PLASMA
ACCELERATOR SYSTEMS FOR
COMPACT
RESEARCH
INFRASTRUCTURES

PACRI

The road towards the EuPRAXA@ELI-ERIC Technical Design Report

Alexander Molodozhentsev

ELI ERIC / ELI Beamlines

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the European Union

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PACRI Annual Meeting
March 24, 2026

CONTENT

- ELI ERIC / ELI Beamlines
- Main Objectives for ELI @ EuPRAXIA
- Phasing of ELI @ EuPRAXIA Project at ELI Beamlines
- From Physics to TDR: LPA-Driven Roadmap and Timeline
- Current Status: where we are now

ELI ERIC

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Extreme Light Infrastructure

eli | beamlines

- Secondary sources – beamlines of high energy photons, electrons, protons, neutrons, muons
- Medical imaging and diagnostics, radiotherapy
- New materials
- X-ray optics
- Plasma Physics, HED and High-field Physics
- Fusion

eli | attophysics

- Ultrafast physical processes
- Chemical, medical and materials science analysis
- Attosecond measurement techniques
- Biological imaging technologies
- Artificial photosynthesis
- Nanoscience

eli

ELI ERIC / ELI Beamlines

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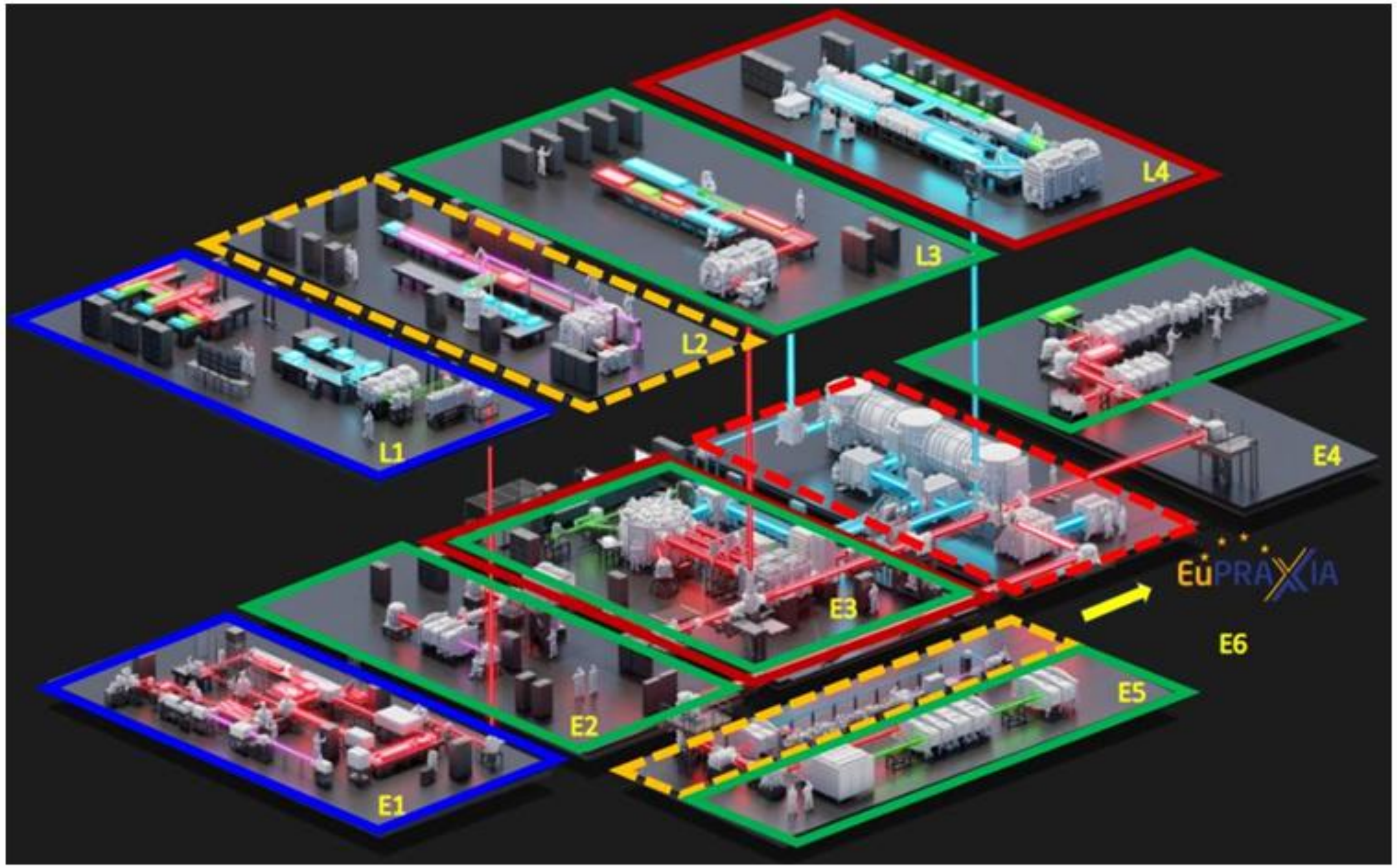
L1 (40mJ) 100mJ / 1kHz
L2 (3J) 5J / 20-100Hz
L3 (15J) 30J / (3.3Hz) 10Hz
L4 1.5kJ / 10PW

- 🟦 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 10PW (Call8)
- 🟨 🟨 🟨 L2-LUIS (R&D)

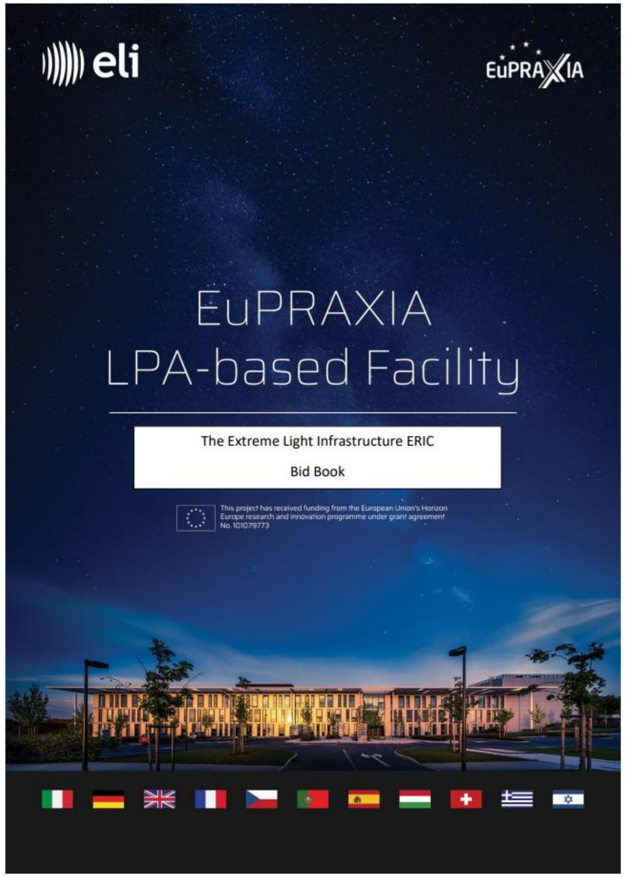


E1/L1: Material & Bio-molecular app.
E1/L1: ALFA-kHz low-energy electron beam
E2/L3: X-ray sources (Betatron)
E3/L3+L4: Plasma Physics
E4/L3: ELIMED-Proton Acceleration
E5/L3: ELBA-Electron Acceleration
E5/L2: LPA-based FEL-oriented (LUIS)

ELI ERIC / ELI Beamlines

EuPRAXIA LPA-based pillar (2nd site) at ELI Beamline (March 25, 2025)

- ✓ ELI Beamlines is one of the leading European research facilities in laser-plasma technology.
- ✓ **Through collaborating with the EuPRAXIA Consortium partners**, ELI Beamlines is positioned to build the Laser-Plasma-Accelerator-based EuPRAXIA pillar, aiming to deliver the electron beam for different practical applications.



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EuPRAXIA

EuPRAXIA
LPA-based Facility

The Extreme Light Infrastructure ERIC

Bid Book

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

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Main Objectives for ELI @ EuPRAXIA

- Laser-Plasma-Accelerator-based **Compact Free Electron Laser**
  - **PHASE1:** 1 GeV electron beam energy → "Soft" X-ray photon beam ⇨ **L2-laser / 5 J @ 100 Hz**
  - **PHASE2:** 5 GeV electron beam energy → "Hard" X-ray photon beam ⇨ **NOVEL-laser / 20 J @ 100 Hz**
- Laser-Plasma-Accelerator-based **Betatron Radiation Source** ⇨ **L3-laser / 30 J @ 10 Hz**
- Laser-Plasma-Accelerator-based **Low Energy Position Source** ⇨ **L1-laser / 100 mJ @ 1 kHz**

The development of PHASE1 at ELI Beamlines is based on ELI Beamlines' **existing infrastructure**.

