



# Fusion energy research with high power lasers in Europe: The HiPER+ programme

Petra Koester on behalf of the HiPER+ collaboration

*Conferenza Italiana sui Plasmi (CIP), Feb 3-5, 2026, Frascati*

## Outline

- Introduction Inertial Confinement Fusion
- The HiPER+ project: Conceptual design for a European Implosion Facility
- Technological challenges
- Physics challenges

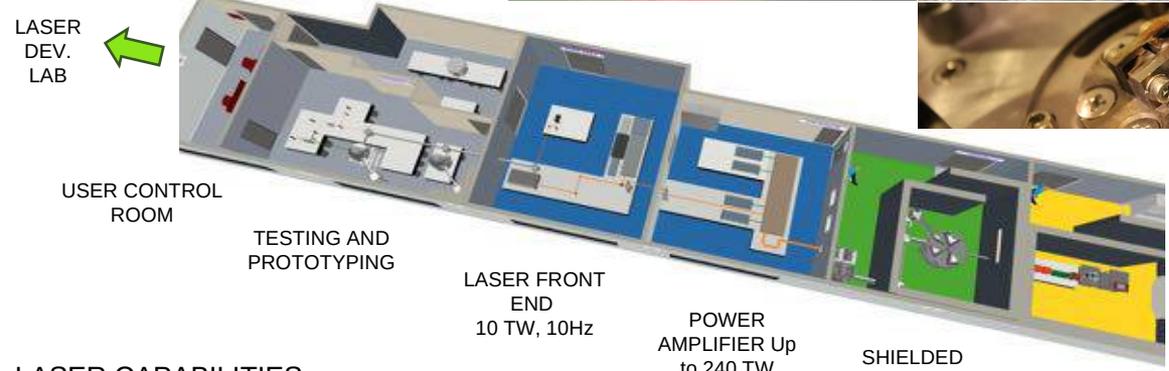
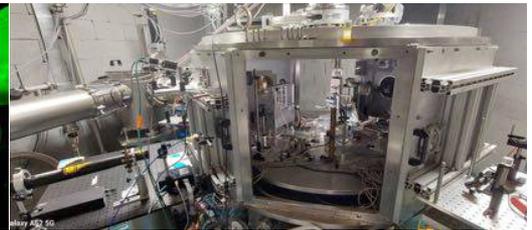
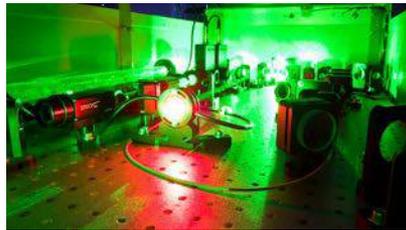
# The Intense Laser Irradiation Laboratory @ INO-CNR Pisa



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 Petra Koester Researcher	 Federica Baffigi Researcher	 Lorenzo Fulgentini Technologist	 Daniele Palla Researcher
 Martina Salvadori Researcher	 Costanza Panaino Senior Researcher	 Simona Piccinini Researcher	 Emma Hume Research Fellow
 Alessandro Fregosi Research Fellow	 Mohamed Ezzat Research Fellow	 Federico Avella PhD Student	 David Gregocki PhD Student

## Main research areas:

- Laser-plasma acceleration
- Laser-driven X-ray sources
- Inertial confinement fusion
- Laser development
- Flash radiotherapy



