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APPLICATIONS

ELI-Beamlines as the candidate for the EuPRAXIA "LPA-based FEL" site

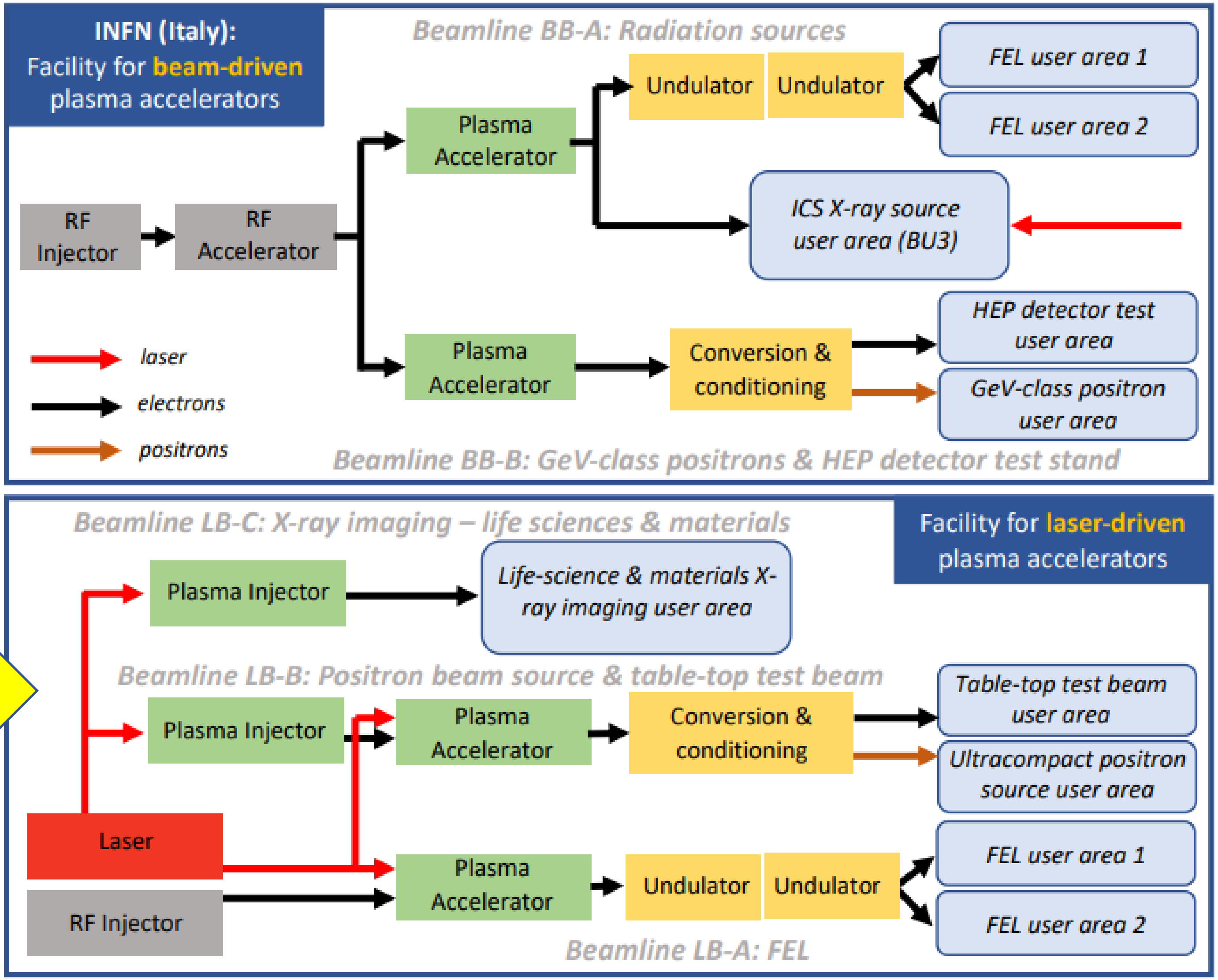
Alexander Molodozhentsev (ELI-Beamlines)

EAAC / Round table discussion / Elba, September 19, 2023

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

Phased Implementation of Construction Sites

	Laser-driven	Beam-driven
Phase 1	✓ FEL beamline to 1 GeV + user area 1 ✓ Ultracompact positron source beamline + positron user area	✓ FEL beamline to 1 GeV + user area 1 ✓ GeV-class positrons beamline + positron user area
Phase 2	✓ X-ray imaging beamline + user area ✓ Table-top test beams user area ✓ FEL user area 2 ✓ FEL to 5 GeV	✓ ICS source beamline + user area ✓ HEP detector tests user area ✓ FEL user area 2 ✓ FEL to 5 GeV
Phase 3	✓ High-field physics beamline / user area ✓ Other future developments	✓ Medical imaging beamline / user area ✓ Other future developments



Laser requirements:

high-repetition rate (20-100Hz) nx100TW laser system

Selection Criteria 2nd EuPRAXIA Site

(from CDR, fulfilled by 1st Site LNF/INFN)

Legal/Political	Technical	Financial
Compliance of host institution with **EuPRAXIA Access** Policy	Site provides sufficient **space** (about 175 m x 35 m)	Commitment to **sustainability** of EuPRAXIA (host lab covers site operation costs)
Compliance of host institution with **EuPRAXIA Open Innovation** and **Open Science** Policy	Laboratory has **infrastructures** in one or several of RF accelerators, laser installations, user access.	**Previous investments** into local infrastructures of relevance for EuPRAXIA (leverage effect)
Agreement of host institution with the **long-term scientific agenda** of EuPRAXIA	Site provides required **services** and facilities for support of external users, including E infrastructure	Existence of one or a mix of **funding sources** able to finance implementation of the site
Laboratory has existing groups in place to guarantee **safety** requirements (laser, radio-protection, access control) and rules		

Note: approach reduces cost (pre-invest) and risks of cost-overun.

