Future for Inertial Fusion Energy in Europe

Dimitri Batani – University of Bordeaux
On behalf of the HIPER+ Coordination group

HiPER+
EUROPEAN LASER FUSION ENERGY

The future of Inertial Fusion Energy in Europe
The HIPER+ proposal

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- Michael Tatarakis, director, Institute of Plasma Physics and Lasers, Hellenic Mediterranean University, Rethymno, Greece

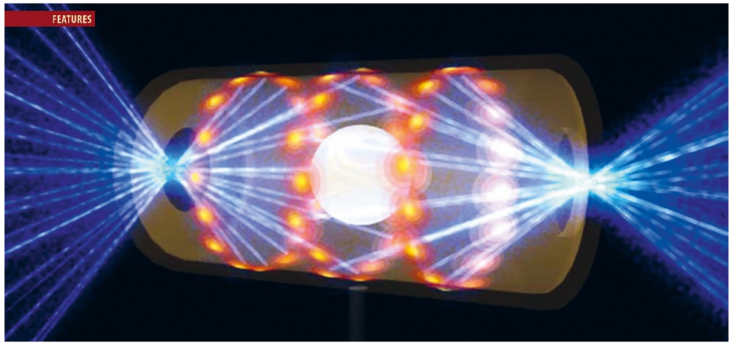
The voyage of nuclear fusion has started about 80 years ago (Sacharov, Teller, …) and despite progress has provided many disillusions…

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

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

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.

Large impact of NIF results



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

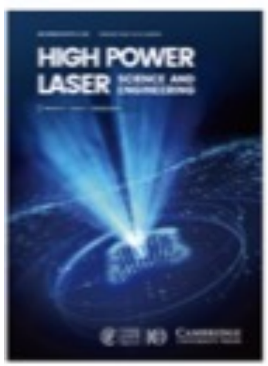
HiPER+ Project

Letter to launch the HiPER+ project has been so-far signed by more than 150 European scientists

https://www.clpu.es/Laser_Fusion_HiPER

Contribution Report of the "HiPER+ group" to the **ESFRI Landscape analysis** of Research Infrastructures (April 2023)

Contacts with **EURATOM, EUROFusion**



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

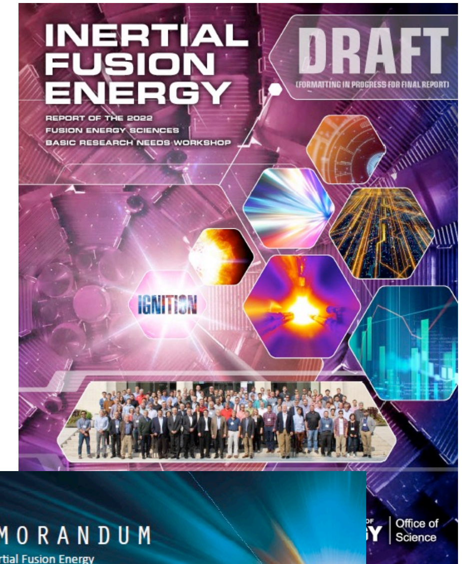
Part of: HPL Perspectives

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

Large impact of NIF results

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



For the first time in the U.S., they think on the possibility of developing national projects on Inertial Fusion Energy (IFE) as a future source of energy

- **Basic Research Needs** report: a foundational guide for DOE to establish a national IFE program in the USA

Germany has suddenly changed its attitude towards IFE

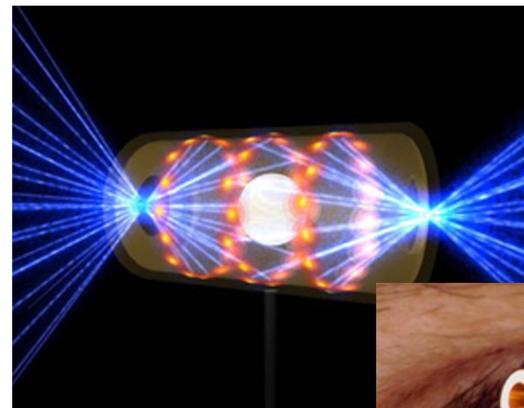
- **Memorandum** on laser IFE for the federal ministry of education and research of Germany (May 2023) and more recently statement of allocation of 1 B€ to fusion research

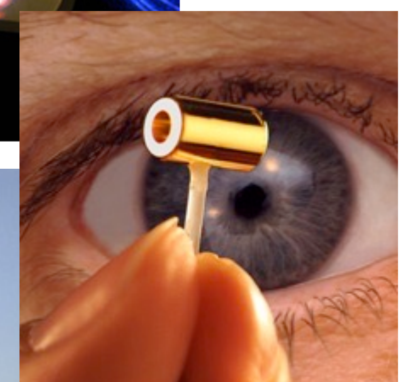
German scientists immediately got involved within HiPER+. Creating even larger collaboration with the German scientific community is a priority or HiPER+

Inertial Fusion beyond NIF results

NIF results represent a breakthrough. However, INDIRECT DRIVE used at NIF **does not seem 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:

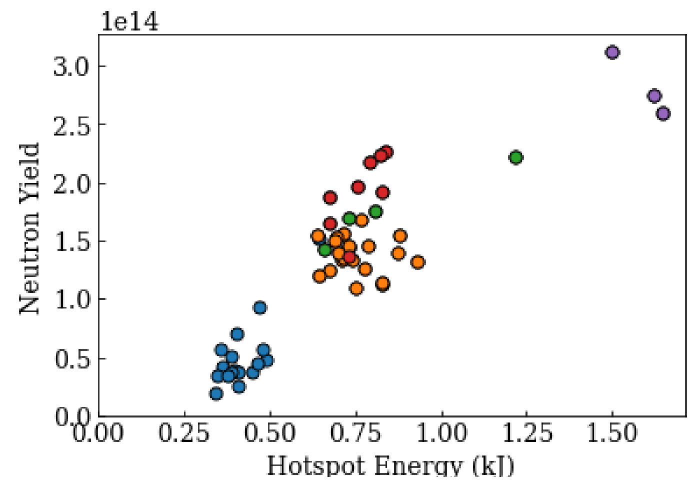
- Science: Investigate the **DIRECT DRIVE** approach which can provide the gain needed for energy production
- Technology: Address the engineering issues related to IFE: high repetition rate lasers, target development, damages to optics, tritium breeding, …

Progress in direct drive experiments

Recent experiments at **OMEGA** show a steady progress in the **DIRECT DRIVE** experiments: increase of neutron yield by 10 times and energy coupling to the hot spot by 6 times (recent experiments used a **deep learning approach** to optimize implosions).

DIRECT DRIVE EXPERIMENTS AT OMEGA: 30 KJ

Laser direct drive experiments couple 3-6 times more energy to the hot spot compared to the NIF indirect drive experiments



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

However, we know that Direct Drive is more subject to the growth and the impact of **hydro instabilities** which distort the target during implosion and may finally break it

How to mitigate the impact of hydro instabilities in Direct Drive?

Separation of the compression phase and the ignition phase

Fast Ignition exotic and non-scalable physics

requires $\geq 100\ kJ$ 10 ps laser facility ☹

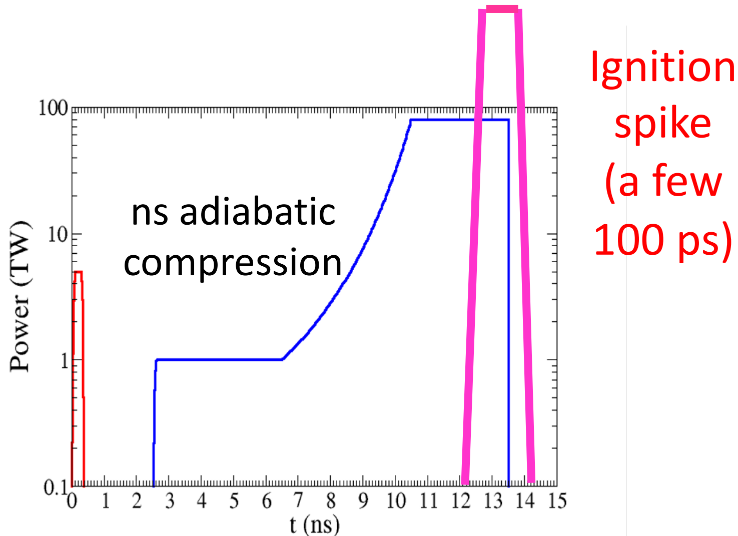
Shock Ignition compatible with present-day laser technology ☺

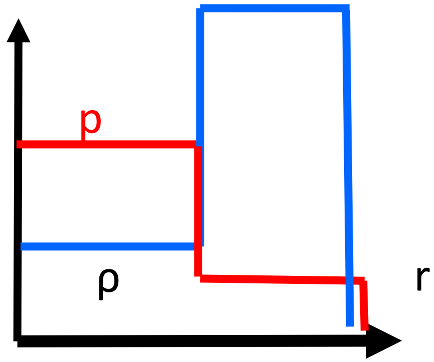
Shock Ignition

- 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 at lower implosion velocity V ≈ 240 km/s are intrinsically more resistant against the effect of hydro instabilities

- A final laser spike launches a strong converging shock (≥ 300 Mbar at the ablation front). This requires laser intensities ≈ $10^{16}\ W/cm^2$





- Non isobaric fuel assembly implies higher gains

A Shock-Augmented approach to Laser Fusion

Concept:

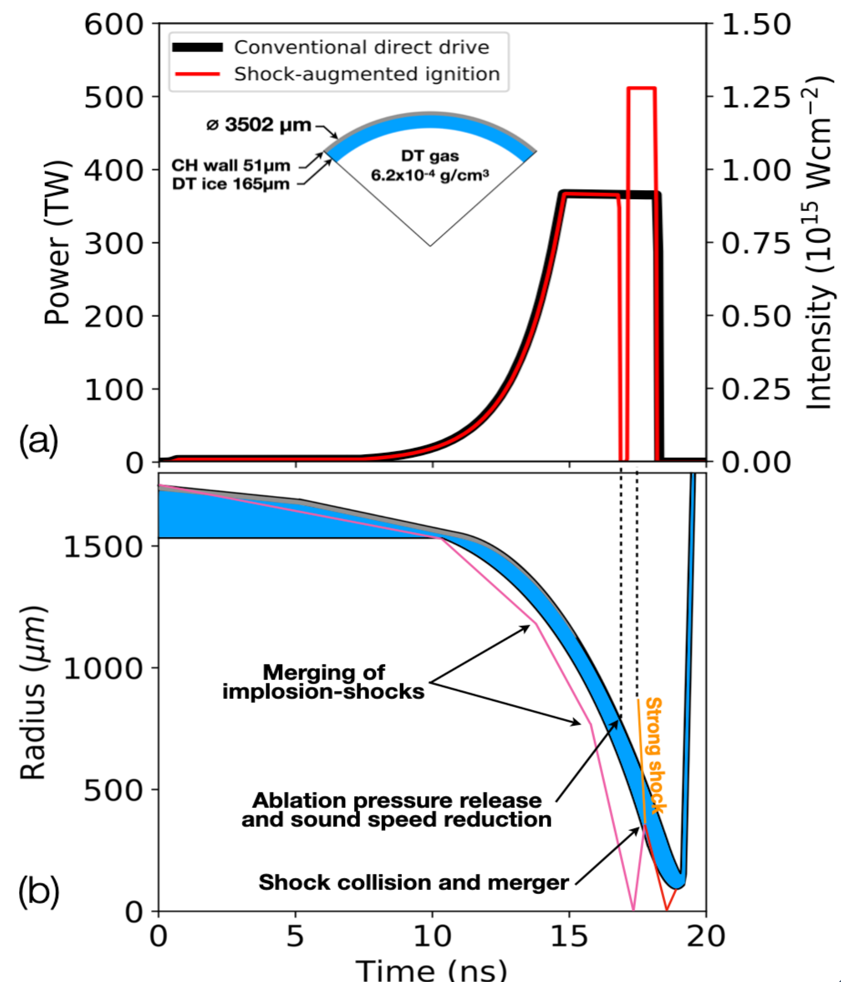
- Generate a very strong shock without very high power or intensity
- Mitigate the challenges related to parametric instabilities and hot electrons

Method:

- Dip in power: pre-conditions ablation plasma
- Rise in power: launches strong shock

Preliminary experiments done at Omega and NIF

R.Scott et al., *Physical Review Letters* (2022)



Needs for direct drive and shock ignition

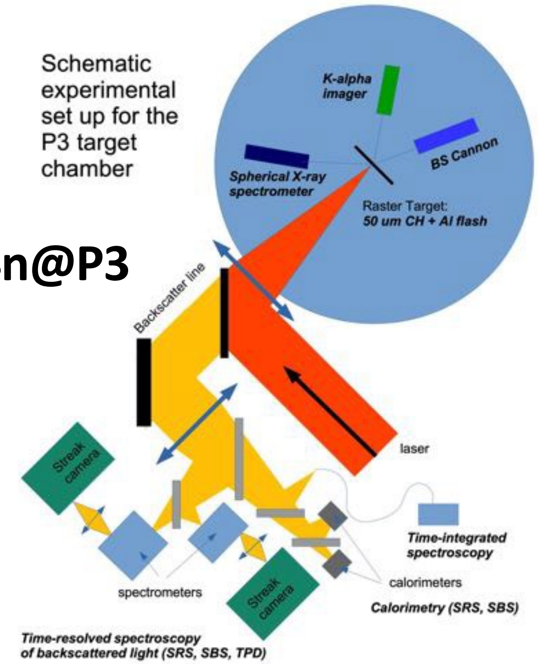
- Interesting physics needs to be understood and mastered:
  - Parametric instabilities (and CBET)
  - Hot electrons generation and their impact
  - Acceptable degree of non uniformity in irradiation during compression / ignition phases
  - Polar Direct Drive ?
- Development of a full program relies on:
  - Scientific credibility: physics issues addressed using intermediate-scale facilities: in Europe (PALS, ORION, Vulcan, Phelix, LULI), in the US (OMEGA), in Japan (Gekko), in China (SG II UP, SG III P), …
  - International collaboration is a key issue
- ELI pillars can play a vey important role:
  - Allows studying much of the physics of direct drive and shock ignition:
    - Parametric instabilities and hot electron generation and their effects
    - Hydrodynamics and Shock generation vs. Laser pulse profile
    - Optimization of ablators for IFE targets, Use of foam targets
    - Diagnostics development including laser-driven secondary sources
    - Comparison with advanced simulations
- *Need for a programmatic mission-oriented access !!!*
    - We are ready to identify research items to be investigated on ELI facilities and contribute to writing a “White paper” if needed

