LIF-relevant Research, Experiments, and Technological Development at ELI Beamlines

D. Margarone, V. Tikhonchuk, S. Weber,
L. Giuffrida, B. Rus

LIF kick-off meeting

ELI Beamlines

Dolní Břežany, Czechia

ELI Beamlines

the High-Energy Beam Pillar of the Extreme Light Infrastructure

ELI Beamlines mission profile

- Operate cutting edge, high-peak power femtosecond laser systems with high energy, high repetition-rate capability
- Explore interaction of light with matter (plasma) at ultrahigh laser intensities
- Offer secondary sources (X-rays and accelerated particles) with unique capabilities to users
- Enable pioneering research not only in plasma physics, high-field physics, nuclear fusion and laboratory astrophysics, but also in material science, biology, chemistry, medicine and other disciplines with strong multidisciplinary application potential

ELI BL Facility Status (Nov 2023)

user operations, commissioning, development

L1-E1 user operation (call1,2,3)

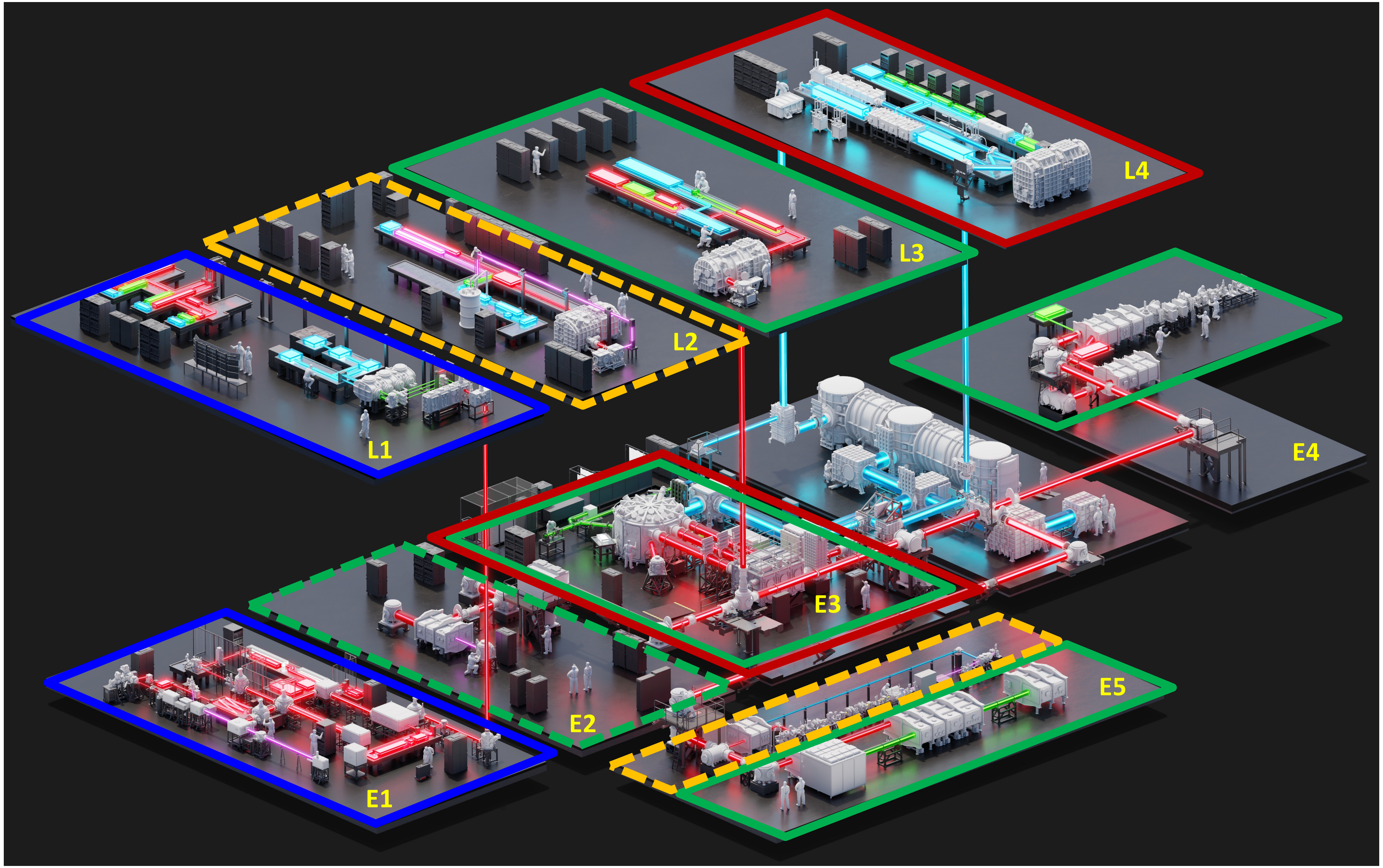
L3-P3/ELIMAIA user operation (call2)

L3-ELBA/ELIMED commissioning (call3)

L4n-P3 user operations (call2,3)

L3-Gammatron to be commissioned

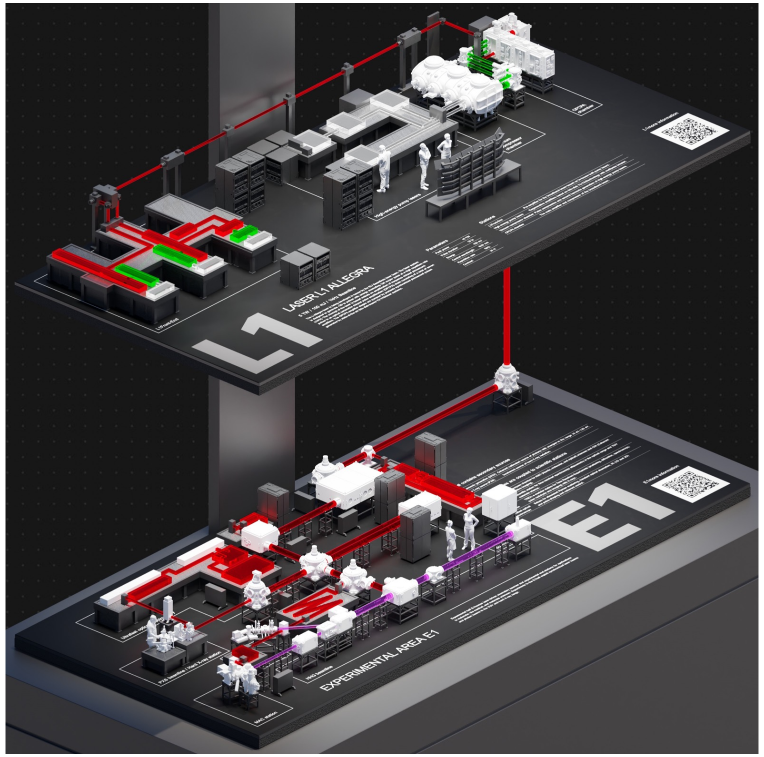
L2-LUIS R&D



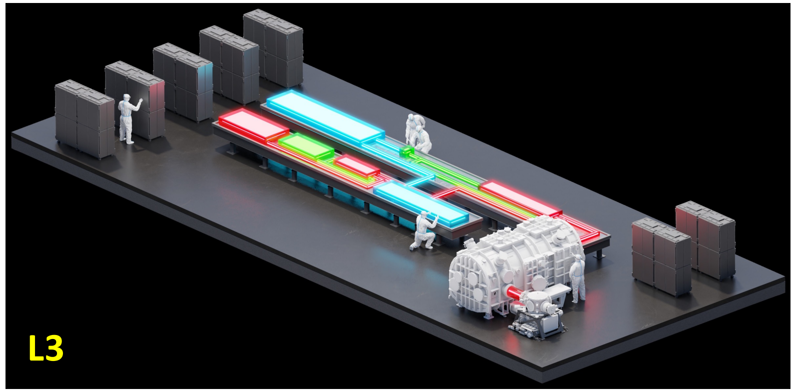
Experimental Chains Status

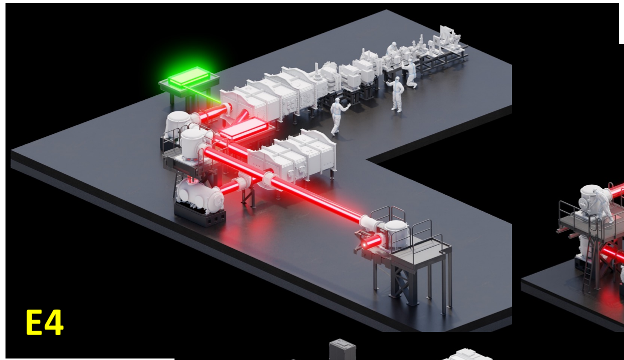
lasers – secondary sources – endstation

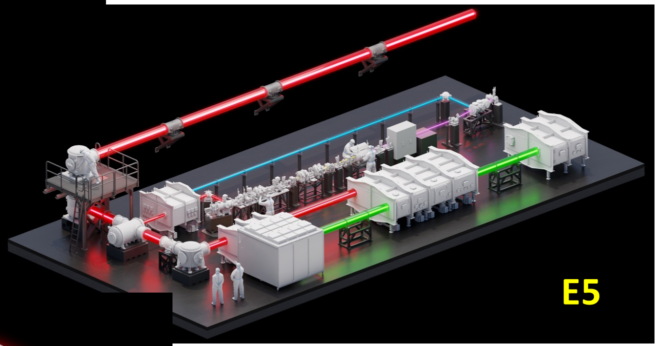
L1 – HHG (XUV) - MAC
L1 – PXS (X-rays) - TREX

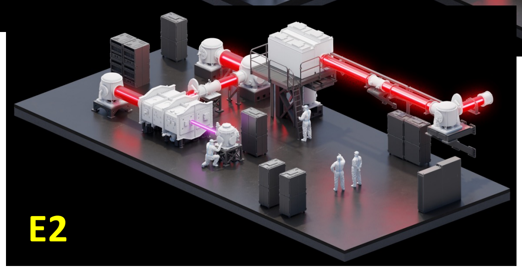


L3 – ELIMAIA (Ion Acc.) - ELIMED
L3 – ELBA/LUIS (El. Acc.)
L3 – Gammatron (hard X-rays)
L3 – P3 (pump probe)

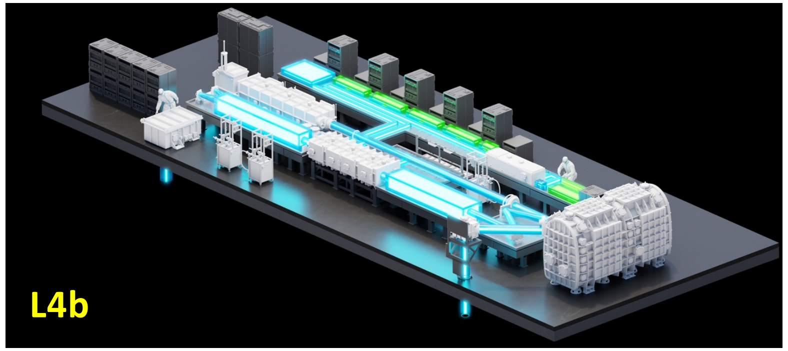


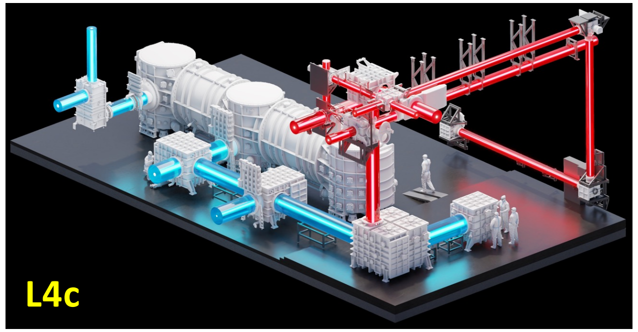


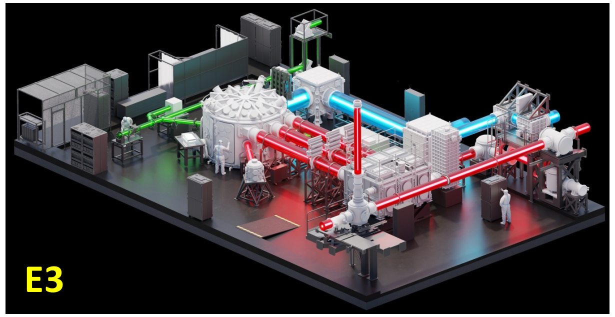




L4 – P3 (Plasma Physics Platform)







eli

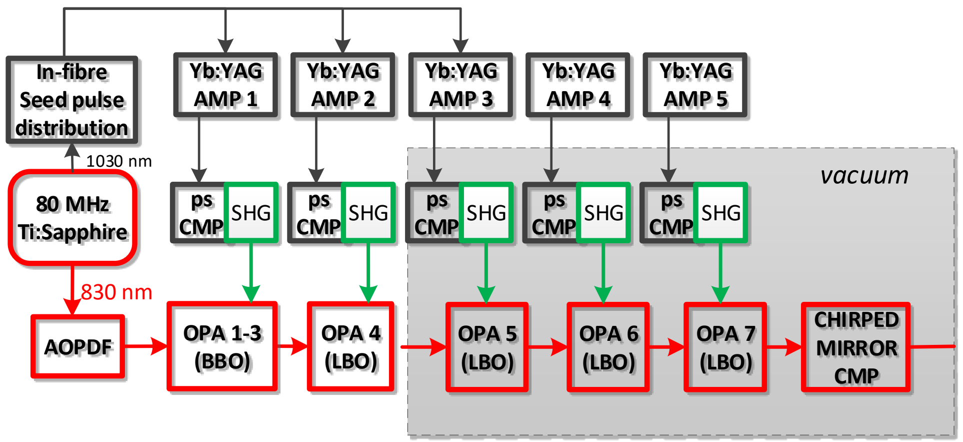
bedrich.rus@eli-beams.eu

L1-ALLEGRA & L2-DUHA Lasers

high repetition rate laser systems (0.1-1 kHz)

L1-ALLEGRA 100 mJ / 12 fs /1 kHz repetition laser system

(in operation)



Thin disk Yb:YAG (diode-pumped) pump lasers, ps OPCPA for short pulse generation

7 OPCPA stages, 3 final stages in vacuum, compression by chirped mirrors

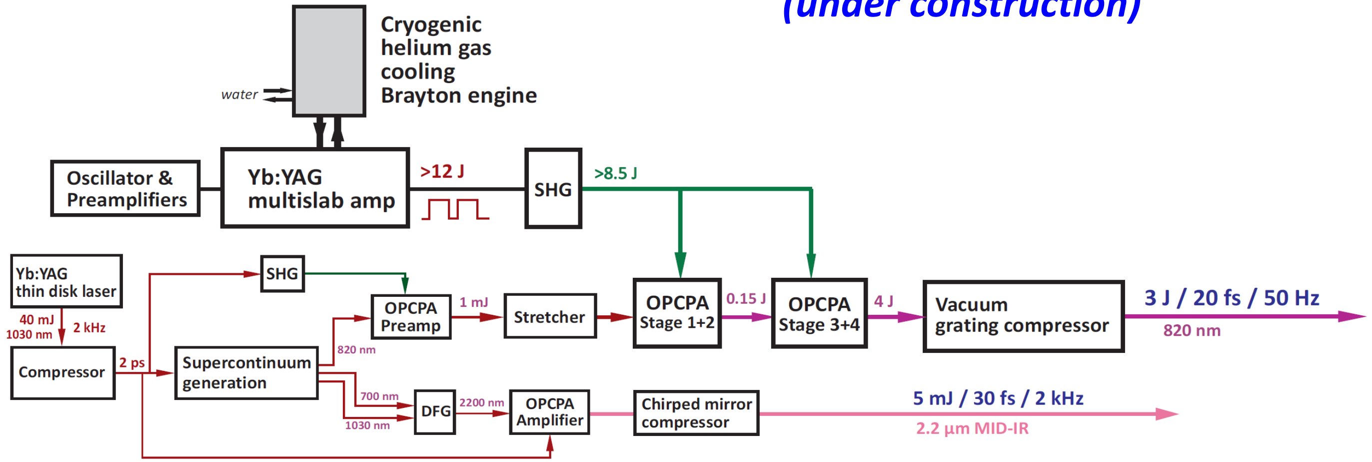
Routine operation for experiments at 30/50 mJ

