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Inertial Confinement Fusion: recent results and perspectives

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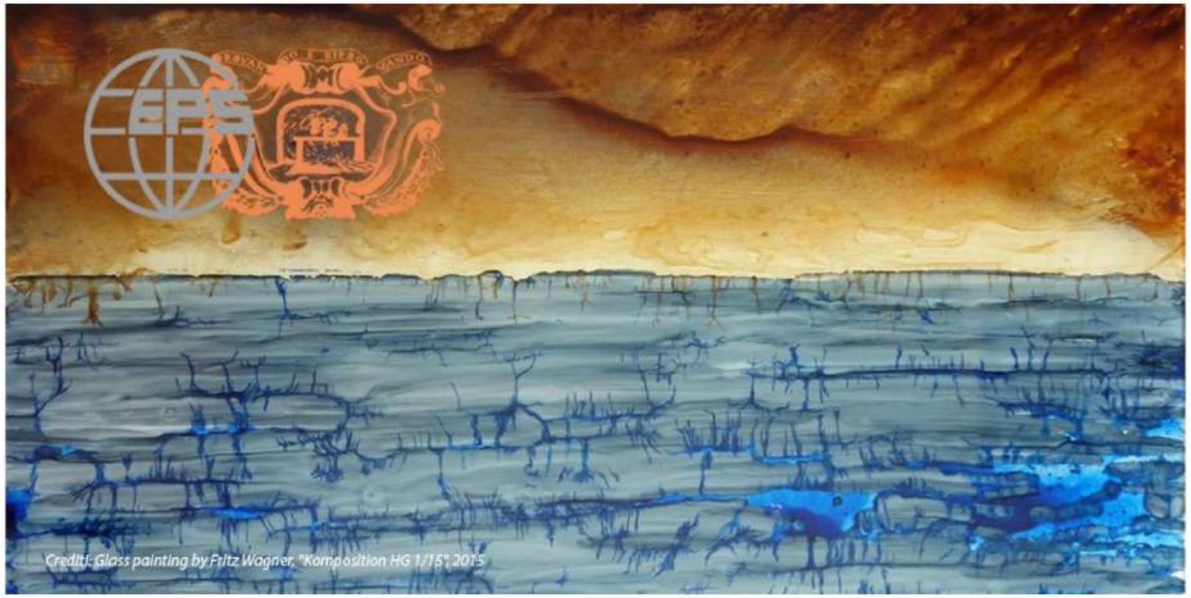
Coordinator of the PETAL+ project: diagnostics for LMJ



Joint EPS-SIF International School on Energy 2023

Course 7 - Joint EPS-SIF International School on Energy
Global Challenges for Energy Sustainability

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The voyage of nuclear fusion has started about 80 years ago (Sacharov, Teller, …) and despite progress has provided many disillusions…

60 years ago the laser was invented, opening the field of “Inertial Fusion” (Basov, Nuckolls, …)

Today for the first time in history we have the demonstration of ignition, the scientific feasibility of fusion, which concludes the first part of this travel.

In December 2022, experiments performed at the National Ignition Facility (NIF) in the U.S. have demonstrated a net energy gain from an inertial confinement fusion (ICF) experiment

Gain = 3.15MJ/2.05 MJ = 1.54

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DOI:10.1063/PT.6.2.20221213a

13 Dec 2022 in Politics & Policy

National Ignition Facility surpasses long-awaited fusion milestone

The shot at Lawrence Livermore National Laboratory on 5 December is the first-ever controlled fusion reaction to produce an energy gain.

David Kramer

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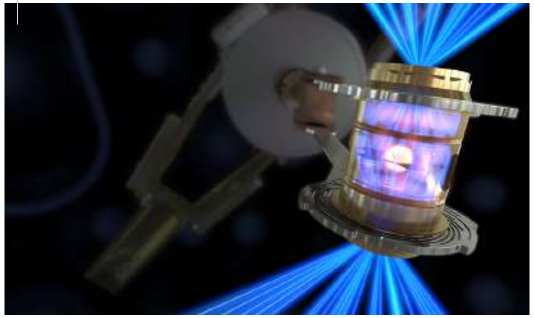
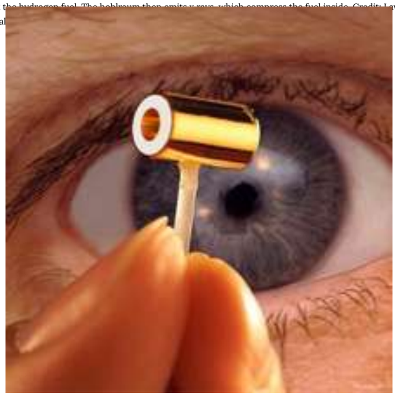


In the indirect-drive method used at the National Ignition Facility, a UV laser is fired at a cylinder called a hohlraum rather than at th... ...rence Livermore National...



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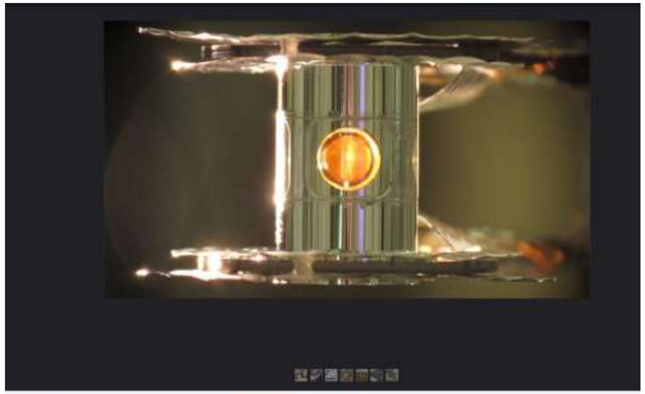
NUCLEAR FUSION | NEWS

National Ignition Facility demonstrates net fusion energy gain in world first

14 Dec 2022

Big gains: the record-breaking shot at the National Ignition Facility was made at just after 1 a.m. local time on 5 December. (Courtesy: LLNL)

The US National Ignition Facility (target chamber shown) is the size of three American football fields. Credit: Lawrence Livermore National Laboratory



Lawrence Livermore Natio... + Segui

NIF reaches milestone: Experiments show initial gain in fusion fuel

A metallic case called a hohlraum holds the fuel capsule for NIF experiments. Target handling systems precisely position the target and freeze it to cryogenic temperatures (18 kelvins, or -427 degrees Fahrenheit) so that a fusion reaction is more easily achieved. Photo by Eduard Dewald/LLNL.

Read more: NIF experiments show initial gain in fusion fuel

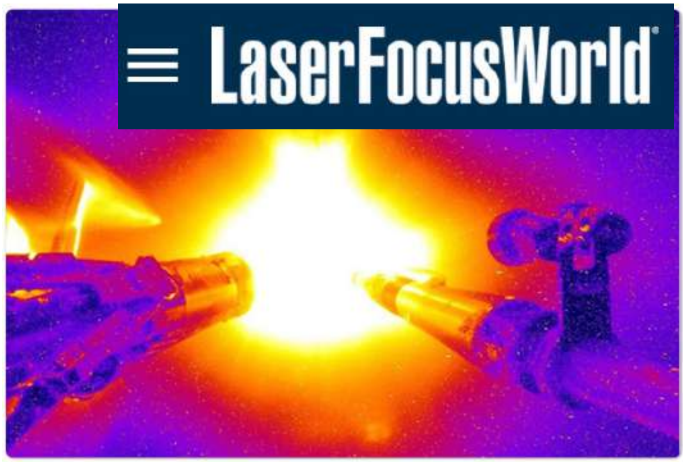
13.923 visualizzaz 7 preferiti 0 commenti

Scattata il 12 febbraio 2014

Tutti i diritti riservati

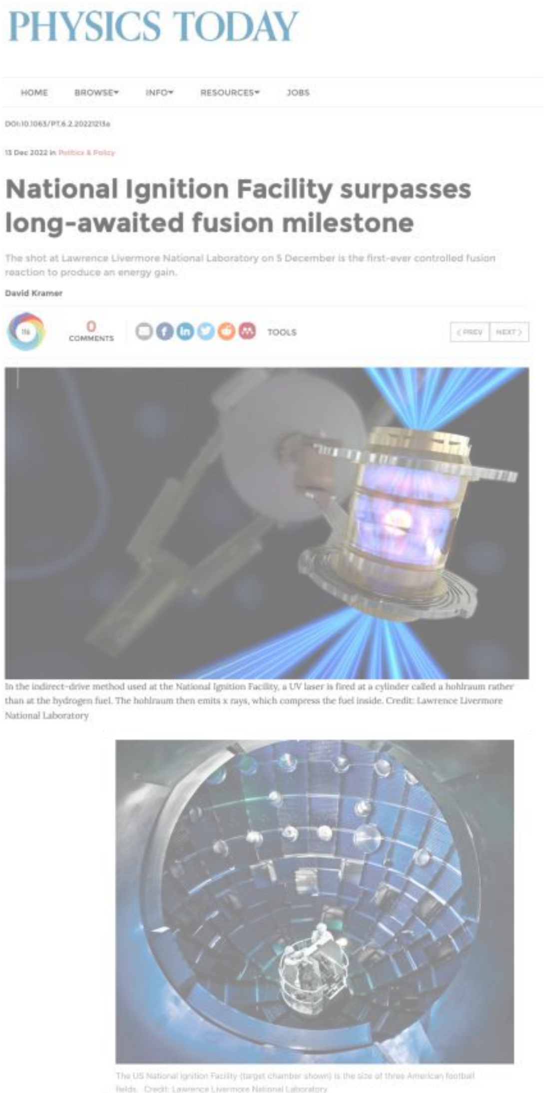
Mostra EXIF

Questa foto è presente in 1 album



Colorized image of a NIF "Big Foot" deuterium-tritium (DT) implosion.

In December 2022, experim
Facility (NIF) in the U.S. hav
an inertial confinement fusi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The shot at Lawrence Livermore National Laboratory on 5 December is the first-ever controlled fusion reaction to produce an energy gain.

David Kramer

In the indirect-drive method used at the National Ignition Facility, a UV laser is fired at a cylinder called a hohlraum rather than at the hydrogen fuel. The hohlraum then emits x rays, which compress the fuel inside. Credit: Lawrence Livermore National Laboratory

Gain =
3.15MJ/


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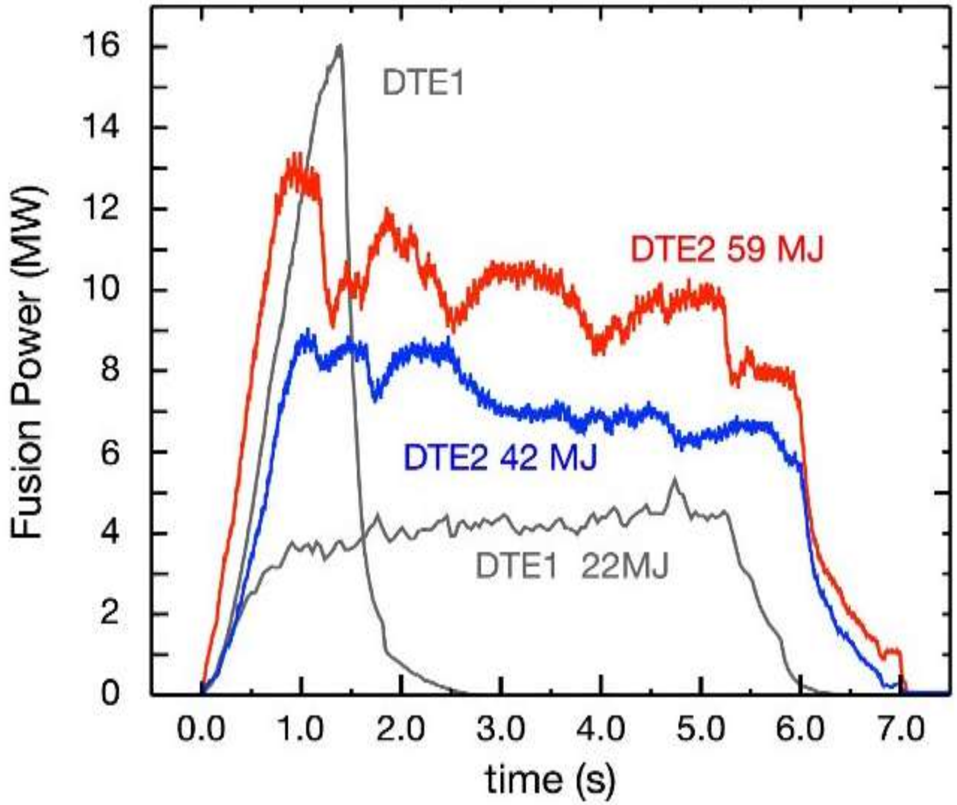
NUCLEAR FUSION | NEWS

National Ignition Fac
in world first

14 Dec 2022

Big gains: the record-breaking shot on 5 December. (Courtesy: LLNL)

It has been an exciting year for fusion. In MCF, JET has produced 59 MJ of fusion energy with a discharge sustained for 5 seconds..



- The principle of Inertial Confinement Fusion (ICF)
- The quest for ignition on NIF
- Beyond NIF ignition, towards high gain - The Shock Ignition approach
- Present and Perspectives of Inertial Fusion Energy (IFE) Technical and scientific challenges
- Hydrogen boron fusion?

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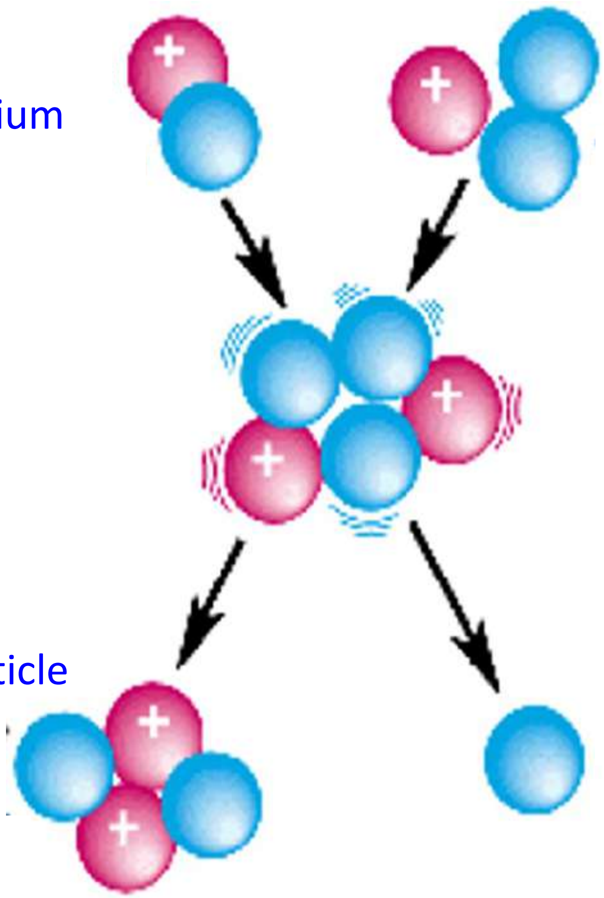
Thermonuclear Fusion



- Need to have high temperatures to overcome Coulomb repulsion

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

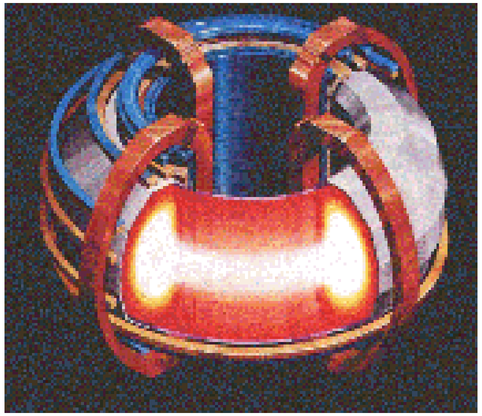
- Need to have many fusion reactions to allow for energy gain, i.e. large number of particles and/or long confinement time.

  Lawson's criterium

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

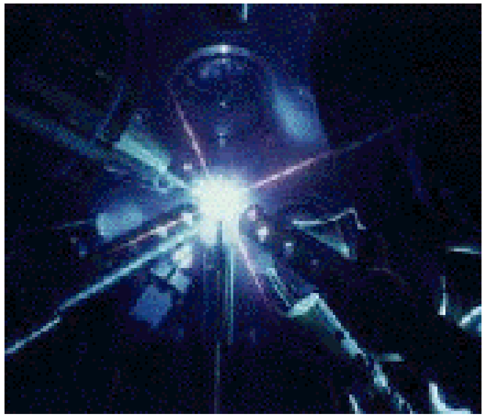
$D + T \rightarrow He^4 + n + 17.6$ MeV

Two approaches for creating conditions for fusion:



Magnetic Confinement

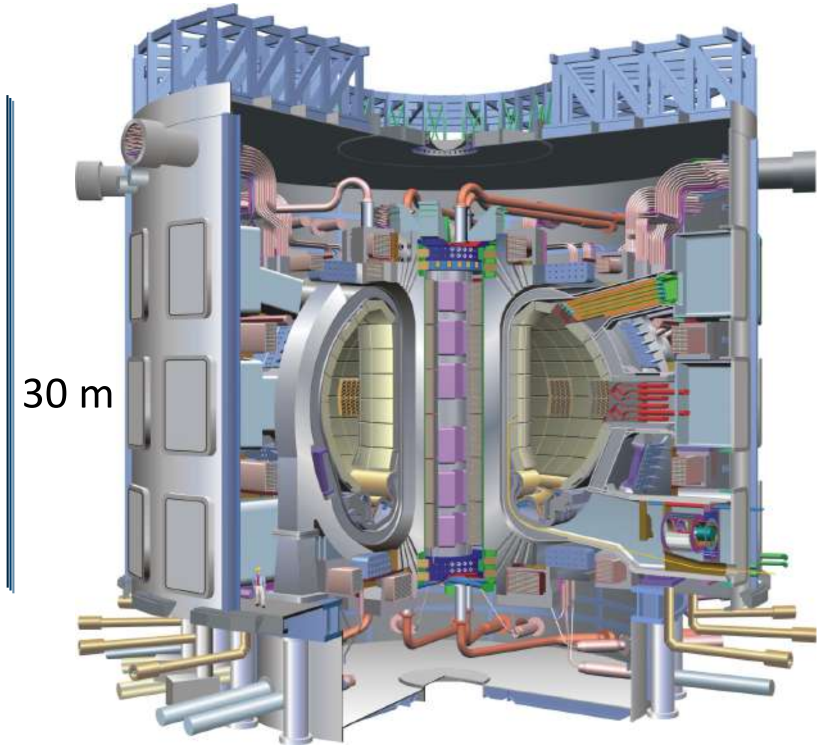
Low plasma density
Long times (~sec)



Inertial Confinement

Very high densities (compression ~ 1000 times solid density)
Very short times (~ nsec)

Europe has a very strong commitment to MCF mainly via the ITER project



> 25 B€

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

How small?

