EUROfusion Science Meeting on Status of Enabling Research Projects

27 Sep 2022, 9:00 → 9:40

Inertial Fusion Project:
Advancing shock ignition for direct-drive inertial fusion
ENR-IFE.01.CEA

Speaker: Dimitri Batani
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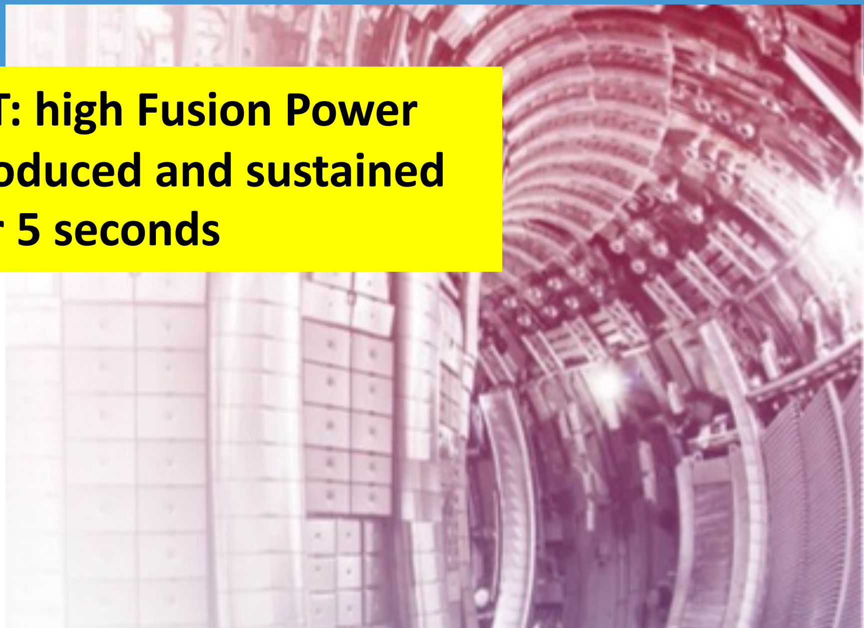
Plan of Presentation

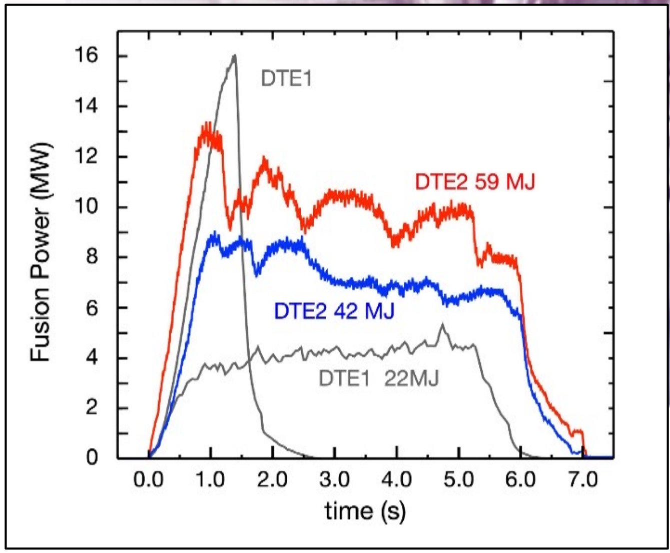
- The status of Inertial Fusion Energy (IFE) research
- Future perspectives: Direct Drive and Shock Ignition: Open Scientific Issues
- Our ER Project: participants, organization
- Scientific achievements per WP
- Some “science politics” issues

I believe we did a lot of work: this presentation is not exhaustive of all what has been done but rather just presents some significant examples

2021 has been an important year for fusion...

JET: high Fusion Power produced and sustained for 5 seconds





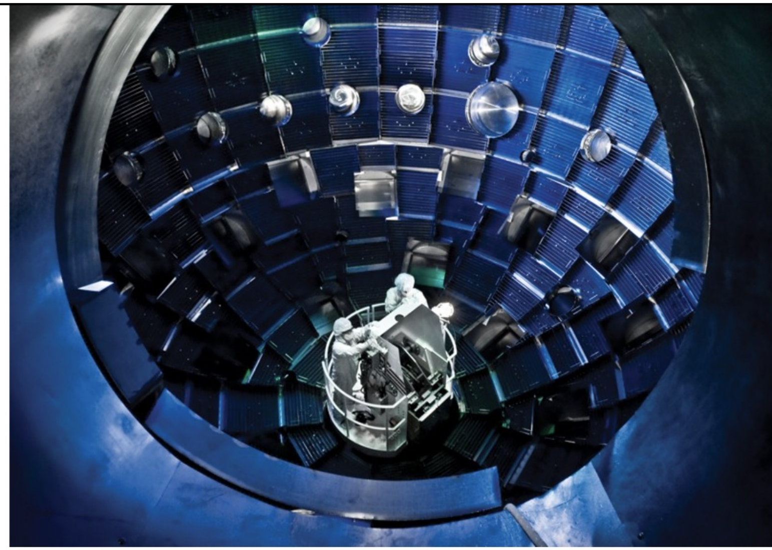
COMMENTARY

NIF achieves breakthrough in laser fusion

America's National Ignition Facility measured a record of 70% conversion in their laser fusion experiments. For a brief moment the fusion was self-sustaining. A moment that excites people around the globe.

Andreas Thoss

Aug. 23, 2021



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

(Download Image)

On Aug. 8, 2021, an experiment at the National Ignition Facility put researchers at the threshold of fusion ignition, achieving a yield of more than 1.3 megajoules — an 8X improvement over experiments conducted in spring 2021 and a 25X increase over NIF's 2018 record yield. Credit: John Jett, LLNL.

National Ignition Facility experiment puts researchers at threshold of fusion ignition

Progress in Inertial Fusion after NIC

nature

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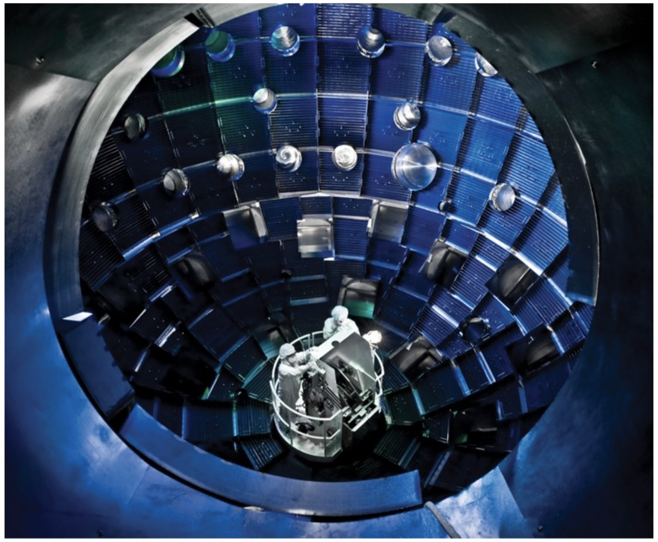
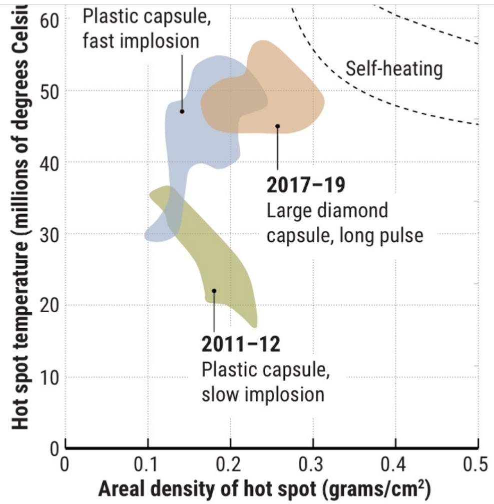
NEWS EXPLAINER | 27 August 2021



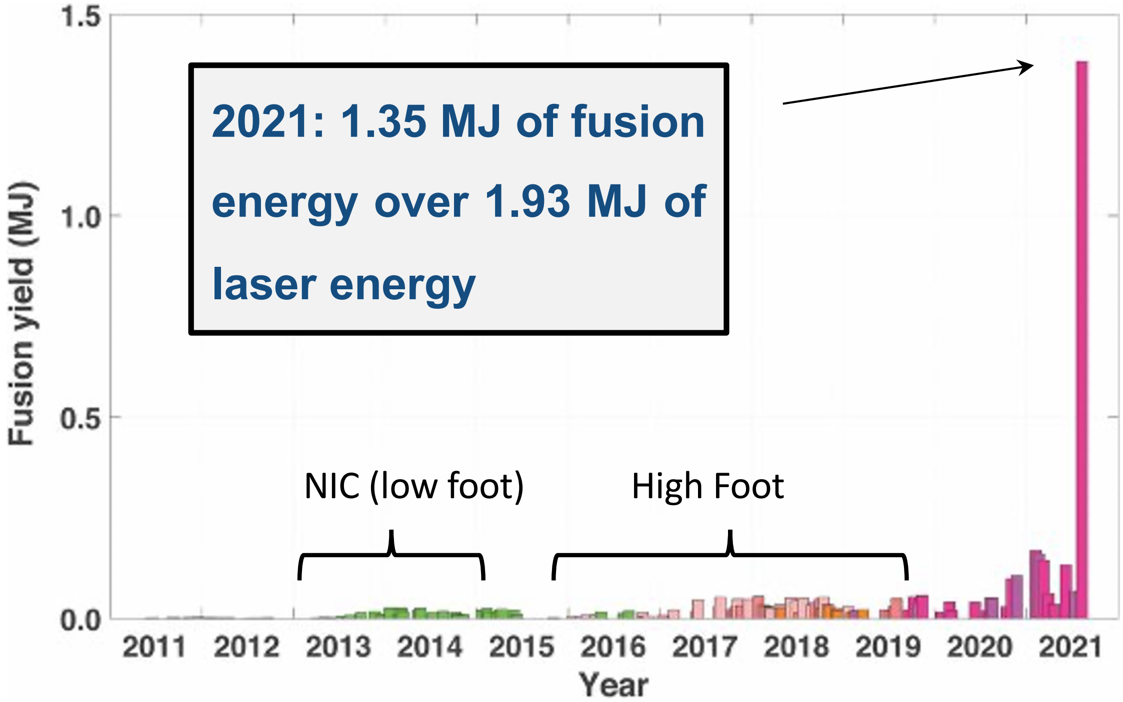
The US National Ignition Facility (target chamber shown) is the size of three American football fields. Credit: Lawrence Livermore National Laboratory

2013-2014: High-Foot Campaign up to 26 kJ of fusion energy, mostly due to α-particle self heating

