Plasma photocathodes
A pathway to high-brightness electron beams at ELI Beamlines

Fahim Habib[1,2], L. Berman[2], T. Heinemann[3], B. Hidding[3], P. Tomassini[1], + Collaborators

Collaborators: D. Campbell[2], M. Cerchez[3], A. Debus[4], A. Döpp[5], F. M. Foerster[5], G. M. Grittani[1], E. Hartmann[3], E. Hemsing[6], M. J. Hogan[6], J. Couperus Cabadağ[4], A. Irman[4], S. Karsch[5], A. Knetsch[6], T. Kurz[4], G. G. Manahan[2], D. Margarone[1], B. W. J. McNeil[2], A. Molonoghenzev[1], A. Nutter[2], R. Pausch[4], T. Raubenheimer[6], J. B. Rosenzweig[7], S. Schoebel[4], U. Schramm[4], A. Sutherland[2], P. Ufer[4], T. Wilson[3]

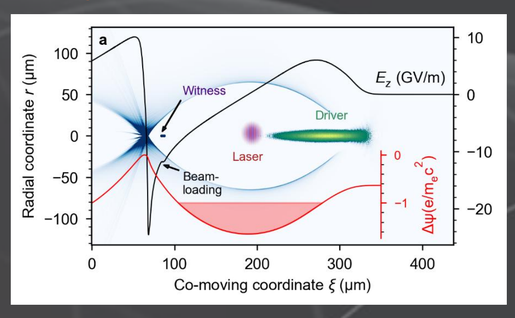
1. Extreme Light Infrastructure ERIC, Dolní Břežany, Czech Rep.; 2. University of Strathclyde, Glasgow, UK; 3. HHU, Düsseldorf, Germany;
4. HZDR, Dresden, Germany; 5. LMU, München, Germany; 6. SLAC National Accelerator Laboratory, Menlo Park, USA; 7. UCLA, Los Angeles, USA.

Abstract.

Laser-plasma accelerators (LPAs) can now drive free-electron lasers (FELs) [1], but reaching higher photon energies is limited by electron-beam brightness and stability at GeV energies. Plasma photocathode injection in beam-driven plasma wakefield acceleration (PWFA) [2,3,4] or in an LPA via Resonant Multi-Pulse Ionization (ReMPI) injection could address both challenges [5,6]. Both methods could yield ultra-low-emittance, ultra-high 6D brightness, tuneable beams down to hundreds of attoseconds, meeting the requirements for future plasma-driven FELs and marking a step towards soft-to-hard XFELs [7,8]. We show, on the example of electron beams from plasma photocathode PWFA in a Hybrid LWPA→PWFA configuration [9,10], how these ultra-high-brightness beams could drive next-generation plasma-based XFELs. Then, we elaborate on the possibility of realising these opportunities within EuPRAXIA@ELI Beamlines, as the capabilities and experimental infrastructure at ELI Beamlines are the ideal environment for this vision.

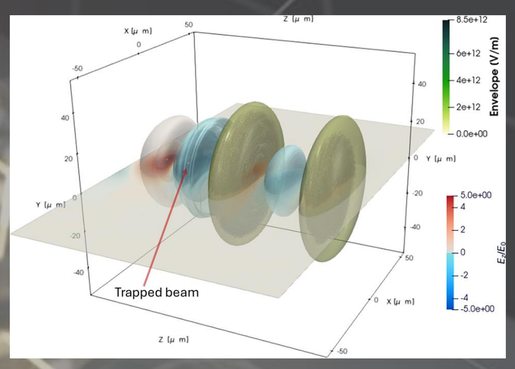
Plasma photocathode in PWFA (Trojan Horse injection)

- **Concept:** Drive bunch → nonlinear PWFA wake in low-threshold gas; high-threshold dopant inside bubble
- **Release:** Low intensity trigger laser ionises dopant inside the blowout → direct injection (Trojan Horse)
- **Emittance:** Cold electrons born at rest in linear GV/m fields → tens-of-nm normalised emittance
- **Brightness:** Ultra low emittance + low energy spread + high current + ultra high 6D brightness → compact XFEL driver