The energy released by burning a given mass of DT is

$$E_F = N_F \varepsilon_{DT} = \frac{M_{DT}}{2m_i} \phi \, \varepsilon_{DT}$$

Where ε_{DT} =17.6 MeV. In practical units:

$$E_F(MJ) = 3.5 \;\; 10^5 \, \phi \, M_{DT}(g)$$

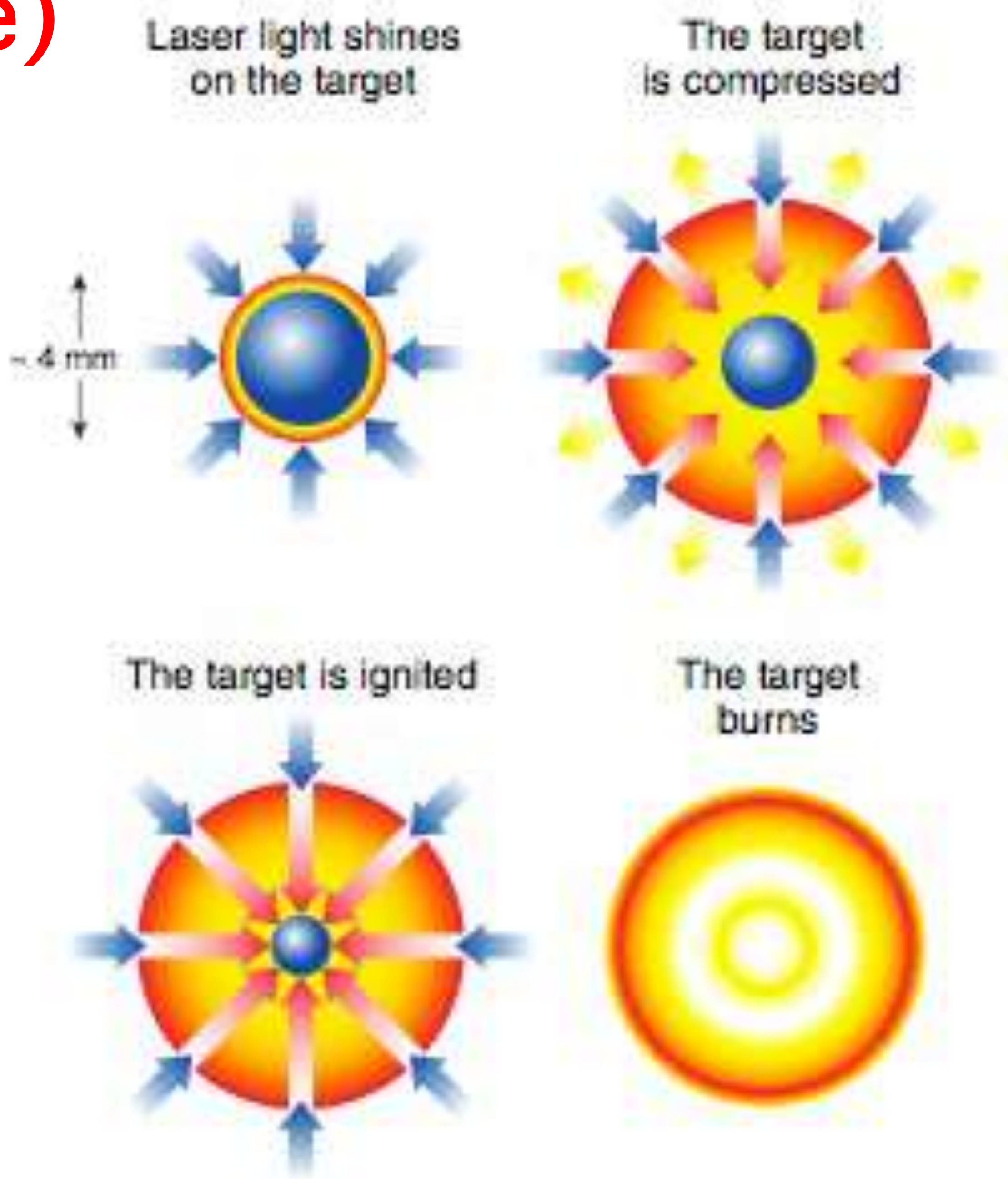
For M_{DT}= 1mg and assuming ϕ = 100%, we get

$$E_F = 350 \; MJ$$

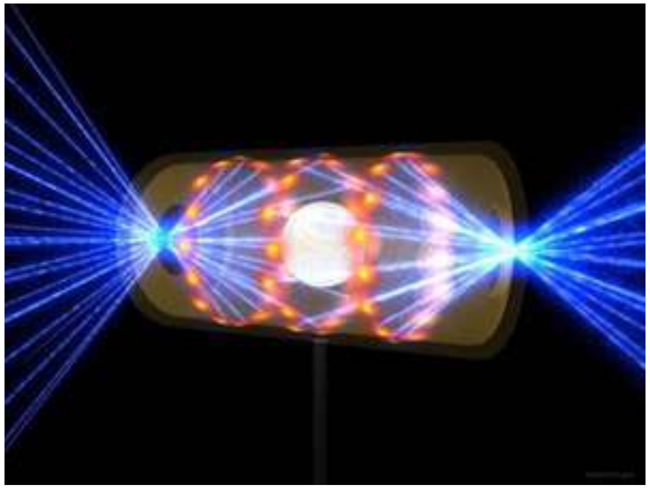
This is equivalent to the explosion of 73 kg of TNT !!

Principle of Inertial Confinement

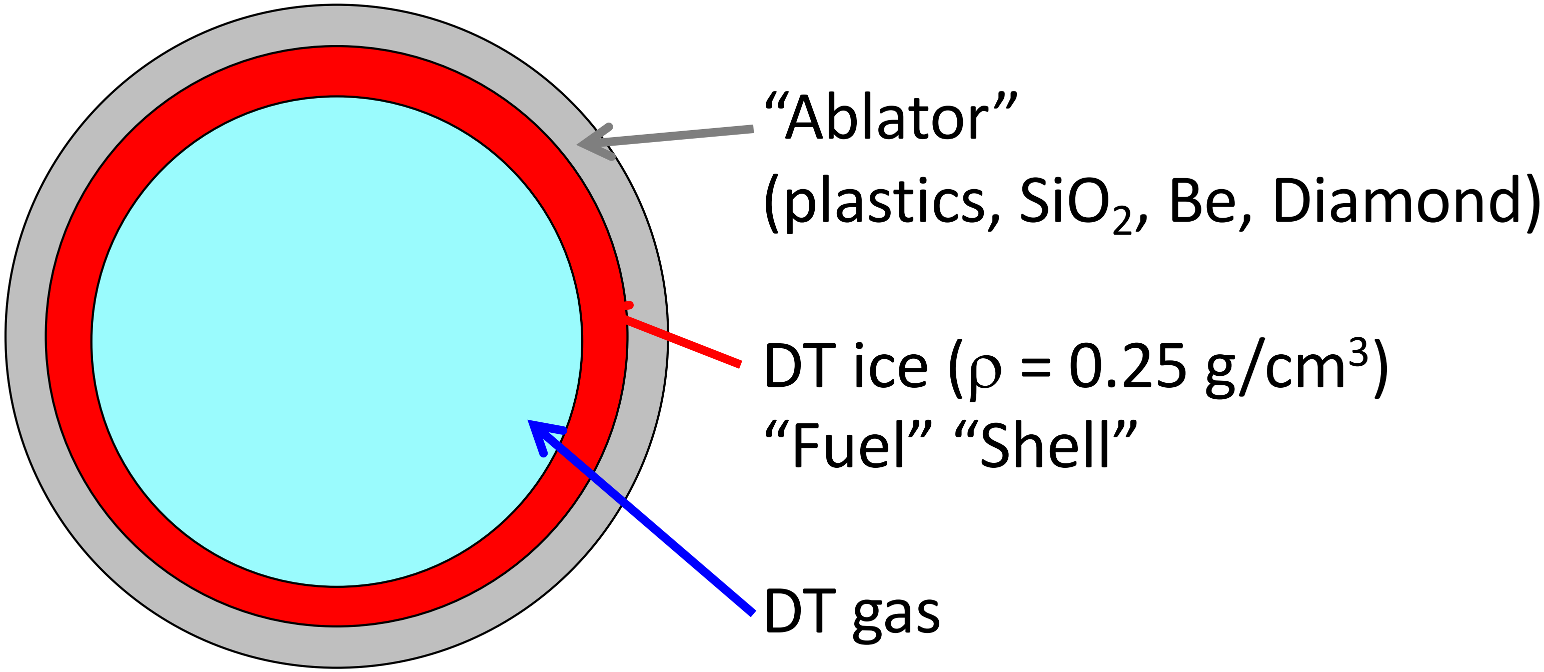
(direct drive)



(indirect drive)



ICF typical targets



External radius ≈ mm

DT mass ≈ mg

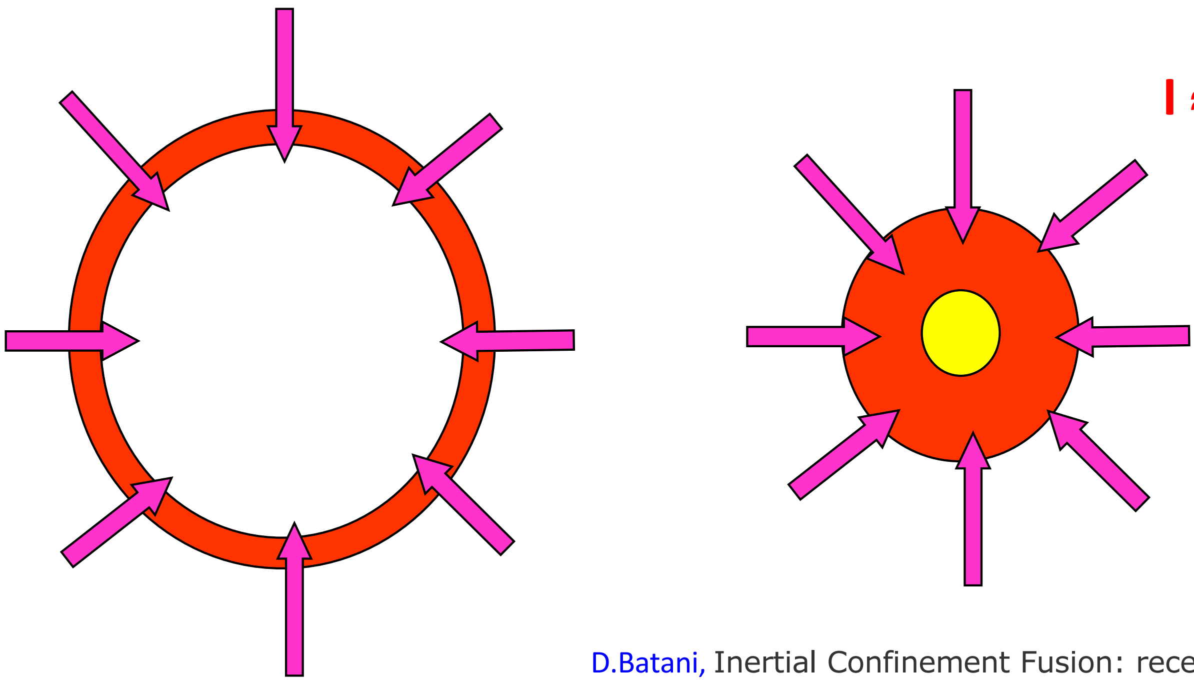
Inertial Fusion: ignition

Ignition («breakeven») takes place when the energy released by fusion reactions equals the energy delivered by the driver (laser).

To reach ignition we need:

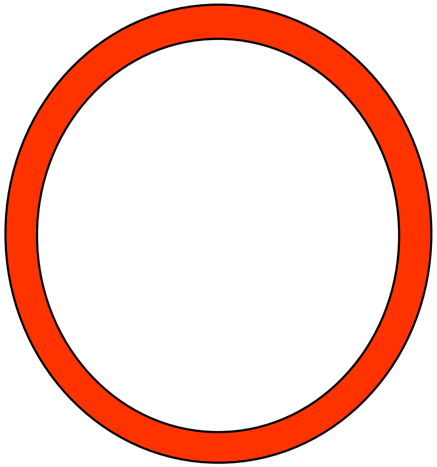
- Compress the fuel at 1000 g/cm^3, i.e. 4000 times the density of solid DT ice
- Heat the central part of the target at temperatures of ≈ 5 - 10 keV

(this is called ignition by central hot spot)



I ≈ 10^{14} W/cm^2 10 ns

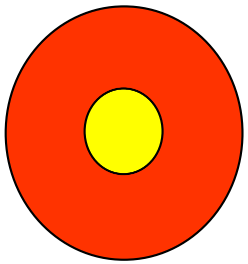
Why do we need a hot spot?



INITIAL CONDITIONS

CRYOGENIC SHELL

- $R_{in} \approx$ 2 mm, $R_{in} / \Delta r \approx 30$ ($\Delta r \approx 67$ µm)
- $V \approx 4 \pi R_{in}^2 \Delta r \approx 3.2 \;\; 10^{-3}$ cm^3
- $\rho_{in} \approx 2.5 \times$ 0.1 g/ cm^3, $M \approx 0.82$ mg



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

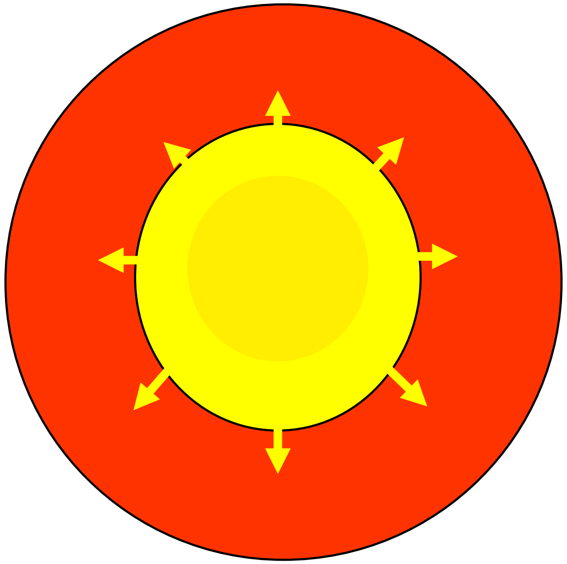
If $T_{fin} \approx 10$ keV, total thermal energy in fuel $E \approx 2\,(3/2\; N_{DT}\, T) \approx 1$ MJ !!

"Volume ignition" is NOT achievable !

Principle of Inertial Confinement

nuclear burn wave

Energy deposition from α-particles => Increase in temperature => more fuel reaches conditions for nuclear fusion => more α-particles created

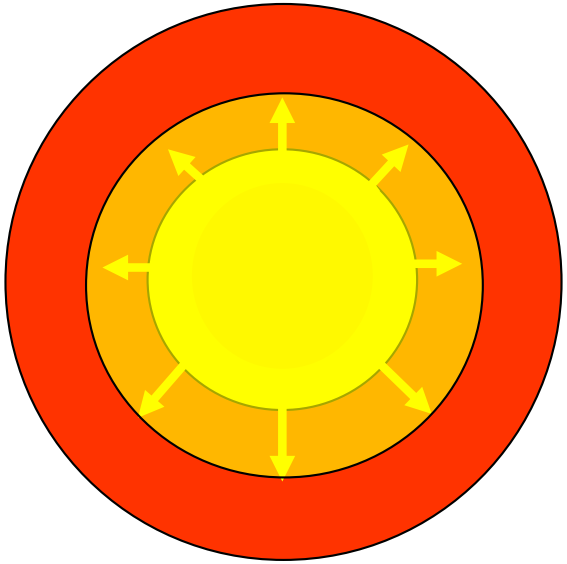


Principle of Inertial Confinement

nuclear burn wave

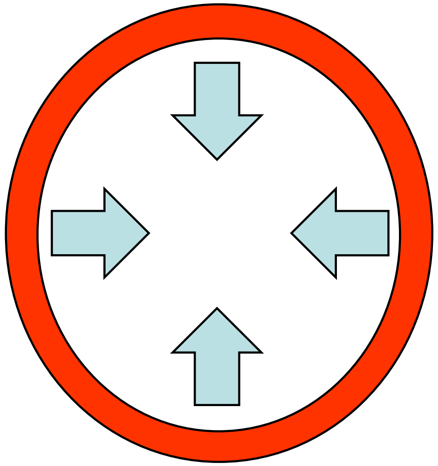
Energy deposition from α-particles => Increase in temperature => more fuel reaches conditions for nuclear fusion => more α-particles created

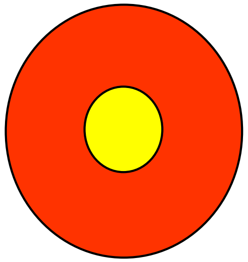
We create a propagation nuclear burn wave starting from the hot spot



Self–heating regime (dominated by α-particle energy deposition)

Hot spot formation





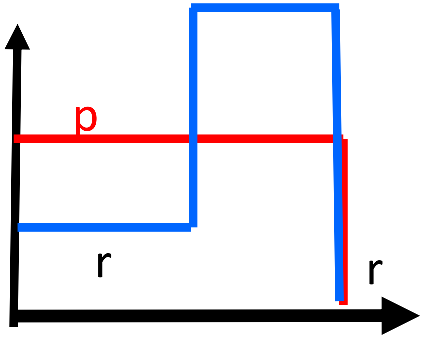
The hot spot is formed by the compression of the DT gas initially contained within the shell.
As the pressure increases, the imploding shell gradually slows down.
When the pressure of the gas equals the external pressure, the shell stops. This is called «stagnation».

At stagnation, we want
$\rho_{shell} \approx 1000$ g/cm^3 and $T_{hs} \approx 10$ keV

Equality of pressures implies
Shell (fuel): $\rho_{shell} \approx 1000$ g/cm^3 $T_{shell} \approx 1$ keV
Hot spot: $\rho_{hs} \approx 100$ g/cm^3 $T_{hs} \approx 10$ keV

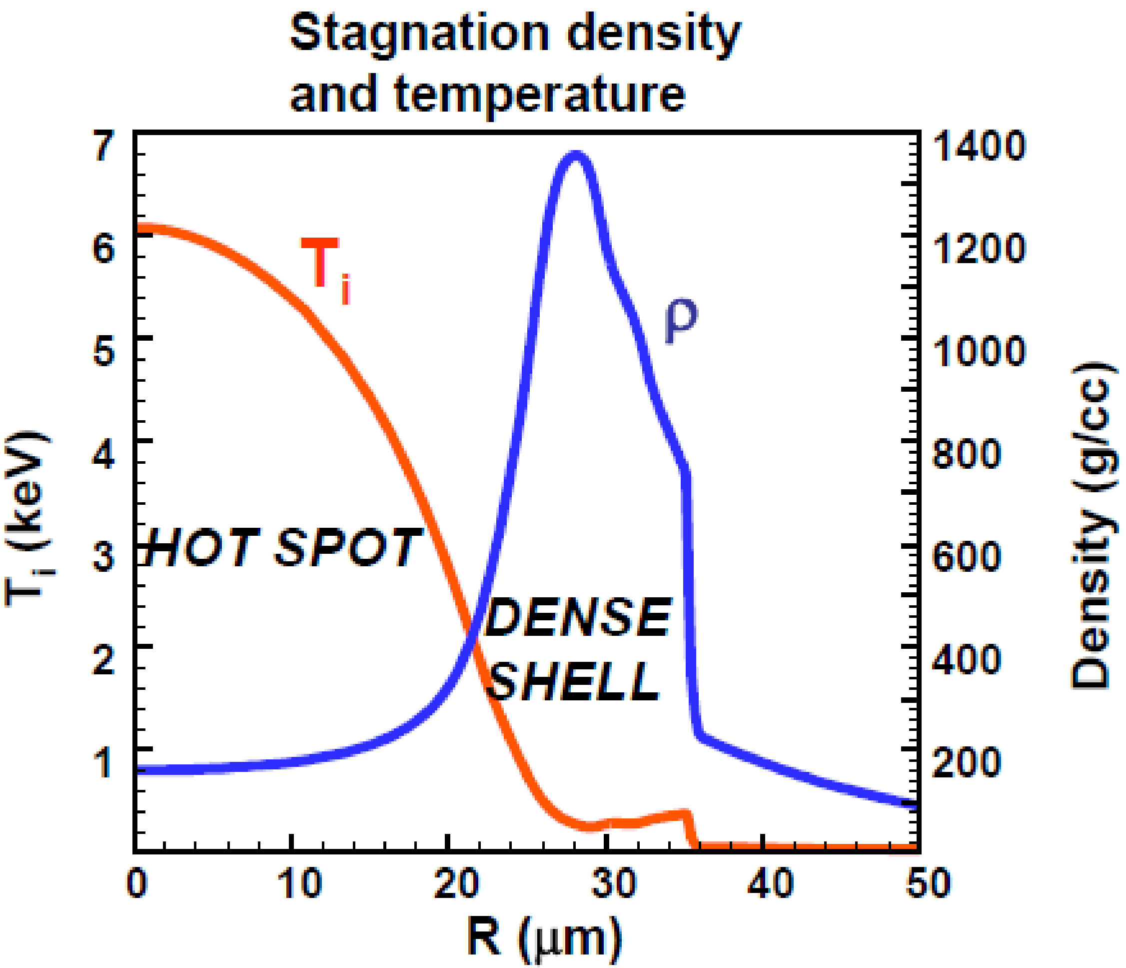
If $R_{hs} \approx 40$ µm, then $m_{hs} \approx 2.7\ 10^{-5}$ g and $E_{hs} \approx 30$ kJ

Isobaric fuel assembly



The temperature in the hot spot comes from the conversion of kinetic energy of imploding shell…
Hence this scheme requires high implosion velocities!

