EAAC 2025
2025-09-22, Elba, Italy

Fahim Habib* et al.

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Plasma-based energy and brightness booster stages for the next-generation XFELs

Department of Physics, University of Strathclyde
Scottish Centre for the Application of Plasma-Based Accelerators (SCAPA)
Scottish Universities Physics Alliance (SUPA)
The Cockcroft Institute

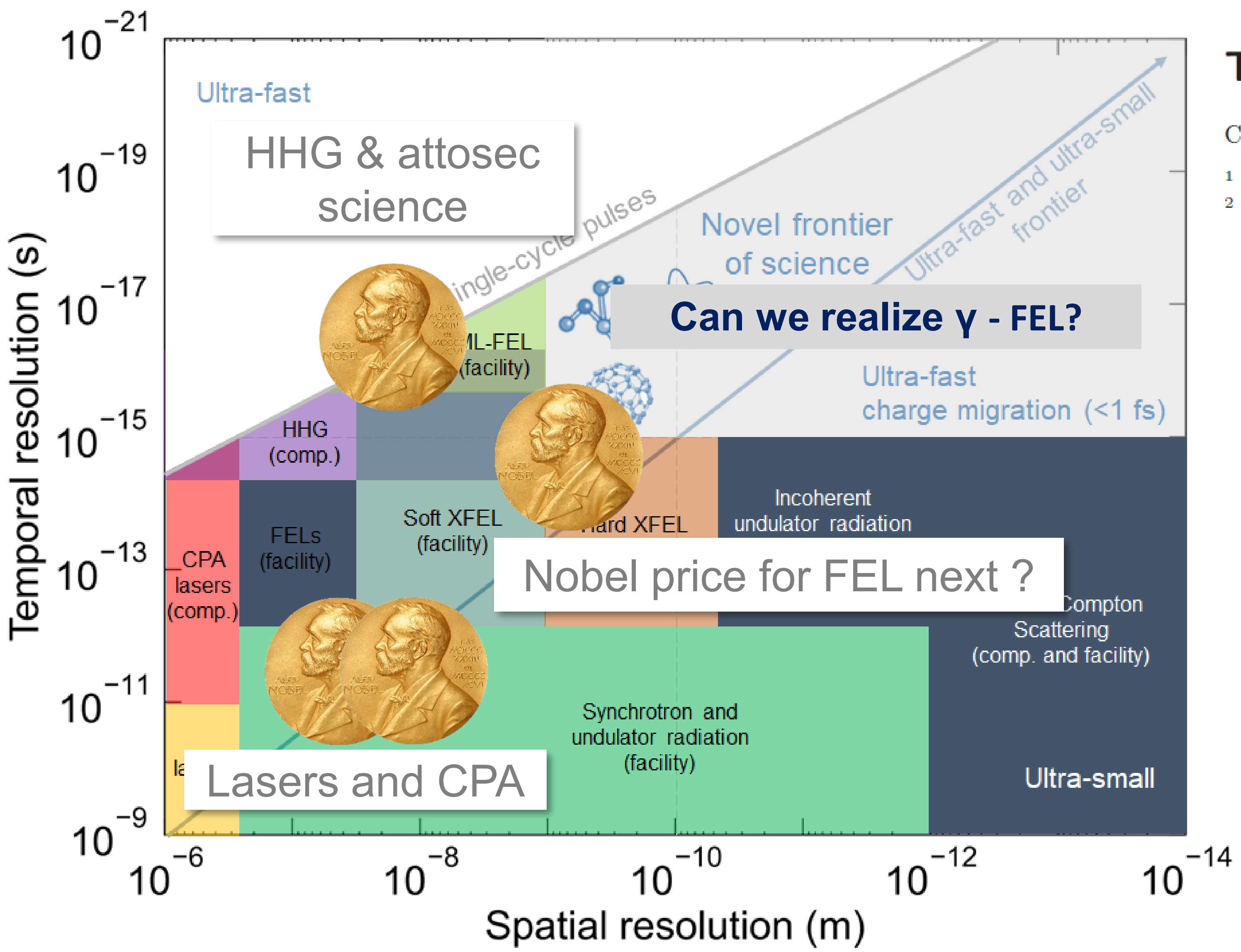
University of Strathclyde Glasgow

Science and Technology Facilities Council

Science and Technology Facilities Council
ASTeC

The Cockcroft Institute of Accelerator Science and Technology

Frontier of spatiotemporal resolution for fundamental science



The history of X-ray free-electron lasers

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Received 7 December 2011 / Received in final form 16 March 2012
Published online (Inserted Later)

