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EuPRAXIA
Preparatory Phase

Attractivity for users in the inertial fusion field

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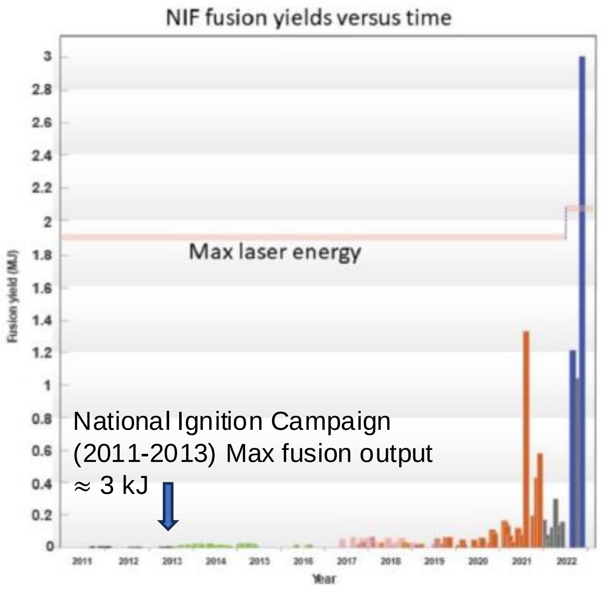
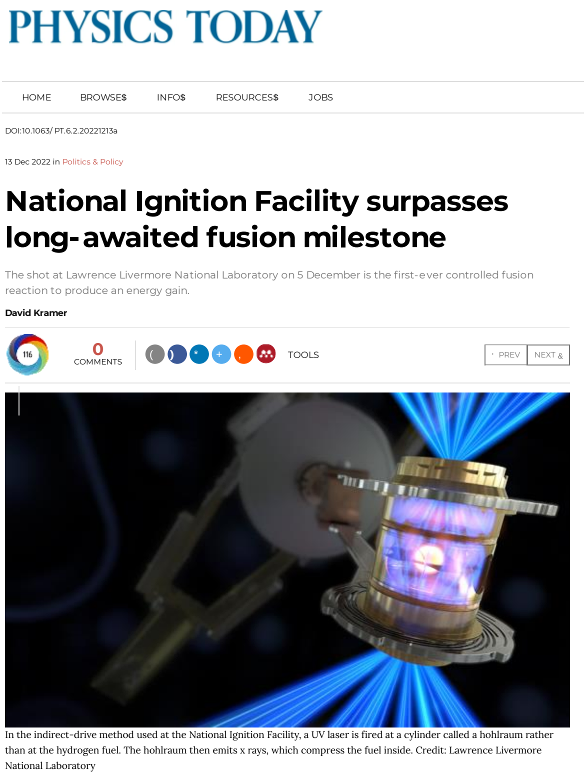
Inertial Fusion Ignition

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**

LONG AND DIFFICULT WAY TO SUCCESS

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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

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 the hydrogen fuel. The hohlraum then emits x rays, which compress the fuel inside. Credit: Lawrence Livermore National Laboratory

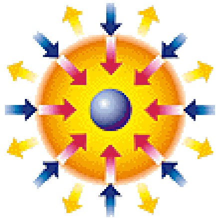
Major impact of NIF Ignition demonstration

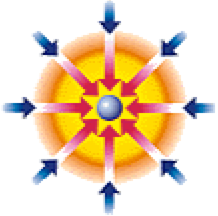
Broad research programmes on IFE being engaged worldwide

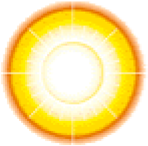
Inertial Fusion Case

Investigating Underlying Physics of Direct-Drive Inertial Fusion Energy


Phase 1: laser irradiation


Phase 2: Compression


Phase 3: Ignition


Phase 4: Burn

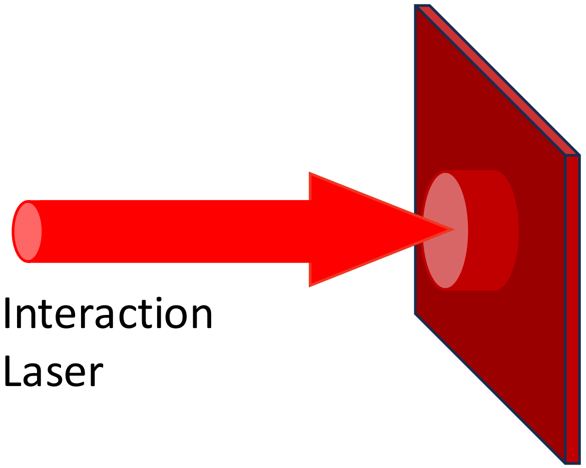
Physics issues to be understood:

