The future of Inertial Fusion Energy in Europe and world-wide

Dimitri Batani [1], Michael Tatarakis [2]

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2) Director of Institute of Plasma Physics & Lasers, Hellenic Mediterranean University

on behalf of the HiPER+ Initiative team

The question we were asked: “After the big historic achievements at Livermore, it seems there is an acceleration on inertial fusion. In your opinion, what should be needed to succeed in this acceleration and how industry could contribute to this?”

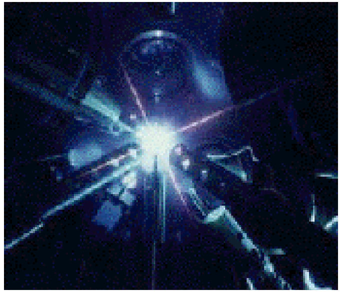
Hiper+ initiative group

- Dimitri Batani, Université de Bordeaux, celia, France
- Arnaud Colaïtis, Université de Bordeaux, celia, France
- Fabrizio Consoli, Enea, 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, United Kingdom
- Michael Tatarakis, Institute of Plasma Physics and Lasers, Hellenic Mediterranean University, Greece
- Vladimir Tikhonchuk, Université de Bordeaux, France & ELI-Beamlines, Czech Republic
- Luca Volpe universidad politecnica de madrid & Centro de Laseres Pulsados, Spain

Two approaches for creating conditions for fusion:

Magnetic Confinement

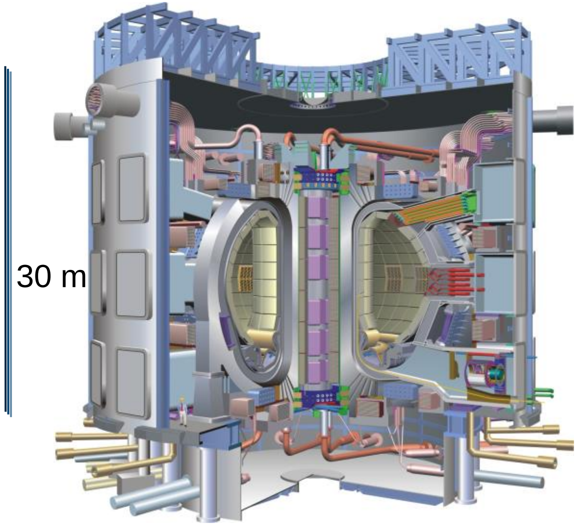
Low plasma density
Long times (∼sec)



Inertial Confinement

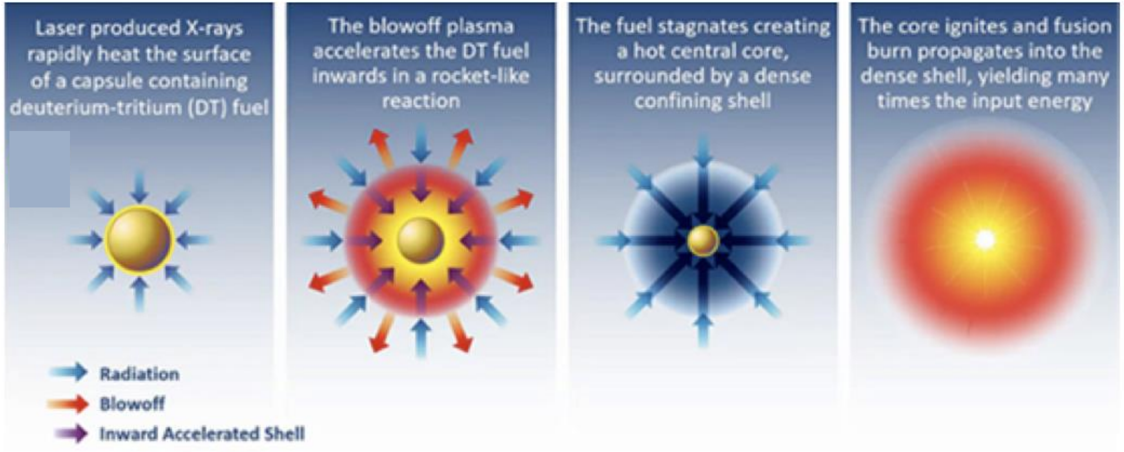
Very high densities (compression ∼ 1000 times solid density)
Very short times (∼ nsec)

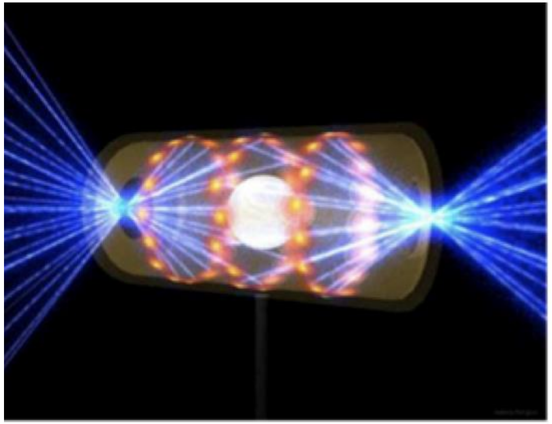
Europe has a very strong commitment to MCF mainly via the ITER project



> 20 B€

The principle of inertial fusion





Sequence of four stages of process in the laser direct drive scheme

NIF indirect laser drive irradiating the hohlraum enclosing the DT-filled capsule

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

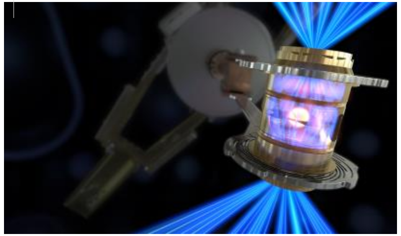
13 Dec 2022 in Politics & Policy

National Ignition Facility surpasses long-awaited fusion milestone

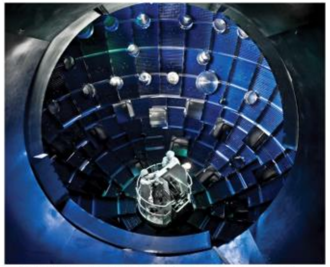
The shot at Lawrence Livermore National Laboratory on 5 December is the first-ever controlled fusion reaction to produce an energy gain.

