Progress towards Laser Fusion in Europe

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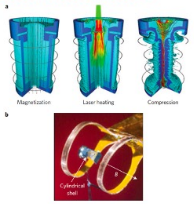
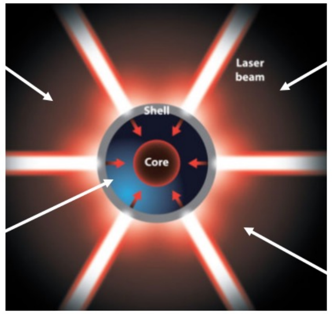
Laboratoire pour L'Utilisation des Lasers Intenses

The fusion effort in Europe is articulated between mid and large scale facilities

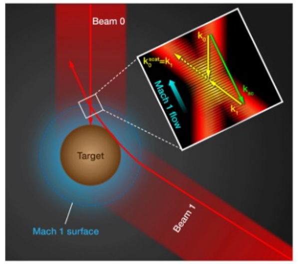
Detailed studies of the microphysics of ignition target are carried out on mid scale facilities through out Europe

Atomic physic/ magnetized plasma

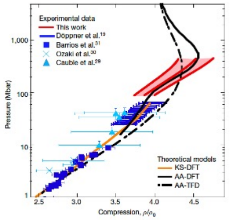




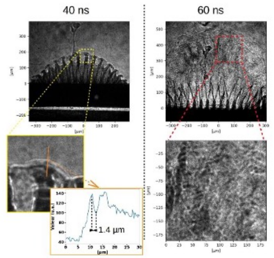
Laser Plasma Interaction



Equation of state



Hydrodynamic instabilities



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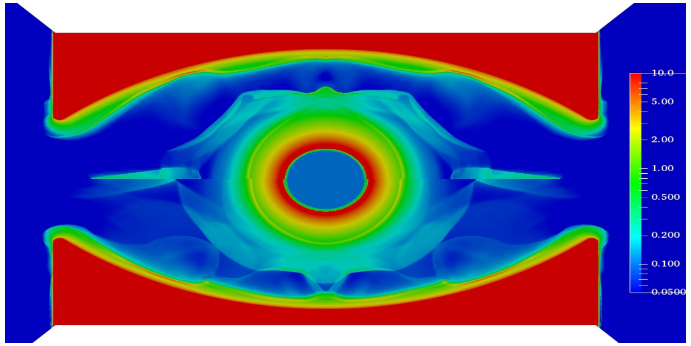
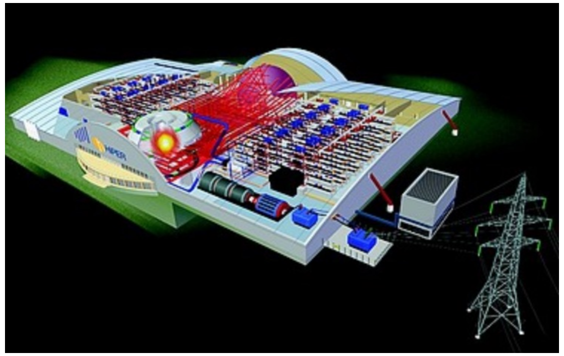


Studies toward IFE



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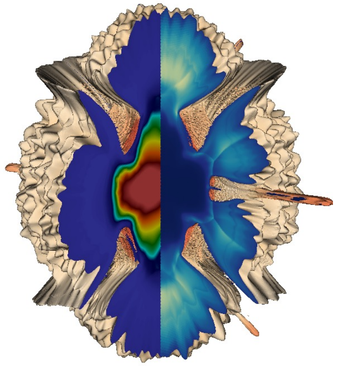


LLNL

Motivation

- Hydro instabilities have been a major source of neutron yield reduction on the NIF

Questions to be answered:

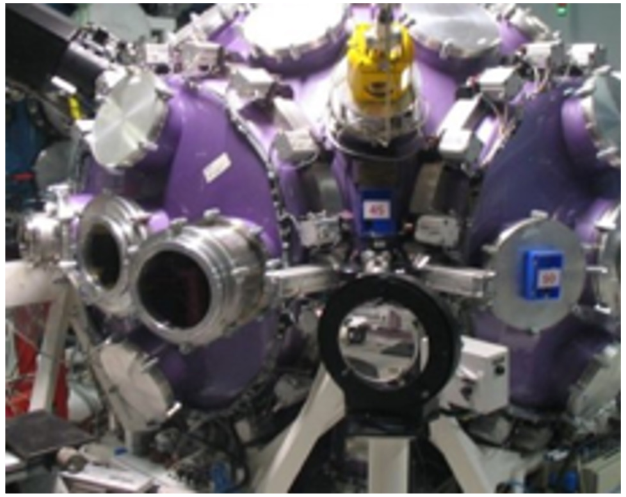
- Evolution of Rayleigh Taylor instabilities in decelerating phase
- Impact of Attwood number on RT growth

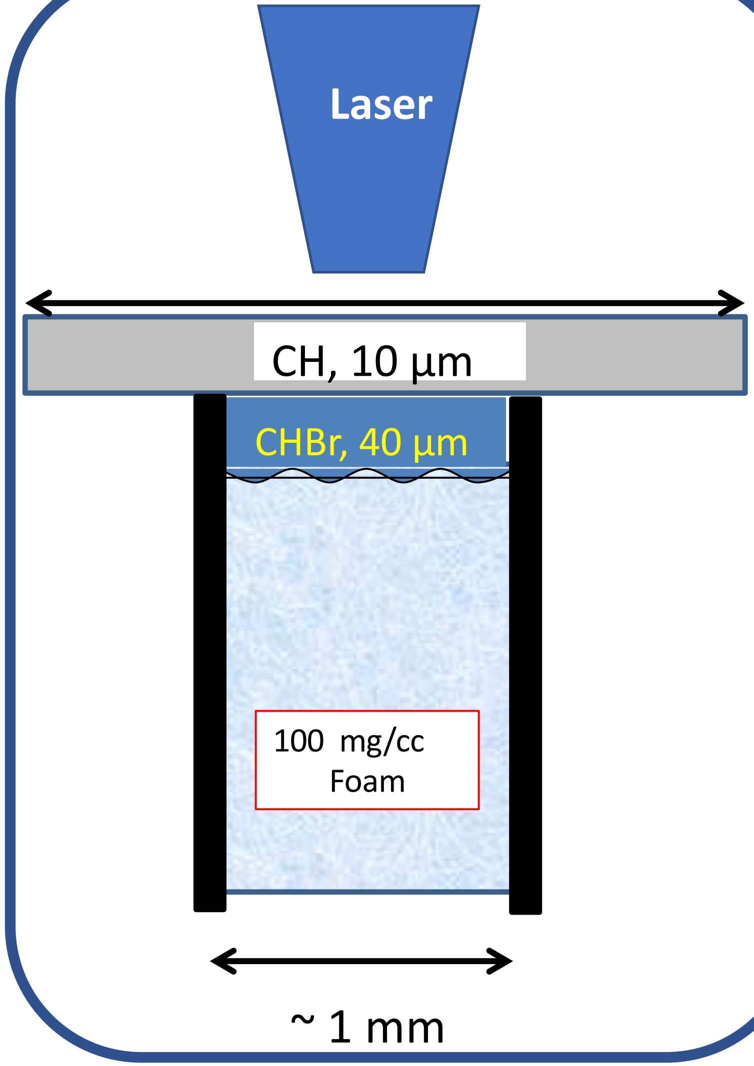
Collaboration

- PI: LULI, with CELIA, CEA, Nagoya University, Freie Universitat Berlin, CEA DAM

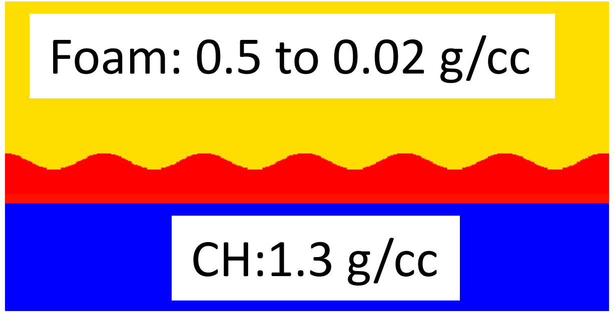
Study of instability growth in the decelerating phase on the LULI2000 facility

Long Pulse Laser 500 J , 2w
~1.5ns (1.3ns)





Varying the foam density



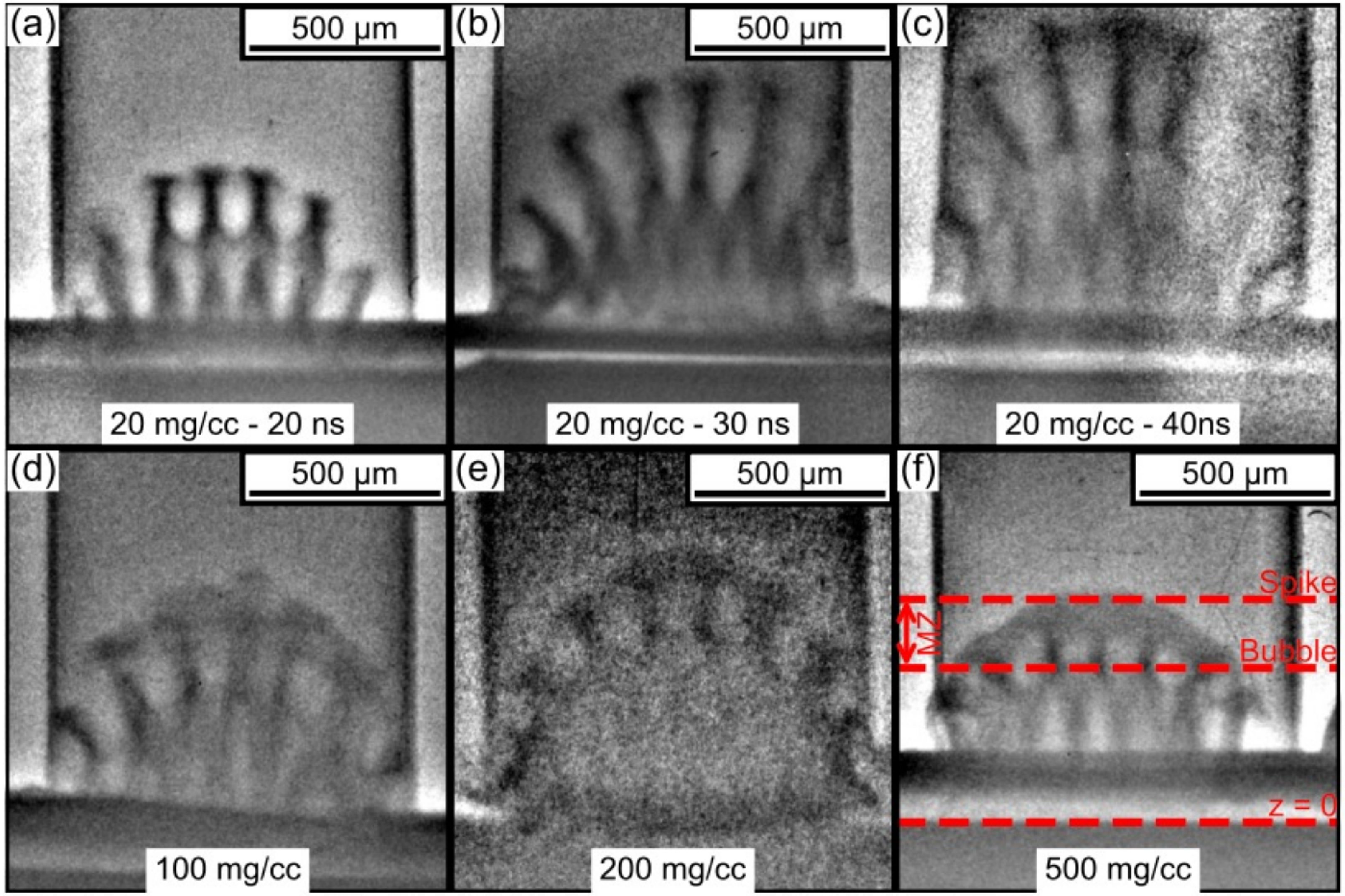
Mono-mode target:
λ = 120 µm
Amp. = 10 µm

Linear growth rate:

$$n_0 = \left(\frac{2\pi A_n g}{\lambda}\right)^{1/2}$$

Rigon, G., et al.instability experiments on the LULI2000 laser in scaled conditions for young supernova remnants. *Physical Review E*, *100*(2), 021201.

