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Dolní Břežany, Czech Republic

Inertial Confinement Fusion

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IMPULSE

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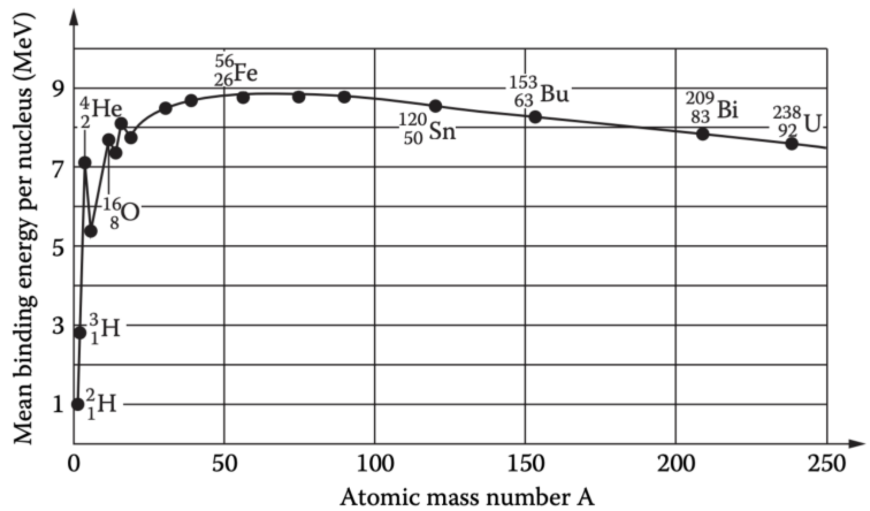
Outline

- **Basic principles of energy production from fusion reactions**
- **Physics of inertial confinement fusion**
- **Recent results from the inertial fusion research**

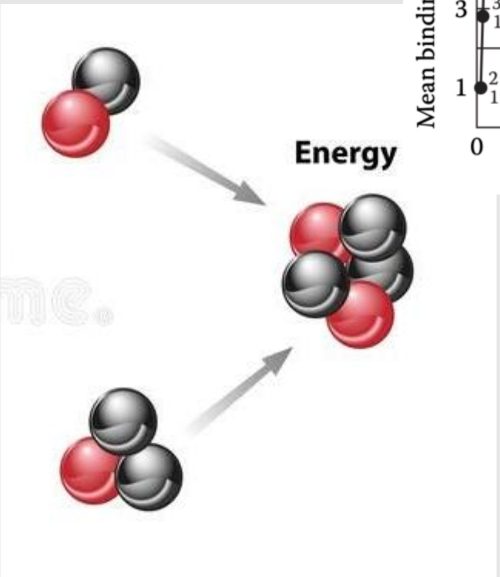
Basic principles of energy production from fusion reactions

Energy from nuclear reactions

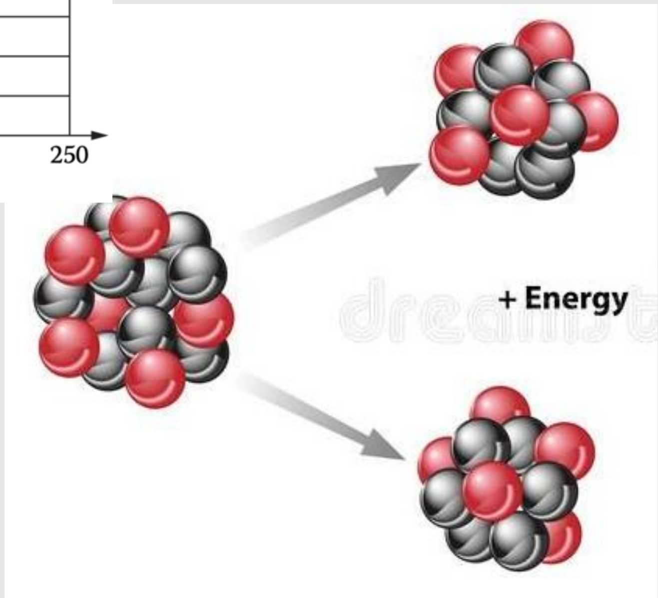
Understanding of the mass deficit in nuclei has led to energy release from nuclear reactions: A. Eddington 1920s



Fusion
D + T



Fission
U + n



Two major differences:

- **Charged particles**
- **High energy neutrons: 1 MeV vs 14 MeV**

Not yet in 70 years

Achieved in 10 years

Energy production in fusion reactions

The major obstacle are elastic collisions: cross section of elastic collisions

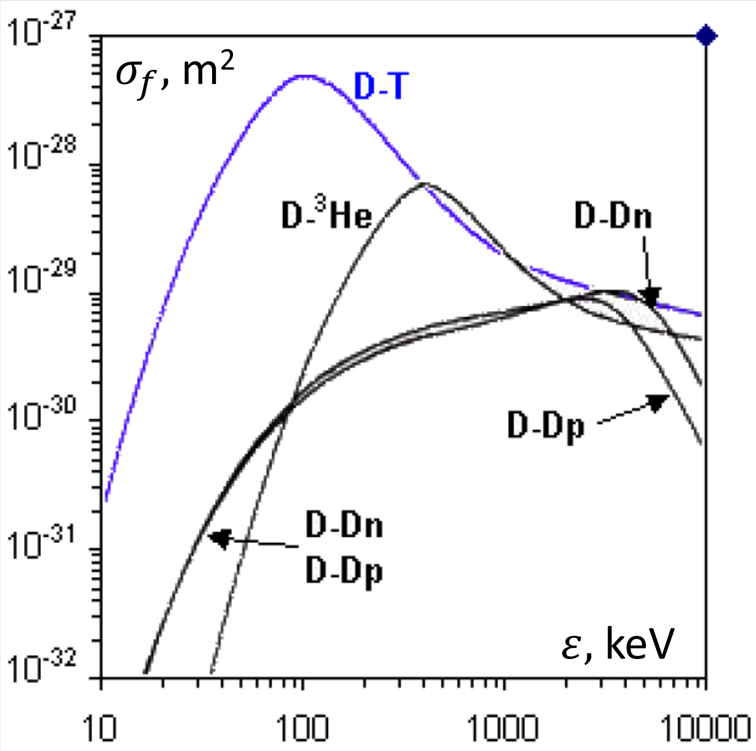
$$\sigma_{\text{elast}} \cong (\hbar/m_r v)^2$$

is more than 4 orders of magnitude larger than the fusion reaction cross section:

$$\sigma_{\text{fus}} \cong (\hbar/m_r v)^2 \exp -\sqrt{\varepsilon_G/\varepsilon}$$

$\varepsilon_G \sim 2$ MeV - Gamov energy; for $\varepsilon = 100$ keV, $\sigma_{\text{elast}} \cong 10^{-19}$ cm², compared to $\sigma_{\text{fus DT}} \cong 3 \times 10^{-24}$ cm²

The only solution to overcome elastic collisions is to heat the fuel and to maintain it for a time sufficient for the ions to fuse: two main conditions: **heating and confinement.** Fusion proceeds in a near thermal equilibrium in the **plasma state**



D + T -> He^4 + n + 17.6 MeV
D + D -> He^3 + n + 3.3 MeV
D + D -> T + p + 4.0 MeV
D + He^3 -> He^4 + p + 18.3 MeV

Energy balance in fusion reactions

Fusion reactions proceed in a local thermal equilibrium at high temperatures: PLASMA

The intrinsic yield is defined as a ratio of the fusion energy to the fuel thermal energy

$E_{\rm fus} = \frac{1}{2} N_i \varepsilon_{\rm fus}$ $E_{\rm th} = \frac{3}{2}(N_i + N_e) T_{\rm ig}$ $Y = E_{\rm fus}/E_{\rm th}$ $T_{\rm igDT} \cong 12$ keV

$\varepsilon_{\rm DT} \cong 17.6$ MeV $(\rm n + \alpha)$

Intrinsic gain $Y_{\rm DT} \cong 300$

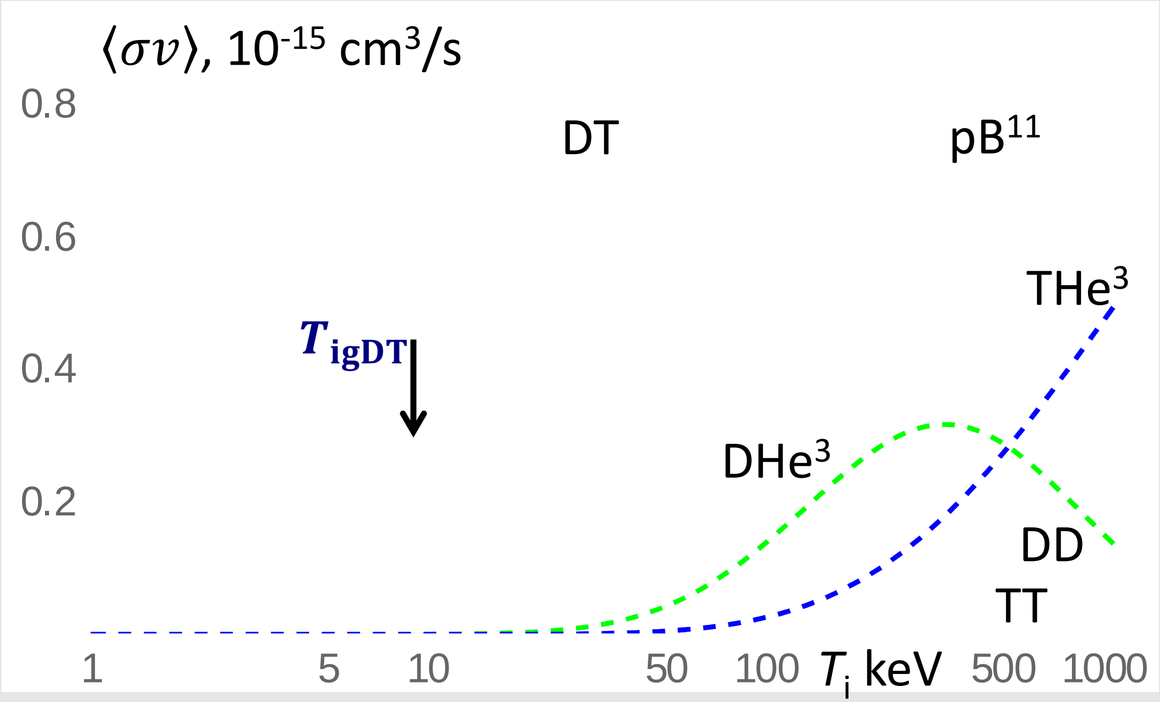
Disadvantages of DT:

- **Tritium**
- **neutrons**

Two other potential fuels (aneutronic):

$Y_{\rm DHe^3} \cong 60$ $(\rm p + \alpha)$

$Y_{\rm pB^{11}} \cong 5$ (3α)



D + T -> He^4 + n + 17.6 MeV p + B^{11} -> $3He^4$ + 8.7 MeV

Lawson criterion for energy production

The life time of a hot plasma is limited: useful energy has to be produced within the energy confinement time: released fusion energy > plasma internal energy

$$E_{\mathrm{fus}} = \varepsilon_\alpha \tfrac{1}{4} N_i^2 \langle \sigma_{\mathrm{DT}} v \rangle t_{\mathrm{conf}} > E_{\mathrm{th}} = 3 N_i T$$

$$\varepsilon_{\mathrm{DT}} \cong 17.6\ \mathrm{MeV}$$
$$\varepsilon_\alpha = 0.2\varepsilon_{\mathrm{DT}} \cong 3.5\ \mathrm{MeV}$$

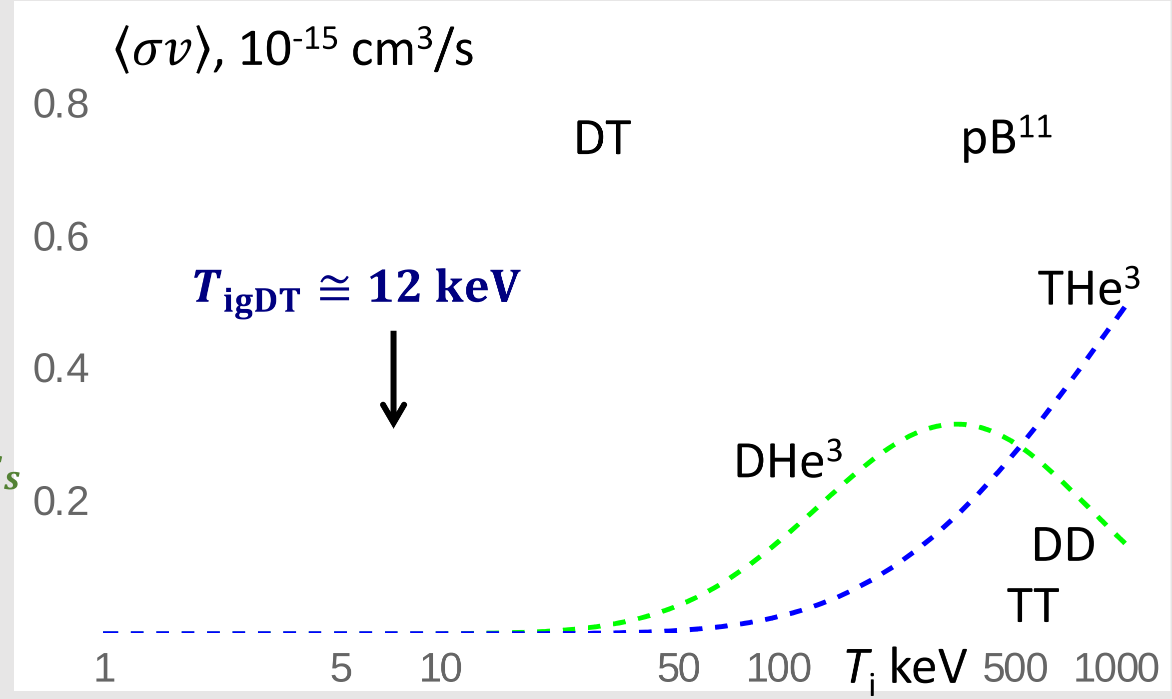
Magnetic fusion:

$$N_i\, t_{\mathrm{conf}} > \frac{12T}{\varepsilon_\alpha \langle \sigma_{\mathrm{DT}} v \rangle}$$

minimum @ $T_{\mathrm{igDT}} \cong 12\ \mathrm{keV}$

pressure × time > 8.3 atm·s

Need for a long confinement



Inertial fusion: $t_{\mathrm{conf}} = R_{\mathrm{fuel}}/4c_s$

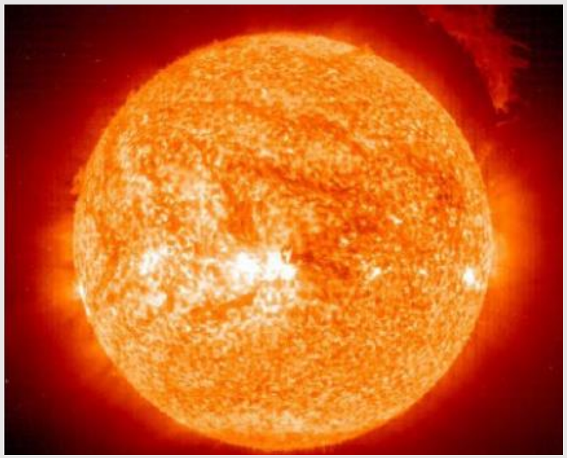
$$N_i\, R_{\mathrm{fuel}} > \frac{48 T c_s}{\varepsilon_\alpha \langle \sigma_{\mathrm{DT}} v \rangle}$$

