CICLO DI LEZIONI SEMINARIO SU FUSIONE NUCLEARE: INTRODUZIONE E PROSPETTIVE

DIPARTIMENTO DI FISICA, UNIVERSITÀ DI PISA, 20 MAGGIO 2024

Experimental Roadmap for Inertial Fusion in Europe

Leonida Antonio GIZZI
Consiglio Nazionale delle Ricerche
Istituto Nazionale di Ottica,
Pisa, Italy

CNR Campus in Pisa

Consiglio Nazionale delle Ricerche

Area della Ricerca di Pisa

CNR – Istituto Nazionale di Ottica

Intense Laser Irradiation Lab

Pisa, Italy

A node of the Italian ELI Network
A founding member of the EuPRAXIA ESFRI infrastructure

Intense Laser Irradiation Laboratory

Istituto Nazionale di Ottica – Consiglio Nazionale delle Ricerche

http://www.ilil.ino.it

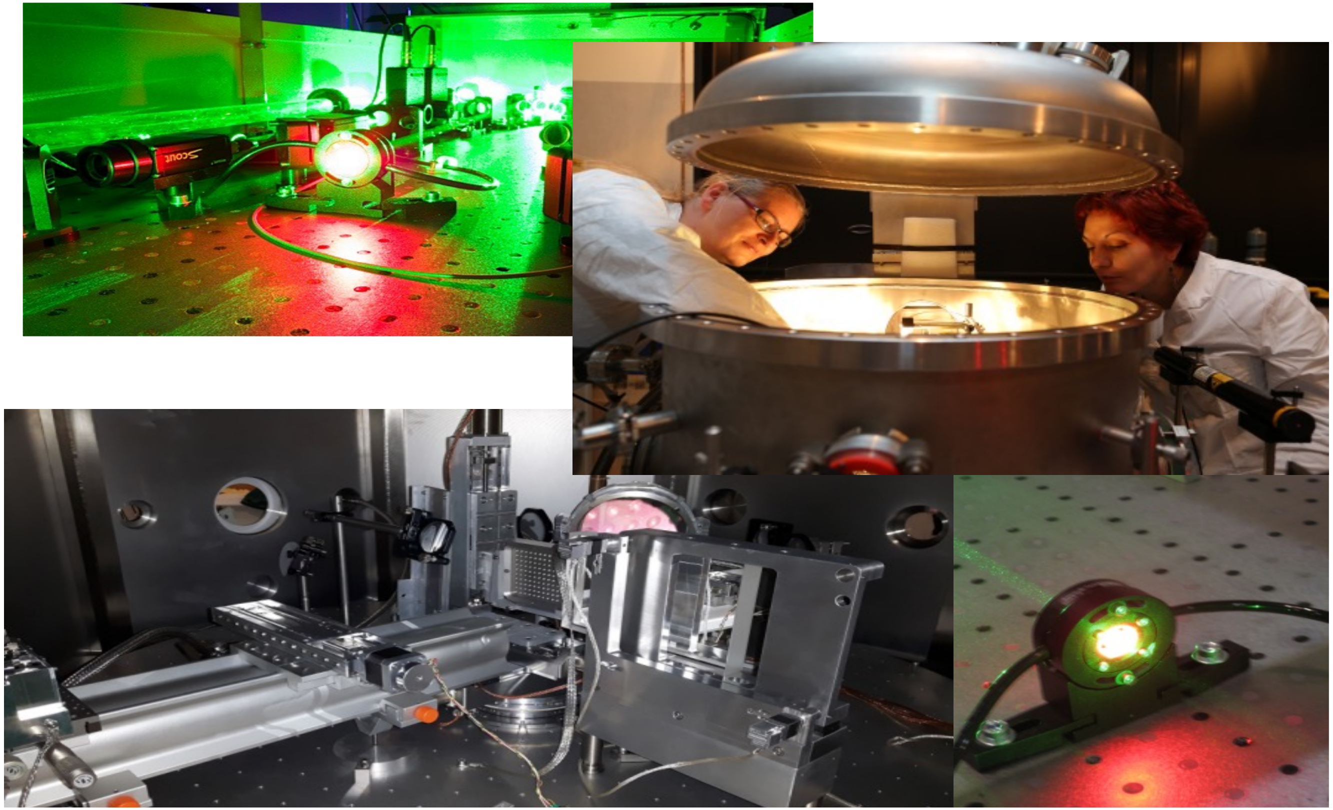
CNRINO
CONSIGLIO NAZIONALE DELLE RICERCHE
ISTITUTO NAZIONALE DI OTTICA

Intense Laser Irradiation Laboratory

CNR, Pisa, Italy

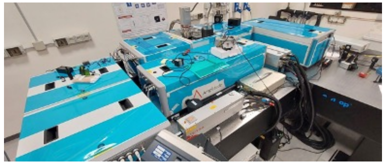
PEOPLE

Leonida A. GIZZI (Head)
Fernando BRANDI
Gabriele CRISTOFORETTI
Petra KOESTER
Luca LABATE
Federica BAFFIGI
Lorenzo FULGENTINI
Gabriele BANDINI
Costanza PANAINO
Simona PICCININI
Martina SALVADORI
Emma HUME
Alessandro FREGOSI
Daniele PALLA
Federico AVELLA (PhD)
David GREGOCKI (PhD)
Simon VLACHOS (PhD)



Intense Laser Irradiation Laboratory

CNR, Pisa, Italy

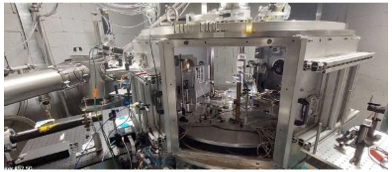


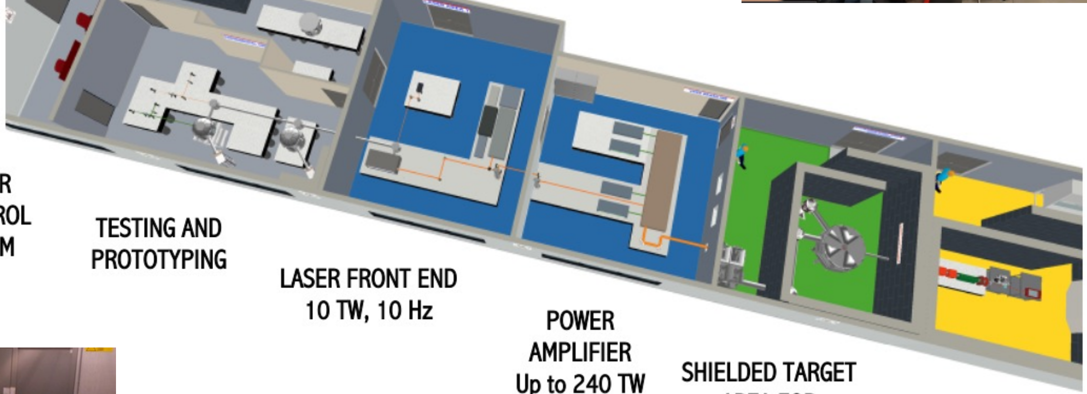
NEW HAP LASER
DEV. LAB

A member of Laserlab-Europe-AISBL

Laserlab
Europe

LASER CAPABILITIES:
- 220 TW, Ti:Sa, 5 Hz, 27 fs (upgrade in progress);
- 1kHz, >20 mJ, Ti:Sa + OPA
- 100 Hz, >1J, TiSA (procurement in progress)





USER
CONTROL
ROOM

TESTING AND
PROTOTYPING

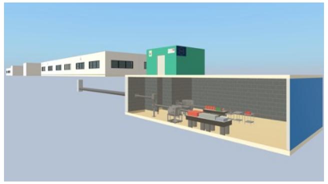
LASER FRONT END
10 TW, 10 Hz

POWER
AMPLIFIER
Up to 240 TW

SHIELDED TARGET
AREA FOR
PARTICLE
ACCELERATION

NEW BEAMLINE for
PRE-CLINICAL
STUDIES

NEW
HIGH DOSE
UNDERGROUND
BUNKER



THE
Tuscany Health Ecosystem

iFAST

I-PHOQS
INTEGRATED INFRASTRUCTURE INITIATIVE
IN PHOTONIC AND QUANTUM SCIENCES

eli

ESFRI

PNRR

EuPRAXIA
Advanced Photon Source

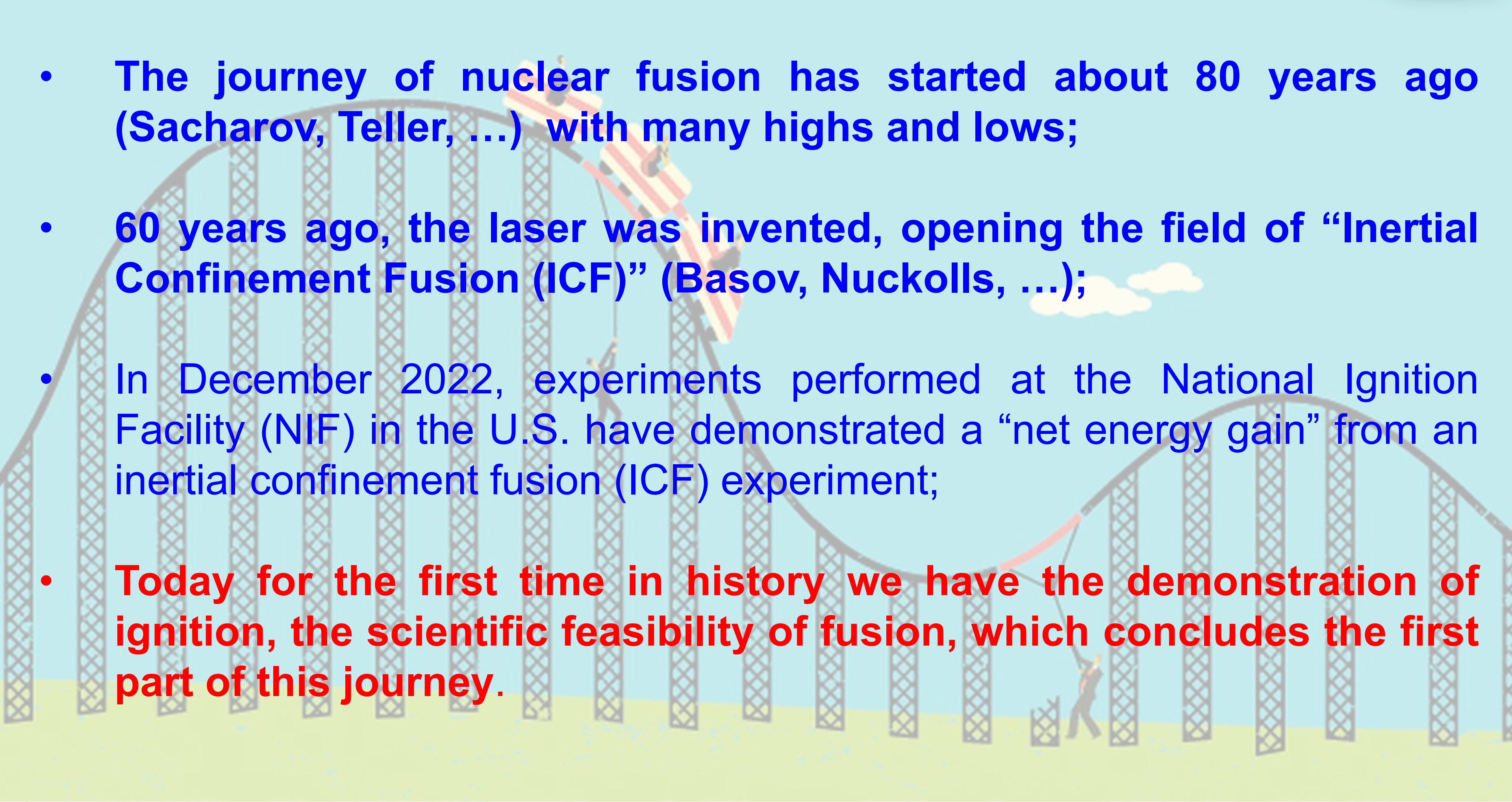
CONTENTS

- Recap on ICF status
- Physics of laser-plasma interactions
- Experimental platforms and Roadmap
- HiPER+ programme outlook
- Summary

CONTENTS

- **Recap on ICF status**
- Physics of laser-plasma interactions
- Experimental platforms and Roadmap
- HiPER+ programme outlook
- Summary

A LONG-LASTING JOURNEY



- **The journey of nuclear fusion has started about 80 years ago (Sacharov, Teller, …) with many highs and lows;**

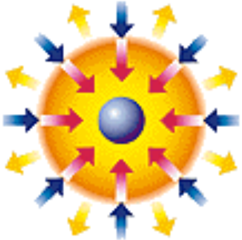
- **60 years ago, the laser was invented, opening the field of "Inertial Confinement Fusion (ICF)" (Basov, Nuckolls, …);**

- 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 journey**.

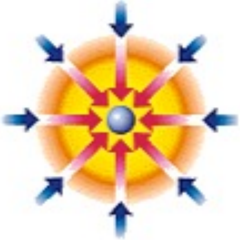
The original Direct Drive scheme*

Fase 1: irraggiamento tramite laser della capsula contenente DT



Fase 2: Compressione e riscaldamento

Con l’ ignizione, il processo di fusione si autosostiene con il calore generato dagli stessi eventi di fusione



Fase 3: Ignizione della fusione

La fusione completa del combustibile avviene per il breve tempo durante il quale la pallina resta compressa (inerzia)

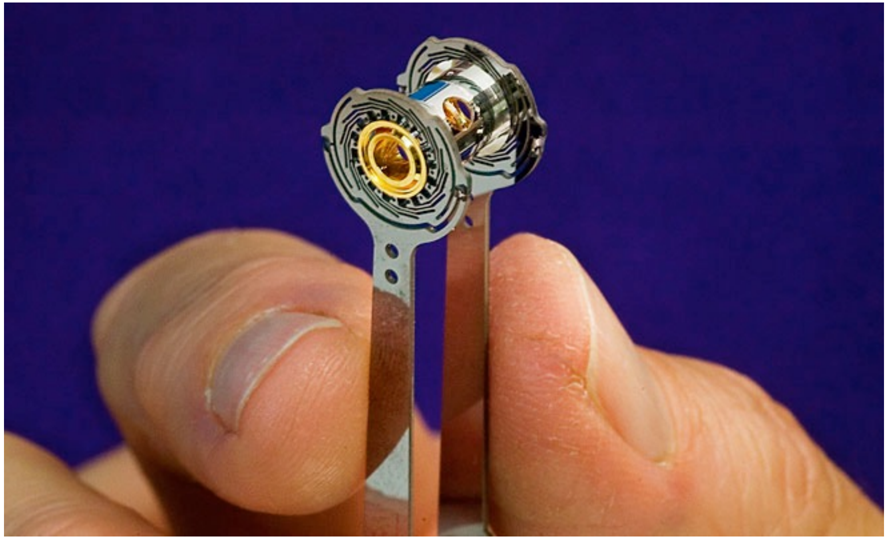
Fase 4: “Burn”

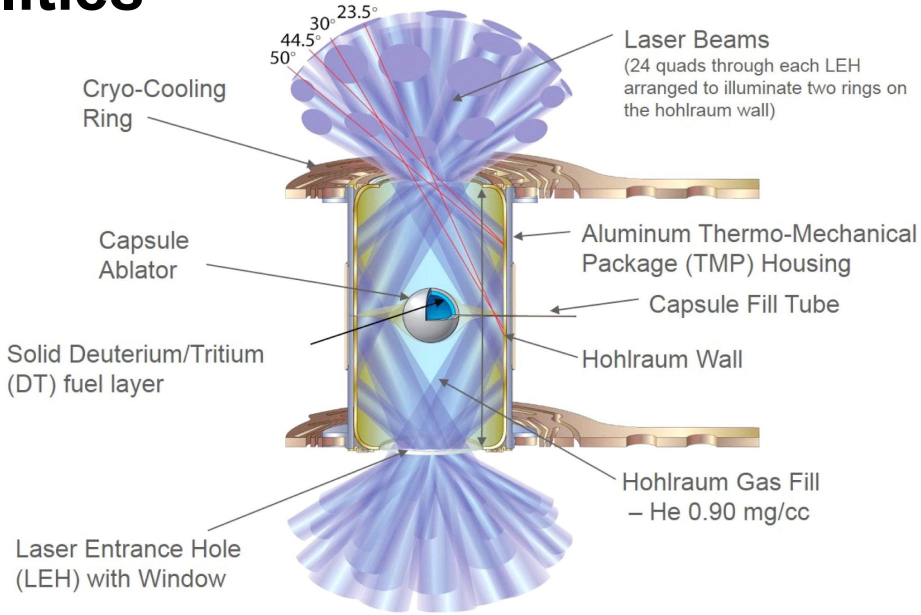
*N. G. Basov, O. N. Krokhin, and G. V. Sklizkov, in *Laser Interaction and Related Plasma Phenomena* (Springer, 1972), p. 389.

*J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, Nature 239, 139 (1972).