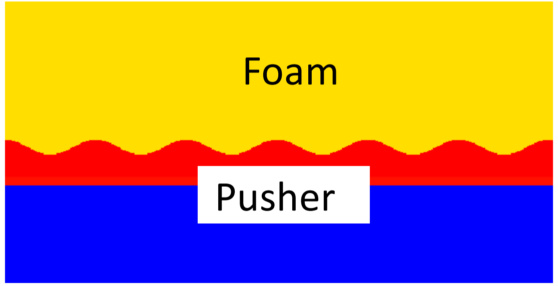
Time resolved radiography of Rayleigh Taylor Instabilities were obtained with a 20-25 µm resolution

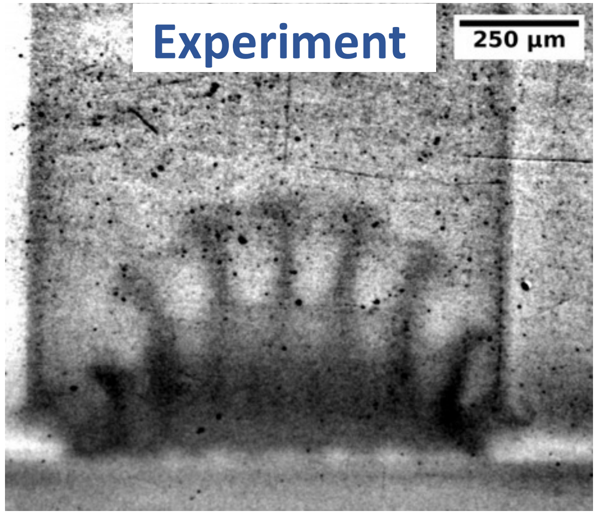


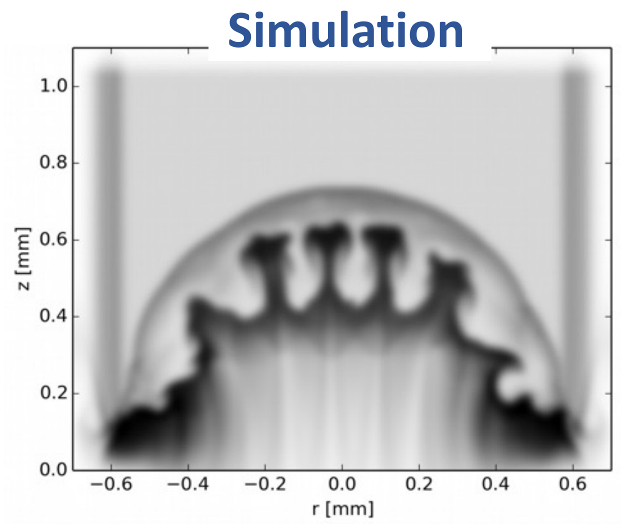
2D Flash simulation results are close to experiments but not perfect

Initial modulation

Mono-mode

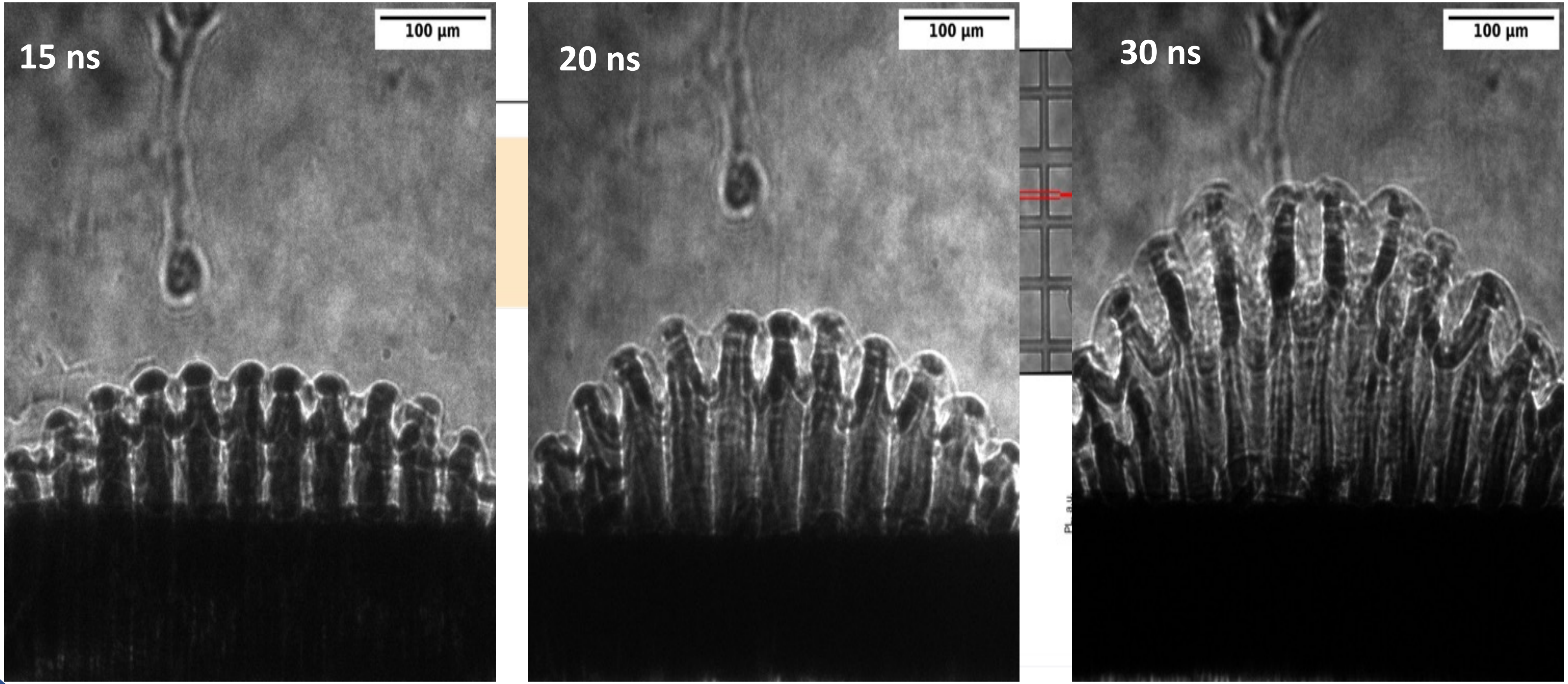






- **RTI growth, the perturbation has a faster growth with a low- density foam, so in the case of high Atwood number and low deceleration.**
- **The obtained growths cannot be explained using classical RTI models such as the buoyancy- drag model**
- **Updated RTI growth model in FLASH**

The special resolution was dramatically increased by going to a XFEL (SACLA)



Conclusion: Hydrodynamic instabilities

- The obtained growths rate cannot be explained using classical RTI models such as the buoyancy- drag model

- Updated RTI growth model in FLASH

- High resolution X-ray radiography of relevant ICF system can be achieved on XFEL

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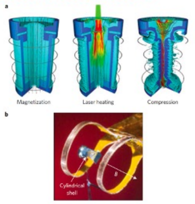
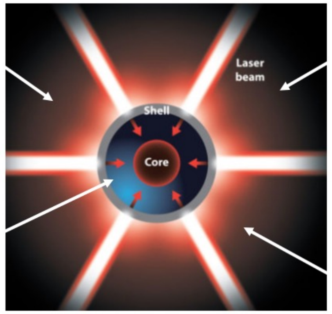
Detailed studies of the microphysics of ignition target are carried out on mid scale facilities through out Europe

Atomic physic/ magnetized plasma





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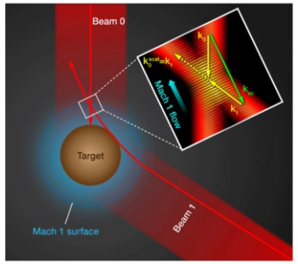
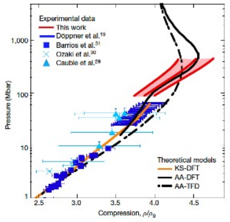


Equation of state



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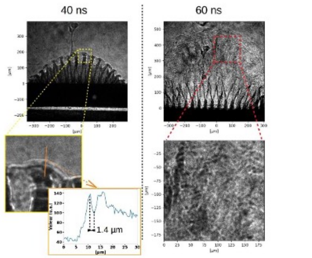

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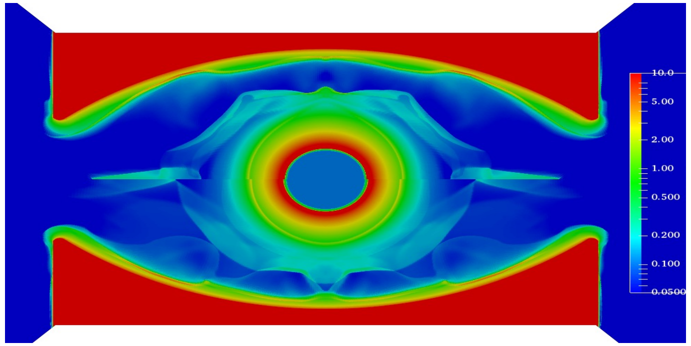

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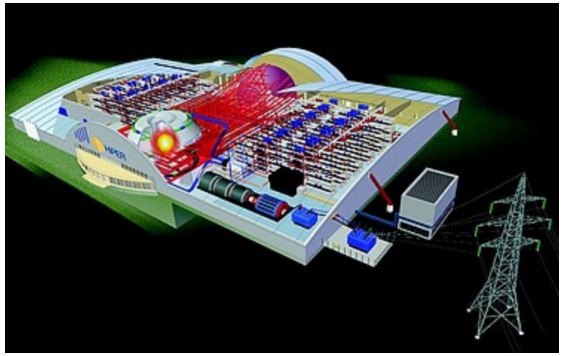
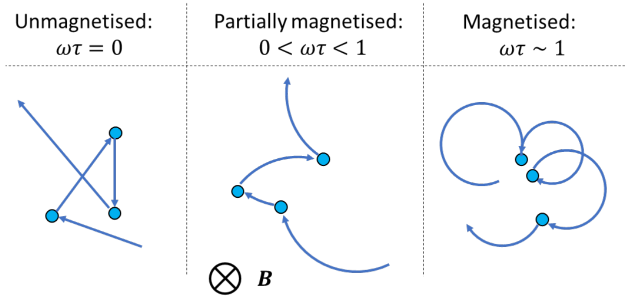


Magnetized plasmas

Motivation

- Magnetized ICF could increase neutron yield by reducing thermal loss



Questions to be answered:

- Impact of B field on temperature
- Impact of B field on LPI

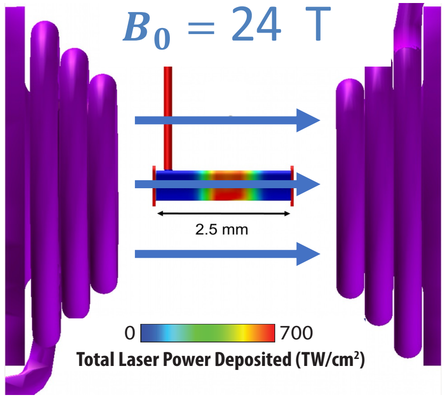
Collaboration

- PI: CELIA, Bordeaux University with CEA, UCSD
- PI: LULI with UCSD, Eli NP, LNCMI, CELIA, Observatoire de Paris

Study the impact of magnetic field on compressed plasmas

Experiment at OMEGA

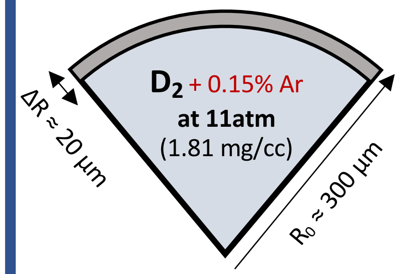
Seed B-field driven externally by a **capacitor bank discharge** (stable over ~µs)