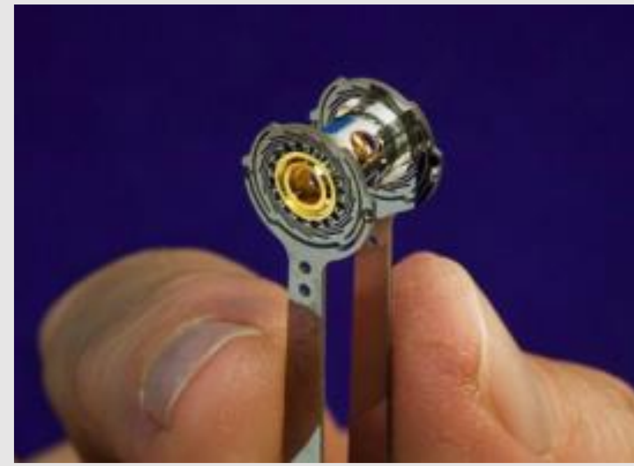
areal density > 2.5 g/cm²

Need for a strong compression: $\rho_0 = 0.25\ \mathrm{g/cm^3}$

Plasma confinement

Three methods of confinement are known, inertial confinement is the most compact





Size:	**$7x10^5$ km**	**5 m**	**1 mm**
Density:	**10^4 solid**	**10^{-5} air**	**10^3 solid**
Confinement time:	**10^5 years**	**10 s**	**10^{-10} s**
Temperature:	**< 1 keV**	**15 keV**	**5-15 keV**
Operation:	**continuous**	**continuous**	**pulsed**

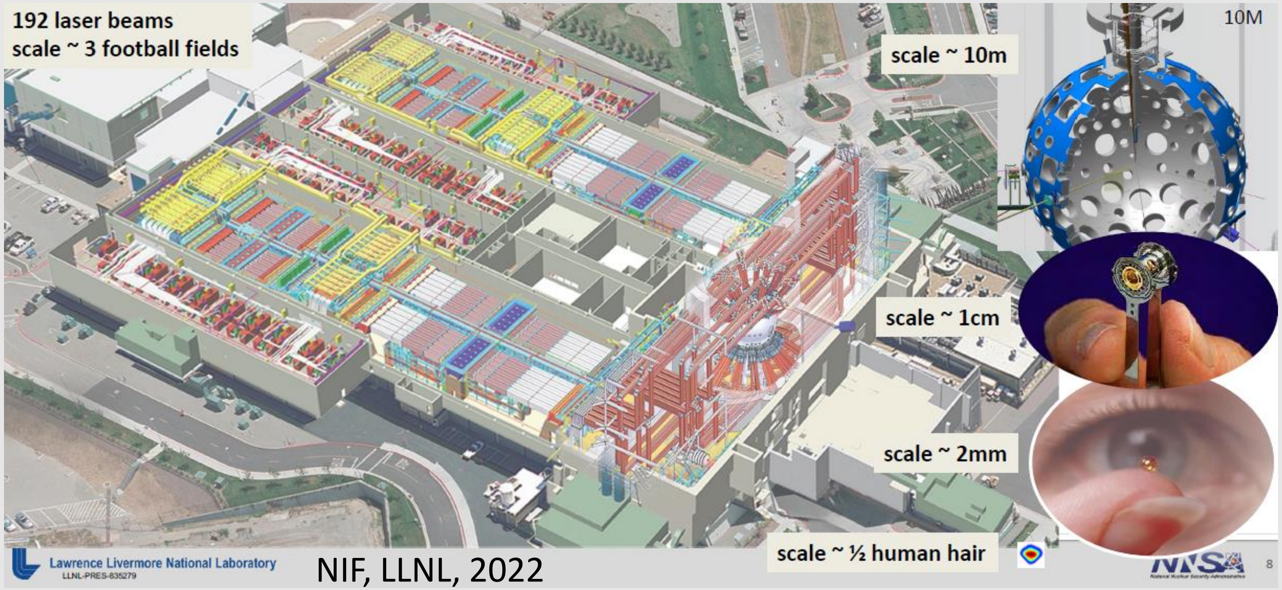
The most natural process in Universe, which is extremely difficult to realize on the Earth

Laser fusion facilities

There are only few lasers capable to deliver energies at a MJ scale with multiple beams of a ns pulse length

National Ignition facility operates since 2009 with maximum energy 1.9 MJ and power 450 TW (actually 2.15 MJ)

Laser MegaJoule will have energy 1.5 MJ with 176 beams (actually 300 kJ)



NIF, LLNL, 2022

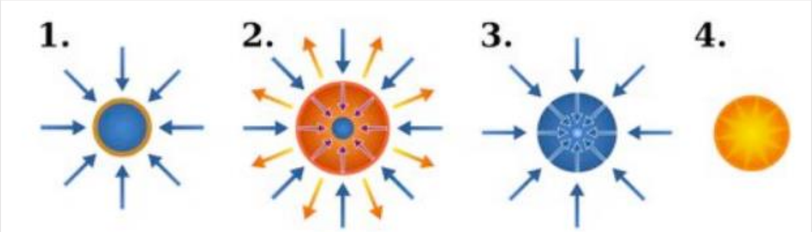
Energy concentration in time and in space

ELI laser facilities can make a significant contribution to HED science: coupling kJ and ps laser beams at high rep. rate

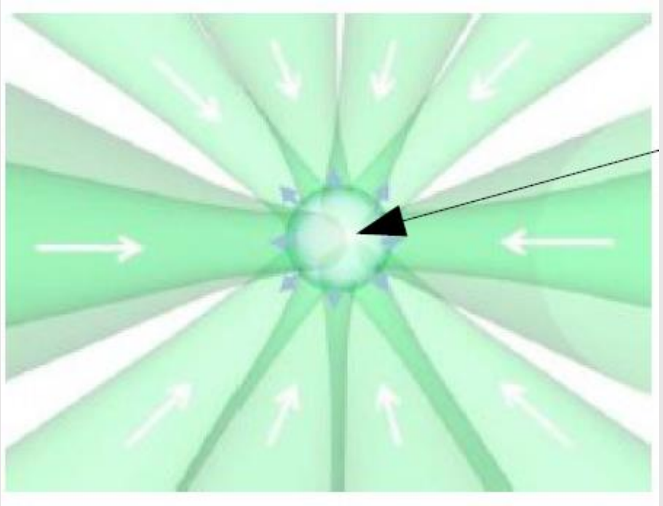
Principles of ICF: implosion and ignition

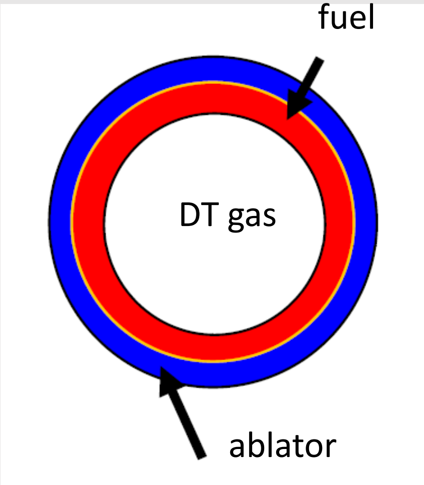
ICF is realized in four steps:

- **Shell implosion**
- **Fuel compression**
- **Ignition of fusion**
- **Combustion**



Compression of fuel is achieved by laser ablation and implosion of a spherical shell





Principle of power amplification: (i) laser energy is converted into the kinetic energy of the inward moving fuel (efficiency < 10-15%, long time ~10 ns); (ii) at stagnation, kinetic energy is converted into the internal energy of collapsed fuel (efficiency < 40%)

Hot spot ignition concept

If all fuel will be compressed and heated, the energy gain is limited by the intrinsic yield

It is too small to provide economically efficient fusion energy production

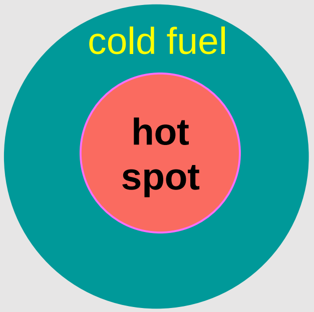
There are two ways to increase the fusion energy yield:

- **Continuous operation of power plant – constraint on the confinement system → low plasma density (magnetic confinement fusion)**
- **Pulsed operation – constraint on the confinement time → high plasma density → burn cold fuel (inertial confinement fusion)**

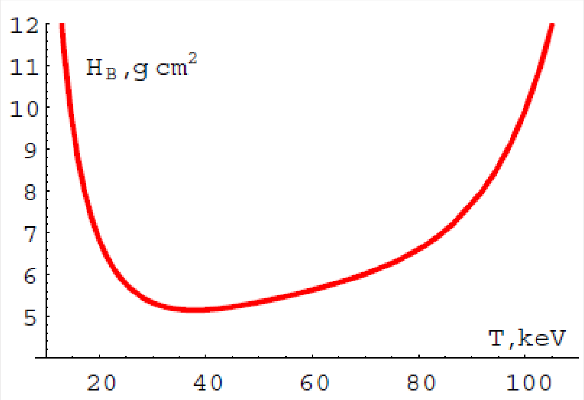
Fusion gain in the ICF scheme is increased by the hot spot concept: this is a two-step process

- **all fuel is compressed to the density needed for an efficient fusion burn**
- **a small fraction of fuel is compressed and heated to the temperature needed for the positive yield**

Compression requires less energy then heating, so the fuel can be ignited with a smaller amount of laser energy
Alpha-particles produced in the hot spot provide additional energy for burning the remaining part of the fuel



Conditions on the fusion energy production



All fuel cannot be burnt in the inertial fusion scheme

- **confinement time:** $t_{\mathrm{conf}} = R_f/4c_s$
- **burn fraction**

$$\Phi_B = \frac{1}{2} n_i \langle \sigma_{\mathrm{DT}} v \rangle t_{\mathrm{conf}} \rightarrow \frac{\rho_f R_f}{H_B(T) + \rho_f R_f}$$

$H_B = 8 m_i c_s / \langle \sigma_{\mathrm{DT}} v \rangle$ **minimum value is 5.5 g/cm^2** → **Fusion burn fraction of 30%:**

$$\rho_f R_f \geq 2.5\ \mathrm{g/cm^2}$$

For a fuel mass of 1 mg (total fusion energy is 340 MJ = 80 kg TNT) and fuel density $\rho_0 = 0.25$ g/cm^3, the radius of a liquid fuel droplet R_0 =1 mm and areal density $\rho_0 R_0 = 0.025$ g/cm^2