2020: More than 150 kJ of fusion energy



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

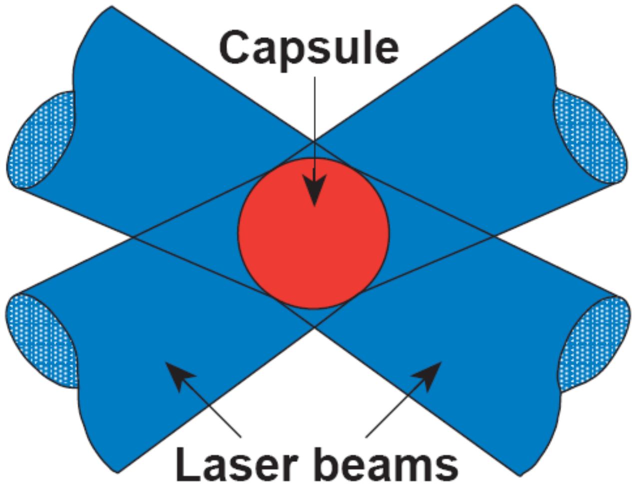


- ✓ Improved radiation uniformity
- ✓ Improved target quality

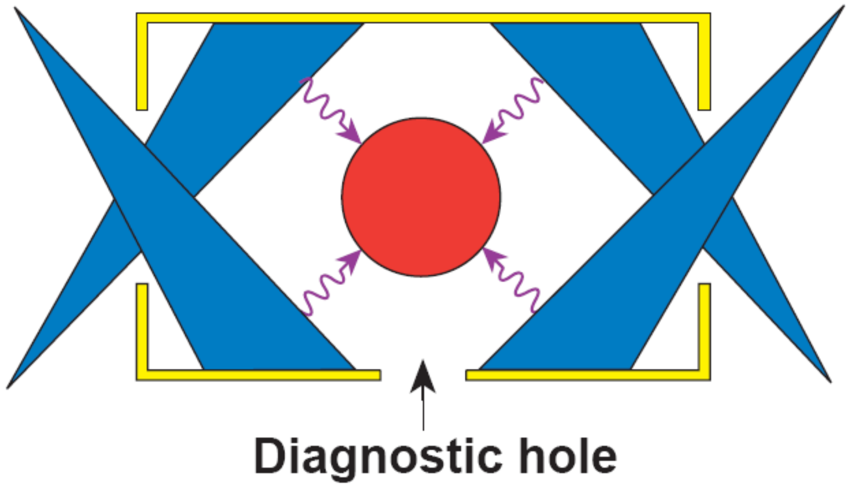
} Reduced impact of Rayleigh Taylor instability

Inertial confinement: direct vs. indirect drive

Direct-drive target



Indirect-drive target



***Hohlraum* using**
a cylindrical high-Z case

Direct: higher efficiency, more problems with uniformity

Indirect: better uniformity but reduction of efficiency

In both case you need MJ-class laser systems

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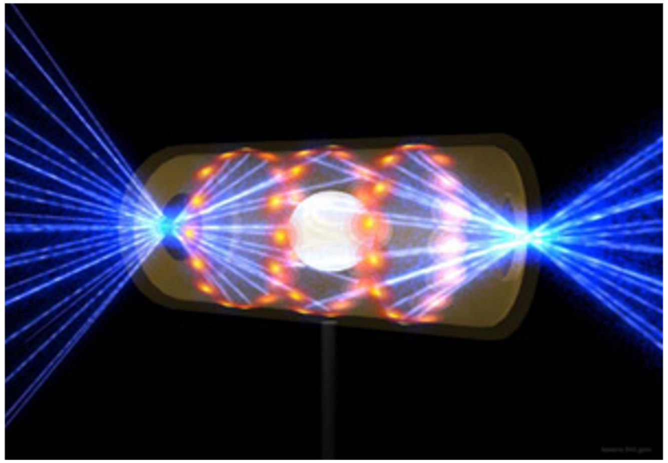
Inertial Fusion beyond NIF results

NIF results provide a validation of the Inertial Fusion concept, basically reaching breakeven, and opening the pathway to gain.

However, INDIRECT DRIVE used at NIF **does not seem compatible** with requirements for Inertial Fusion Energy (IFE), i.e. 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 related to proliferation

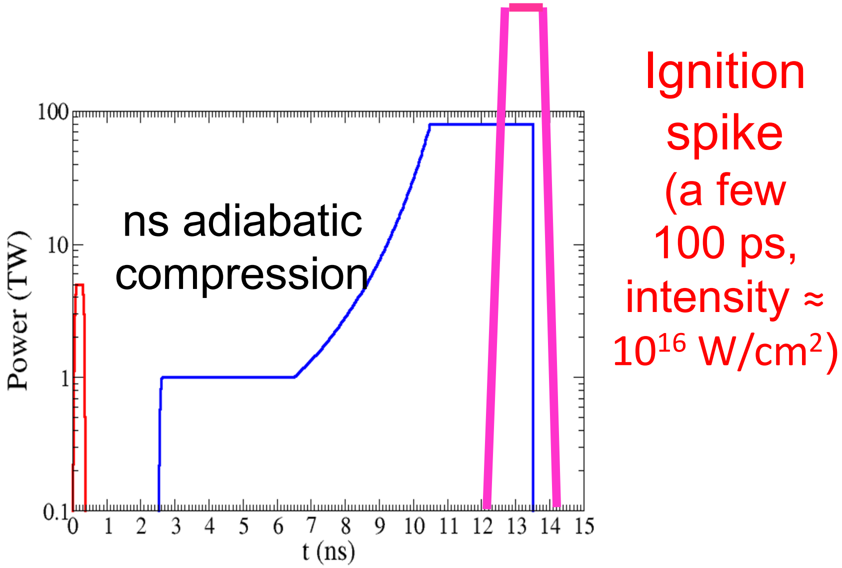


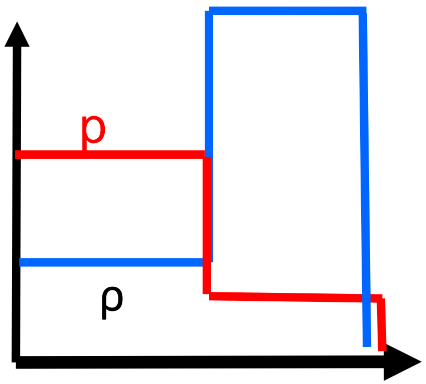
It is now **timely to go beyond NIF results** and investigate the **DIRECT DRIVE** approach which can provide the gain needed for energy production.

Among direct drive options, **SHOCK IGNITION** is particularly interesting due to the possibility of strongly mitigating hydro instabilities

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. Lower implosion velocity V ≈ 240 km/s
- ***More resistant against the effects of RT instability !!***
- A final laser spike launches a strong converging shock (≥ <u>300 Mbar</u> at the ablation front)
- Non isobaric fuel assembly implies higher gains





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

Unknowns of Shock Ignition

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

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

- Are we really able to couple the high-intensity laser beam to the payload through an extended plasma corona? Are we really able to create a strong shock?

- Requirements for uniformity are relaxed but what is the real degree of non-uniformities which we can be tolerated in the implosion phase / in the ignition phase?

  - Experiments done on European Laser Facilities in planar geometry, to study the basic physics of shock ignition.
  - Spherical integrated experiments in international laser facilities

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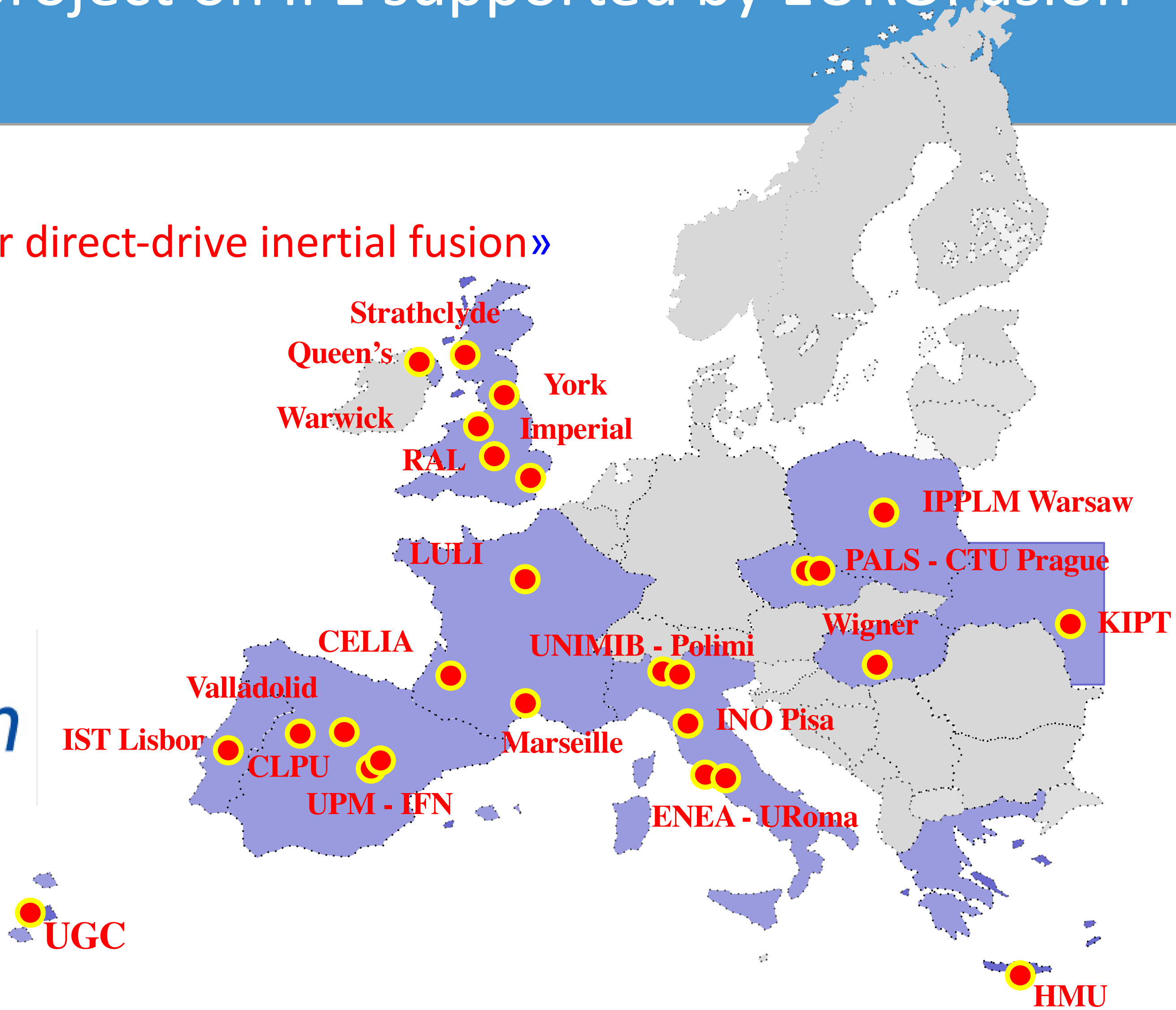
Currently only one project on IFE supported by EUROFusion

Enabling Research project
«Advancing shock ignition for direct-drive inertial fusion»