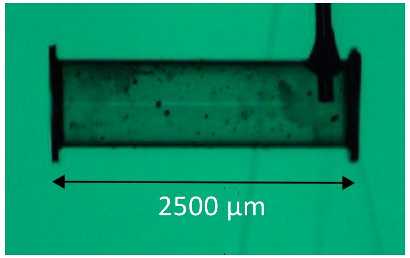


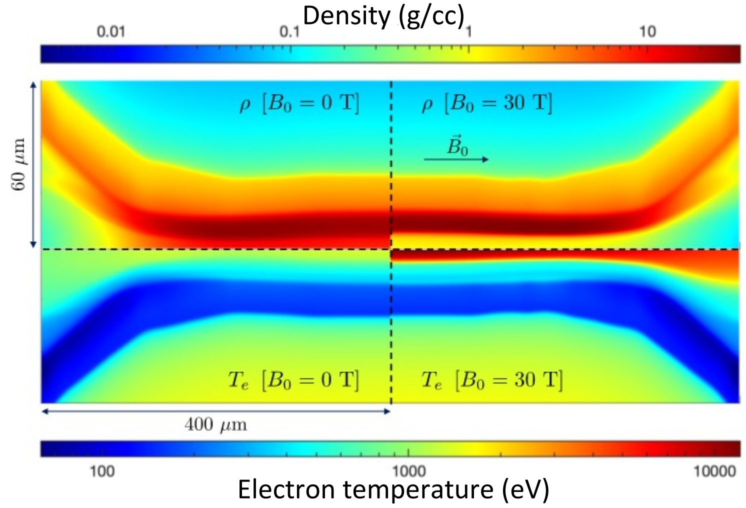
Laser drive: 40 UV beams, 1.5 ns, total energy of 14.5 kJ, > 5x10^{14} W/cm^2 across 650 µm

Experimental setup

Cylindric plastic shells filled with D2 at 11 atm with 0.15% atomic concentration



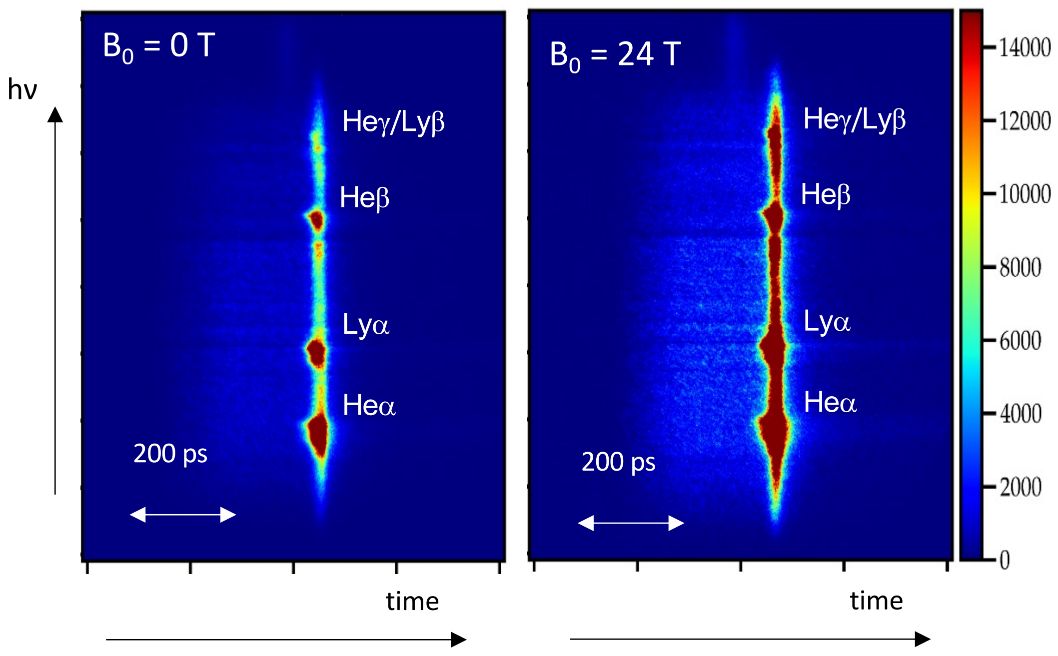




Spectroscopic data show a clear evidence of increased temperature with applied B field

Time-resolved spectroscopy

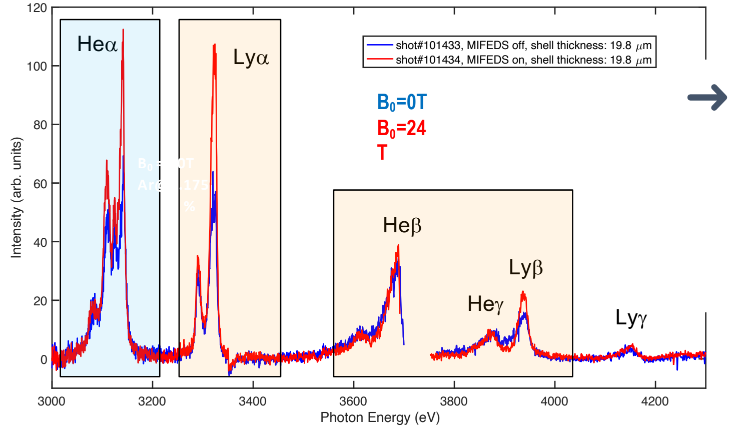
Unmagnetized (B_0 = 0) ***Magnetized (B_0 = 24 T)***



→ Most of the Ar emission occurs within the 100ps around stagnation

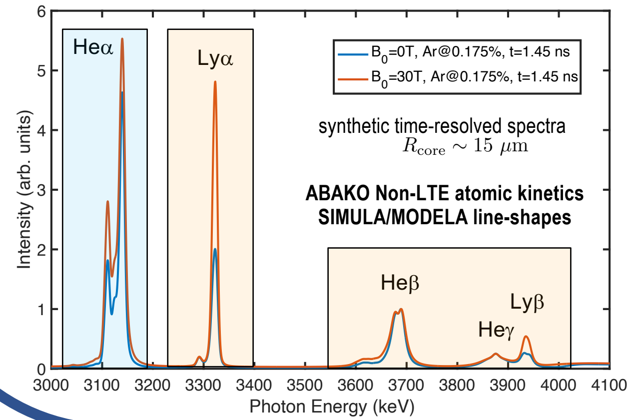
Ar K-shell spectra characterize core plasma conditions

Experimental time-integrated Ar K-shell emission



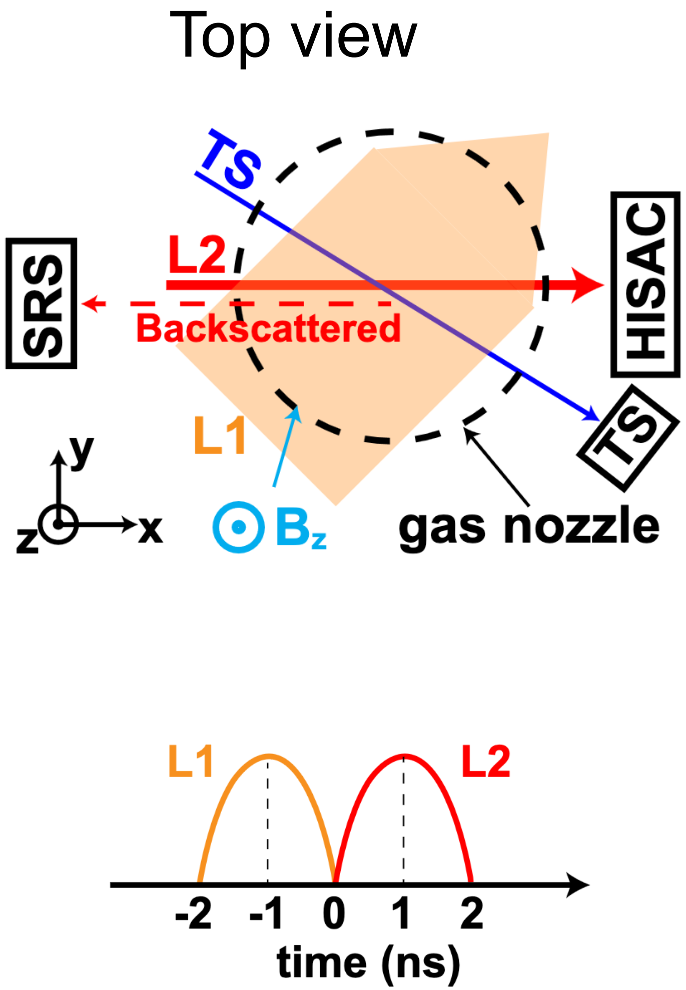
→ Systematic intensity ratios suggest a hotter core for the magnetized implosions

Modelled Ar K-shell emission



→ Observations qualitatively predicted by synthetic spectra simulations

LPI studies in presence of magnetic field @ LULI

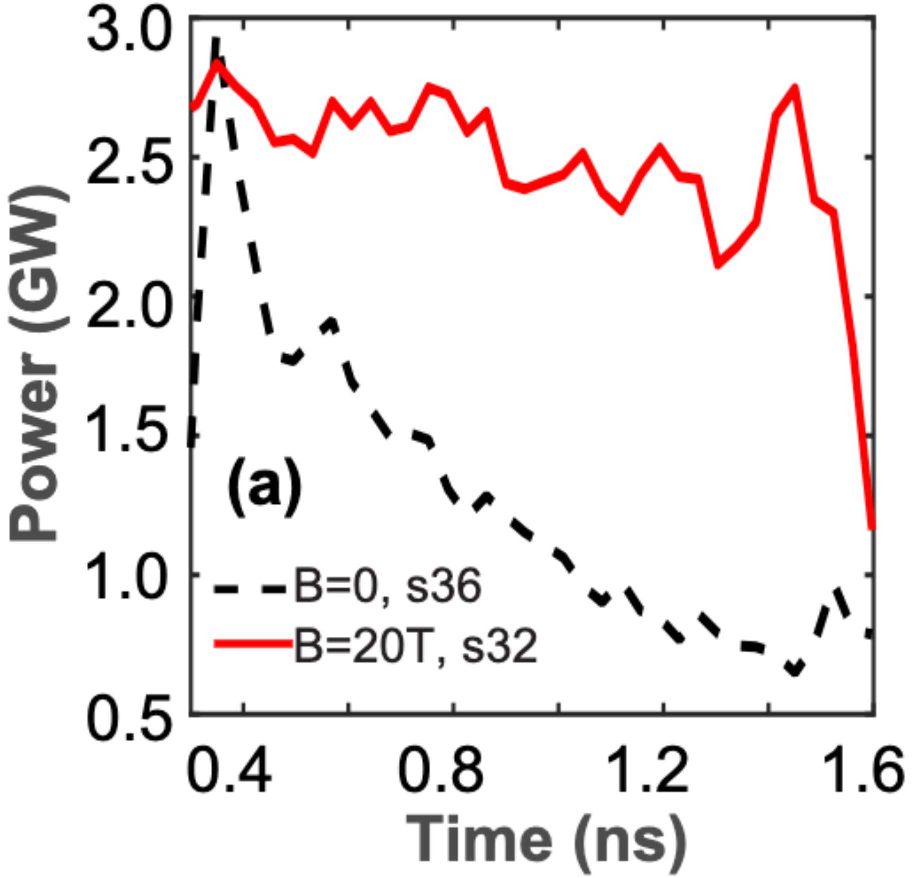


- **Laser:**
  - L1: 30 J, 2x0.3 mm² with RPP, 3×10^{12} W/cm²
  - L2: 50 J, 77x60 μm^2, single speckle with f/22, 1.4×10^{15} W/cm²
- **Ambient gas:**
  - H_2, ~0.02-0.08 n_c; ~2 mm
- **B-field**:
  - 20 T, in the z-direction along the gas.
- **Diagnostics:**
  - HISAC: high-speed 2D spatially-resolved sampling camera, 30 ps resolution
  - TS: Thomson scattering, 2ω, 1 ns,
  - SRS: Backscattered stimulated Raman