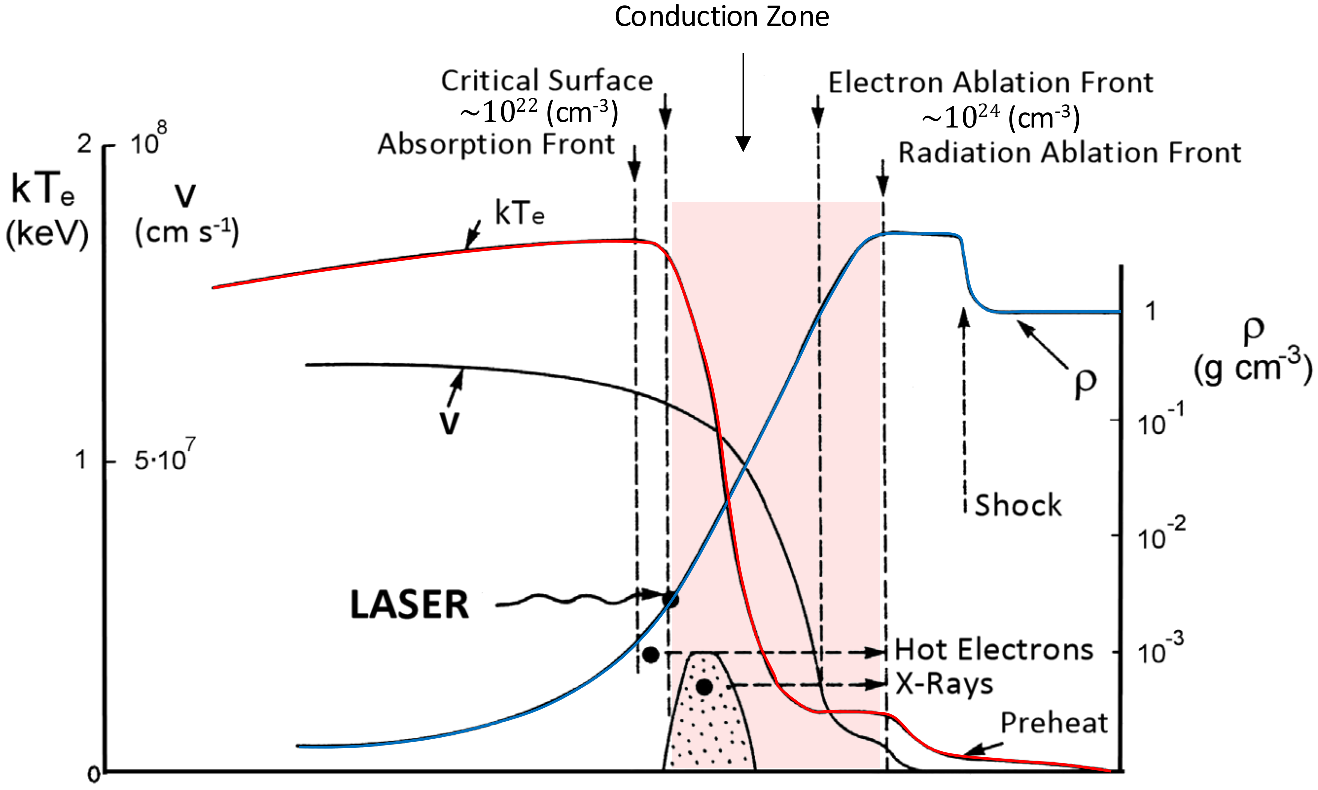
- Plasma production and characterization
- Parametric instabilities in implosion-like and shock-ignition-like Laser-Plasma interaction;
  - ✓ Stimulated Brillouin Scattering (SBS)
  - ✓ Stimulated Raman Scattering (SRS), side SRS
  - ✓ Two Plasmon Decay
  - ✓ Cross-beam Energy Transfer (CBET)
  - ✓ Filamentation
  - ✓ 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)

Needed platform for investigating matter under extreme conditions and High Energy Density plasmas