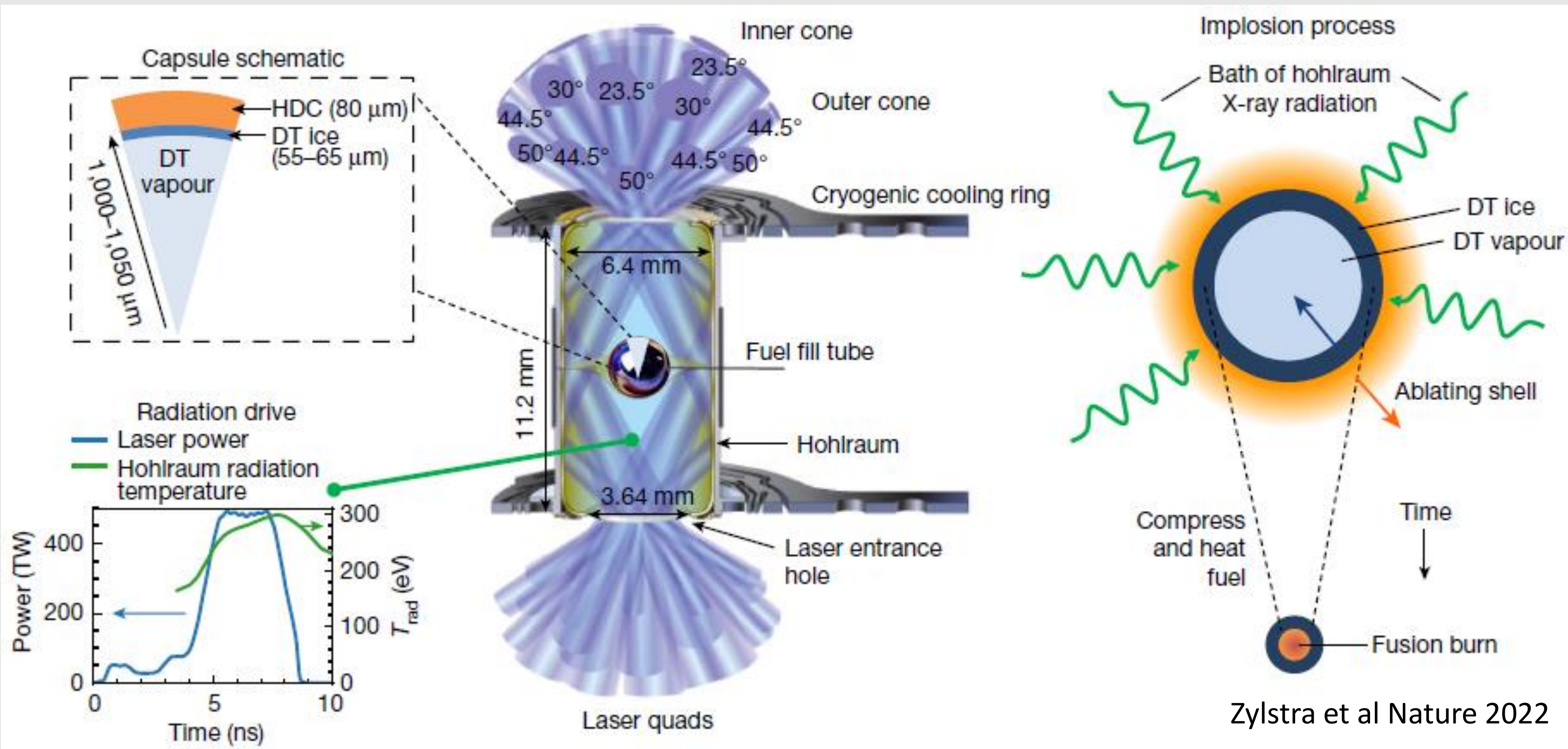
Increase of $\rho_f R_f$ by a factor of 100 requires a compression in volume of 10^3, that is, radial compression $C_R > 10$

For $\rho_f = 500$ g/cm^3, the radius of a compressed fuel droplet $R_f = 40$ µm and confinement time ~ 40 ps (to compare with magnetic confinement of ~ 4 s)

Mainstream scheme: indirect drive

Standard ICF approach uses a single, temporally shaped laser pulse for compression and ignition. Laser energy is converted into thermal X-rays that symmetrically irradiate the pellet. Low efficiency but good symmetry.

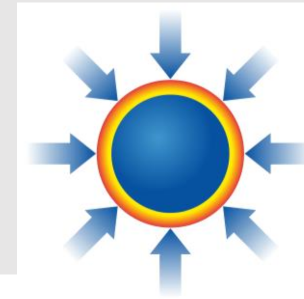
NIF best result: 3.6 MJ fusion energy with 2.15 MJ laser energy, 15 kJ delivered to hot spot

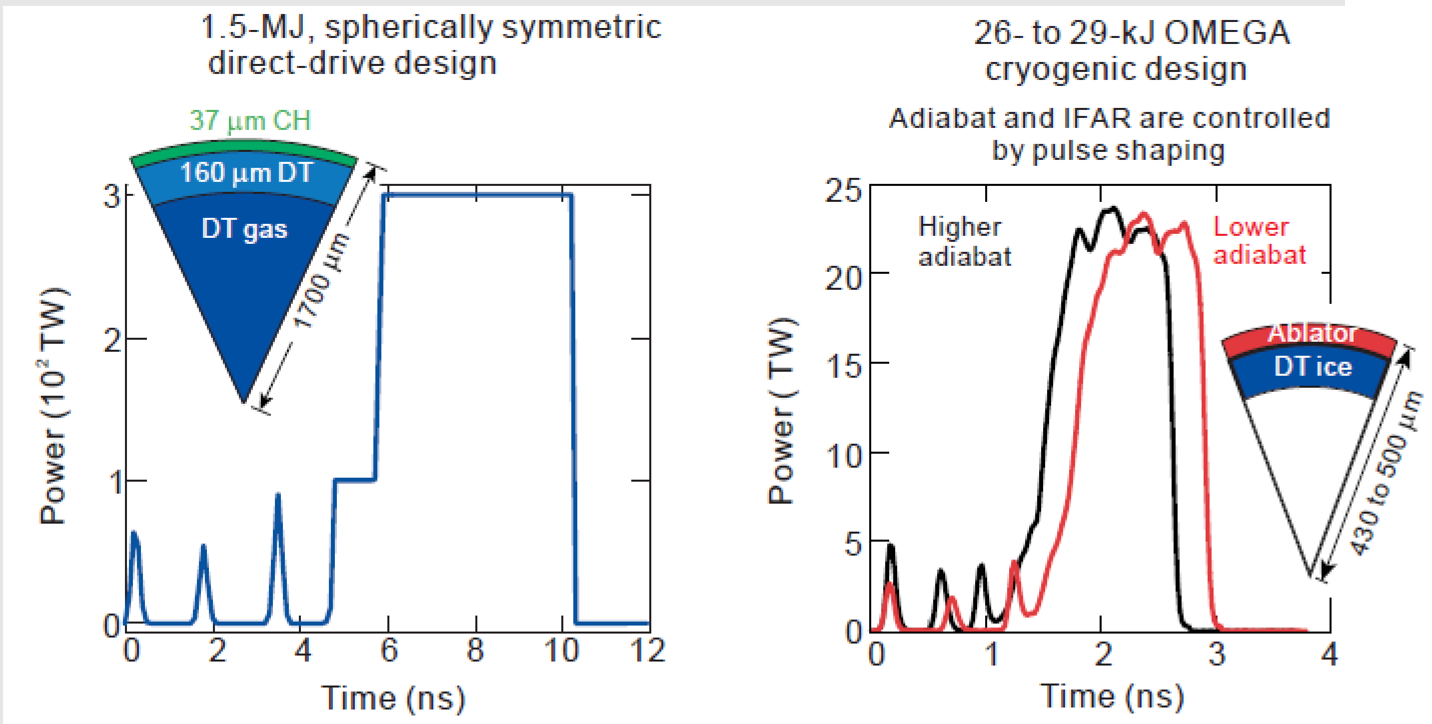


Zylstra et al Nature 2022

Mainstream scheme: direct drive

Standard ICF approach uses a single laser pulse for compression and ignition. Laser energy is delivered directly on the pellet. Much better energy coupling to hot spot but there are issues related to the laser energy deposition and implosion symmetry





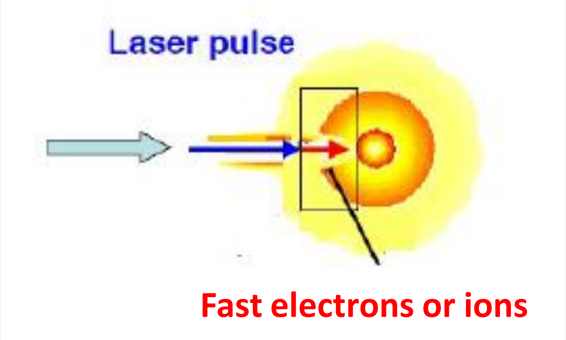
S Craxton et al Phys Plasmas 2015
V Gopalaswamy et al. Nature 2019

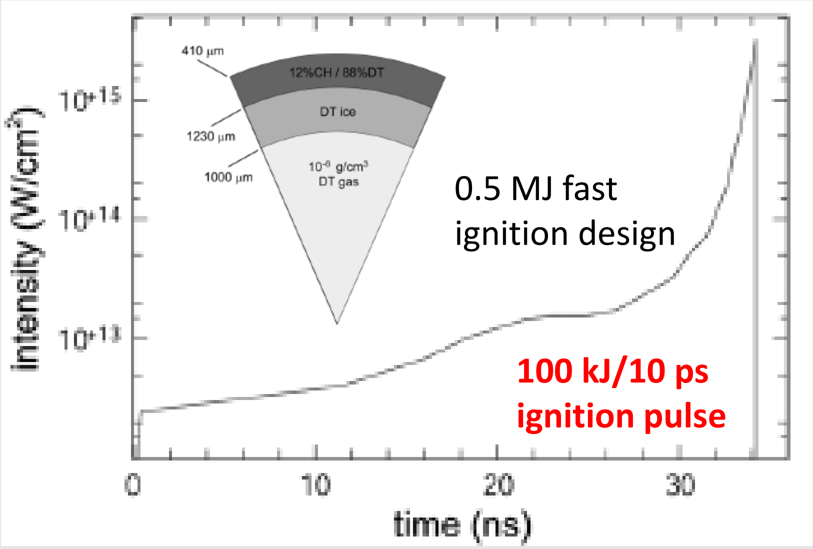
Best result on OMEGA: hot spot energy 0.8 kJ and neutron yield 3.2e14

Alternative ignition schemes: fast ignition

Alternative schemes – fast and shock ignition – use two separate laser pulses for compression and for ignition. This allows for a better stability of implosion and lower total laser energy in exchange for higher laser power and higher laser intensity

Fast ignition uses a lower intensity main pulse for a more stable fuel compression. Ignition is achieved with a laser-driven intense beam of electrons or ions creating a hot spot off center





Clark & Tabak Nucl Fusion 2007

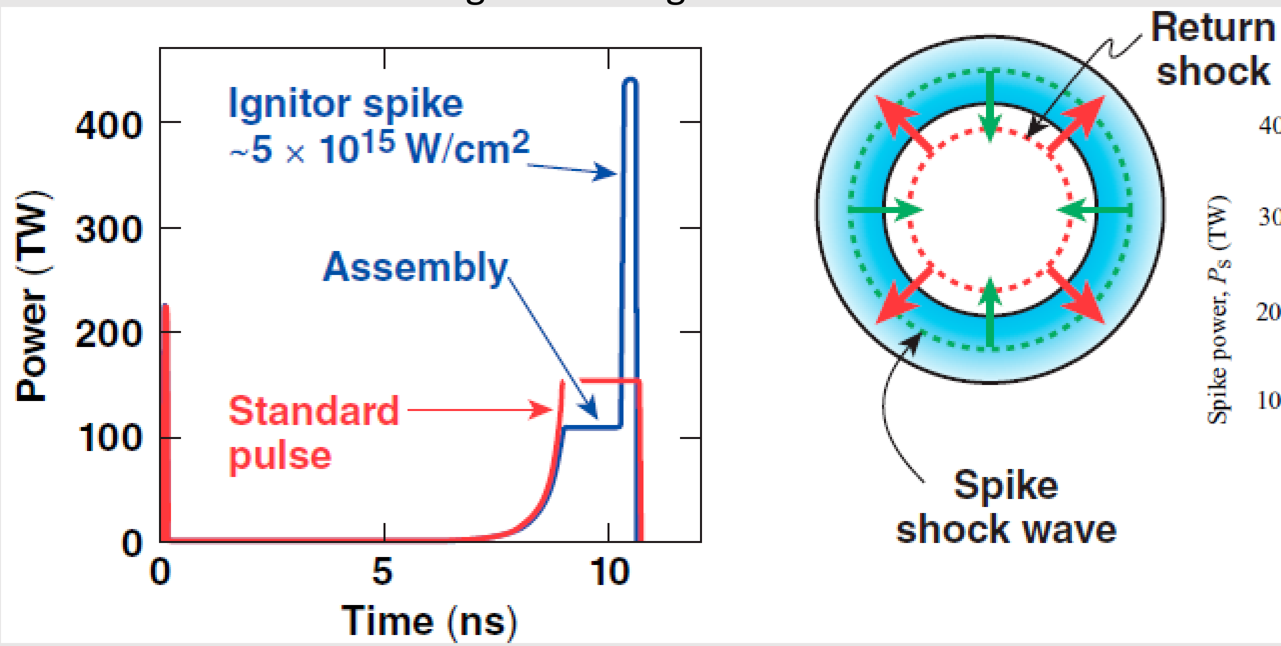
Issues:

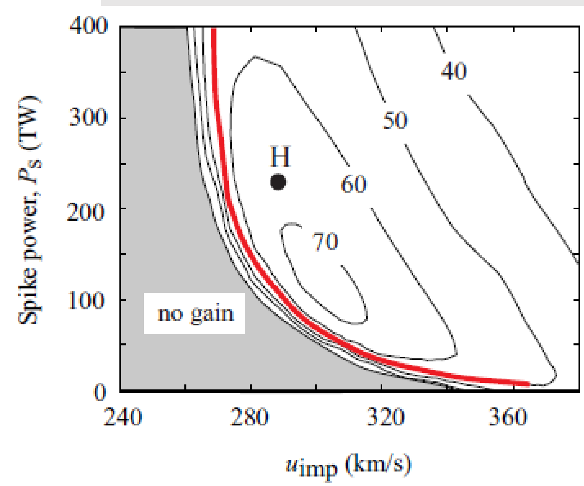
- **The need of extremely high intensity lasers ~ 10 PW to drive electron or ion beams**
- **Focusing of intense beams into a small hot spot**
- **Ion FI is not yet explored experimentally**

Alternative ignition schemes: shock ignition

In shock ignition the shell is imploded at a lower velocity and the central hot spot is created by a strong convergent shock driven by a 1 ns laser spike of a high power and high intensity