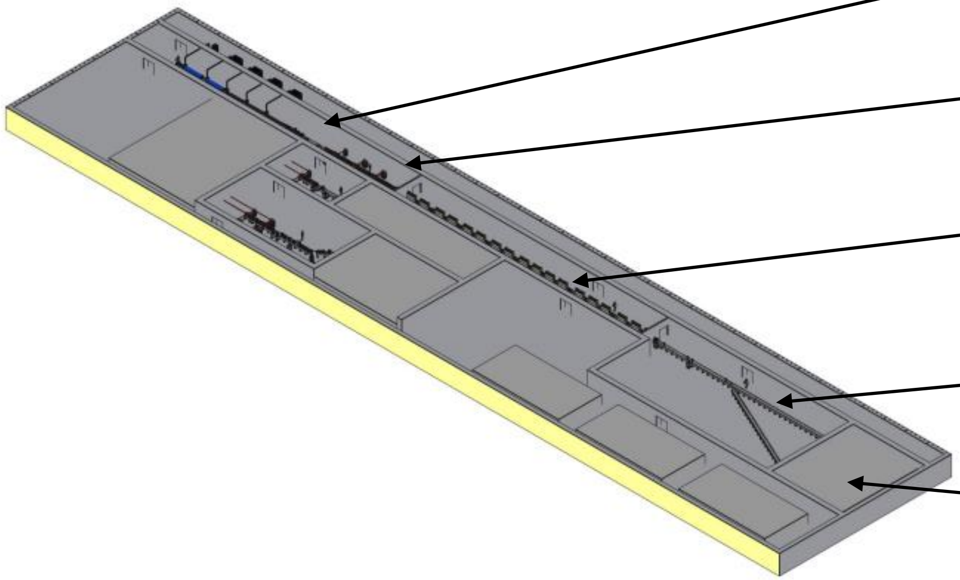
ELI-Beamlines status as a candidate

Main concept of the LPA-based FEL facility

32.9 CAD Model of the Conceptual EuPRAXIA Facility Layout 587

32.9 CAD Model of the Conceptual EuPRAXIA Facility Layout

Some example screenshots of the CAD model of the proposed EuPRAXIA facility layout are shown below. The current model is conceptual, but will form a basis for the detailed technical layout to be developed in the next phase of EuPRAXIA. The full CAD model is available upon request.



1 – compact LP-accelerator

2 – dedicated e- beam line

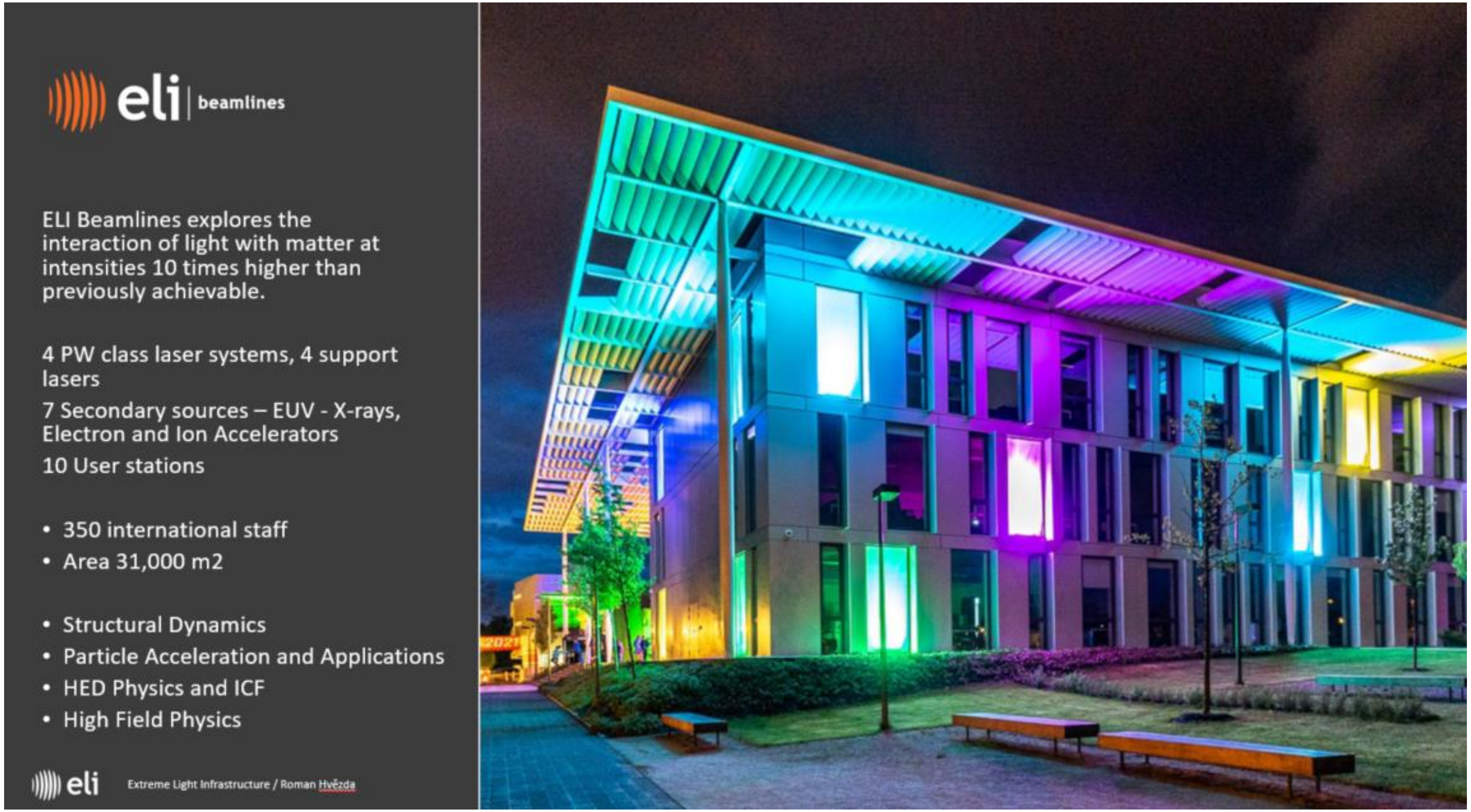
3 – undulator line

4 – photon beam transport

5 – user area (at least 3 stations with Pump @ Probe setup)

Figure 32.27: Screenshot of the CAD model of the proposed EuPRAXIA facility layout. Here, the laser-driven plasma acceleration construction site is shown in a perspective view.

ELI-Beamlines (ELI-ERIC)

