COST ACTION CA24131
European Network for radiation-detection based Research and Innovation addressing increasing societal CHallenges (ENRICH)

ENRICH

Jaroslav Nejdl

Extreme Light Infrastructure ERIC
ELI Beamlines Facility, Czech Republic

Laser-Driven X-ray Sources at ELI Beamlines for Ultrafast Spectroscopy, Diffraction, and Imaging

COST ENRICH Annual Meeting, July 14 2026, Krakow, Poland

COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

Outline

- The ELI European Research Infrastructure Consortium (ELI ERIC)
  - ELI ERIC Mission
- The ELI Beamlines Facility
  - Laser systems
  - Laser-driven X-ray sources and selected applications
    - HHG Beamline
    - Plasma X-ray source (Cu-Kα)
    - Plasma betatron beamline (Gammatron)

ELI's Mission

Enables **cutting-edge research** by managing access to **world-class lasers** and technologies through open, peer-reviewed, excellence-based access for a **broad user community**.

ELI advances science by providing cutting-edge instruments for users, fostering **collaboration across disciplines** and borders, and supporting excellence through training, **technology development**, and outreach to new communities.

eli

eli

ELI Facilities

- **ELI Beamlines**, development of ultra-intense lasers (TW – PW) for exploring extreme conditions and driving secondary sources (XUV, x-ray, electrons, ions)

Prague (Dolní Břežany), CZ

- **ELI Attosecond Light Pulse Source (ALPS)**, ultrashort pulse generation, THz and x-ray sources for time-resolved investigation of nonrelativistic and relativistic interaction of light with all the four states of matter.

Szeged, HU

- **ELI Nuclear Physics** with 2 ultra-intense lasers (10 PW) and brilliant gamma beams (up to 19 MeV) from linear accelerator (Compton back scattering) to produce and explore new nuclear states or generate neutron beams.

Magurele, RO

Bringing together a world of science

ELI ERIC

- ▪ Host
- ■ Member
- ■ Observer

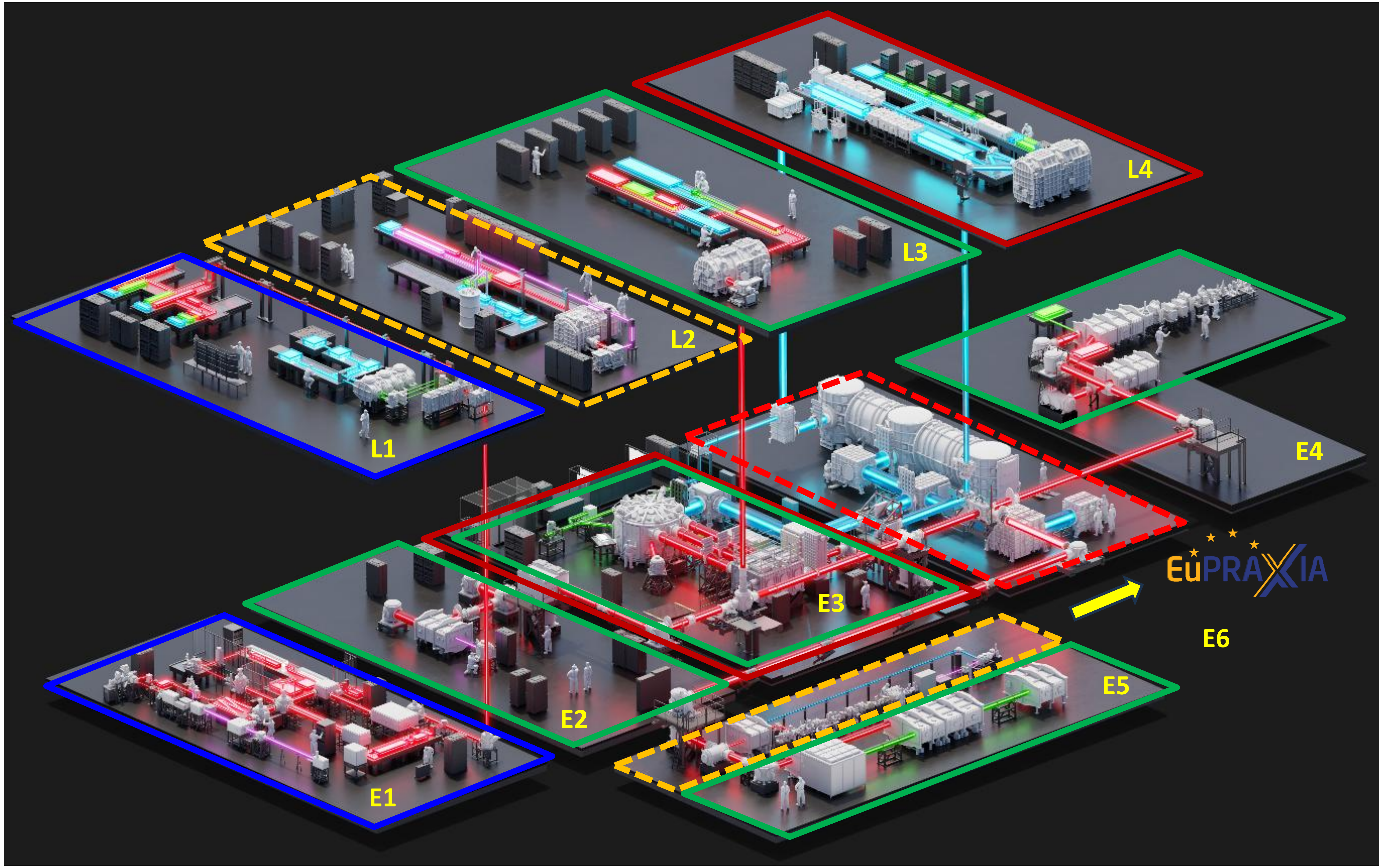
ELI Beamlines

Dolní Břežany, Czechia

ELI Beamlines Facility Offer

user operations, commissioning, development

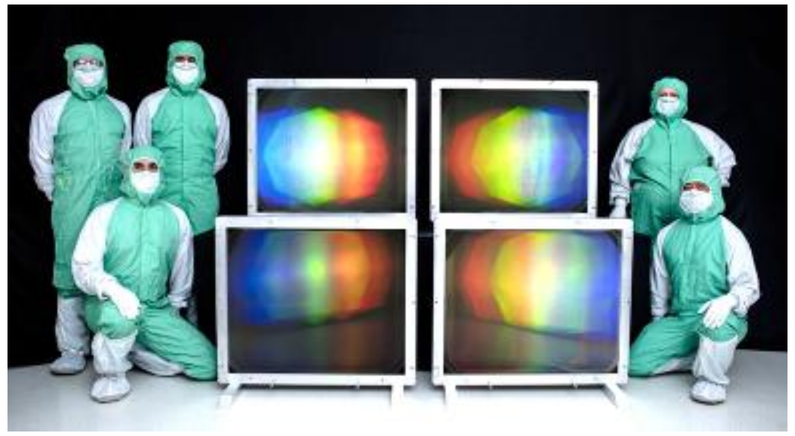
- L1-E1 user operation (Call1)
- L3-ELIMAIA user operation (Call2)
- L3-ELBA/ELIMED user operation (Call3)
- L3-Gammatron (Call5)
- L3-P3 SFL/LFL (IFE mission)
- L4n-P3 user operations (Call2)
- L4f 10 PW (Call8)
- L2-LUIS (R&D)

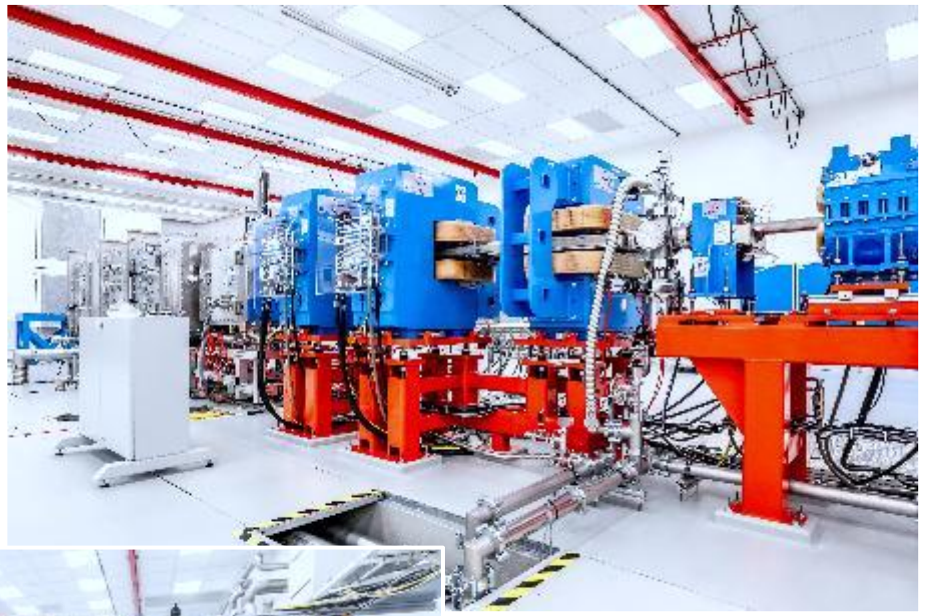


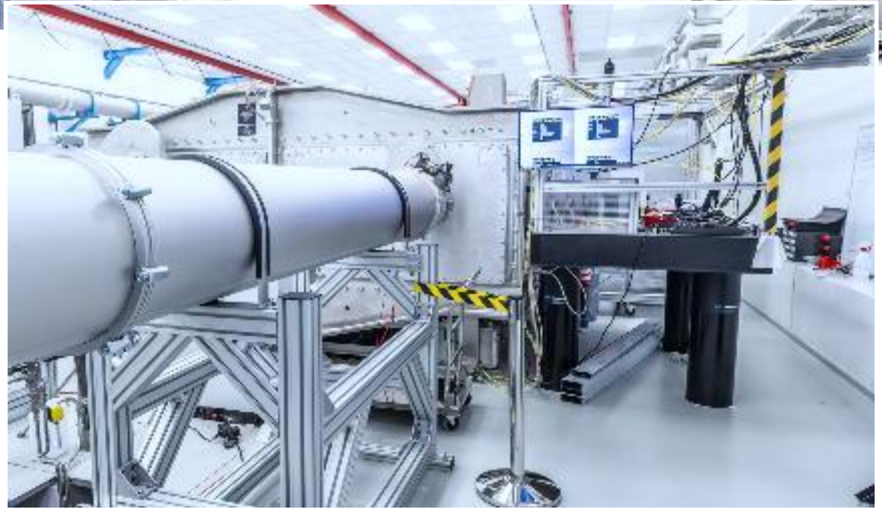
ELI BL Instrument Current Performances

primary/secondary sources offer

Primary source	Performance on target
L1-ALLEGRA	~50 mJ, 15 fs, 3 TW, 1 kHz, 800 nm
L3-HAPLS	15 J, 30 fs, 0.5 PW, up to 3.3 Hz, 850 nm
L4n-ATON	1.2 kJ (0.6 kJ@2w), 2-10 ns, 1 shot/2 min, 1055 nm
L4f-ATON	0.8 kJ, 150 fs, 0.5 PW, 1 shot/2 min
L2-DUHA	under implementation





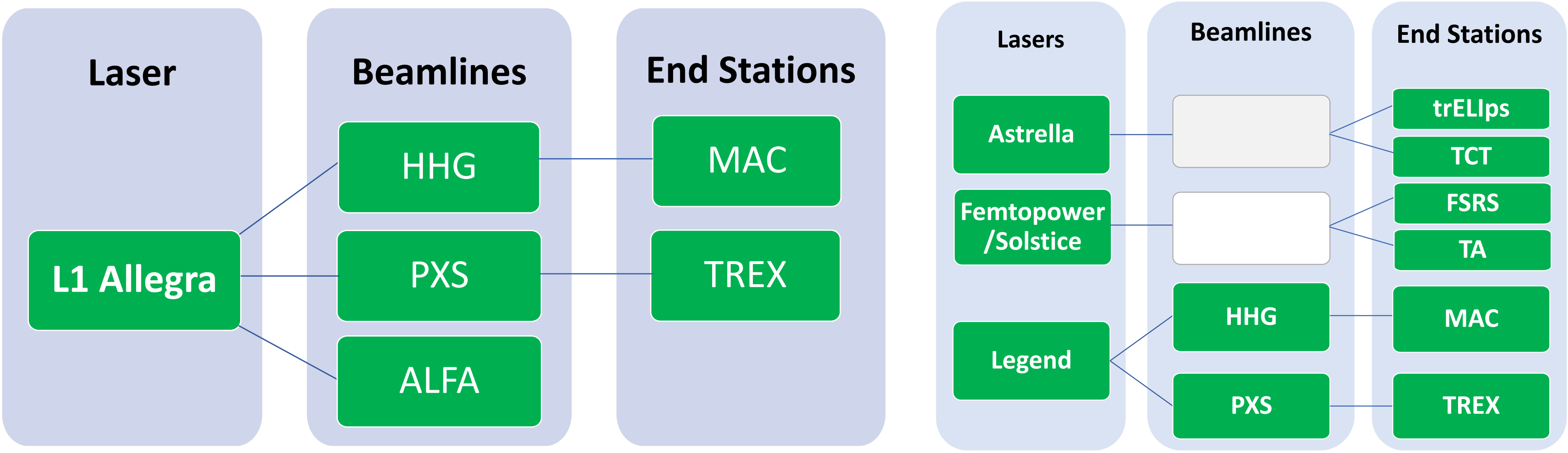


Secondary source	Performance on target
HHG	5-120 nm photons, 1 kHz
PXS	3-30 keV, 8 keV photons, 1 kHz
ALFA	30 MeV electrons, 1 kHz
ELIMAIA	40 MeV protons, up to 1 Hz
ELBA	4-5 GeV electrons, up to 3.3 Hz
Gammatron	20 keV X-rays, up to 3.3 Hz
LUIS	under implementation

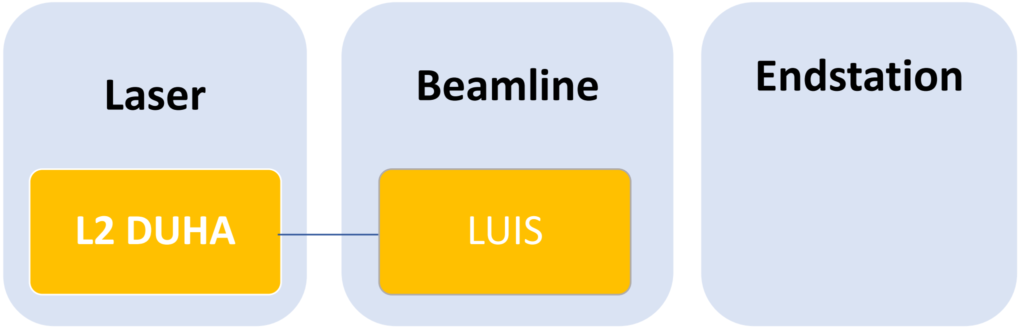
Instrument Dependencies

experimental chains

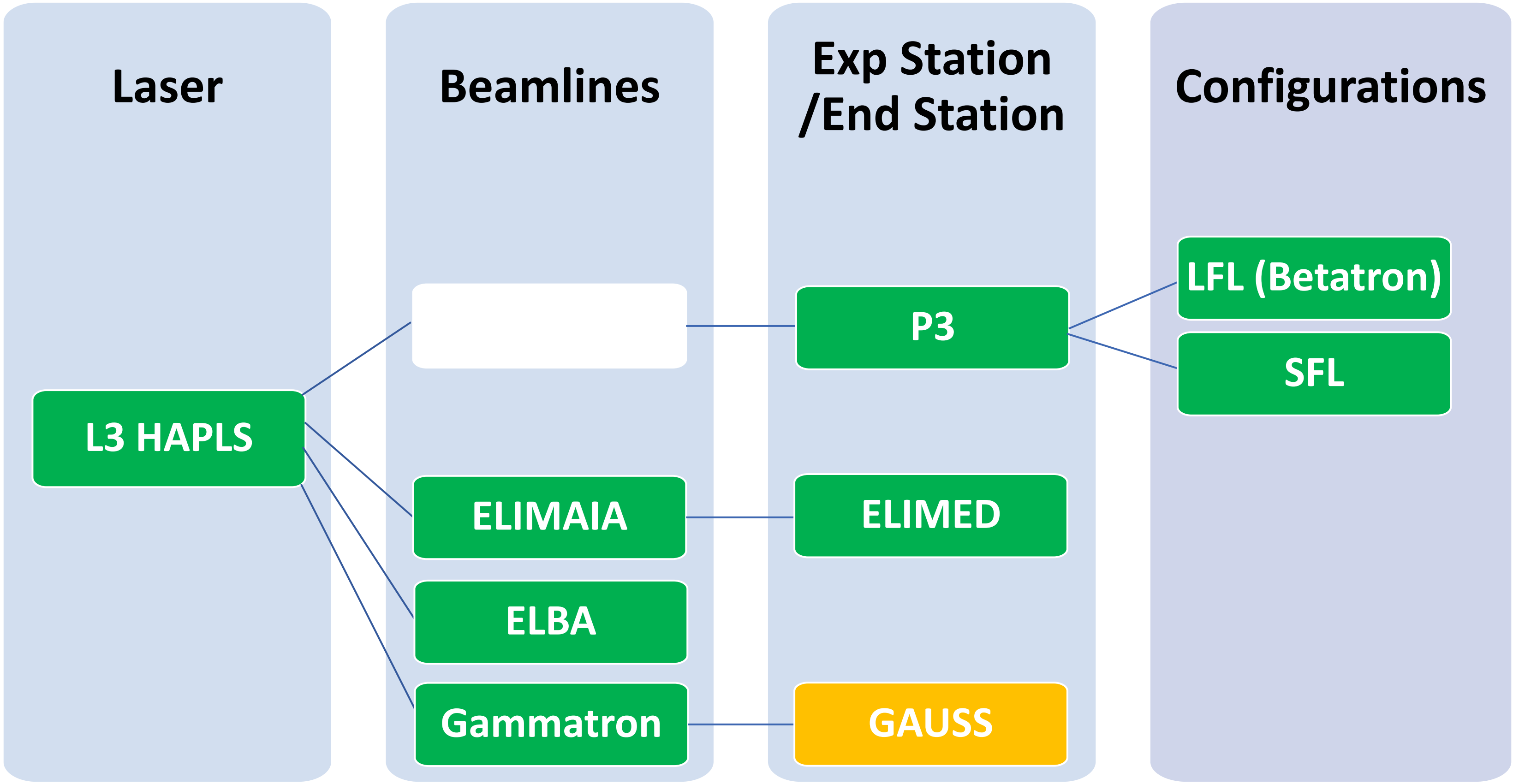
kHz-driven exp



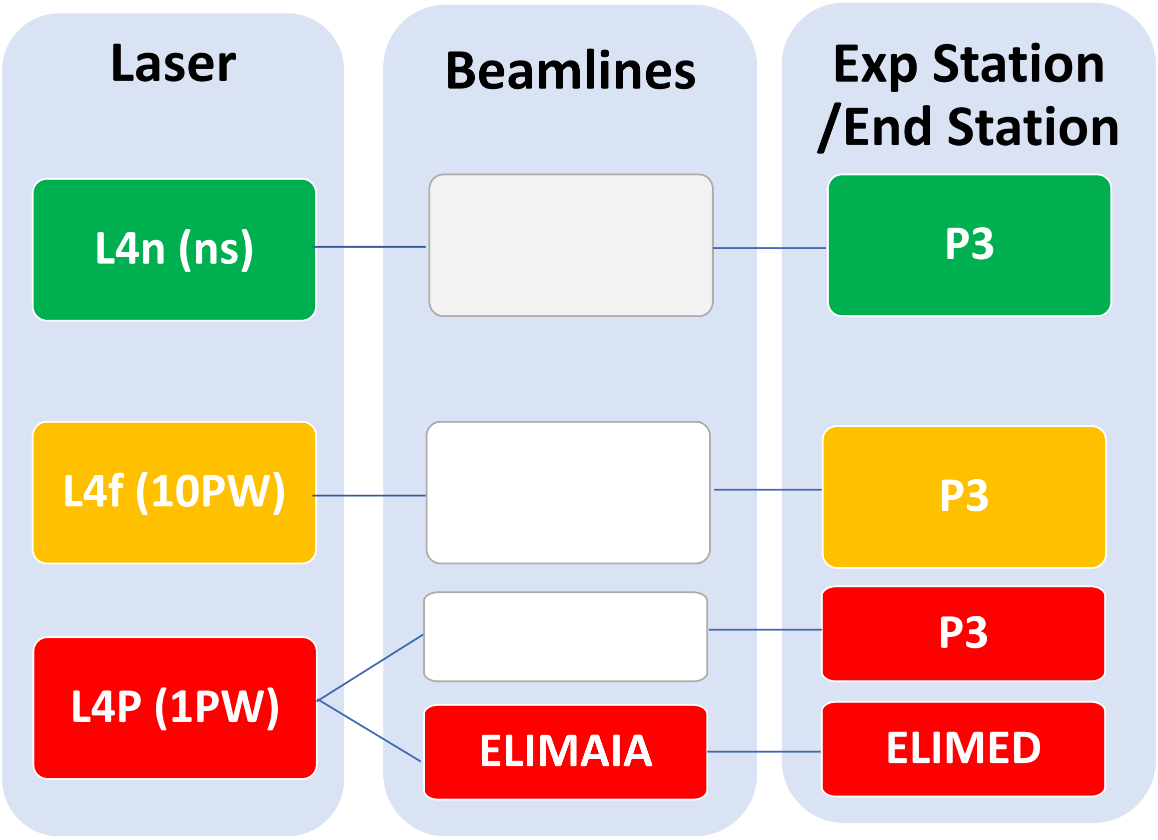
20-100Hz-driven exp



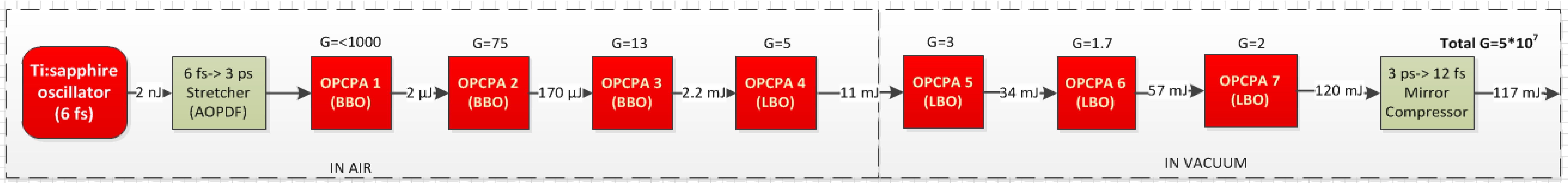
PW-driven exp



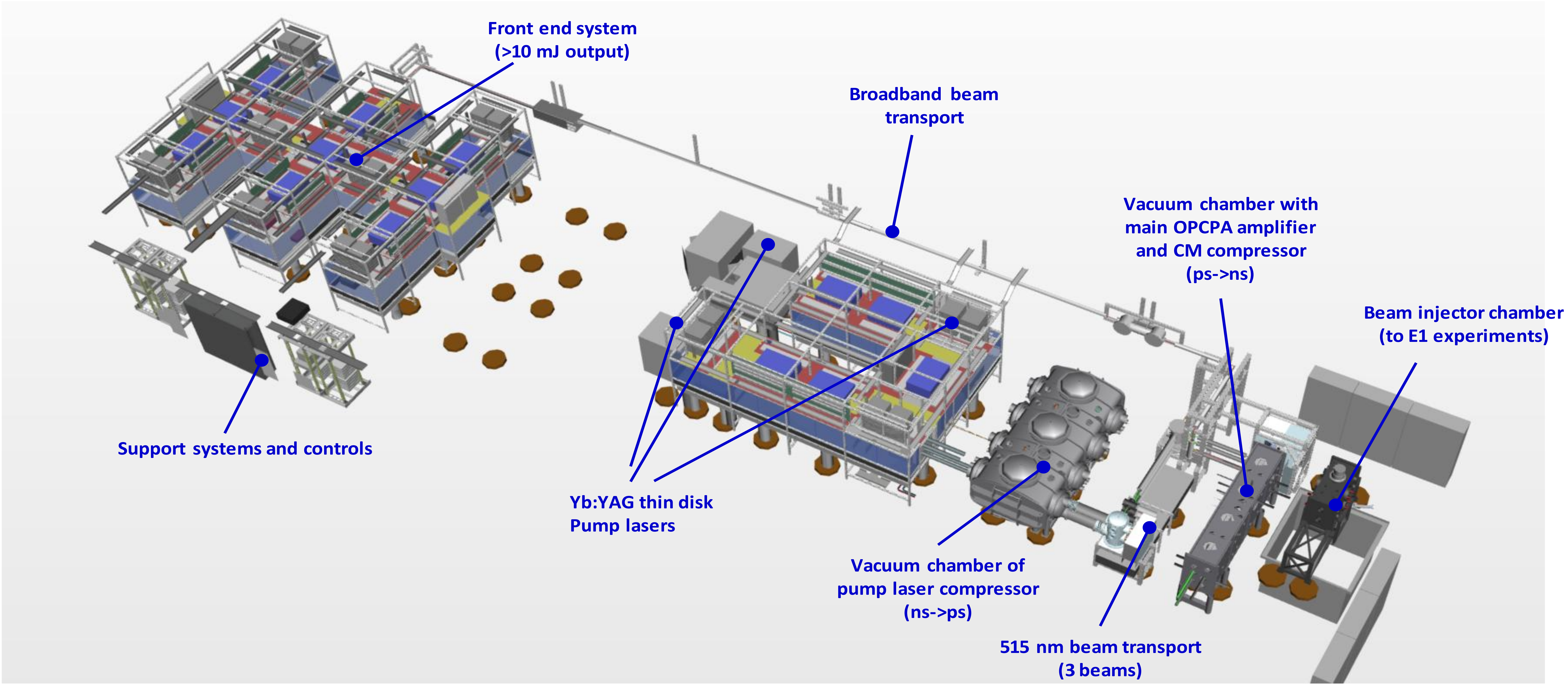
kJ-driven exp



Laser drivers: **L1 Allegra**

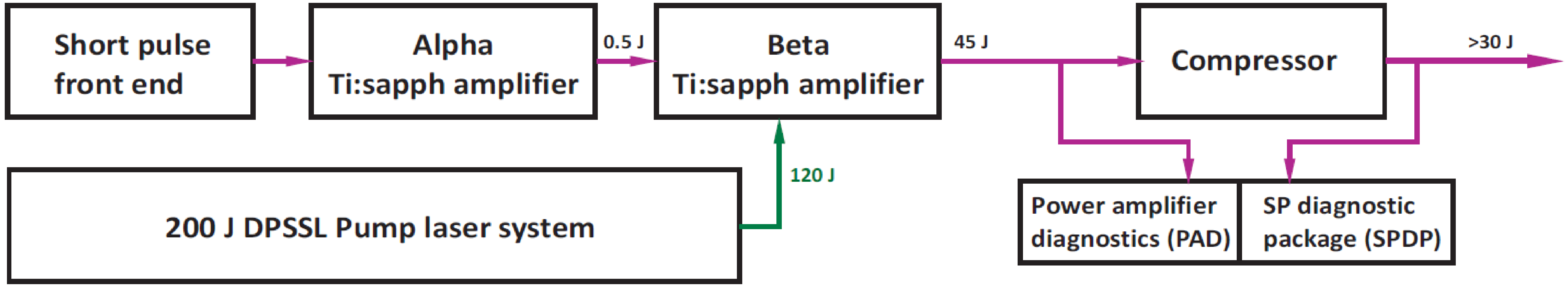


50 mJ / 15 fs / 1 kHz laser system, very high temporal pulse contrast $>10^{11}$ using ps pump pulses



