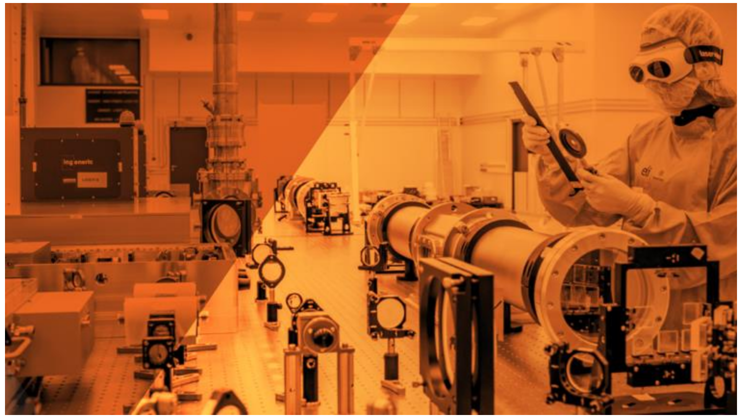
Laser-Plasma-Accelerator-Based Compact Free Electron Laser PROGRAM at ELI Beamlines

Alexander Molodozhentsev

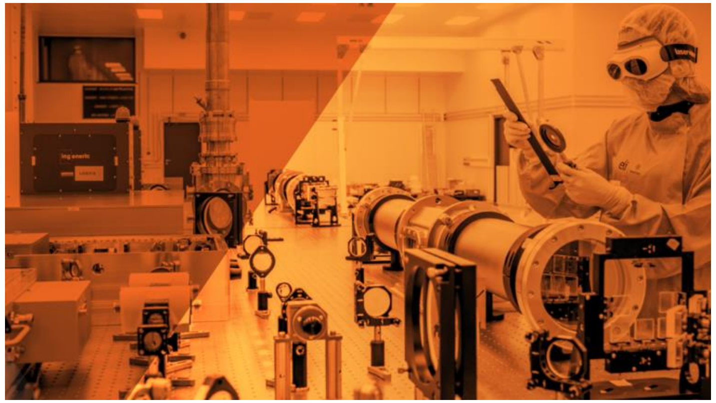
ELI ERIC / ELI Beamlines, Czech Republic



This work was supported by the Ministry of Education, Youth and Sports of the Czech Republic through the e-INFRA CZ (ID:90254). This work was also supported by the project 'Advanced Research using High Intensity Laser produced Photons and Particles' (ADONIS) (CZ.02.1.01/0.0/0.0/16019/0000789) from European Regional Development Fund (ERDF). This project has received funding from the European Union´s Horizon Europe research (EuPRAXIA PP and DN Project, and PACRI Project).

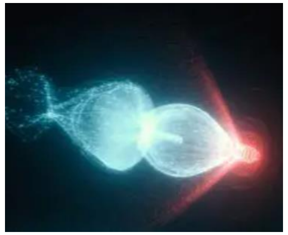
Content

- Motivations and Challenges
- ELI Beamlines and LUIS Project:
  - Laser development at ELI Beamlines
  - Laser-Plasma electron Accelerator development
  - LPA-based Incoherent / Coherent Undulator Radiation Source
- LPA-based compact FEL development in Connection with EuPRAXIA-ESFRI Project

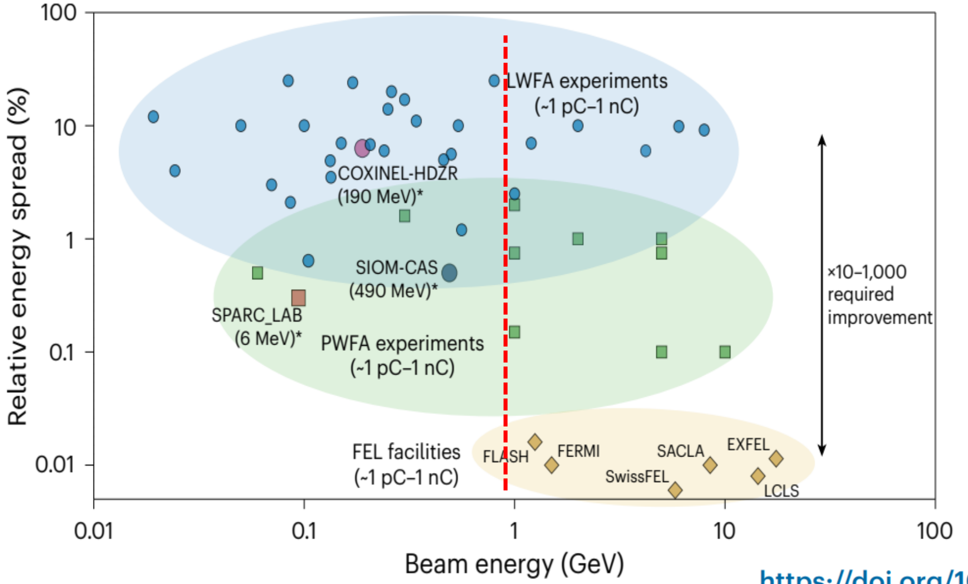


• Motivations and Challenges

Laser-Plasma Accelerator: "n cm" scale



Plasma Accelerators



LINAC: "n100 m" scale

https://doi.org/10.1038/s41566-024-01474-3

Motivations for Laser-Plasma-Accelerator-based Free Electron Laser:

- ✓ Electron beam energy, obtained experimentally by many LPA teams, exceeded the 1 GeV range with the peak current of a few kA and the bunch duration of a few fsec.
- ✓ LPA-based compact accelerator can produce a high-energy, high-quality electron beam.
- ✓ Control of the 'slice' energy spread
- ✓ Laser repetition rate > 5 Hz

➔ Development of the NEXT generation of FEL

F. Grüner, et al., Appl. Phys. B 86, 431 (2007)
T. Eichner, et al., PR AB 10, 082401 (2007)
M. Fuchs, et al., Nat. Phys. 5, 826 (2009)

Challenges for Laser-Plasma Accelerator aiming for FEL

- The RMS relative energy spread of the electron beam **should be < 1 %**
- The RMS transverse divergence of the electron beam **should be < 1 mrad**
- **Preservation of the quality** of the high-energy electron beam (1 – 5 GeV)
- **High repetition rate** (~ 100 Hz)
- **Stable and repeatable operation**

Motivations and Challenges

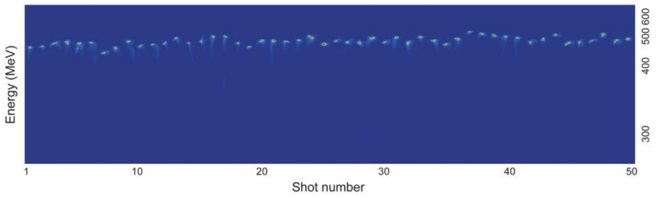
Challenges for Laser-Plasma Accelerator aiming for FEL

- The RMS relative energy spread of the electron beam **should be < 1 %**
- The RMS transverse divergence of the electron beam **should be < 1 mrad**
- **Preservation of the quality** of the high-energy electron beam (1 – 5 GeV)
- **High repetition rate** (~ 100 Hz)
- **Stable and repeatable operation**