NIF-like target (1 MJ)



$$n_e = n_i \;= 2.4\rho \quad 10^{23} cm^{-3}$$

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

LL

$-\rho_{fin} R_{fin} \approx 10^3$ g/ cm$^3 \times$ 40 μm

= 4 g/ cm^2

-$n_i = n_e \approx 2.5\ 10^{26}$ cm^{-3}

HOT SPOT

$-\rho_{fin} R_{fin} \approx 130$ g/ cm$^3 \times$ 22 μm

= 0.3 g/ cm^2

-$n_i = n_e \approx 3\ 10^{25}$ cm^{-3}

The hot spot is a perfect gas…

PRESSURE (hot spot)

-P ≈ 600 GBar

Spherical geometry

Notice:

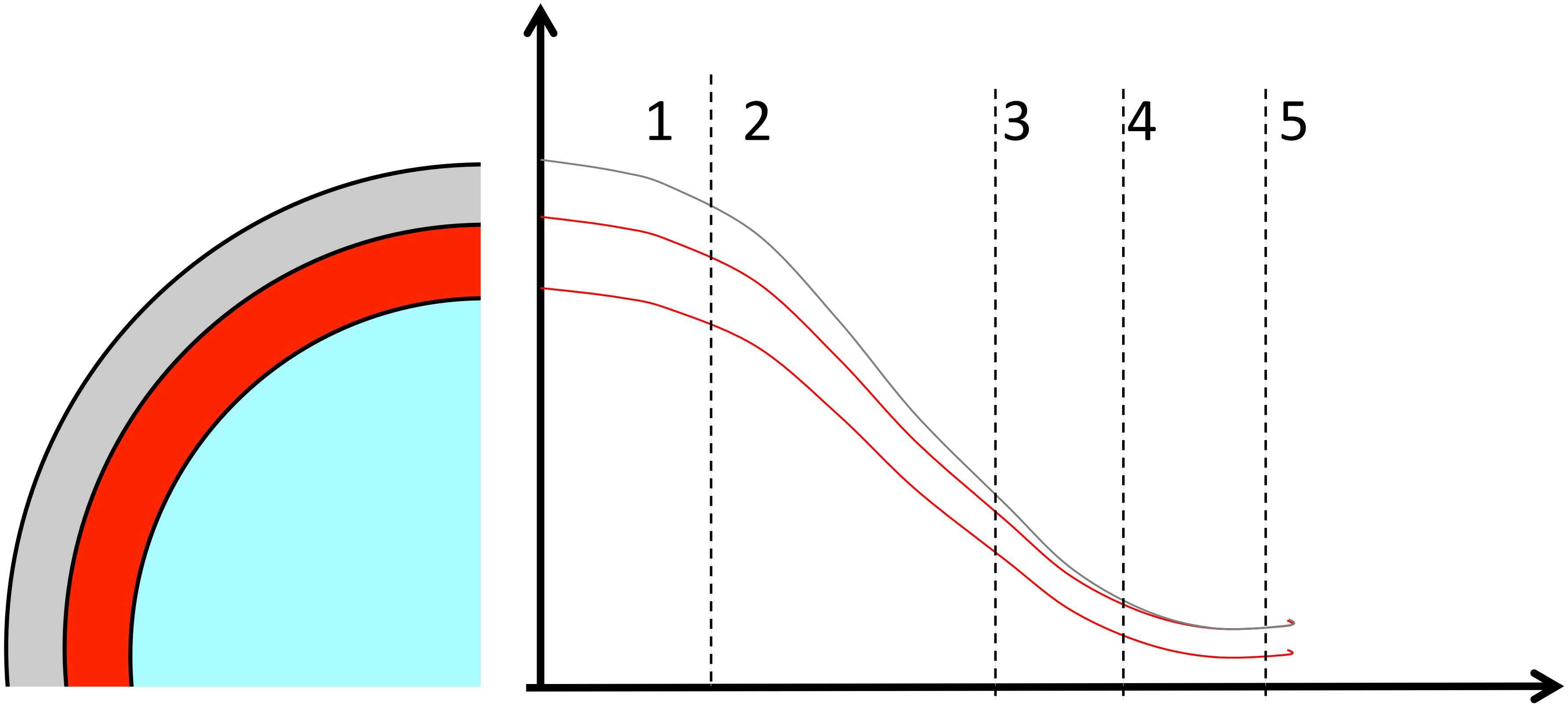
Ablation Pressure P $\approx$ 50 MBar

Pressure at stagnation P $\approx$ 500 Gbar

Amplification of a factor $\times$ 10000 due to convergence

Spherical geometry is essential for ignition

Implosion dynamics



1 ablation and acceleration

2 free flight

3 deceleration

4 stagnation

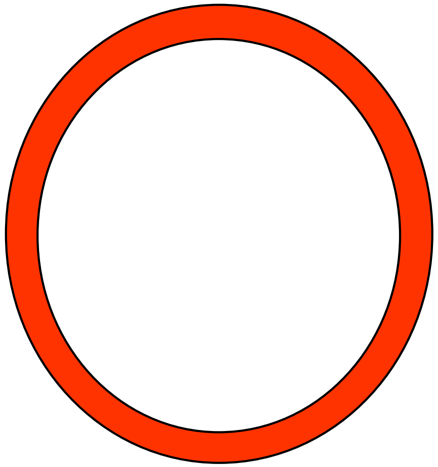
5 explosion

Some orders of magnitude

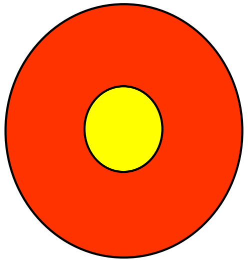
If the mass of fuel is 1 mg, in order to achieve $E_{hs} \approx 30$ kJ you need an implosion velocity $V \approx 350$ km/s

$$\frac{1}{2} m V^2 = 2\, E_{hs}$$

Why do we need MJ lasers?



About 90% of the laser energy is just « lost » to create the ablating plasma (the « engine » of the inward acceleration)

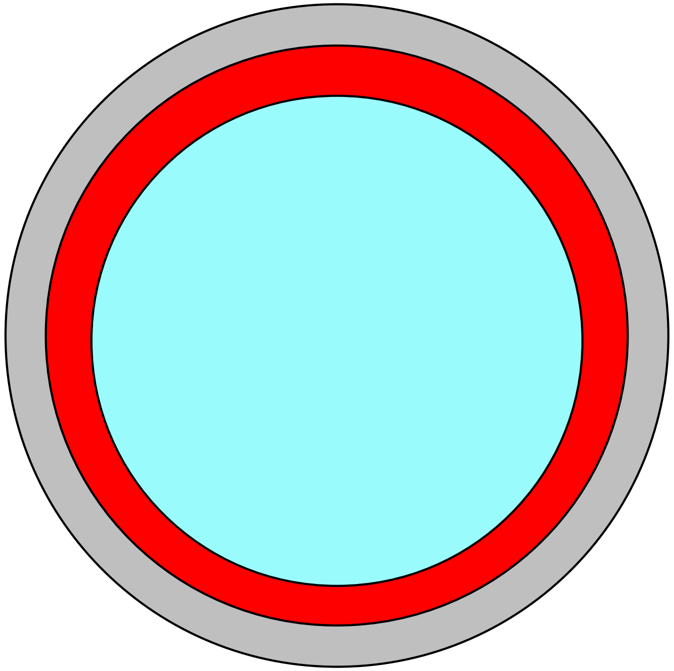


The conversion efficiency from laser energy to the shell kinetic energy is very low ≈ 10 %

Roughly half of this energy goes in compression of the fuel and half in heating and compression of the hot spot

Hence $E_{hs} \approx 30$ kJ implies $E_{laser} \approx 1$ MJ

Some orders of magnitude



If $R \approx 2$ mm
and before stagnation
$V_{implosion} = 400\ \mu m/ns = 400\ km/s$

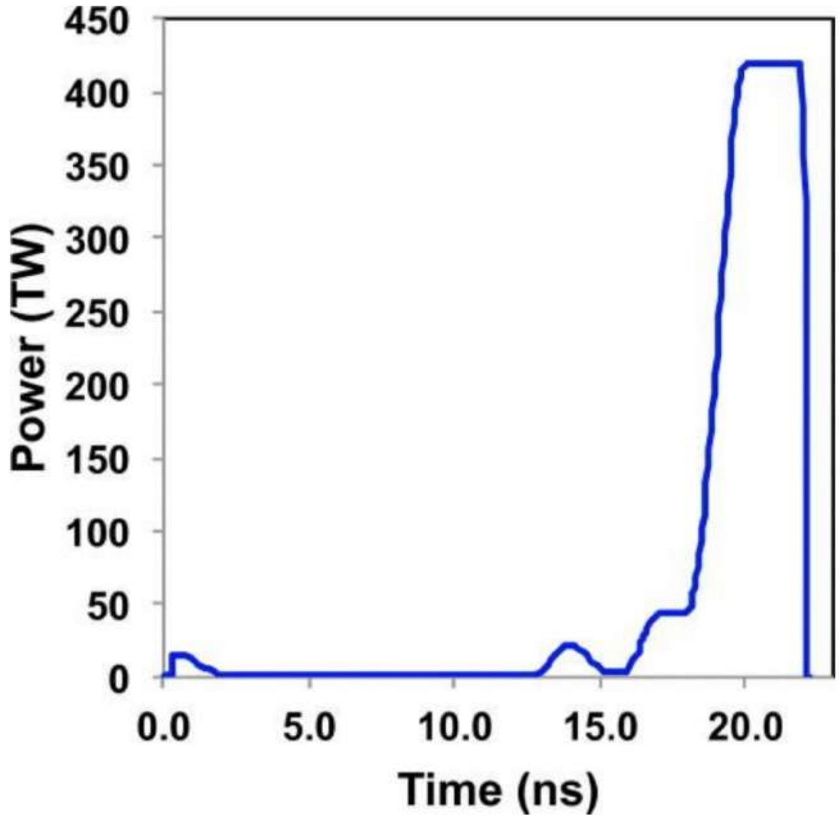
then $V_{average} \approx 200\ \mu m/ns$

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

Then if
$E_{laser} = 1.5\ MJ \qquad S = 4\pi R^2 = 0.5\ cm^2$

We get
$I_L = E_{laser} / (S\ t_{laser}) \approx 3\ 10^{14}\ W/cm^2$

Need of quasi adiabatic implosion

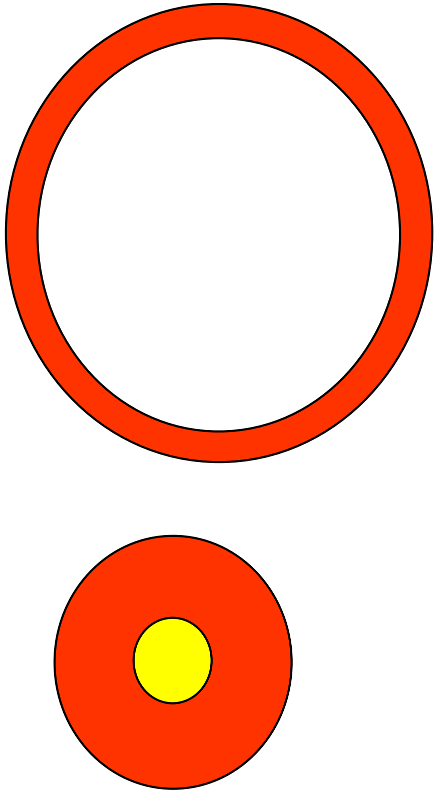


In order to reach $\rho_{shell} \approx 1000\ g/cm^3$ we must realize a « gentle » quasi-adiabatic compression.

If we compress too fast we heat the fuel, and a heated material is much more difficult to be compressed

We introduce an adiabat-parameter α which is the ratio of the pressure achieved in the compression to the pressure of a perfect adiabatic compression (i.e. for perfect adiabt α =1)

Target stability



The high implosion velocity guarantees a sufficient shell kinetic energy before stagnation

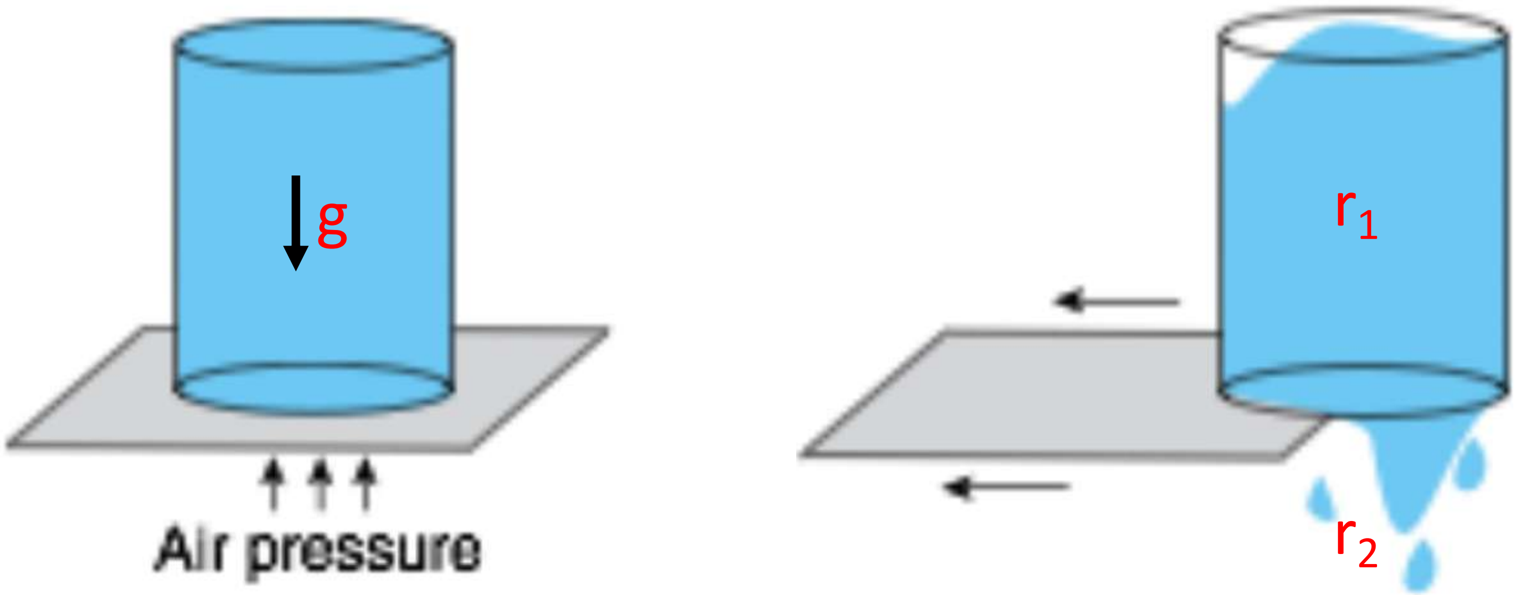
$V_i \approx 400$ km/s $M_{DT} = 1$ mg

$$E_{kin} \approx \frac{1}{2} M_{DT} V_i^2 = 60 \text{ kJ}$$

But in order to reach such high implosion velocity we need to use a small mass, i.e. a « thin » shell.

Unfortunately, such thin shells are very sensitive to deformations and can break during implosion, thereby stopping the process.

Rayleigh-Taylor Instability



The surface modulations are amplified in time

$$Z(x,t) = Z_0 \cos(kx)\, e^{\gamma t}$$

Classical growth rate of the instability

$$\gamma = \sqrt{Akg} \qquad A = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$$

In laser-plasmas this is partially stabilized

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

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- Hydrogen boron fusion?

National Ignition Campaign (2009-12)

- NIF @ 1.5 MJ. Designed for $G=E_{fusion}/E_{laser}=20$
  $G=1$ implies $N_{neutron} \approx 5\ 10^{17}$ (but they only got $\approx 10^{15}$)

Problems:

- Incomplete EOS data of materials at high pressures in hydrodynamics simulations
- Incomplete data on opacities
- Underestimation of the impact of parametric instabilities in the gas inside the holhraum
- Significant problem on how to keep the pellet inside the holhraum
- Underestimation of impact of Rayleigh Taylor instability [Measured convergence ratio lower than predicted (using the implosion velocity extracted from experiment). The shell breaks before end of the implosion]

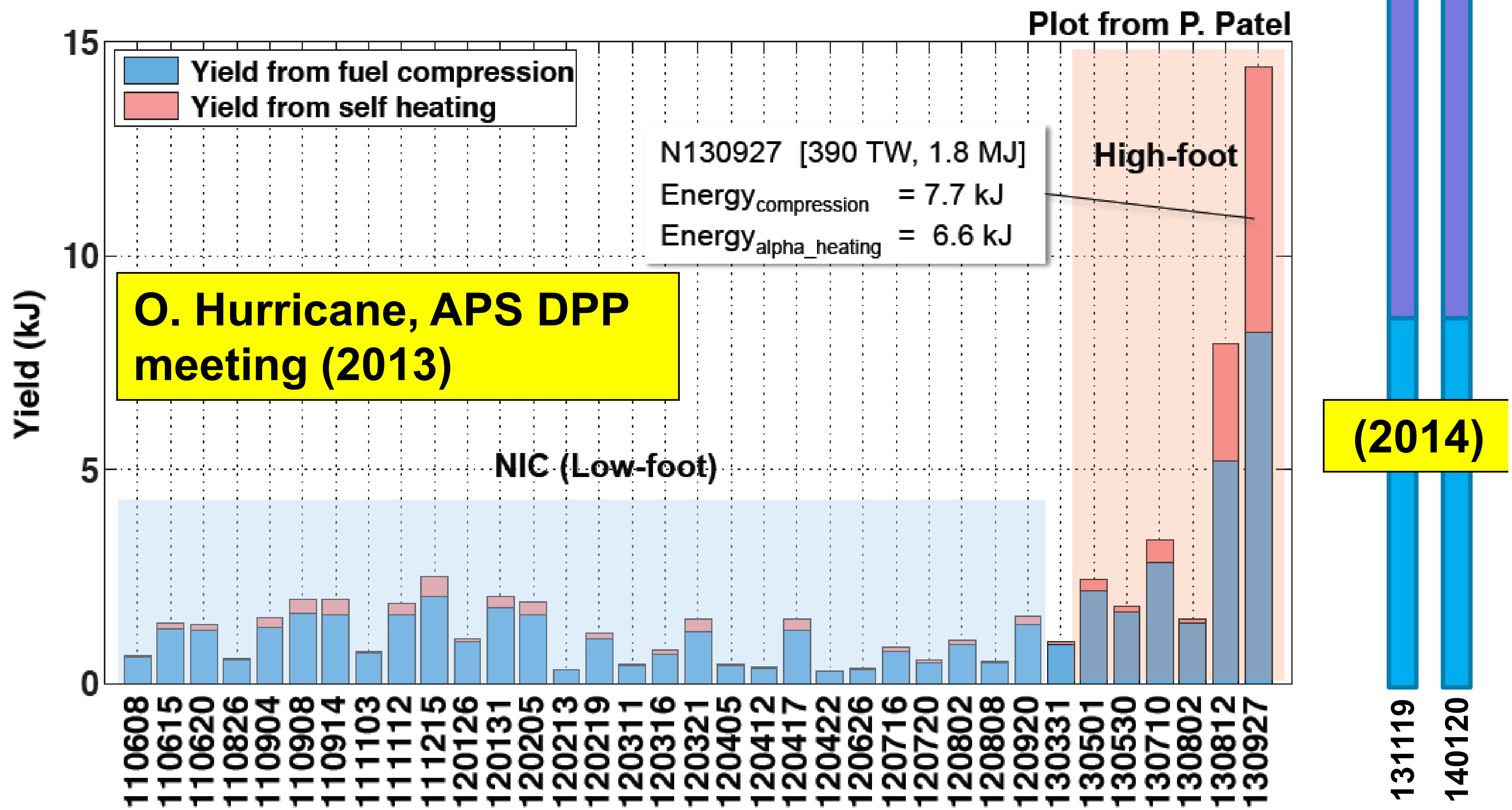
National Ignition Campaign (2009-12)