David Kramer

0 COMMENTS TOOLS PREV NEXT



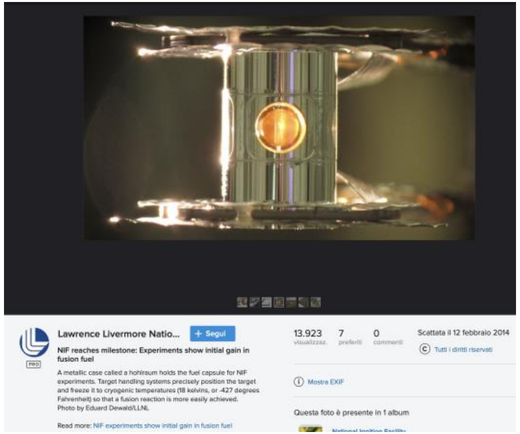
In the indirect-drive method used at the National Ignition Facility, a UV laser is fired at a cylinder called a hohlraum rather than at the hydrogen fuel. The hohlraum then emits x rays, which compress the fuel inside. Credit: Lawrence Livermore National Laboratory

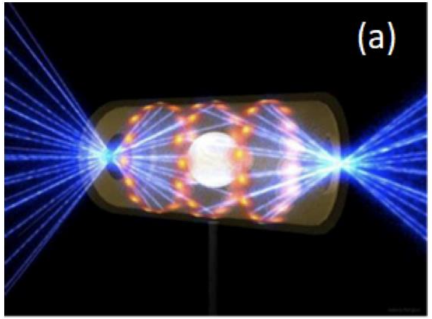


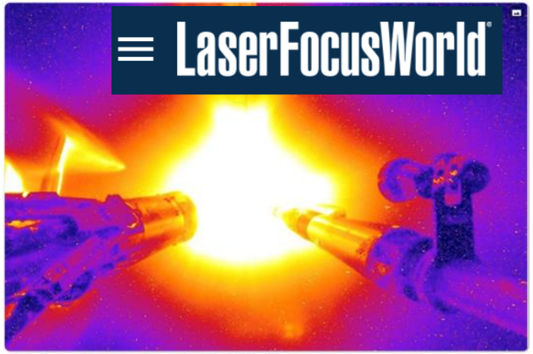
The US National Ignition Facility (target chamber shown) is the size of three American football fields. Credit: Lawrence Livermore National Laboratory

Gain = 3.15MJ/2.05 MJ = 1.54

physicsworld





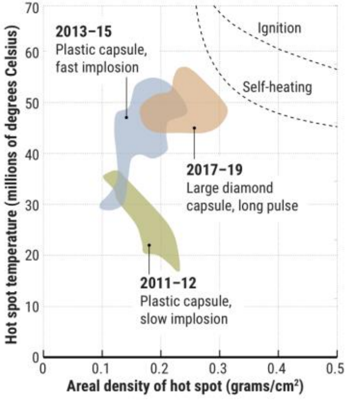


Colorized image of a NIF "Big Foot" deuterium-tritium (DT) implosion.

Long and difficult way to the success

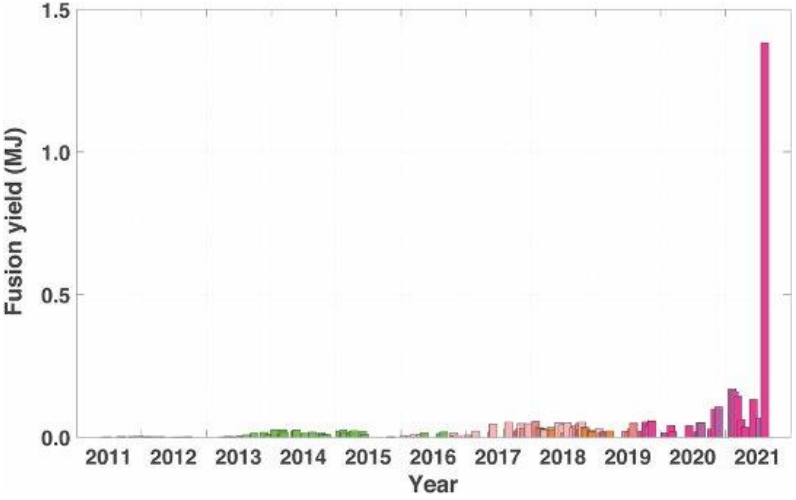
2014: High Foot implosions: achieving implosions where a large fraction of the total fusion output was due to α-particle self-heating ($E_{\alpha\text{-heating}} \approx$ 6.6 kJ, $E_{compression} \approx$7.7 kJ)

August 2021



GRAPHIC: PRAV PATEL/LLNL, ADAPTED BY N. DESAI/*SCIENCE*

2020: More than 150 kJ of fusion energy



The NIF result paves the way to the possibility of developing Inertial Fusion Energy (IFE) as a future source of energy

NIF success initiates reflections on national projects to fusion energy:

- **Basic Research Needs** report: a foundational guide for DOE to establish a national IFE program in the USA
- **Memorandum** on laser IFE for the federal ministry of education and research of Germany (May 2023)
- Preparation of **Taranis Project** in France (Thales, CEA, CELIA, LULI)
- Contribution Report of the “HiPER+ group” to the ESFRI **Landscape analysis** of Research Infrastructures (April 2023)
- …

Also, it has prompted interest from **private companies** (start ups working in IFE)

Focused Energy
Marvel Fusion

First Light Fusion

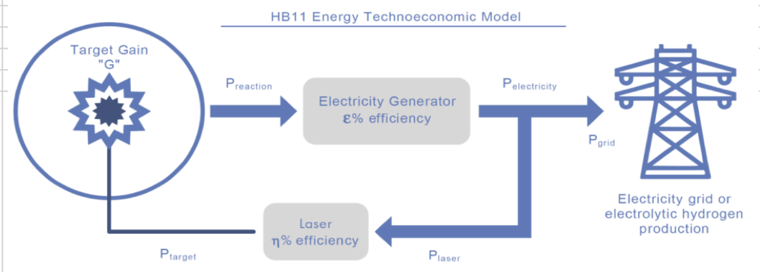
HB11 Energy

Innoven
Xcimer Energy Corporation
and several more…

- May 2023, USA, 8 U.S. IFE companies received 46 M$ from government to pursue pilot plants

Requirements for Energy production

We should work at ≈ Hz repetition frequency and Gains ≥ few 100

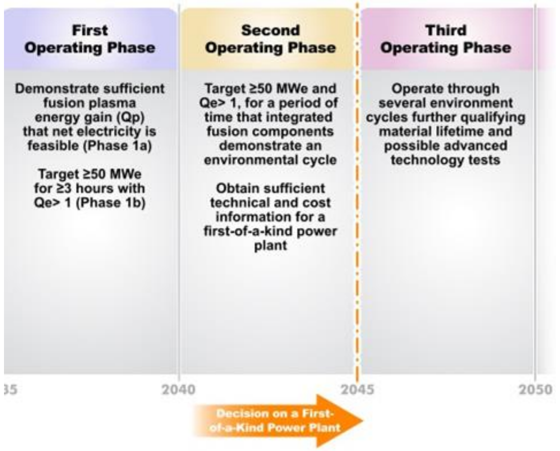


Parameters		
Laser efficiency	η	**10%**
Target Gain (scientific)	G	**1000**
Thermal energy efficiency	ε	**30%**

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").