How to Attack the Challenges

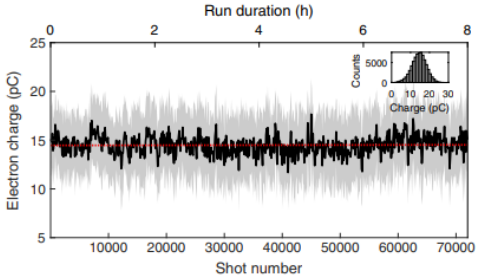
Experimental results
High Quality e-beam / SIOM team (China)

Energy ~ 500 MeV
Energy spread ~ 0.2-1.2% (RMS)
Divergence ~ 0.1-0.4 mrad (RMS)
Q_b=10-50 pC **with limited statistics**



https://doi.org/10.1038/s41586-021-03678-x

Experimental results
Stable operation / LUX team (DESY)



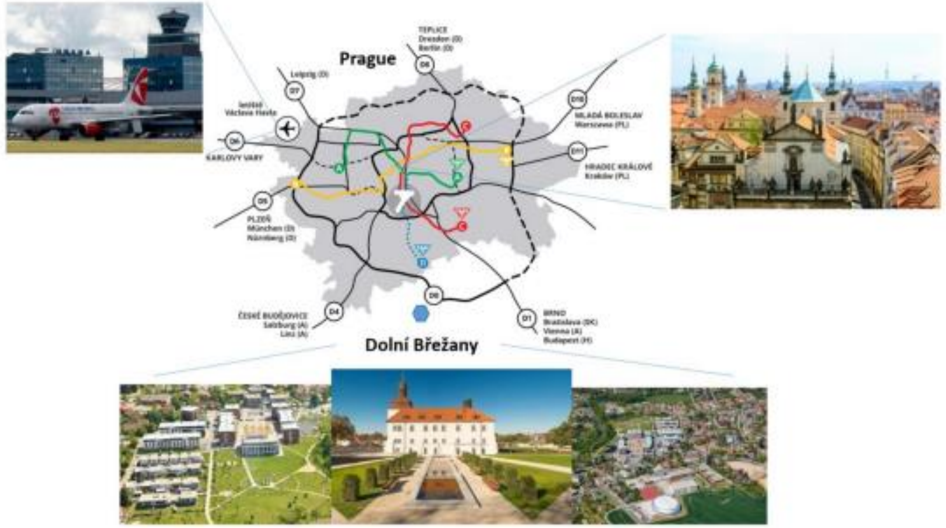
Energy ~ 80 MeV
Energy spread ~ 1.3 % (RMS)
Divergence ~ 5 mrad
Q_b ~ 15 pC (**72'000 shots/6h**)

DOI: 10.1103/PhysRevAccelBeams.25.031301

ELI Beamlines (ELI ERIC in the Czech Republic)

ELI Beamlines facility was opened in October 2015.

The implementation phase was completed in 2019 by the commissioning of the main laser and experimental systems.



eli | beamlines

ELI Beamlines explores the interaction of light with matter at intensities 10 times higher than previously achievable.

4 PW class laser systems, 4 support lasers

7 Secondary sources – EUV - X-rays, Electron and Ion Accelerators

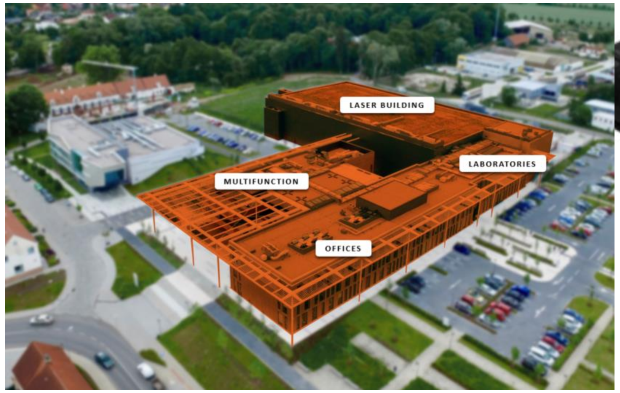
10 User stations

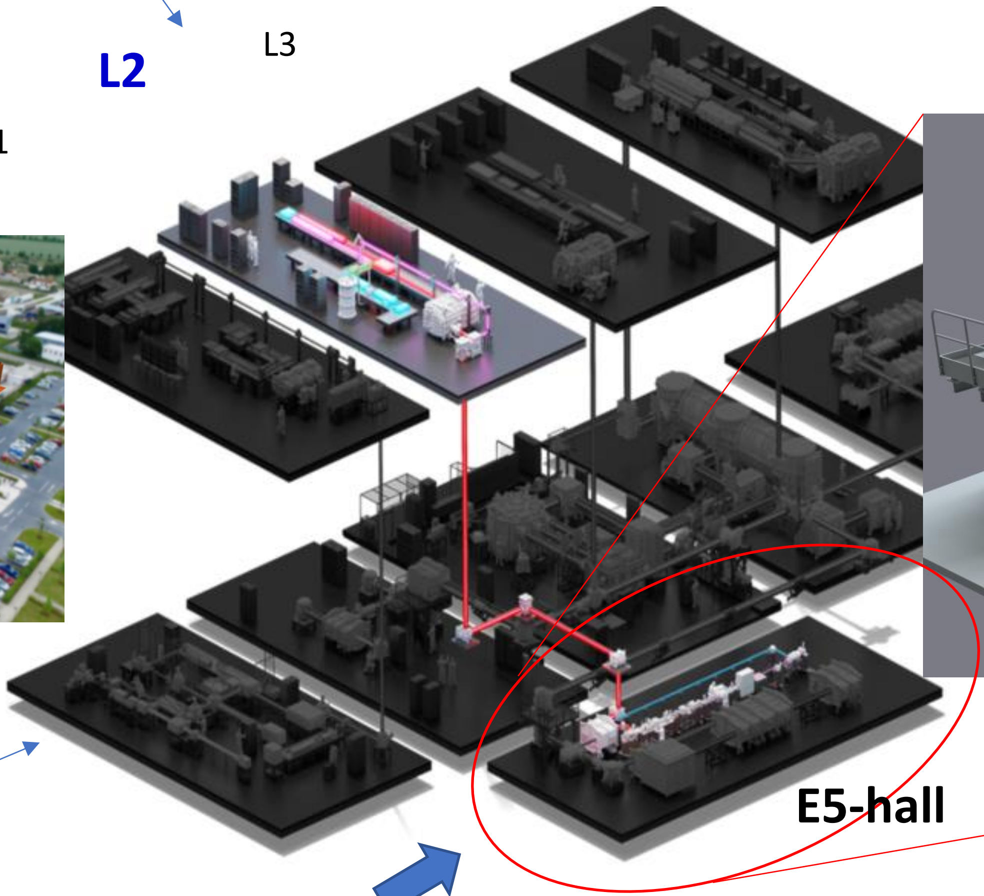
- 350 international staff
- Area 31,000 m2

- Structural Dynamics
- Particle Acceleration and Applications
- HED Physics and ICF
- High Field Physics