- NIF @ 1.5 MJ. Designed for $G=E_{fusion}/E_{laser}$ =20
  G=1 implies $N_{neutron} \approx 5\ 10^{17}$ (but they only got $\approx 10^{15}$)

This clearly shows that the goal of achieving ignition is still a scientific challenge rather than a technological challenge.
As such it is somewhat “unpredictable”

(and this is true for MCF too…)

We finally have an implosion where a large fraction of the total fusion output is from α-particle self-heating

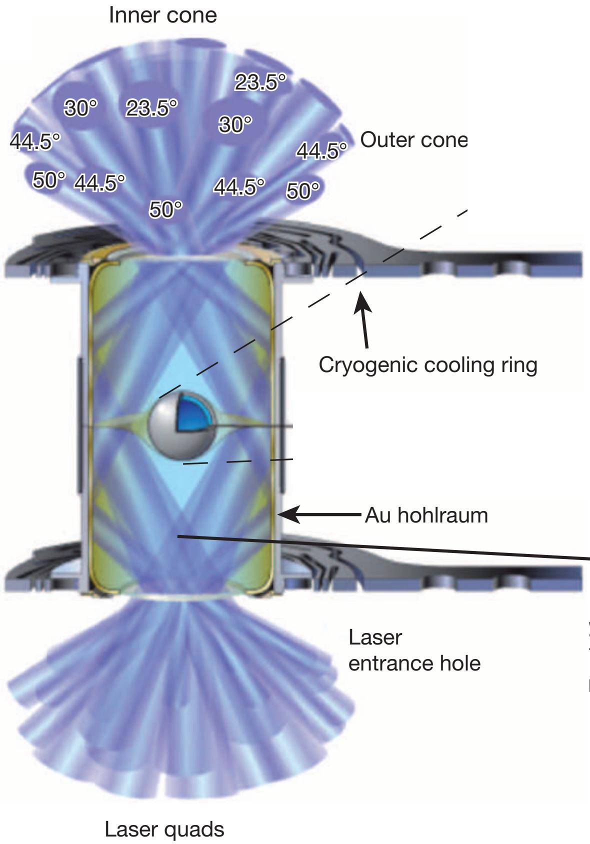


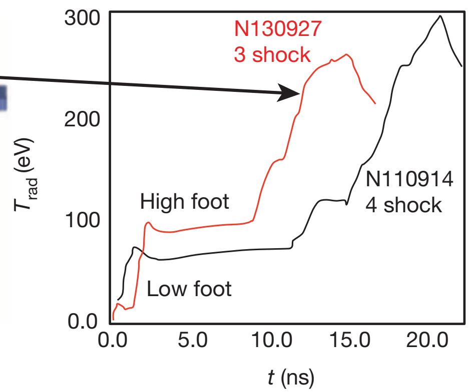
Joint WCI/NIF Team:
D. Callahan, E. Dewald, T. Dittrich,T. Doeppner, D. Hinkel, L. Berzak Hopkins, O. Hurricane, P. Kervin, J. Lee Kline (LANL), S. LePape, T. Ma, J. Milovich, J. Moody, A. Pak, H.-S. Park, B. Remington, H. Robey, J. Salmonson, NIF operations, NIF cryo, NIF targets, GA, LLE, & M.I.T.

NIF results after NIC

High-foot implosions (O.Hurricane, et al. Nature 2014) have allowed entering a novel “α-heating regime”

Quantity	$N131119^{425\,TW}_{1.9\,MJ}$	$N130927^{390\,TW}_{1.8\,MJ}$
$Y_{13\text{–}15}$ (neutron)	$(5.2 \pm 0.097) \times 10^{15}$	$(4.4 \pm 0.11) \times 10^{15}$
T_{ion} (keV) D–T	5.0 ± 0.2	4.63 ± 0.31
T_{ion} (keV) D–D	4.3 ± 0.2	3.77 ± 0.2
DSR (%)	4.0 ± 0.4	3.85 ± 0.41
τ_x (ps)	152.0 ± 33.0	161.0 ± 33.0
$P0_x$, $P0_n$ (μm)	35.8 ± 1.0, 34 ± 4	35.3 ± 1.1, 32 ± 4
$P2/P0_x$	-0.34 ± 0.039	-0.143 ± 0.044
$P3/P0_x$	0.015 ± 0.027	-0.004 ± 0.023
$P4/P0_x$	-0.009 ± 0.039	-0.05 ± 0.023
Y_{total} (neutron)	6.1×10^{15}	5.1×10^{15}
E_{fusion} (kJ)	17.3	14.4
r_{hs} (μm)	36.6	35.5
$(\rho r)_{hs}$ (g cm^{-2})	0.12–0.15	0.12–0.18
E_{hs} (kJ)	3.9–4.4	3.5–4.2
E_α (kJ)	2.2–2.6	2.0–2.4
$E_{DT,total}$ (kJ)	8.5–9.4	10.2–12.0
G_{fuel}	1.8–2.0	1.2–1.4

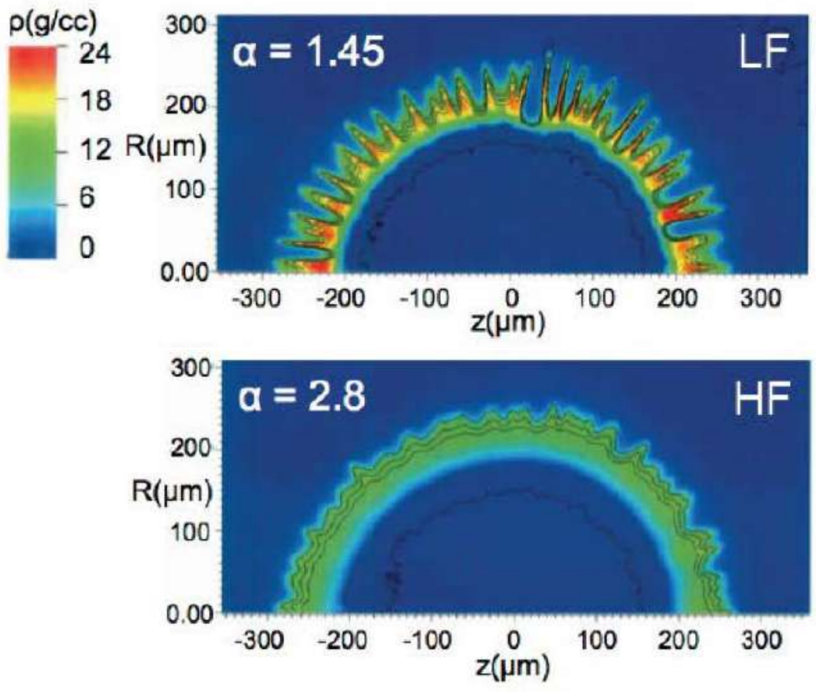




This also shows that the MAIN problem towards ignition is REALLY the impact of hydro instabilities related to non-uniformities

The best NIF implosions used the High-Foot laser pulse that drives stronger shocks in the "foot"

O. Hurricane, APS DPP meeting (2013)



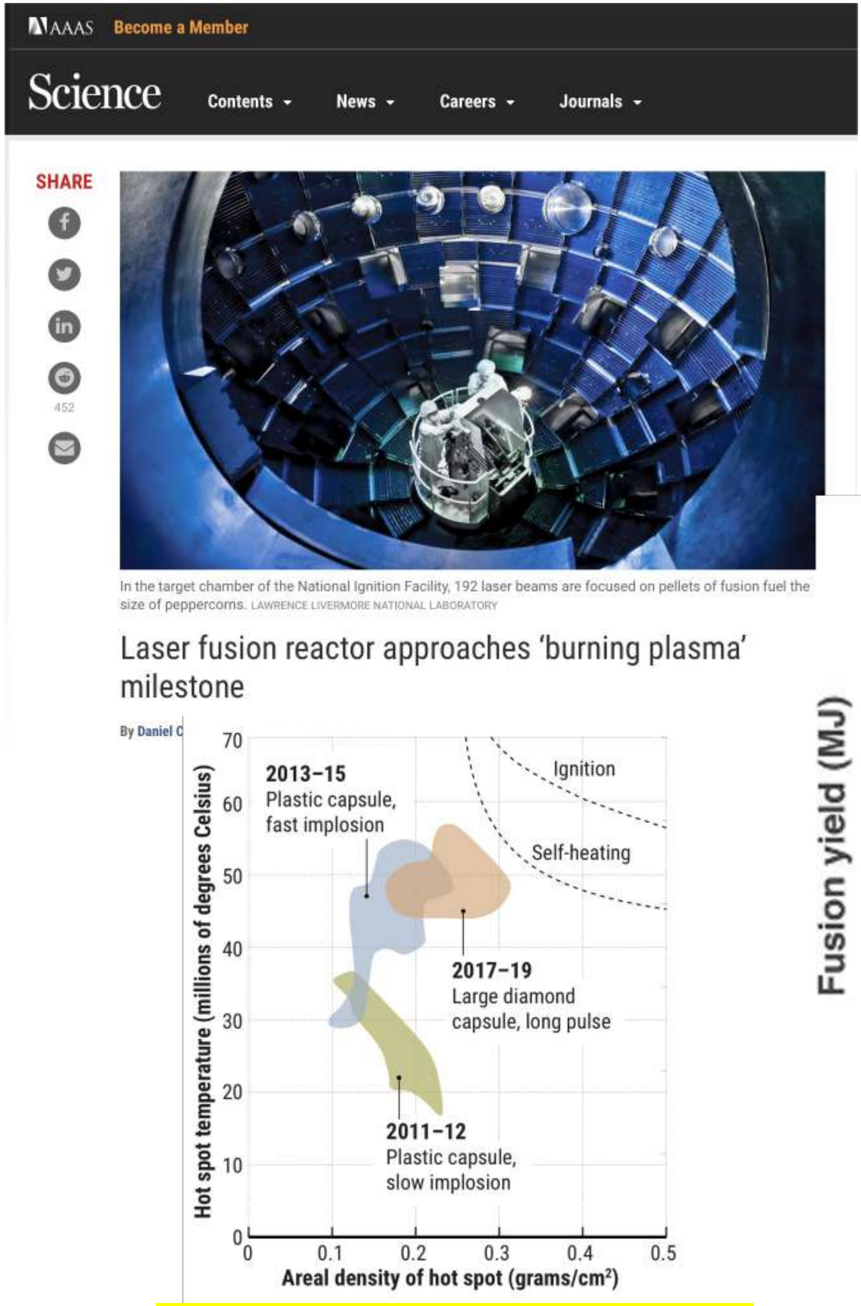
The high foot pulse set the imploding shell on a higher isentrope α (nothing to do with α-particles) because it launches stronger shocks in the "foot" of the pulse

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

Increase with α

From α ≈1.2 - 1.3 to α ≈2.5 -3

More recent results on NIF (2020-2021)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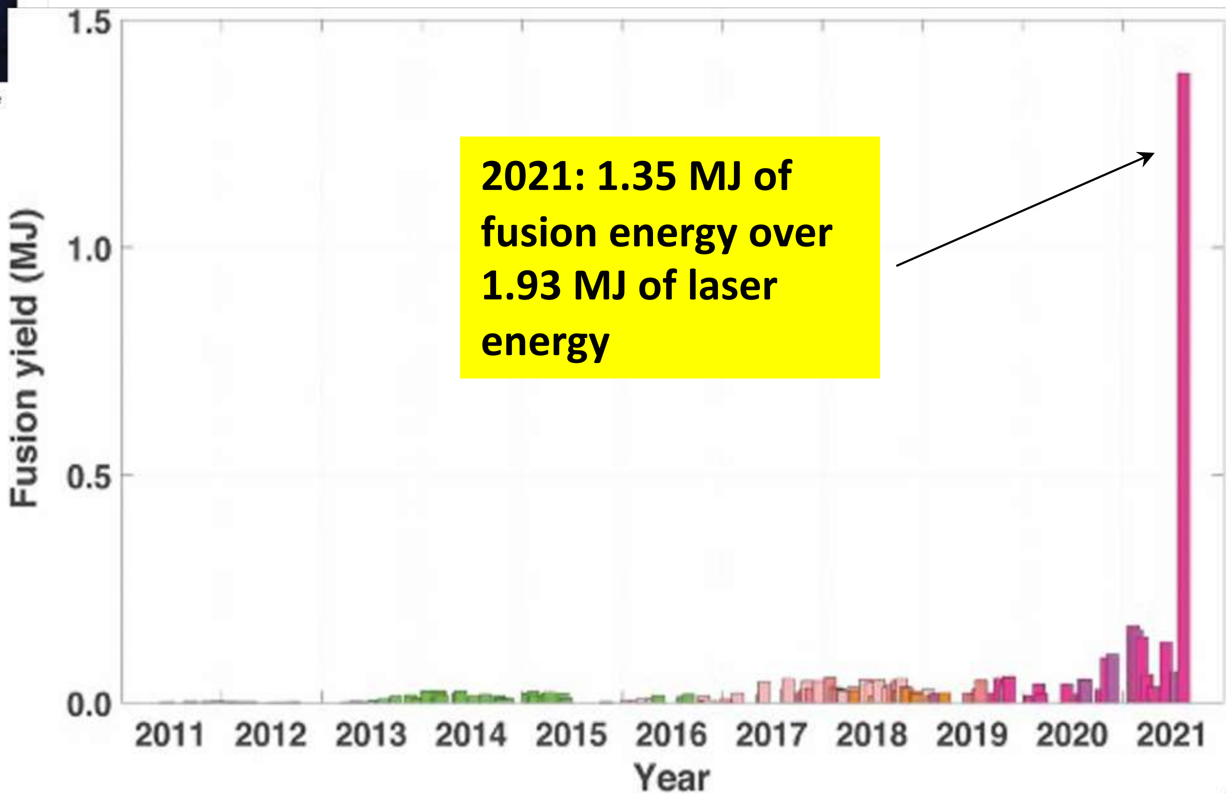
452

In the target chamber of the National Ignition Facility, 192 laser beams are focused on pellets of fusion fuel the size of peppercorns. LAWRENCE LIVERMORE NATIONAL LABORATORY

Laser fusion reactor approaches 'burning plasma' milestone

By Daniel C

2020: More than 150 kJ of fusion energy



2021: 1.35 MJ of fusion energy over 1.93 MJ of laser energy

"Gain" in the fuel

In December 2022, experiments performed at the National Ignition Facility (NIF) in the U.S. have demonstrated a net energy gain from an inertial confinement fusion (ICF) experiment

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DOI:10.1063/PT.6.2.20221213a

13 Dec 2022 in Politics & Policy

National Ignition Facility surpasses long-awaited fusion milestone

The shot at Lawrence Livermore National Laboratory on 5 December is the first-ever controlled fusion reaction to produce an energy gain.

David Kramer

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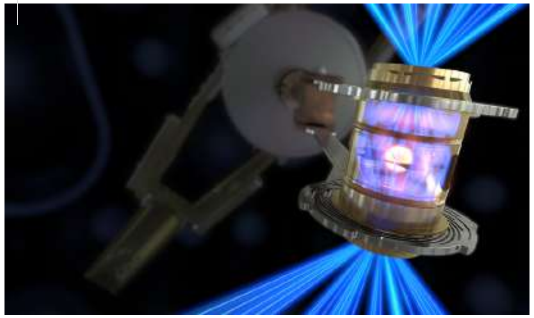
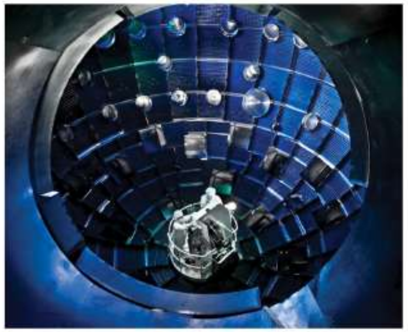


In the indirect-drive method used at the National Ignition Facility, a UV laser is fired at a cylinder called a hohlraum rather than at the hydrogen fuel. The hohlraum then emits x rays, which compress the fuel inside. Credit: Lawrence Livermore National Laboratory



The US National Ignition Facility (target chamber shown) is the size of three American football fields. Credit: Lawrence Livermore National Laboratory

Gain = 3.15MJ/2.05 MJ = 1.54

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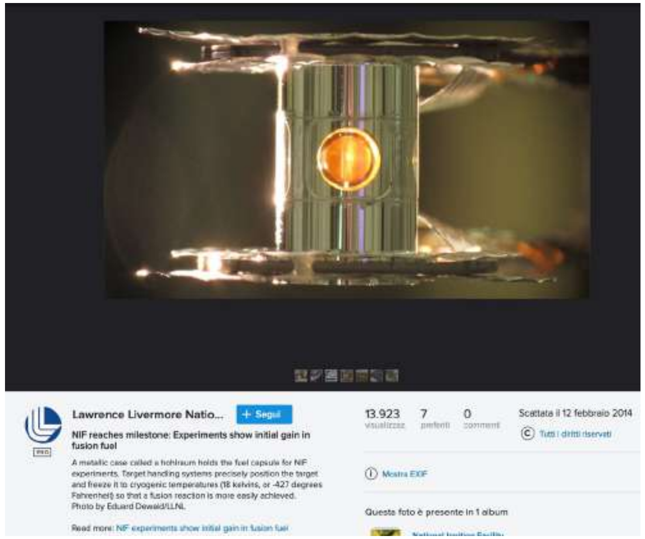
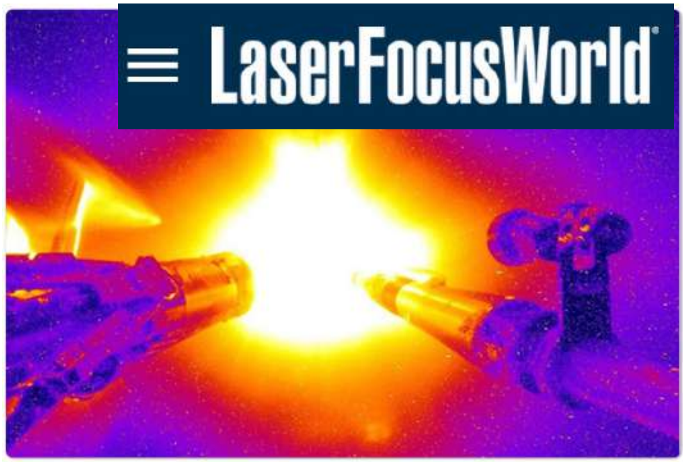
NUCLEAR FUSION | NEWS

National Ignition Facility demonstrates net fusion energy gain in world first

14 Dec 2022

Big gains: the record-breaking shot at the National Ignition Facility was made at just after 1 a.m. local time on 5 December. (Courtesy: LLNL)





Colorized image of a NIF "Big Foot" deuterium-tritium (DT) implosion.