INDIRECT DRIVE

Configuration to overcome irradiation non-uniformities and seeding of Hydrodynamic instabilities



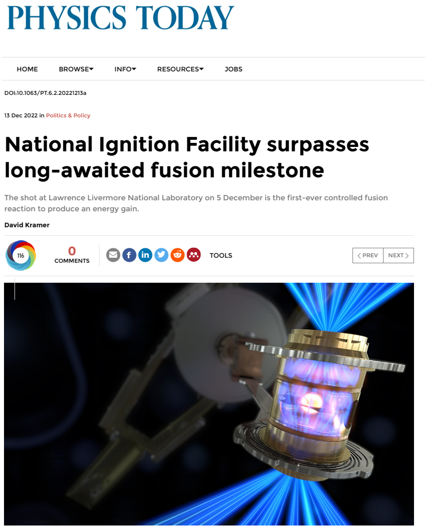


John Lindl; Development of the indirect-drive approach to inertial confinement fusion and the target physics basis for ignition and gain. *Phys. Plasmas* 1 November 1995; 2 (11): 3933–4024. https://doi.org/10.1063/1.871025

BREAKTHROUGH

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

Gain = 3.15MJ / 2.05 MJ = 1.54



PHYSICS TODAY

HOME BROWSE▾ INFO▾ RESOURCES▾ JOBS

DOI:10.1063/PT.6.2.20221213a

13 Dec 2022 in Politics & Policy

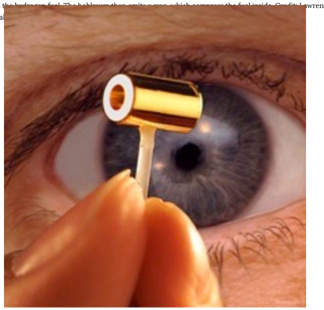
National Ignition Facility surpasses long-awaited fusion milestone

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

David Kramer

116 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 t[illegible]awrence Livermore National



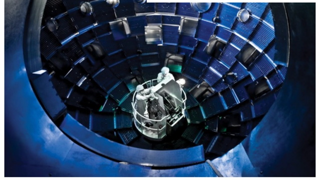
physicsworld

NUCLEAR FUSION | NEWS

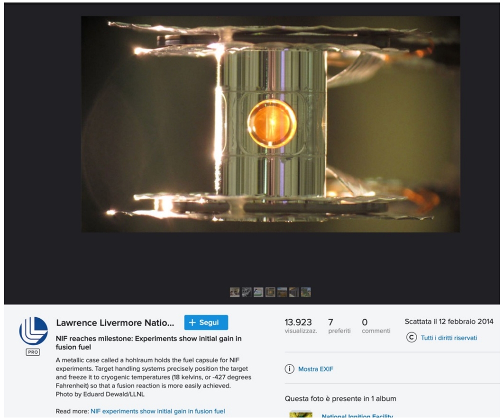
National Ignition Facility demonstrates net fusion energy gain in world first

14 Dec 2022

Big gains: the record-breaking shot at the National Ignition Facility was made at just after 1 a.m. local time on 5 December. (Courtesy: LLNL)



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



Lawrence Livermore Natio... + Segui

NIF reaches milestone: Experiments show initial gain in fusion fuel

A metallic case called a hohlraum holds the fuel capsule for NIF experiments. Target handling systems precisely position the target and freeze it to cryogenic temperatures (18 kelvins, or -427 degrees Fahrenheit) so that a fusion reaction is more easily achieved.
Photo by Eduard Dewald/LLNL

Read more: NIF experiments show initial gain in fusion fuel

13.923 visualizzaz. 7 preferiti 0 commenti

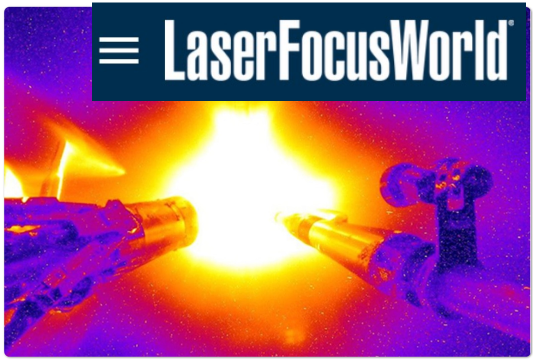
Scattata il 12 febbraio 2014

Tutti i diritti riservati

Mostra EXIF

Questa foto è presente in 1 album

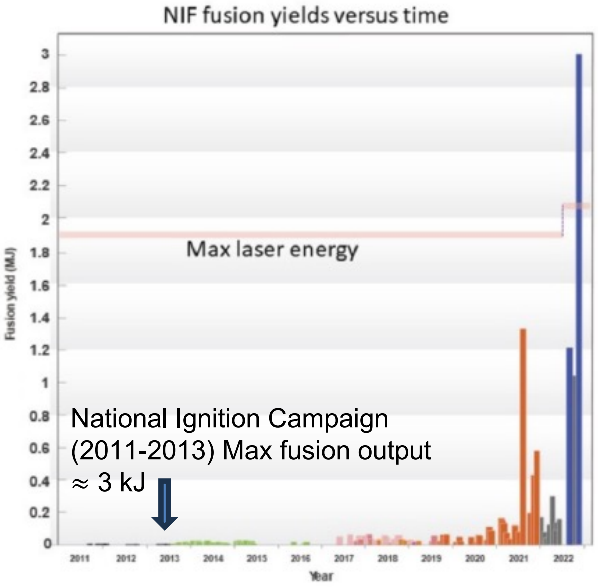
National Ignition Facility



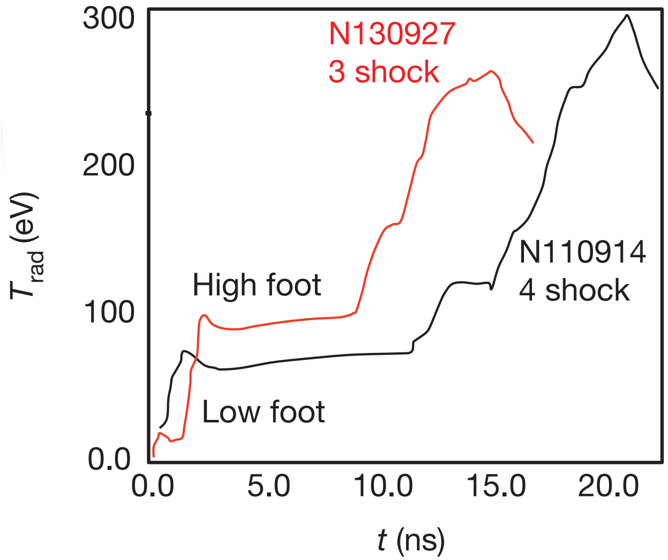
Colorized image of a NIF “Big Foot” deuterium-tritium (DT) implosion.

MAIN IMPROVEMENTS

LONG AND DIFFICULT WAY TO SUCCESS


NIF fusion yields versus time

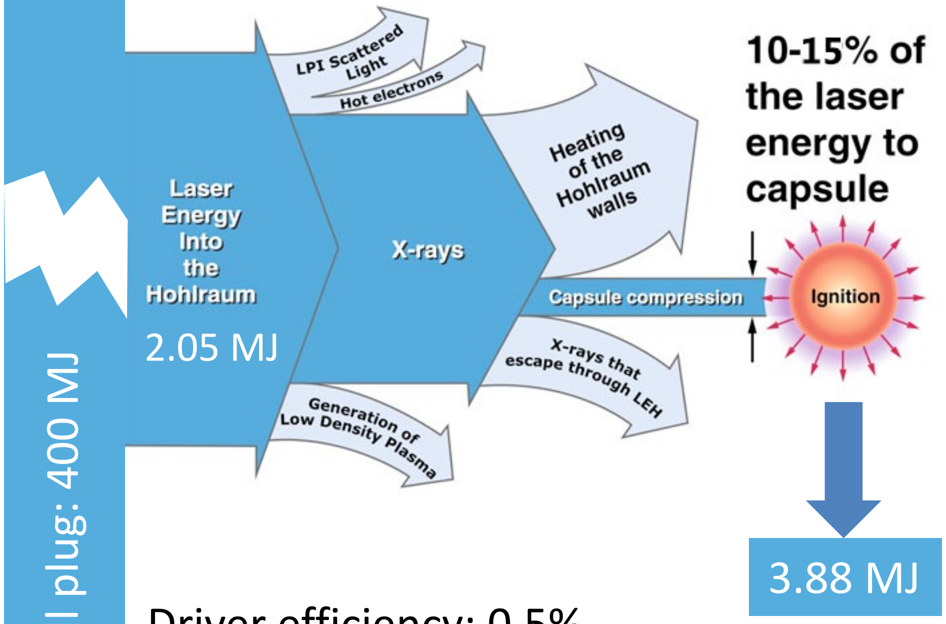
“High foot” implosions



In addition to using higher foot, NIF result was obtained thanks to:
Different ablators (HDC: synthetic diamond)
Different gas pressure in the holhraum
Reduced holhraum size and bigger pellet
Improved radiation uniformity
Improved target quality (roughness)

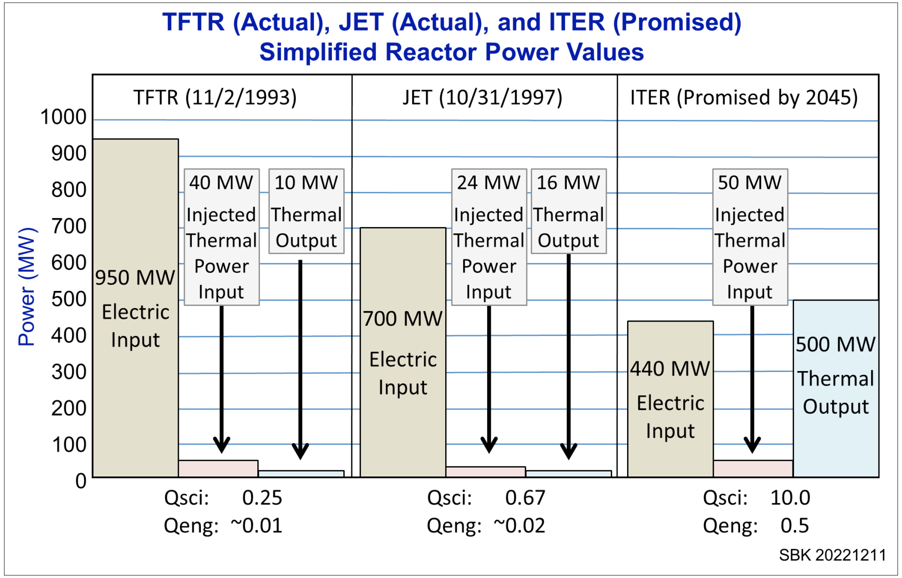
ENERGETICS OF FUSION

ICF (pulse: Energy)



Driver efficiency: 0.5%

MCF (CW: Power)

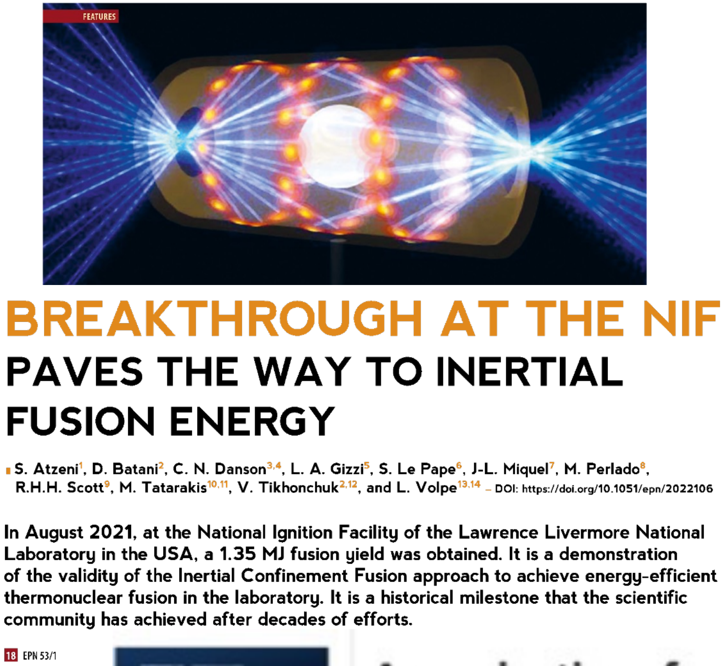


https://news.newenergytimes.net/

Driver efficiency: 2-3%

Driver efficiency of lasers still at the 1st generation: 20-40x improvement possible

MAJOR 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

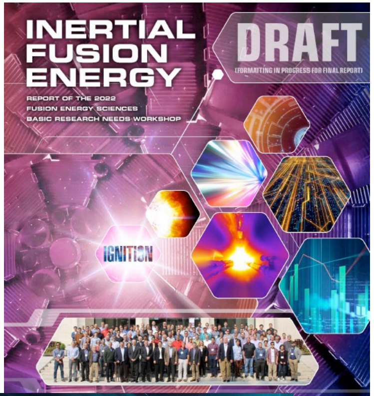
S. Atzeni, D. Batani, C. N. Danson, L. A. Gizzi, M. Perlado, M. Tatarakis, V. Tikhonchuk and L. Volpe Show author de

MAJOR 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 U.S is evaluating 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



INERTIAL FUSION ENERGY

REPORT OF THE 2022
FUSION ENERGY SCIENCES
BASIC RESEARCH NEEDS WORKSHOP

DRAFT
(FORMATTING IN PROGRESS FOR FINAL REPORT)

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+

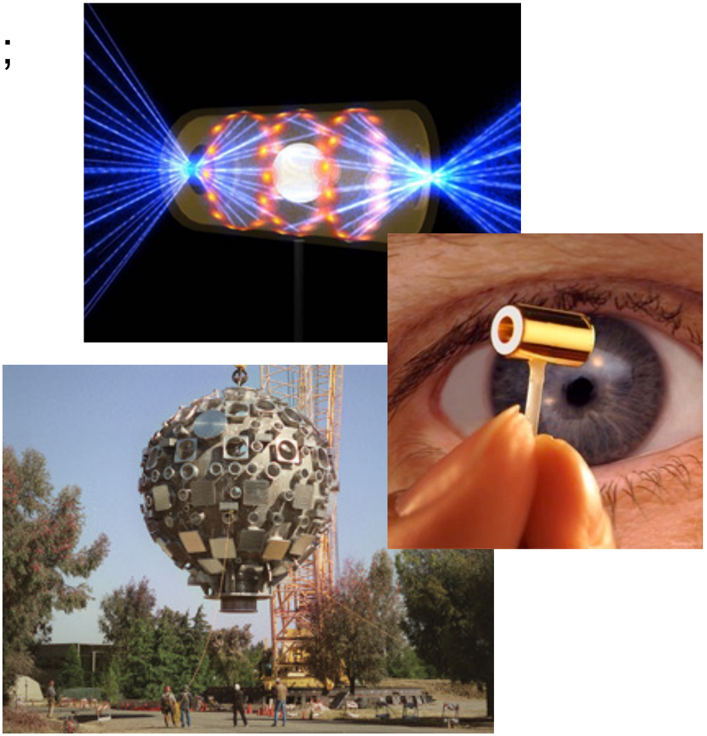
MEMORANDUM
Laser Inertial Fusion Energy

EXPERT COMISSION
Prof. Dr. Constantin Leon Haefner (Head)
Neil Alexander, PhD
Prof. Riccardo Betti, PhD
Omar Hurricane, PhD
Tammy Ma, PhD
Prof. Dr. Robert Stieglitz
Prof. Dr. Hartmut Zohm

MAJOR IMPACT OF NIF RESULTS

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

- Complex targets;
- Massive targets (lot of high-Z material in chamber);
- Intrinsic low gain due to step of X-ray conversion;
- “Political” issues due to the military/defense use.



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

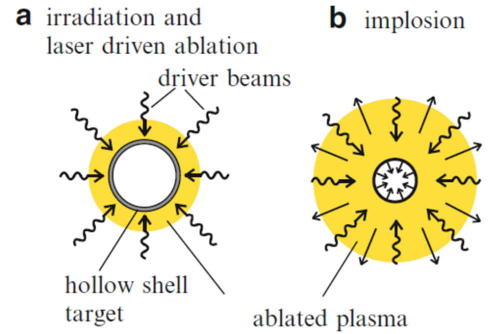
- Science: Investigate the original **DIRECT DRIVE** approach which can provide the gain needed for energy production
- Technology: Address the engineering issues related to IFE: **high repetition rate lasers**, **target development**, **damages to optics**, **tritium breeding**, …

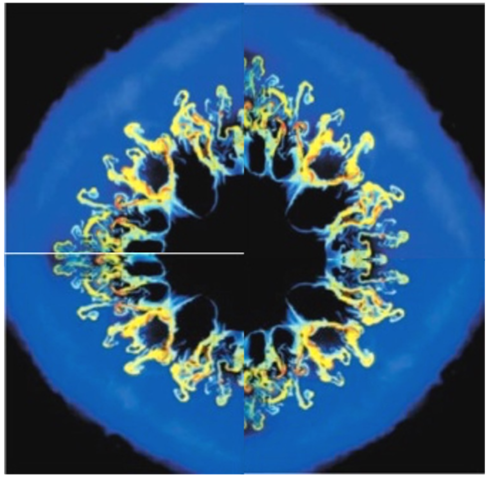
DIRECT DRIVE ICF

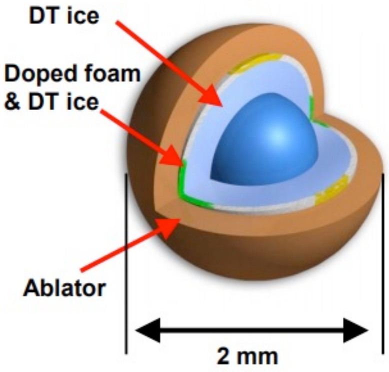
Pros:

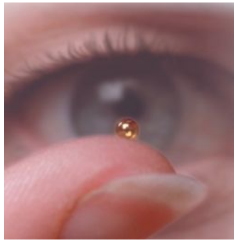
- Coupling efficiency 4-5% → we can compress larger mass capsules and we need lower pressures to get ignition 140 Gbar vs. 350 Gbar compared to ID
- simpler targets, potentially compatible with high-repetition rate operation for inertial fusion energy reactors.