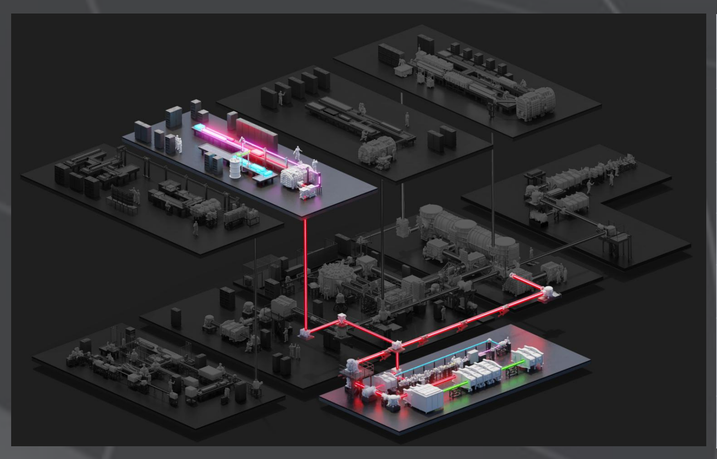
Plasma photocathode in LPA (ReMPI)

- **Concept:** 200 TW Ti:Sa pulse split into two-pulse driver train (multi-ring delay mask) → resonant LWFA wake in Ar/He two-stage target
- **Release:** Frequency-tripled ionization pulse extracts Argon L-shell electrons at the wake node → direct injection, dark-current-free (ReMPI)
- **Emittance:** Electrons born near-rest in linear fields → ultra-low normalised emittance
- **Brightness:** GeV-scale, attosecond-duration beams with ultra-high 6D brightness → compact XFEL driver



ELI Beamlines facility

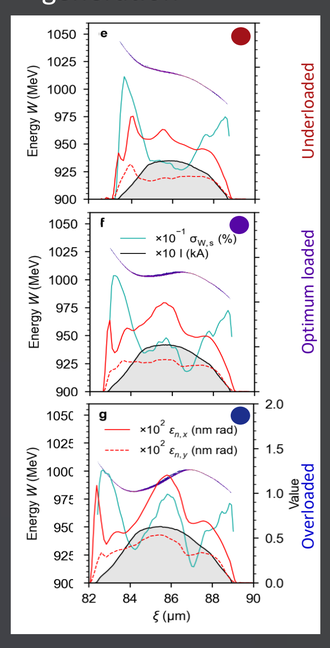
- Multiple high-power laser systems on site: L1-ALLEGRA, L2-DUHA, L3-HAPLS, L4-ATON (10 PW)
- Multi-beam configuration is what makes an LPA-driver + Hybrid PWFA-witness possible at ELI Beamlines
- Large experimental halls → Ideal for plasma-based XFELs and secondary light sources
- EuPRAXIA second pillar @ ELI Beamlines: LPA-driven site
- ELI Beamlines combines the key building blocks for next-generation plasma-based XFEL

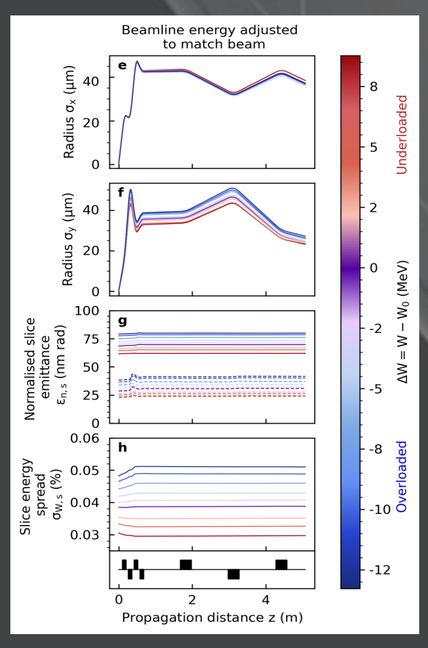


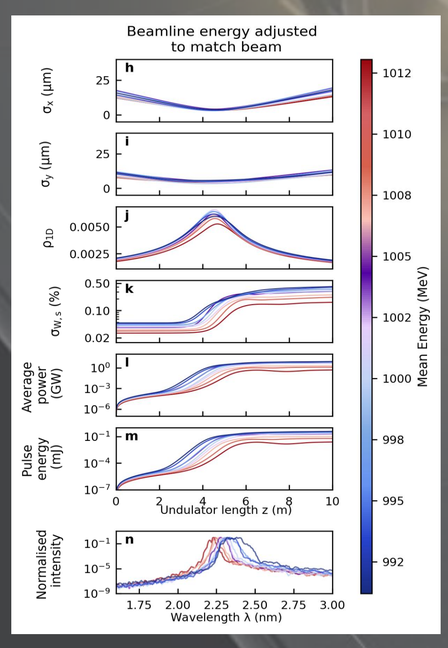
System	Output	Design Performance	Actual Performance
L1-ALLEGRA	Main (810 nm)	100 mJ / <15 fs / 1 kHz	55 mJ / 15 fs / 1 kHz
	Secondary	12 mJ / 12 fs / 1 kHz	—
L2-DUHA	Main (810-820 nm)	>3-4 J / 25 fs / 20 Hz	Commissioning 2026
	Mid-IR (2.2 μm)	5 mJ / 30 fs / 2 kHz	—
L3-HAPLS	Main (810 nm)	30 J / <30 fs / 10 Hz	13 J/27 J / 28 fs / 3.3 Hz
	Secondary (810 nm)	1 J / 30 fs / 10 Hz	—

