Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

Nuclear Fusion by Inertial Confinement Scheme using lasers

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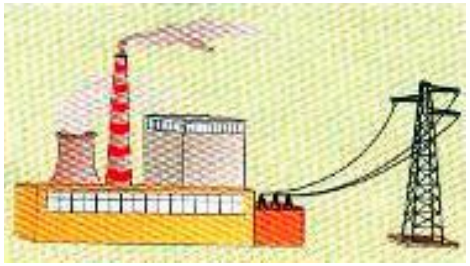
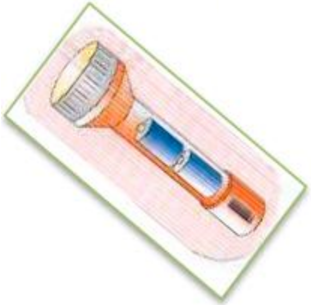
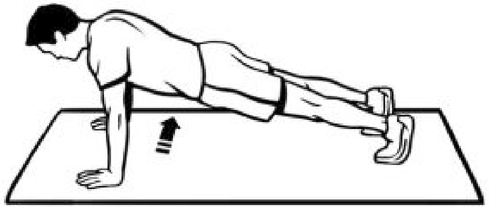
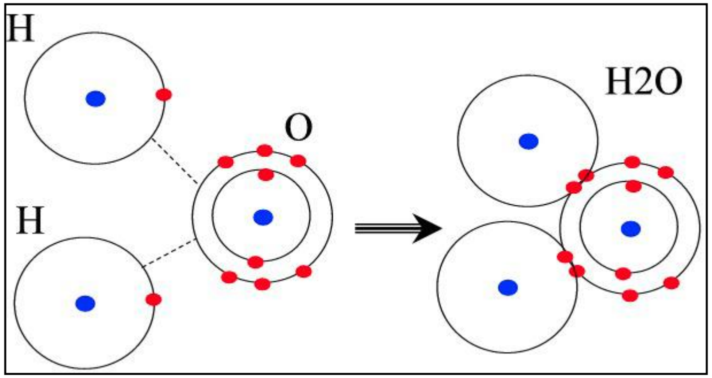
Chemical energy

- **In everyday life we use energy developed in chemical reactions with the formation or breaking of atomic or molecular bonds.**

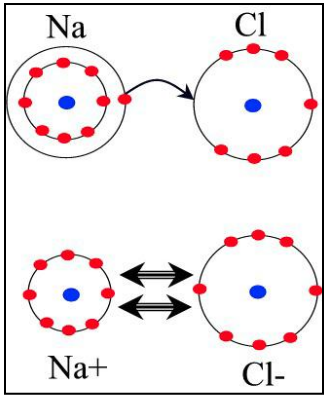





- **Examples of chemical bonds**

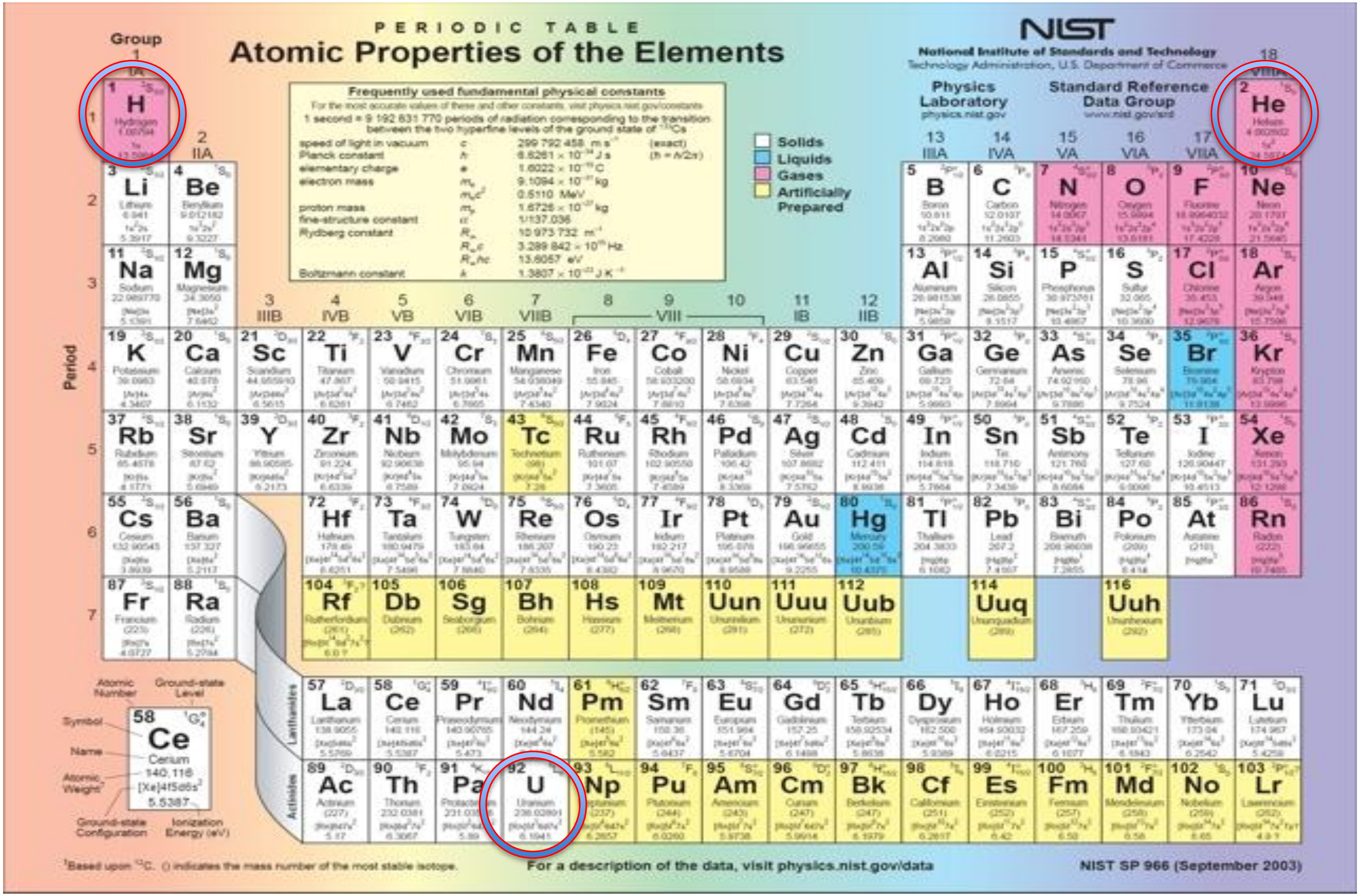


Covalent



Ionic

Periodic table of Elements



Nuclear Energy

- **The total potential energy of a nucleus is significantly greater than the energy that binds electrons to the nucleus.**

- **Therefore, the energy released in most nuclear reactions is significantly greater than that of chemical reactions.**

- **To give an idea of the orders of magnitude, the binding energy of the electron to the hydrogen nucleus is 13.6 eV while the energy released by the simplest nuclear fusion reaction (Deuterium – Tritium) is equal to 17.6 MeV, that is, more than a million times the first.**

- **With one gram of Deuterium and Tritium it is estimated that the energy developed by ~10 tons of coal could be produced.**

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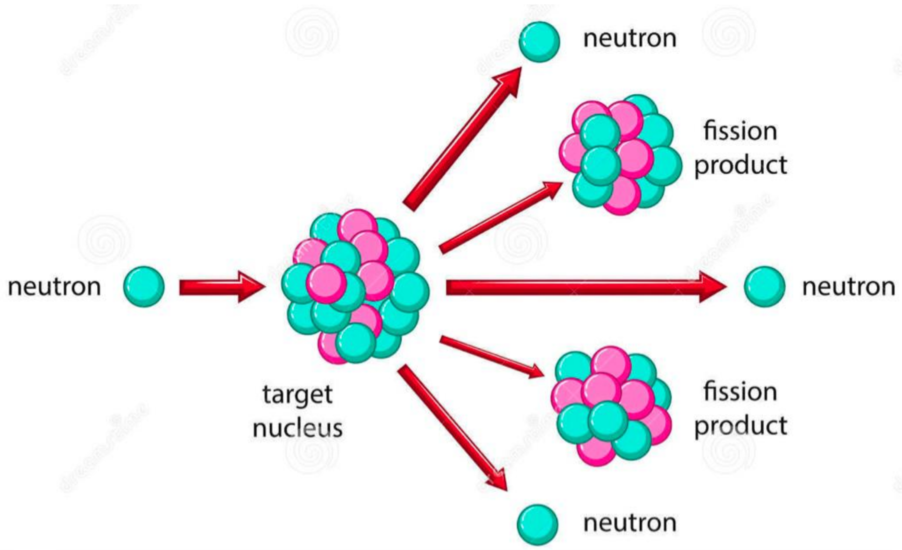
Nuclear Energy: Fission

Heavy nuclei split into nuclei of lower atomic number

Example of Fission Reaction of Uranium 235

$^{235}U + n \rightarrow {}^{236}U$ "unstable" $\rightarrow {}^{141}Ba + {}^{92}Kr + 3\ n + 200$ MeV



The total energy released by the fission of 1 g ^{235}U ⇔ $8*10^{10}$ Joule ≈ $2*10^{7}$ kcal ⇔ 3 tons of anthracite.

The reaction, triggered by spontaneously produced neutrons, is then sustained by the neutrons produced (suitably slowed down)

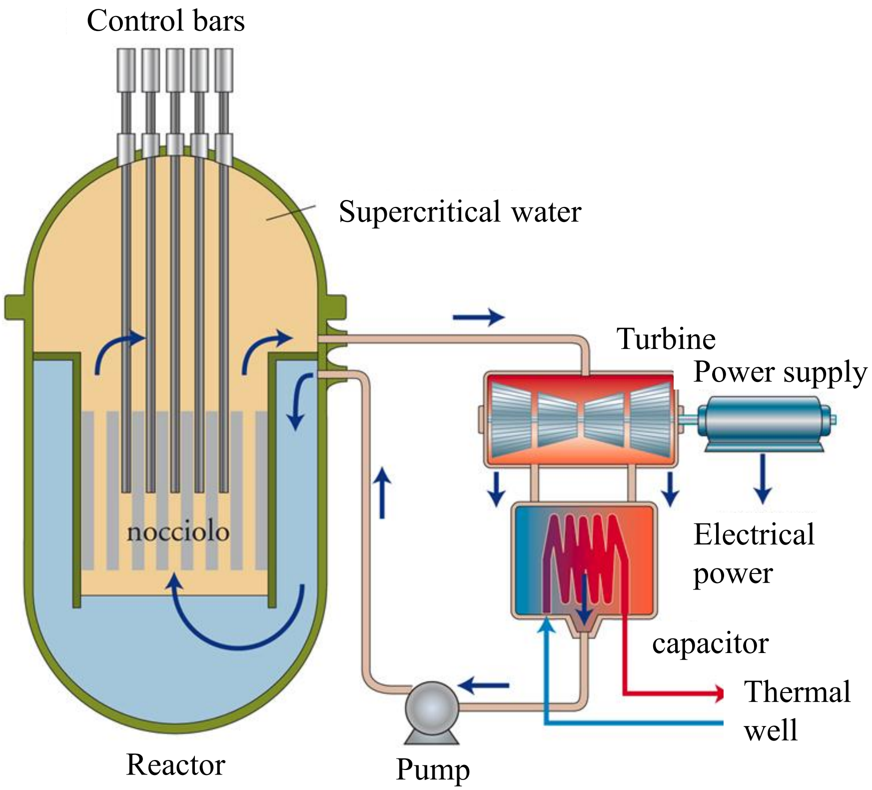
Nuclear Energy: Fission

Advantages

- Relatively simple and well-known technology
- Low atmospheric releases

Disadvantages

- Production of radioactive waste
- Possibility of loss of control
- Limited reserves of low-cost U
- Possibility of producing fissile material for war purposes (^{239}Pu from ^{238}U)



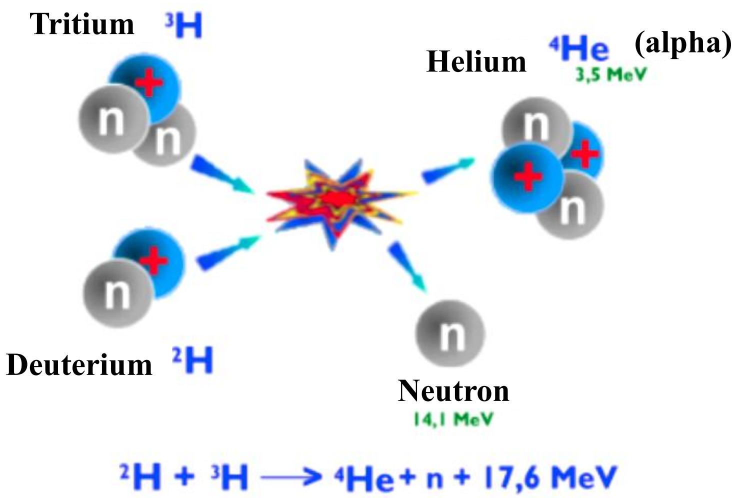
Nuclear Fission Power Plant

Nuclear Energy: Fusion

Nuclei of low atomic number join together to form a nucleus of higher atomic number

The most promising reaction for a reactor:

D + T $\rightarrow$ ^{4}He (3,5 MeV) + n (14,1 MeV)



Fusion reactions are hindered by Coulomb repulsion between nuclei. The energy at the center of mass must exceed a high threshold.