April 2021 – March 2024

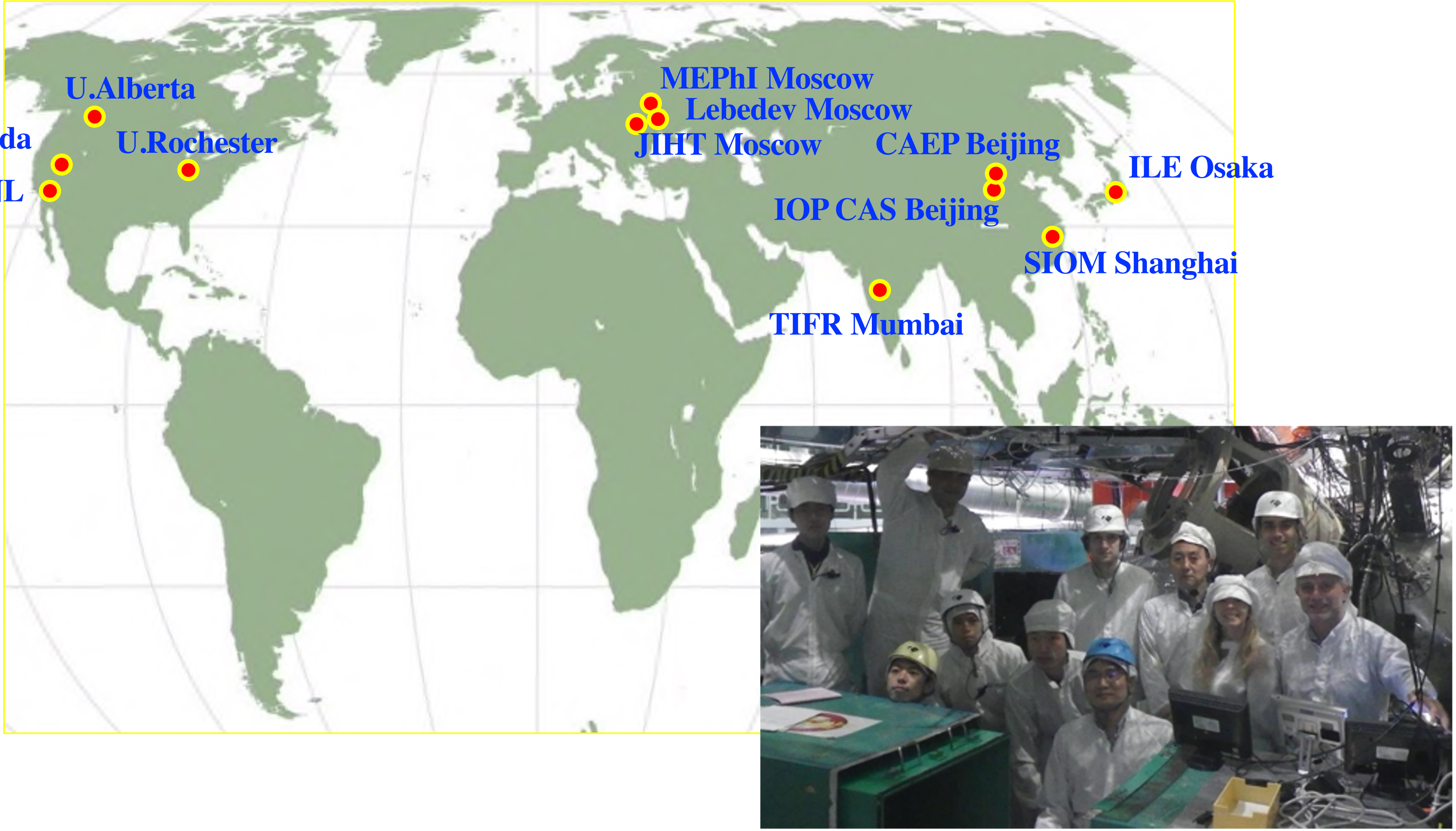
PI Dimitri Batani
Co-PI Stefano Atzeni

EUROfusion



10 countries, 24 groups, and 99 researchers involved in the project with about 70% "in kind" contributions in terms of PM

The International Dimension



Experiment at the laser Gekko, Osaka

Our project is organized in 5 work packages

- WP1: characterization of hot electrons and hot-electron-driven SI
- WP2: hydrodynamic instabilities and mitigation strategies in DD-SI, including use of foams
- WP3: bipolar SI: direct drive compression and bipolar spike irradiation, new approaches to DD SI, advanced concepts & advanced fuels
- WP4: parametric instabilities and cross beam energy transfer, mitigation using broadband lasers
- WP5: magnetic-field-assisted inertial fusion implosion and ignition.

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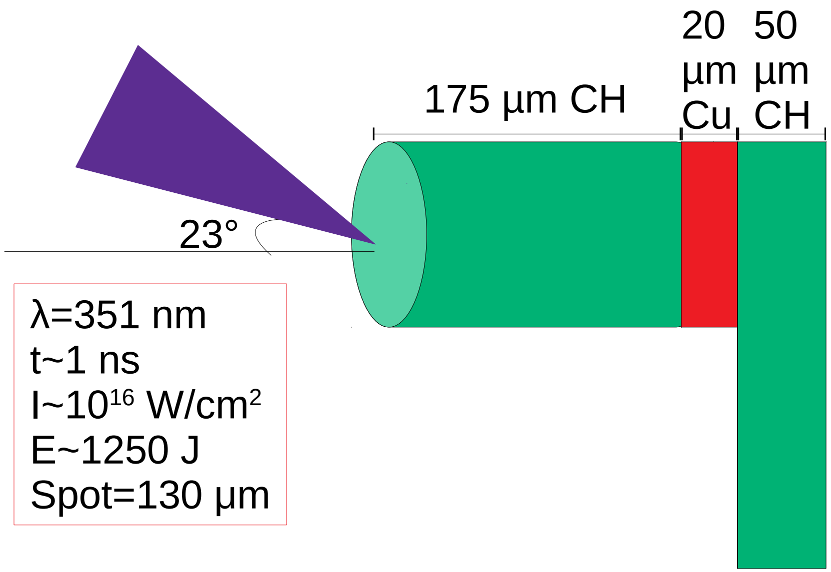
  - WP1: characterization of hot electrons and hot-electron-driven SI

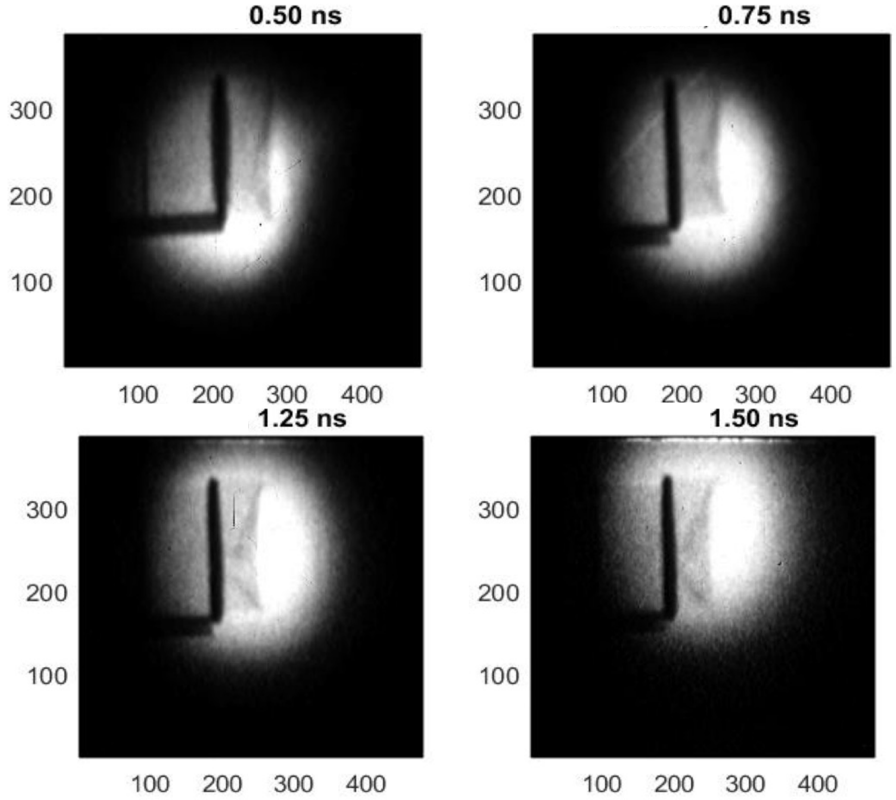
Experiment at Omega EP facility

Omega Experiment: Laser beam with characteristics relevant to SI scheme focused on multi-layer planar target to produce a strong shock and hot electrons



Shock propagation:

Time resolved X-ray radiography



Hot electrons:

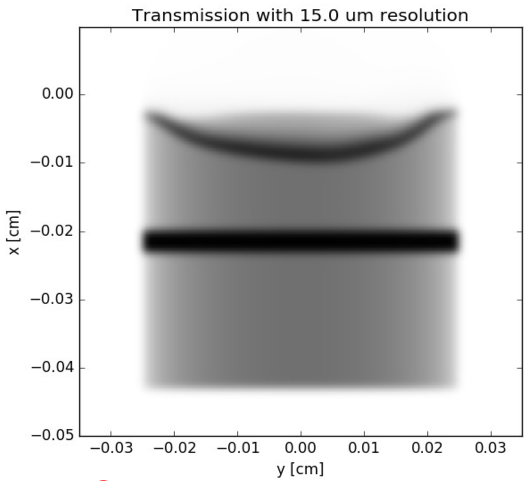
Bremsstrahlung and K_α signal on spectrometers

A. Tentori et al. Physics of Plasmas 28, 103302 (2021)

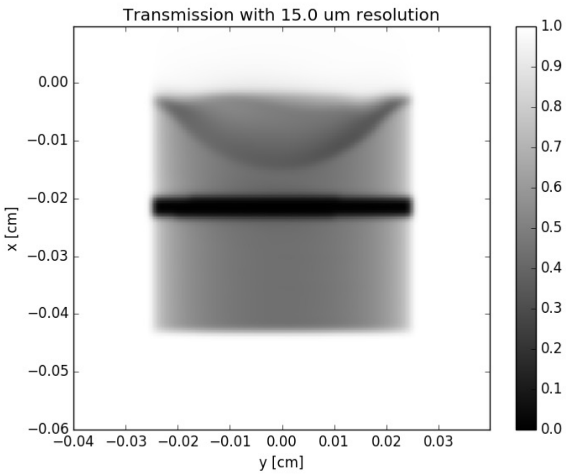
Experimental results reproduced only taking hot electrons into account

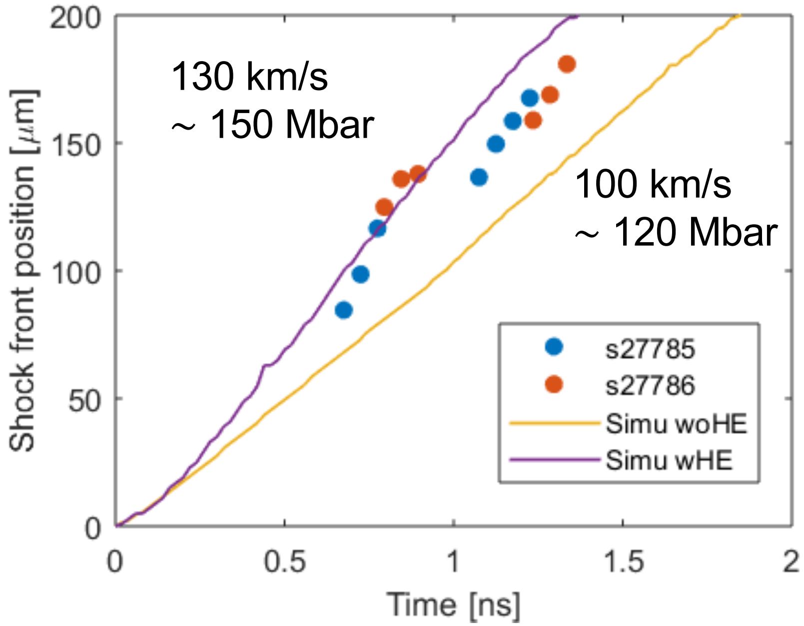
Hot electrons measurement by Bremsstrahlung and K_α must be compared to hydro results to completely constraint the HE distribution. In our experiment T_{hot} ~ 26 keV with an energy conversion of 11% *(good news for Shock Ignition)*