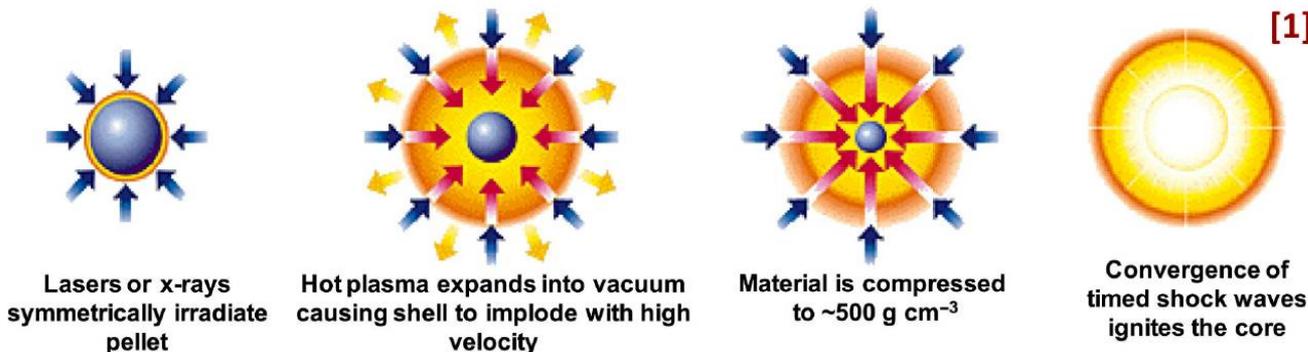
## LASER CAPABILITIES:

- 220 TW, Ti:Sa, up to 5 Hz, 23 fs;
- 1kHz, 20 mJ, Ti:Sa + 1kHz 2 mJ @ 2um, OPA
- 100 Hz, 1J, TiSA (procurement in progress)

NEW BEAMLINE FOR PRE-CLINICAL STUDIES

## Inertial fusion

- ★ ICF uses lasers (direct drive) or laser-produced X-rays (indirect drive) to irradiate a fuel pellet
- ★ Surface of the shell is ablated → leads to an implosion of the shell
- ★ This compresses and heats the fuel to fusion conditions

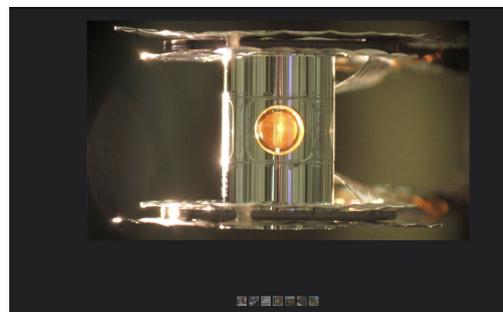


**[1]** C. Edwards & C. Danson, *HPLSE 3*, E4 (2015)

# Breakthrough at National Ignition Facility

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 with ID

$$\text{Gain} = 3.15\text{MJ (fusion yield)} / 2.05\text{ MJ (laser input energy)} = 1.54$$



Lawrence Livermore Natio... + Segui

NIF reaches milestone: Experiments show initial gain in fusion fuel

13.923 visualizzazioni 7 profitti 0 commenti

Scattata il 12 febbraio 2024

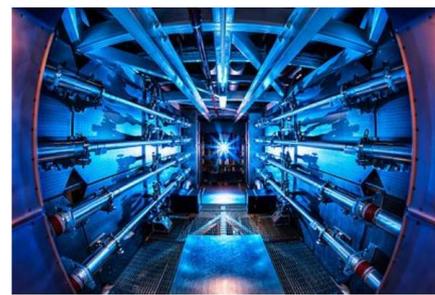
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Mostra DOP

Questo foto è presente in 1 album

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DOI:10.1063/PT.6.2.20220124

18 Dec 2022 In Physics & Policy

**National Ignition Facility surpasses long-awaited fusion milestone**

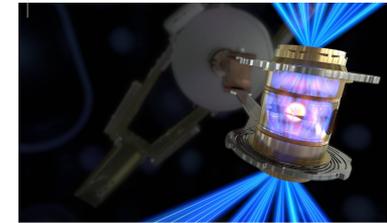
The shot at Lawrence Livermore National Laboratory on 5 December is the first-ever controlled fusion reaction to produce an energy gain.