0.7 MJ shock ignition design





S Atzeni et al Nucl Fusion 2014

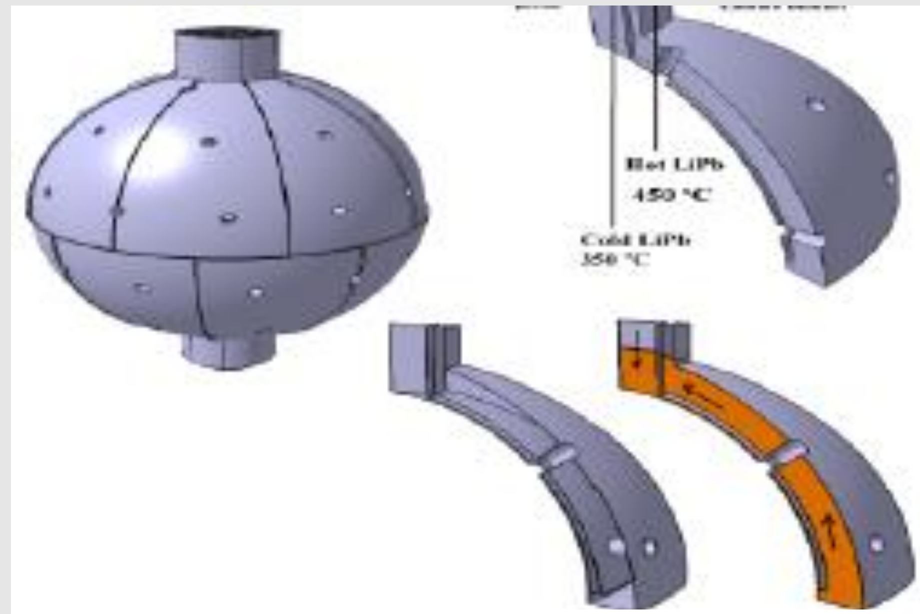
- **Timing of the spike: tuning the collision time of the spike-driven and return shock**
- **Fuel preheat by the spike-driven hot electrons**
- **Ablation pressure of 300 Mbar is demonstrated**

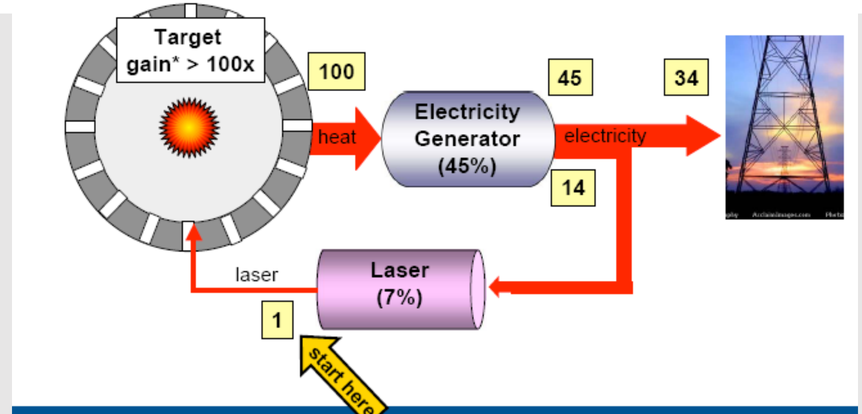
Roadmap to the fusion energy: beyond ignition

Producing fusion reactions with energy yield > 1 is the first step in the program for commercial fusion energy. It requires large-scale cooperation and coordination between national laboratories, universities, industry, private companies and governments.,

Major milestones:

- **Demonstration of repetitive shots with energy release larger than the laser efficiency: gain > 100**
- **Construction of a robust laser system operating continuously with Hz repetition rate: efficiency 10%, optical materials**
- **Design and construction of a reactor with the wall withstanding the neutron flux: construction materials**
- **Efficient target fabrication and injection systems**
- **Energy recovery and tritium breeding system**
- **Safety and security, waste management**

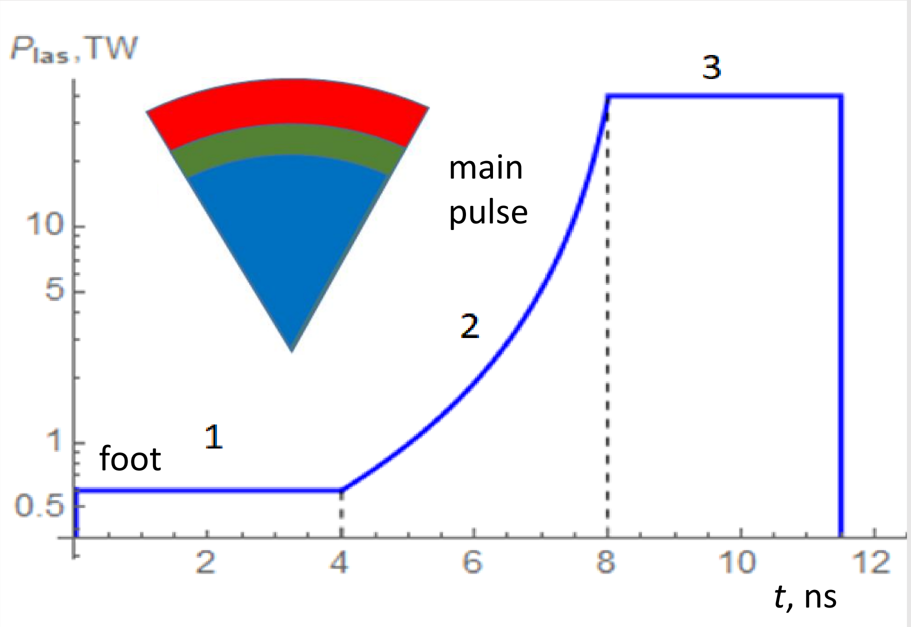


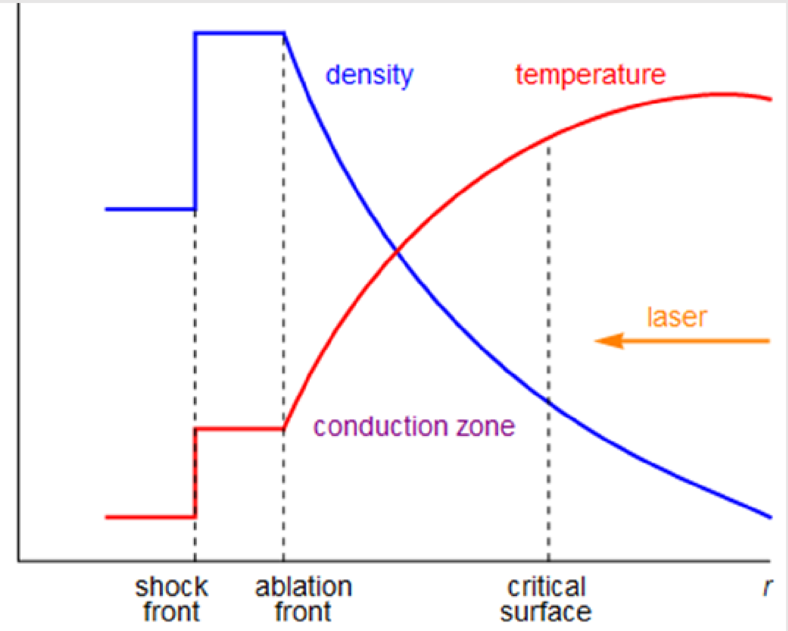


Physics of inertial confinement fusion

Laser target implosion

Shell-like spherical target is best suited for hot spot creation: ablator-solid DT-gas DT





Target implosion is driven by laser assisted ablation:

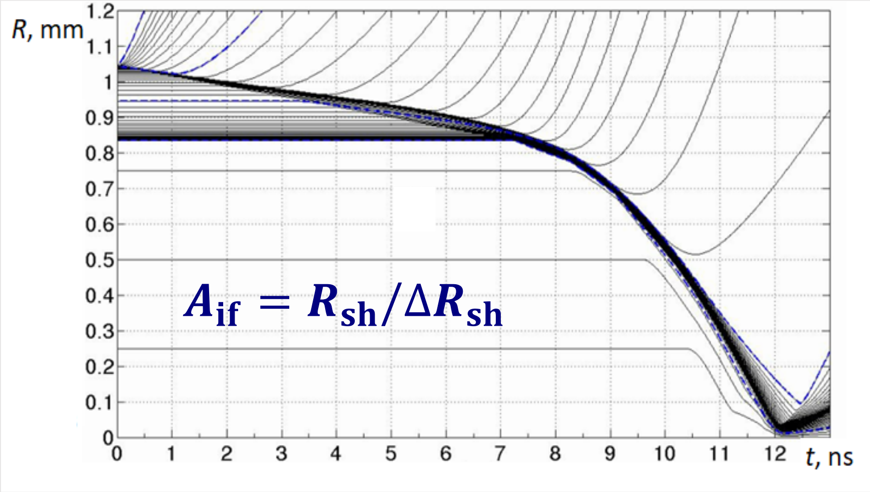
- **Laser absorption at near-critical density $\rho_{cr} \cong 0.01 - 0.1$ g/cm³** $\quad I_{\text{las abs}} = 4\rho_{cr} c_s^3$
- **Electron energy transport to the ablation surface: balance with ion outflow**
- **Ablation pressure is defined by the recoil momentum**

$$p_{\text{abl}} = \rho_{cr} c_s^2 = 57 \left(\frac{I_{\text{las}}}{10^{15}\ \text{W/cm2}}\right)^{2/3} \left(\frac{\lambda_{\text{las}}}{1\ \mu\text{m}}\right)^{-2/3} \text{Mbar}$$

Laser target implosion

Implosion proceeds in three steps:

- **shell pre-compression by a first shock: set the adiabat α,**
- **isentropic shell acceleration: 3 shocks,**
- **free flight of the fuel: compression, stagnation and ignition**
- **at stagnation: $P_{\mathrm{sh}} = P_{\mathrm{h}}$**



- **Shell implosion velocity is proportional to the ablation velocity: $U_{\mathrm{imp}} = D_{\mathrm{abl}} A_{\mathrm{if}}$**
- **Fuel compression is proportional to the implosion velocity: shell kinetic energy is equal to the work done for shell compression: $\frac{1}{2} M_{\mathrm{sh}} U_{\mathrm{imp}}^2 = 4\pi \int_{R_f}^{R_0} R^2 p_{\mathrm{sh}}(R)\, dR$**
- **Low hydrodynamic efficiency: $\eta_{\mathrm{hydro}} \leq 10\%$**

$$C_R = R_0/R_f \cong \left(1 + M_{\mathrm{sh}} U_{\mathrm{imp}}^2 / 4 A_{\mathrm{if}} E_{\mathrm{int}}\right)^3$$

Hot spot energy balance

Energy conveyed to hot spot by implosion should overcome the radiation and thermal losses:

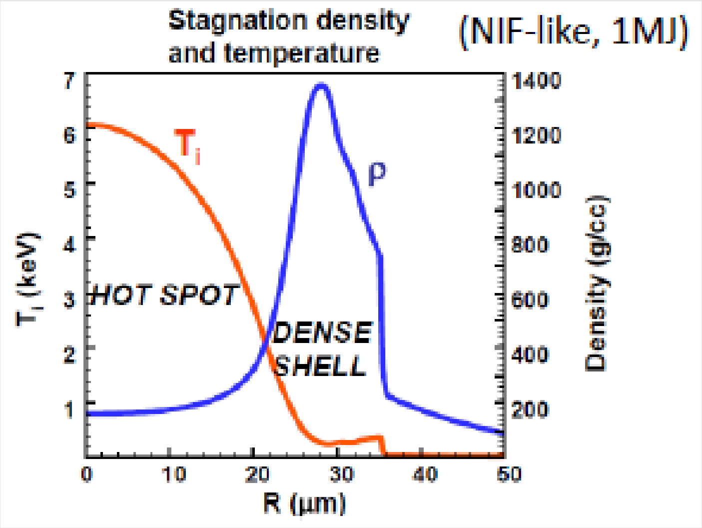
$$\frac{dE_h}{dt} = -\frac{4\pi}{3} P_h \frac{dV_h}{dt} + (f_\alpha W_\alpha - W_{\rm br}) V_h - q_e S_h$$

Alpha heating

Pressure work

Radiation losses

Thermal losses



Fusion energy: $W_\alpha = 1.5 \times 10^{19} \left(\frac{n_e}{10^{25}\ \mathrm{cm}^{-3}}\right)^2 \left(\frac{T_e}{1\ \mathrm{keV}}\right)^2$ W/cm³

Radiation losses: $W_{\rm br} = 5.3 \times 10^{19} \left(\frac{n_e}{10^{25}\ \mathrm{cm}^{-3}}\right)^2 \left(\frac{T_e}{1\ \mathrm{keV}}\right)^{1/2}$ W/cm³ T_{min} = 4 keV