Mimicking ICF interaction

PLANAR GEOMETRY





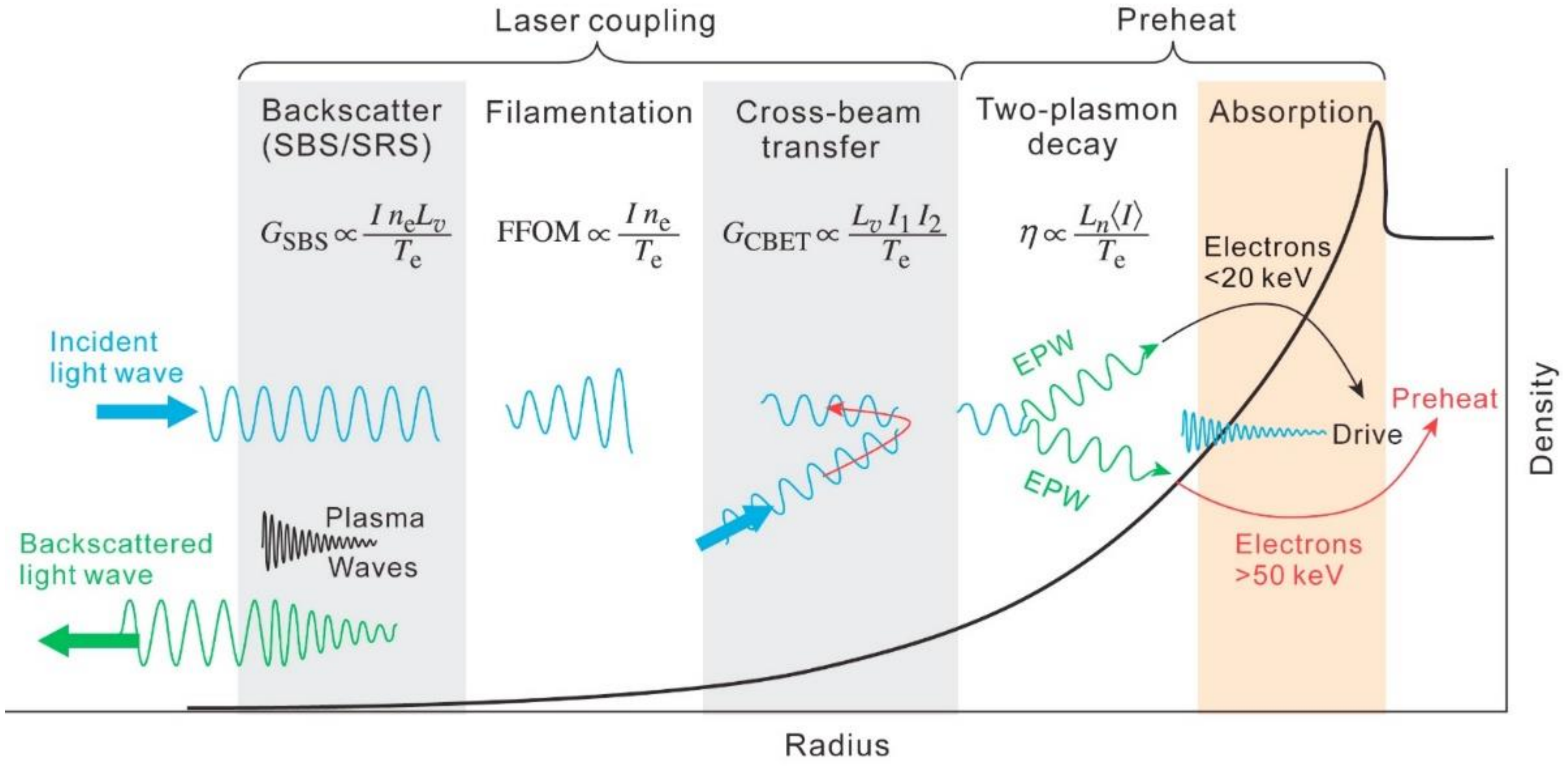
In a idealized ICF situation, laser light is absorbed by collisional absorption (inverse Bremsstrahlung) near the critical density surface $n_c(cm^{-3}) = 1.1 \cdot 10^{21}/\lambda_{\mu m}^2$ and successively the energy is transported to the ablation front, mainly via thermal electrons through the conduction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

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

Mimicking ICF interaction

Funded by the European Union

Several open physics issues at different densities



- Plasma density mapping and scalelength is crucial for investigating LPI
- A wide range of plasma conditions exists in ICF
- Higher densities not accessible in the optical range
- Shock driving is relevant for studies of material under extreme conditions