David Kramer

0 COMMENTS

TOOLS

PREV NEXT



## Ignition shots

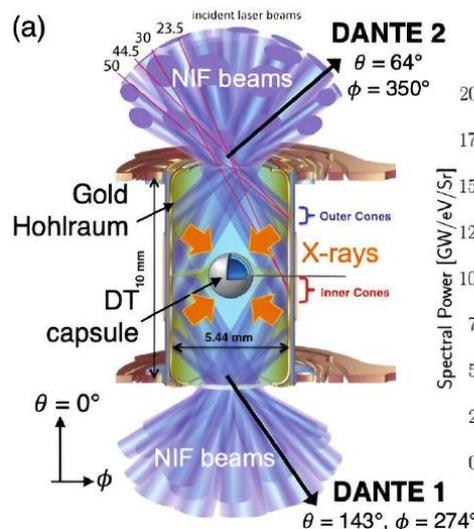


April 7, 2025

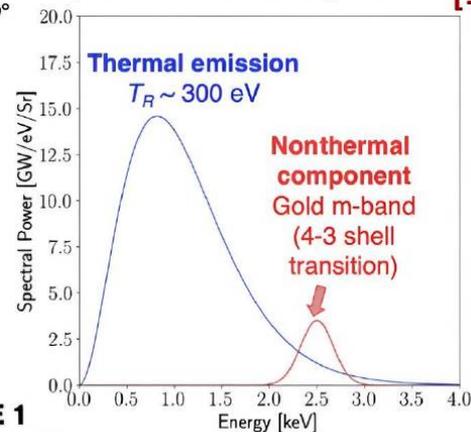
Yield: 8.6 MJ  
Laser energy: 2.08 MJ  
Gain: 4.13

## NIF result obtained with Indirect Drive

At NIF the lasers strike the interior walls of a **hohlraum** which generates an X-ray “oven” to compress the pellet



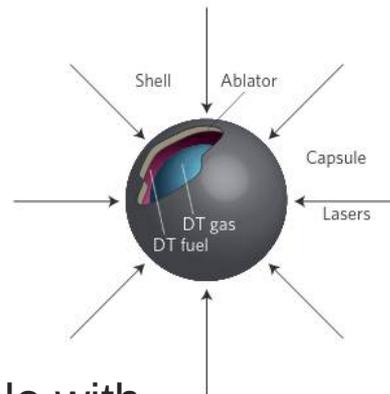
(b) Representative x-ray spectrum observed by Dante [1]



[1] H. Abu-Shawareb *et al.*, (The Indirect Drive ICF Collaboration), PRL **132**, 065102 (2024)

## Next step towards Inertial Fusion Energy: Direct Drive

Lasers irradiate the capsule directly



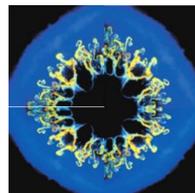
### Pros:

- Simpler targetry (no hohlraum), potentially compatible with high-repetition rate operation for inertial fusion
- Higher coupling efficiency, allowing for larger mass capsules and lower pressures to get ignition

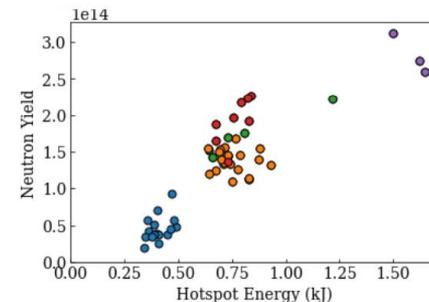
### Cons:

- More prone to hydrodynamic instabilities (Richtmyer-Meshkov instability (RMI), Rayleigh-Taylor) seeded by laser irradiation non-uniformities and target imperfections.