Nuclear Energy: Fusion

Reaction	σ (10 keV) (barn)	σ (100 keV) (barn)	σ_{max} (barn)	ϵ_{max} (keV)
$D + T \rightarrow \alpha + n$	2.72×10^{-2}	3.43	5.0	64
$D + D \rightarrow T + p$	2.81×10^{-4}	3.3×10^{-2}	0.096	1250
$D + D \rightarrow {}^3He + n$	2.78×10^{-4}	3.7×10^{-2}	0.11	1750
$T + T \rightarrow \alpha + 2n$	7.90×10^{-4}	3.4×10^{-2}	0.16	1000
$D + {}^3He \rightarrow \alpha + p$	2.2×10^{-7}	0.1	0.9	250
$p + {}^6Li \rightarrow \alpha + {}^3He$	6×10^{-10}	7×10^{-3}	0.22	1500
$p + {}^{11}B \rightarrow 3\alpha$	(4.6×10^{-17})	3×10^{-4}	1.2	550
$p + p \rightarrow D + e^+ + \nu$	(3.6×10^{-26})	(4.4×10^{-25})		
$p + {}^{12}C \rightarrow {}^{13}N + \gamma$	(1.9×10^{-26})	2.0×10^{-10}	1.0×10^{-4}	400
${}^{12}C + {}^{12}C$ (all branches)		(5.0×10^{-103})		

S. Atzeni and **J. Meyer-ter-Vehn,** The Physics of Inertial Fusion, Clarendon Press, 2009

Nuclear Energy: Fusion

Advantages

- Nearly unlimited reserves
- Low fuel cost
- No radioactive waste
- No CO_2
- Intrinsically safe
- Non-proliferating

Fuel required to produce 1 GW/year		
Conventional	**Fission**	**Fusion**
Carbon ≈ $3*10^6$ tonn	UO_2 ≈ 24 tonn (≈ $1m^3$) 3% ^{235}U = 0.72 tonn ^{235}U	H_20 ≈ $2*10^4$ tonn = D-T≈ 0.34 tonn
CO2 ≈ $9*10^6$ tonn	$^{141}Ba + ^{93}Kr$	released He

Disadvantages

- Complexity of physical systems to be used
- Technological difficulties

High probability reaction conditions are needed
This can occur in a system of particles at very high temperatures

A temperature <u>T ≈ 100 million degrees</u> is required

Reactions of Nuclear Fusion in plasmas

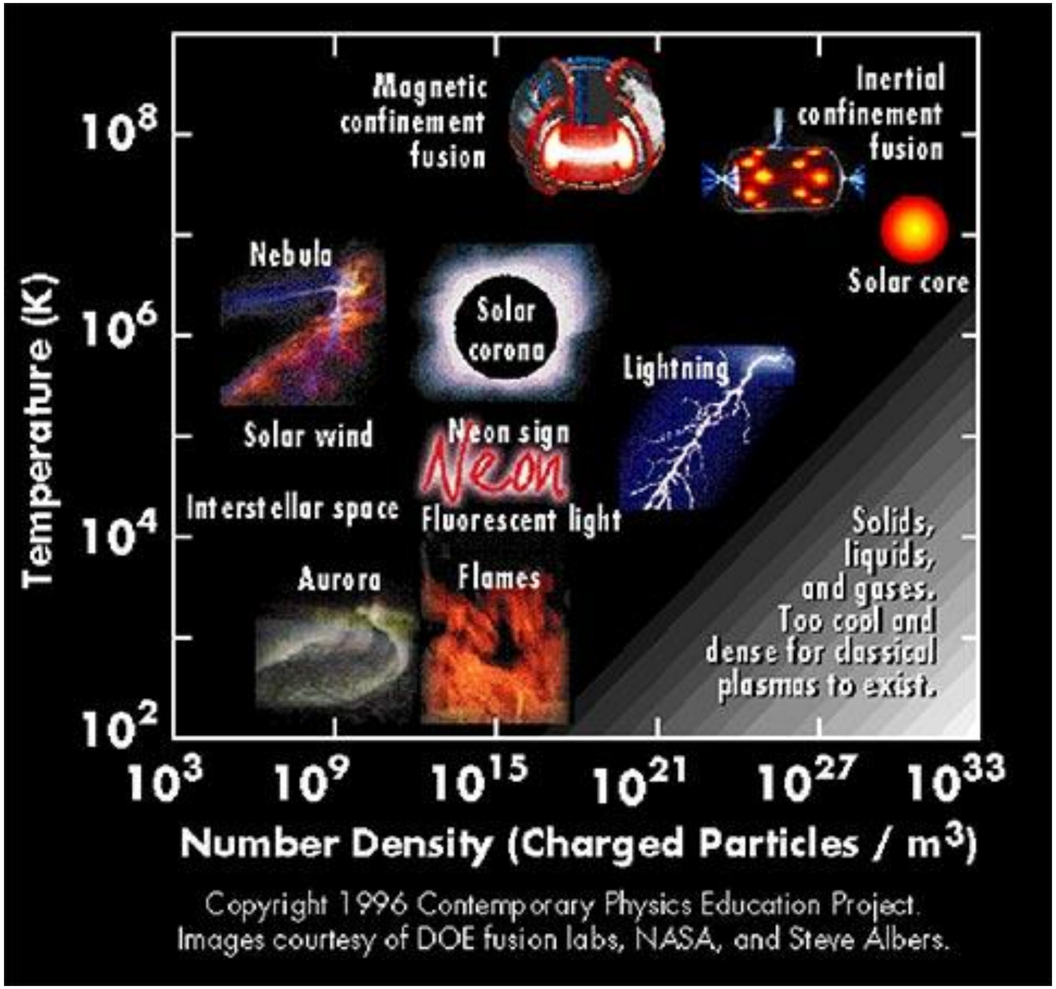
eV

10^4

10^2

1

10^{-2}



1 **eV** = 11605 ° K

Plasma confinement

Magnetic Confinement

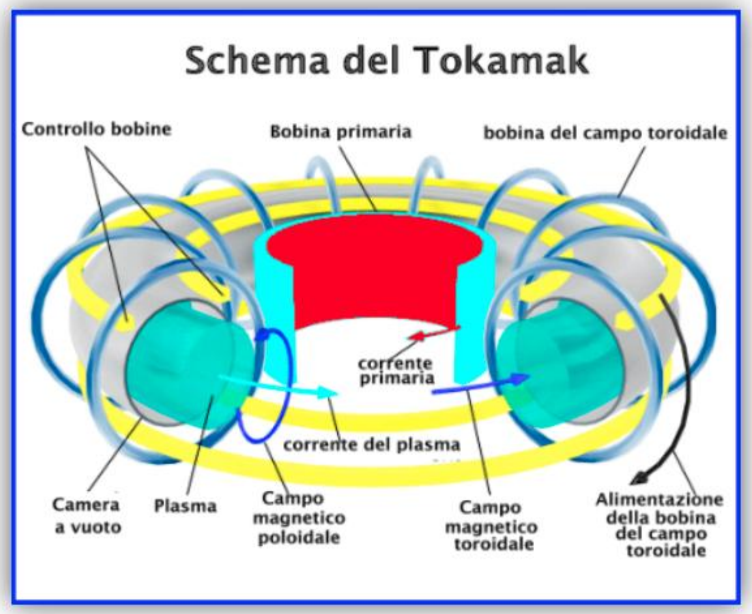
B ~10^4 Gauss

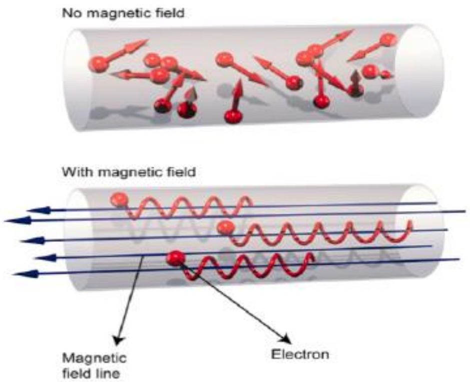
Heating

Interactions with walls

Instabilities

Disruptions





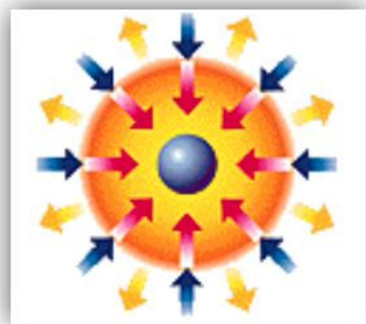
Inertial Confinement

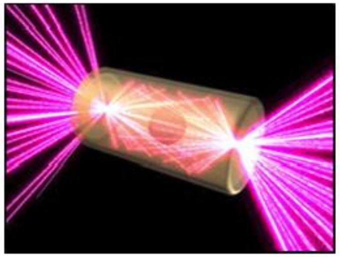
Compression

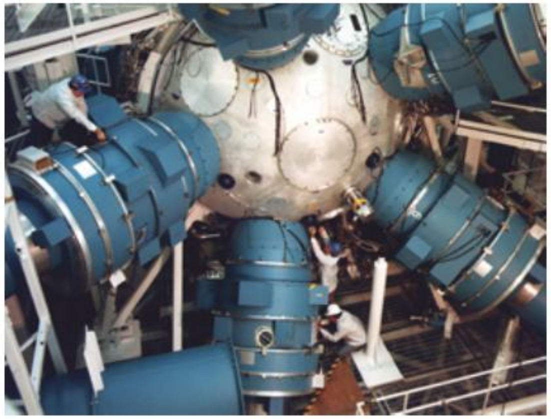
Driver at high power

Target realization

instabilities







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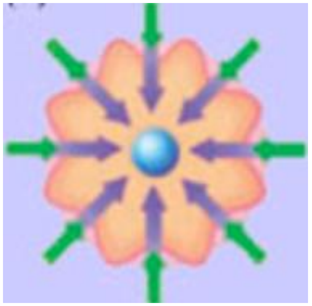
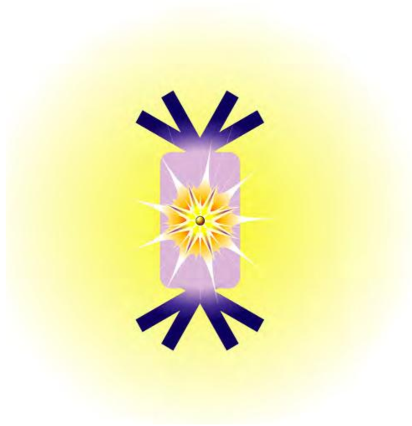
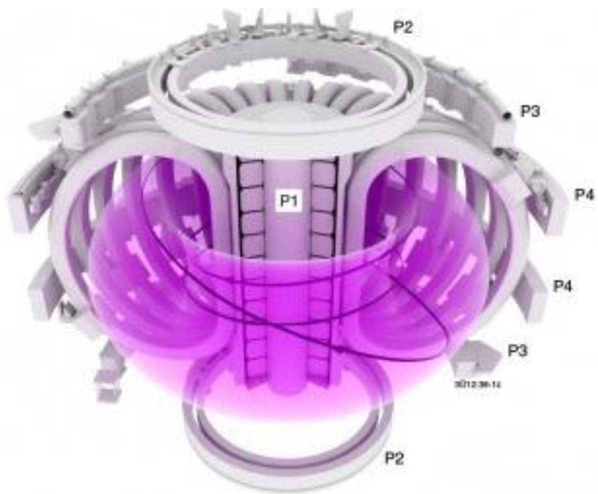
Inertial vs. Magnetic Confinement