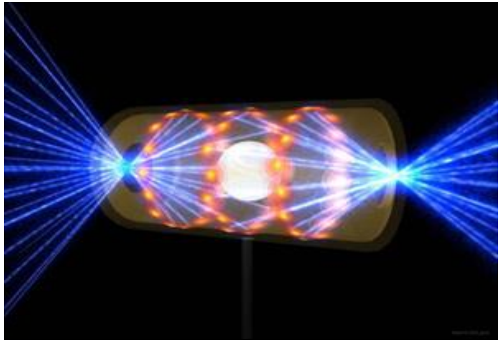


HiPER+: Inertial Fusion beyond NIF results

NIF results provide a validation of the Inertial Fusion concept, achieving ignition beyond breakeven, and opening the pathway to gain.

However, INDIRECT DRIVE used at NIF **is not compatible** with requirements for future fusion reactors:

- Complicated targets
- Massive targets (lot of high-Z material in chamber)
- Intrinsic low gain due to step of X-ray conversion.
- “Political” issues

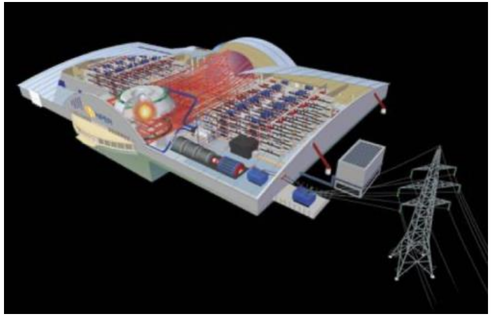


It is now **timely** to go beyond NIF results:

- Science: Investigate the **DIRECT DRIVE** approach which can provide the gain needed for energy production and develop pathway technologies to the commercial fusion reactor
- Technology: Address the engineering issues related to IFE: high repetition rate lasers, development of cheap targets, damages to optics, tritium breeding, …

Europe and IFE: the HIPER Project

2005-2014 European Project “HIPER” (High Power Laser Energy Research Facility)

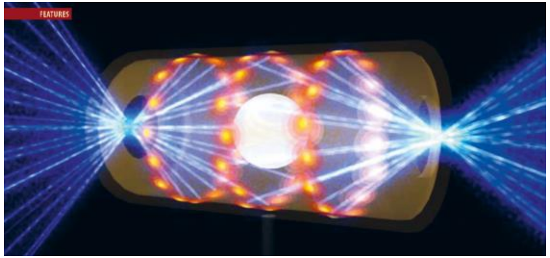


HiPER

HiPER, conceived as a large-scale laser system designed to demonstrate significant energy production form ICF, was listed on the ESFRI large scale facility roadmap and awarded preparatory phase funding (~2 M€) by the EU with additional funding from STFC, UK, and the Ministry of Education, Czech Republic, and work in kind form many other partners

The project was based on the assumption that NIF would ignite during the National ignition Campaign (2009-2012)

www.hiper-laser.org



BREAKTHROUGH AT THE NIF PAVES THE WAY TO INERTIAL FUSION ENERGY

S. Atzeni[1], D. Batani[2], C. N. Danson[3,4], L. A. Gizzi[5], S. Le Pape[6], J-L. Miquel[7], M. Perlado[8], R.H.H. Scott[9], M. Tatarakis[10,11], V. Tikhonchuk[2,12], and L. Volpe[13,14] – DOI: https://doi.org/10.1051/epn/2022106

In August 2021, at the National Ignition Facility of the Lawrence Livermore National Laboratory in the USA, a 1.35 MJ fusion yield was obtained. It is a demonstration of the validity of the Inertial Confinement Fusion approach to achieve energy-efficient thermonuclear fusion in the laboratory. It is a historical milestone that the scientific community has achieved after decades of efforts.

18 EPN 53/1

HiPER+ Project

Letter to launch an HiPER+ project has been so-far signed by more than 100 European scientists

https://www.clpu.es/Laser_Fusion_HiPER

High Power Laser

An evaluation of sustainability and societal impact of high-power laser and fusion technologies: a case for a new European research infrastructure

Part of: HPL Perspectives

Published online by Cambridge University Press: 21 September 2021

S. Atzeni, D. Batani, C. N. Danson, L. A. Gizzi, M. Perlado, M. Tatarakis, V. Tikhonchuk and L. Volpe Show author de

The HiPER+ initiative

Following the results at NIF in 2021 and the ignition shots in 2022, we have launched the HiPER+ initiative which has been so-far signed by more than 100 European scientists

- Publication of an article on the need of a new European IFE facility in HPLSE, September 2021
- Publication on inertial fusion energy in Europhysics News, February 2022
- Meeting with EUROFusion on IFE, March 2022
- Letter to European Commission, March 2022
- Contribution Report of the “HiPER+ group” to the ESFRI Landscape analysis of Research Infrastructures (April 2023) stakeholder
- May 18, 2023, Hiper+ Roadmap distributed to the scientific community

At the moment HiPER+ is structured as a consortium among individual researchers.

We believe there is a **clear need** for a coherent IFE program in Europe

- IFE development in Europe requires design and construction of a dedicated R&D laser facility to study direct-drive fusion.
- No national country in Europe can meet the challenge alone
- Staged approach and transition from a fundamental academic research to the focused programmatic R&D project, from TRL 1-3 (PROOF-OF-PRINCIPLE) to TRL 4-7 (TECHNOLOGY VALIDATION)

EUROPEAN COMMISSION
DIRECTORATE-GENERAL FOR RESEARCH & INNOVATION

Directorate C - Clean Planet
The Director

Brussels,
rtd.c.4.dir(2022)2594050

Dear Prof. Batani, Prof. Tikhonchuk,

April 2022

Thank you for your recent letters to Commissioner Mariya Gabriel and Director-General Jean-Eric Paquet, which bear the proposal for a coordinated international project on Inertial Fusion Energy (IFE) in Europe.