100 mJ under development (multipass thin-disk pump)

Auxiliary 15 mJ /12 fs beam in commissioning, availability summer 2024

L2-DUHA 3 J / 20 fs / 50 to 100 Hz 100 TW system

(under construction)



3 J / 20 fs output pulses based on ns OPCPA

Cryogenic He-cooled (diode-pumped) Yb:YAG laser (rebuilt head originally supplied by RAL)

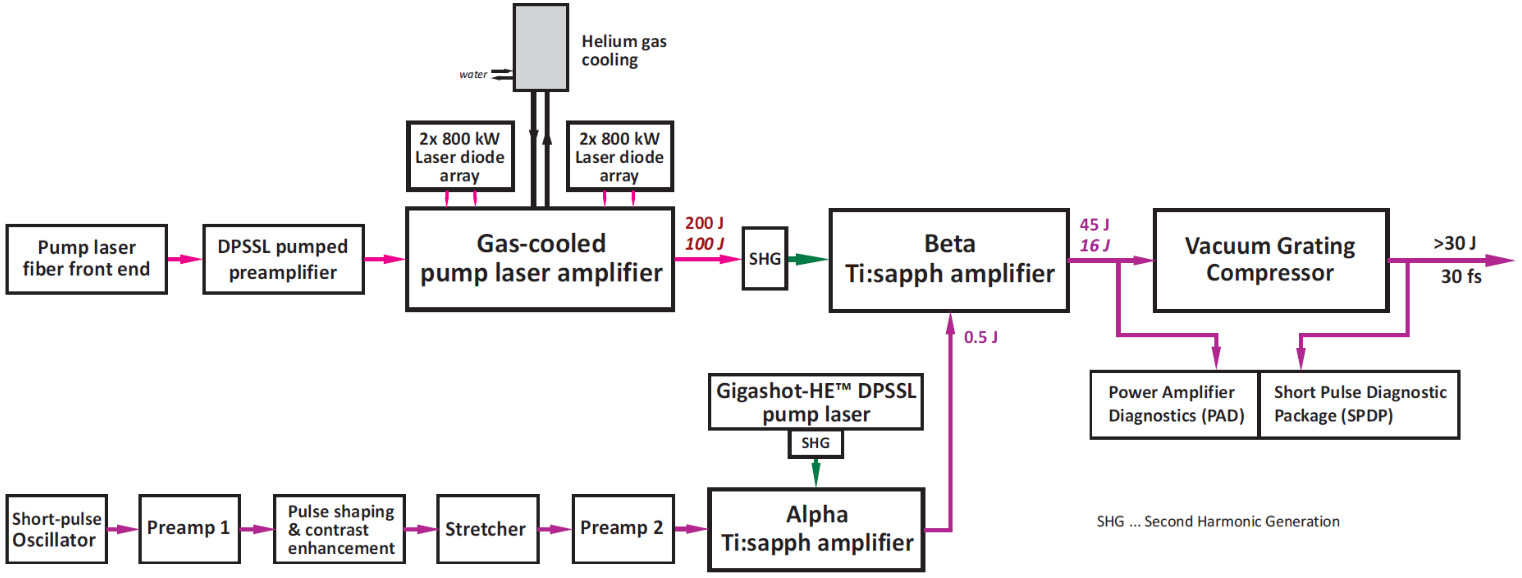
Laser diodes now for 50 Hz, additional diode stacks needed for upgrade to 100 Hz

Cryogenic cooling system built for 100 Hz rep rate (cooling capacity 2 kW)

Expected availability for experiments: end 2024

L3-HAPLS 1PW/10Hz Laser

high-peak, high-average power laser system (currently 0.5PW/3.3Hz)



Designed for >30 J / <30 fs output pulses

Helium-cooled (diode-pumped) Nd:glass pump laser

World's highest peak power laser diode arrays (4x 800 kW)

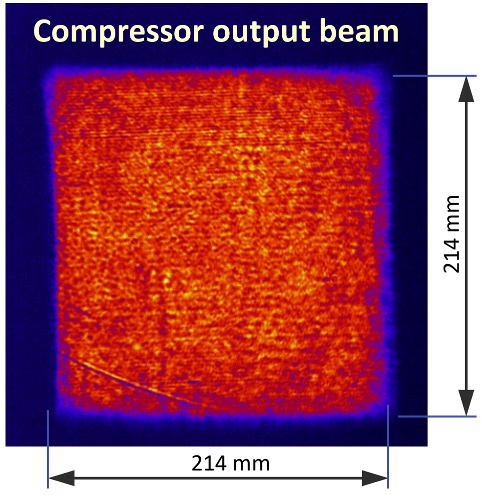
Ti:sapphire short-pulse chain, He-cooled power amplifier

Currently 13.3 J / 0.5 PW / 3⅓ Hz

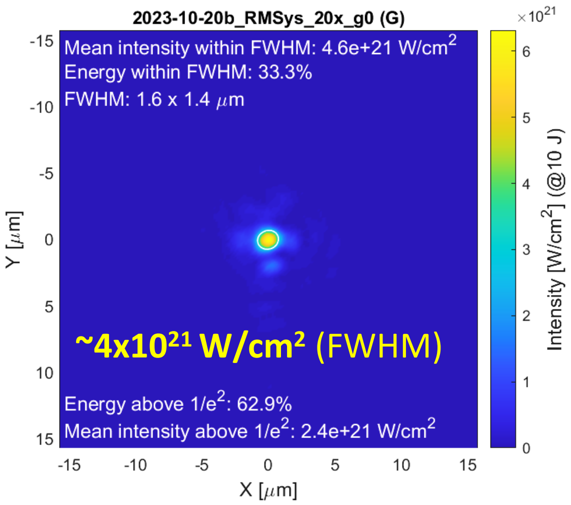
Temporal contrast >1:10^{10}

Now routine operation for user experiments at up to 10J, typically >7h beam time delivered daily

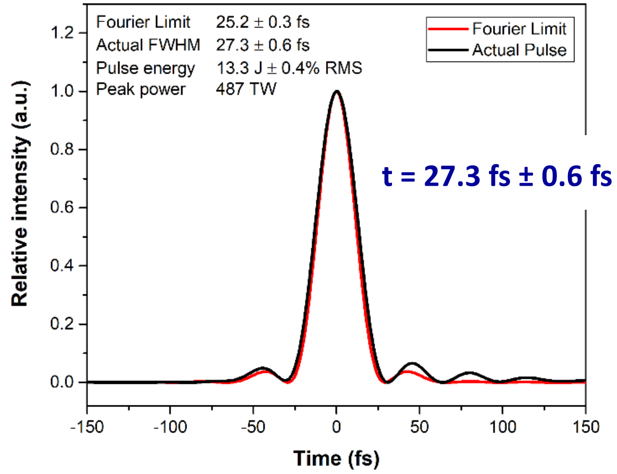
Ramping to full design parameters (PW) in progress



Focal spot with short *f#1.5* OAP



Pulse duration

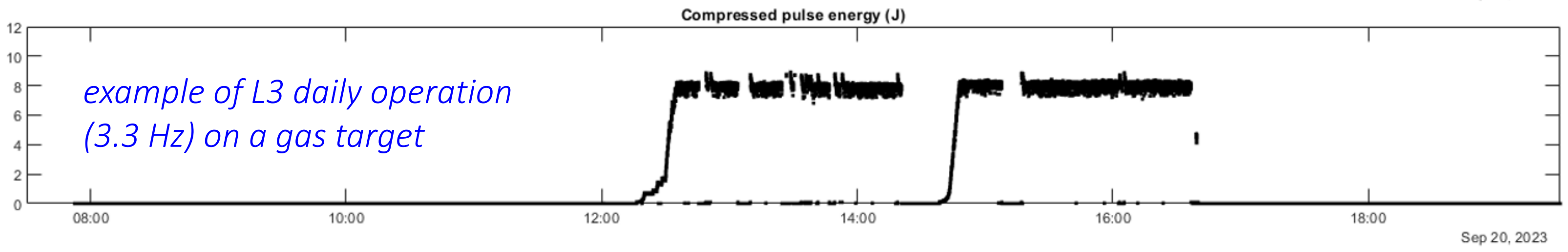


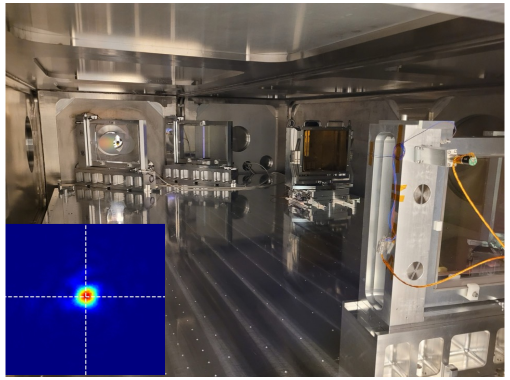
L3 for high rep. secondary sources

the ELBA Electron Accelerator

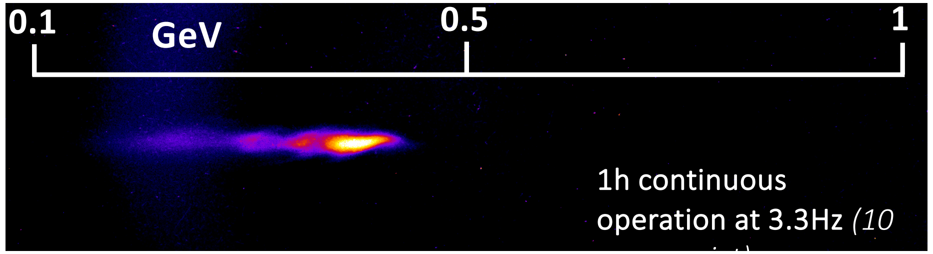
"Stable acceleration of high-quality GeV-scale electron beams at a high repetition rate", G. Sarri (QUB, UK)

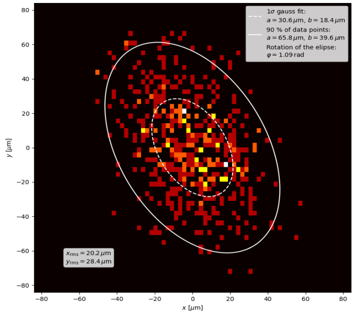
ELBA user-assisted commissioning results





- ✓ 3.3 Hz operation
- ✓ ~20k consecutive shots on target
- ✓ ~2 hours net time

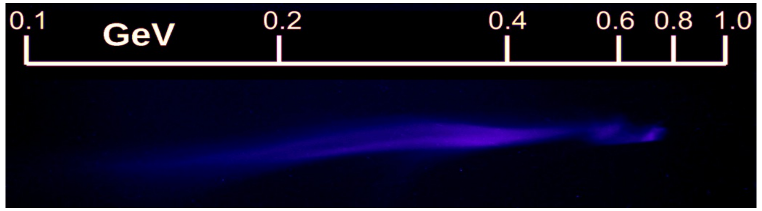




e⁻ pointing (~1mrad)

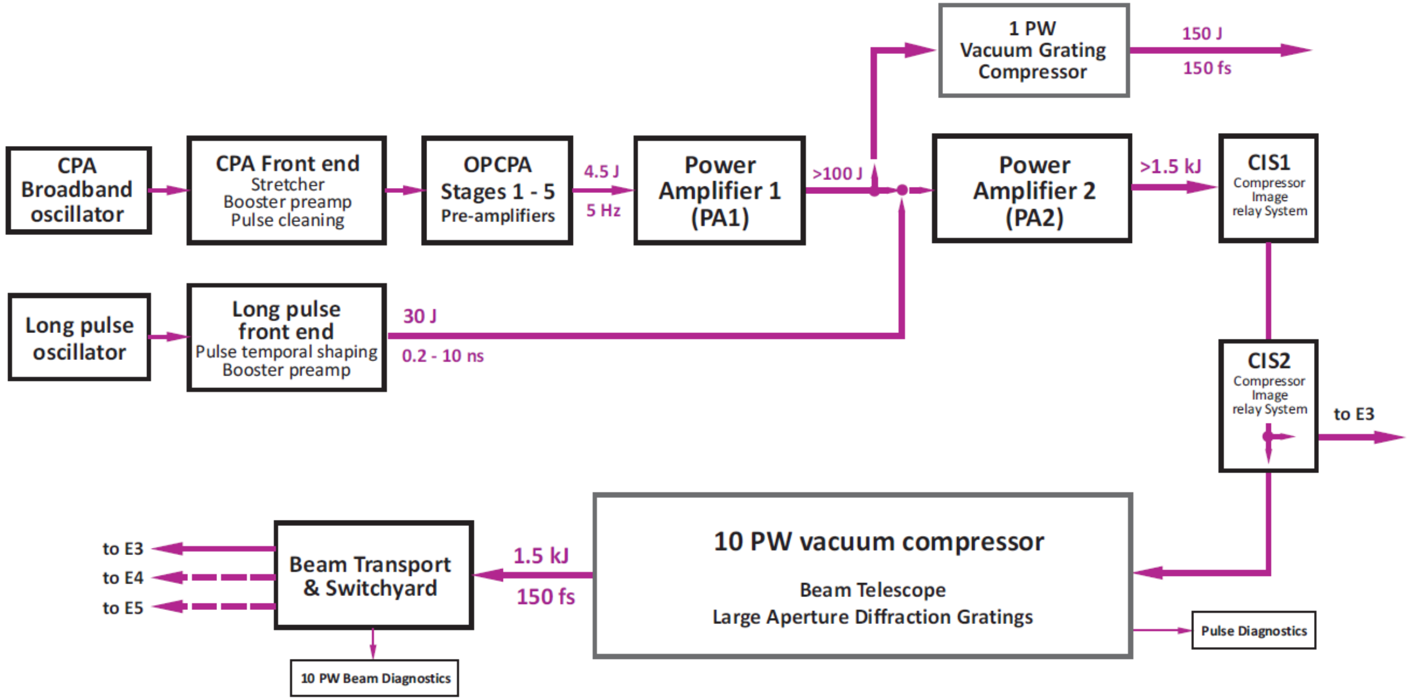
0.2 Hz operation *(stable and high quality, 20mm gas-jet)*

3.3 Hz burst operation *(10 shots due to gas load, 20mm gas-jet)*



L4-ATON 10PW/10Hz Laser

high-energy, 10PW laser with shapeable long-pulse capability (1.5kJ/150fs or ns)



Mixed Nd:glass in the power amplifiers providing spectral bandwidth >15 nm

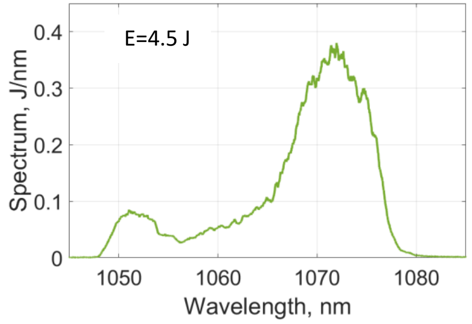
Most energetic 10 PW laser ever built

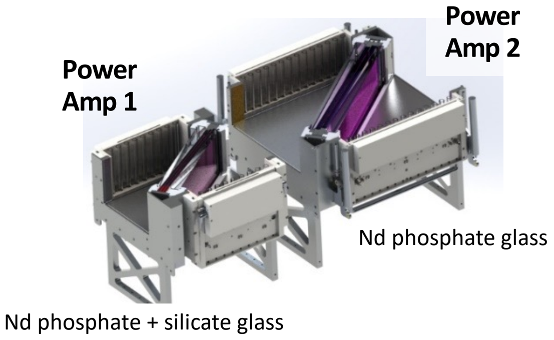
Advanced liquid cooling to achieve 1 shot /1 minute