Simulation woHE

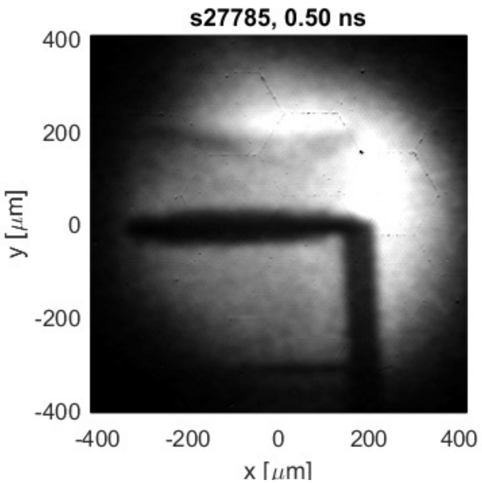


Simulation wHE





0.5 ns

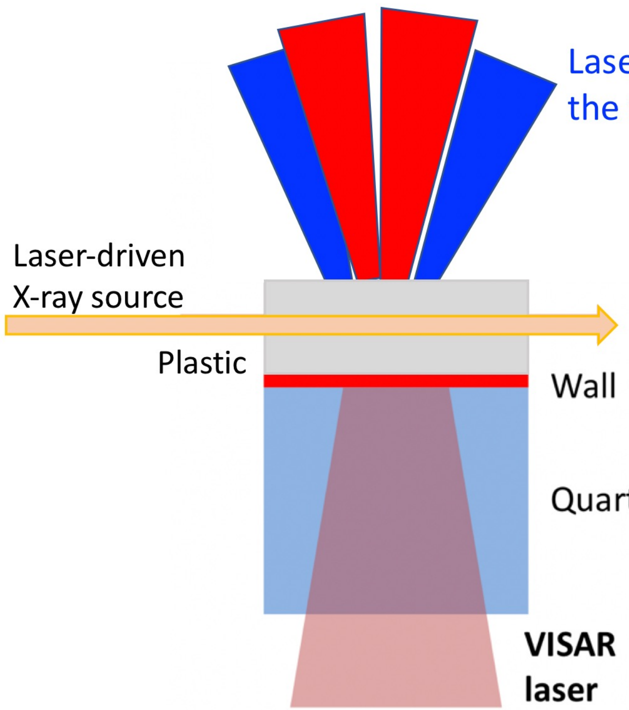


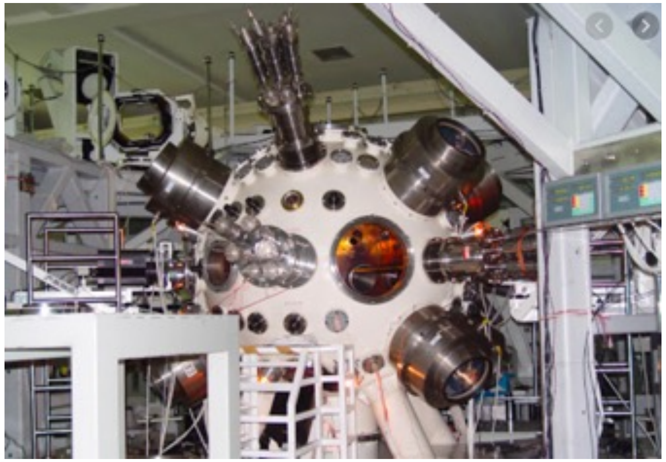
Experiment

Effect of the HE on the hydrodynamic:
- **Faster shock**
- **Expansion of shocked CH**
- **Expansion of the Cu layer**

Planned Experiment on SG II UP in Shanghai

Goal: mimicking the shock ignition process in planar geometry





Interaction chamber at SIOM, Shanghai

Postponed to End 2023

Letter of Interest / Statement on future collaboration

This document expresses the interest of the research groups taking part in the EUROFusion Enabling Research Project ENR-IFE19.CEA-01 to promote collaboration with the Shanghai Institute of Optics and Fine Mechanics (SIOM) of the Chinese Academic Science in the field of studies related to the physics of laser-produced plasmas, the physics of direct-drive inertial confinement fusion with lasers (ICF) and in particular the Shock Ignition (SI) approach to ICF.

....

3. The two parts agree to perform common experimental work on laser facilities, including in particular the SG-II system at SIOM. The research groups from the EUROFusion Enabling Research Project ENR-IFE19.CEA-01 express the interest to perform experiments on the SG-II laser facility. Joint experimental proposals for physical experiments will be prepared and submitted for selection to the facility.

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Signature by Principal Investigators of Both Parties

Part A: Shanghai Institute of Optics and Fine Mechanics, CAS
PI: Jianqiang Zhu — Email: jqzhu@siom.ac.cn
TEL: 86-21-69918202 — FAX: 86-21-69918101
Signature: — Date:

Party B: EUROFusion Enabling Research Project: ENR-IFE19.CEA-01
PI: Dimitri Batani — Email: dimitri.batani@u-borderaux.fr
TEL: + 335 40 00 37 53 — Fax: +33 5 40 00 25 80
Signature: — Date:

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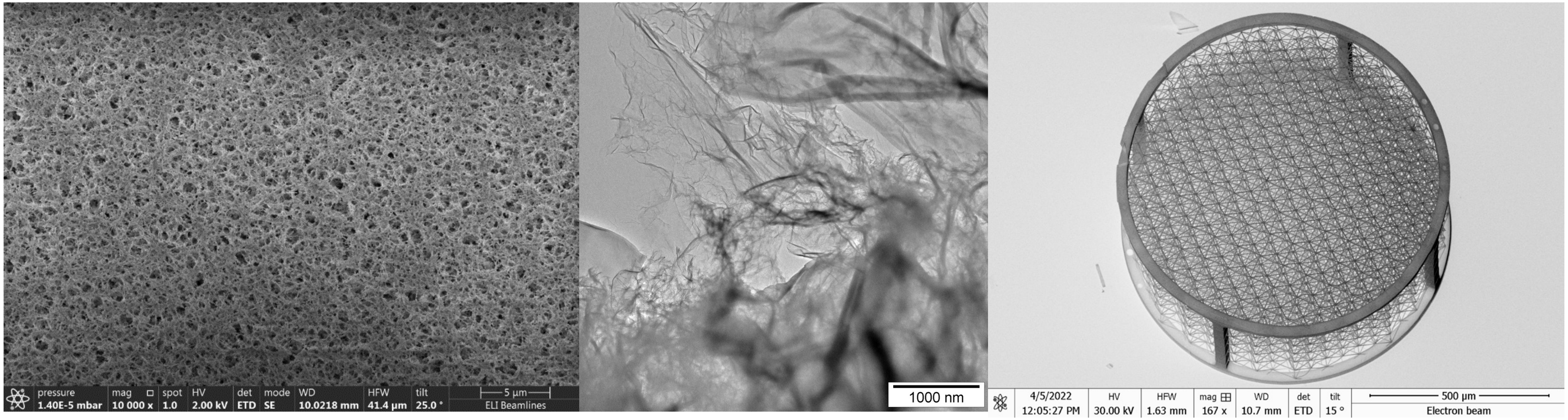
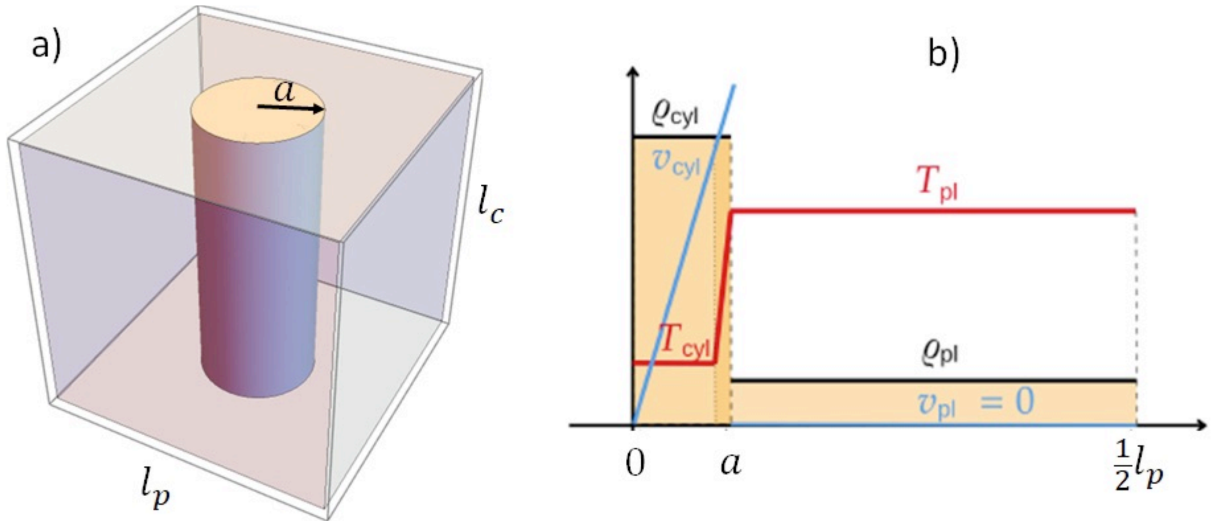
  - WP2: hydrodynamic instabilities and mitigation strategies in DD-SI, including use of foams

Experiments with foams

PALS experiment 2022: Three types of low density porous solid materials



Cylinder and plasma region of the microscale cell: 3D view of the microscale cell (a); one-dimensional cut parallel with the parallelepiped face (b)