In December 2022, experiments performed at the National Ignition Facility (NIF) in the U.S. have demonstrated a net energy gain from an inertial confinement fusion (ICF) experiment

In addition to using higher foot, NIF result was obtained thanks to:

- Different ablators (HDC: synthetic diamond)
- Different gas pressure in the holhraum
- Reduced holhraum size and bigger pellet
- Improved radiation uniformity
- Improved target quality (roughness)

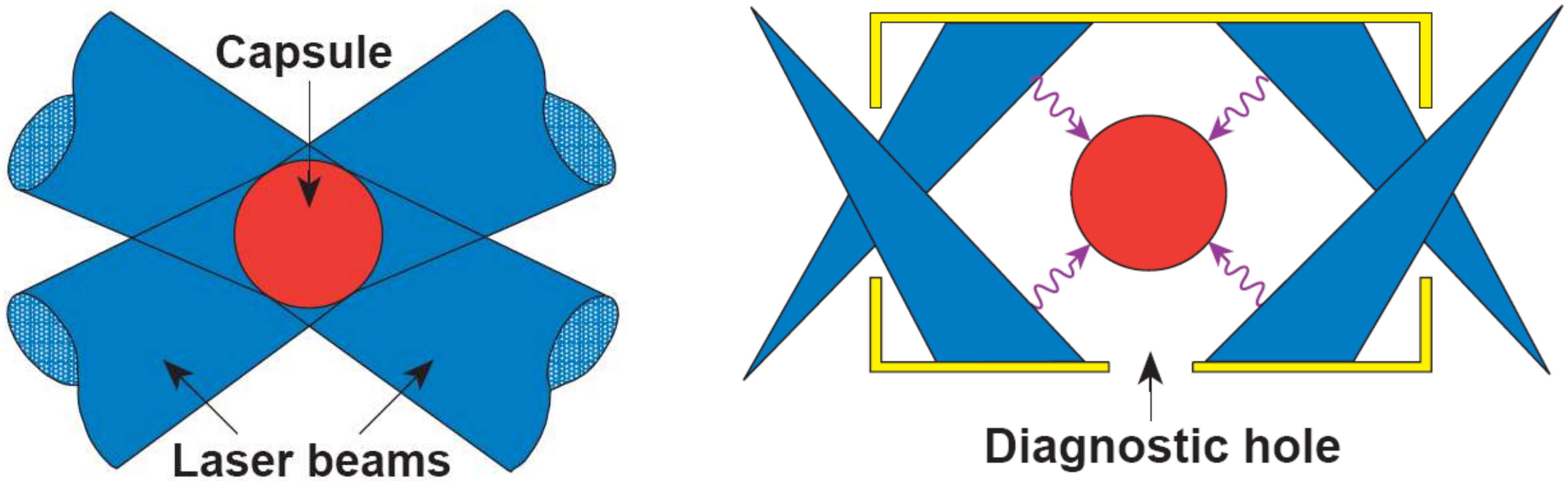
Notice: $\alpha \approx 2.5$ -3 has been “good” to show ignition but does NOT scale to HIGH GAIN !!

- The principle of Inertial Confinement Fusion (ICF)
- The quest for ignition on NIF
- Beyond NIF ignition, towards high gain - The Shock Ignition approach
- Present and Perspectives of Inertial Fusion Energy (IFE) Technical and scientific challenges
- Hydrogen boron fusion?

Inertial confinement: direct vs. indirect drive

Direct-drive target

Indirect-drive target



Hohlraum using
a cylindrical high-Z case

Direct: higher efficiency, more problems with uniformity

Indirect: better uniformity but reduction of efficiency

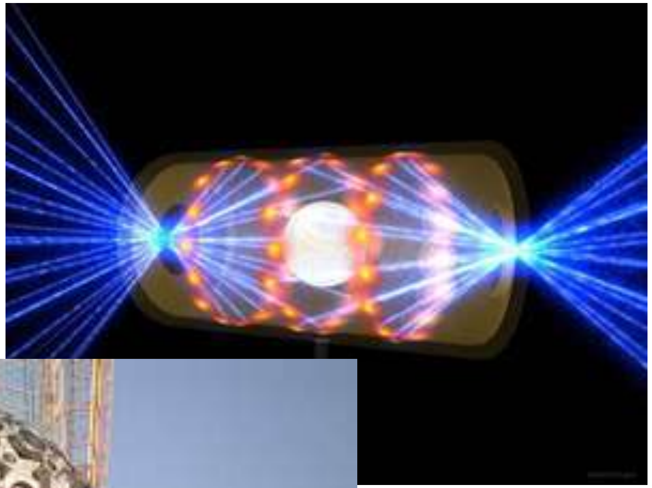
In both case you need MJ-class laser systems

NIF and indirect drive

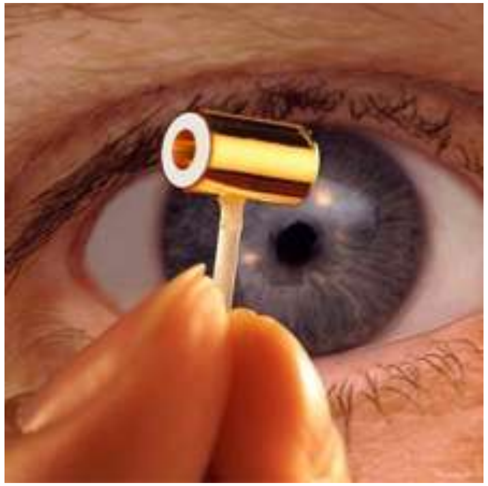
The National Ignition Facility (NIF) demonstrated ignition, the scientific feasibility of nuclear fusion. This is an enormous scientific achievement !

However…. NIF is based on INDIRECT DRIVE which does not seem compatible with requirements for fusion reactors:

- Complicated targets
- Massive targets (lot of high-Z material in chamber)
- Above all: intrinsic low gain due to X-ray conversion.



In addition, indirect drive poses "political" problems…
Therefore we need DIRECT DRIVE



Unfortunately, Direct Drive is prone to the impact of non-uniformities and hydrodynamic instabilities

How to solve the problem?

Separation of the compression phase and the ignition phase

Fast Ignition exotic and non-scalable physics
requires $\geq 100\ kJ$ 10 ps laser facility ☹

Shock Ignition compatible with present-day laser technology ☺

Shock Ignition

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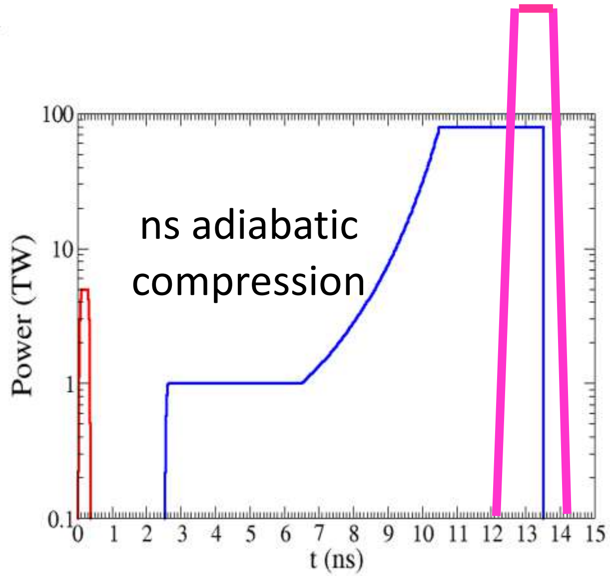
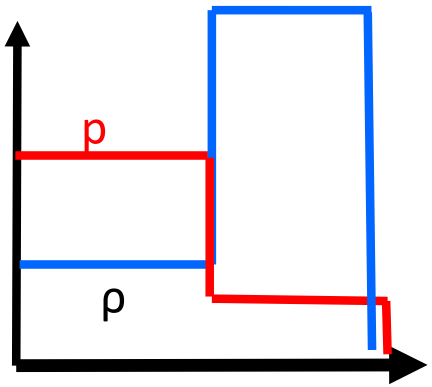
- Scheme proposed by R. Betti, J.Perkins et al. [PRL 98 (2007)] and anticipated by V.A.Shcherbakov [Sov.J. Plasma Phys. 9, 240 (1983)]
- Thicker and more massive target. Lower implosion velocity V ≈ 240 km/s
- A final laser spike launches a strong converging shock (≥ 300 Mbar at the ablation front)
- Non isobaric fuel assembly implies higher gains

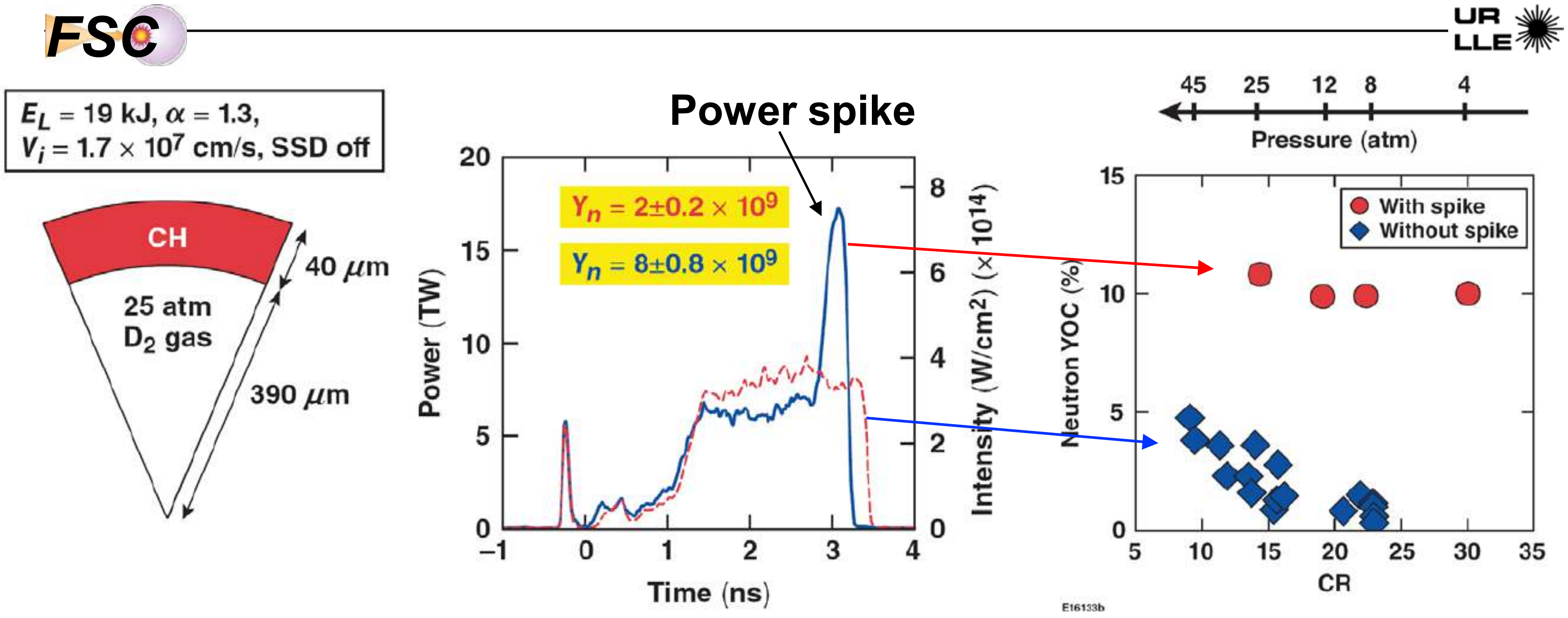


Ignition spike (a few 100 ps)



- Shock ignition is compatible with present-day laser technology ☺

Shock-ignition experiments on OMEGA have shown improved performance with a shock launching spike at the end of the laser pulse



The neutron yield increases considerably when a shock is launched at the end of the pulse.

The measured-to-calculated neutron-yield ratios are close to 10% for a hot-spot convergence ratio of 30.

W. Theobald,et al Phys. Plasmas (2008)

Unknowns of Shock Ignition

- Effect of laser-plasma instabilities at intensities up to ≈ 10^{16} W/cm^2. SRS, SBS and TPD. How they develop? How much light do they reflect?

- Are there many hot electrons and at what energy? What is their effect? *(usually in ICF hot electrons are dangerous since they preheat the target… Here they came at late times, large fuel ρr, so they could indeed be not harmful or even beneficial, increasing laser-target coupling in presence of a very extended plasma corona…)*

- Are we really able to couple the high-intensity laser beam to the payload through an extended plasma corona? Are we really able to create a strong shock? (P ≥300 Mbar)

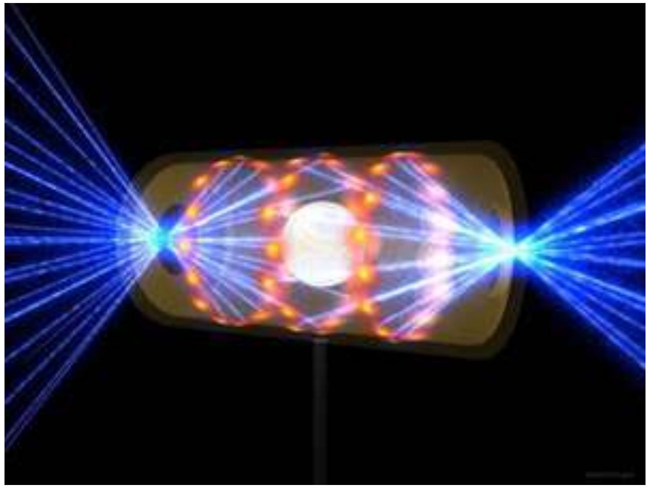
Elements of a Roadmap for shock ignition

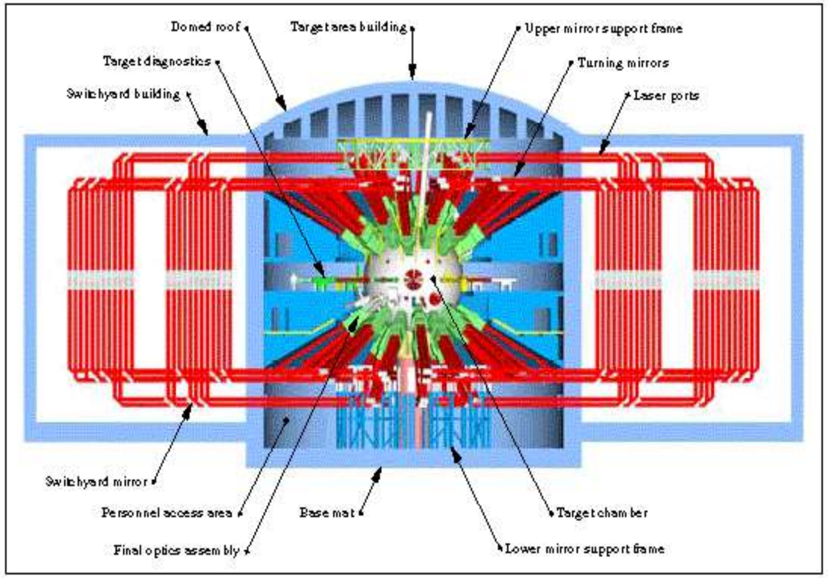
- Interesting physics needs to be understood and mastered:
  - Parametric instabilities (and CBET)
  - Hot electrons generation and their impact
  - Different wavelengths?
  - Acceptable degree of non uniformity in irradiation
  - Non uniform spike?

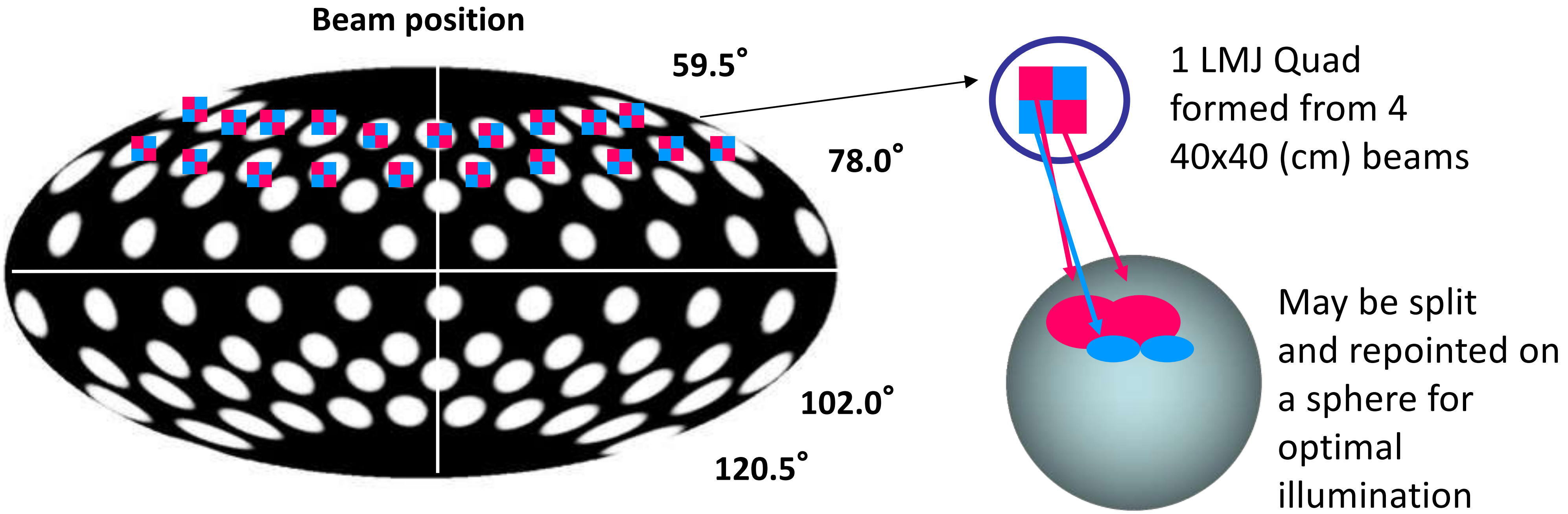
- SI can be demonstrated at NIF, LMJ or or the Shenguang-III laser facility in China

- Development of a full program relies on:
  - Scientific credibility: physics issues addressed elsewhere using intermediate-scale facilities: OMEGA, PALS, ORION, Vulcan, Phelix, Gekko, LULI, SG II, …
  - International collaboration is a key issue

Polar Direct Drive (PDD)







Elements of a Roadmap for shock ignition

How to approach the final goal of "Performing shock ignition demonstration experiments" ?

