Future for Inertial Fusion Energy in Europe

IFE Facility Opportunities- Hiper+

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

HiPER+
EUROPEAN LASER FUSION ENERGY

Inertial Fusion beyond NIF results

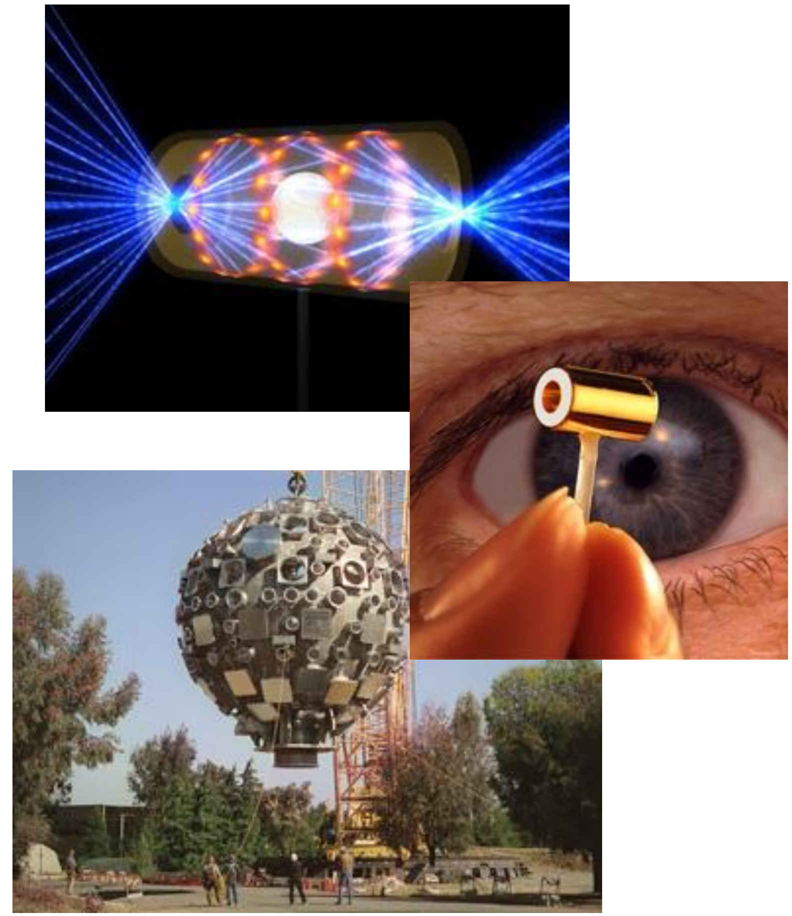
NIF results represent a breakthrough. However, INDIRECT DRIVE used at NIF **does not seem compatible** with requirements for future fusion reactors:

- 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, …

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

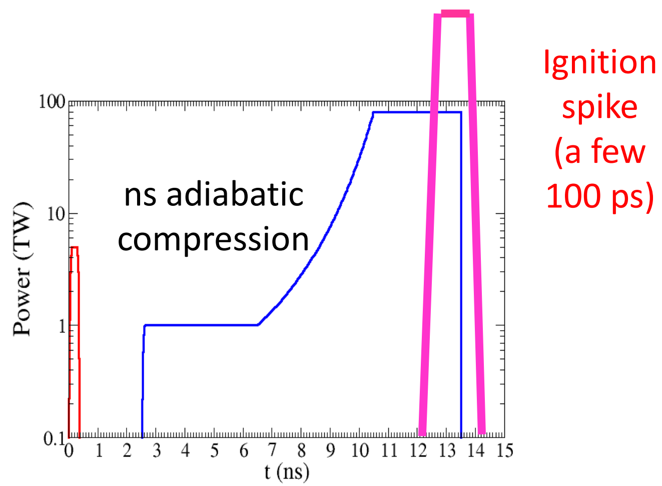


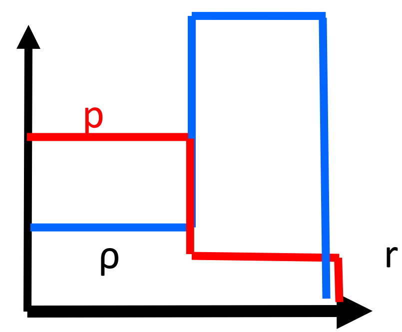
How to mitigate hydro instabilities in Direct Drive?