Laser drivers: **L3 HAPLS**

HAPLS: High repetition rate Advanced Petawatt Laser System



L3-HAPLS with compressor at ELI-Beamlines

Parameter	Design	Current
Peak power	1 PW	**500 TW**
Repetition rate	10 Hz	**3.3 Hz**
Pulse energy	30 J	**15 J**
Pulse duration	30 fs	**30 fs**

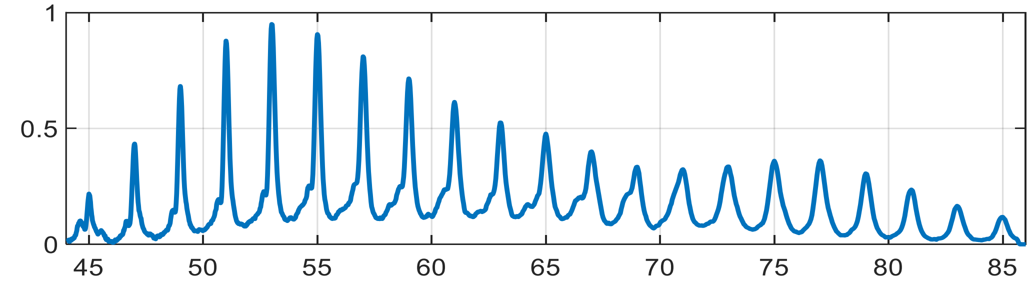
Laser driven X-ray sources: several approaches

E1

L1 driver

1 kHz, 100 mJ, 20 fs

High-order harmonic beamline



	Legend: 10 mJ, 35 fs	L1 Allegra: >20 mJ, ~15fs
Wavelength	10 -120 nm	5 -120 nm
Photons/shot	10^7 to 10^9	few 10^9 -10^{12}
Duration	< 20 fs	< 10 fs
Polarization	Linear	Lin./Circ./Eliptic

Ti:sapphire backup

1 kHz, 12 mJ, 35 fs
& 10 Hz, 100 mJ, 40 fs

Plasma X-ray source

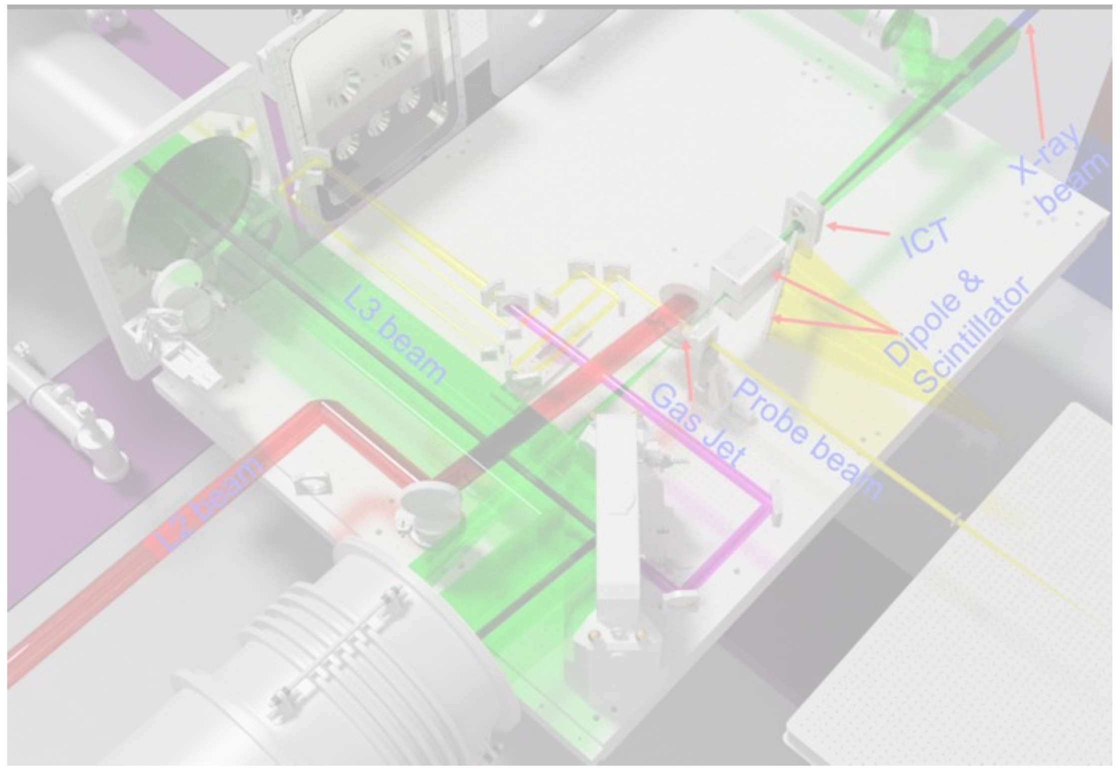
	10 mJ, 35 fs	20 mJ, 15 fs
photon energy	3 - 40 keV	3 – 80 keV
Kα photons /shot/(4π sr)	> 10^8	> 10^9
Source size	30 µm	30 µm
pulse duration	< 300 fs	<300 fs

E2/E3

L3 driver

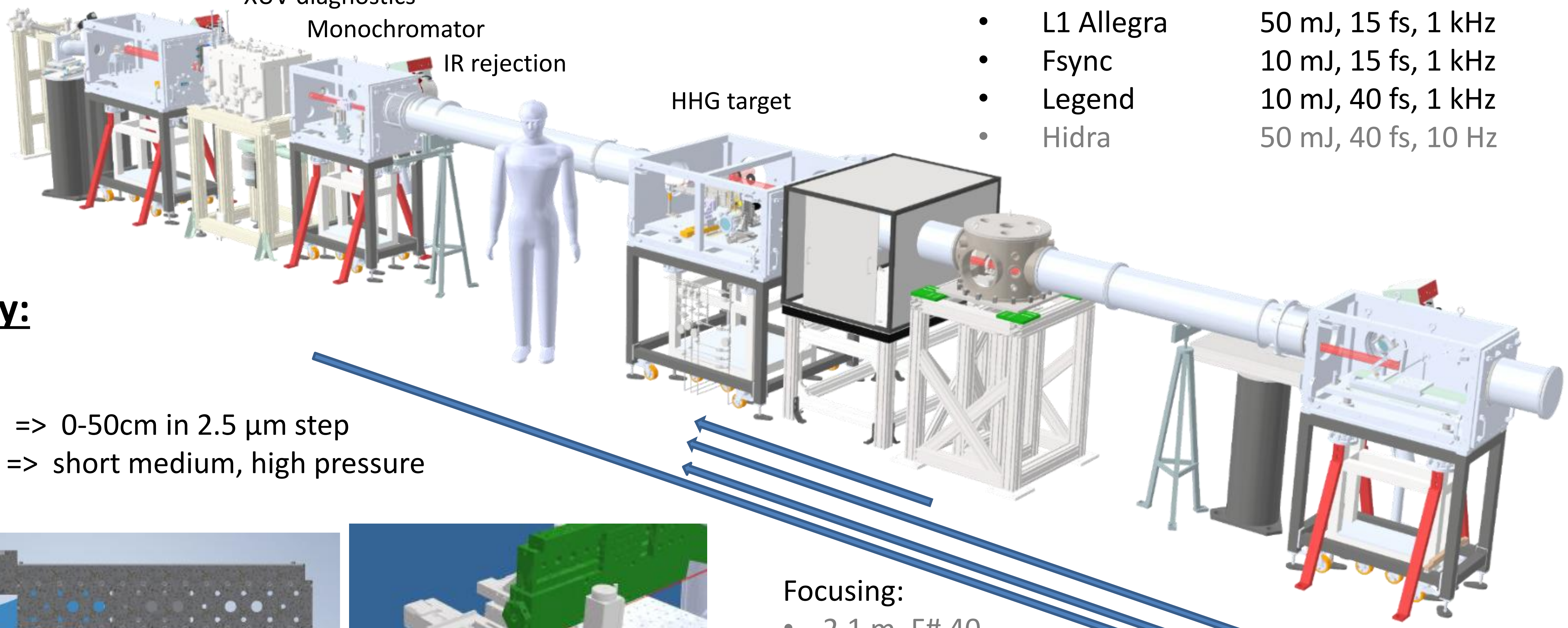
10 Hz, 30 J, 30 fs

Betatron / inverse Compton



	Betatron	ICS
photon energy	10- 100 keV	50 – 5000 keV
photons/shot	> 10^9	> 10^8
Source size	< 5 µm	< 5 µm
pulse duration	~30 fs	< 30 fs

User-oriented HHG Beamline

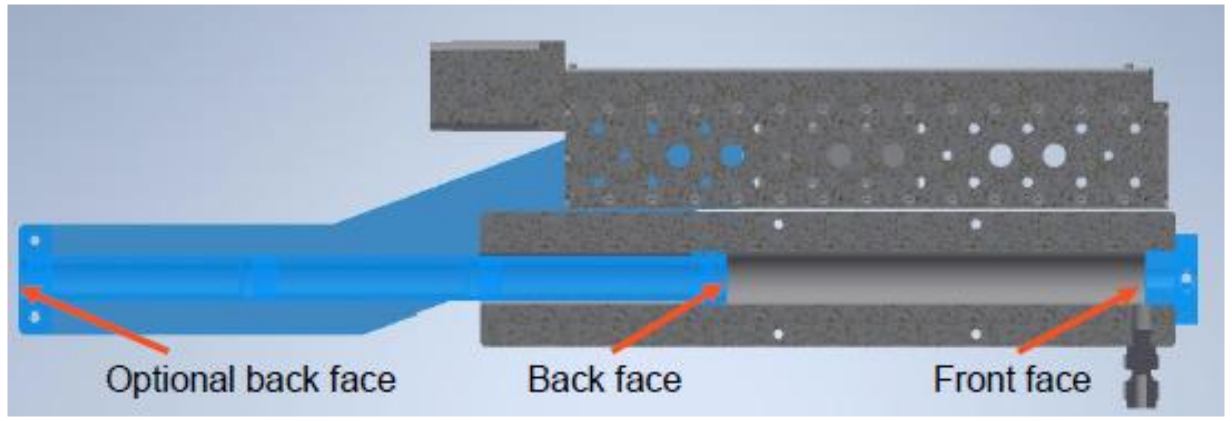


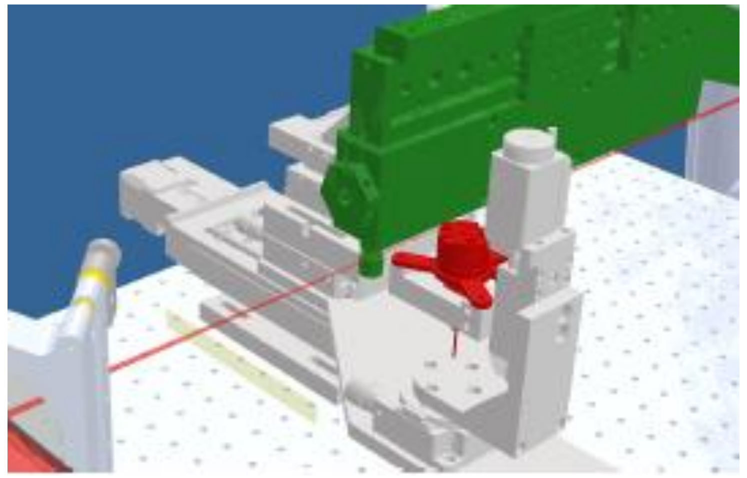
Available driving lasers

•	L1 Allegra	50 mJ, 15 fs, 1 kHz
•	Fsync	10 mJ, 15 fs, 1 kHz
•	Legend	10 mJ, 40 fs, 1 kHz
•	Hidra	50 mJ, 40 fs, 10 Hz

Targetry:

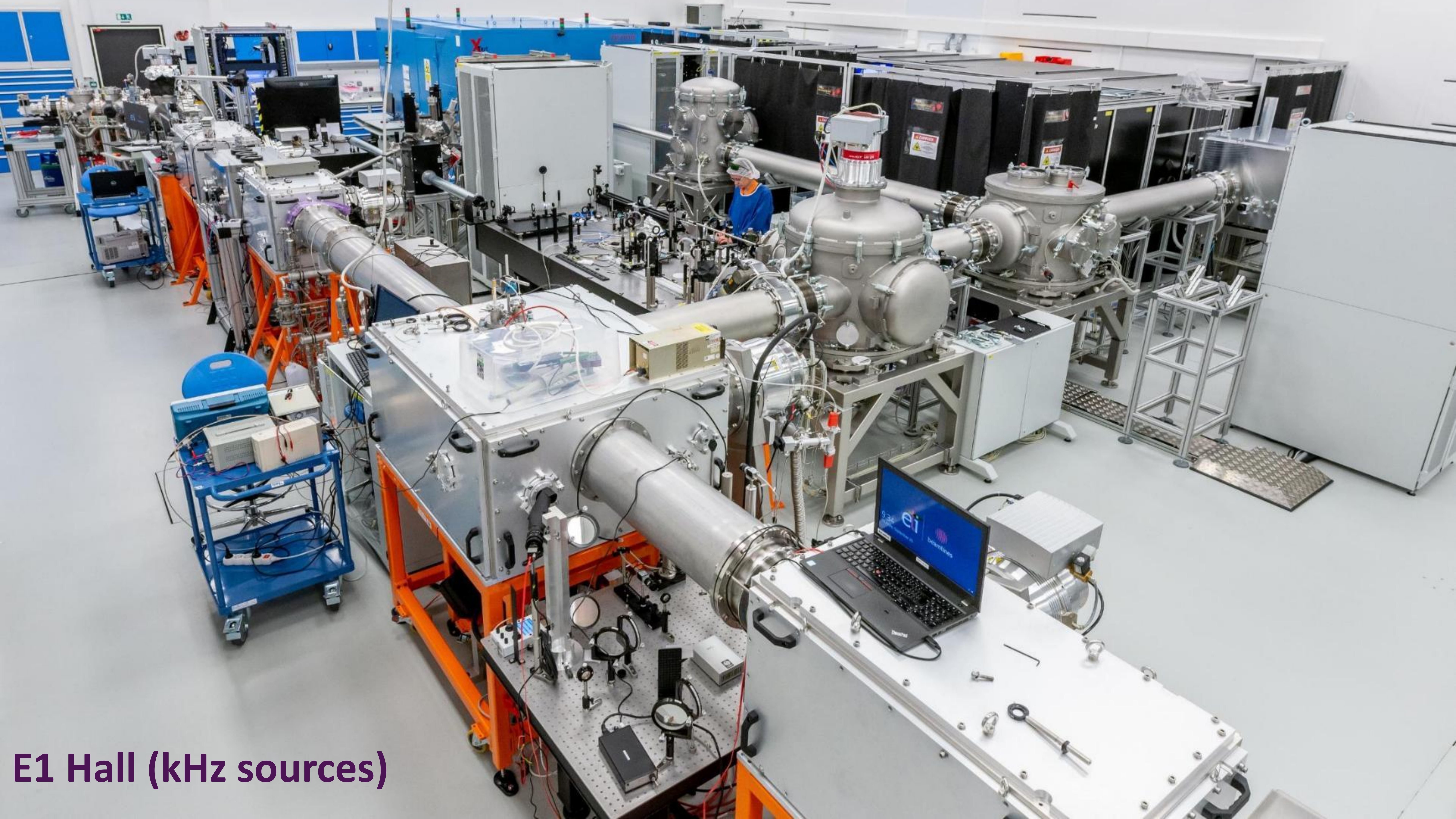
- **Motorized gas cell** => 0-50cm in 2.5 µm step
- **Even-Lavie valve** => short medium, high pressure





Focusing:
- 2.1 m, F# 40
- 5 m, F# 100
- 14.5 m, F# 300

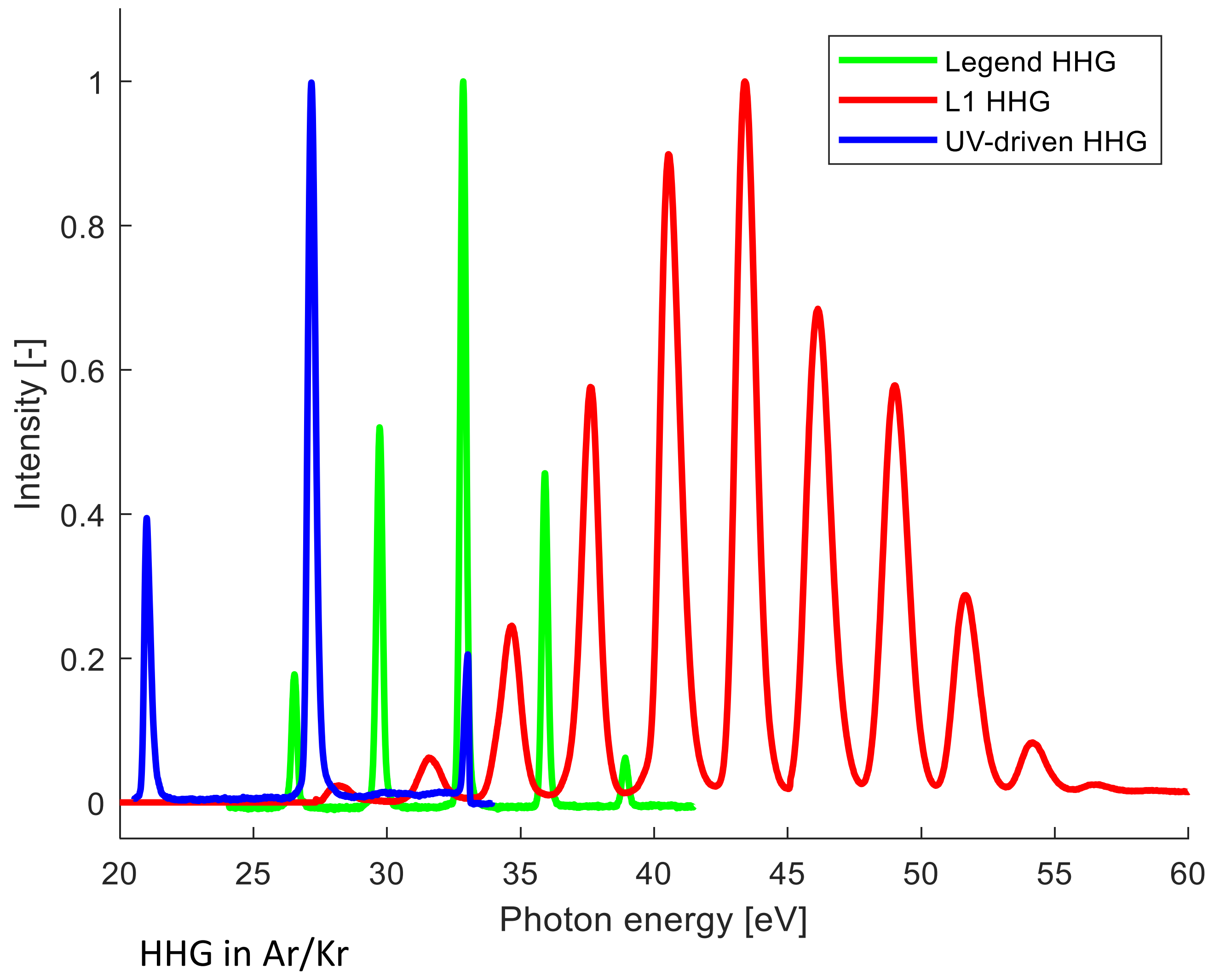
O. Hort et al., Opt. Exp. **27**, 8871 (2019)



E1 Hall (kHz sources)

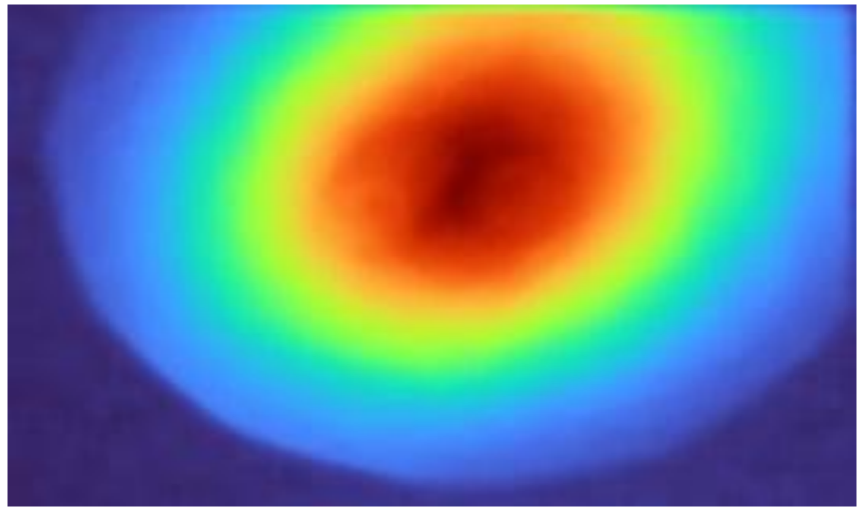
User-oriented HHG Beamline

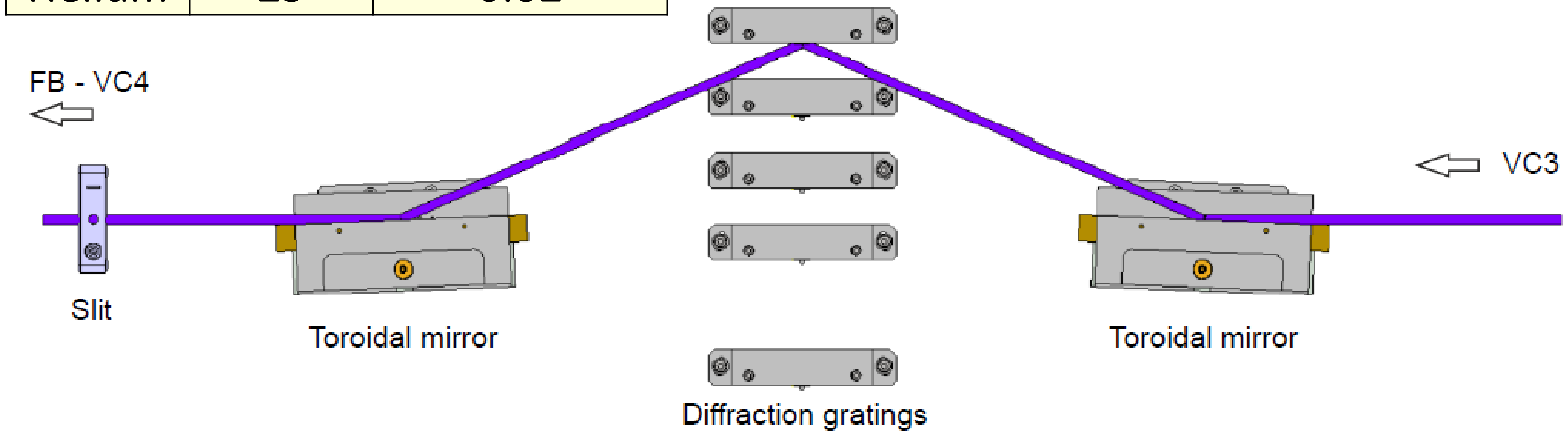
- Basic set of diagnostics (XUV pulse energy, spectrum, WF)
- Grating monochromator (1 mrad CA, 20% eff.)