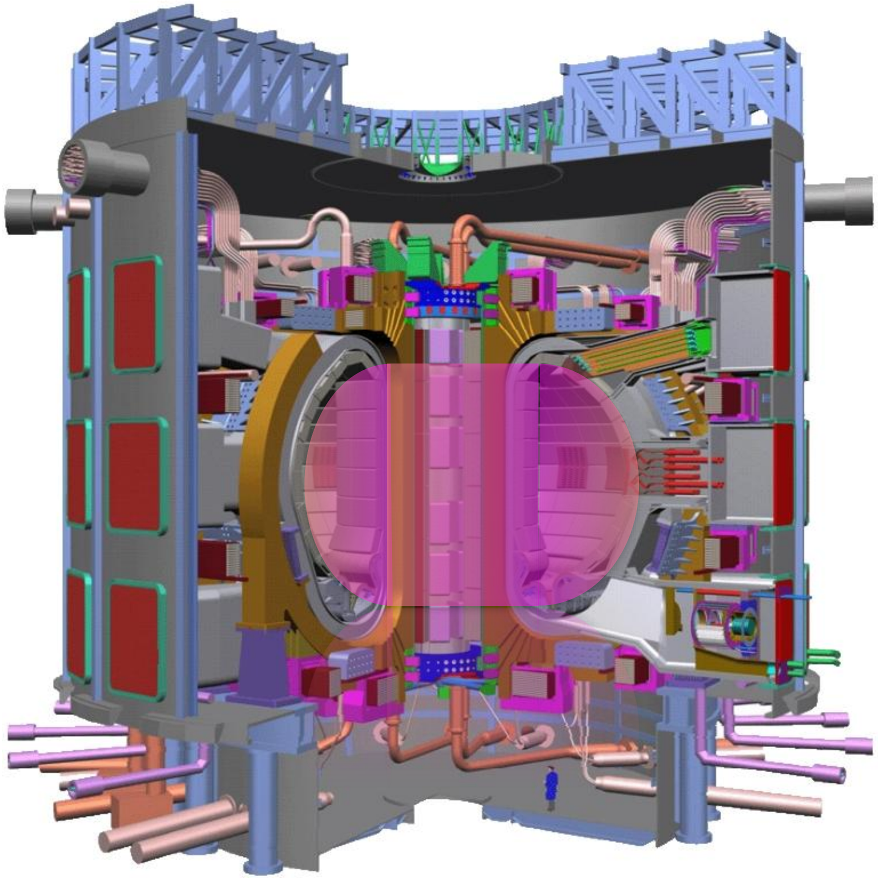




	ICF	MCF	
n_e	10^{25}	10^{14}	cm^{-3}
τ	10^{-10}	10	s
$n_e\tau$	$\cong 10^{14}$- 10^{15}		s cm^{-3}
T_e	$\cong$ 10		keV
Volume	10^{-9}	$\cong 10^{3}$	m^3
Pressure	10^{8}	1	Bar



Interaction chamber



ITER
Vacuum Vessel R=6 m r= 2m

Laser Mega Joule
E_L=1.8MJ 240 beams
Target chamber R=5m

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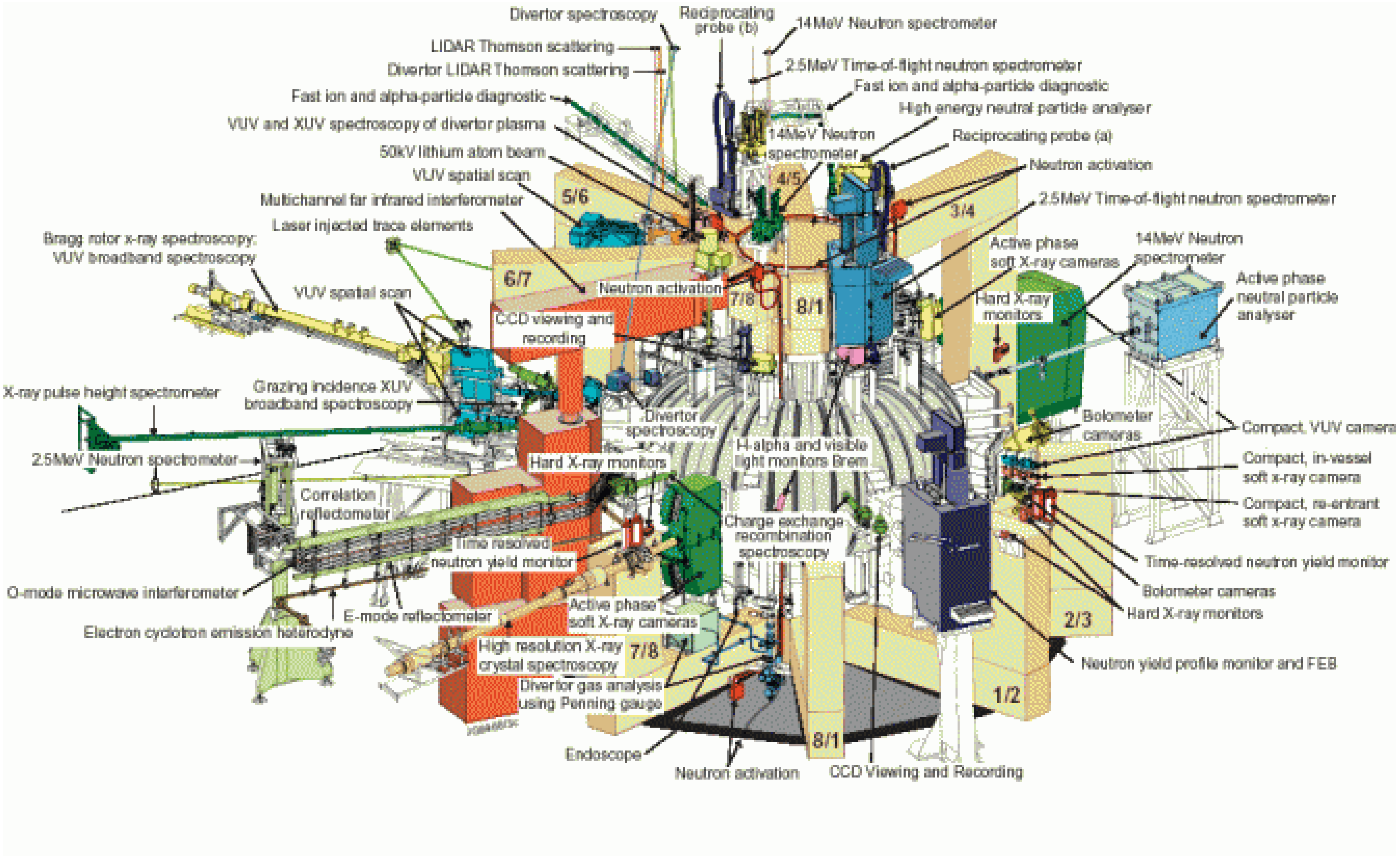
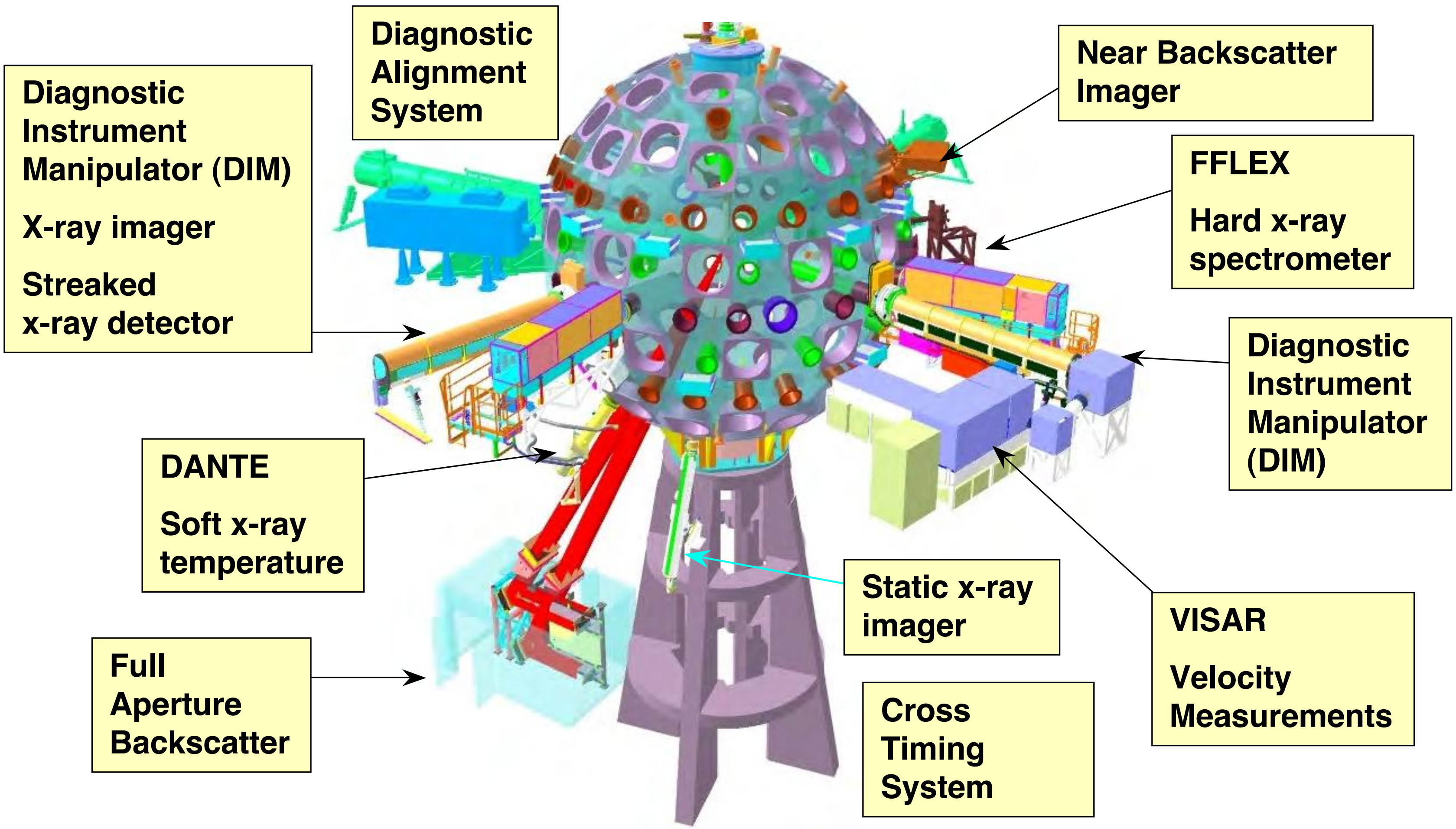
Tokamak Diagnostics



NIF Diagnostics



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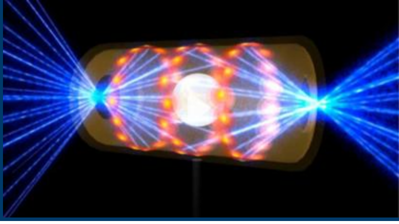
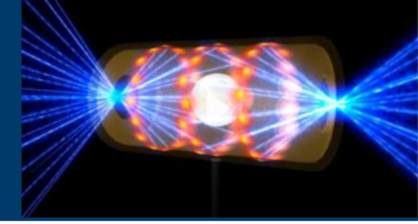
Inertial Fusion

A New Starting Point: NIF Successes 5th December 2022



- **On December 5, 2022, a historic result was achieved at the National Ignition Facility (NIF) of Lawrence Livermoore National Laboratories: <u>for the first time, more fusion energy was obtained, using an inertial approach, than that of the lasers used to generate the experiment.</u>**

A New Starting Point: NIF Successes 5th December 2022



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The New York Times

By Kenneth Chang

Dec. 13, 2022

Scientists Achieve Nuclear Fusion Breakthrough With Blast of 192 Lasers

nature

NEWS EXPLAINER | 13 December 2022

Nuclear-fusion lab achieves 'ignition': what does it mean?

Researchers at the US National Ignition Facility created a reaction that made more energy than they put in.

Jeff Tollefson & Elizabeth Gibney

CNN politics

US scientists reach long-awaited nuclear fusion breakthrough, source says

By Ella Nilsen and René Marsh, CNN

Updated 2:29 AM EST, Tue December 13, 2022

The Washington Post

Democracy Dies in Darkness

U.S. to announce fusion energy 'breakthrough'

By Evan Halper and Pranshu Verma

December 11, 2022 at 9:29 p.m. EST

What Does The US Fusion Breakthrough Mean? Is It Just Hype?