Separation of compression and ignition phases

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
- Compatible with present-day laser technology ☺

A Shock-Augmented approach to Laser Fusion

Concept:

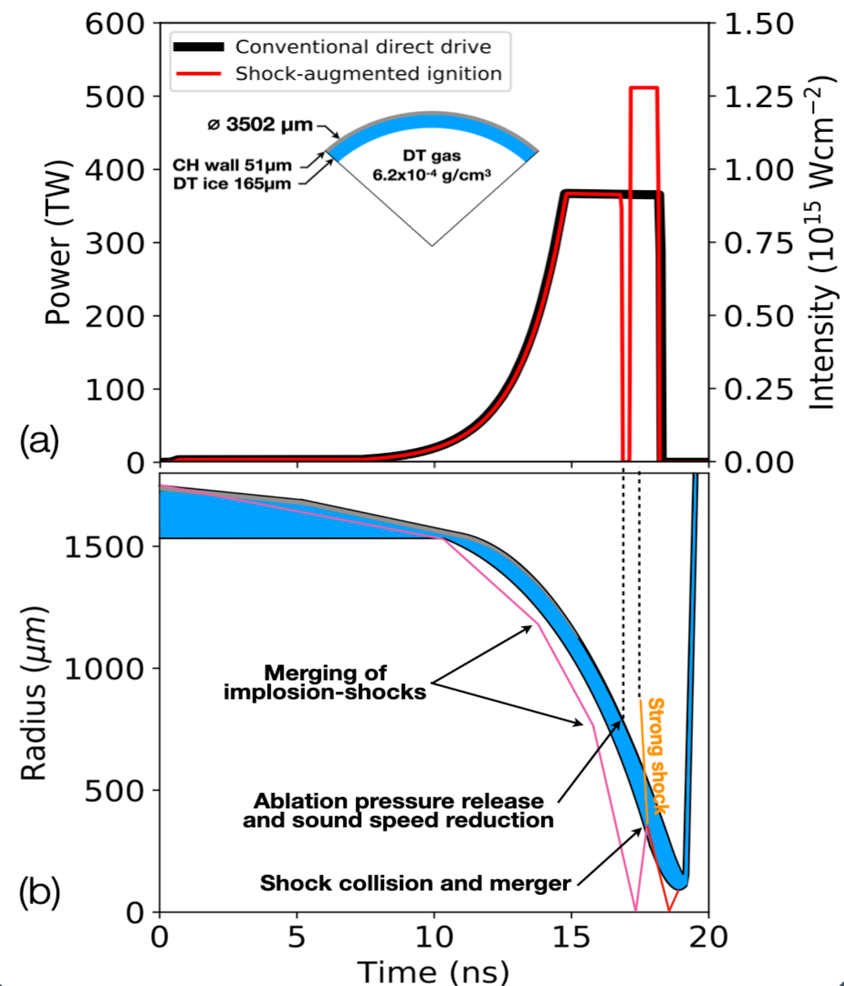
- Generate a very strong shock without very high power or intensity
- Mitigate the challenges related to parametric instabilities and hot electrons

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
- *Need for a programmatic mission-oriented access !!!*
- *Technical challenges to be addressed*

Challenge 1: Lasers

- Today's laser efficiency (electricity to laser energy) is < 1%
- NIF, 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…

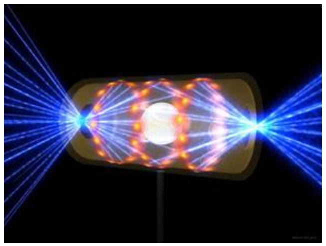
Challenge 2: Targets

- 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)

The HiPER+ Project

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HIGH POWER LASER SCIENCE AND ENGINEERING

REVIEW

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[11], Michael Tatarakis[12,13], Vladimir Tikhonchuk[1,14], and Luca Volpe[6,15]

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

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.