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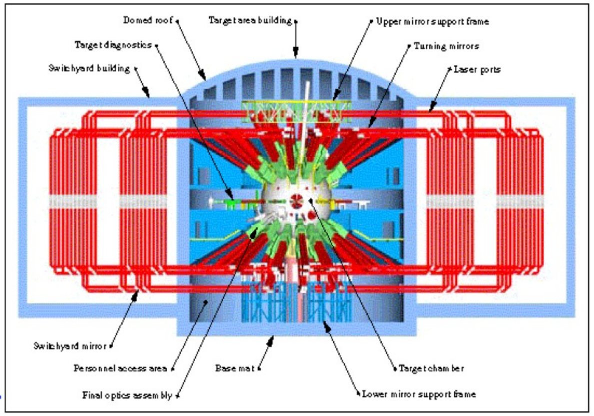
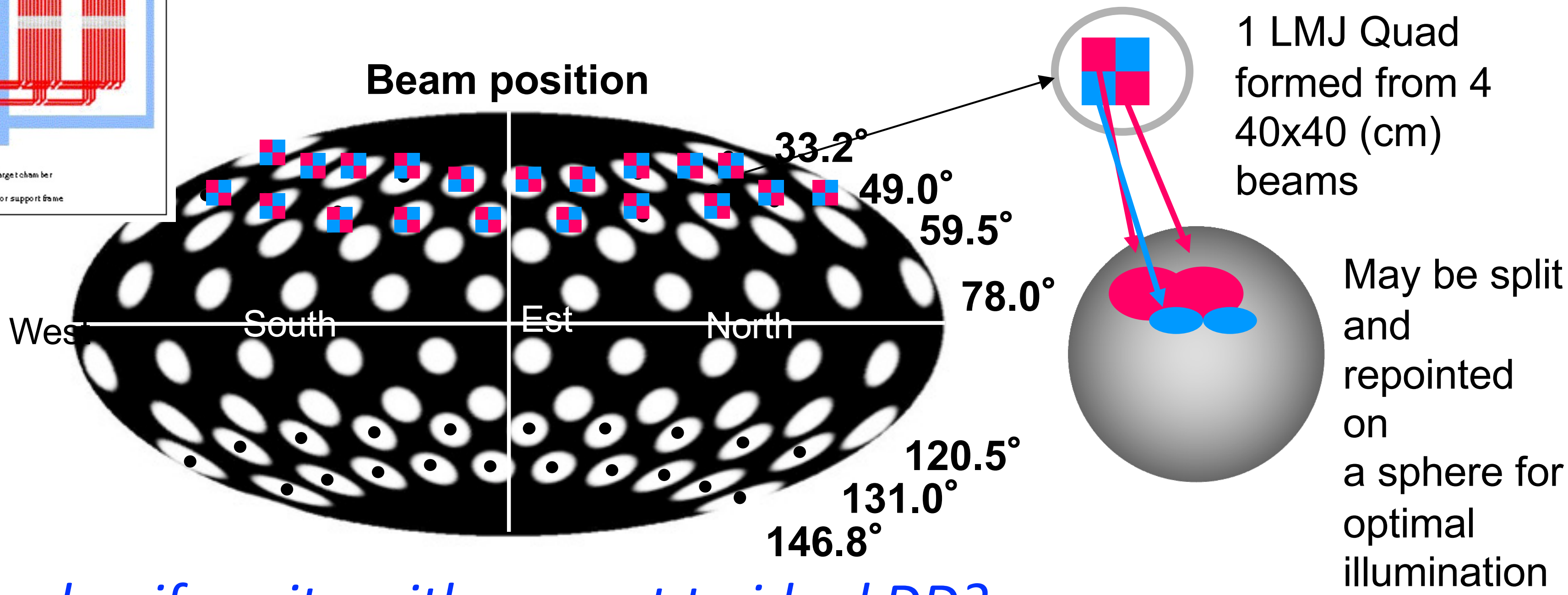
  - WP3: new approaches to DD SI (including bipolar spike irradiation), advanced concepts & advanced fuels

Polar Direct Drive (PDD)



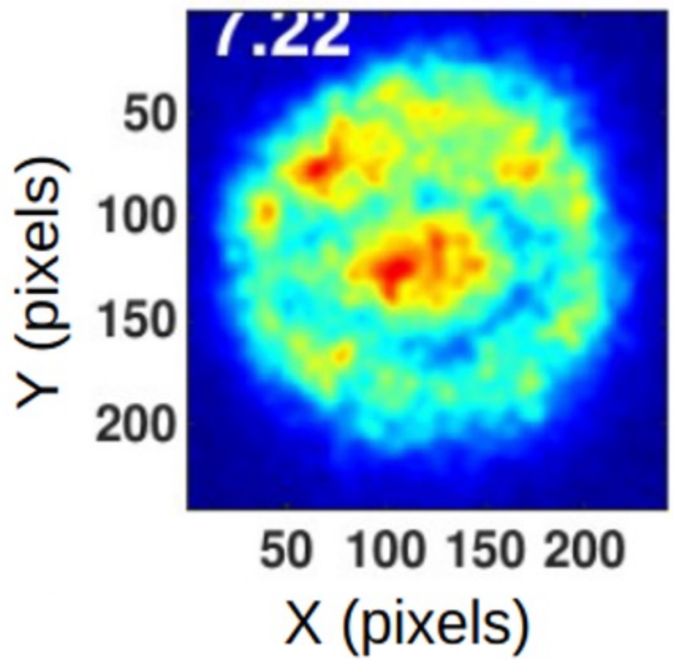
An example of how it could be done on the LMJ laser facility…



- *Reduced uniformity with respect to ideal DD?*
- *Problem of CBET (Cross Beam Energy Transfer)*
- *Possibility of using bipolar illumination for the ignition phase?*

PDD compression and bipolar SI

We address these issues by improved 3D radiative-hydrodynamics modeling capabilities at ignition-scale, and validating them against experimental results in the PDD geometry from the NIF SSS campaign for strong shock generation in solid-spheres. These results allow a «confident» modeling of ignition-scale bi-polar designs

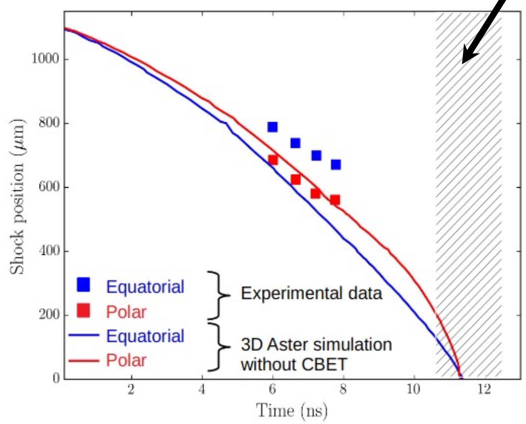


Solid Sphere driven by 184 NIF beams
Backlighter image during the implosion
(backlighter: Zn foil)

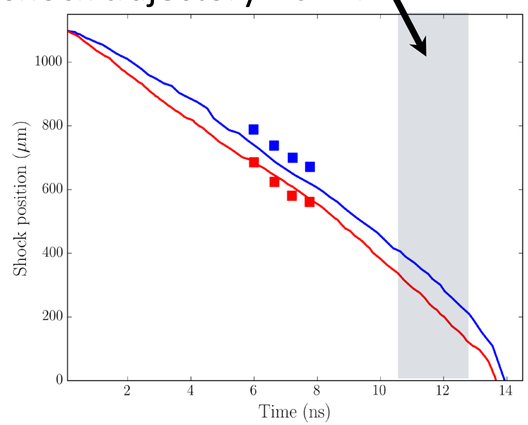
- Integrated modeling with state-of-the-art CBET reproduces correctly the polar and equatorial shock trajectory in the experiment, and it is consistent with the lack of observed shock collapse in the diagnostic window.
- No tuning of the model was used, which gives confidence in the modeling tool.
- The modeling is being applied to another set of SSS experiments and used in conjunction for other Tasks in WP3

region where no shock flash was observed in the data

shock trajectory - no CBET

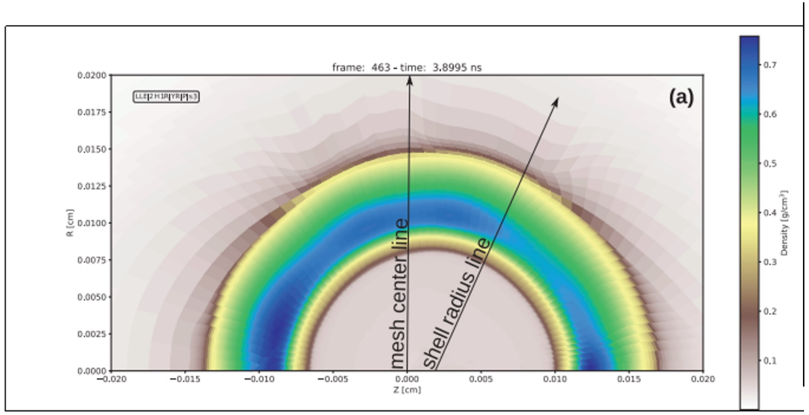


shock trajectory - CBET



Dynamic Shell Approach

Novel approach proposed by V.Goncharov, et al. [Phys. Rev. Lett. **125**, 065001 (2020)] at Rochester, which uses wetted foam spheres as targets where the laser pulse shape dynamically generate an imploding shell

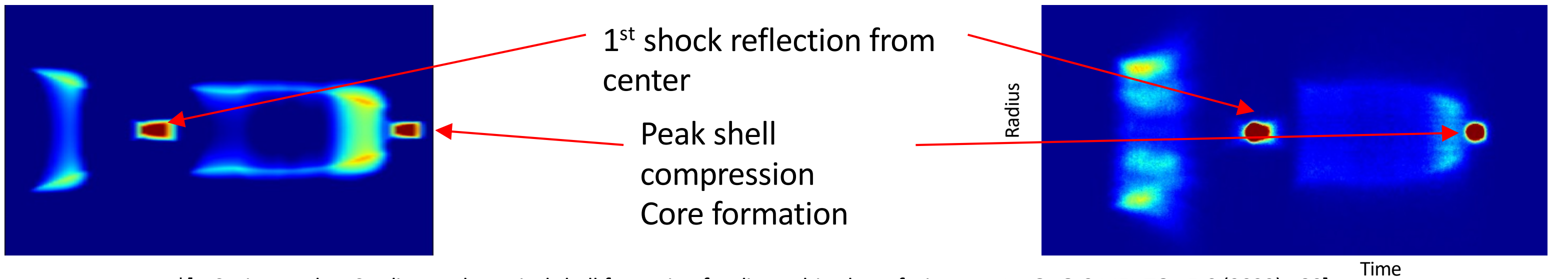


2D density map of a dynamic shell target near stagnation, in a case with a pre-imposed low mode asymmetry

Simulations, performed in 2D and 3D by the groups at U. Roma and CELIA, suggest that the DS design has a better stability to low mode perturbations compared to traditional solid-state cryogenic targets. These results, obtained for sub-scale high adiabat targets, need to be confirmed for ignition-scale low adiabat targets.

In parallel, we participated in the analysis of an OMEGA experiment conducted in Aug. 2022, in collaboration with the LLE. The experiment has demonstrated a successful dynamic shell formation from a foam ball.

