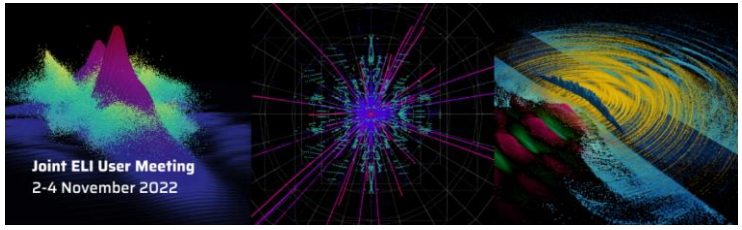
ELI Beamlines:
Overview and Status

Daniele Margarone
Director of Research and Operations
ELI Beamlines Facility



Outline

- **ELI Beamlines**
  facility overview

- **User Programme**
  - *current user offer*
  - *future user capabilities*

- **Flagship Experiments**

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ELI Beamlines (mission profile)

Dolní Břežany, Czech Republic

- ✓ Provide unique tools to support scientific excellence worldwide
- ✓ Explore interaction of light with matter (plasma) at ultrahigh intensities (up to 10^{23} W/cm^2)
- ✓ Develop and operate four leading edge, high-power femtosecond laser systems (L1, L2, L3, L4) with high energy, high repetition-rate capability (10TW @1kHz, 100TW @ 100Hz, 1PW @10Hz, 10PW @0.01Hz)
- ✓ Offer secondary sources (X-rays and accelerated particles) with unique capabilities to users
- ✓ Enable pioneering research not only in plasma physics, laboratory astrophysics, and material science, but also in biomedicine, chemistry and other disciplines with strong multidisciplinary application potential

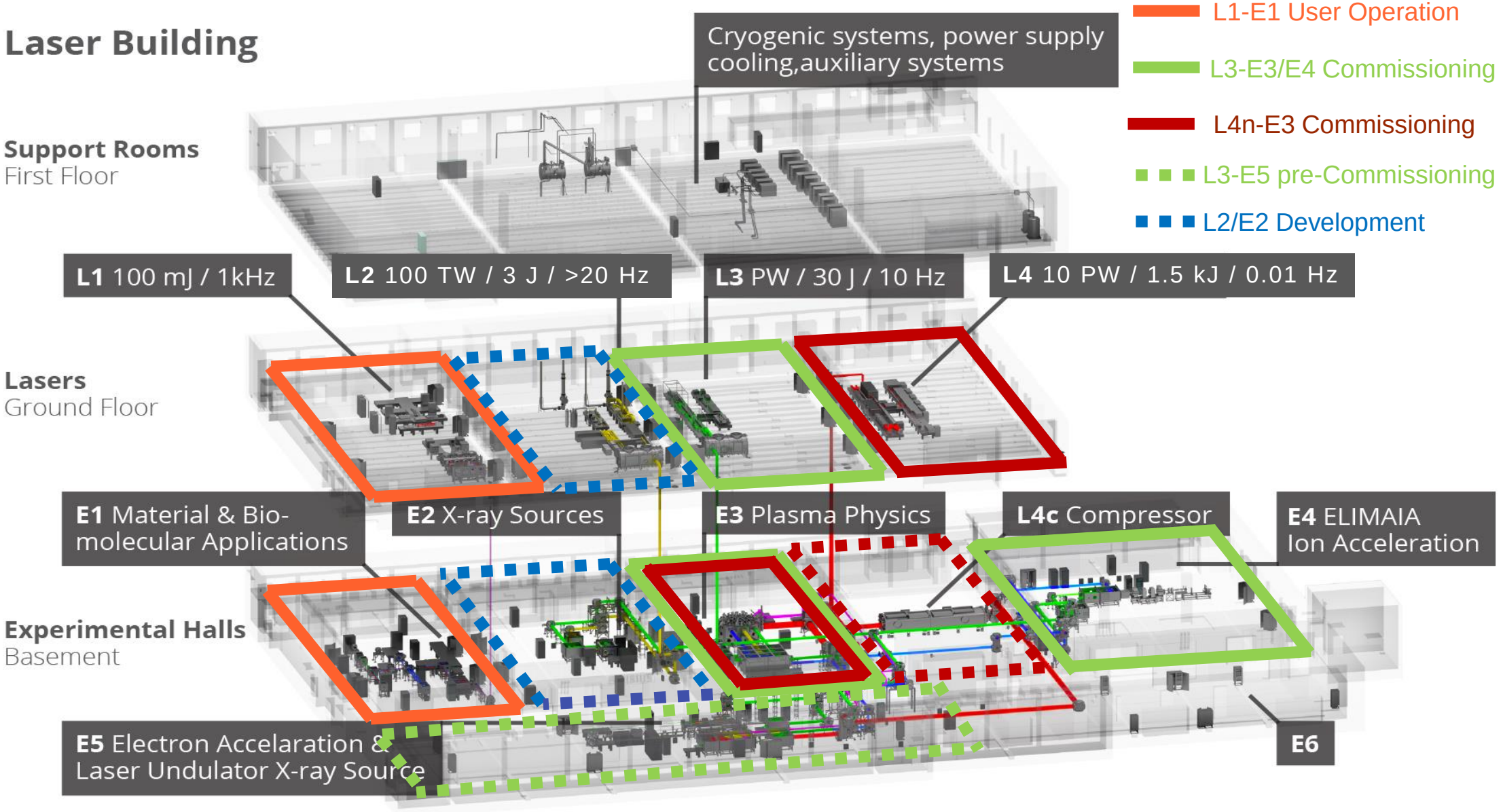
Paradigm shift

Dolní Břežany (before ELI BL)

First large research infrastructure in a CEE region

ELI Beamlines Facility

the High Energy Beams Pillar of ELI



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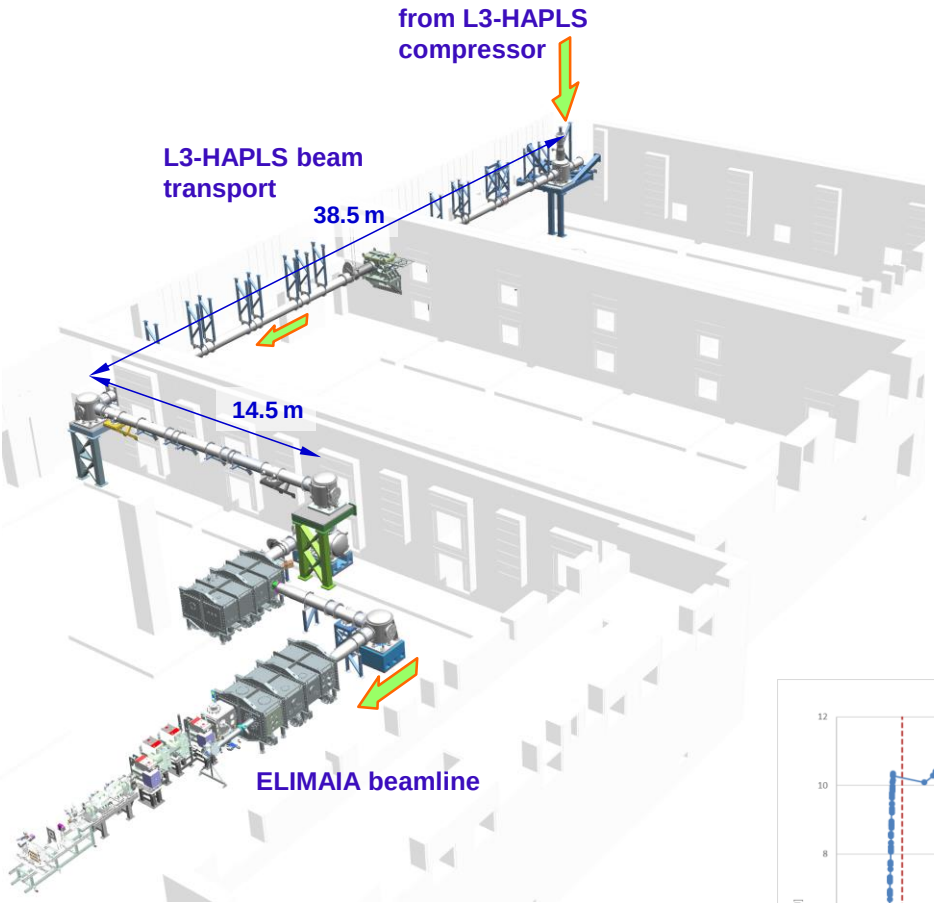
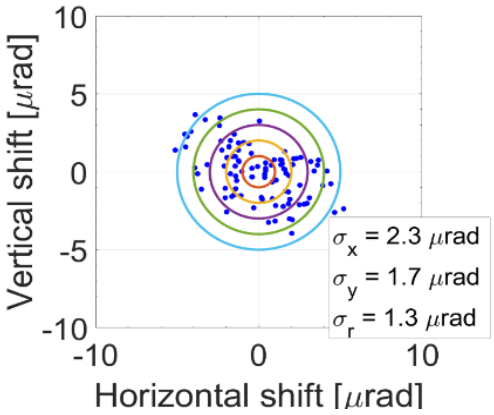
Laser beam transport

example: L3-to-E4

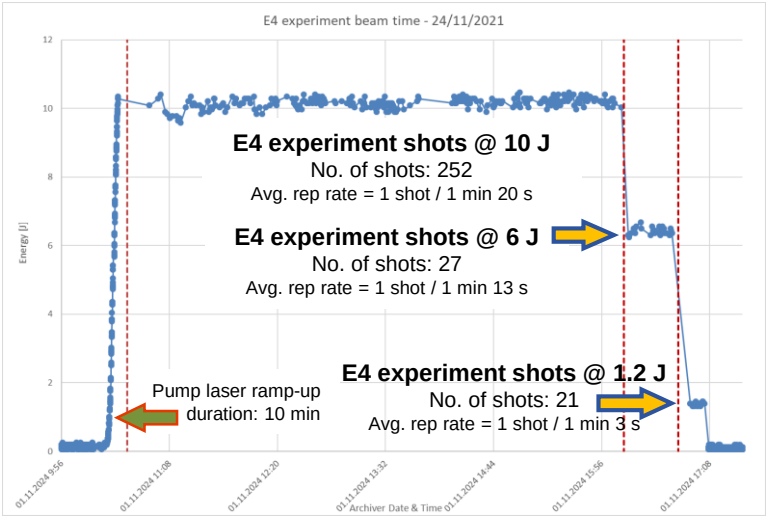
- ✓ 78 m beam path: from L3 compressor output to ELIMAIA target (E4)
- ✓ Optical beam path: 13 turning mirrors (8 in L3-BT section and 5 in ELIMAIA chambers)
- ✓ Excellent pointing stability of the integrated system: 1.3 µrad (FWHM) jitter over 54 min of continuous operation (shot-to-shot linear fluctuation on target <1 µm FWHM)





Example of operation day (E4 ELIMAIA beamline)

Total net time: 6 hr 40 min 43 s, 300 shots, total energy 2.76 kJ



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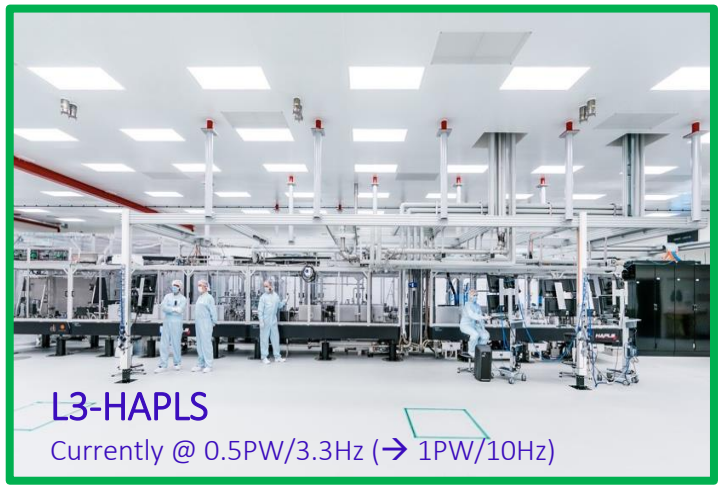
Current User Offer (2022)

L1-ALEGRA
Currently @ >3TW/1kHz (→ > 5TW/1kHz)