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

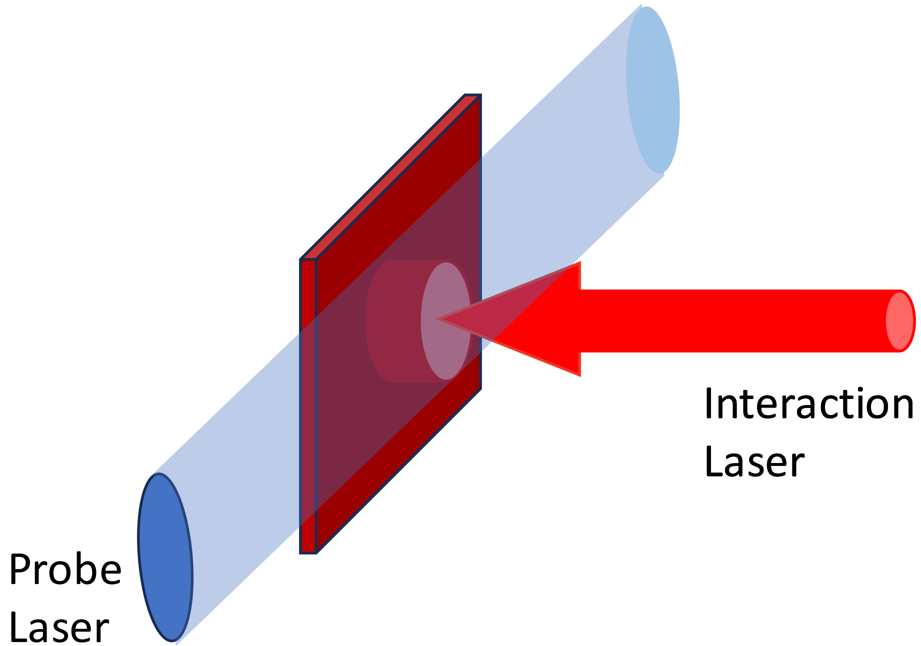
Density characterization needed including scalelength, density fluctuations, temporal evolution

Probing full range of plasma conditions

Funded by the European Union

Investigating Underlying Physics of Direct-Drive Inertial Fusion Energy

PLANAR GEOMETRY



Needed platform for investigating matter under extreme conditions and High Energy Density plasmas

Probing Wavelength vs Density in Plasmas

Funded by the European Union

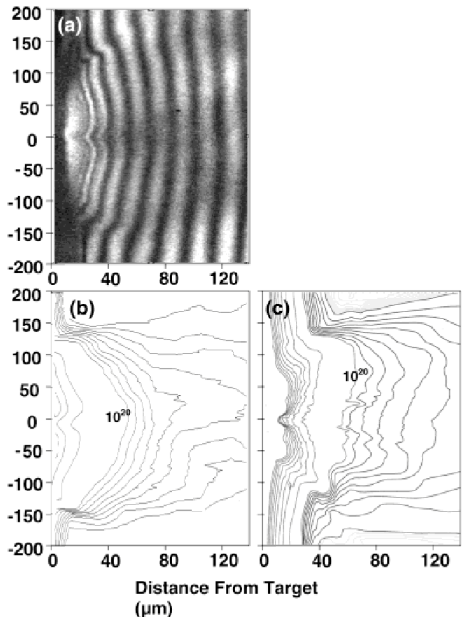
Plasma density characterization and mapping has been developed strongly using interferometry with optical or X-ray probe

Optical probing can address densities << $n_c = 1.1 \times 10^{21} \lambda_L^{-2} cm^{-3}$
Higher densities require shorter wavelengths

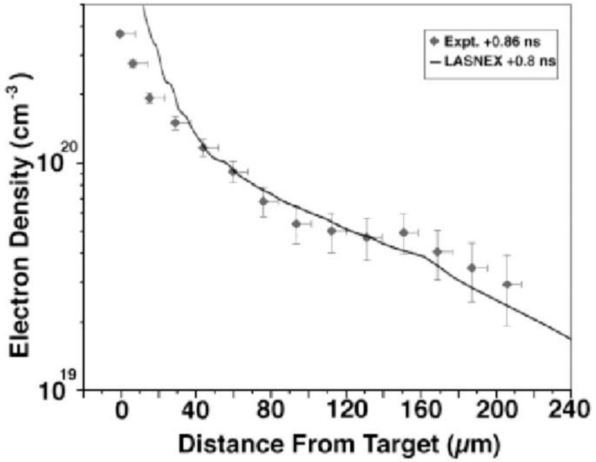
Critical Density (cm-3)	Wavelength (nm)
1,00E+19	10000
1,00E+20	3162
1,00E+21	1000
1,00E+22	316
1,00E+23	100
1,00E+24	32
1,00E+25	10
1,00E+26	3

Scattering and refraction lead to much shorter optimum wavelength

Plasma-based X-ray laser



Dunn, James et al. "Picosecond 14.7 nm interferometry of high intensity laser-produced plasmas." Laser and Particle Beams 23 (2005): 9-13.