Synthetic streak image

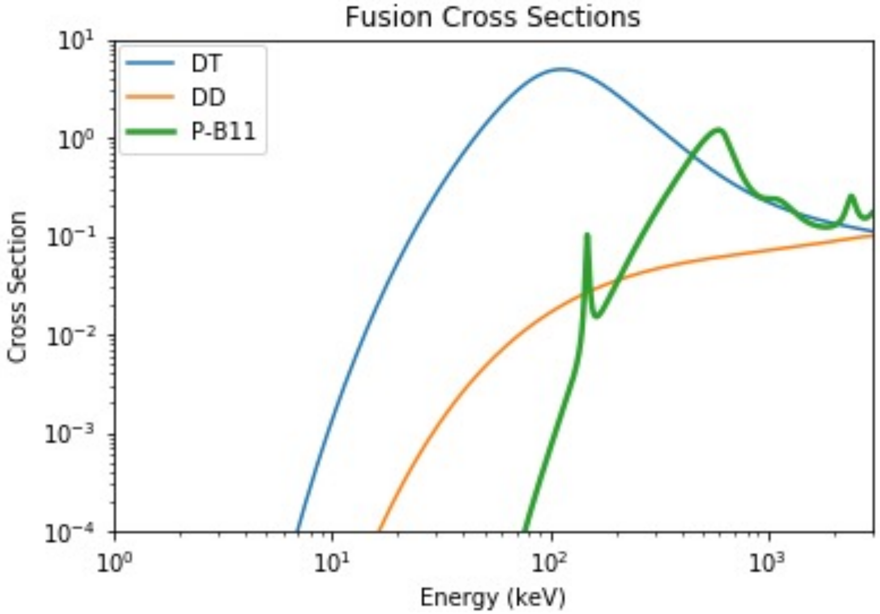


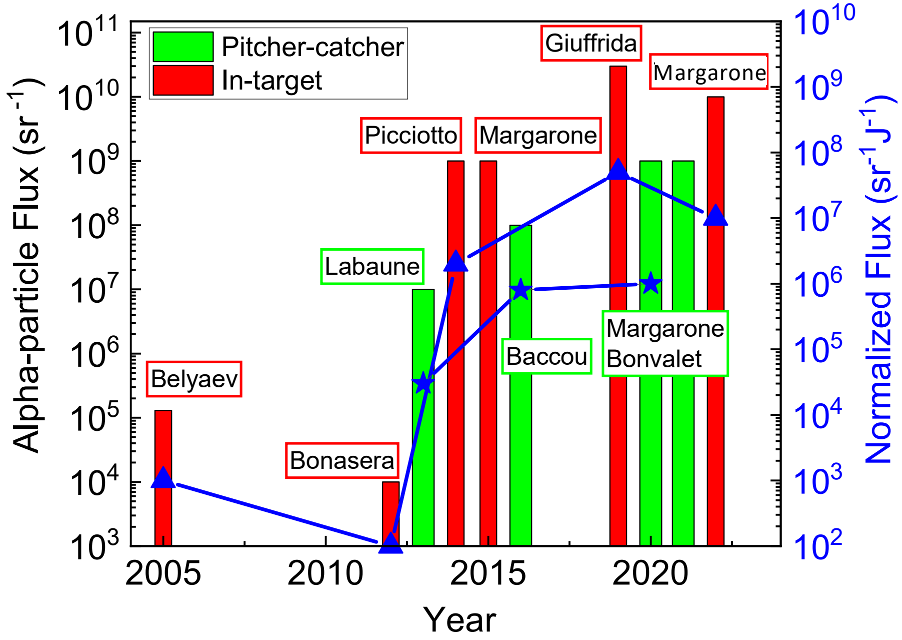
Experimental streak image, courtesy of LLE

*[L. Savino et al., « Studies on dynamical shell formation for direct-drive laser fusion », IL NUOVO CIMENTO 45 C (2022) 180]

Hydrogen-Boron Fusion

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





- ✓ Aneutronic Energy Production (futuristic)
- ✓ Development of high-brightness α-particle sources for applications
- ✓ High brightness: short duration / small source size
- ✓ Production of Short half-life radioisotopes for imaging or therapy

- V.S.Belyaev, et al. Phys. Rev. E 72, 026406 (2005)
- A.Bonasera, et al. in "Fission and Properties of Neutron-Rich Nuclei" (Sanibel Island, World Scientific) 503 (2008)
- C.Labaune, et al. Nat. Commun. 4, 2506 (2013)
- A.Picciotto, et al. Physical Review X 4, 031030 (2014)
- L.Giuffrida, et al. Phys. Rev. E 101, 013204 (2020)
- D.Margarone, et al. Frontiers In Physics, 8, 343 (2020)
- D.Margarone, et al. Applied Sciences, 12, 1444 (2022)

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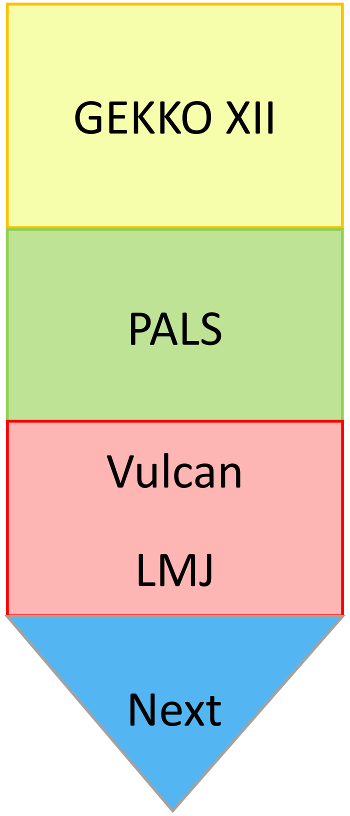
  - WP4: parametric instabilities and cross beam energy transfer, mitigation using broadband lasers

Study of Parametric Instabilities approaching Shock Ignition: our experiments



Multi beam	Lambda (nm)	Intensity (W/cm^2)	$I\lambda^2$ ($W\mu m^2/cm^2$)	L (μm)	T (keV)
YES	351	1.5×10^{15}	2×10^{14}	100	1-2
NO	438	5×10^{15}	1×10^{15}	100	1-2
	1314	1.5×10^{16}	2.5×10^{16}	100	3-4
NO	532	1×10^{16}	3×10^{15}	400	1-2
YES	351	3.5×10^{15}	4.3×10^{14}	480	4.5

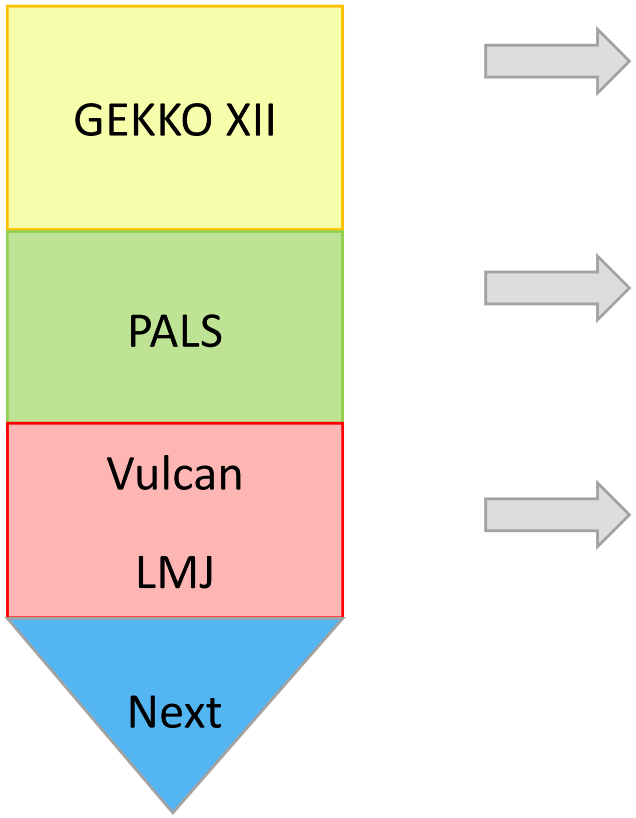
Vulcan TAW – September / October 2022
Vulcan TAW – Summer 2023
PALS – ?

Ongoing (P.I. LA. Gizzi)
Scheduled (P.I. N. Woolsey)
Submitted

Shock Ignition regime
Multibeam 3ω, $I = 10^{16}$ W/cm^2
L=500 μm, $T \geq 5$ keV

It is necessary to understand the role of different experimental parameters

Parametric Instabilities approaching SI



Role of multibeam irradiation, collective effects on LPI

Origin of HE and the competition SRS/TPD at high temperature and high laser Intensity

Competition SRS/TPD in long plasmas and high laser Intensity

Shock Ignition regime
Multibeam 3ω, I = 10^{16} W/cm^2
L=500 μm, T=3-5 keV

Vulcan – Mitigation of LPI — Ongoing (P.I. LA. Gizzi)
Vulcan – Side SRS — Scheduled (P.I. N. Woolsey)
PALS – Side SRS and foam — Submitted
Vulcan / Gekko ? – CBET: 4 heating beams + 2 interaction beams and detuning of beams — Idea…

Parametric Instabilities - Results

Experiments at **PALS** (Prague, Czech Rep.) in 2020 (PI. D.Batani) and 2021 (PI G.Cristoforetti) show that HE are mainly generated by SRS at SI intensity, with small role of TPD and HE temperatures in the range 25-50 keV *[T.Pisarczyk, et al. PPCF (2020)]*

Experiments at **Gekko** XII (Osaka, Japan) in 2020, 2021 and 2022 (PI G.Cristoforetti) show that multibeam irradiation has a relevant effect on TPD and SRS threshold and HE generation ***[****T. Tamagawa et al., Rev. Sci. Instrum. (2022)****]***

Experiments at **Vulcan** *[G.Cristoforetti et al., High Power Laser Science and Engineering, (2021)]*, **LMJ** *[S.Baton, et al. High Energy Density Physics (2020), P. Koester et al., Review of Scientific Instruments (2021)]*, and **Omega** suggest SRS driven at low densities and absence of TPD. Filamentation is determinant. However, the plasma temperature is still too low and far from real SI conditions

Recent relevant simulations by the Warwick group (kinetic effects) and Prague group (LPI in filaments)

Ongoing experiment at **Vulcan** TAW laser (UK), 12 Sep / 14 Oct 2022
Aim: Investigate the effects of broadband on LPI and HE generation. We compare 3 different oscillators with different bandwidth (Fourier-limited, 0.7 nm and 1.7 nm)

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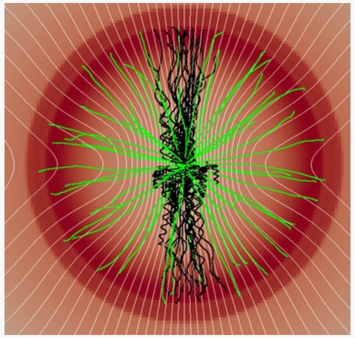
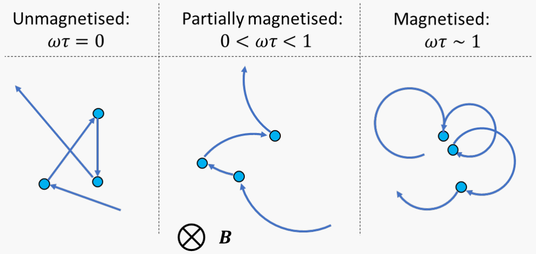
Design of Magneto-Inertial Fusion Experiments

Magnetised ICF

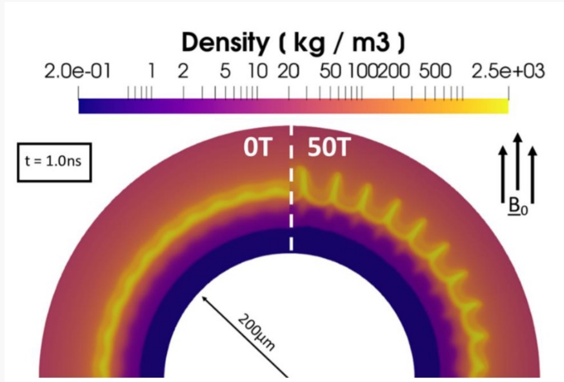
***Magnetised** & **Unmagnetized** α trajectories*





Magnetization reduces thermal conduction losses from the hotspot.