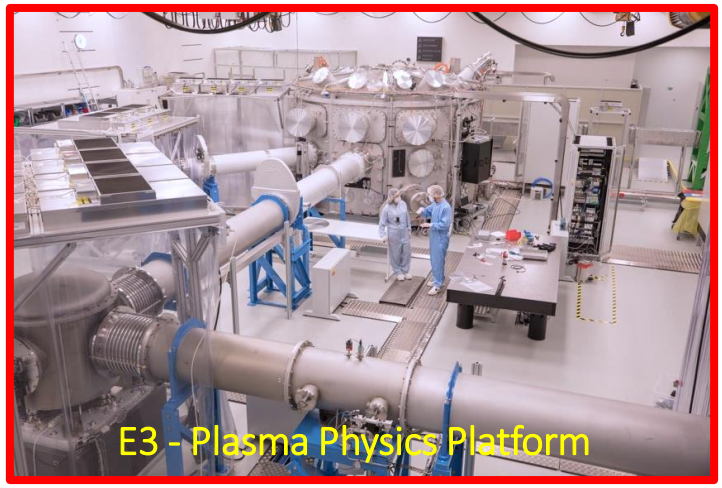


L3-HAPLS
Currently @ 0.5PW/3.3Hz (→ 1PW/10Hz)

L4-ATON
Currently @ 1.2kJ/0.55-10ns/0.01Hz (→ 10PW/0.01Hz)

E1: HHG&PXS + MAC/TREX/ELIps/SRS

E4 - ELIMAIA - ELIMED



E3 - Plasma Physics Platform

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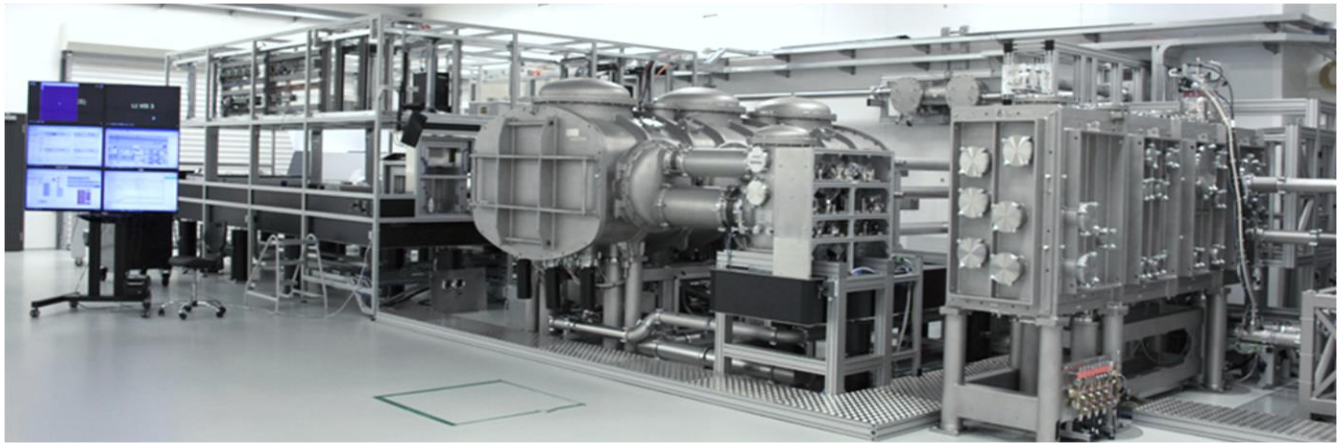
L1 ALEGRA laser status

R. Antipenkov, P. Bakule, B. Rus (Dep.91)



- Picosecond OPCPA architecture: inherently high temporal pulse contrast
- System designed and built at ELI-Beamlines (using commercial thin-disk pump lasers)

Achieved 55 mJ / <15 fs pulses @ 1 kHz

Routine operation for users

- ~30 mJ on target in E1

- Availability in experimental halls: E1 hall
- available on average 6.8 hours per day for planned user experiments in E1 hall

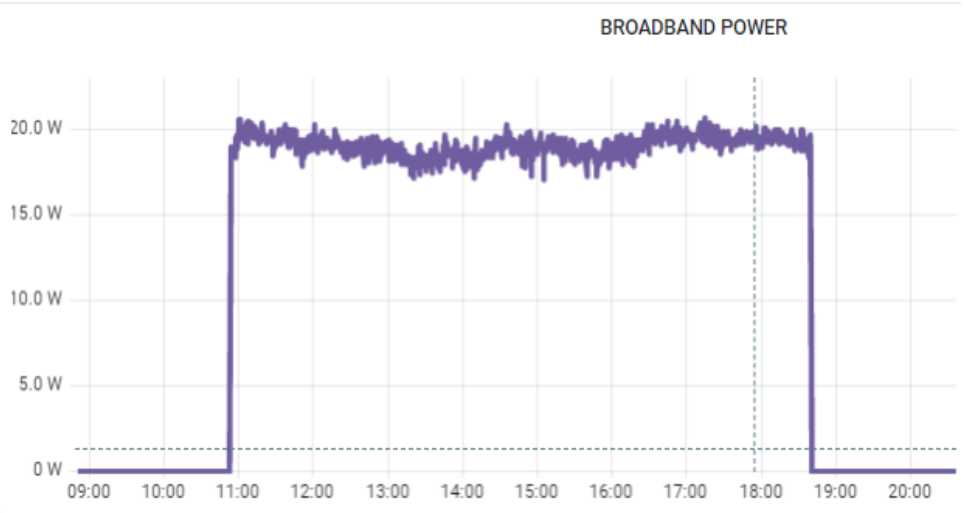
L1 ALLEGRA Major Upgrade completion dates

Jun 2023

- second beam >10mJ, 15 fs, synchronized with L1, any delay with <100fs precision

Dec 2023

- 100 mJ, 15 fs output from L1 ALLEGRA (requires completion of 0.5 J, 1030 nm amplifier)



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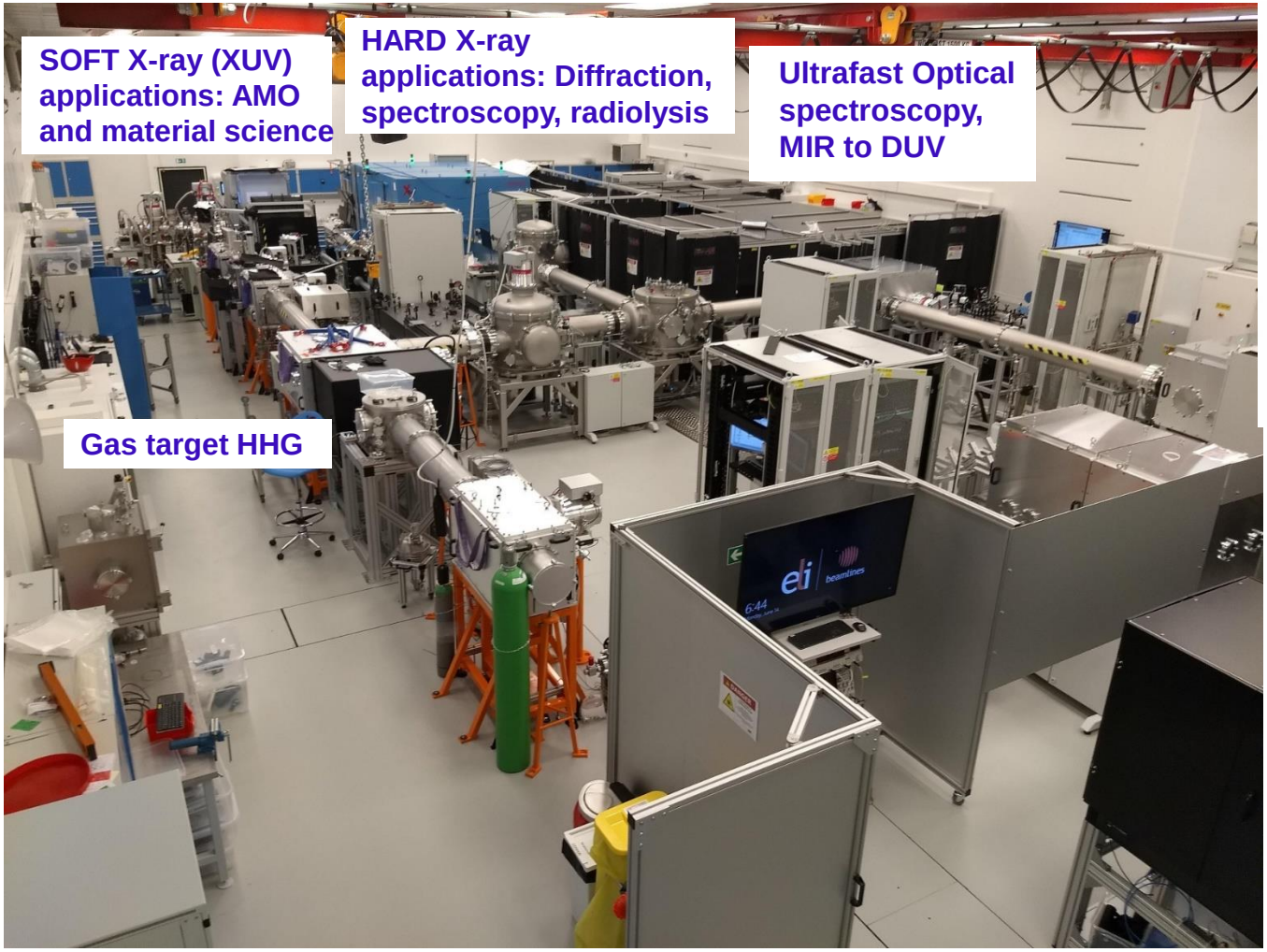
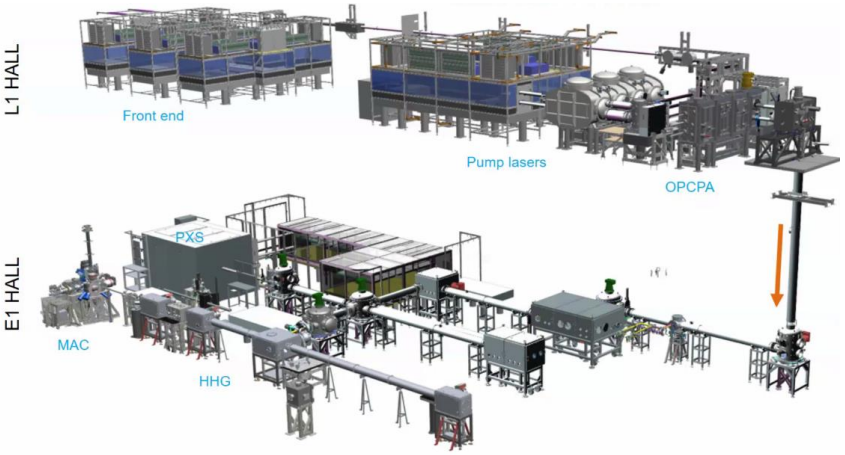
E1 Experimental hall

X-ray beamlines & end-stations

beamlines

J. Andreasson et al. (Dep.88)

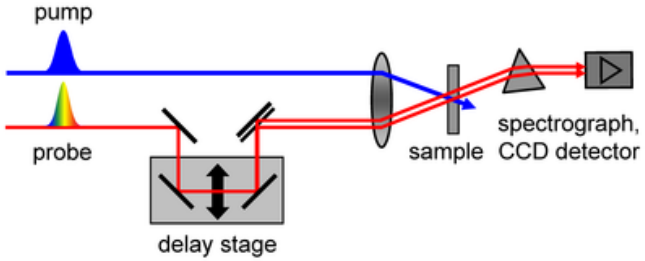




***Function* is fundamentally related to dynamics!**

In the E1 experimental hall we have developed beamlines and stations for **photon science experiments in the mid IR to Hard X-ray range at kHz**

These are used for **time resolved experiments** using **pump-probe** techniques to study **femtosecond** to millisecond dynamics