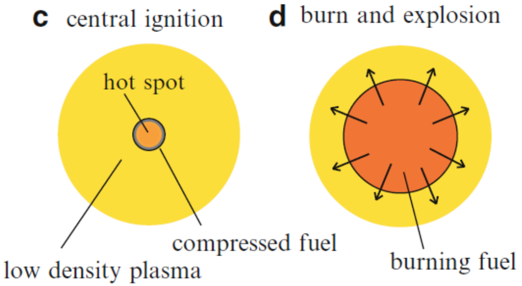
Cons: Direct Drive is prone to hydro-instabilities (Rayleigh-Taylor) due to direct laser irradiation non-uniformities and target imperfections.









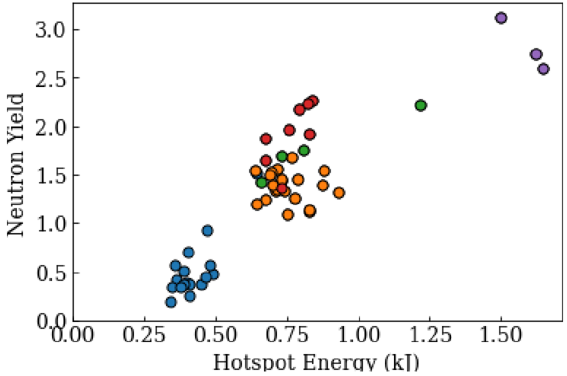


EXPERIMENTAL EVIDENCE OF DIRECT DRIVE

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).

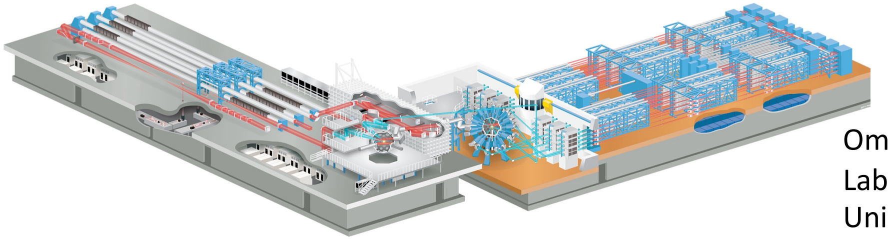
DIRECT DRIVE
EXPERIMENTS
AT OMEGA: 30 KJ

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



Omega Laser
Laboratory for Laser Energetics
University of Rochester

MITIGATION STRATEGIES?

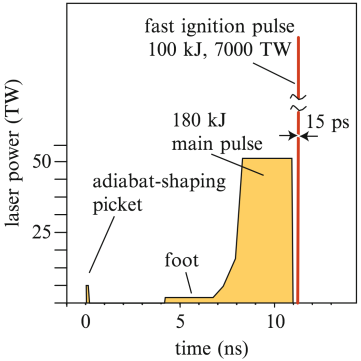
How to mitigate the impact of hydro instabilities in Direct Drive?

Separation of the compression phase and the ignition phase.

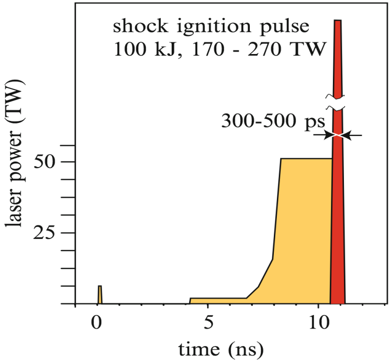
Options:

Fast Ignition exotic and non-scalable physics

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



Shock Ignition compatible with present-day laser technology ☺

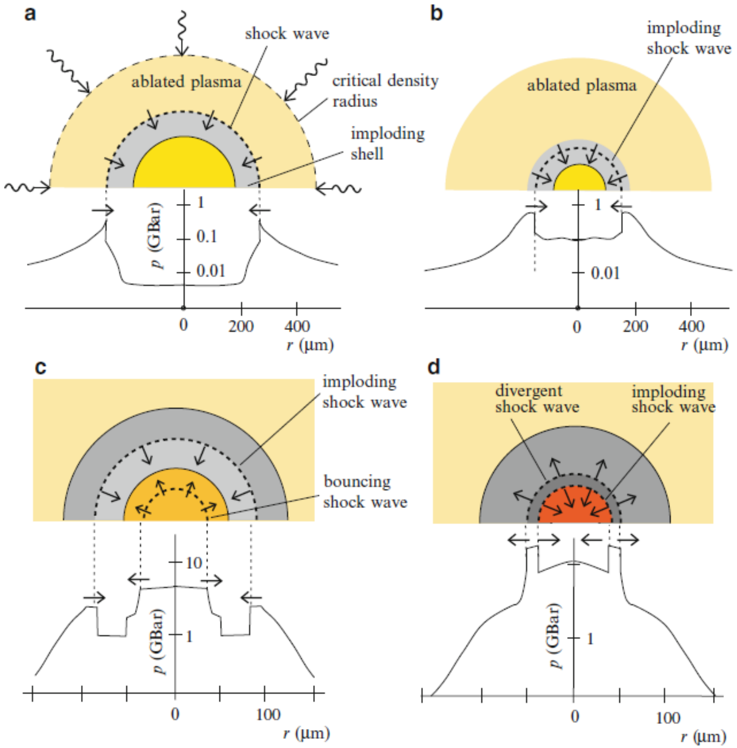


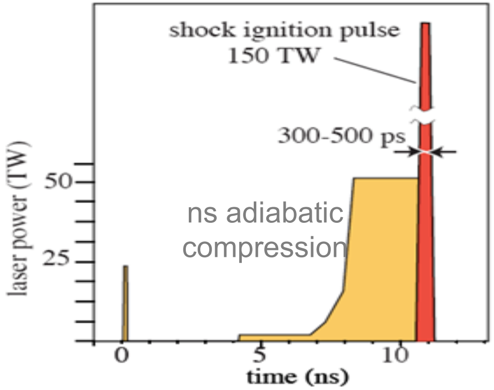
SHOCK IGNITION: BASICS

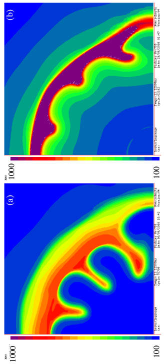
Scheme proposed by R. Betti, J.Perkins et al. [PRL 98 (2007)] and anticipated by V.A.Shcherbakov [Sov.J. Plasma Phys. 9, 240 (1983)];

- Separation of compression and ignition phase:
  - > Thicker and massive targets
  - > Lower implosion velocity ~240 km/s (vs. 350-400 km/s of DD hot spot ignition)
  - > Lower growth of R-T instability
- Strong shock at end of compression phase to generate hot spot (intensity: 10^{15}-10^{16} W/cm^2)
- Geometrical amplification of spherically converging shock (ablation pressure ≈300 Mbar)
- Higher gain possible

Phases of Shock Ignition ICF

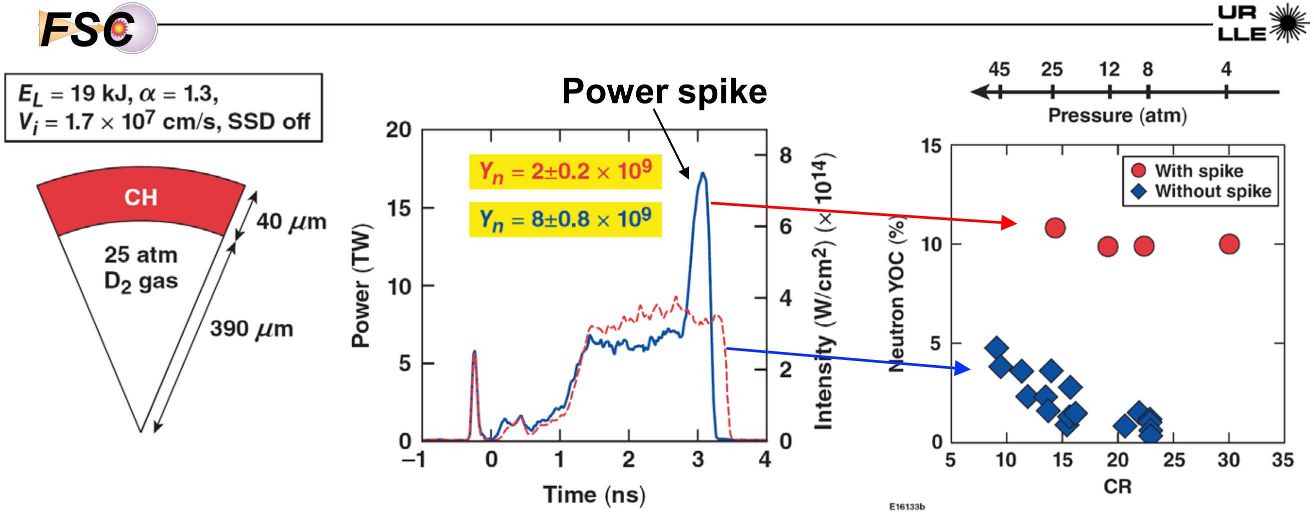






EXPERIMENTAL EVIDENCE OF SHOCK IGNITION

Shock-ignition experiments on OMEGA have shown improved performance with a shock launching spike at the end of the laser pulse



The neutron yield increases considerably when a shock is launched at the end of the pulse.

The measured-to-calculated neutron-yield ratios are close to 10% for a hot-spot convergence ratio of 30.

W. Theobald,et al Phys. Plasmas (2008)

NEW: SHOCK-AUGMENTED DIRECT DRIVE

Concept:

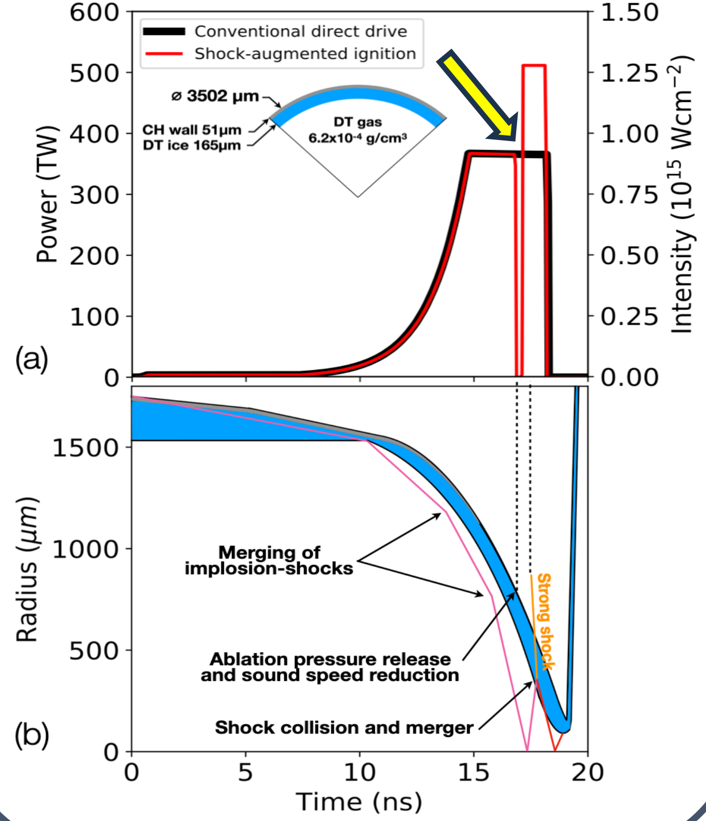
- Generate a very strong shock without very high power or intensity
- Mitigate the challenges related to parametric instabilities and hot electrons

Method:

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

Preliminary experiments done at Omega and NIF

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



EXPERIMENTAL ROADMAP MOTIVATION

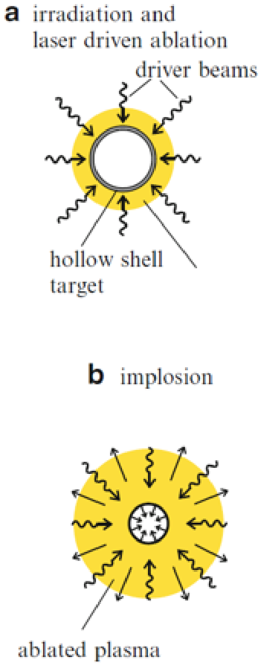
Physics issues to be understood:

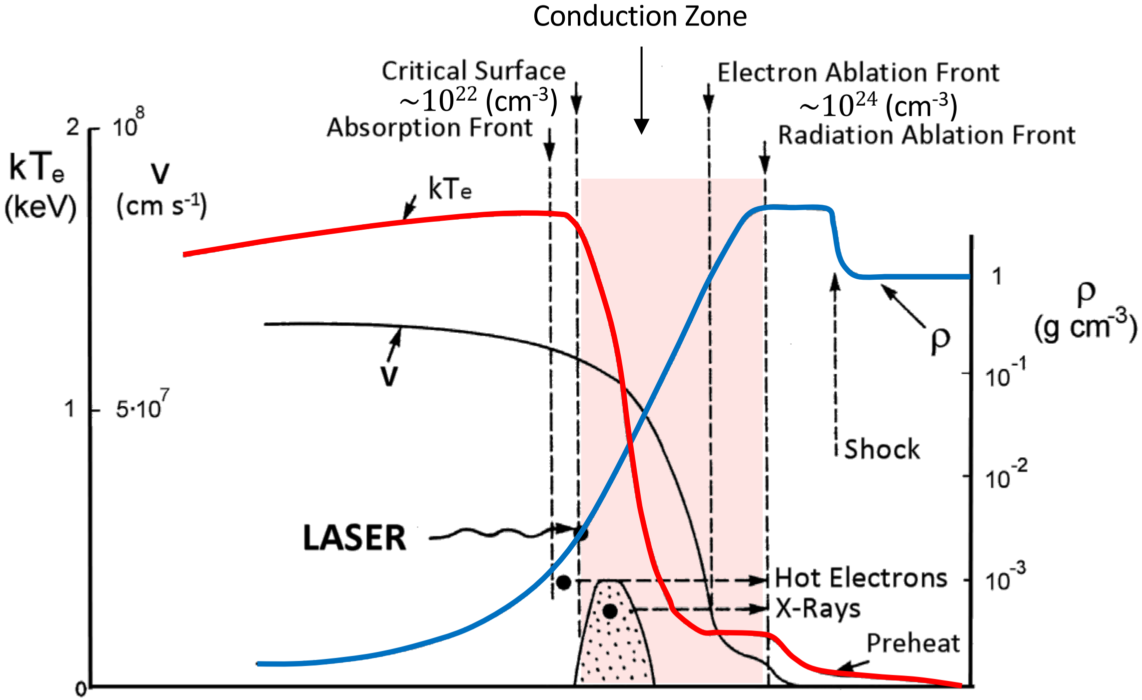
- Plasma production and characterization
- Parametric instabilities in implosion-like and shock-ignition-like Laser-Plasma interaction;
  - ✓ Stimulated Brillouin Scattering (SBS)
  - ✓ Stimulated Raman Scattering (SRS), side SRS
  - ✓ Two Plasmon Decay
  - ✓ Cross-beam Energy Transfer (CBET)
  - ✓ Filamentation
  - ✓ Speckles from smoothing
- Hot electrons generation and their impact
- Acceptable degree of non uniformity in irradiation during compression / ignition phases
- Multiple beam irradiation
- Broadband and Chirped pulse irradiation
- Polar Direct Drive
- 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 tools (Hydro, PIC)

CONTENTS

- Recap on ICF status
- **Physics of laser-plasma interactions**
- Experimental platforms and Roadmap
- HiPER+ programme outlook
- Summary