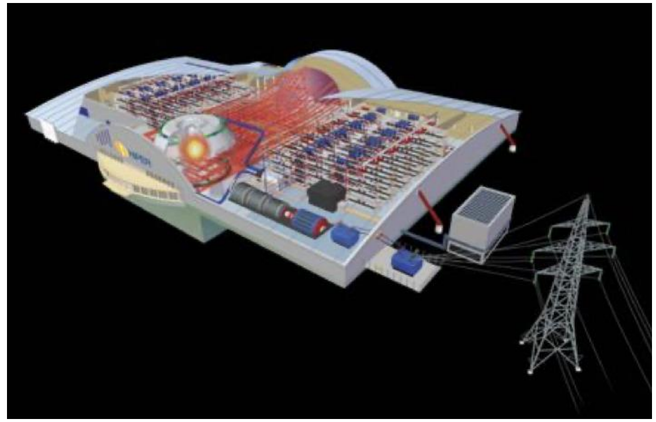
This **UNIQUE** facility will enhance the level of IFE research in Europe and create conditions for European leadership in associated technologies

- 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, 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 ~ 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.

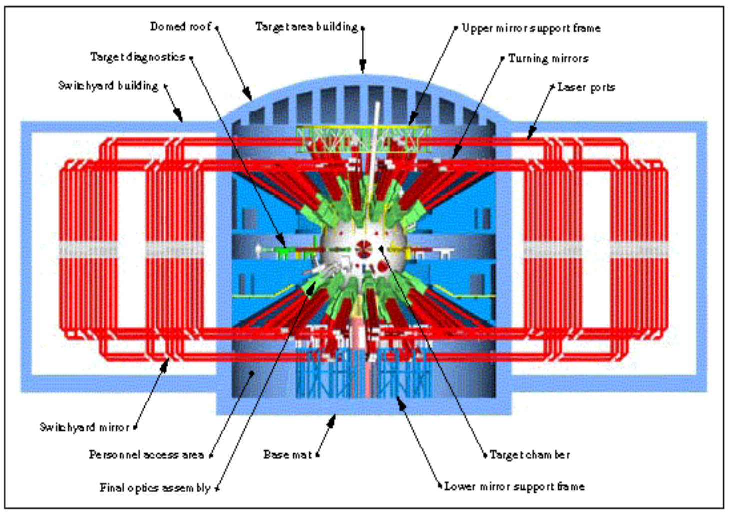
We can make the jump by federating the groups around an IFE test facility in Europe with strong international collaboration

On what we build:
Laser Facilities in Europe

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

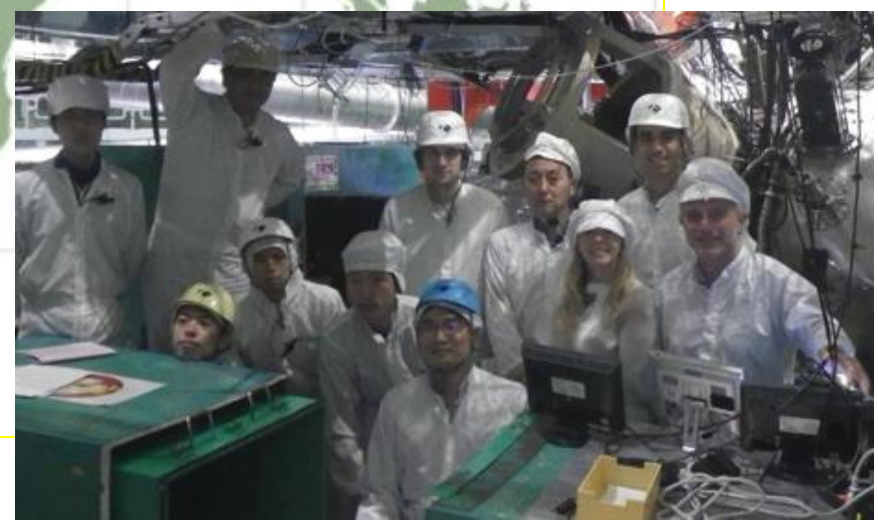
- Systems like Vulcan and Orion (UK), LULI2000 (France) Phelix (Germany), PALS (Czech Republic) and the three **ELI pillars** enable the **study of the physics of direct drive inertial fusion**