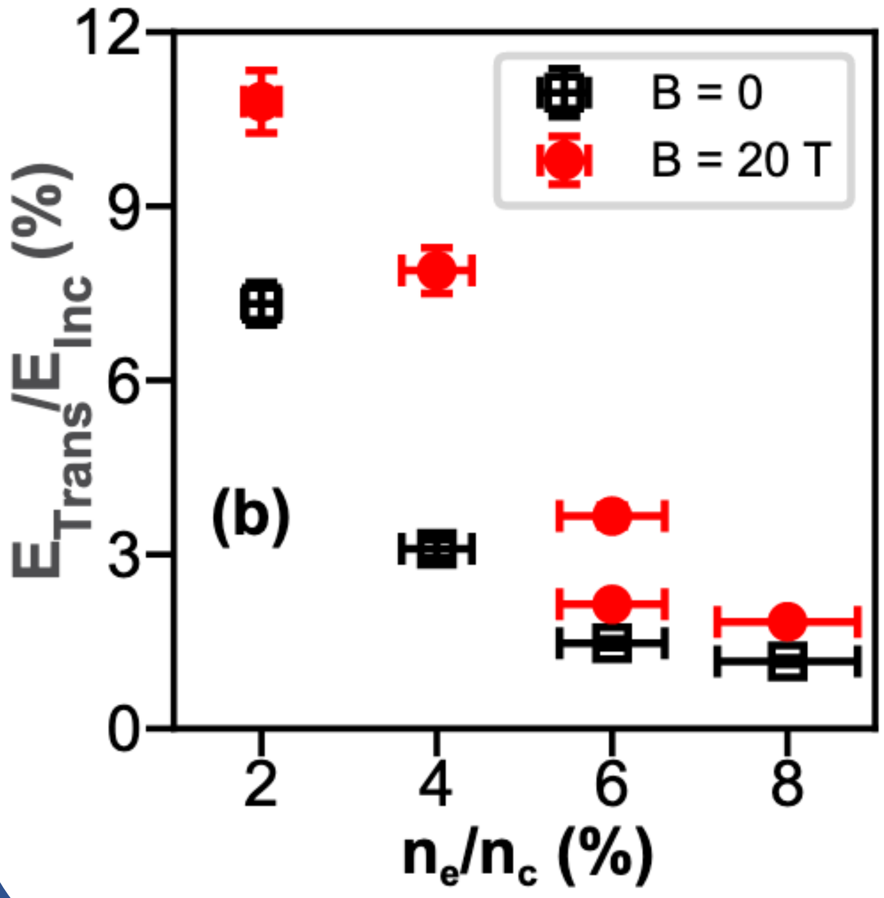
Yao, W.,et al., (2022). Dynamics of nanosecond laser pulse propagation and of associated instabilities in a magnetized underdense plasma, Phys. Rev. Lett. 130, 265101

Transmitted laser energy is higher in magnetized plasma

Transmitted power

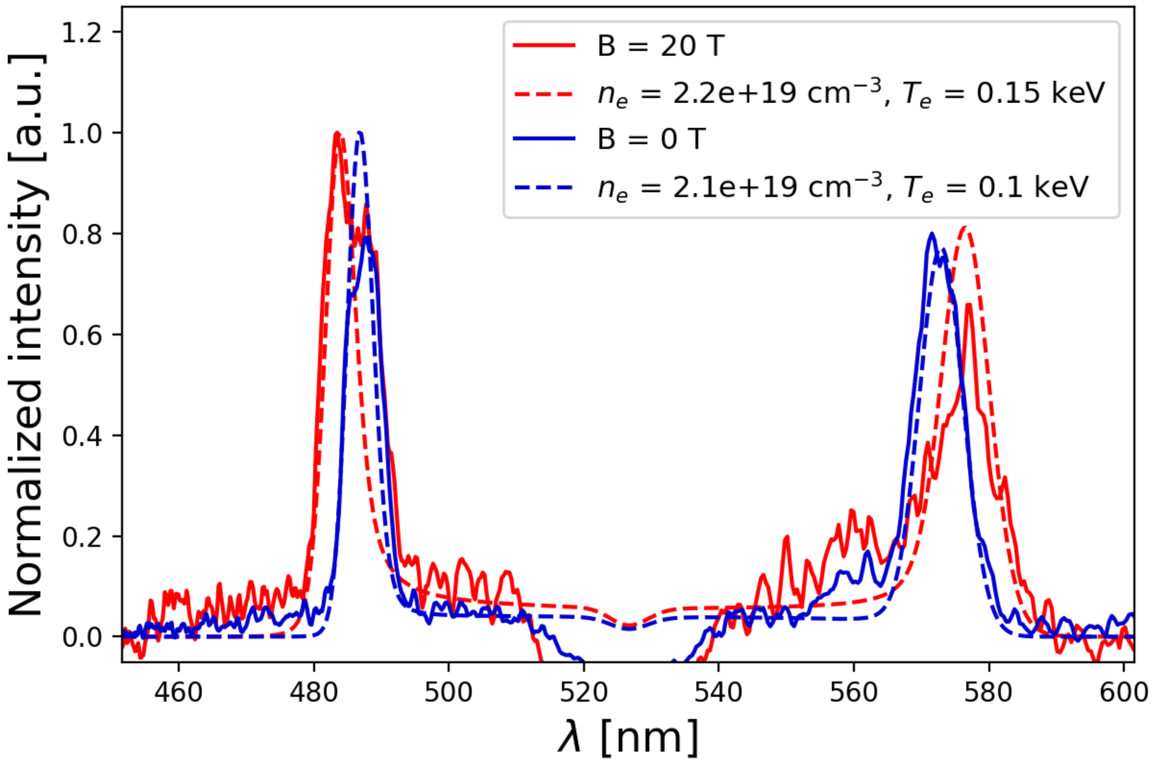


Transmitted power
with density

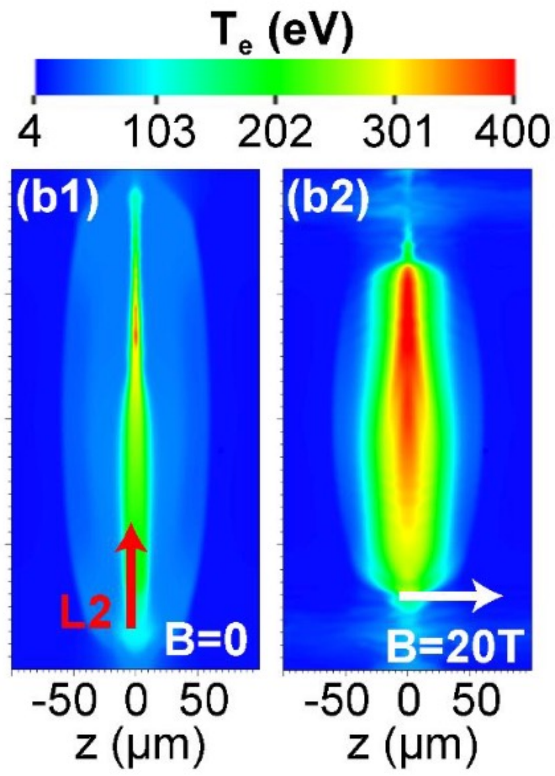


Higher temperature from TS measurement explains higher transmission in presence of B field

Thomson scattering data and fits

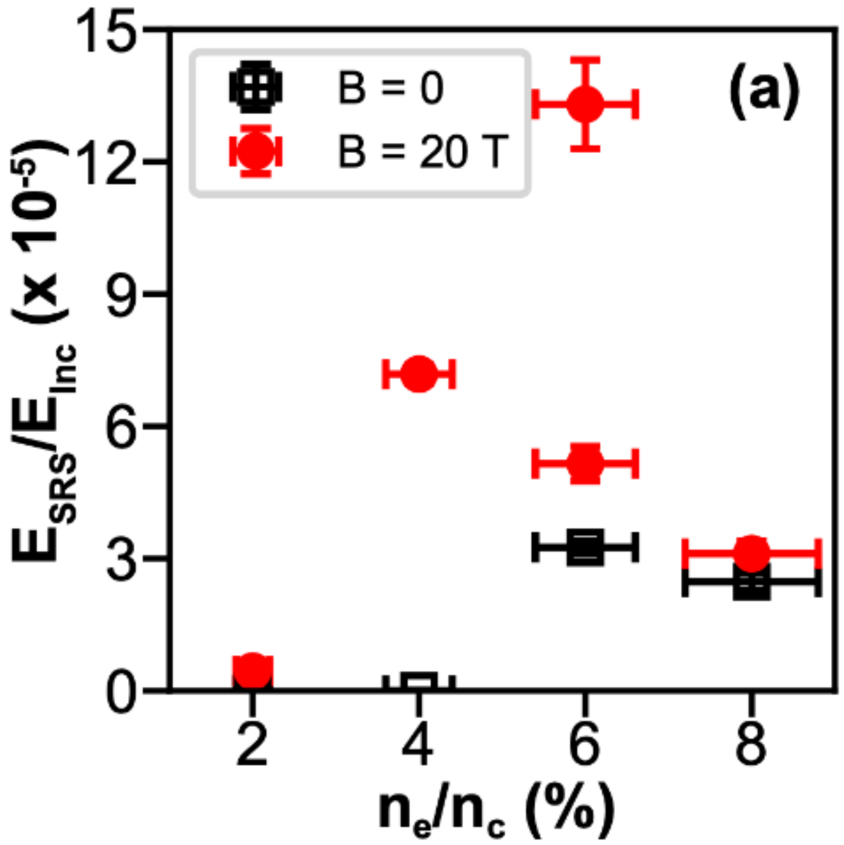


Flash simulations

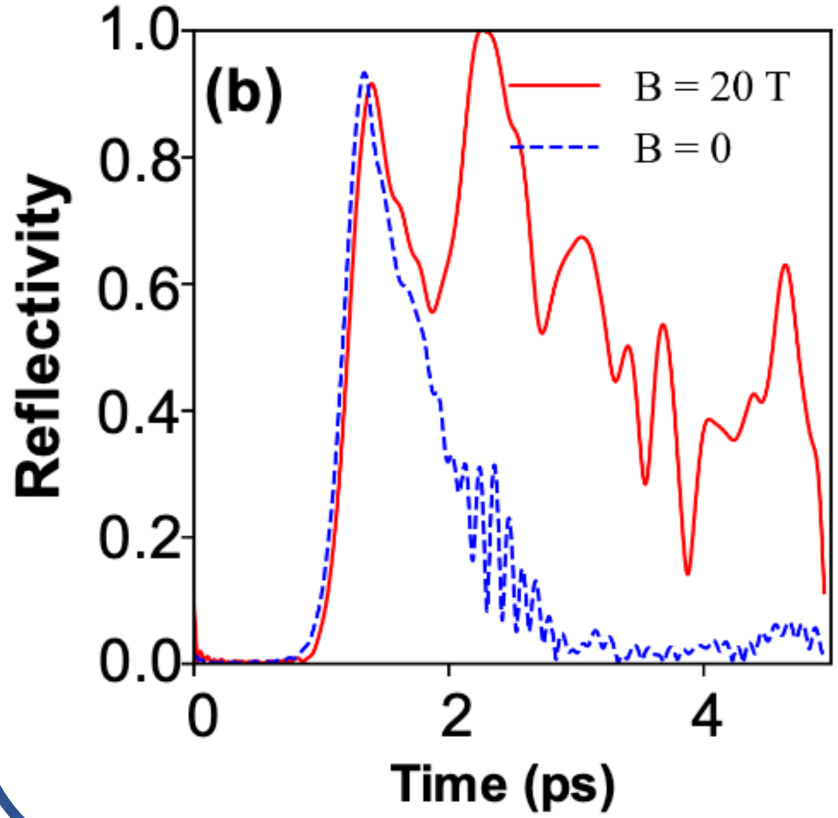


Backscattered SRS signals show clear enhancement, instead of mitigation, with B-field

Experimental data



PIC simulation result (SMILEI)



Conclusion : magnetized plasmas

- Higher temperature observed in magnetized plasma (20 T)
  - higher plasma transmission
  - higher SRS reflectivity

- Follow up experiment on the LMJ S. Fujioka, P. Nicolaï

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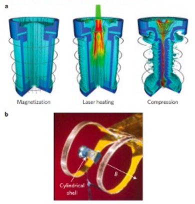
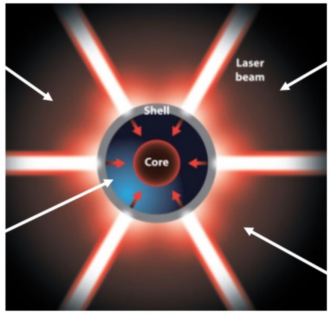
Detailed studies of the microphysics of ignition target are carried out on mid scale facilities through out Europe

Atomic physic/
magnetized plasma





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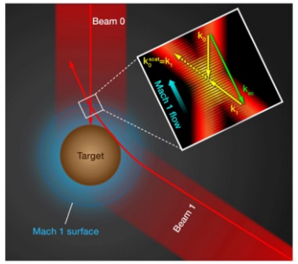

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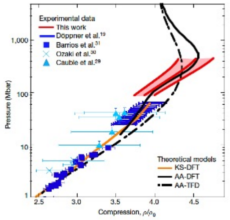
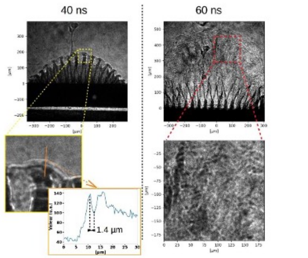