COLLISIONAL ABSORPTION

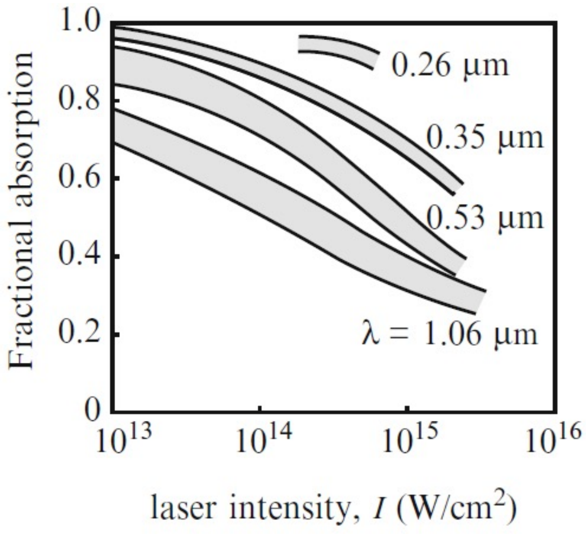


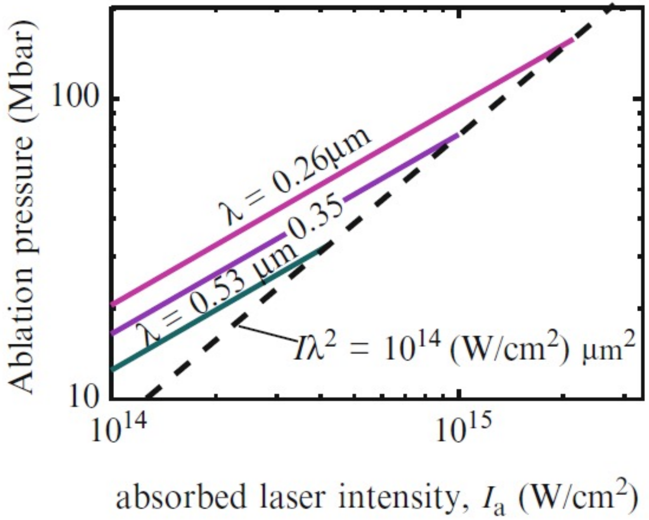


In a idealized ICF situation, laser light is absorbed by collisional absorption (inverse Bremsstrahlung) near the critical density surface $n_c(cm^{-3}) = 1.1 \cdot 10^{21}/\lambda_{\mu m}^2$ and successively the energy is transported to the ablation front, mainly via thermal electrons through the conduction zone.

$$n_c = \frac{m_e \omega^2}{4\pi e^2} \qquad (\omega_0 = \omega_p = 4\pi e^2 n_e / m_e) \qquad \frac{dI_L}{dz} = -k_{IB} I_L \qquad k_{IB} \propto \frac{Z(n_e/n_c)^2}{T_e^{3/2}(1 - n_e/n_c)^{1/2}}$$

SHORTER WAVELENGTH IRRADIATION





S. Atzeni, Chapter 10, Laser Plasma Interaction and Application

$$\nu_{eff} \approx \nu_c \frac{v_{th}^3}{(v_{osc}^2 + v_{th}^2)^{3/2}}$$

$$P_{abl} \approx 57\left(\eta_{abs} I_L / \lambda_{L\mu m}\right)^{2/3} MBar$$

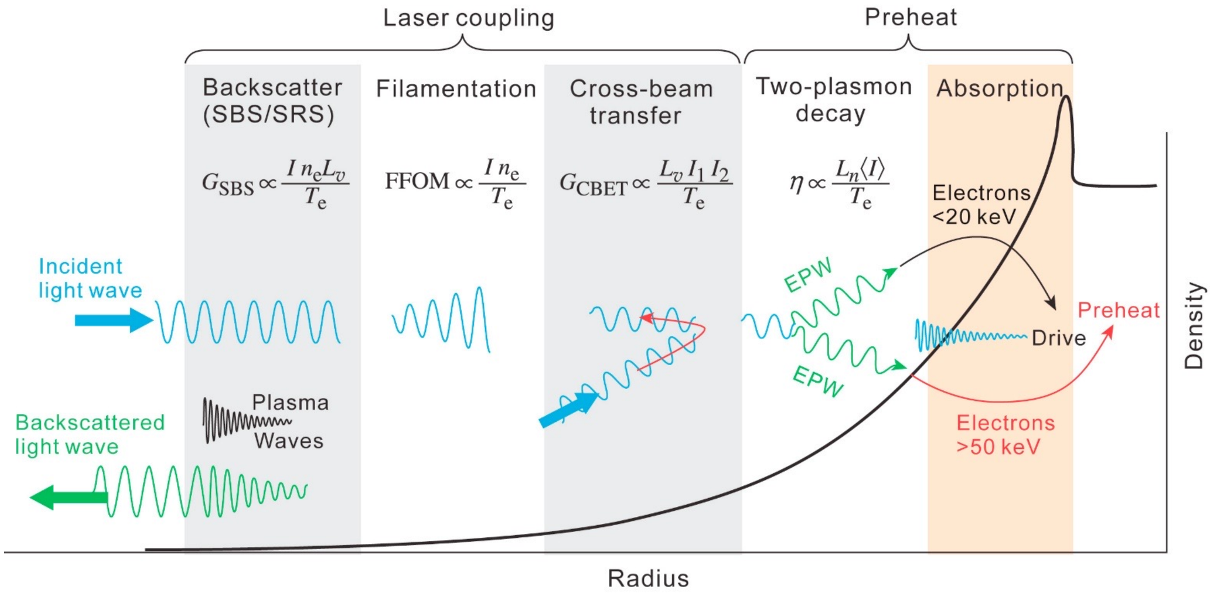
$$v_{osc}/c \approx 0.85\lambda_{\mu m} I_L^{1/2}$$

- At higher laser intensities the effective collision frequency I is reduced by quiver motion in laser field
- -> non-linear inverse Bremsstrahlung
- UV light is more efficiently absorbed because it propagates to higher densities

The ablation pressure obtained is larger for UV laser light due to a shorter conduction zone

L.A.Gizzi, A.J.Mackinnon, D.Riley, S.M.Viana, O.Willi, *Measurements of thermal transport in plasmas produced by picosecond laser pulses,* Laser Part. Beams, **13** (1995).

LASER-PLASMA INTERACTION



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

In real ICF conditions, for $I\lambda^2_{\mu m} > 10^{14}\, W\, cm^{-2}$, many «**non collisional**» mechanisms – or parametric instabilities - are driven in the plasma corona, producing:

- the scattering of a significant percentage of laser energy (SRS, SBS)
- the unbalance of multiple laser beams irradiation (CBET)
- Small scale modulation of beam irradiation (filamentation)
- Suprathermal (or hot) electrons, produced by damping of SRS and TPD plasma waves, prehating the fuel

PARAMETRIC INSTABILITIES

- Parametric Instabilities are 3-waves coupling processes where the e.m. laser excites ion-acoustic or electron plasma waves
- Thresholds are given by the damping of daughter waves
- In inhomogeneous plasmas, the threshold of convective instabilities depends on the resonance region ($\nabla n, \nabla$v)

$$\omega_1 = \omega_2 + \omega_3$$
$$\vec{k}_1 = \vec{k}_2 + \vec{k}_3$$

Stimulated Raman Scattering (SRS)

absolute	convective
~10^{14} W/cm^2	~10^{15} W/cm^2

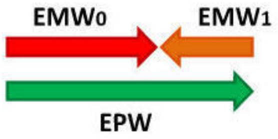
Stimulated Brillouin Scattering (SBS) & Cross Beam Energy Transfer (CBET)

~10^{14} W/cm^2

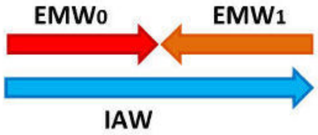
Two Plasmon Decay

~10^{14} W/cm^2

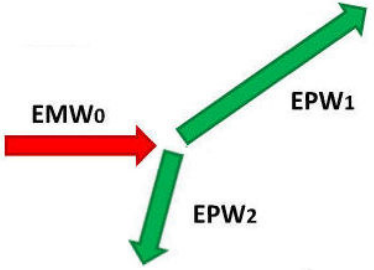
SRS



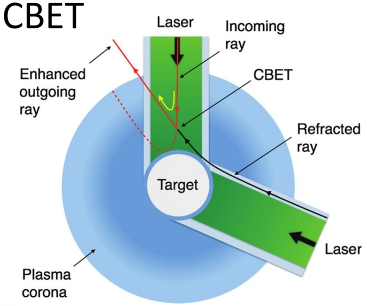
SBS



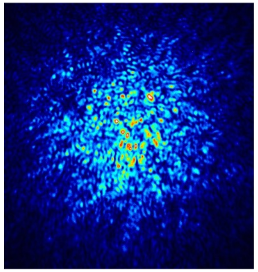
TPD

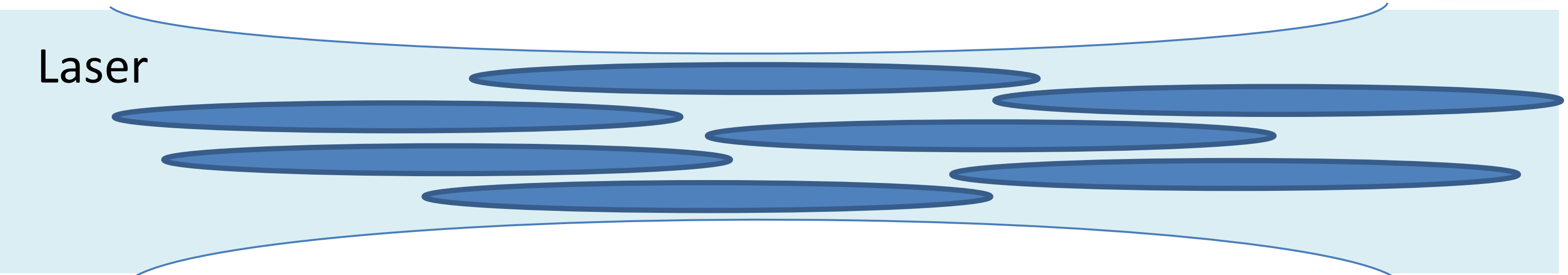


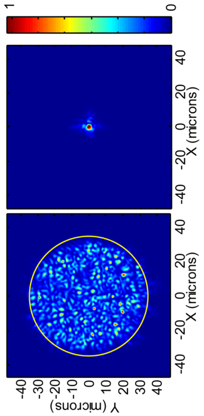
CBET



BEAM SMOOTHING WITH PHASE PLATES







Speckle size

$\lambda_\perp \approx 1.2F\lambda_0 \quad \lambda_\parallel \approx 8F^2\lambda_0$

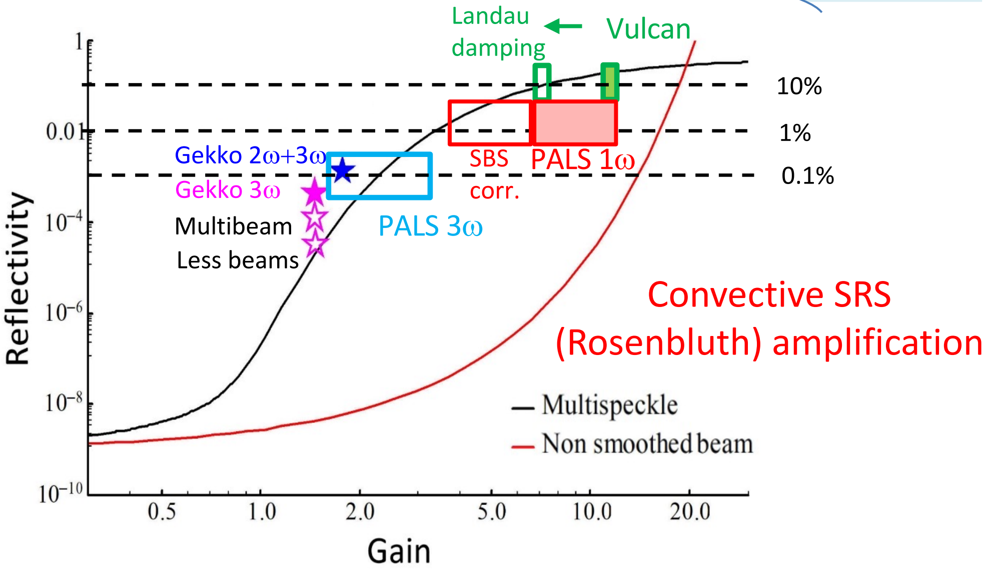
for F=10 and λ=0.355 nm

$\lambda_\perp \approx 4.2\ \mu m \quad \lambda_\parallel \approx 280\ \mu m$

Intensity distribution

$$u = I_{sp} / \langle I \rangle \qquad f(u) \propto u e^{-u}$$

High-energy tail up to $\approx 10\langle I \rangle$



We need a multispeckle model, including local intensity and saturation

For more info see *G. Cristoforetti et al., High Power Laser Science and Engineering*, (2021), Vol. 9, e60

SELF FOCUSING AND FILAMENTATION

Self focusing of laser light can amplify intensity perturbations and induce filamentation

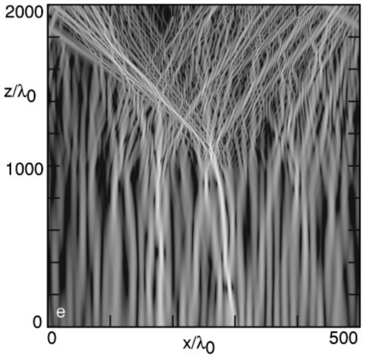
- Thermal effects → the rise in temperature induces a hydrodynamic expansion which leads to an increase of the index of refraction
- Ponderomotive effects → ponderomotive force pushes electrons away from the region where the laser beam is more intense, therefore increasing the refractive index

$$P > P_c \approx 32 T_{keV} \frac{\sqrt{1-n_e/n_c}}{n_e/n_c}$$

Schmitt and Afeyan, PoP 1998

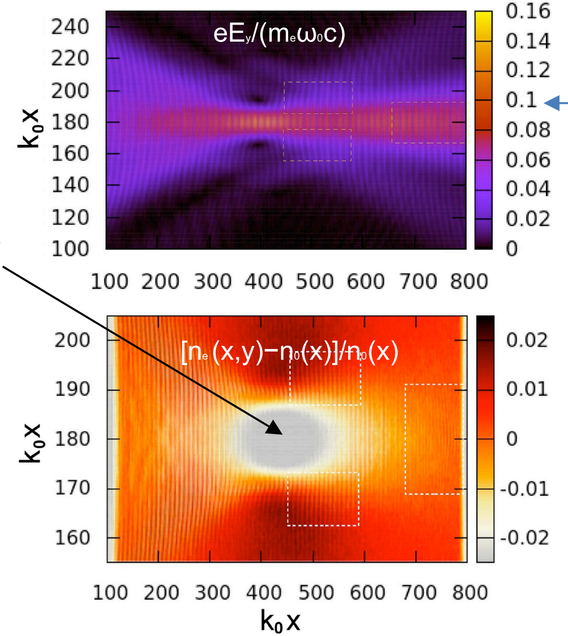
Laser

0.35 µm
2×10^{15} W/cm^2



Filamentation can produce:

- Local higher intensity but also plasma smoothing
- density depletion and profile modification
- Laser angular spreading
- Laser spectral broadening

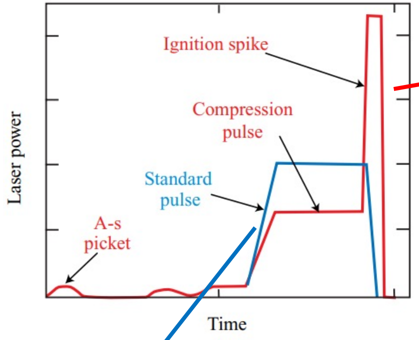


no SRS

Initial value

Cristoforetti et al., HPLSE, (2021), Vol. 9, e60

LPI: CLASSICAL DIRECT DRIVE VS. SHOCK IGNITION



Shock Ignition

I ≈ 10^{16} W/cm^2
implosion velocity ~240 km/s
T ≈ 5 keV
L_n ≈ 500 μm

Regime dominated by parametric instabilities in kinetic regime (R= 40-50%) and HE generation.

SBS, SRS, (TPD)
HE mainly driven by SRS

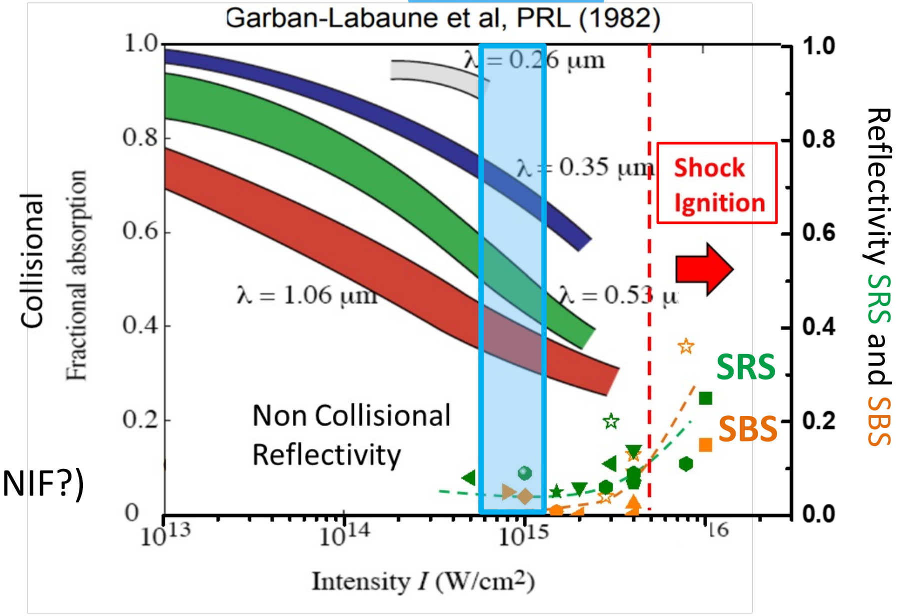
Classical Direct Drive

I ≈ 10^{15} W/cm^2
Implosion velocity ~350-400 km/s
T ≈ 5 keV
L_n ≈ 500 μm

SBS, TPD, (SRS)

HE mainly driven by collective TPD at OMEGA (NIF?)