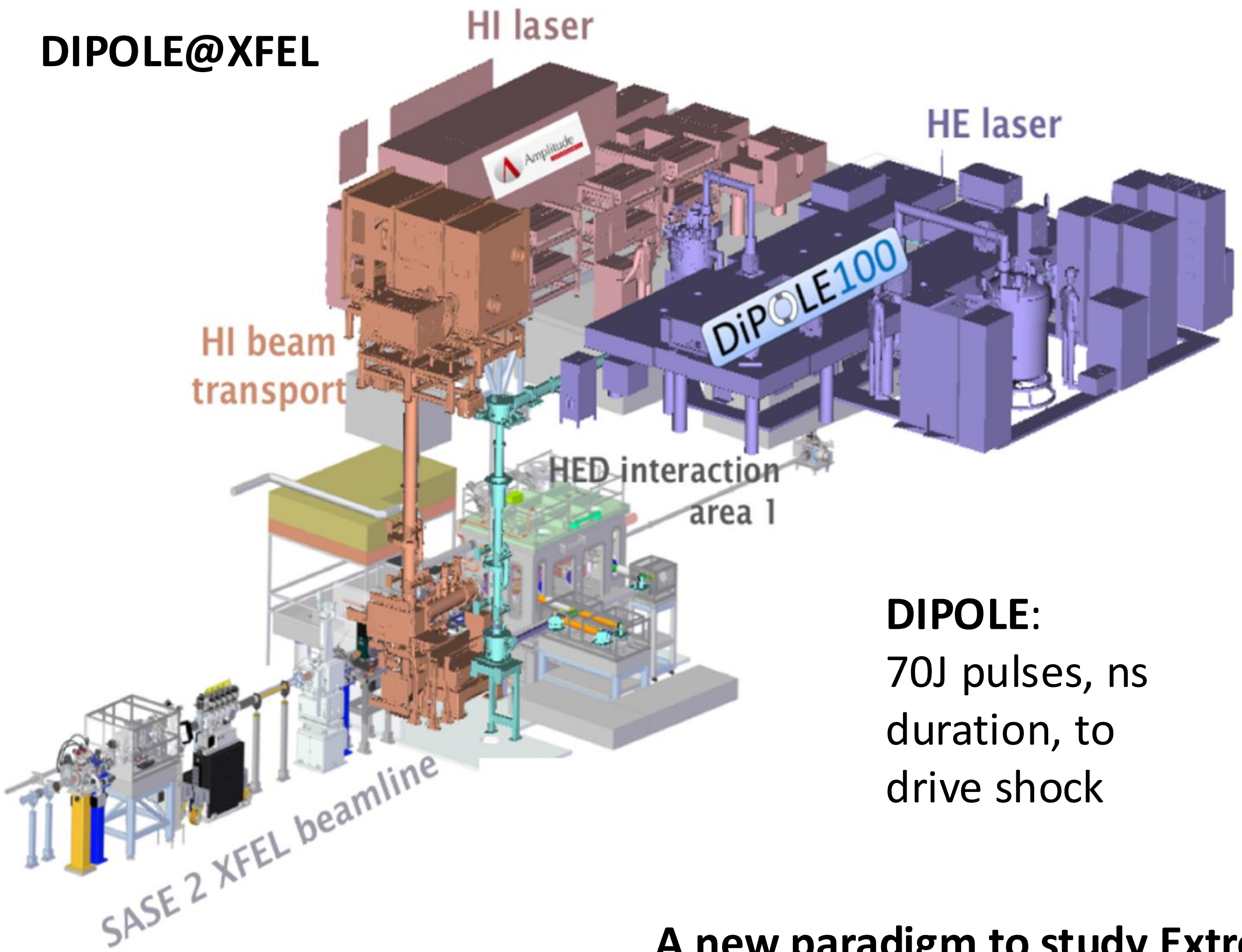
Fully laser-plasma based platform can be developed, but has limitations in X-ray laser performance