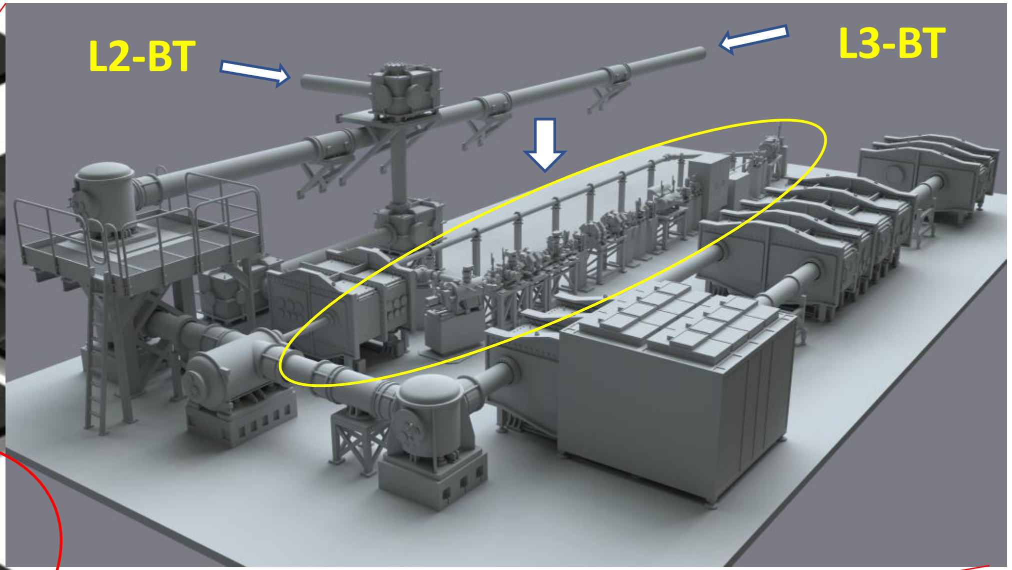
Laser System	Power	Energy	Rep Rate	Pulse Duration	Wavelength
L1 ALLEGRA	5 TW	100 mJ	1 kHz	15 fs	800 nm
		10 mJ	1 kHz	<20 fs	800 nm
L2 DUHA	100 TW	2 J	50 Hz	20 fs	820 nm
		5 mJ	2 kHz	30 fs	2.2 µm
L3 HAPLS	1 PW	>30 J	10 Hz	28 fs	850 nm
L4 ATON	10 PW	1.8 kJ	0.016 Hz	150 fs	1055 nm
	1 PW	150 J	0.016 Hz	150 fs	1055 nm
		1.5 kJ	0.016 Hz	0.5-10 ns	10505 nm

ELI Beamlines (ELI ERIC in the Czech Republic)





LUIS technology



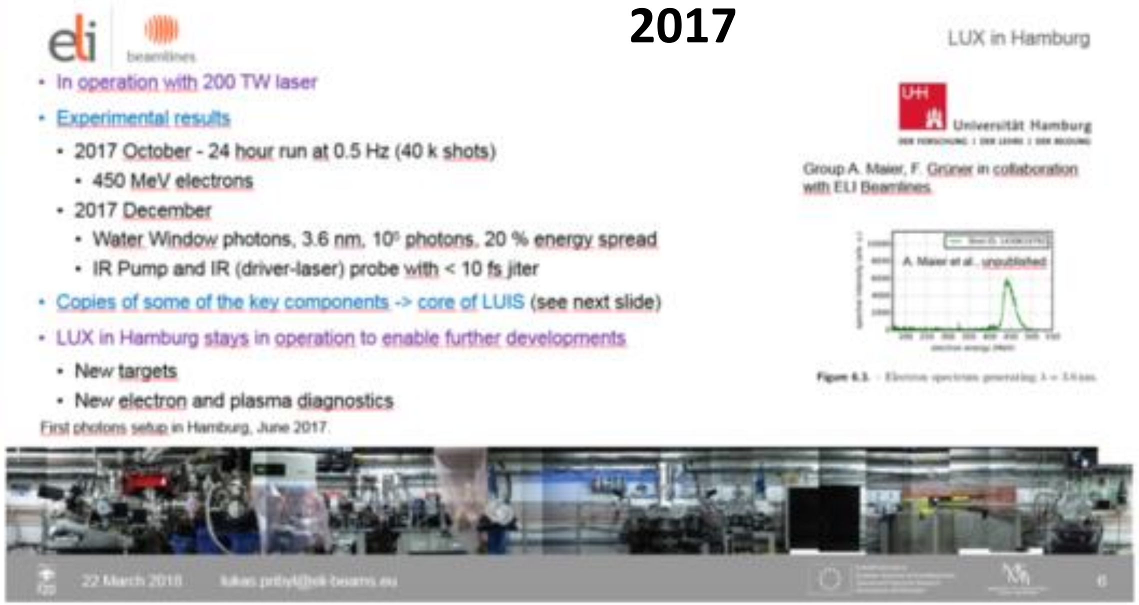
E5 experimental area (length of the hall is around 50 m with a possible extension up to 100 m : **E5+E6**).

LUIS Project at ELI Beamlines

→ LWFA-based undulator incoherent photon radiation source (We ~ 450 MeV, $\lambda_{ph,1}$ ~ 4 nm)
→ based on the LUX development at DESY (UHH/ELI Beamlines Collaboration)
→ based on a novel high-repetition rate high-power laser system (L2-DUHA: 200 TW / 20-50-100 Hz)

LUX team:
UHH-CFEL and ELI-Beamlines

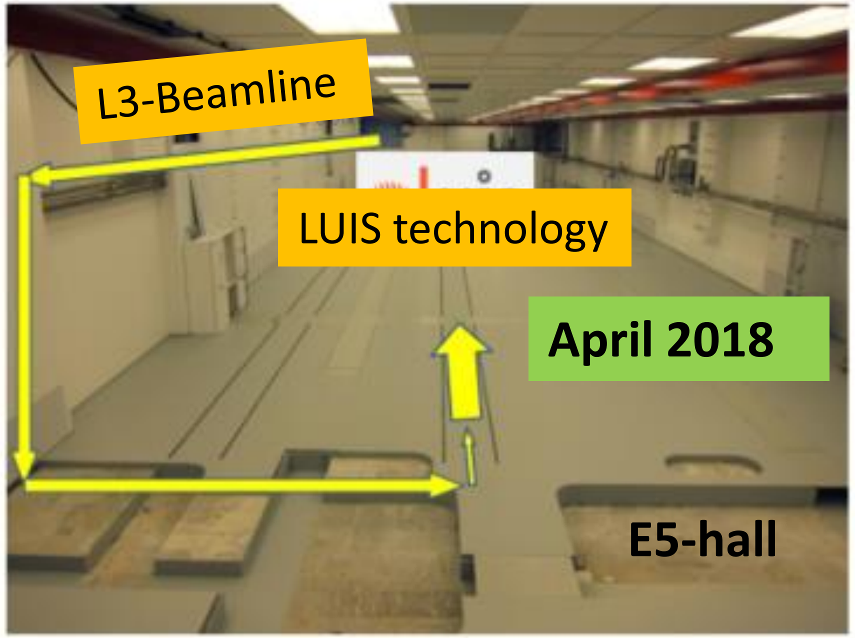
Achievement: incoherent photon radiation



LUIS Project at ELI Beamlines

→ LWFA-based undulator <u>incoherent</u> photon radiation source (W_e ~ 450 MeV, $\lambda_{ph,1}$ ~ 4 nm)
→ based on the LUX development at DESY (UHH/ELI Beamlines Collaboration)
→ based on a novel high-repetition rate high-power laser system (L2-DUHA: 150TW / 20-50 Hz)