Generation of ns kJ pulses with programmable temporal shape (in 125-ps steps) by the Long Pulse Front End (LPFE)

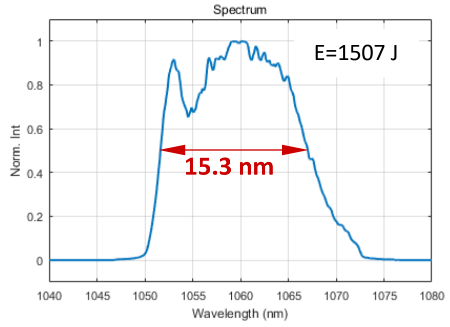
Compact dimensions, laser tables footprint 19.8 m x 6.1 m

Pre-amps OPCPA output spectrum





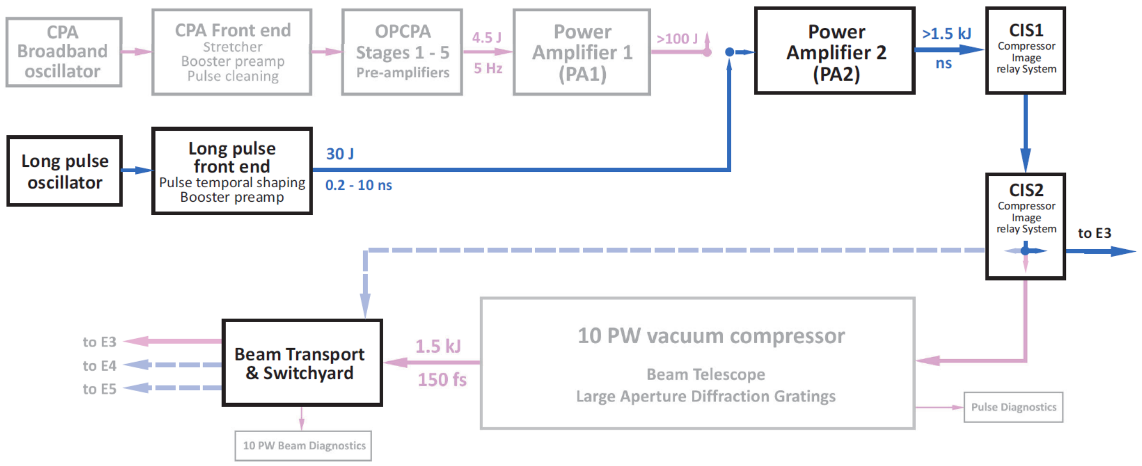
CPA PA2 output spectrum



L4-ATON Status

preparation of long-pulse regime (L4n) & commissioning of 10PW (L4f) compressor

Long Pulse operation for users: custom pulse shapes

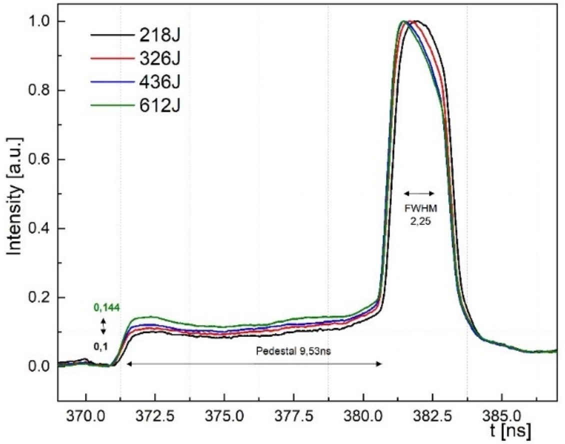


Parameters currently available for experiments:

- Pulse lengths 2 to 10 ns, shapeable
- 700 J with current KDP 2ω converter (250 mm), eq. to 1.5 kJ in full beam; Full-aperture KDP in late 2024
- Pulse energy stability 1%
- 1 shot / 2 min
- Beam intensity spatial profile modulation (P-V) below +/-15%
- Bandwidth in LP regime ~0.5 nm
- Bandwidth in CPA regime ~14 nm (before the KDP converter)

Example of a custom-shaped temporal profile, delivered to E3

Main pulse 2.25 ns FWHM (70% of pulse energy) preceded by ~10 ns pedestal (30% of energy)



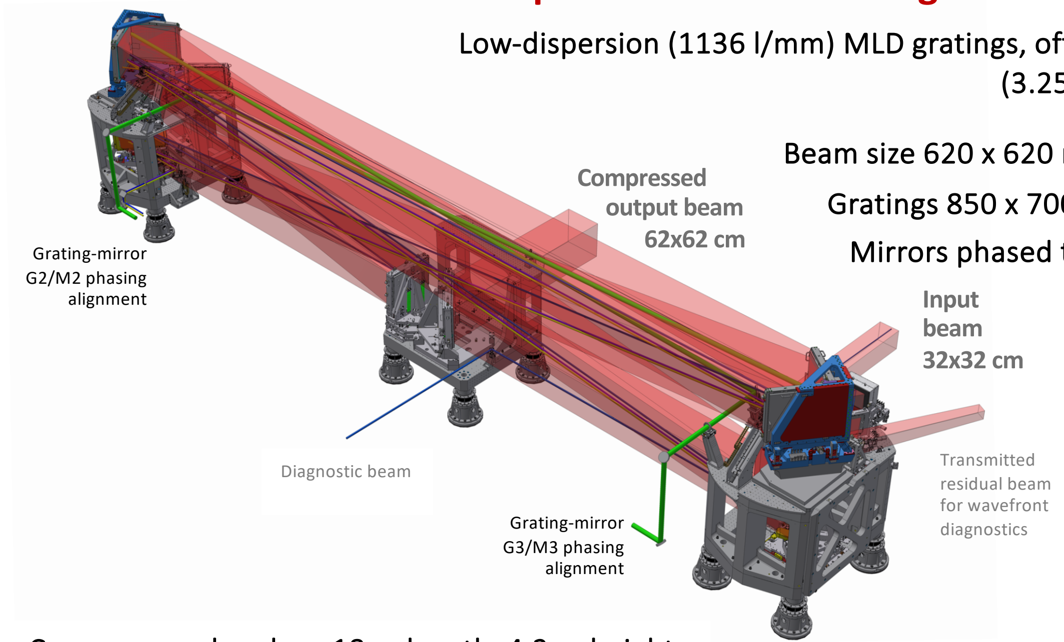
10PW compressor commissioning

Low-dispersion (1136 l/mm) MLD gratings, off plane-of-incidence (3.25°) Littrow geometry

Beam size 620 x 620 mm, fluence 0.4 J/cm^2

Gratings 850 x 700 mm made by LLNL

Mirrors phased to gratings G2 and G3



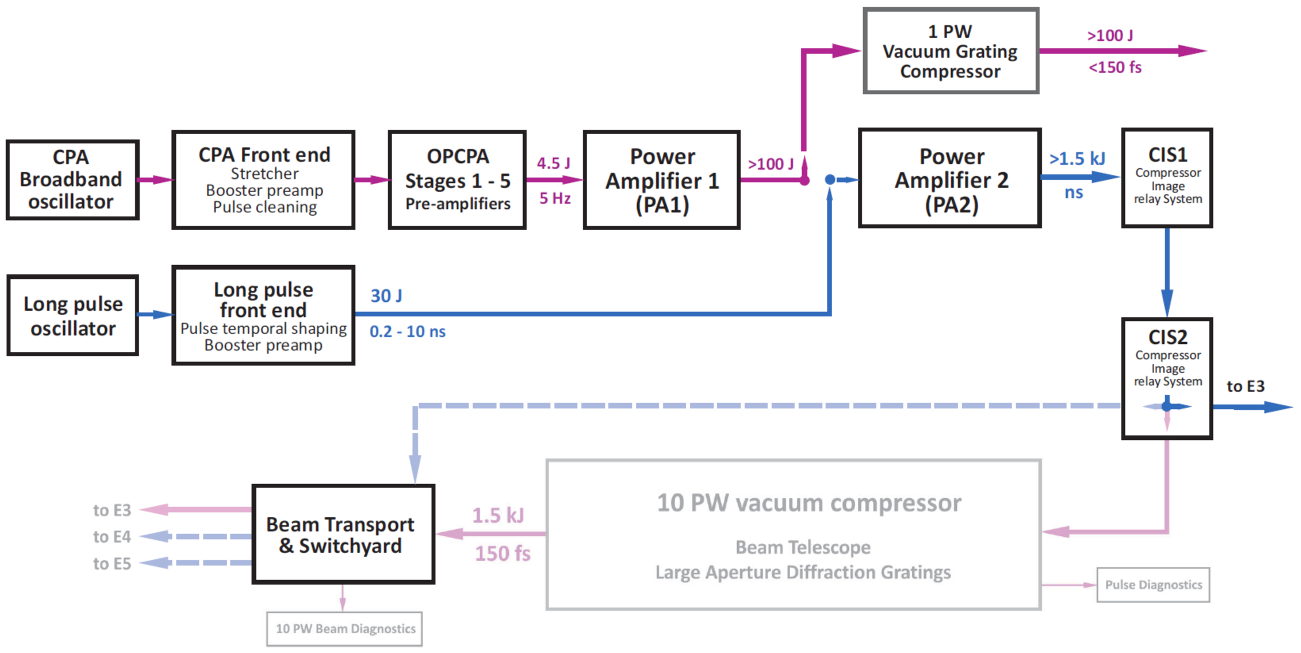
Compressor chamber: 18 m length, 4.2 m height

- First light from full compressor, demonstrating 200 J/ 150 fs — Aug - Sept 2024
- Demonstration of 5 PW (800 J / 150 fs) — Oct 2024
- Demonstration of 10 PW (1500 J / 150 fs) — Jan 2025

L4P (1PW, 150J/150fs) aux. beam

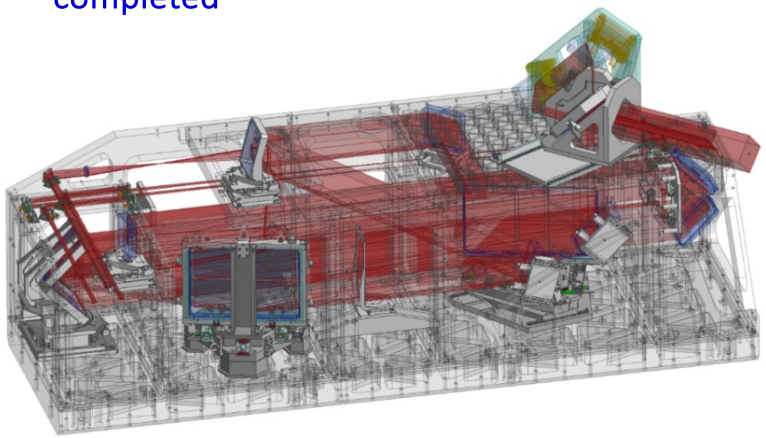
compression of the CPA output of Power Amplifier 1

Prospect for using the full potential of the L4 laser: two temporally synchronized outputs (1.5 kJ long pulse + 150 J/ 150 fs PW pulse)



- Double-pass grating compressor
- MLD gratings 1740 l/mm, size 750 x 530 mm and 910 x 530 mm
- Output beam size Clear Aperture 200x200 mm, 170x170 mm FWHM
- Temporal contrast expected high >1:10^{11} due to OPCPA front end

Compressor chamber and its full internal optomechanical structure completed



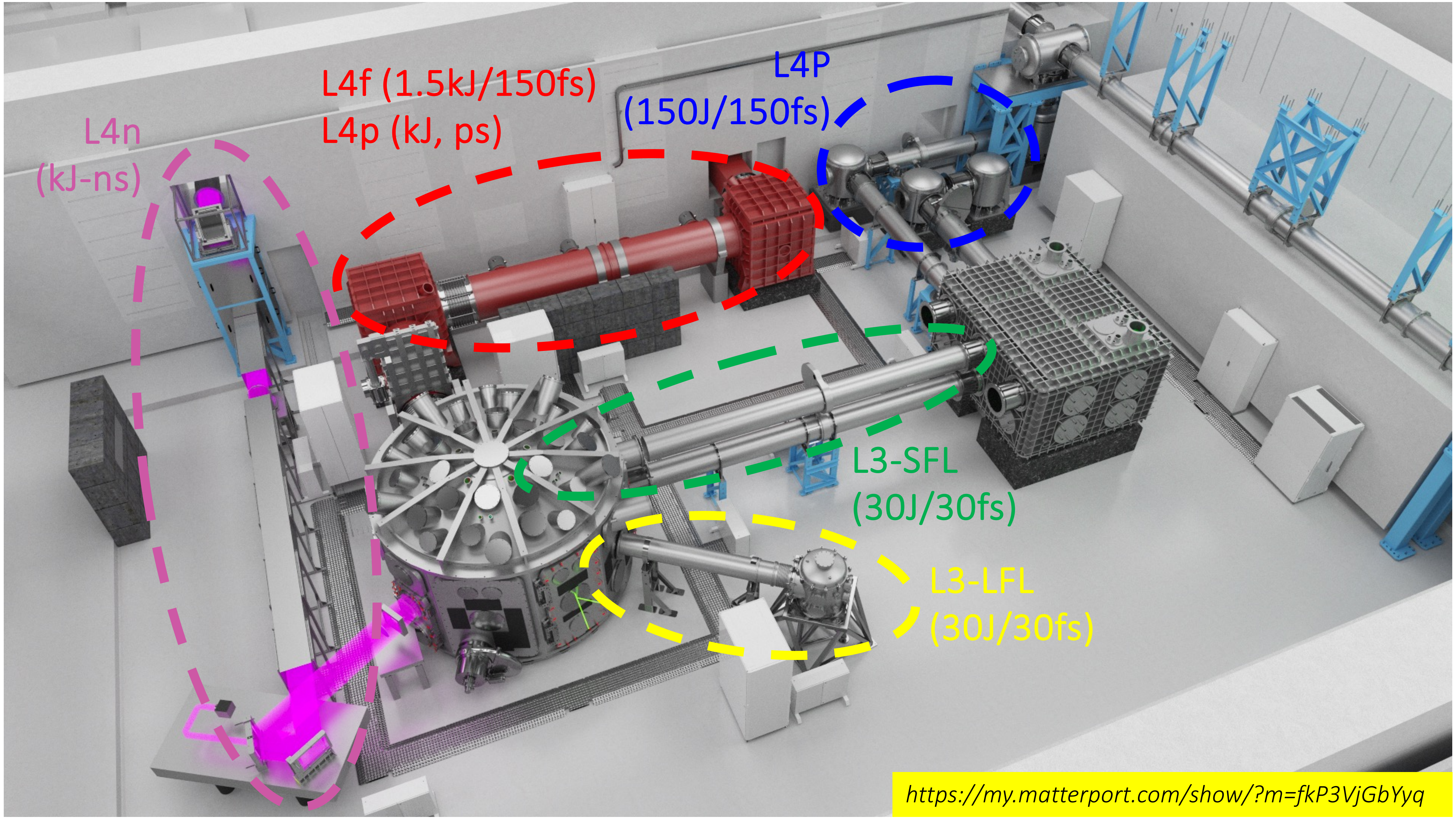
Remaining components and subsystems to be implemented:

- Imprint of the gratings
- Compressor mirrors
- Additional stretcher 1740 l/mm
- L4PW beam delivery to experimental halls E3 and E4