Hydrodynamic instabilities



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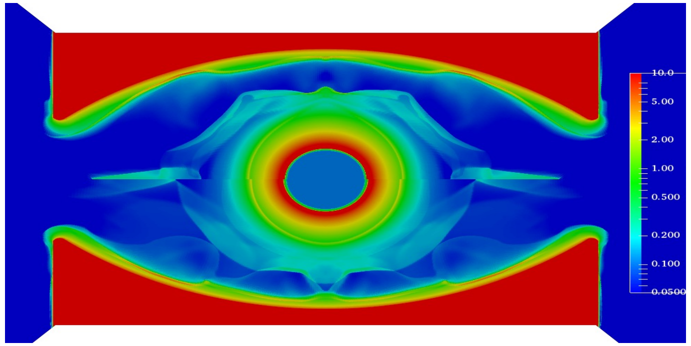

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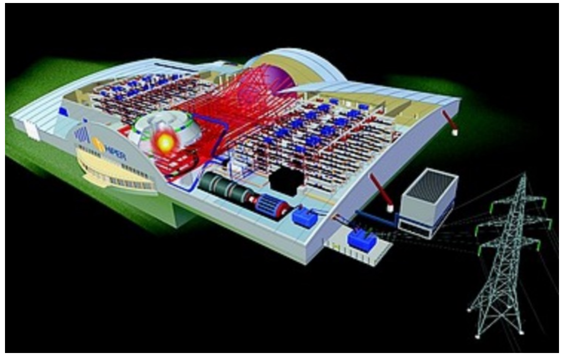
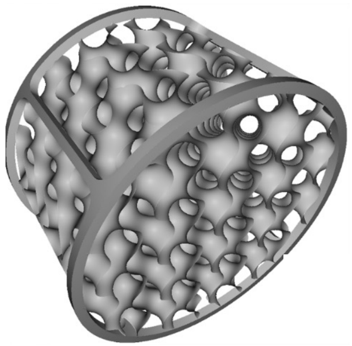


Low density medium

Motivation

- ○ Wetted foam experiments on the NIF have shown promising results
- ○ In direct drive, foam have been showed to reduce laser imprint



Questions to be answered:

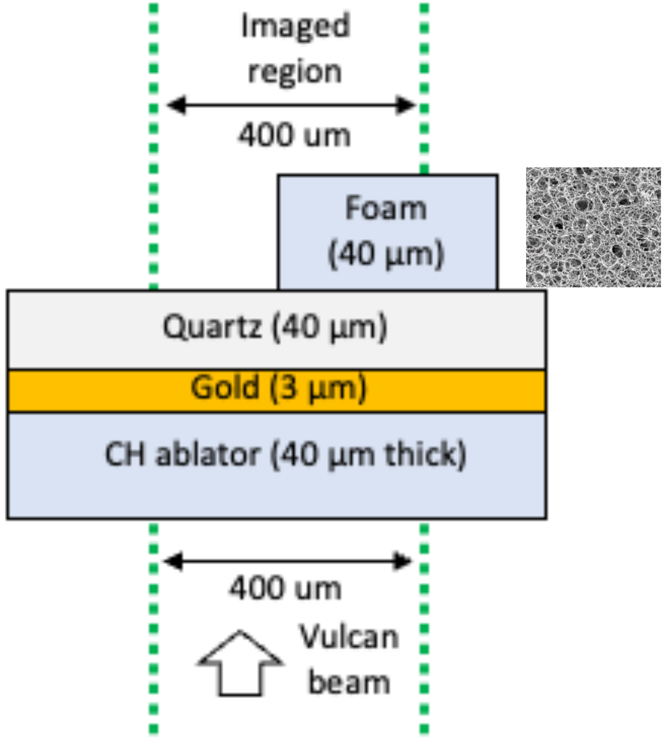
- ○ Equation of state
- ○ Homogenization

Collaboration

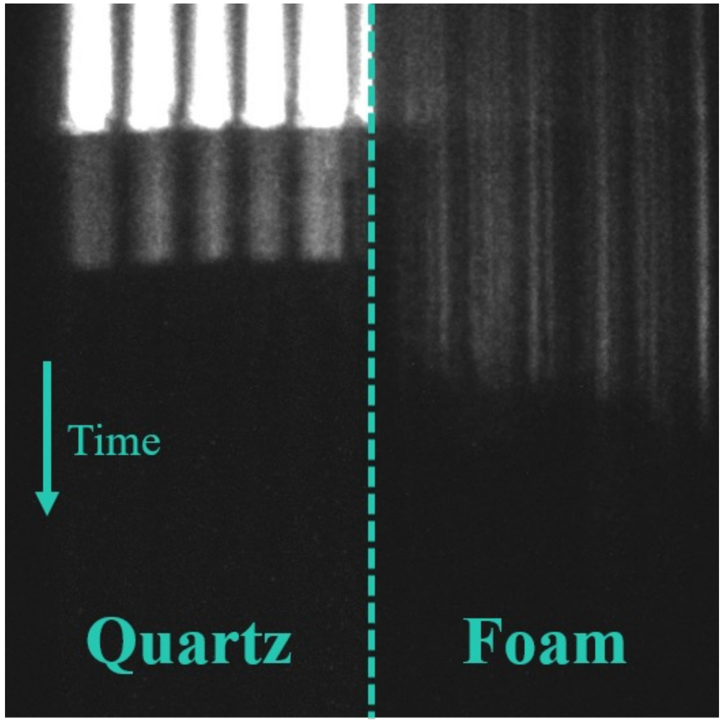
- Oxford University, Rutherford Appleton laboratory, York University, ENEA, LULI, GSI, Institute of Plasma Physics and Laser Microfusion, Freie Universitat berlin, AWE, LLE
- CELIA, ELI Beamlines, FNSPE, Institute of Plasma Physics & Institute of Physics