Melanie Windridge Contributor

I write about fusion energy, sustainability and science with adventure

Forbes

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Dec 15, 2022, 06:59pm EST

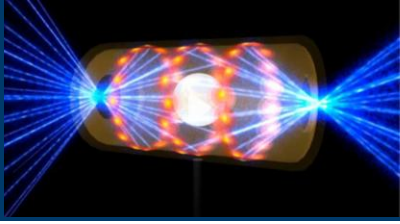
ENERGY.GOV

Department of Energy

DOE National Laboratory Makes History by Achieving Fusion Ignition

DECEMBER 13, 2022

A New Starting Point: NIF Successes
5th December 2022



ANSA.it

MONDO

Wp, gli Usa verso la svolta sulla fusione nucleare

Domani l'annuncio dell'amministrazione Biden

Redazione Ansa

ROMA - Dicembre 12, 2022 - News

la Repubblica

Fusione nucleare, gli Stati Uniti verso la svolta: domani l'annuncio

di Luca Fraioli

LA STAMPA

Fusione nucleare, il sogno degli scienziati si sta per avverare negli Stati Uniti: "Più vicini a un'energia illimitata e pulita"

Il Messaggero

Fusione Nucleare, la svolta storica negli Stati Uniti: «Energia illimitata, pulita ed economica»

Per la prima volta è stata realizzata una fusione nucleare che ha prodotto più energia di quella spesa per innescarla

CORRIERE DELLA SERA

Fusione nucleare, l'annuncio del dipartimento dell'Energia Usa: «Svolta storica: ricreate le condizioni di stelle e sole»

di Giovanni Caprara

il Giornale.it

Transizione energetica

"Scoperta scientifica senza precedenti". La svolta sulla fusione nucleare

13 Dicembre 2022 - 16:13

il Fatto Quotidiano

Fusione nucleare, Usa confermano il successo: "Data storica. Primo passo verso un'energia pulita che potrebbe rivoluzionare il mondo"

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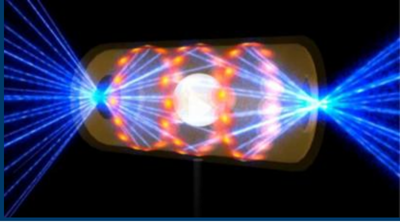
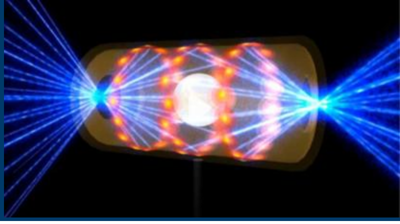
A New Starting Point: NIF Successes 5th December 2022



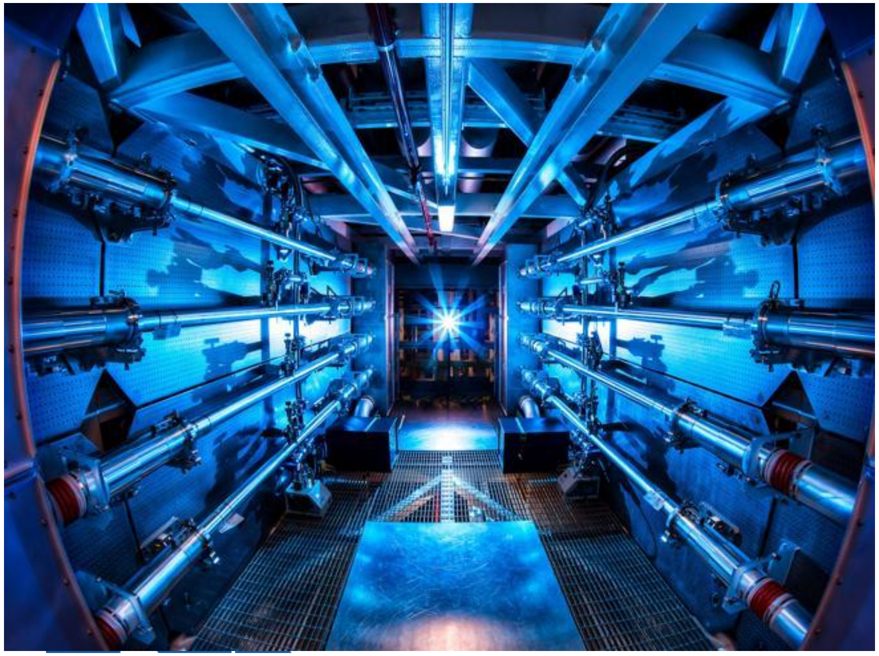
But… what happened?

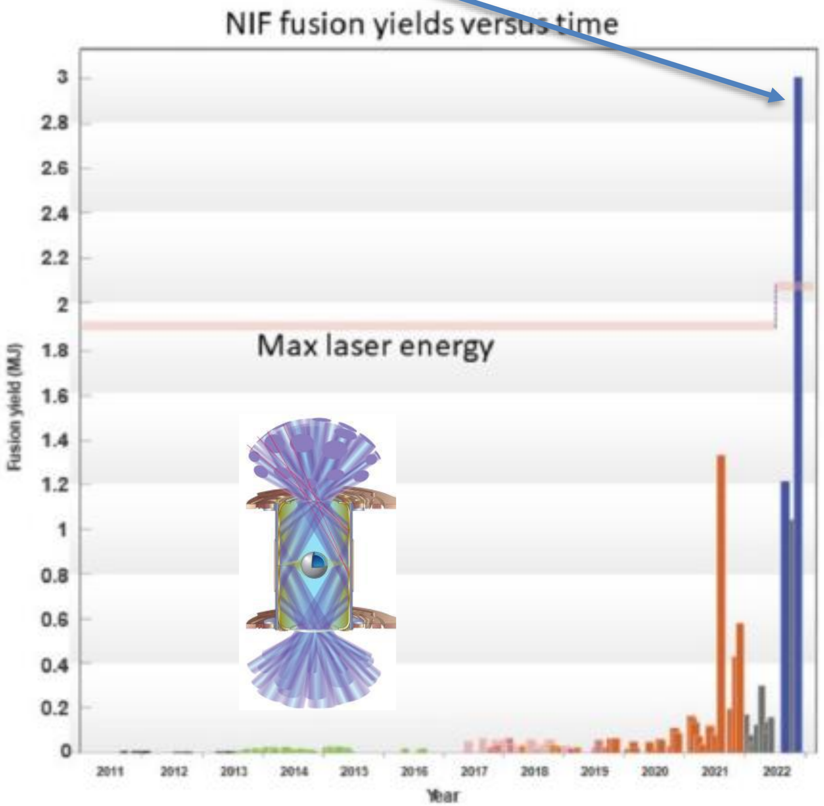
A New Starting Point: NIF Successes 5th December 2022



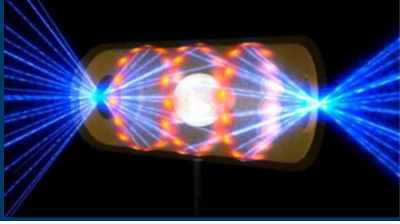
But… what happened?

- For the first time in history, 3.15 MJ of fusion energy was produced with an inertial scheme, compared to 2.05 MJ of laser energy. That is, 3.15 - 2.05 = 1.10 MJ of excess energy was produced. With a gain of 1.53 (= 153%).





A New Starting Point: NIF Successes
5th December 2022



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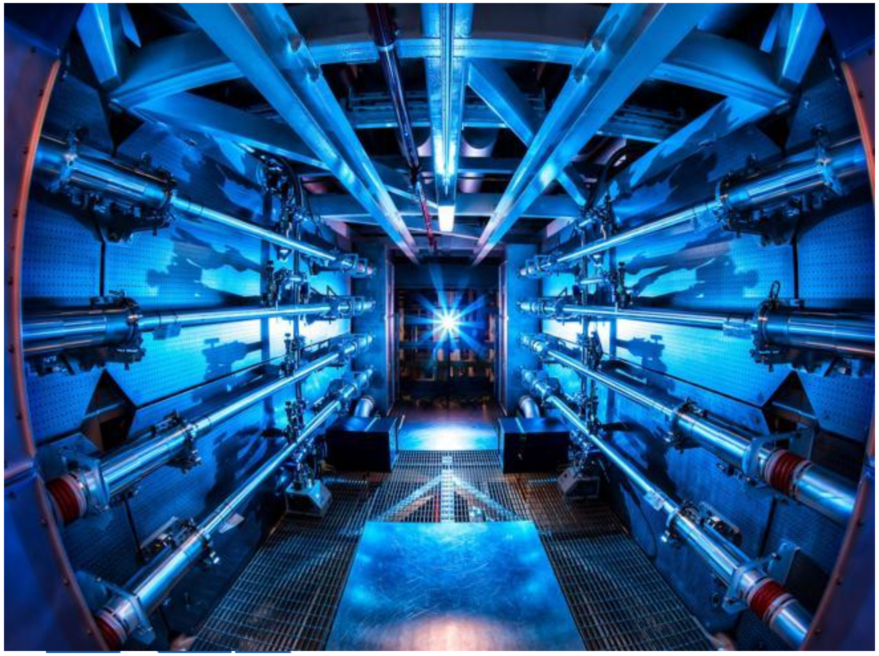
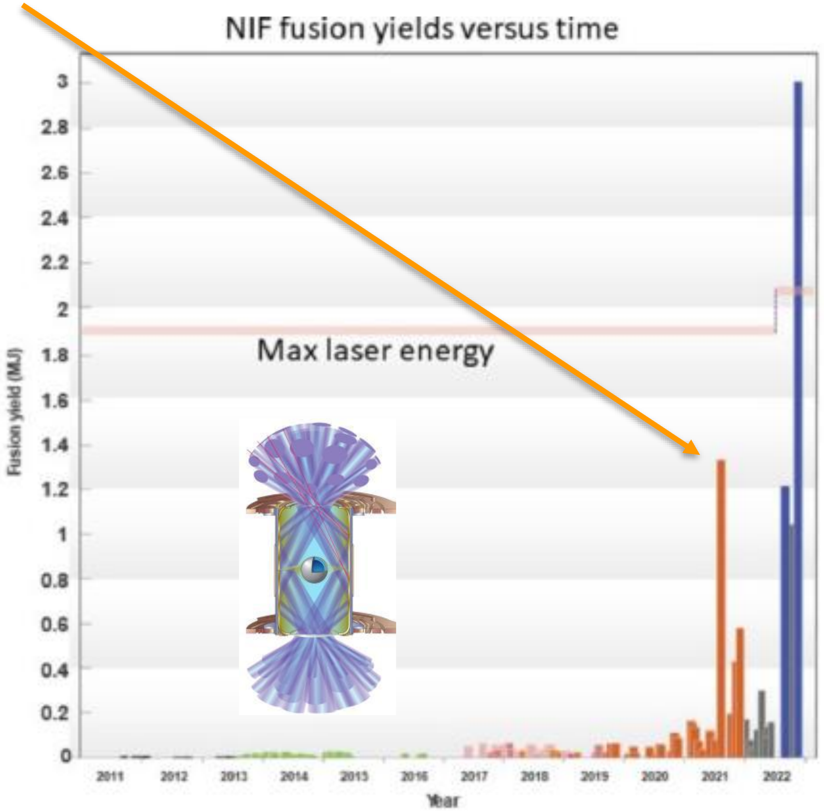
- **The result comes after constant progress over the years, and in particular after the great results of August 2021, in which 1.35 MJ had already been obtained**





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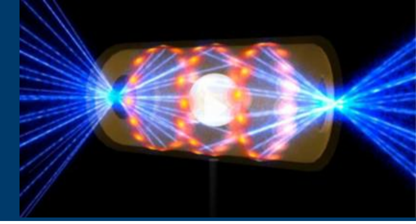

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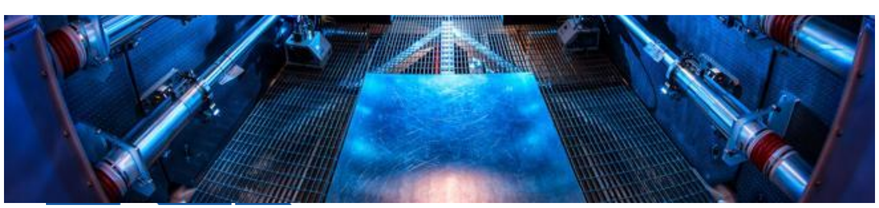
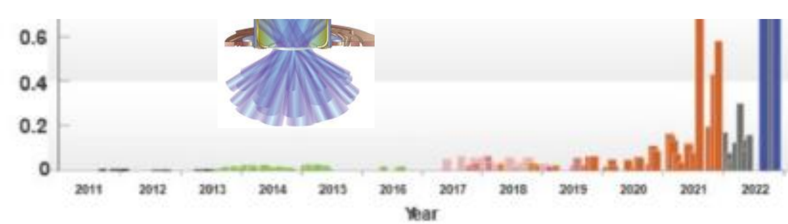
- **The result comes after constant progress over the years, and in particular after the great results of August 2021, in which 1.35 MJ had already been obtained**