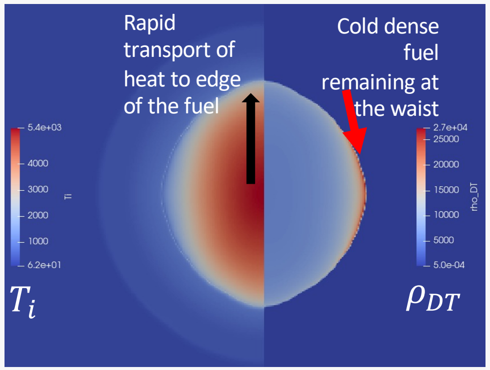
Magnetised Direct Drive



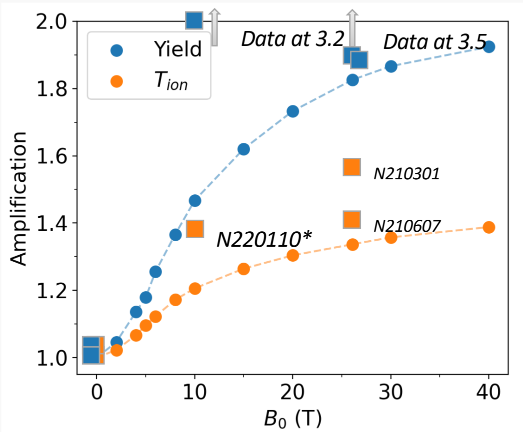
C.A. Walsh *et al.*, Nucl. Fus. **60**, 106006 (2020)

Enhanced ablation surface instability growth at poles of the capsule.

Magnetised Indirect Drive



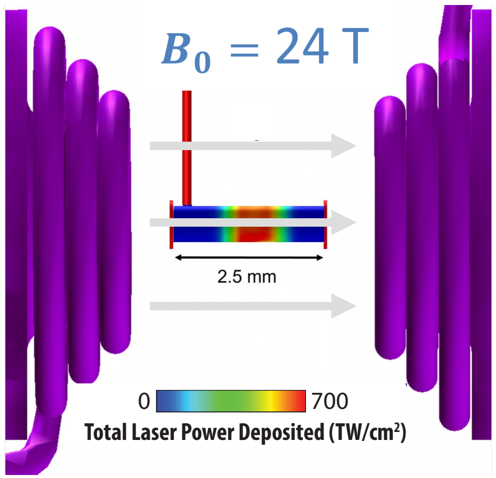
Hotspot thermal conduction suppressed along waist leading to elongated hotspot



Up to 2 times yield enhancement from initial 40T field predicted.

Experiment at OMEGA

Seed B-field driven externally by a **capacitor bank discharge** (stable over ~μs)



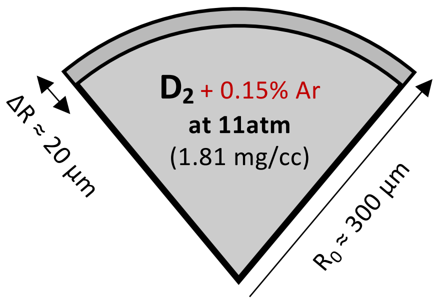
Laser drive: 40 UV beams, 1.5 ns, total energy of 14.5 kJ, > 5x10^{14} W/cm^2 across 650 μm

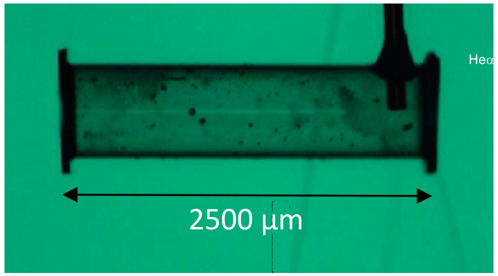
Implosion experiments at OMEGA with seed B-fields

Experimental setup

Cylindric plastic shells filled with D_2 at 11 atm with 0.15% atomic concentration of Ar doping for spectroscopic tracing

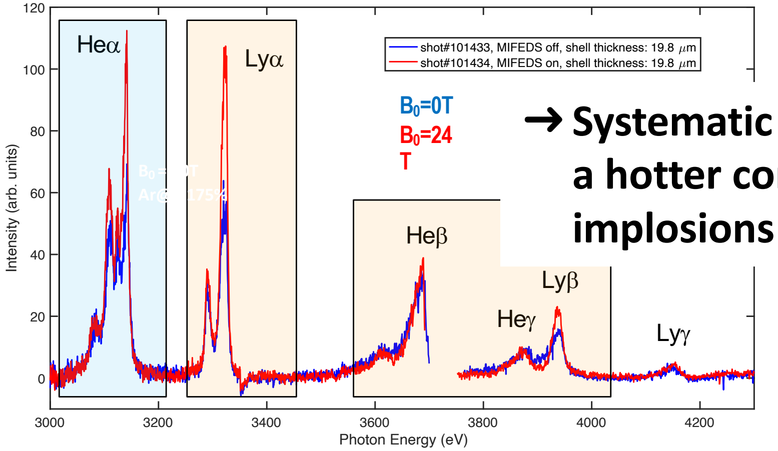
Parylene shell





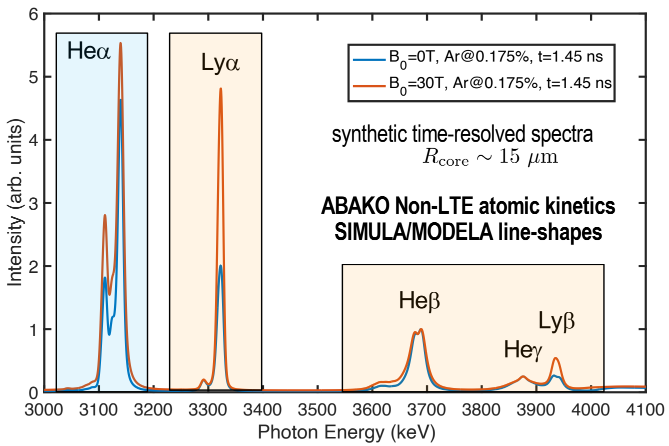
Ar K-shell spectra characterize core plasma conditions

Experimental time-integrated Ar K-shell emission



→ **Systematic intensity ratios suggest a hotter core for the magnetized implosions**

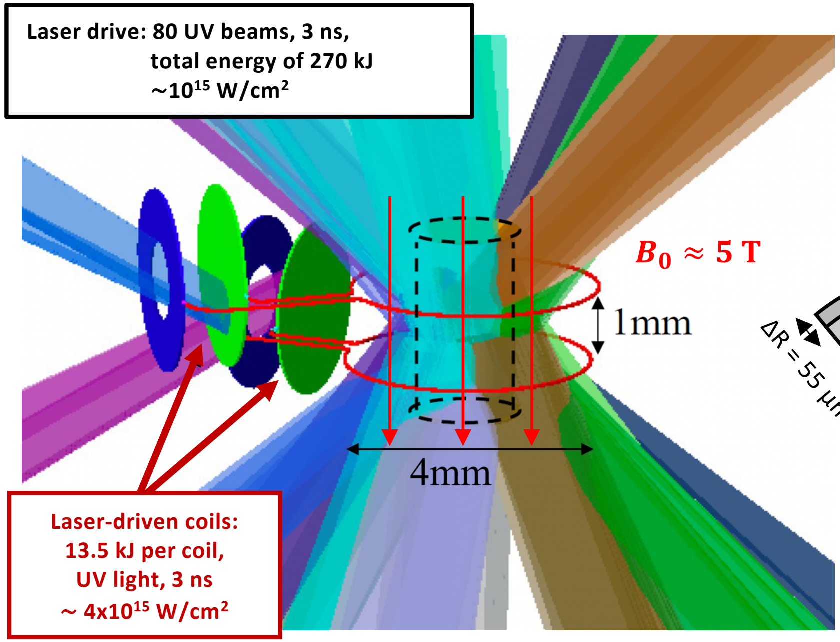
Modelled Ar K-shell emission

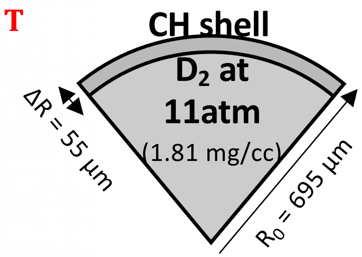


→ **Observations qualitatively predicted by synthetic spectra simulations**

Platform extended for LMJ with 20x higher drive energy

***Setup at LMJ** – shots scheduled in 2024 - 2026*



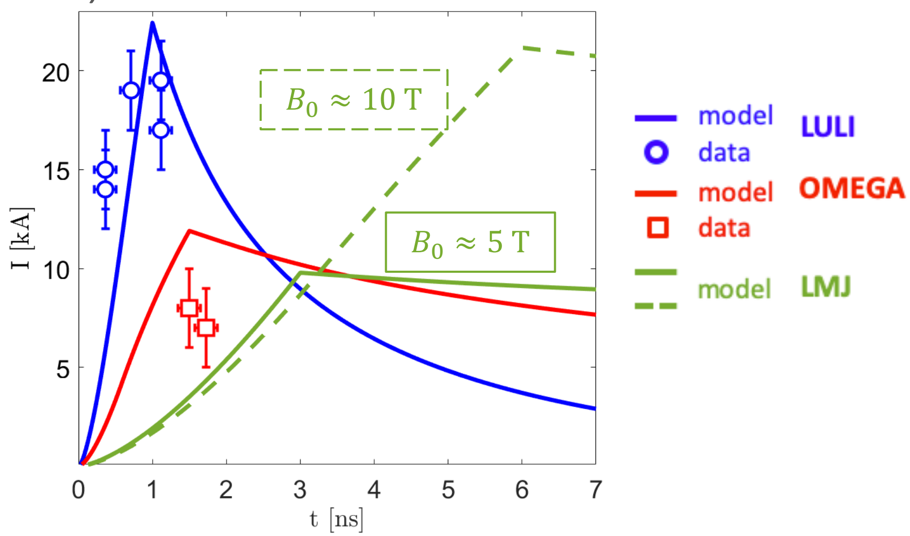


Compared to OMEGA :

- 20x more laser-drive energy
- 2.3x larger targets

  ➔ **Greater compression** or **larger core for equivalent compression ratio**

***Current evolution in laser-driven coils from <u>model</u>** (curves)* ***and <u>benchmarking data</u> from preparatory experiments** (symbols)*



G.Pérez-Callejo et al., Phys. Rev. E, 106, 035206 (2022)

- External pulsed power for B-field unavailable at LMJ
  - **Alternative use of laser-driven coils with predicted seed B-field in the 5 to 10 T range**
- Preliminary shots done in 2022 to characterize magnetic field generation

Plan of Presentation

- The status of Inertial Fusion Energy (IFE) research
- Future perspectives: Direct Drive and Shock Ignition: Open Scientific Issues
- Our ER Project: participants, organization
- Scientific achievements per WP
- Some “science politics” issues

