HPXM 2023
Frascati, Italy, June 19-23, 2023

Science and technology of Laser-driven X-ray sources at ELI Beamlines

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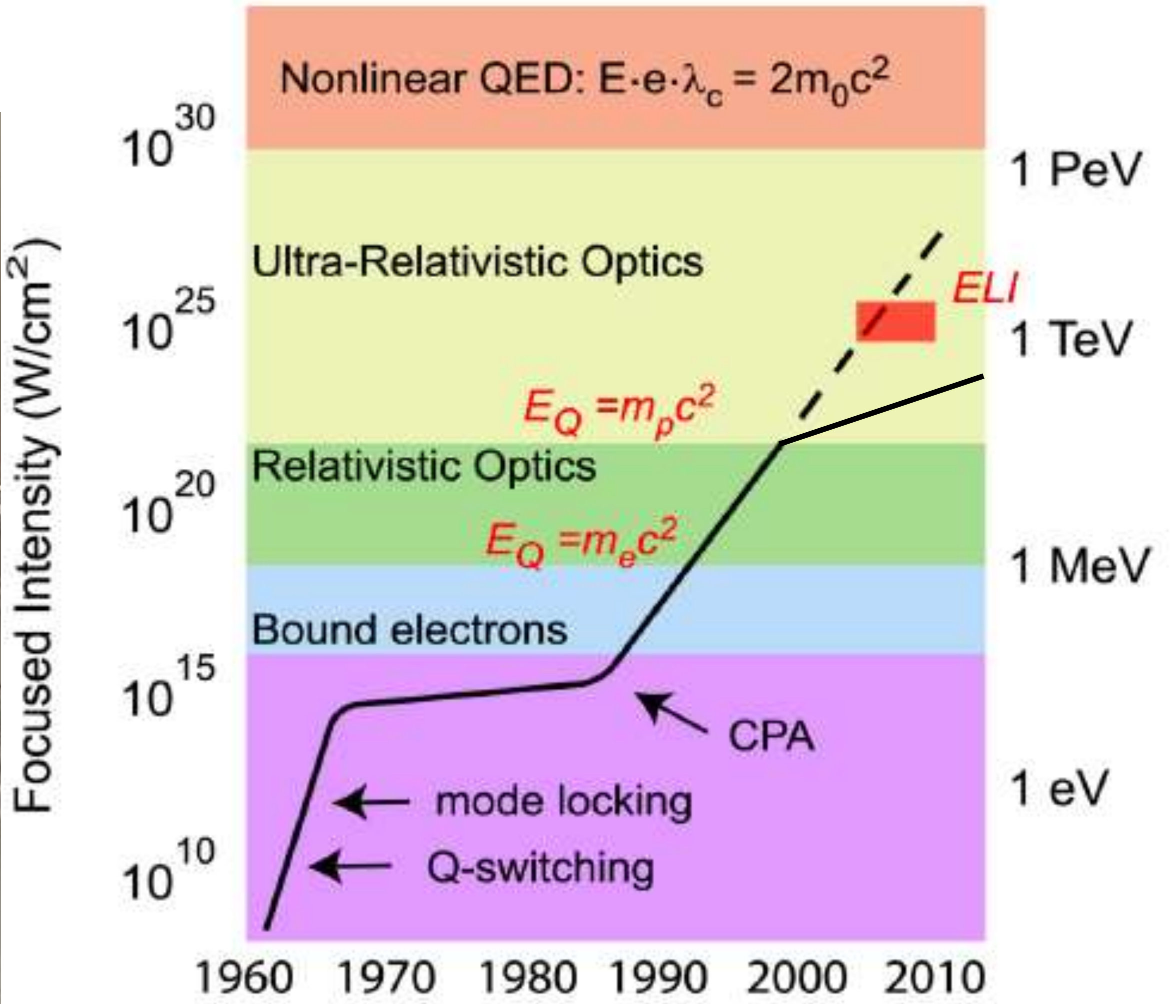
Supported within: Advanced research using high intensity laser produced photons and particles (ADONIS) Reg. n. CZ.02.1.01/0.0/0.0/16_019/0000789

Laser technology: huge development in last 60 years

10 PW laser
commissioned at ELI NP

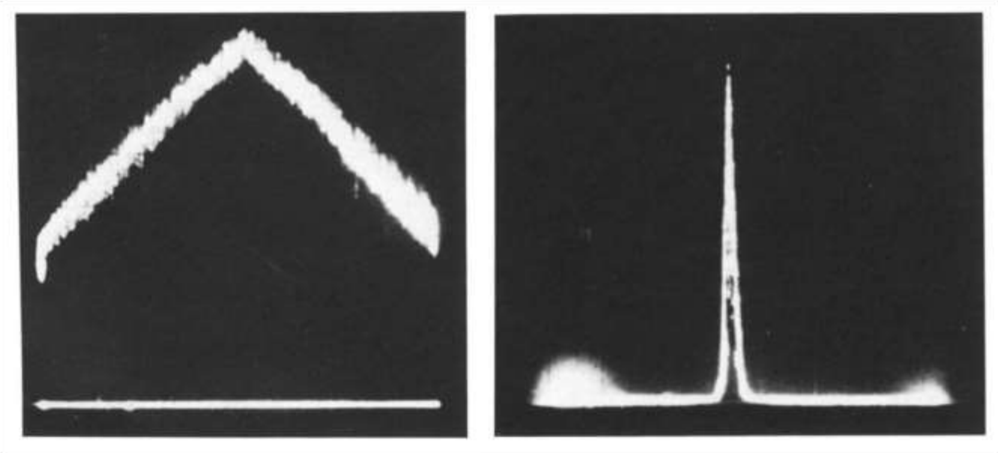


G. Mourou *et al.* Rev. Mod. Phys . **78**, p. 309 (2006)

From Nobel Prize to Extreme Light

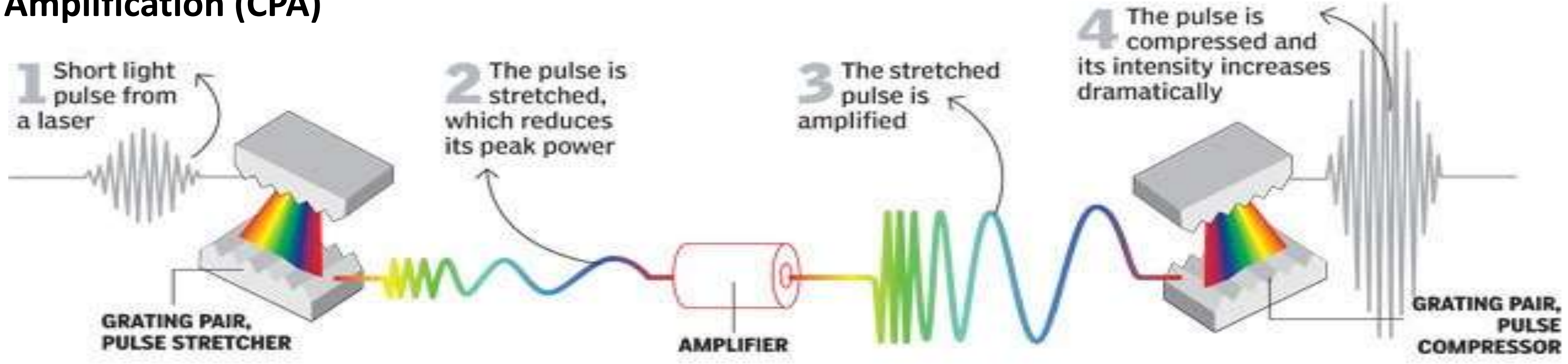
A Technological Breakthrough Enables ELI

Gérard Mourou and Donna Strickland *won the* ***2018 Nobel Prize for Physics*** *for proposing* ***"Chirped Pulse Amplification"*** *for high-power, ultrafast, extremely intense lasers.* ***Mourou proposed ELI in 2004.***



Images of stretched and compressed pulses, from Strickland's 1985 paper on Chirped Pulse Amplification (CPA) which led to petawatt-class lasers

Chirped Pulse Amplification (CPA)



eli beamlines

High peak power lasers

energy, power, intensity

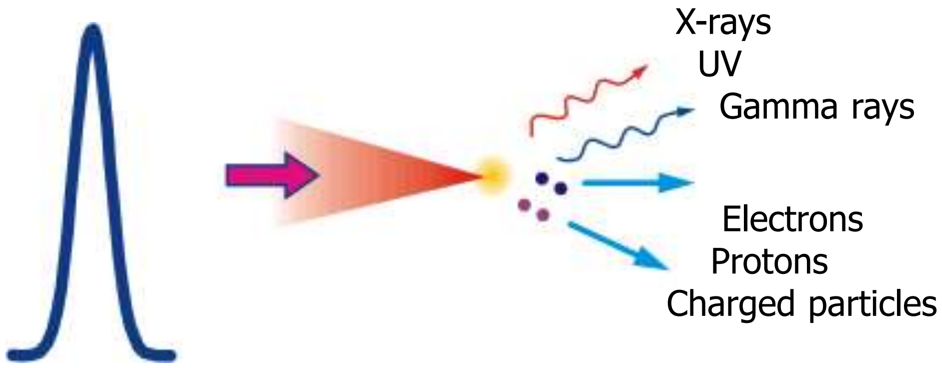
Laser pulse example:

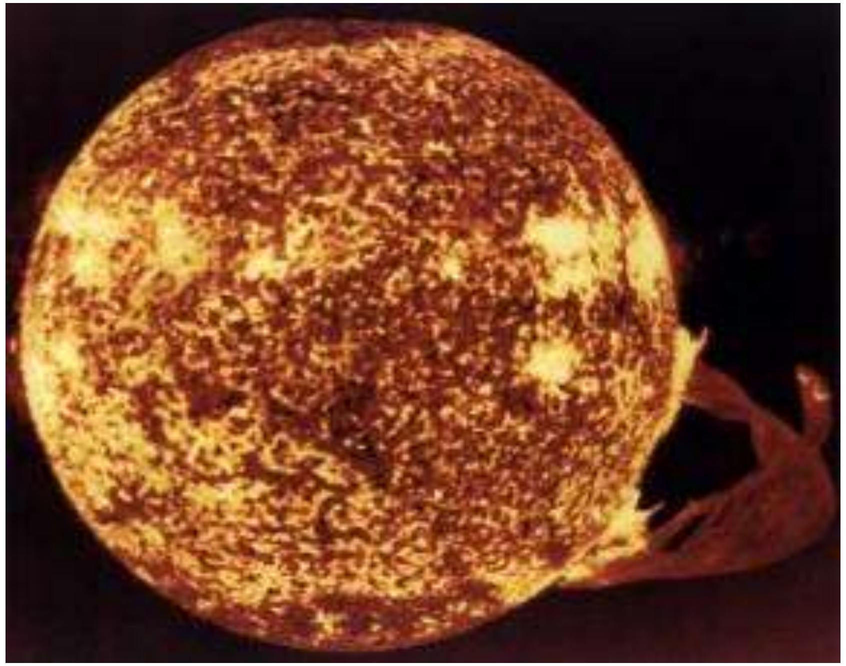
- energy 30 J (heating two drops of water from 20°C to 100° C)
- duration 30 fs (= 3×10^{-14} s), spatial length 10 μm
- Peak power 10^{15} W = 1 PW = 10^{6} GW (!!!)

Focusing the beam to area of 1 μm^2

Intensity in focus 10^{23} Wcm^{-2}

~ The Sun emitting all its power ($4\text{x}10^{26}$ W) from area smaller than 1 m^2





Femtosecond lasers:

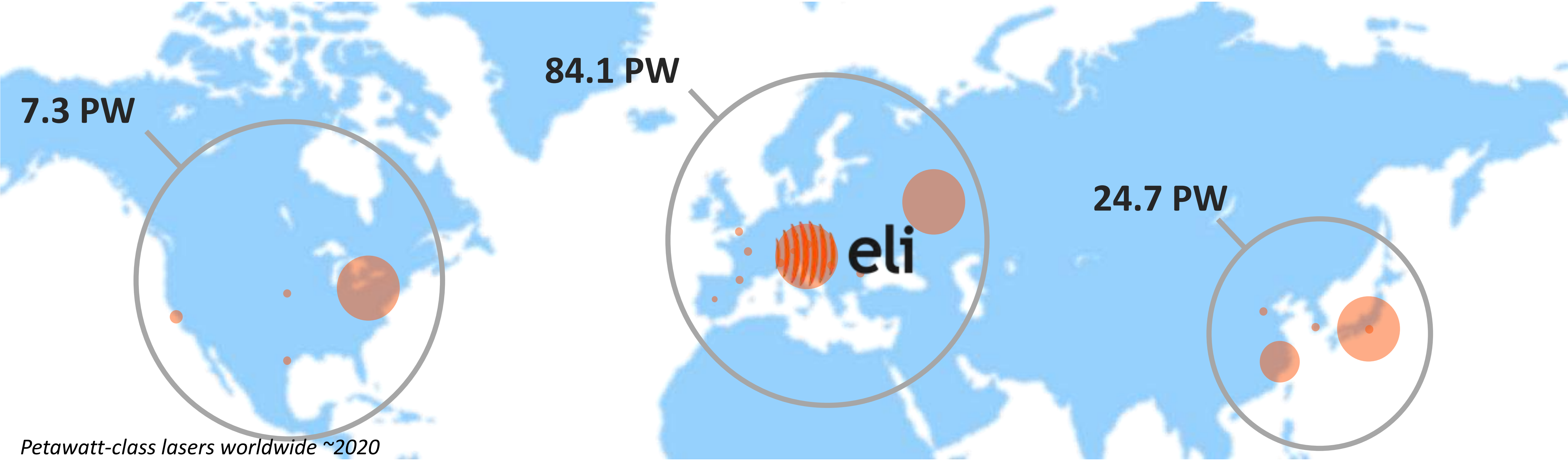
- Most intense pulsed sources of EM fields in the lab

Outline

- Brief introduction of ELI and ELI Beamlines
- Lasers driving X-ray sources at ELI Beamlines
- X-ray sources at ELI BL
  - HHG from gases
  - Plasma X-ray sources
  - X-rays from relativistic electrons
    - Betatron & Inverse Compton sources
    - Laser-driven Undulator X-ray source
- How can YOU benefit from ELI

Europe leads the world in *high-power* laser technology

- **Investment** in high-power laser systems in Europe is connected to **a strong and relatively consolidated** community in Laserlab Europe beginning in 2001.
- **The ELI Facilities** are introducing **5 PW+ lasers, (3x10PW and 2xPW@10Hz)** plus a **diverse set of secondary sources** with unique specs.



Petawatt-class lasers worldwide ~2020
Courtesy of J.L. Collier, CLF RAL, UK

Extreme Light Infrastructure (ELI)

ELI comprises three branches:

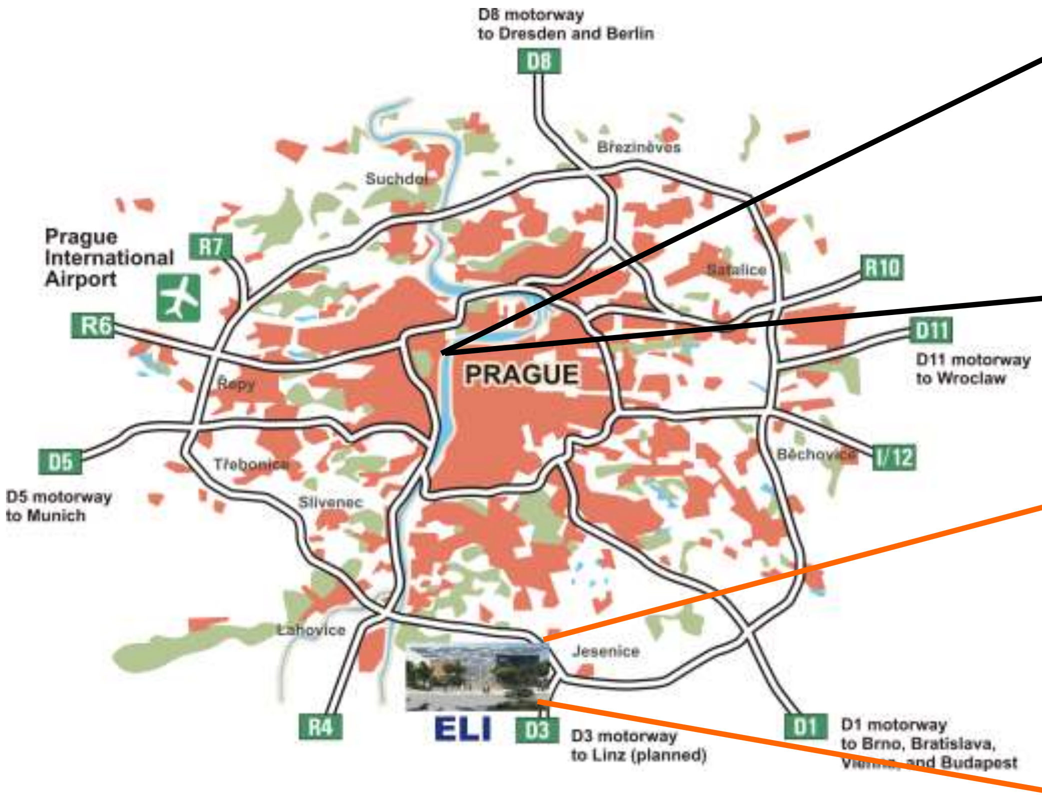
- **Attosecond Laser Science**
  new regimes of time resolution
  (ELI ALPS, Szeged, HU)

- **High-Energy Beam Facility**
  ultra-short pulses of high-energy particles and radiation
  (ELI Beamlines, Prague, CZ)

- **Nuclear Physics Facility**
  brilliant gamma beams (up to 19 MeV) and brilliant neutron beam
  (ELI NP, Magurele, RO)



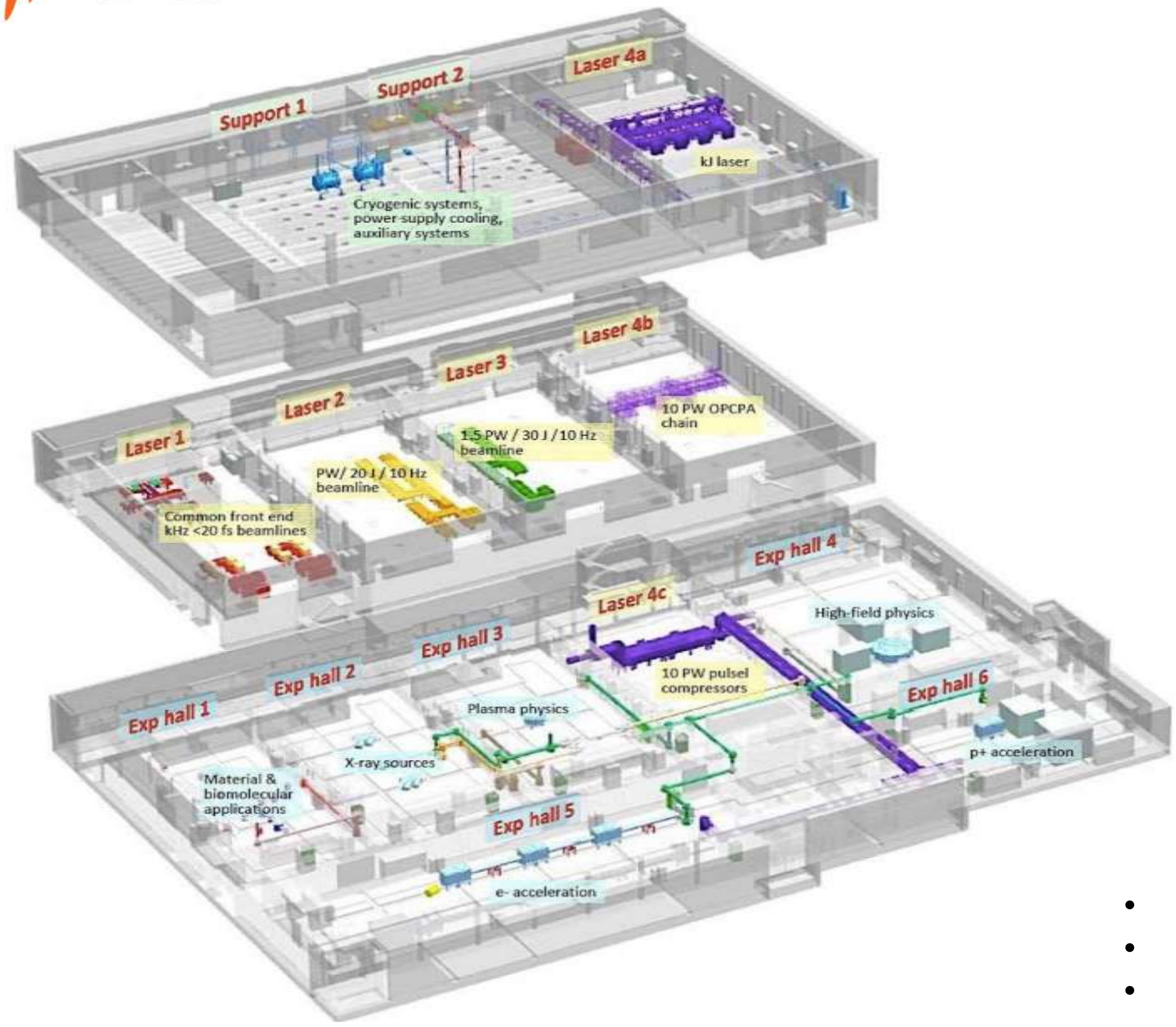
ELI Beamlines, Prague, Czech Republic



2011 – 2022 ELI Beamlines

- Facility with New Generation of High-Power Lasers
- User-oriented X-ray beamlines (driven by lasers)

Facility layout and laser drivers for X-ray sources

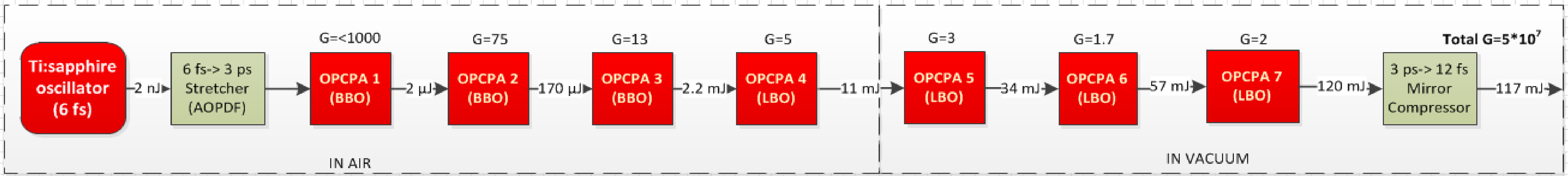


Laser	L1	L2	L3	L4
Energy (J)	0.1	5	30	1200
Pulse duration (fs)	15	20	30	120
Wavelength (nm)	830	850	820	1060
Rep. rate	1 kHz	20 - 50 Hz	10 Hz	1/min