Planar Geometry

"Physics" Issues:
- Parametric instabilities
- Role of hot electrons
- Shock Formation

"Hydro" Issues:
- Smoothing
- Hydro instabilities

Spherical Geometry

"Physics" Issues:
- Parametric instabilities
- Role of hot electrons
- Shock Formation

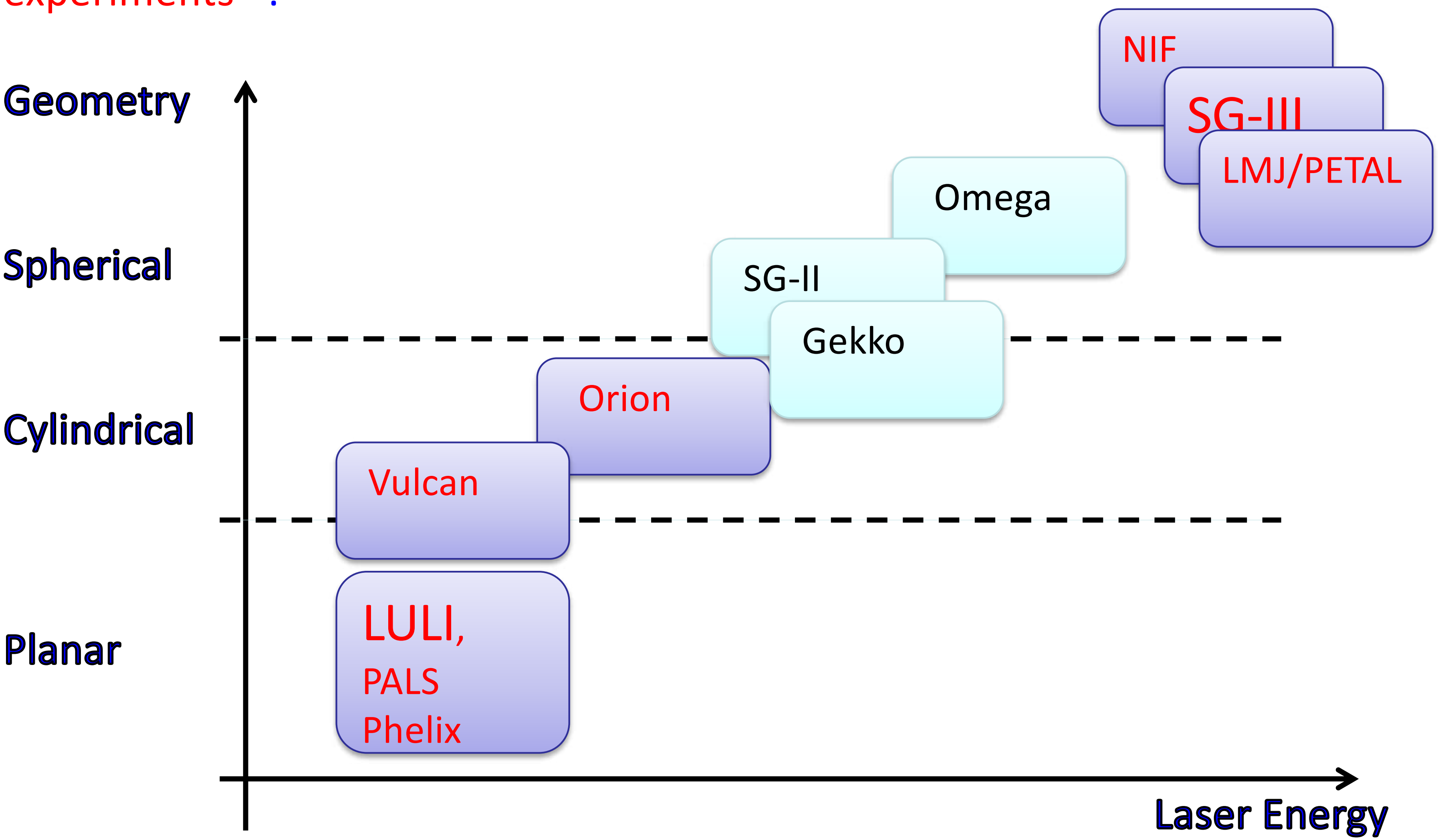
"Hydro" Issues:
- Smoothing
- Hydro instabilities
- Implosion
- Uniformity control for implosion

Demonstration of Shock Ignition

Demonstration of PDD

Elements of a Roadmap for shock ignition

How to approach the final goal of "Performing shock ignition demonstration experiments" ?



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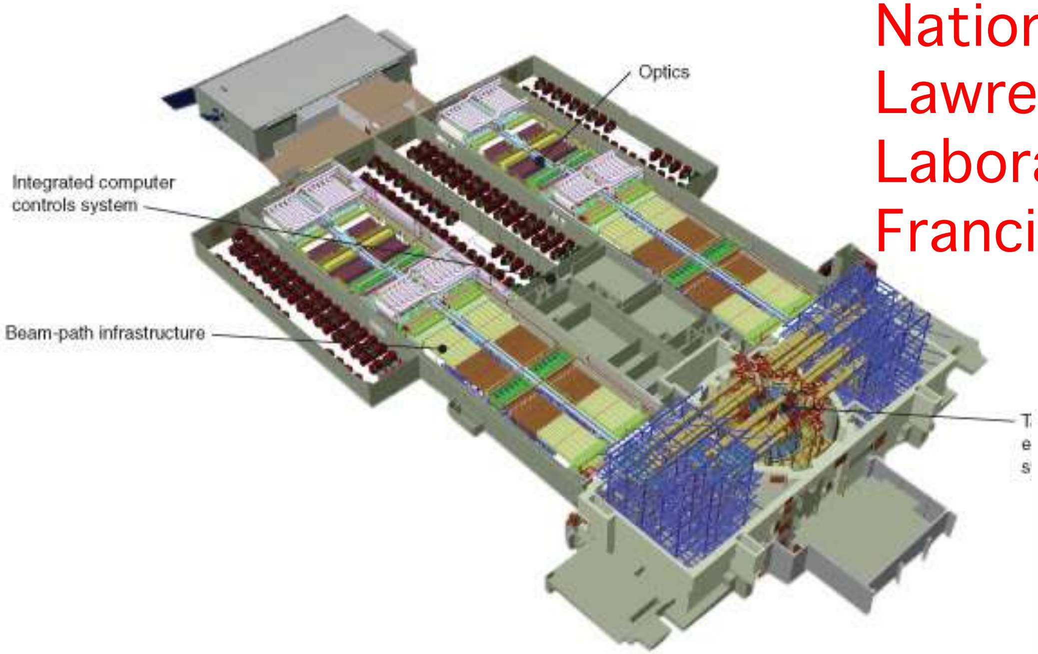
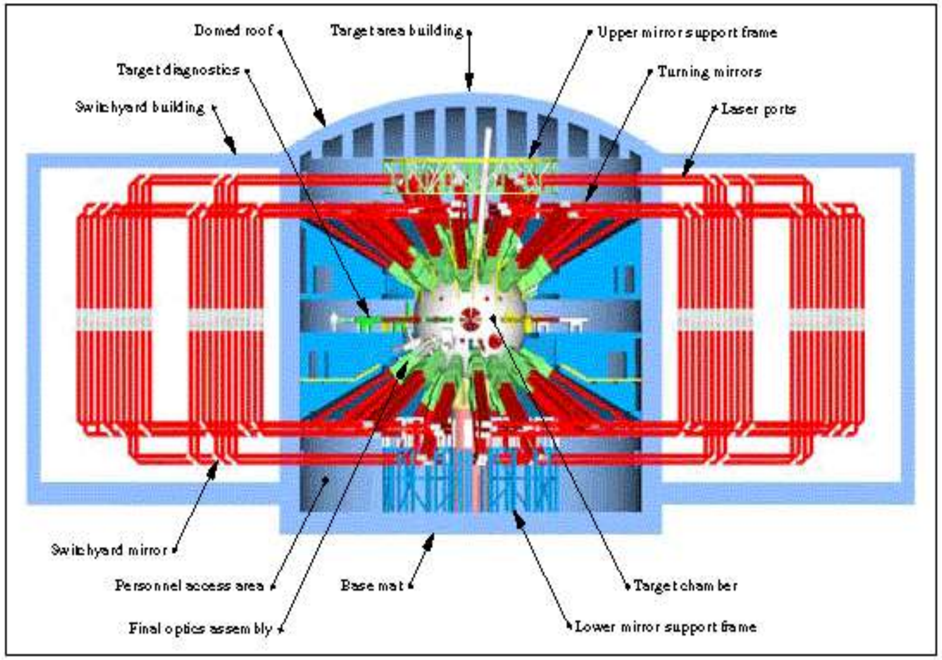
Big «Megajoule» lasers For inertial fusion

National Ignition Facility (NIF) Lawrence Livermore National Laboratory, California, near San Francisco



Laser Megajoule (LMJ) CEA CESTA, Le Barp, near Bordeaux



NIF: Installation

NIF: Interaction chamber

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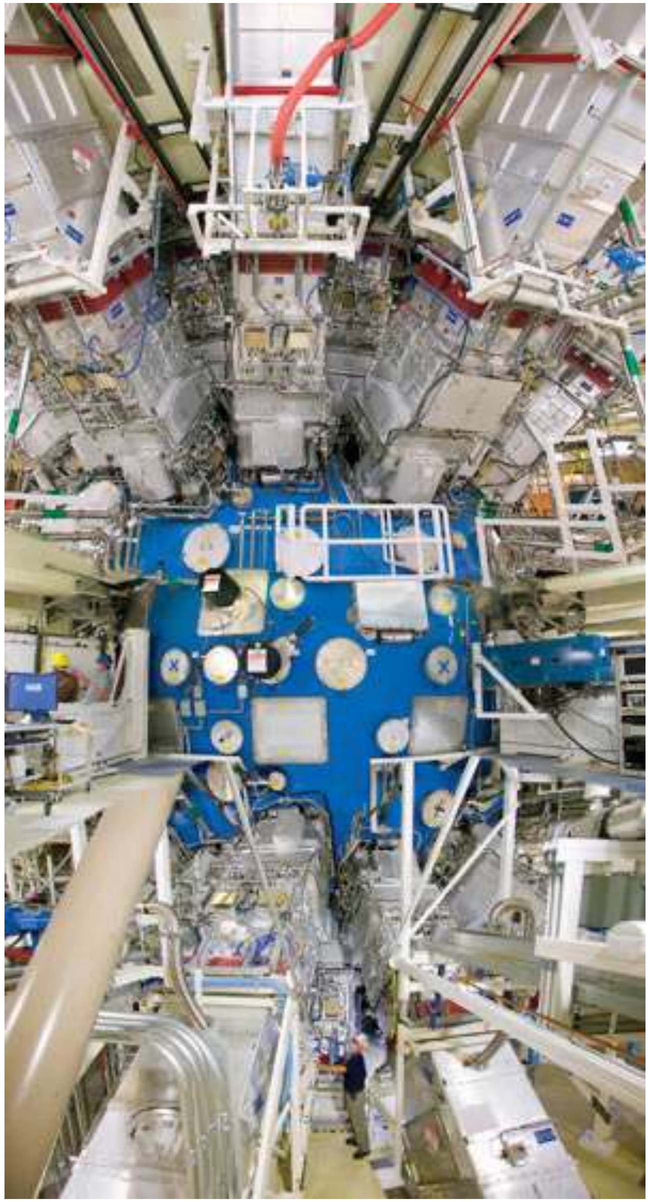
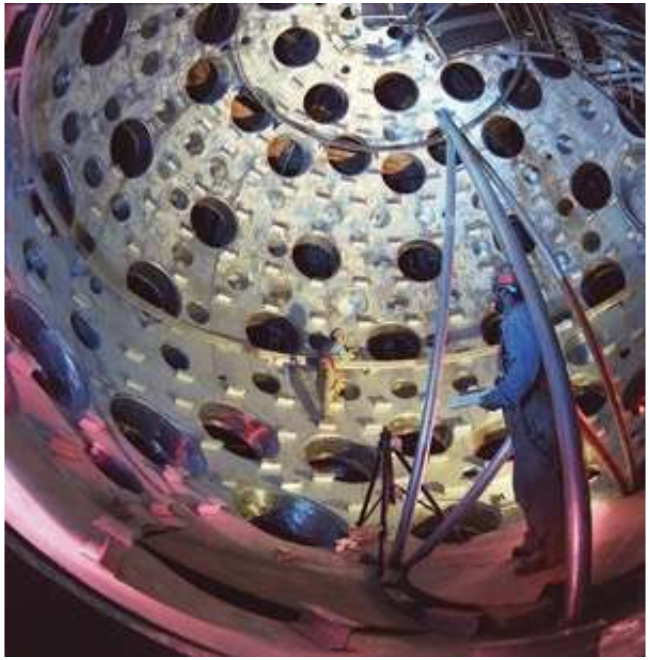
NIF: laser and chamber



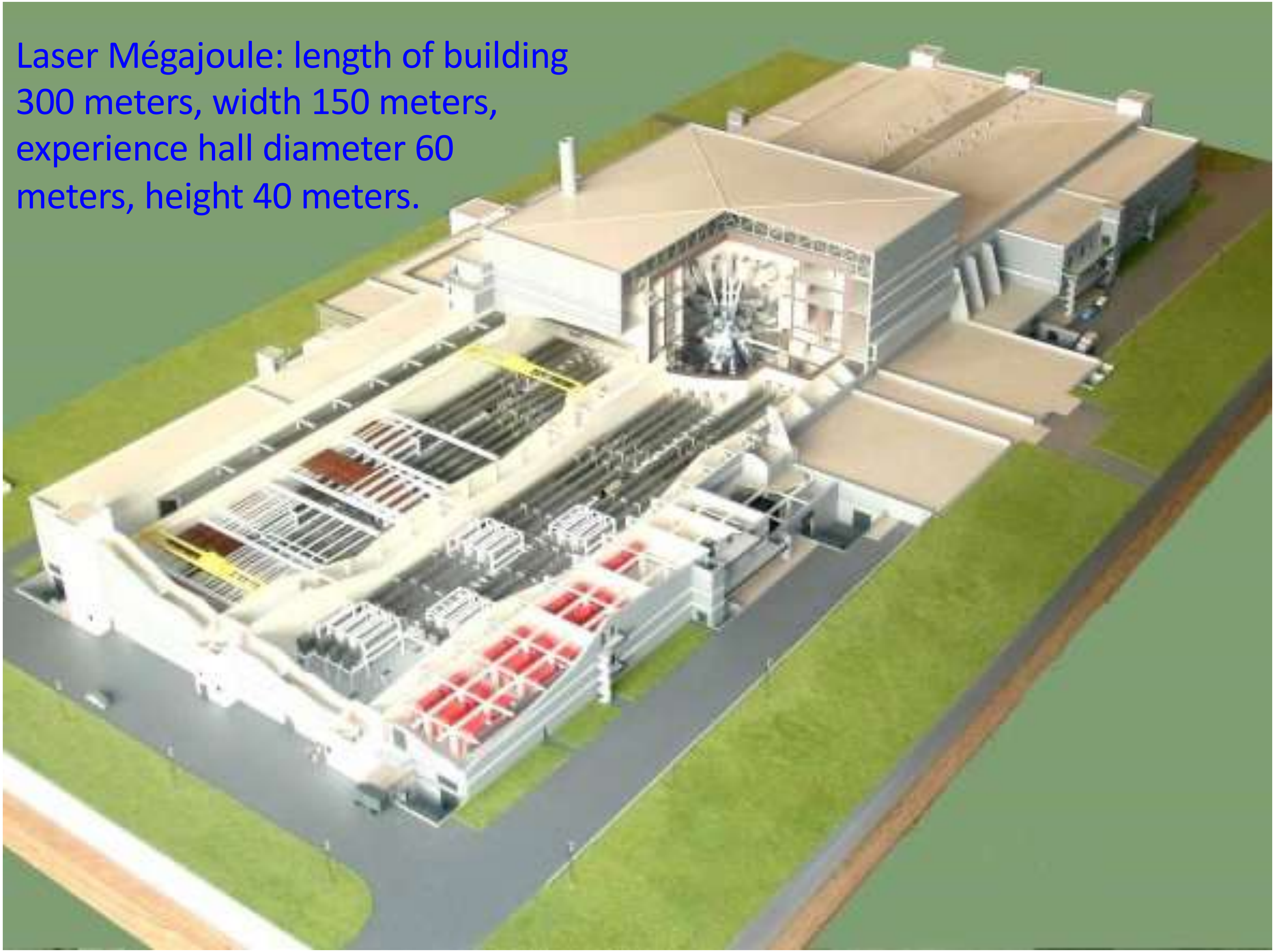


Diameter

≈ 10 m

Aluminum

Boron concrete


Laser Mégajoule: length of building
300 meters, width 150 meters,
experience hall diameter 60
meters, height 40 meters.

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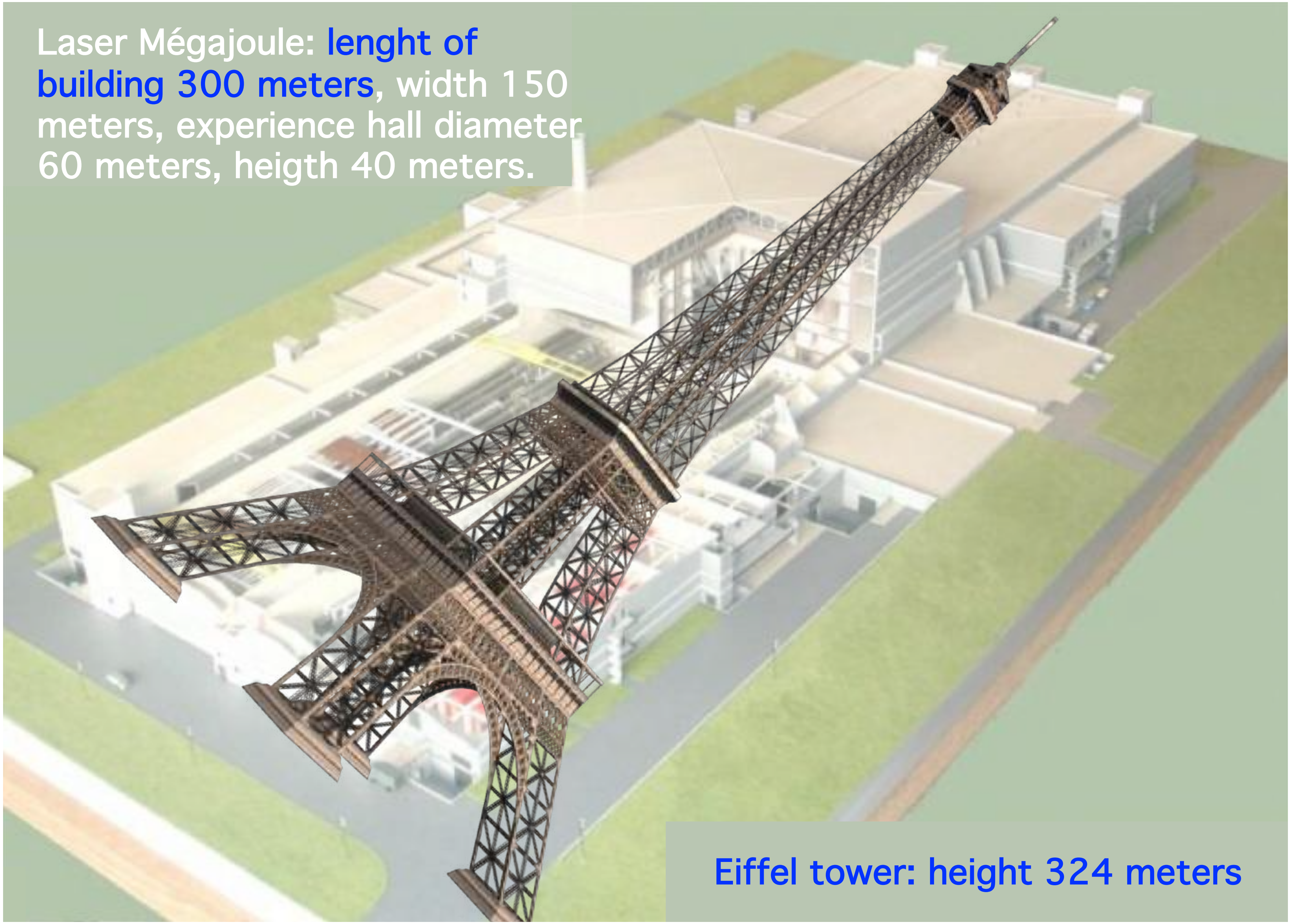
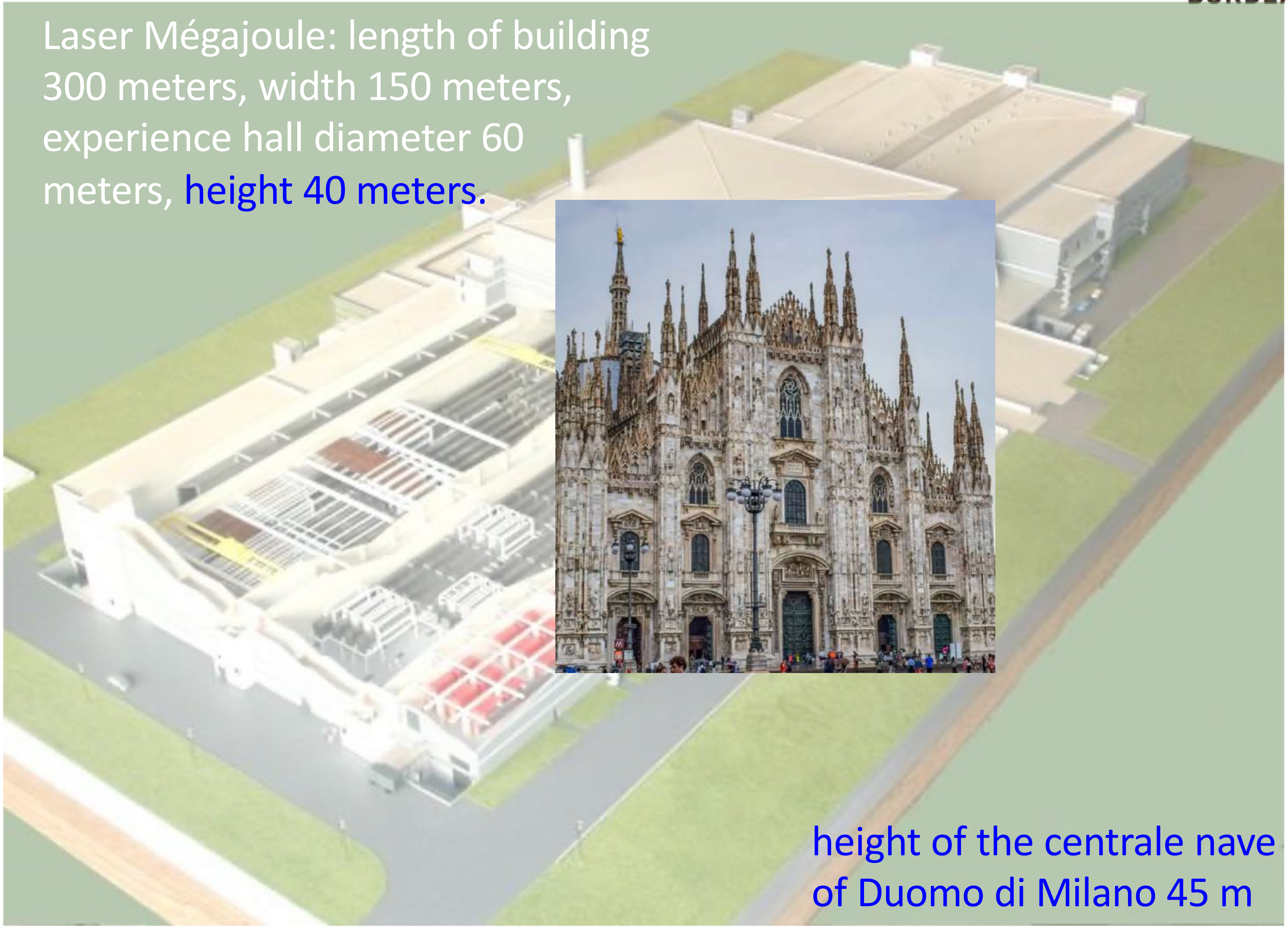




Laser Mégajoule: length of building 300 meters, width 150 meters, experience hall diameter 60 meters, height 40 meters.