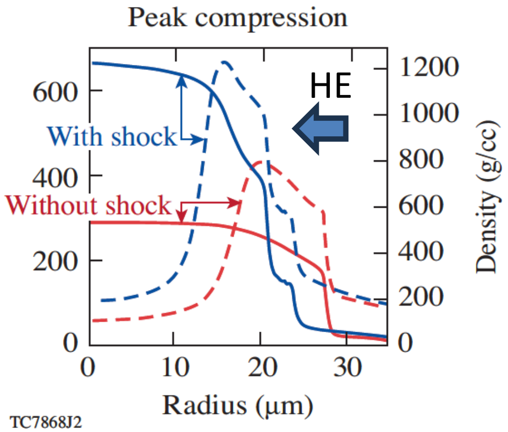
Classical Direct Drive

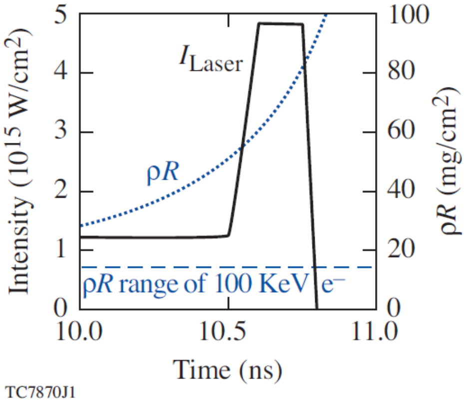

Garban-Labaune et al, PRL (1982)

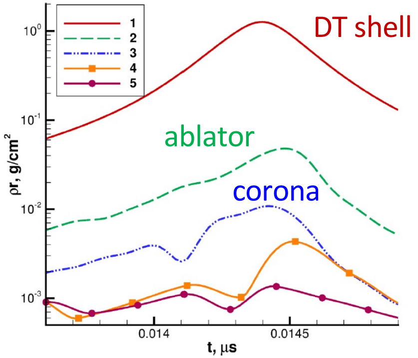
SHOCK IGNITION: HOT ELECTRONS

Differently from classical Direct-Drive ICF, in Shock Ignition scheme the effect of hot electrons (HE) could be beneficial* increasing the ignitor pressure since electrons are expected to stop in the high-ρR shell. e.g. for $E_{hot} \approx 80$ keV → range 0.01 g/cm^2

Betti et al., J. of Phys. Conf. Ser. 112, 022024, 2008

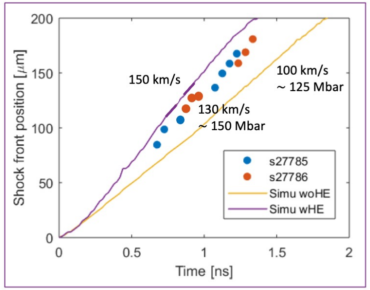






Gus'kov et al., HEDP 36, 022024, 2008

Similar result



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

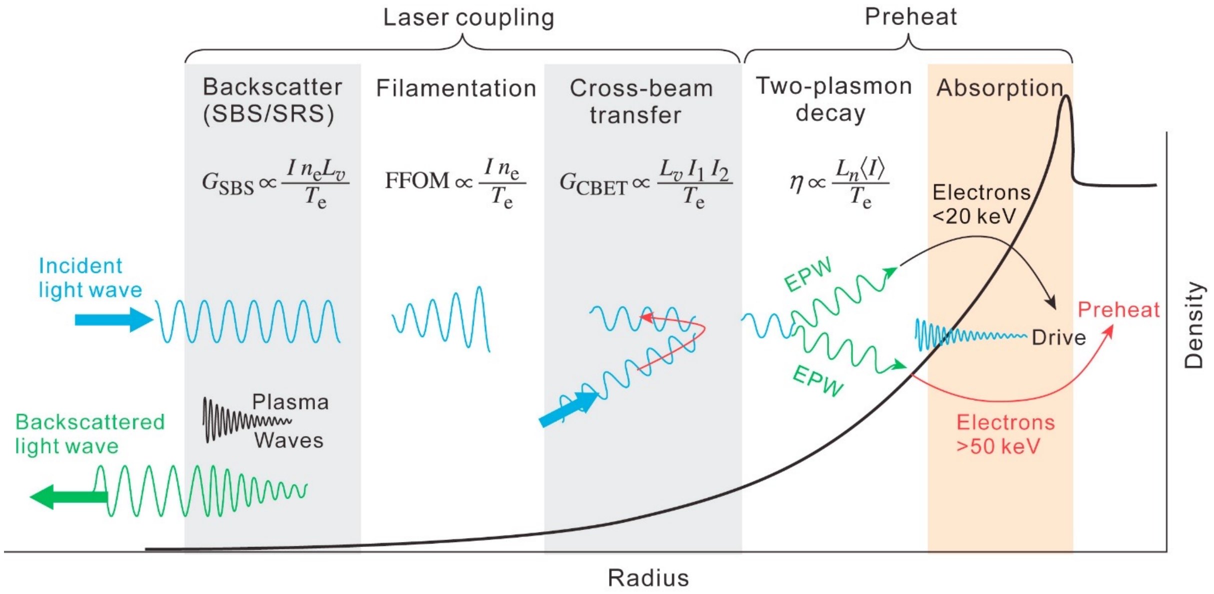
*the positive effect is dominant for HE temperatures lower than 60 keV

It is important

- Characterize HE in conditions as much as possible close to SI
- Understand the source of HE (SRS, TPD, other)

SHOCK IGNITION: PARAMETRIC INSTABILITIES

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



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

- **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…)

ROLE OF LASER BANDWIDTH ON LPI

One way of controlling or modifying instabilities consists in increasing the bandwidth, i.e. reducing the longitudinal coherence time of the driving laser pulse;

The role of bandwidth was extensively investigated in the past at implosion-like laser intensities (≈1E14) and large underdense plasmas, as temporal and spatial smoothing;

The ruling parameter in homogeneus plasmas is $\gamma_o / \Delta\omega_L$ where γ_o is the growth rate of the instability and $\Delta\omega_L$ is the laser bandwidth

J.J. Thomson and J.I.Karush, The Physics of Fluids **17**, 1608 (1974)

In inhomogeneous plasmas the effect is partially compensated by the broadening of the coupling region.

P. N. Guzdar, et al., Phys. Fluids B **3**, 2882 (1991).

Bandwidth can still limit amplification gain of instabilities arising from filamentation seeded by laser speckles (RPP) and self-focusing.

H. A. Rose, Phys. Plasmas **2**, 2216 (1995).

Recent numerical simulation studies show universal scaling of the instability threshold intensity with the laser coherence time

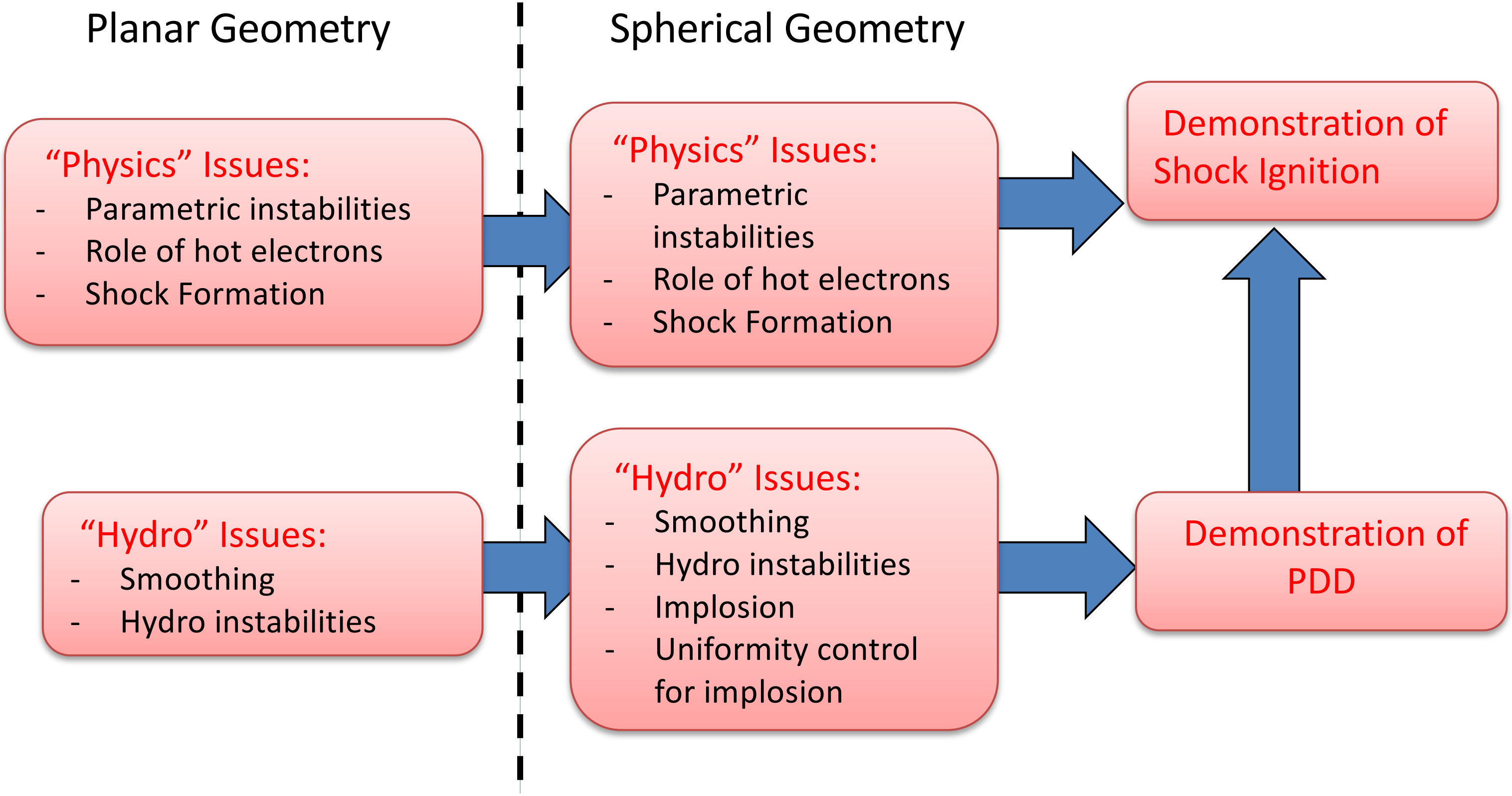
K. Follet et al., Phys. Plasmas 26, 062111 (2019);

CONTENTS

- Recap on ICF status
- Physics of laser-plasma interactions
- **Experimental platforms and Roadmap**
- HiPER+ programme outlook
- Summary

EXPERIMENTAL ROADMAP TOWARDS SHOCK IGNITION IFE

How to approach the final goal of "Performing shock ignition demonstration experiments" ?



Planar Geometry

"Physics" Issues:
- Parametric instabilities
- Role of hot electrons
- Shock Formation

"Hydro" Issues:
- Smoothing
- Hydro instabilities

Spherical Geometry

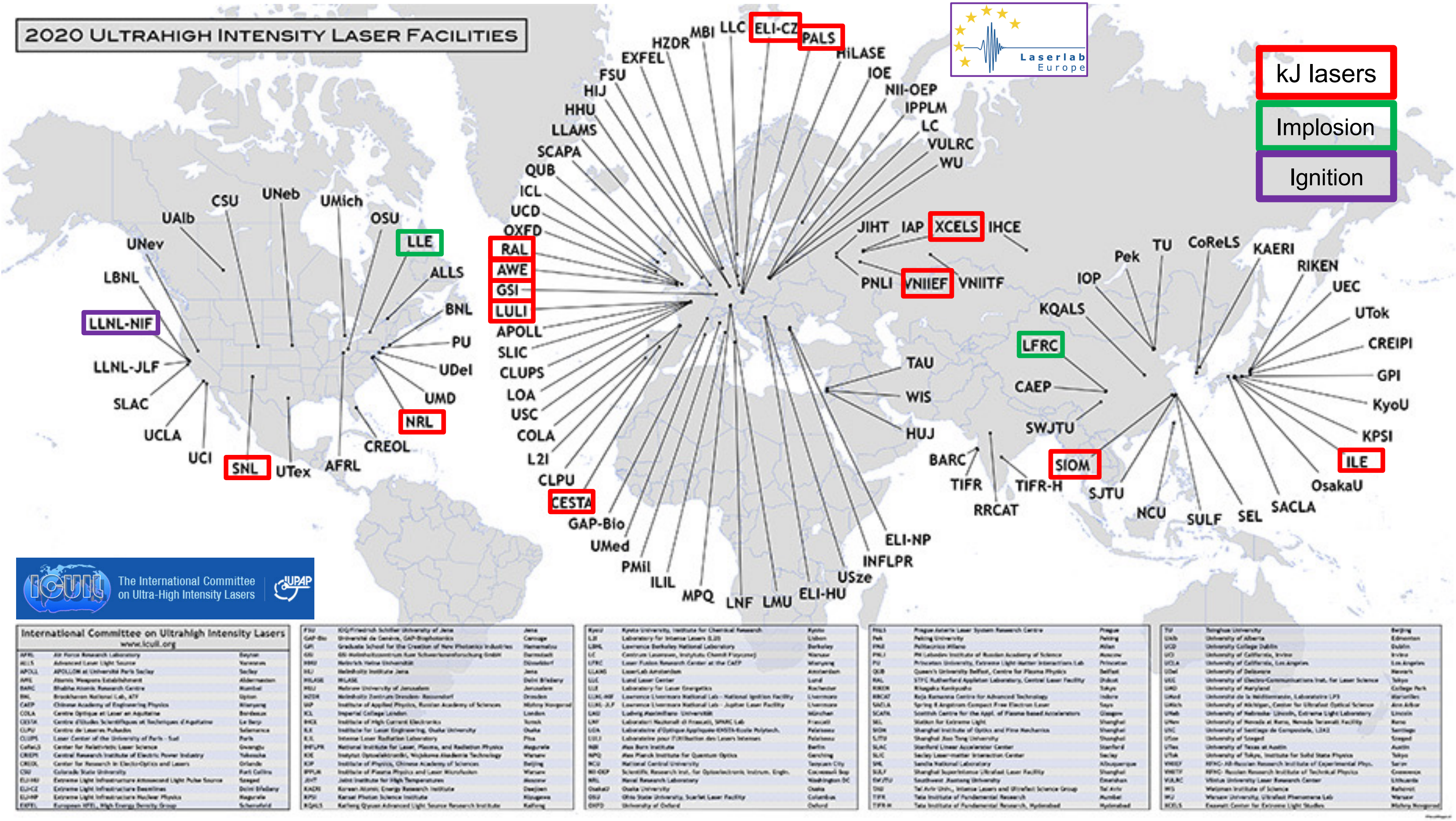
"Physics" Issues:
- Parametric instabilities
- Role of hot electrons
- Shock Formation

"Hydro" Issues:
- Smoothing
- Hydro instabilities
- Implosion
- Uniformity control for implosion