Water-Window soft X-ray free-electron laser at EuPRAXIA@ELI Beamlines

- Water-window photons (2.3 to 4.4 nm) allow imaging biological samples in their native water environment
- XFEL can be tuned across the water window via the plasma stage or undulator
- Hybrid LWFA→PWFA equipped with plasma photocathode leads to self-stabilisation of beam parameters
- Next-gen hybrid-enabled ultra-high brightness beams meet the brightness and stability requirements of a compact water-window FEL
- We found a path to stabilise water-window XFEL for robust soft X-rays photon-pulse generation

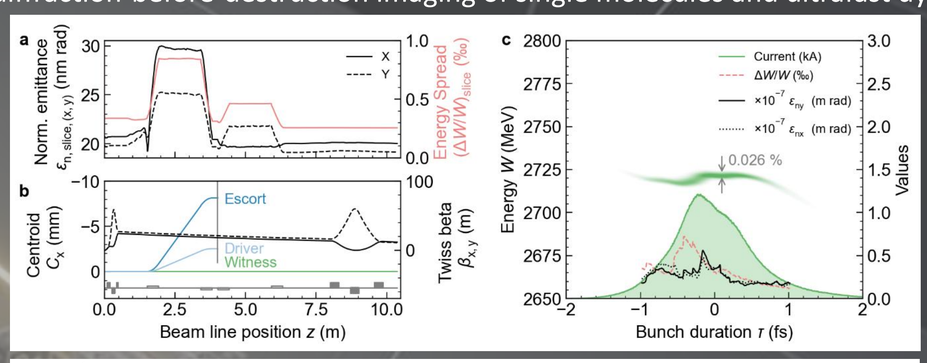


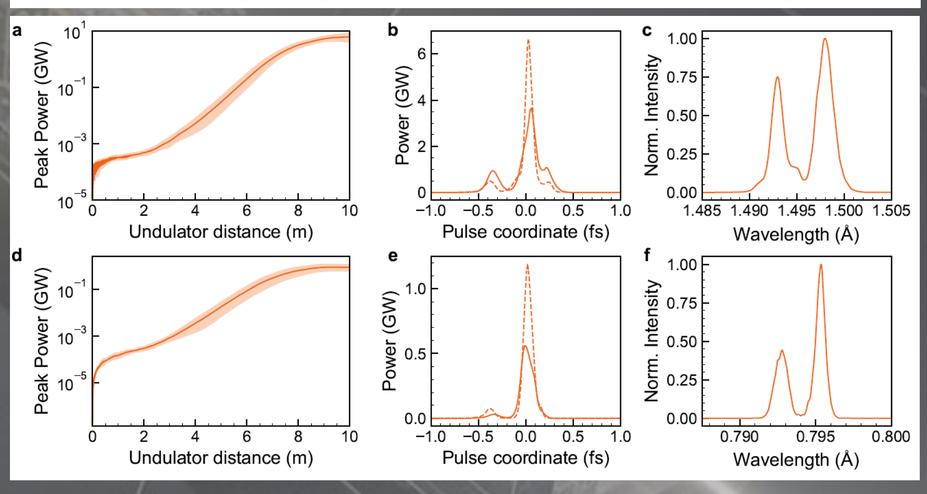




Attosecond-Angstrom FEL at EuPRAXIA@ELI Beamlines

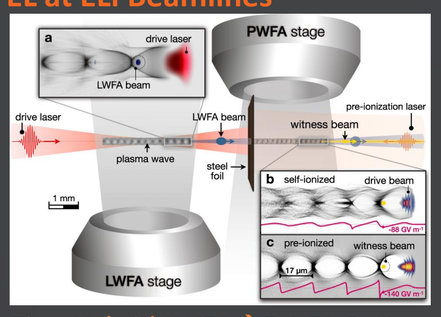
- Ultra-high brightness beams at multi-GeV energies open the path to sub-Angstrom XFELs
- Angstrom wavelength resolves atomic structure; attosecond duration catches the dynamics at the natural time scale
- Enables diffraction-before-destruction imaging of single molecules and ultrafast dynamics