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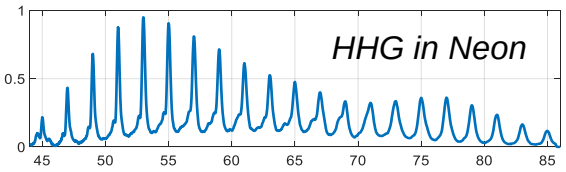
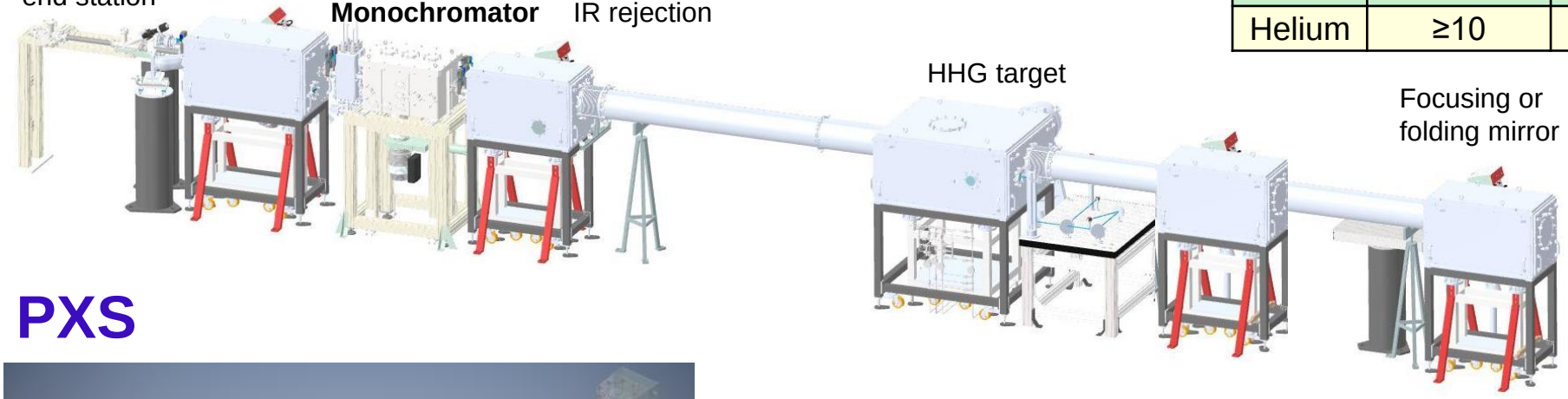
HHG & PXS kHz beamlines in E1

O. Hort, D.D. Mai, J. Nejdl, S.V. Bulanov (Dep.86)

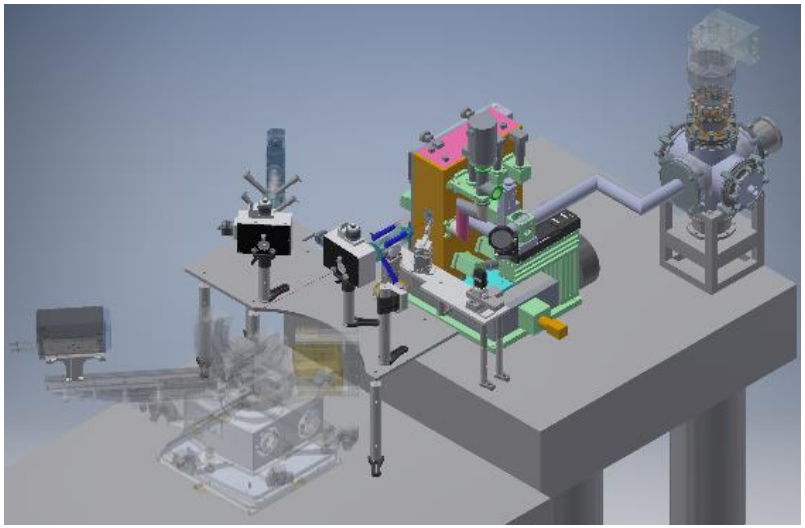
HHG



Gas	λ_{XUV} (nm)	XUV energy (μJ)
Xenon	≥50	2
Argon	≥30	0.2
Neon	≥13	0.02
Helium	≥10	0.02



PXS



- ✓ **Cu tape target,** Liquid metal jet (in commissioning), Water jet
- ✓ **X-ray optics**: Montel (monochrom.) or polycapillary

X-ray source parameters	L1 @ 20mJ
Photons per shot into 4p srad	3×10^{11}
8 keV photons/shot on target	~ 10^{6}
Source size	< 50 μm
X-ray pulse duration	< 300 fs

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E1 hall user experiments

capabilities and support technologies

beamlines

J. Andreasson et al. (Dep.88)

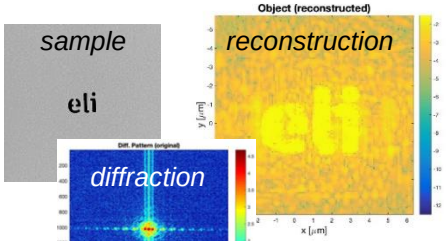
Operation of user end stations for:

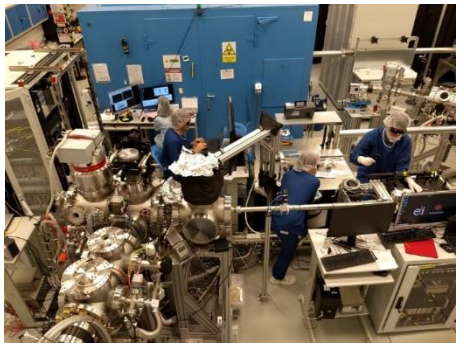
1. MAC: Science with Coherent XUV radiation
   - Atomic, Molecular and Optical (AMO) science
   - Coherent Diffractive Imaging (CDI)
   - XUV Material science
   - HHG source development

2. TREX: Hard X-ray science
   - Diffraction and spectroscopy
   - Plasma X-ray source development
   - Pulse Radiolysis

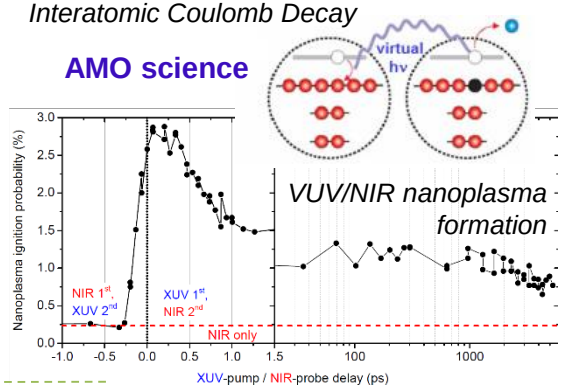
3: Ultrafast optical spectroscopy
   - Femtosecond Stimulated Raman Scattering (SRS) and Transient absorption
   - time resolved spectroscopic ellipsometry
   - Transient Current Technique
   - 2D IR spectroscopy

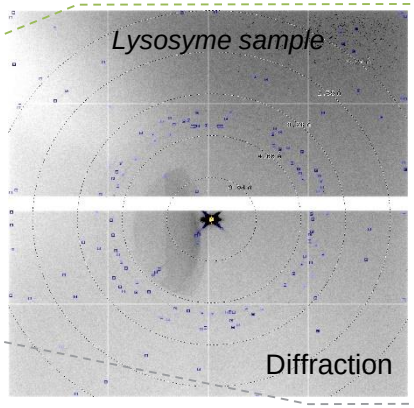
For technical details of available instruments and beamlines:
https://www.eli-beams.eu/calls/the-extreme-light-infrastructure-call-for-users/

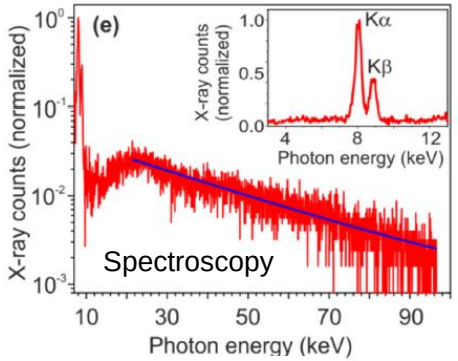


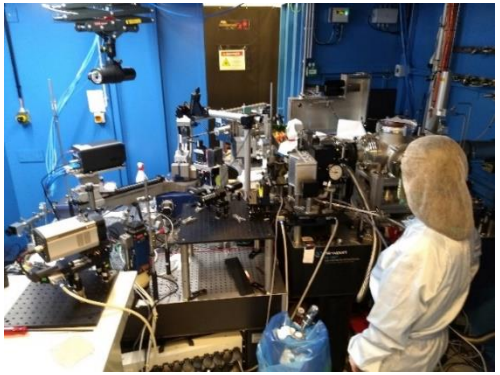


Interatomic Coulomb Decay

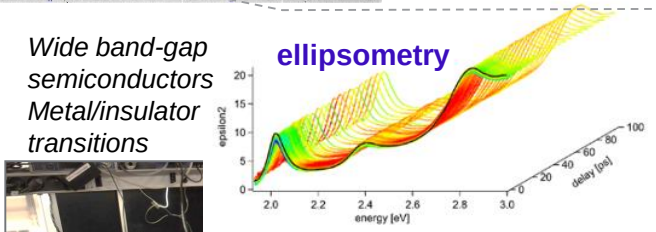


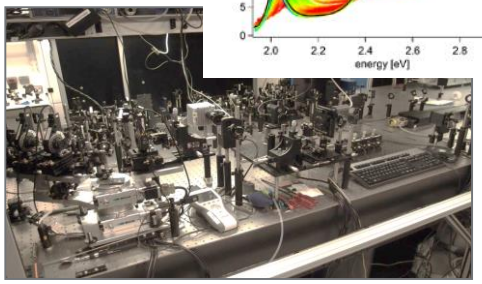




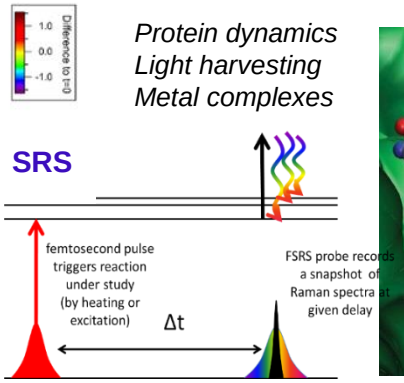


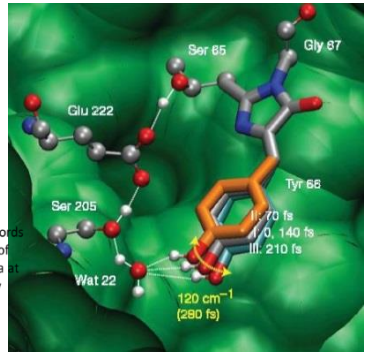
Wide band-gap semiconductors
Metal/insulator transitions





Protein dynamics
Light harvesting
Metal complexes





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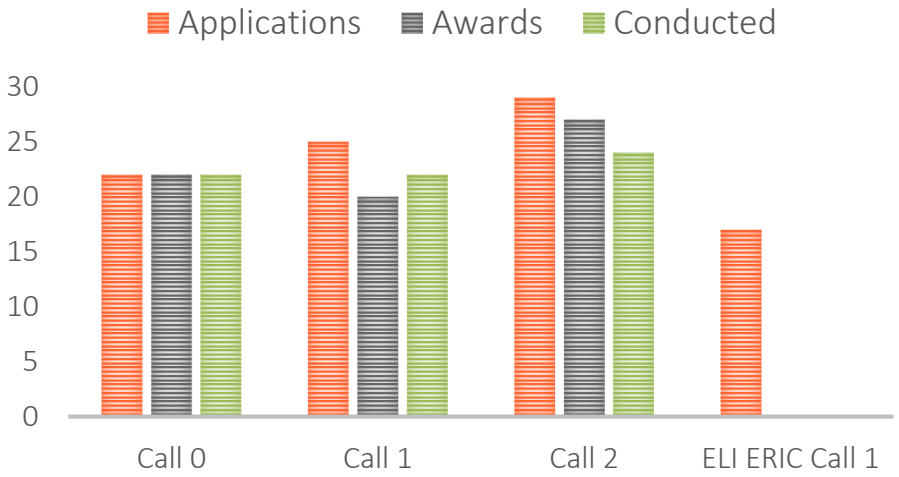
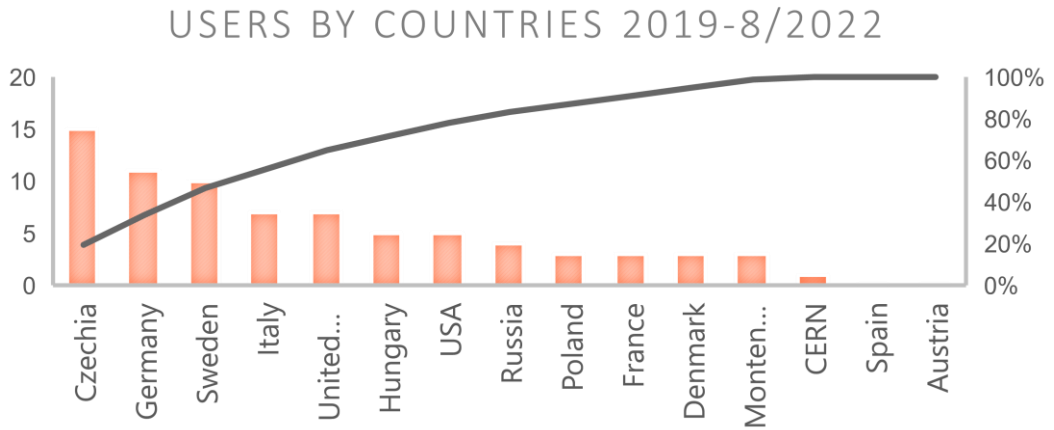
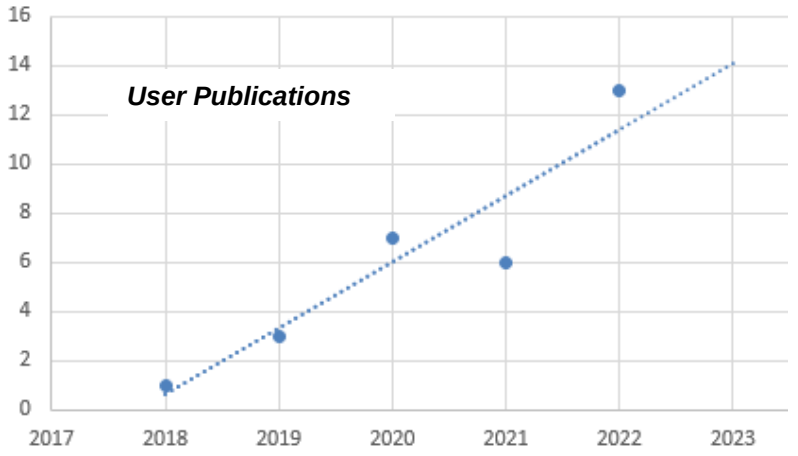
L1-to-E1 kHz user programme