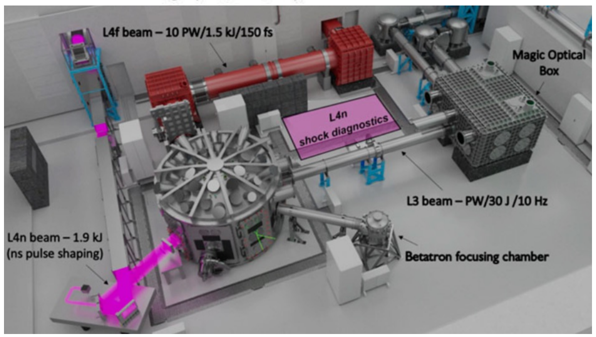
ELI L4n: User Assisted Commissioning Experiment

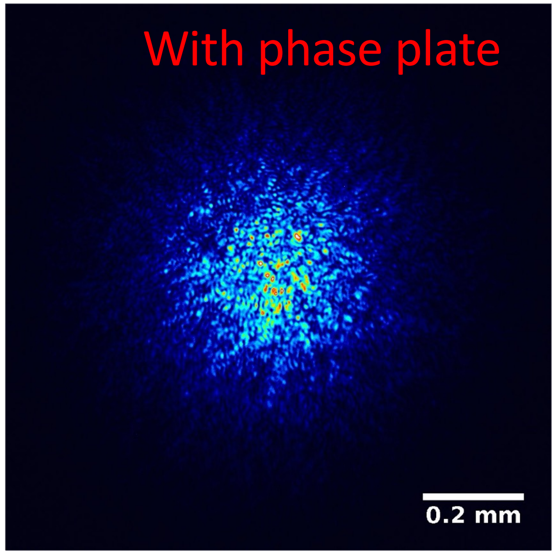
LPI studies for ICF Shock Ignition at ELI Beamlines, including role of bandwidth

L.A. Gizzi, S. Atzeni, D. Batani, G.Cristoforetti, K. Batani, P. Koester, K.Lancaster, N.F. Wasser, N. Woolsey

L4n@P3







- Laser pulse is frequency doubled, ω = 1053.2 nm → 2ω = 526.6 nm
- Employed **narrowband** and **broadband** laser profiles
- Streak images with the FABS diagnostic: bandwidth of **2.7 nm** for the **broadband/chirped**

SINGLE pulse experiment

1. **Interaction with thin and thick targets**
2. **SRS, TPD, SBS, for narrow band and broadband/chirped**
3. **Time resolved spectroscopy**
4. **Calorimetry**
5. **Fast electrons**

Preliminary

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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 quench parametric instabilities)

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

Today, laser systems like L4n at ELI-beamlines already offer higher repetition rate (≈ 1 shot /min) and larger broadband…

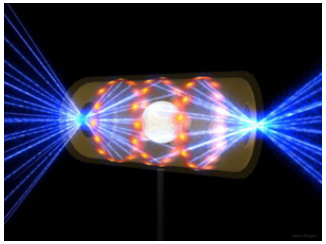
Challenge 2: Targets

- Today's cryogenic target costs ≈ 10000 \$.
- They require many days of preparation and characterization
- They need $\approx$ hour to be inserted 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 !!



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.
- Facing the problem of huge EMP
- 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)

HIGH POWER LASER
SCIENCE AND ENGINEERING

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doi:10.1017/hpl.2023.80

REVIEW SPECIAL ISSUE ON ICF

Future for inertial-fusion energy in Europe: a roadmap

Dimitri Batani[1], Arnaud Colaïtis[1], Fabrizio Consoli[2], Colin N. Danson[3,4], Leonida Antonio Gizzi[5], Javier Honrubia[6], Thomas Kühl[7], Sebastien Le Pape[8], Jean-Luc Miquel[9], Jose Manuel Perlado[10], R. H. H. Scott, Michael Tatarakis[12,13], Vladimir Tikhonchuk[1,14], and Luca Volpe[6,15]

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.

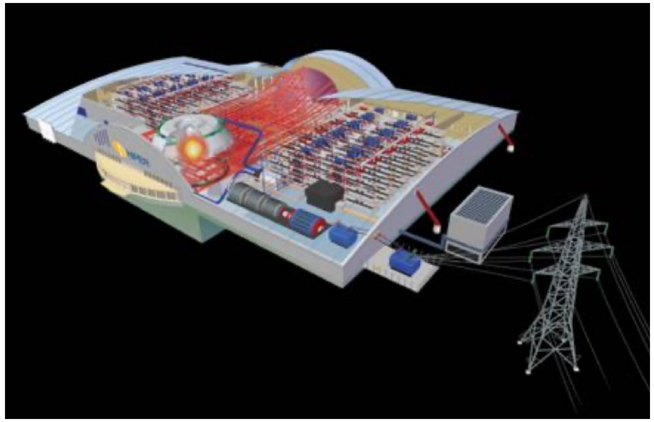
This **UNIQUE** facility will enhance the level of IFE research in Europe and create conditions for European leadership in associated technologies

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

- Possible Prototype at few 100 kJ level engaging industry for developments. Need of high repetition rate and large bandwidth, associated to PW kJ beams for diagnostics

On what we build: The EU IFE community

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 from 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