Gas	λ_{XUV} (nm)	Estim. XUV energy (μJ)
Xenon	≥50	2
Argon	≥30	0.2
Neon	≥10	0.02
Helium	≥5	0.02

XUV beam profile



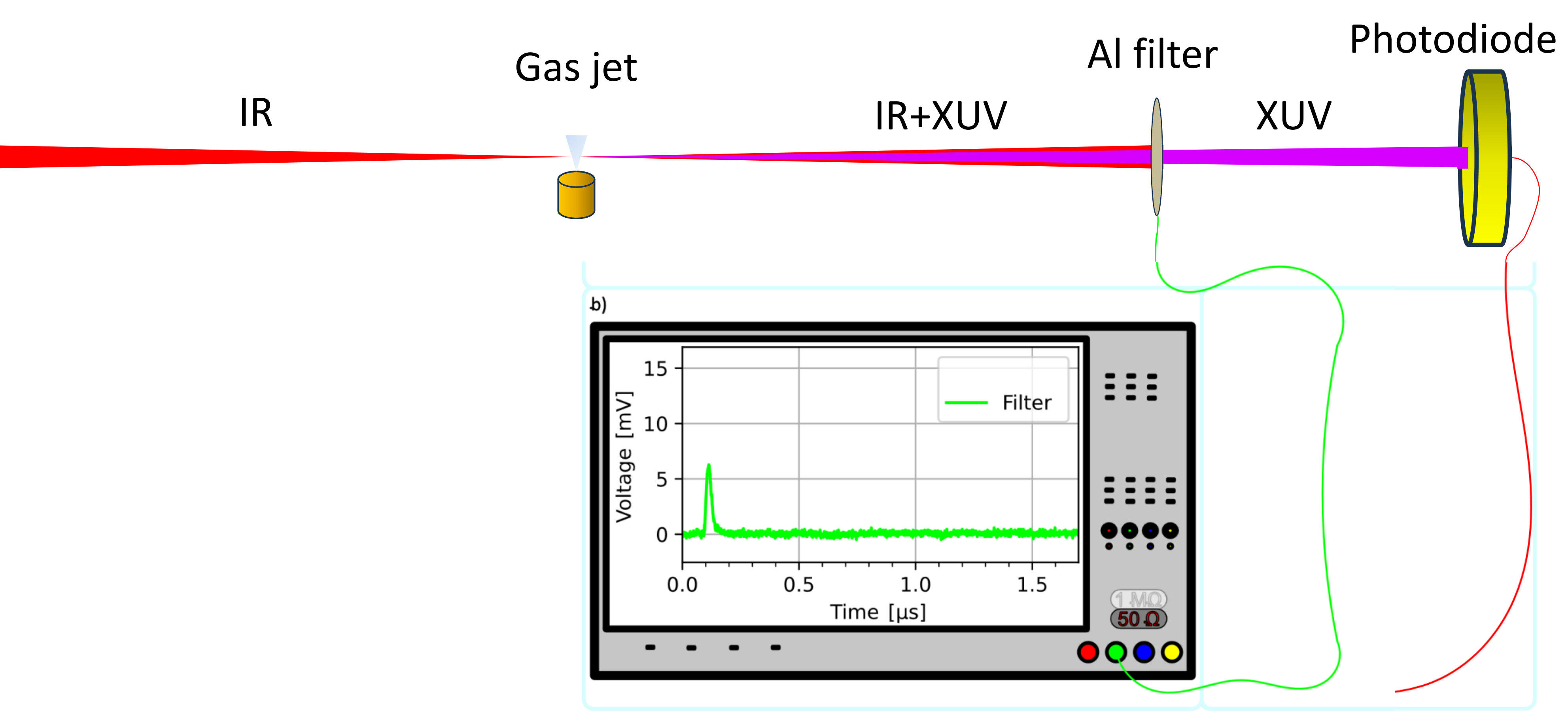


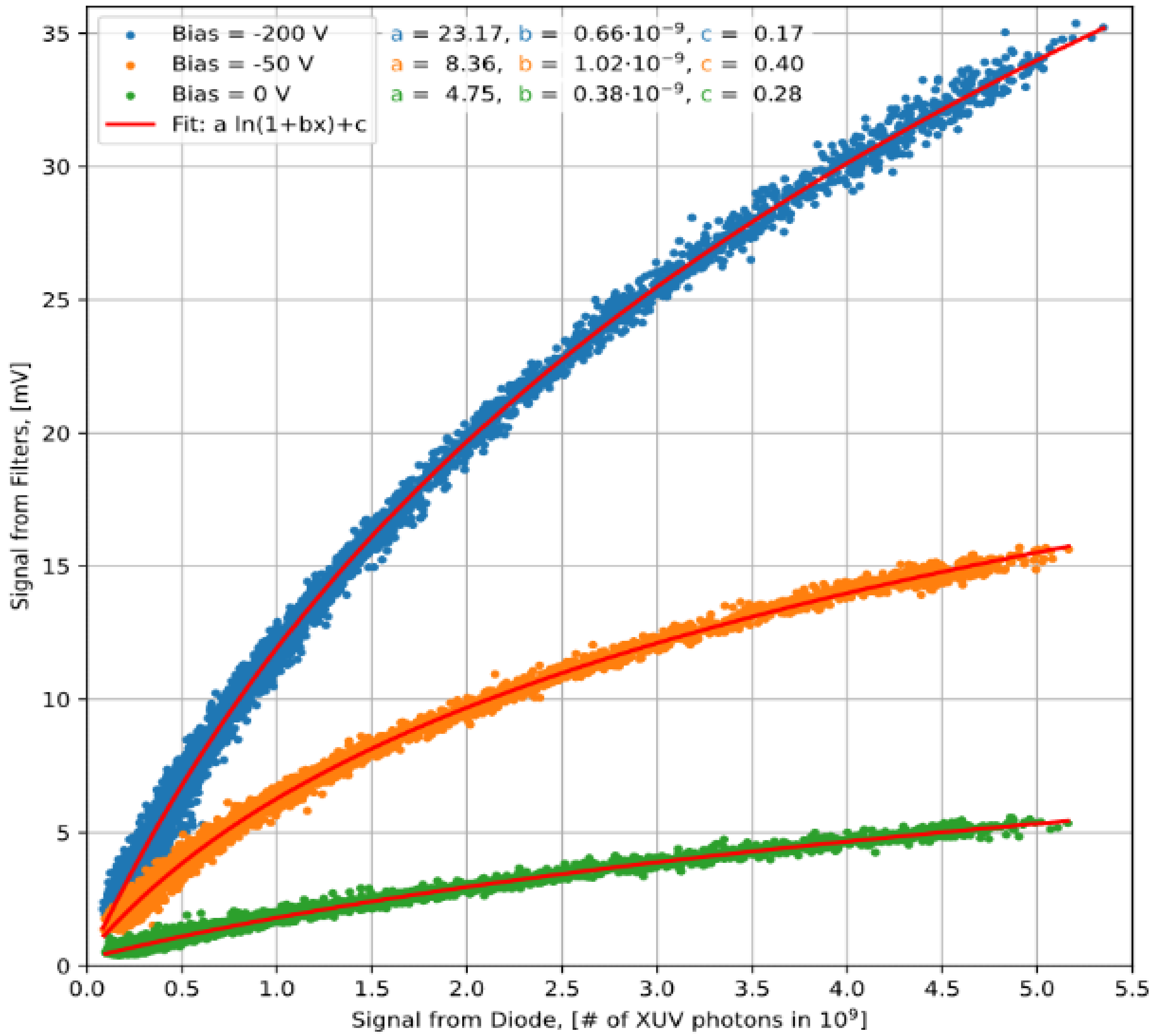
O. Hort et al., Opt. Exp. **27**, 8871 (2019)

Online measurement of XUV pulse energy

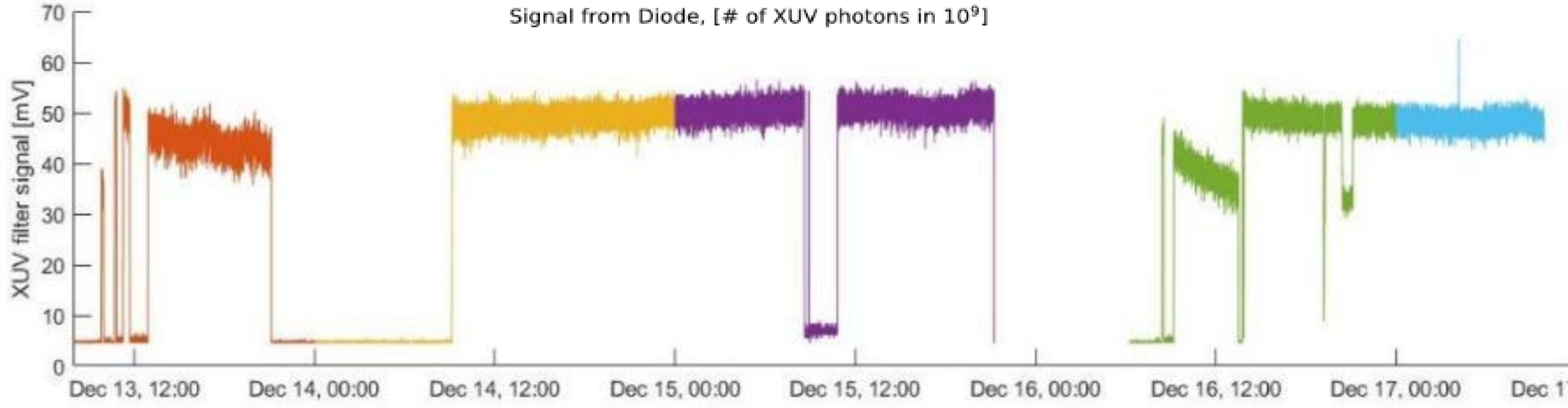
Before experiment

During experiment





- Measuring the photoelectric charge from metallic filters:
  - absolute online XUV pulse energy measurement
  - monitoring the XUV beam performance



M. Staněk et al. Appl. Phys. Lett. **125** (9): 091109 (2024).

HHG Beamline end-station

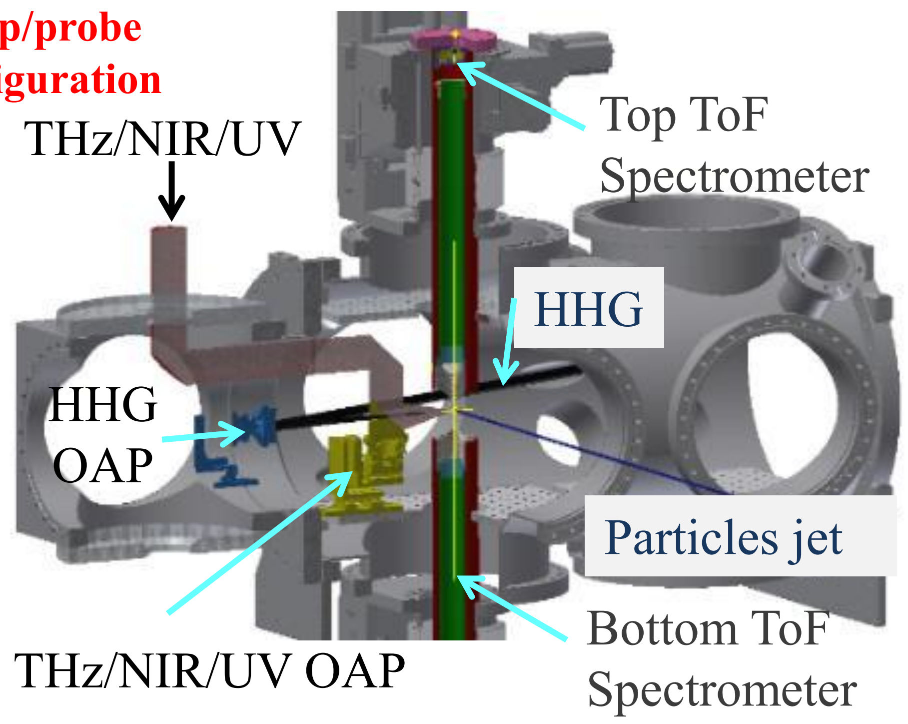
- Multipurpose chamber for AMO science and CDI
  - Sample delivery systems:

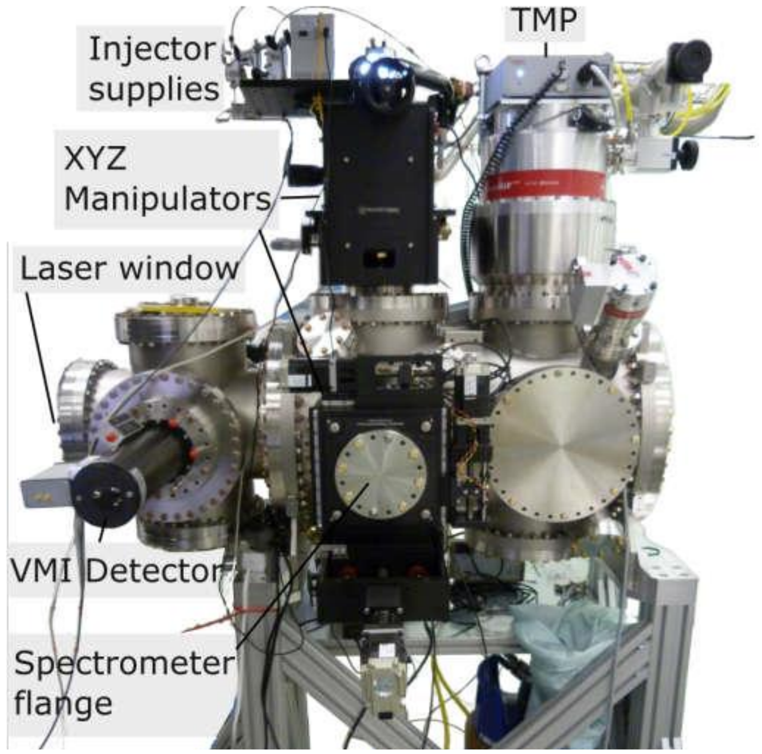
gas jets; microfluidic gas-dynamic nozzle
aerosol nano-particle injector;
cluster source (cryo-cooled Even-Lavie valve)

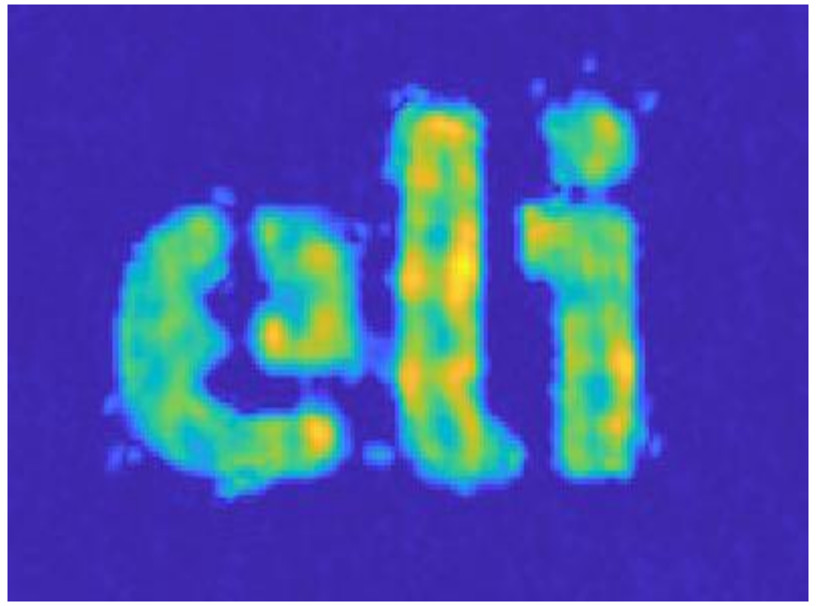
  - Diagnostics:

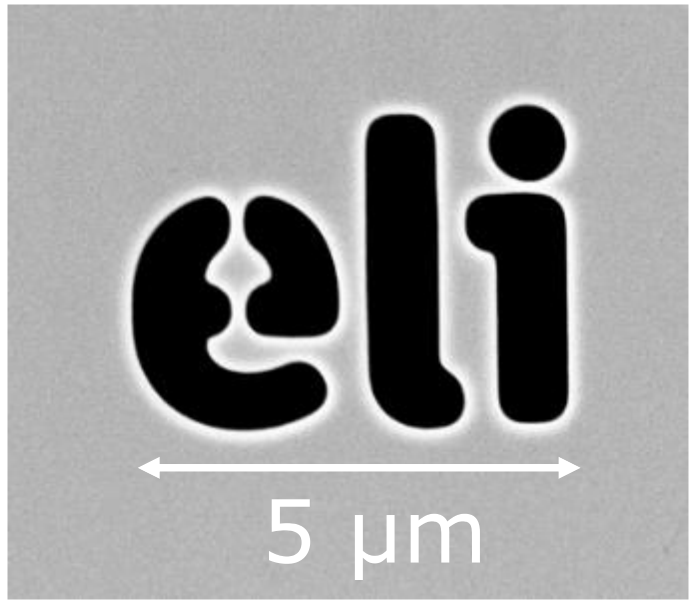
Velocity map imaging spectrometer (Timepix)
Magnetic bottle electron spectrometer
Electron and ion time of flight spectrometers
Various area detectors (X-ray CCDs, MCPs)

- Pump beams (200 – 800 nm) with fs pulses



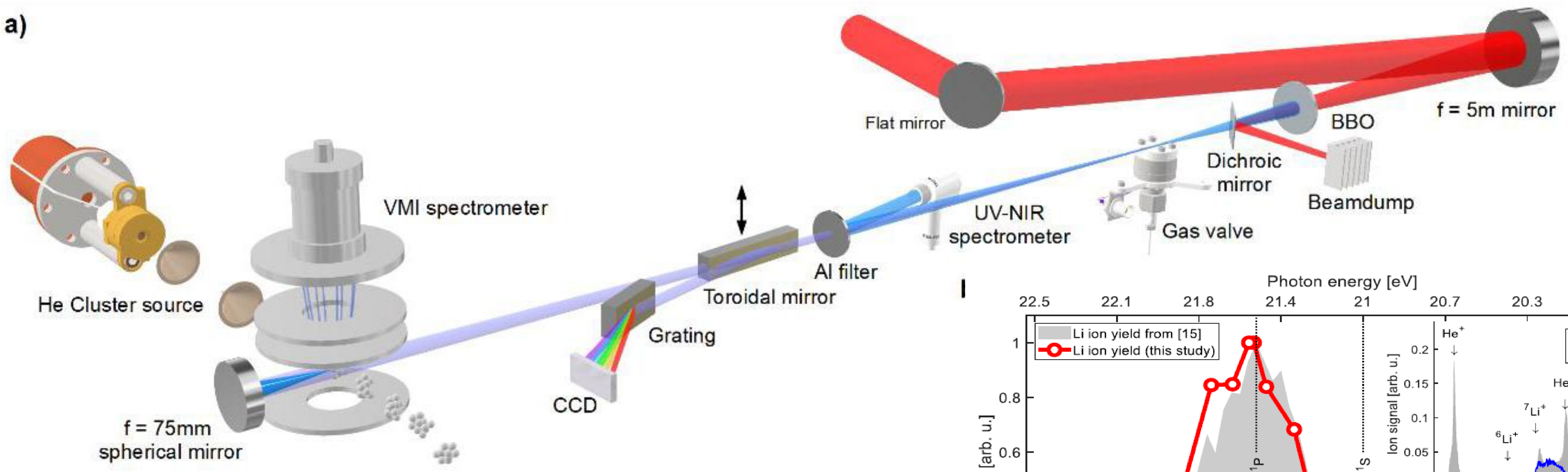


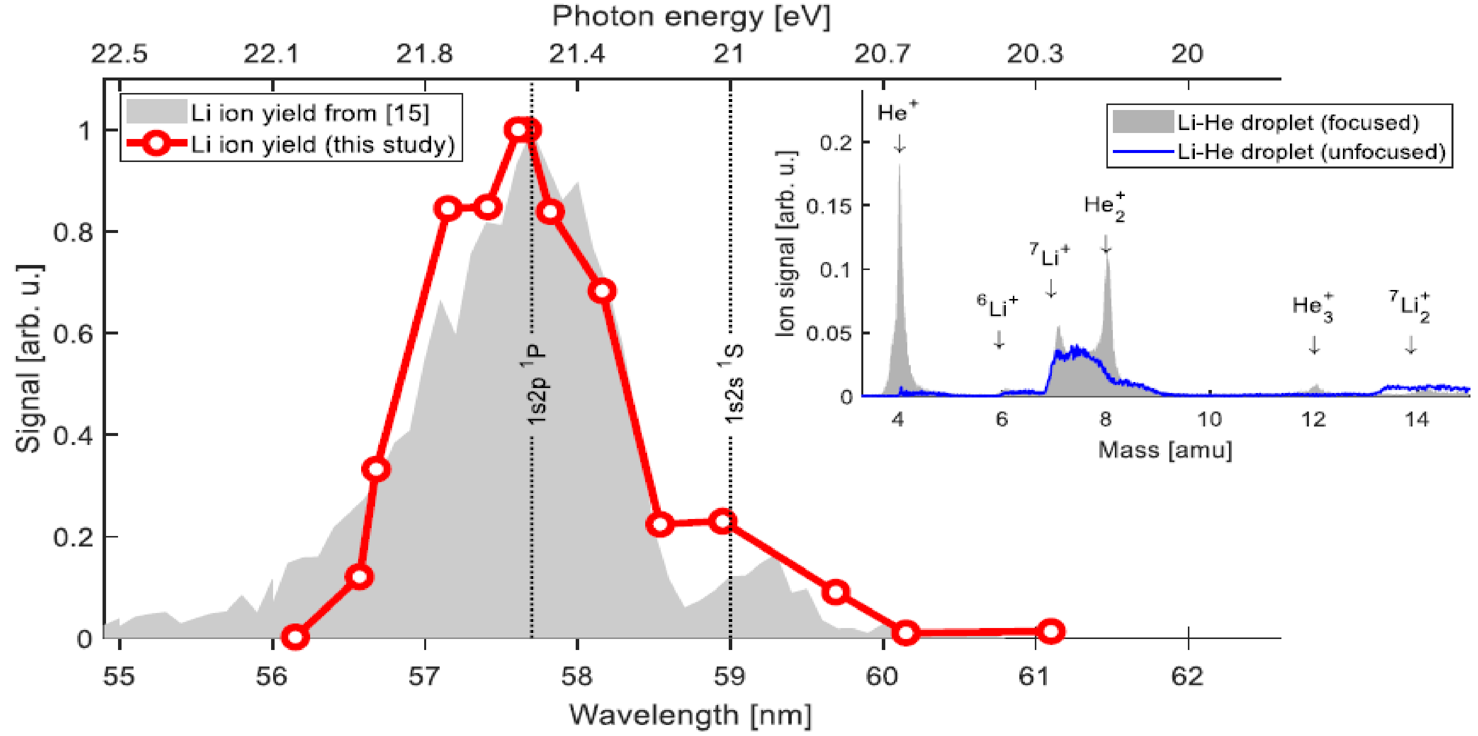




E. Klimešová et al. Eur. Phys. J. Spec. Top. **230**, 4183 (2021)

Precise wavelength tuning for ultrafast spectroscopy





- L1 laser = broadband OPCPA laser system (Δλ=200 nm)
- 200 μm BBO → narrow-band phase-matching – stable & tunable
- Tuning the H7 (~21.5 eV) around the He resonance (in Li-doped He nanodroplets)
- Concept demonstrated up to H17 (52 eV)

L. Jurkovičová et al., Commun. Phys. **7**, 26 (2024).

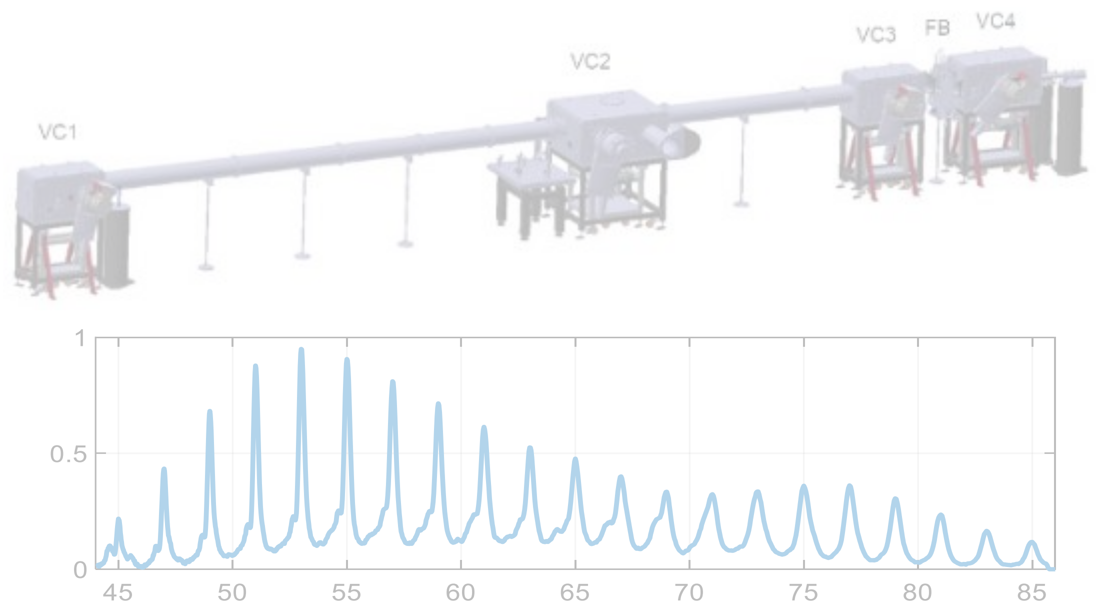
Laser driven X-ray sources: several approaches

E1

L1 driver
1 kHz, 100 mJ, 20 fs

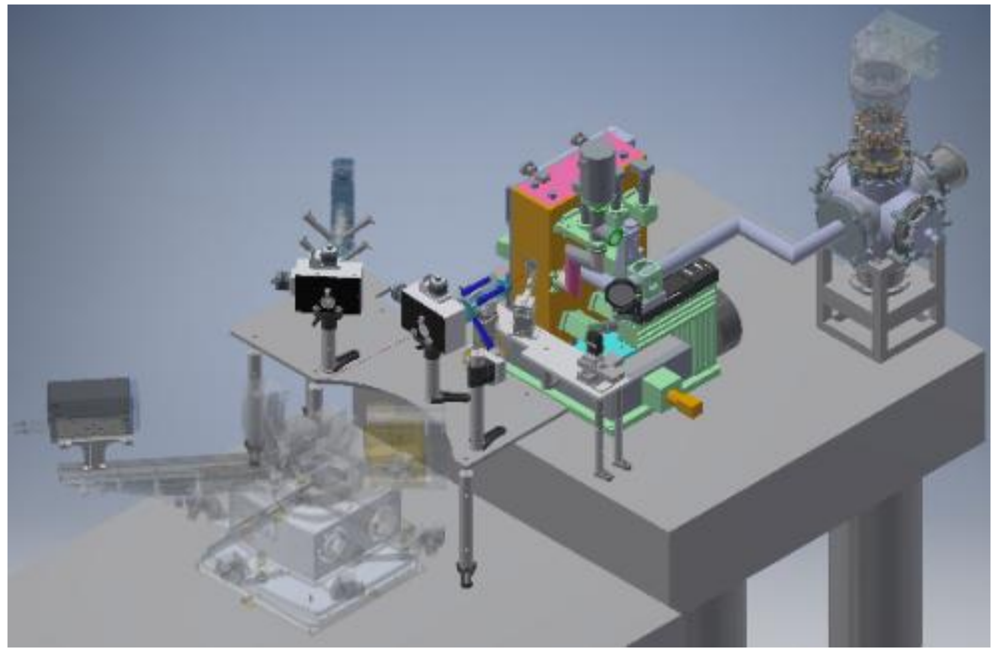
Ti:sapphire backup
1 kHz, 12 mJ, 35 fs
& 10 Hz, 100 mJ, 40 fs