E5-Hall at ELI-Beamlines



Laser development at ELI Beamlines

Commissioning (schedule) – **2nd half of 2025**

L2-DUHA laser: LUIS dedicated

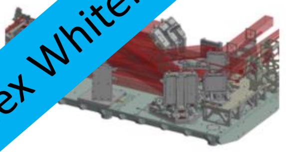
Parameters	Primary Acceptance Criteria	Design Requirement
Maximum pulse energy after compression, focused in the capillary	2 J	5 J
Minimum pulse energy after compression, focused in the capillary	0.5 J	0.5 J
Pulse energy variation	0.2 J	0.1 J
Pulse duration FWHM [1] (after compression)	30 ÷ 40 fs	30 ÷ 40 fs
Pulse duration adjustment	2 fs	1 fs
Maximum peak power (after compression), focused in the capillary	53 (30fs) TW 40 (40fs) TW	158 (30fs) TW 118 (40fs) TW
Minimum peak power after compression, focused in the capillary	13 (30fs) TW 10 (40fs) TW	15.8 (30fs) TW 11.8 (40fs) TW
Repetition rate	1 Hz	3.33 Hz (10-25-50 Hz)
Beam format [2]	Circular / 8th order SG	Circular / 8th order SG
Laser spot size (FWHM) on the off-axis parabola (focal length ~ 2 m)	80 mm	80 mm
Central wavelength	820 nm	820 nm
Beam quality (encircled energy in diffraction limited spot) [3]	0.80	0.95
Output relative pulse energy RMS stability	2.5 %	< 1%
Output beam RMS pointing stability	< 2 μrad	< 1 μrad

Main laser parameters, required for the LUIS development

Main expected electron beam parameters

Electron beam parameters from the LPA-source	Units	Commissioning stage	User-operation stage
Energy	*MeV*	300 ÷ 600	300 ÷ 600
RMS energy spread	%	< 5	< 1 → 0.5
Energy fluctuation (shot-to-shot)	%	< 5	< 1
Bunch charge	*pC*	~ 100	~ 50
Bunch charge fluctuation (shot-to-shot)	%	< 20	< 5 → 1
RMS transverse beam divergence	*mrad*	< 5	< 1 → 0.5
RMS norm. transverse emittance	*π mm.mrad*	< 2	< 1 → 0.2
Bunch duration (FWHM)	*fsec*	< 5	< 2

- Cryogenic helium-cooled pump laser using diode-pumped Yb:YAG slabs
- Designed for 50 Hz operation, currently at 20 Hz due to pump laser diodes
- Incorporates an OPCPA short-pulse chain
- Output pulses of 3 J with a duration of 25 fs
- Serves as the driver for a laser-driven XFEL testbed station
- Offers an auxiliary MID-IR (2.2 μm) beam
- Currently in the final phase of integration and testing
- Compressed pulses expected to be available in 2024

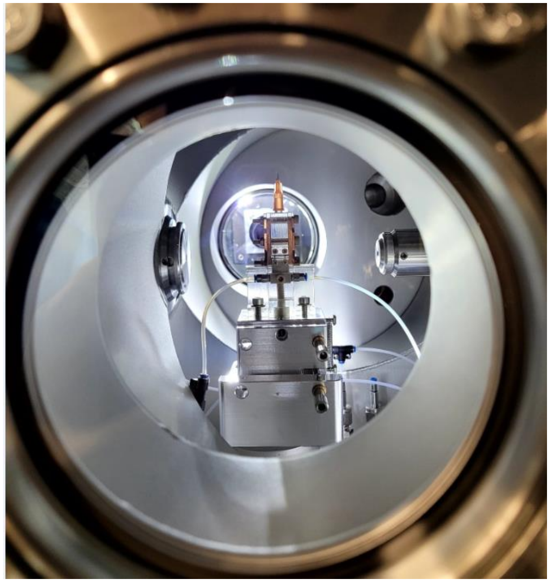


Alex Whitehead talk: 04.18

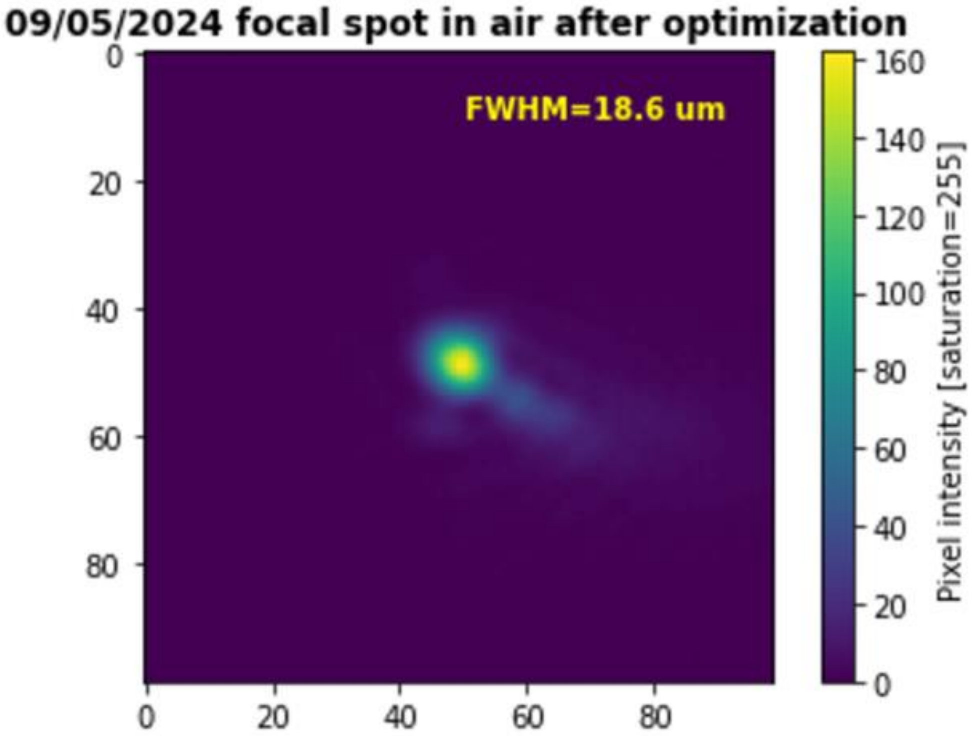
Credit: Bedrich Rus

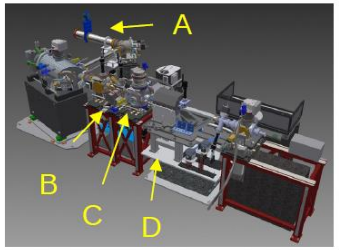
Laser-Plasma electron Accelerator (LUIS)

LUIS target chamber



Sapphire capillary
- Gas-cell (~ 2 cm)
- Optional: Preformed plasma channel





(C) Target chamber

(D) Laser and e-beam diagnostics

All technologies are <u>fully integrated and tested</u> in the E5-hall including support/safety subsystems (vacuum/gas, MSS, PSI, central control system)

Technology verification **was done** using the L3-cropped beam / May 2024

○ Laser-Plasma electron Accelerator (LUIS)

PIC modeling of the laser-plasma interaction and electron beam acceleration
Motivation: high-quality high-energy electron beam, suitable for LPA-based FEL