- **This is followed by a series of subsequent results**
  - **July 2023 (3.9 MJ of fusion energy using 2.05 MJ laser = gain 1.90)**
  - **February 2024 (5.2 MJ of fusion energy using 2.2 MJ laser = gain 2.36)**
  - **April 2025 (8.6 MJ of fusion energy using 2.08 MJ laser = gain 4.13)**

https://lasers.llnl.gov/about/keys-to-success/nif-sets-power-energy-records





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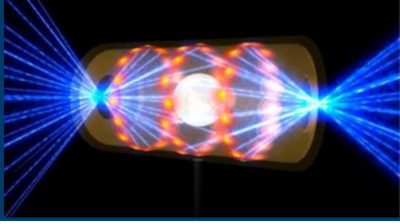
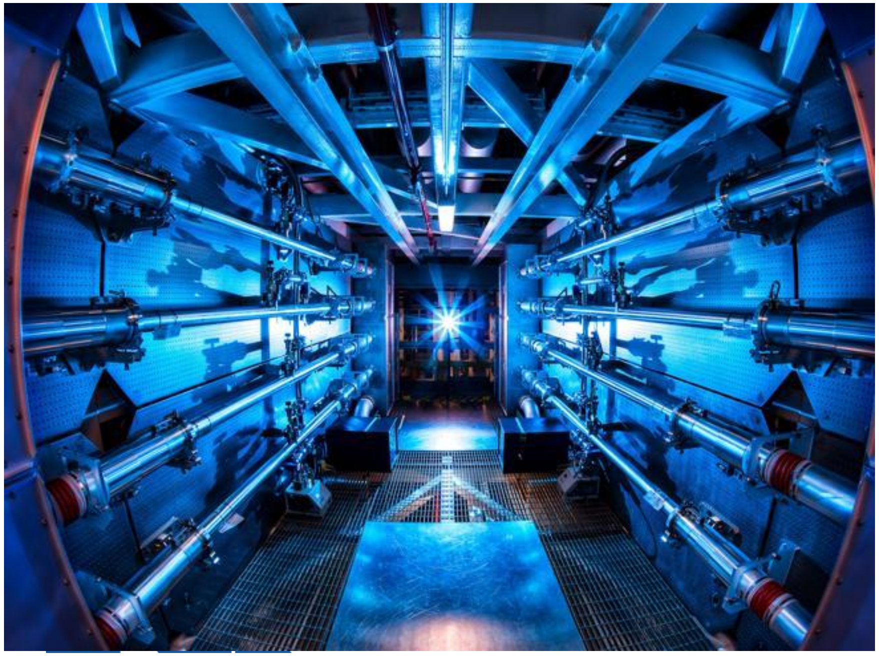
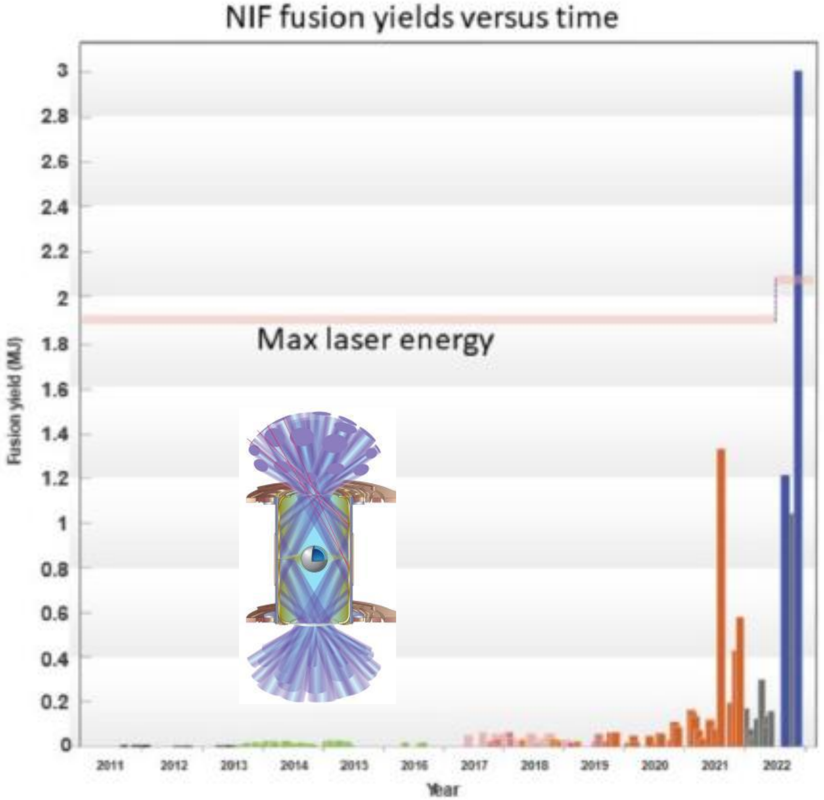
5th December 2022



- **Reactor? Not yet, we need to balance the laser energy**

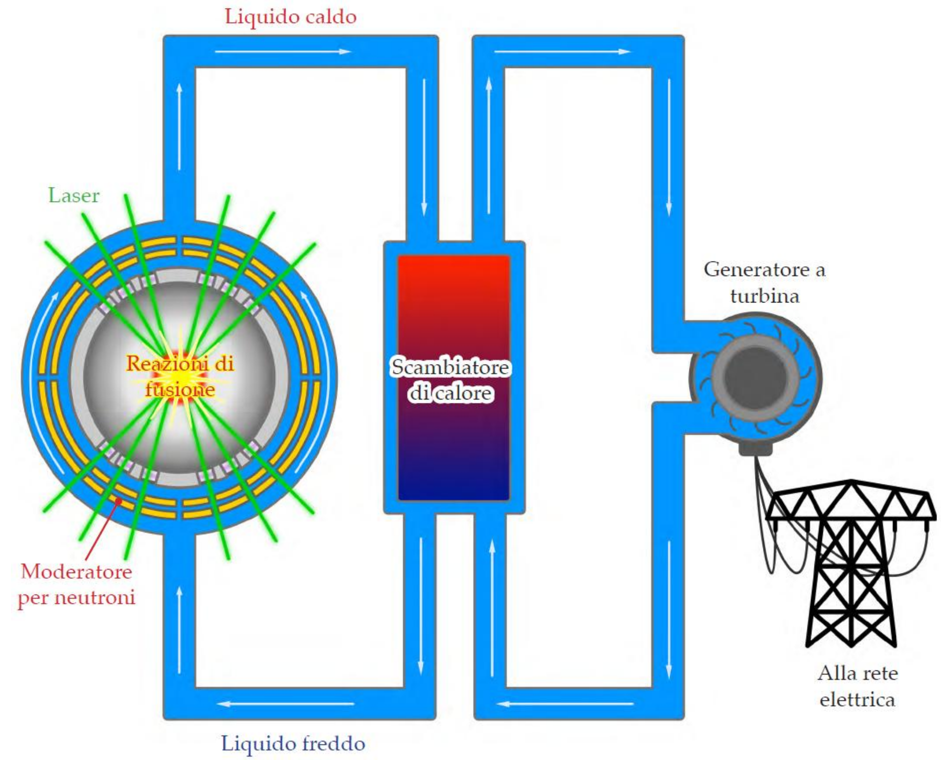
  → we need 2 orders of magnitude of increase

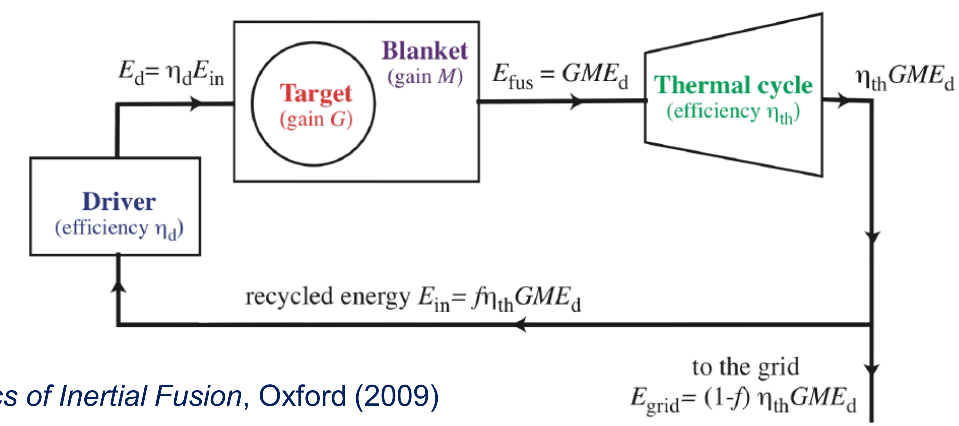




Possible Inertial Confinement Nuclear Fusion Reactor

- $D + T \rightarrow He^4 + n$, but also other reactions such as $H + {}^{11}B$ are studied, although more difficult
- The neutrons generated carry most of the energy produced by the fusion reactions
- They are slowed down inside a moderator material, which is heated and cooled by a liquid circuit
- The heat absorbed by the liquid is transferred, via an exchanger, to a second circuit, which sets a turbine in motion
- The electrical energy produced by the turbine is then fed into the electrical grid. Part of it is used to power the reaction driver
- In a future reactor the targets will be irradiated by lasers at a frequency of a few Hertz





S. Atzeni and J. Meyer-ter-Vehn: *The Physics of Inertial Fusion*, Oxford (2009)

Let's clarify better what *Inertial Confinement Nuclear Fusion is*

- **A spherical fuel capsule (D + T$\rightarrow$ α (3.5 MeV) + n (14.1 MeV)), with mass of a few mg and a diameter of a few millimeters, is uniformly irradiated along its surface by high-intensity radiation.**

- **This is followed by ablation and compression of the same, with subsequent ignition and transformation of the fuel.**

- **Ignition is the point at which a nuclear fusion becomes self-sustaining. This happens when the energy provided by the reaction heats the fuel faster than it cools, and therefore there is no need for further external heating**

- **Fuel completely exhausted at each interaction $\rightarrow$ in view of a reactor, need for an intrinsically pulsed process, at frequencies of the order of Hertz.**

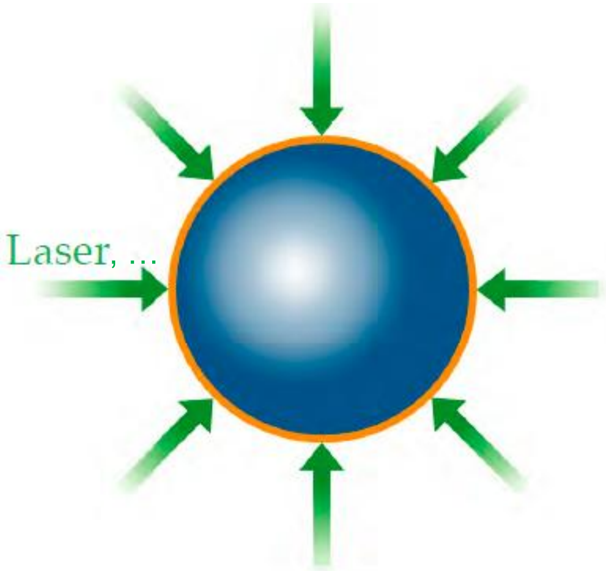
- **Does not involve any type of real confinement, but relies completely on inertia.**

- **Several possible approaches. Irradiation by lasers, X-rays, particles.**

- **Ignition demonstrated in the past at large X-ray fluxes, produced by nuclear fission explosions**

- **Problems for laboratory execution**

Nuclear Fusion by Inertial Confinement

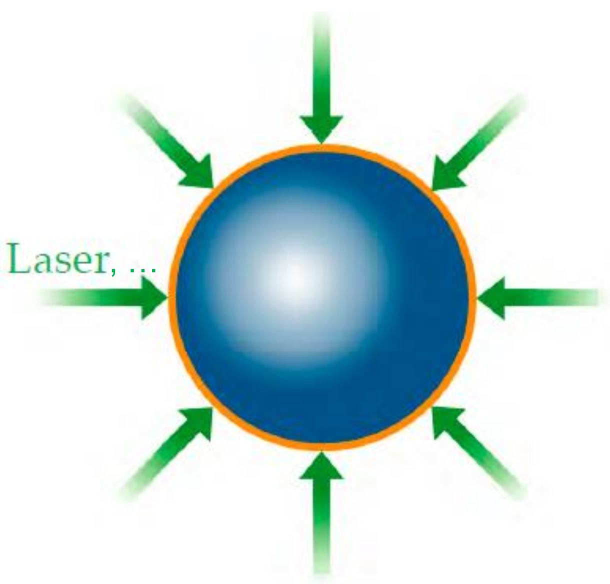


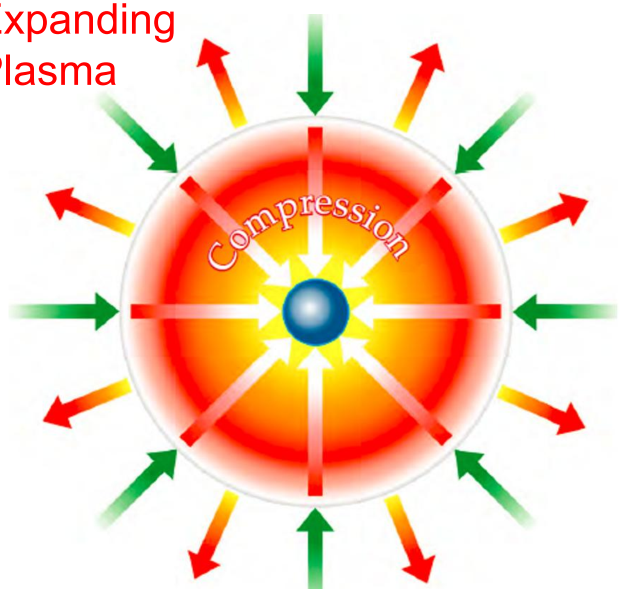
1) Irradiation
Expanding Plasma

- Radiation (laser, X-ray, particles, etc.) rapidly heats the surface of the capsule made up of D and T, ablating it and creating a plasma shell around it that expands at high speed.
- In this way, by reaction, the combustible material is compressed towards the center of the capsule.