ELI Beamlines: Phasing

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Preparatory Phase

TDR preparation

R&D → Experimental verification

Prototyping → Low Energy LPA-based compact FEL

Implementation Phase

L2-laser for LPA-based FEL is under development → with the PACRI partners

L3-based Betatron Source → Setup is OPEN for USERS / **USER Call**

L1-based low-energy electron beam (1 kHz) → USER Call

Infrastructure preparation → integration of existing experimental halls (E5 and E6)

Parallel development

LPA-based FEL: 1 GeV case

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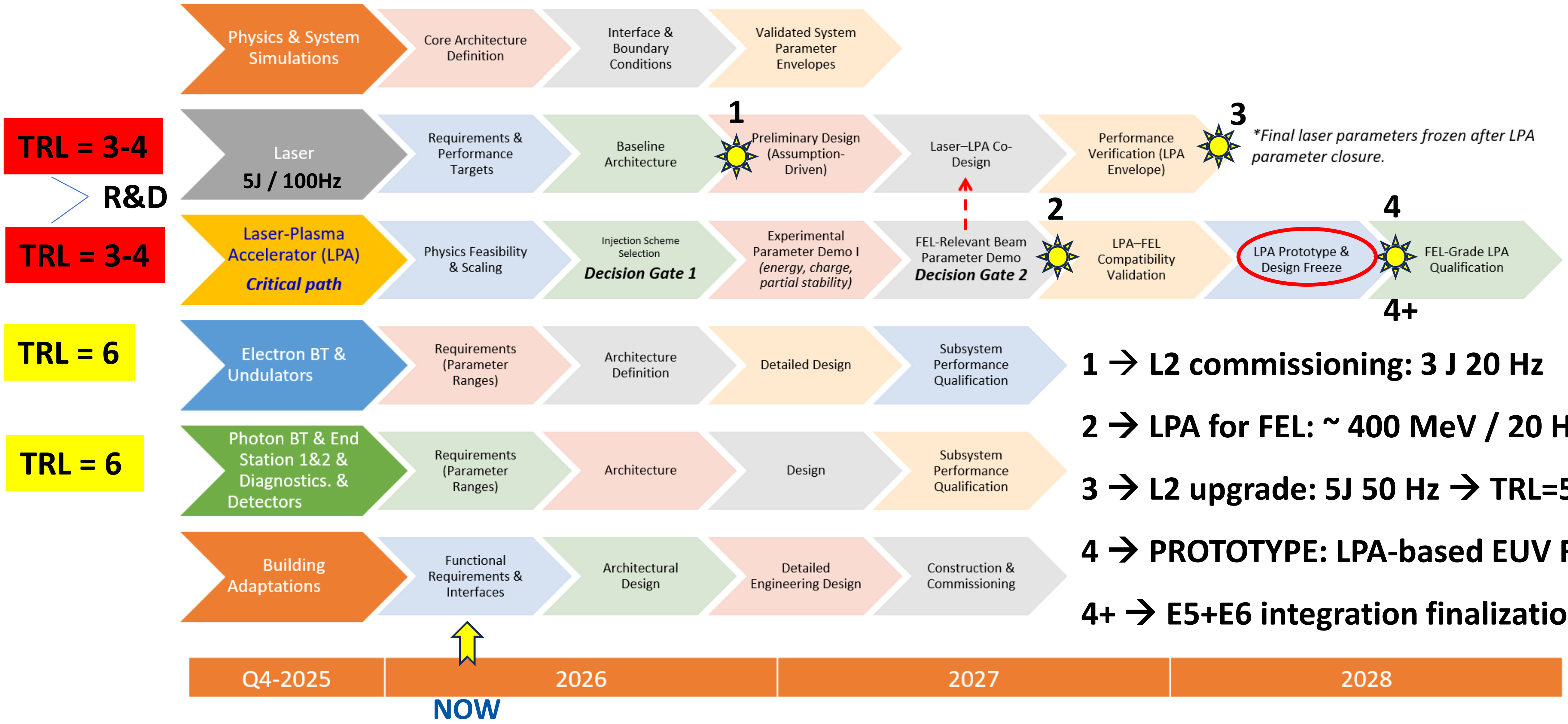
eli

From Physics to TDR: LPA-Driven Roadmap



Physics & System Simulations
- Core Architecture Definition
- Interface & Boundary Conditions
- Validated System Parameter Envelopes

TRL = 3-4

R&D

Laser 5J / 100Hz
- Requirements & Performance Targets
- Baseline Architecture
- 1 Preliminary Design (Assumption-Driven)
- Laser–LPA Co-Design
- Performance Verification (LPA Envelope)
- 3

**Final laser parameters frozen after LPA parameter closure.*

TRL = 3-4

Laser-Plasma Accelerator (LPA) ***Critical path***
- Physics Feasibility & Scaling
- Injection Scheme Selection ***Decision Gate 1***
- Experimental Parameter Demo I *(energy, charge, partial stability)*
- FEL-Relevant Beam Parameter Demo ***Decision Gate 2***
- 2 LPA–FEL Compatibility Validation
- LPA Prototype & Design Freeze
- 4 FEL-Grade LPA Qualification 4+

TRL = 6

Electron BT & Undulators
- Requirements (Parameter Ranges)
- Architecture Definition
- Detailed Design
- Subsystem Performance Qualification

TRL = 6

Photon BT & End Station 1&2 & Diagnostics. & Detectors
- Requirements (Parameter Ranges)
- Architecture
- Design
- Subsystem Performance Qualification

Building Adaptations
- Functional Requirements & Interfaces
- Architectural Design
- Detailed Engineering Design
- Construction & Commissioning

Q4-2025 | 2026 | 2027 | 2028

NOW

1 → L2 commissioning: 3 J 20 Hz

2 → LPA for FEL: ~ 400 MeV / 20 Hz → TRL=5-6

3 → L2 upgrade: 5J 50 Hz → TRL=5-6

4 → PROTOTYPE: LPA-based EUV FEL → TRL=5-6

4+ → E5+E6 integration finalization

Current Status: LPA-based FEL

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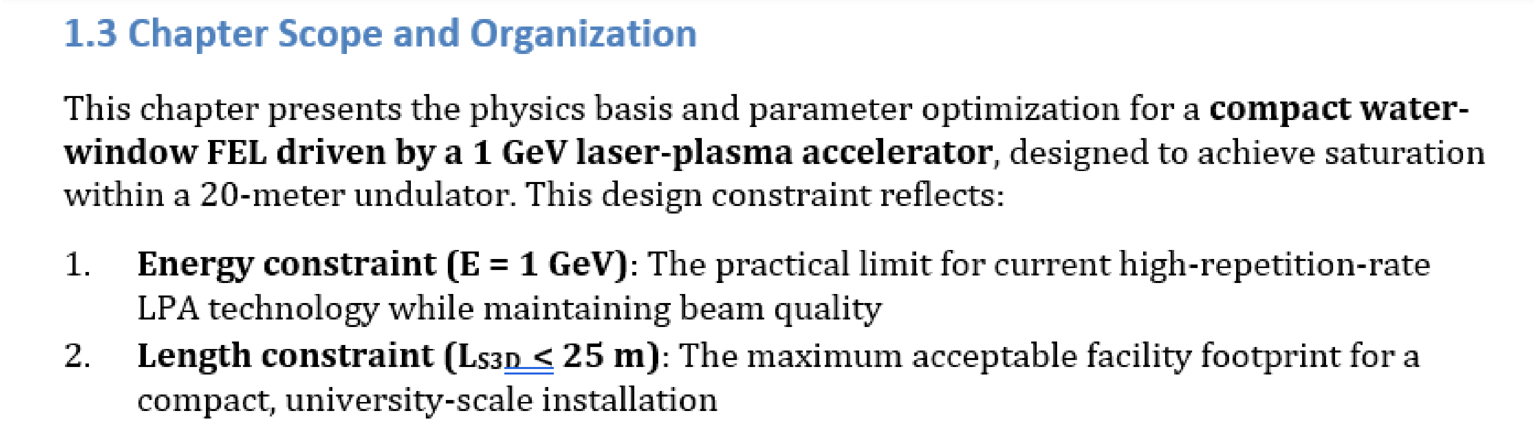
Physics and System Simulations

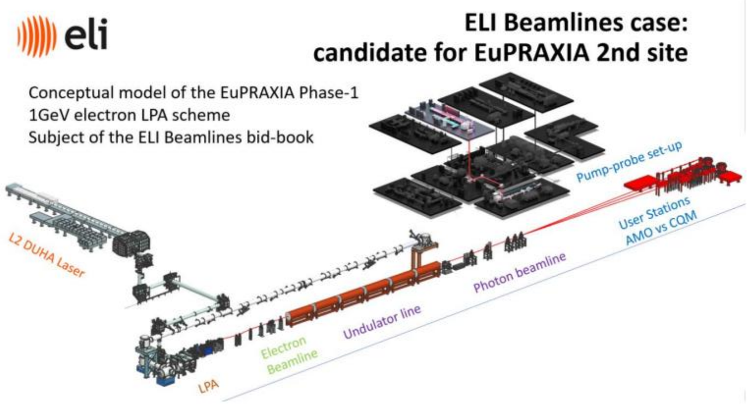
TDR-Chapter: FEL Physics and Choice of Main Parameter → Drafted