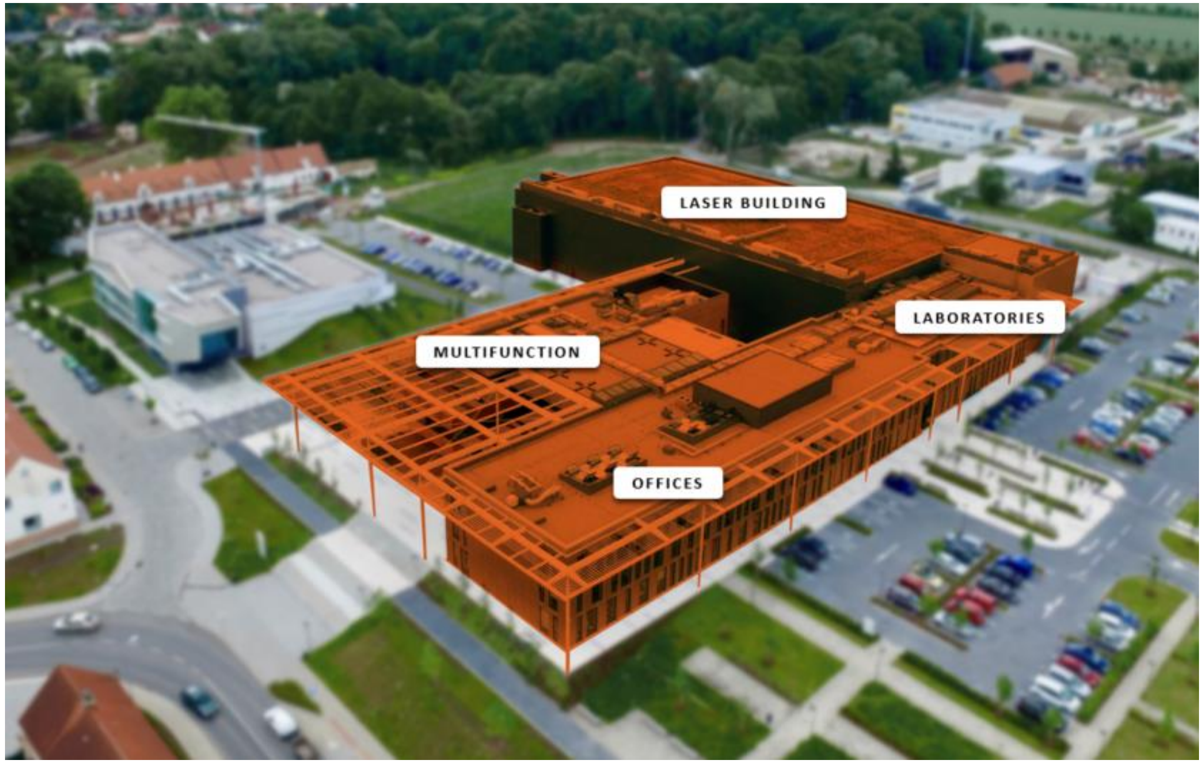


ELI-Beamlines is located in Dolni Brezany, near Prague
https://www.eli-beams.eu/

By car:
15 min from the Prague Airport

ELI-Beamlines (ELI-ERIC)

Funded by the European Union



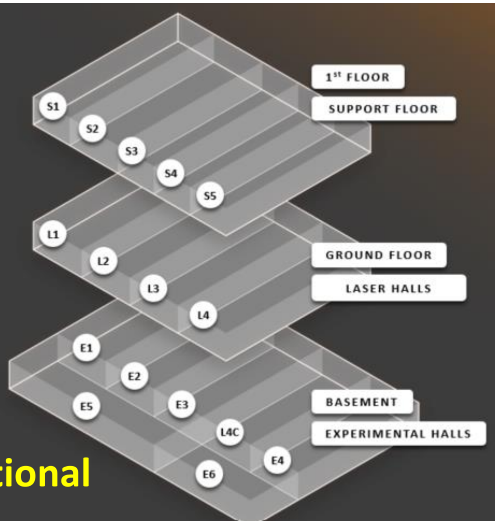
ELI-Beamlines facility (near Prague)

Laser building
18 000 m^2 Cleanrooms

Support Rooms
Includes a coating facility, vacuum testing lab, user labs, and cooling systems and capacitors for lasers.

Laser Halls
Comprises four large state-of-the-art laser systems.

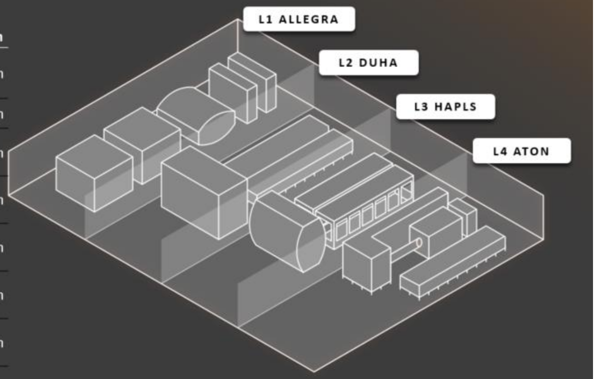
Experimental Halls
Consists of six experimental halls, along with a 10 PW compressor and a Pulse Distribution System.