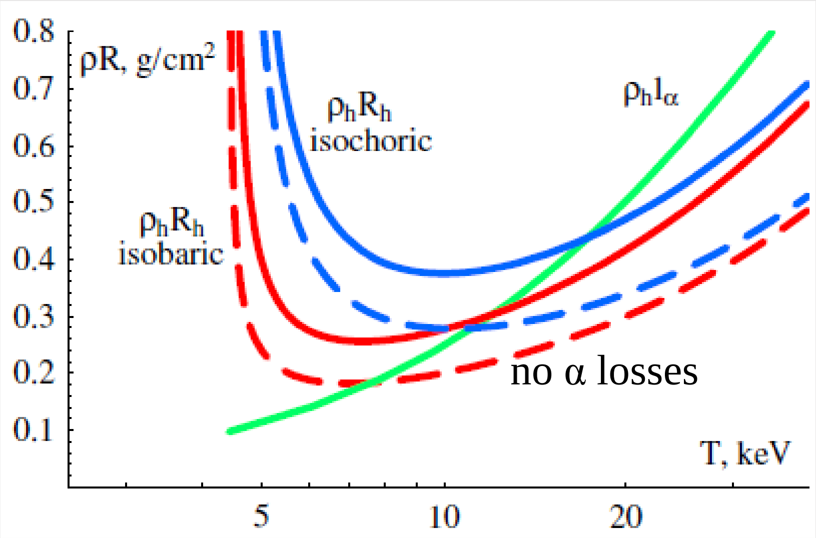
Thermal losses: $q_e = 0.57 \kappa_{\rm SH} T_e / R_h \propto n_e T_e^{7/2}$ dominate at high temperatures

Ignition: explosive temperature growth if alpha heating dominates: $\frac{dT_h}{dt} \propto T_h^2$

Hot spot energy balance

Standard hot spot ignition is isobaric at stagnation: ***hot spot pressure = cold shell pressure***

Alternative ignition schemes are isochoric: ***hot spot pressure > cold shell pressure***



Hot spot pressure and energy at ignition conditions:

$$\rho_h R_h T_h > 0.3\ \mathrm{g/cm^2} \times 5\ \mathrm{keV}$$

$$P_h > 100\left(\frac{R_h}{100\ \mu\mathrm{m}}\right)^{-1}\mathrm{Gbar}$$

$$E_h \propto P_h R_h^3 > 5.2\left(\frac{\rho_h}{100\ \mathrm{g/cm3}}\right)^{-2}\mathrm{kJ}$$

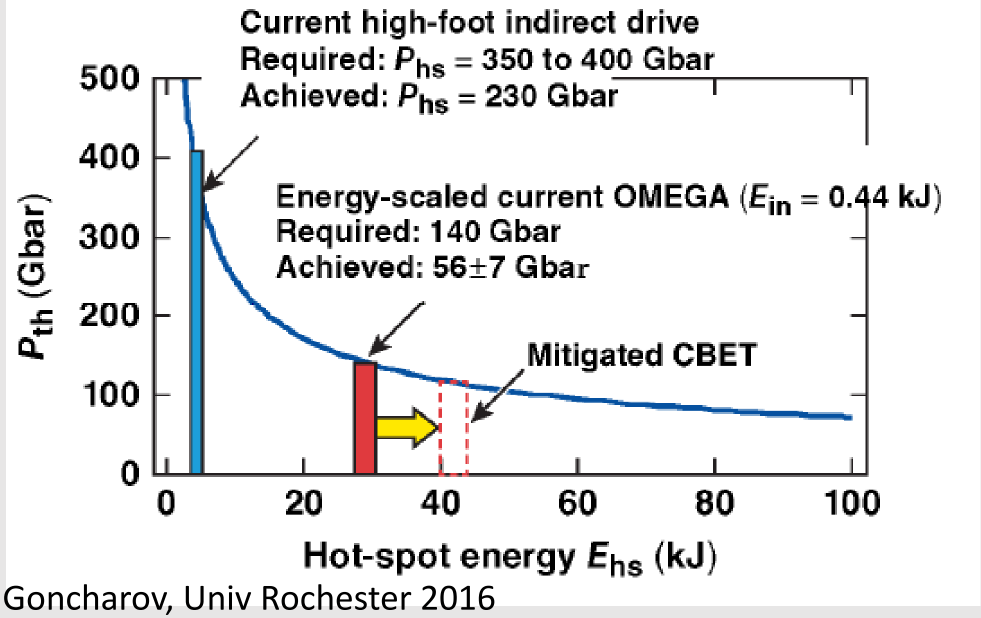
$$P_h > 250\left(\frac{E_h}{10\ \mathrm{kJ}}\right)^{-1/2}\mathrm{Gbar}$$

Direct drive scheme has larger energy coupling efficiency: 3-4 times more energy can be deposited in the hot spot for the same laser energy

Alternative ignition schemes require higher areal density and/or higher temperature in order to compensate mechanical work

Comparison direct vs indirect drive

Direct drive scheme has larger energy coupling efficiency: 3-4 times more energy can be deposited in the hot spot for the same laser energy



Goncharov, Univ Rochester 2016

$$P_h > 250\left(\frac{E_h}{10\ \text{kJ}}\right)^{-1/2} \text{Gbar}$$

Fusion yield is proportional to the ignition parameter

$$\bar{P}_h = \frac{P_h}{250\ \text{Gbar}}\sqrt{\frac{E_h}{10\ \text{kJ}}}$$

Direct drive ignition requires shell compression $C > 22$ and hot spot pressure 120 Gbar

Indirect drive ignition requires compression $C > 30$ and pressure > 350 Gbar

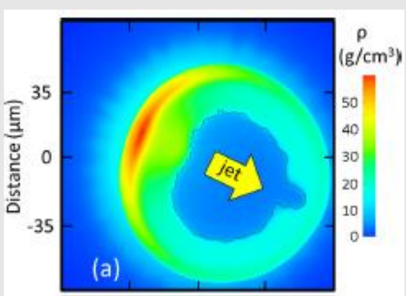
Three-dimensional effects: degradation of 1D performance

Implosion of a thin solid shell is intrinsically unstable process. Two undesirable effects: shell breakout and mixing of hot and cold material.

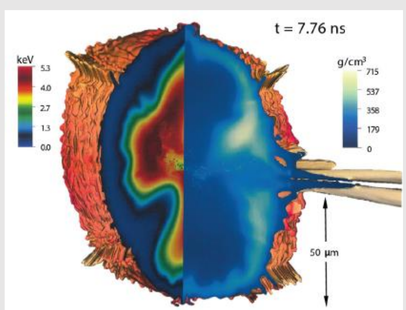
Two sources of initial perturbations:

- **large scale perturbations (target positioning, target defects, tent, filling tube, laser imbalance – low modes)**
- **small scale perturbations (laser beam intensity modulations and small-scale target defects – high modes)**

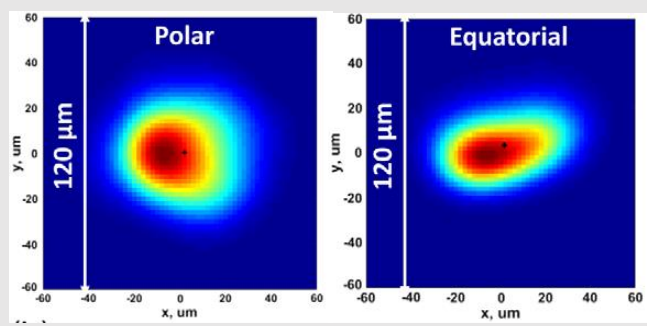
Large progress is achieved in controlling the low modes: improved target design, more efficient ablators, thinner tent, better laser beam focusing precision and reduction of time jitter



Igumenshchev et al PoP 2017



Clark et al NF 2019



Le Pape et al PRL 2018

Neutron imaging

Hydrodynamic instability: perturbation of shell thickness

Shell perturbations are unstable during the acceleration phase (outer surface) and deceleration phase (inner surface):

Richtmyer-Meshkov instability: oscillations of the ablation surface induced by a corrugated shock front

$$\omega_{RM} \cong k\sqrt{D_{\mathrm{abl}} c_s} \qquad \delta v \cong k \xi_0 D_{\mathrm{shock}}$$

Large-amplitude oscillations seed a RT instability at the acceleration phase

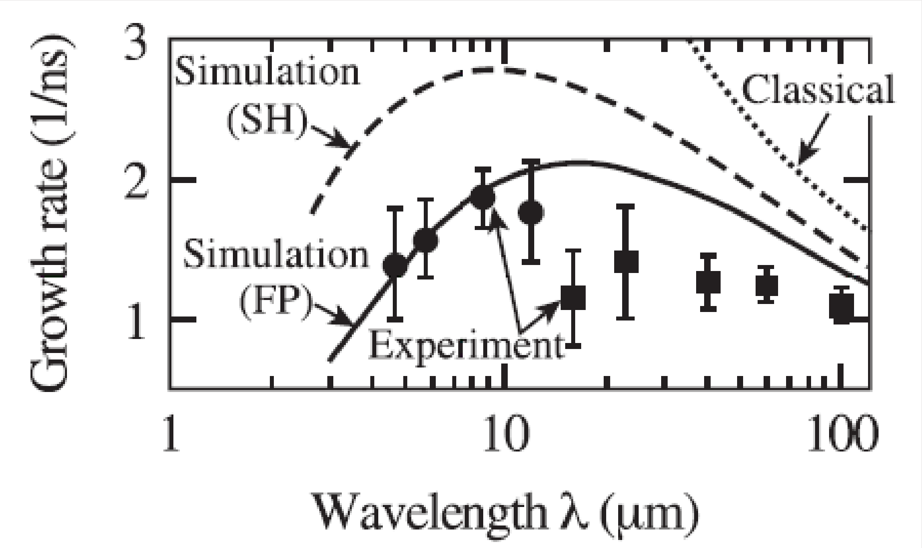
Rayleigh-Taylor instability: exponential temporal growth rate under acceleration:

- **classical RT instability – strong growth**

$$\gamma_{\mathrm{RT}} \cong \alpha\sqrt{kg}$$

- **ablative stabilization: laser heating and mass flow provide a significant reduction of the RT gain**

$$\gamma_{\mathrm{RT}} \cong \alpha\sqrt{\frac{kg}{1+kl_c}} - \beta k D_{\mathrm{abl}}$$



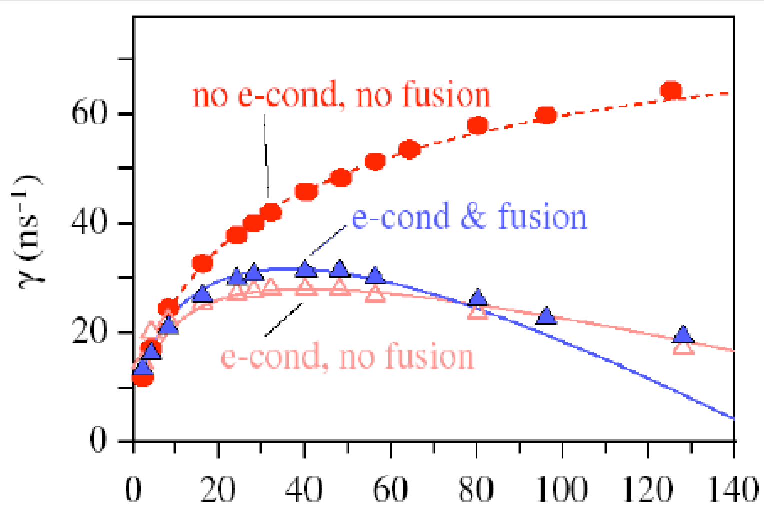
Sakaiya et al PRL 2002

The most dangerous mode $k\,\delta R \sim 1$ corresponds to exponential gain $\sim\sqrt{A_{\mathrm{if}}}$

Hydrodynamic instability at the inner shell surface

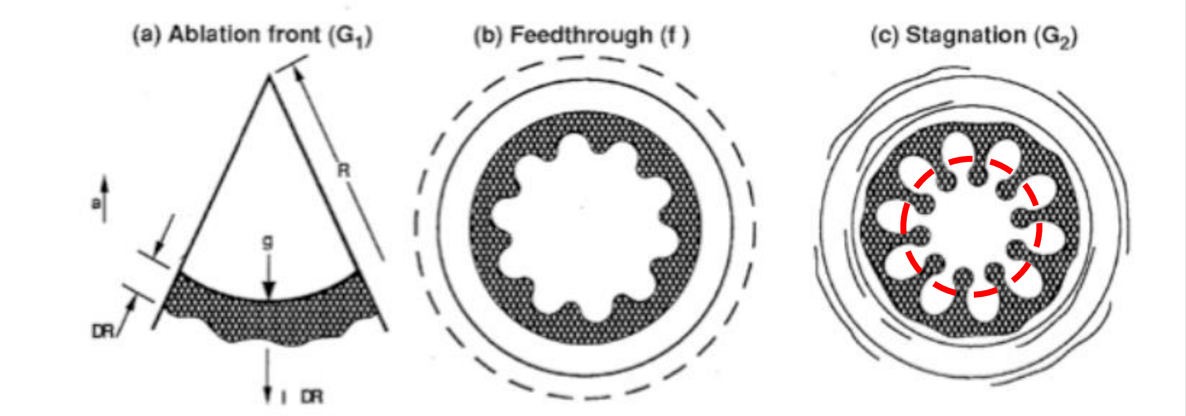
Rayleigh-Taylor instability is also excited at the inner shell surface just before stagnation – strong deceleration, fast instability growth

- outer perturbations penetrate through the shell and seed the instability
- Electron heat flux from the hot spot stabilizes growth of high modes



Atzeni et al PPCF 2004

Inner Rayleigh-Taylor instability reduces the effective radius and temperature of hot spot and thus compromises the ignition conditions



Atzeni Univ Roma 2015

Laser beam smoothing techniques

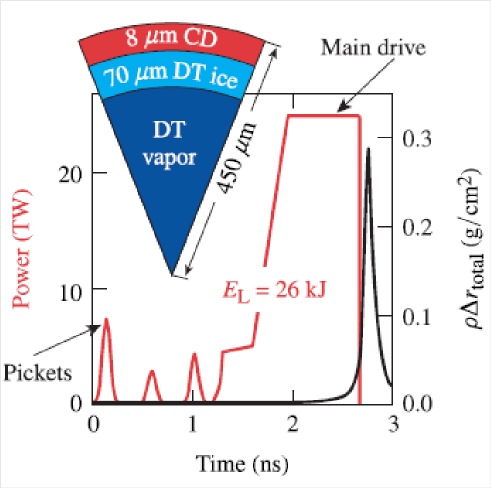
Laser imprint: intrinsic laser beam intensity modulations present the major source of density perturbations in the direct drive scheme