Expected implementation in 2025-2026, funding sought

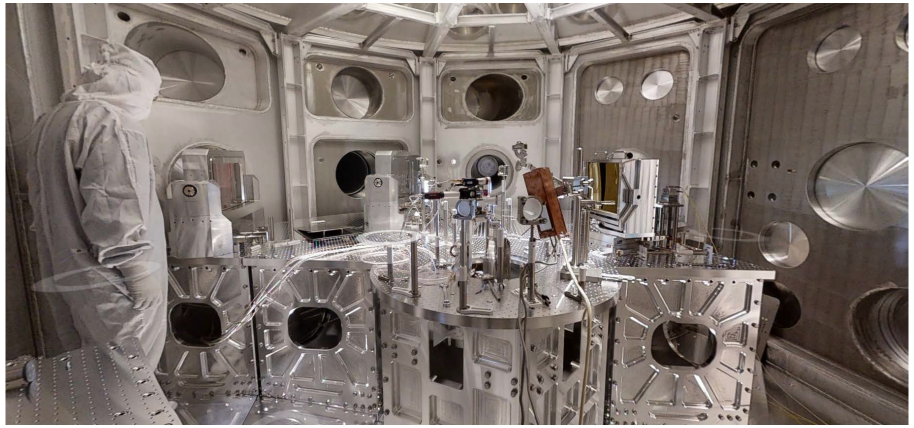
E3 Experimental Hall

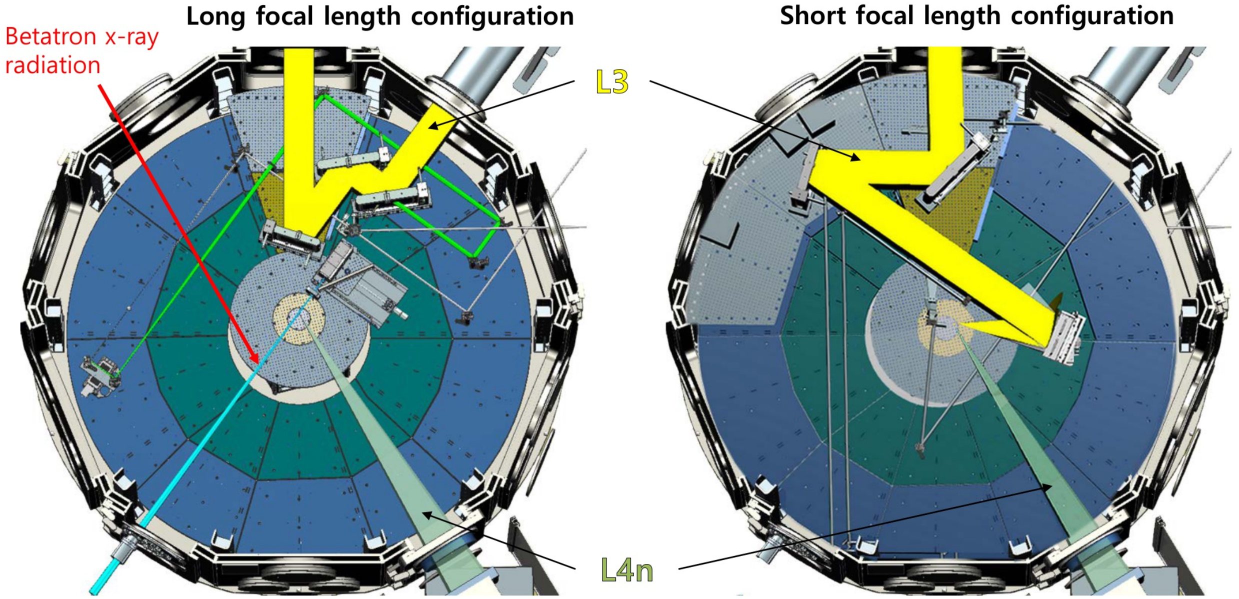
multi-beam availability (1-10PW & kJ-ns)



P3: Plasma Physics Platform

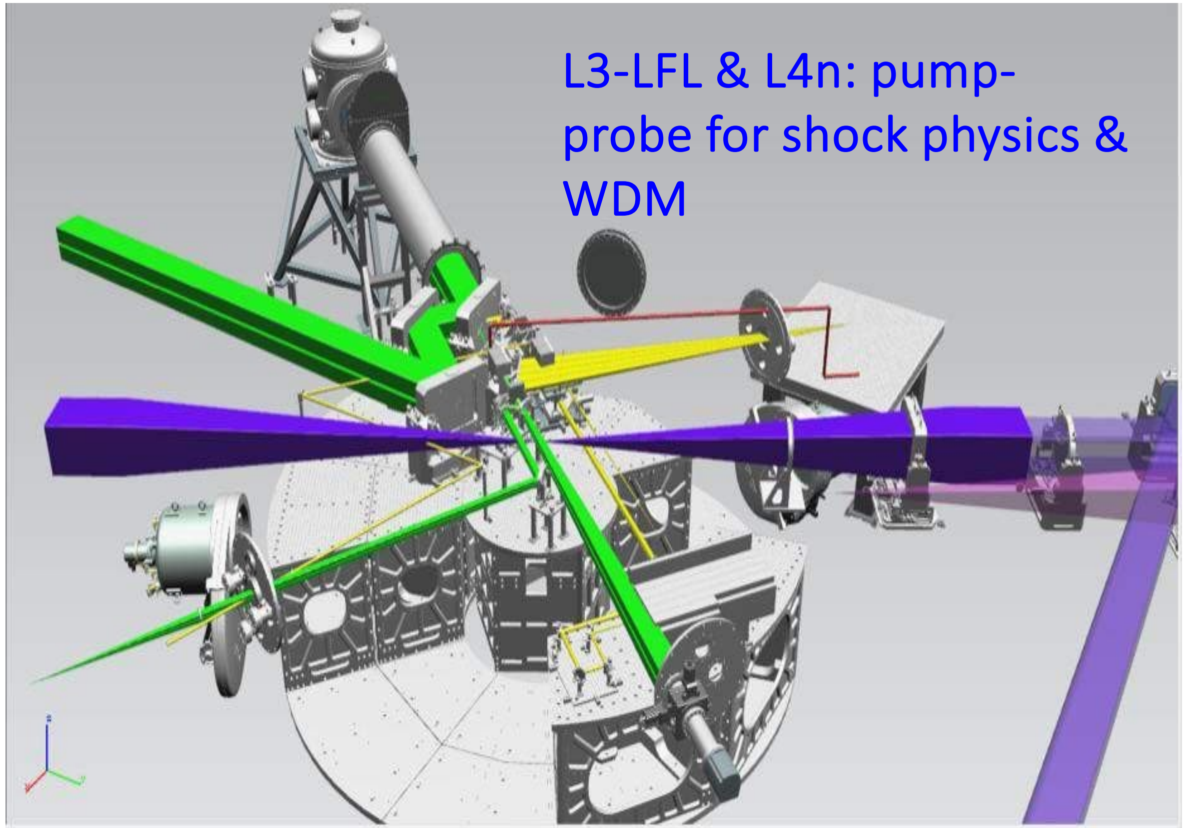
experimental setups - stefan.weber@eli-beams.eu





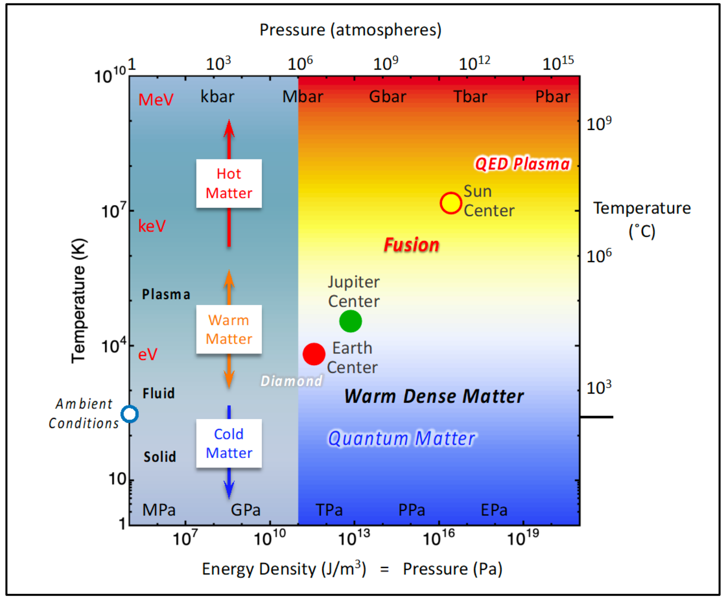
Angle L4n and x-rays at TCC = 112°

Angle L4n and L3 at TCC = 58°

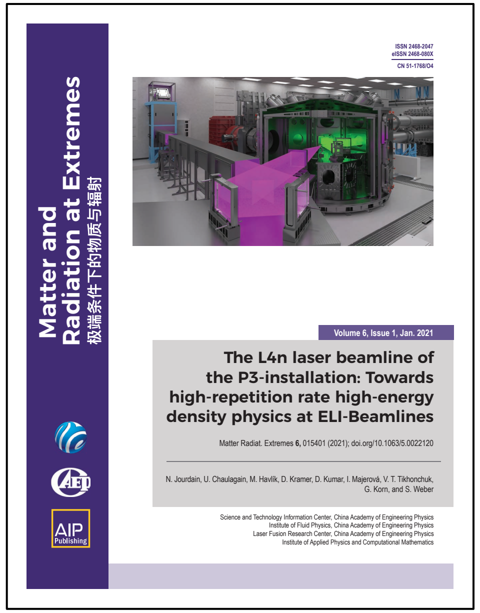


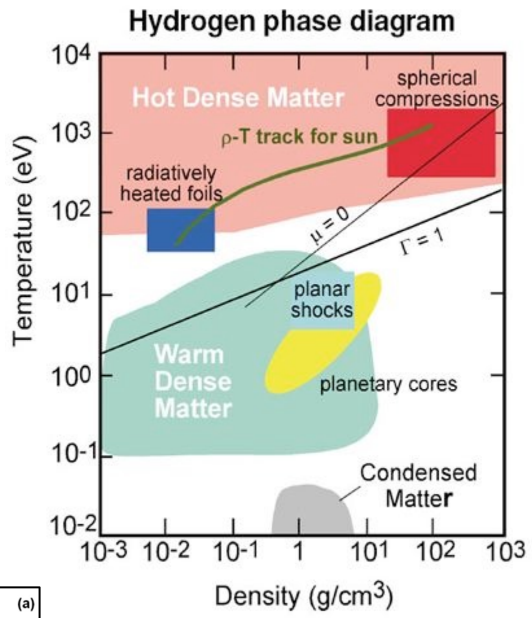
Fusion Research at P3

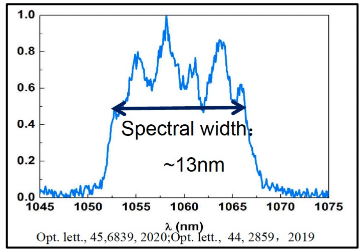
opportunities for the IFE community

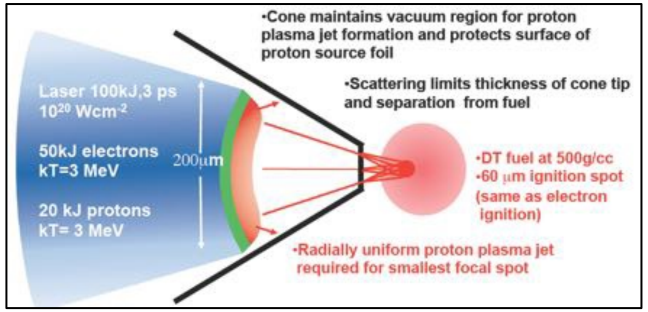


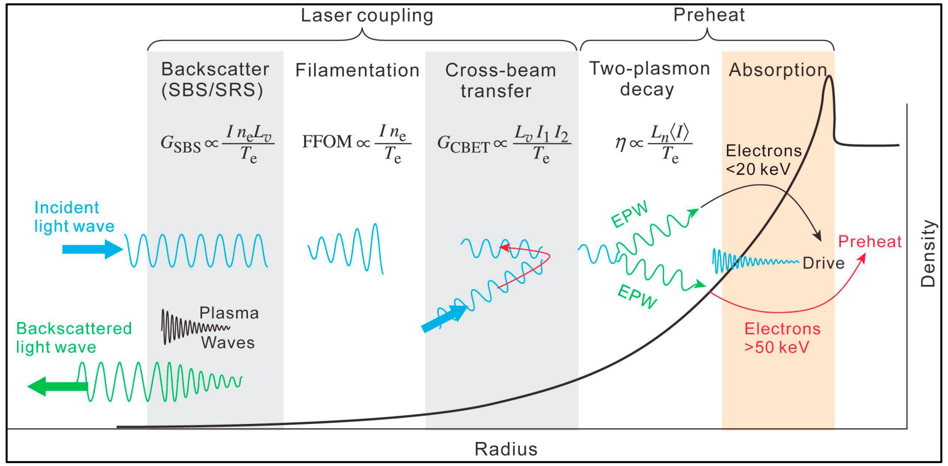
- **Physics studies**
  - LPI, transport, hot electrons, stopping power
  - Opacities, EoS (also off-Hugoniot)
  - WDM (now), HDM (a bit later)
  - Neutron-related studies (D-D or pitcher-catcher)
  - Proton-related studies
  - Magnetized laser-plasma interaction
- **Technology operation studies**
  - Secondary issues: debris, emp
  - Repetion-rate related issues
  - Targetry/diagnostics
- **Training**
- **Laser-related studies**
  - 2-omega operation (1-omega in the future)
  - Broadband operation
- Development of **dedicated simulation tools**