statistics





Call	Number of applications	No of experiments performed	Number of beamtime weeks
ERIC Call 1	17		
Call 2	29	24	58
Call 1	22	22	60.5
Covid Call	0	1	1,5
Call 0	22	19	24
Sum	90	66	144

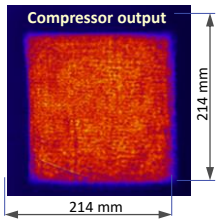


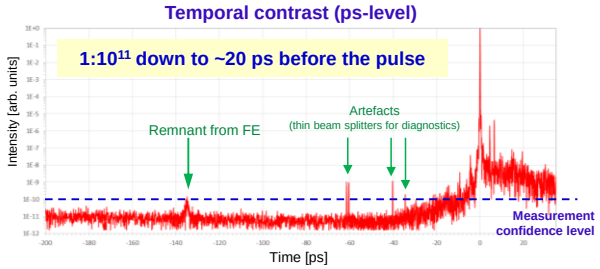
L3 HAPLS laser status

High repetition rate Advanced Petawatt Laser System

J. Cupal, B. Rus (Dep.91)

- 1 PW 10 Hz repetition rate beamline
- Nd:glass helium-cooled DPSLL pump laser
- Ti:sapphire short-pulse chain, helium-cooled power amplifier
- World's highest peak power laser diode arrays
- High level of automation

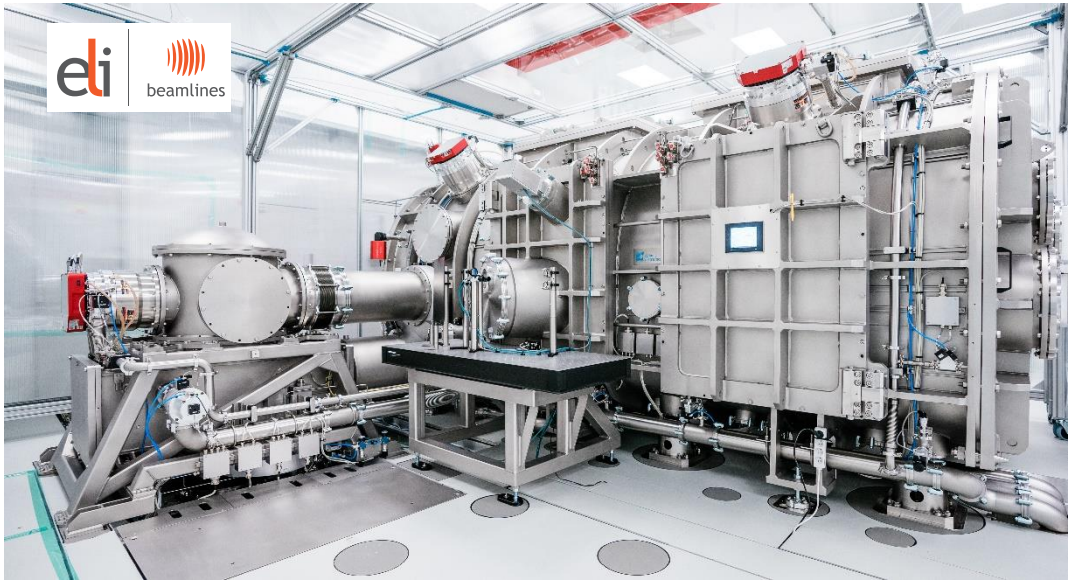




Design performance: 1 PW / 10 Hz
30 J / <30 fs

Current performance: 0.5 PW / 0.5 Hz, 3⅓ Hz
13.3 J / 27.3 fs

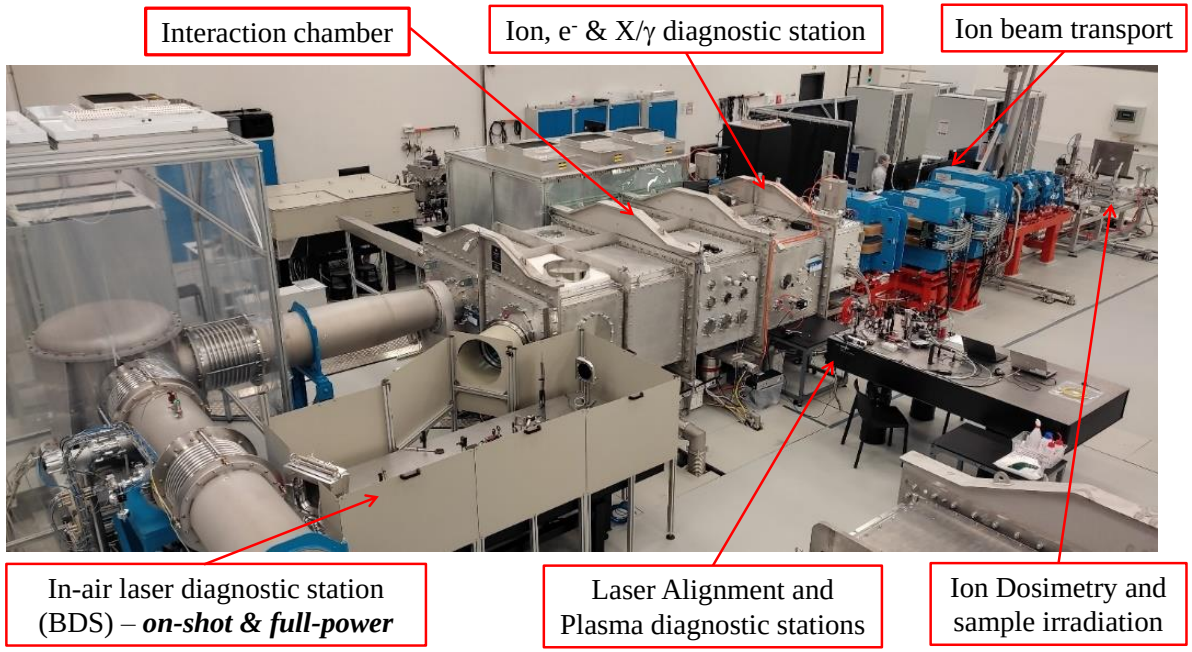
Ramping to PW / 10 Hz in progress:
- 1 PW / shot-on-demand spring - summer 2023
- 1 PW / 3⅓ Hz spring - summer 2024
- 1 PW / 10 Hz spring - summer 2025



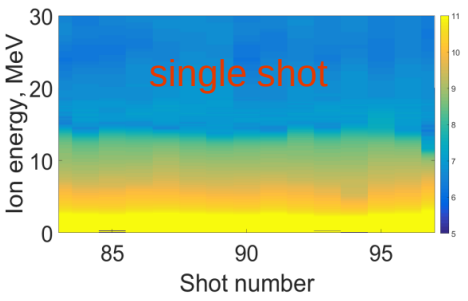
ELIMAIA beamline (E4)

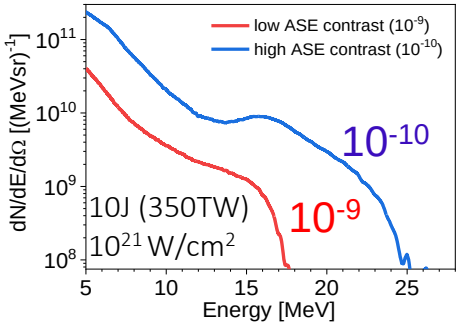
Ion Accelerator section

F. Schillaci, L. Giuffrida et al. (Dep.87)

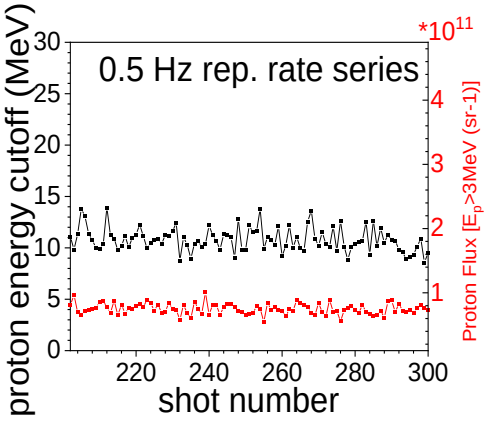


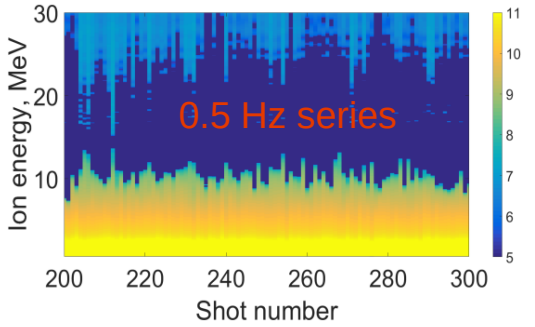
Ion Accelerator	Available	Design
Laser intensity	$1{\cdot}10^{21}$ W/cm^2	$5{\cdot}10^{21}$ W/cm^2
Laser energy	>10J	30J
Laser pulse width	<30 fs	<30 fs
Repetition rate	up to 0.5 Hz	10 Hz
Proton energy cutoff	25 MeV	100 MeV
Proton flux (>3 MeV)	~ $1{\cdot}10^{10}$/sr	~ $1{\cdot}10^{11}$/sr





Fluctuations	100 consecutive shots	
Laser energy	0,3%	9.95±0.02 J
Laser intensity	0.8%	$(1.39\pm0.01){\cdot}10^{21}$ W/cm^2
T_{hot}	4%	3.06±0.12 MeV
Photon flux	1%	
Proton energy *(cutoff)*	**1.2%**	14.48±0.17 MeV
Proton flux: *(>3 MeV)*	5.3%	$6.07{\cdot}10^{10}\pm0.32{*}10^{10}$ sr^{-1}