HED studies of X-ray laser FEL: XFEL

Funded by the European Union

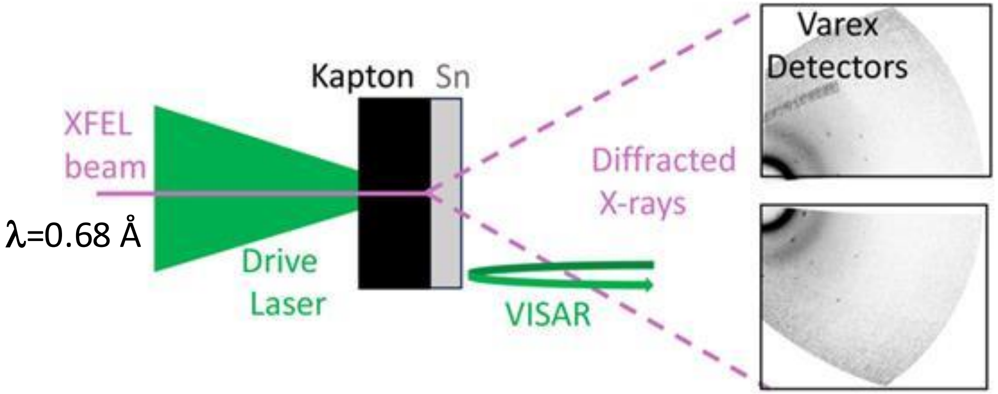
Coupling high energy lasers with XFEL beamline to investigate extreme states of matter with X-ray probing

DIPOLE@XFEL



DIPOLE: 70J pulses, ns duration, to drive shock

First experiment on X-ray diffraction of laser shocked material: large community

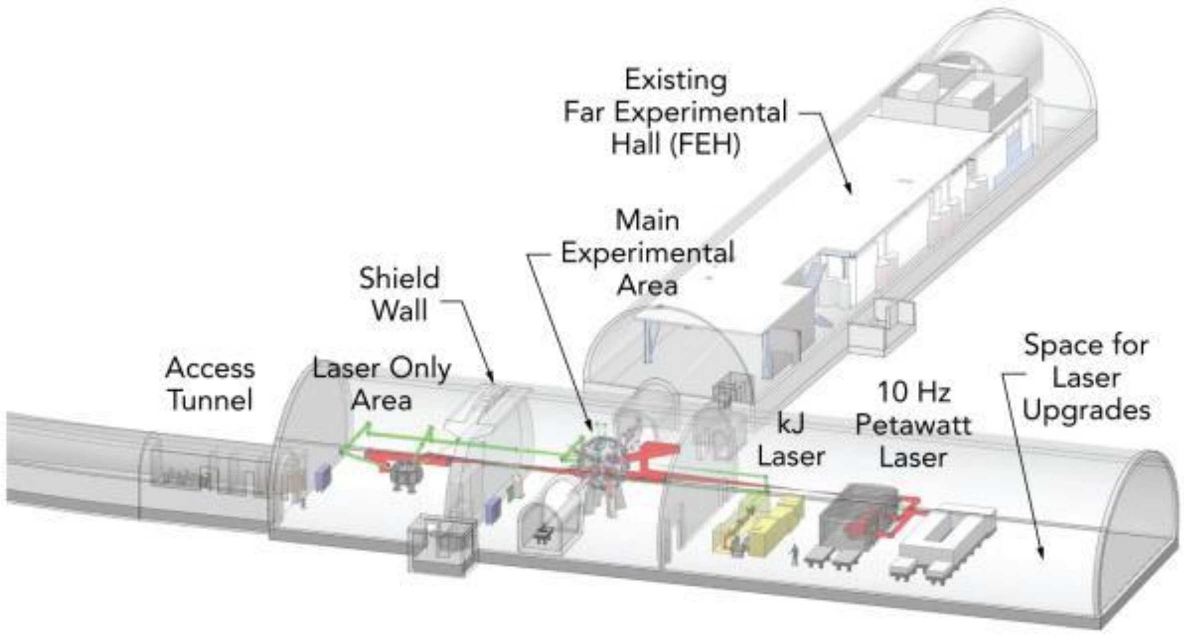


M. G. Gorman et al., Shock compression experiments using the DiPOLE 100-X laser on the high energy density instrument at the **European x-ray free electron laser**: Quantitative structural analysis of liquid Sn. *J. Appl. Phys.* 28 April 2024; 135 (16): 5902. https://doi.org/10.1063/5.0201702