Infrastructure is FULLY functional

Laser Floor

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

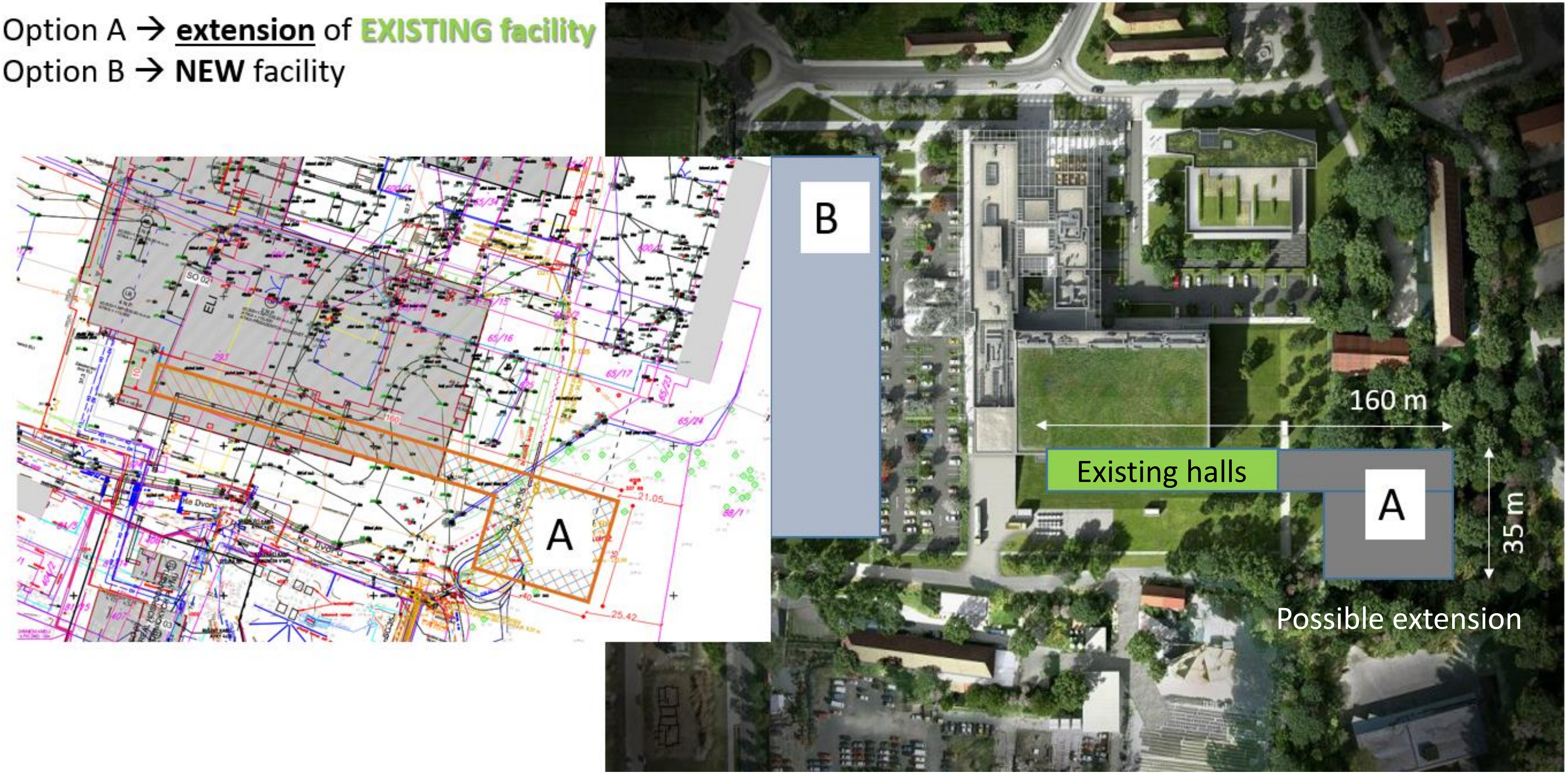


eli Extreme Light Infrastructure / Roman Hvězda

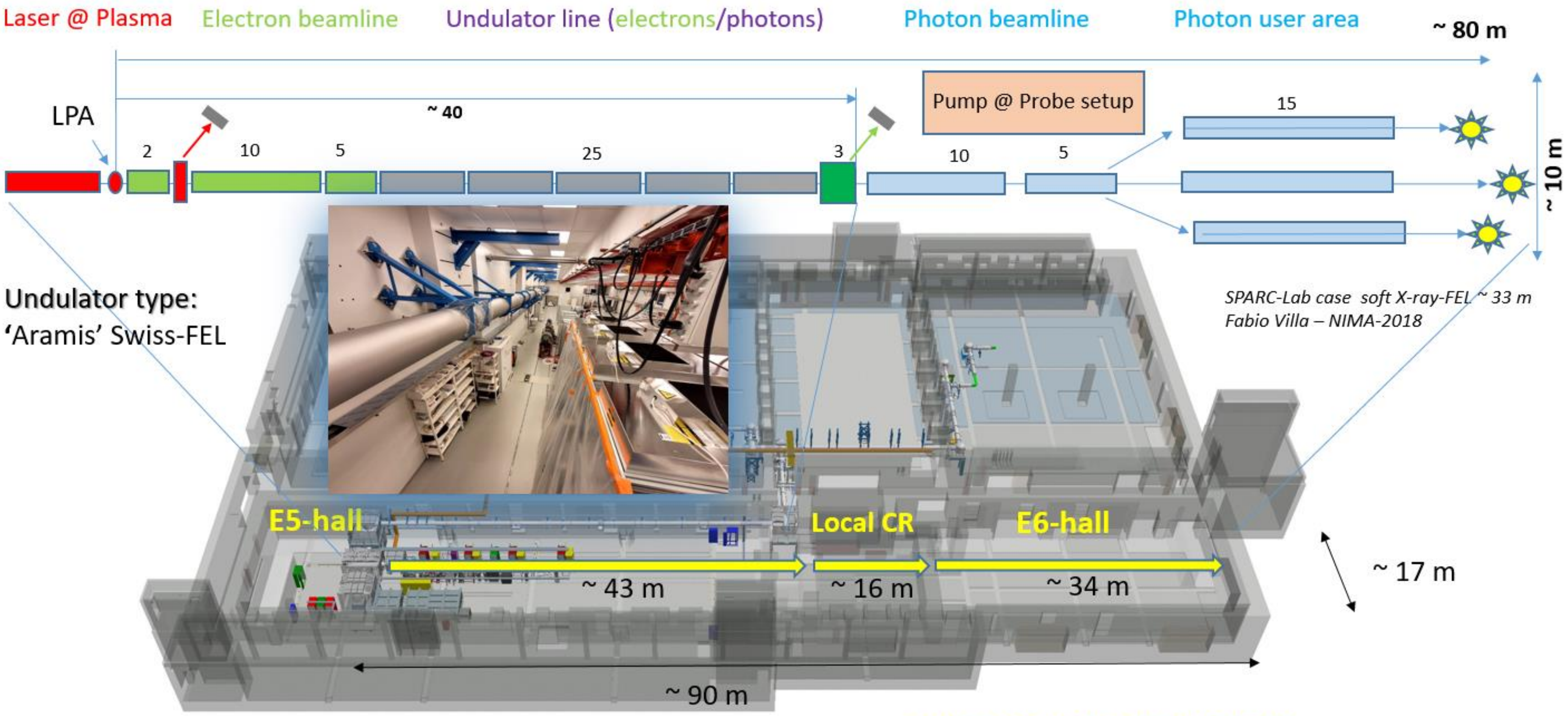
ELI-Beamlines: infrastructure (5 GeV case)