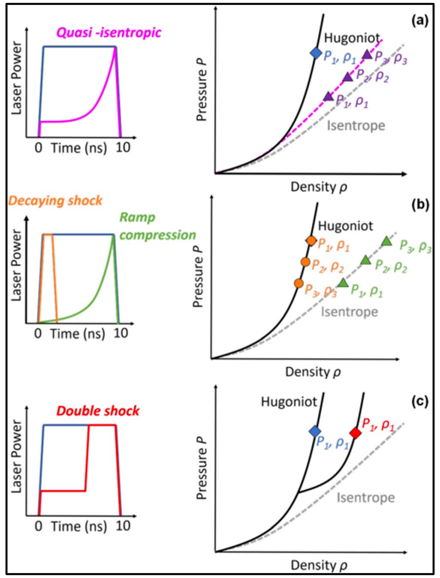


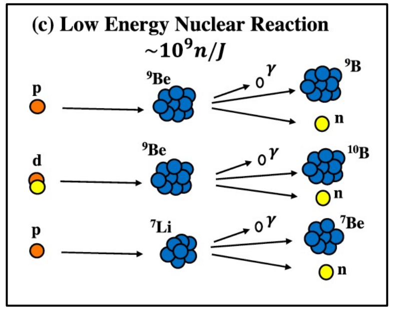






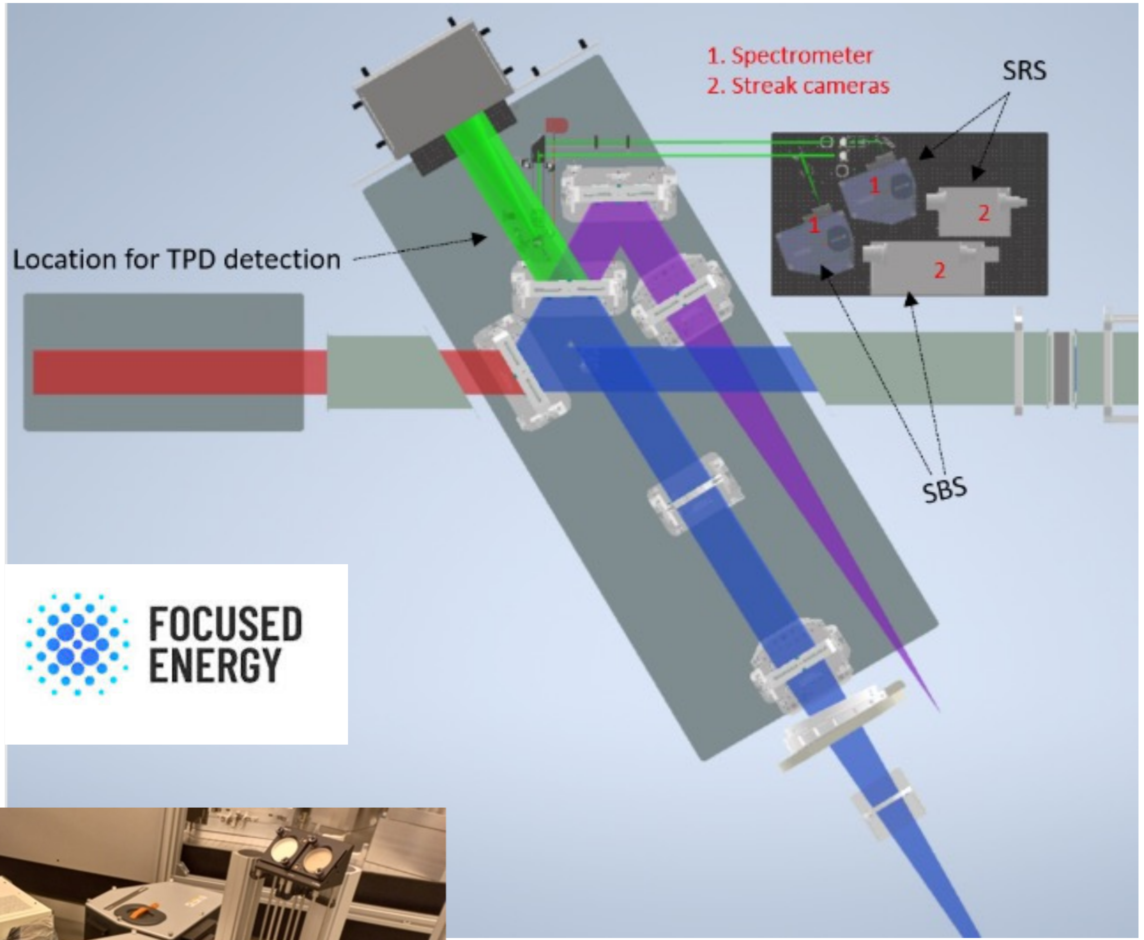




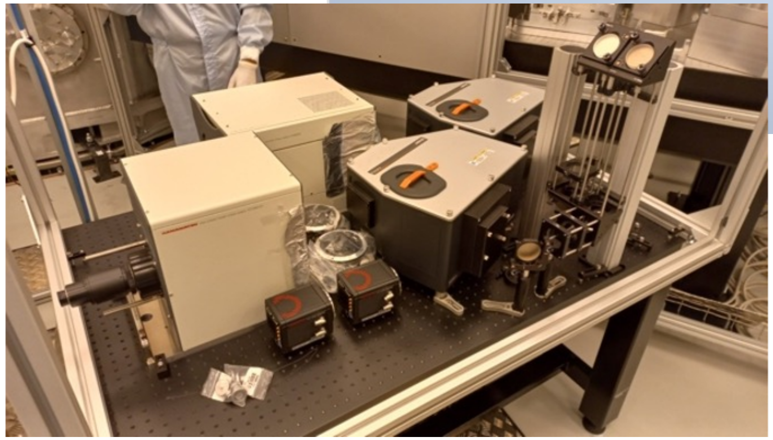


P3 LPI back-scatter diagnostics

time-resolved Raman, Brillouin, and TPD scattering



FOCUSED ENERGY



Full aperture backscatter diagnostics for characterization of laser plasma instabilities at the extreme light infrastructure (ELI) beamlines

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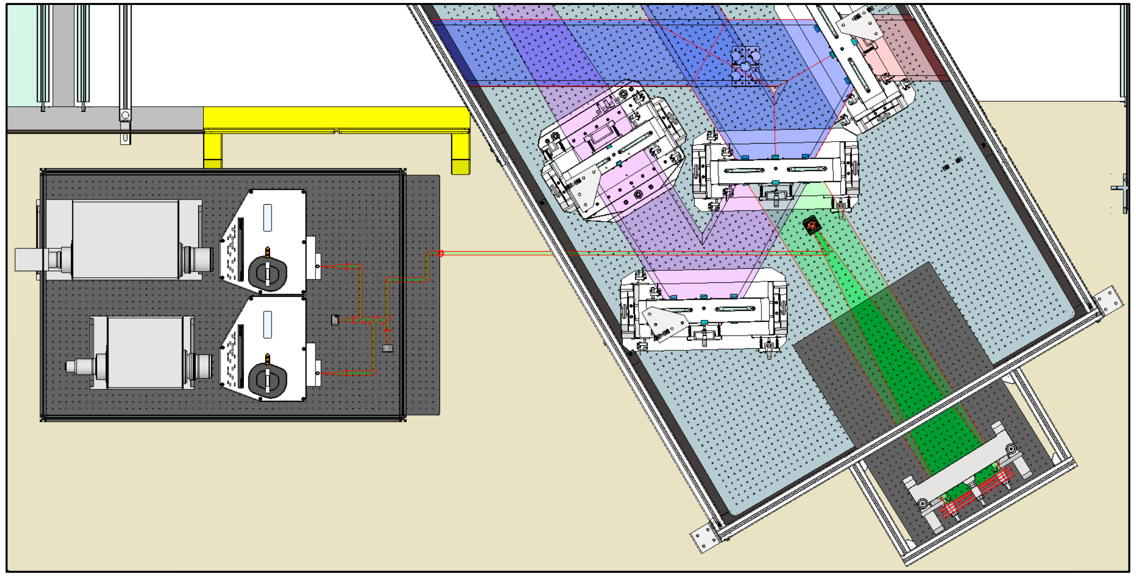
F. Wasser,[1,2,a)] Ş. Zähter,[1] M. Sokol,[1] M. Rivers,[3] S. Atzeni,[1] F. P. Condamine,[4] G. Cristoforetti,[5] G. Fauvel,[4] N. Fischer,[1] L. A. Gizzi,[5] A. Hannasch,[1] M. Hesse,[1] T. Laštovička,[4] P. Lutz,[1] P. Rubovič,[4] G. Schaumann,[1] N. Schott,[1,6] R. L. Singh,[4] W. Theobald,[1] S. Weber,[4] T. Ditmire,[3] T. Forner,[1] and M. Roth[1,6]

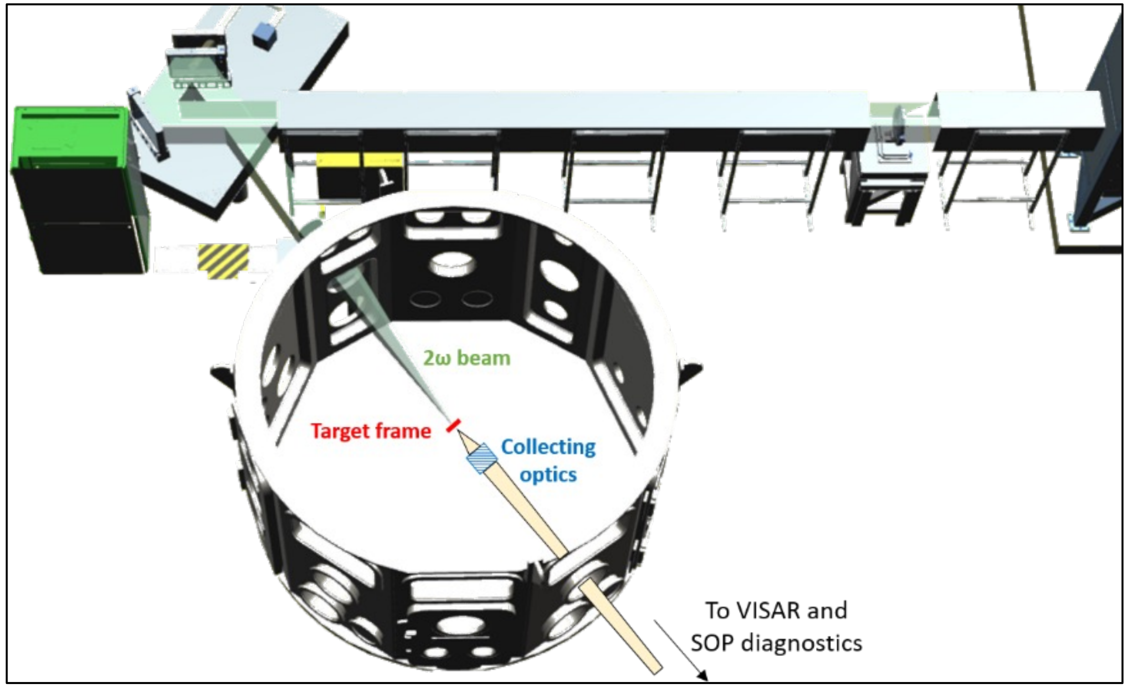
AFFILIATIONS

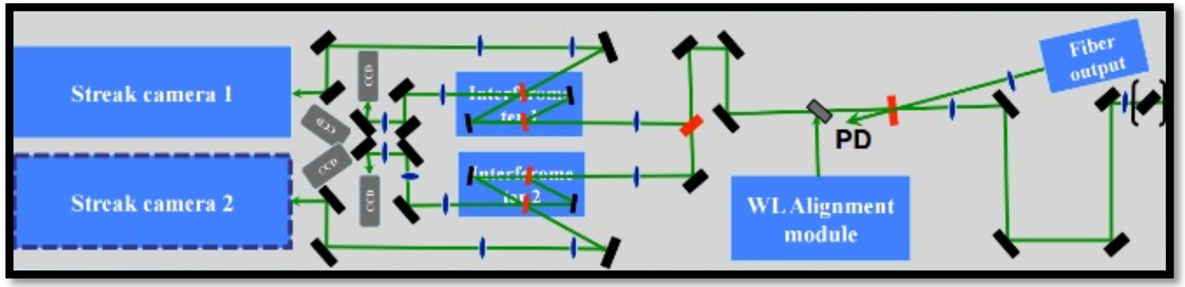
[1] Focused Energy GmbH, Im Tiefen See 45, 64293 Darmstadt, Germany
[2] IU Internationale Hochschule GmbH, Darmstädter Landstrasse 110, 60598 Frankfurt am Main, Germany
[3] University of Texas, 110 Inner Campus Dr., Austin, Texas 78712, USA
[4] Extreme Light Infrastructure ERIC, ELI-Beamlines Facility, 25241 Dolní Břežany, Czech Republic
[5] Intense Laser Irradiation Laboratory, INO-CNR, Pisa, Italy
[6] Technische Universität Darmstadt, Schlossgartenstrasse 9, 64289 Darmstadt, Germany



P3 VISAR/SOP diagnostics

EoS & shock physics (user assisted commissioning)

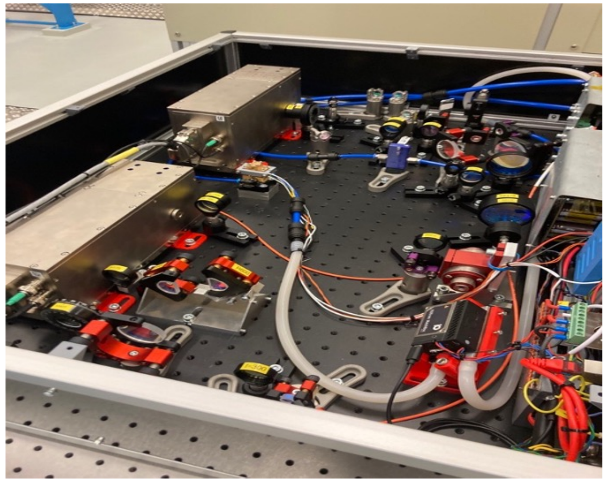




➔ 2-arm VISAR + SOP installed; commissioning in collaboration with SLAC/MEC group & Rostock University (D. Kraus) ~June 2023 *(paper in preparation)*

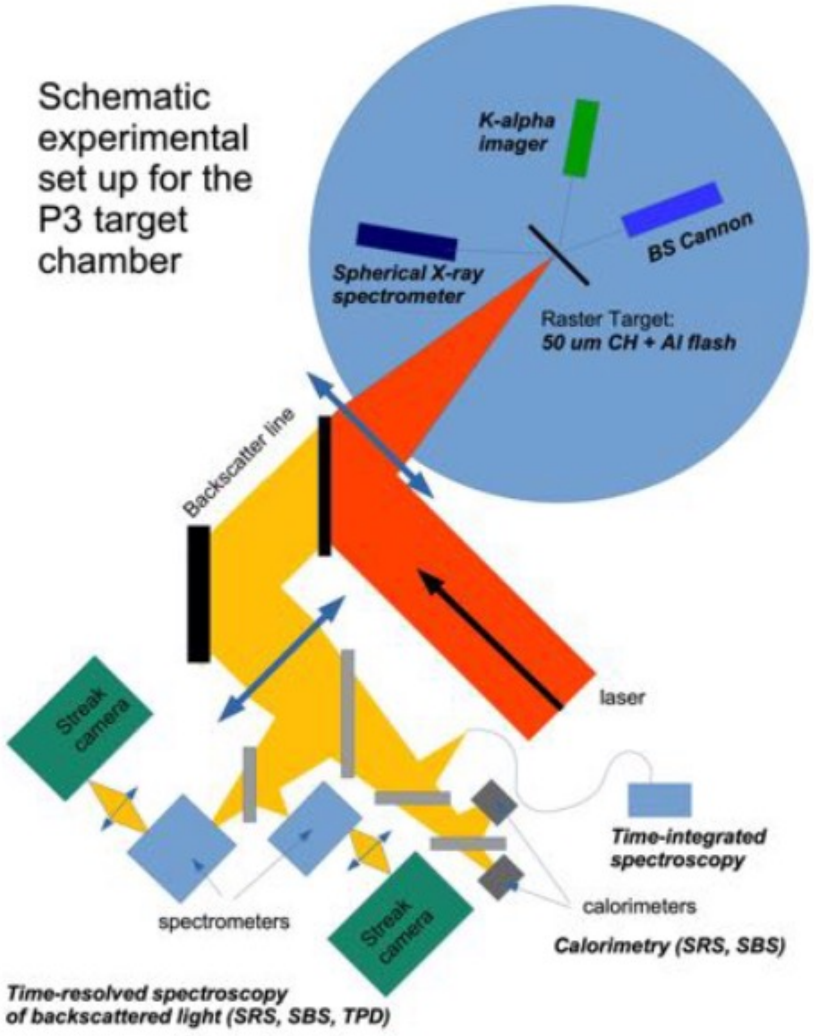
➔ VISAR laser:

- 1030/515 nm
- 50…100 ns
- Max. 10 Hz
- max. 17 mJ @ 1030 nm / max. 8 mJ @ 512 nm
- Streaks: ~ 5 ps resolution



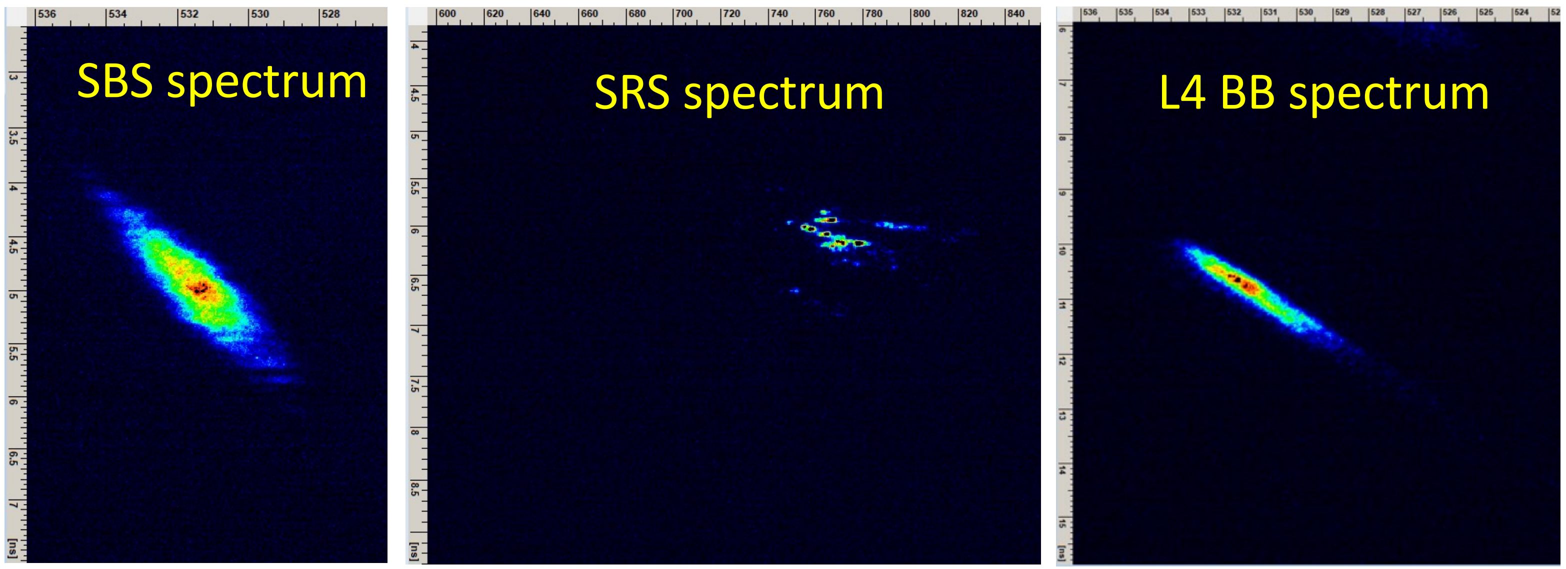
User-assisted commissioning exp. with L4n-P3

"LPI studies for ICF shock ignition, including role of bandwith" - L. Gizzi et al.