High-order harmonic beamline



	Legend: 10 mJ, 35 fs	L1 Allegra: >20 mJ, ~15fs
Wavelength	10 -120 nm	5 -120 nm
Photons/shot	10^7 to 10^9	few 10^9 -10^{12}
Duration	< 20 fs	< 10 fs
Polarization	Linear	Lin./Circ./Eliptic

Plasma X-ray source

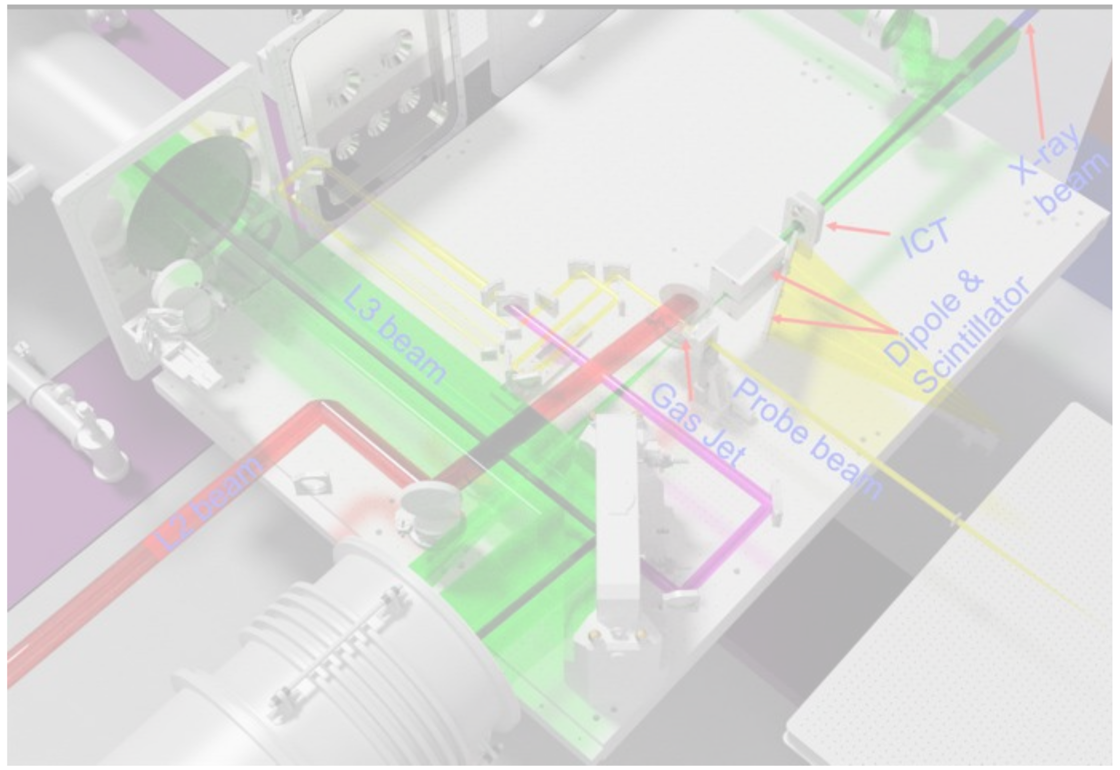


	10 mJ, 35 fs	20 mJ, 15 fs
photon energy	3 - 40 keV	3 – 80 keV
Kα photons /shot/(4π sr)	> 10^8	> 10^9
Source size	30 µm	30 µm
pulse duration	< 300 fs	<300 fs

E2/E3

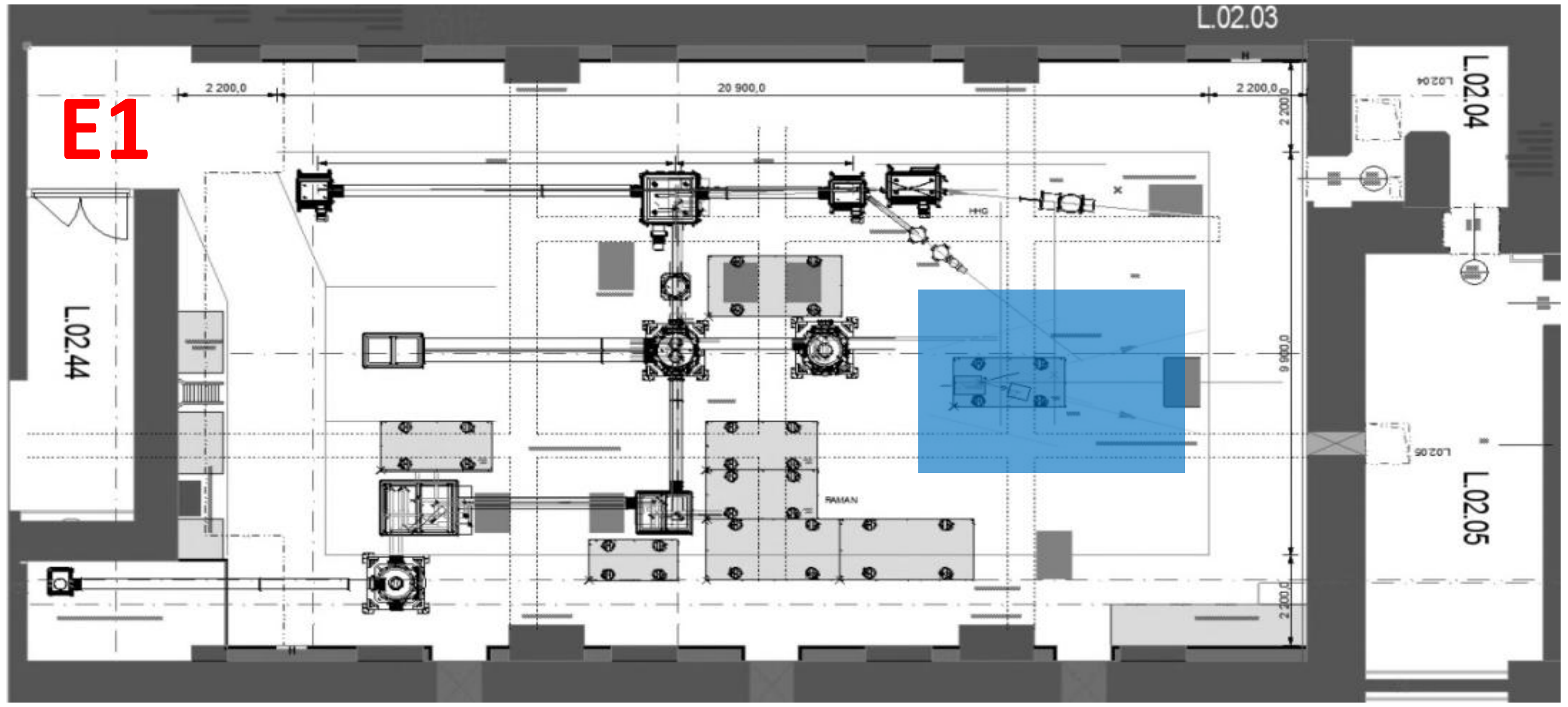
L3 driver
10 Hz, 30 J, 30 fs

Betatron / inverse Compton



	Betatron	ICS
photon energy	10- 100 keV	50 – 5000 keV
photons/shot	> 10^9	> 10^8
Source size	< 5 µm	< 5 µm
pulse duration	~30 fs	< 30 fs

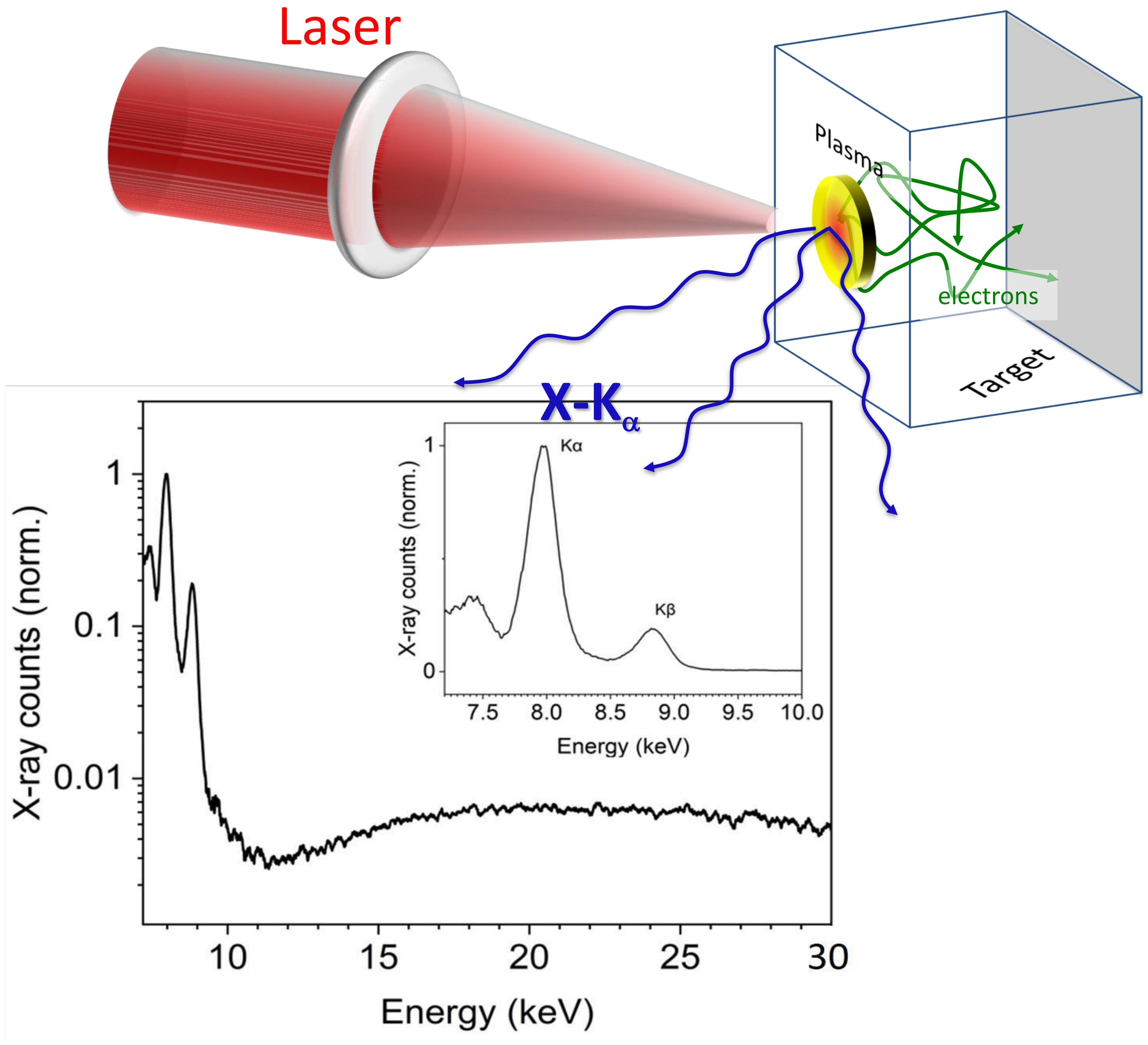
1 kHz Plasma X-ray Source (PXS)



High-intensity laser ($I > 10^{16}$ Wcm^{-2})

interacting with high-density target:

- **Cu tape**
- Liquid metal jet
- Water jet



Y. Pulnova et al. J. Synchrotron Rad. 32, 486-495 (2025)

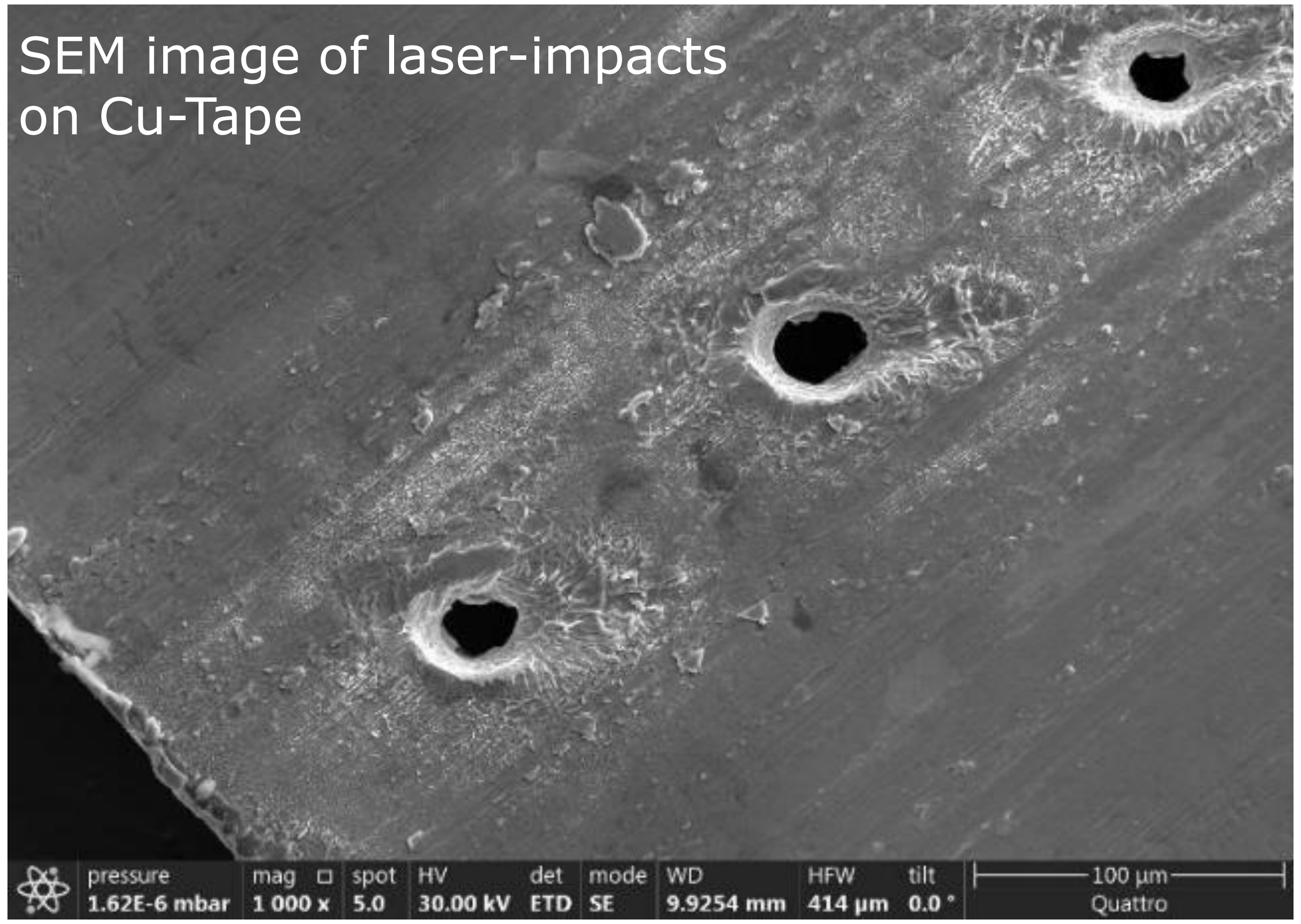
Plasma X-ray Source (PXS)

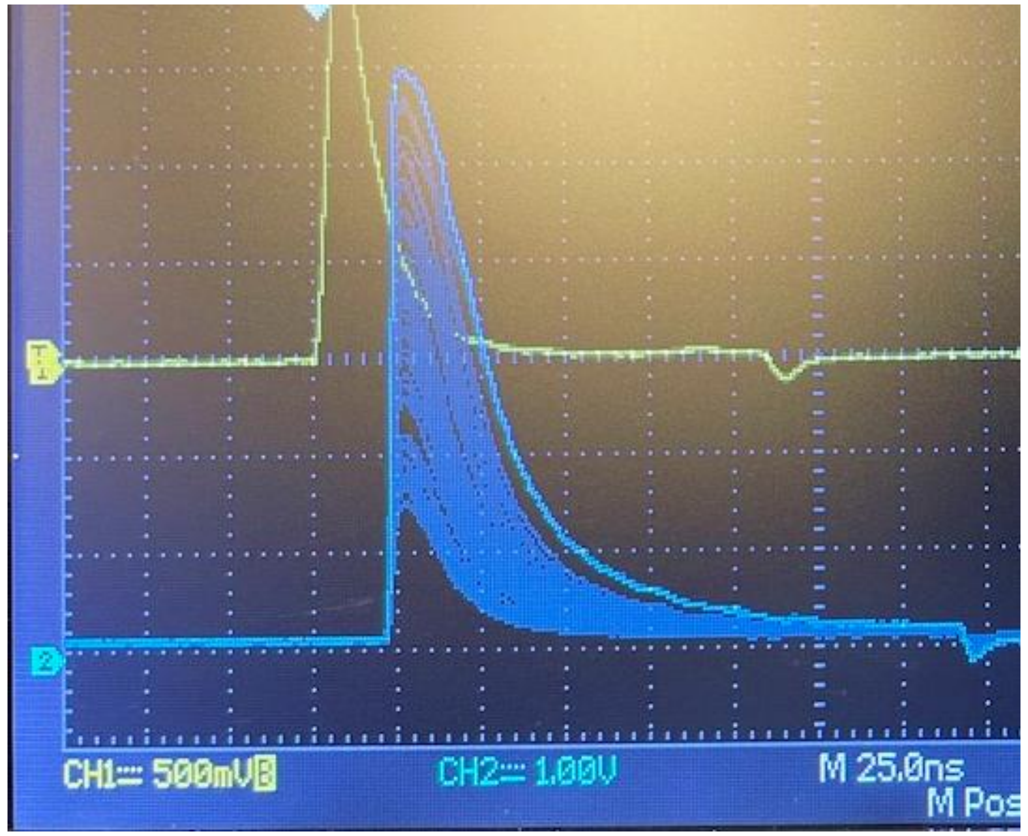
Cu Tape source

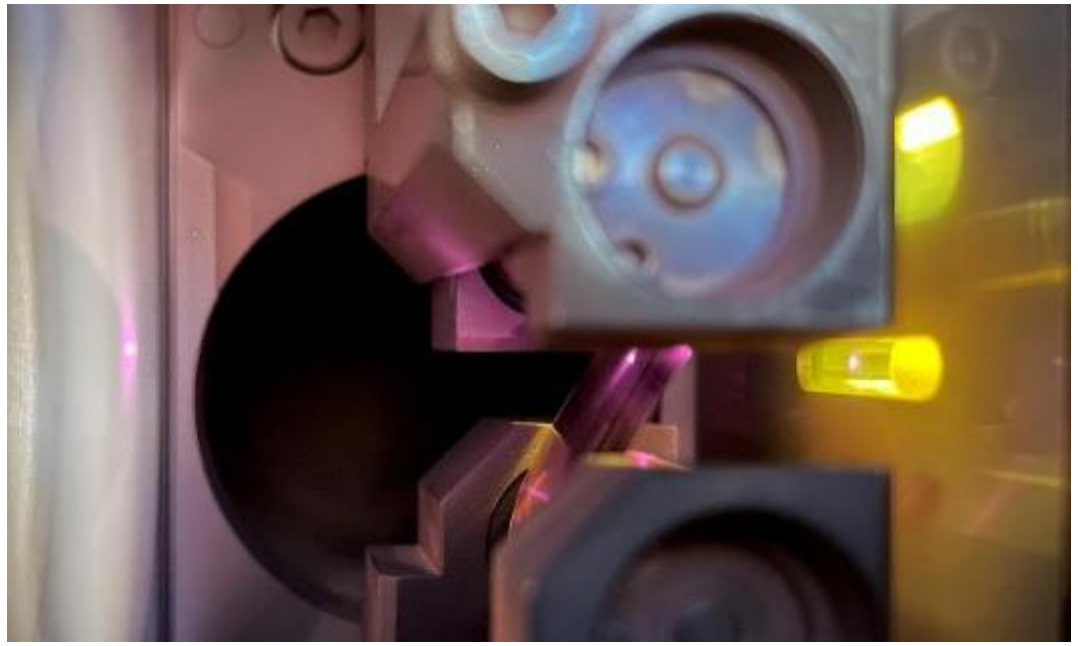
Driven by L1 laser (20 mJ, 1 kHz)

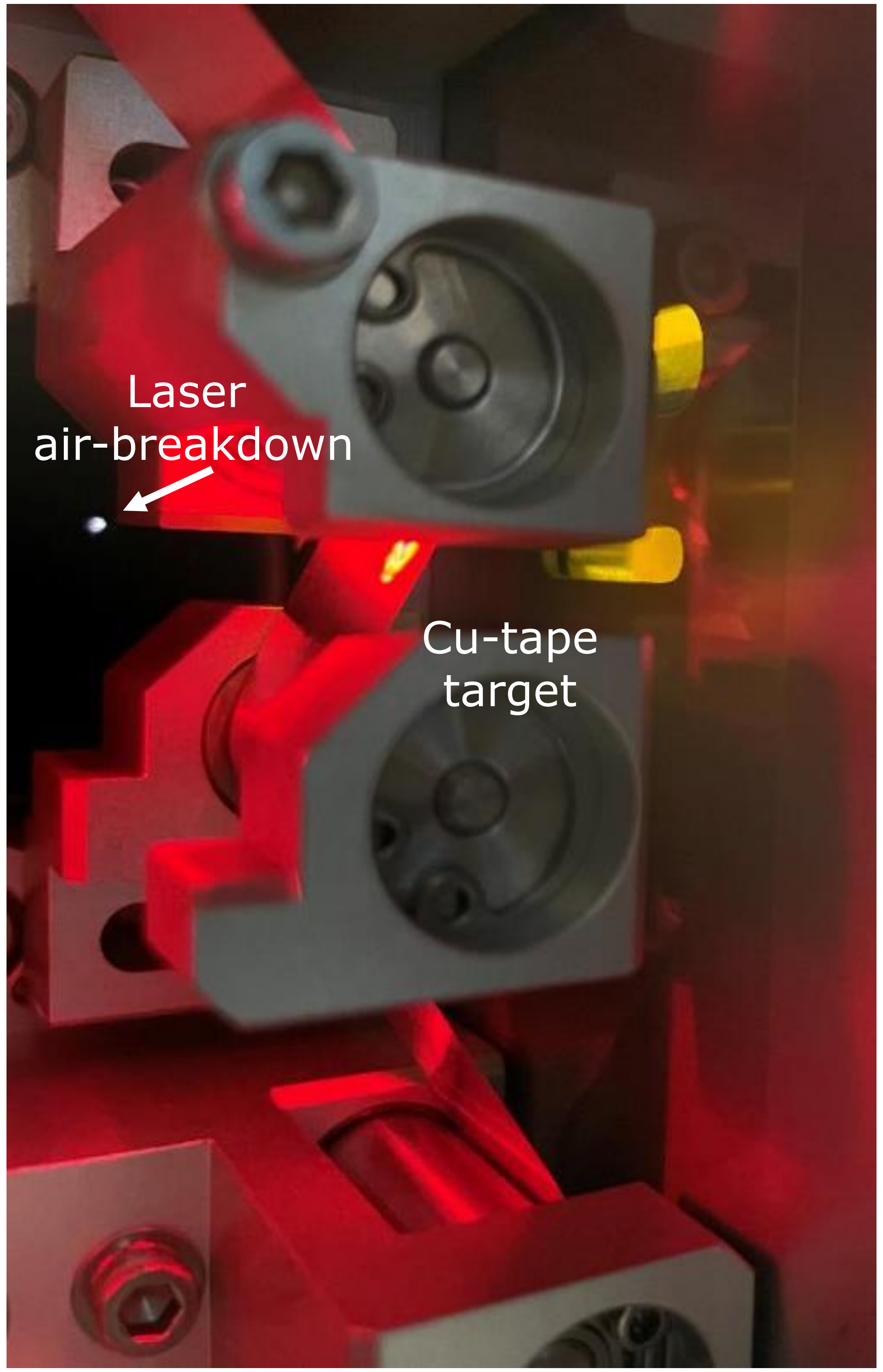
$>10^{13}$ X-ray photons/s/4π

$\Leftrightarrow$ 10^{8} K_{α} photons/shot/srad









Y. Pulnova et al. J. Synchrotron Rad. 32, 486-495 (2025)

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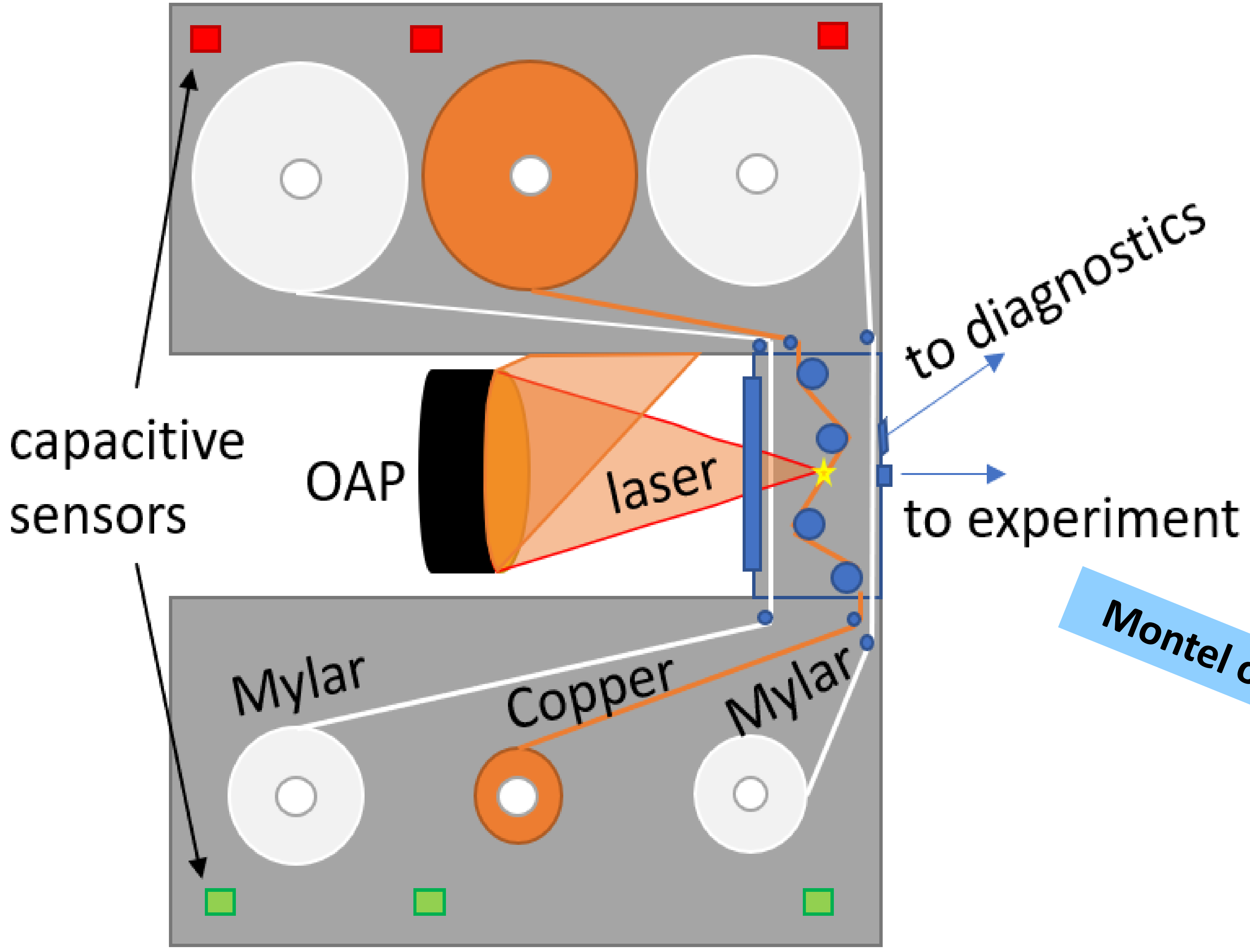
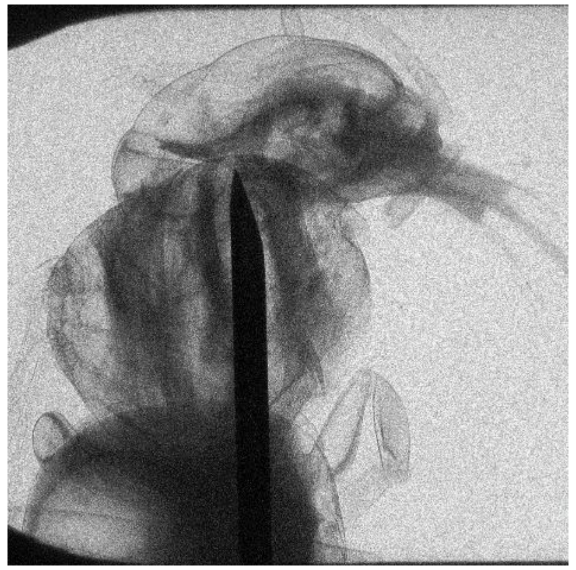