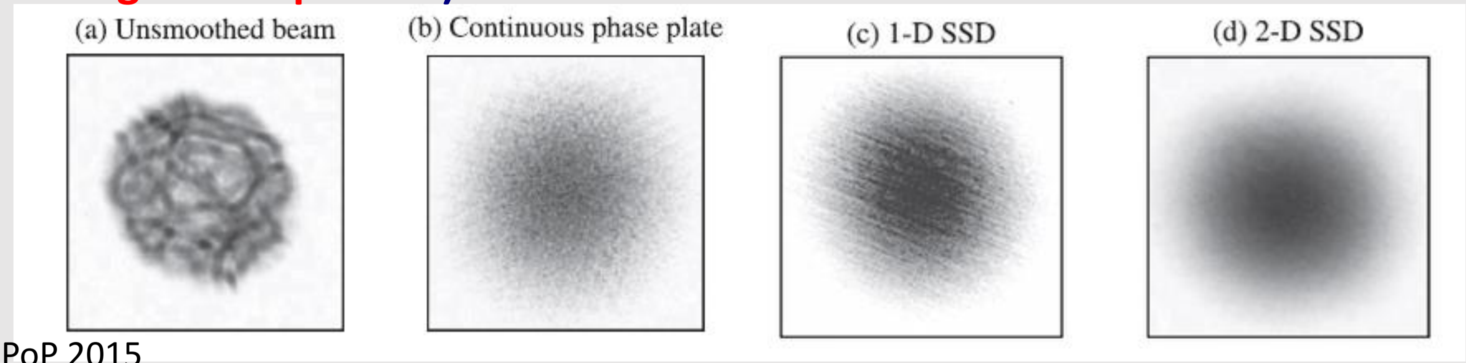
Amplification of perturbations by shell convergence

$$\delta R_0/R_c = C_R\, \delta R_0/R_0 \ll 1 \quad \rightarrow \quad \delta I_{\mathrm{las}}/I_{\mathrm{las}} \ll 1/C_{\mathrm{R}} \sim \text{a few \%}$$

Methods of suppression of laser-driven perturbations:

- **Laser piquet – a short prepulse vaporizing a thin layer of ablator and creating a plasma that smoothens pressure perturbations by the lateral heat transport**
- **Laser beam smoothing in spatial domain (random phase plates or continuous phase plate)**
- **Laser beam smoothing in temporal domain (spectral broadening and dispersion)**



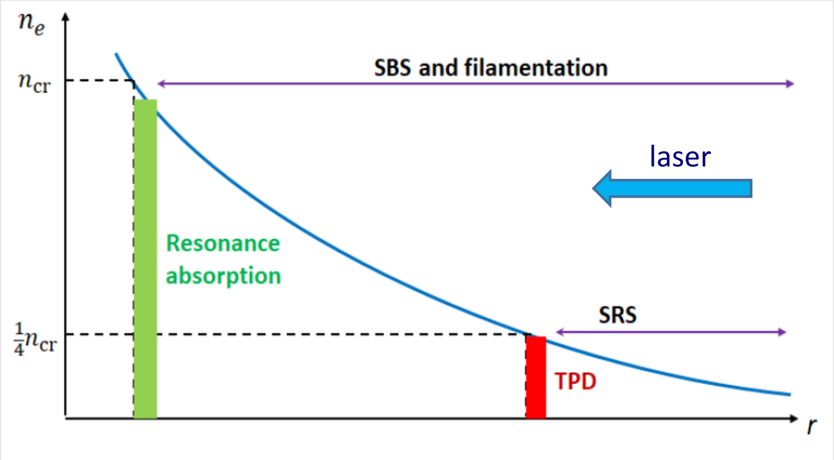


Craxton et al PoP 2015

Electromagnetic instabilities

Laser intensities needed to drive a 100 Mbar pressures are in the range of 10^{15} W/cm^2
Instabilities related to excitation of plasma waves degrade the efficiency and quality of laser absorption (typically 60-70%):

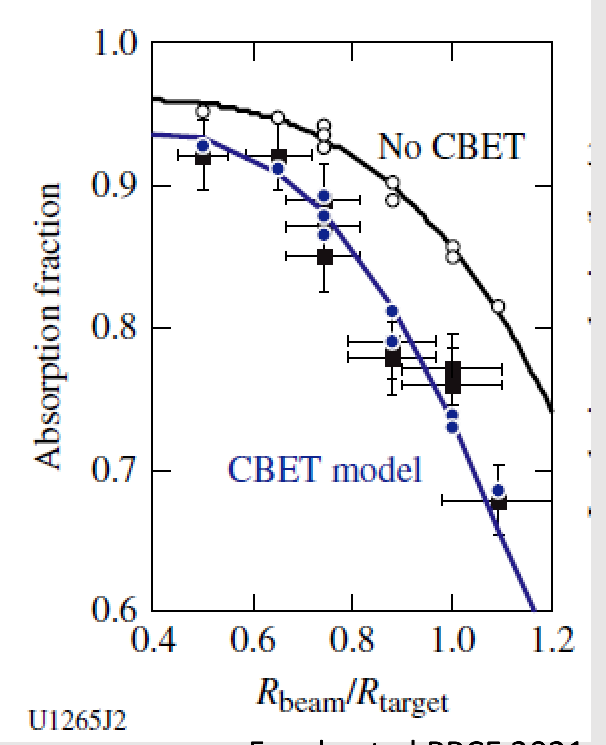
- **Filamentation** deteriorate the homogeneity of laser energy deposition, excitation of secondary instabilities
- **Stimulated Brillouin and Raman** instabilities reflect the laser light and reduce absorption
- **Stimulated Raman**, resonance absorption and **two plasmon instability** generate supra-thermal electrons which penetrate the core and prematurely preheat the fuel
- **Cross beam energy transfer** reduces the laser energy absorption and creates pressure asymmetry



These instabilities can be partially mitigated by laser beam smoothing techniques: spatial smoothing and spectrum broadening

Cross beam energy transfer (CBET)

A homogeneous laser irradiation of the target requires overlapping of many laser beams on the target surface. The beams, however, may interact in a plasma exchange their energy. Cross beam energy transfer deteriorates the homogeneity of laser energy deposition and reduces absorption and ablation pressure up to 40% in the direct drive experiments



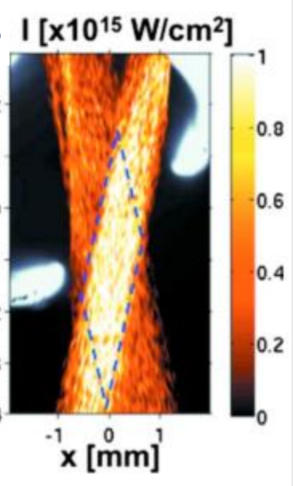
Froula et al PPCF 2021

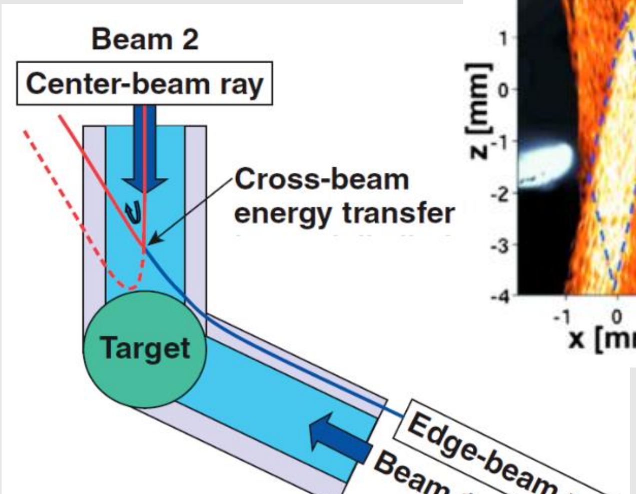
CBET is a process of resonant interaction of two laser waves with a Doppler shifted ion acoustic wave

$$\Delta\boldsymbol{\omega} - \Delta\boldsymbol{k} \cdot \boldsymbol{u} = |\Delta\boldsymbol{k}| c_s$$

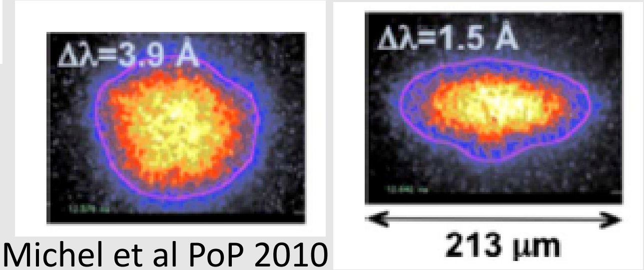
Outgoing – downshifted (in the plasma frame) wave takes energy from incoming (upshifted) laser wave

Indirect drive





Direct drive



Michel et al PoP 2010

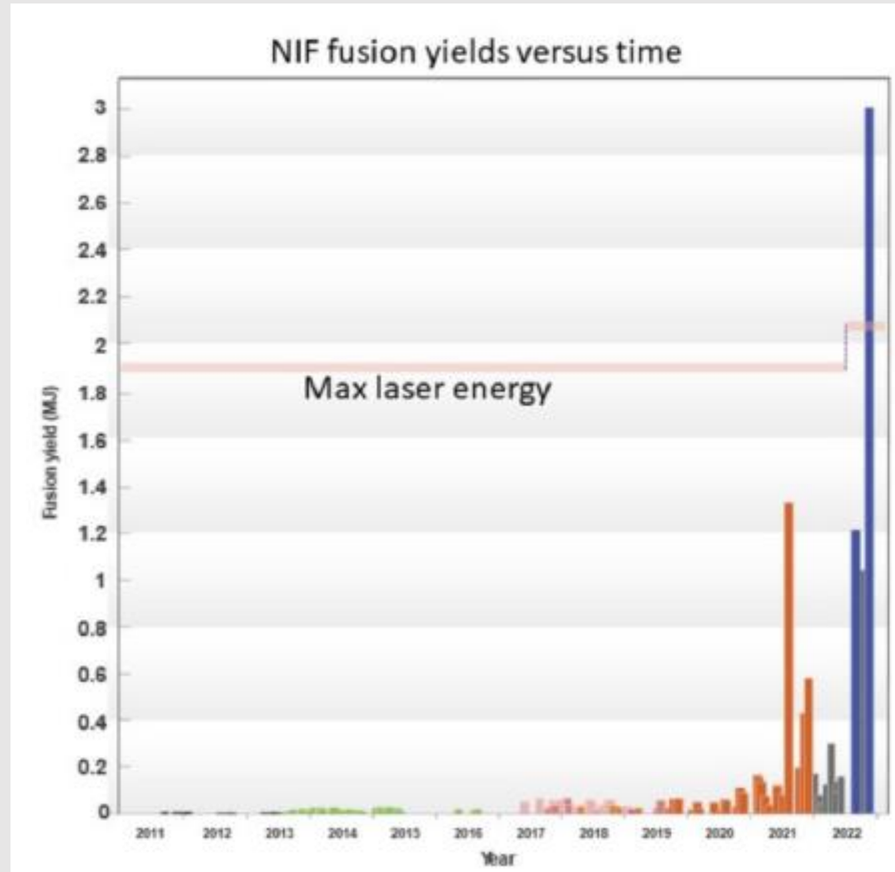
Use of CBET in NIF experiment for compensation of SRS and improving implosion symmetry

Recent results from inertial confinement fusion

Recent progress in inertial fusion: USA NIF

National Ignition Facility has demonstrated the energy yield > 1 in December 2022 & July 2023

National Ignition Facility experiment puts researchers at threshold of fusion ignition



December 2022: gain 1.5 = 3 MJ

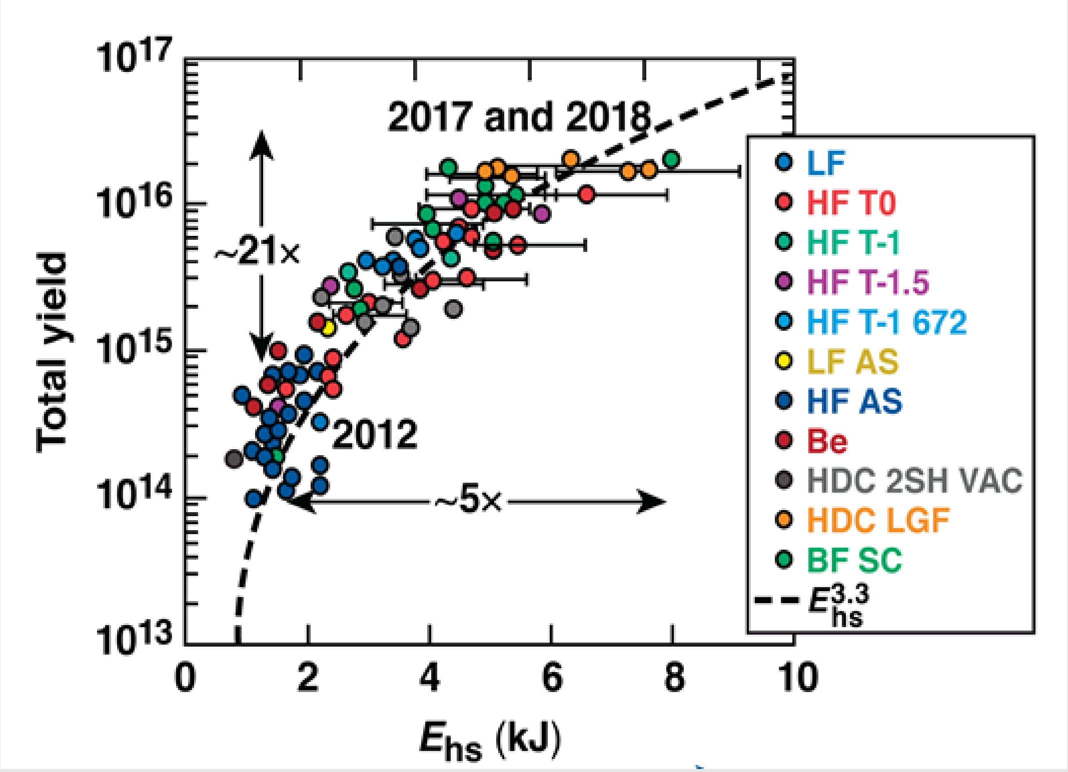
July 2023: gain 1.7 = 3.5 MJ

A convincing demonstration of ICF as a reliable path to the inertial fusion energy