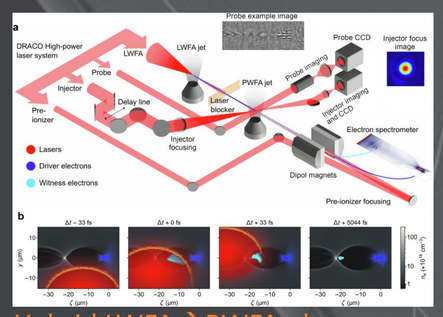


Path to Hybrid LWFA→PWFA based XFEL at ELI Beamlines

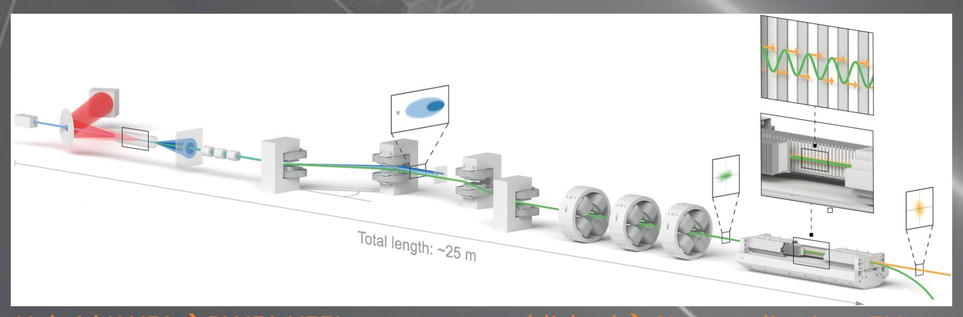
- L2/L3 laser can drive a high-charge LPA stage
- LPA beam enables a PWFA plasma photocathode
- A compact route to FEL-grade beams
- Direct ReMPI-based ultra-high brightness beams or via Hybrid LWFA--PWFA opens novel possibilities
- Beam brightness directly impacts EuPRAXIA@ELI-BL facility CAPEX



First Hybrid LWFA→PWFA PoC experiment [6]



Hybrid LWFA→PWFA plasma photocathode PoC experiment [7]



Hybrid LWFA→PWFA XFEL concepts established→ Next realise it at ELI Beamlines [4,5]

Conclusion

- A Hybrid LWFA→PWFA stage at ELI Beamlines is a realistic route to ultra-compact PWFA
- Plasma photocathodes turn LPA and PWFA into credible approaches for plasma XFELs
- Success opens the door to water-window and attosecond-angstrom XFELs
- ELI Beamlines provides the laser, engineering and experimental infrastructure this vision needs
- EuPRAXIA@ELI Beamlines gives the programmatic structure for it to be realised

References

[1] Galletti et al. Nat.Photon. 18, 780–791 (2024)
[2] Hidding et al. Phys.Rev.Lett. 108, 035001 (2012)
[3] Habib et al., Ann.Phys., vol. 535, 2200655, (2023)
[4] Manahan & Habib et al. Nat Commun 8, 15705 (2017)
[5] Tomassini et al. Phys.Plasmas, vol. 24, no. 10, 103120, (2017)
[6] Tomassini et al. Sci.Rep. 15, no. 1, 40794, (2025)
[7] Habib et al., Nat.Commun. 14, 1054, (2023)
[8] Berman et al., Nat.Commun.(2026)-accepted
[9] Kurz & Heinemann et al. Nat Commun 12, 2895 (2021)
[10] Ufer & Nutter et al. Commun. Phys. 9, 273 (2026)

Acknowledgements
This research used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 using NERSC award HEP-ERCAP0031797. This poster presentation has received support from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101079773. It is supported by in-kind contributions by its partners and by additional funding from the UK and Switzerland. Portions of this research were carried out at the ELI Beamlines Facility, a European user facility operated by the Extreme Light Infrastructure ERIC.

The Extreme Light Infrastructure ERIC (ELI ERIC)
Za Radnicí 835, 252 41 Dolní Břežany, Czech Republic
www.eli-laser.eu