EOS studies of 260 mg/cc TMPA plastic foam @RAL

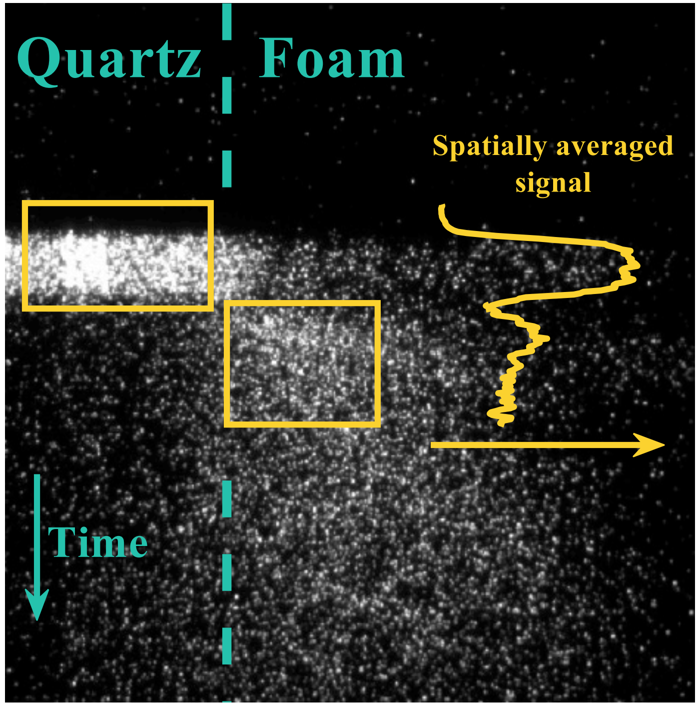
Target design



pressure and particle velocity from VISAR

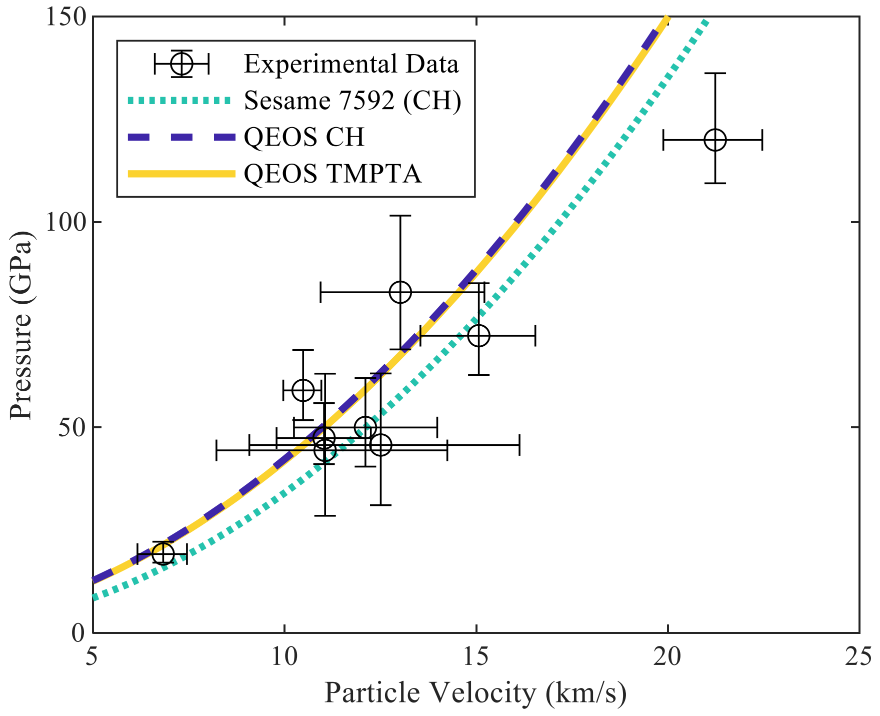


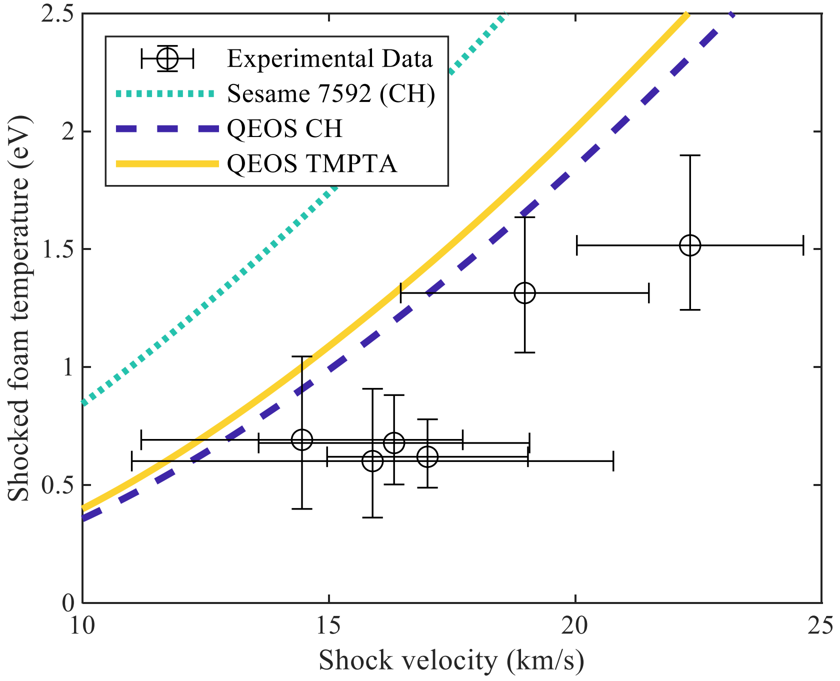
Temperature from SOP



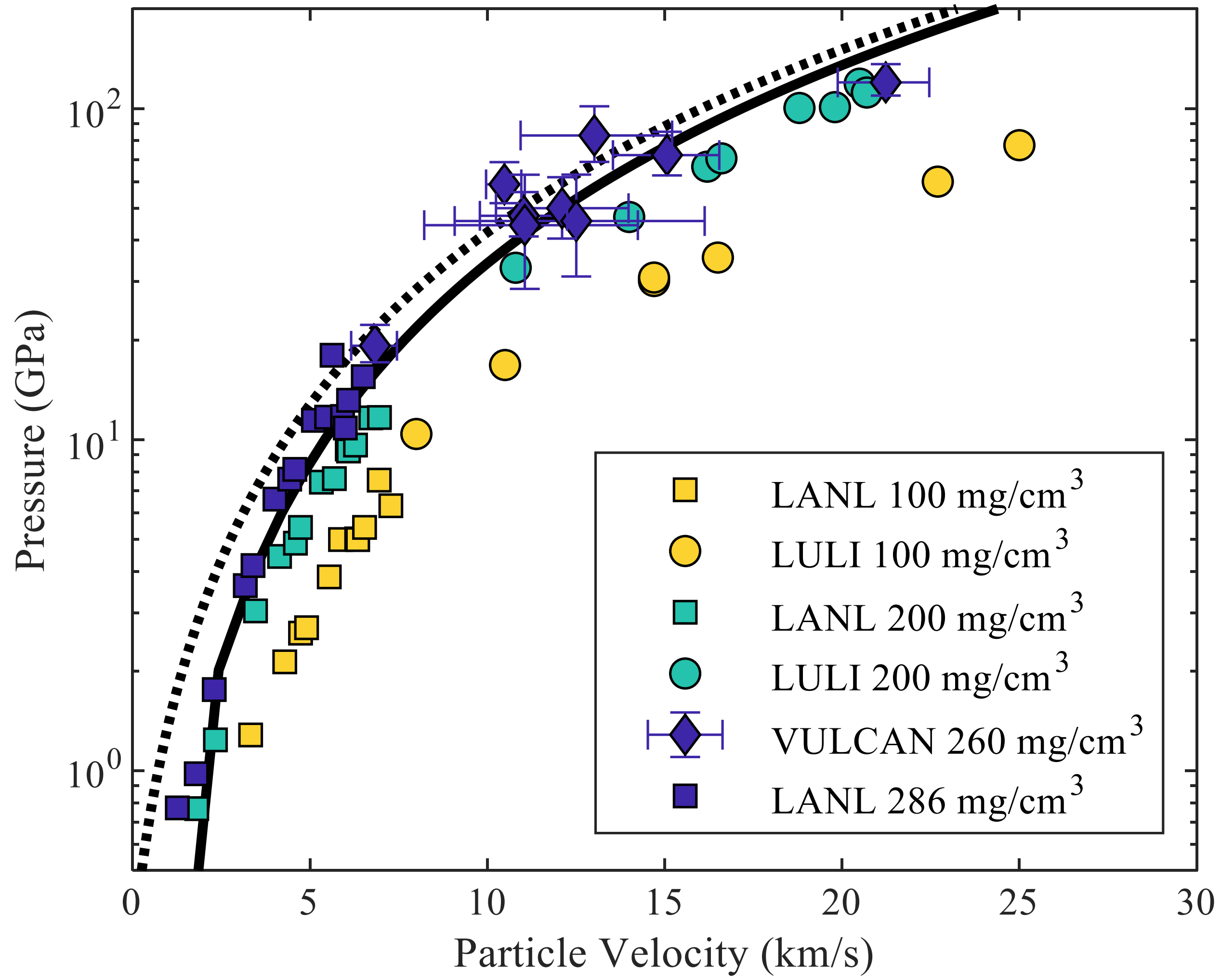
Paddock, R. W., et al. (2023). Measuring the principal Hugoniot of inertial-confinement-fusion-relevant TMPTA plastic foams. *Physical Review E*, *107*(2), 025206.

EOS models of the low-density homogeneous plastic appear to well describe the experimental data



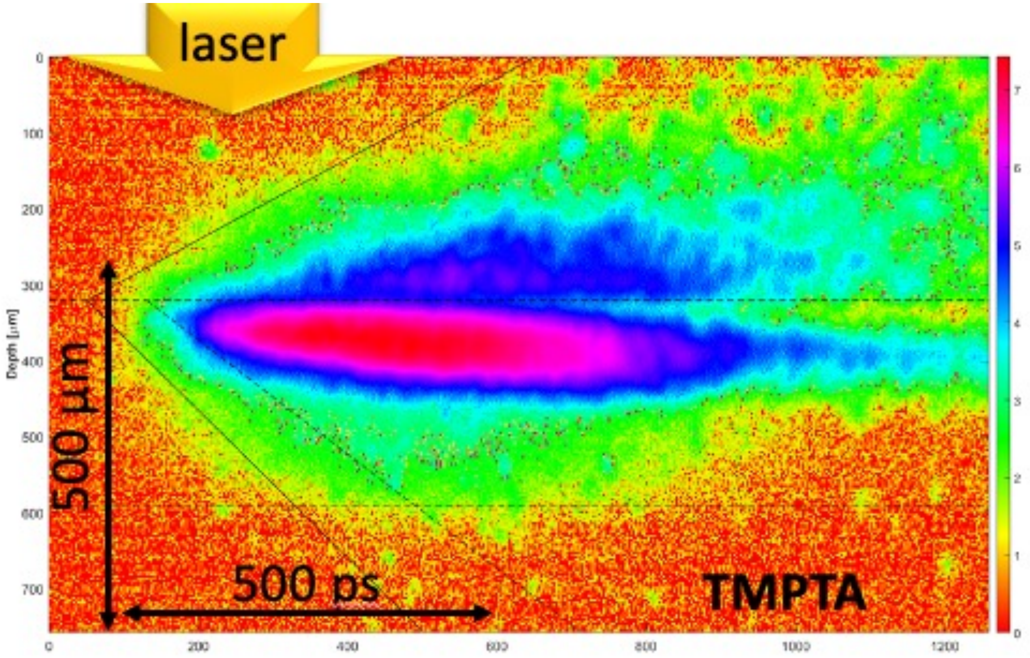


These results are consistent with previous experiments

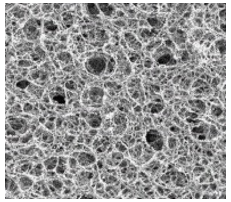


Studies of dynamical properties of foam at PALS facility

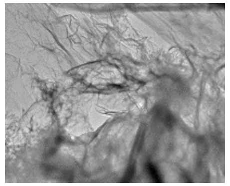
Velocity of ionization wave: X ray streak camera



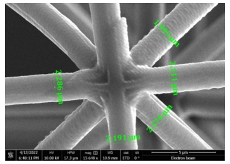
7-10 mg/cc foam
Doped with Cl



TMPTA

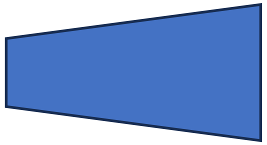


CNT



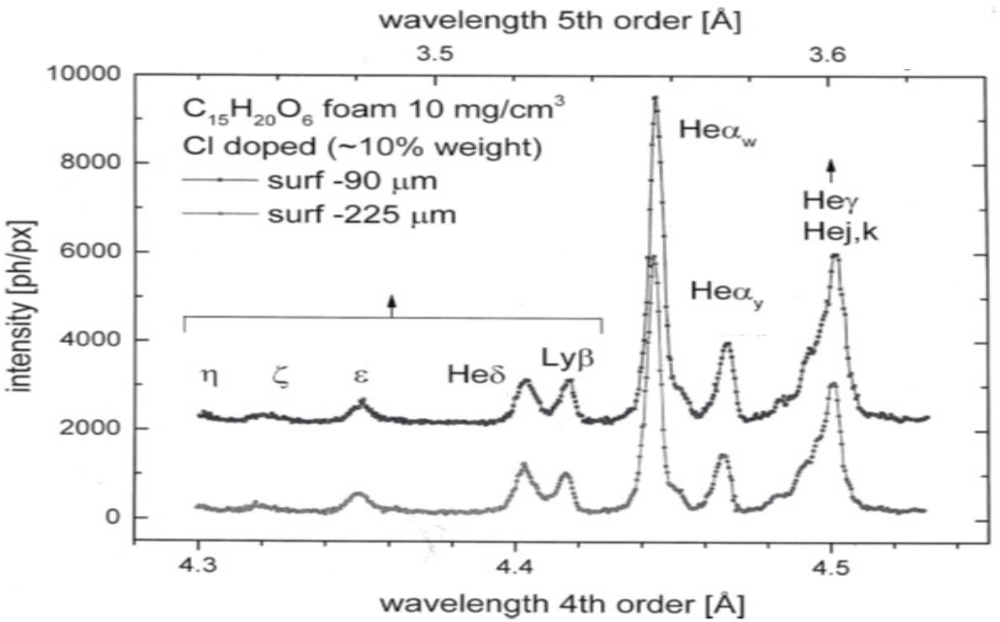
AM

Laser: 200J,
300ps @ 438 nm



Studies of dynamical properties of foam at PALS facility

Plasma temperature: electrons – ratio of Lyβ/Heδ lines, ions – broadening of inter-combination line $He\alpha_y$ of a dopant (chlorine)



7-10 mg/cc foam
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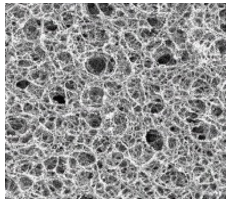

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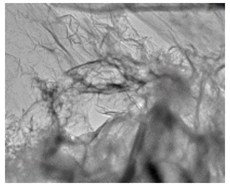
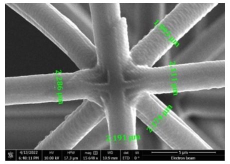
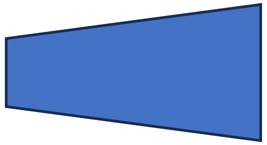


CNT



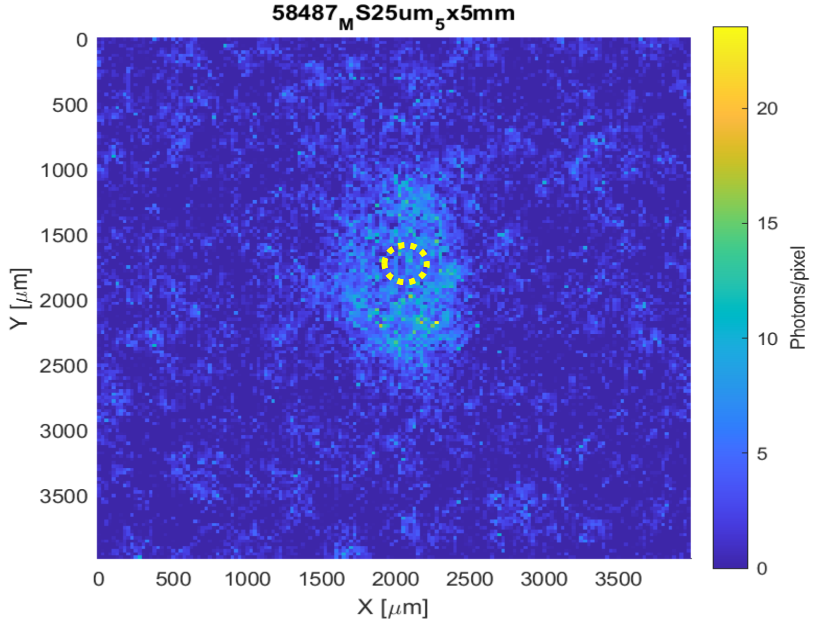
AM

Laser: 200J, 300ps @ 438 nm

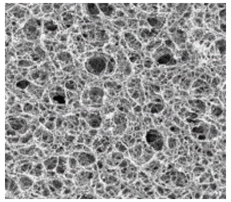


Studies of dynamical properties of foam at PALS facility

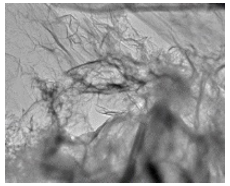
Hot electron generation: Kα emission from the substrate (copper foil)