→ Mixing of ablator material into fuel,  
degraded performance



Recent experiments at OMEGA (LLE, Rochester University, US) show a steady progress in the neutron yield



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

# The HiPER+ project: On what we build



2005-2014 European Project "HiPER" (High Power Laser Energy Research Facility)



EUROFusion within Enabling Research projects. One-two projects per year related to IFE at the level of ~ 300 k€ per year per project (2017-2025)



3 Laserlab Expert groups related to ICF



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

High Power Laser Science and Engineering, (2023)  
doi:10.1017/hpl.2023.80

REVIEW SPECIAL ISSUE ON ICF

## Future for inertial-fusion energy in Europe: a roadmap

Dimitri Batani<sup>1</sup>, Arnaud Colaütis<sup>1</sup>, Fabrizio Consoli<sup>2</sup>, Colin N. Danson<sup>3,4</sup>, Leonida Antonio Gizzi<sup>5</sup>, Javier Honrubia<sup>6</sup>, Thomas Kühl<sup>7</sup>, Sebastien Le Pape<sup>8</sup>, Jean-Luc Miquel<sup>9</sup>, Jose Manuel Perlado<sup>10</sup>, R. H. H. Scott<sup>11</sup>, Michael Tatarakis<sup>12,13</sup>, Vladimir Tikhonchuk<sup>1,14</sup>, and Luca Volpe<sup>6,15</sup>

## The EU IFE community:

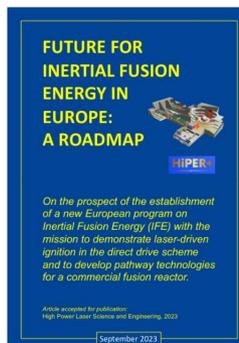
- Role of EU of scientists with ground-breaking contributions to ICF and important work on shock ignition done in the last 10 years within EUROfusion projects;
- Important, and often pioneering contributions in laser-plasma physics and applications;
- Effective international collaboration in direct drive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

But: 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.

## Identification of the main gaps:

- Absence of implosion facility
  - Dedicated to direct drive
  - European
  - Open and civilian
- Technological missing steps in lasers, targets, materials