Important “side” activities from our network

Together with the BPIF section of the PPD of EPS we are supporting an initiative to launch a new European project on IFE (project HIPER+)

Strong activity on summer schools, i.e. the school on “Plasmas in Superstrong Fields” Erice, Sicily, July 2022

Collaboration with the Coordinated Research Project of IAEA on “Pathways to Inertial Fusion Energy”

Collaboration with the LASERLAB expert groups on “Micro- and nano-structured materials for experiments with high-power lasers” and on “Inertial Confinement Fusion / Inertial Fusion Energy”

Collaboration with the (approved) COST project ProBoNo «PROton BOron Nuclear fusion: from energy production to medical applicatiOns”

Attention to the new “industrial environment” for Nuclear Fusion

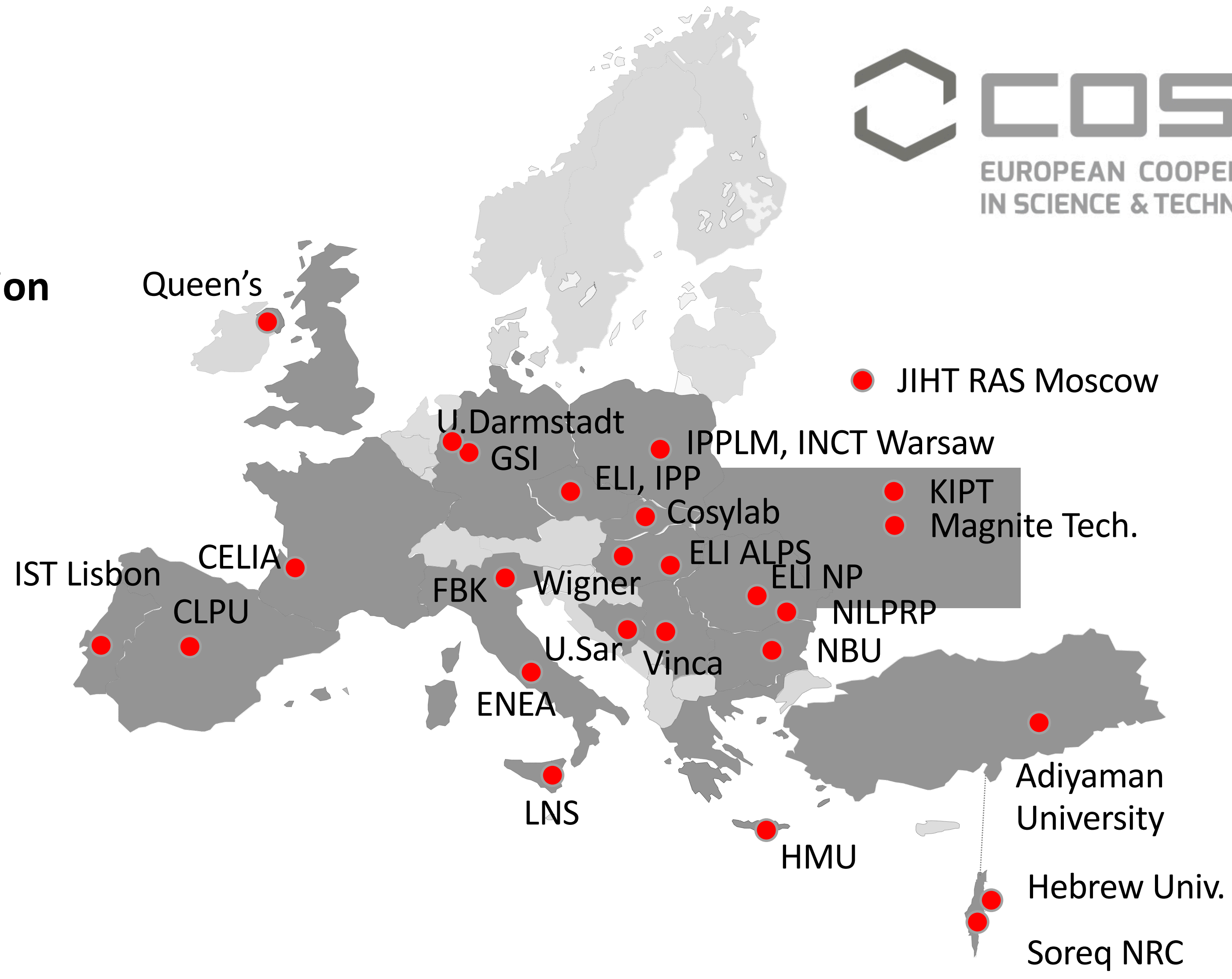
The Industrial Endeavours

RED: inertial fusion

pB Fusion – COST Action

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

Coordinated by IPPLM Warsaw

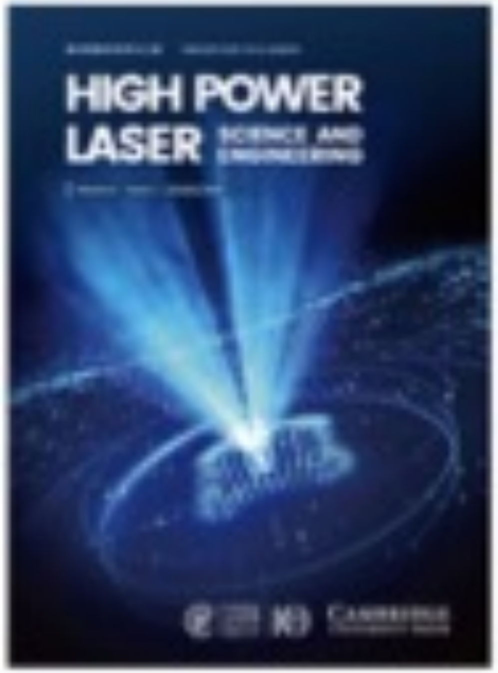


HIPER+ initiative

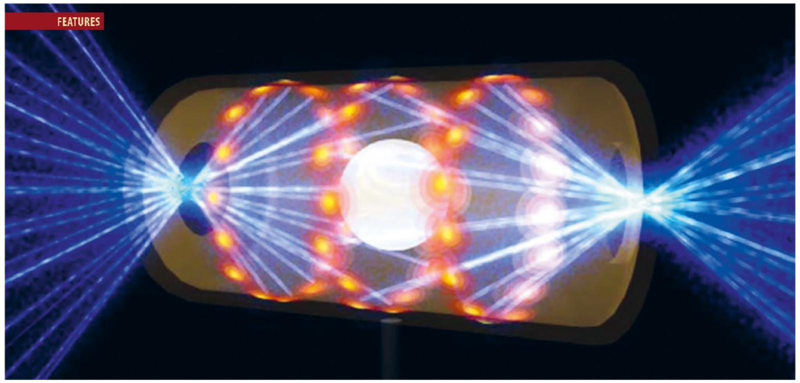
There is a community in Europe interested in "relaunching" HiPER (Letter so-far signed by more than 100 European scientists)
https://www.clpu.es/Laser_Fusion_HiPER

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

S.Atzeni, D.Batani, C.N.Danson, L.A.Gizzi, M.Perlado, M.Tatarakis, V.Tikhonchuk, L.Volpe
High Power Laser Science and Engineering (2022)



EUROPHYSICS NEWS



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.

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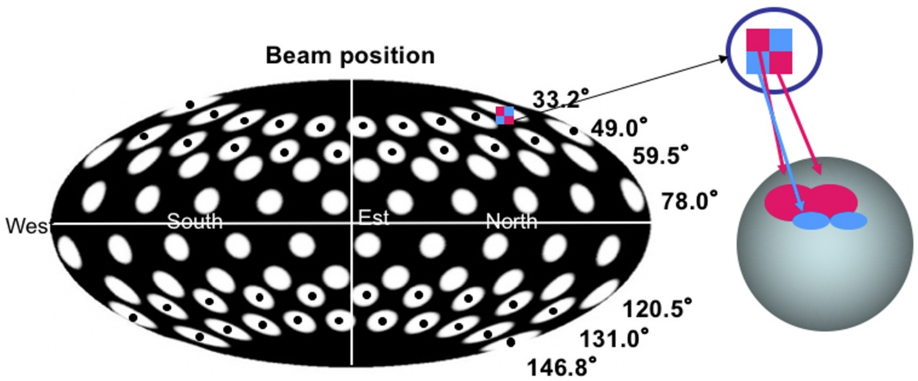
HIPER+ Laser Facilities in Europe

- The European IFE community has profited of large investments in Europe in high-energy laser facilities.
- Systems like Vulcan and Orion (UK), LULI2000 (France) Phelix (Germany), PALS (Czech Republic) and now ELI enable the **study of the physics of direct drive inertial fusion**.
- However, these do not allow implosions and integrated experiments…
- Academic access to the **Laser Megajoule** (CEA/DAM): possible but extremely limited;
  - Not available to support IFE programme like ILE (Rochester).
  - Not designed for direct drive research (although configurable for PDD)



IFE development in Europe requires a dedicated laser facility to study direct-drive fusion.
The validation of ICF concept established at NIF implies that the next steps should be at a level of a **IFE test facility** followed by a **DEMO in inertial fusion**.

Conclusions:

- We believe that a substantial work has been done and that it is at the edge of the international research on IFE. This will continue in next two years.
- The final goal is indeed to prepare the «**Post NIF**» phase which we believe should be based on **Direct Drive**

ANNEX: ANNUAL WP-PEP – 2023

23A. SCOPE DESCRIPTION FOR NEXT YEAR (→ "OBJECTIVES" IN AWP)

The content of this section is meant to be pasted into the section named "Objectives" in the AWP.

Project reference *(as on IMS)*	Objectives in 2022
ENR-IFE.01.CEA	Report on HE effects in SI-designed targets Report on the evaluation on the impact of RT for SI-designed targets Report on using foams to mitigate hydro instabilities growth Report on feasibility of bipolar shock ignition and proposal for experiments on LMJ/NIF Report on LPI and CBET in SI conditions Report on the characterization of magnetized HED plasmas over the implosion and at stagnation

Conclusions:

- We believe that a substantial work has been done and that it is at the edge of the international research on IFE. This will continue in next two years.
- The final goal is indeed to prepare the «**Post NIF**» phase which we believe should be based on **Direct Drive**

- The major difficulties which we have encountered / are still facing are:
  - ✓ The effect of the **COVID** Pandemics which has brought to delaying many experiments or to cancelling others, and has limited exchanges/contacts in general
  - ✓ The effects of **BREXIT** which made the collaboration between the EU and the UK communities more difficult (the UK IFE community is one of the strongest in Europe)
  - ✓ The effects of the **Russian aggression to Ukraine** have made difficult the relations with Ukrainian scientists and almost impossible those with Russian scientists
  - ✓ The effect of the energetic crisis which might imply that the activity of some laser facilities (e.g. Phelix at GSI Darmstadt) will be "suspended" in 2023
  - ✓ The limited financial support, taking into account that this is the ONLY project supporting IFE research in Europe (and not just networking), makes difficult to realize some objectives (e.g. buying shot days on laser facilities like Omega or Gekko). Access to laser facilities is therefore limited by competitive access….

Thank you for your attention !