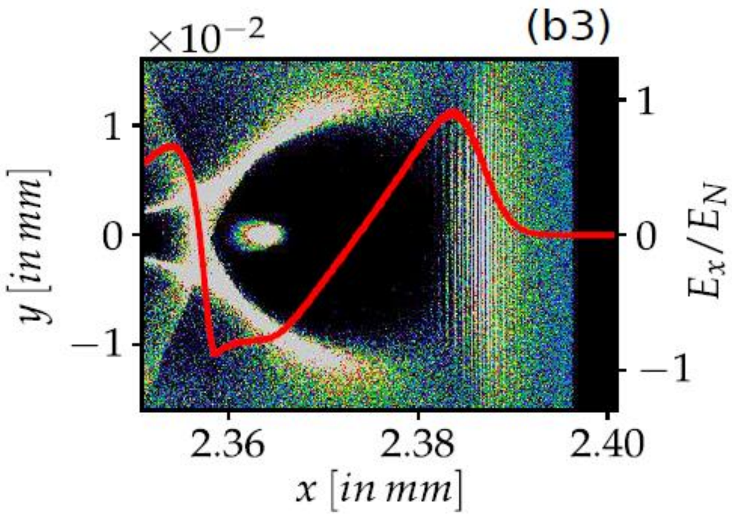
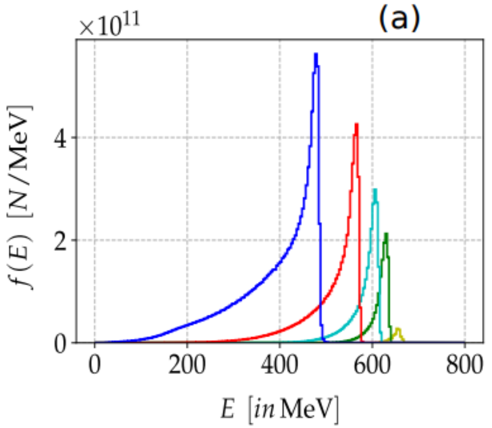


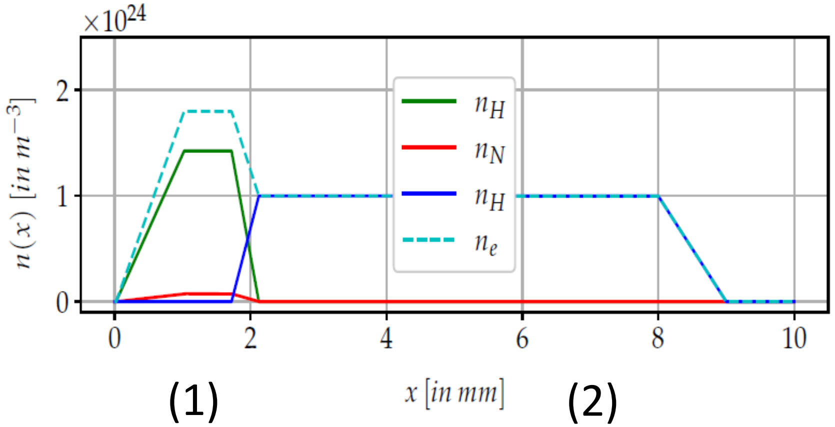
Table: Simulation Parameters ($I_0 = 1.0 \times 10^{19}$ W/cm^2; $P_L = 51$ TW)

Wavelength (λ_L)	Spot size (w_{fwhm})	Pulse duration (τ_{fwhm})	I_0 (W/cm^2)
0.8 μm	30 μm	30 fs	1.0×10^{19}
Laser frequency (ω_L)	Laser energy (E_L)	a_0	Power (P_L)
2.35×10^{15} Hz	1.53 J	2.16	51×10^{12} W
Hydrogen density in platua (n_p)	Net mixed density (n_m)	Percentage of mixer	ω_L/ω_p
$(1.0 - 1.5) \times 10^{18}$ cm^{-3}	$(1.5 - 2.0) \times 10^{18}$ cm^{-3}	95% + 5% of n_m	33



Energy ~ 400 -600 MeV
Spread (FWHM) < 2%
Divergence (FWHM) < 2 mrad
Bunch charge ~ 15-30 pC

Credit: Srimanta Maity



(1) (2)

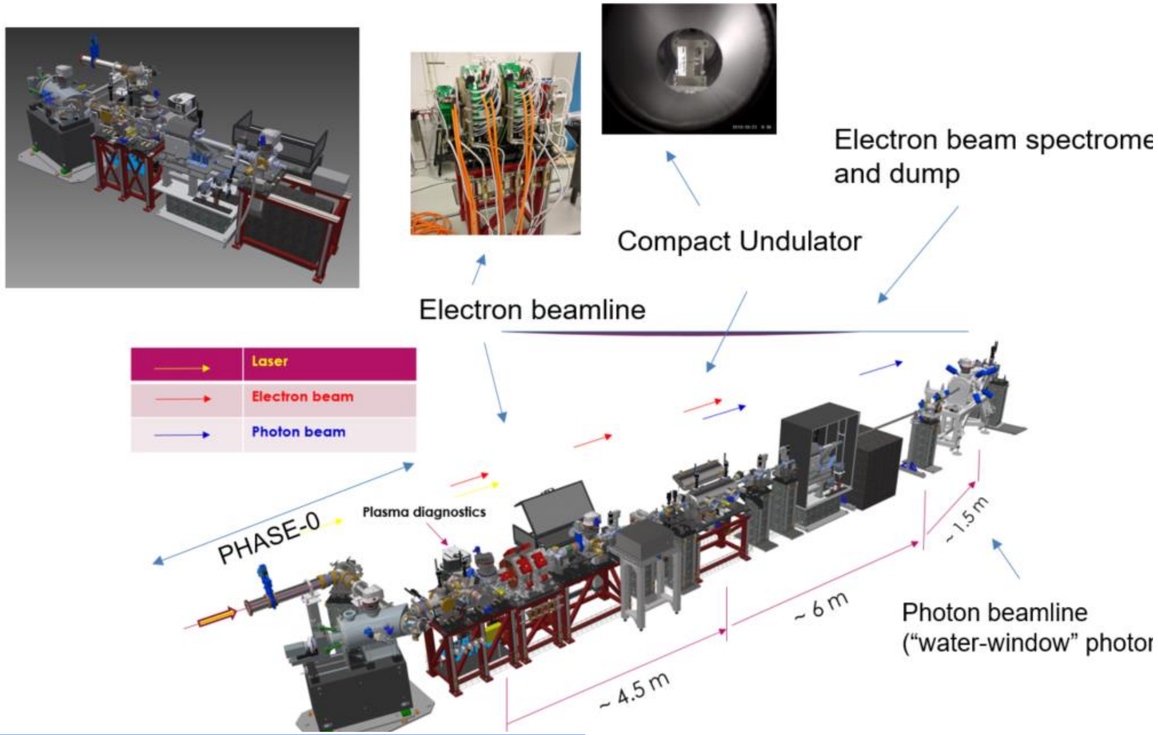
Staging approach in the gas-cell
(1) Self-truncated ionization injection
(2) Acceleration

https://doi.org/10.1088/1361-6587/ad238e

LUIS:
LPA-based Incoherent Undulator Radiation Source

PHASE-0
2025

PHASE-1
2026



Undulator parameters

Undulator period	mm	5
Number of period		100
Total length	mm	500
On-axis magnetic field	T	0.6
K-value		0.28