At the European Commission, we are well aware of the recent experimental results at the US National Ignition Facility, and of the excitement those results have prompted in the IFE community worldwide. To a certain extent, the Euratom Research and Training Programme already funds IFE research through the Enabling Research Projects of the EUROfusion consortium. The Euratom Programme, however, is strongly focused on the development of the magnetic fusion concept along the European Fusion Roadmap, and it is therefore not the right instrument to fund IFE activities at the scale envisaged in your proposal.

The European Strategy Forum on Research Infrastructures (ESFRI) appears to be a better suited framework to discuss the idea of a European IFE facility, as the HiPER project, which your proposal builds upon, was included in the 2006 ESFRI Roadmap. I recall that at least three EU Member States or Associated Countries are needed to support an ESFRI proposal. No less importantly, proposal evaluation is based on strict criteria which require that a sound scientific and business case is made upon submission. General information on ESFRI can be found in the dedicated website (https://www.esfri.eu) and further information can be requested through the functional mailbox info@str-esfri.eu.

Wishing you every success with the development of your project, I remain at your disposal for further clarification or information.

Yours faithfully,

e-signed

Rosalinde van der Vlies

What is needed – What is new

We propose a facility which will be able to demonstrate **ignition and gain in DIRECT DRIVE** and will also address the critical scientific and technical issues needed to move towards fusion reactors and commercialization of energy :

- laser architecture and conversion efficiency,
- high repetition rate,
- target production and injection...
- study of radiation damage, optics lifetime,
- first wall and mantle issues, tritium breeding, etc.

This **UNIQUE** facility will assure **European LEADERSHIP** in IFE for meeting future energy needs but also in associated technologies

- Laser energy is in the range of 1 MJ. The cost would be ~2 B€.

- Possible Prototype in Europe at few 100 kJ level engaging industry for developments. Need of high repetition rate and large bandwidth (to quench parametric instabilities), associated to PW beams for diagnostics

The design will take advantage of results obtained by/through international collaborations at NIF, Omega and other intermediate facilities.

Our view to support IFE programme in Europe

Awareness:

- Proposing to start a B€ project in Europe today is challenging.

We will therefore engage a double pathway (institutional/industrial-private) approach:

Institutional path

- Support from **ESFRI** to initiate the IFE project.
- EUROFusion and EURATOM endorsement
- Seek support to IFE activities through **ad hoc national programmes**.
- Strengthen the **IFE ecosystem** in Europe to attract investments.

Engagement of industry

- Several companies in industrial fusion attract major Venture Capital investments.
- Potential to exploit interest for HIGH PROFILE scientific research with a large technology development base.
- Europe already increasing engagement in high power, high energy laser development (e.g. Trumpf, Amplitude, Thales …).

More in general, synergy between MCF and ICF industrial effort will strongly benefit fusion technologies (reactor design, fusion diagnostics, first wall, tritium breeding, ...)

Development of public-private partnership

Embracing the concept of public-private partnerships (PPPs) within IFE can prepare the conditions for essential capital when conditions are mature. PPPs can be implemented in various ways such as:

- ✓ Conclusion of cooperation agreements.
- ✓ Laser technologies for IFE platforms.
- ✓ Collaboration studies in common IFE areas of interest.
- ✓ Technology development actions such as in targetry, diagnostics, large scale simulations, materials, reactor.
- ✓ Participation in HiPER+ training activities,
- ✓ Mutual support in lobbying strategies and dissemination activities.
- ✓ Exchange of knowledge where commonly decided.

And speaking about the development of public-private partnership ….

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

Hydrogen-Boron Fusion

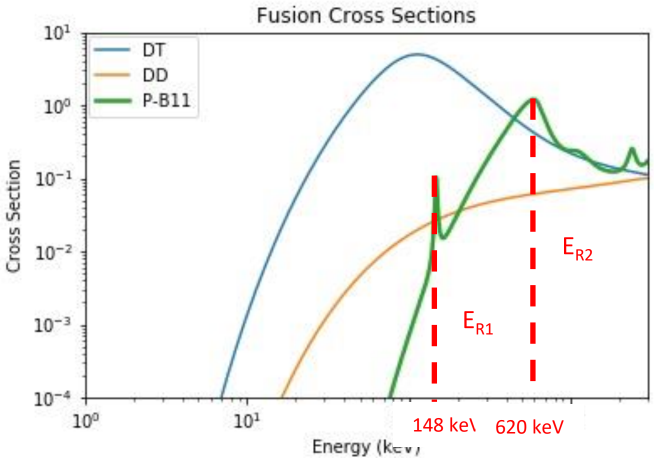
CHALLENGES

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

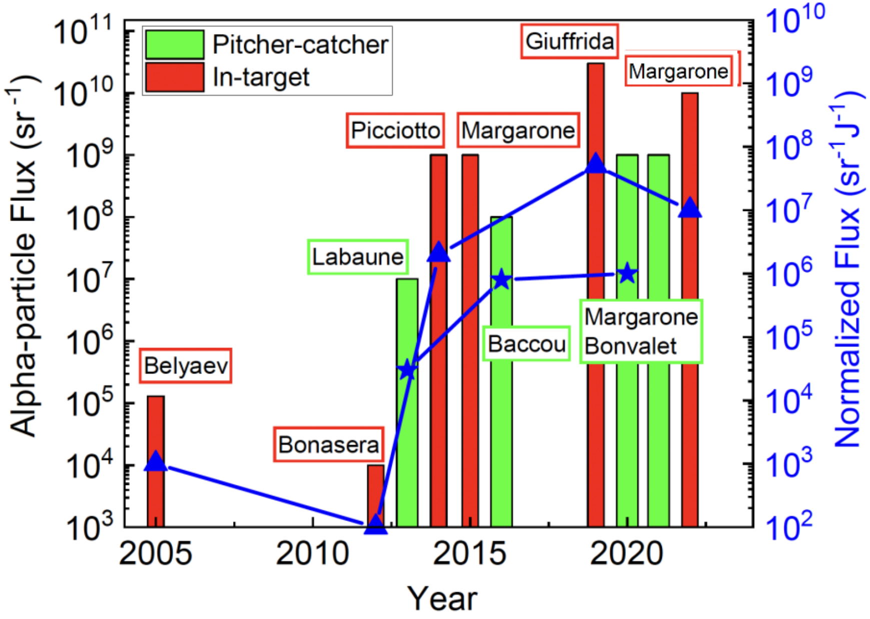
First studies by Oliphant & Rutherford,
L. Proc. R. Soc. London A 141, 259 (1933)