1.3 Chapter Scope and Organization

This chapter presents the physics basis and parameter optimization for a **compact water-window FEL driven by a 1 GeV laser-plasma accelerator**, designed to achieve saturation within a 20-meter undulator. This design constraint reflects:

1. **Energy constraint (E = 1 GeV)**: The practical limit for current high-repetition-rate LPA technology while maintaining beam quality
2. **Length constraint ($L_{S3D} \leq 25$ m)**: The maximum acceptable facility footprint for a compact, university-scale installation



ELI Beamlines case: candidate for EuPRAXIA 2nd site

Conceptual model of the EuPRAXIA Phase-1
1GeV electron LPA scheme
Subject of the ELI Beamlines bid-book

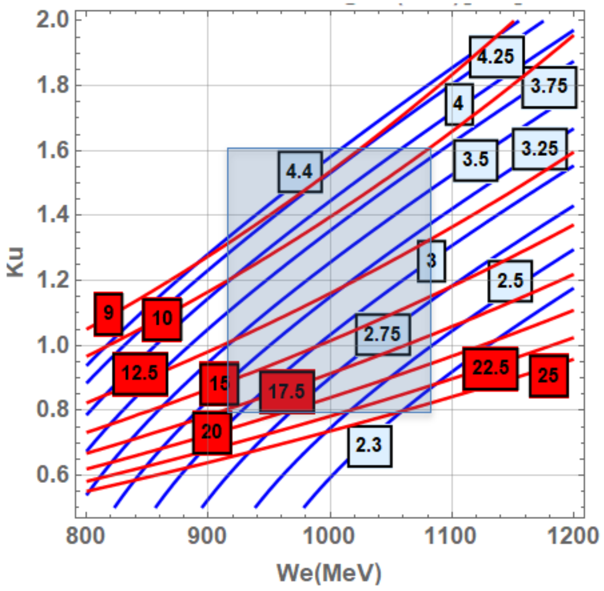


Figure 1: Dependence of the photon radiation wavelength (fundamental harmonic) (blue line, in nm) and the estimated 3D saturation length (red line, in m) on the electron beam energy (W_e) and the undulator parameter (K_u). The highlighted area indicates the K_u-W_e area, covering the entire "water window" of photon radiation (2.3-4.4 nm), using the LPA-based FEL setup with a maximum undulator length of less than 25 m. The peak current is 2.5 kA. The normalized rms transverse emittance in both plans is 0.4 mm.mrad. The relative energy spread is 0.2%.

Current Status: LPA-based FEL

Funded by
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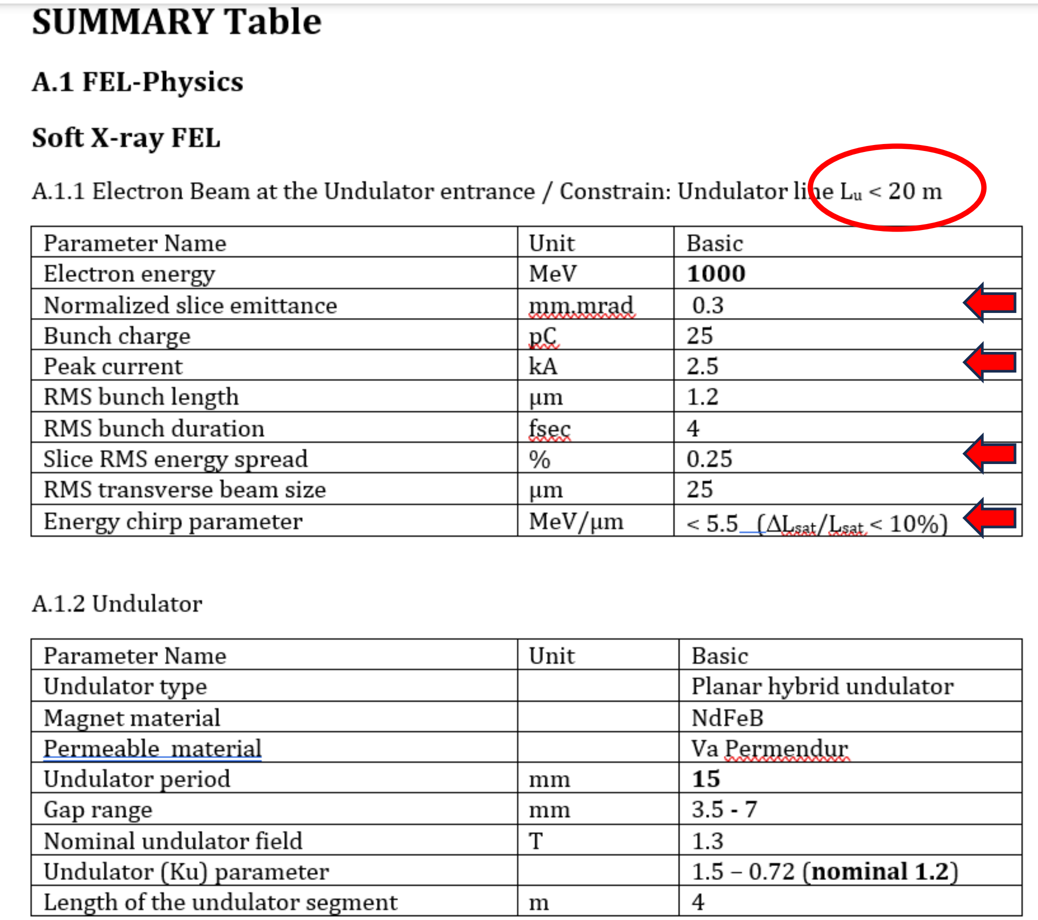
Physics and System Simulations

TDR-Chapter: FEL Physics and Choice of Main Parameter → Drafted



SUMMARY Table

A.1 FEL-Physics

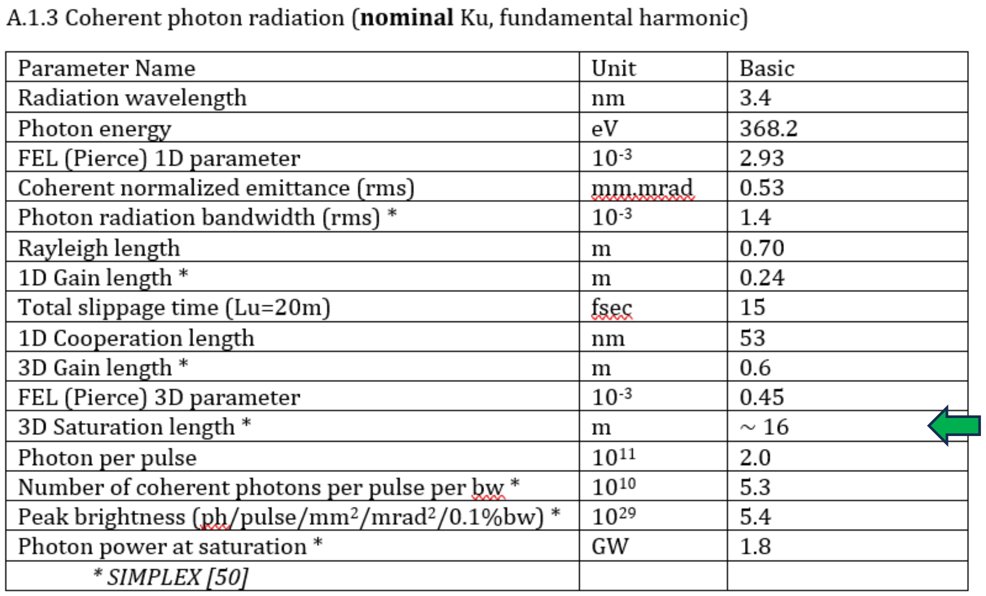
Soft X-ray FEL

A.1.1 Electron Beam at the Undulator entrance / Constrain: Undulator line $L_u < 20$ m

Parameter Name	Unit	Basic
Electron energy	MeV	**1000**
Normalized slice emittance	mm.mrad	0.3
Bunch charge	pC	25
Peak current	kA	2.5
RMS bunch length	μm	1.2
RMS bunch duration	fsec	4
Slice RMS energy spread	%	0.25
RMS transverse beam size	μm	25
Energy chirp parameter	MeV/μm	< 5.5 ($\Delta L_{sat}/L_{sat} < 10\%$)

A.1.2 Undulator

Parameter Name	Unit	Basic
Undulator type		Planar hybrid undulator
Magnet material		NdFeB
Permeable material		Va Permendur
Undulator period	mm	**15**
Gap range	mm	3.5 - 7
Nominal undulator field	T	1.3
Undulator (Ku) parameter		1.5 – 0.72 (**nominal 1.2**)
Length of the undulator segment	m	4