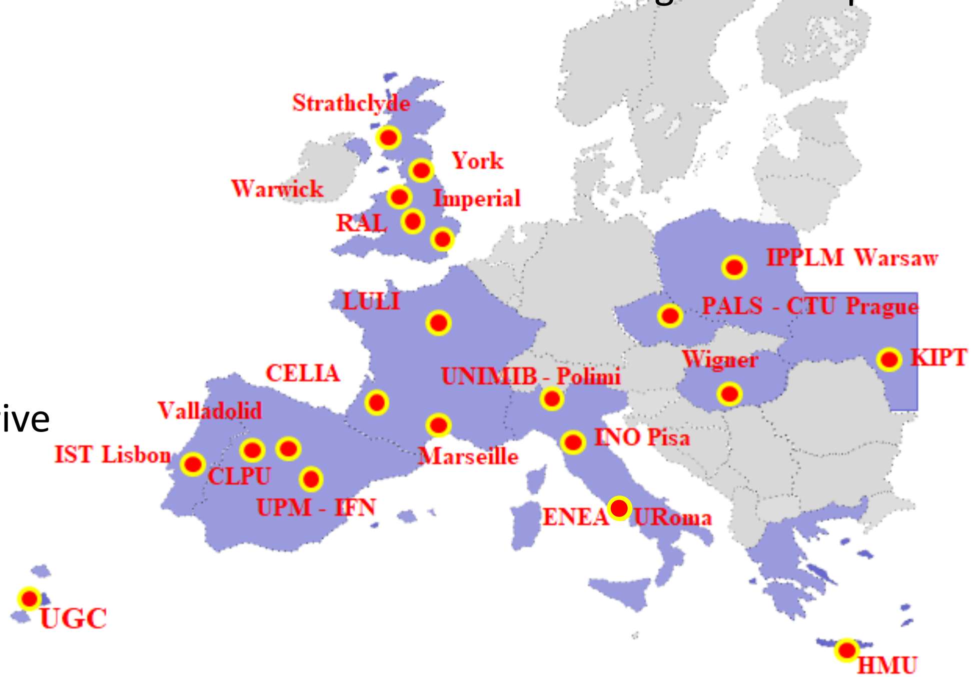
On what we build: The EU IFE community

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
EUROFusion supports projects related to direct-drive and shock ignition at the level of $\sim 300\ k€$ /year (2017-2024)

24 groups and more than 100 researchers involved throughout Europe



On what we build:
The EU IFE community

Around ~ 30 laboratories and ≥ 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;
- 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.

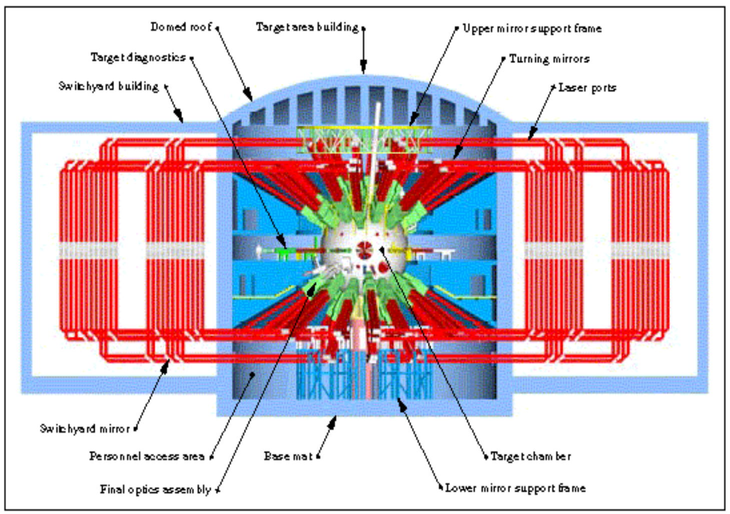
We can make the jump by federating the groups around an IFE test facility in Europe with strong international collaboration

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 **ELI pillars** enable the **study of the physics of direct drive inertial fusion**

- 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:
The International Dimension

Experiment at the laser Gekko, Osaka

On what we build:

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 …)