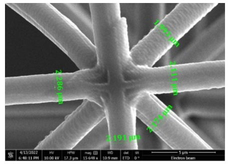
7-10 mg/cc foam
Doped with Cl



TMPTA



CNT



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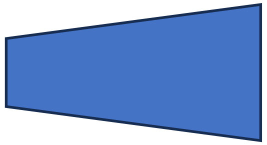
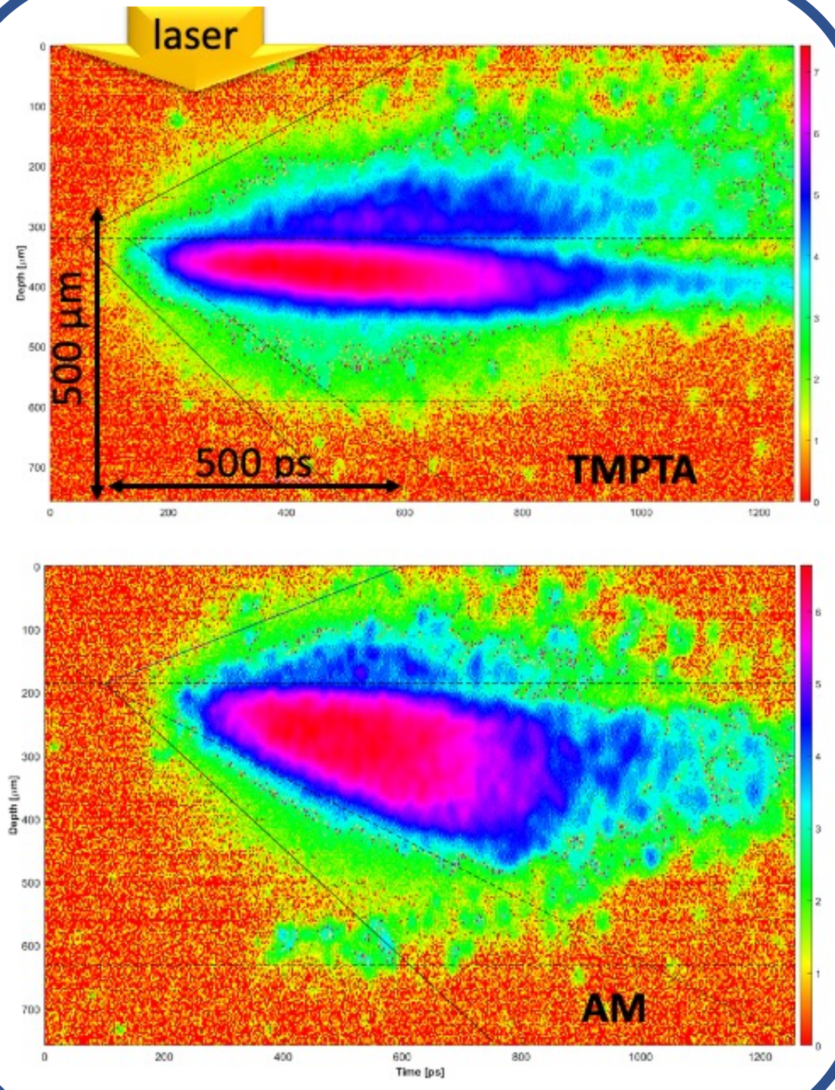


Lower ionization front velocity hot electron generation are observed

- Slowing down of the ionization front in structured targets
- Generation of hot electrons: large beam divergence, efficient electron generation in AM targets, less efficient in CNT and TMPTA
- Increased ion temperature: $T_e \sim 0.9$ keV, $T_i \sim 2.5 - 3.5$ keV large ion-to-electron temperature ratio: $T_i/T_e \sim 3 - 5$

	Density	Front velocity	HE yield
AM	8.5 mg/cc	430-540 μm/ns	3%
CNT	7 mg/cc	300-500 μm/ns	0.1%
TMPTA	10 mg/cc	600-800 μm/ns	0.3%
Solid CH		1600 μm/ns	4%



Reduced foam models implemented in FLASH are in good agreement with observations

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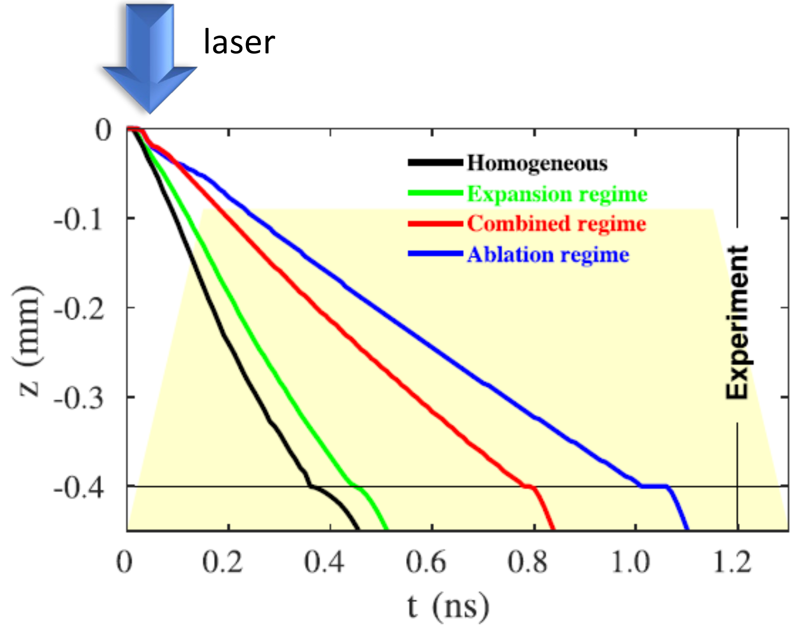
Microscopic model based on PIC simulation is implemented in FLASH -> slowing down of IF observed



L. Hudec et al. Phys. Plasmas 30, 042704 (2023)
V. Tikhonchuk et al. MRE 6, 025902 (2021)

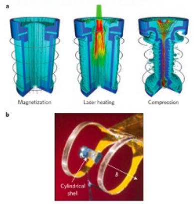
Conclusion: low density medium

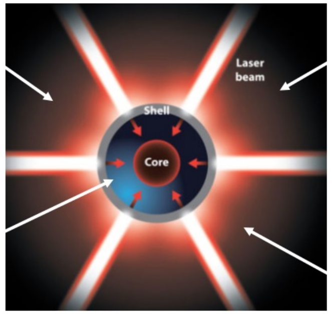
- EOS of TMPA foams @ 260 mg/cc well described by current EOS models
- Ionization front velocity is significantly lower in foams
- Strong electon / ion temperature ratio in foam plasmas

The fusion effort in Europe is articulated between mid and large scale facilities

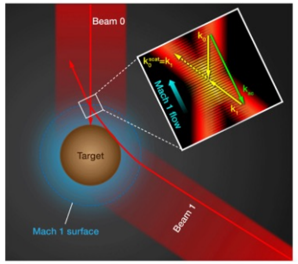
Detailed studies of the microphysics of ignition target are carried out on mid scale facilities through out Europe

Atomic physic/ magnetized plasma

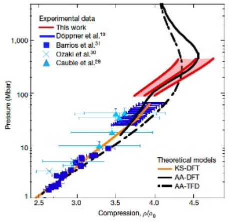




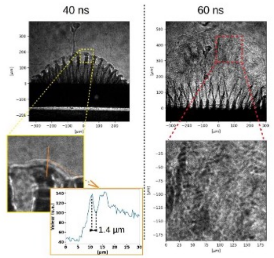
Laser Plasma Interaction



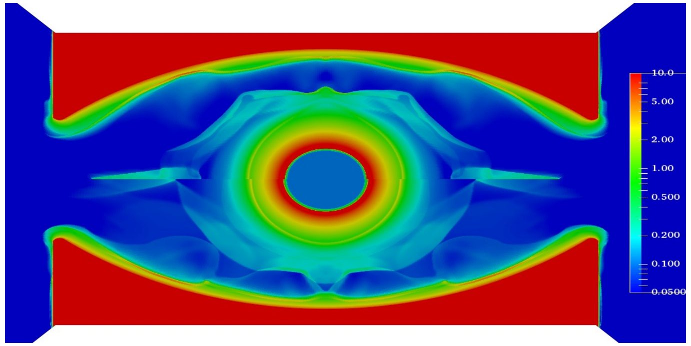
Equation of state



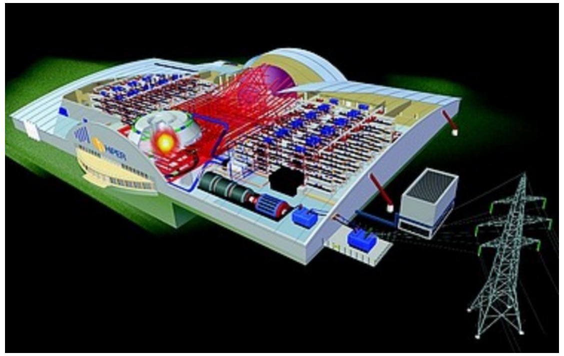
Hydrodynamic instabilities



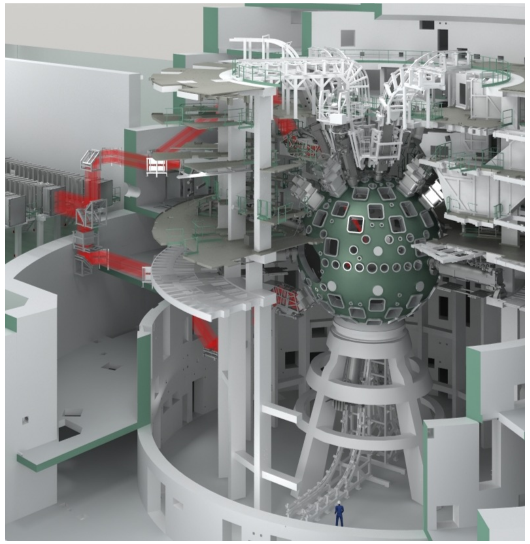
Indirect drive implosion using rugby hohlraums are carried out on the Laser Mega Joule @ CEA DAM



Studies toward IFE



Laser MégaJoule status



11 bundles are operational for experiments + PETAL (ps beams) leading up to ~ 300 kJ

Several more bundles are assembled, commissioning done or pending

Next configuration with 16 bundles in 2025, final configuration with 22 bundles (176 beams) + PETAL

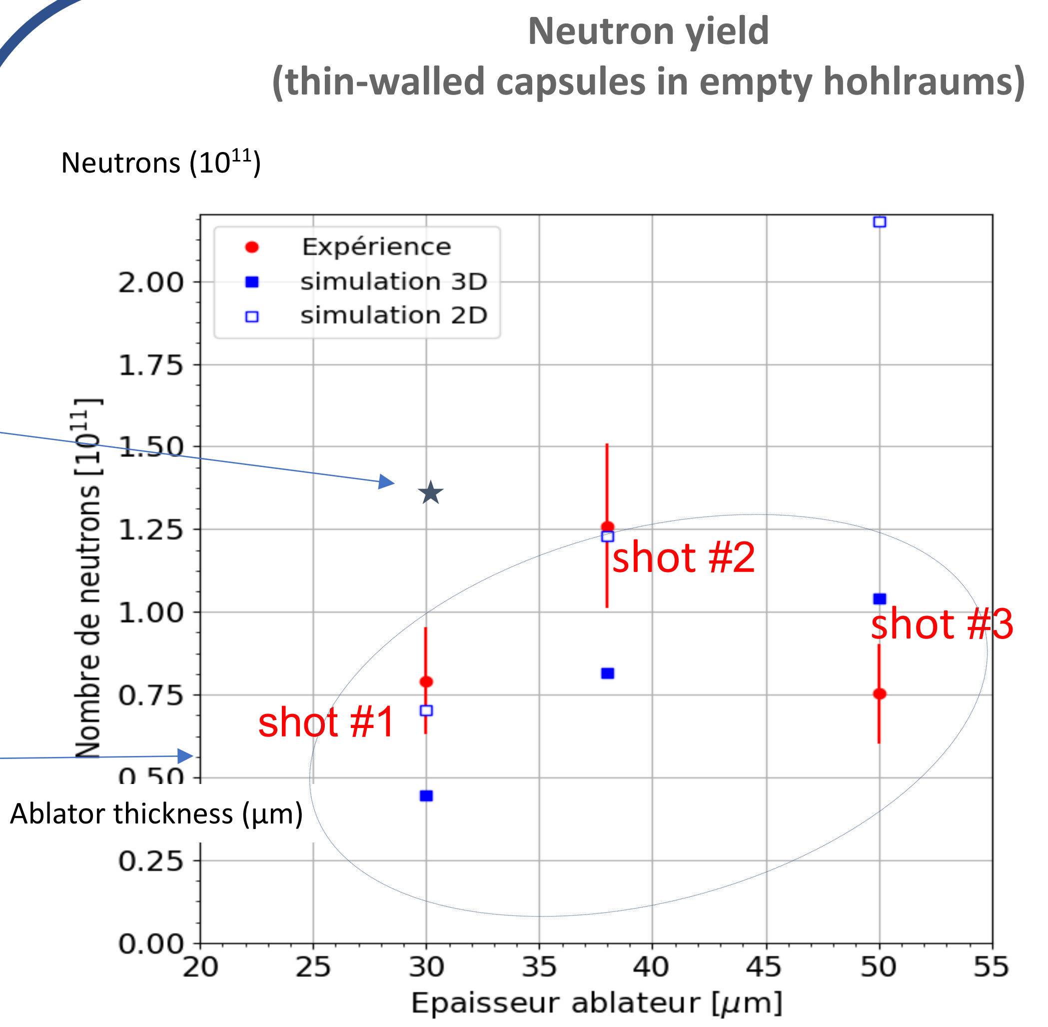
16 diagnostics are operational

5 additional are being commissioned for 2023 experiments

higher neutron production with more laser energy and better irradiation symmetry

Neutron yield in 2022 experiments with 10 bundles : increased yield due to higher laser energy and better (5-fold) irradiation symmetry