Ref. S. Atzeni and J. Meyer-ter-Vehn: *The Physics of Inertial Fusion*, Oxford (2009)

Nuclear Fusion by Inertial Confinement





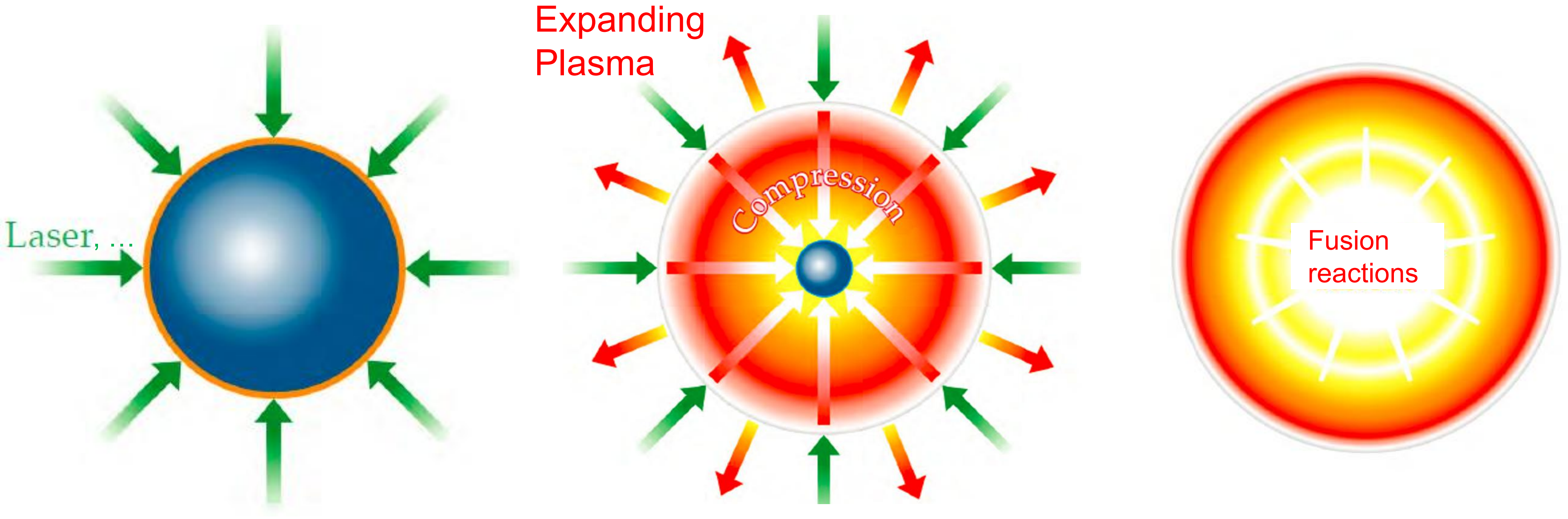
1) Irradiation
Expanding Plasma

2) Expanding plasma and fuel implosion

- During the final part of the compression, the fuel in the center of the capsule reaches a maximum density of <u>more than 1000 times that of the solid</u> and a temperature of tens of keV = <u>100,000,000 K.</u>

Ref. S. Atzeni and J. Meyer-ter-Vehn: *The Physics of Inertial Fusion*, Oxford (2009)

Nuclear Fusion by Inertial Confinement



1) Irradiation
Expanding Plasma

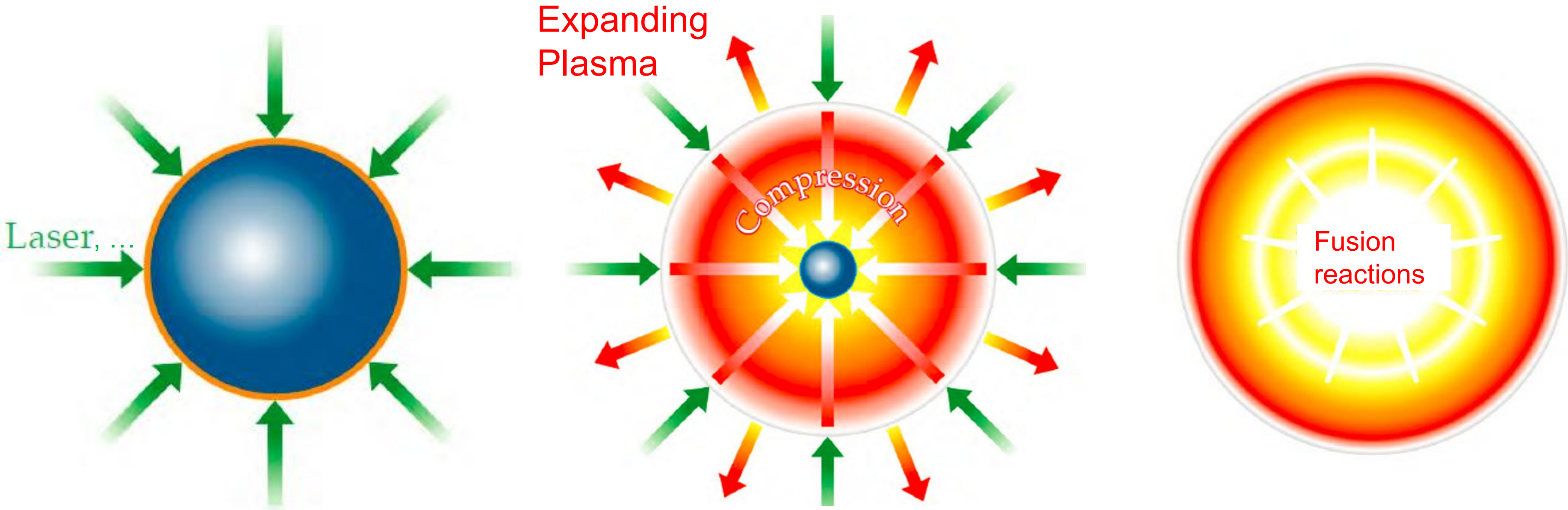
2) Expanding plasma and fuel implosion

3) Trigger of fusion processes

- The density and temperature reached by the fuel in the center of the capsule are such as to trigger thermonuclear reactions in the center of the capsule.

Ref. S. Atzeni and J. Meyer-ter-Vehn: *The Physics of Inertial Fusion*, Oxford (2009)

Nuclear Fusion by Inertial Confinement



1) Irradiation
Expanding Plasma

2) Expanding plasma and fuel implosion

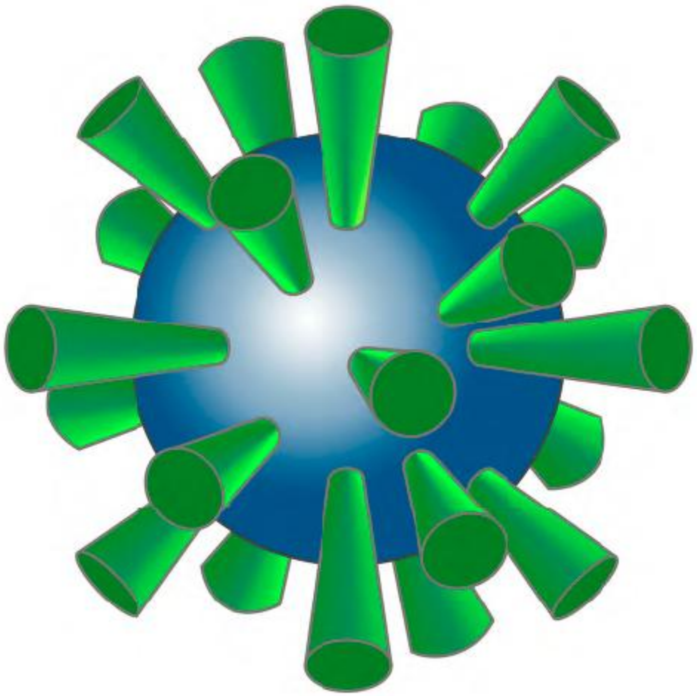
3) Trigger of fusion processes

→ 4) Fuel transformation

- Fusion reactions then propagate from the center towards the outside of the sphere.

Ref. S. Atzeni and J. Meyer-ter-Vehn: *The Physics of Inertial Fusion*, Oxford (2009)

Schemes of irradiation: Direct Drive



- **Compression and ignition phases of the fuel as a result of spherical implosion, and therefore intrinsically linked to each other.**
- **Target illuminated directly by lasers; implosion speed 300-400 km/s**
- **Minimal inhomogeneities in the surface illumination or in the target trigger hydrodynamic instabilities (Rayleigh-Taylor,…)**
- **Consequent reduction of the symmetry and compression efficiency of the capsule**

  → obstacle to ignition

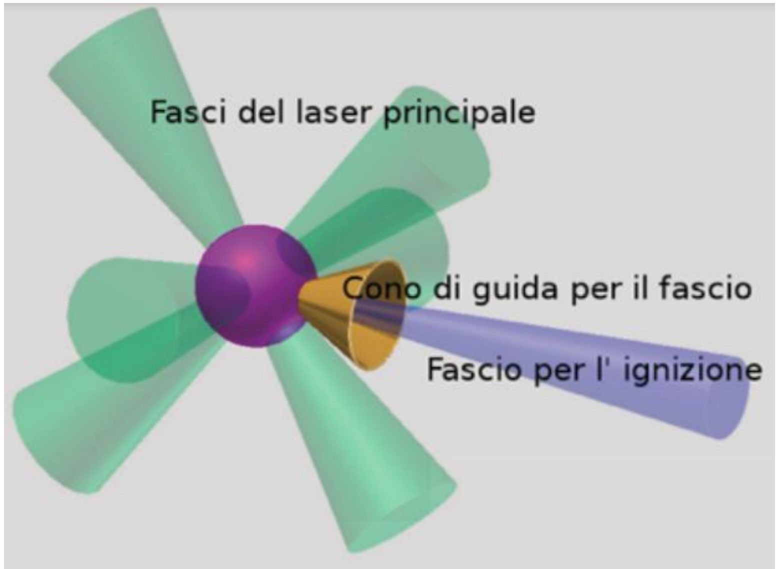
Possible solutions:

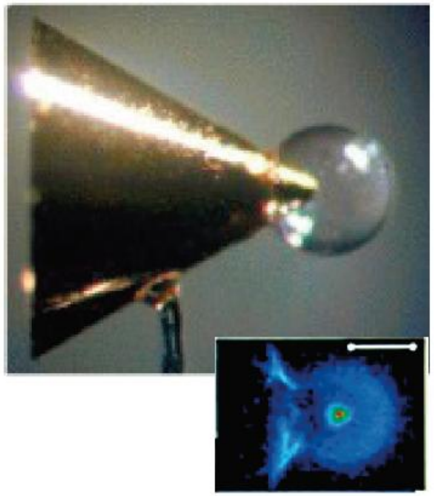
- ➢ **Improve the uniformity of irradiation and target finishing.**
- ➢ **Use *porous absorbers (foam)*, which interact with the laser and also promote homogenization of the interaction**
- ➢ **Use advanced direct irradiation schemes, separating the compression and ignition phases: Fast Ignition and Shock Ignition**
- ➢ **Use Indirect Drive scheme**

Direct Drive – Fast Ignition

- **Compression of the target for efficient ignition, but with lower implosion velocities (250-300 km/s) → very relaxed requirements regarding symmetry.**

- **Subsequent ignition phase, to be achieved by a separate mechanism.**
  - **Impact with accelerated macroparticles**
  - **Interaction with a high intensity laser beam**
  - **Interaction with an electron beam**
  - **Interaction with a proton or ion beam (C?)**
  - **Use of a gold cone to keep a corridor open during the plasma implosion**