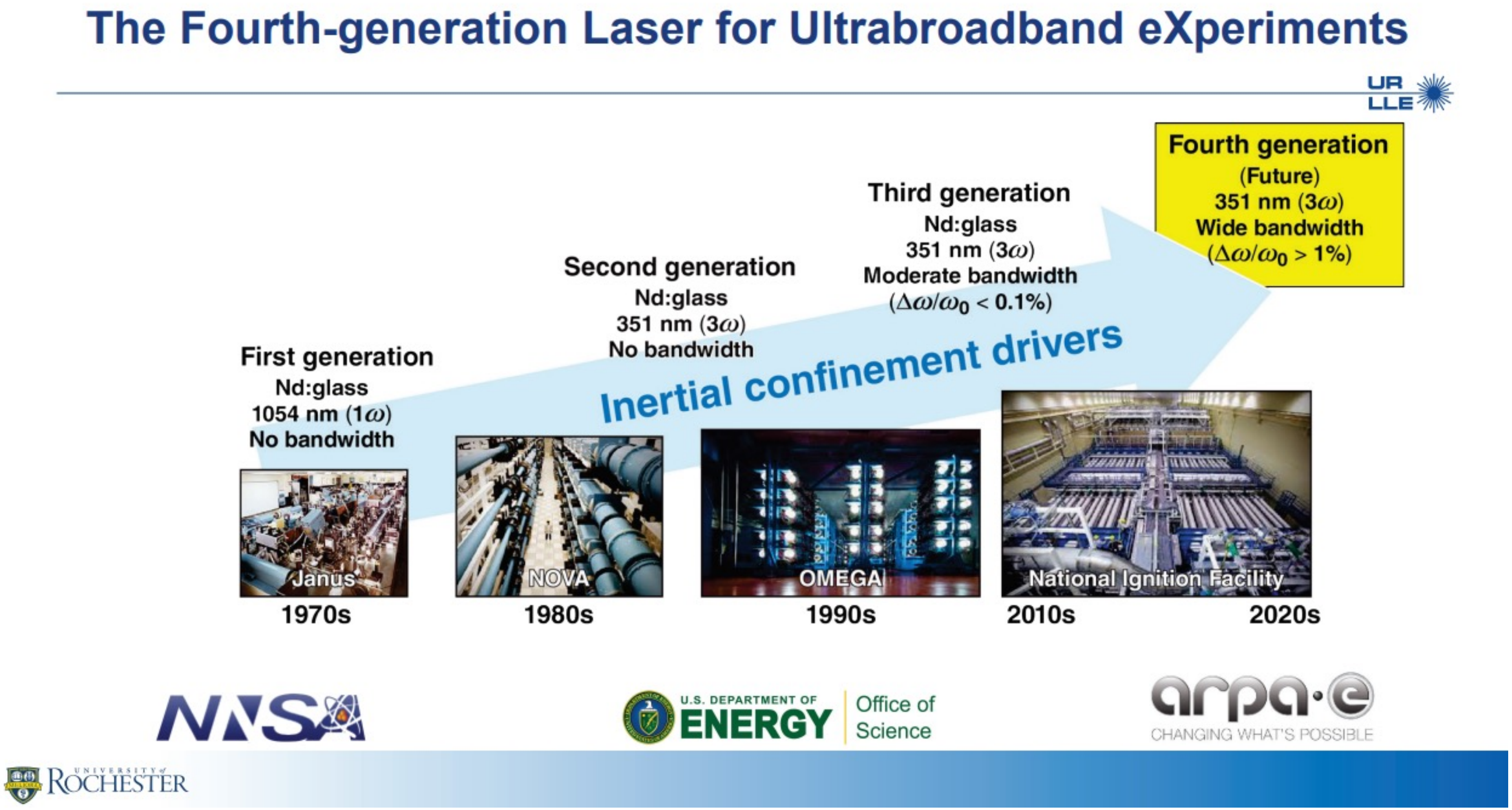
Demonstration of Shock Ignition

Demonstration of PDD

LASER FACILITIES



FUTURE DEVELOPMENTS



The Fourth-generation Laser for Ultrabroadband eXperiments

UR LLE

Fourth generation
(Future)
351 nm (3ω)
Wide bandwidth
($\Delta\omega/\omega_0 > 1\%$)

Third generation
Nd:glass
351 nm (3ω)
Moderate bandwidth
($\Delta\omega/\omega_0 < 0.1\%$)

Second generation
Nd:glass
351 nm (3ω)
No bandwidth

First generation
Nd:glass
1054 nm (1ω)
No bandwidth

Inertial confinement drivers

Janus — 1970s

NOVA — 1980s

OMEGA — 1990s

National Ignition Facility — 2010s — 2020s

NNSA

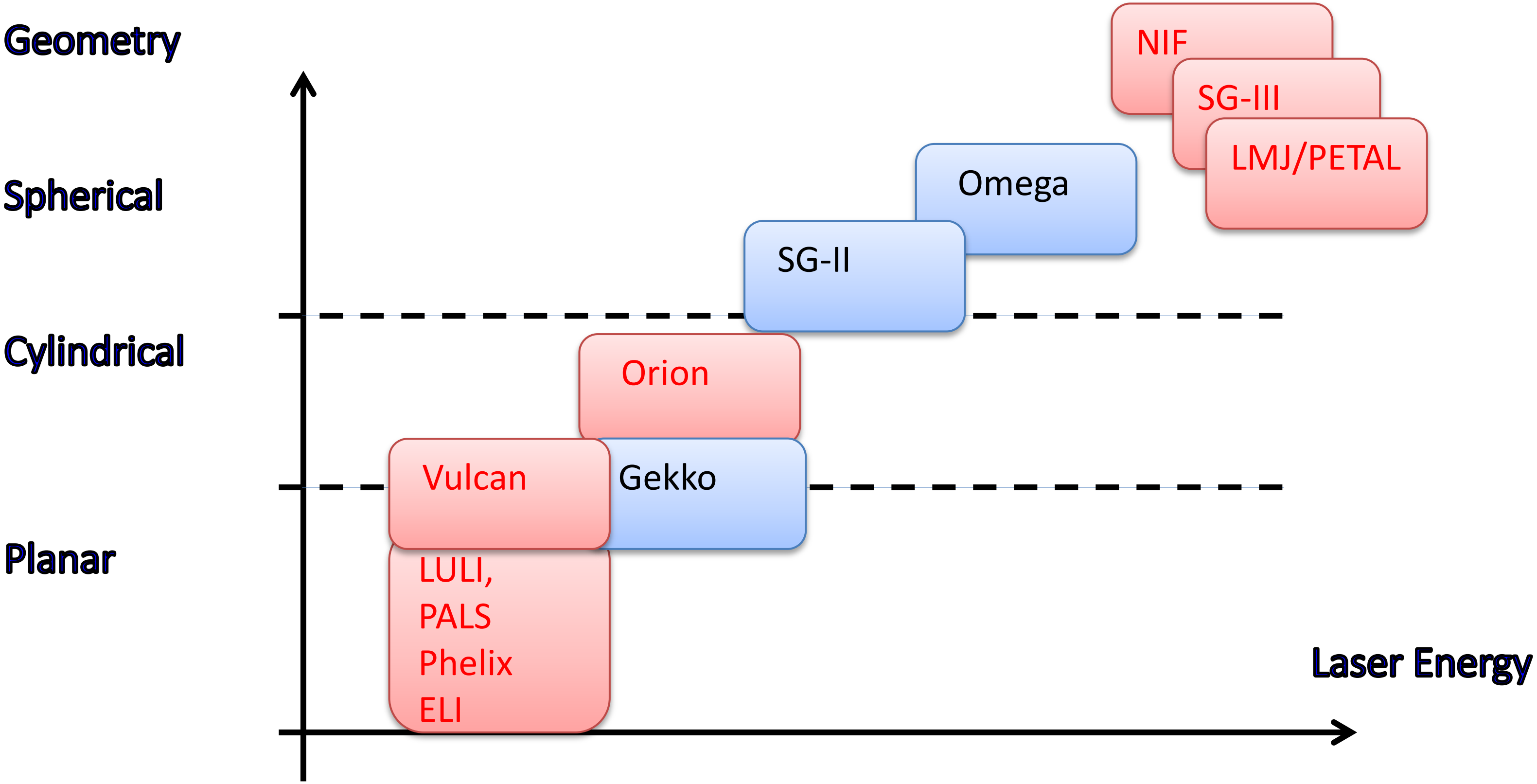
U.S. DEPARTMENT OF ENERGY | Office of Science

arpa·e CHANGING WHAT'S POSSIBLE

UNIVERSITY of ROCHESTER

EXPERIMENTAL ROADMAP TOWARDS SHOCK IGNITION IFE

How to approach the final goal of “Performing shock ignition demonstration experiments” ?



LASERS FOR PLANAR STUDIES

	Multi beam	**Lambda** (nm)	**Intensity** (W/cm^2)	**Iλ^2** (Wμm^2/cm^2)	**L** (μm)	**T** (keV)	**Bandwidth / Chirp**
GEKKO XII	YES	351	1.5×10^{15}	2×10^{14}	100	1-2	NO/NO
PALS	NO	438 1314	5×10^{15} 1.5×10^{16}	1×10^{15} 2.5×10^{16}	100 100	1-2 3-4	NO/NO
ELI-L4	NO	532	10^{14} - 10^{15}	$3\times(10^{13}$-$10^{14})$	100	1	NO/YES
Vulcan	YES	532	1×10^{16}	3×10^{15}	400	1-2	NO/YES
LMJ	YES	351	3.5×10^{15}	4.3×10^{14}	480	4.5	NO/NO

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

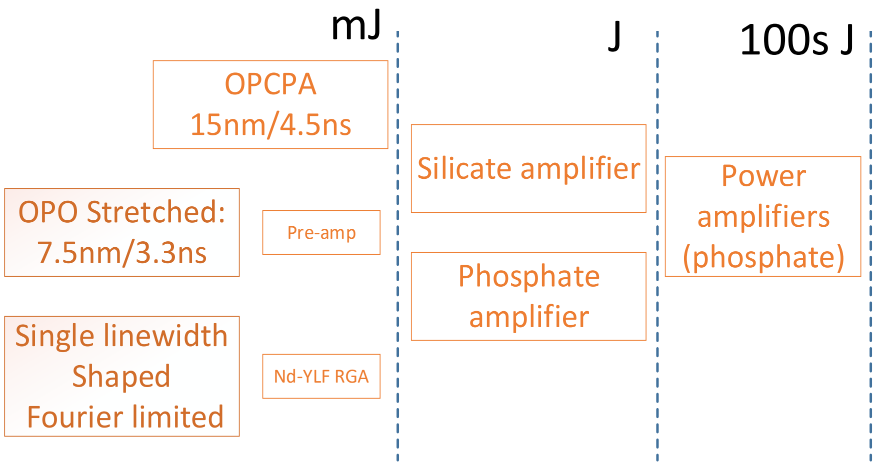
Different facilities can be used to investigate the role of different parameters

Lack of dedicated facility in Europe

VULCAN BROADBAND/CHIRP OPTIONS

6 MAIN BEAMS FOR PLASMA FORMATION AND HEATING,
2 BROADBAND (CHIRPED) BEAMS (7&8) FOR INTERACTION

BROADBAND BEAMS (1w, 1µm)



P. Oliveira, Vulcan, STFC

Pulse energy at 2ω ranging from 100 J to 300 J
Interaction at SI intensity possible, but relatively small focal spot – hydro modelling needed to unfold

Option **Beam 7** 397 J @ 1ω	SHG Duration (ps)	SHG Bandwidth (nm)	SHG Energy (J)
Single linewidth	770	Fourier limited	325
OPO phosphate	682	0.77	266
OPO silicate	921	1	210
OPCPA Silicate	1100	1.77	227

Option **Beam 8** 298 J at 1ω	SHG Duration (ps)	SHG Bandwidth (nm)	SHG Energy (J)
Single linewidth	760	Fourier limited	200
OPO phosphate	633	0.73	153
OPO silicate	882	1	112
OPCPA Silicate	900	1.7	123

VULCAN TAW EXPERIMENTAL SET UP

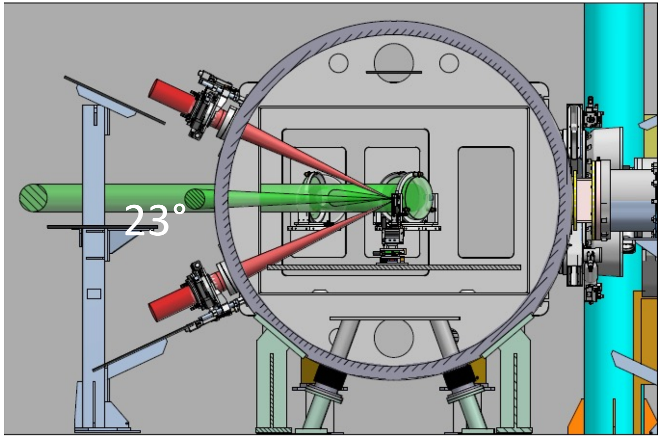
LASER IRRADIATION DESIGN (PLANAR GEOMETRY)

4 driver/heating beams (long beams)

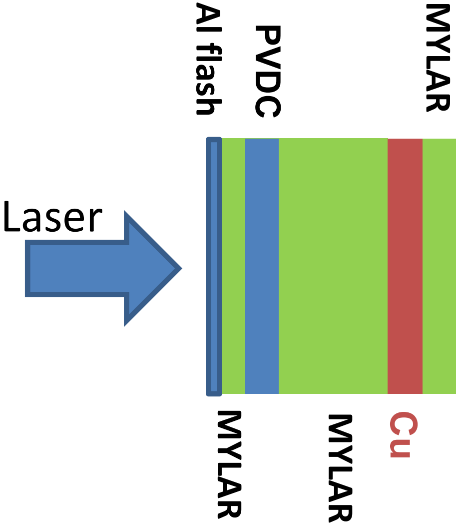
E=250 J x 4, λ=1053 nm, 3 ns
FWHM=800 μm, I ≈ 3×10^{13} W/cm^2

interaction beam B8 bypassing compressor

E≈85 J, λ=527 nm, 0.7 ns, RPP
FWHM ≈ 40 μm, I ≈ 10^{16} W/cm^2
f/# ≈2.5



🟩 Interaction beams
🟥 Heating beams



TARGET DESIGN

- Al flash
- Cl dopant for Te measurement
- Mylar layer for fast electron transport
- Cu for k-alpha measurement

VULCAN TAW EXPERIMENTS

INO-CNR (Italy), York Univ. and CLF (UK), Hellenic Mediterranean Univ. (Greece), Celia (France), Focused Energy

LASER IRRADIATION DESIGN (PLANAR)

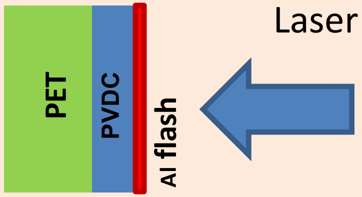
4 driver/heating beams (long beams)
E=250 J x 4, λ=1053 nm, 3 ns
FWHM=800 μm, I ≈ 3×10^{13} W/cm^2

interaction beam B8 bypassing compressor
E= 100-150 J, λ=527 nm, 0.7-1.0 ns, RPP
FWHM ≈ 40 μm, I ≈ 10^{16} W/cm^2 , f/# ≈2.5

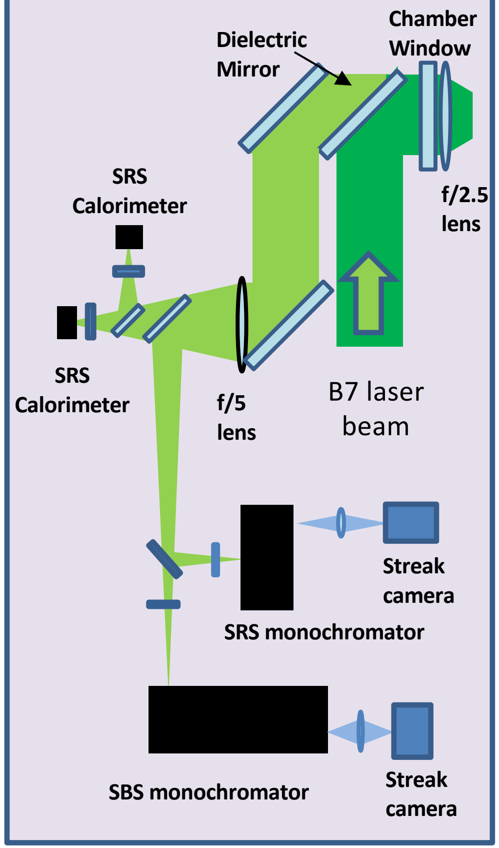
3 oscillators:

Option	SHG Duration (ps)	SHG Bandwidth (nm) (%)	Chirp Rate (nm/ns)
Narrowband	770	Fourier limited	0
OPO phosphate amp.	680	0.77 nm 0.15%	0.95
OPCPA Silicate amp.	1100	1.77 nm 0.34%	1.22