Montel optics

polychromatic
high flux
small source size

Imaging
Radiolysis
Spectroscopy



OR

monochromatic
low divergence

Diffraction

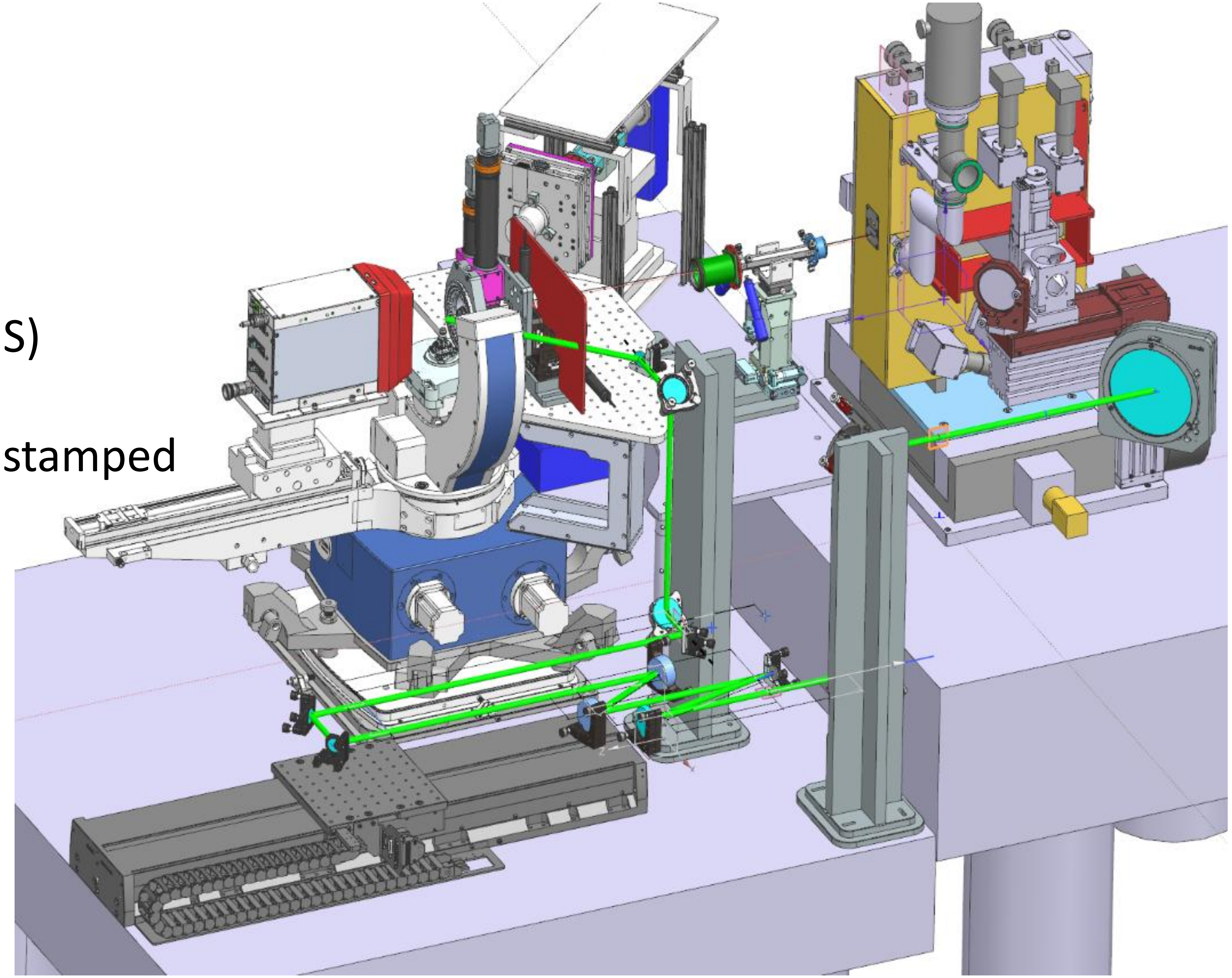
Currently 10^6 photons/s on the sample

Y. Pulnova et al. J. Synchrotron Rad. 32, 486-495 (2025)

Plasma X-ray Source (PXS)

Cu Tape source – recent upgrades

- Source size ~ 20 µm
- improving shot-to-shot stability (25% RMS)
- Single-shot X-ray flux measured and timestamped
- Improved diagnostics (plasma, X-ray)
- Jungfrau 1.5 M detector (1 kHz readout)
- Pump-line integrated (mid 2026)



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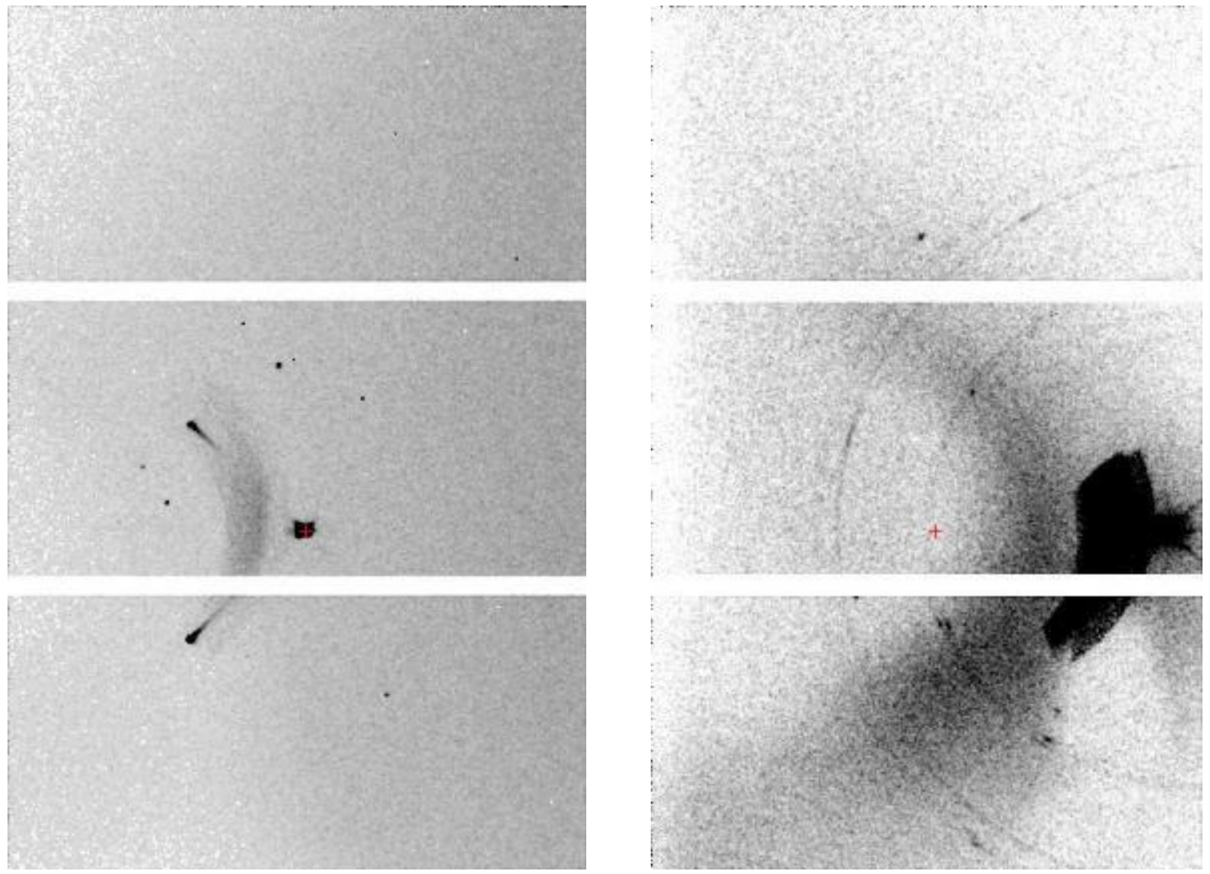

(Left) Iron acetyl acetonate single-crystal diffraction
(Right) Two-dimensional X-ray powder diffraction from 4-Phenylazophenol

Y. Pulnova et al. J. Synchrotron Rad. 32, 486-495 (2025)

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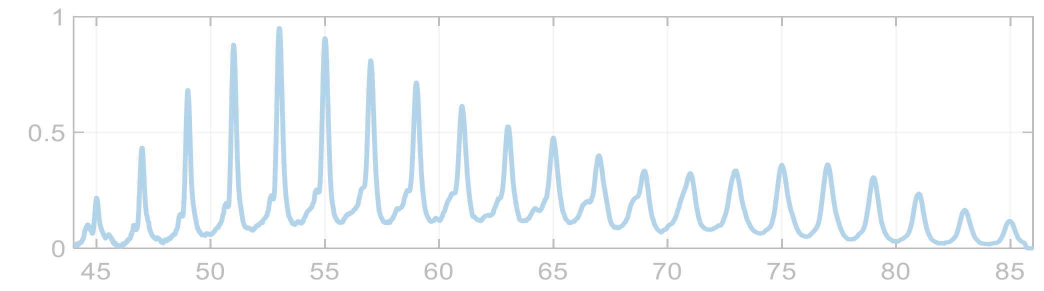

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E2/E3

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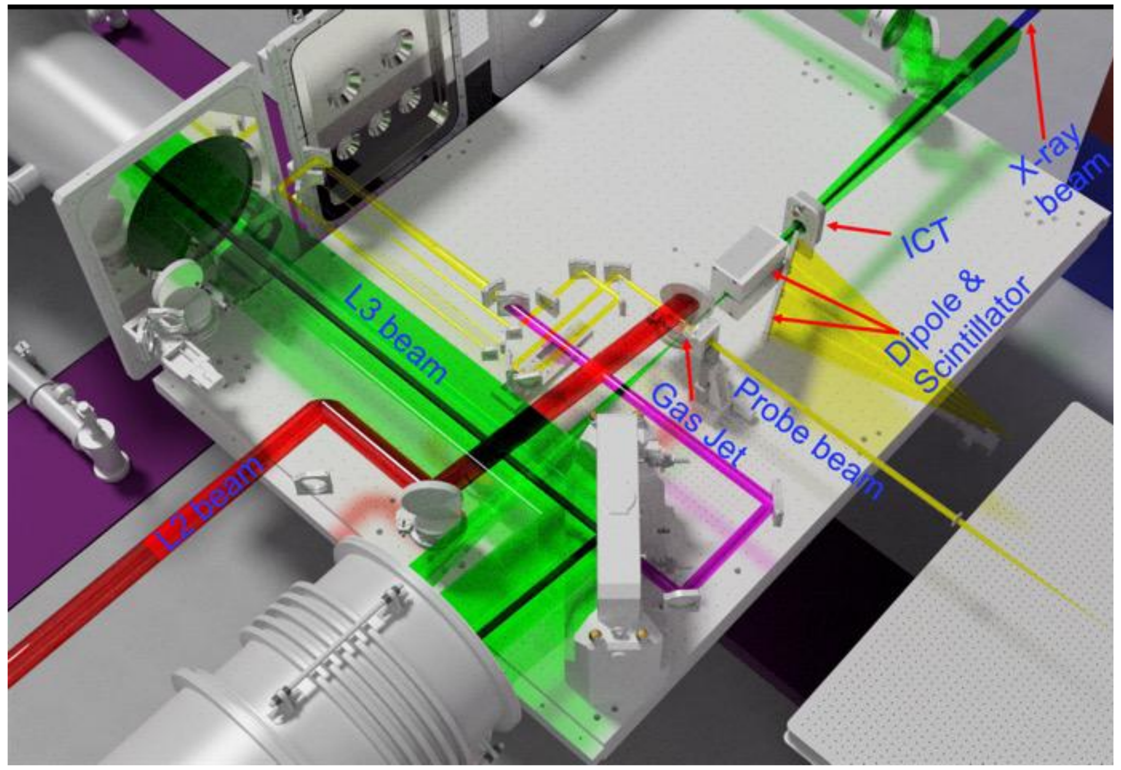

	Betatron	ICS
photon energy	10- 100 keV	50 – 5000 keV
photons/shot	> 10^9	> 10^8
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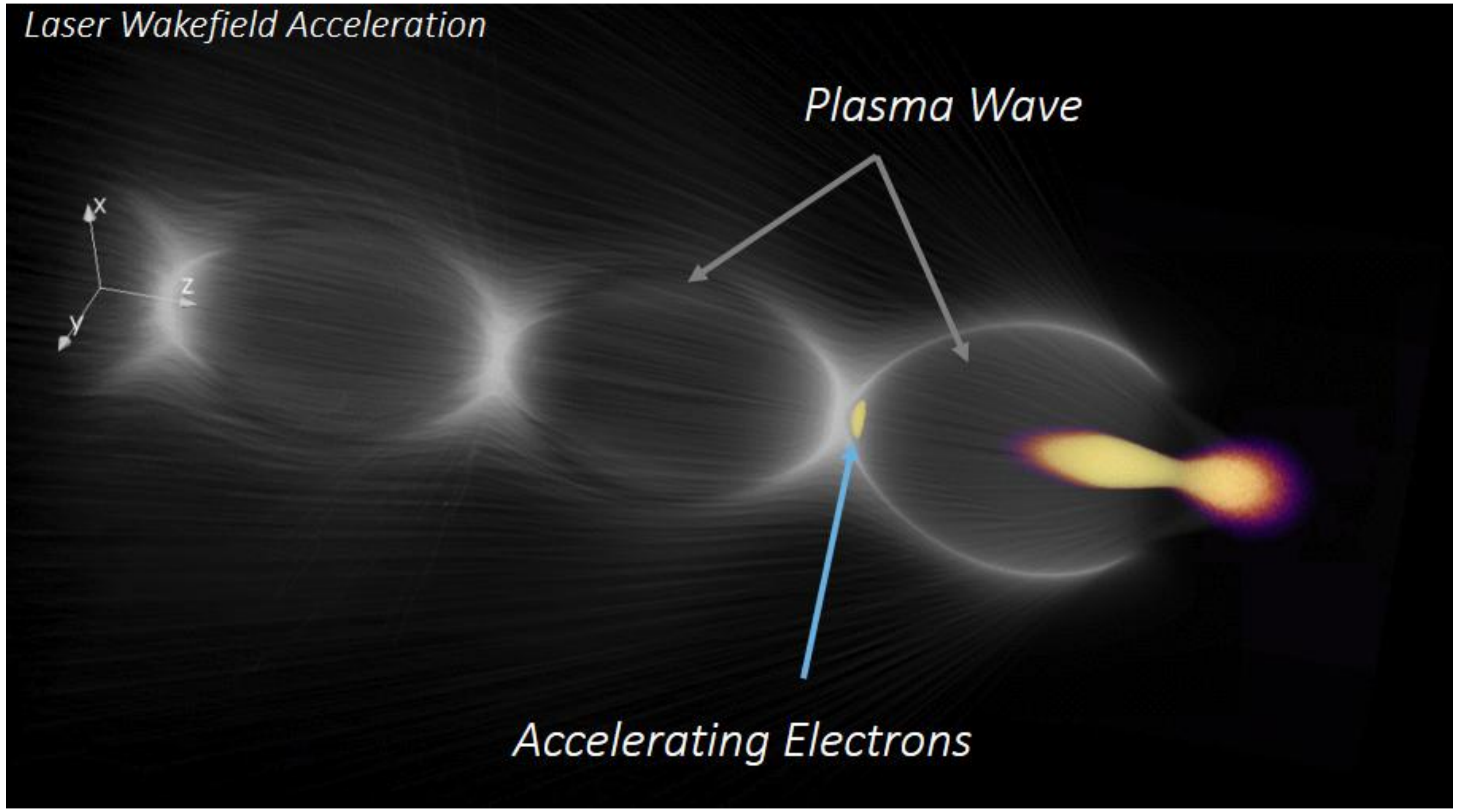
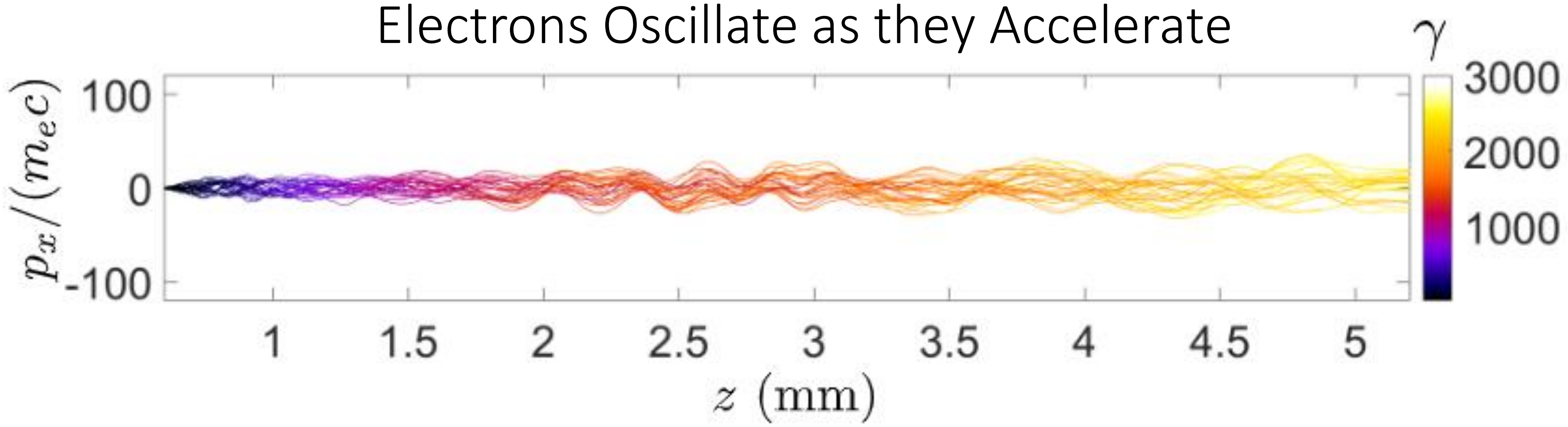
pulse duration	~30 fs	< 30 fs

Laser plasma accelerator based Betatron X-ray source





Characteristics of Betatron radiation

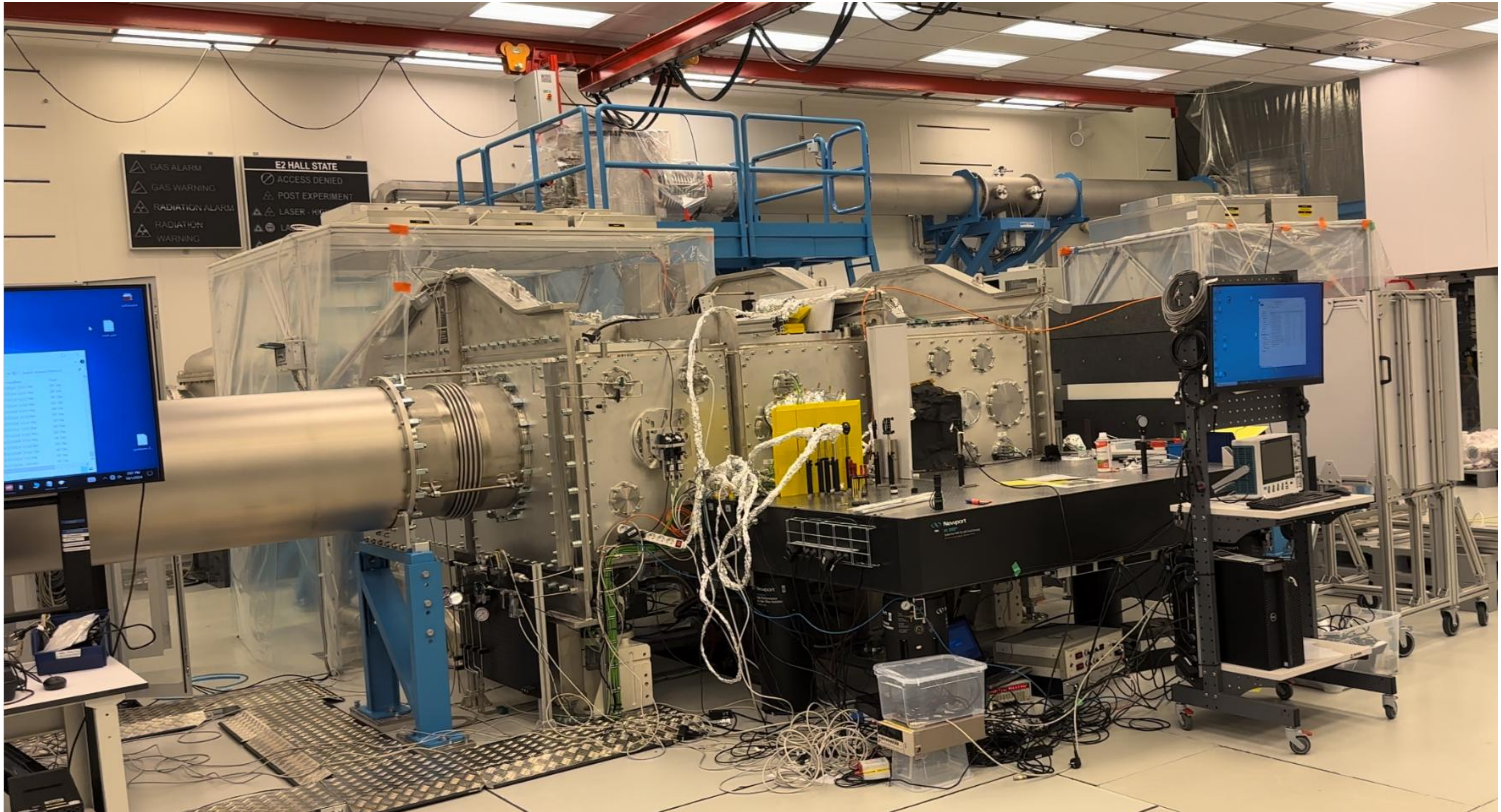
- Source size: few μm
- Broadband, crit. energy: 5 - 50 keV
- Number of Photons: 10^9 - 10^{11}/shot
- Beam divergence < 20 mrad
- Pulse duration ~ 10 fs

- Critical energy:

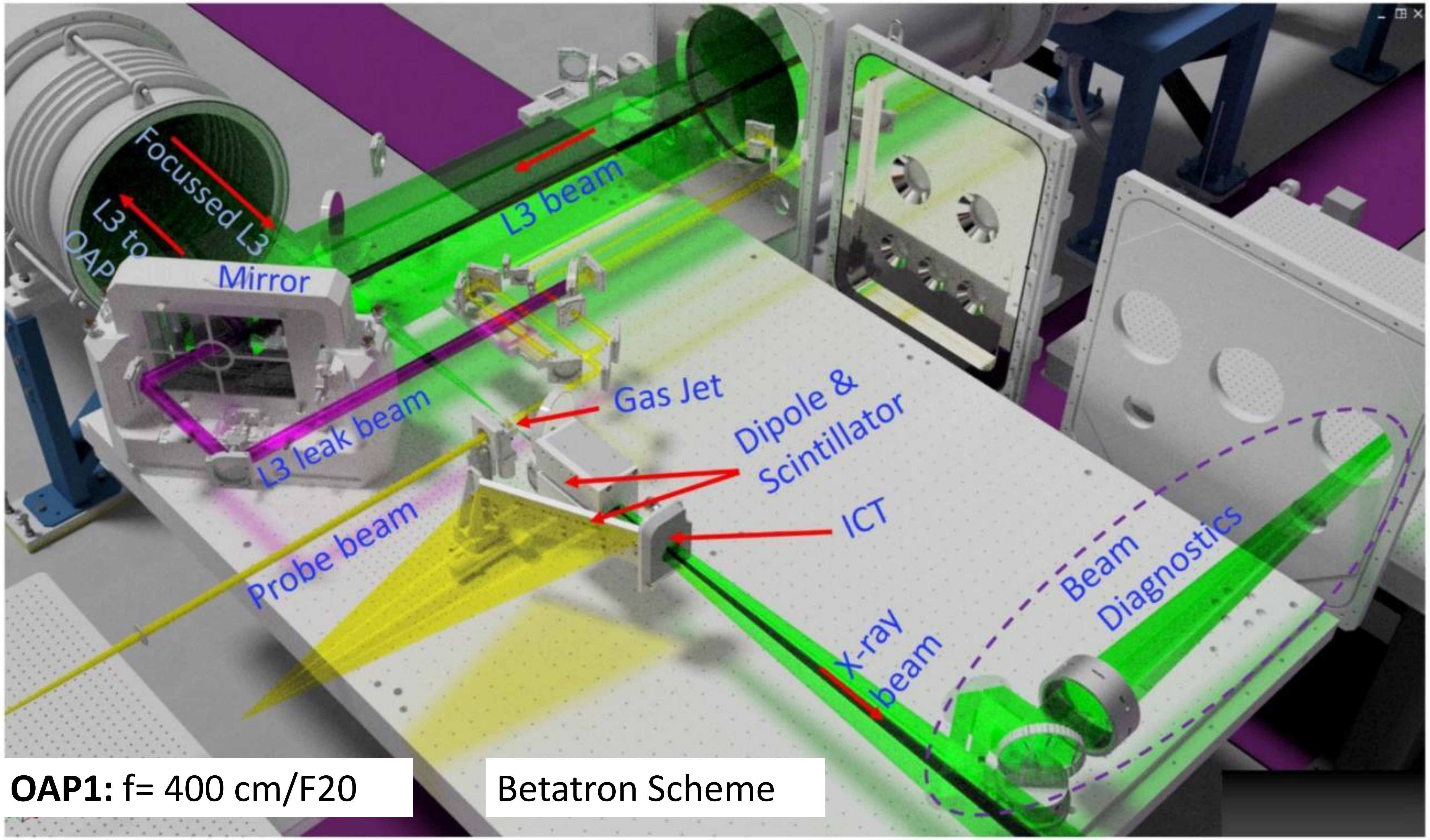
$$E_c = \frac{3}{2} K \gamma^2 \hbar \omega_\beta = 5.24 \times 10^{-21} * \gamma^2 * n_e\,[\mathrm{cm}^{-3}]\, r_b$$

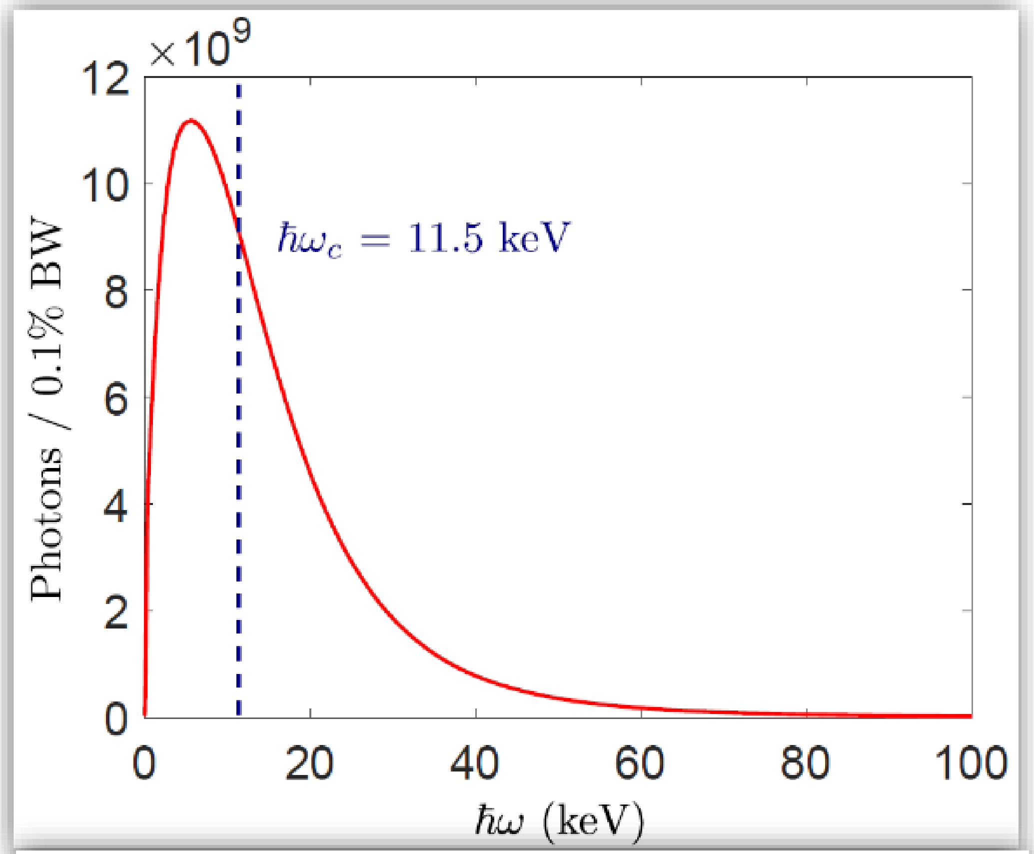
- Total emitted X-ray radiation: $W_{tot} \propto N e\, \gamma^{5/2}\, r_b^2$

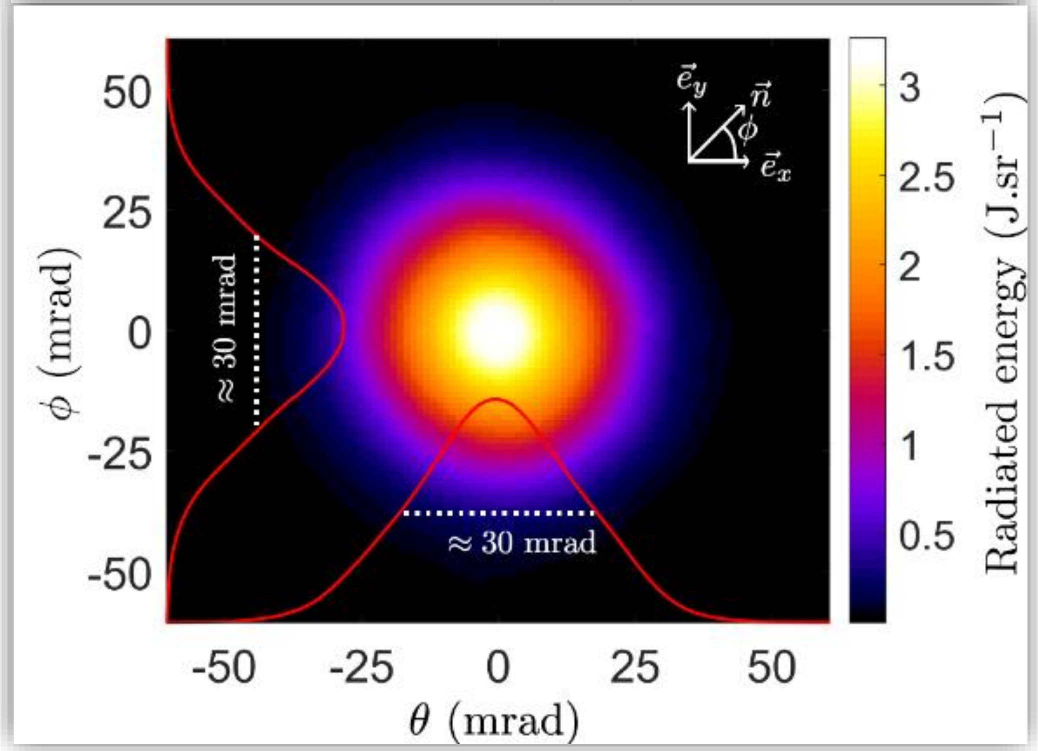
ELI Gammatron Beamline



ELI Gammatron Beamline

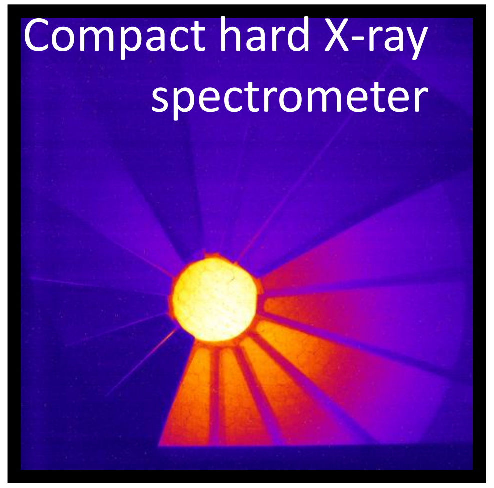


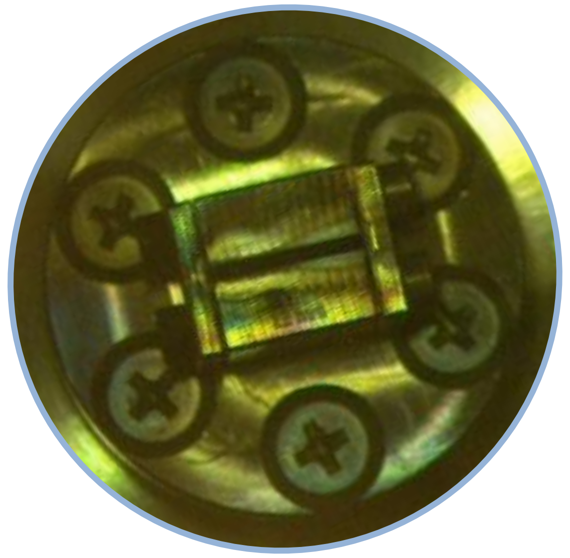


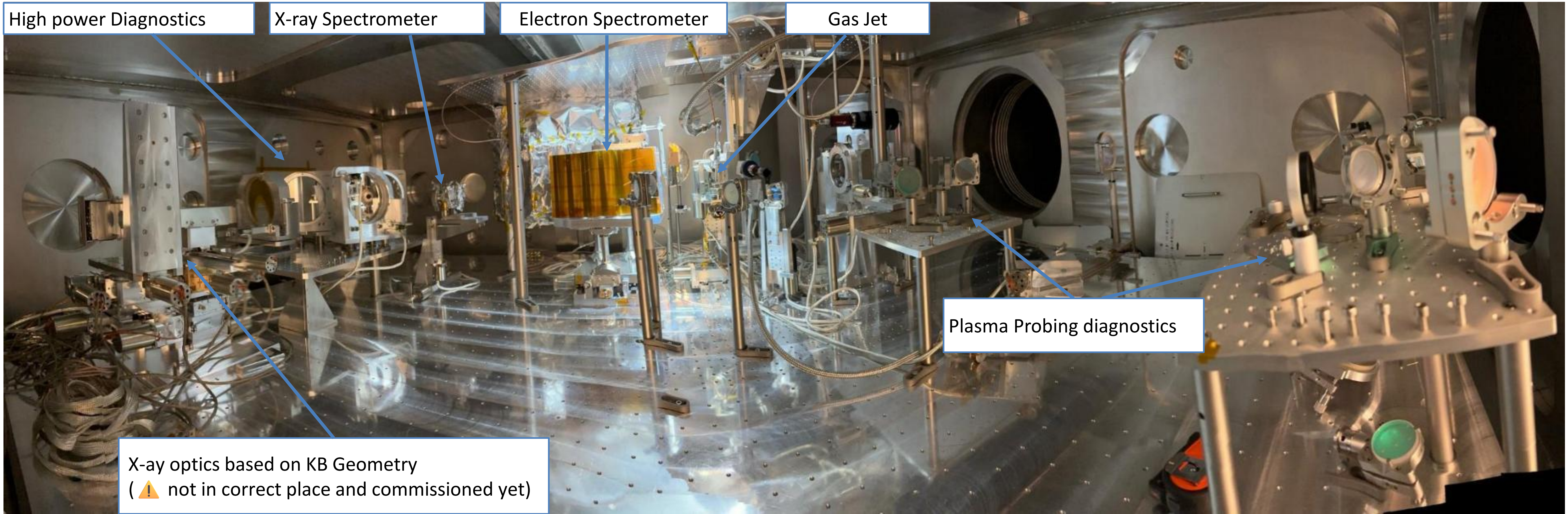


Chaulagain et al., Photonics 2022, 9(11), 853 (2022); Raclavský et al., Photonics 8, 579 (2021)

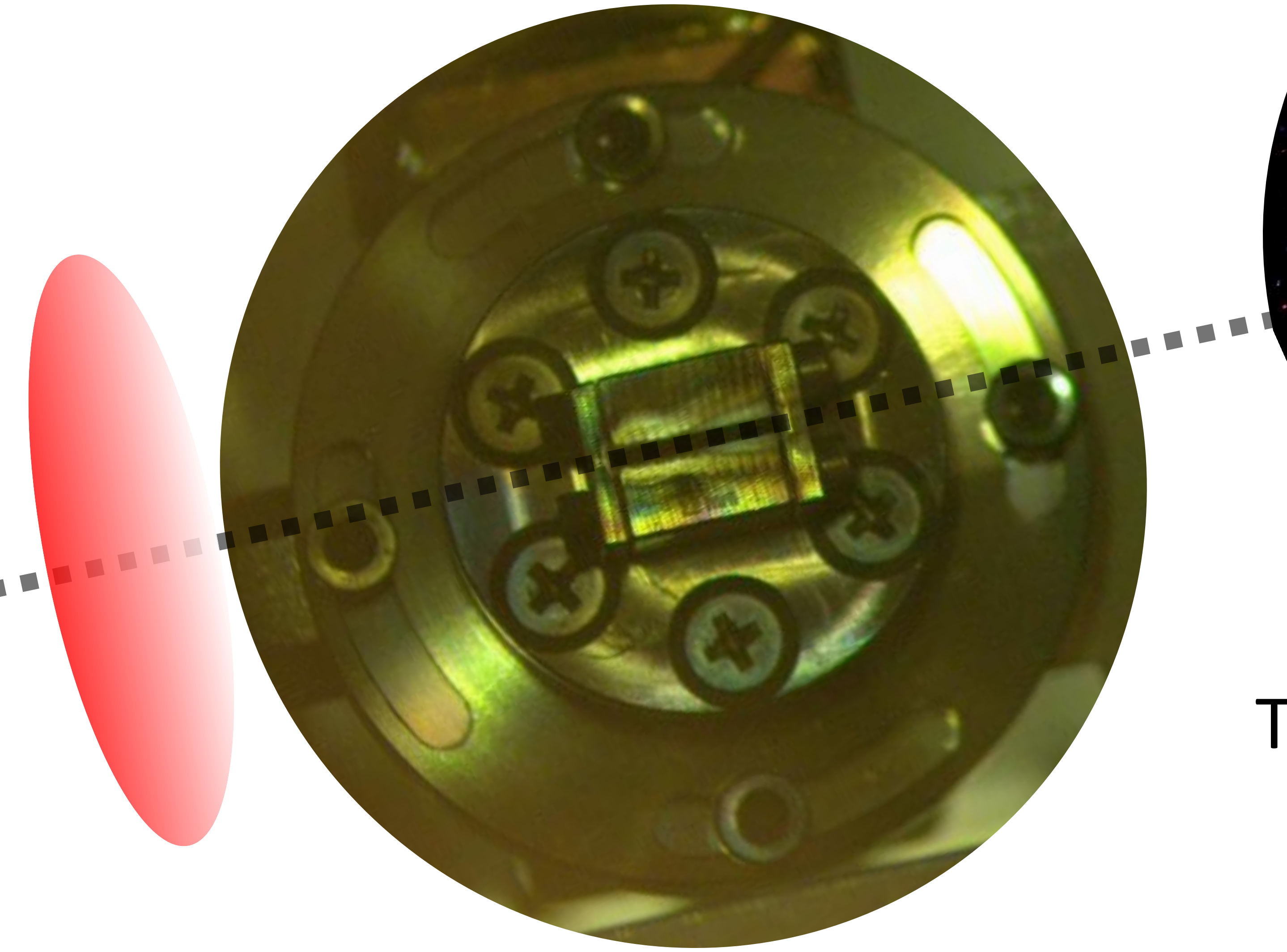
ELI Gammatron Beamline

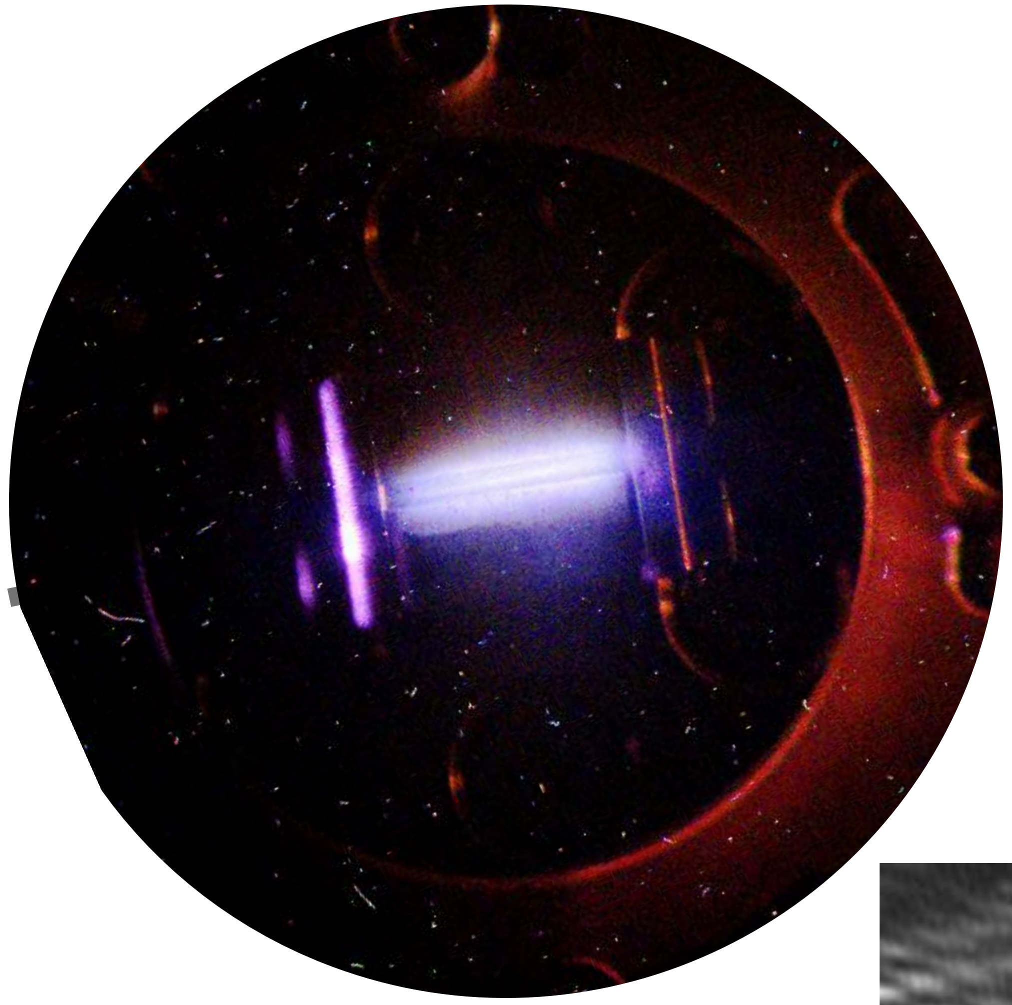




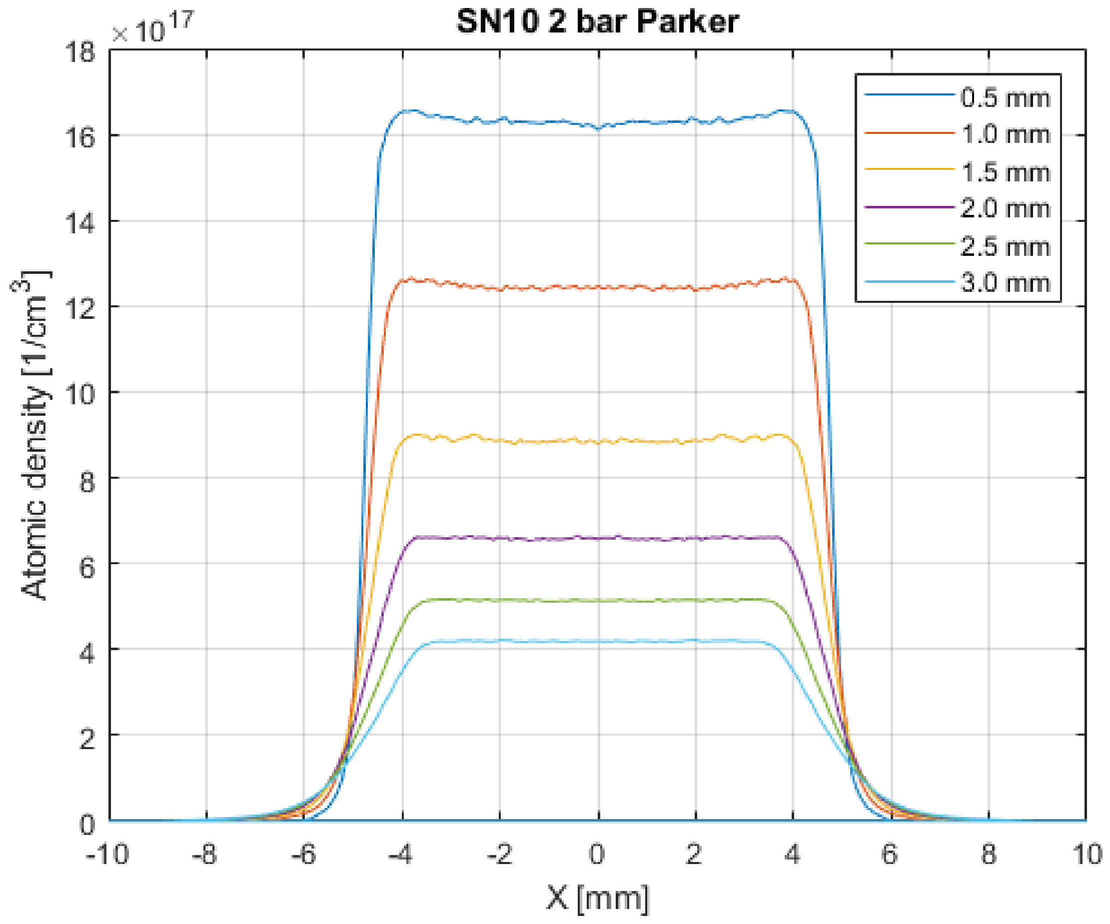


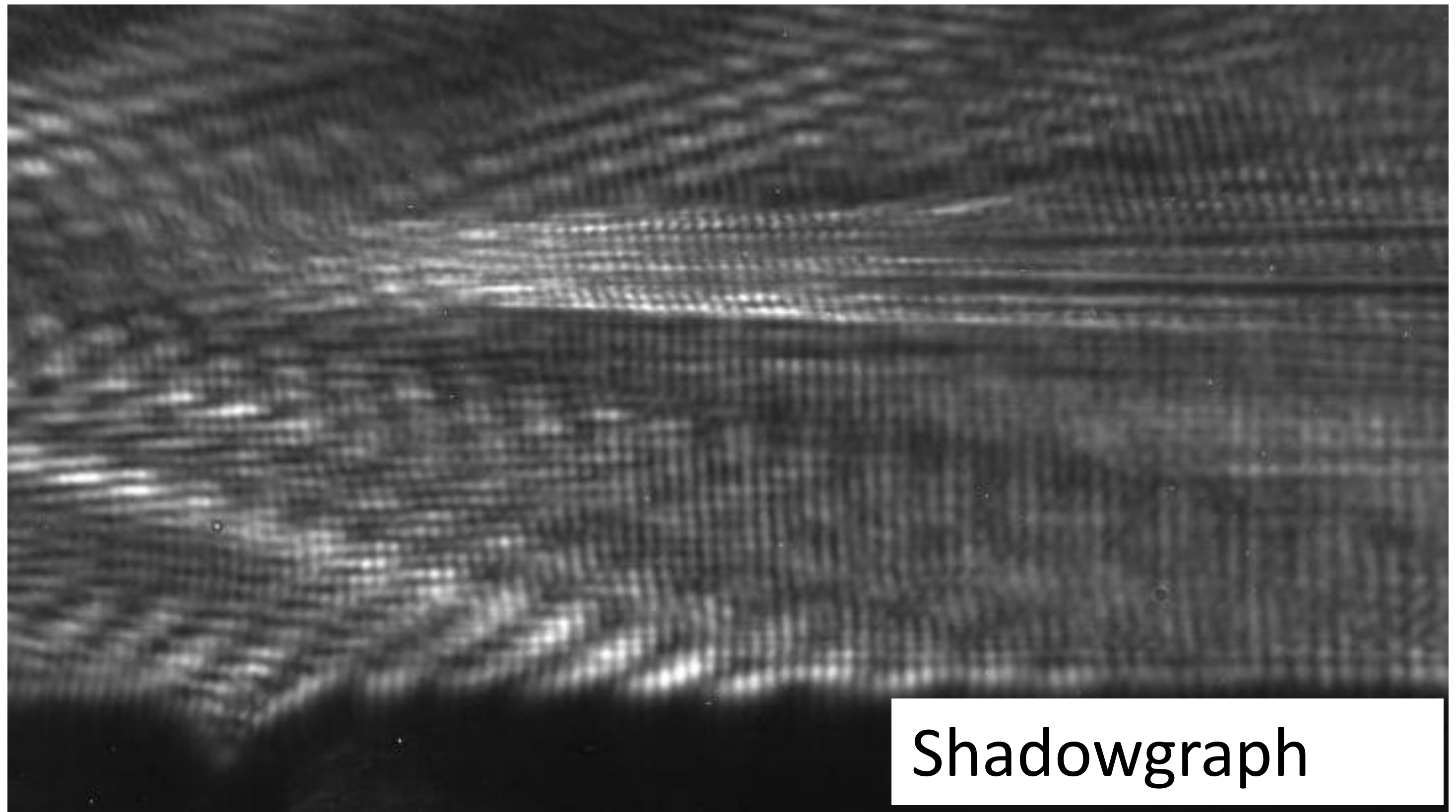
ELI Gammatron Beamline: Recent results





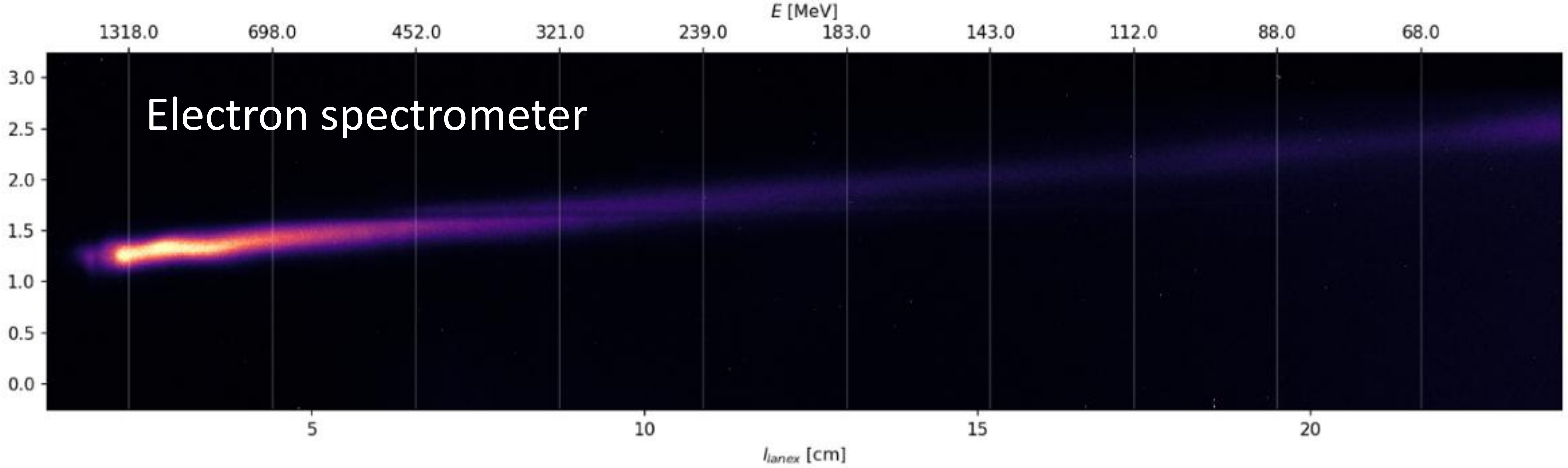
Thomson Scattering
(top view)