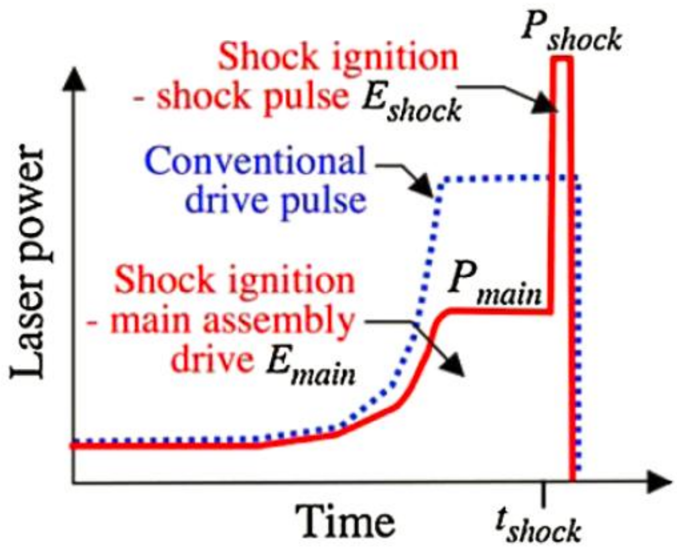




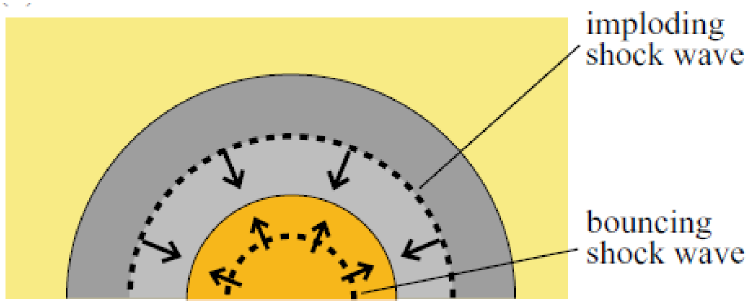
Kodama et al, Nature 412, 798 (2001)

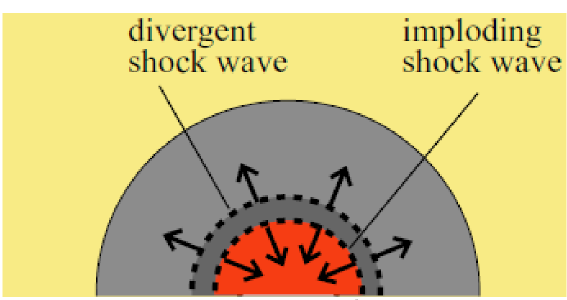
Direct Drive – Shock Ignition

- Compression with implosion speed 200-300 km/s → very relaxed requirements regarding symmetry.
- This phase creates a first convergent shock wave, which is reflected when it reaches the central area, becoming divergent
- Subsequently, a second convergent shock wave, of greater intensity, interacts with the one that has now become divergent.
- Effect: production of a shock wave of much higher intensity than in the previous cases, which generates ignition



Perkins et al, Phys. Rev. Lett., 103, 045004 (2009)





Atzeni et al, Nucl. Fusion 54, 054008 (2014)

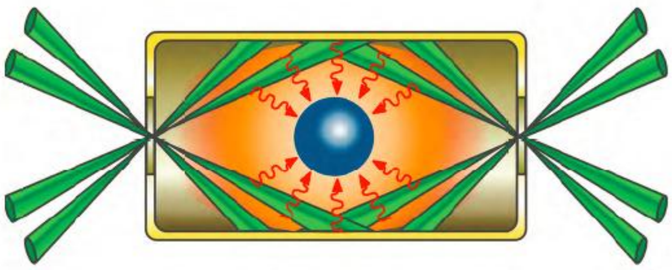
Schemes of irradiation: Indirect Drive

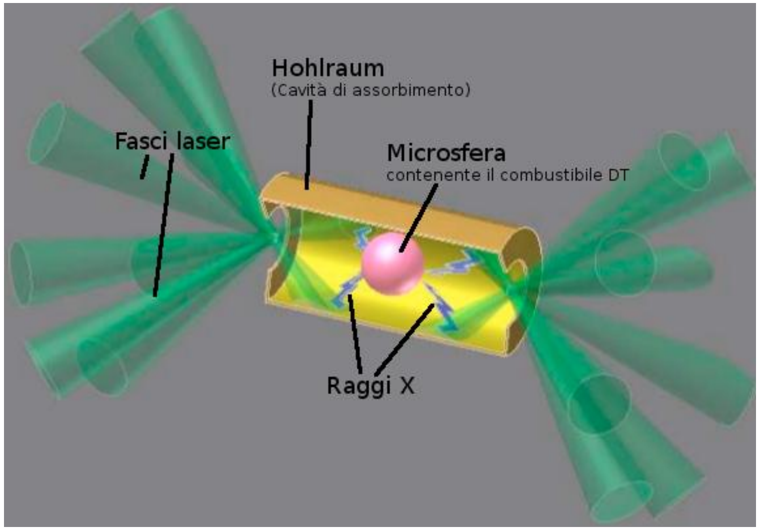
- **Laser interaction with the inner wall of a gold (or high-Z material) cylinder «Hohlraum», passing through two holes on the bases of the cylinder.**

- **Each interaction produces thermal X-ray emission.**

- **X-rays interact with the fuel capsule, ablating it, generating compression and then ignition.**

- **Thermal distribution of X-ray photons, which fill the cavity acting homogeneously on the target, → high radiation symmetry, avoiding the triggering of hydrodynamic instabilities**



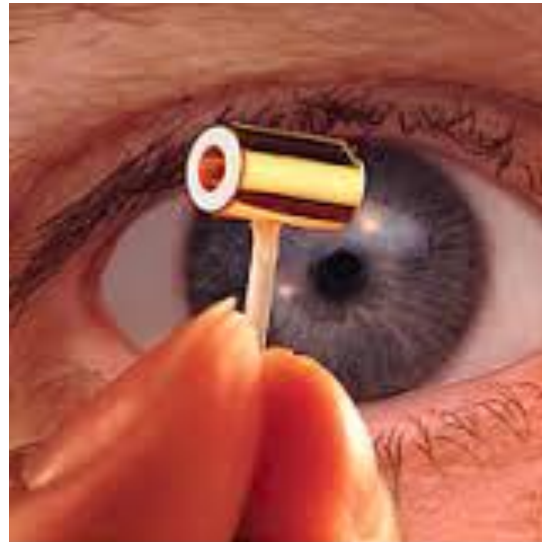


Price:

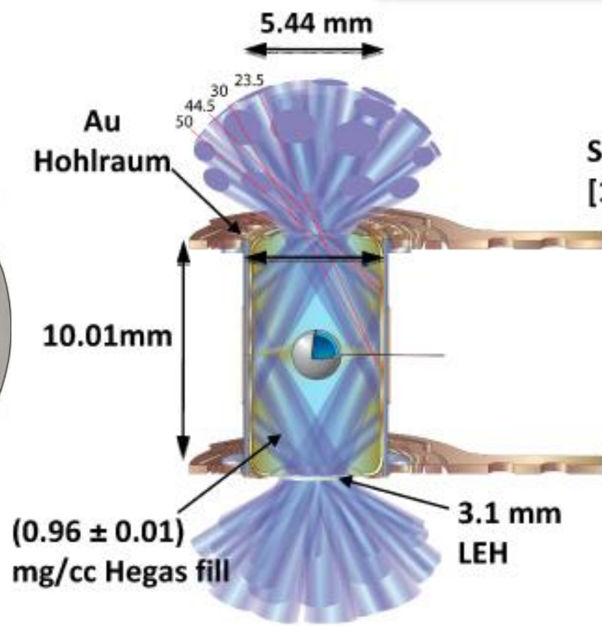
- **High fraction of laser energy lost in heating the Hohlraum**
- **Aperture opacity**
- **Beam interaction**

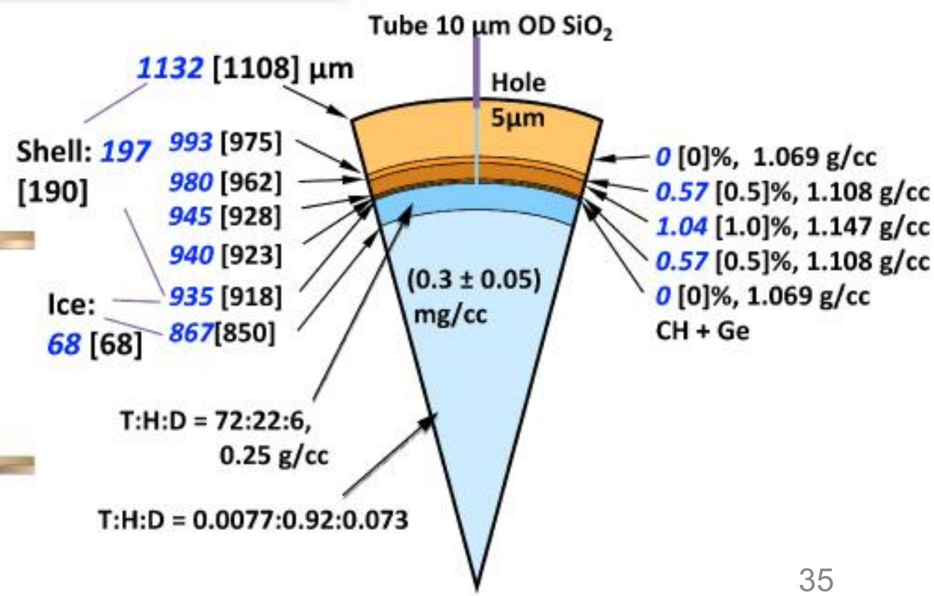
APPROACH USED AT NIF

Nuclear Fusion by Inertial Confinement: Targets



Dimensions:
Diameter: 0.1 mm - 5 mm;
thickness: 10 μm - 500 μm
shape, surface finish,
composition, filling…