TARGET DESIGN

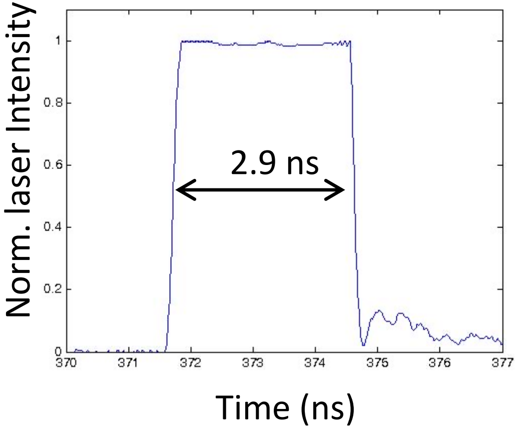


BACKSCATTERING DIAGNOSTICS



TIMING OF LASER PULSES

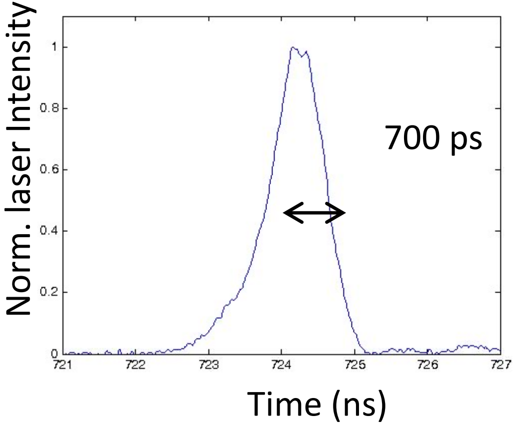
Long pulse heating beams

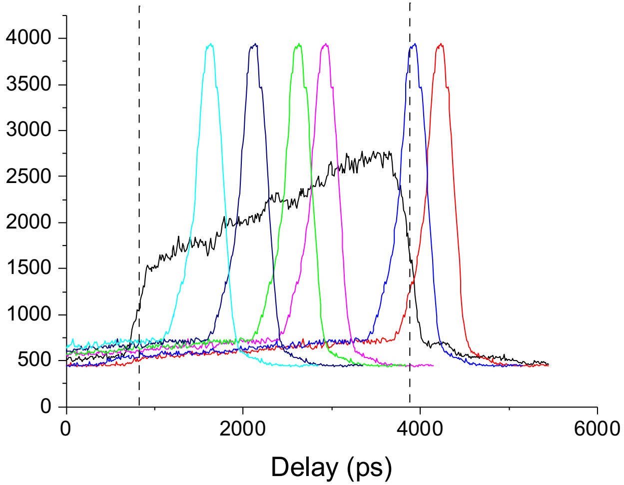


- 4 driver beams F/#10
- RPP
- FWHM 800x570 μm
- λ= 1054 nm
- Δt = 2.9 ns
- E_{tot} = 700-900 J
- I = 3×10^{13} W/cm^2

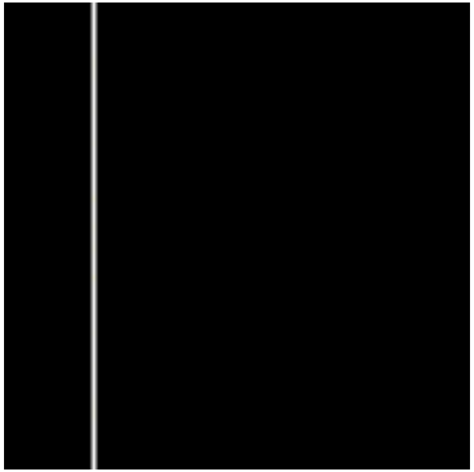
- Main beam F/#2.5
- RPP
- FWHM 24x30 μm
- λ= 527 nm
- Δt = 700 ps
- E_{tot} = 40-100 J
- I = $(0.5-1.3)\times10^{16}$ W/cm^2

Interaction beam (B 7/8)





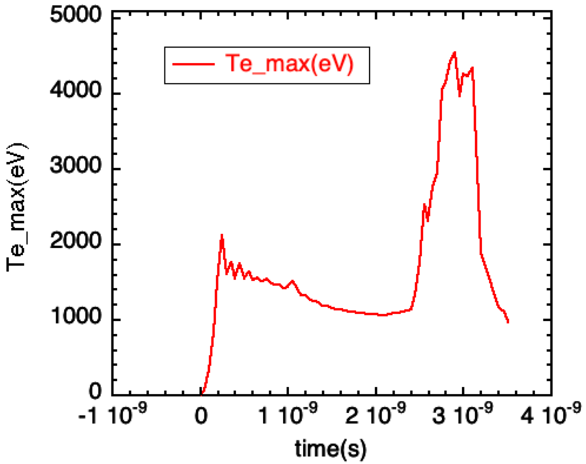
HYDRODYNAMIC SIMULATIONS



4 Driver beams + interaction beam
@ 1E16 W/cm2, delay -300 in figure

T_e ranges between 2 keV and 5 keV at the densities of interest for SRS (0.1 $n_c < n_e <$ 0.25 n_c)

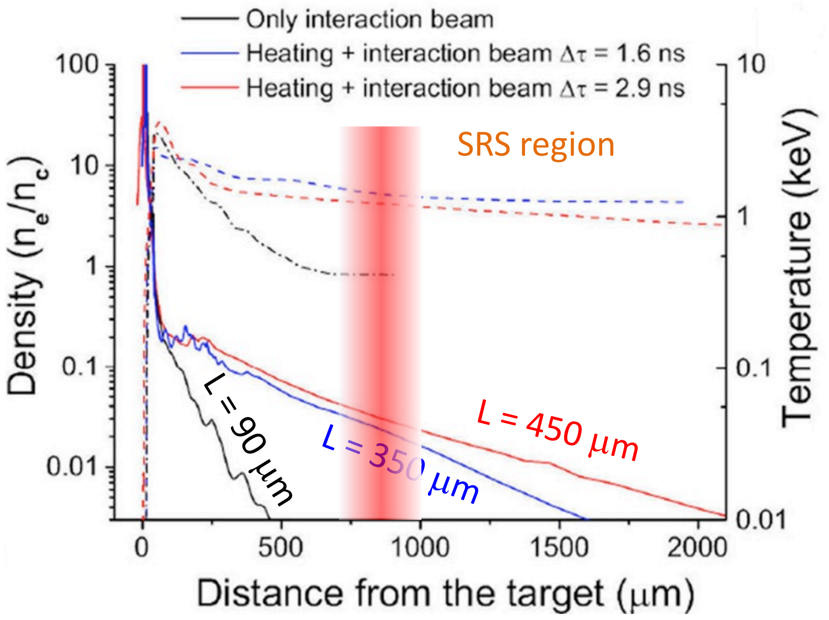
density scalelength L is in the range 300-1000 mm at the beginning of interaction



*S. Atzeni et al 2016 J. Phys.: Conf. Ser.688 012005

INTERACTION CONDITIONS - 1

DUED hydrodyamic simulations by. A. Schiavi and S. Atzeni

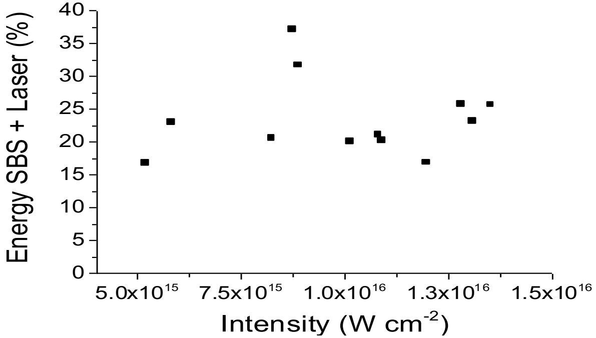


T ≈ 1 keV
L = 90 – 450 μm

Depending on the delay
of the main pulse

PARAMETRIC INSTABILITIES QUICK LOOK

SBS + Laser

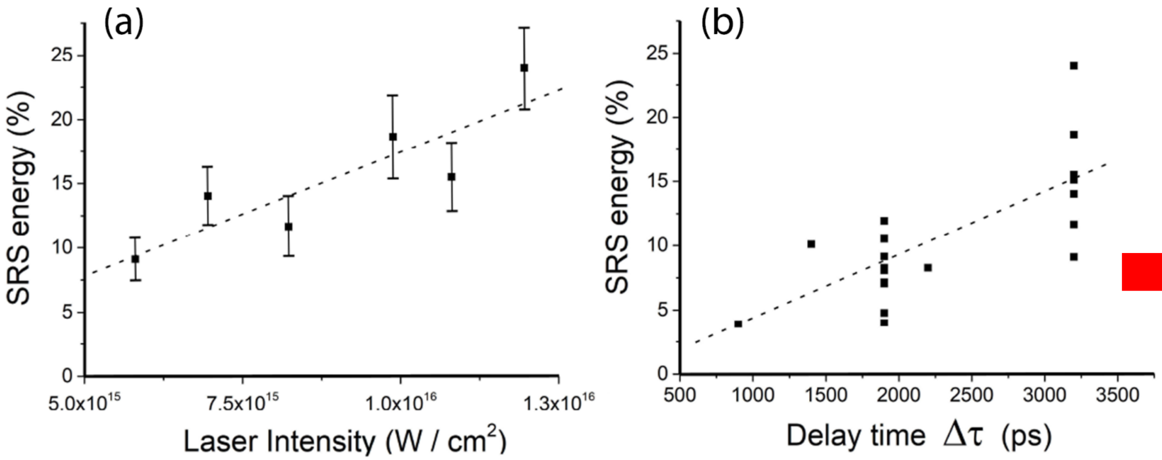


No clear dependence upon laser intensity and relative timing (delay)

TPD

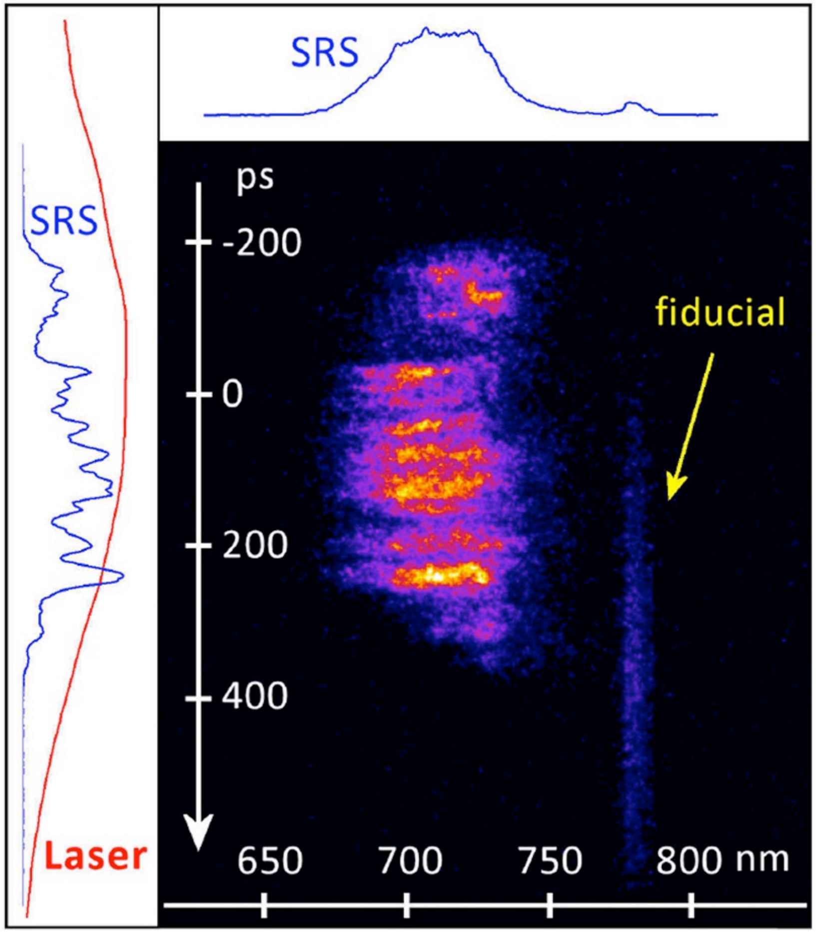
not observed for all experimental conditions

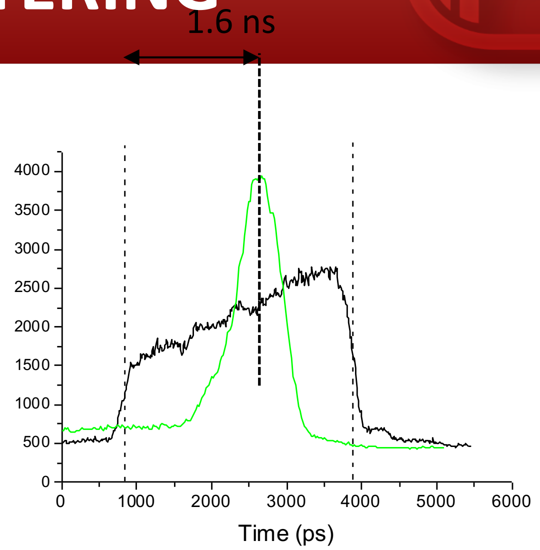
SRS



- No heating beams (no preformed plasma, short scalelength): **NO SRS**
- **SRS increases** with relative delay between heating and interaction (longer scalelength)
- **SRS increases** with interaction beam energy/intensity

STIMULATED RAMAN SCATTERING





$I = 1.1 \times 10^{16}$ W/cm^2

$L = 350\ \mu m$

SRS driven at low densities

$n = 0.03\text{-}0.07\ n_c$

$k_e \lambda_D = 0.3\text{-}0.5$
Strongly kinetic regime

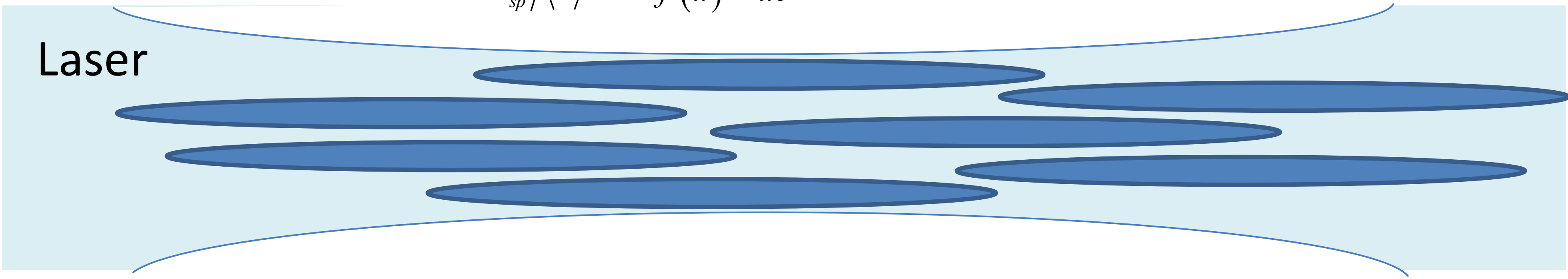
LOCAL INTERACTION CONDITIONS (RPP)

Speckle
Intensity distribution

$\lambda_\perp \approx 1.2F\lambda_0 = 1.6\ \mu m$ $\lambda_\parallel \approx 8F^2\lambda_0 = 30\ \mu m$

$u = I_{sp}/\langle I\rangle$ $f(u) \propto u e^{-u}$

High-energy tail up to $\approx 10\langle I\rangle = 10^{17}$ W cm^{-2}



2) Speckles with intensity $I_{sp} >$ 3-4 <I> undergo self-focussing, modifying local intensity and density profile

2D3V EMI2d
PIC simulations

Due to the fast growth rate, SRS can adapt very rapidly to ponderomotively induced profile modifications

Modelling by **S. Hüller, A. Heron**

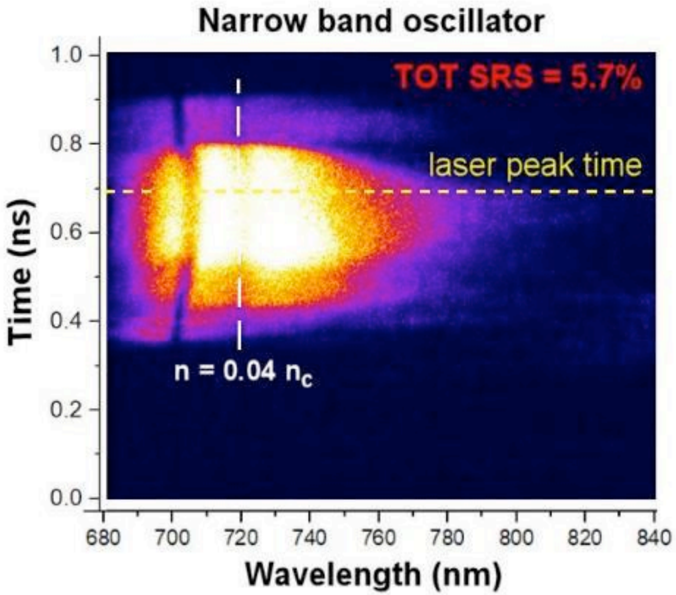
3) Role of kinetic effects on SRS growth

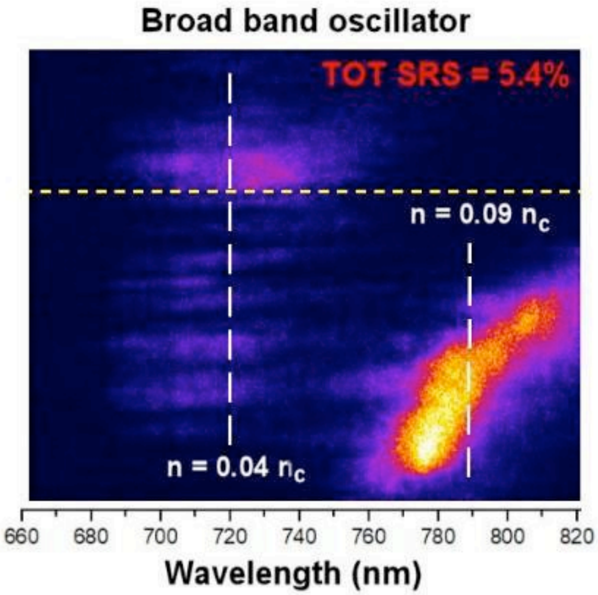
2D and 3D simulations with the wave-coupling code SIERA