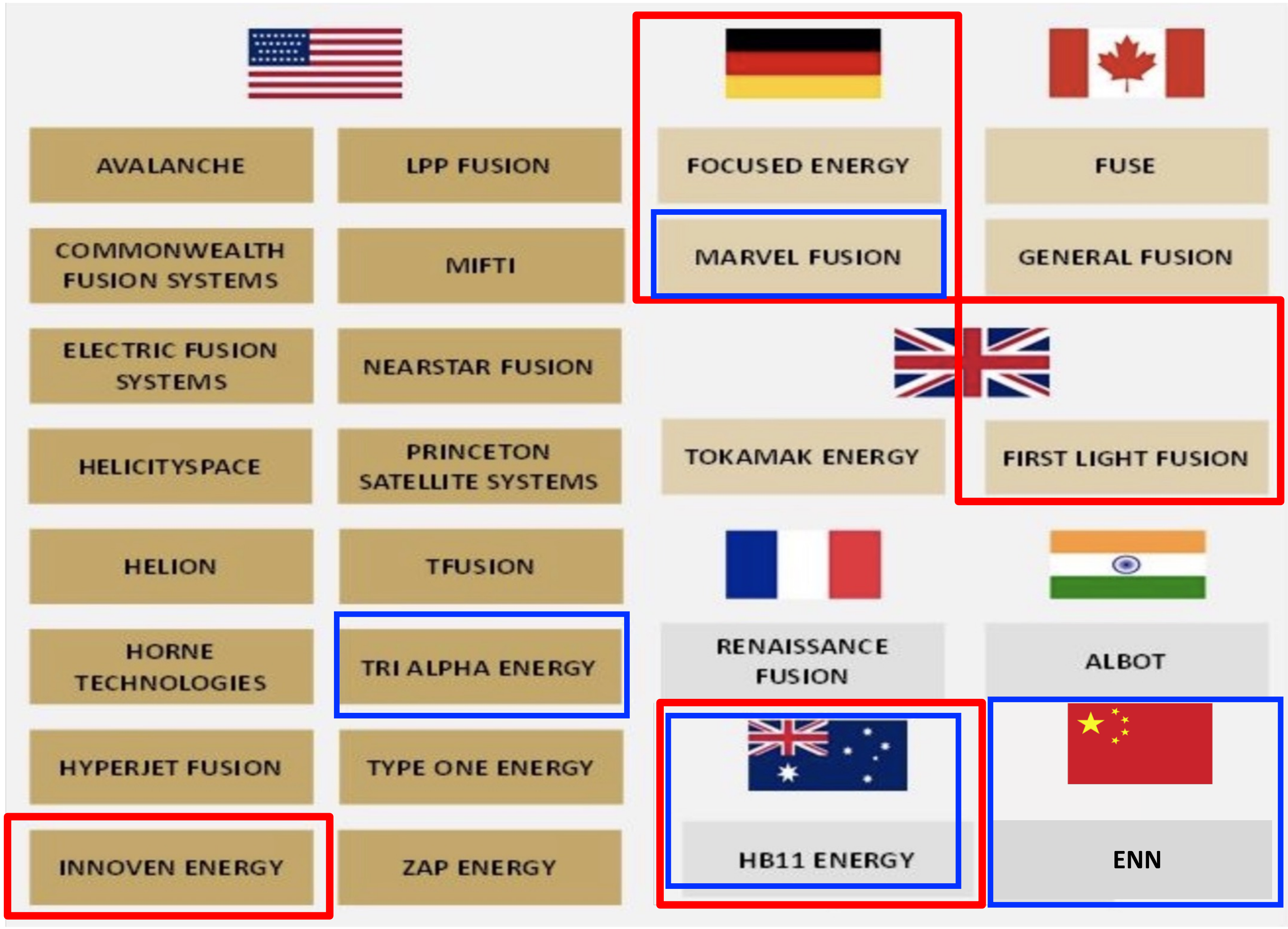
Awareness:

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

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

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

On what we build: the company context



Inertial fusion

Proton boron fusion

Synergy with companies and start-ups could accelerate the realisation of projects in IFE

HiPER+ and the world around

- **The HiPER+ project has the vocation to be inclusive. We want to assemble the wider European scientific community related to laser-plasmas and IFE**

  We are very open to wide collaborations, and this includes research on alternative approaches (fast ignition, magnetized inertial fusion, proton boron fusion). A diversified research on IFE is very important at this stage.

  However, at the level of European projects, it is also our duty to show what is the **most reliable approach** to be pursued now and in the next decade…

- **There are private initiatives to build laser facilities for IFE studies (Taranis in France, Focused Energy in Germany).**
  There is no contradiction between such projects and our initiatives. On the contrary if realized such projects could be a «seed» of a larger HiPER+ facility.
  Indeed, no European countries (nor company) has the possibility to pay and build for a full-scale ignition facility
  Also, a critical mass of scientists is needed, and it is possible to get it only at the European level

HiPER+ timeline

3 major steps of 10 years each: produce knowledge, build the 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**

Synergies with companies and national projects could somewhat accelerate this time scale…

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 reached 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

HIPER+ in summary

The unique European value of our HiPER+ proposal is based on:
- Truly European profile of the initiative for EU cooperation for IFE
- Legacy of the previous European HiPER project
- Continued collaborative scientific activity based on COST and EUROFUSION projects
- Open and continued effort through position papers and invitation letters in engaging the whole community and leading ICF groups, avoiding fragmentation to be a credible and properly sized community in front of National and EU funding agencies
- Engagement of discussion with EURATOM, ESFRI, and EUROFUSION representatives.

The proposed Direct drive shock-ignition scheme is being put forward with priority because:
- Previous studies in HiPER showed major laser challenges for other schemes (e.g. p/e fast ignition)
- Existing ICF installations are partially compatible with Shock Ignition making full scale studies possible soon
- Most activities carried out within EUROFUSION projects were oriented to Shock Ignition making the science case reliable and sound
- DD-SI has only moderate implications with defense applications, reducing the risk of potential dual-use claims: No obvious dual use is a founding approach of HiPER+

The HiPER+ approach is inclusive and aware of all private initiatives but:
- HiPER+ sees IFE as a long-term scientific enterprise that needs to address major scientific challenges through open scientific research
- HiPER+ does not share the view of those that claim achievement of commercial fusion in a short timescale
- Industrial or commercial approach is highly valued by the HiPER+ community for the development of components (e.g. laser, targets, materials ...) and novel / complementary approaches
- HiPER+ is looking forward to cooperating with private companies for future research and developing projects and initiatives.