A.1.3 Coherent photon radiation (**nominal** Ku, fundamental harmonic)

Parameter Name	Unit	Basic
Radiation wavelength	nm	3.4
Photon energy	eV	368.2
FEL (Pierce) 1D parameter	10^{-3}	2.93
Coherent normalized emittance (rms)	mm.mrad	0.53
Photon radiation bandwidth (rms) *	10^{-3}	1.4
Rayleigh length	m	0.70
1D Gain length *	m	0.24
Total slippage time (Lu=20m)	fsec	15
1D Cooperation length	nm	53
3D Gain length *	m	0.6
FEL (Pierce) 3D parameter	10^{-3}	0.45
3D Saturation length *	m	~ 16
Photon per pulse	10^{11}	2.0
Number of coherent photons per pulse per bw *	10^{10}	5.3
Peak brightness (ph/pulse/mm²/mrad²/0.1%bw) *	10^{29}	5.4
Photon power at saturation *	GW	1.8
** SIMPLEX [50]*		

Tolerance analysis is needed:

Beam "shot-to-shot" stability
Beam pointing stability / Laser Jitter effects

Current Status: LPA-based FEL

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Physics and System Simulations

S2E modelling: LPA PIC

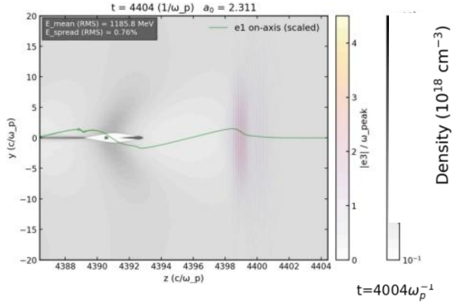
LPA-based FEL: “shock injection”

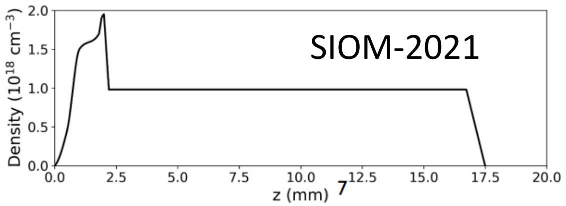
Experimental verification was performed

SIOM-2021-2025, Osaka-2024-2025

TRL = 4

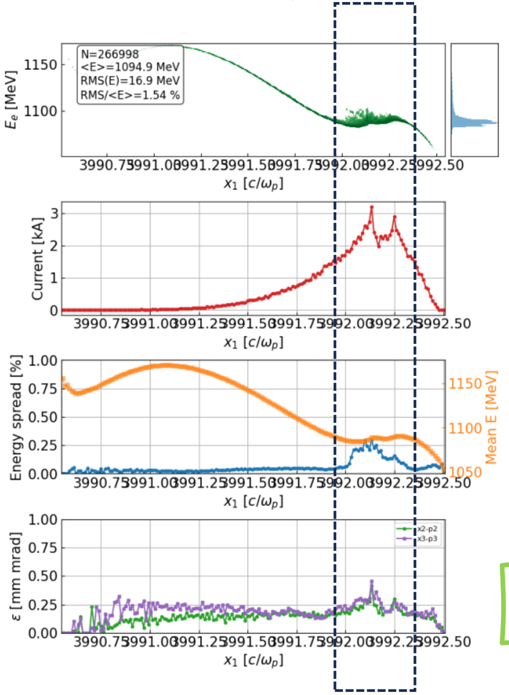
W_e = 1000 MeV
I_p ~ 2.5 kA
$\varepsilon_n < 0.5\ \mu m$
$\sigma_{\Delta\gamma/\gamma} < 0.5\ \%$





1000 MeV (IST)

Xuezhi Wu, J.Vieira (IST)



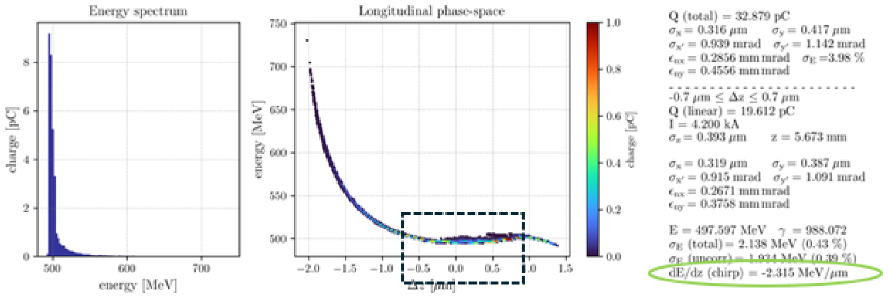
Energy chirp
- minimized

2 - 3 kA

< 0.25 %

< 0.25 - 0.4 μm

500 MeV (ELI Beamlines)

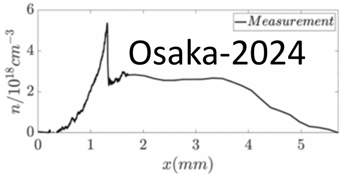


Q (total) = 32.879 pC
σ_x = 0.316 μm σ_y = 0.417 μm
$\sigma_{x'}$ = 0.939 mrad $\sigma_{y'}$ = 1.142 mrad
ϵ_{nx} = 0.2856 mm mrad σ_E =3.98 %
ϵ_{ny} = 0.4556 mm mrad

-0.7 μm ≤ Δz ≤ 0.7 μm
Q (linear) = 19.612 pC
I = 4.200 kA
σ_z = 0.393 μm z = 5.673 mm

σ_x = 0.319 μm σ_y = 0.387 μm
$\sigma_{x'}$ = 0.915 mrad $\sigma_{y'}$ = 1.091 mrad
ϵ_{nx} = 0.2671 mm mrad
ϵ_{ny} = 0.3758 mm mrad

E = 497.597 MeV γ = 988.072
σ_E (total) = 2.138 MeV (0.43 %)
σ_E (uncorr) = 1.934 MeV (0.39 %)
dE/dz (chirp) = -2.315 MeV/μm



Total charge – OK
Peak current – OK
“Slice” energy spread – OK
“Slice” rms norm. emittance -- OK

Detailed information → Jorge Vieira

Martin Matys, Mihail Miceski (ELI Beamlines)
Francesco Massimo (University of Sacley)

LPA-PIC Collaboration (IST, ELI, CNRS, Sacley, CEA, SCAPA)

Current Status: LPA-based FEL

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Physics and System Simulations

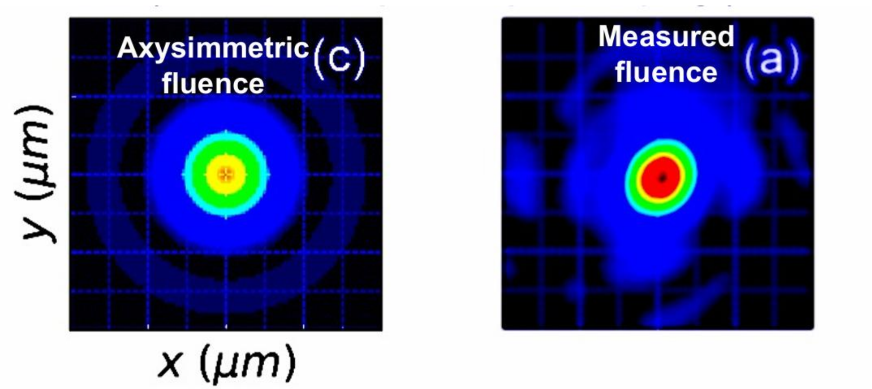
S2E modelling: LPA PIC

Plasma density tapering at the EXIT of the plasma unit

Minimize the transverse divergence of the electrons
Control the transverse emittance

PIC modelling in the case of the realistic laser beam profile

I. Moulanier et al., JOSA B 2023



- easier to simulate
- quantitatively less accurate

- more difficult to simulate
- quantitatively accurate

In progress

LPA-PIC Collaboration (IST, ELI, CNRS, Sacley, CEA, SCAPA)