- No effect on SRS growth at this high laser intensity
- Broadening of the scattered spectrum

G. Cristoforetti et al., High Power Laser Science and Engineering, (2021), Vol. 9, e60

NARROWBAND VS BROADBAND/CHIRPED


Narrow band oscillator


Broad band oscillator

λ_{SRS}	n_e/n_c
710	0.033
820	0.1
900	0.15
950	0.18

$\Delta\lambda/\lambda \approx 0.002\%$
Coherence time τ= 500 ps

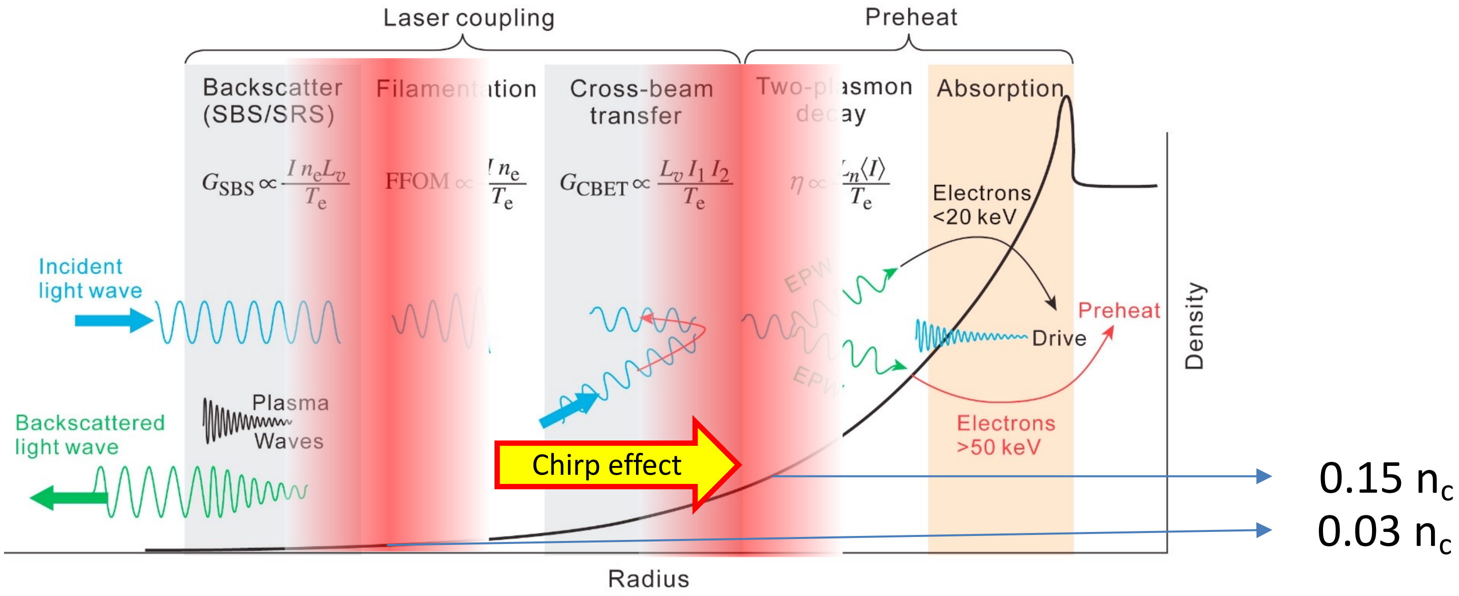
$\Delta\lambda/\lambda \approx 0.3\%$
Coherence time τ= 1 ps

- SRS driven in filaments at 0.05 nc
- No TPD and SRS at higher densities, for pump depletion

- SRS is observed at higher densities
- SRS at lower densities strongly reduced
- *TPD spectral range not measured*

PRELIMINARY CONCLUSIONS

- In spite of the much higher intensity (>1E15) compared to earlier studies, a chirped bandwidth as small as 1 nm (0.2%) has a strong effect on LPI
- The coupling with *chirped-broadband* laser pulse moves to much higher density compared to narrowband laser pulse;
- As observed at lower (implosion-like) intensities, the bandwidth mainly acts on filamentation, limiting its growth and allowing laser light to propagate further;



PARTIAL LPI SCENARIO

- Multi-speckle modelling is needed to depict SRS growth (work in progress)
- In long scale plasmas and SI intensities, SRS is driven in filaments at low densities in strong kinetic regime and can reach 40-50% instantaneous reflectivities (In agreement with *Baton et al., High Energy Density Physics 36, 100796, 2020);*
- HE generated by SRS at these densities could have a low non-dangerous low temperature (here T = 10-15 keV), as measured in the experiment;
- TPD and high-density SRS is not observed, for pump depletion and plasma-induced smoothing after a few speckles layer (*Scott et al., Phys. Rev. Lett. 127, 065001, 2021)*
- This scenario may change completely for even modest bandwidth laser pulses due to the seeding of filamentation by RPP laser speckles.

CONTENTS

- Recap on ICF status
- Physics of laser-plasma interactions
- Experimental platforms and Roadmap
- **HiPER+ programme outlook**
- Summary

ON WHAT WE BUILD: THE EU IFE COMMUNITY

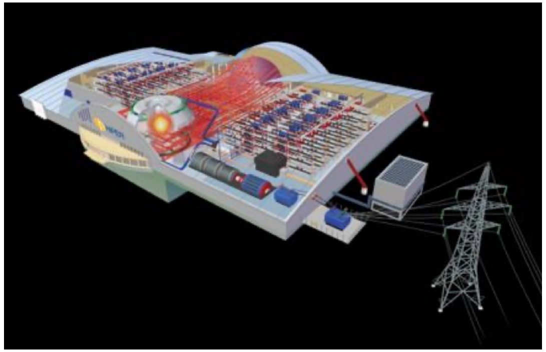
2005-2014 European Project “HIPER” (High Power Laser Energy Research Facility)


European Strategy Forum on Research Infrastructures

ESFRI

EUROPEAN ROADMAP FOR RESEARCH INFRASTRUCTURES

Report 2006



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

THE HiPER+ PROGRAMME

High Power Laser Science and Engineering, (2023), Vol. 11, e83, 31 pages.
doi:10.1017/hpl.2023.80

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]


FUTURE FOR
INERTIAL FUSION
ENERGY IN
EUROPE:
A ROADMAP

HiPER+

On the prospect of the establishment of a new European program on Inertial Fusion Energy (IFE) with the mission to demonstrate laser-driven ignition in the direct drive scheme and to develop pathway technologies for a commercial fusion reactor.

Article accepted for publication:
High Power Laser Science and Engineering, 2023

September 2023

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

HiPER+
EUROPEAN LASER FUSION ENERGY

CHALLENGE 1: LASER

- 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:

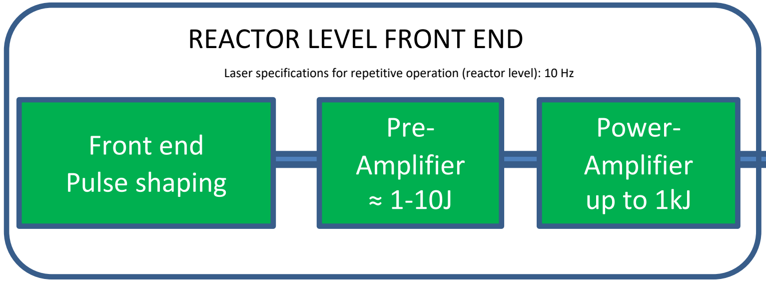
- Develop more efficient laser (≥ 10%)
- Develop high repetition frequency laser (10 Hz)
- Think about the possibility of using 2ω light (532 nm) to reduce damage to optics
- Develop broadband lasers (to quench parametric instabilities)

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 bandwidth…

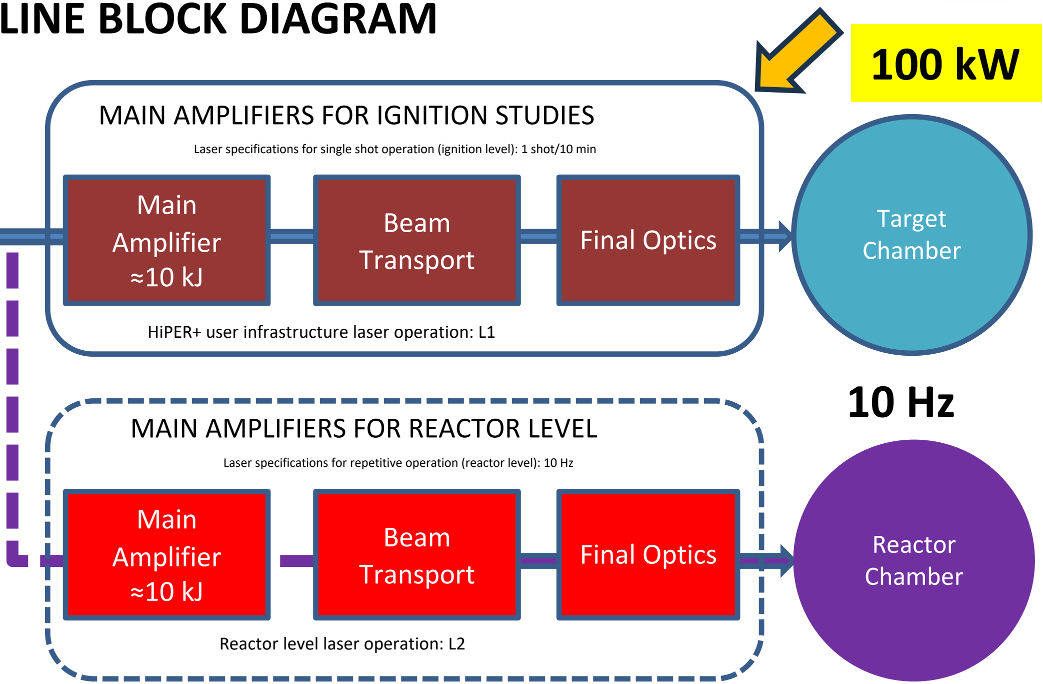
HiPER+ LASER CONCEPT FOR IFE

SINGLE LASER BEAMLINE BLOCK DIAGRAM



REACTOR LEVEL FRONT END

Laser specifications for repetitive operation (reactor level): 10 Hz



MAIN AMPLIFIERS FOR IGNITION STUDIES

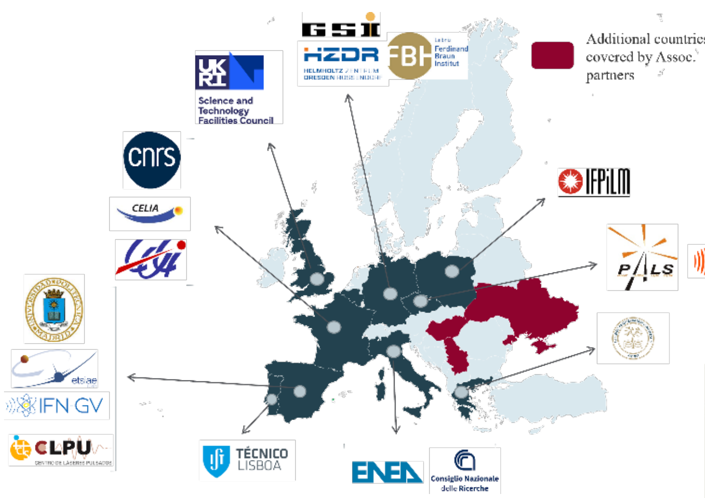
Laser specifications for single shot operation (ignition level): 1 shot/10 min

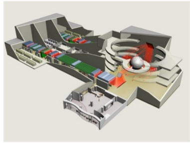
HiPER+ user infrastructure laser operation: L1

MAIN AMPLIFIERS FOR REACTOR LEVEL

Laser specifications for repetitive operation (reactor level): 10 Hz

Reactor level laser operation: L2





HiPER+ EUROPEAN LASER FUSION ENERGY

An InfraDEV EU proposal for Inertial Fusion Energy - 2024

HiPER+ EUROPEAN LASER FUSION ENERGY

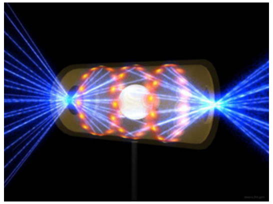
CHALLENGE 2: TARGETS

- Today's cryogenic target costs $\approx$ 100000 $.
- 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 $\approx$ 1 Hz
- Design of the target insertion and tracking system

All this does NOT seem possible with indirect drive !!



HiPER+
EUROPEAN LASER FUSION ENERGY

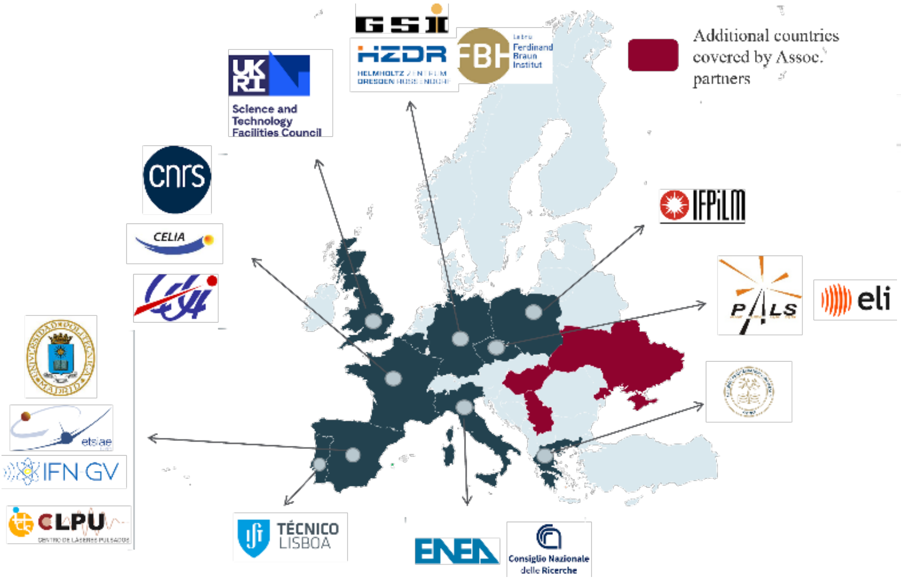
CHALLENGE 3: MATERIALS

- 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

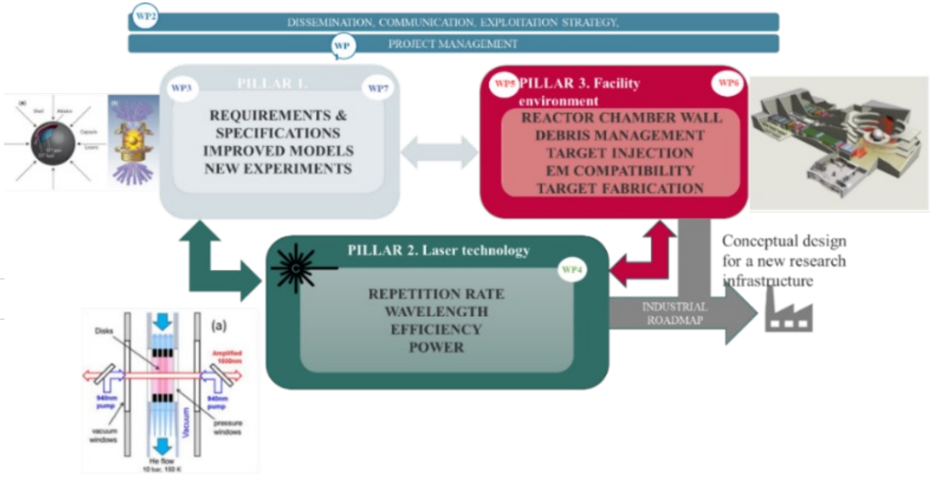
Many of these issues are common to MCF too (synergies possible)

HiPER+ RESEARCH INFRASTRUCTURE APPROACH*

Consortium



Main blocks



WP2 DISSEMINATION, COMMUNICATION, EXPLOITATION STRATEGY,

WP PROJECT MANAGEMENT

WP3 PILLAR 1. WP7

REQUIREMENTS & SPECIFICATIONS
IMPROVED MODELS
NEW EXPERIMENTS

WP5 PILLAR 3. Facility environment WP6

REACTOR CHAMBER WALL
DEBRIS MANAGEMENT
TARGET INJECTION
EM COMPATIBILITY
TARGET FABRICATION

PILLAR 2. Laser technology WP4

REPETITION RATE
WAVELENGTH
EFFICIENCY
POWER

INDUSTRIAL ROADMAP

Conceptual design for a new research infrastructure

European Commission

*European proposal (Infradev Horizon Europe Call 2024)

INFRADEV: Developing, consolidating and optimising the European research infrastructures landscape, maintaining global leadership

HiPER+
EUROPEAN LASER FUSION ENERGY

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

SUMMARY

- Inertial fusion ignition achieved
- Possible pathway: direct drive and shock ignition
- Facility needed to develop the EU experimental programme
- HiPER+ programme is a unique EU platform for IFE