Funded by the European Union

Option A → **extension** of **EXISTING facility**
Option B → **NEW** facility



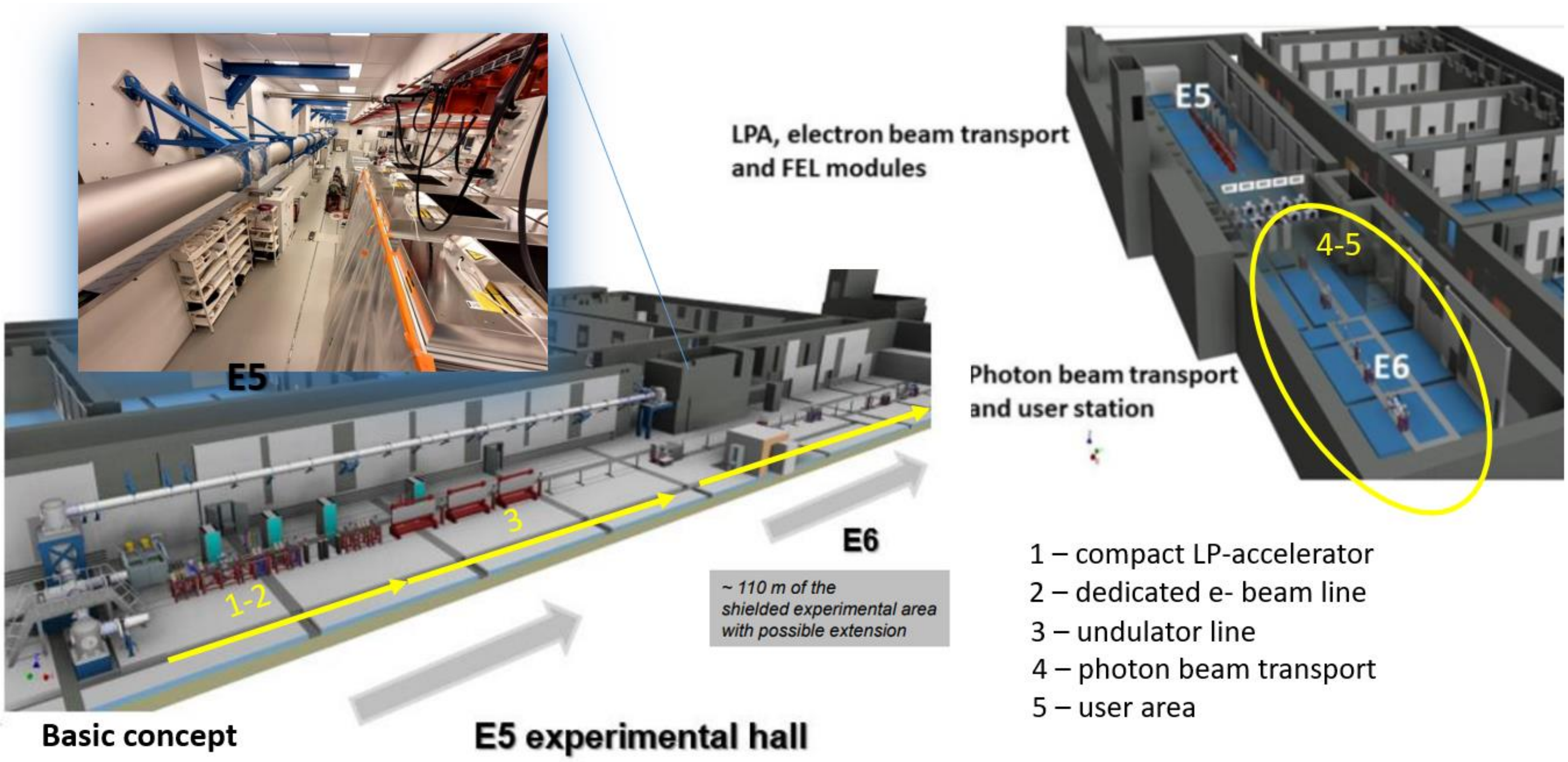
1-GeV LPA-based FEL at ELI-Beamlines



EXISTING INFRASTRUCTURE at ELI-Beamlines

1-GeV LPA-based FEL at ELI-Beamlines

Funded by the European Union



1 – compact LP-accelerator
2 – dedicated e- beam line
3 – undulator line
4 – photon beam transport
5 – user area

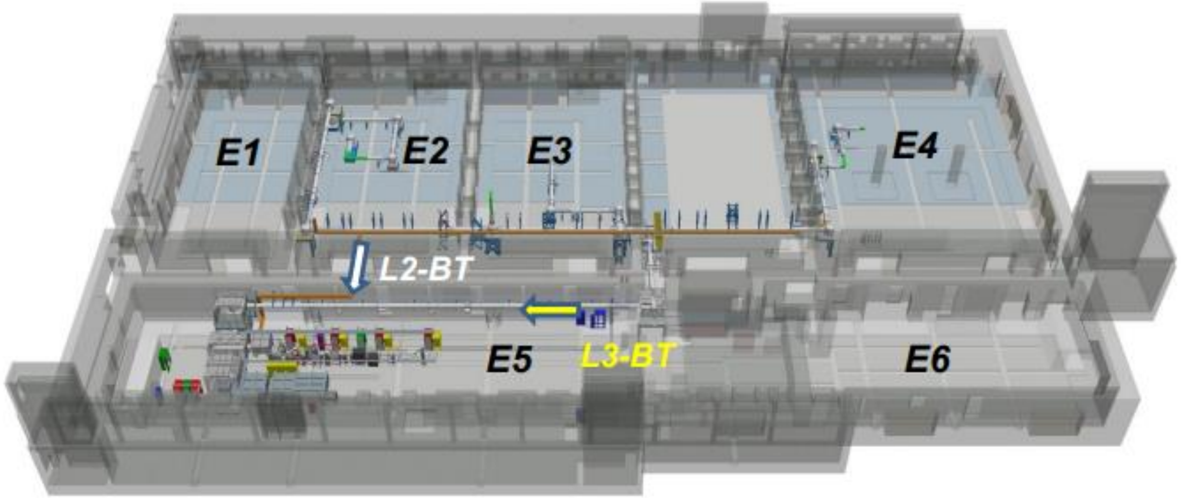
Laser development at ELI-Beamlines

Funded by the European Union

L3-laser beam transport (~ 90 m long) is fully in operation with an ability to be used in E3/E4/E5 halls
L2-laser beam transport to the E5-LUIS experimental area is under preparation (plan: 3Q-2024)

Lasers	Energy	Pulse	Rep Rate	STATUS
L2 “Amos”	3 → 5 J	< 30 fsec	10 → 25 (50) Hz	In progress
L3 “HAPLS”	30 J	30 fsec	3.3 →10 Hz	In progress 2019: 16 J / 3.3 Hz

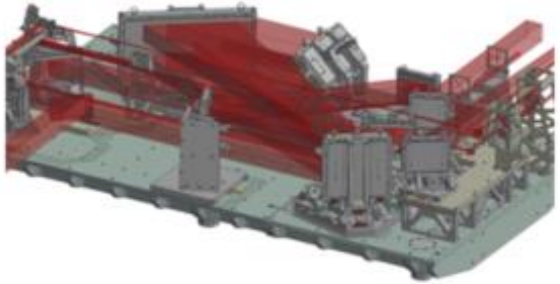
L3-to-E5 and L2-to-E5:
LUIS development (undulator radiation)
Electron Beam Acceleration platform



Laser development at ELI-Beamlines

Funded by the European Union

L2-DUHA laser system, dedicated to LUIS (in collaboration with STFC/UK)



- 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

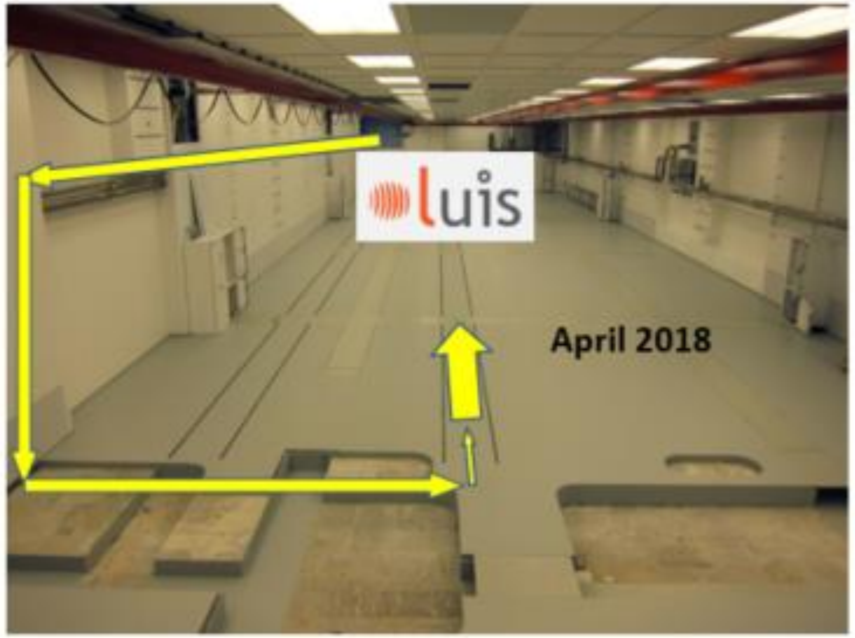
Credit: Bedrich Rus

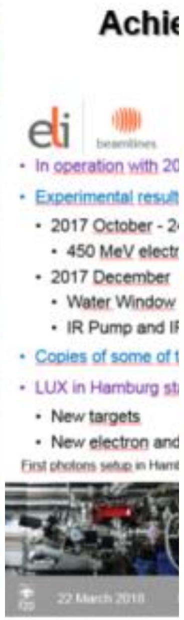
LUIS Project at ELI-Beamlines: main objectives