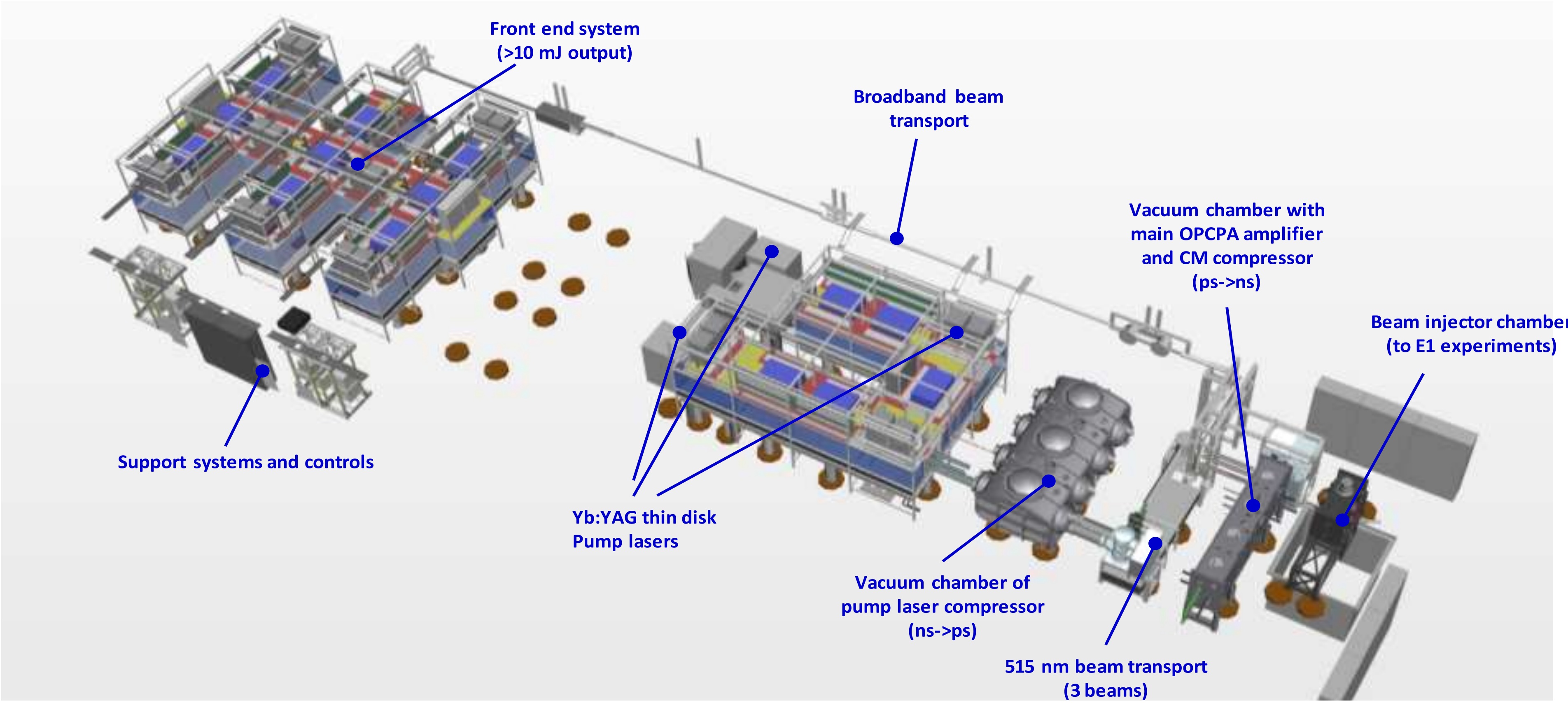
+ Commercial lasers (L1 backup)

- Coherent LEGEND Elite DUO: 1kHz, 12 mJ @ 35 fs
- Coherent Astrella: 1 kHz, 2x6 mJ @ 45 fs
- Coherent Hidra: 10 Hz, 100 mJ @ 40 fs

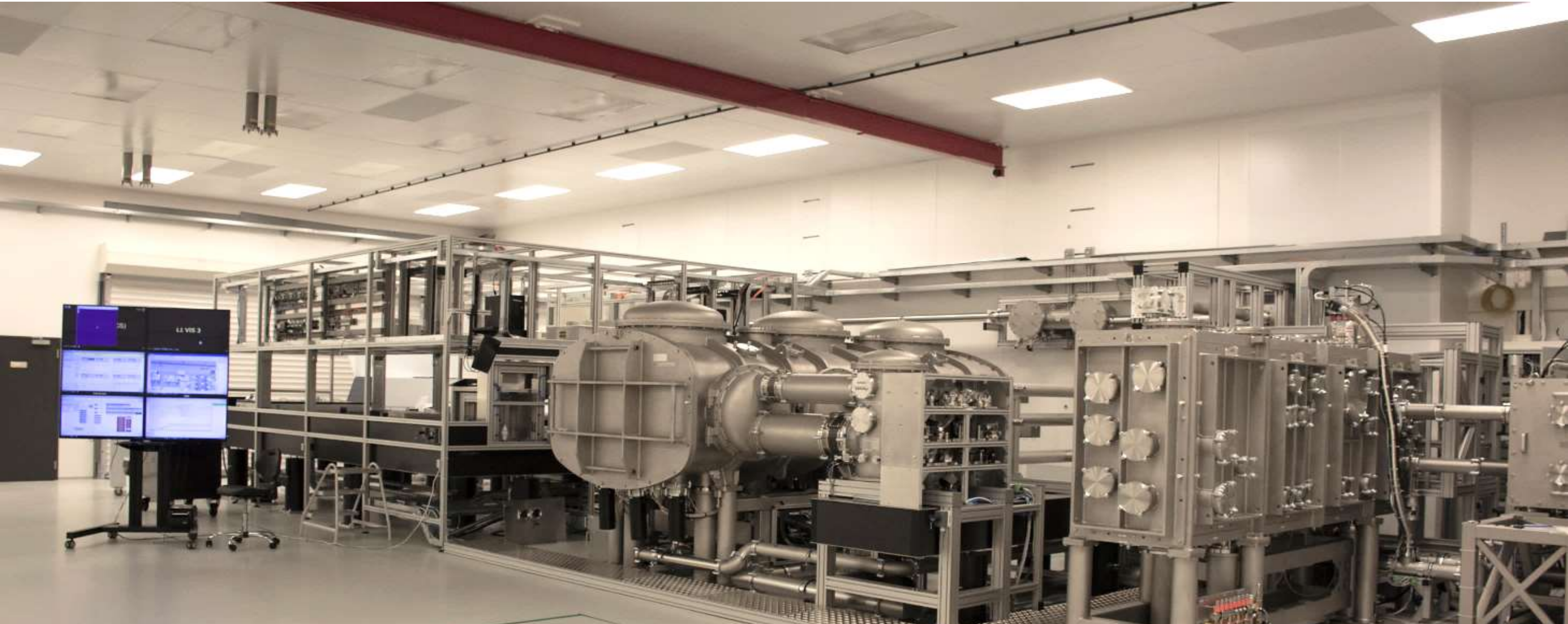
Laser drivers: L1 Allegra



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



Laser drivers for X-ray sources: L1 Allegra



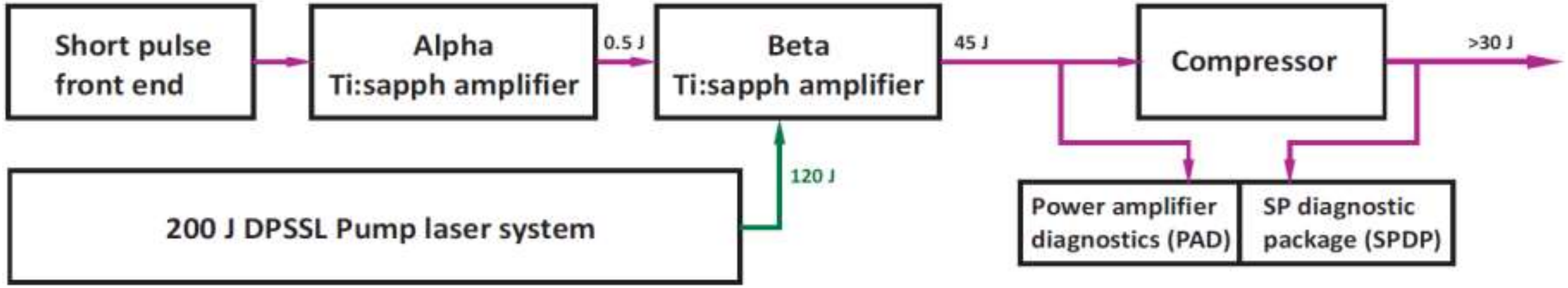
Available for experiments:

Now	**50 mJ / 15 fs / 1 kHz**
design	100 mJ / 15 fs / 1 kHz

R. Antipenkov et al., Proc. SPIE 11034, 110340M (2019)

Laser drivers: L3 HAPLS

HAPLS: High repetition rate Advanced Petawatt Laser System



L3-HAPLS with compressor at ELI-Beamlines

Parameter	Value
Peak power	≥1PW
Repetition rate	10 Hz
Pulse energy	≥30 J
Pulse duration	≤30 fs
Central wavelength	820 nm
Pump laser technology	DPSSL

Laser drivers for X-ray sources: L3 HAPLS

Now	**12 J / 30 fs / 3.3 Hz**
design	>30 J / 30 fs / 10 Hz

Laser driven X-ray sources: several approaches

E1

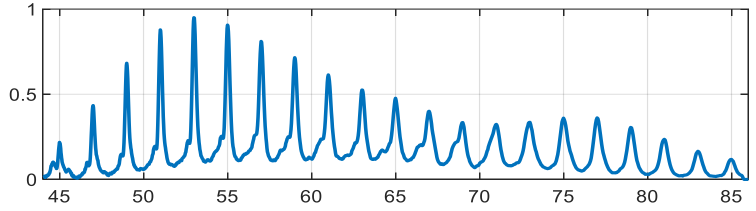
L1 driver

1 kHz, 100 mJ, 20 fs

Ti:sapphire backup

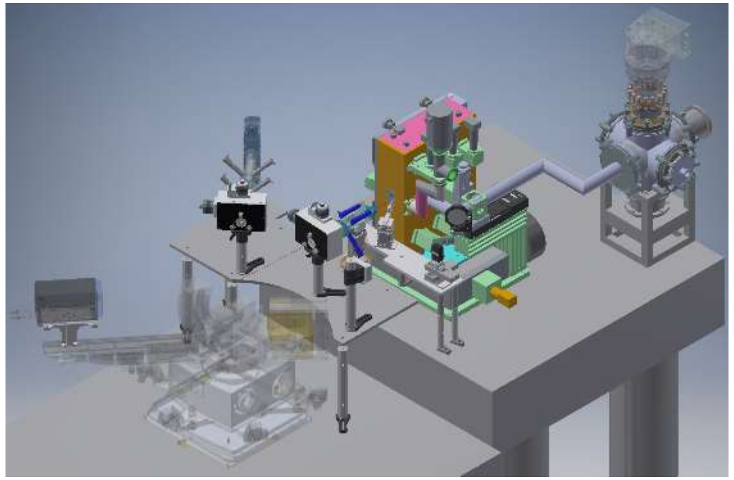
1 kHz, 12 mJ, 35 fs
& 10 Hz, 100 mJ, 40 fs

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



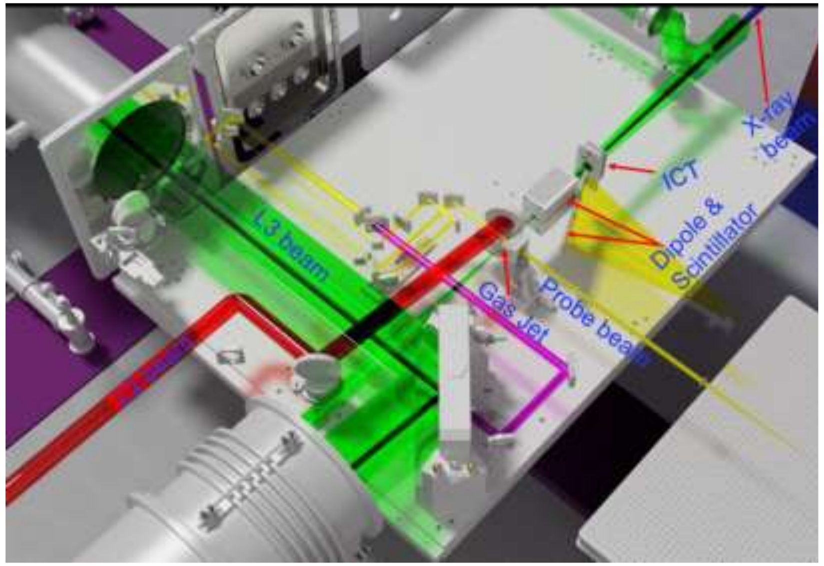
	10 mJ, 35 fs	100 mJ laser (15 fs)
photon energy	3 - 40 keV	3 – 80 keV
photons/(4π sr line or 1keV @10keV)	> 10^8	> 10^9
Source size	< 50 µm	< 50 µm
pulse duration	< 300 fs	<300 fs

E2/E3

L3 driver

10 Hz, 30 J, 30 fs

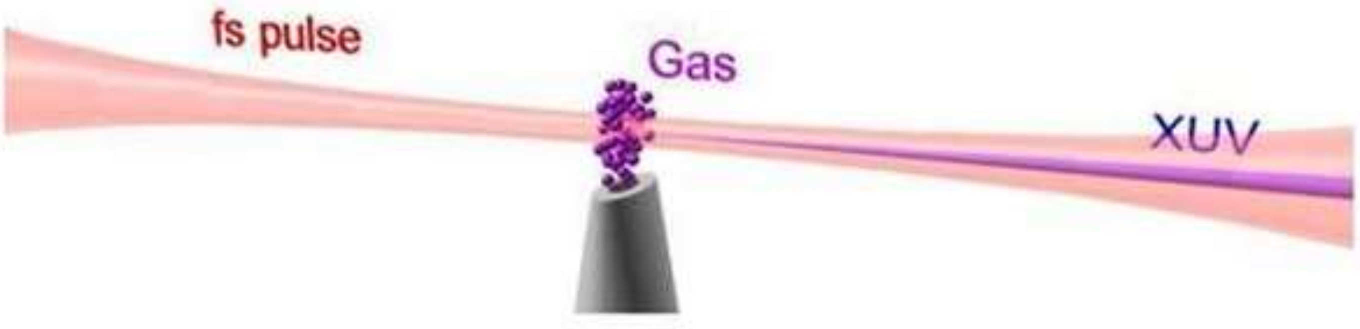
Betatron / inverse Compton

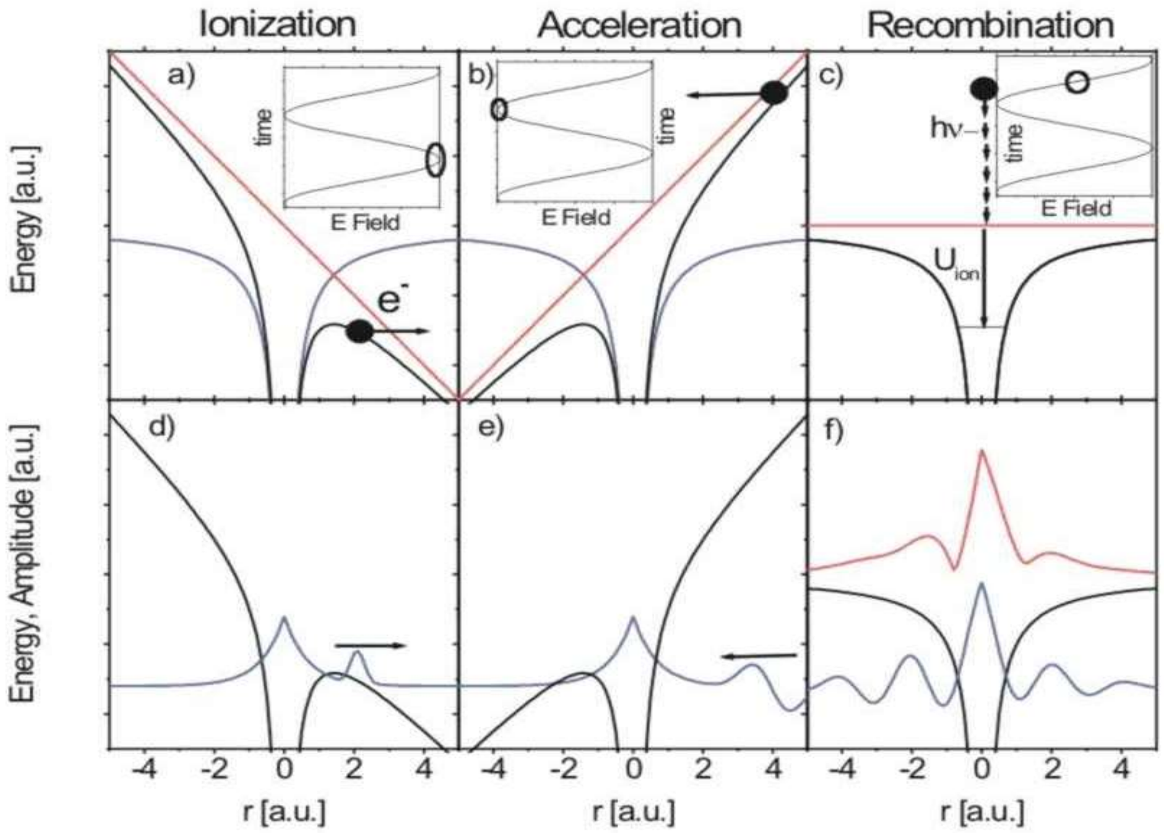


	Betatron	Compton
photon energy	10- 100 keV	50 – 5000 keV
photons/shot	> 10^9	> 10^8
Source size	< 5 µm	< 5 µm
pulse duration	~30 fs	< 30 fs

High-order harmonic generation from gas

- Interaction of linearly polarized intense laser pulse with matter (valence electron)



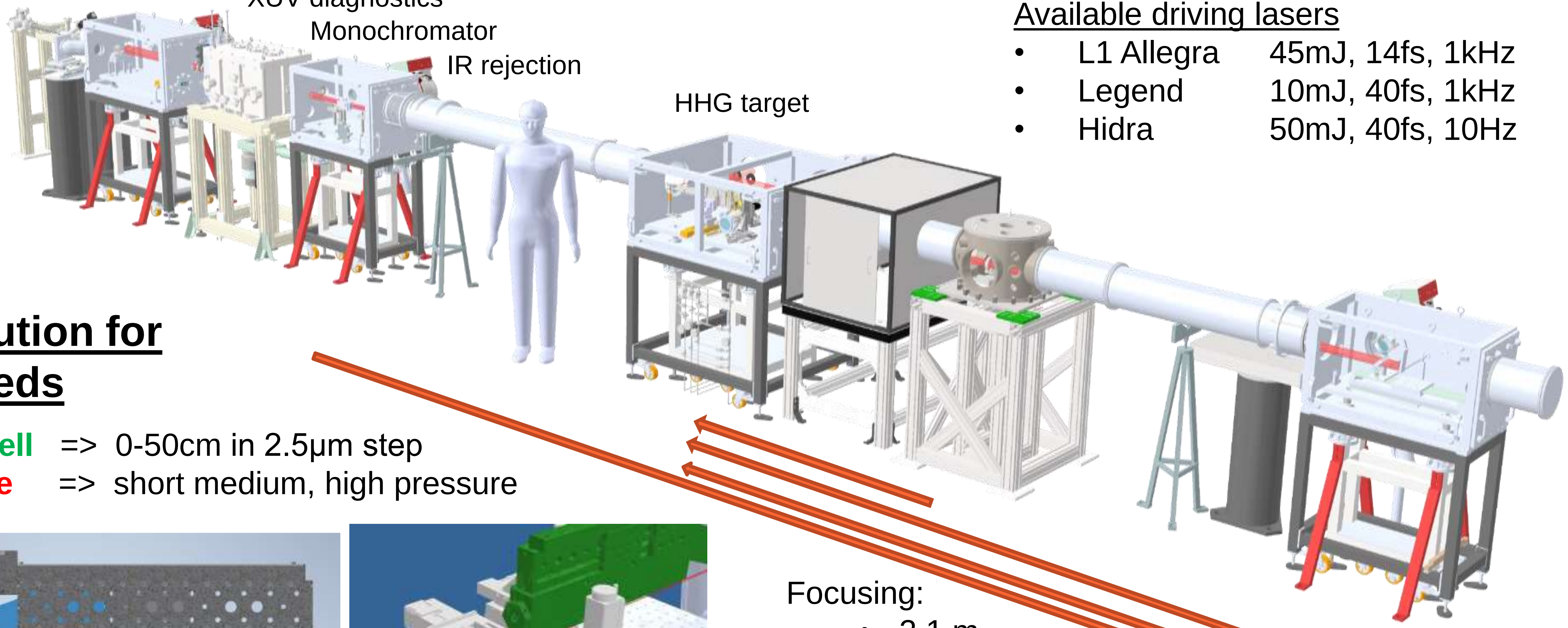


- Three step model:
  - Ionization
  - Acceleration
  - Recombination

P. B. Corkum, Phys. Rev. Lett., **71**, 1994 (1993)

http://www.stanford.edu/~mguehr/research_HHG.html

User oriented HHG beamline

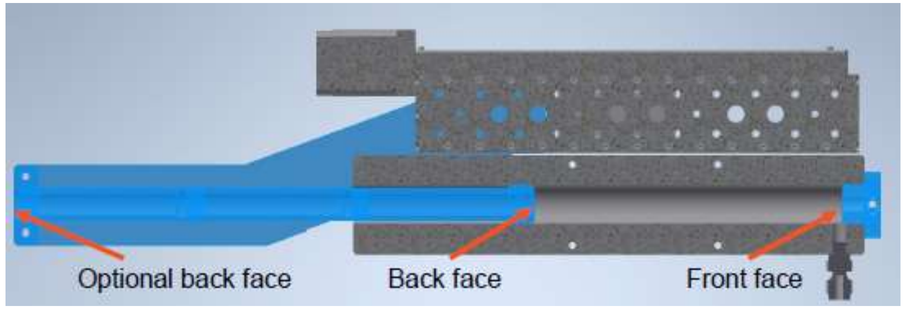


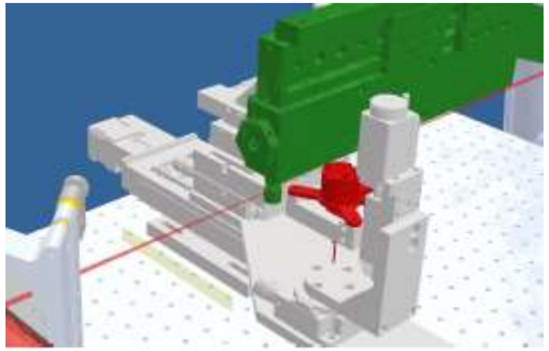
<u>Available driving lasers</u>

- L1 Allegra 45mJ, 14fs, 1kHz
- Legend 10mJ, 40fs, 1kHz
- Hidra 50mJ, 40fs, 10Hz

<u>Versatile solution for user needs</u>

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

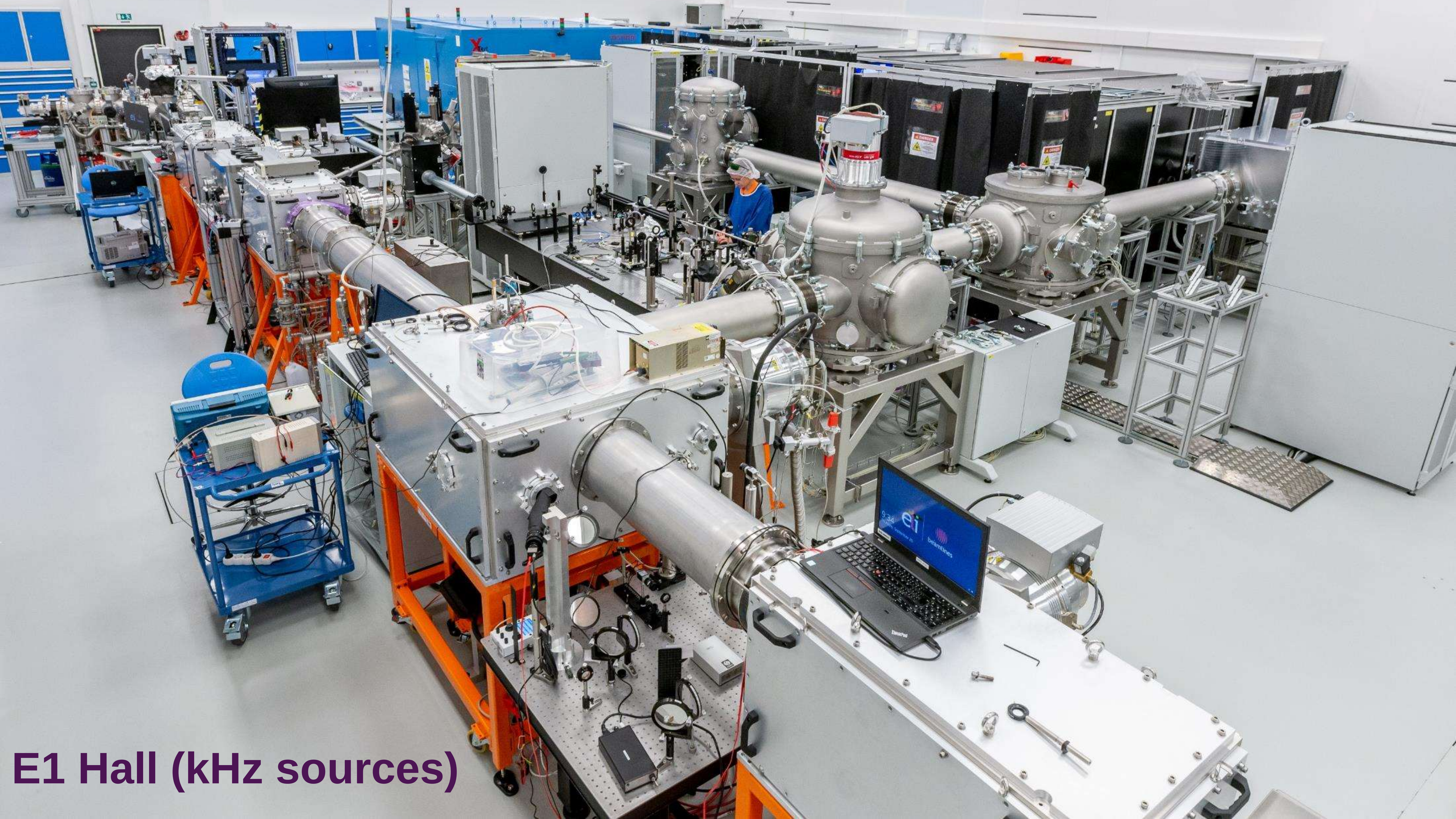




Focusing:

- 2.1 m
- 5 m
- 14.5 m

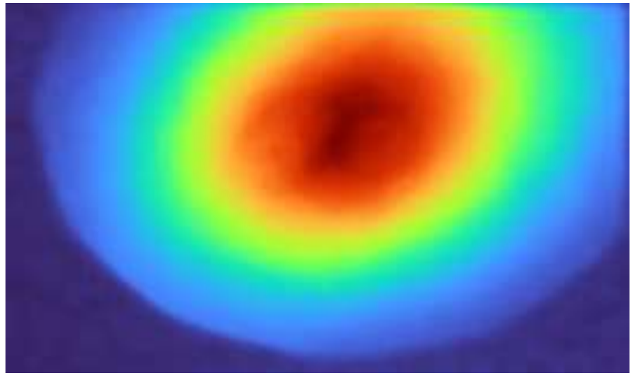
O. Hort et al., Opt. Exp. **27**, 8871 (2019)



E1 Hall (kHz sources)

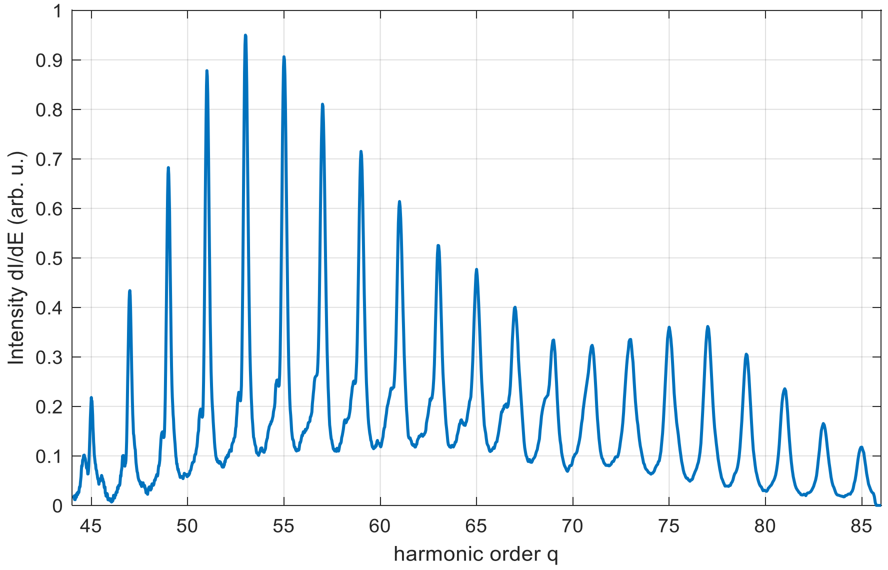
User oriented HHG beamline

Measured XUV beam profile

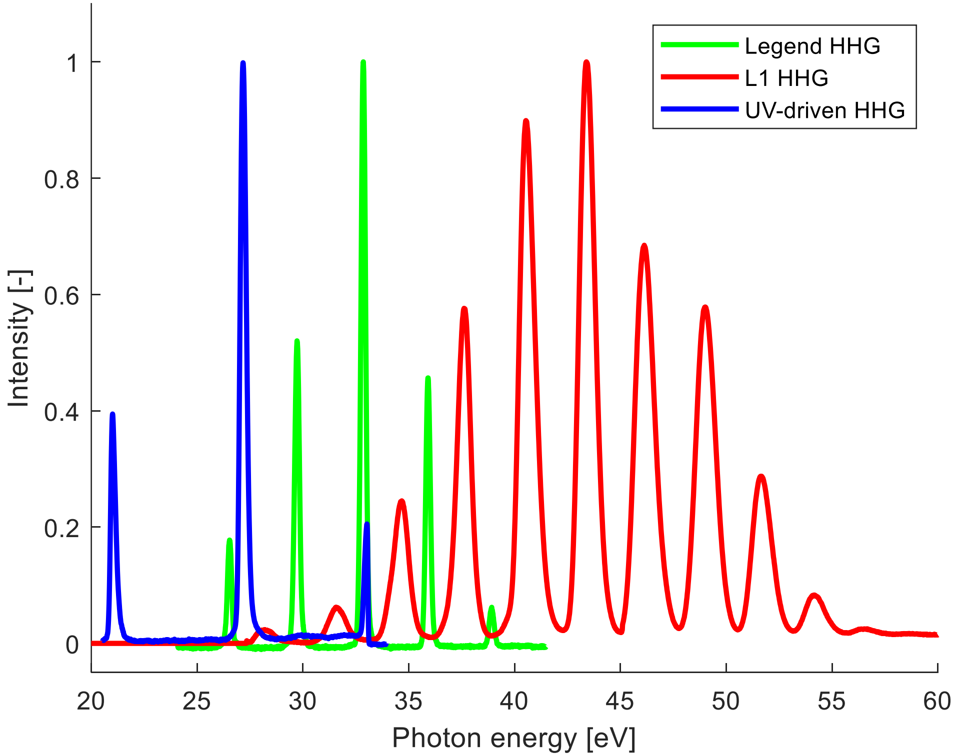


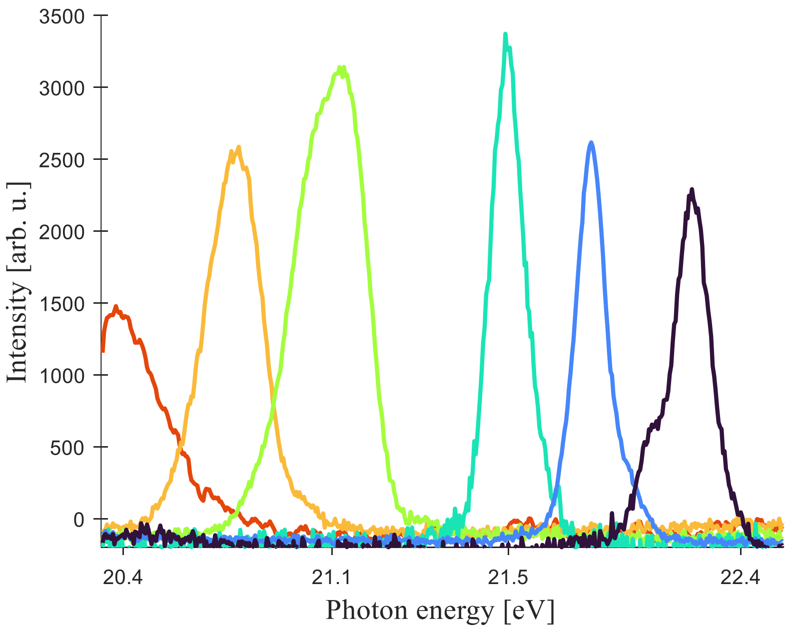
Gas	λ_{XUV} (nm)	Estim. XUV energy (μJ)
Xenon	≥50	2
Argon	≥30	0.2
Neon	≥10	0.02
Helium	≥5	0.02

neon

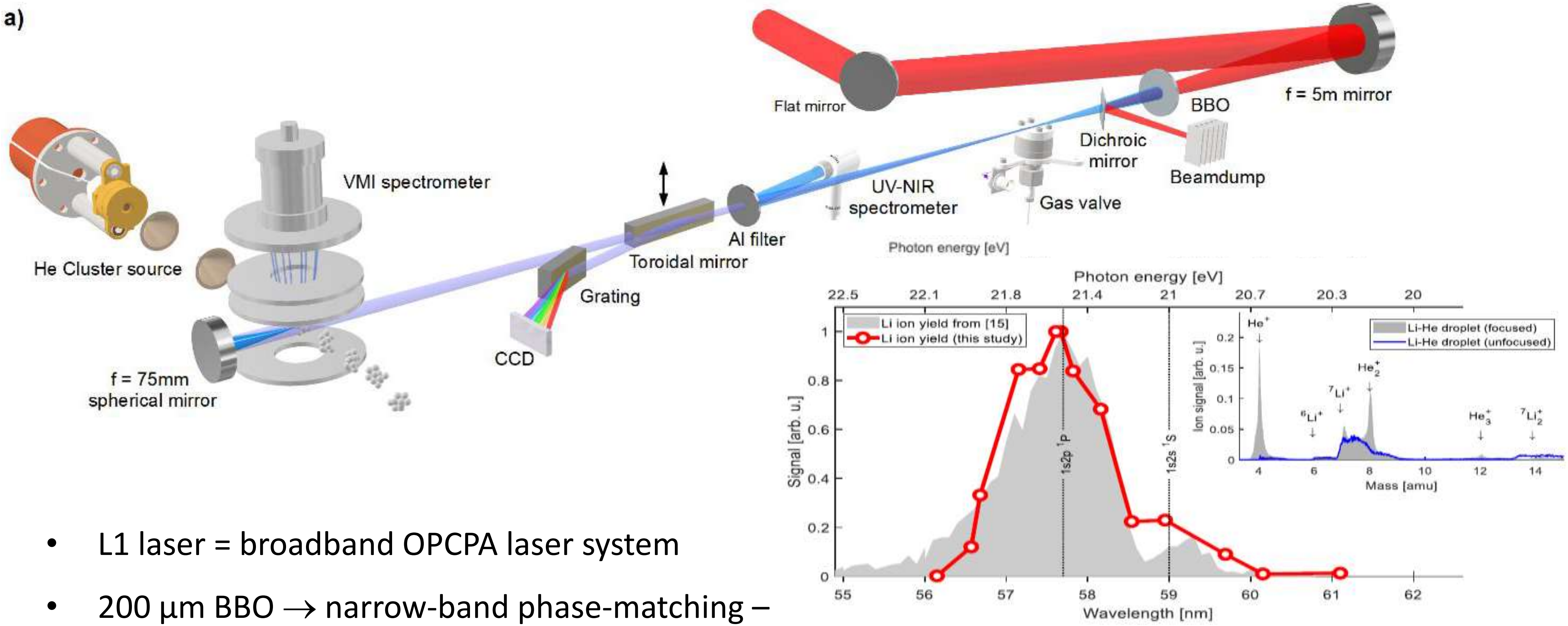


L1: λ=830 nm, τ=15 fs, 10 mJ





Precise spectral tuning for spectroscopy



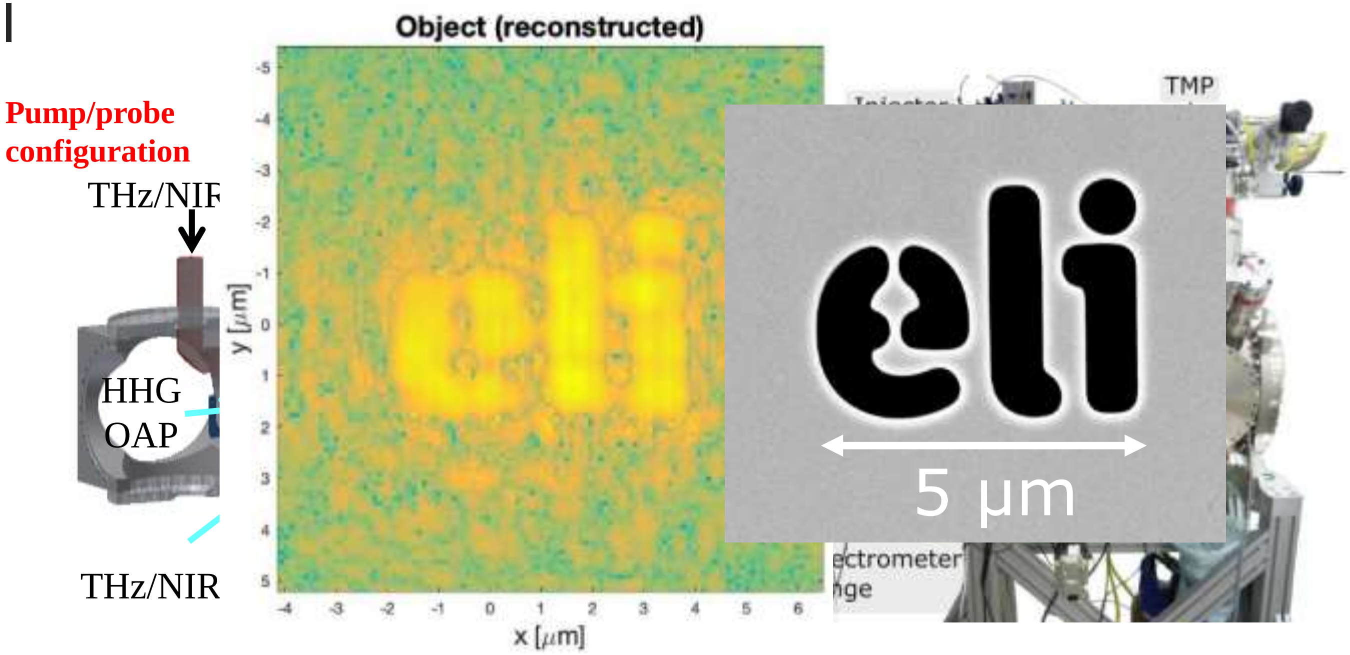
- L1 laser = broadband OPCPA laser system
- 200 µm BBO → narrow-band phase-matching –
- Tuning the H7 (~21.5 eV) around the He resonance (in Li-doped He nanodroplets)
- Interatomic Coulomb Decay ($He^* \rightarrow Li^+$) & Collective auto-ionization ($He^*+He^* \rightarrow He + He^+$)

HHG Beamline end-stations

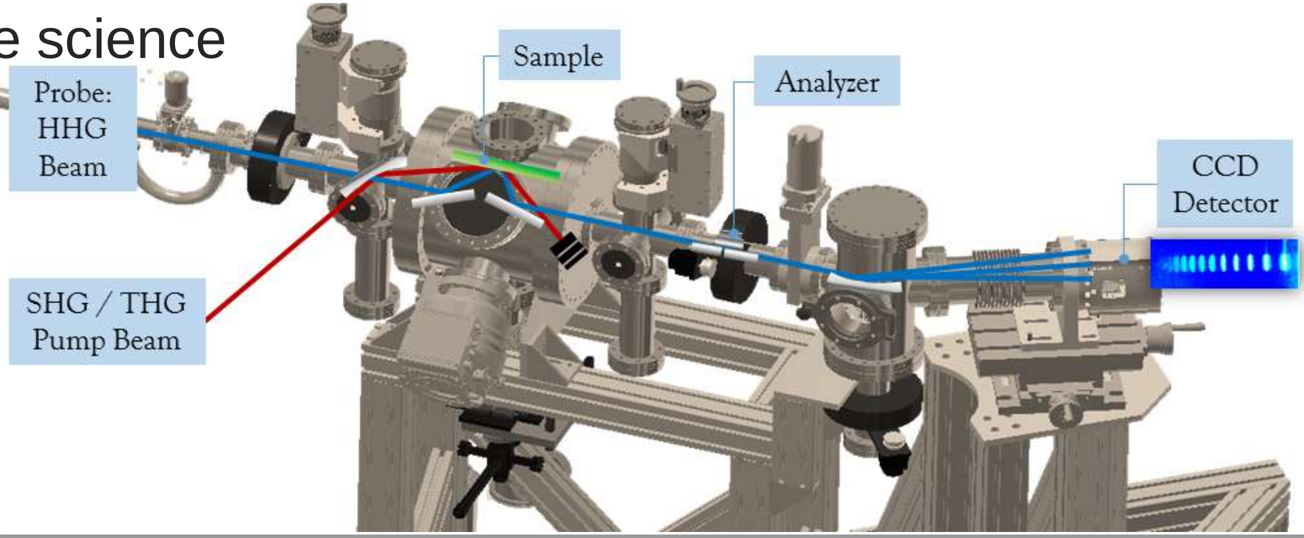
- Multipurpose chamber for AMO science and CDI
  - Sample delivery systems:

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

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



- VUV Magneto-optical ellipsometer (ELIps) for surface science
  - Multiple grazing incidence reflection polarizers
  - Spectrally resolved (FF spectrometer)
  - Cryogenic cooling of the sample
  - Switchable magnetic field (±1.5 T)

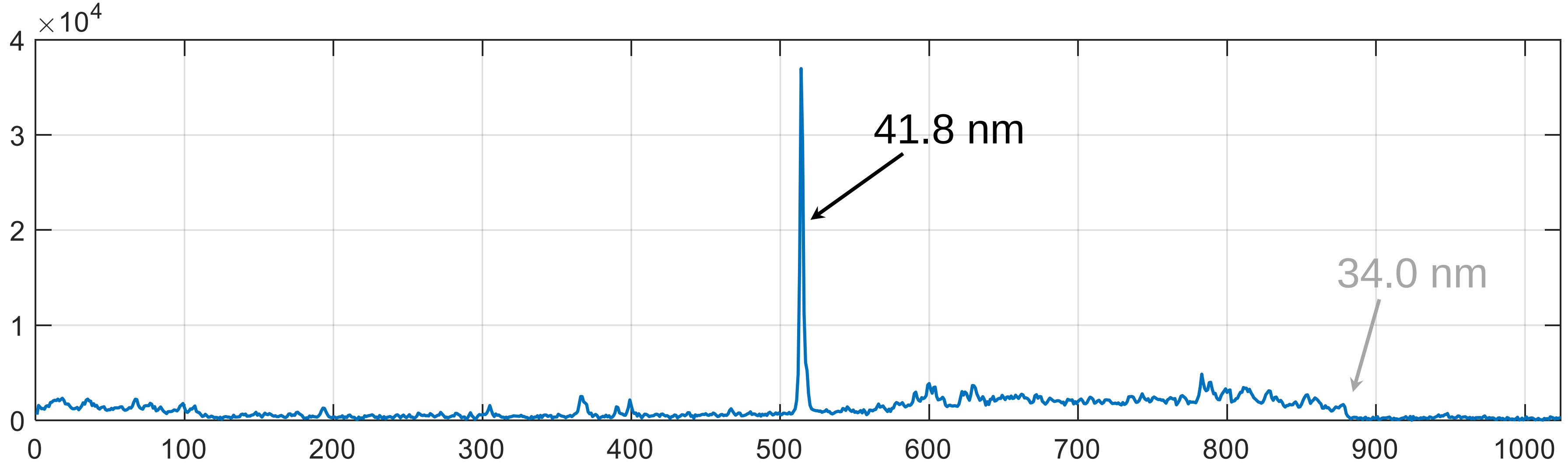


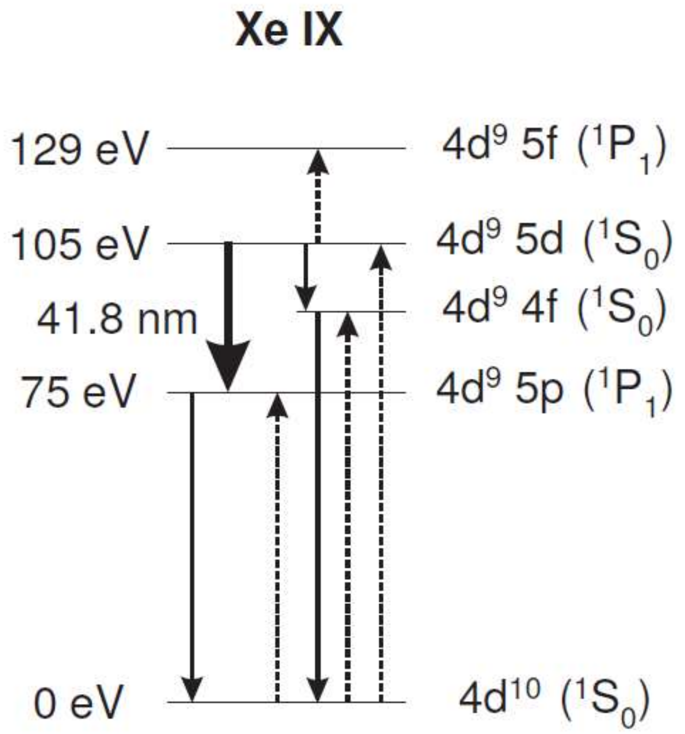
- Pump beams (Mid IR to UV) with fs pulses

An user experiment on the source: XRL

Plasma X-ray laser S. Sebban's group, LOA, ENSTA, Paris-Tech, France

- L1 laser (~ 20 mJ on target, 15 fs, 1 kHz) focused by F#8 parabola into mm-long Xe cell
- Xe^{+8} by optical field ionization (Intensity > few 10^{16} Wcm^{-2})
- Population inversion pumped by collisions with hot electrons (circ. polarization of the laser)
- 5d-5p lasing line @ 41.8 nm
- **The very first XRL working at 1 kHz repetition rate!**





B. Lemoff et al. Phys. Rev. Lett., 74 1574 (1995), S. Sebban et al. Phys. Rev. Lett., 86 3004 (2001)

Laser driven X-ray sources: several approaches

E1

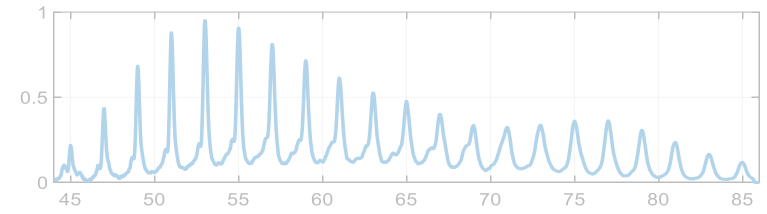
L1 driver

1 kHz, 100 mJ, 20 fs

Ti:sapphire backup

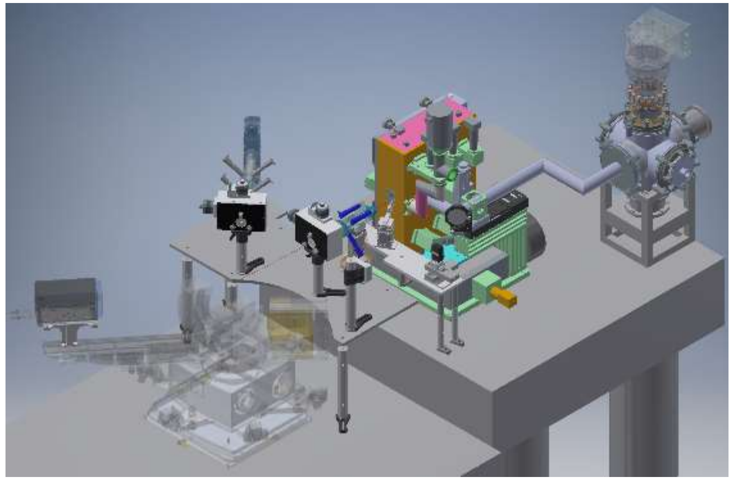
1 kHz, 12 mJ, 35 fs
& 10 Hz, 100 mJ, 40 fs