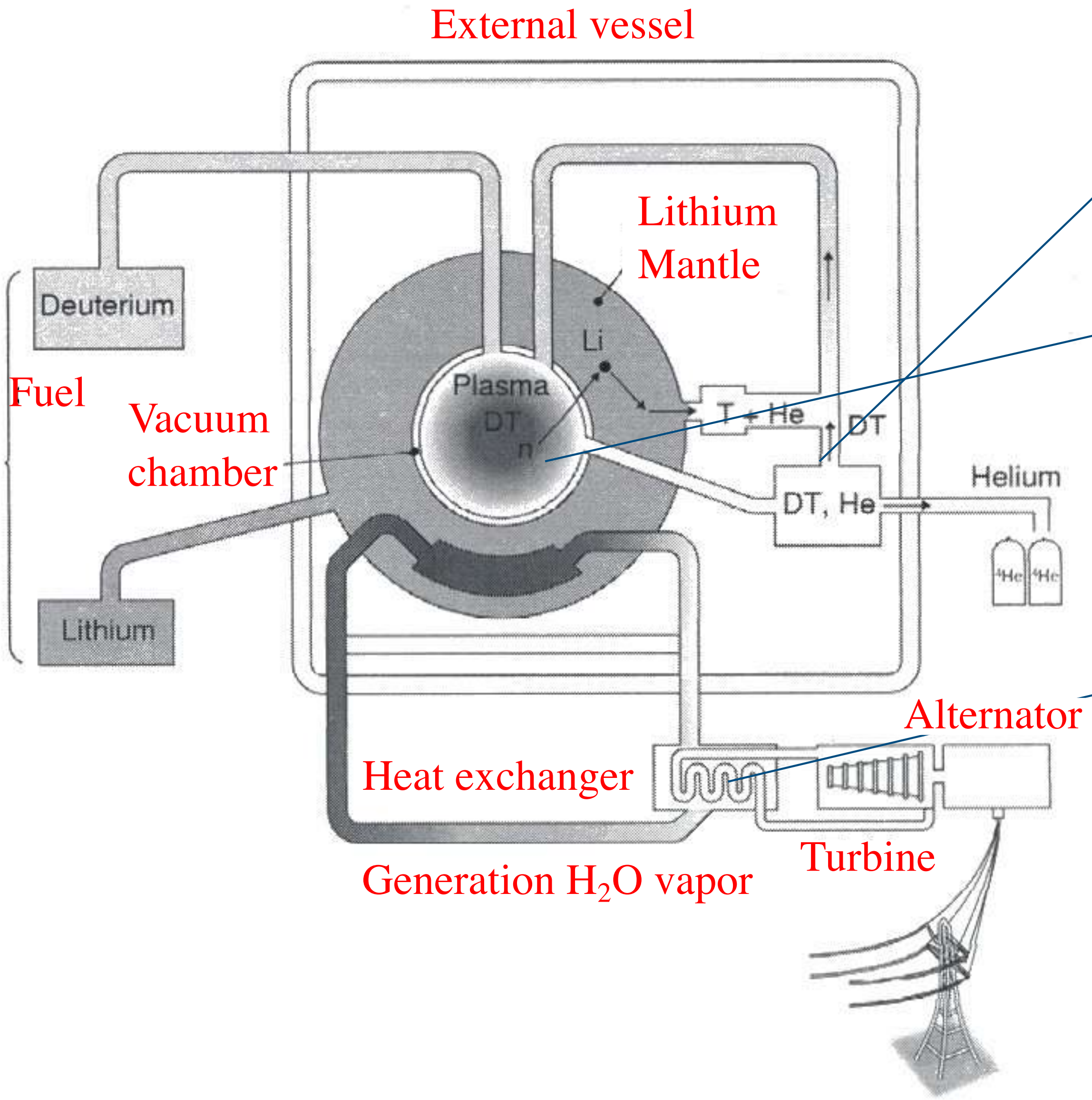
height of the centrale nave of Duomo di Milano 45 m

These are «single shot» machines !!

How to go from this to a fusion reactor?

Principle of a nuclear fusion reactor

Problem of Tritium breeding $\mathrm{n} + \mathrm{Li}^6 \longrightarrow \mathrm{He}^4(2.1\,\mathrm{MeV}) + \mathrm{T}(2.7\,\mathrm{MeV})$



Separation of unused fuel and He
Problems in T management

First wall:
- Stuctural and themo-mechanical problems
- Problems form neutron activation of materials

Liquid Metal exchanger?
- Problems simular to fast breeder fission reactors
- Probems of T diffisuion

VERY COMPLEX SYSTEM:
- Technology
- Radioprotection, Safety

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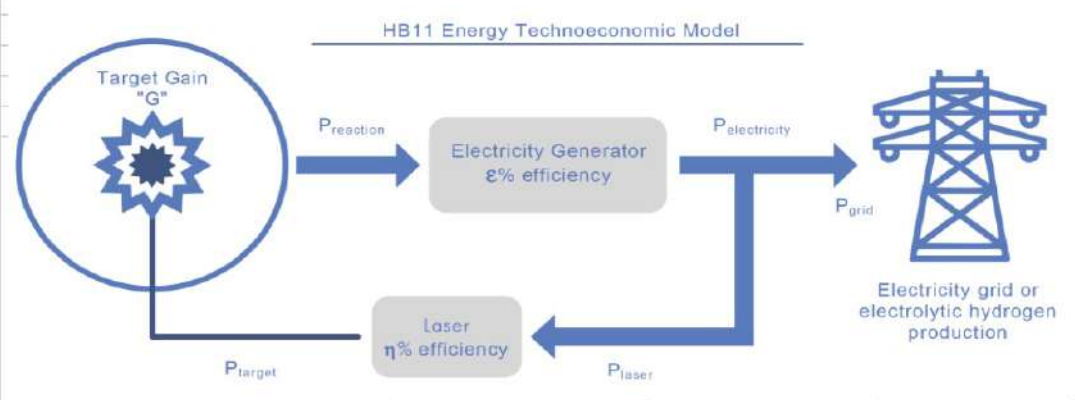
Requirements for Energy production

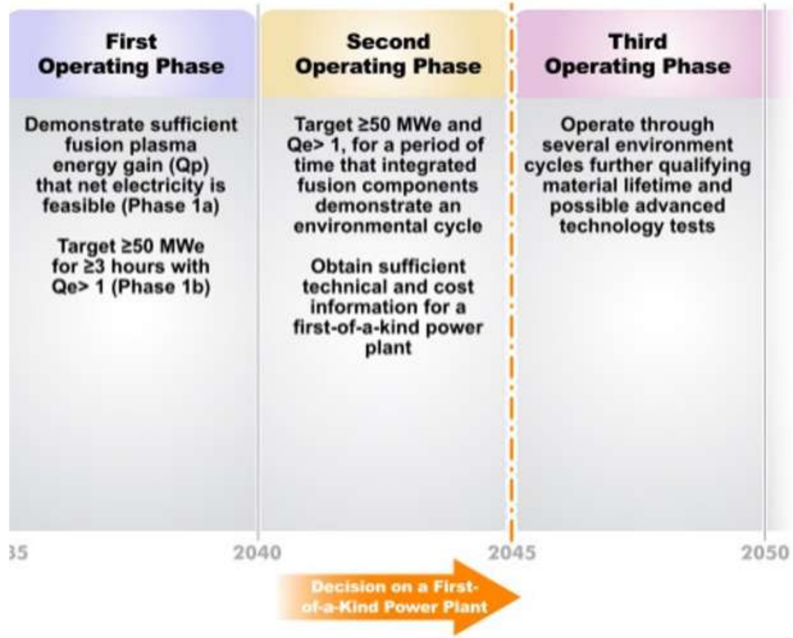


Parameters		
Laser efficiency	η	10%
Target Gain (scientific)	G	1000
Thermal energy efficiency	ε	30%

Energy Flow			
		Power plant (MW)	Per pulse (kJ)
Energy Input into laser	P_{laser}	6,9	10000
Energy output from laser	P_{target}	0,7	1000
Target output	$P_{reaction}$	689,7	1000000
Electricity output	$P_{electricity}$	206,9	300000
Power to grid	P_{grid}	200	290000

Energy System (e << $P_{electricity}$)		
Recirculating power fraction f =	1 / εηG	3%
Required target gain - G =	1/εηf	1000
Pulse required per second (Hz)		1

The guidelines from the U.S. National Academies of Sciences, Engineering, and Medicine (NASEM) to the U.S. Department of Energy, require the realization of a 50 MW Fusion Plant that produces electricity from fusion at the lowest possible capital cost ("Pilot Plant").



Gains of ≈ 1000 are theoretically possible

$$E_F(MJ) = 3.5\ \ 10^5\ \phi\ M_{DT}(g)$$

For M_{DT}= 1mg and ϕ = 100%, we get $E_F = 350\ MJ$. Then

$$G = E_F/E_{laser} = 175$$

Hence $G = 1000$ needs M_{DT}= 6 mg

Notice that NIF results ($E_F = 3.15$ MJ) mean that $\phi \approx 1$ % only !

Challenge 1: Lasers

- Today's laser efficiency (electricity to laser energy) is < 1%
- NIG, LMJ, SG-III can fire typically 1 shot/day
- They use 350 nm light (near UV, 3ω of Nd:glass lasers)

In order to think about a reactor, we need:

- Develop more efficient laser (≥ 10%)
- Develop high repetition frequency laser (10 Hz)
- Think about the possibility of using 2ω light (532 nm) to reduce damage to optics
- Develop broadband lasers (to kill parametric instabilities)

Possible by using diode pump lasers (efficiency up to 20% but not yet demonstrated with high energy systems)

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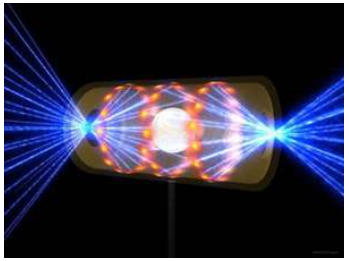
Challenge 2: Targets

- Today's cryogenic target costs ≈ 10000 \$.
- They require many days of preparation and characterization
- They need ≈ hour to be injected in the chamber and properly aligned

In order to think about a reactor, we need:

- Develop cheap technology (< 1\$/target)
- Develop capability of mass production of targets
- Develop techniques for target injection and alignment at ≈ 1 Hz
- Design of the target insertion and tracking system

All this does NOT seem possible with indirect drive !!
In principle Shock Ignition could allow using "full spheres" instead of shells



Challenge 3: Materials

- Problems of tritium breeding and handling system
- Problems of activation of materials. Identification of adequate materials for chamber construction and protection.
- Development of a laser-based neutron source. Testing materials in pulsed regime.
- Resolving security and safety issues.
- Development of remote handling techniques
- Cooling system and energy recovery system. Systems for material control, replacement and refurbishing

Many of these issues are common to MCF too (synergies possible)

The timeline to develop a direct-drive reactor is ~30 years

3 major steps of 10 years each: produce knowledge, construct machine, produce and analyze results for the technology transfer

Years 1-10 | Years 11-20 | Years 21-30

R&D | Pilot IFE reactor | DEMO-IFE reactor

For comparison:

NIF high gain experiments starting in 2028

LMJ full operation at 1.3 MJ expected in 2027

First plasma in ITER expected not before ~2025

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$$ {}^{2}_{1}D + {}^{3}_{1}T \rightarrow \alpha + {}^{1}_{0}n + 17.6 \text{ MeV} $$

Hydrogen-Boron Fusion

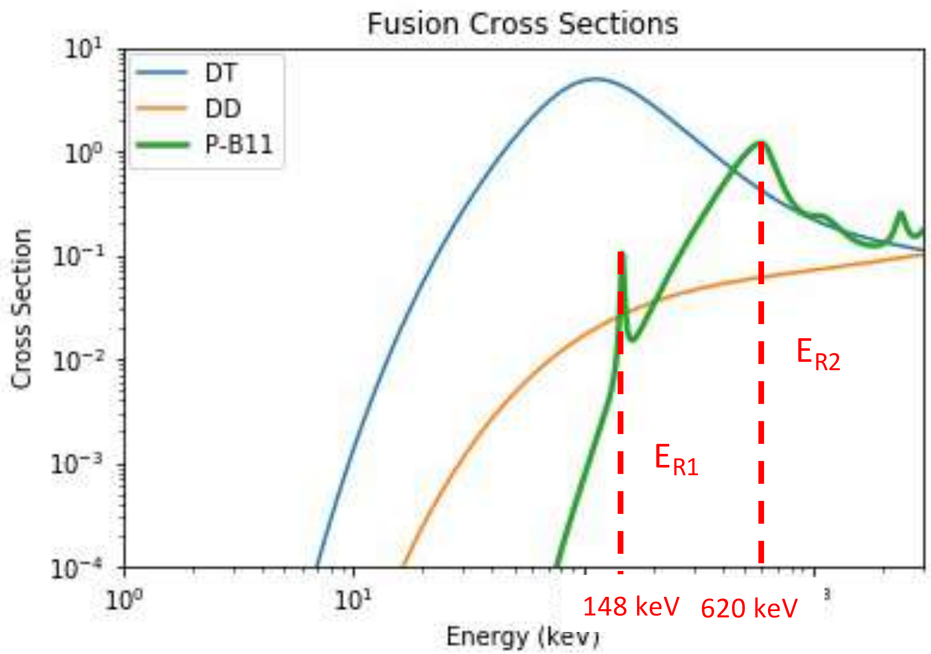
CHALLENGES

- ✓ Fuel cycle (tritium breeding)
- ✓ Material activation due to neutrons
- ✓ Economy of cost

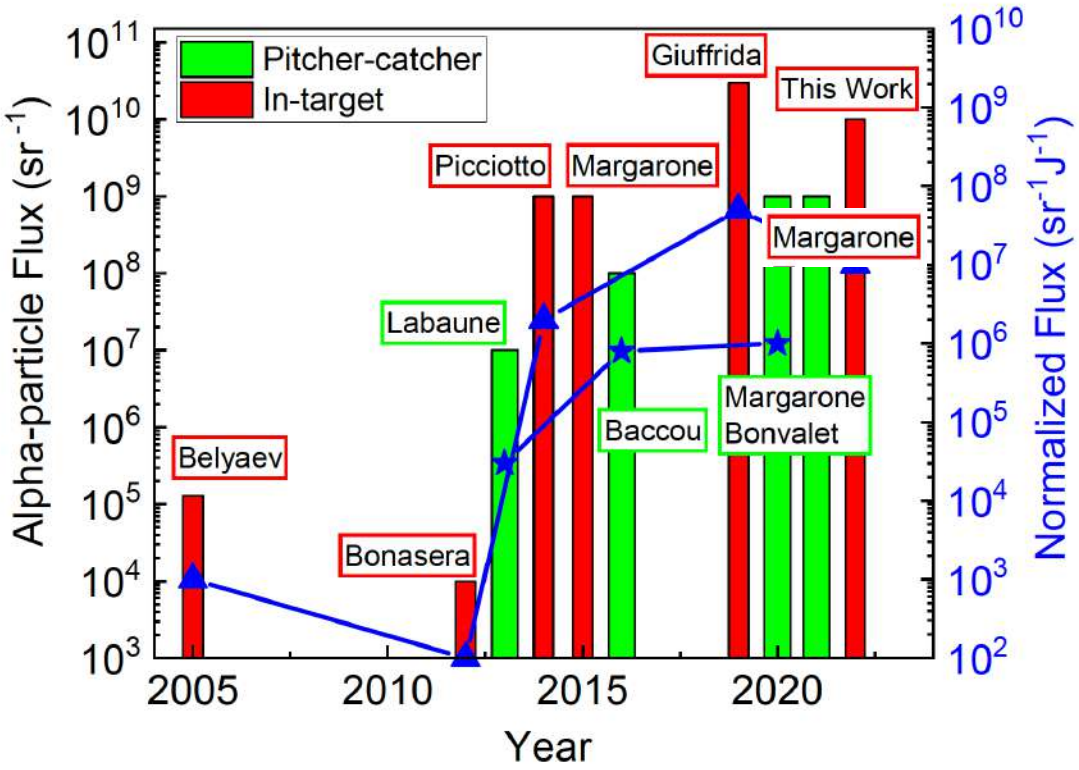
First studies by Oliphant & Rutherford,
L. Proc. R. Soc. London A 141, 259 (1933)

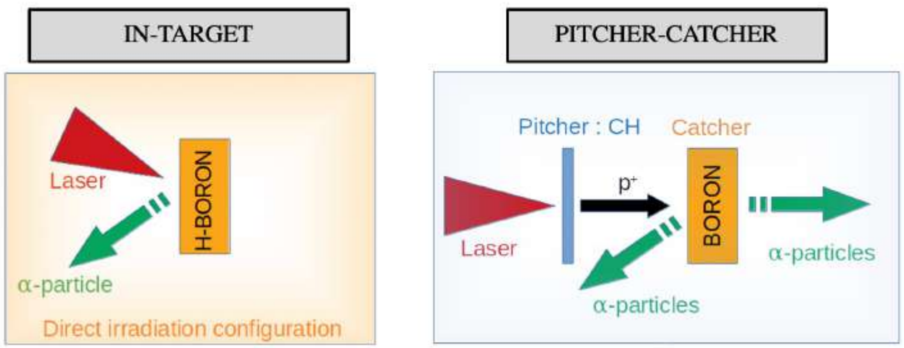
$$ p + {}^{11}B \rightarrow \alpha + {}^{8}Be \rightarrow \alpha + (\alpha + \alpha) + 8.7 \text{ MeV} $$