Current Status: LPA-based FEL

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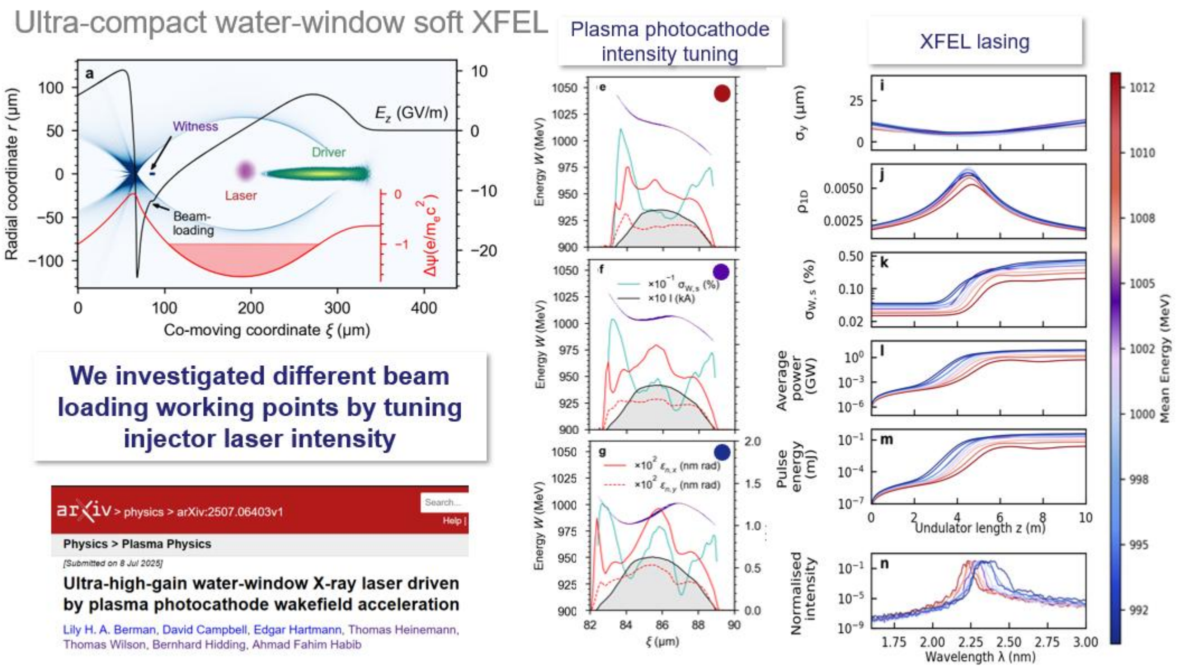
Physics and System Simulations

S2E modelling: LPA PIC

Hybrid scheme



We investigated different beam loading working points by tuning injector laser intensity

arXiv > physics > arXiv:2507.06403v1

Physics > Plasma Physics

[Submitted on 8 Jul 2025]

Ultra-high-gain water-window X-ray laser driven by plasma photocathode wakefield acceleration

Lily H. A. Berman, David Campbell, Edgar Hartmann, Thomas Heinemann, Thomas Wilson, Bernhard Hidding, Ahmad Fahim Habib

Alterative approaches

ReMPI scheme
Experimental campaign (November 2026, ELI NP)

HIGH QUALITY ELECTRON BUNCHES FOR A … PHYS. REV. ACCEL. BEAMS **22**, 111302 (2019)

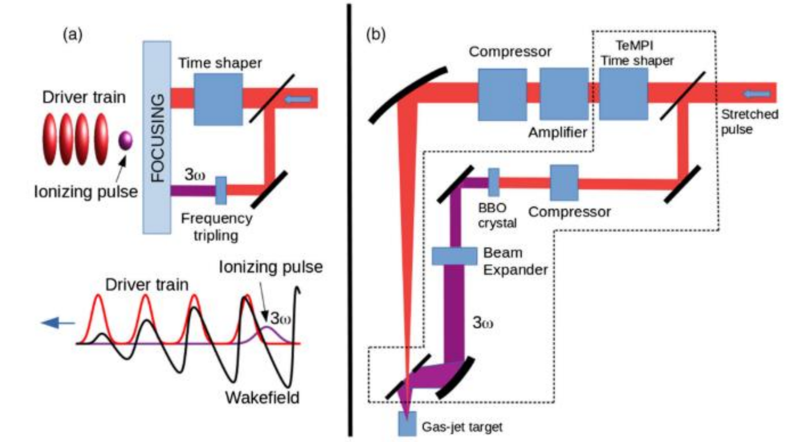


FIG. 1. The ReMPI setup. (a) Conceptual scheme: the incoming pulse passes through a beam-splitter; a portion (top line) is time shaped as a train of pulses, while a smaller portion is frequency tripled and tightly focused in the rear of the train. The driver train (four pulses, red line) resonantly excites an high-amplitude plasma wave (black line) and the ionizing pulse (perpendicular polarization, purple) is approximately placed in the node of the wakefield. (b) Experimental setup: the stretched pulse passes through a beam-splitter. The most energetic portion is time shaped through the passage into a TeMPI time-splitter (see text), further amplified and re-compressed by the grating compressor. The diver train is finally focused on the target (a gas-jet, gas-cell or a capillary delivering a mixture of H/He and a dopant (N, Ar), thus exciting a large-amplitude plasma wave. The low-energy portion of the initial pulse is amplified, frequency tripled through the passage into a thin nonlinear BBO crystal, temporally recompressed and radially magnified by using a reflective-beam expander. The 3ω ionizing pulse is finally tightly focused with a short parabola and made collinear with the driver train by using an holed mirror. The region inside the dashed lines constitutes the experimental apparatus needed in addition to a standard LWFA setup.

Both schemes **should be experimentally verified → TRL = 3**

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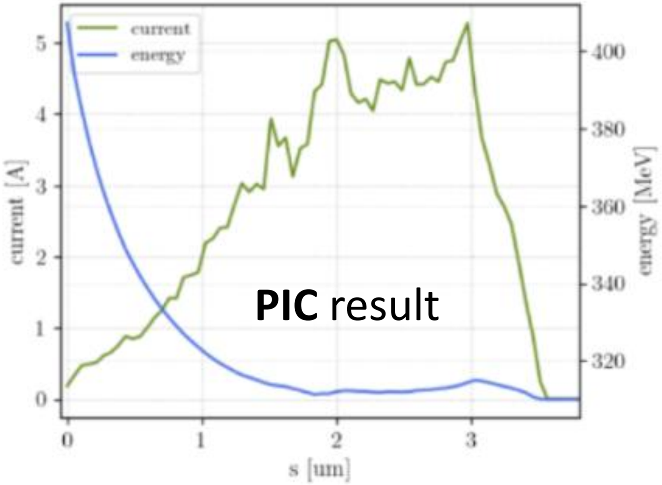
Current Status: LPA-based FEL

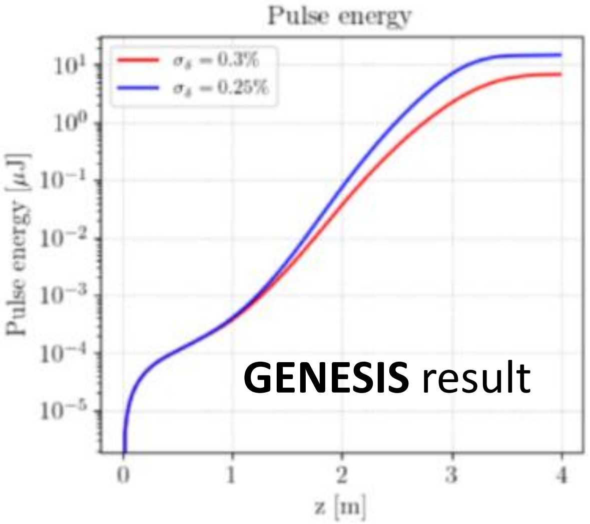
Physics and System Simulations

S2E modelling: LPA PIC + Electron Bea Line + SASE FEL

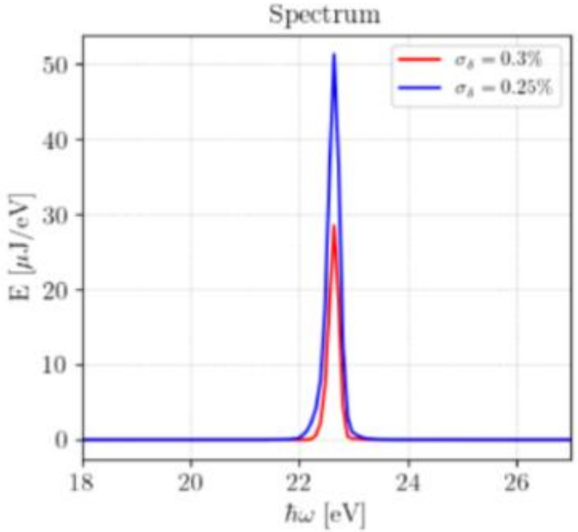
Verification of the Self-Amplified Spontaneous Emission regime along the UNDULATOR line
LPA-based FEL prototype (W_e ~ 315 MeV)



PIC result



GENESIS result



NEXT:

- **Verification for 1000 MeV case**
- Use the 6D distribution from the LPA PIC modelling

LPA-FEL Collaboration (ELI, ENEA, PSI)