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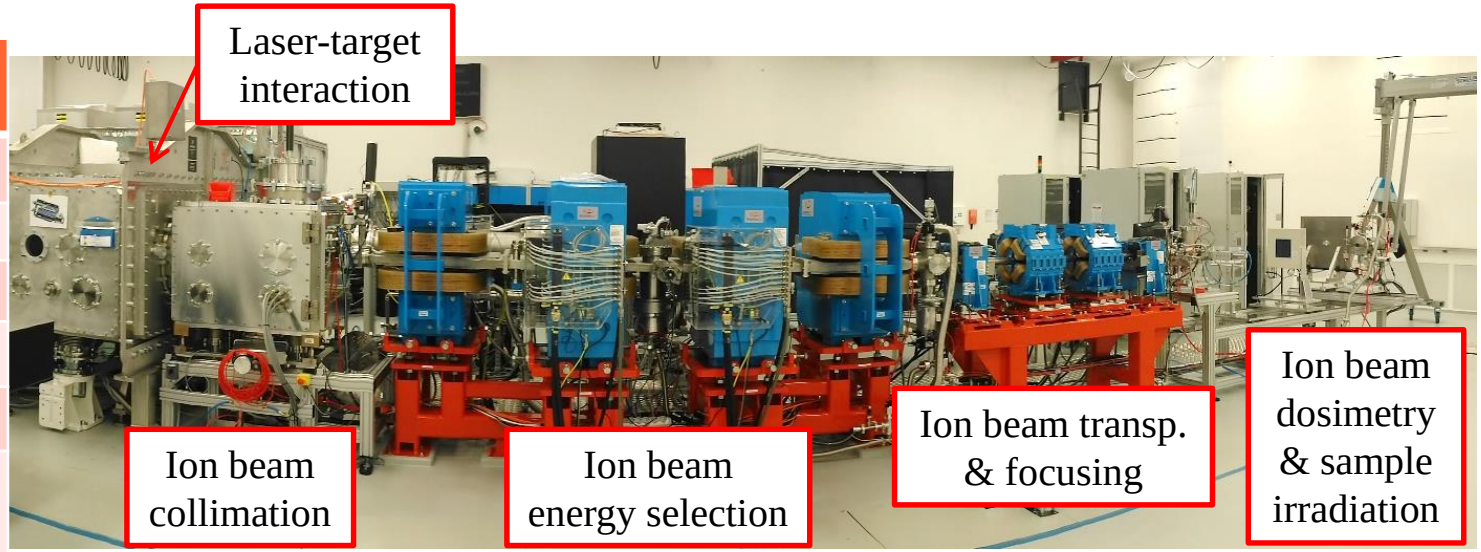
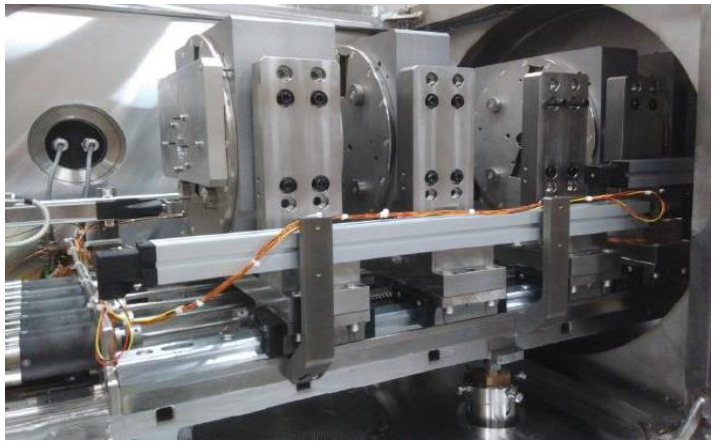
F. Schillaci, L. Giuffridaet al. (Dep.87)

ELIMAIA beamline (E4)

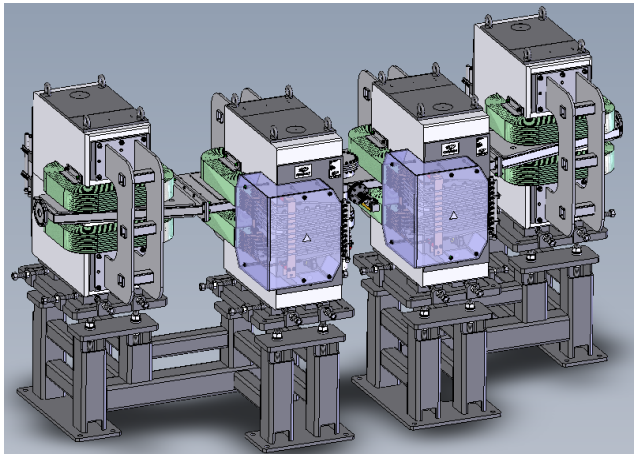
ELIMED ion beam transport and dosimetry section

ELIMED Station	Design parameters @ user sample
Proton energy	5-60 MeV
Ions/shot	$1 \cdot 10^8$-$1 \cdot 10^{10}$/sr
Bunch duration	1-10 ns (>10^9 Gy/s)
Ion beam aperture	~ 1deg (FWHM)
Ion beam spot size	0.1-10 mm (FWHM)
Repetition rate	Possible active modulation (1Hz)

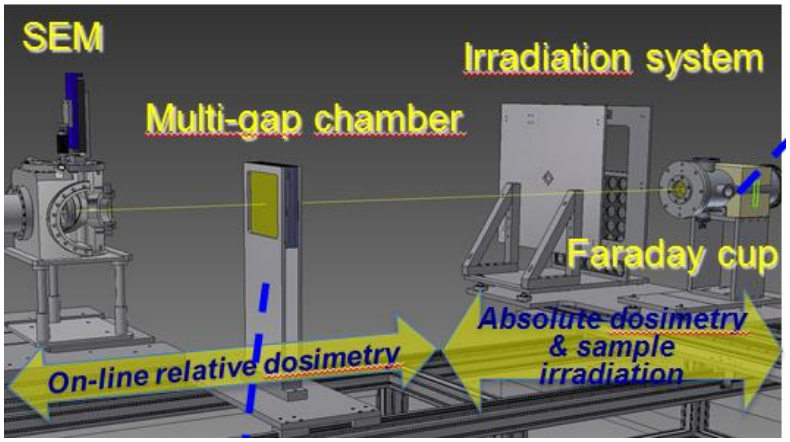




Ion beam collimation system:
5 PMQs, 36mm magnetic bore, 100 T/m gradient with 2% uniformity



Ion beam energy selection system:
4 electro-dipoles, 55mm bore, 0.06 – 1.226 T with 0.5% uniformity, linear resolution with slit aperture size, active energy modulation possible



Dosimetry and Irradiation system (in-air):
SEM for beam current monitor, Multi-gap chamber for relative-online dosimetry, FC for absolute dosimetry, automated sample irradiation system

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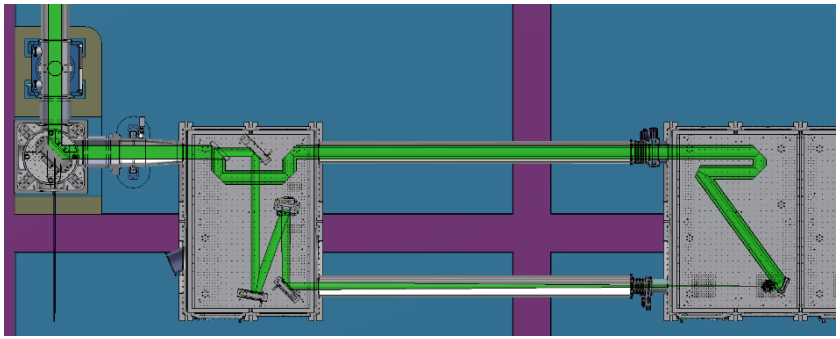
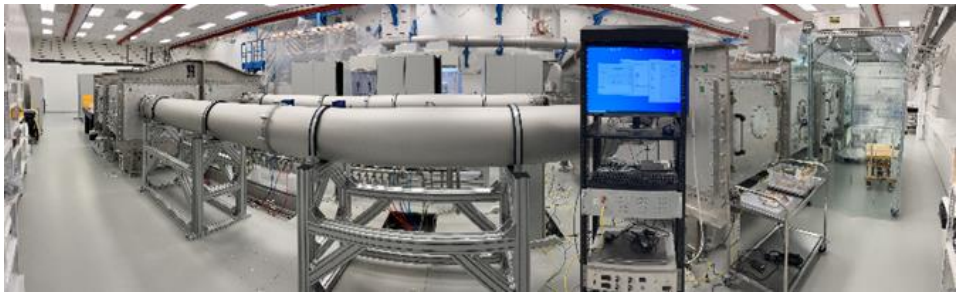
ELI-ELBA beamline (E5)

status and plan

G. Grittani, S.V. Bulanov (Dep.86)

- Electron acceleration line installed
- Counter Propagation line procured, waiting for delivery, installation completed by March 2023
- Set-up accommodates different wavefront splitters configuration, so the split ratio could be changed depending on user requirements
- Involvement of user for experimental diagnostics, data analysis and modeling is key to success





First Light (Spring 2022) — LWFA Accelerator (Autumn 2022) — Laser Electron Collider (2023)

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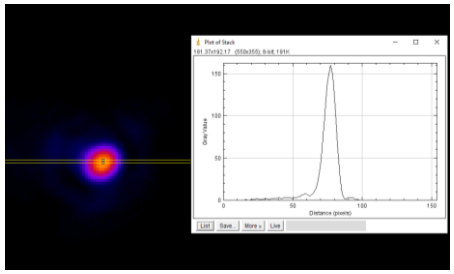
ALFA: kHz electron acceleration with L1

pilot experimental results

G. Grittani, S.V. Bulanov (Dep.86)

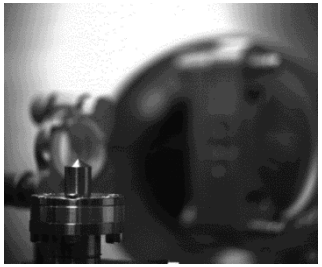
Laser focal spot



ALFA (Allegra Laser For Acceleration)

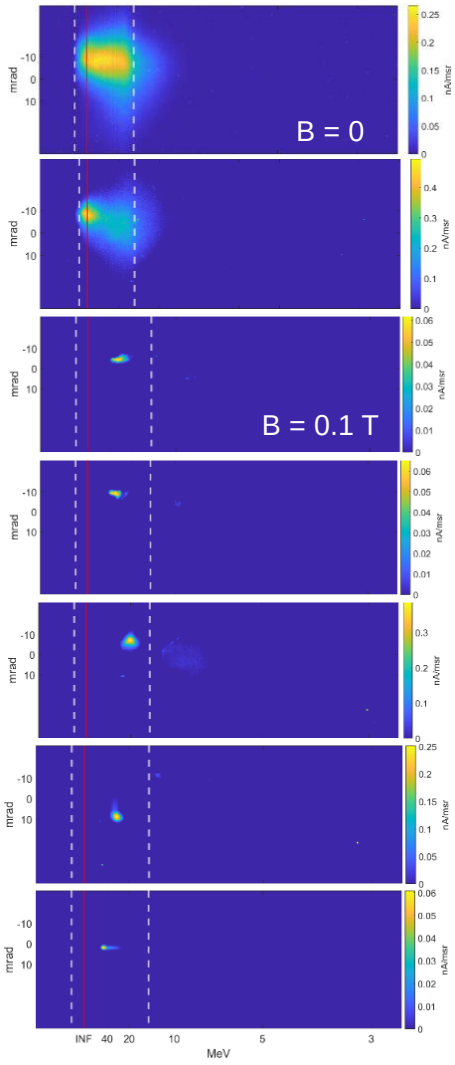
- 55 mJ (100 mJ planned)
- 16 fs on target
- 1 kHz on target
- 1-2 µrad pointing stability
- electron beam energy >50 MeV within reach with current laser parameters

Supersonic nozzle

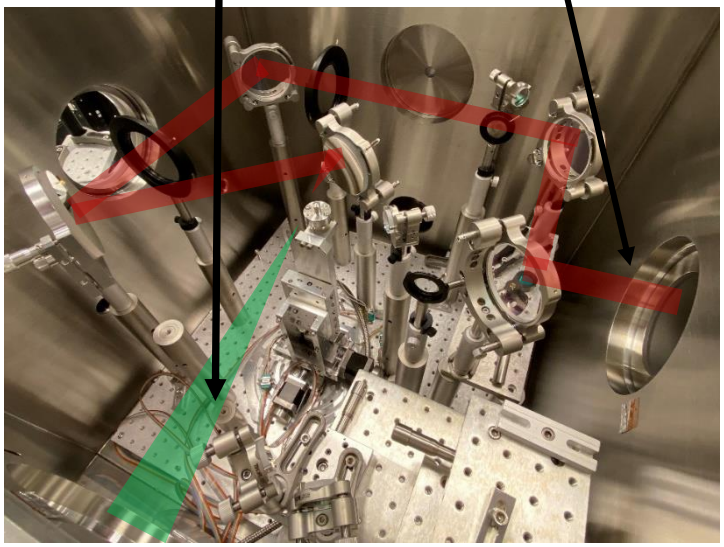


N_2 (98%)/He(2%)