Funded by the European Union

LUIS at ELI-Beamlines → LWFA-based undulator incoherent/coherent photon radiation source
→ based on the LUX development at DESY (UHH/ELI-Beamlines)
→ based on a novel high-repetition rate high-power laser system (L2-DUHA)

E5-Hall at ELI-Beamlines



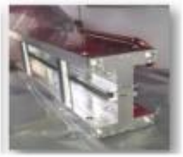


LUIS Project at ELI-Beamlines

LUIS: incoherent photon radiation for users

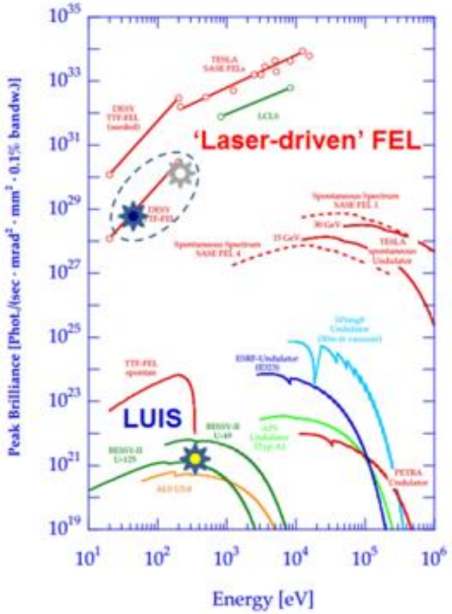
Phase1 with upgrade to Phase4
→ in collaboration with UHH_LUX team (Dr. A.Maier)

Electron beam ~ 400 ÷ 600 MeV
$\lambda_{ph,1}$ *~ 4.2 ÷ 1.7 nm, > 10^5 photons/pulse (1%bw)*
Peak brilliance > 10^{20} *ph/pulse/mm ^{2}/mrad ^{2}/ 0.1%BW*



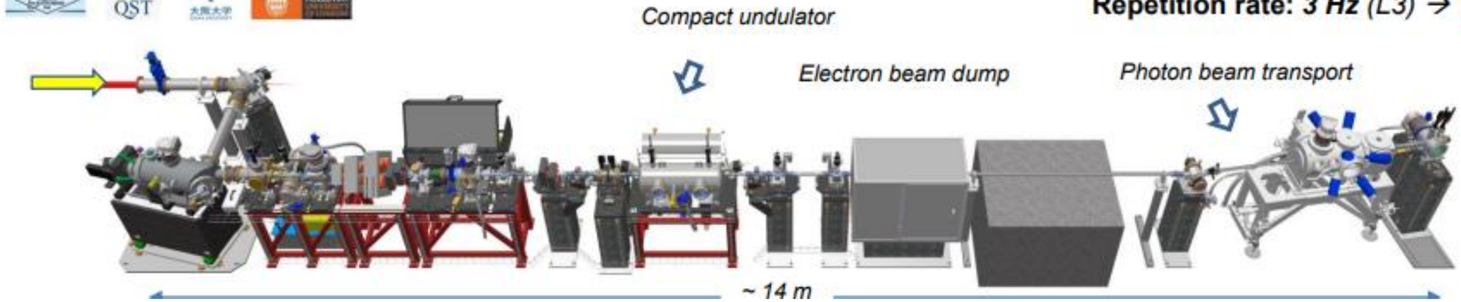
$K_0 = 0.28$
$L = 0.5$ m
$B_0 = 0.6T$

BEAST2 (UHH)			400 MeV	600 MeV
Fundamental (h=1) harmonic wavelength	λ_p	nm	4.23	1.88
Spread of the wavelength	$\delta\lambda_p$	%		1
Radiated on-axis photon energy of single electron (h=1)	E_{ph}	keV	0.293	0.658
Peak current (charge) (σ_z=1μm)	I_{peak}	kA (pC)		~ 2.63 (27.6)
RMS divergence of radiation (diffraction limited)	σ'_r	μrad	29.1	19.4
Effective RMS source radius (diffraction limited)	σ_r	μm	11.6	7.72
Photon flux per shot [ph/shot/mrad²/0.1%bw] *	Flux		2.95×10^{5}	6.63×10^{5}
Peak Brightness (10fs, 1Hz) * [photons/sec/mm²/mrad²/0.1%bw]	B		1.2×10^{20}	3.8×10^{20}
Normalized RMS electron beam emittance [π mm.mrad]	ϵ_n		1	1



Repetition rate: *3 Hz* *(L3)* → *25 Hz* *(L2)*

2022-2023: L3 laser
2024: L2 laser



LUIS Project at ELI-Beamlines

LUIS: incol

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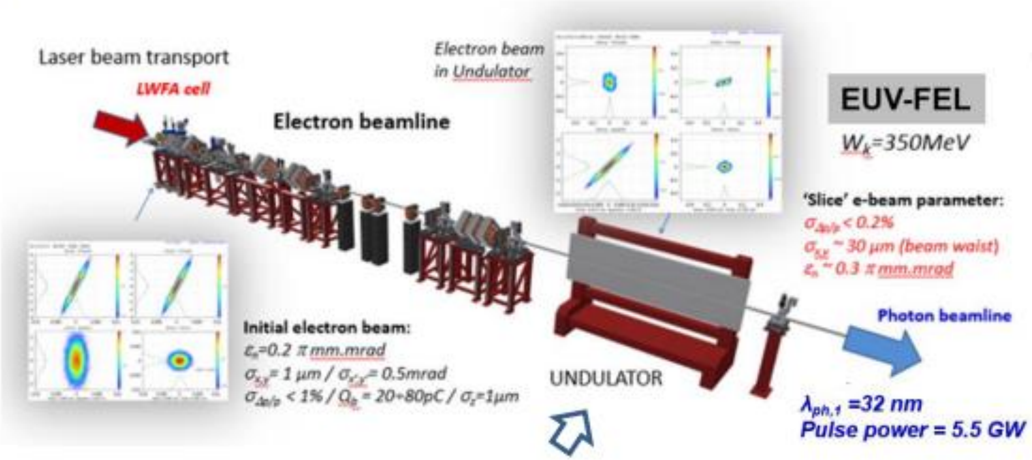
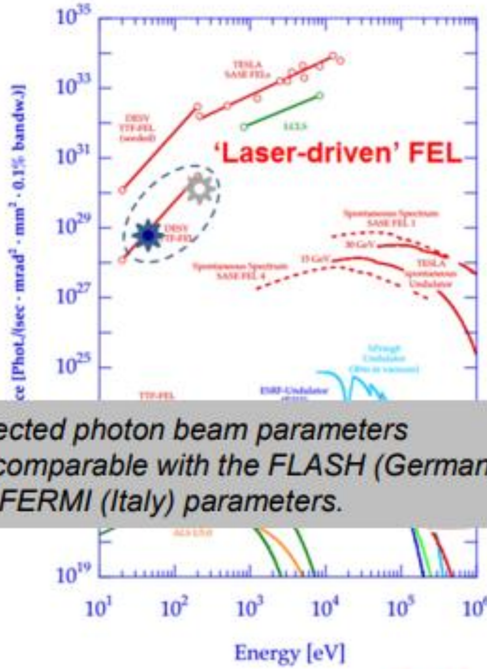
2022-2023: L3 laser
2024: L2 laser