- **Broadband L4n commissioning**
- Narrow Band L4n shots with different pulse shape (Gaussian and rectangular)
- **~600 shots on target** (~500 above 500J at 1w)
- Time resolved spectroscopy of backscattered light (SRS, SBS and TPD)
- BS Cannon
- K-alpha imager
- Spherical X-ray Spectroscopy

P3-LPI user assisted commissioning results



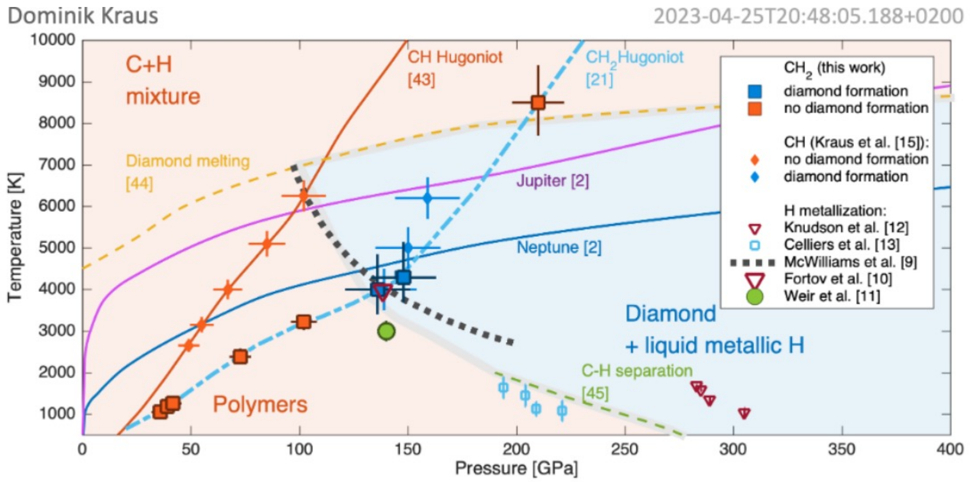
User-assisted commissioning exp. with L4n-P3

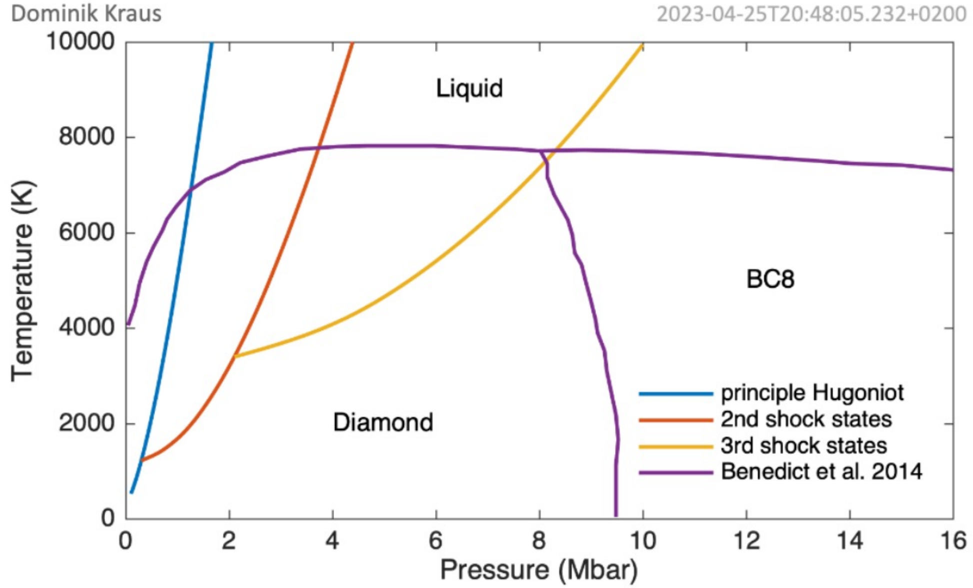
"EoS studies for planetary interiors" - D. Kraus et al.

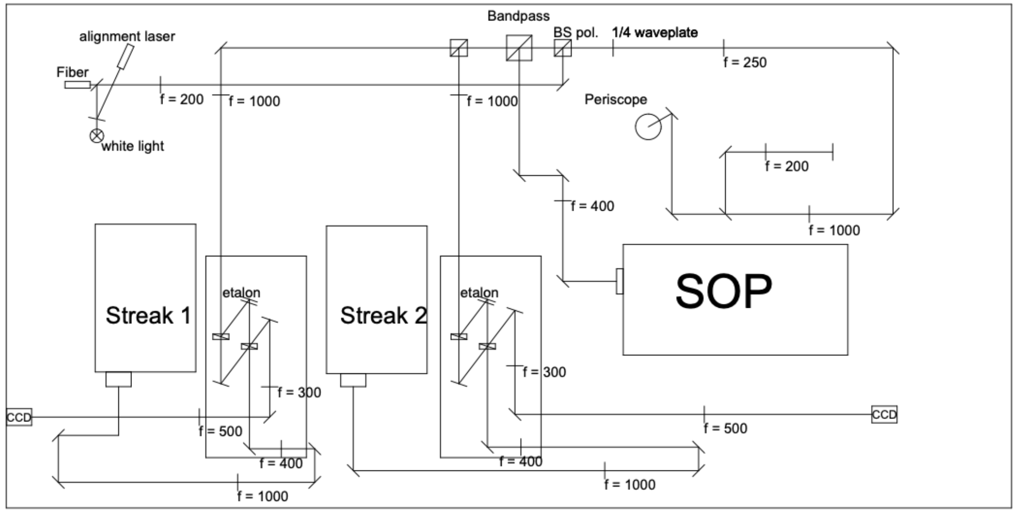
eli

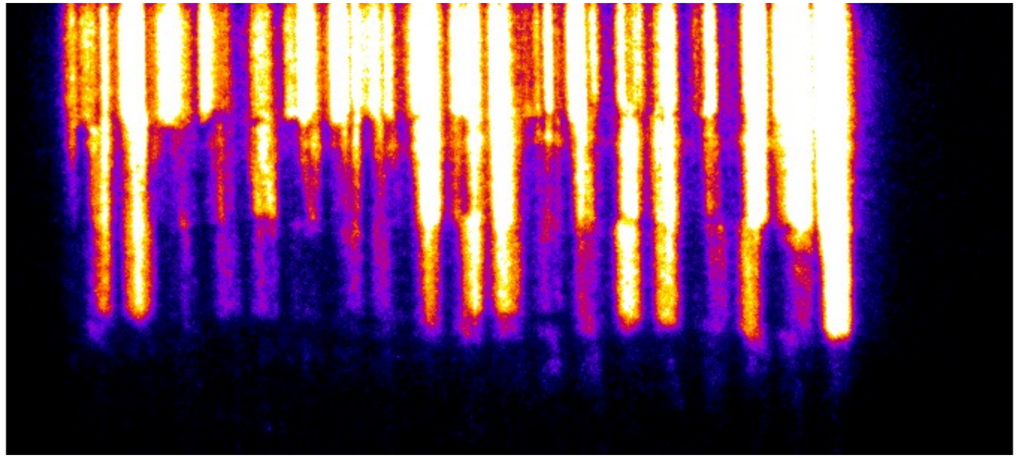
Universität Rostock

SLAC NATIONAL ACCELERATOR LABORATORY







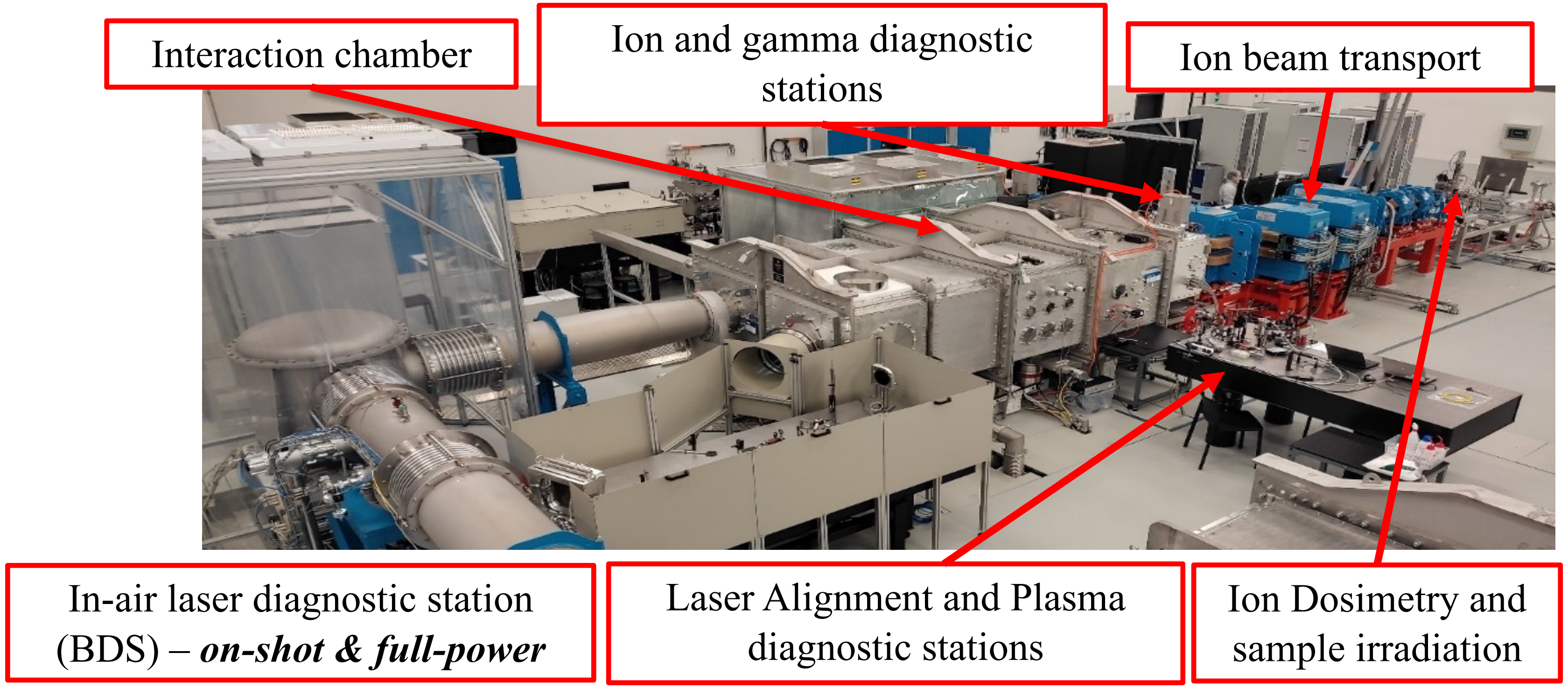


- ✓ Ablator/Quartz/PET shocked target (20ns time window)
- ✓ The 3 different layers are visible
- ✓ Quartz reflective + high velocity = pressure of several Mbar

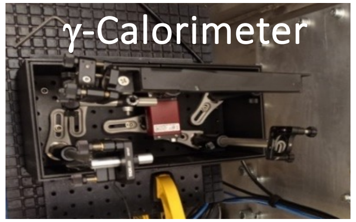
E4 Experimental Hall

the ELIMAIA Ion Accelerator - *lorenzo.giuffrida@eli-beams.eu*

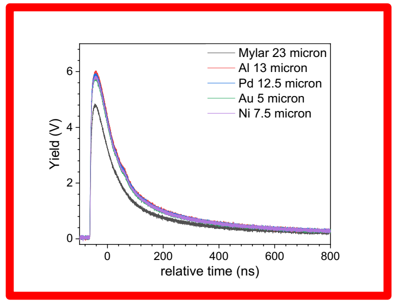
L3 HAPLS @ ELIMAIA		
Laser parameters	**Available**	**2024-2025**
Energy on target	~10 J	30 J
Focal spot	~1.5*1.5 □m	~1.5*1.5 □m
Pulse duration	27 fs	<30 fs
Intensity	>3E21 W/cm^2	~1E22 W/cm^2
Rep. rate on target	up to **1 Hz**	3-10 Hz