- 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 …)

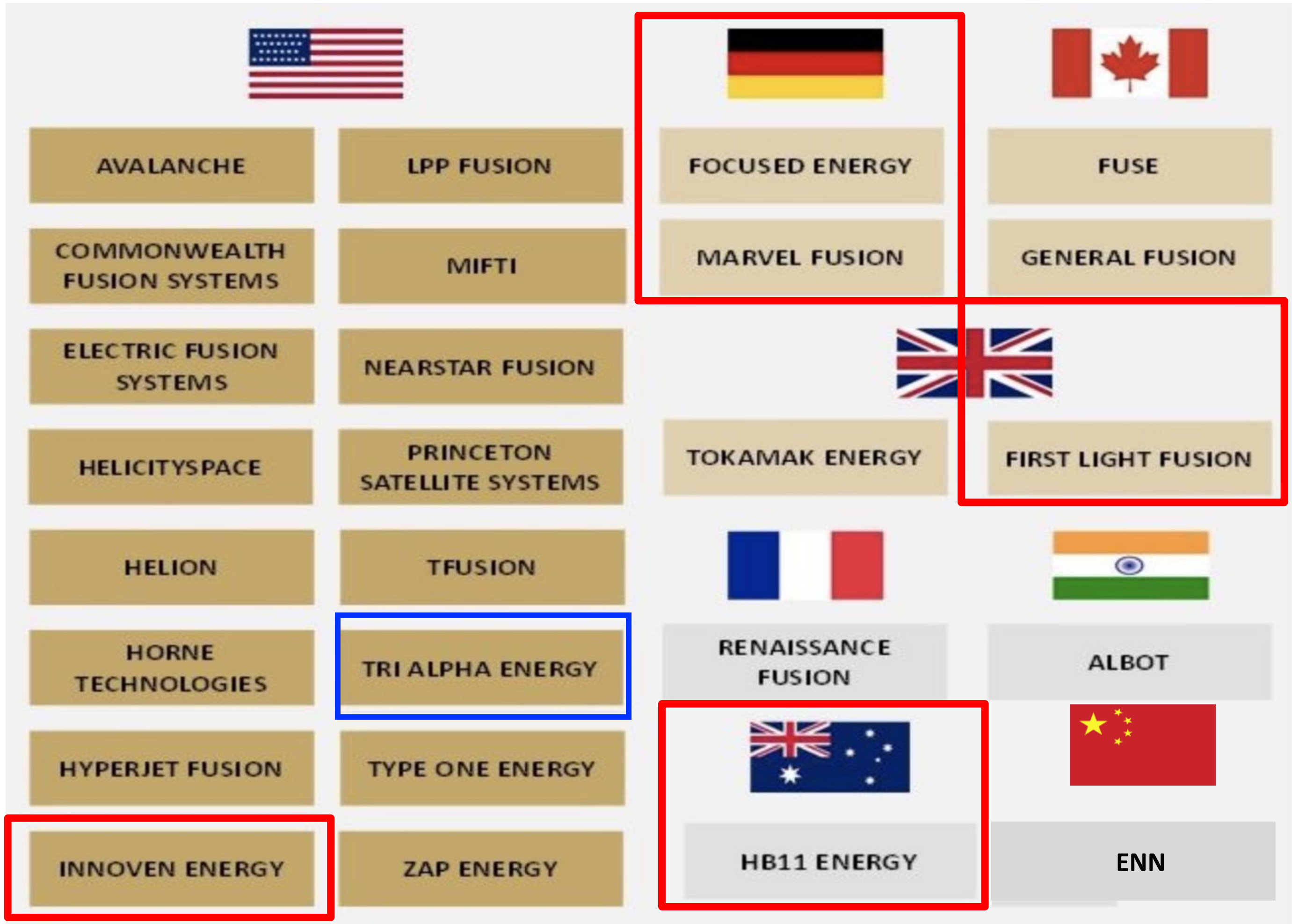
Awareness:

- 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

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+ 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.

Thank you for your attention !