LUIS: coherent photon radiation **from EUV** to hard X-ray

(1) Upgrade of the electron beam transport to get the electron beam parameters, suitable for EUV FEL (producing incoherent photon radiation for users)
W_e ~ 300 ÷ 600 MeV



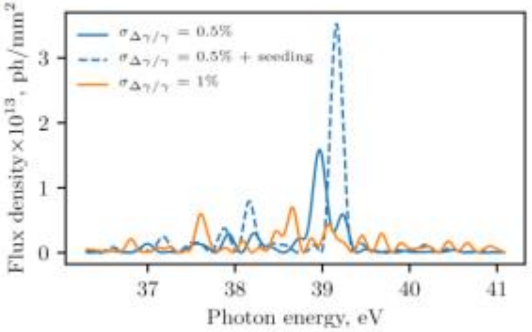


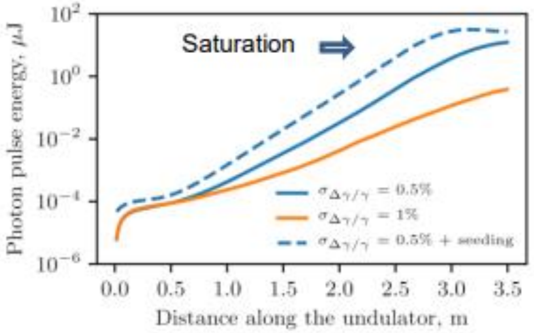
Expected photon beam parameters are comparable with the FLASH (Germany) and FERMI (Italy) parameters.

Repetition rate: *3 Hz* (L3) → *25 Hz* (L2)

(2) Replace compact undulator by a single-unit FEL undulator
W_e ~ 350 MeV

'In-vacuum' hybrid PM planar
→ **SwissFEL** type



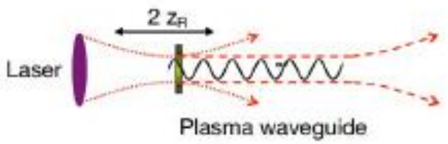


Plasma formation and diagnostics at ELI-Beamlines

Funded by the European Union

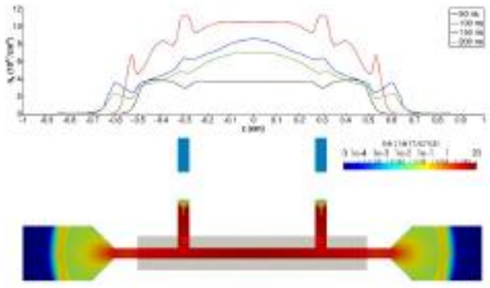
Test setup in LUIS-Lab: discharge in the Sapphire capillary

Plasma sources as waveguides

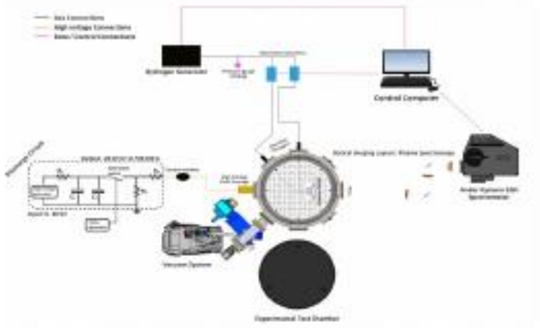


Advantages:

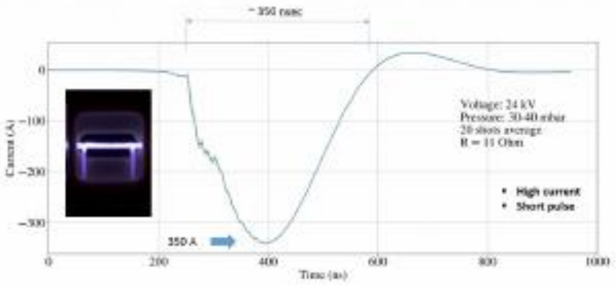
- overcome the diffraction limit
- increasing the LWFA acceleration length
- reduce required laser pulse energy
- use high repetition rate of the laser
- improve stability of LWFA using capillary
- active plasma lens with the magnetic field gradient ~ 400 T/m



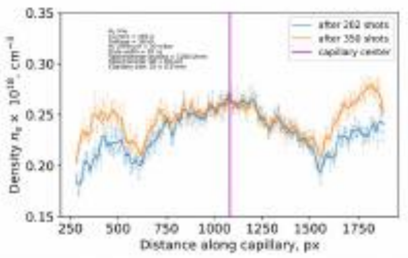
Modelling of the discharge plasma formation in the capillary (ELI-BL/KIAM collaboration)



Plasma diagnostics setup in the LUIS-Lab, using the emission spectroscopy



Plasma channel in the Sapphire capillary, created at ELI-Beamlines



Plasma density characterization along the channel (I = 200 A)