X/γ-ray diagnostics

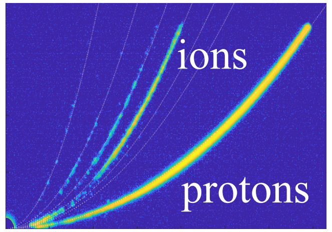


γ-Scintillator detector

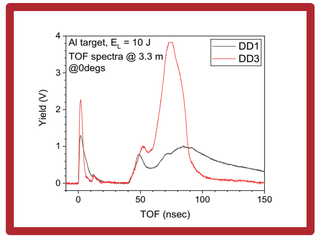


Ion diagnostics

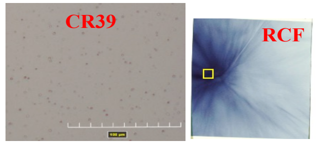
TP raw data



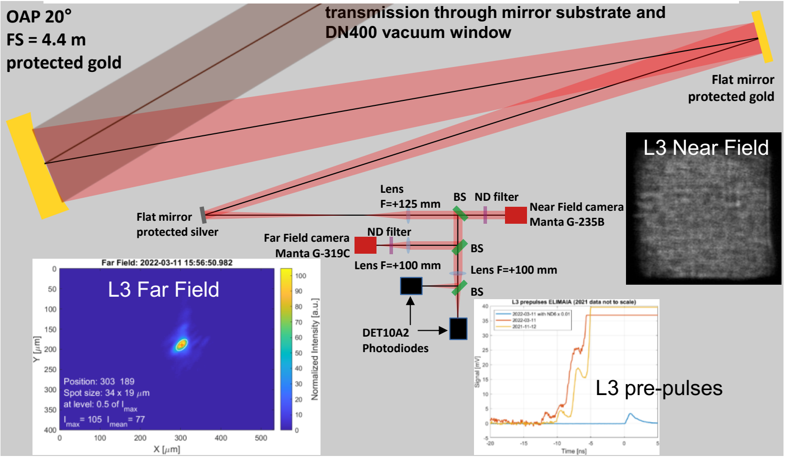
TOF signal



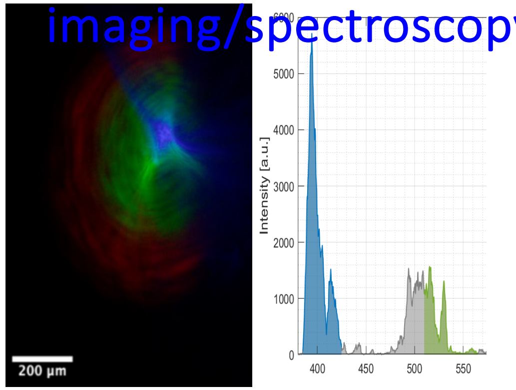
Passive detectors



On-shot laser diagnostics

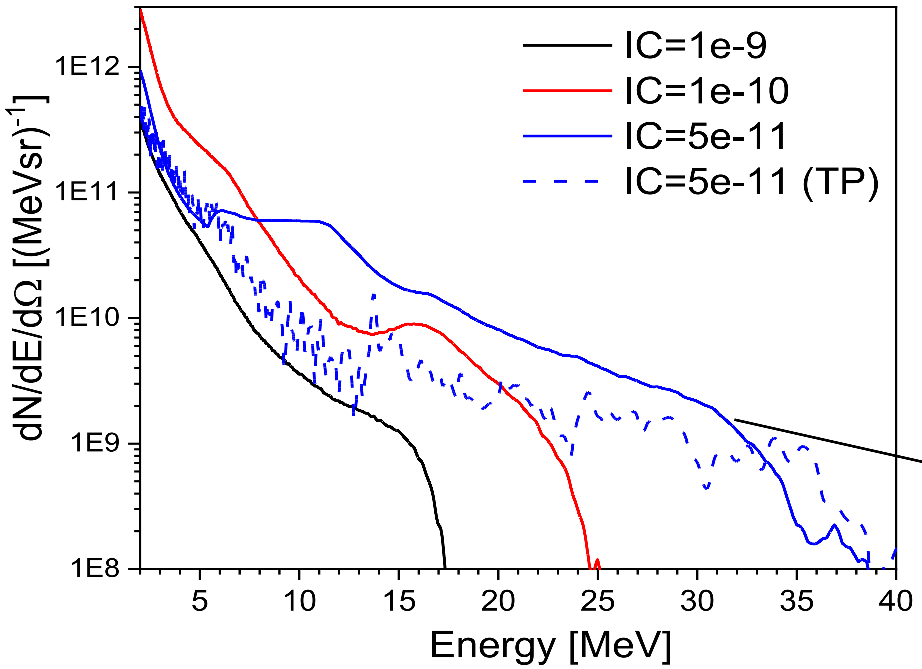


Plasma imaging/spectroscopy



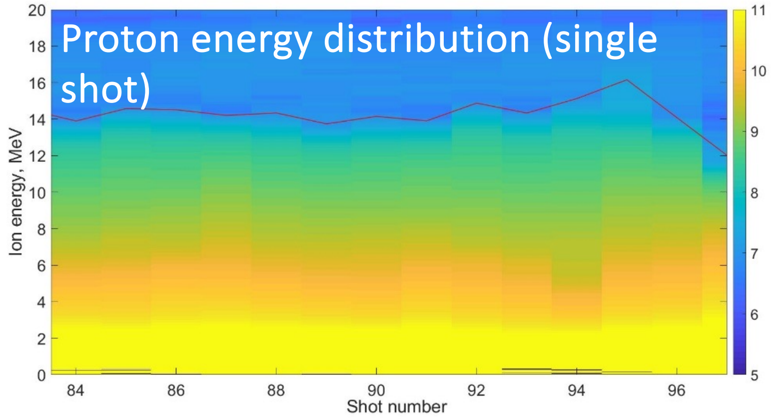
ELIMAIA Accelerator performance

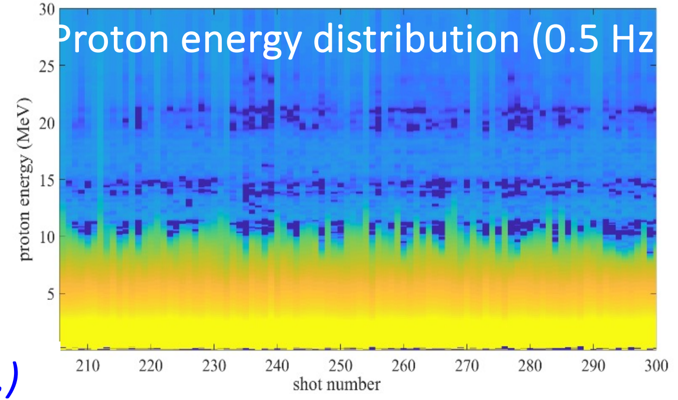
source stability and repetition rate



Laser/secondary source stability	
Laser energy	0.3%
Laser intensity @FWHM	0.8%
$T_{hot\ el.}$	3.96%
γ-ray flux	1%
E_{pMAX}	1.2%
Proton flux (>3 MeV)	5.3%

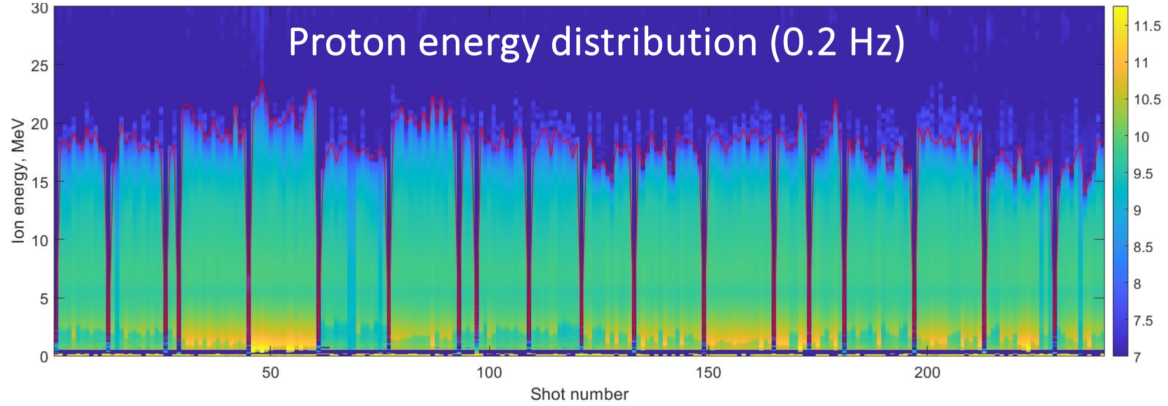
- ✓ Max proton energy ~40 MeV (10J on target)
- ✓ Flux above 3 MeV: 8.5E11 /sr



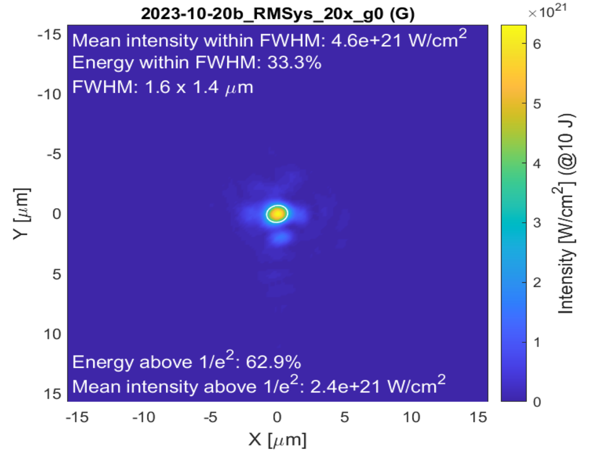


Lawrence Livermore National Laboratory

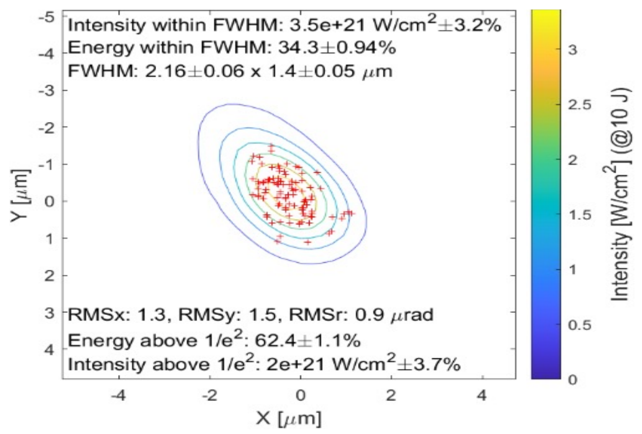
GDD, TOD, FOD scan *(M. Hill et al.)*



Focal spot on target >3E21 W/cm^2



Laser pointing stability ~1 □rad

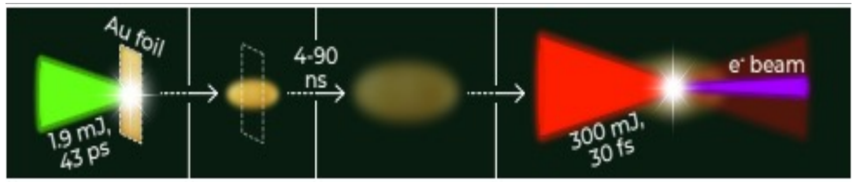


Fusion Research at ELIMAIA

opportunities for the IFE community

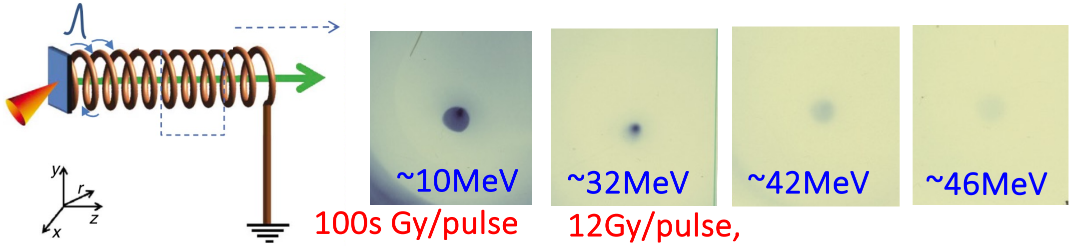
"Photoneutron generation by Undepleted Direct Laser Acceleration", I. Pomerantz (TAU, Israel)

Goal: enhanced neutron yield at high rep. rate



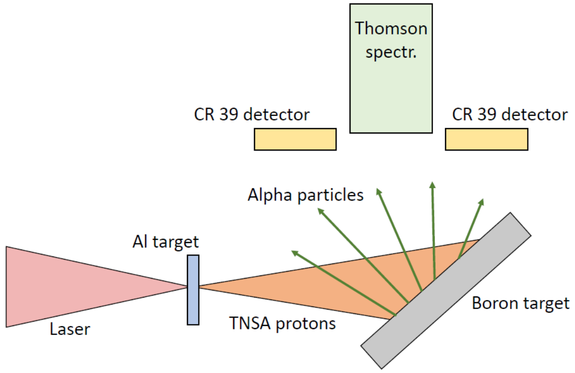
"Compact, high-rep dose delivery system employing helical coil targets", S. Kar (QUB, UK)

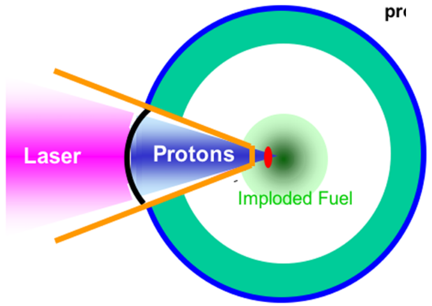
Proton beam from "coil target" (collimation and post-acceleration)



"High-Repetition-Rate regime for laser-triggered nuclear fusion reactions", F. Consoli (ENEA, IT)

α-particle source (high rep. rate) through laser-driven pB fusion



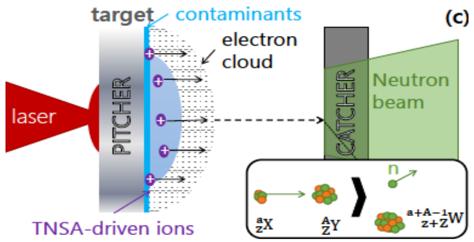


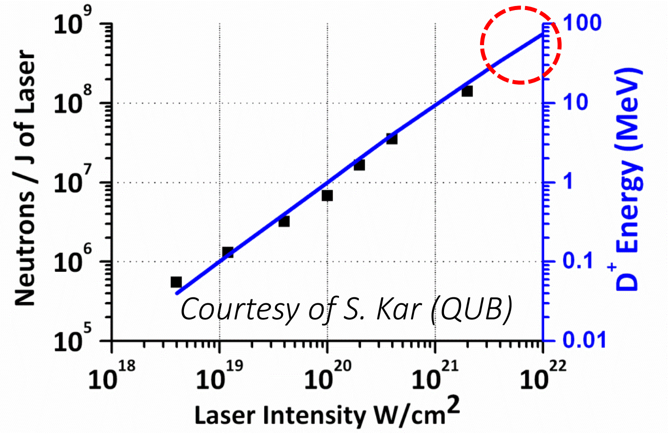
Proton beam generation and collimation for **Fast Ignition studies** ?

High rep. rate fast neutron source for nuclear reactor **first-wall studies** ?

L3(PW): >1E9/shot @10Hz

L4P(PW): >1E10/shot @1shot/min

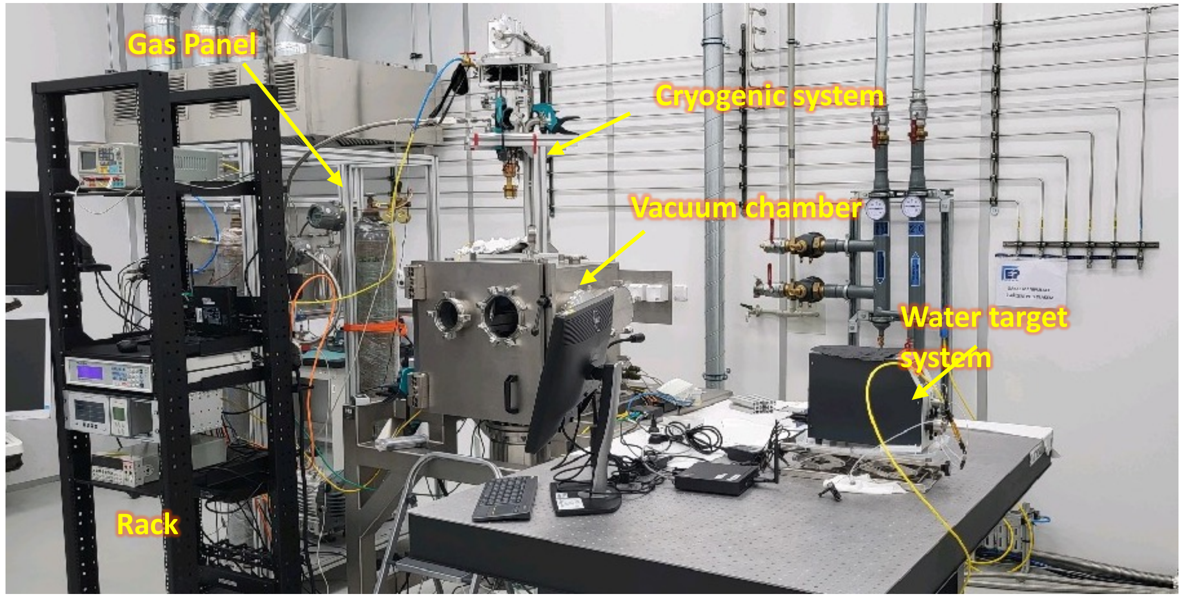


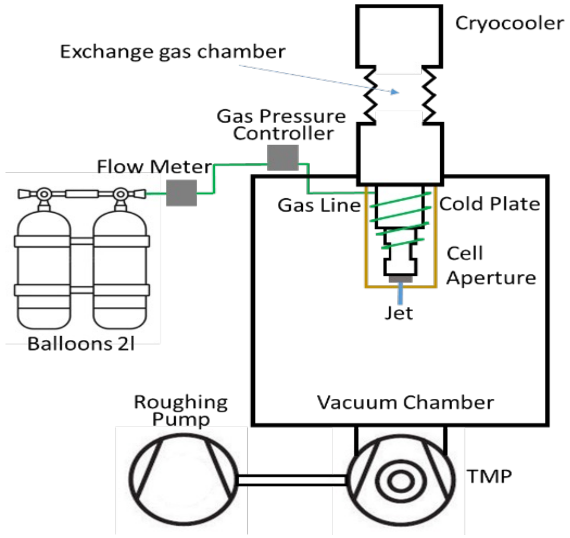


R&D on Cryogenic Targets

ELI Beamlines internal R&D – timofej.chagovets@eli-beams.eu

Cryogenic/Liquid Jet Target Laboratory (S2 hall)

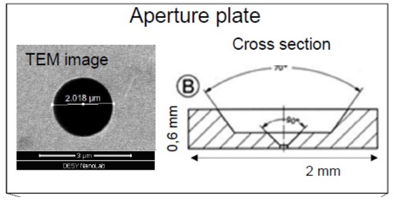


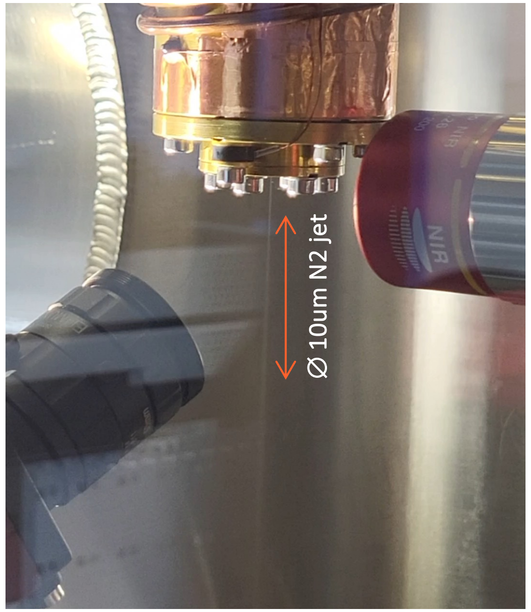


Cryogenic (liquid/solid) Targets

Cryogenic system at ELI Beamlines

- Portable He-free cryostat (0.5W at 4.2K)
- Various cryogenic gases:
  - currently tested (N2,Ar)
  - potentially (H2, Xe, Kr, He)
- Continuous target production
- Different target thickness:
  - currently tested 10um cylindrical aperture
  - potentially 5-25um
- Variable jet velocity 10-30 m/s





R&D on printed Foam Targets

why, and why printed?