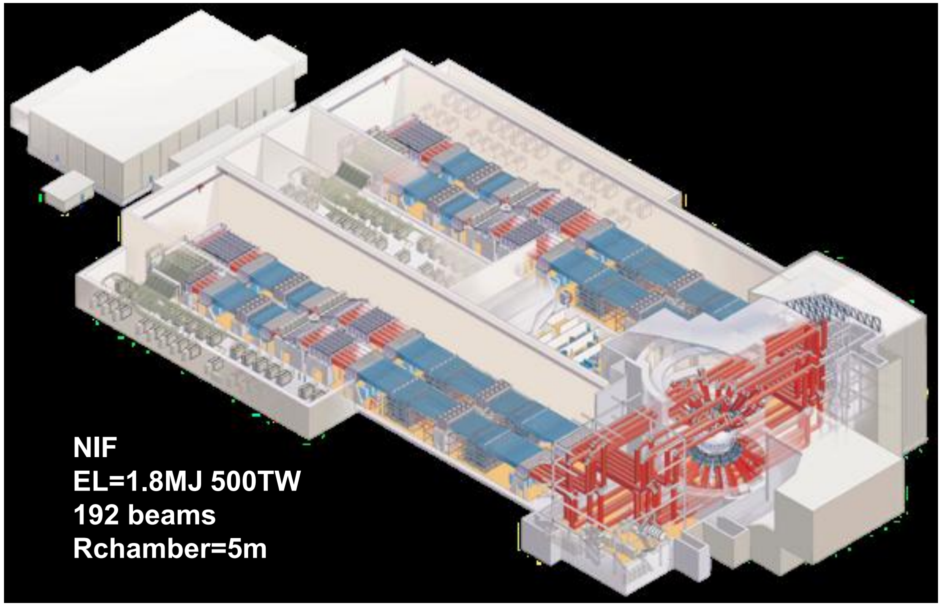


Lasers for Nuclear Fusion by Inertial Confinement

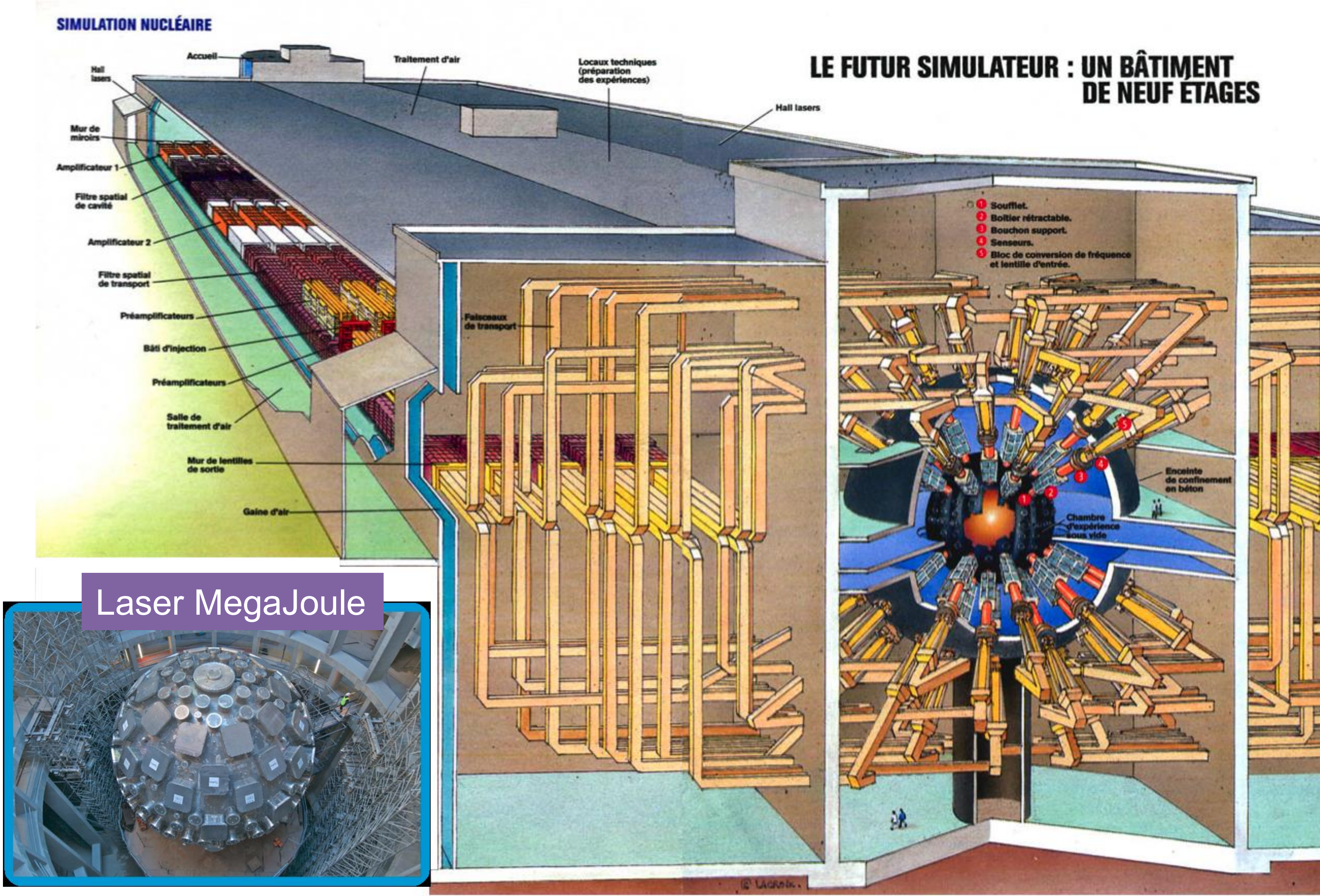
Typical laser	
Active medium	Nd: Glass phosphate, KrF,Iodine
Energy (Joule)	$0.1 < E_{laser} < 2*10^6$
Power (W)	$P_{laser} < 5*10^8$
Pulse duration (ns)	$0.5 < \Delta\tau < 60$
Wavelength (nm)	$0.25 < \lambda < 1.3$
Harmonic generation	1^{st}- 3^{rd} KDP Crystals
n. Beams	1 < n < 288 (400)
I (W/cm^2)	$10^{14} < I < 10^{21}$
Contrast	$>10^{6-8}$
Beam Smoothing	Phase plates / ISI PLates
Spot Size	100 micron –5 mm

List of Facilities		
Nation	**Facility**	**Beams**
USA	National Ignition Facility (NIF)	192 – MJ facility
France	Laser Mega Joule (LMJ)	176 – MJ facility
Russia	UFL-2M	192 – MJ facility
China	Shengguang III	48 fasci – 180 kJ in totale

Lasers for Nuclear Fusion by Inertial Confinement



Nuclear Fusion by Inertial Confinement: LASER MEGAJOULE - France



Other laser facilities

USA: **OMEGA** laser, 60 ns and two ps laser beams: about 40 kJ total energy. Higher energy facility for direct irradiation studies, including Shock Ignition.

France: **LULI2000** laser, with 2 laser beams of 1 kJ each with nanosecond duration.

UK: **ORION**, 10 ns and 2 ps beams, about 6 kJ total energy;
- **Vulcan 20-20** will have a total of about 10 kJ laser energy.

Czech Republic, Hungary and Romania: three locations of the ELI–ERIC laser infrastructure: ELI-BEAMLINES (Czech Republic), ELI-ALPS (Hungary) and ELI-NP (Romania), which together comprise the most powerful lasers in the world. In the Czech Republic, the PALS laser facility (1 kJ, 0.3 ns) is also operational

Russia is building the **UFL-2M** laser with characteristics on the scale of NIF and LMJ. Completion is expected in the next few years.

Japan: **GEKKO XII** laser with 12 beams at ns, total energy of 10 kJ, and **LFEX** laser of another 10 kJ but at ps

China: **ShenGuang-III** laser, 48 laser beams for a total of 180 kJ of energy, for indirect irradiation scheme. **ShenGuang-II-UP** laser, with a total of 9 laser beams for about 40 kJ at ns, but also ps and fs, used for direct irradiation Shock Ignition and Fast Ignition.

What is done in Europe?

- EUROfusion: Enabling Research,
  - one on FOAM materials (S. Le Pape)
  - one on Magnetized Inertial Fusion (J. Santos)

- Laserlab Europe AISBL supports 3 ICF-related groups:
  - Expert group in IFE
  - Expert group in micro- nano-structured materials
  - Expert group in laser-generated Electromagnetic Pulses

- COST actions. The one now active:
  - “Proton Boron Nuclear Fusion: from energy production to medical applications” (2022-2026)

- IAEA (International Atomic Energy Association)
  - Coordinated Research Projects of : “Advanced Research Activity on Materials, Technologies and Devices for Inertial Confinement Fusion” (2020-2025)

What is done in Europe?

Historical European IFE contributions

- Of the highest importance: theory, numerical modeling, experiments, diagnostics and training of a new generation of researchers.
- Pioneers in high energy density physics, laser-plasma interaction, parametric instabilities, production and transport of fast electrons, high energy lasers
- A large number of experiments performed on direct-drive ICF schemes on laser facilities with energy up to kJ
- Strong international collaborations in the direct-drive field, especially with LLE
- They have an undisputed role in the technological development of high energy and intensity lasers.

What happens after NIF results: great excitement both in the public and private sectors

- **USA:** The US Department Of Energy (DOE) has given a large increase to funding on Inertial Fusion companies and institutions

- **Germany** has publicly declared its strong involvement and economic support for inertial fusion activities → Significant funding to companies that operate on inertial (Marvel Fusion, Focused Energy)

- **France:** TARANIS project, with creation of GenF Company (CEA, CNRS, THALES, French Investment Bank). 12 M€ Phase 1, 36 months. Planned Phase 2 (200 M€ - 2027) and an additional 600 M€ to establish a demonstration plant

- **UK:** UPLiFT project. Consortium led by CLF. Phase 1 (£10 million over four years): IFE laser design, prototype construction, implosion capsule target manufacturing, high gain physics, and extensive development of the hydrodynamic code 'Odin'.

- **Italy:** Italian National Platform for Sustainable Nuclear Energy (PNNS). Study and coordination group of the main Italian stakeholders in the nuclear sector. Coordinated ENEA and RSE company, reporting to the MASE. WG3: "Nuclear Fusion Technologies". Inertial Fusion included, requested investment about 1.5 B€.

- **Australia**: HB11 Company

What happens after NIF results: great excitement both in the public and private sectors

- **EURATOM CSA (Coordination and Support Action) GO4FUSION: "STRATEGIC ALLIANCE FOR BUILDING EUROPEAN FUSION ENERGY PARTNERSHIP".**
  - **The project will lay the groundwork for a strong, collaborative European fusion energy community, preparing for the future establishment of a Public-Private Partnership (PPP) and includes IFE activities**

- **At European level there is also the important HIPER+ initiative**

HIPER+ group: a roadmap for IFE in Europe

- Dimitri Batani, Université de Bordeaux, Celia, France
- Arnaud Colaïtis, Université de Bordeaux, Celia, France
- Fabrizio Consoli, ENEA C.R. Frascati, Italy
- Colin Danson, AWE & Blackett laboratory, United Kingdom
- Leonida Gizzi, Istituto Nazionale di Ottica, CNR, Pisa, Italy
- Javier Honrubia, estiae, universidad politecnica de madrid, Spain
- Thomas Kuehl, gsi, Darmstadt, Germany
- Sébastien Le Pape, ecole poytechnique, LULI, Palaiseau, France
- Jean-Luc Miquel, Association Lasers and Plasmas & CEA/dam, France
- Manolo Perlado, instituto Fusión Nuclear "G. Velarde", Madrid, Spain
- Robbie Scott, Central Laser Facility, Rutherford Appleton Laboratory, Harwell, UK
- Michael Tatarakis, Institute of Plasma Physics and Lasers, Hellenic Mediterranean University, Greece
- Vladimir Tikhonchuk, Université de Bordeaux, France & ELI-Beamlines, Czech Republic
- Luca Volpe, Estiae, Eniversidad politecnica de Madrid & Centro de Laseres Pulsados, Spain

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HIGH POWER LASER
SCIENCE AND ENGINEERING

REVIEW

Future for inertial-fusion energy in Europe: a roadmap

ENEA

HIPER+ group

- **The initiative aims to establish an IFE program in Europe, with the mission of demonstrating laser-based nuclear fusion ignition and developing technologies for a future fusion reactor for civil energy purposes.**

- **Born from the need for a coherent IFE program in Europe, combined with the design and construction of a dedicated laser facility for research and development activities**

- **Next steps**
  - **Demonstration of direct-drive ignition on a high repetition facility: 1 - 10**
  - **Construction of an IFE pilot reactor and demonstration of the technology readiness level: 11 - 20**
  - **Construction of a demonstration power plant – prototype in operational conditions: 21 – 30**

HIPER+ group

- Program structured in different axes
  - Axis A: Physics and Technology for IFE
  - Axis B: Development of laser technology for IFE, construction of IFE laser systems
  - Axis C: Materials science and target and reactor technology
  - Axis D: IFE community building, project management and skills development

Nuclear Fusion by Inertial Confinement in Italy

- **ENEA – Centro Ricerche Frascati**
- **Università di Roma La Sapienza**
- **CNR-INO Pisa**
- **Università di Pisa**
- **Università di Tor Vergata**
- **Politecnico di Milano**
- **INFN**

Nuclear Fusion by Inertial Confinement in Italy

- **No direct government funding to IFE activities, so far**
- **Some very small funding from some PRIN projects (Projects of Significant National Interest)**
- **Recent activities by RSE company, also with MoU with Blue Laser Fusion (Nobel Price S. Nakamura), mentioned by Prime Minister G. Meloni**
- **Recently, interest from INFN to IFE activities with INFN-funded project FUSION (coordination by INFN and ENEA), involving several Italian Institutions for small overall funding**

Nuclear Fusion by Inertial Confinement in Italia: ENEA – Centro Ricerche Frascati

- ENEA – Centro Ricerche Frascati. Hystorical place
  - ABC is operating at the ENEA Frascati Research Center. It is the laser with the largest Italian laser plant, and has the highest energy per pulse in Italy.
  - Both experimental and theoretical activities are here performed, together with the renowned development of advanced and tailored diagnostics
    - Laser-generated Electromagnetic Pulses (EMPs)
    - Foam materials
    - Low-rate nuclear fusion reactions (p+11B,…)
    - Diagnostics (RF-Microwave, ions, electrons, UV, X, Gamma)
    - Further activities on Inertial Confinement Fusion
  - Over the years, participation to
    - EUROfusion Enabling Research projects
    - COST action
    - Laserlab Europe AISBL
    - IAEA project
    - PRIN
    - INFN Fusion Project

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Theoretical and numerical tasks in Inertial Fusion

- **Example: HIPER+ program structured in different axes**
  - **Axis A: Physics and Technology for IFE**
  - **Axis B: Development of laser technology for IFE, construction of IFE laser systems**
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  - **Axis D: IFE community building, project management and skills development**

Theoretical and numerical tasks in Inertial Fusion

- **Example: HIPER+ program structured in different axes**

  - **Axis A: Physics and Technology for IFE**
    - **Hydrodynamic simulation, with multiphysics inclusion**
    - **Particle-In-Cell PIC simulation**
    - **Montecarlo simulation**
    - **Molecular dynamic simulation**
    - **Electromagnetic simulation (time and frequency domain)**
    - **Big Data analysis and predictions based on AI**
    - **Necessity to have multi-scale and multi-physics simulations, with stages interconnected in real time**
    - **CAD design**

Theoretical and numerical tasks in Inertial Fusion

- **Example: HIPER+ program structured in different axes**

  - **Axis A: Physics and Technology for IFE**

  - **Axis B: Development of laser technology for IFE, construction of IFE laser systems**
    - **Ray tracing and optical simulations**
    - **Thermal simulation**
    - **Mechanical simulation**
    - **System simulation**
    - **CAD design**

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Theoretical and numerical tasks in Inertial Fusion

- **Example: HIPER+ program structured in different axes**
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Theoretical and numerical tasks in Inertial Fusion

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  - **Axis C: Materials science and target and reactor technology**
  - **Axis D: IFE community building, project management and skills development**
    - **Ph.D.s,**
    - **post-docs**
    - **contract researchers**
    - **permanent positions, at different levels**
      - **Positions for Physicians, Engineers, Mathematicians, Chemists, Technicians,…**

ENEA

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