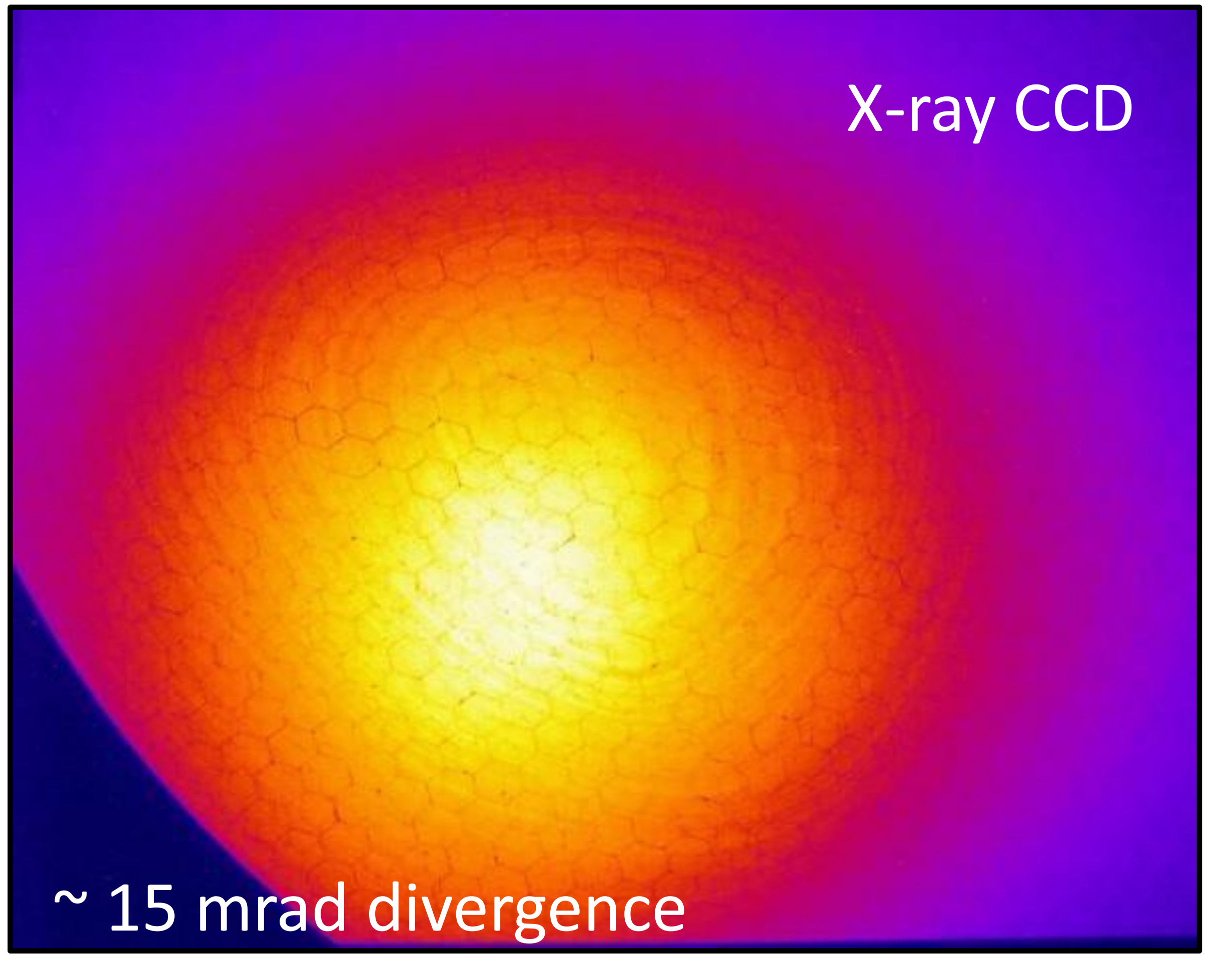


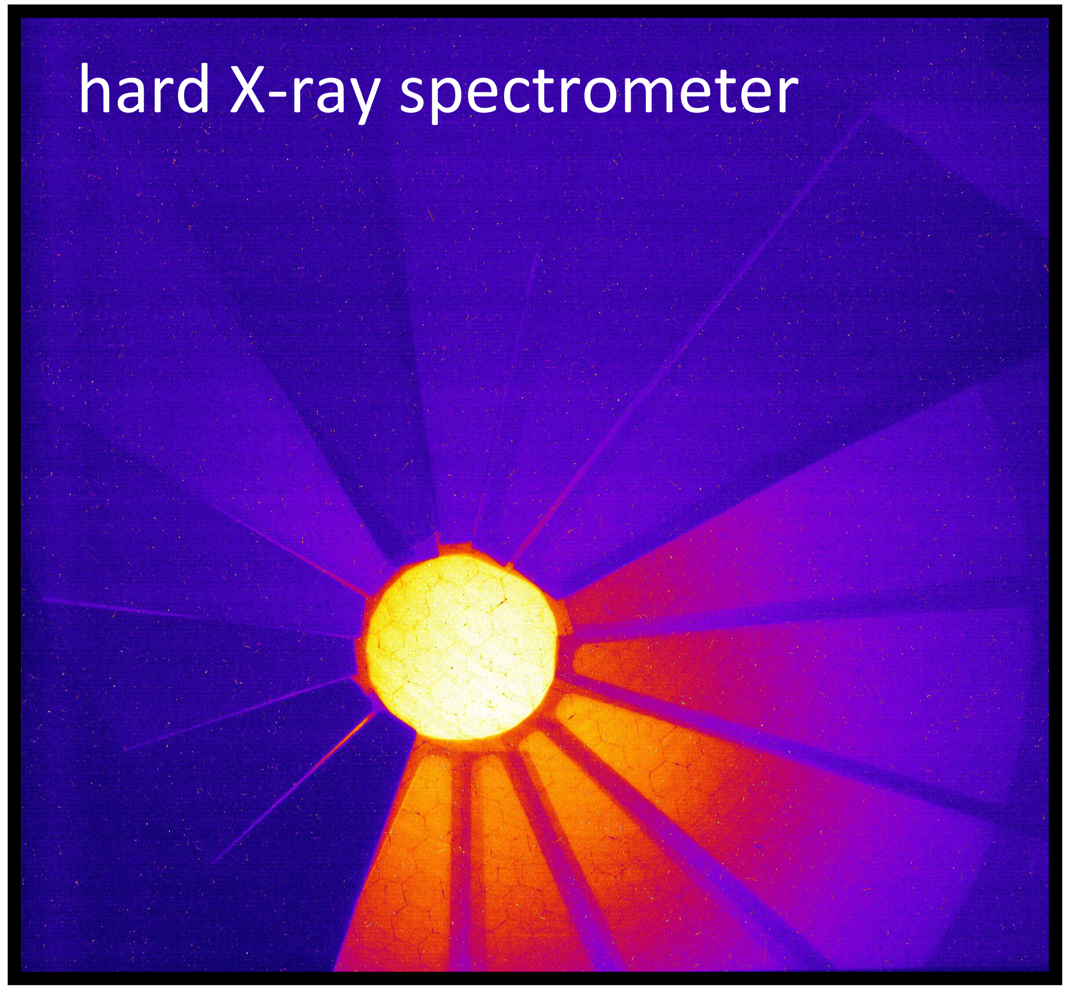
ELI Gammatron Beamline: Commissioning

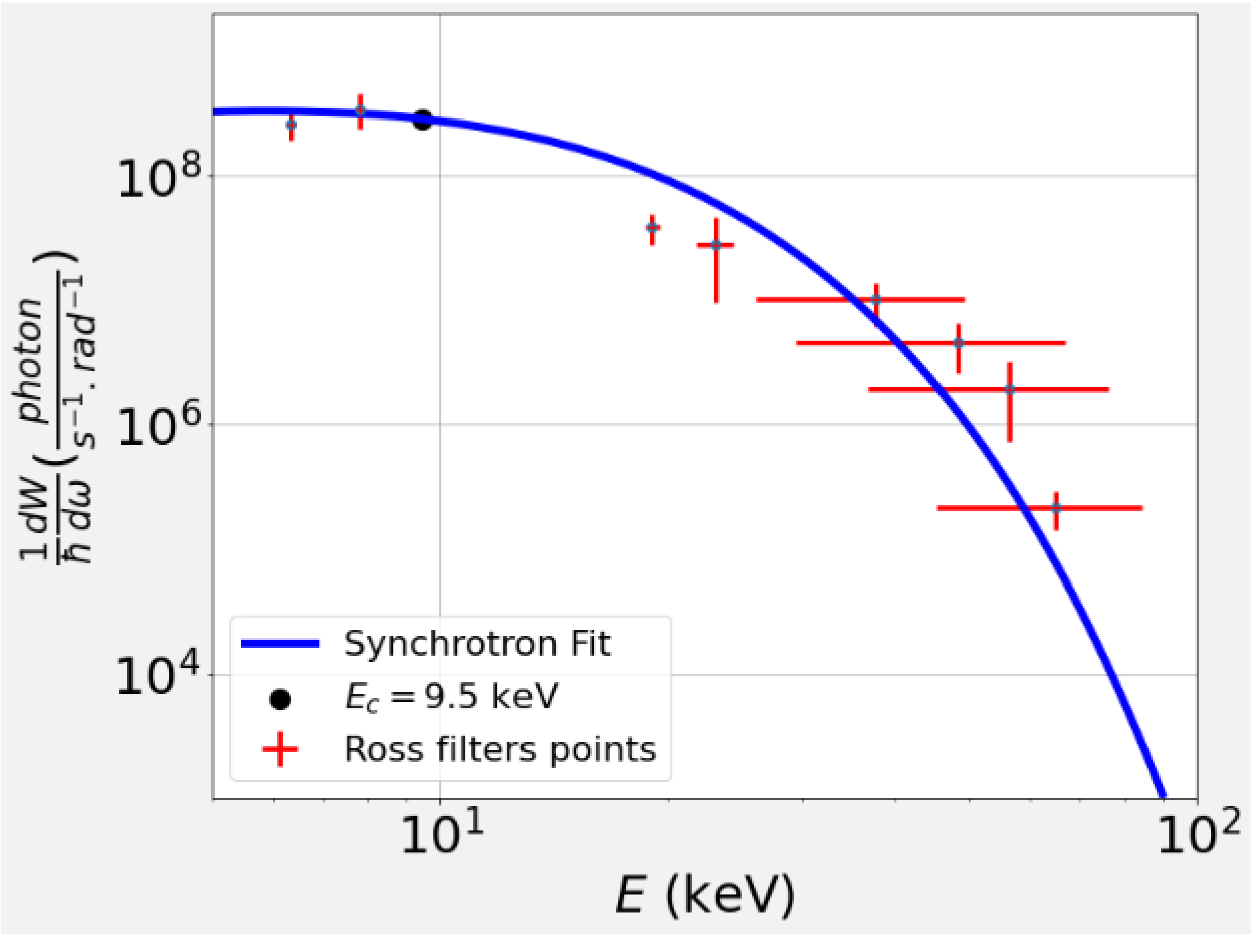
- 10 J, 30 fs laser
- F# 20 focusing
- Single shots



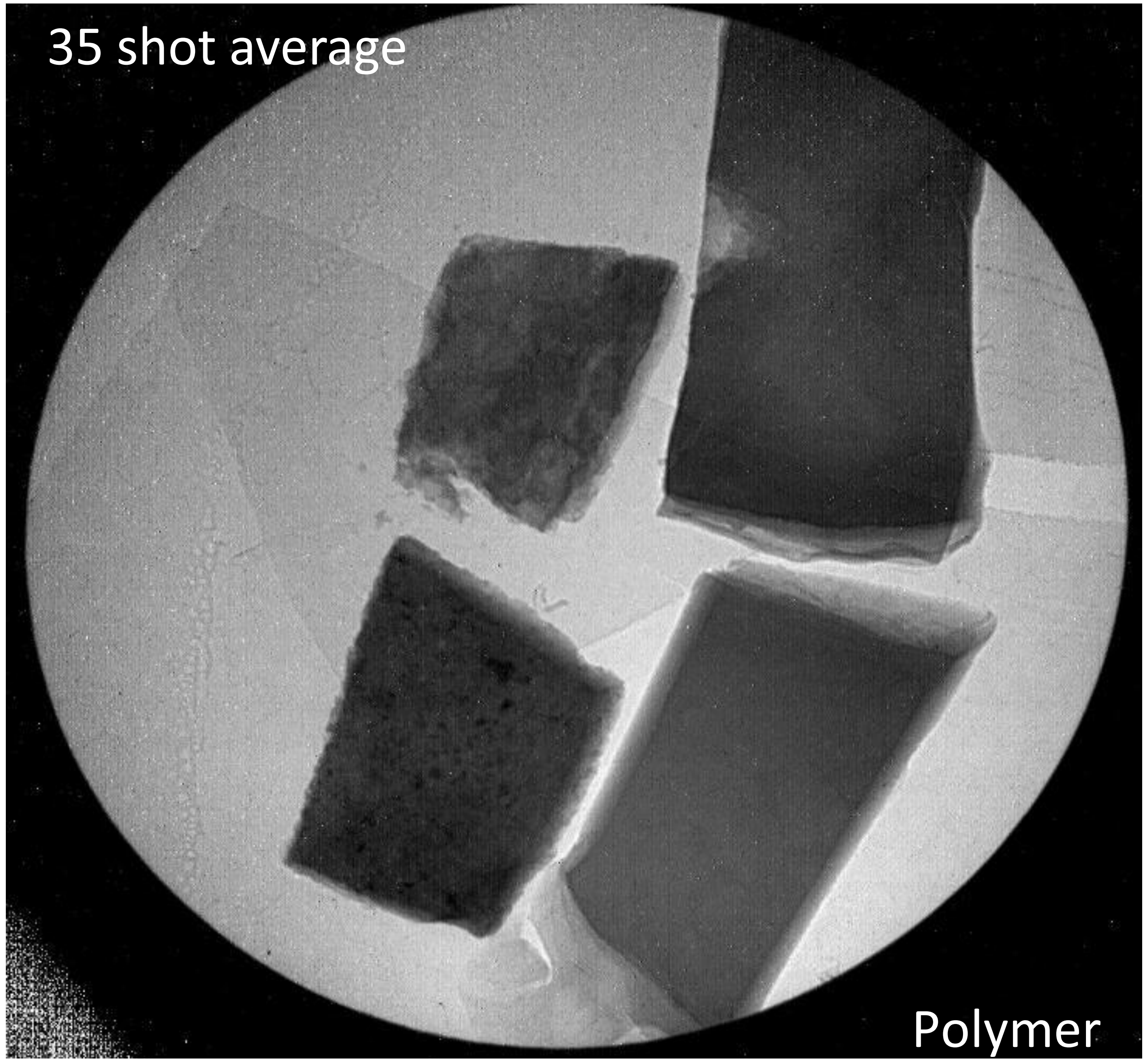
12 bar, He + 5% N_2 admixture, 3 mm above the nozzle