Current Status: Electron Beam Line

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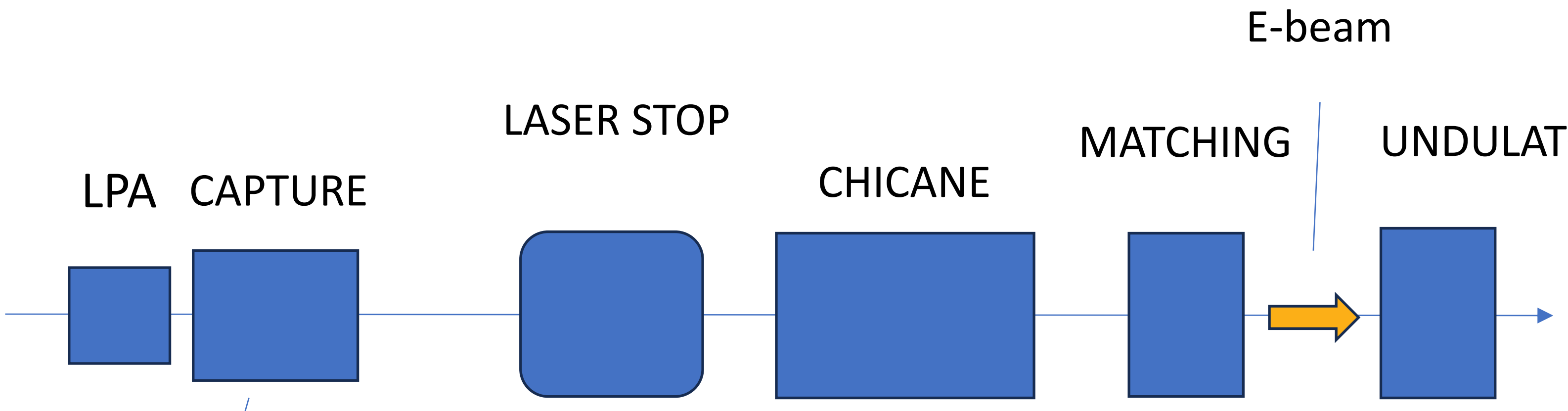
Physics and System Simulations

S2E modelling: **LPA PIC + Electron Beam Line** + SASE FEL

**BLOCK STRUCTURE
of Electron Beam Line**



PQMs → **TRL=6**
or
Active Plasma Lens → **TRL=3**

EDMs → **TRL = 6**

EQMs → **TRL=6**

Similar to:

LUX / DESY
COXINEL
BELLA
SIOM
Osaka

In progress

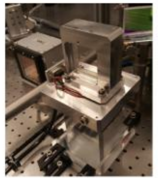
Main Challenge: preservation of the e-beam parameters required for SASE-FEL

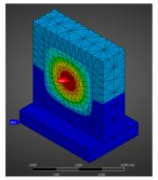
Current Status: Laser

Collaboration: PACRI

Work to contribute to TDR preparation

- kW-class pump laser OPCPA characteristics
- Impact of non-radial symmetry of square pulses on electron beam acceleration
- Simulations of kW pumped OPCPA underway to evaluate variations in phase matching angle and impact on efficiency/spectrum based on current crystals and mounts.

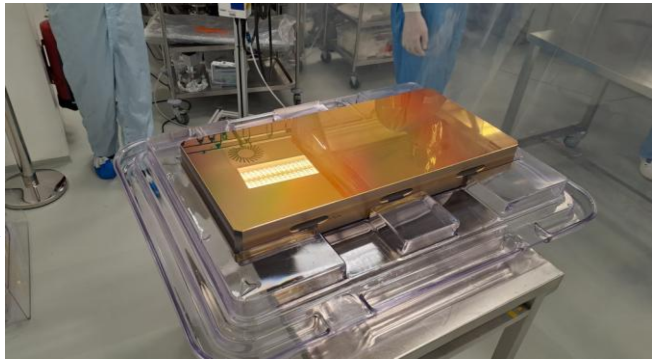


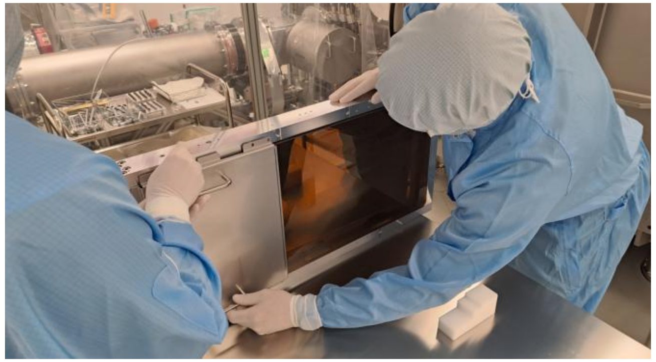


Implementation

Primary focus on laser commissioning in L2 hall

- Booster Laser profile troubleshooting
- High energy amplification
- Compressor Population





Detailed information → Tyler Green Talk

Current Status: Plasma Source

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Collaboration: PACRI

Gas-Cell Capillary

- Excellent guiding properties
- Possible discharge plasma channel formation
- High beam quality potential
- Limited lifetime at high rep-rate
- Complex cooling system for long lifetime

Shock-Front Gas Target

- Complex gas flow
- Excellent beam quality
- Precise jet profiling required
- Continuous gas flow
- Differential pumping

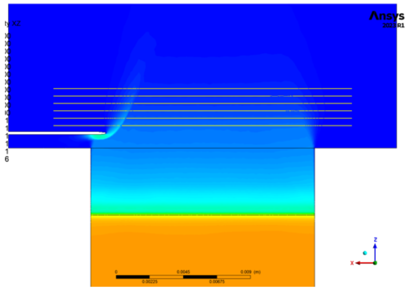
Common issue
Lifetime

Plasma debris and laser-induced damage at high rep-rate.

Gas Target prototyping for ELI-TDR

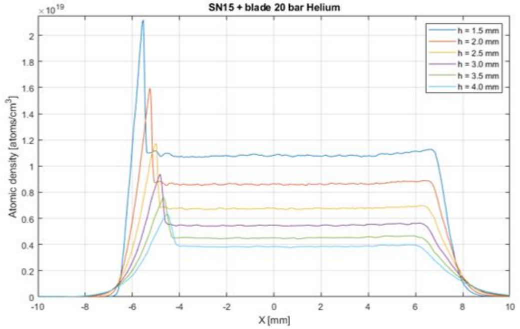
* sebastian.lorenz@eli-beams.eu

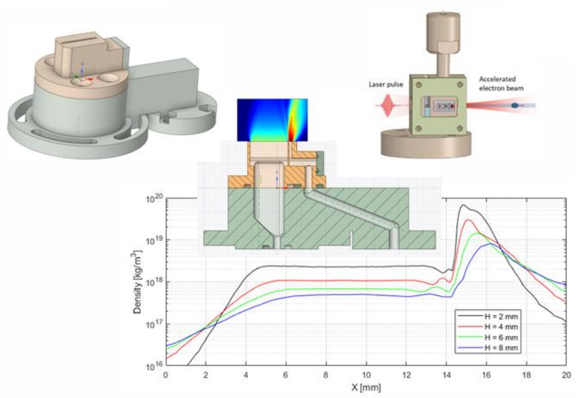
15 mm slit nozzle with blade



Hydrodynamic simulation / ANSYS

Variation of the density along the gas nozzle for different positions of the blade (1.5-4 mm)