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

- ✓ 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



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

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

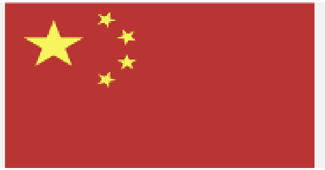
- V.S.Belyaev, et al. Phys. Rev. E 72, 026406 (2005)
- A.Bonasera, et al. Fission and Properties of Neutron-Rich Nuclei (Sanibel Island, USA: World Scientific) 503 (2008)
- C.Labaune, et al. Nat. Commun. 4, 2506 (2013)
- A.Picciotto, et al. Physical Review X 4, 031030 (2014)
- C. Baccou, Rev. Sci. Instrum 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

HB11 ENERGY

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HB11 Energy is developing Laser Hydrogen Boron-11 fusion to provide a new source of unlimited, clean, safe and reliable energy. Our mission is to generate electricity using laser-ignited non-thermal fusion.

HB11 ENERGY
LASER BORON FUSION

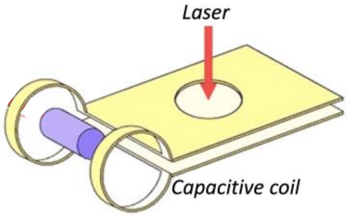
Legends of laser fusion. From left: Heinrich Hora, Nikolai Basov, Edward Teller, John Nuckolls and Chiyoe Yamanaka.

“Since the discovery of lasers in 1960, the pursuit of Hydrogen Boron-11 fusion has been my dream. Despite much skepticism over 60 years of research, this dream has come true at a time when its potential as a new source of unlimited, clean, safe and reliable energy is needed more than ever.”

– Professor Heinrich Hora
Theoretical Physicist and Founder of HB11 Energy

HB11 FUSION – LASER INDUCED MAGNETIC FIELD

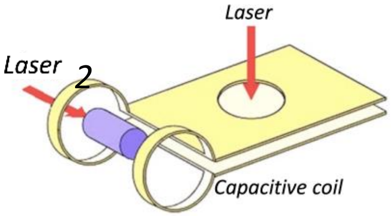
MAGNETIC CONFINEMENT
LASER AND CAPACITIVE COIL TARGET



Magnetic field confine protons and alpha particles within the target

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

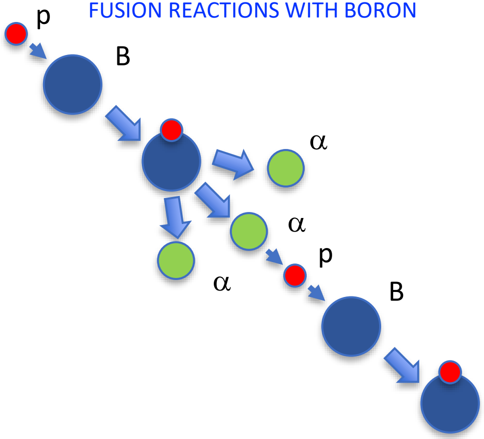
LASER ION ACCELERATION
OF HYDROGEN VIA ps LASER PULSES



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)

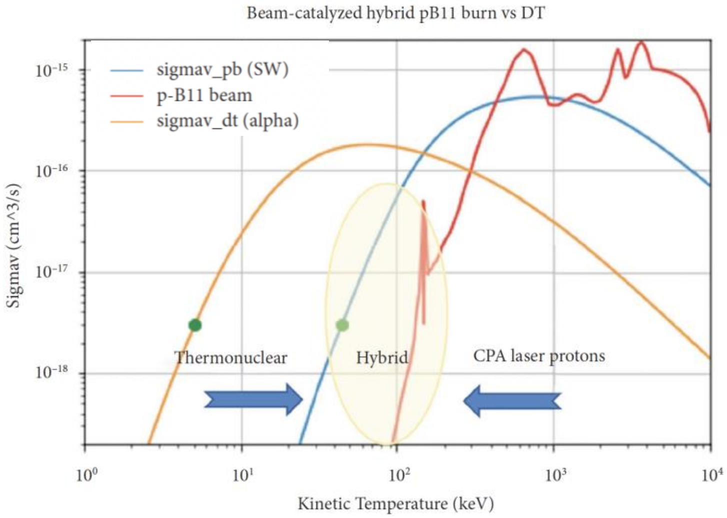
HB11 ENERGY LASER BORON FUSION

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…

The short-term scientific goal of HB11 is to work with the Academic community to understand the physics of proton-boron fusion and remove the locks toward the achievement of pB fusion for energy, and with other industrial partners to explore the technology of lasers, targets, diagnostics, …

Intermediate steps before fusion may include the development of high-brightness laser-driven sources of α-particles