Neutron yield in 2019 experiments with 6 bundles



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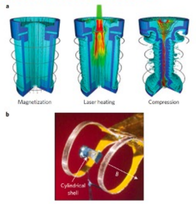
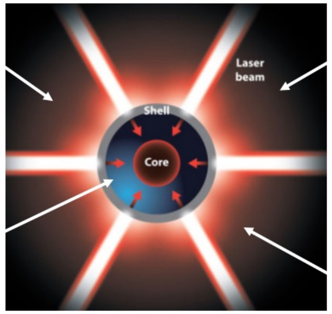
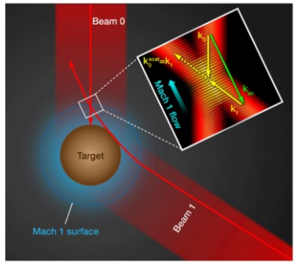




Laser Plasma Interaction



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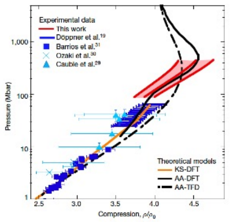
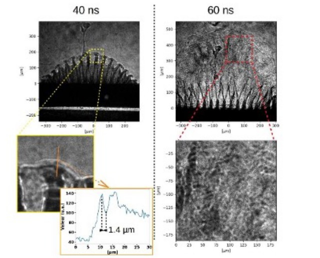


Hydrodynamic instabilities



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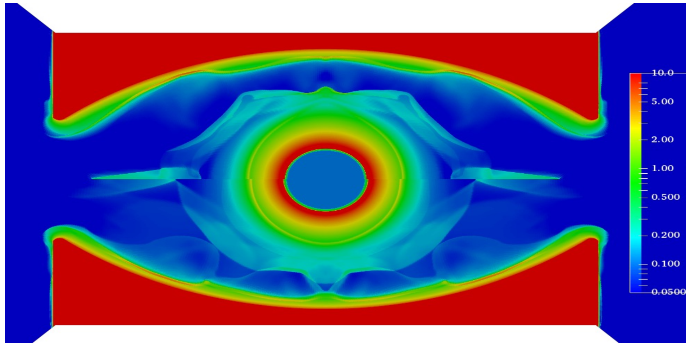
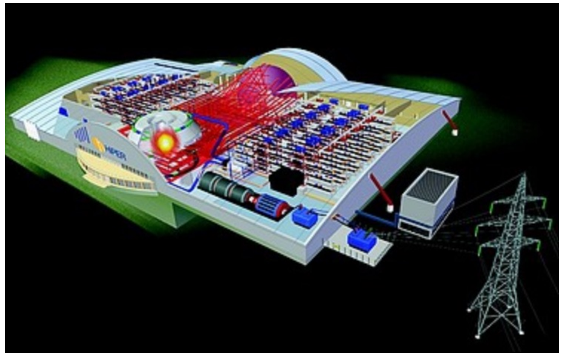


Studies toward IFE



In parallel, shock ignition is investigated for high gain direct drive ignition for IFE

EUROfusion

HiPER+ EUROPEAN LASER FUSION ENERGY

Eurofusion and laserlab are supporting the effort

ENABLING RESEARCH: CFP-FSD-AWP21-ENR-01-CEA-02

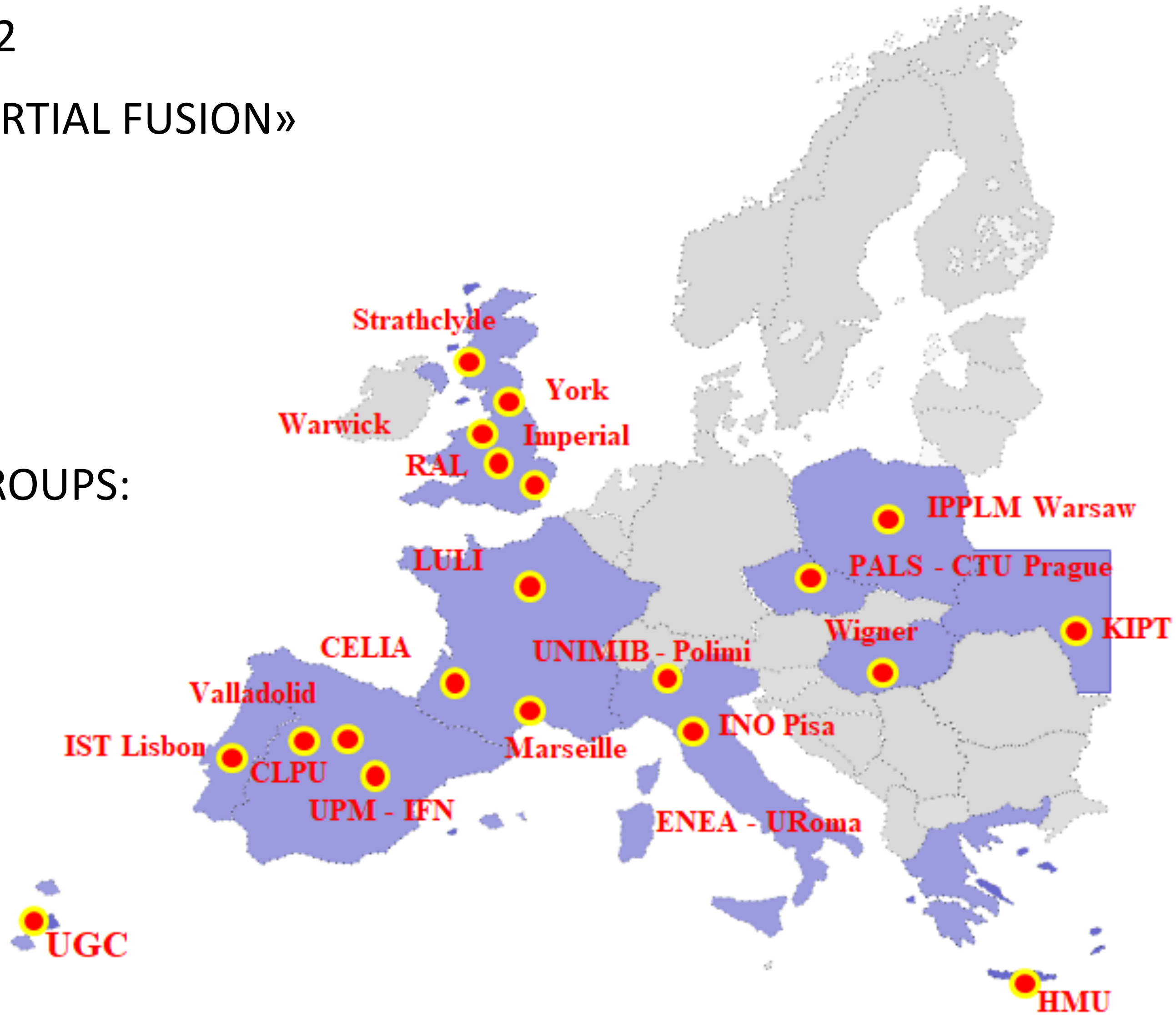
«ADVANCING SHOCK IGNITION FOR DIRECT-DRIVE INERTIAL FUSION»

- DURATION: APRIL 2021 – MARCH 2024
- PI DIMITRI BATANI
- CO-PI STEFANO ATZENI

LASERLAB EUROPE AISBL SUPPORTS 3 ICF-RELATED GROUPS:

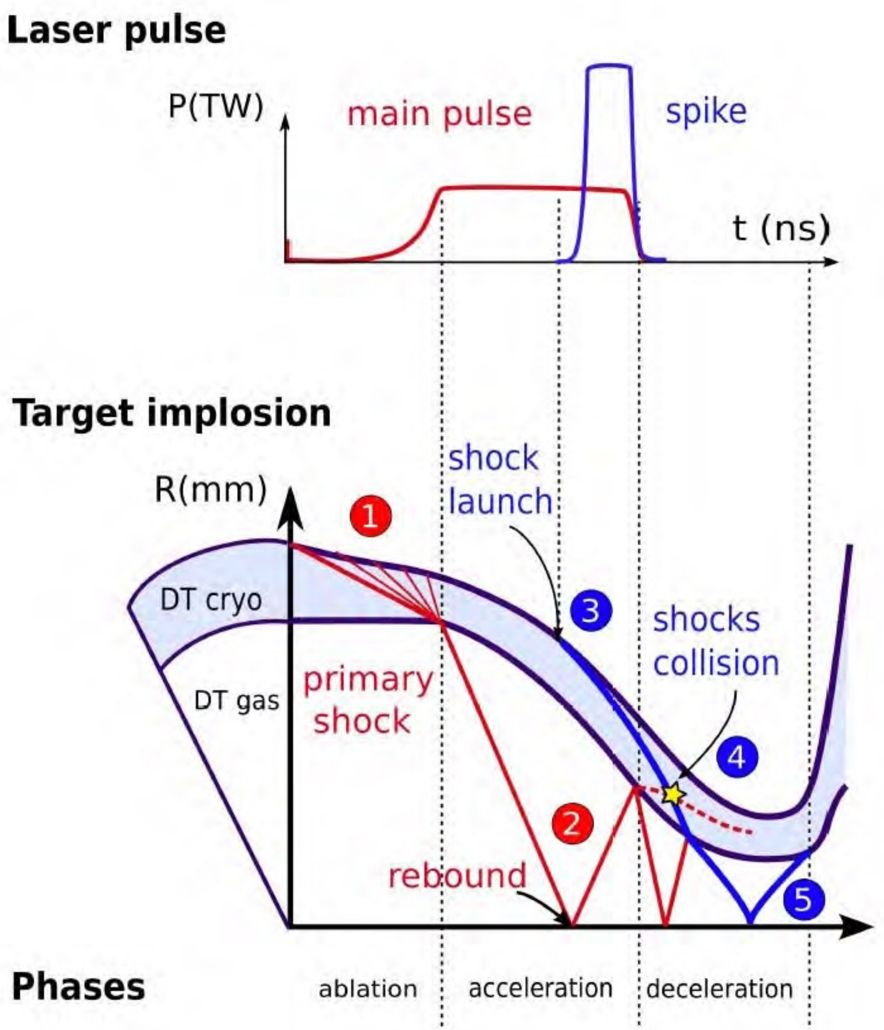
- EXPERT GROUP IN ICF/IFE
- EXPERT GROUP IN MICRO-STRUCTURED MATERIALS
- EXPERT GROUP IN LASER-GENERATED EMP

24 groups and 99 researchers involved in the project with about 70% “in kind” contributions



Shock ignition as a pathway to IFE

- Direct drive is envisioned as the most favorable scheme for IFE
- To be economically available an IFE reactor requires: a gain >100 @ a repetition rate of 10-15 Hz are required
- Decoupling heating from compression should lead to more stable more robust implosion -> shock ignition



Conclusion

- Mid-scale facility throughout Europe are carrying out microphysics studies of ICF relevant systems providing key information on

    - Hydrodynamic instabilities
    - Magnetized plasma
    - Low density medium for ICF

- The indirect drive effort on the LMJ is ramping up providing key information on rugby hohlraum for ignition

Conclusion

- **Eurofusion is supporting IFE projects in Europe**

  2 new enabling research project are starting in 2024

  Magnetized inertial confinement fusion led by J. Santos
  Foams as a Pathway to Energy from high gain direct drive ignition led by S. Le Pape

- **Following the HIPER initiative (2009-2013), a renewed European consortium HIPER+ is aggregating the European ICF community, an European IFE roadmap has been laid out**

Batani, D., Colaïtis, A., Consoli, F., Danson, C. N., Gizzi, L. A., Honrubia, J., ... & Volpe, L. (2023). Future for inertial-fusion energy in Europe: a roadmap. High Power Laser Science and Engineering, 11, e83.

Conclusion

In individual countries

- In Germany, the government posture toward IFE changed dramatically and large investments are being made
- In the UK an IFE consortium ”uplift” is regrouping the UK academic players, an UK IFE roadmap has been laid out
- In France, the academic community (CEA, CNRS) together with industrial partners (Thales) has answered a call from the government on innovative nuclear reactors
- Fusion start ups are growing in Europe. The European academic community is working in close relation with these initiative providing key expertise and laser access.