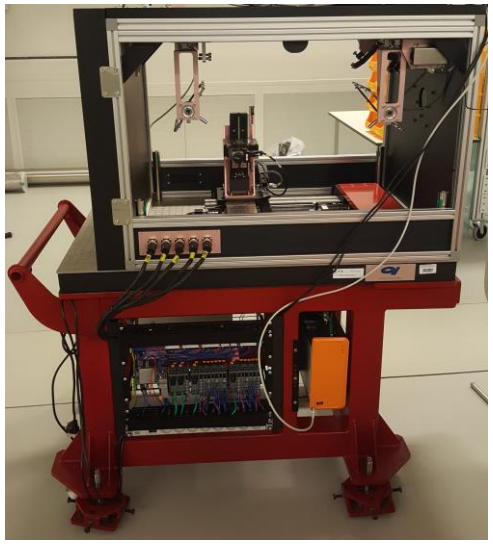
$n_e = 5.7 \times 10^{19} cm^{-3}$



Electron Beam L1 Laser



In-air User Station for sample irradiation



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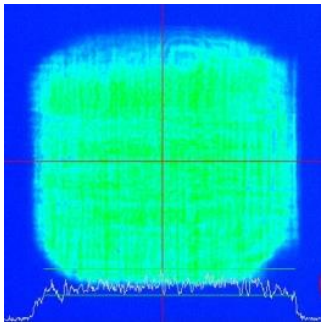
L4 ATON laser

kJ CPA system to provide 10 PW peak power

P. Trojek, B. Rus et al. (Dep.91)

Parameter	Achieved value
CPA pulse energy	1512 J significant headroom, higher energy possible
Bandwidth FWHM	~14 nm Gaussian fit non-optimized compressibility **154 fs**
Long pulse (LP) energy	1180 J significant headroom, higher energy possible
Pulse width / temporal shaping	<0.5-10 ns 125 ps with 60 ps rise time
Current shot rate	**1 per 2 minutes** (high beam wavefront quality) 1 per minute (moderate quality)

- Mixed Nd:glass in the power amplifiers providing spectral bandwidth >15 nm
  Pulse compression to ≤150 fs
- Advanced liquid cooling to achieve 1 shot /1 minute
- Nanosecond kJ pulses with programmable temporal shape
- Compact dimensions, laser tables footprint 19.8 m x 6.1 m
- Developed by National Energetics / EKSPLA / ELI-Beamlines



PA2 Beam size

- **323x323 mm kJ LP**
- **620x620 mm 10 PW**

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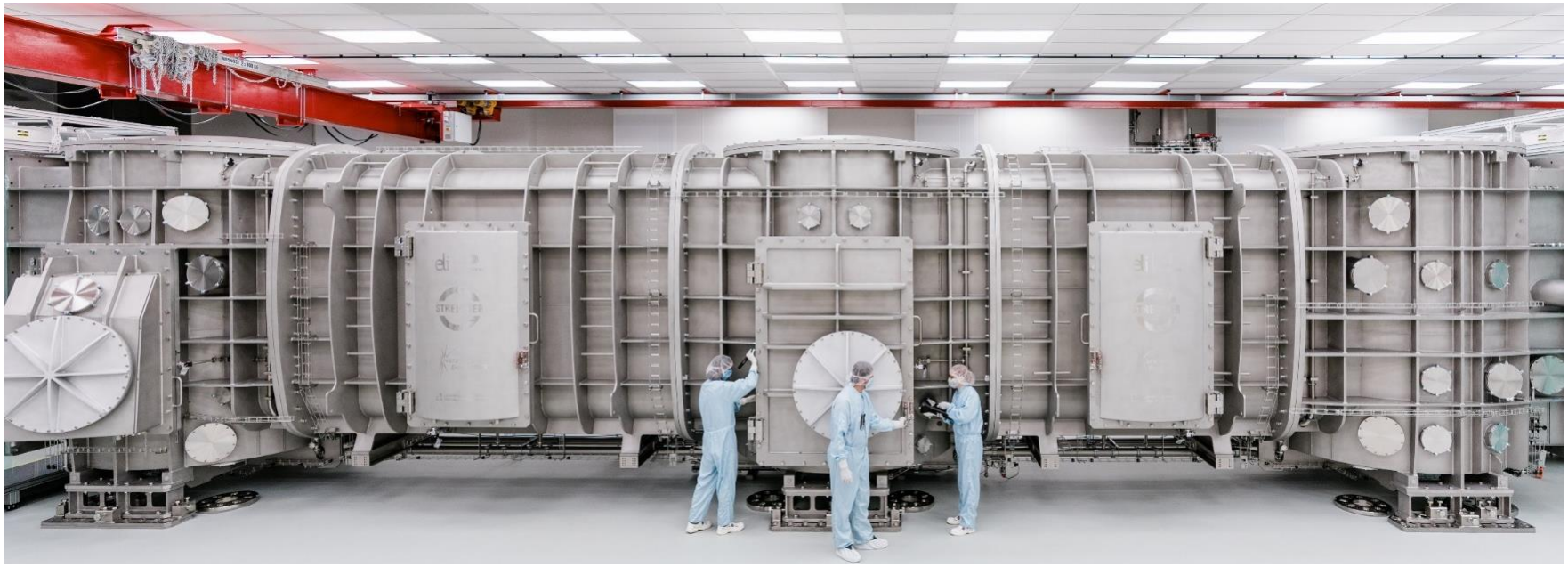
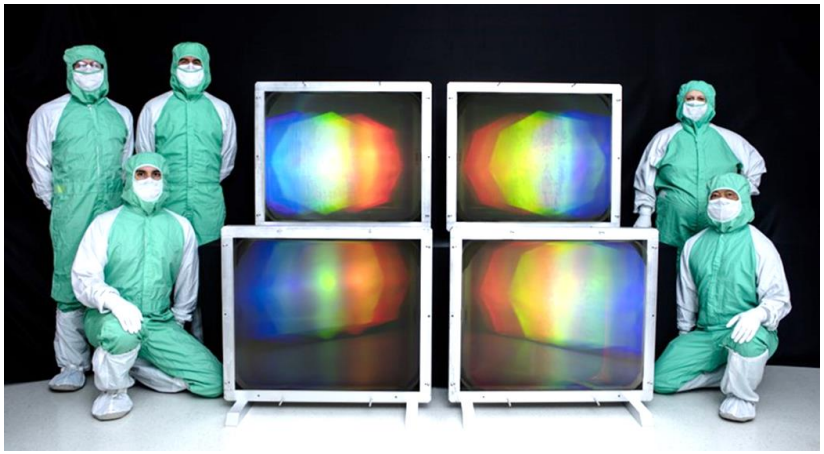
L4 ATON laser

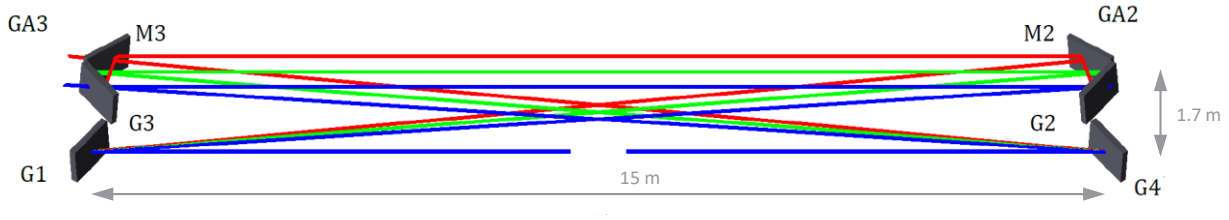
10 PW compressor

beamlines

P. Trojek, B. Rus et al. (Dep.91)







Courtesy of Diffractive Optics Group, NIF&PS, LLNL
High-energy, low-dispersion (HELD) multi-layer dielectric (MLD) diffraction gratings for L4

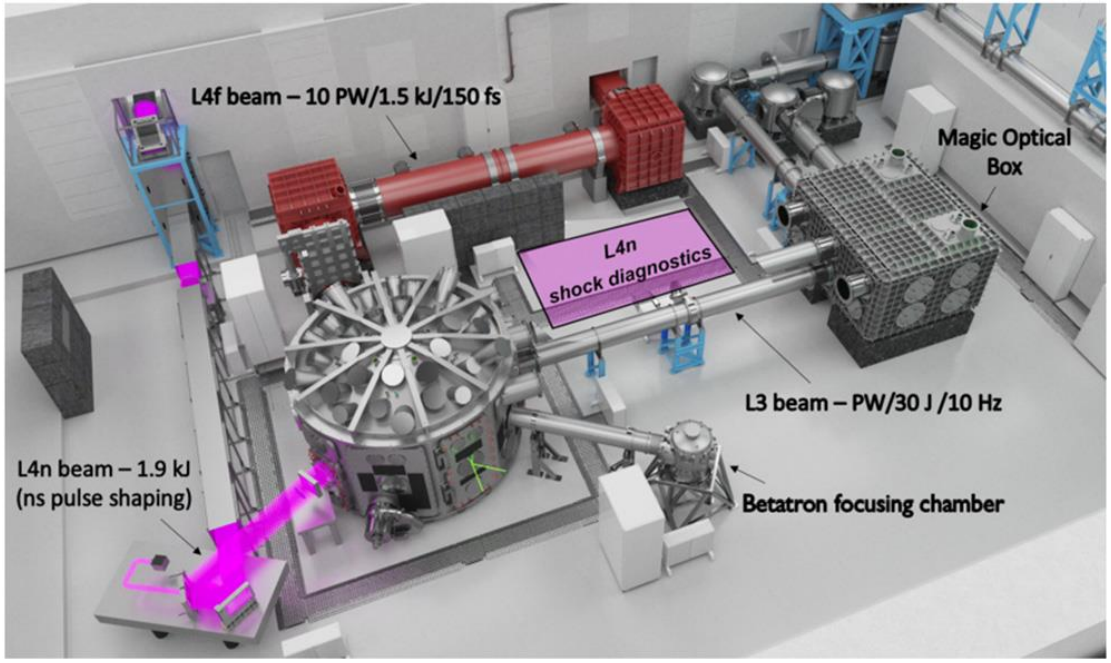
P3 experimental platform (E3)

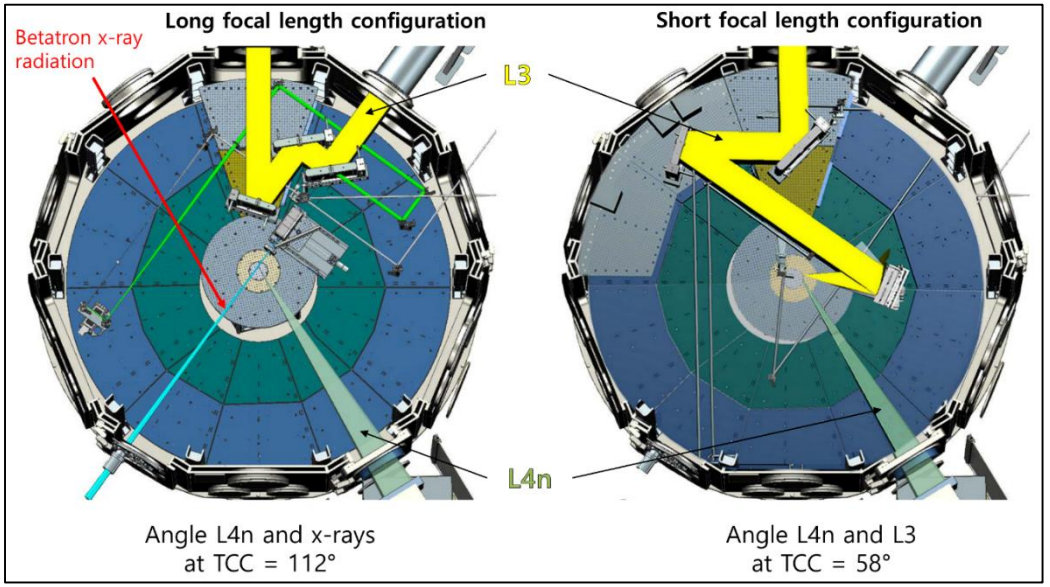
L4-ns + L3

beamlines

S. Weber et al. (Dep.89)

- ➔ **L4n as driver** to generate shocks & **L3 as diagnostic** tool
- ➔ **L3-SFL**: energetic protons (radiography), K-alpha, gammas (few MeVs); f/3 OAP, focal length 0.75 m
- ➔ **L3-LFL**: betatron broadband radiation, potentially electrons (?!); f/20 spherical mirror, focal length ~5 m