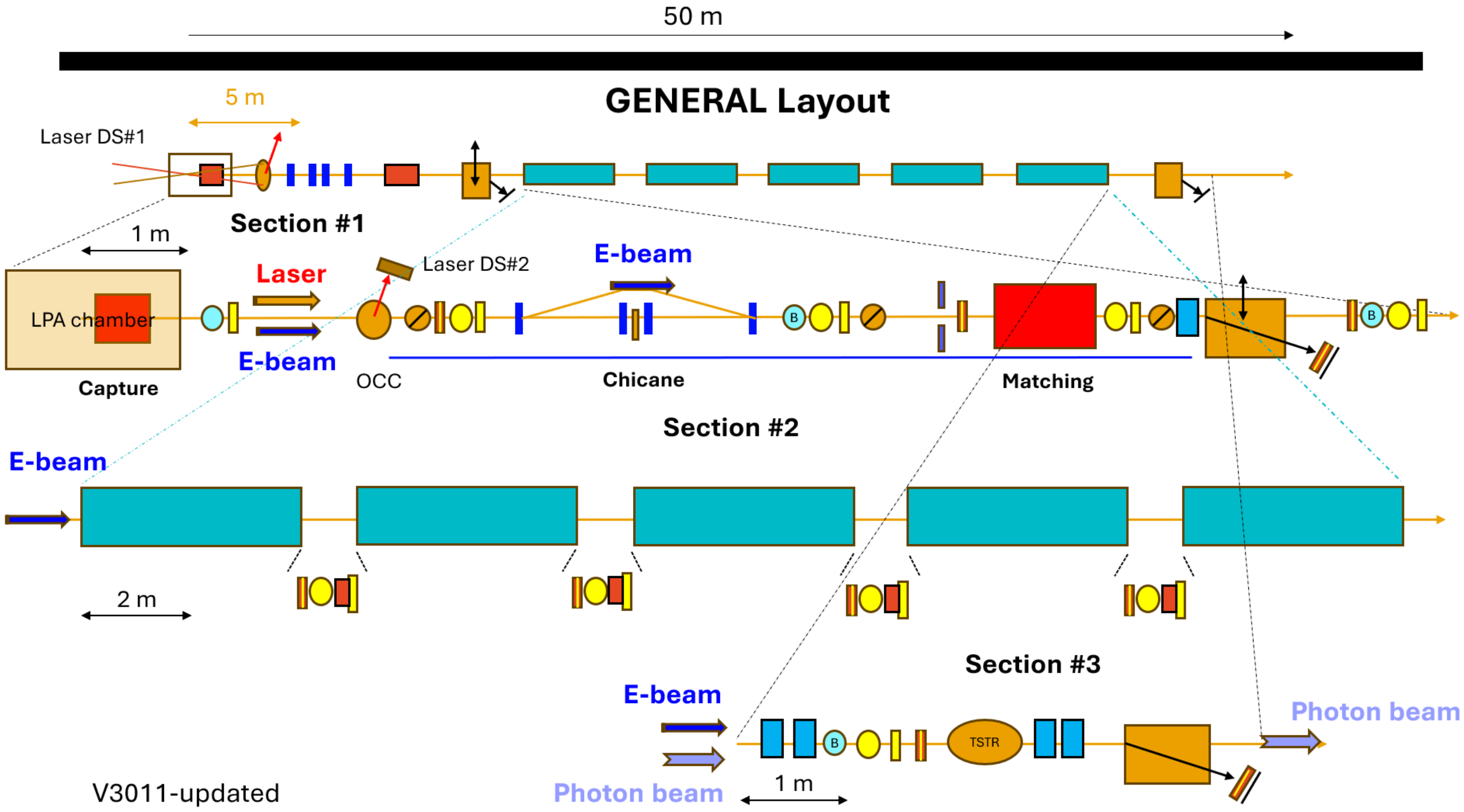


Detailed information → Jorge Vieira and Angelo Biagioni

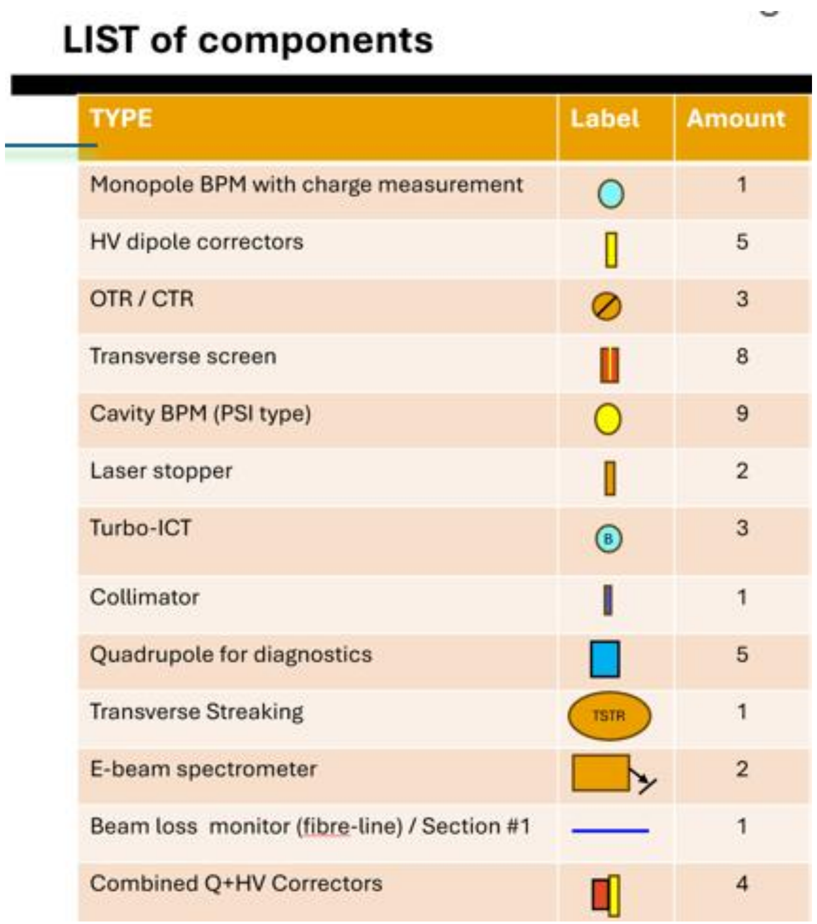
PACRI Current Status: Electron beamline and Undulator

Funded by the European Union

Collaboration: PP/WP9+WP13 + PACRI + SWISSELITE (PSI/ELI)



V3011-updated



LIST of components

TYPE	Label	Amount
Monopole BPM with charge measurement	○	1
HV dipole correctors	▯	5
OTR / CTR	⊘	3
Transverse screen	▮	8
Cavity BPM (PSI type)	●	9
Laser stopper	▯	2
Turbo-ICT	Ⓑ	3
Collimator	▮	1
Quadrupole for diagnostics	■	5
Transverse Streaking	TSTR	1
E-beam spectrometer	■	2
Beam loss monitor (fibre-line) / Section #1	—	1
Combined Q+HV Correctors	▮▯	4

Current Status: Photon Beamlines

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Collaboration: ELI BL+FLASH (DESY)+FERMI+INFN+PSI

MAIN Components

Coordinator: J. Andreasson

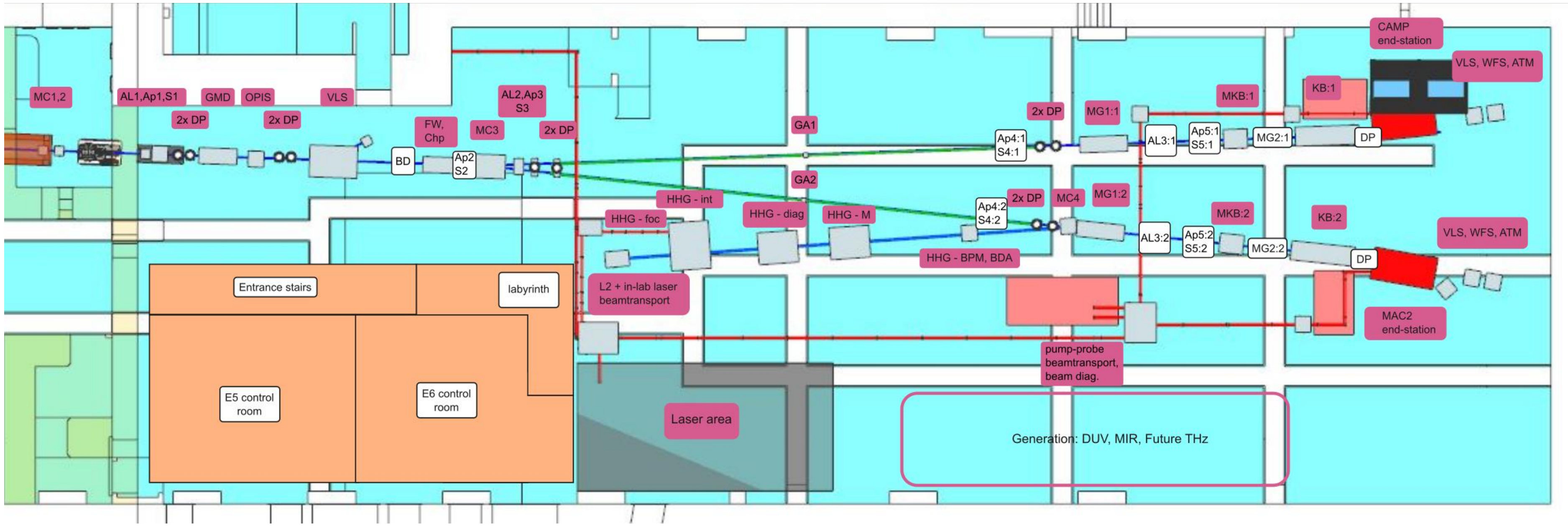
MC1,2: Mirror chamber, alignment and deflecting mirrors
AL: Alignment laser
Ap: Aperture
S: Screen
DP: Differential pumping
GDM: Gas Monitor Detector
OPIS: Online photoionization spectrometer
VLS: Variable line spacing spectrometer
BD: Beam dump
FW: Filter wheel

Chp: Chopper
GA: Gas attenuator
MG: Monochromator grating
MKB: Vertical mirror for KB focusing optics
KB: KB focusing optics
WFS: Wavefront sensor
ATM: Arrival time monitor
HHG: High Harmonic Beamline

Science Case is Drafted

- AMO science
- Chemistry and catalysis
- Condensed matter physics
- Life science and imaging

CONCEPT of Photon Beamlines in E6



E6 hall at ELI Beamlines

Current Status: LPA-based FEL

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Extra TDR-related work packages are activated:

- Low Energy Position Source
- Safety and Radiation Protection
- Integrated Control Systems and DAQ
- Infrastructure Integration
- Engineering Design
- Quality and Risk Assessments