SUBMITTED in Journal

Laser-Plasma electron Accelerator at ELI-Beamlines

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

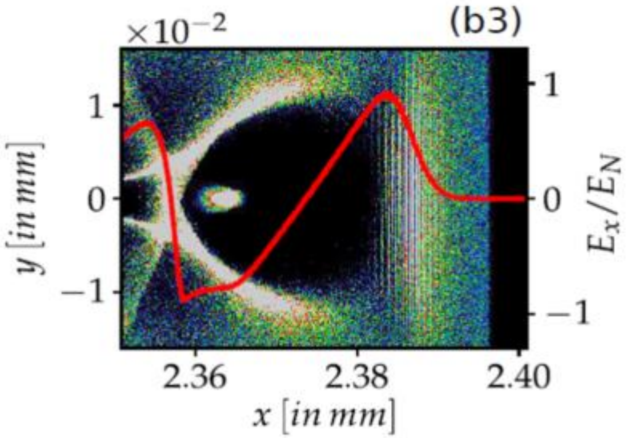
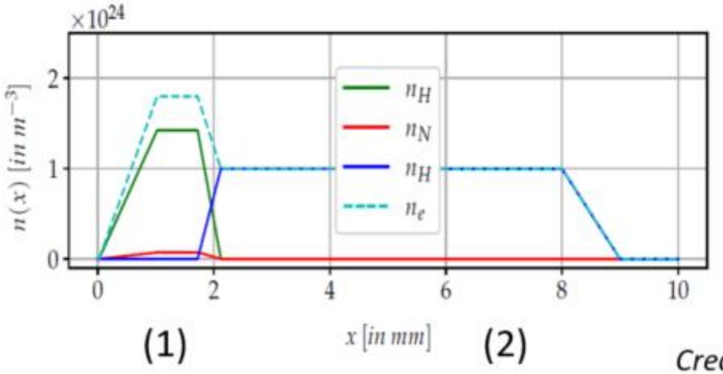
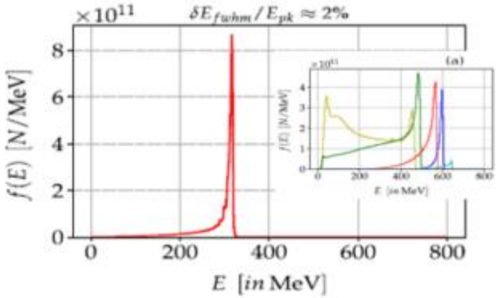


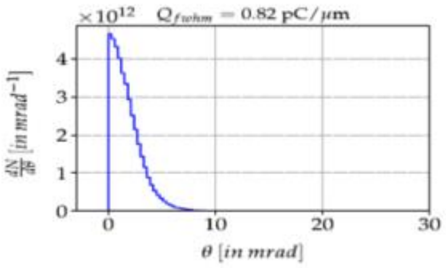
Table: Simulation Parameters ($I_0 = 1.0 \times 10^{19}$ W/cm^2; $P_L = 51$ TW)

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



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





Energy ~ 300 (up to 600) MeV
Spread (FWHM) ~ 2%
Divergence (FWHM) ~ 2 mrad
Bunch charge ~ 15 pC

Credit: S.Maity

SUBMITTED for publishing

1-GeV LPA-based FEL at ELI-Beamlines

Funded by the European Union

PRE-INVESTED BUDGET

... wo personal cost

ELI-beamlines building (offices, labs, halls)	Total: ~ 100 MEur
L2-LUIS technology	
L2-laser hall (including relevant technology)	~ 5 MEur
L2-DUHA laser	~ 5.5 MEur
L2-to-E5 laser beam transport	~ 1.5 MEur
E5 experimental hall @ Local Control Room (including vacuum, cooling, cabling, gases, compressed air, CS, MSI, PSS, Radiation-MS)	~ 10 MEur
E5 LUIS technology	~ 2.5 MEur
(L2-Hall) + (E5-Hall) + (L2-Laser) + (L2-BT) + LUIS	**~ 25 MEur**

L2-hall and DUHA-Laser

E5-hall and LUIS

Funded by the European Union

PRE-INVESTMENT in strong teaming

- ✓ "Large Project" Team to lead **BIG Projects**
- ✓ **Motivated team**
- ✓ **Connection with European Universities and Research Centers**
- ✓ **Strong connection with Industrial partners**

1-GeV LPA-based FEL at ELI-Beamlines

Funded by the European Union

REQUIRED EXTRA Investment and Time

Building	Budget estimation	Time Schedule
E5+E6	~ 2 MEur	~ 2 years
Control Room, Engineering, Safety (E5+E6)	~ 4 MEur	~ 2.5 years
Laser-L2 (upgrade to 100 Hz)	~ 2 MEur	~ 1.5 year (L2-hall)
E-beam line	~ 2 MEur	~ 2 years (location: E5)
Undulator line	~ 20 MEur (HPMU)	~ + 2.5 years (location: E5)
Photon beam lines → 3 user end-stations	~ 6 MEur	~ + 2 years (location: E6)
TOTAL Investment	**~ 36 MEur**	**Commissioning in 4-5 years ***

** from beginning of financing*

Required extra **NON-Investment** (personal and operational cost)

○ **Operation** (electricity incl. laser + maintenance and materials)	~ 1.5 MEur/year and 2 MEur/year → 3.5 MEur/year
○ **Personal** (50 FTE including support teams)	~ 3 MEur / year
TOTAL NON-Investment	**~ 6 – 7 MEur/year**

ELI-Beamlines: infrastructure (5 GeV case)

Funded by the European Union

Option-A (very rough estimation)

Extension of E6 hall → extra 60 meters length

→ **Budget estimation for E6 extension**

permission @ TDR ~ 10% (NON-invest) of total budget → 1.5 year

underground work ~ **11 MEur** (Invest) → 2 years

→ **Finalization of extended infrastructure (shielding, engineering) ~ 20 MEur**

→ **Budget for other key components → TBD**

ELI-Beamlines as EuPRAXIA Excellence Centre

Funded by the European Union

Science Goals

Goal	Eupraxia Flagship Science Goals	ELI Beamlines Excellence Centre Contribution
G1	Free-electron laser (FEL) X-rays with 10^9-10^{13} photons per pulse (0.2 nm to 36 nm)	LPA-based undulator radiation soft X-ray source
G2	Betatron X-rays (10^{10} photons/pulse, rep.rate up to 100 Hz, energy 5-18 keV) for the medical research	Operation of Betatron X-ray source
G4	Electron and positron beams from a few 100 MeV up to 5 GeV for High-Energy-Physics-related R&D	High-energy LPA-based electron beams (up to 10 GeV)
G5	Photons from an inverse Compton scattering (600MeV photons)	Development of Gammatron beamline based on ICS in E2 experimental hall
G7	Access to cutting-edge laser technology with short pulse length in combination with high-energy photon pulses and short electron/positron bunches.	Multi-discipline user-oriented Facility Expertise in pump-probe scheme on high rep rated applications as well as high energy sources

eli *Extreme Light Infrastructure / Roman Hvězda*

- Operate cutting edge, high-power femtosecond laser systems
- Explore interaction of light with matter (plasma) at ultrahigh laser intensities
- Offer secondary sources (X-rays and accelerated particles: electron and proton beams) with unique capabilities to users
- Enable pioneering research in plasma physics, nuclear fusion, laboratory astrophysics, material science, biology, chemistry, medicine with strong multidisciplinary application potential

ELI Beamlines as EuPRAXIA Excellence Centre

Incubator for the Application of Novel Accelerator Technology to Laser Science Users

ELI-Beamlines as the candidate for the EuPRAXIA “LPA-based FEL” site

How we are planning to reach the EuPRAXIA goal at ELI-Beamlines:

in COLLABORATION with the EuPRAXIA community

→ EuPRAXIA workshop at ELI-Beamlines (October 2, 2023)

THANK YOU FOR YOUR ATTENTION