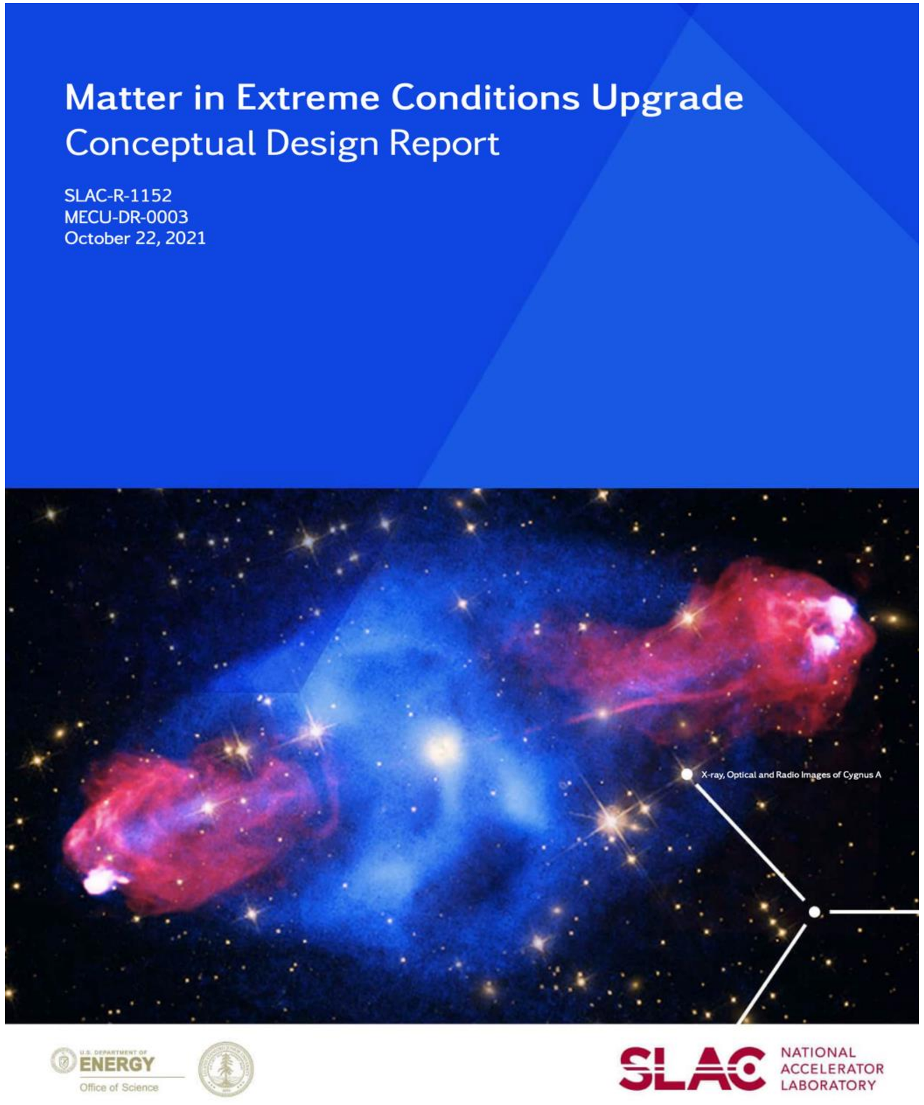
A new paradigm to study Extreme Matter States and HED/ICF relevant

Funded by the European Union

MEC Upgrade (MEC-U) @ LCLS



"The capabilities and research goals of MEC-U are driven by several DOE-FES strategic goals and will provide a world-leading facility to attract and retain a new generation of plasma and fusion science leaders."

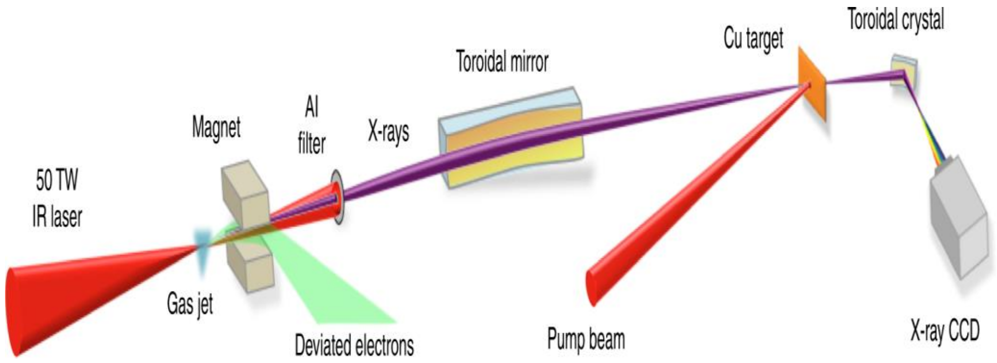


https://www.osti.gov/servlets/purl/1866100

First stage: probing HED plasmas with betatron source

Betatron source can be used for

- X-ray absorption spectroscopy
- X-ray phase contrast imaging
- Investigate ionization dynamics
- Map density fluctuations
- ….