Current Status: Betatron

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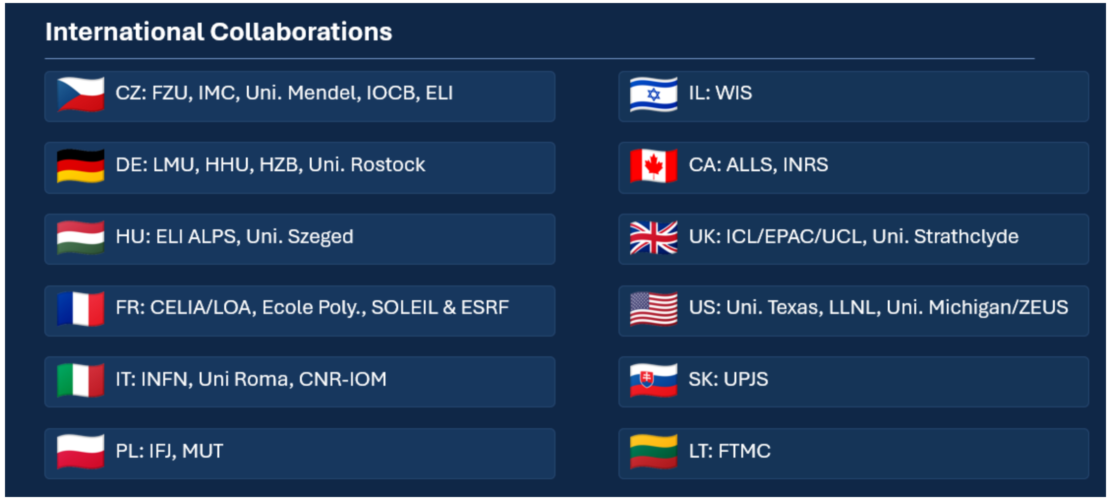
Setup:

- fully commissioned
- open for users → User Call #8 is activated

Science Case is Drafted

- Magnetic Materials and Spin Dynamics
- Energy Materials and Energy Conversion
- Ultrafast Structural and Electronic Dynamics in Biology and Chemistry
- Ultrafast Pink-Beam Serial Crystallography
- Industrial applications

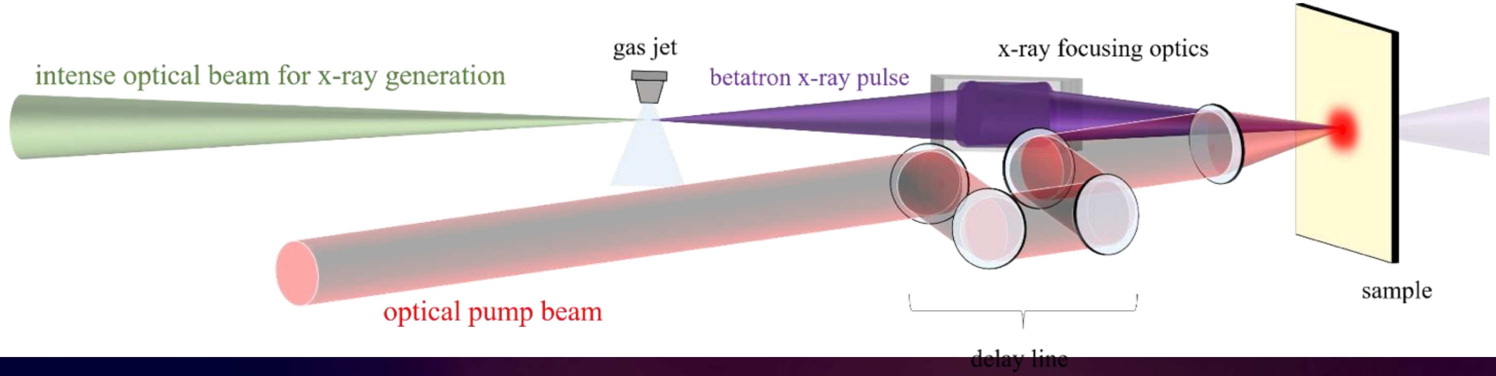
Broadband X-ray (1-20 keV) beamline



International Collaborations

CZ: FZU, IMC, Uni. Mendel, IOCB, ELI
DE: LMU, HHU, HZB, Uni. Rostock
HU: ELI ALPS, Uni. Szeged
FR: CELIA/LOA, Ecole Poly., SOLEIL & ESRF
IT: INFN, Uni Roma, CNR-IOM
PL: IFJ, MUT
IL: WIS
CA: ALLS, INRS
UK: ICL/EPAC/UCL, Uni. Strathclyde
US: Uni. Texas, LLNL, Uni. Michigan/ZEUS
SK: UPJS
LT: FTMC

Coordinator: U.Chaulagain



ELI-TDR Timeline

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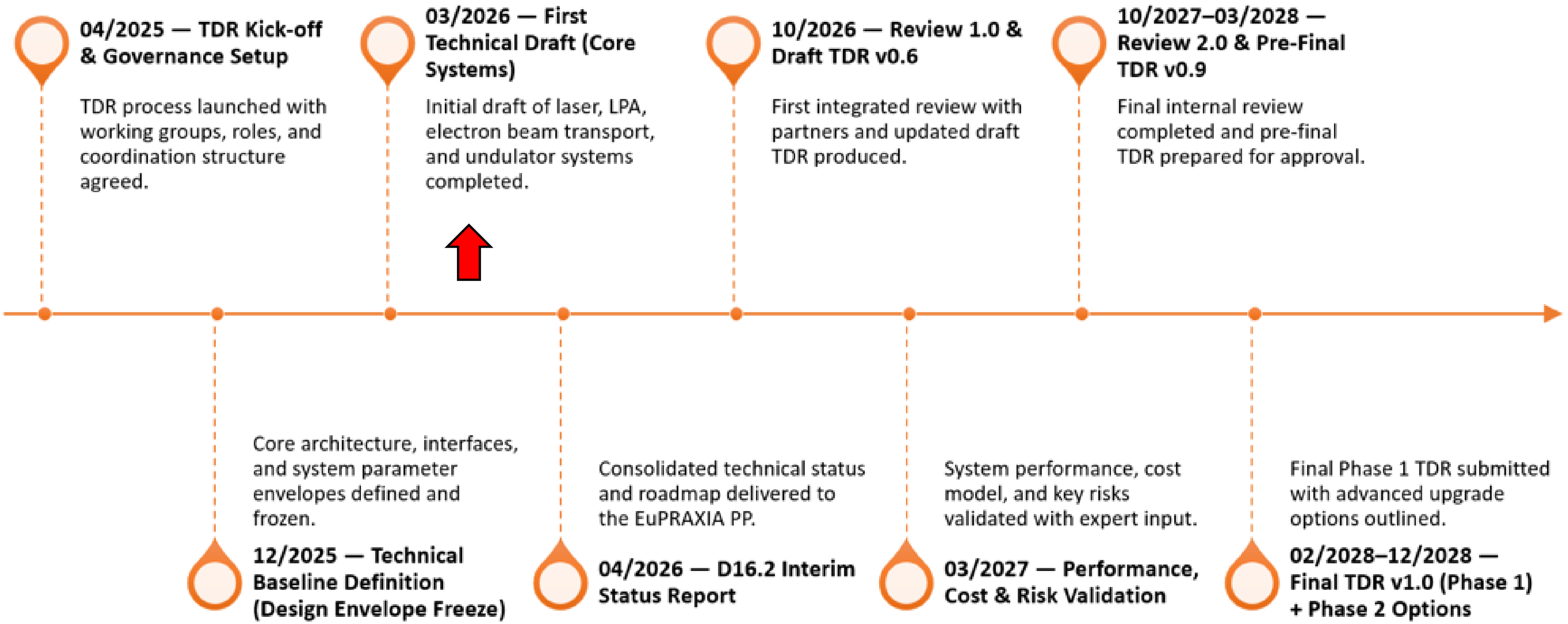
Consolidated efforts of all EuPRAXIA members are required to be on time with the ELI-TDR preparation



04/2025 — TDR Kick-off & Governance Setup

TDR process launched with working groups, roles, and coordination structure agreed.

12/2025 — Technical Baseline Definition (Design Envelope Freeze)

Core architecture, interfaces, and system parameter envelopes defined and frozen.

03/2026 — First Technical Draft (Core Systems)

Initial draft of laser, LPA, electron beam transport, and undulator systems completed.

04/2026 — D16.2 Interim Status Report

Consolidated technical status and roadmap delivered to the EuPRAXIA PP.

10/2026 — Review 1.0 & Draft TDR v0.6

First integrated review with partners and updated draft TDR produced.

03/2027 — Performance, Cost & Risk Validation

System performance, cost model, and key risks validated with expert input.

10/2027–03/2028 — Review 2.0 & Pre-Final TDR v0.9

Final internal review completed and pre-final TDR prepared for approval.

02/2028–12/2028 — Final TDR v1.0 (Phase 1) + Phase 2 Options

Final Phase 1 TDR submitted with advanced upgrade options outlined.

Implementation phase … in PARALLEL: LASER & Betatron & Positron

Thank you for your attention