Advantages

- Near-critical densities possible
  (difficult with gas jets, impossible for solid homogeneous materials)
- Wide density range from 1..100s of mg/cc
- Low debris
- Control over topology, density, pore size, flexibility (density gradients)
  ➔ intelligent design
- Printed foams: control & metrology

Applications

- Very promising for particle acceleration & radiation sources
- ICF: imprint reduction, wetted foams, parameter control (speed of ionization wave etc.); parametric instabilities (SBS, SRS)

Challenges

- Stability of very low density foams
- Understanding homogenization
- Numerical simulation
- Doping
- H → D replacement

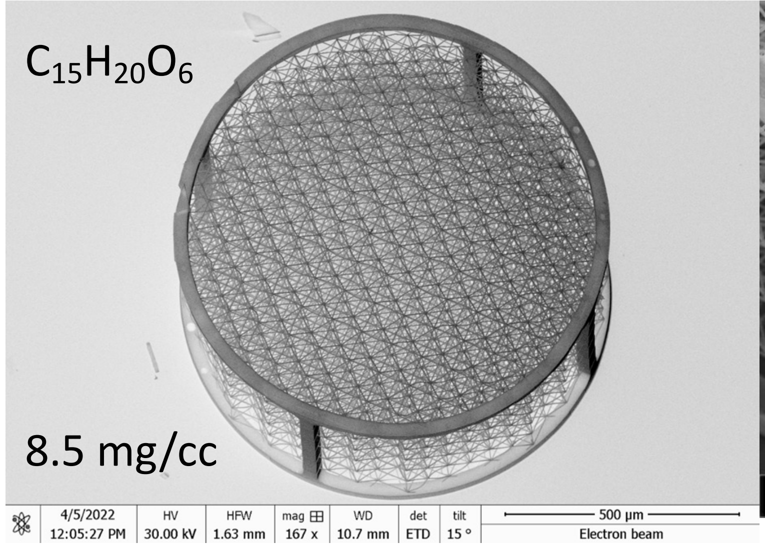
Nanoscribe Photonic Professional GT2

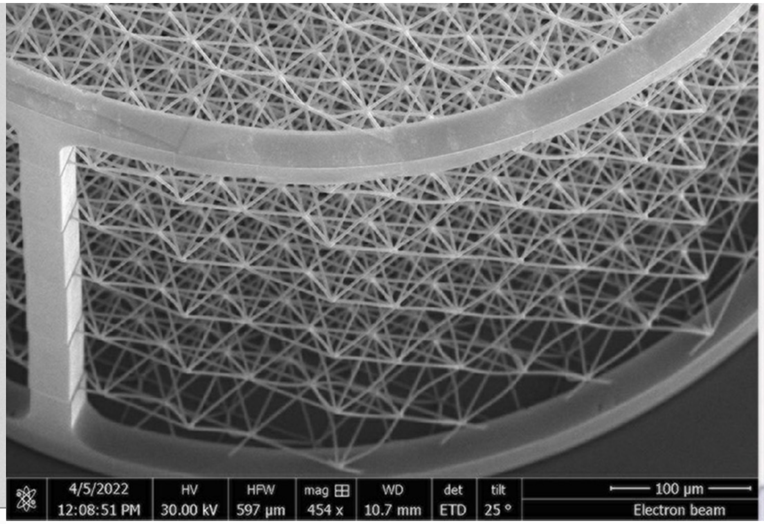
- Two-Photon Polymerization Laser Lithography (2-PP LL)
- IP-Dip2 resin (Nanoscribe GmbH)
- 63x objective (NA 1.4, Carl Zeiss) – corresponding to approx. 200 x 200 x 600 nm^3 “ellipsoidal” building blocks
- Dip-in-Laser Lithography (DiLL) mode
- Block sizes were cubes with a side of 100 µm with offset of 2 µm in the horizontal plane and 3 µm in the vertical direction
- 25 mW power (50% of nominal) to avoid overexposure
- Prize tag: ~ 500’000 EURO !
- Note: these machines can not yet do mass production !

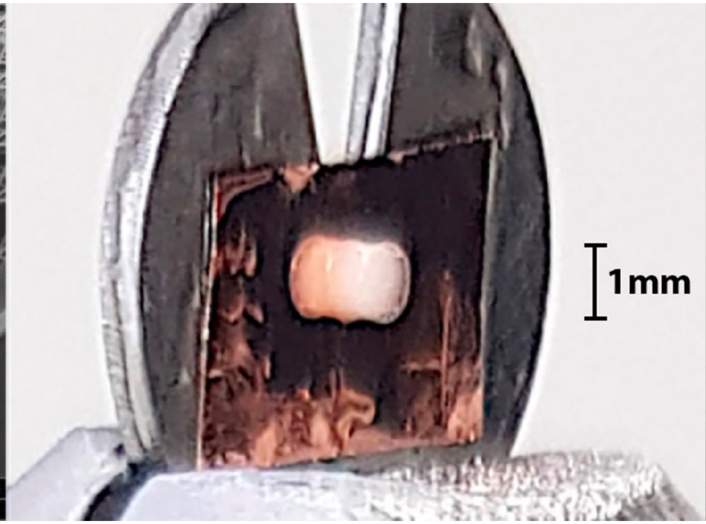
Printed Foam Targets

additive manufacturing

- ➔ Extremely versatile, controllable for density, geometry, topology of mesh
- ➔ Big interest at present in the ICF community







Journal of Applied Physics | ARTICLE | scitation.org/journal/jap

Additive manufactured foam targets for experiments on high-power laser-matter interaction

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T. Wiste,[1,a)] O. Maliuk,[2] V. Tikhonchuk,[1,3] T. Lastovicka,[1] J. Homola,[2] K. Chadt,[2] and S. Weber[1]

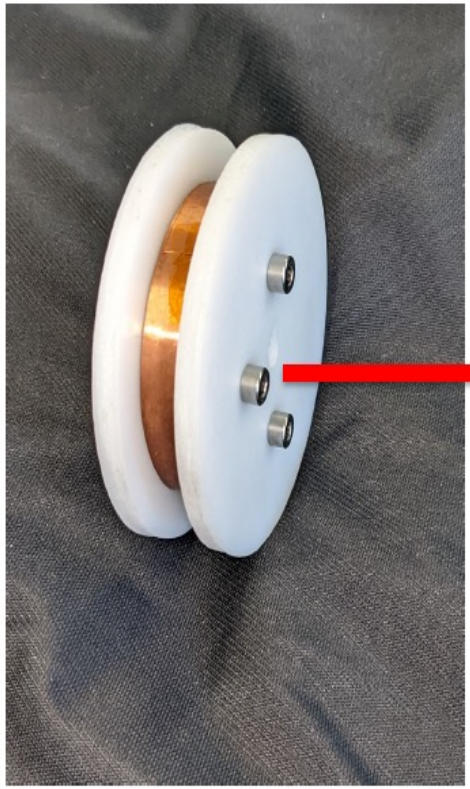
AFFILIATIONS

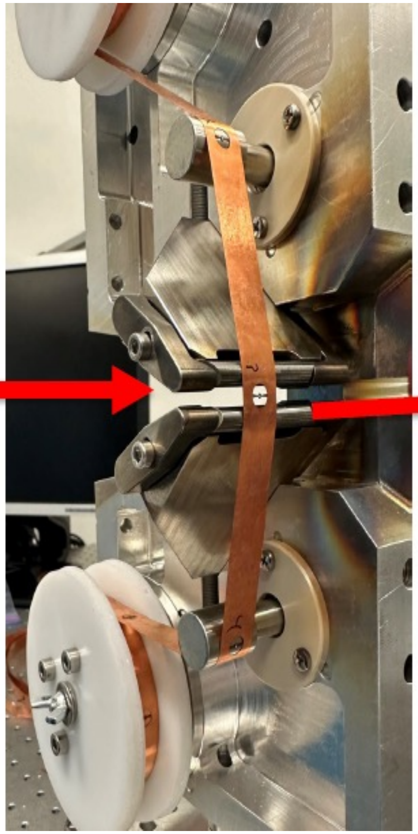
[1]Extreme Light Infrastructure ERIC, ELI Beamlines Facility, Dolní Břežany, Czech Republic
[2]Institute of Photonics and Electronics, Czech Academy of Sciences, Prague, Czech Republic
[3]CELIA, University of Bordeaux-CNRS-CEA, Talence, France

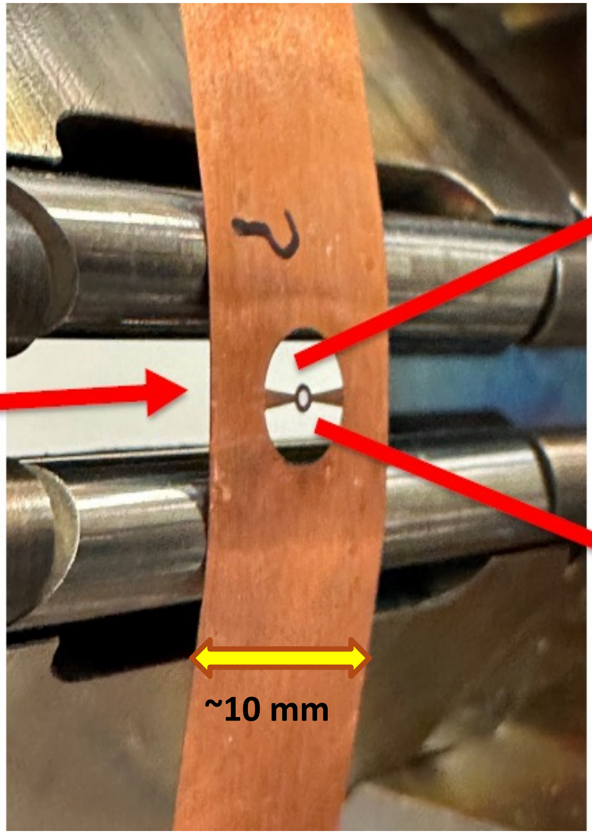
- Classic: chemical foam in a target
- 3D-printed foams are free-standing for maximized diagnostic access
- Caveat: single-shot target, not suitable for rep-rate

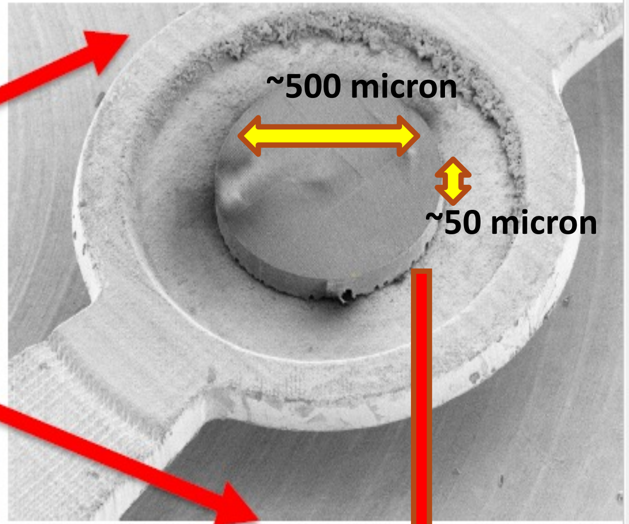
Foam Targets on Tape

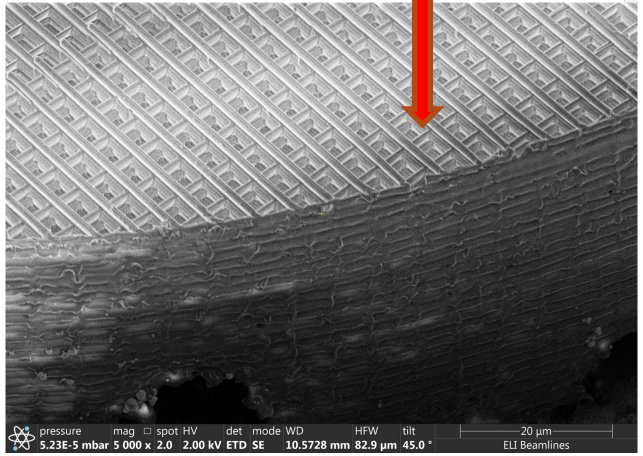
courtesy General Atomics (manuelm@fusion.gat.com, andrew.forsman@ga.com)











- Tested 160 targets with 250 to 650 mg/cc in logpile structure
- 80 J, 50 μm focal spot (contained in target), 2 ns, 527 nm
- Spacing protects following targets
- Can easily have hundreds of targets on one roll
- Tape can also be much thicker & different material
- Large gap reduces debris production
- Can be rolled, bent, flattened w/o damaging the target → very robust
- Tape is protecting subsequent targets from debris, emp, radiation….

Wrap up

a few hints for the round tables

- ELI Beamlines is a unique facility that can contribute to laser-based fusion research by offering cutting-edge laser and secondary source technologies to the specialized user community.

- The LIF project is an excellent "seed" to build up such a user community in Germany and Europe (bilateral or multi-lateral projects, public-private partnership, development of common strategies).

- IFE is based on 4 major areas (ELI Beamlines can contribute to all of them):
  - ✓ Science - The high rep. rate of L4n (unique) and L3/L4P back-lighters can support the IFE community studying open scientific issues in the next 4-5 years. *What should be further developed (targetry, diagnostics, pump-probe capability)?*
  - ✓ Technology – The laser performances can be further enhanced to facilitate the IFE community. *What should be further developed (higher L4ns energy on target at 2w in narrow/broadband, L4PW studies for advanced proton acceleration/guiding/pump-probe)?*
  - ✓ Materials – *Enhancing target fabrication and metrology capabilities (foam targets, cryogenic targets, etc.) and neutron sources for first-wall studies (L4PW)?*
  - ✓ Training and networking – Training PhD students, young scientists, engineers, and technicians. *Can we develop training programmes in collaboration with German (and other EU countries) universities, research organizations c*

MarvelFusion FOCUSED ENERGY