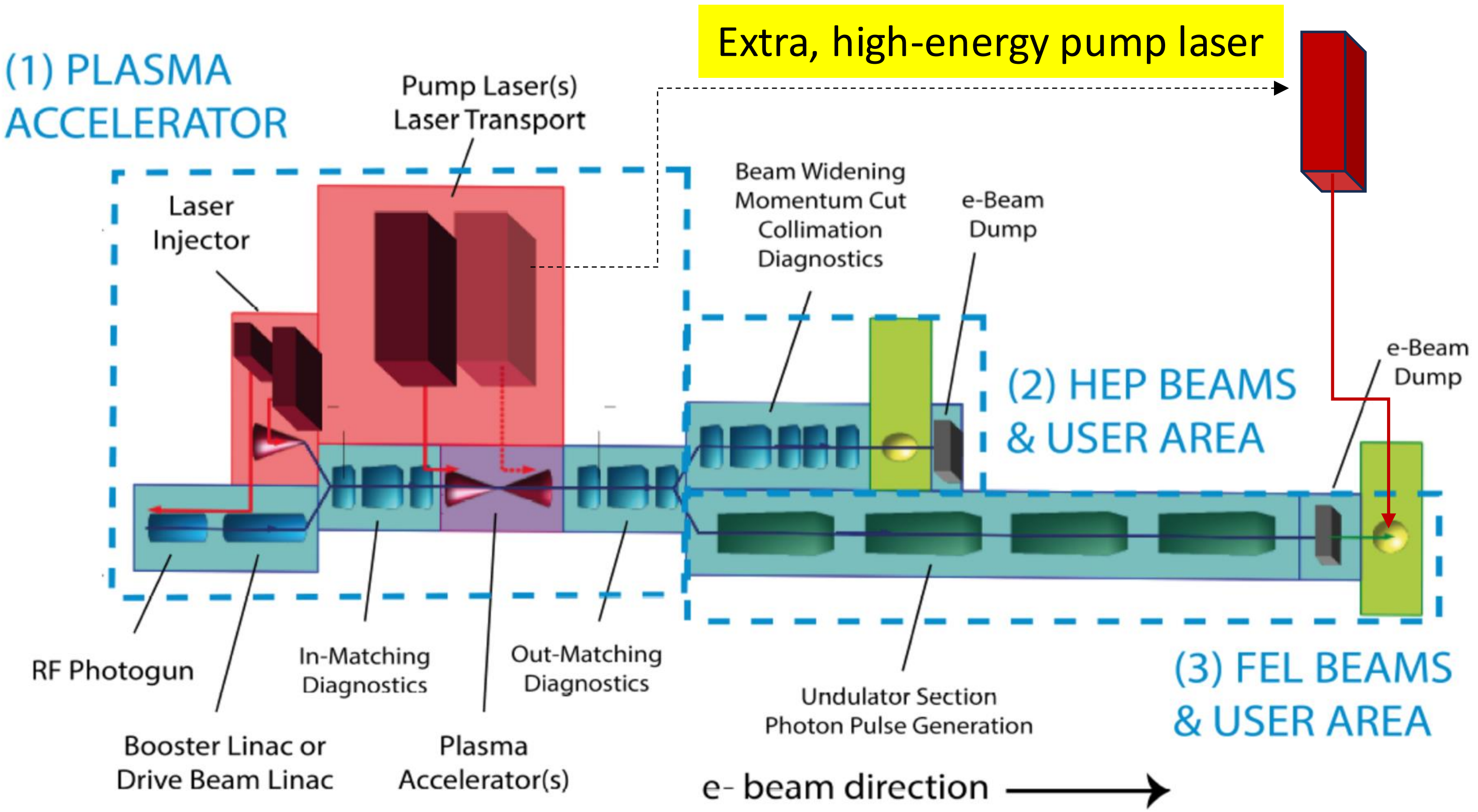
Mahieu, B., Jourdain, N., Ta Phuoc, K. *et al.* Probing warm dense matter using femtosecond X-ray absorption spectroscopy with a laser-produced betatron source. *Nat Commun* **9**, 3276 (2018). https://doi.org/10.1038/s41467-018-05791-4

Accessible with moderate beam parameters, but boosted by high repetition rate
Pump beam available from unused Ti:Sa pump lasers

Funded by the European Union

Full case: X-ray FEL to probe HED and Fusion relevant plasmas

Need of a high energy laser co-located with the X-ray FEL to produce ICF-relevant plasma: specifications of a PUMP laser



Conclusions

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- Fusion energy is a strong case with major socio-economic impact and Inertial Fusion Energy is attracting increasing attention
- High Energy Density research is a main topic in the portfolio of many physics research infrastructures
- X-ray FEL sources are establishing instruments and capabilities for HED and Inertial Fusion research
- EuPRAXIA can attract the users of this community with a modest effort and enter this highly developing field.

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- EuAPS

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