Long and difficult way to the success

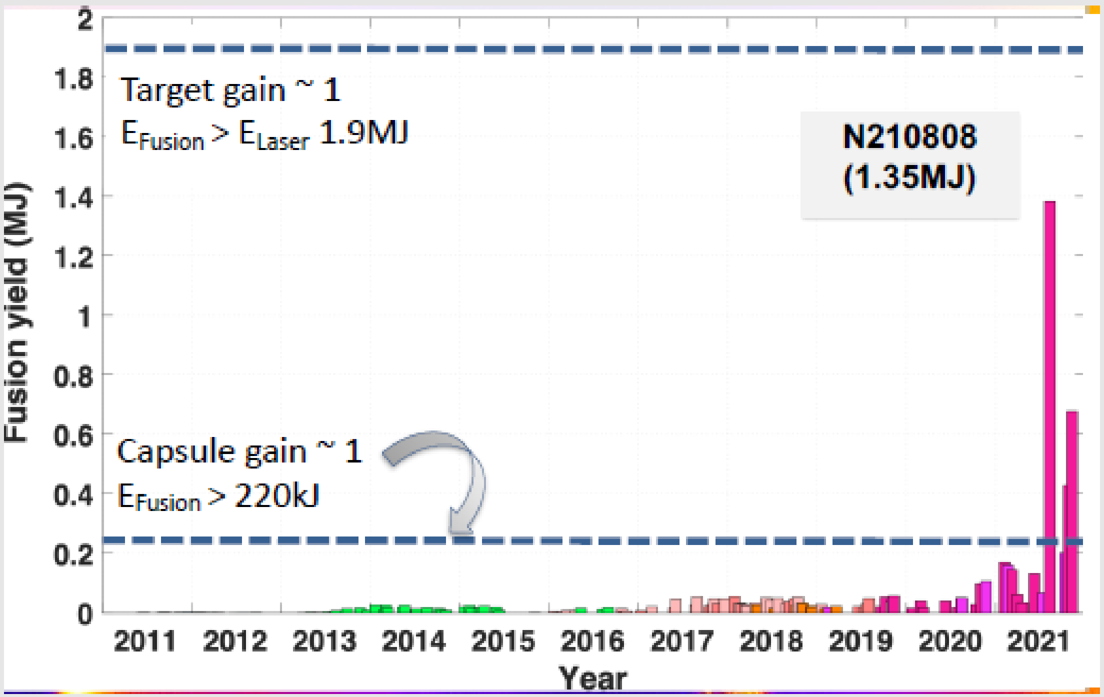
NIF success is the result of persistent work for 15 years with small but important improvements

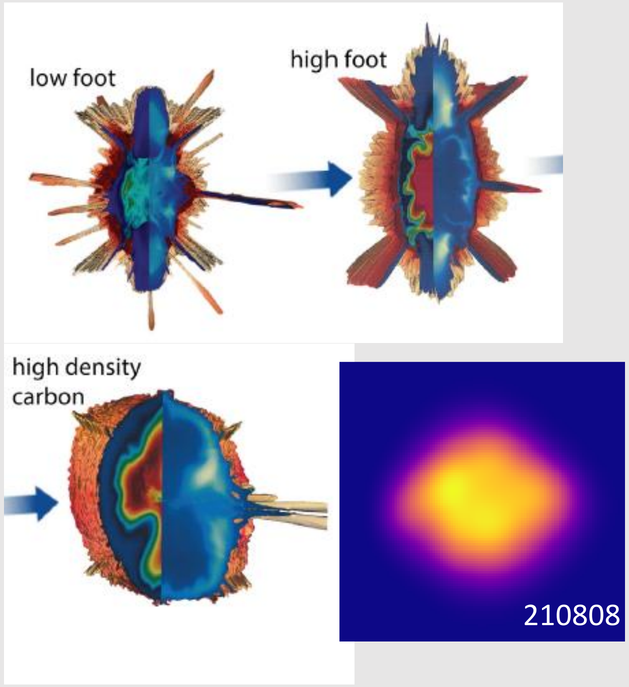
- **Quality of experiments: control of implosion symmetry**
- **Quality and number of diagnostics: neutron imaging**
- **Quality of target fabrication high precision low roughness**
- **Target design: new materials – HDC**
- **Predictive capabilities of codes**
- **More physics included: burning plasma**
- **Quality of laser beams: energy balance and synchronization**
- **Laser energy and performance: 10% increase**



Step-by-step improvements

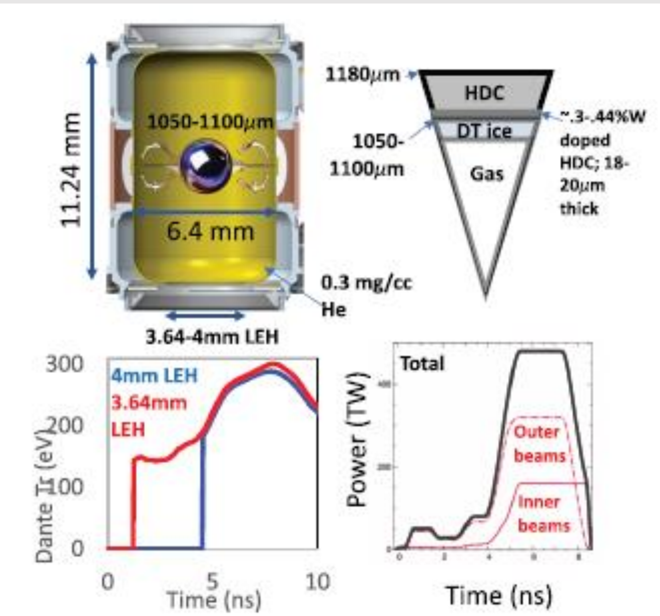
1) LF – original design 2010-12: low adiabat 1.6, long pulse, high density gas fill, slow implosion: failure, max yield 2.5 kJ: low mode asymmetry, tent, RT instability, mixing
2) HF – high foot 2013-15, med adiabat 2.8, high gas fill: max yield 25 kJ: RTI and low mode asymmetry; HDC-VAC – plastic ablator is replaced a diamond shell, no gas fill
3) Since 2016: HDC low gas fill, Be ablator, adiabat shaping, hot spot energy 7 kJ, max yield 56 kJ: improved symmetry and more stable implosion, mixing due to fill tube
4) Since 2019: HYBRID design: larger HDC capsule, 5 µm fill tube, reduced hohlraum size (dep U, gold lined), increase of x-ray coupling, reduced adiabat <2.0, control of asymmetry with CBET, increased ablation velocity > 400 km/s





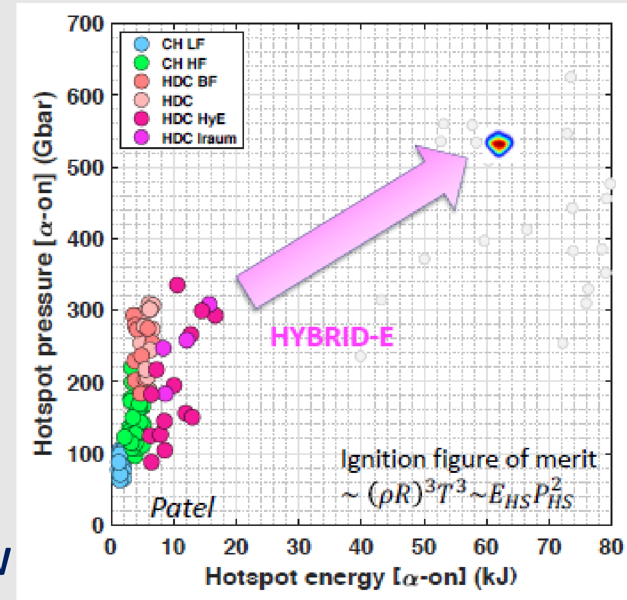
NIF ignition campaign

HYBRID-E campaign the most successful, for the first time, it is provided conditions for the regime of burning plasma: 7 expts in 2020-21 with the yield 100-170 kJ: HS gain >12



Kritcher et al PoP 2021

- Larger capsule
- Smaller hohlraum
- CBET control
- Smaller LEH
- Larger DT mass
- Low gas fill 0.3 mg/cc
- Suppressed SBS and HE
- Tungsten preheat shield
- 3-shock pulse shape
- 95% shell ablated: 400 km/s
- Max laser capability: 480 TW
- Capsule kin energy > 200 kJ
- Hot spot energy > 10 kJ



Zylstra, LLNL 2022

Issues and problems:

- Robustness & reproducibility
- Low mode asymmetries
- Hydro instabilities
- Quality of HDC shell (voids)
- Compressibility of the fuel
- Laser beam energy balance

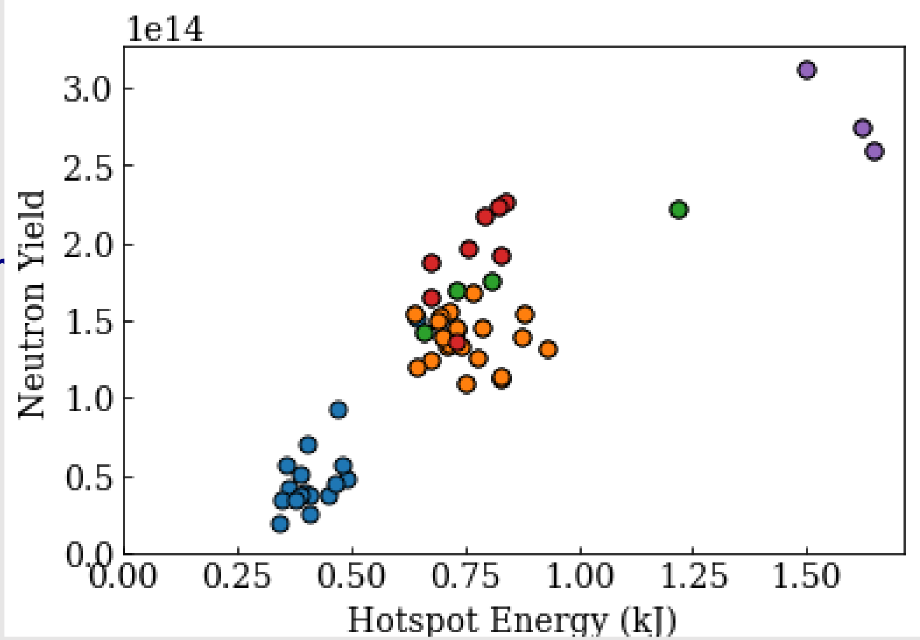
Direct drive inertial fusion: USA Omega

Direct drive scheme offers an efficient use of laser energy, but it is sensitive to hydrodynamic and electromagnetic instabilities

Omega laser facility is dedicated to the direct drive experiments: 30 kJ/60 beams at the LLE, University of Rochester; high laser beam quality: RPP, PS and 2D SSD

Neutron yield increase was demonstrated in 2019 in an Optimization Campaign, where implosion design was guided by statistical methods:

1) **First set of 15 experiments was guided by 1D simulations corrected by the training data from the previous experimental campaigns**
2) **Data from these experiments were used for optimization of target design and improved scaling laws for yield and areal density**
3) **Second series experiments guided by the scaling laws produced a record yield and high areal density**



V Gopalaswamy et al. Nature 2019
V Goncharov EUROfusion seminar 2022

Direct drive inertial fusion: USA Omega

Direct drive scheme can be demonstrated on NIF or LMJ

Hydrodynamic scaling from Omega to NIF:

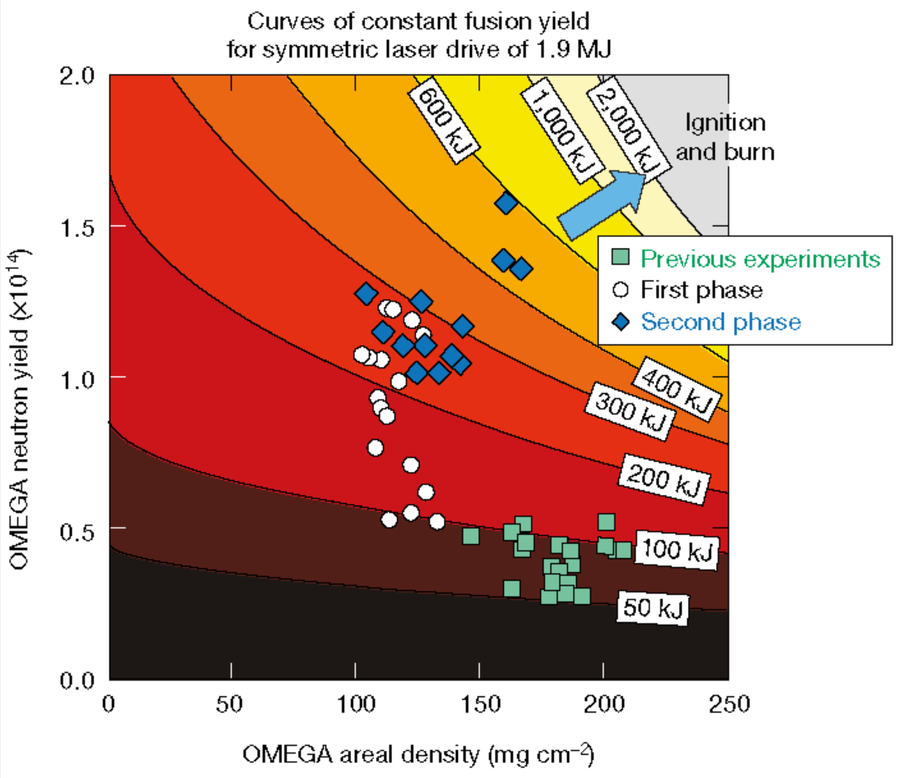
Factor 70: from 30 kJ to 2.1 MJ

Same performance implies

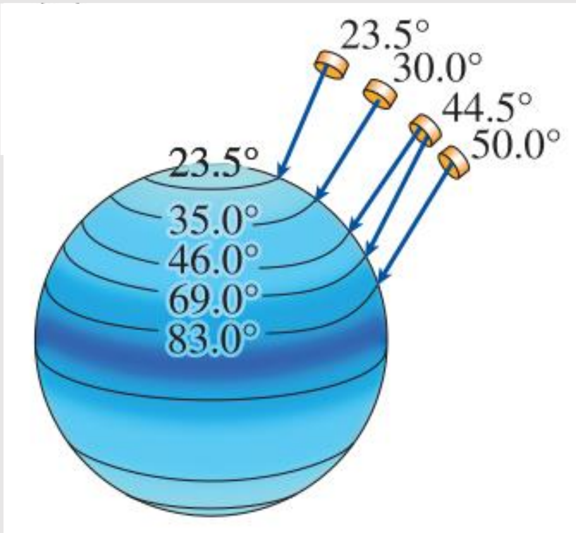
$I_{las} = \text{const}, \alpha_{if} = \text{const}, v_{imp} = \text{const}$

$M_{fuel} \propto E_{las}, \ R_{target} \propto E_{las}^{1/3}, \ t_{imp} \propto E_{las}^{1/3}$

$E_{las}^{1/3} \cong 4.2\times$ **higher efficiency is expected at NIF in the direct drive implosions**



V Gopalaswamy et al. Nature 2019



Direct drive experiments are conducted on NIF in the Polar Direct Drive geometry: assessment of the scaling

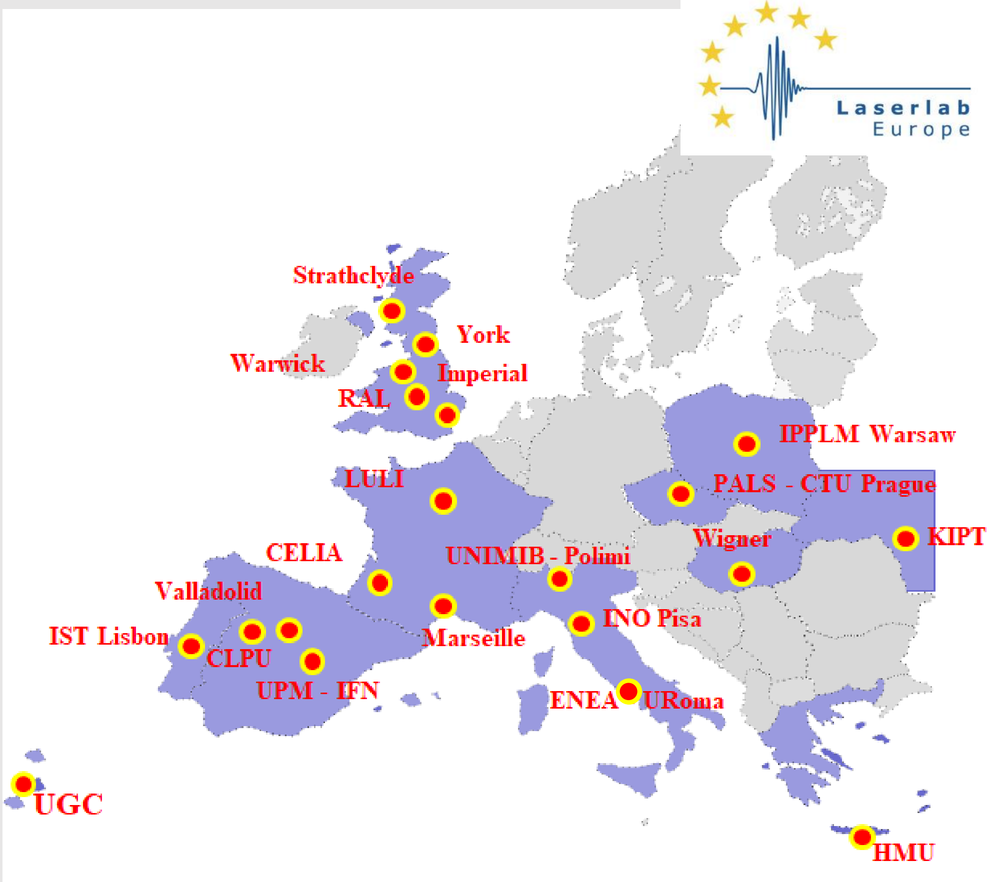
European approach to inertial fusion:

Academic research in Europe is oriented towards ICF energy production

Europe does not have its multi-beam laser installation permitting integrated ICF experiments

First ICF international project HiPER 2007 – 2013: 26 laboratories from 10 countries

- EUROfusion projects
- Laserlab Europe network
- Direct drive shock ignition
- Experiments on European lasers PALS, LULI, VULCAN, ELI, LMJ
- Implosion experiments on OMEGA
- High rep rate experiments on ELI L4n
- Private companies initiative
- German Memorandum on IFE



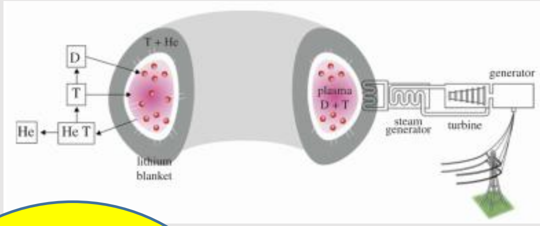
Concluding remarks

- Inertial fusion energy is confirmed as a viable and promising approach
- Need for an international approach
- Support from the private sector: > 6 B$
- Need for the European Laser Fusion Facility
- Role of ELI in laser-plasma interaction experiments and laser technology development

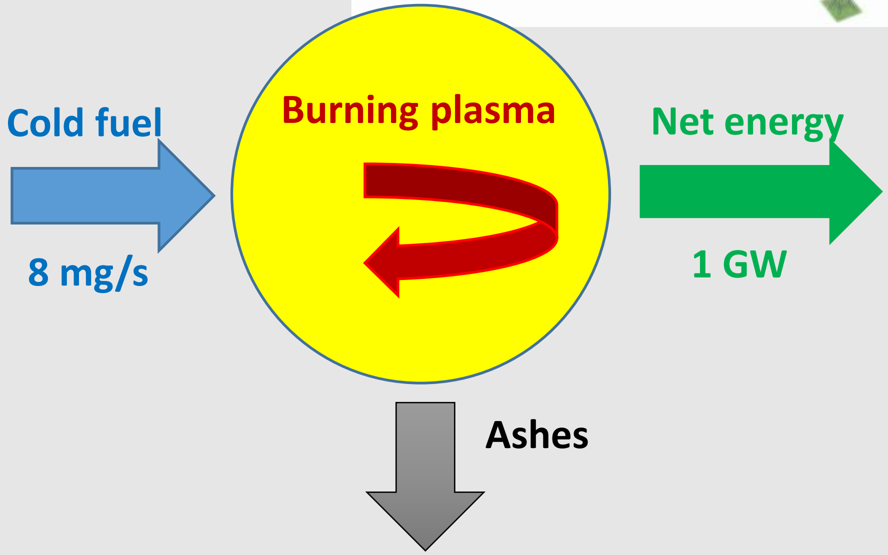
Magnetic vs inertial: pro and contra

Standard power plant produces 1 GW electrical energy, that is about 2.5 GW fusion

Magnetic fusion is a continuous process: external energy is needed only to start the process – self-heating process



- Plasma density $n_i \leq 10^{14}$ cm^{-3} is limited by the available magnetic field strength $B \leq 10$ T
- Small reaction rate ~ 0.05 s^{-1}
- Large number of particles $\sim 4 \times 10^{22}$
- Large fuel mass ~ 0.15 g
- Large tritium inventory
- Large plasma volume ~ 400 m^3
- Large heating energy ~ 200 MJ
- Long confinement time ~ 4 s
- Small heating power ~ 40 MW
- Known (but complicated) technology
- Big capital investments
- Many installations, long experience
- International program: JET → ITER

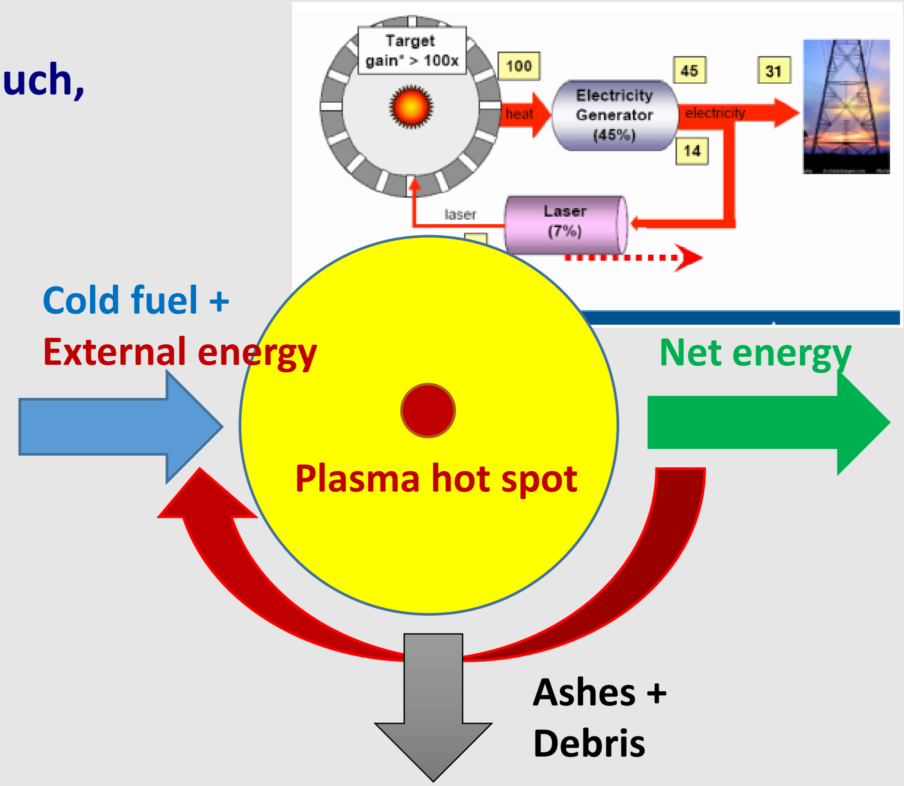


- Magnetic confinement in a toroidal geometry
- Self-heating process needs to be demonstrated
- Continuous fuel burn needs to be demonstrated

Inertial vs magnetic: pro and contra

Inertial fusion is a pulsed process: external energy is needed at the start of each cycle

- One explosion/s 2.5 GJ = 600 kg TNT/s too much, typical figure: 250 MJ/shot
- Small fuel mass ~ 2 mg
- Low tritium inventory
- Heating energy is reduced to $5-10$ kJ by heating only $\sim 1\%$ of the fuel
- Strong compression > 2000 in volume
- Short combustion time ~ 100 ps
- Low driver efficiency $\leq 10\%$
- Incomplete combustion $\leq 30\%$, debris
- Potentially compact reactor and low capital investments, max laser energy $\leq 1-3$ MJ
- Separable technology, but does not yet corresponds to the reactor requirements (energy, power, rep-rate)
- Limited number of installations: NIF and LMJ, double use



- Thin spherical shell: unstable implosion
- Ignition from the hot spot is demonstrated
- Operation in the rep-rate regime needs to be demonstrated

Tikhonchuk Phil. Trans. R.Soc 2020

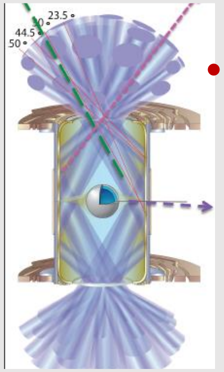
Direct vs indirect: pro and contra

Ignition conditions impose a relation between the hot spot areal mass and temperature

$(\rho R)_{hs} T_i > 0.3\ \mathrm{g/cm^2} \times 5\ \mathrm{keV}$ minimum hot spot energy $\sim 5 - 10$ kJ

In indirect drive approach target is irradiated by x-rays in a hohlraum

- More homogeneous irradiation, more stable implosion
- Nonlinear laser plasma interaction effects are suppressed, lower fuel preheat
- Good target protection from external perturbations
- Weak laser energy coupling to target
- Difficult target diagnostics
- Large amount of debris: hohlraum mass = fuel mass $\times$ 1000 or more
- Double use, defense funded installations



In direct drive approach target is irradiated by overlapping laser beams

- More efficient laser energy coupling to the target
- Small amount of debris
- Better diagnostic and implosion control
- High risk of nonlinear laser plasma interaction and fuel preheat
- Target protection needs to be reinforced
- Very few dedicated installations, laser beam geometry incompatible with ID