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



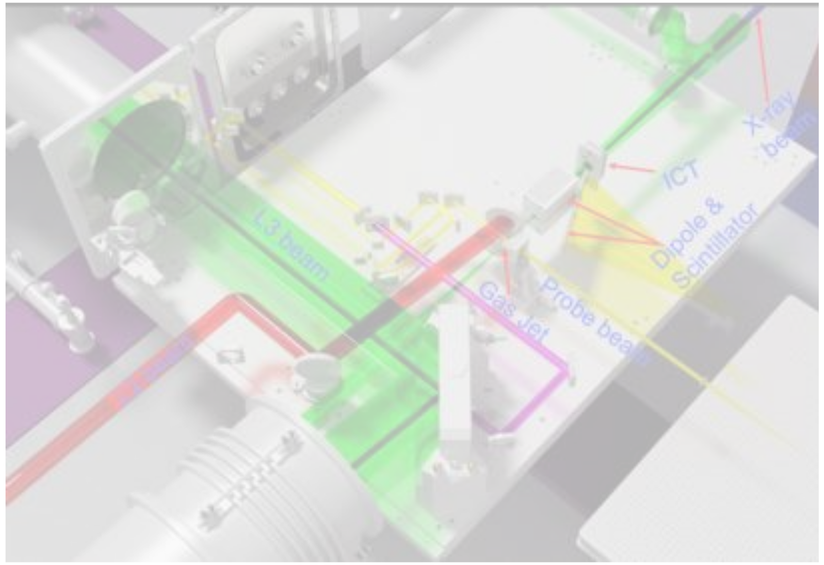
	10 mJ, 35 fs	100 mJ laser (15 fs)
photon energy	3 - 40 keV	3 – 80 keV
photons/(4π sr line or 1keV @10keV)	> 10^8	> 10^9
Source size	< 50 µm	< 50 µm
pulse duration	< 300 fs	<300 fs

E2/E3

L3 driver

10 Hz, 30 J, 30 fs

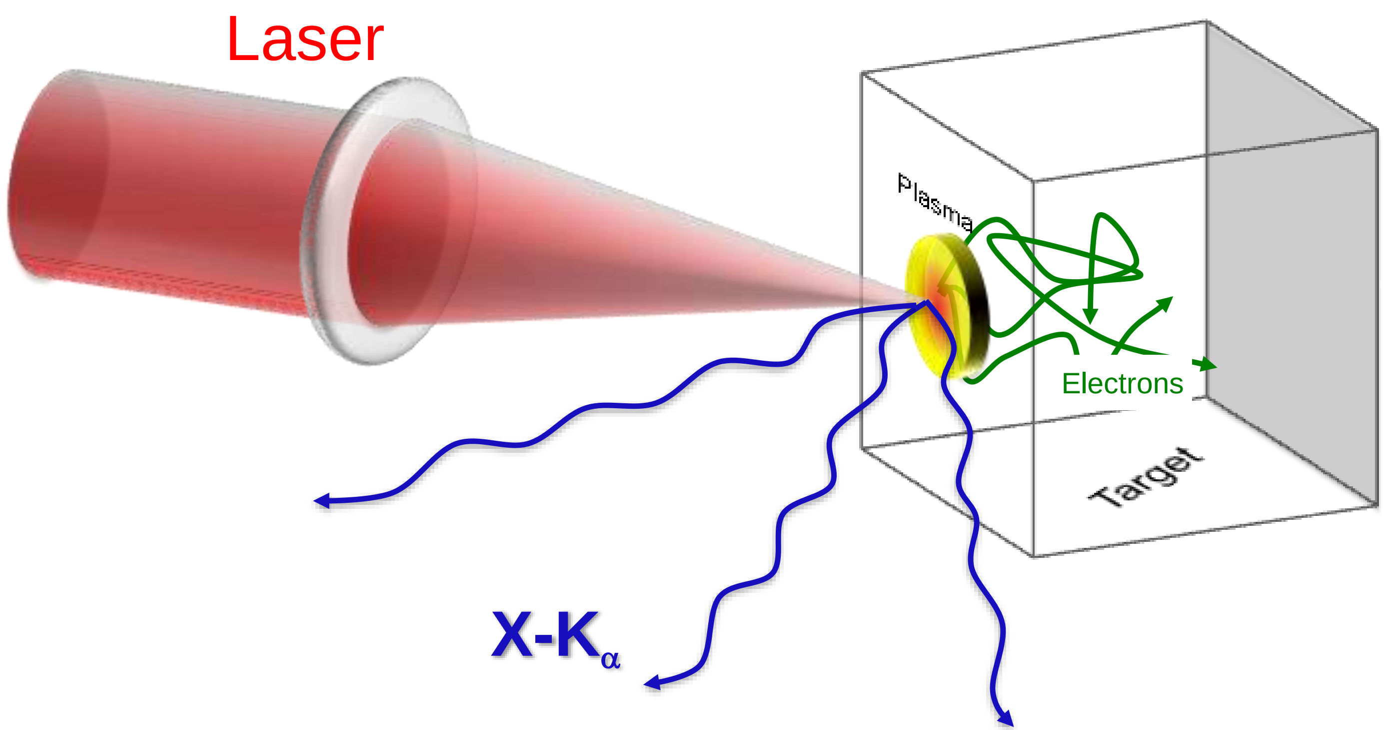
Betatron / inverse Compton

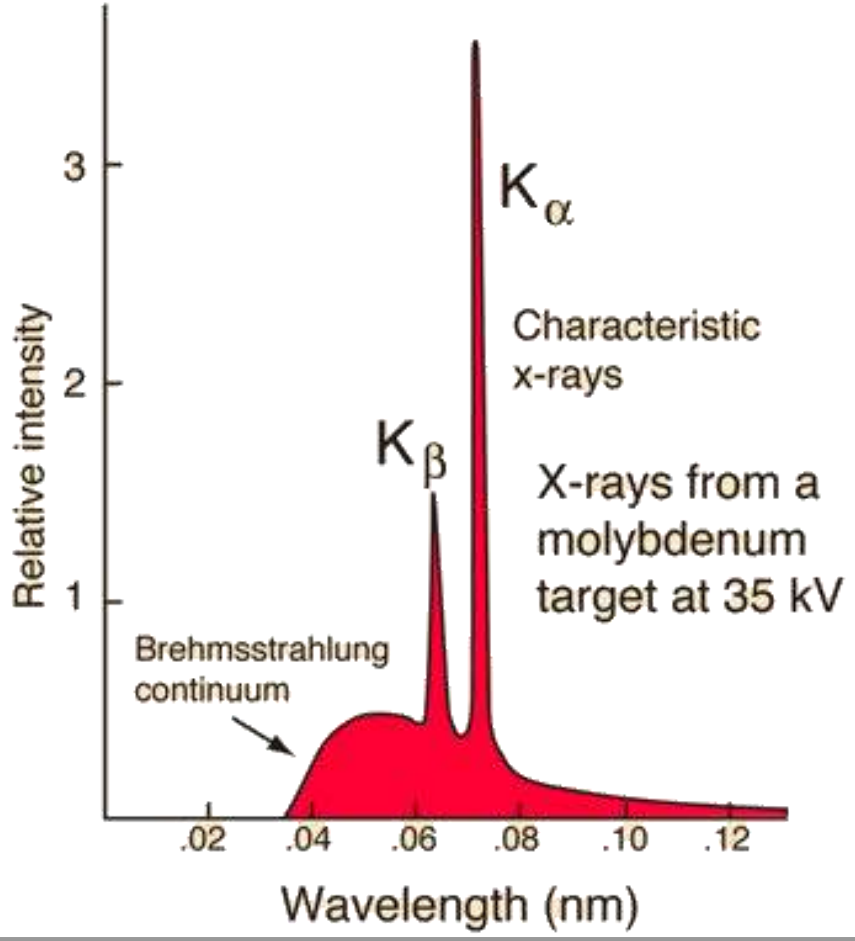


	Betatron	Compton
photon energy	10- 100 keV	50 – 5000 keV
photons/shot	> 10^9	> 10^8
Source size	< 5 µm	< 5 µm
pulse duration	~30 fs	< 30 fs

Laser plasma X-ray source

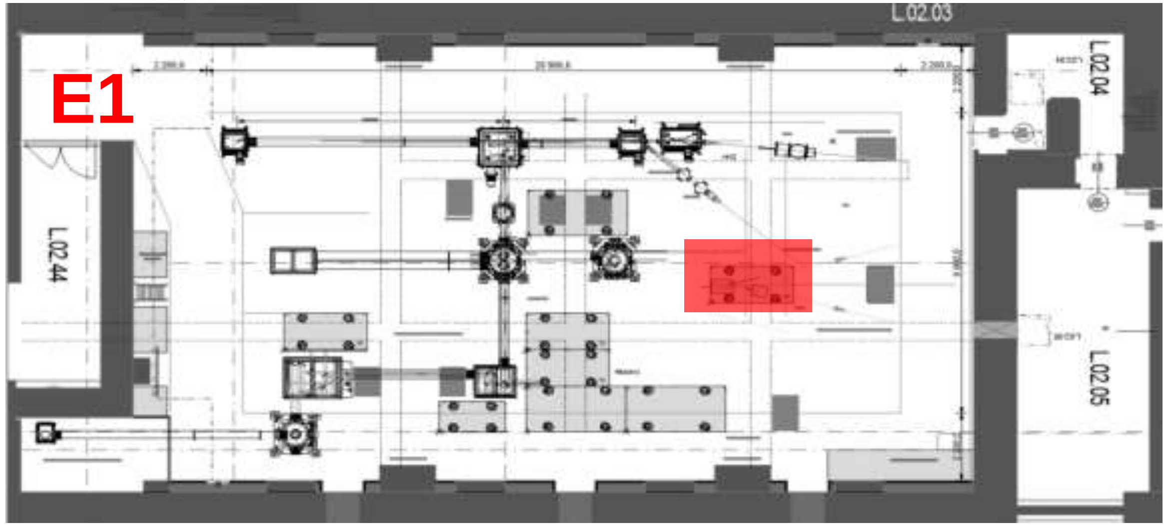
- Creation of "hot" electrons by interaction of intense laser pulse with matter ($I > 10^{16}$ Wcm^{-2})
- Energetic electrons are decelerated in the target
  - generation of bremsstrahlung and characteristic radiation

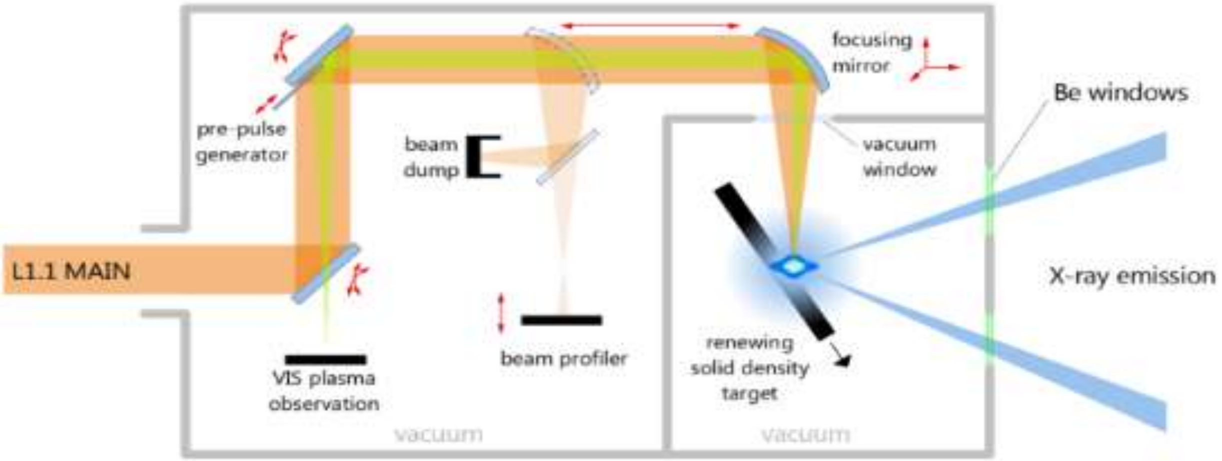




eli beamlines

1 kHz Plasma X-ray Source (PXS)





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

interacting with high-density target:

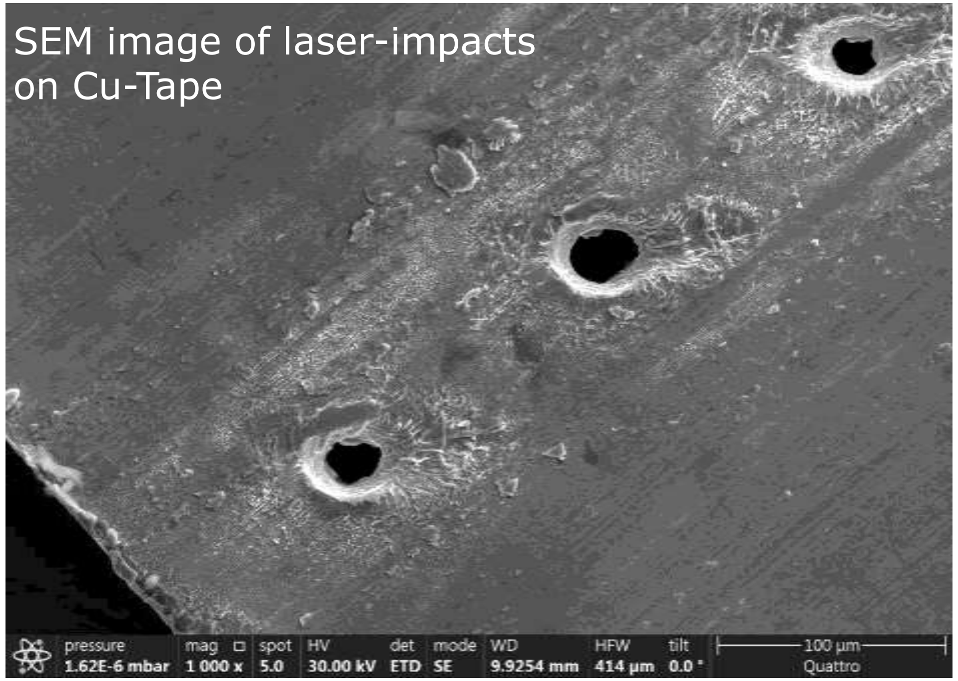
- **Cu tape**
- Liquid metal jet (in commissioning)
- Water jet

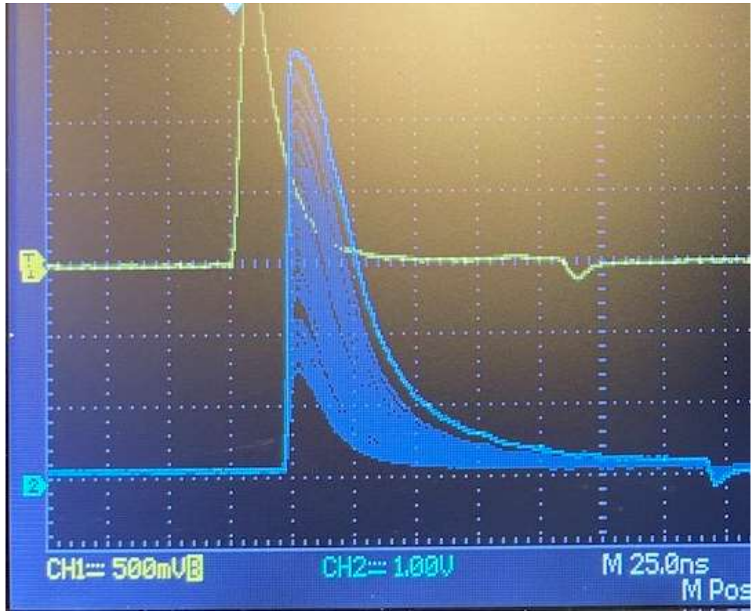
Table 1: X-ray source parameters	Phase I 10 mJ laser	Phase II 50 mJ laser
Photons per shot (photons/(sr line) or photons/(sr 1keV) @10keV)	>10^9	> 10^{11}
Source size	< 50 µm	< 50 µm
Hard X-ray pulse duration (FWHM)	< 300 fs	< 300 fs

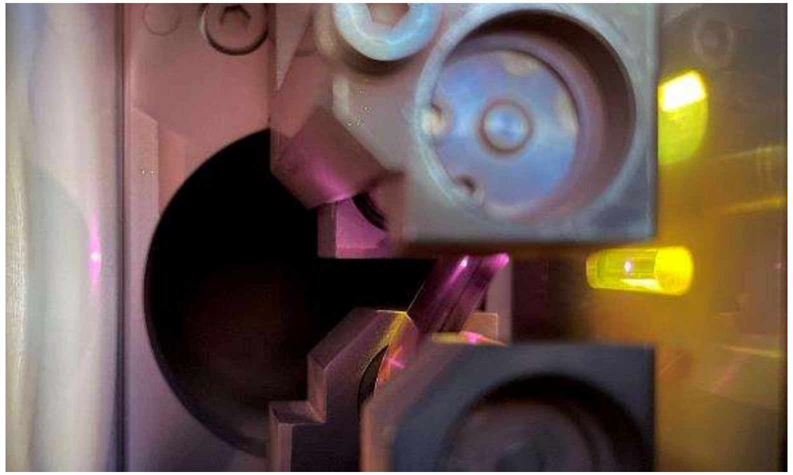
Cu Tape source

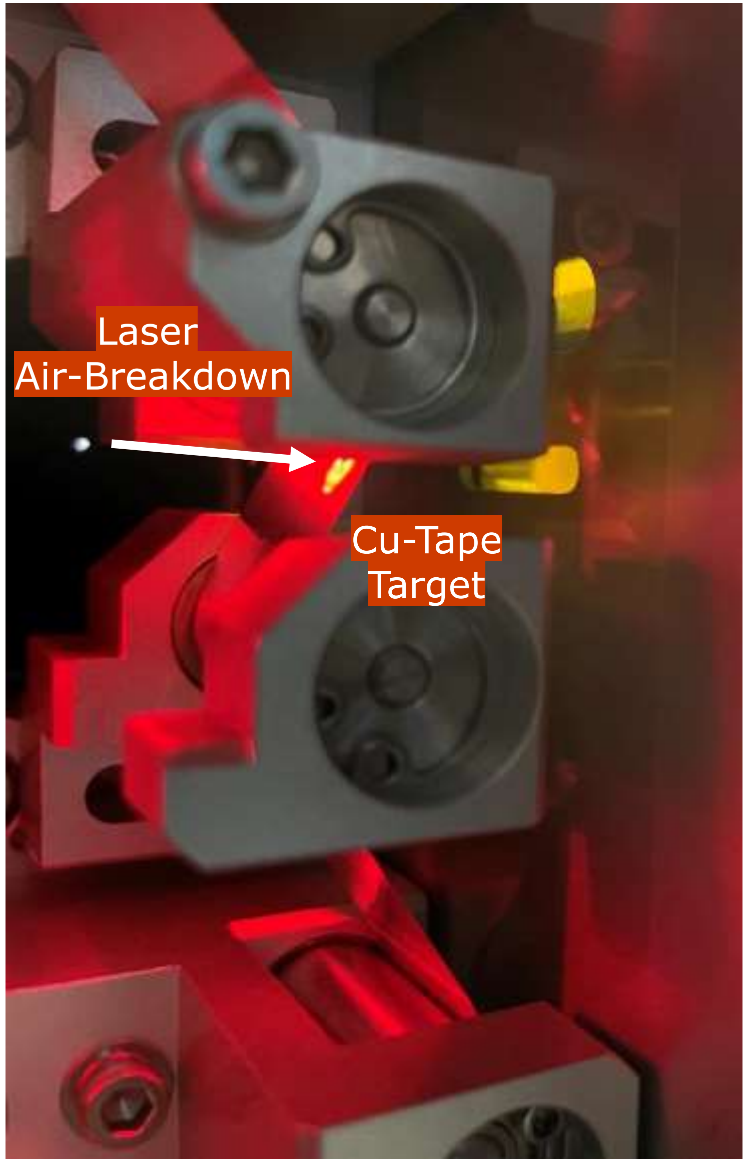
Driven by L1 laser (20 mJ, 1 kHz)