HB11 ENERGY
LASER BORON FUSION

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

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- Bulgaria
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- France
- Germany
- Greece
- Hungary
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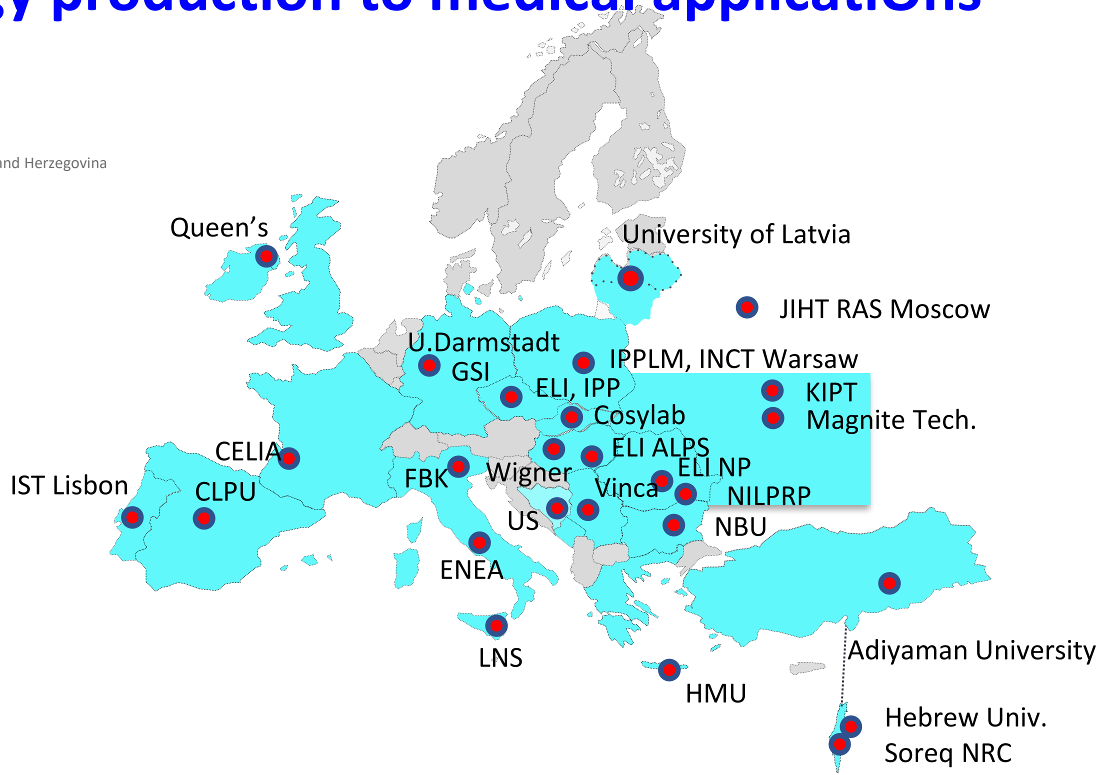
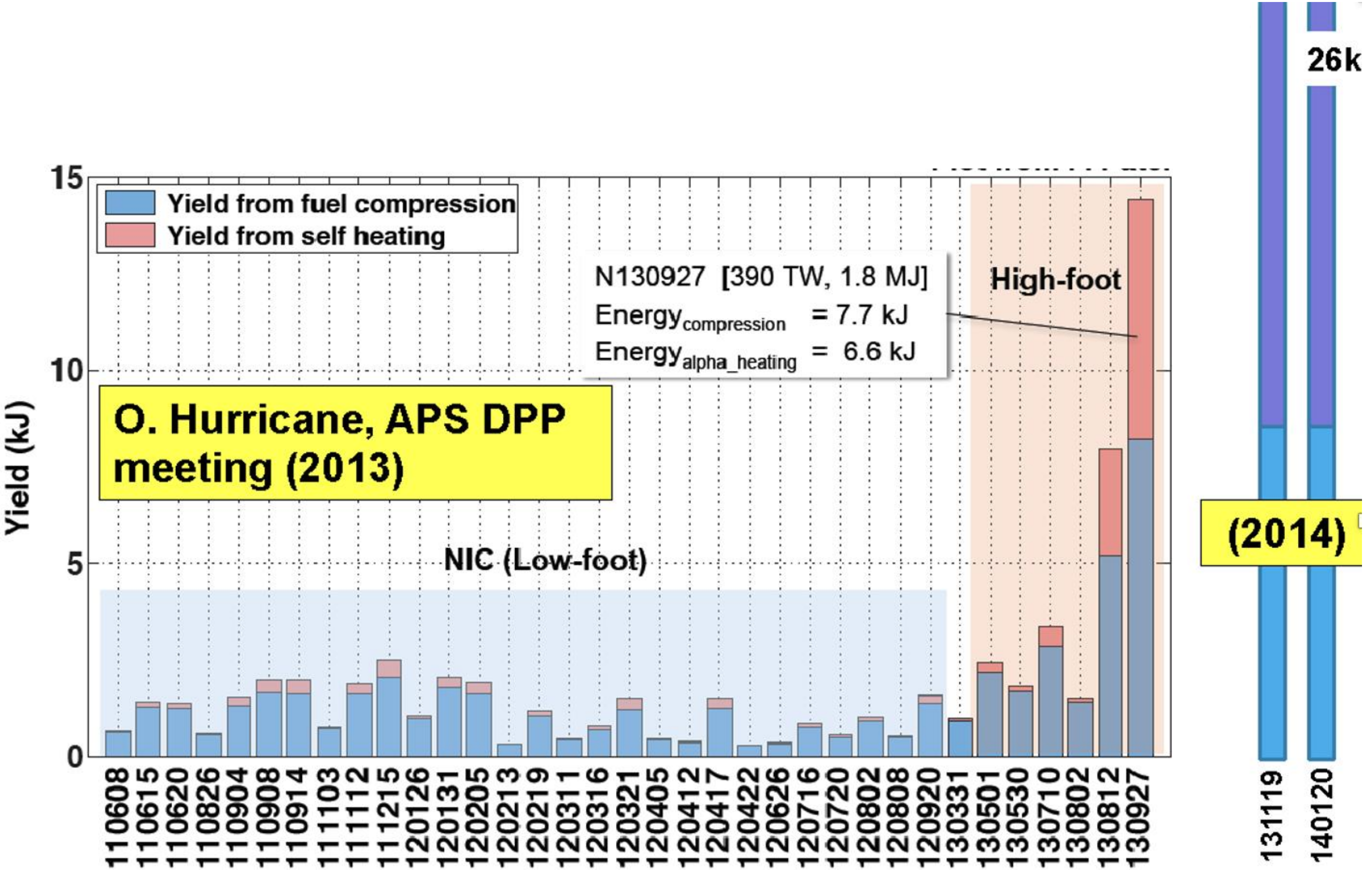
- Ukraine
- United Kingdom
- Bosnia and Herzegovina
- Latvia
- Turkey

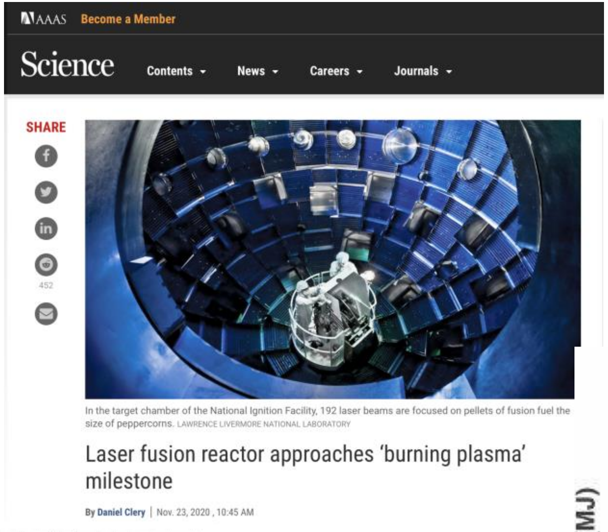


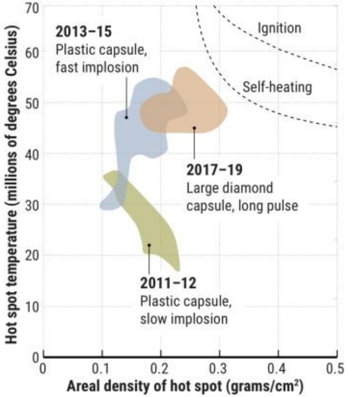
Thank you for your attention !