→ **LUX – collaboration**
HPM planar undulator

Photon beam parameters (PHASE#1) / Estimation

		W_e = 300 MeV / Q_b=30pC	W_e = 600 MeV / Q_b=30pC
Photon energy (1st harmonic)	eV	165	658
Photon wavelength (1st harmonic)	nm	7.5	1.8
Number of photons (0.1%bw)		1.7×10^5	7.1×10^6
Peak Brilliance (at peak current of electron bunch)	*	4.8×10^{20}	1.9×10^{21}
Effective beam size and divergence of the photon beam (1st harmonic)			
Σx,y	µm	114	114
Σx′,y′	mrad	0.087	0.043

* photon/sec/mrad^2/mm^2/0.1%bw

Expected electron beam parameters from LPA

Energy range	MeV	300 – 600
Bunch charge	pC	~ 50
RMS relative energy spread	%	< 5 → **< 1**
RMS divergence	mrad	< 5 → **< 1**

Main challenges:

- High repetition rate (from 20 Hz up to 50 Hz), utilizing the L2-DUHA high power laser
- Stable and repeatable operation
- Improvement of the LPA-based electron beam quality aiming at suitability for LPA-based FEL
- Electron @ Photon beam diagnostics

Laser-Plasma-Accelerator-Based FEL at ELI Beamlines

Future research directions

- *An extensive experimental and numerical development would be necessary to produce electron beams with quality for efficient transport and focusing in demanding applications such as free-electron-lasers. These developments, due to their complexity, will require dedicated permanent facilities and teams.* ***ELI can be a major step in this strategy****.*

Directions of implementation at ELI

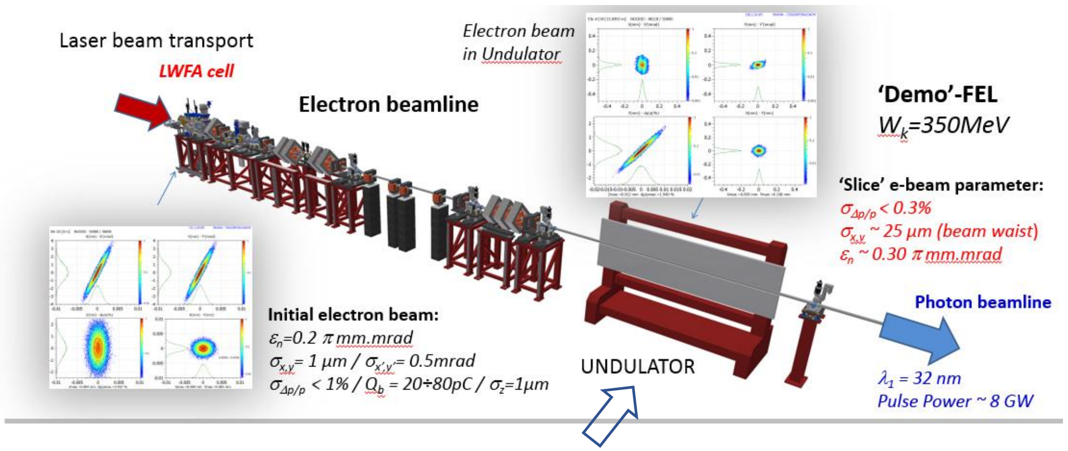
- *The ultimate goal of the* ***Prague ELI-XFEL-beamline*** *is to provide an installation which allows driving the new field of laser-driven XFELs towards future user facilities.*

ELI Whitebook, Mourou et al., 2011

LPA-based Coherent Undulator Radiation Source

EUV-FEL (W_e = 350 MeV / λ_1 ~ 28 nm) as a possible usage of the LUIS beamline in combination with the Swiss-FEL undulator

https://doi.org/10.3390/instruments6010004



Single-unit undulator

'In-vacuum' hybrid PM planar
→ SwissFEL (Aramis) type

λ_u = 15 mm
Gap = 3÷6 mm
*B_{peak} ~ **0.95 T** **
*K_0 = 1.30 **
** gap=4.5mm*

LPA-based EUV-FEL at ELI-Beamlines

10.18429/JACoW-IPAC2024-MOPG32

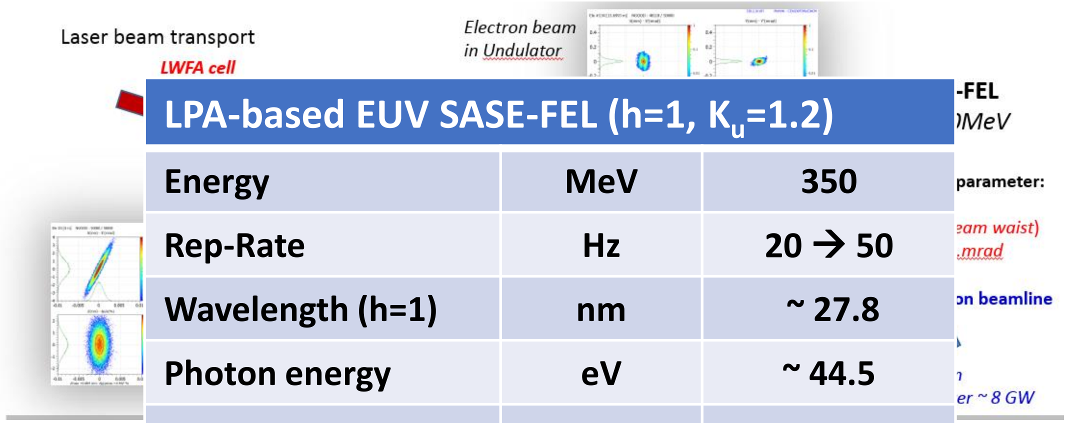
Scientific Goals:

- demonstration of the **SASE EUV-FEL and Seeded FEL** regimes
- saturation in a single undulator unit (~ 4 m)
- L2-aux beam + HHG → for seeding signal

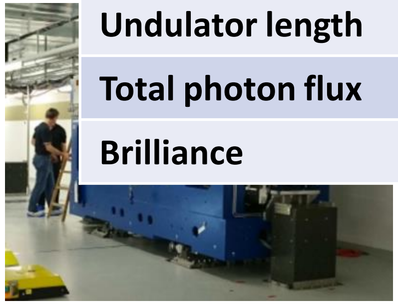
LPA-based Coherent Undulator Radiation Source

EUV-FEL (W_e = 350 MeV / λ_1 ~ 28 nm) as a possible usage of the LUIS beamline in combination with the Swiss-FEL undulator

https://doi.org/10.3390/instruments6010004



LPA-based EUV SASE-FEL (h=1, K_u=1.2)		
Energy	MeV	350
Rep-Rate	Hz	20 → 50
Wavelength (h=1)	nm	~ 27.8
Photon energy	eV	~ 44.5
Peak power	GW	~ 2.1
Undulator length	m	~ 4
Total photon flux		~ 1.6×10^{13}
Brilliance	0.1%bw	~ 4×10^{29}