=> up to $3x10^{11}$ photons/shot/4pi

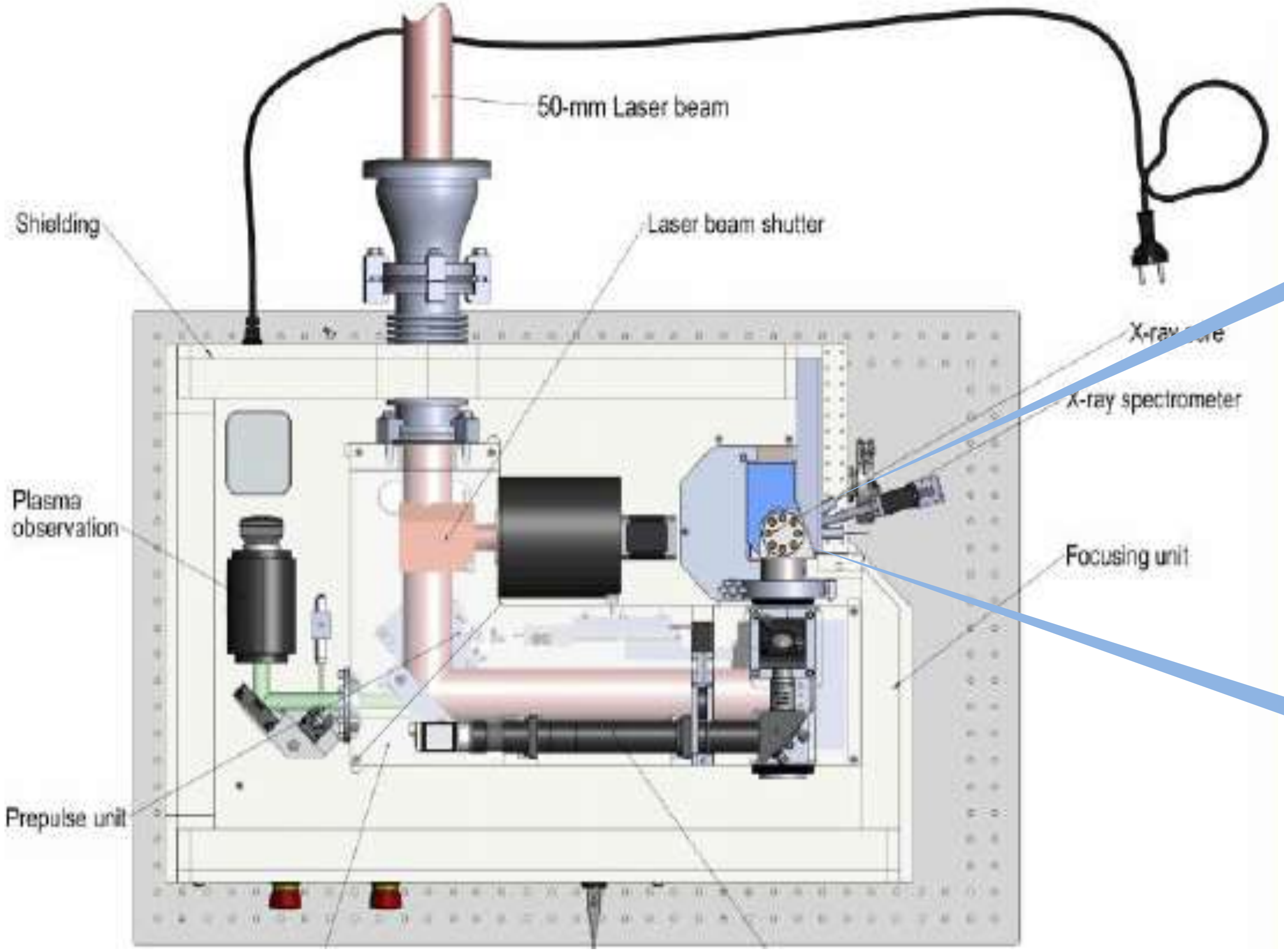






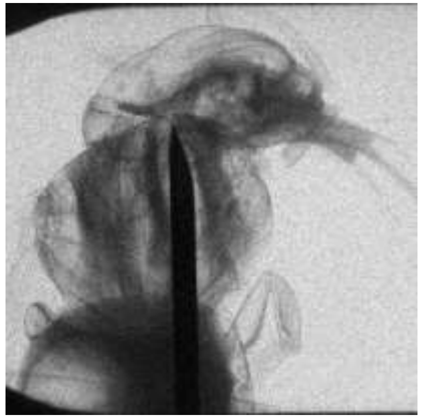


Plasma X-ray Source (PXS) - two beamlines



PXS-BL2
- polychromatic
- high flux
- small spot size
- OR point source

Imaging
Radiolysis
Spectroscopy

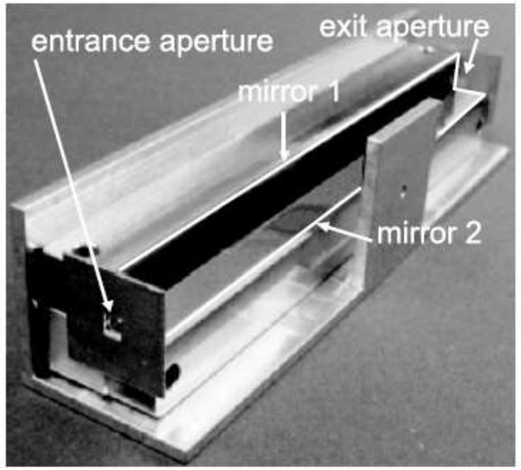


PXS-BL1
- monochromatic
- low divergence

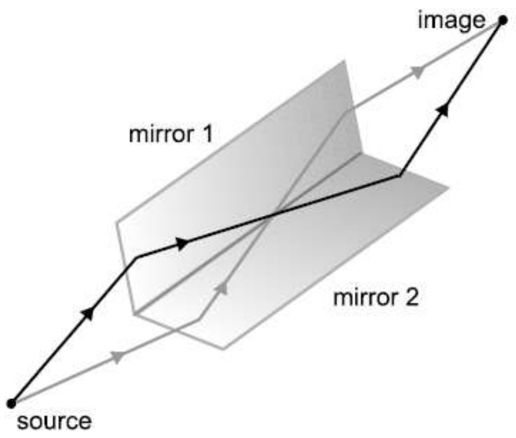
Diffraction

Currently 10^6 photons/shot on sample

Montel optics at TREX diffractometer

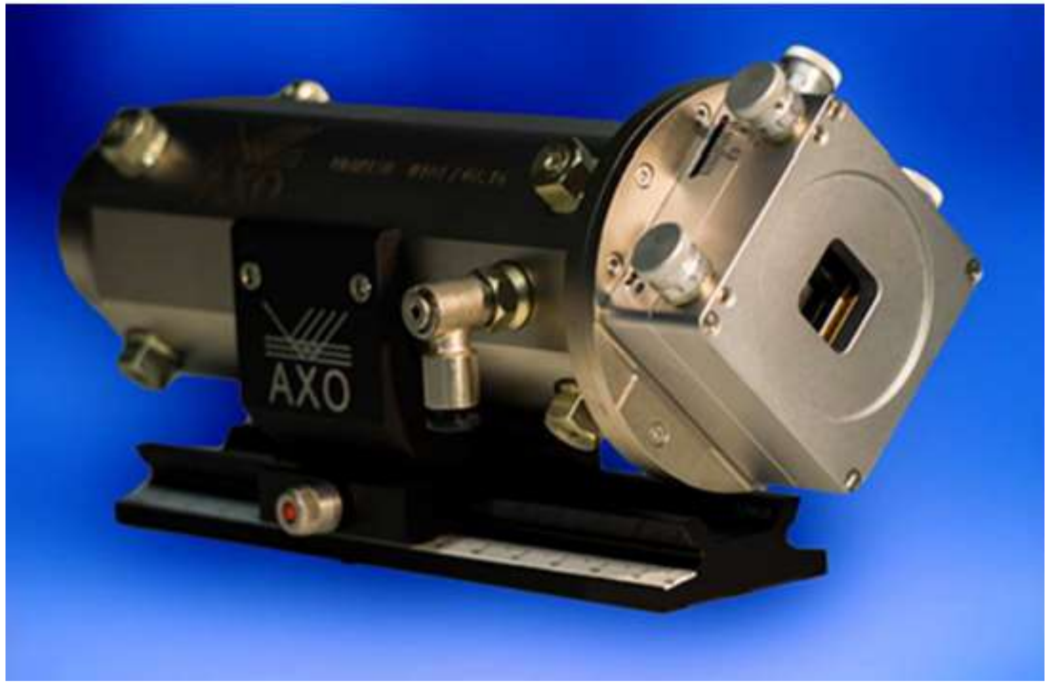


a



b

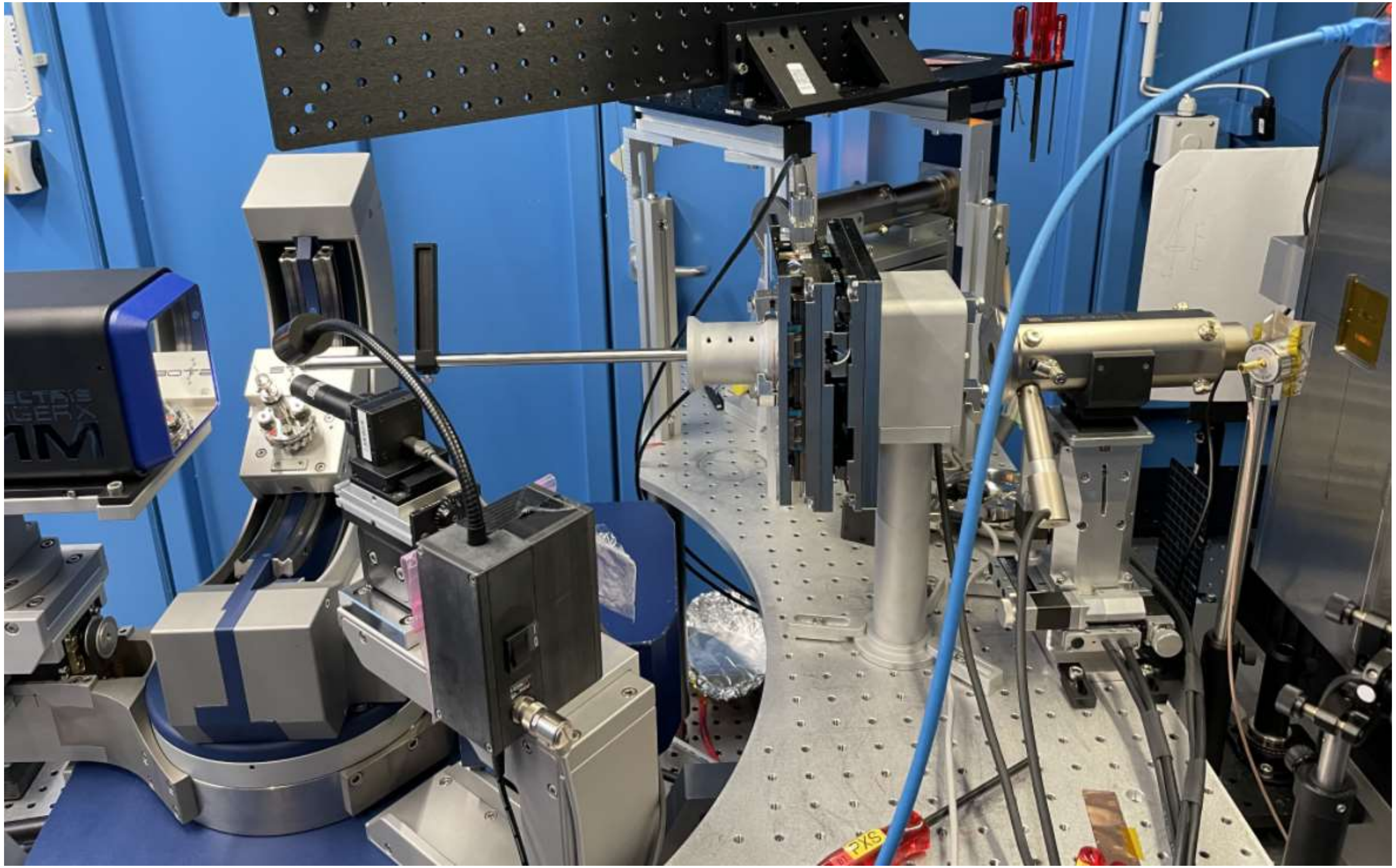
Fig. Montel optic: (a) photograph; (b) principle scheme

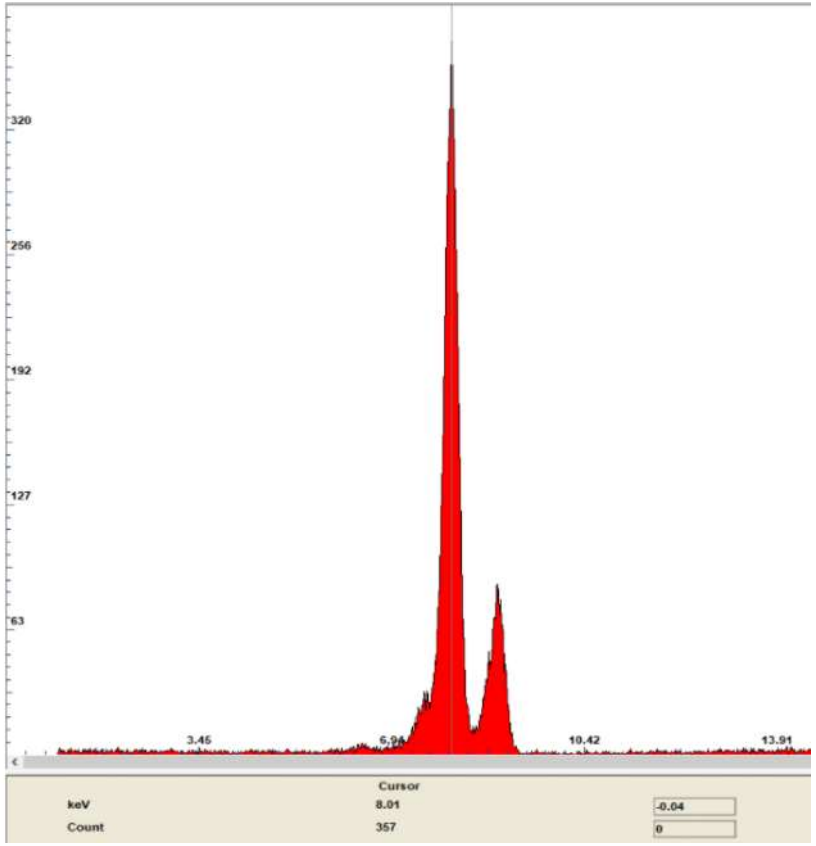


Ni/C multilayer coating
for 8.046 keV radiation (Cu K-alpha)

- Focal distances: $f_1 + f_2 = 805$ mm
- Primary focal distance: $f_1 = 190$ mm
- Secondary focal distance: $f_2 = 615$ mm
- Focal spot dimension: $\varnothing \approx 0.10$ mm FWHM (for 30 µm FWHM source)
- Deflection angle $2\sqrt{2}\cdot\Theta_B = 3.128^\circ$ (54.6 mrad)
- Collection angle $\Omega_{in} = 16.8$ mrad
- Convergence angle: $\Omega_{out} = 4.8$ mrad

Plasma X-ray Source (PXS) diffraction experiment





Flux from the source:

10^{12} photons/shot/4π sr

Flux on target:

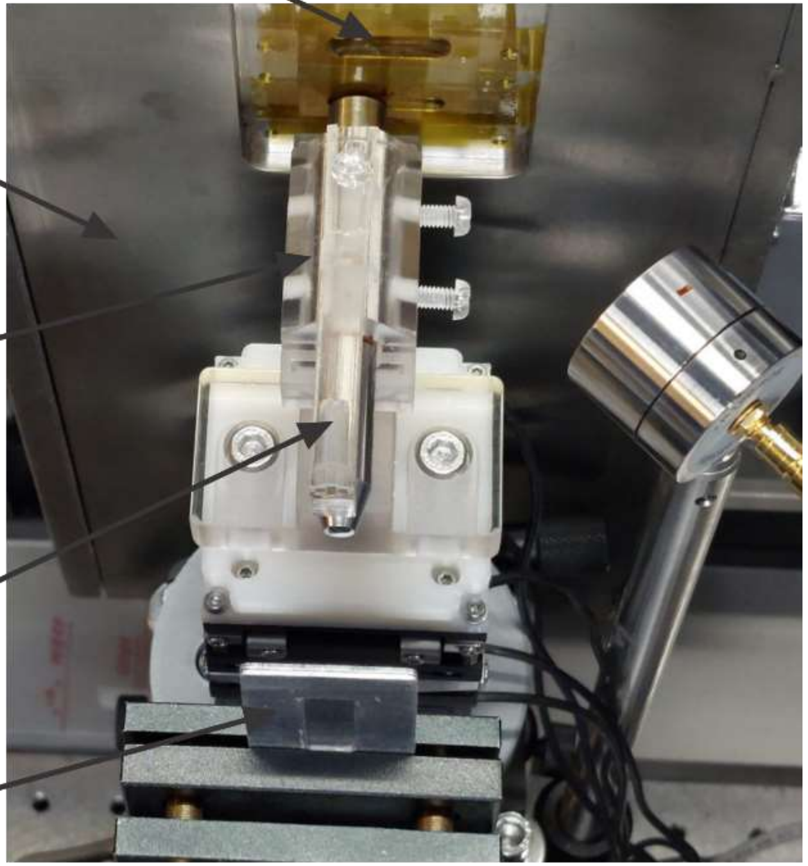
~10^{6} photons/shot

Focusing optics for X-ray spectroscopy (Von Hamos)

Polycapillary – a bunch of curved channels, each guiding a photon to a required target spot, which is the focus
Polycapillary optics *re-images* broadband photons from the source spot to the target

ELI Beamlines E1 polycapillary parameters:

- Input focal distance – 18.0 mm
- Output focal distance – 30.0 mm
- Enclosure length – 77.0 mm
- Enclosure diameter – 10.0 mm
- Output focal spot size - <130 μm
- Output beam convergent angle – 7.4°
- Input FWHM @ 8 keV - >50 μm
- Has Beryllium windows
  [Zymaková et al., J. Synchrotron Rad. **27** (2020)]



Courtesy of A. Zymaková

Laser driven X-ray sources: several approaches

E1

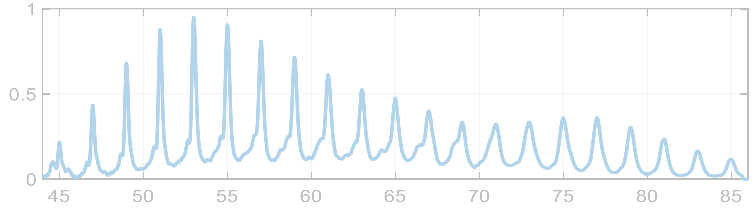
L1 driver

1 kHz, 100 mJ, 20 fs

Ti:sapphire backup

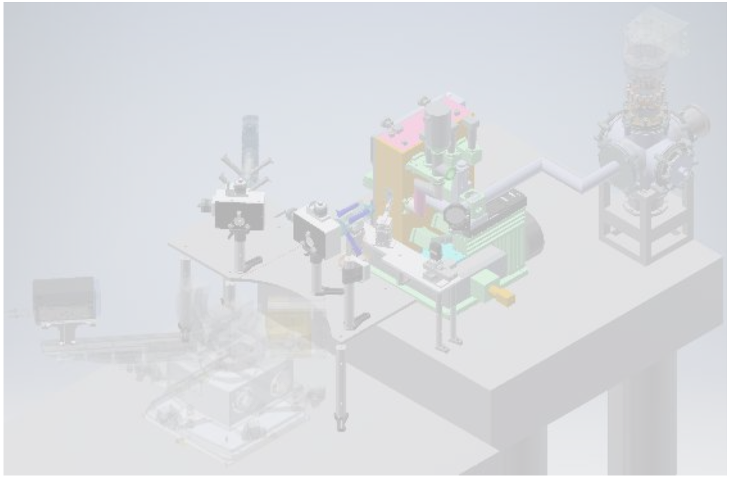
1 kHz, 12 mJ, 35 fs
& 10 Hz, 100 mJ, 40 fs

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



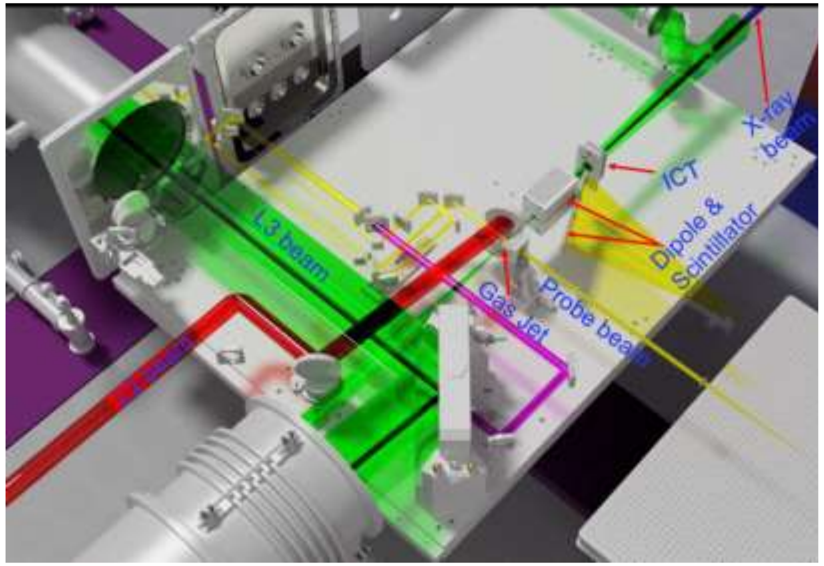
	10 mJ, 35 fs	100 mJ laser (15 fs)
photon energy	3 - 40 keV	3 – 80 keV
photons/(4π sr line or 1keV @10keV)	> 10^8	> 10^9
Source size	< 50 µm	< 50 µm
pulse duration	< 300 fs	<300 fs

E2/E3

L3 driver

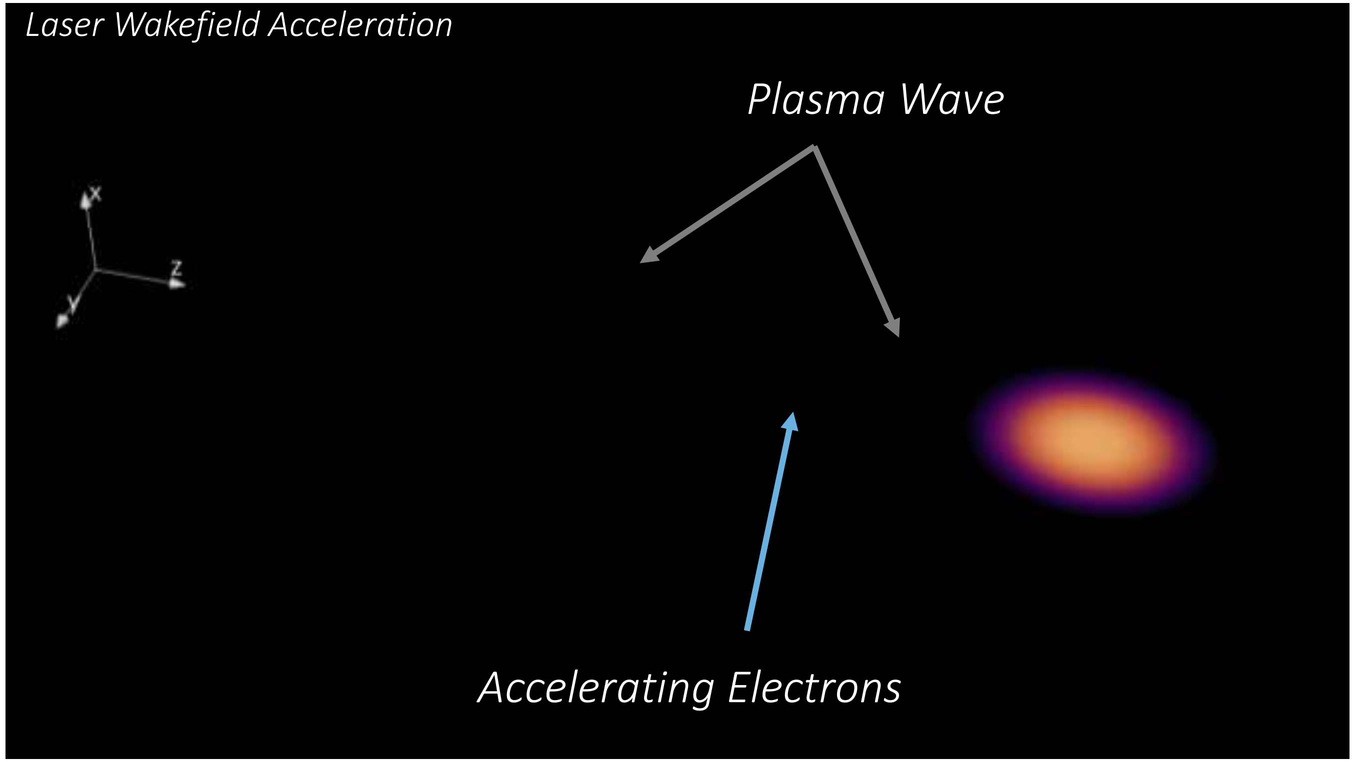
10 Hz, 30 J, 30 fs

Betatron / inverse Compton



	Betatron	Compton
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

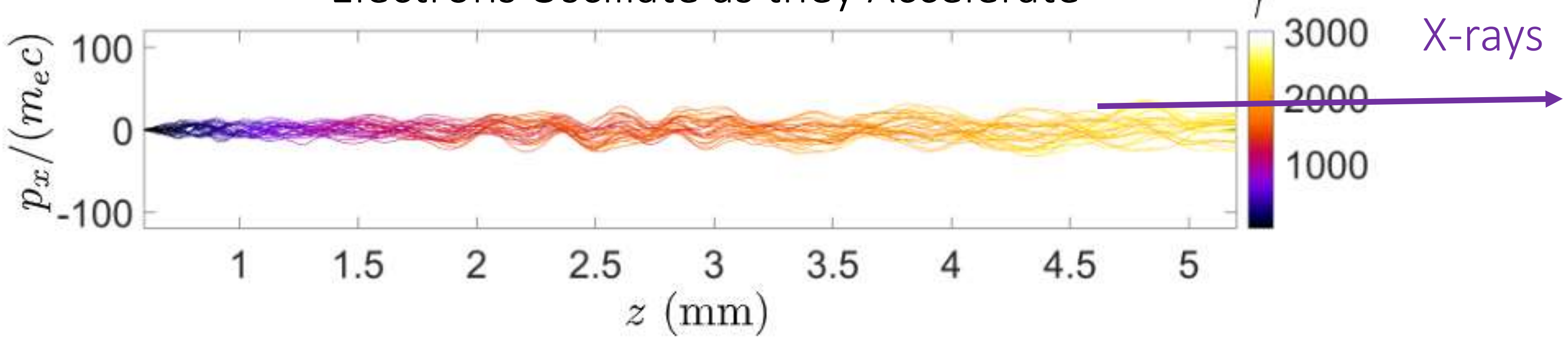
Laser plasma accelerator based Betatron X-ray source