HIPER+ and ELI

ELI offers a full set of advanced laser facilities which will allow studying much of the physics of direct drive and shock ignition, in particular:

- Parametric instabilities and hot electron generation and their effects
- Hydrodynamics and Shock generation vs. Laser pulse profile
- Optimization of ablators for IFE targets, Use of foam targets
- Diagnostics development including laser-driven secondary sources
- Comparison with advanced simulations

But also:

- Fast pulsed neutron sources
- Target injection
- Laser technology, …

The high-repetition-rate of ELI facilities offers a unique possibility of conducting parametric studies and optimizing parameters.

In order to take advantage of these possibilities we need a mission-oriented access (peer-reviewed but programmatic).

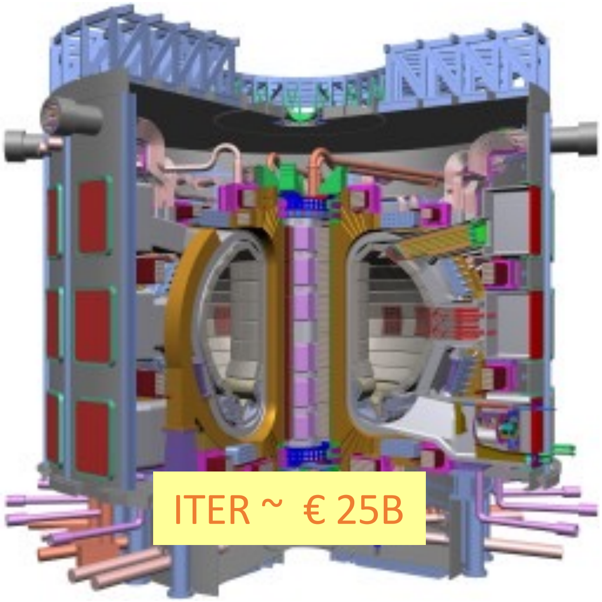
The HiPER+ teams already performed a first experiment at ELI to study laser plasma interactions and impact of parametric instabilities.

We are ready to contribute to identify research items to be investigated on ELI facilities

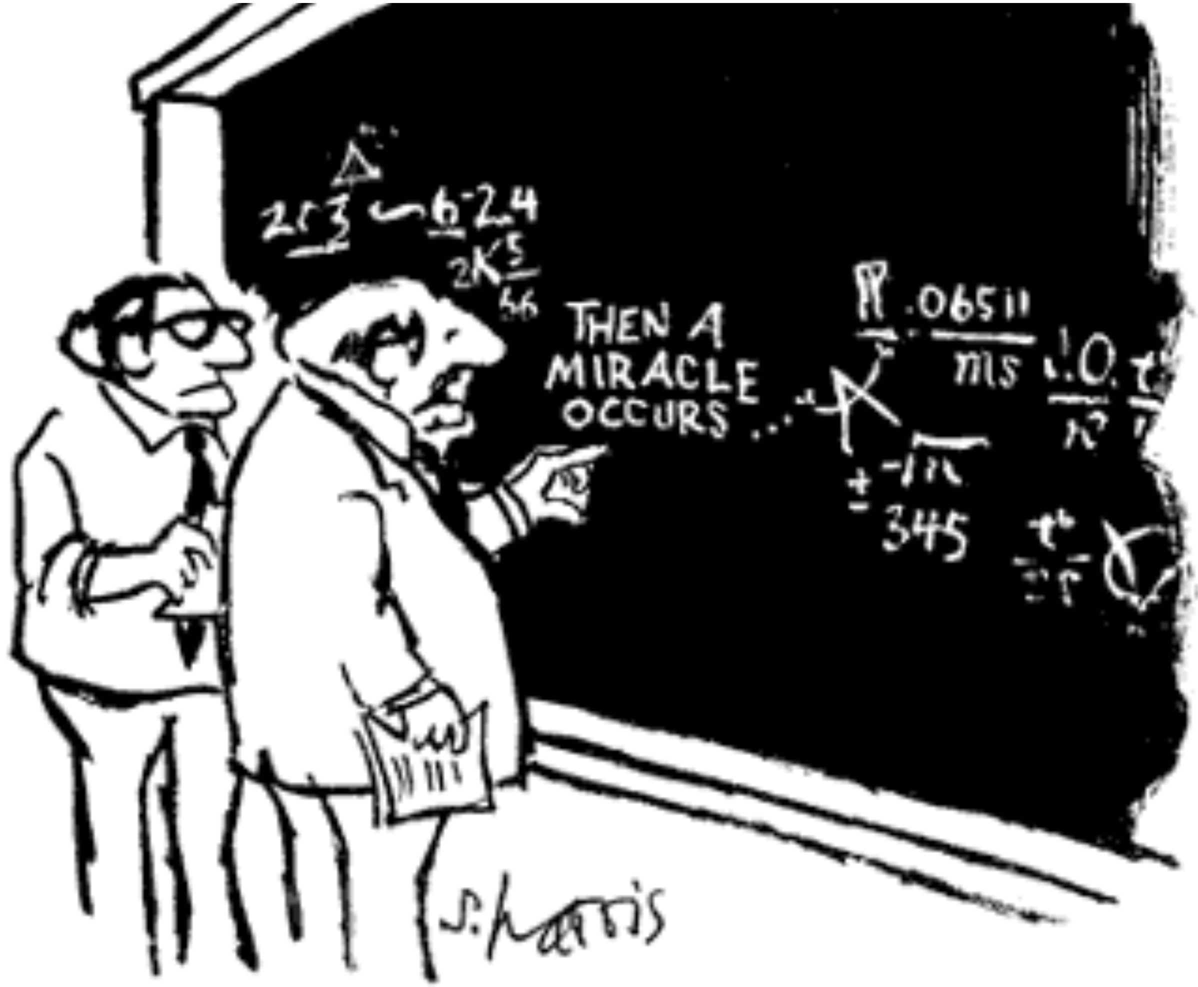
Conclusions:

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…

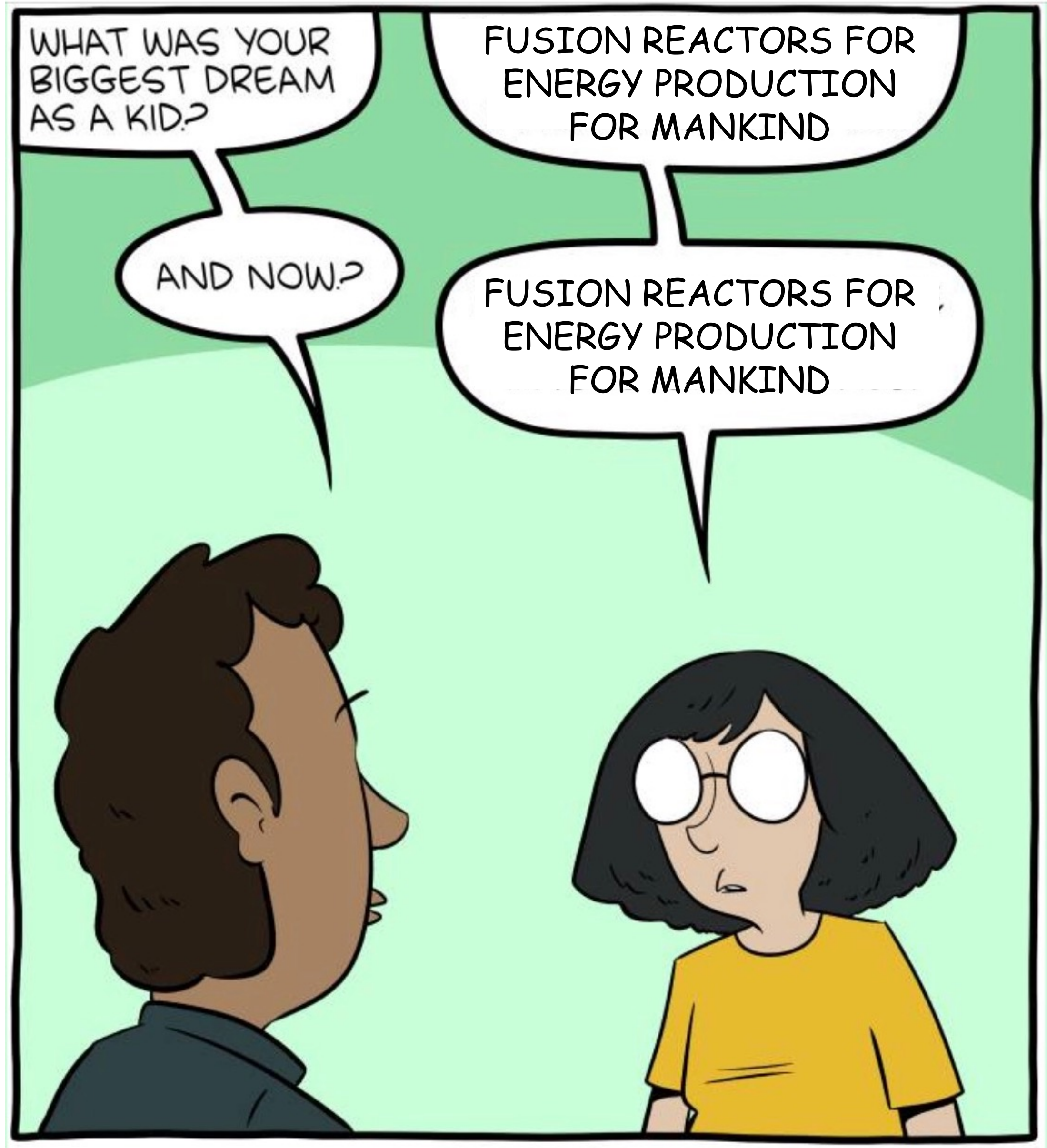


Not everything is understood yet !



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

But for the first time in history the dream may become true !



Thank you for your attention !