➔ L4n and L3 can be synchronized with a jitter of ~20 ps at present

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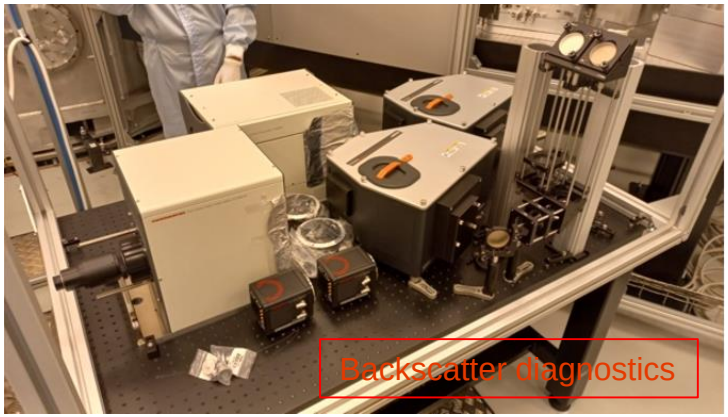
P3 experimental platform (E3)

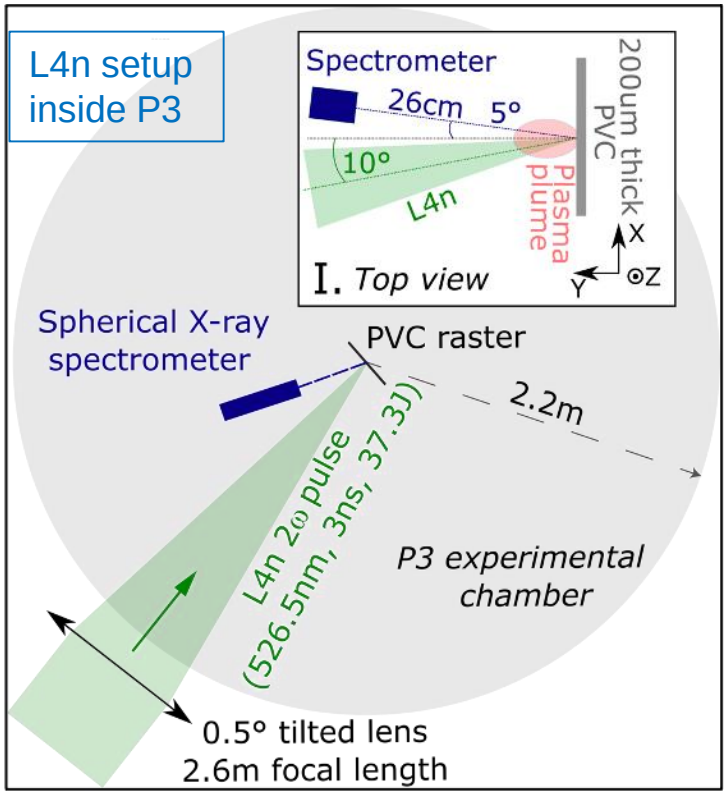
L4-ns @ ~1shot/min

beamlines

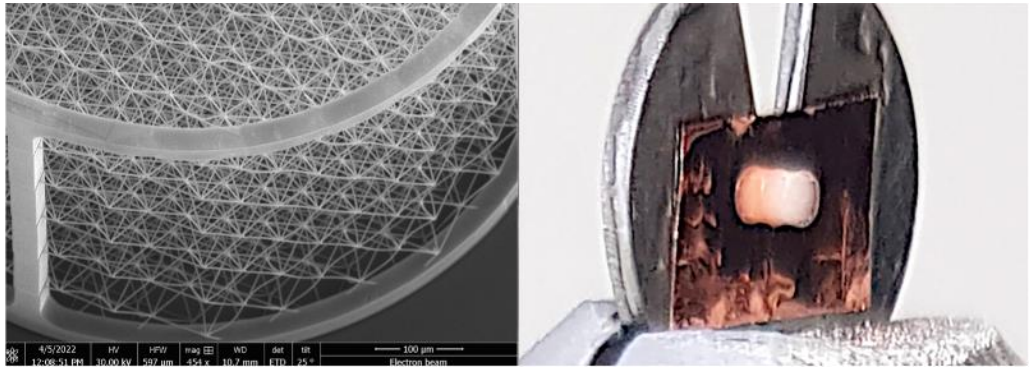
S. Weber et al. (Dep.89)

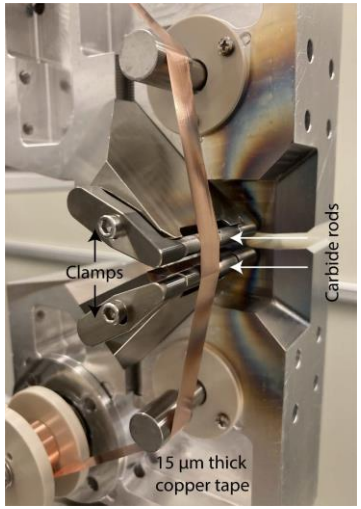
- using P3 as a potential platform for **HEDP** in general and **ICF/IFE** in particular
- time-resolved diagnostics for **LPI** (Raman, Brillouin, TPD) and **shock physics** (VISAR/SOP) in commissioning stage





- Hard X-ray **diagnostic** available inside the chamber
- **Targetry**: solid, gas, multi-layer and foam on tape & raster





multi-layer targets for shocks developed by ELI-NP for P3

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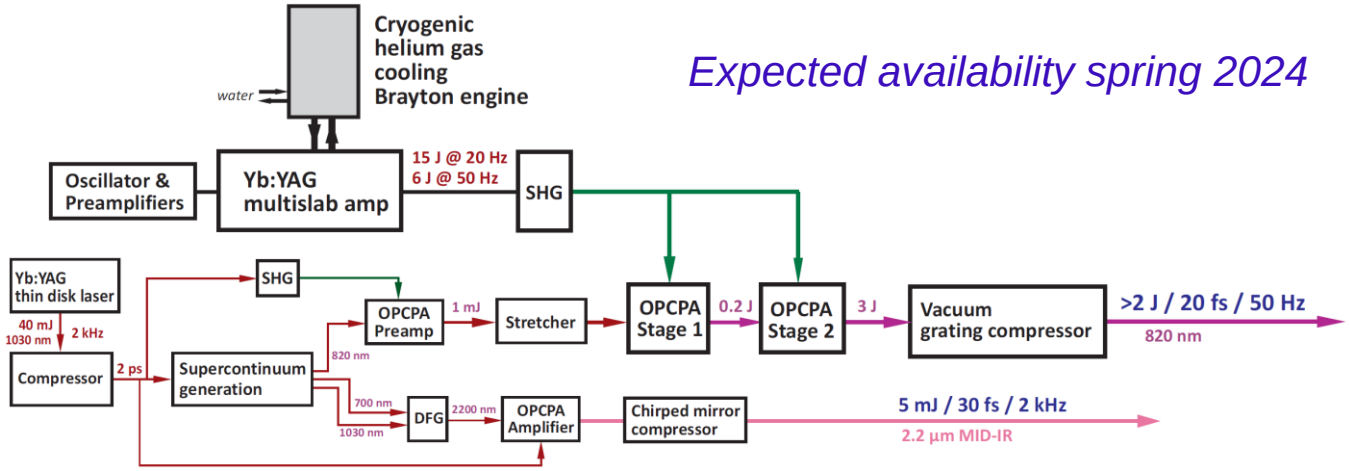
L2 DUHA (R&D – ADONIS)

>100 TW 20/50 Hz system with mid-IR aux beam

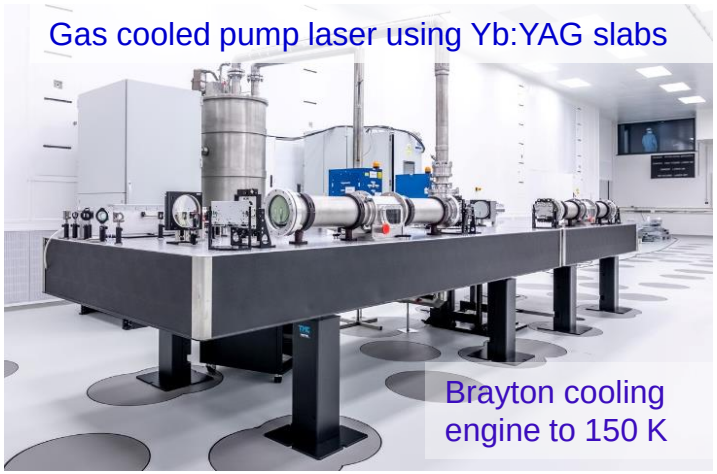
beamlines

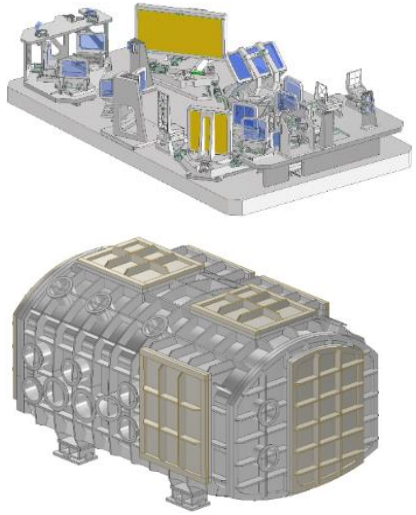
J.T. Green, B. Rus (Dep.91)



Expected availability spring 2024

- 2J / 20fs / 50 Hz (100Hz)
- Nanosecond OPCPA
- Pump laser: 15 J @ 1030 nm DPSSL Yb:YAG
- Thin disk ps laser driving supercontinuum in bulk YAG: seed for high-energy OPCPA @ 820 nm & generation of 2.2 µm in DFG





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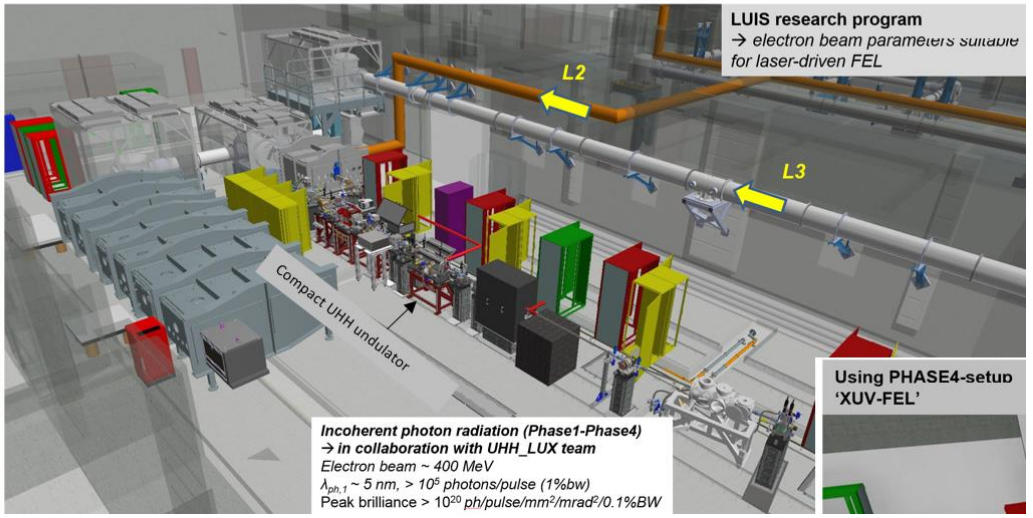
LUIS in E5 (R&D – ADONIS & EUPRAXIA)

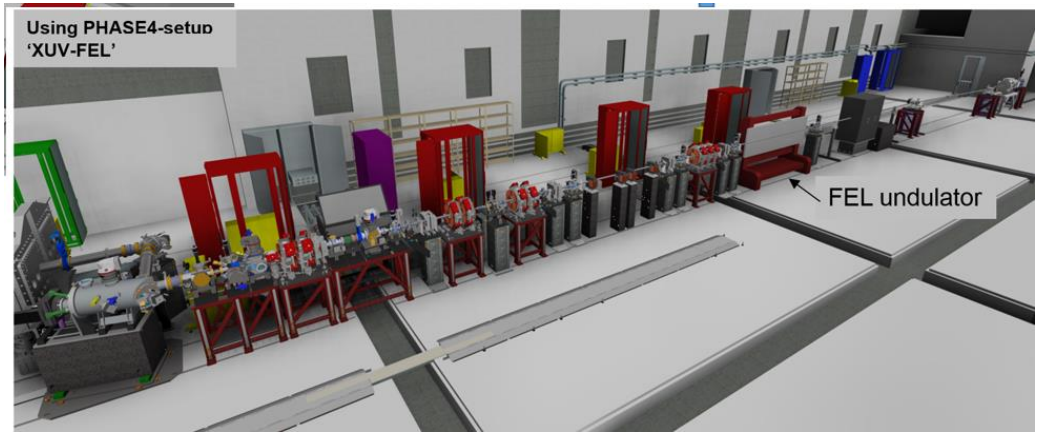
high quality LWFA electron beams for FEL with L2