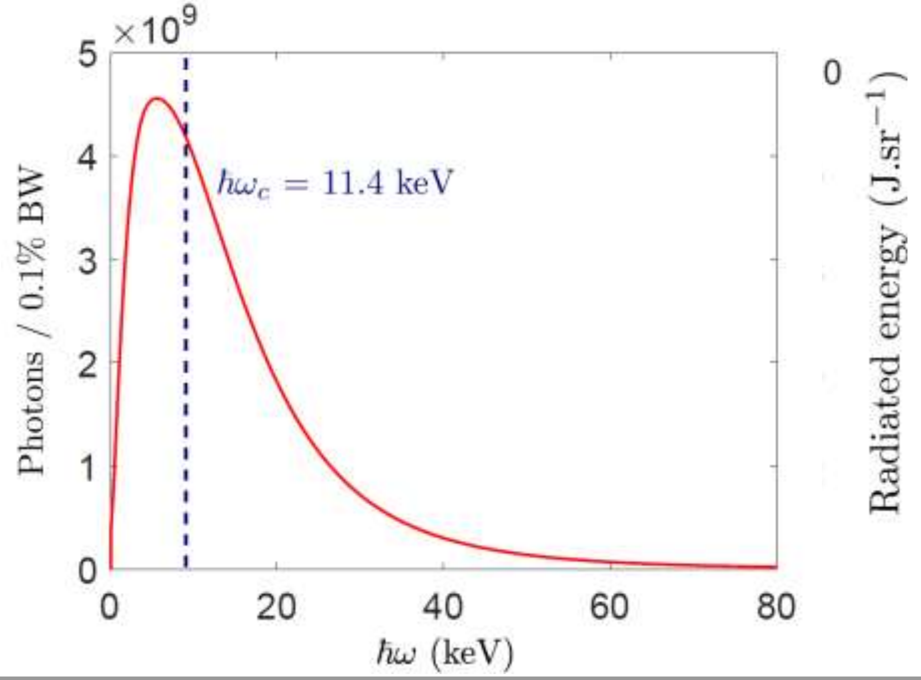


Short laser pulse with relativistic intensity ($I > 10^{18}$ Wcm^{-2}) interacts with underdense plasma (gas target)

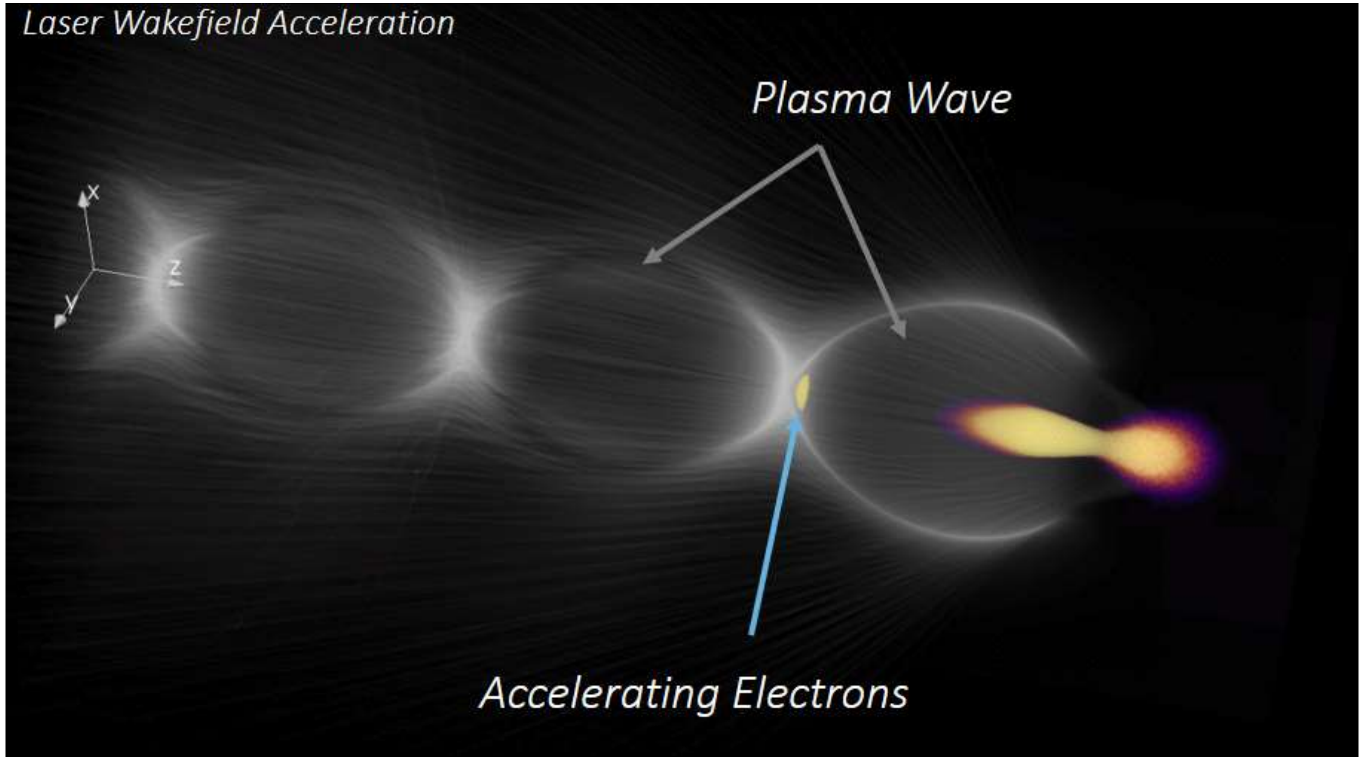
LWFA + transverse oscillations = X-rays

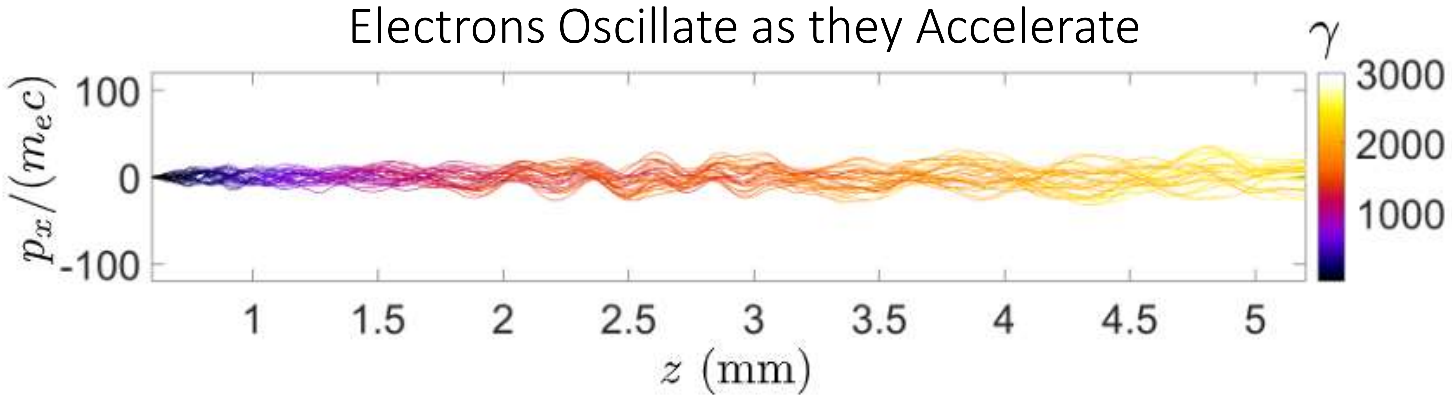
Electrons Oscillate as they Accelerate





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:

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

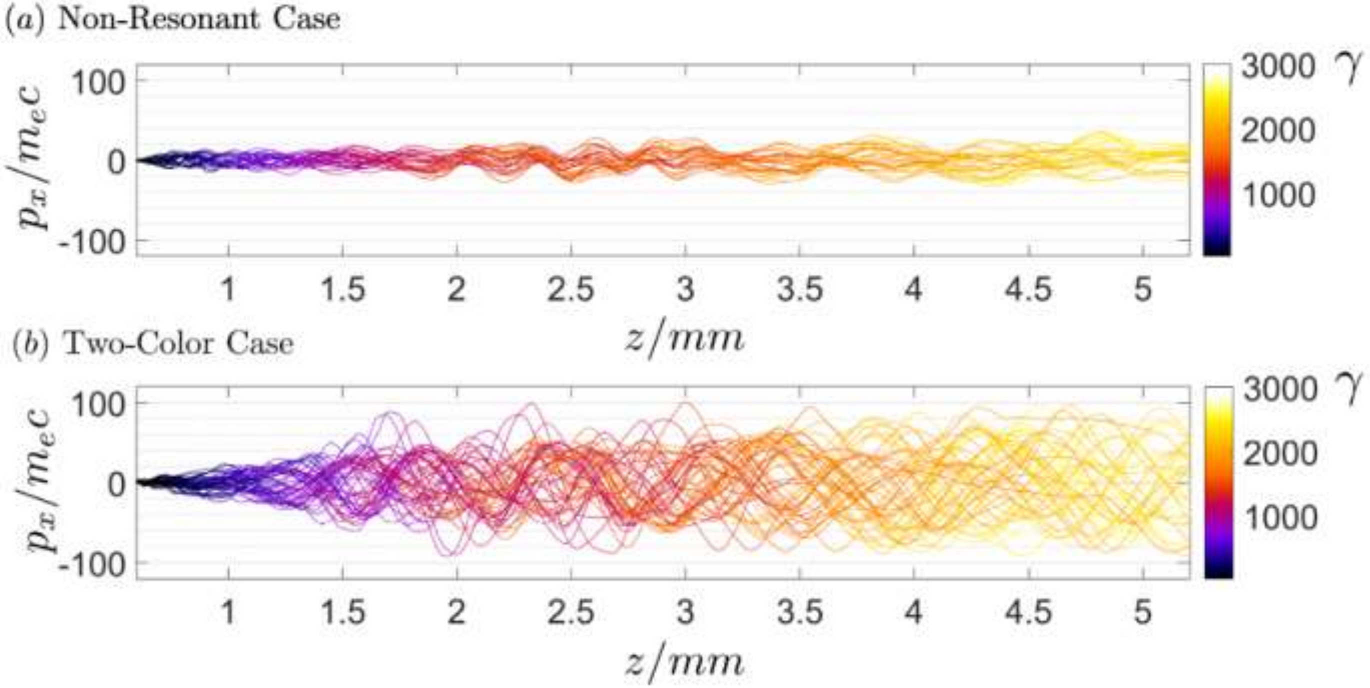
- Total emitted X-ray radiation: $W_{tot} \propto N e\, \gamma^{5/2}\, r_b^2$

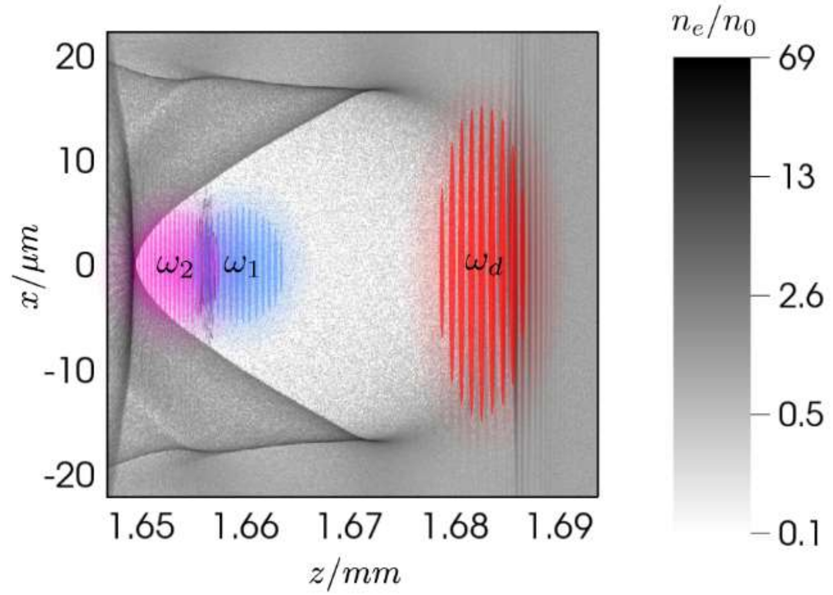
=> Higer energy and brighter radiation for higher γ and r_b

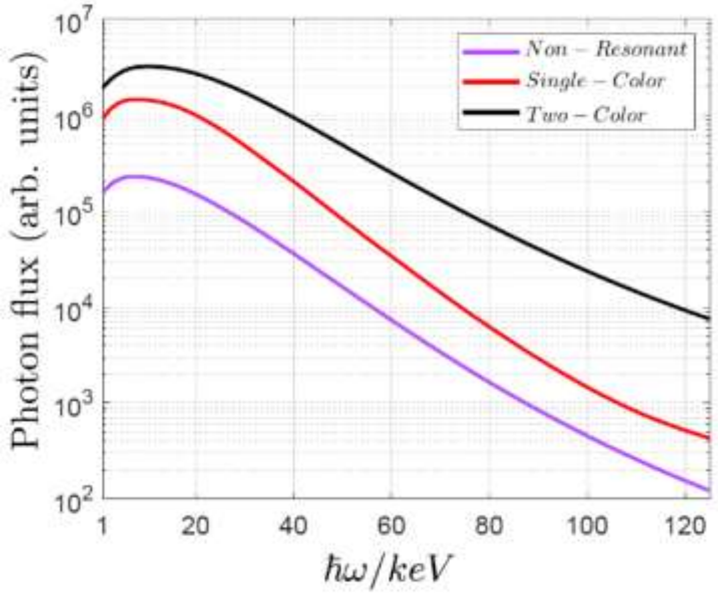
FZU Fyzikální ústav Akademie věd České republiky
Akademie věd České republiky

Advanced plasma Betatron

- Two-color nonlinear resonances in plasma betatron (PIC)
  - Increase of betatron oscillation amplitudes (undulator parameter K)
  - Rel. elecrons resonant with either of the fields and/or combination resonances