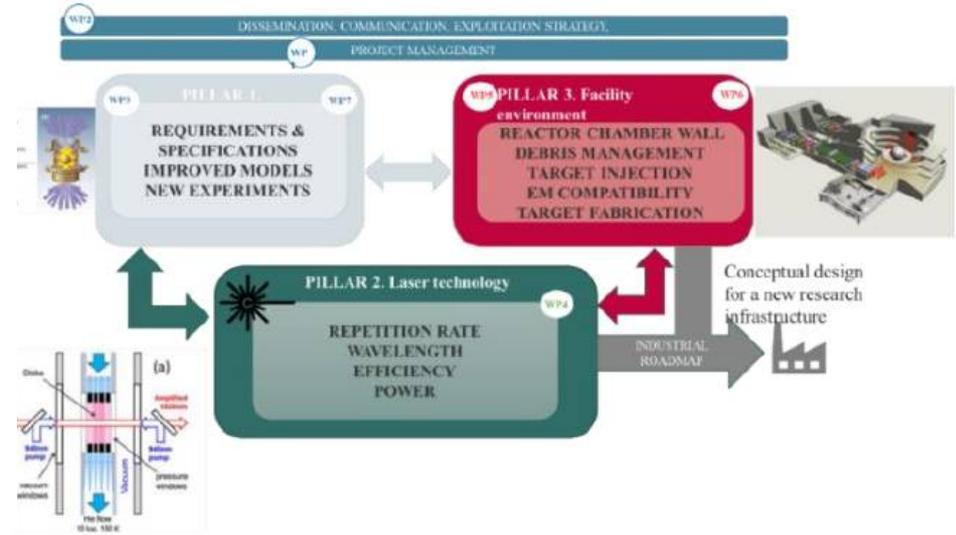
# The HiPER+ project

## Conceptual design report for a European Direct Drive Implosion Facility

### Participants



### Main blocks



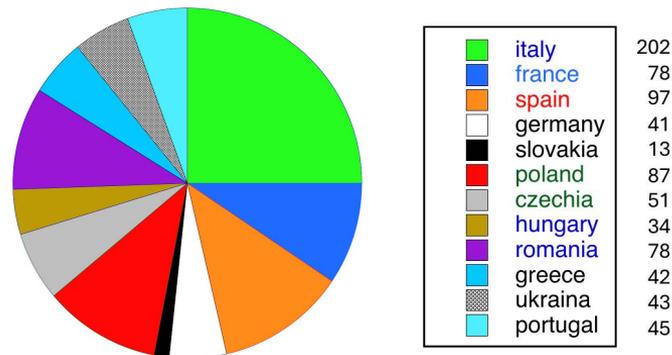
# The HiPER+ project (2026-2027)

24 groups and more than 100 researchers involved throughout Europe

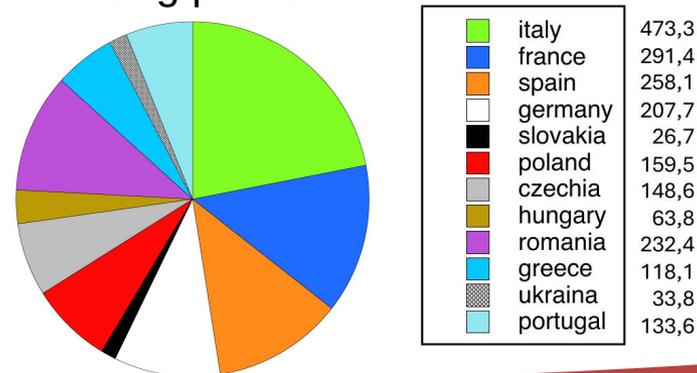
## Italian participation

- ENEA co-coordination of  
WP 4: Targets, Materials, and engineering aspects  
WP 5: Laser-Plasma and Nuclear Fusion Diagnostics
- INO-CNR co-coordination of  
WP 3: Laser Technology  
WP 2: Tailored Experiments
- INFN co-coordination of  
WP 7: Community Building and European Research Landscape Development
- Politecnico di Milano
- Università Milano-Bicocca

PM per Nation



Funding per Nation



## Challenge: Lasers

# IFE relies on a new generation of high power lasers

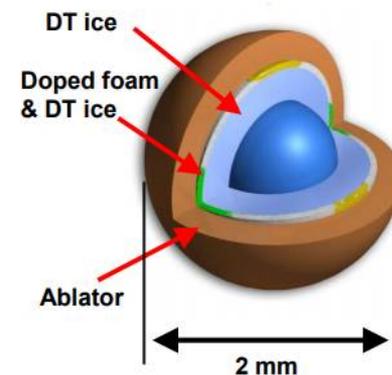
- IFE requires laser sources with extremely high power, but also **high repetition rates** (10–15 shots per second), far beyond today's experimental capabilities.
- **Broadband** laser for suppression of instabilities
- Electrical-to-optical **wall-plug efficiency** above 10%  
Today's laser wall-plug efficiency is  $< 1\%$
- Diode pumped **solid-state lasers** or **gas** lasers under development.
- Think about the possibility of using 2w light (532 nm) to reduce damage to optics.



## Challenge: Targets

# IFE reactor concept requires high-repetition rate operation

- Develop **low-cost** technology ( $< 1\$/\text{target}$ ).  
Today's cryogenic target costs  $\approx 10000\ \$$
- Develop capability of **mass production** of targets
- Develop techniques for **target injection and alignment at  $\approx 1\ \text{Hz}$**   
Today insertion of the target and alignment requires  $\sim$ hours
- Design of the **target insertion and tracking system**