Long and difficult way to the success



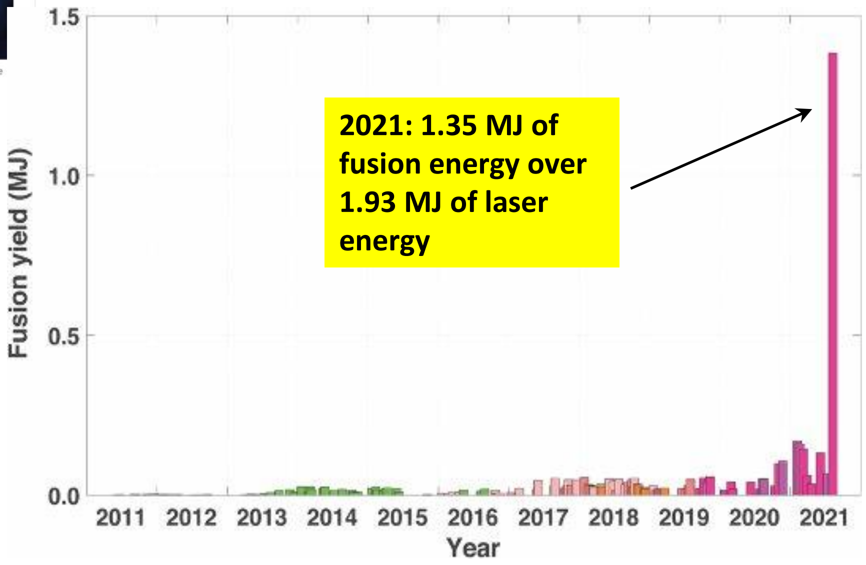
Most recent results on NIF (2020-2021)





GRAPHIC: PRAV PATEL/LLNL, ADAPTED BY N. DESAI/SCIENCE

2020: More than 150 kJ of fusion energy

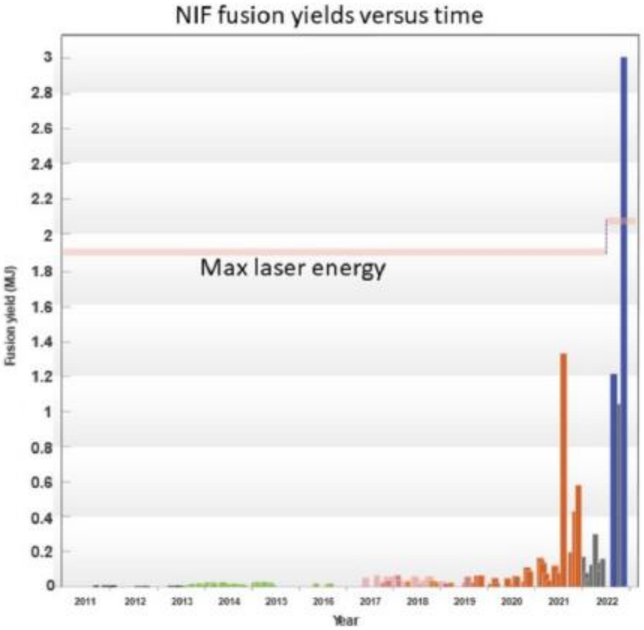


2021: 1.35 MJ of fusion energy over 1.93 MJ of laser energy

The NIF historical results

NIF historical & outstanding results announced in August 2021 and in December 2022 completely changed the perception of the inertial fusion in the world because the fundaments of laser driven fusion are convincingly demonstrated. The December 2022 result has been recently repeated

H. Abu-Shawareb et al, PRL (2022)



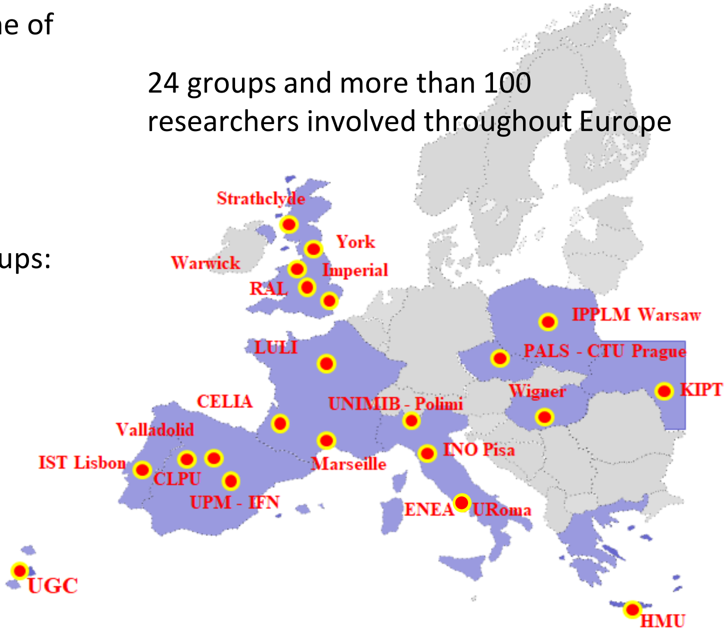
Europe and IFE: after HIPER

COST Action MP1208 «Developing the Physics and the Scientific Community for Inertial Fusion at the time of NIF ignition» 2013-2017

Laserlab Europe AISBL supports 3 ICF-related groups:
Expert group in ICF/IFE
Expert group in micro-structured materials
Expert group in laser-generated EMP

EUROFusion within Enabling Research projects.
Currently EUROFusion supports only one project related to IFE “Advancing shock ignition for direct-drive inertial fusion” at the level of $\sim 800\ k€$ (2021-2024)

24 groups and more than 100 researchers involved throughout Europe



No IFE dedicated installation
No direct support to IFE

On what we build:
The EU IFE community

Around $\sim$ 30 laboratories and $\geq$ 200 researchers

Strengths:

- Role of EU of scientists with ground-breaking contributions to ICF and important work on shock ignition done in the last 10 years within EUROFusion projects;
- Effective international collaboration in direct drive fusion (especially with the University of Rochester)
- Important, and often pioneering contributions in laser-plasma physics and applications;
- Effective international collaboration in direct drive fusion (especially with the University of Rochester, home of the Omega laser facility)

Weakness: No experience in driving implosions due to the lack of a dedicated facility

• Direct-drive implosions were done in the 70's and 80's both at the LULI and Vulcan laser facilities but soon these facilities became non-competitive.