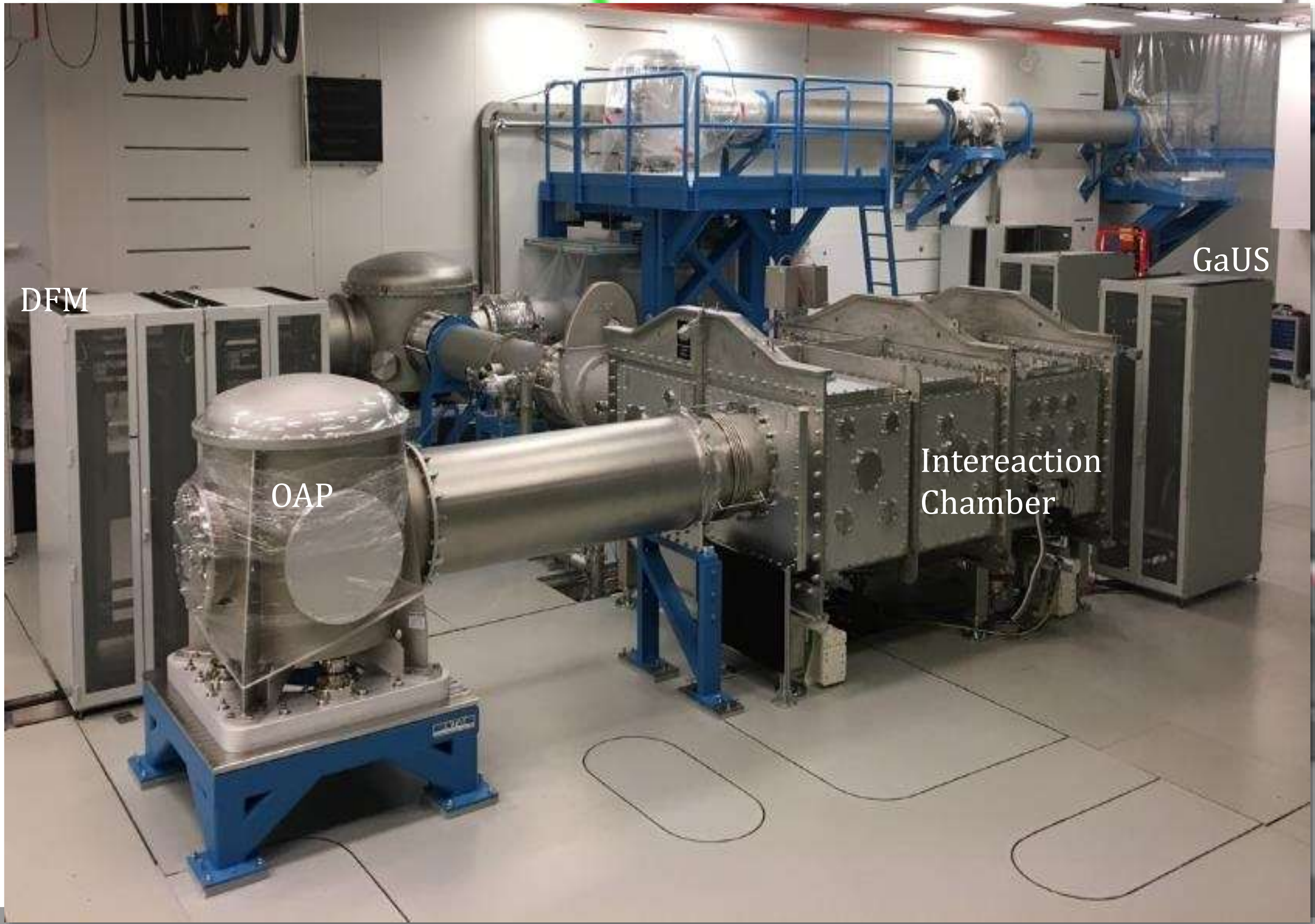


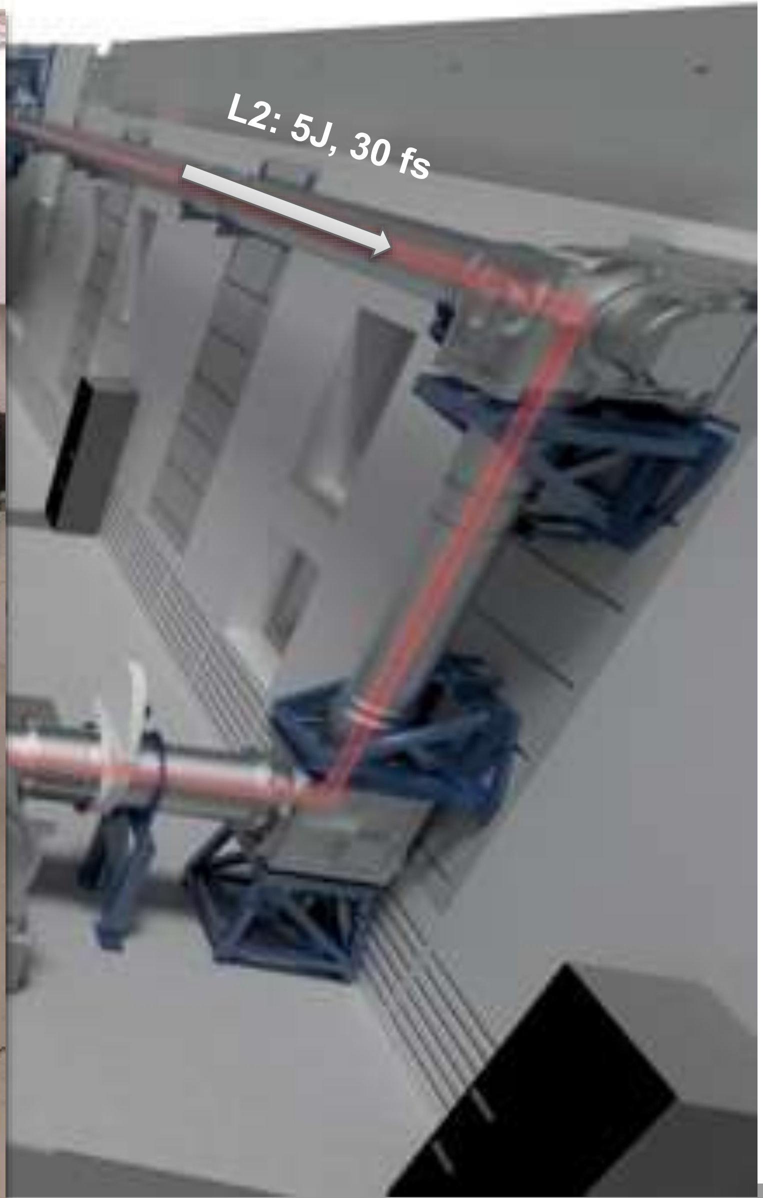




M. Lamač et al. Phys. Rev. Res. 3, 033088 (2021)

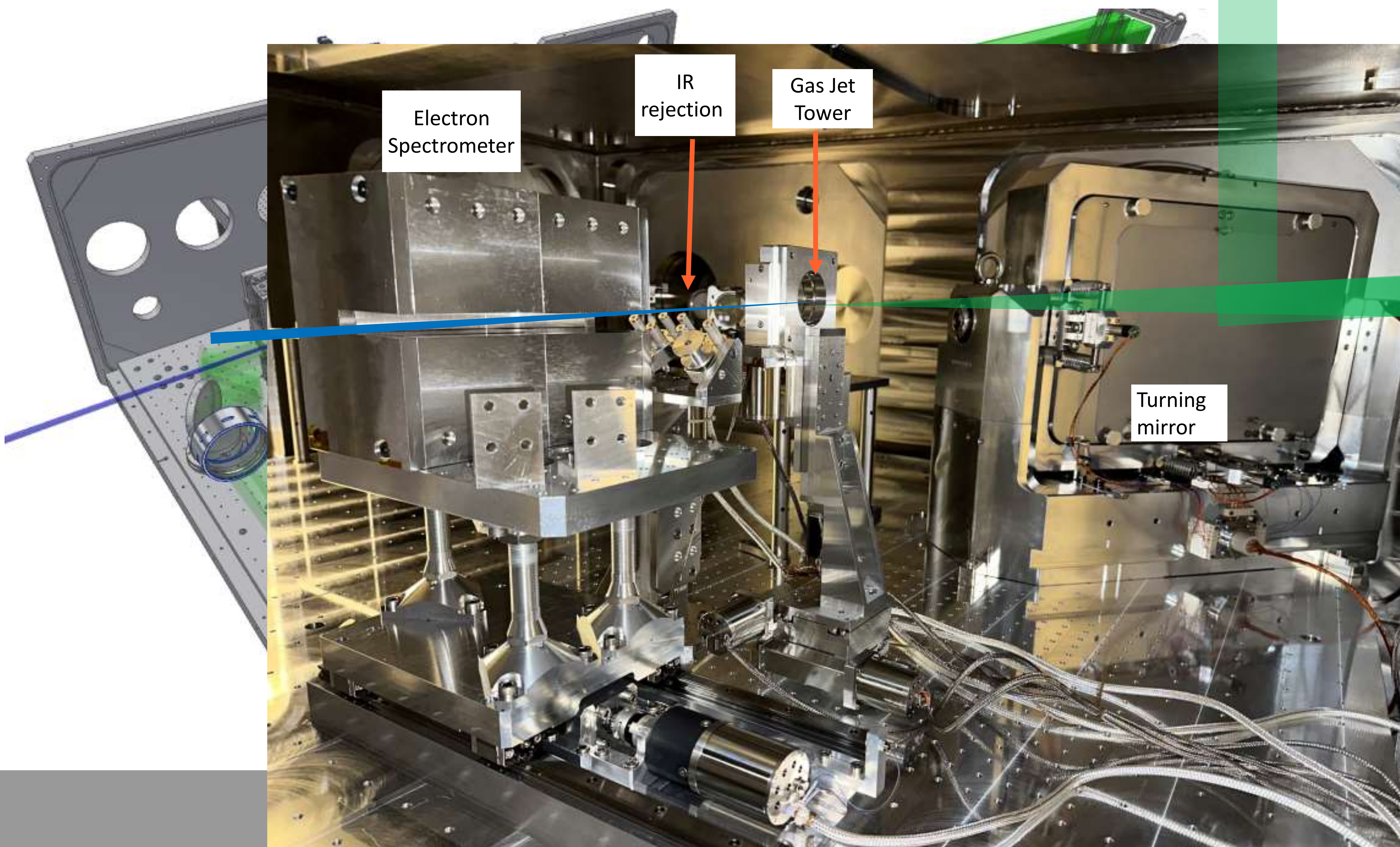
ELI Gammatron Beamline



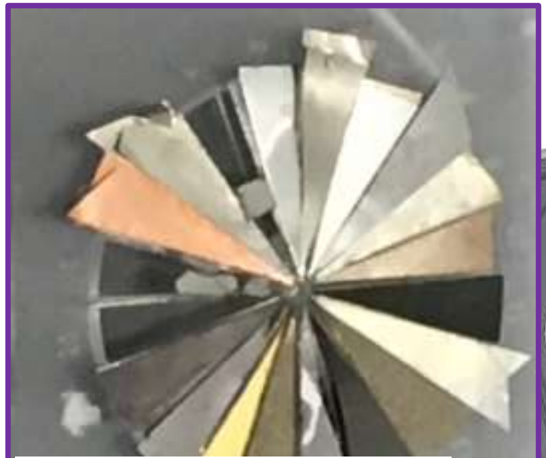


U. Chaulagain et al. Photonics 2022, 9, 853 (2022); M. Raclavský et al. Photonics 8, 579 (2021)

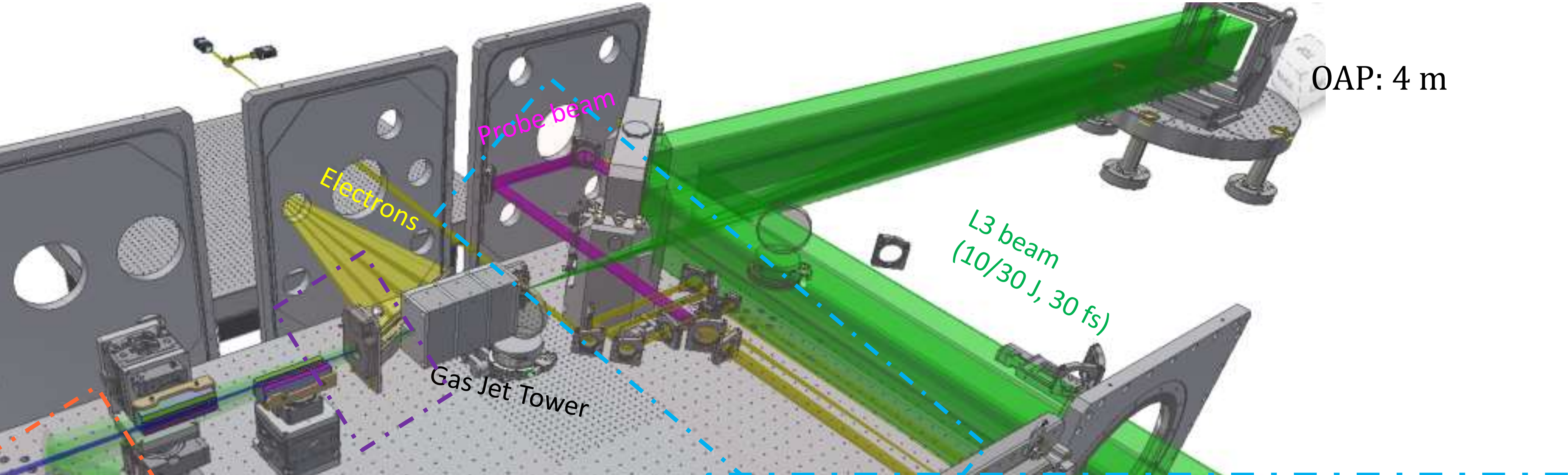
ELI Gammatron Beamline – betatron source



ELI Gammatron Beamline – betatron source



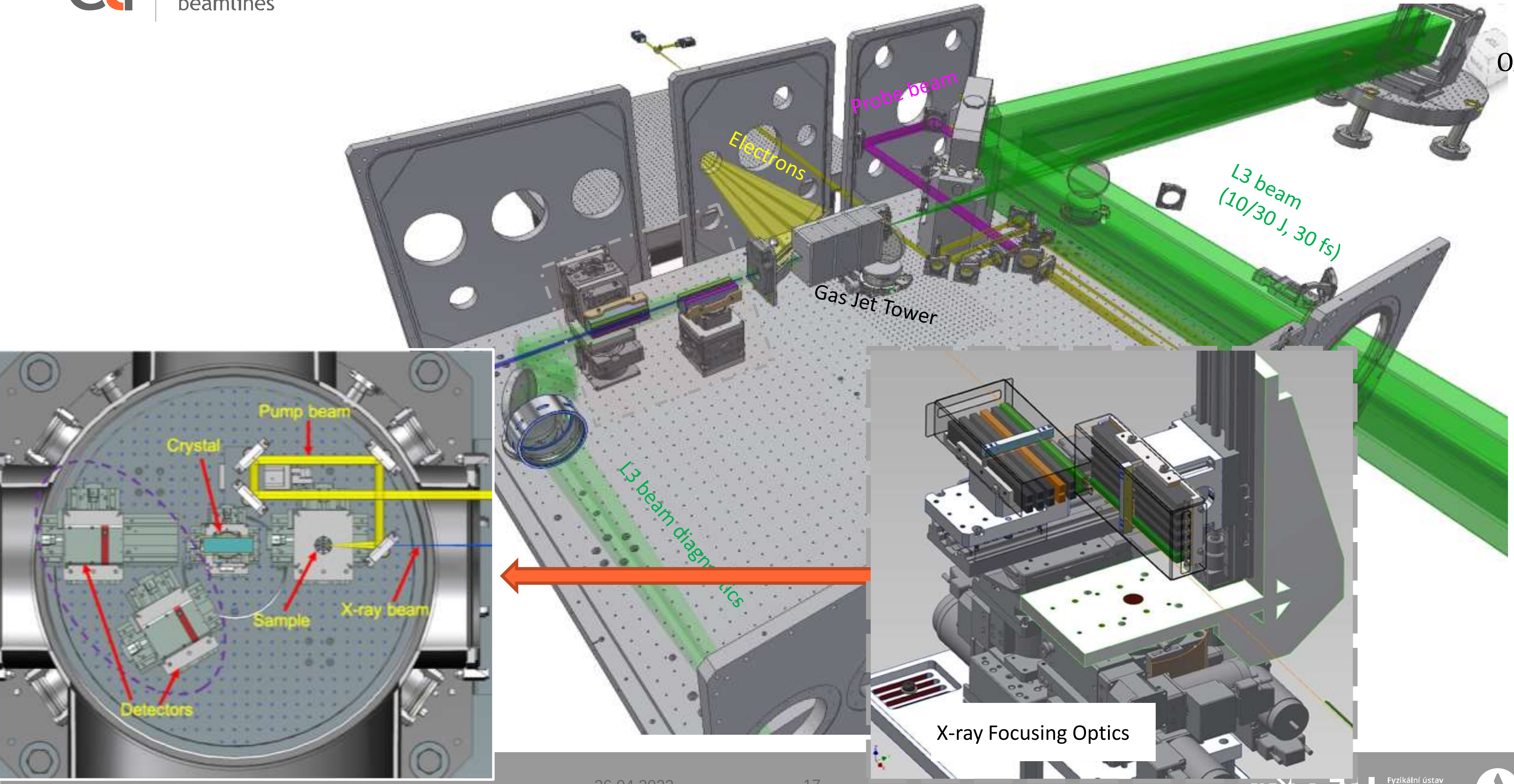
High energy RF Spectrometer (5-88 keV)



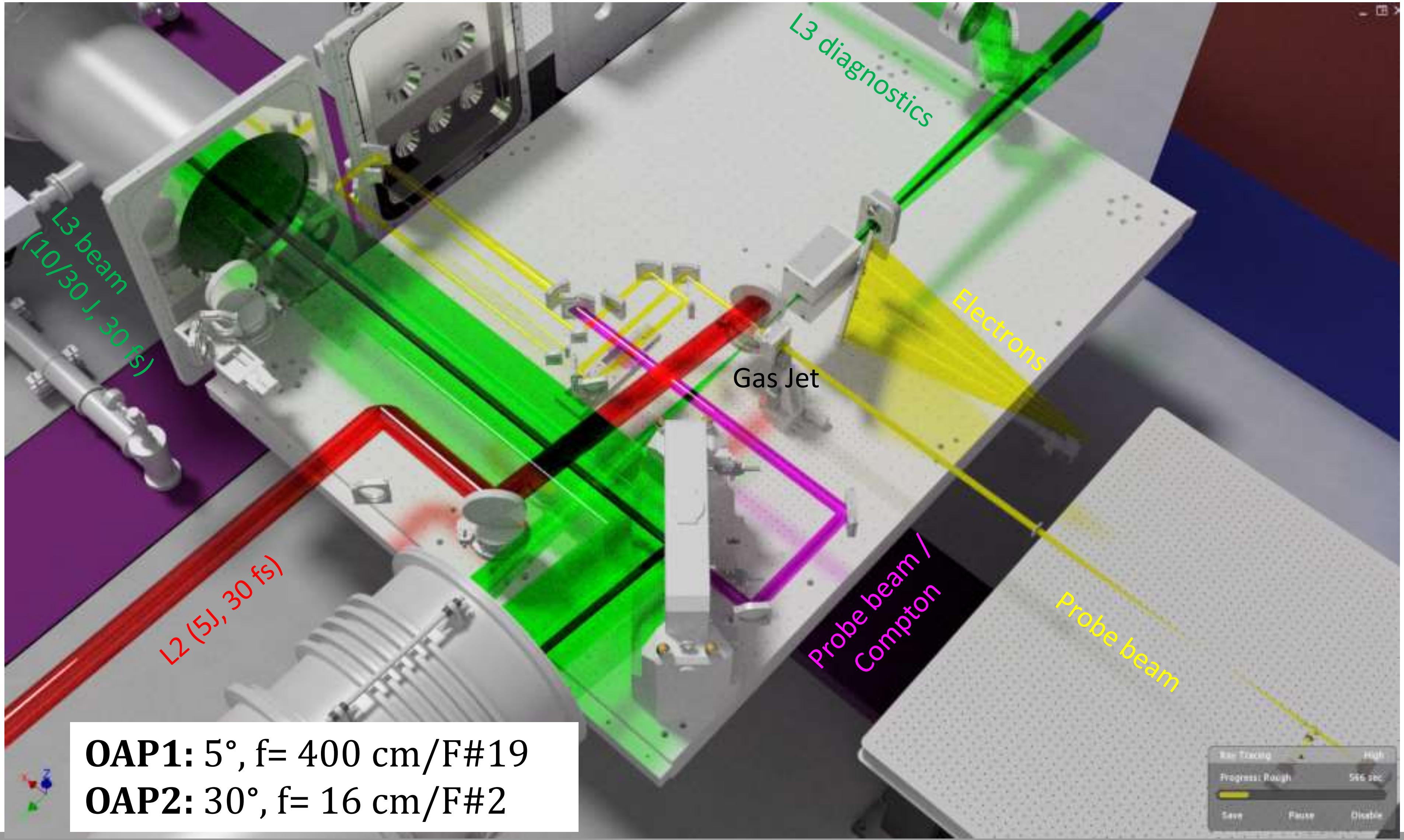
High power beam Diagnostics

Plasma Probing diagnostics

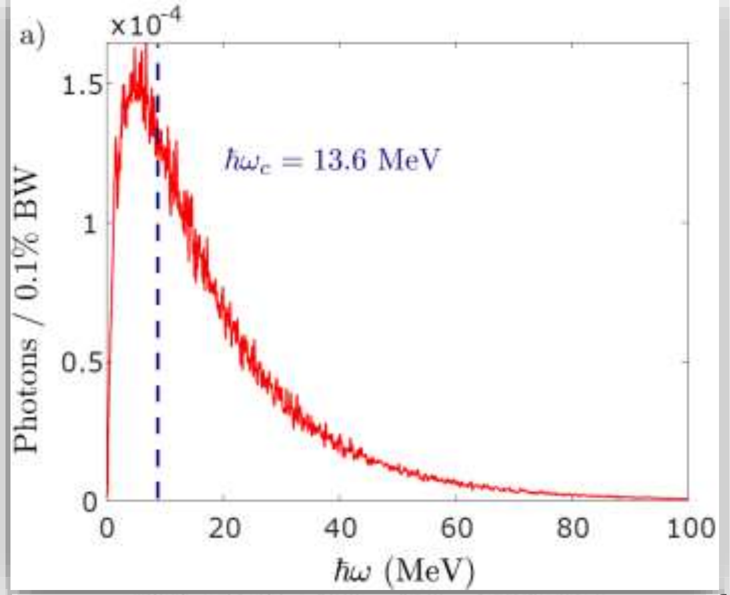
ELI Gammatron Beamline – betatron source

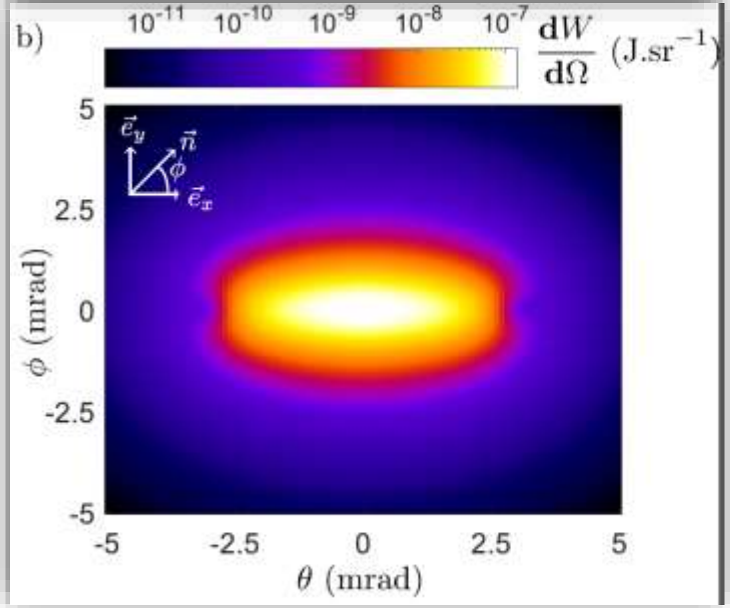


ELI Gammatron Beamline – inverse Compton source

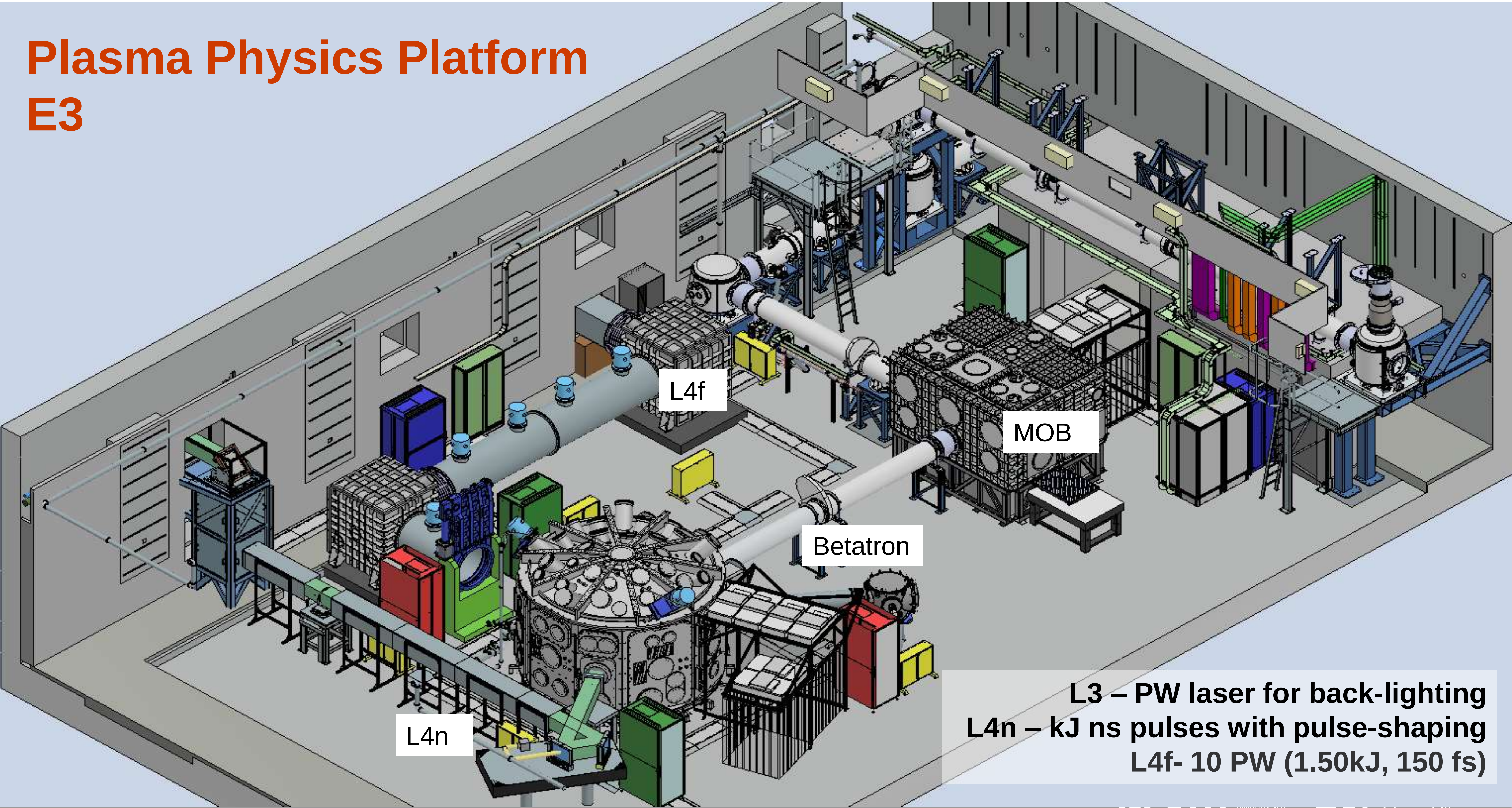


OAP1: 5°, f= 400 cm/F#19
OAP2: 30°, f= 16 cm/F#2



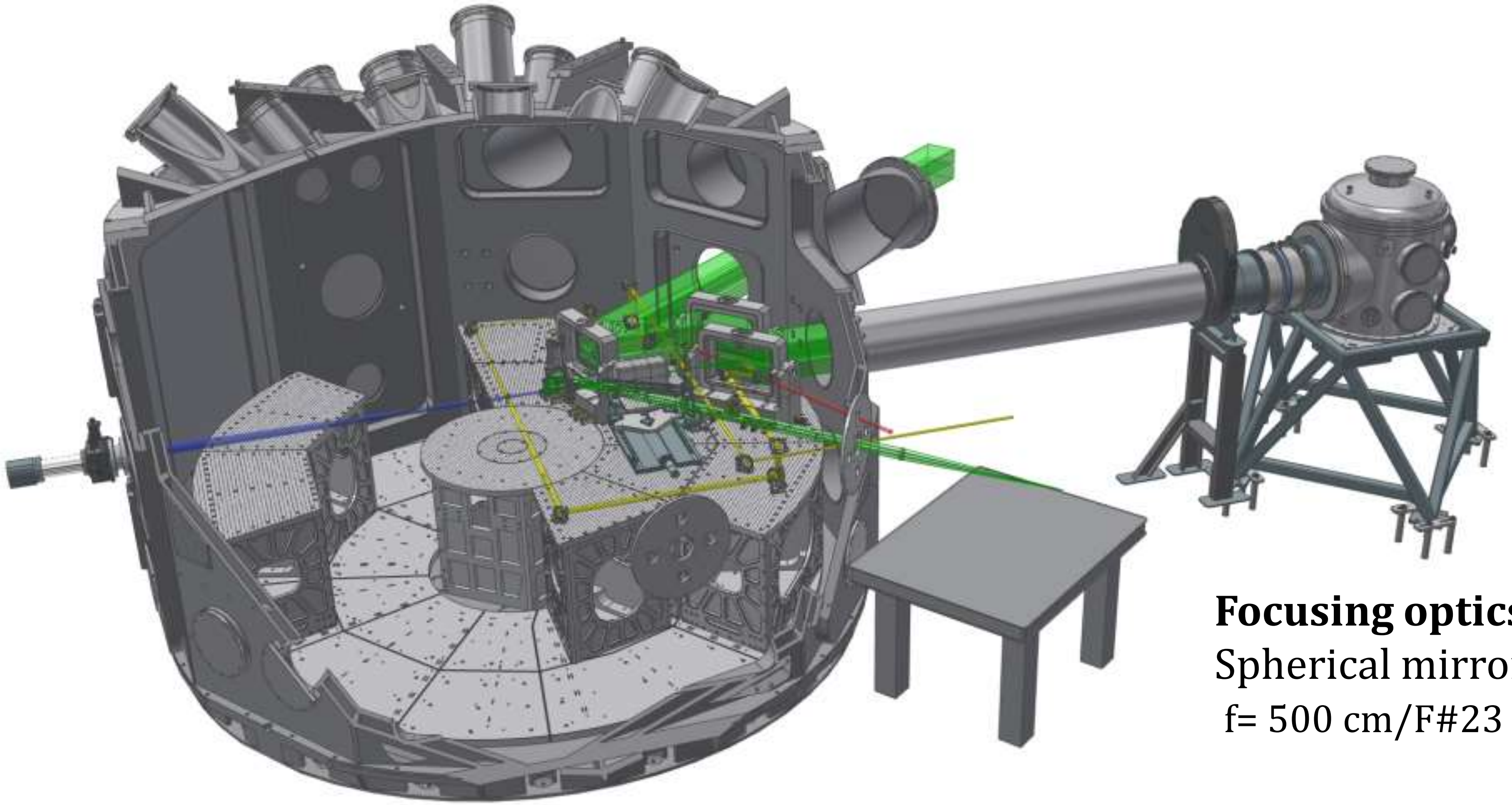


Plasma Physics Platform
E3

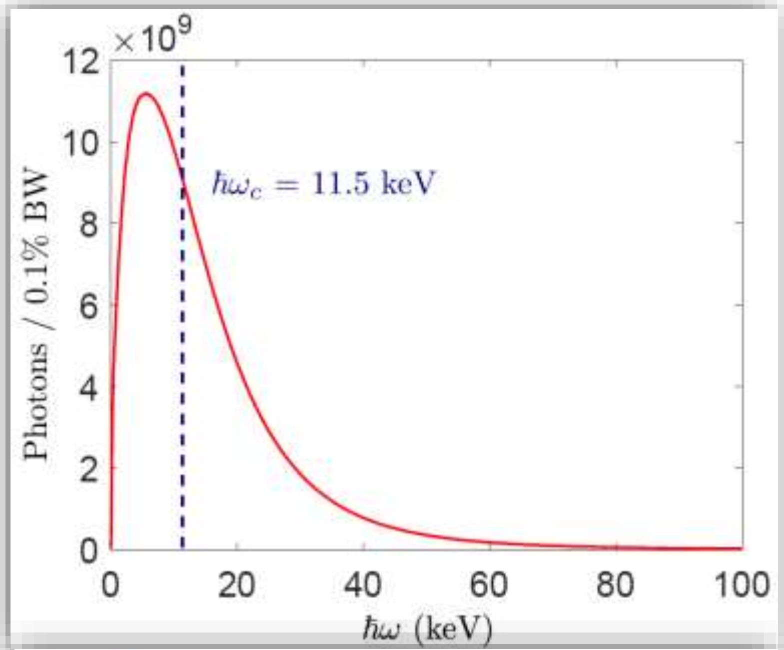


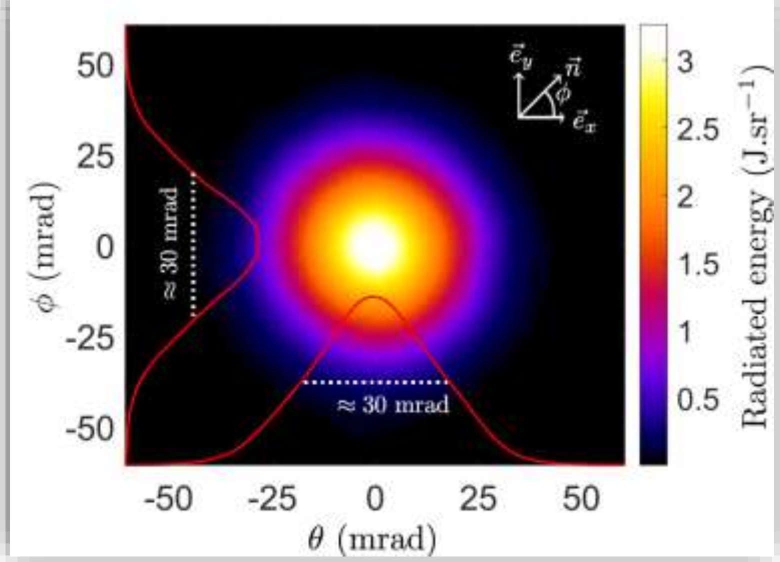
L3 – PW laser for back-lighting
L4n – kJ ns pulses with pulse-shaping
L4f- 10 PW (1.50kJ, 150 fs)