**These challenges seem to be impossible to overcome with indirect drive!**

## Challenge: Materials

# IFE reactor concept needs new material and components

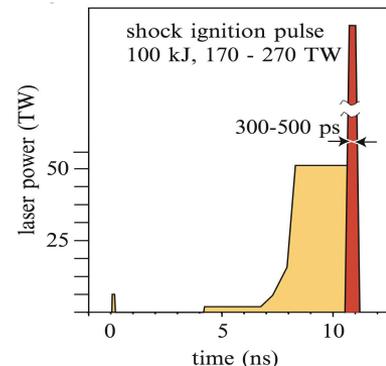
- **Tritium breeding** and handling system
- Issue of activation of materials. Identification of **adequate materials** for chamber construction and protection.
- Security and safety issues.
- Facing the problem of **huge EMP**
- Development of remote handling techniques
- Cooling system and energy recovery system. Systems for material control, replacement and refurbishing

Some of these issues are common to IFE and MFE → possible synergies

## Challenge: Spherical Compression

- **Compression symmetry** - The capsule must be compressed in a perfectly uniform way. Even a small asymmetry can prevent ignition.
- **Hydrodynamic instabilities** - Phenomena such as Rayleigh–Taylor instability amplify microscopic imperfections, reducing compression efficiency.
- **Materials and extreme physics** - During the process, matter reaches **high-density plasma** conditions that are difficult to model and to measure. New theoretical models and advanced diagnostics (e.g. **X-ray FEL**) are required.
- **Understanding ignition and burn** - Predicting when the plasma “turns on” and how the burn front propagates remains one of the greatest uncertainties in the field.

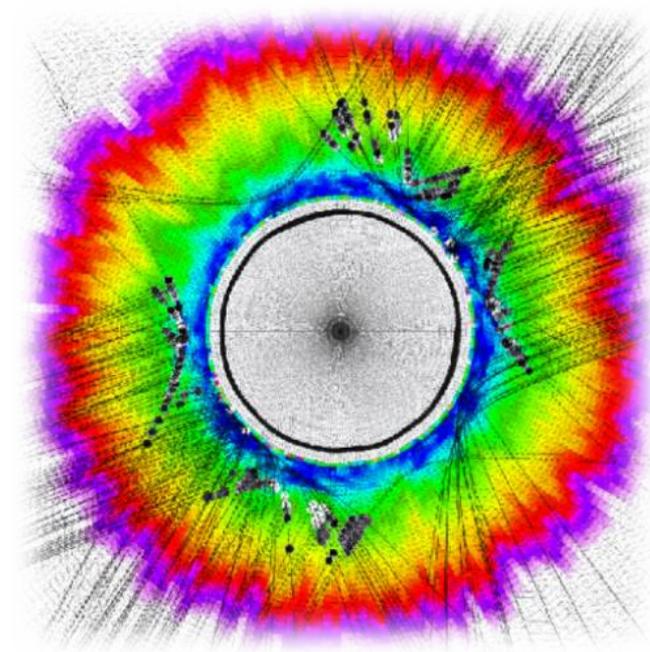
Mitigation strategy:  
Advanced schemes like **Shock Ignition** (separation of compression and ignition phase) and **shock augmented Ignition**.  
→ compatible with present-day laser technologies.



## Challenge: laser-plasma instabilities

Many physical processes occur in the interaction between laser light and the plasma surrounding the pellet

- **Stimulated scattering instabilities** can siphon energy away from the main process and degrade the quality of the implosion;
- To mitigate them, an emerging strategy is the use of **broadband laser systems**
- The **reduced coherence** inhibits these instabilities, improving both symmetry and stability of the compression.