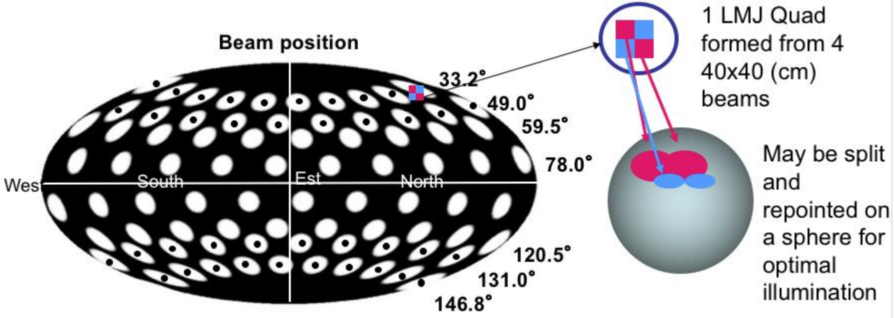
We can make the jump by federating the groups around an IFE test facility in Europe with strong international collaboration

On what we build:
Laser Facilities in Europe

- The EU IFE community can profit of large investments in Europe in high-energy laser facilities.

- Systems like Vulcan and Orion (UK), LULI2000 (France) Phelix (Germany), PALS (Czech Republic) and the three pillars of **ELI** enable the **study of the physics of direct drive inertial fusion** *(ELI previously in the ESFRI roadmap, now an ERIC)*

- Academic access to the **Laser Megajoule** (CEA/DAM): possible but extremely limited;
  - Not available to support IFE programs like Omega at Rochester.
  - Not designed for direct drive research (although configurable for PDD)



Laser Megajoule (LMJ)
At CESTA Le Barp near Bordeaux
Developed for defense application
~ 2 B€

On what we build:

Support from institutions / governments

German government has issued a document in support of development of IFE research

Additional IFE initiatives have been launched / are starting in other countries (e.g. France with Taranis project)

Interest from research agencies (CEA, CNRS, CNR, ENEA, CIEMAT, GSRT …) and countries (Greece, Spain, Italy, …)

EUROFusion is not in condition to fund a HiPER-sized facility but is committed to continue to support Enabling Research projects on IFE

European Leadership in Laser Companies

Europe has the lead in advanced laser Technologies with companies like **Thales**, **Amplitude** (France), **Trumpf** (Germany), …

Consolidated industrial experience in Large Facilities

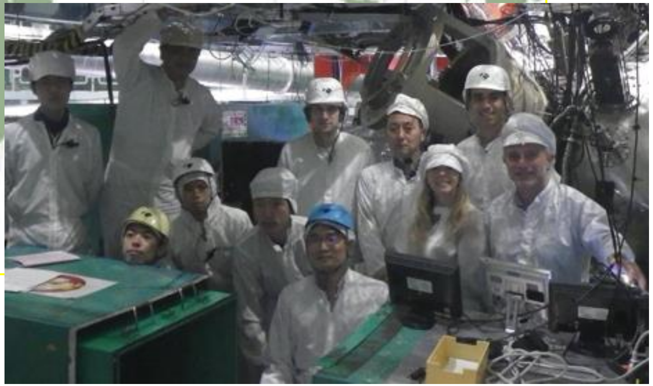
European industry as a major actor of realisation of large research facilities (CERN, European Spallation Source, ITER, XFEL, IFMIF-DONES …)

On what we build:
The International Dimension

After NIF results, US are establishing for the first time an IFE program

New initiatives in Russia, China, Japan

These countries have research programs in both MCF and ICF



Experiment at the laser Gekko, Osaka

The European IFE roadmap of the HiPER+ project

		Years 1-10	Years 11-20	Years 21-30
		R&D IFE	Pilot IFE reactor	DEMO-IFE reactor
A	Physics and technology of IFE.	Achievement of robust ignition. Addressing physics issues, choosing reactor target design.	Optimization of the target performance. Demonstration of reactor operation in burst mode.	Development of IFE operation: improving efficiency, robustness and safety.
B	Development of IFE laser technology. Construction of IFE laser systems.	Development of broadband DPSSL HRR laser technology. Design of laser module prototype. Optics development. Construction of multi-beam sub-ignition facility.	Design of high-gain laser facility operating in a burst mode. Development of supply chain. Resolving issues related to long-term laser operation.	Optimization of the IFE laser technology. Industrial production laser modules for the power plant. Design of DEMO-IFE facility.
C	Material science and reactor technology	Development of resistant optical materials. Identification of adequate materials for chamber construction and protection. Design of target insertion and tracking system. Development of EMP mitigation strategies	Development of a laser-based neutron source and material testing. Mass-production target technology. Resolving security and safety issues. Bases for tritium breeding and handling system.	Final layout assembly of tritium and cooling systems and the energy recovery system. Design of the system of material control, replacement and refurbishing.
D	IFE community building, project management and development	Development of joint numerical tools, coordination of experimental activities. Personnel training. Collaboration with industry and private companies.	Design of a commercial fusion reactor. Establishing an educational and training system for the power plant exploitation	Integrated approach to the IFE power plant operation. Conception of the full lifetime power plant. Licensing and regulations.

Future for Inertial Fusion Energy in Europe: A roadmap

D. Batani[1], A. Colaïtis[1], F. Consoli[2], C. N. Danson[3,4], L. A. Gizzi[5], J. J. Honrubia[6], T. Kühl[7], S. Le Pape[8], J.-L. Miquel[9], J. M. Perlado[10], R. H. H. Scott[11], M. Tatarakis[12,13], V. Tikhonchuk[1,14], and L. Volpe[6,15]

HiPER+ timeline

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

Horizontal structure: timeline

R&D	Pilot IFE reactor	DEMO-IFE reactor

Vertical structure: major axes of research & technology development

A: physics & technology for IFE	B: development of IFE laser technology	C: material science & reactor technology	D: development of community, coordination & management

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

Conceptual Development: HORIZON-INFRA-2024-DEV-01-01: Research infrastructure concept development, Deadline March 2024 ?