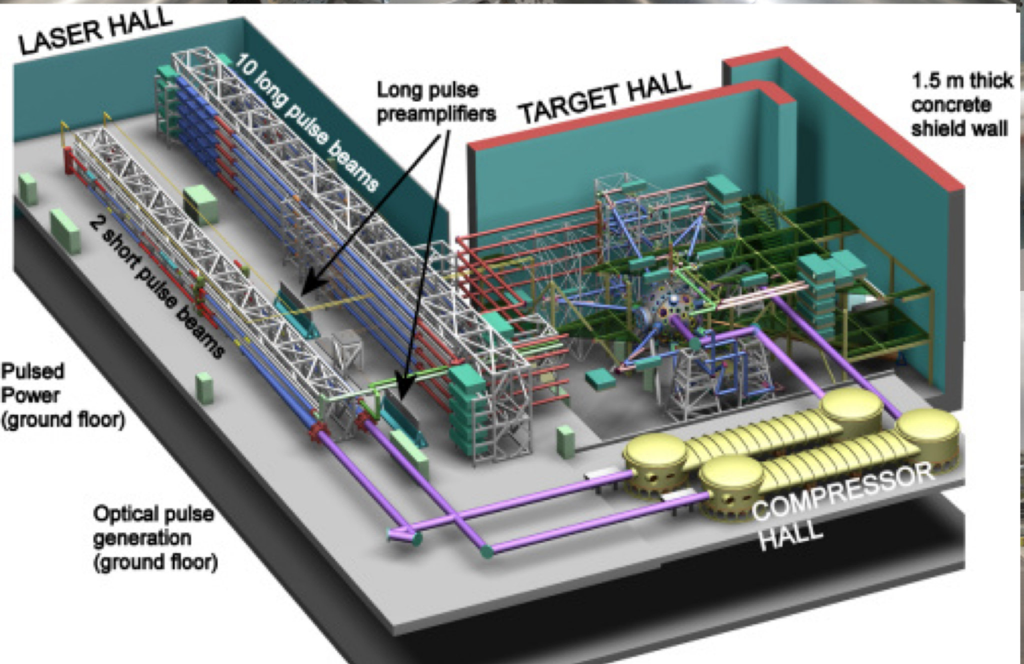
Laser Megajoule (LMJ)

energie atomique • energies alternatives

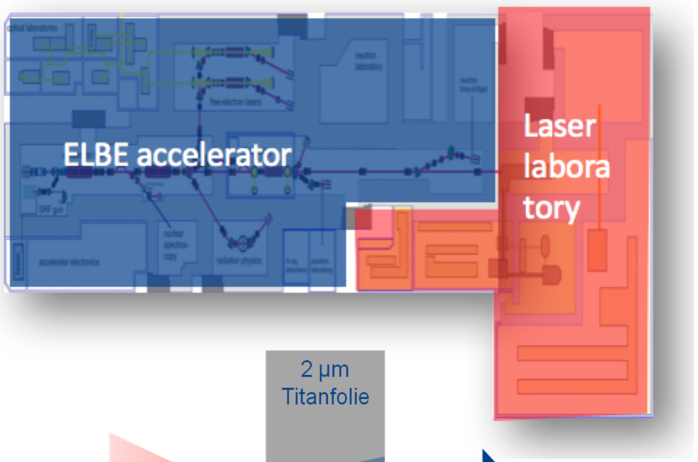


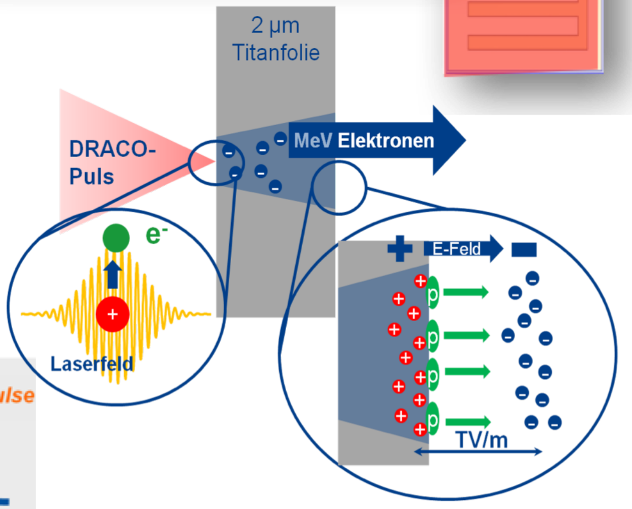


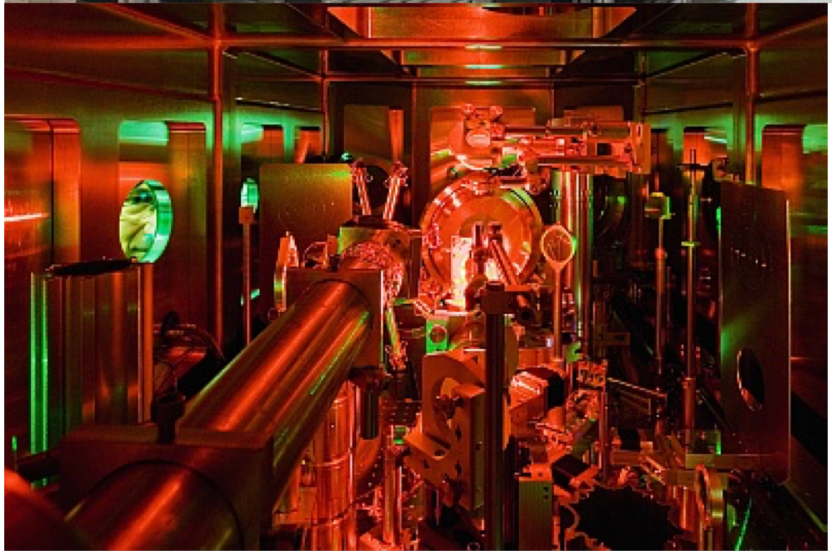
Orion laser

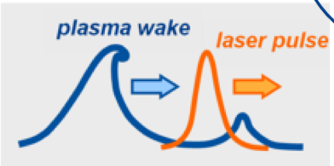

LASER HALL
10 long pulse beams
Long pulse preamplifiers
TARGET HALL
1.5 m thick concrete shield wall
2 short pulse beams
Pulsed Power (ground floor)
Optical pulse generation (ground floor)
COMPRESSOR HALL

DRACO/PENELOPE laser (HZDR)









- Commercial system, in operation since 2008
- 150 TW & 1 PW dual-beam operation
- Additional 1PW system (PENELOPE) under development

Summary of lecture 9

- Inverse bremsstrahlung absorption favours the use of short wavelength lasers.
- Simple models show that the ablation pressure scales as $W^{2/3}$, giving Mbar pressures at irradiances of 10^{14} $\mathrm{Wcm^{-2}}$
- The Lawson criterion: $$n\tau > \frac{12k_BT}{\sigma W}$$
- Plasmas confined by their own inertia require large energies to undergo fusion - but this energy scales inversely with the square of the compression.
- Compression of the fusion fuel can take place by the implosion of spherical targets - the pressure amplification factor being of order the aspect ratio, but we must consider losses and plasma instabilities.