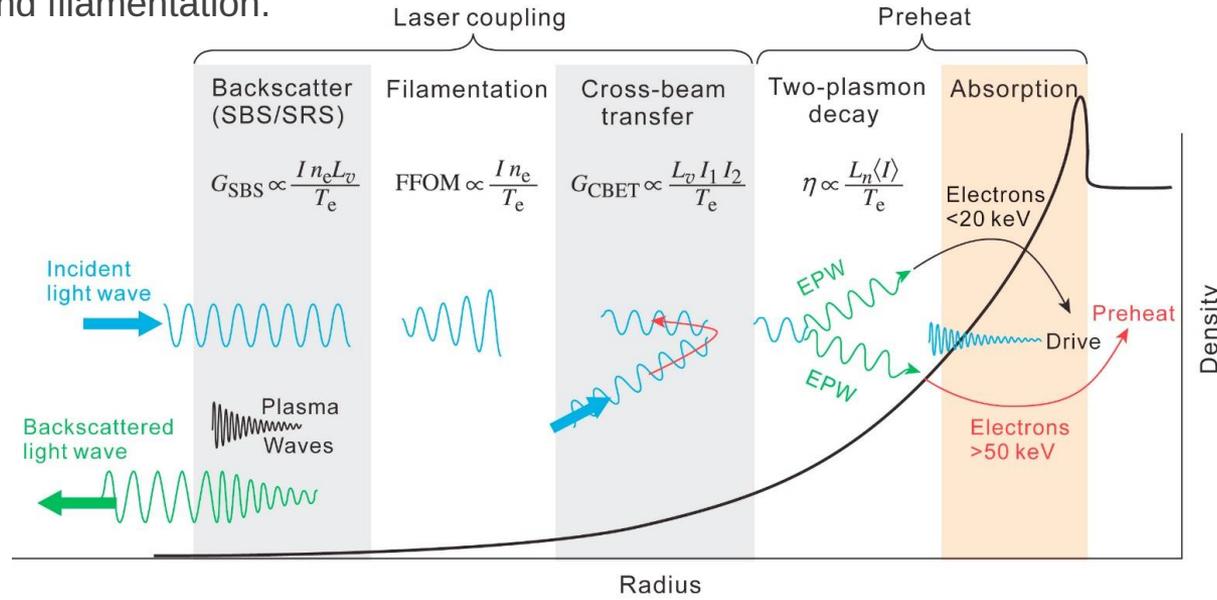


DOI  
10.1088/1741-4326/aab21a

# Parametric Instabilities

Laser-Plasma Interaction of ignition pulse ( $10^{15}$ - $10^{16}$  W/cm<sup>2</sup>) is dominated by **parametric instabilities** including Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS) and Two Plasmon Decay (TPD) – and filamentation.

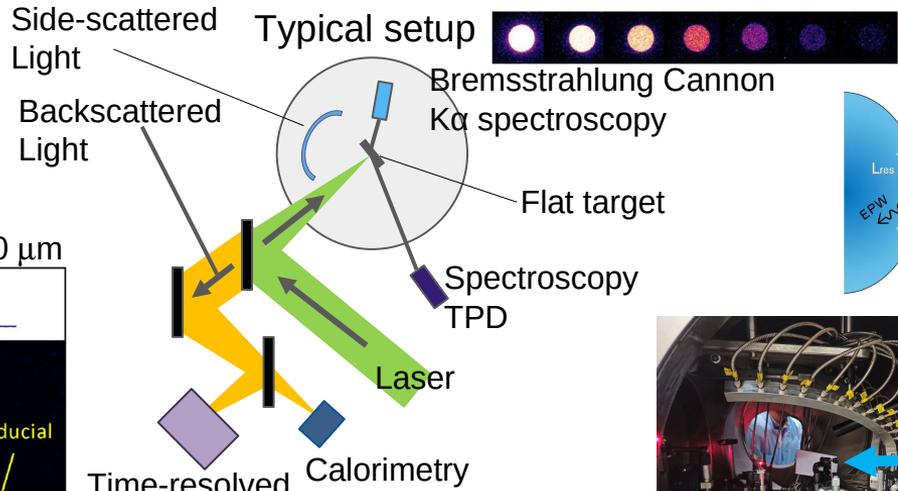
- energy is backscattered by SRS/TPD and SBS (up to ~40-50%) - can increase laser energy requirements
- SRS and TPD generate **fast electrons**, that can preheat the fuel and/or affect the shock pressure



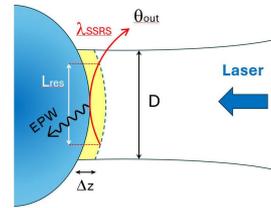
Is it possible to turn off or limit the growth of LPI ?  
(Laser coherence manipulation, Broadband laser, comb diode lasers...)