- ✓ Aneutronic Energy Production (ecologic)
- ✓ Relies on stable fuel elements only (no need to ”create” short-living elements like tritium, no need to handle with fuel radioactivity`)
- ✓ Does not need cryogenic technology (boron in solid state at room temperature)
- ✓ Two main resonances: E_{R1} = 148 keV; E_{R2} = 620 keV



Hydrogen-Boron Fusion





- V.S.Belyaev, et al. Phys. Rev. E 72, 026406 (2005)
- A.Bonasera, et al. Fission and Properties of Neutron-Rich Nuclei" (Sanibel Island, USA: World Scientific) 503–507 (2008)
- C.Labaune, et al. Nat. Commun. 4, 2506 (2013)
- A.Picciotto, et al. Physical Review X 4, 031030 (2014)
- C. Baccou, Rev. Sci. Instrum 86, 083307 (2015)
- L.Giuffrida, et al. Phys. Rev. E 101, 013204 (2020)
- D.Margarone, et al. Frontiers In Physics, 8, 343 (2020)
- J. Bonvalet et al. Phys. Rev. E 103, 053202 (2021)
- D. Margarone et al., Applied Sciences 12, 1444 (2022)

Hydrogen-Boron Fusion

These results (and others) have also stimulated interest from companies and start ups

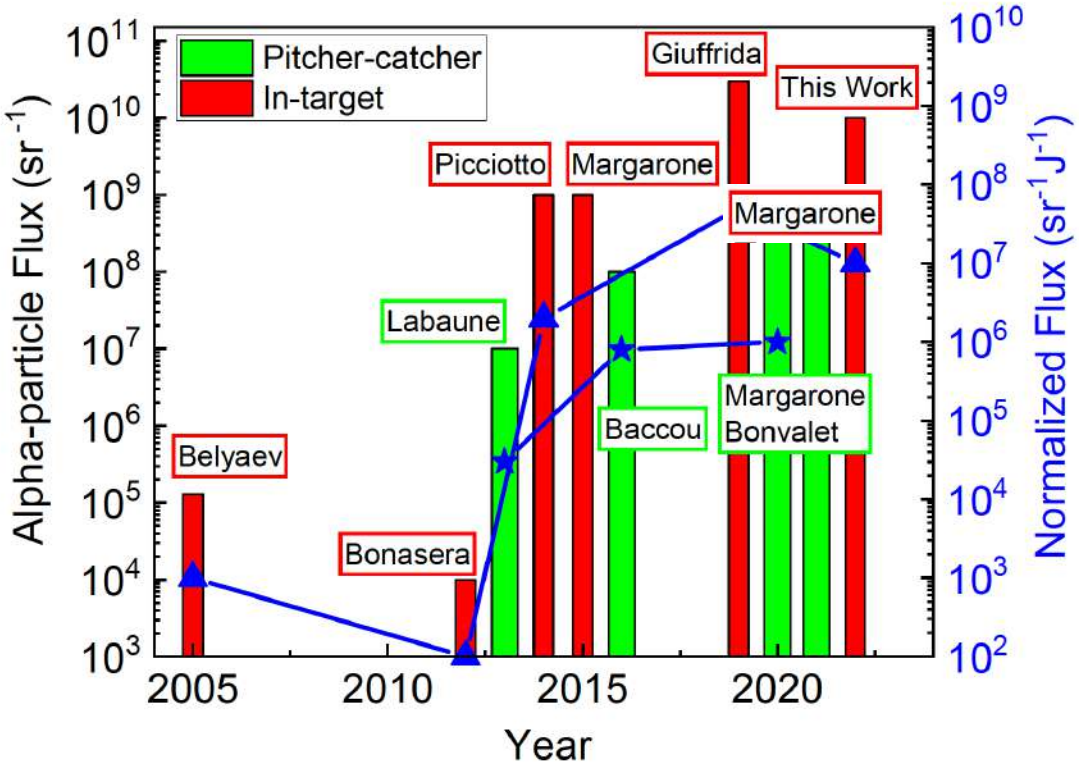
Hb11 Energy

TAE

ENN

Marvel Fusion

Hydrogen-Boron Fusion



Huge increase in α-particle yield in the last 20 years, from $\approx 10^5$ α/shot to $\approx 10^{11}$ α/shot

Increase about 6 orders of magnitude !!

However…

Today's best results $\approx 10^{11}$ α/shot @ 1 kJ

But breakeven (G=1) means $\approx 3.5\ 10^{15}$ α/shot @ 1 kJ

We still miss > 4 orders of magnitude and the physics of «beam fusion» does not scale to ignition

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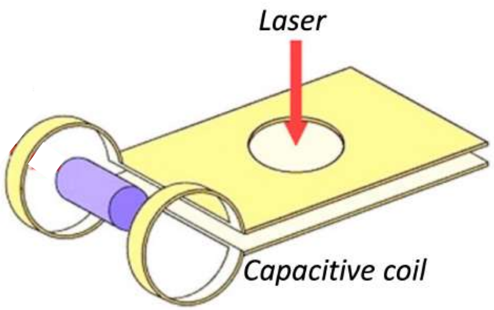
HB11 FUSION – LASER INDUCED MAGNETIC FIELD

MAGNETIC CONFINEMENT

LASER AND CAPACITIVE COIL TARGET

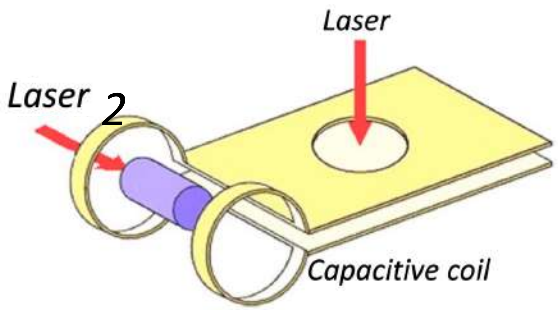


Magnetic field confine protons and alpha particles within the target

S. FUJIOKA et al. *Nat. Sci. Rep. 3*, 1170 (2013)

LASER ION ACCELERATION

OF HYDROGEN VIA ps LASER PULSES

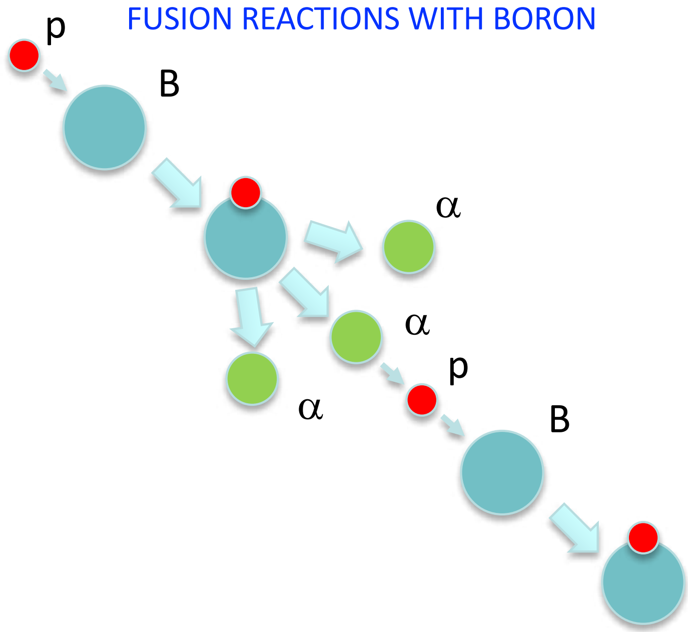


Non-thermal acceleration of protons (and boron)

P. LALOUSIS, H. Hora et. al. *J. Fusion Energy* 34, 62 (2015)

AVALANCHE REACTION

α-PARTCLES KICK HYDROGENS IN THE TARGET ALLOWING THEM TO PRODUCE ADDITIONAL FUSION REACTIONS WITH BORON



H. HORA H., G. MOUROU, et al. *Laser Part. Beams*. 33, 607 (2015)

H. Hora, G. Mourou, et al. *Laser Part. Beams*. 33, 607 (2015)

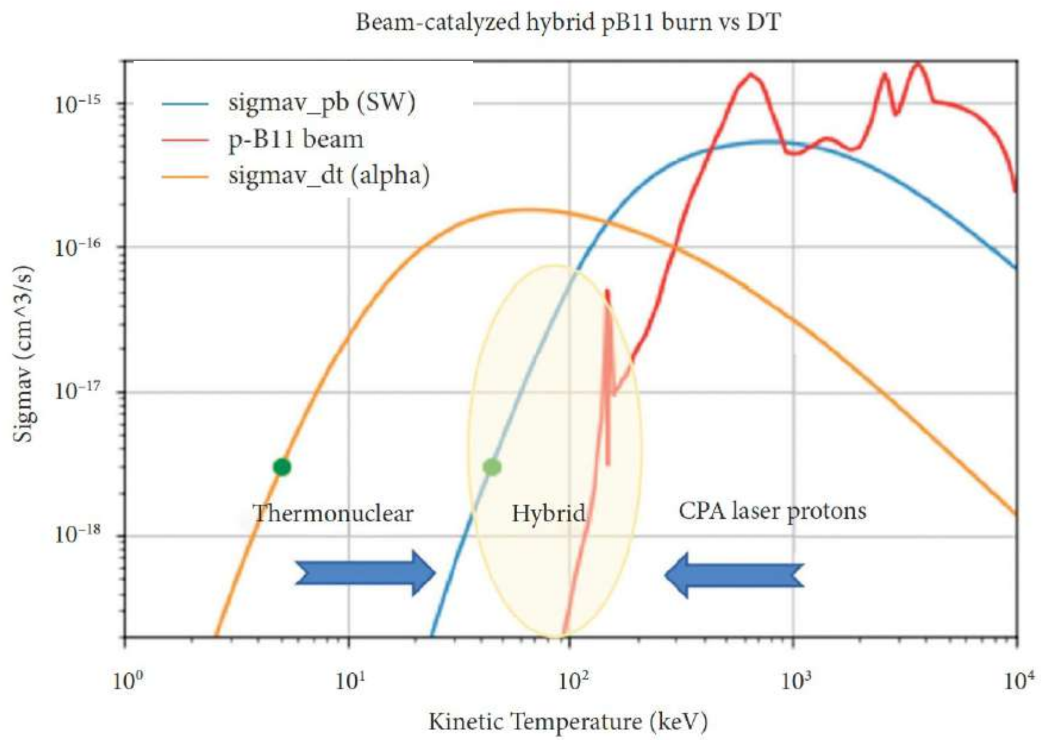
HB11 ENERGY LASER BORON FUSION

HB11 FUSION – HYBRID APPROACH

The hybrid approach proposes to irradiate an imploded hydrogen boron target with a beam of laser-accelerated protons

- ✓ Implosion dramatically increases density (hence reaction rate) and heat the fuel (although at temperatures not sufficient to trigger HB fusion)
- ✓ An external laser-driven proton beam produced by TNSA with a ps multi-kJ laser beam begins the ignition of the fuel

The approch is similar to the classical proton-driven fast ignition approach. The difference is that in proton-driven fast ignition the proton beam is just a way to heat the DT fuel, while here protons are directly responsible of the fusion reactions.



Thomas A. Mehlhorn et al. , *Laser and Particle Beams*, Article ID 2355629, 16p. (2022)

Need to get $T_e/T_i < 1$ and $n_H/n_B > 1$

Relies on degeneracy effects to increase proton range

Hydrogen-Boron Fusion

Interesting and worth to be investigated….

But we do not yet have a full understanding of the involved physics. Hence still a long way to go…

COST Action **CA21128** PROBONO **"PROton BOron Nuclear fusion: from energy production to medical applicatiOns"**

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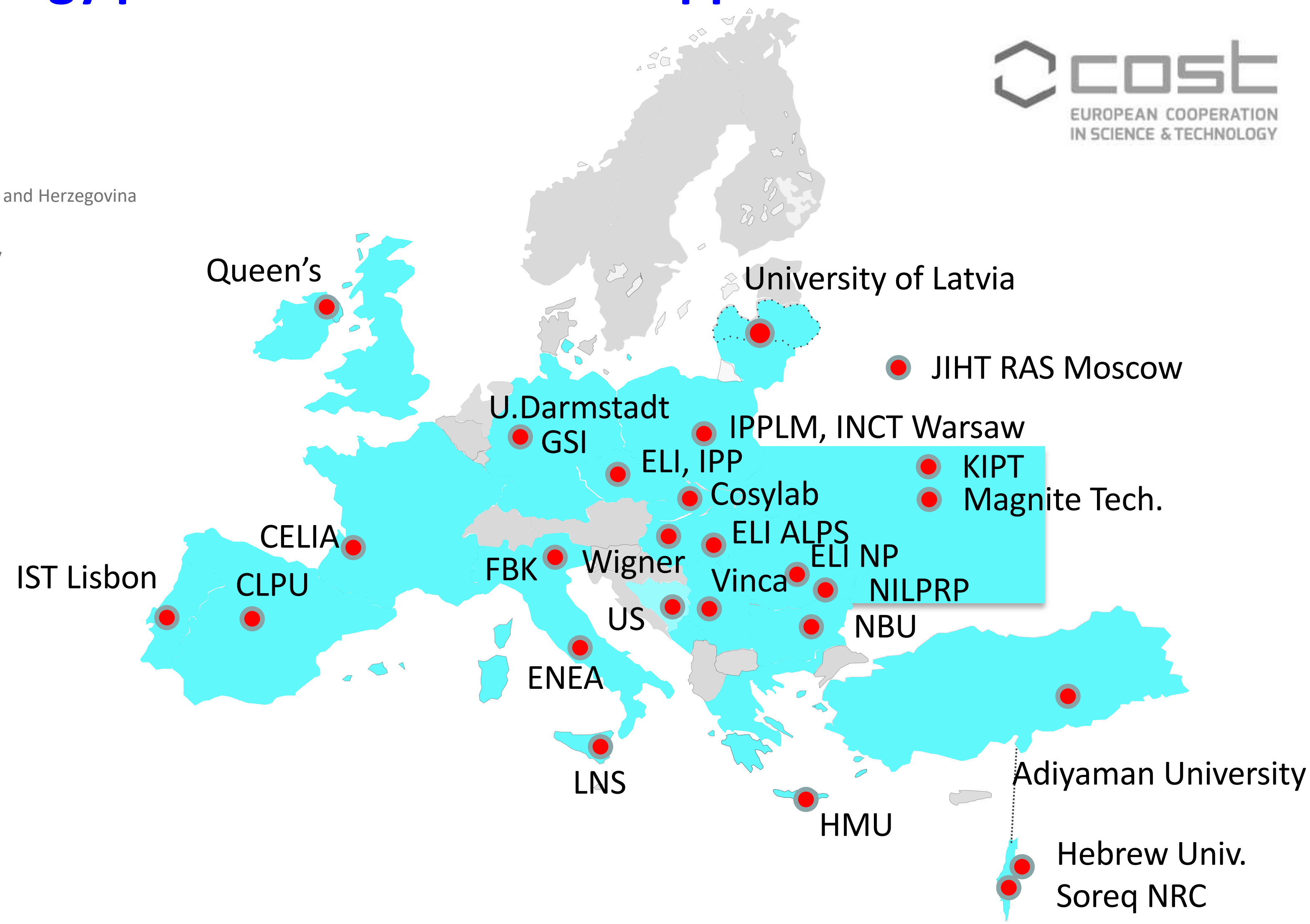
1 Cooperating member

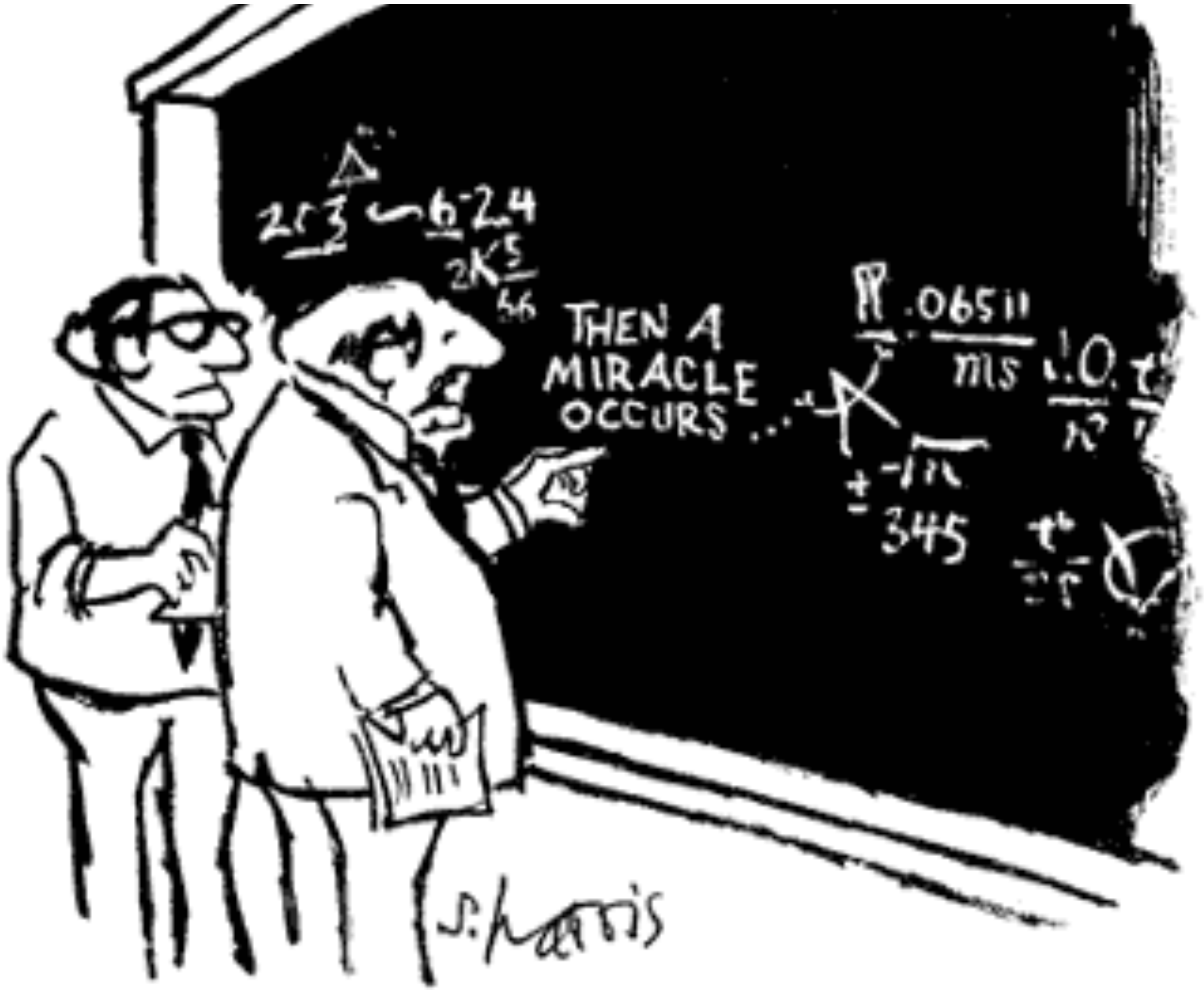
Israel



Conclusions:

Fusion, we are entering a new era

- Commitment to fusion via ITER, NIF, LMJ (multi-€B investment)
- Demonstration of net energy production from laser fusion possible in a few years
- These are fundamental step-changes with huge implications for our science and energy programmes
- Need to define a strategic way forward…



"I think you should be more explicit here in step two."

Thank you for your attention !