A. Molodozhentsev, S.V. Bulanov (Dep.86)

LUIS technologies in the E5-experimental hall

from incoherent to coherent (FEL) photon radiation





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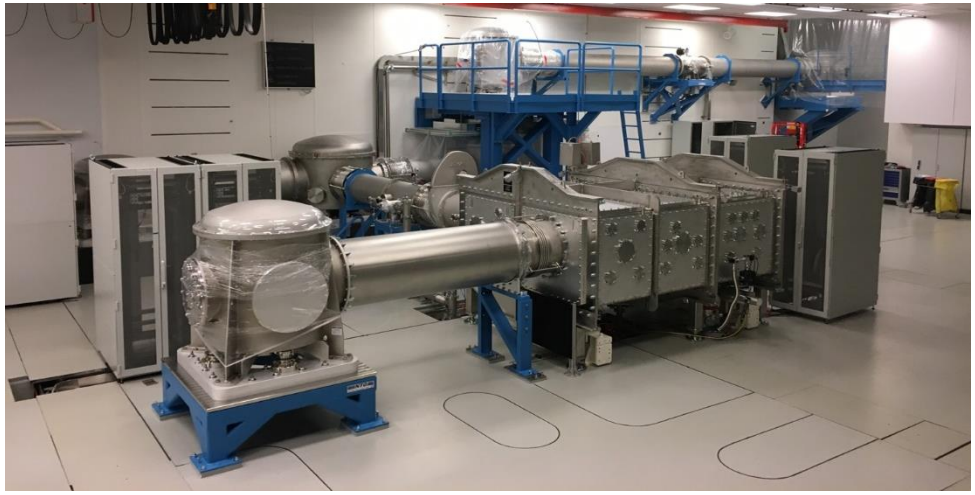
Gammatron beamline in E2 (R&D – ADONIS)

Betatron/Compton X-ray sources in E2/E3

U. Chaulagain, J. Nejdl, S.V. Bulanov (Dep.86)

Driven by L3 (or L2) @ 10Hz (or 100Hz)

	Betatron	Compton
photon energy	10- 100 keV	50 – 5000 keV
photons/shot	> 1E9	> 1E8
Source size	< 5 µm	< 5 µm
pulse duration	~30 fs	< 30 fs



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Outline

- **ELI Beamlines**
  facility overview

- **User Programme**
  - *current user offer*
  - *future user capabilities*

- **Flagship Experiments**

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ELI BL Flagship I (IMPULSE)

XUV tuning in E1, J. Andreasson

Title: *"Studies of collective dynamics at the nanoscale using intense, spectrally-tunable XUV pulses from High-Harmonic Generation"*

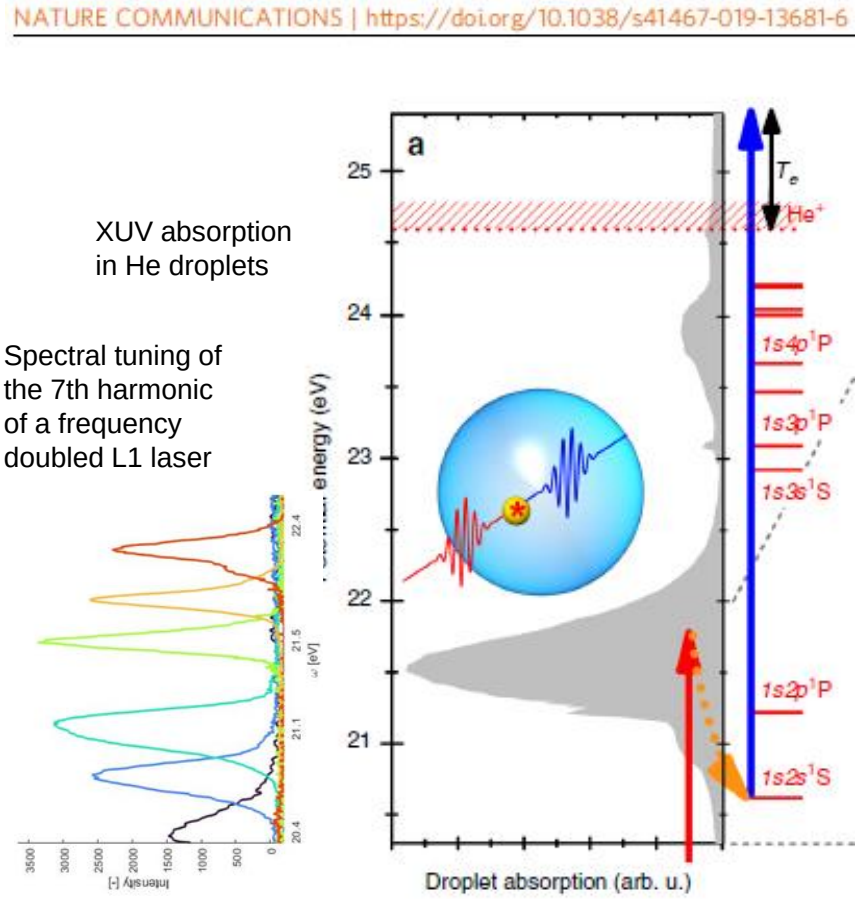
Objectives:

- Experiments targeting "**Resonant excitation of multiply excited pure and doped helium nanodroplets**"
- Extend the applicability of the developed method to cover a **wider range of targets and pulse parameters** (mainly a wider range of XUV energies).

Means: L1 Alegra laser, E1 HHG source, MAC experimental station

Tasks: Improve on the ability to rapidly tune the photon energy to allow a scan to be done in one experimental day. Extend to higher XUV energy ranges

Talk by Marcel Mudrich (afternoon)



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ELI BL Flagship II (IMPULSE)

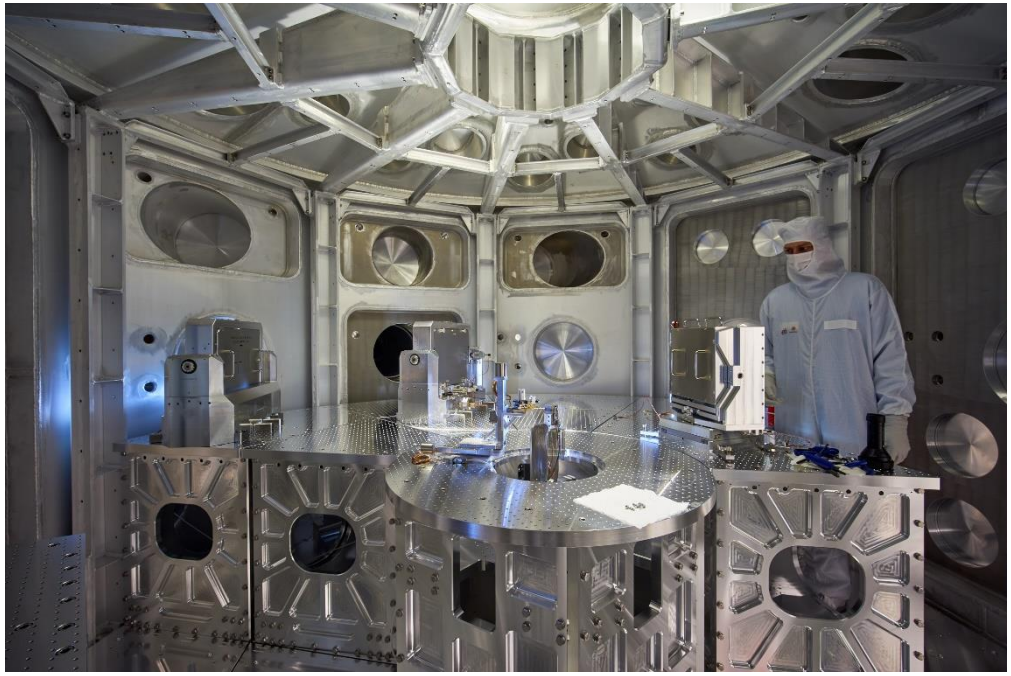
***MULTI-LPI-P3**, S. Weber*

Title: *"Probing dense laser-plasma with ultrafast X-rays & accelerated particles in the context of inertial confinement fusion & laboratory astrophysics"*

Objective: Characterization of shocked material with a variety of diagnostic tools using synchronized **multi-beam configurations**. The **pulse-shaping capabilities of the L4n** driver beam allows to access EOS off the Hugoniot, thereby providing new insight into complex, dynamic states of matter under extreme conditions.

Means: P3 infrastructure and L4n/L3 laser beamlines

Tasks: I. Characterize state of matter with VISAR/SOP.
II. Characterize state of matter with particle/radiation sources.



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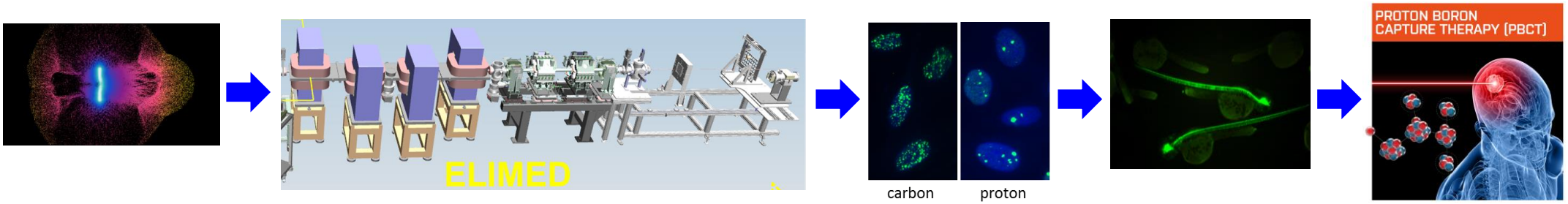
ELI BL Flagship II (IMPULSE)

***FLAIM**, L. Giuffrida*

Talk by Marco Borghesi (afternoon)

FLAIM at ELIMAIA

Flash and ultrahigh dose-rate radiobiology with Laser Accelerated Ions for Medical research

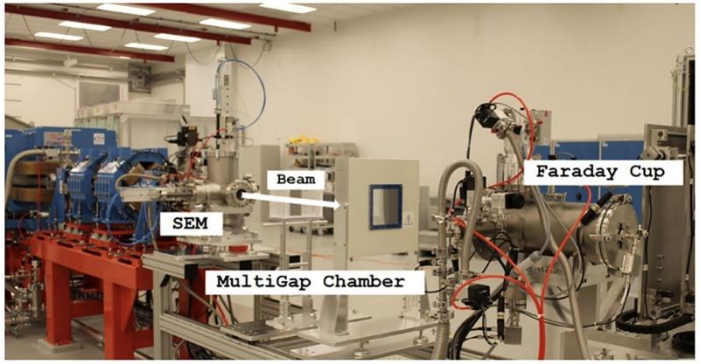


Scientific Impact

- ✓ innovative regimes for ion acceleration (**protons and C-ions**) with a PW-class laser at ELIMAIA at high rep. rate
- ✓ high beam quality through dedicated **ion beam transport** at ELIMAIA/ELIMED for irradiation of biological samples
- ✓ novel **clinical dosimetry** through dedicated on-line, cutting-edge diagnostics available at ELIMAIA/ELIMED
- ✓ **in-vitro** cell (cancer and healthy tissues) and **in-vivo** (zebra fish) **irradiation** with **proton/carbon** beams using **ultrahigh dose-rate and flash** radiotherapy approaches (10^9 Gy/s)

Technical Specifications:

- ✓ Laser parameters on target: **L3** (>10J, <30fs, >10^{21}W/cm^2, 0.01-1 Hz)
- ✓ **on-shot, full-power, on-target** laser, plasma, and ion **diagnostics**
- ✓ dedicated **ion beam transport** (ELIMED)
- ✓ on-shot, high rep. rate **clinical ion dosimetry** (ELIMED)
- ✓ dedicated radiobiology room or use of operational equipment in chemical/bio lab



- ✓ **1st ELI ERIC Call** for User proposals, published in June, submission deadline 31 August 2022 (17 proposals for ELI Beamlines)
- ✓ **ELI BL User Assisted Commissioning Call**, published in October, submission deadline 5 November 2022 (L3 @ ELIMAIA-ELIMED, L4-ns @ P3)
- ✓ **2nd ELI ERIC Call** for User proposals, to be published in January 2023, including high power laser capabilities like L3 HAPLS (PW-class, 3.3 Hz) and L4 ATON (kJ-class, ns)

Questions

Thank you for you kind attention!

Partnership