Froula et al., Plasma Phys. Control. Fusion 54 (2012) 124016

# Experimental investigation of parametric instabilities @ ILIL group

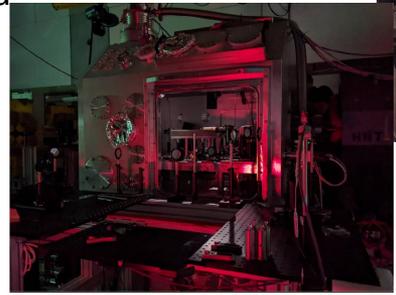
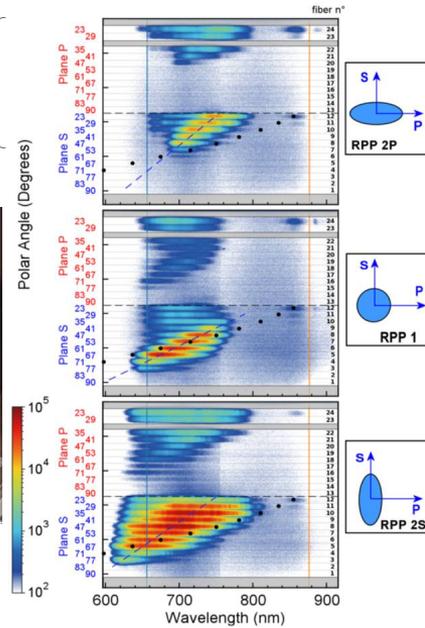
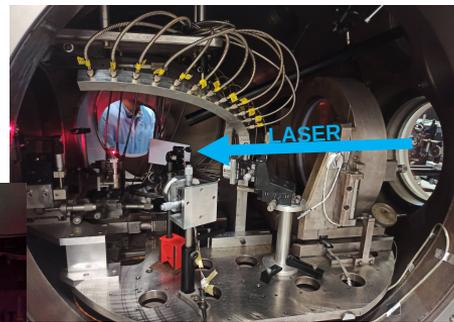
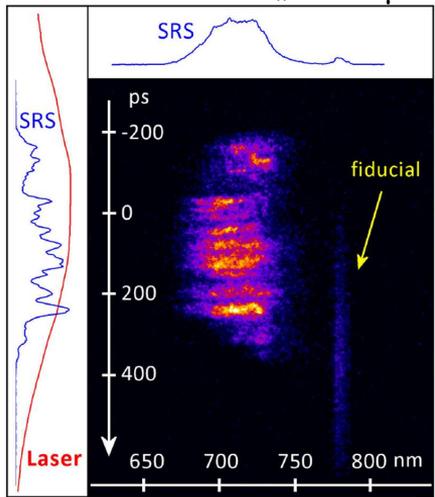


## Side-SRS



## SRS

$I = 1.1 \times 10^{16} \text{ W/cm}^2$   $L_n = 350 \mu\text{m}$



SRS driven in bursts at low densities

Cristoforetti et al., HPLSE, 9, e60, 2021

Cristoforetti et al., Matter Radiat. Extremes **10**, 045401, 2025

## Summary

- NIF results show that Inertial Fusion is achievable.
- Transforming it into a reliable energy source will require a convergence of physics, engineering, advanced materials, and new laser technologies.
- Inertial Fusion Energy is at the very edge of contemporary technology.
- It is a challenge—but also an extraordinary opportunity for a EU-wide collaboration for a staged approach from DD ignition demonstration to the reactor.