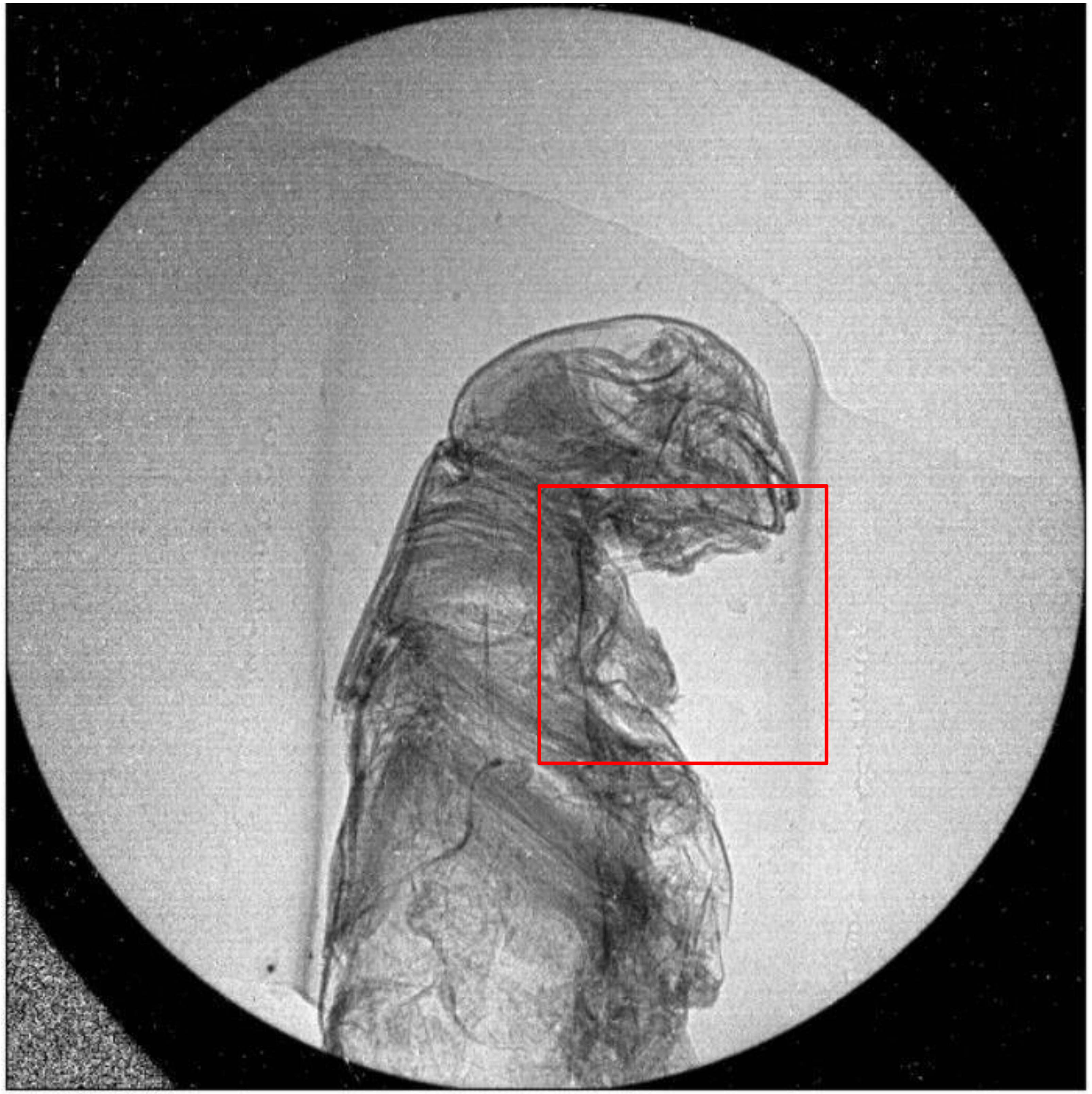
ELI Gammatron Beamline: Commissioning

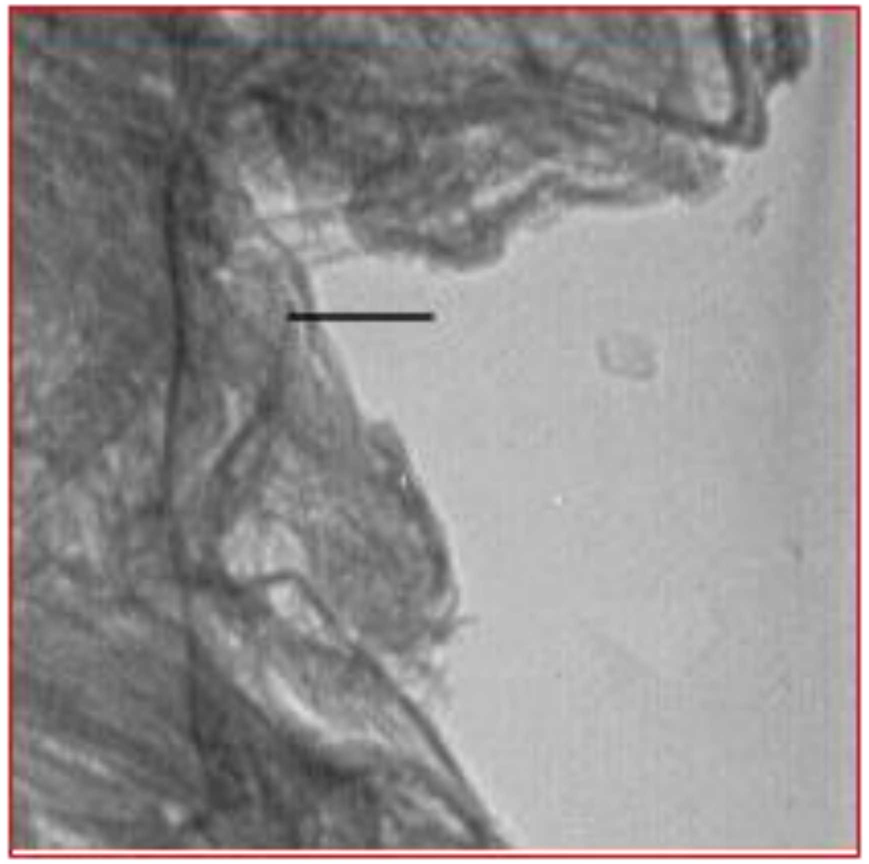


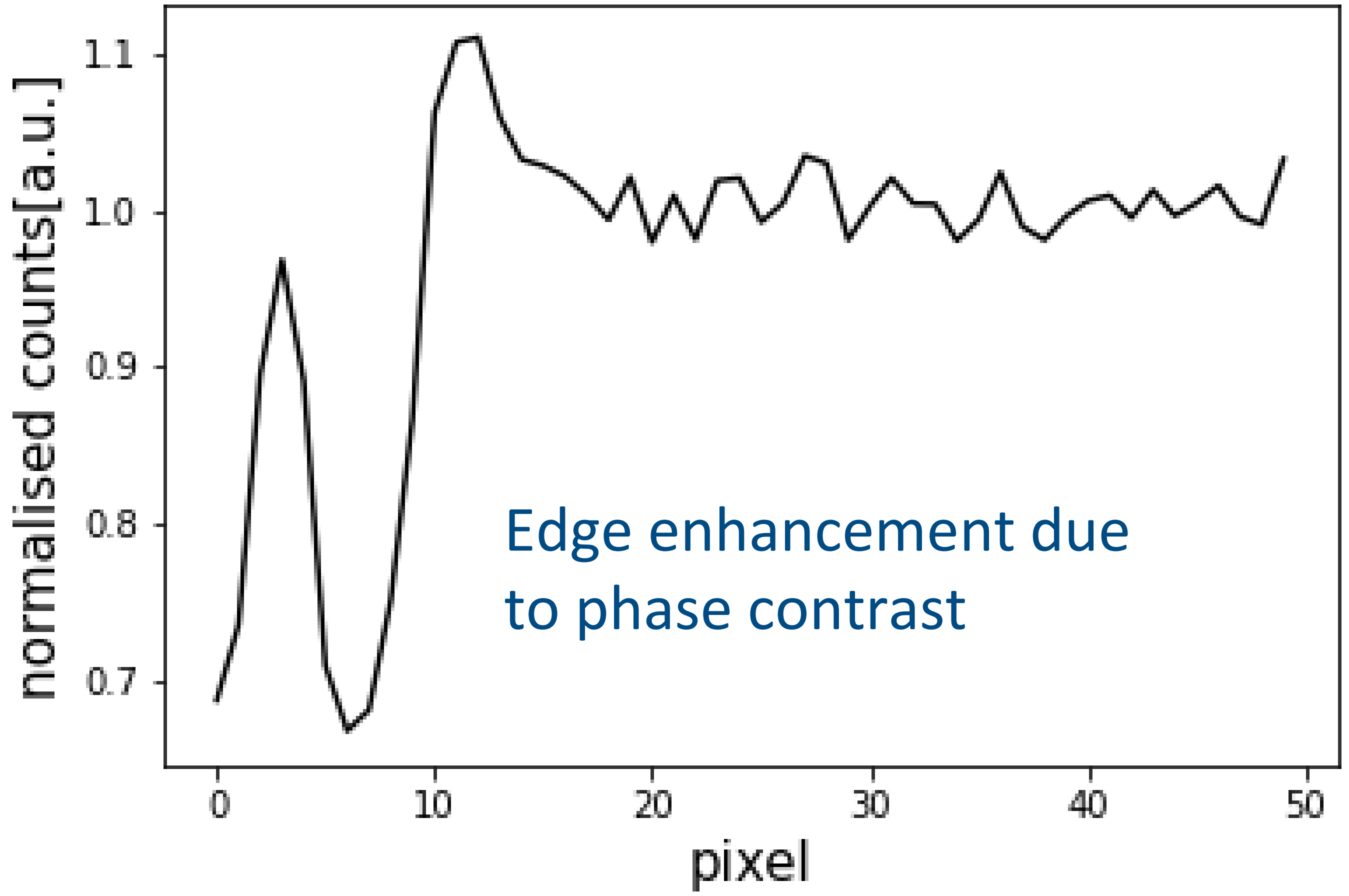
X-ray Imaging/Phase-contrast imaging

Source Sample distance: 70 cm
Source Detector distance:190 cm

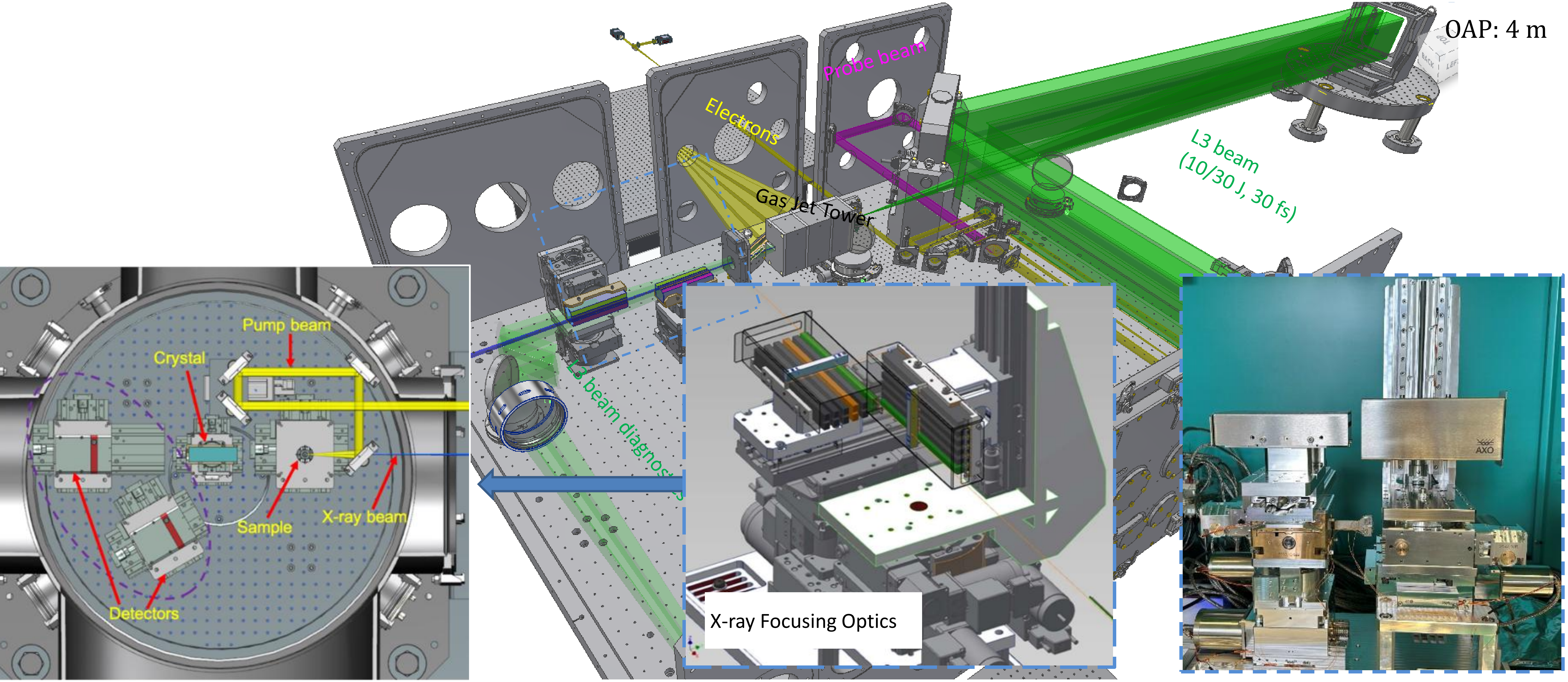
ELI Gammatron Beamline: Commissioning







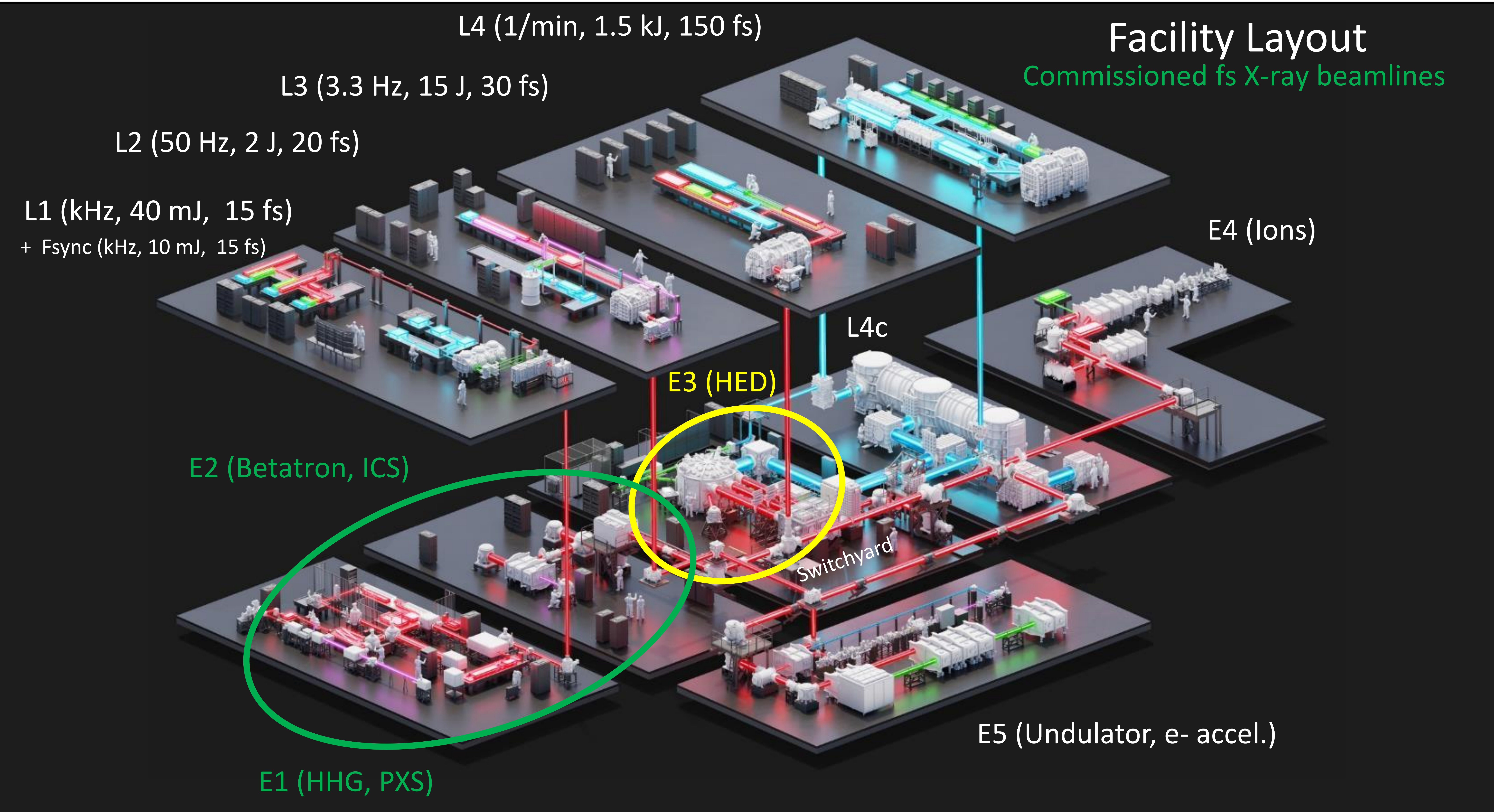
Perspectives



Unique platform for time-resolved X-ray studies at fs scale

Facility Layout

Commissioned fs X-ray beamlines



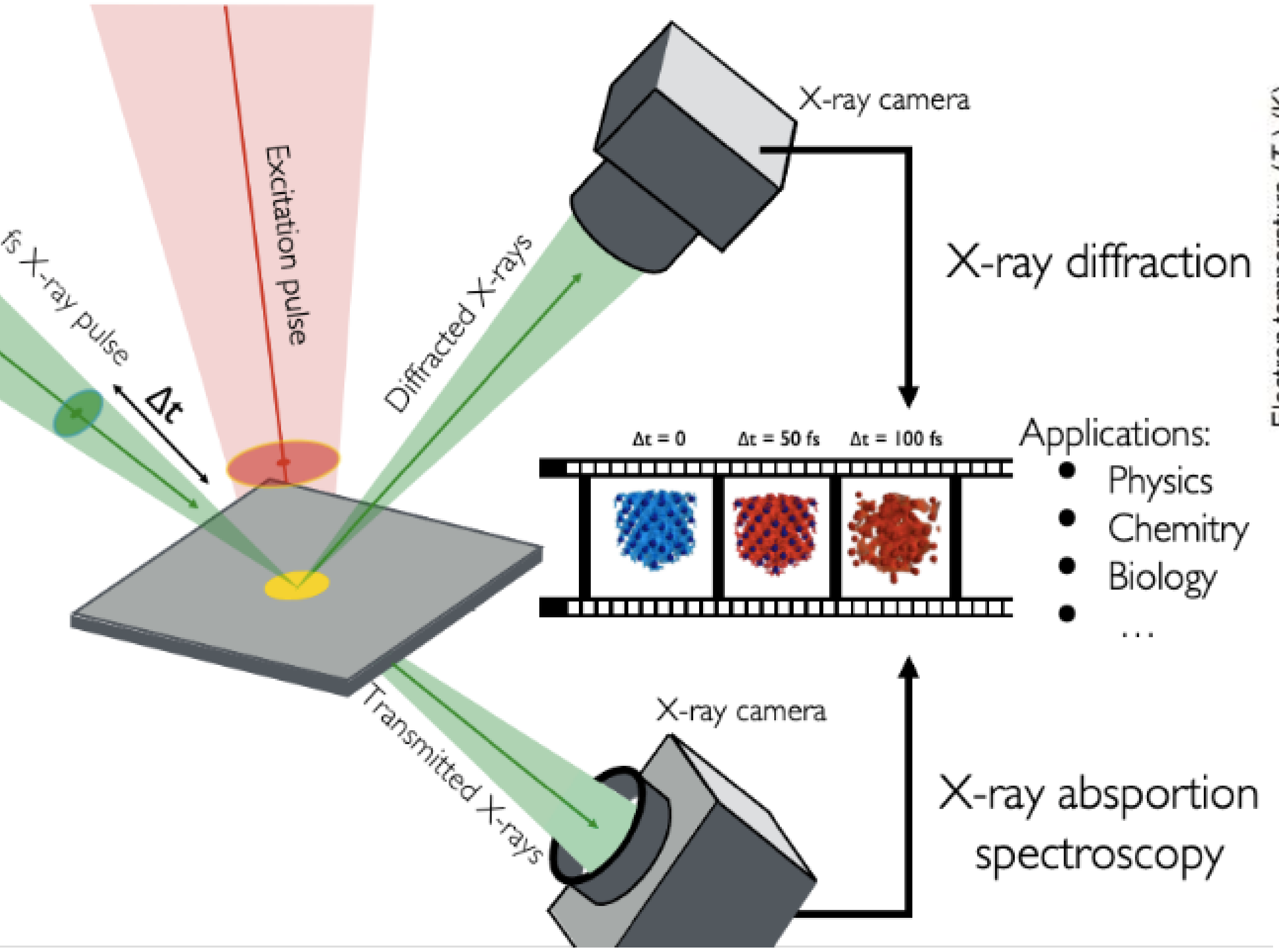
Betatron/Compton Sources in E2/E3

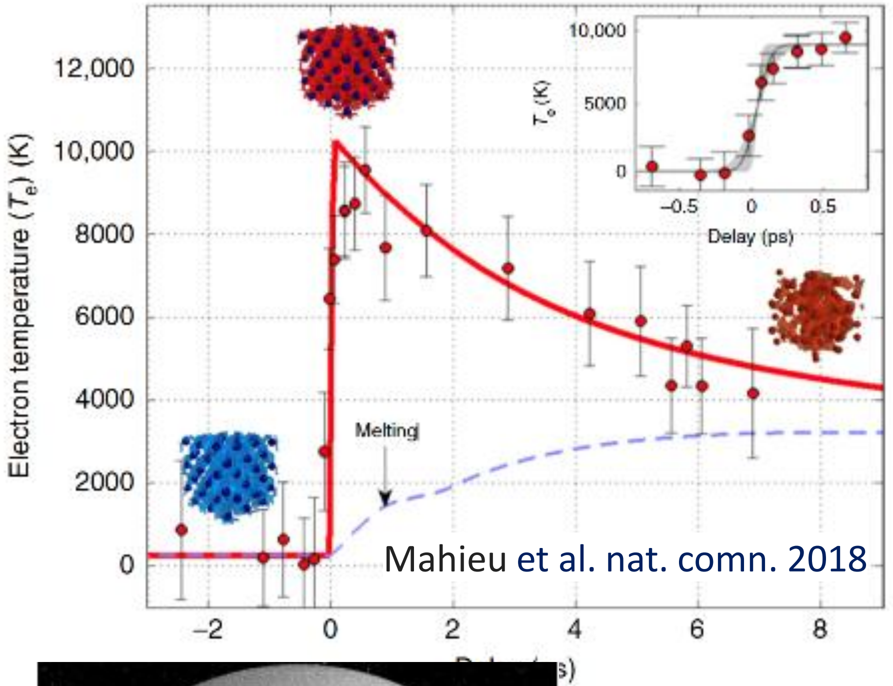
E2: ultrafast X-ray science

- Time-resolved XAS & XES, radiography, Phase contrast imaging, Diffraction etc.
- User access from Q2 2025 **(part of ELI user call 5)**

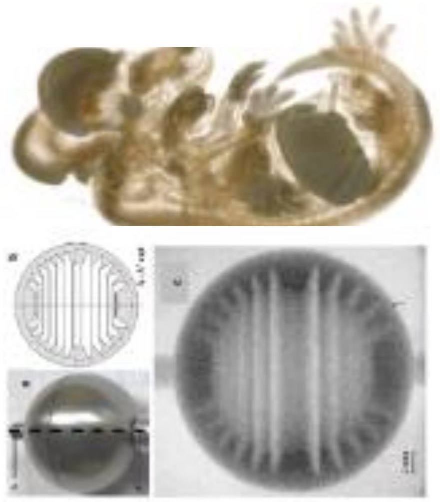
E3: Plasma Physics platform (P3)

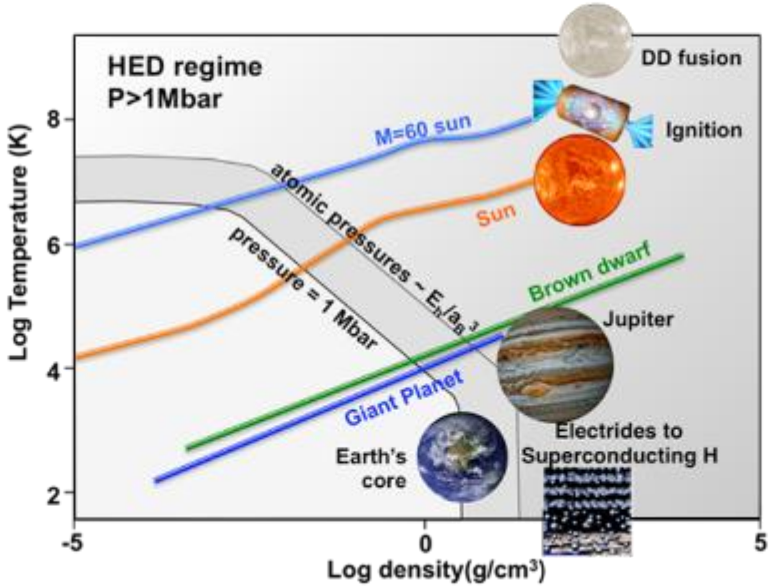
- Betatron source for plasma and WDM diagnostics
- Operational from Q4 2025

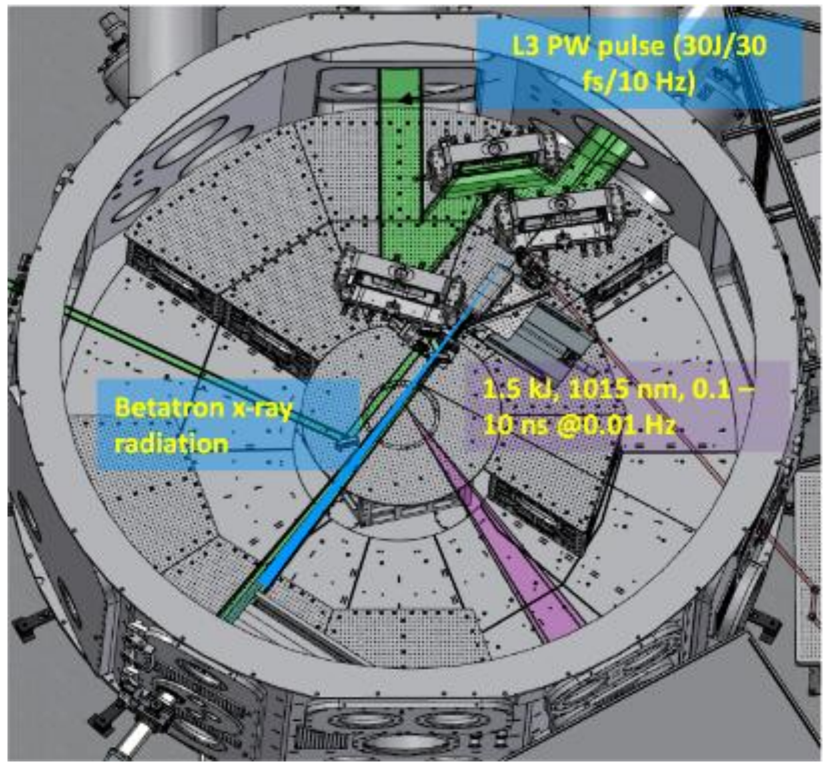


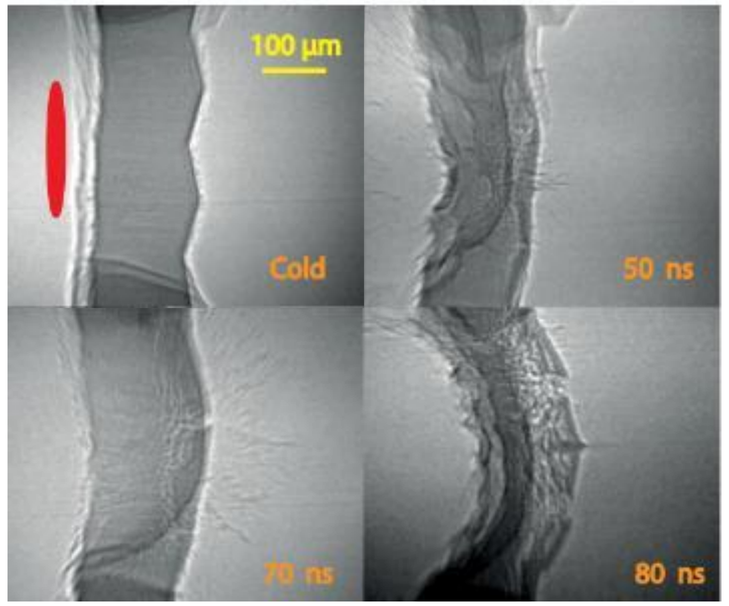


Mahieu et al. nat. comn. 2018

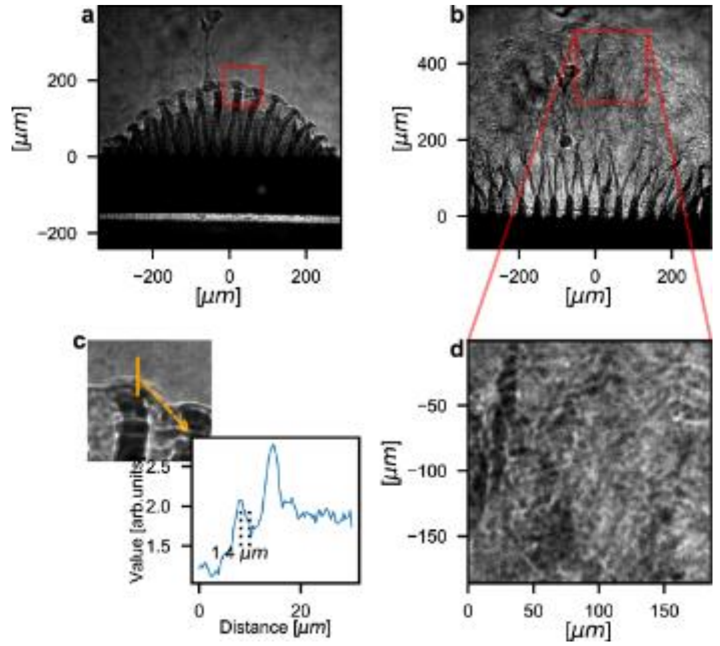








Wood et al., sci. report. 2018



Rigon et al., nat. comn. 2021

One user facility, three modes of access

A flexible model to serve a variety of users

Excellence-based Access
Evaluation of proposals by international peer-review panels.
RESULTS PUBLISHED AND OPEN

Mission-based Access
Thematic research granted on the basis of scientific missions. Proposals reviewed by international panels.
RESULTS PUBLISHED AND OPEN

Proprietary Access
Paid access for industrial or other users.
RESULTS RETAINED BY THE USER

9th ELI Call for Users

Implementation Timeline

Launch Date
15 September 2026

Closing Date
20 October 2026

Beamtime Allocation
January 2027

Implementation Period
May – November 2027

User Portal

https://up.eli-laser.eu

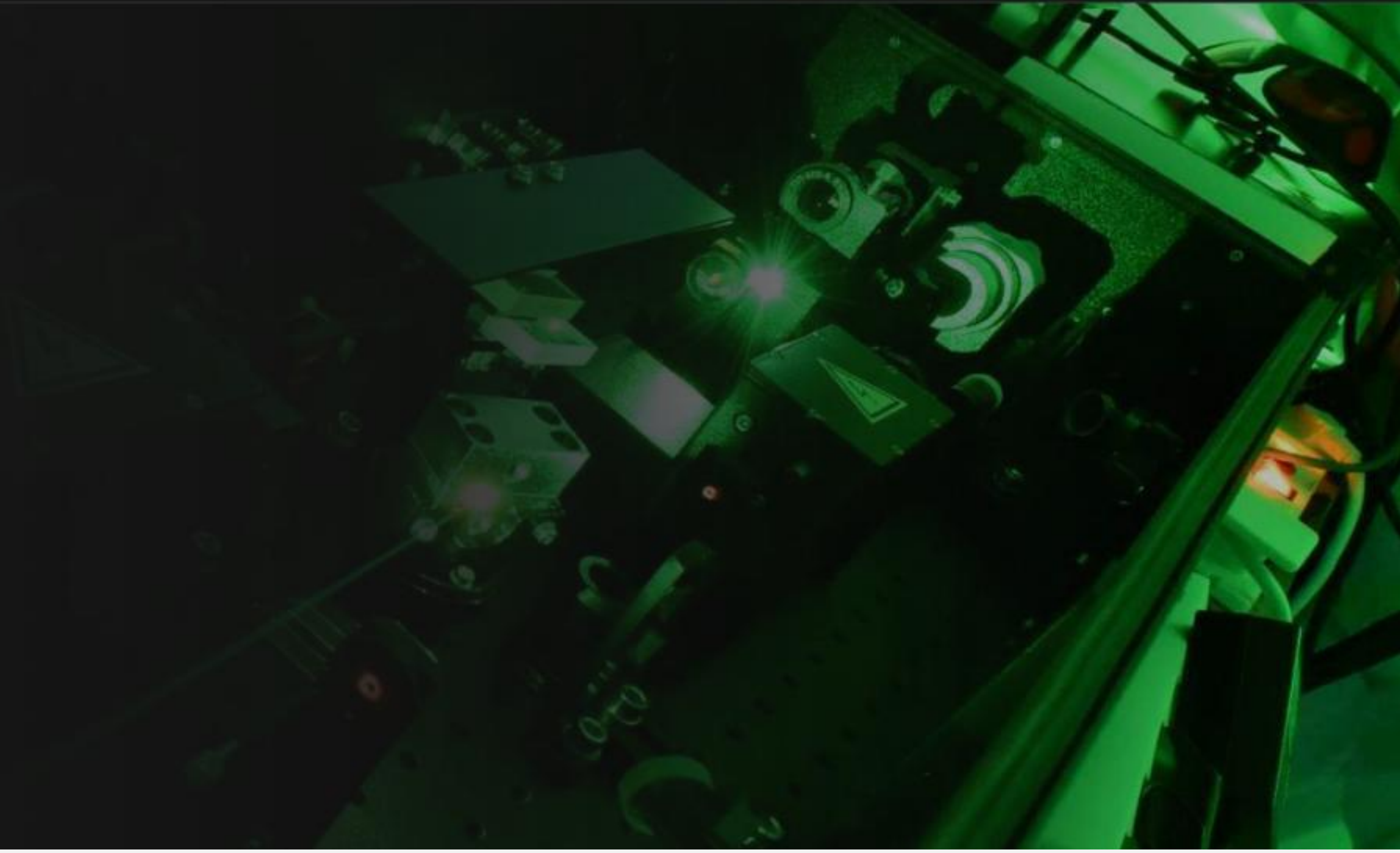
User Portal | User calls | Lasers | Instruments | User guide | News | Terms and Conditions | Contact | My proposals

Access ELI's world-class lasers, equipment and facilities

The ELI User Portal is a portal for researchers and scientists to explore and access comprehensive details on ELI's cutting-edge lasers, equipment, and facilities available for groundbreaking science.

Browse equipment

Apply for beamtime →



The Extreme Light Infrastructure is an international user facility dedicated to multi-disciplinary science and research applications of ultra-intense and ultra-short laser pulses. ELI provides access to world-class high-power, high-repetition-rate laser systems and a wide range of complementary equipment for cutting- edge research in physical, chemical, materials, and medical sciences, as well as breakthrough technological innovations.

Browse the available equipment and find more information below.

The X-ray Team

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We are hiring

Acknowledgements

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