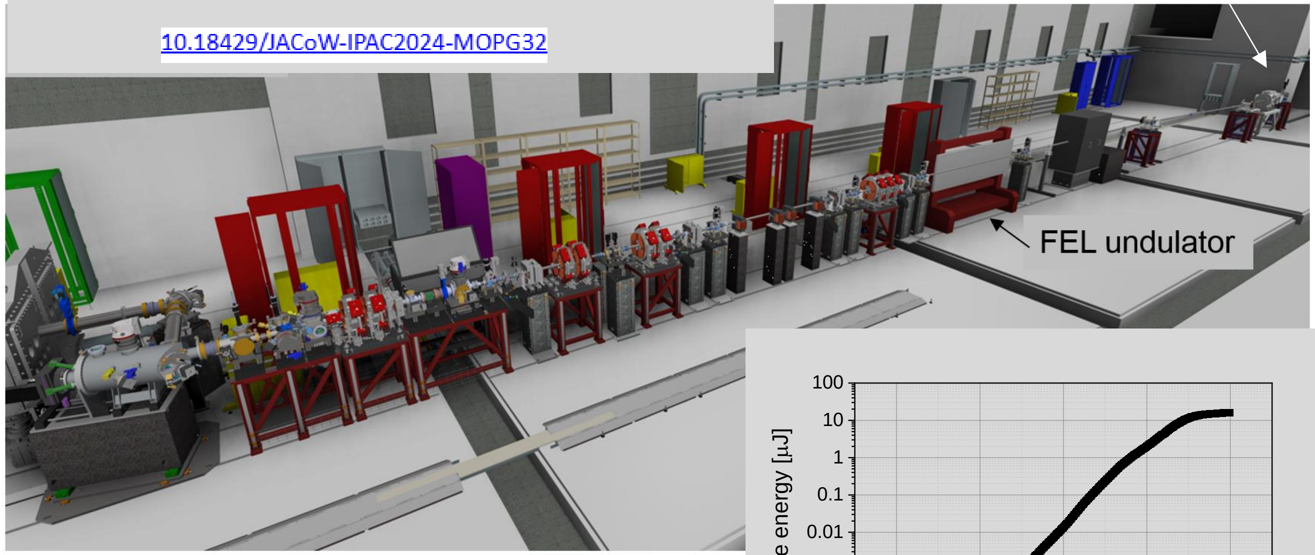


Single-unit undulator

Gap = 3÷6 mm
*B_{peak} ~ **0.95 T ****
*K_0 = 1.30 **
** gap=4.5mm*

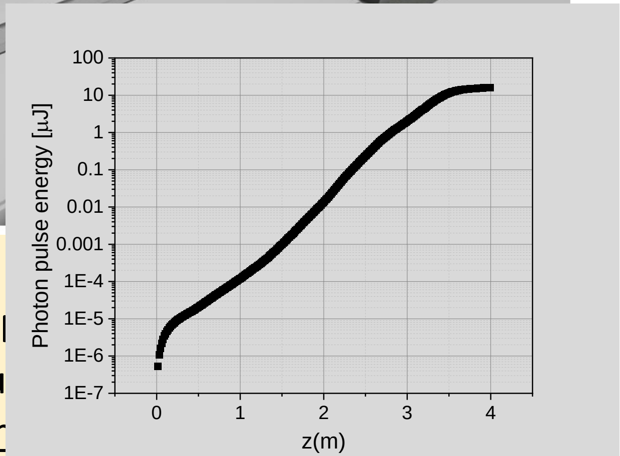
LPA-based EUV-FEL at ELI-Beamlines

10.18429/JACoW-IPAC2024-MOPG32



Scientific Goals:

- demonstration of the **SASE EUV-**
- saturation in a single undulator u
- L2-aux beam + HHG → for seedir



Start-to-End simulations are in progress

LPA-based Coherent Undulator Radiation Source

Connection with the EuPRAXIA (ESFRI) Project

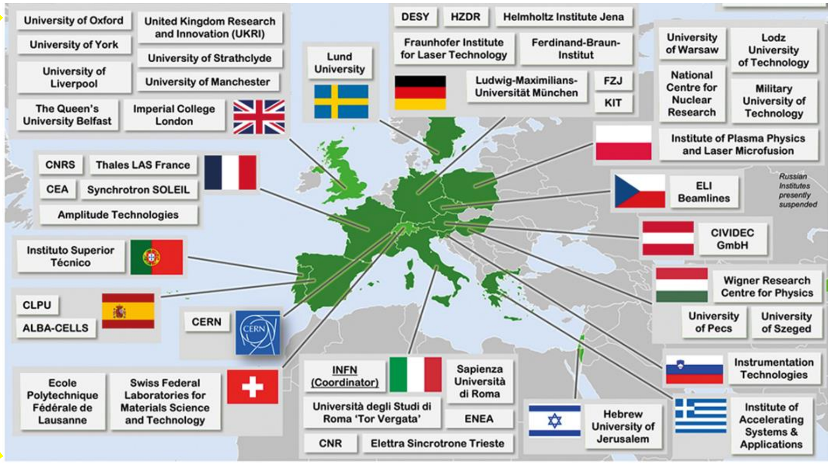
Consortium decision

March 25, 2025

(SITE 1) EuPRAXIA @ SPARClab in Frascati, Italy

(SITE 2) EuPRAXIA @ ELI-Beamlines in Prague, Czech Republic

Leveraged by the EuPRAXIA Preparatory Phase Consortium and its world-class beam and laser facilities

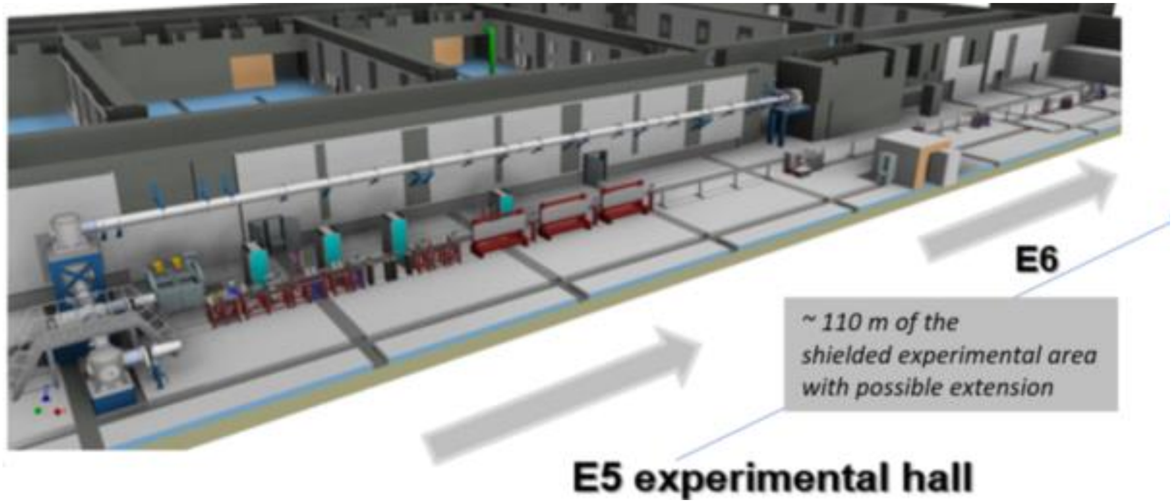


LPA-based Coherent Undulator Radiation Source

Conceptual solution to integrate the entire setup, including the photon beamlines and user stations, into the existing infrastructure of ELI-Beamlines.

LPA-based soft X-ray FEL is one of the goals of **EuPRAXIA Consortium (Phase-1)**.