Betatron Source at Plasma Physics Platform



Focusing optics:
Spherical mirror
f= 500 cm/F#23





First Light (Q1 2022)

Source commissioning (Q3 2023)

User call (Q4 2023)

N. Jourdain, U. Chaulagain et al., MRE 6.1 (2021): 015401

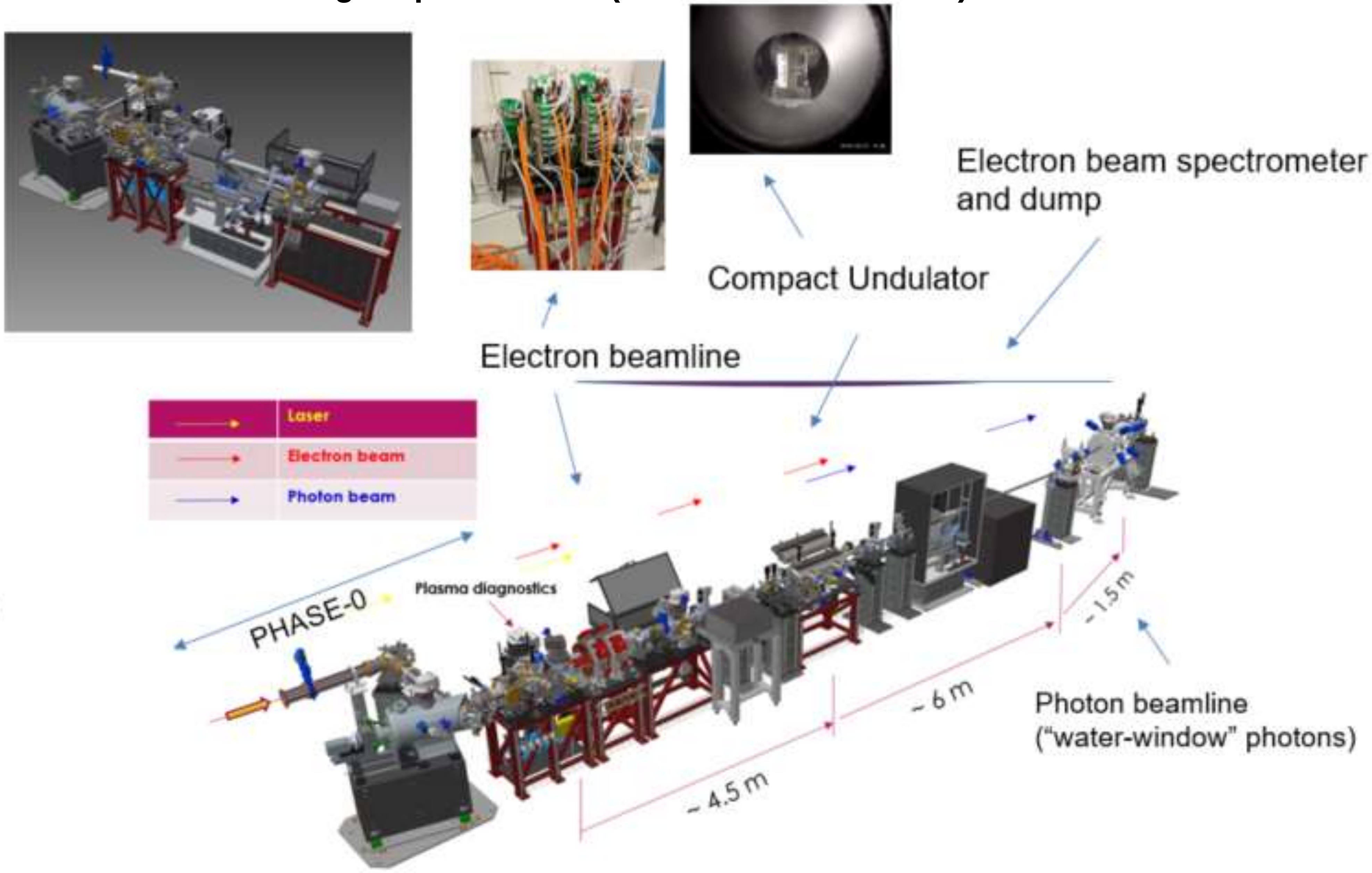
Laser driven Undulator Beamline

Courtesy of A. Molodozhentsev

Goal: Compact LPA-based accelerator at high repetition rate (3 Hz → 20 Hz → 50 Hz)

PHASE-0
2022

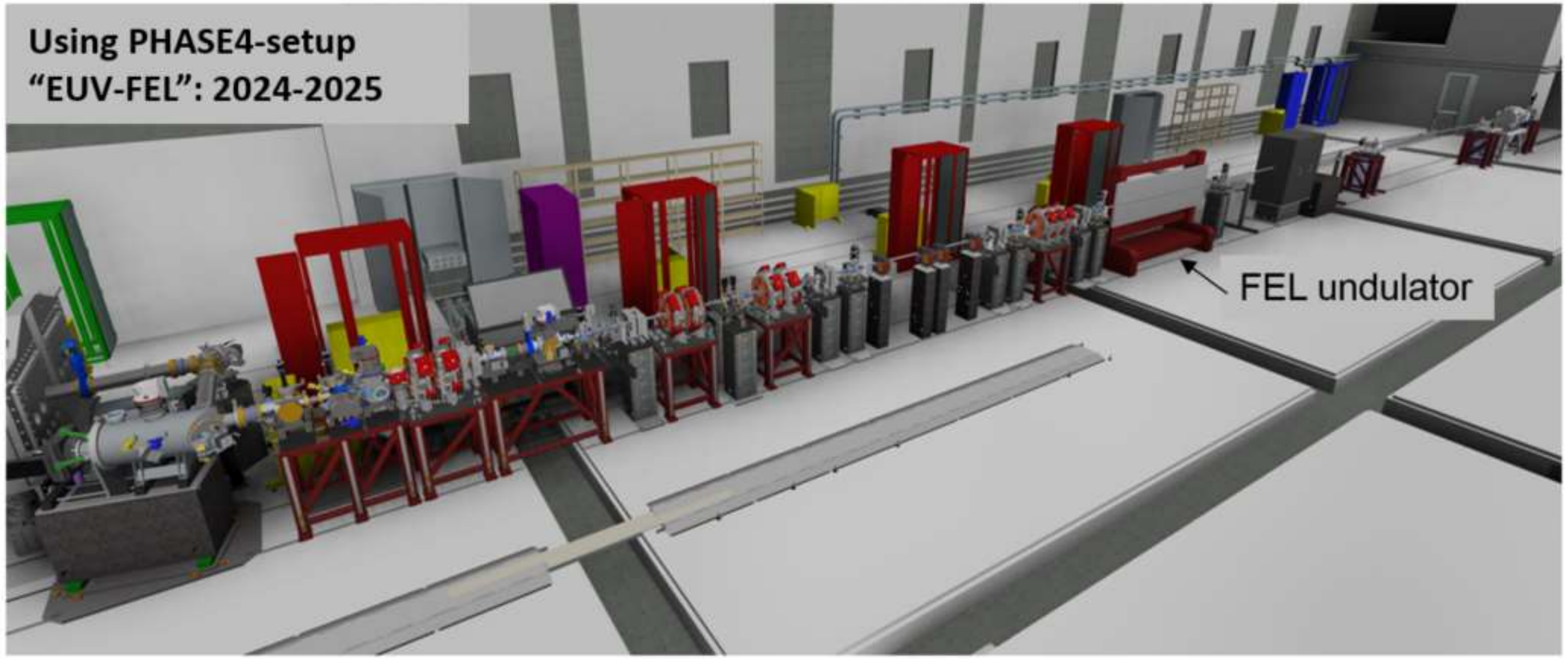
PHASE-1
2023-2024



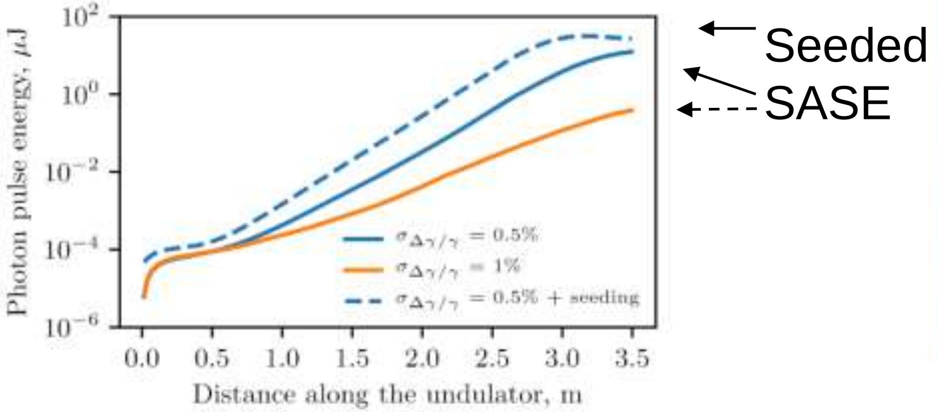
eli beamlines

From incoherent to coherent regime (LPA-based FEL)

Courtesy of A. Molodozhentsev



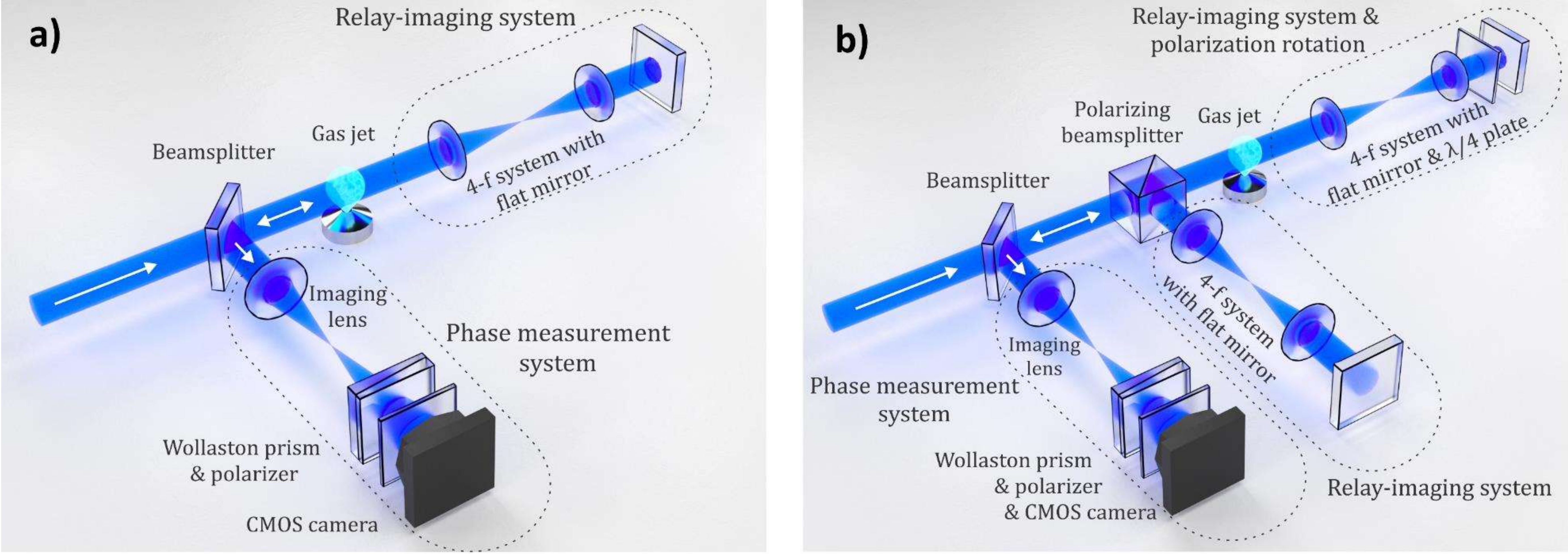
Goal: demonstration of the SASE XUV-FEL regime
- We ~ 350 MeV
- saturation in a single undulator (~ 3 m)
- 'seeded' FEL



Main parameters of EUV-FEL at ELI-Beamlines

Electron beam in Undulator (K_0=1.4)		
Beam energy	MeV	350
Bunch charge	pC	30
RMS bunch duration	fs	3
Peak current	kA	4
Matched beam size	μm	25
Normalized emittance	π mm.mrad	0.24
'Slice' energy spread	%	0.3
Photon coherent radiation at saturation		
Radiation wavelength	nm	32
Pierce parameter, ρ	$\times 10^{-2}$	0.8
Coherent normalized RMS emittance	π mm.mrad	1.7
Cooperation length (3D), L_{coop}	μm	0.26
Gain length (3D), $L_{g,3D}$	m	0.12
Saturation length (3D)	m	2.4
Radiation bandwidth	%	0.65
Photon flux per 0.1%bw	$\times 10^{12}$ #	2.2
Photon brilliance	$\times 10^{30}$ #	1
Photon pulse power	GW	8.2
Photon pulse energy	μJ	63

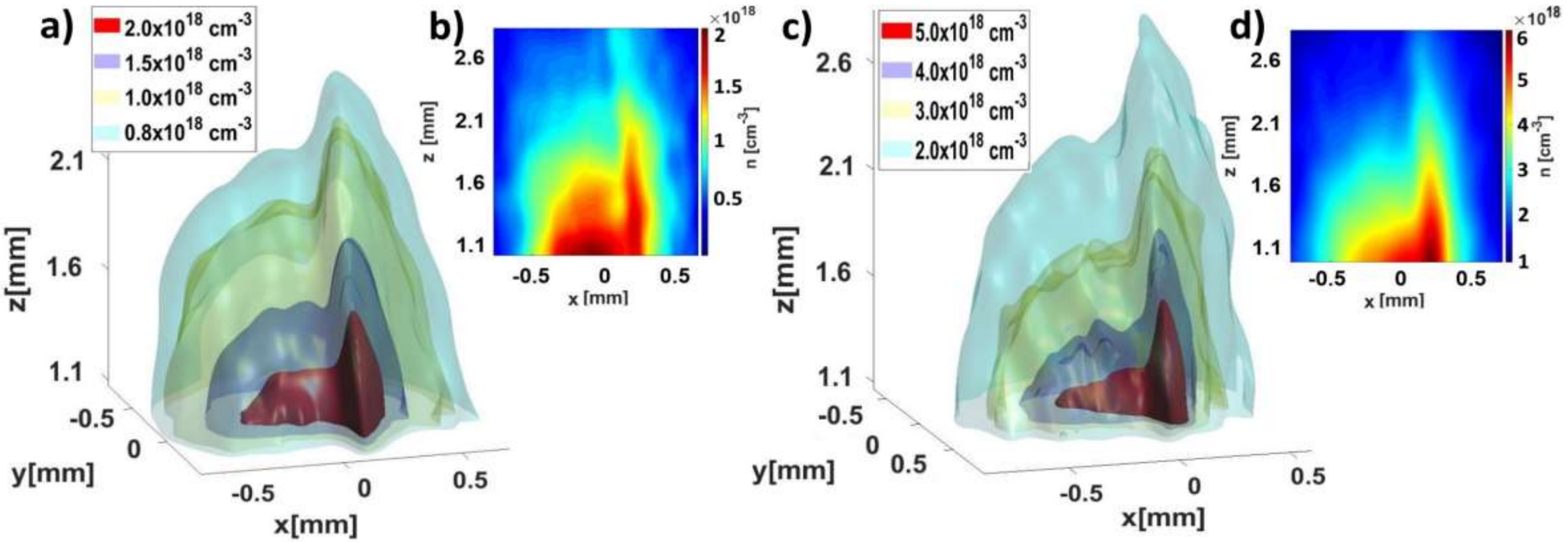
Gas jet characterization (with improved sensitivity)



Two/Four-pass interferometer in which the gas jet is imaged on itself by two **relay-imaging object arms**.

Gas jet characterization (with improved sensitivity)

- **Automated station** for tomography with unprecedented sensitivity available to users
- Pulsed laser (445 nm, 100 ns) being used to **visualize the instabilities** inside the gas jet on nanosecond scale

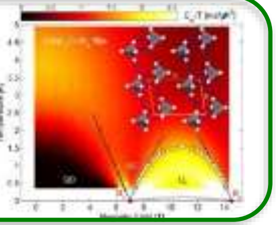


Ar (1.6 bar) **He (7 bar)**

Density isosurfaces of gas jets from 1 mm in diam. supersonic nozzle with a razor blade

Possible application areas

Properties in new **surfaces** and **interfaces**, **charge and spin dynamics** (electronic and magnetic properties)



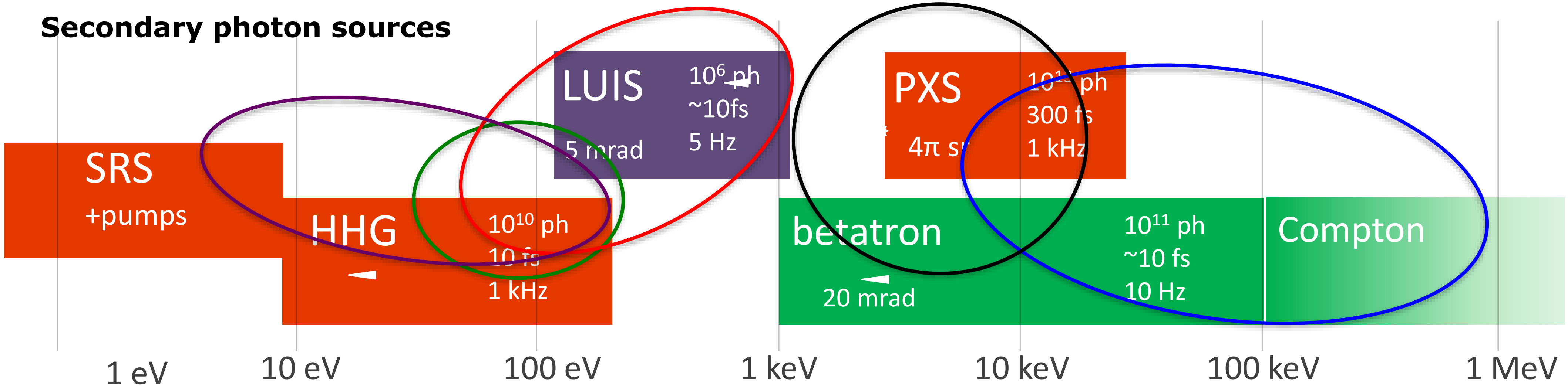
Electron dynamics in molecules. **Structure** of non-reproducible **biological particles**.

X-ray Imaging. Movies of transient effects in large specimens

Initiate and study **transient processes** in molecular dynamics and material sciences

Sub-ps resolution of atomic scale **structural dynamics** (time resolved protein crystallography)

Secondary photon sources



The X-ray Team

Dong-Du Mai, Uddhab Chaulagain, Ondřej Hort, Ondřej Finke, Martin Albrecht, Matej Jurkovič, Marcel Lamač, Marek Raclavský, Kaya H. Rao, Yelizaveta Pulnova, Shirly Espinoza, Mateusz Rebarz, Eva Klimešová, Maria Krikunova, Jakob Andreasson, Sergei Bulanov

Postdoc position open

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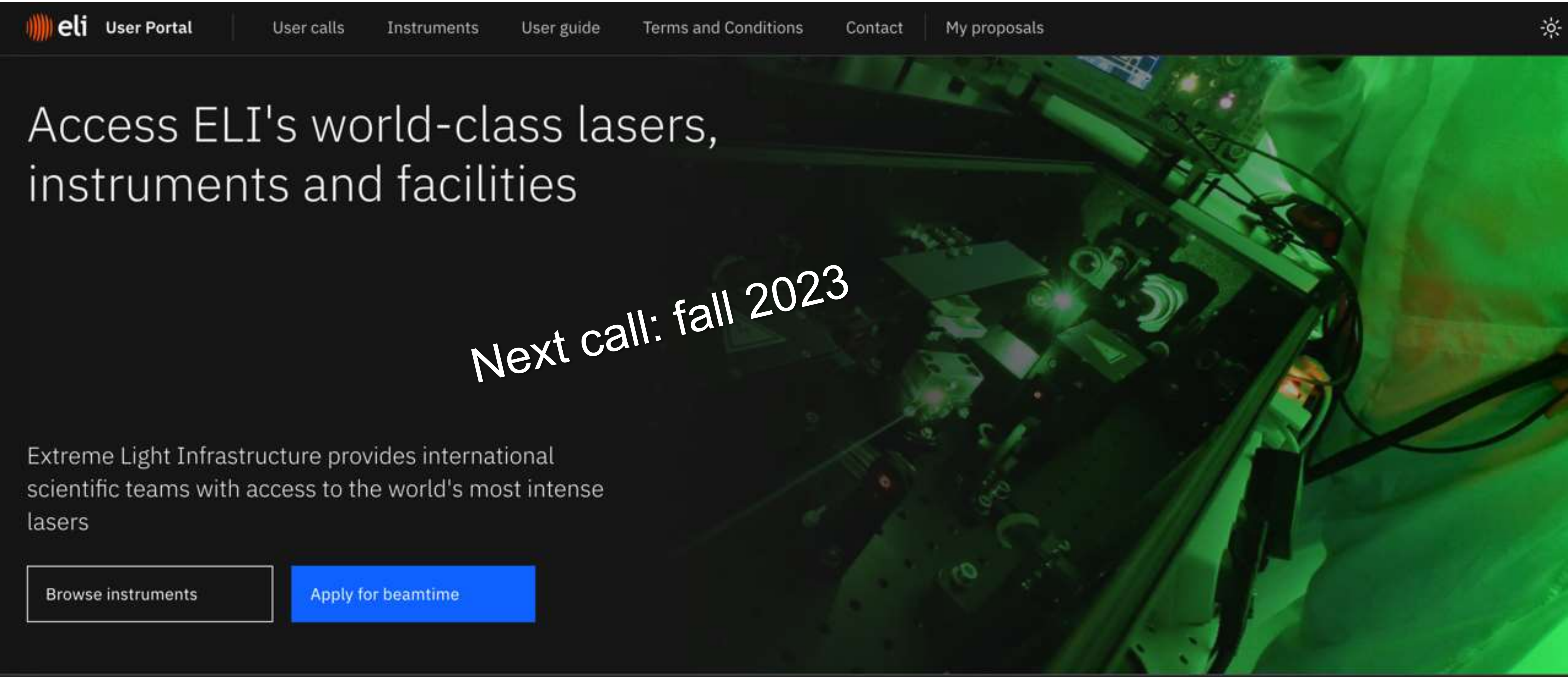
https://up.eli-laser.eu



Thank you for your attention!

Jaroslav.Nejdl@eli-beams.eu