10.18429/JACoW-IPAC2024-MOPG31



The **plasma photocathode** in combination with the **hybrid LWFA-PWFA** approach could reduce the length of the entire setup significantly.
The dedicated R&D is required.

https://doi.org/10.1002/andp.202200655

Laser		
Pulse energy (in focus)	Joule	2.5
Central wavelength	nm	820
Pulse duration	fsec	25
Laser intensity in focus	10^{18} W/cm^2	5
Laser spot radius in focus	µm	30
Repetition rate	Hz	100
LPA-Accelerator		
Plasma density	10^{18} cm^{-3}	1
Plasma length	mm	30
Normalized potential (a_0)		< 1.9
"Slice" electron beam		
Electron beam energy	MeV	1000
Peak current	kA	2.5
Normalized (RMS) emittance	mm.mrad	0.35
RMS relative energy spread	%	0.3
Photon radiation (K=1.6)		
Photon energy	eV	278
Radiation wavelength (h=1)	nm	4.5
Wavelength bandwidth	%	0.1
Total photon flux	10^{11} ph	1.0
Peak power at saturation	GW	0.5
Photon peak brilliance	10^{29}	3.0
Saturation length	m	27
Length without Photon Line	m	50

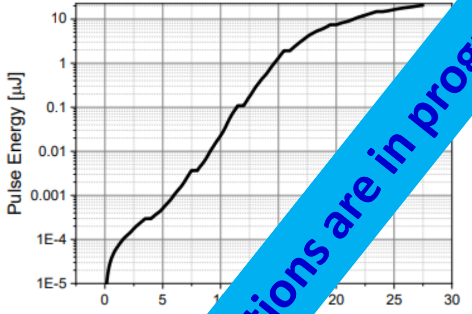
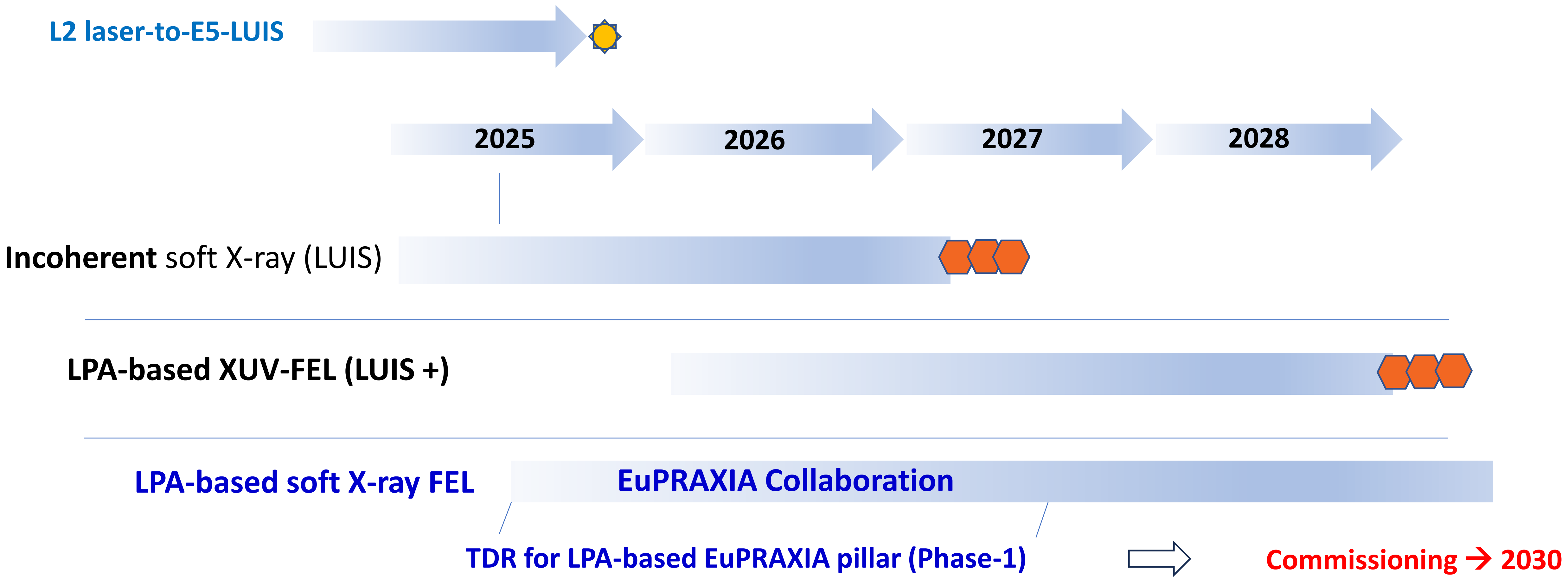


Figure 1: Photon pul... along the undulator sections for the LPA-base... EL with the photon energy of 278 eV.

Start-to-End simulations are in progress

PLASMA ACCELERATOR BASED FREE ELECTRON LASER PROGRAM AT ELI ERIC (ELI Beamlines)

Current schedule aiming … → User operation

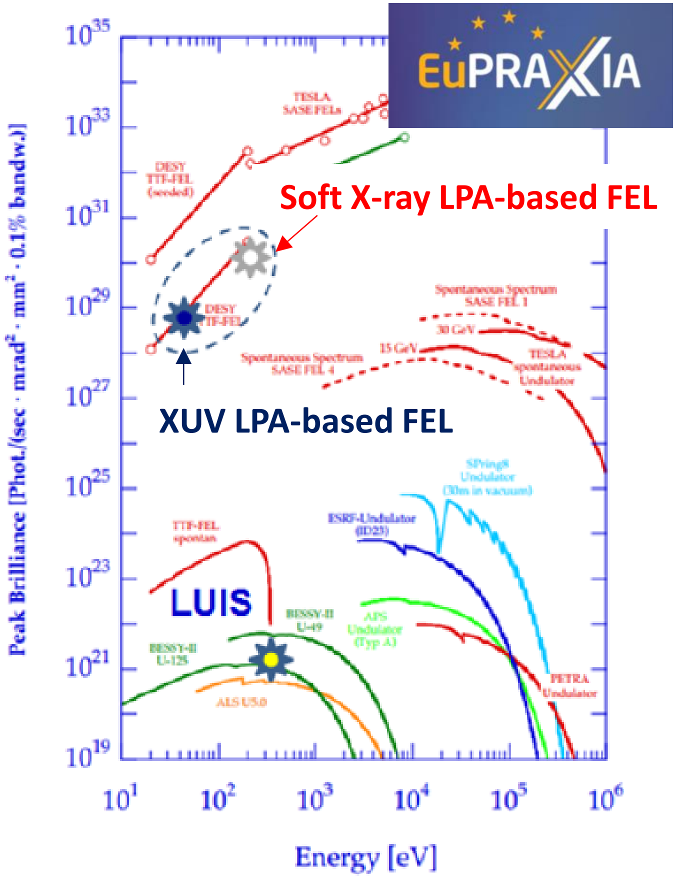


Summary

- ❖ High-power High-Repetition rate novel Laser System (L2-DUHA) is under preparation at ELI-Beamlines → 1st L2-LUIS operation (plan): Q4-2025

- ❖ Incoherent undulator radiation source at ELI-Beamlines → commissioning during 2025-2026

- ❖ Coherent undulator radiation source (LPA-based FEL): → from XUV to soft X-ray FEL (**EuPRAXIA-PHASE1 at ELI Beamlines**)



Thank you for your attention.

Join us in a groundbreaking collaborative effort to establish the EuPRAXIA Laser-Plasma Accelerator pillar at ELI Beamlines.