Abstract. The successful lasing at the SLAC National Accelerator Laboratory of the Linear Coherent Light Source (LCLS), the first X-ray free-electron laser (X-ray FEL), in the wavelength range 1.5 to 15 Å, pulse duration of 60 to few femtoseconds, number of coherent photons per pulse from 10^{13} to 10^{11}, is a landmark event in the development of coherent electromagnetic radiation sources. Until now electrons traversing an undulator magnet in a synchrotron radiation storage ring provided the best X-ray sources. The LCLS has set a new standard, with a peak X-ray brightness higher by ten orders of magnitudes and pulse duration shorter by three orders of magnitudes. LCLS opens a new window in the exploration of matter at the atomic and molecular scales of length and time. Taking a motion picture of chemical processes in a few femtoseconds or less, unraveling the structure and dynamics of complex molecular systems, like proteins, are some of the exciting experiments made possible by LCLS and the other X-ray FELs now being built in Europe and Asia. In this paper, we describe the history of the many theoretical, experimental and technological discoveries and innovations, starting from the 1960s and 1970s, leading to the development of LCLS.

Snapshot of wakefield-driven X-FEL landscape

Experimental efforts

	COXINEL	DESY-LUX	SIOM	LBNL-BELLA
Charge density [pC/MeV]	0.5	4	1–5	2
Repetition rate [Hz]	1–10	1	1–5	5
Mean energy [GeV]	0.18–0.4	0.3	0.84	0.1–0.3
Slice energy spread RMS [%]	NA	0.5	0.24–0.4	0.2–1
Charge [pC]	NA	50	8–25	25
Emittance [mm·mrad]	1	1.5 (horz.), 0.3 (vert.)	0.4	0.3–1
FEL wavelength [nm]	UV-VUV	100	6–10	80
Undulator technology	Cryo-PMU	Cryo-PMU	Planar and TGU	Planar + strong focusing
FEL operation modes	Decompression + seeding	Decompression + SASE	SASE, transverse decompression	Decompression + seeding
Key challenge pursued	Demonstrate FEL gain	Demonstrate FEL gain	Demonstrate FEL gain	Demonstrate FEL gain

Programs in planning

SLAC FACET-II*	DESY - FLASHForward	Strathclyde*	EuPRAXIA at SPARC LAB*
10–500	1	1–100	4
1	10 (10^4 after future upgrades)	Variable	10
5–10	1	1–5	1–5
0.1–1	0.15	0.01–2	0.75
10–100	100	0.1–500	30
1–10	1–20	0.01–1	1
10–50	Soft X-rays	Hard X-rays	4
Compression + pre-bunching	SASE	Multiple	SASE
Attosecond FEL pulses	High average power FEL	Hard X-ray FEL gain	Plasma-FEL user facility

First experimental breakthroughs

SIOM: Wang, W. et al. *Nature* **595**, 516–520 (2021)
→ SASE operation at 27 nm

INFN: Pompili, R. et al. *Nature* **605**, 659–662 (2022)
→SASE operation at 820 nm

INFN: M. Galletti et al. Phys. Rev. Lett. 129, 234801(2022)
→ Seeded operation at 820 nm

COXINEL/HZDR: Labat, M. et al, Nat. Photon. 17, 150–156 (2023)→ Seeded operation at 269 nm

LBNL: Barber, S. K., et al. Physical Review Letters 135.5, 055001 (2025) → SASE at ~400 nm

Conceptual effort/upcoming programs

SLAC FACET-II: C. Emma, et al. APL Photonics 6.7 (2021)

Strathclyde: A. F. Habib et al. Nat. Comm. 14, 1054, (2023)

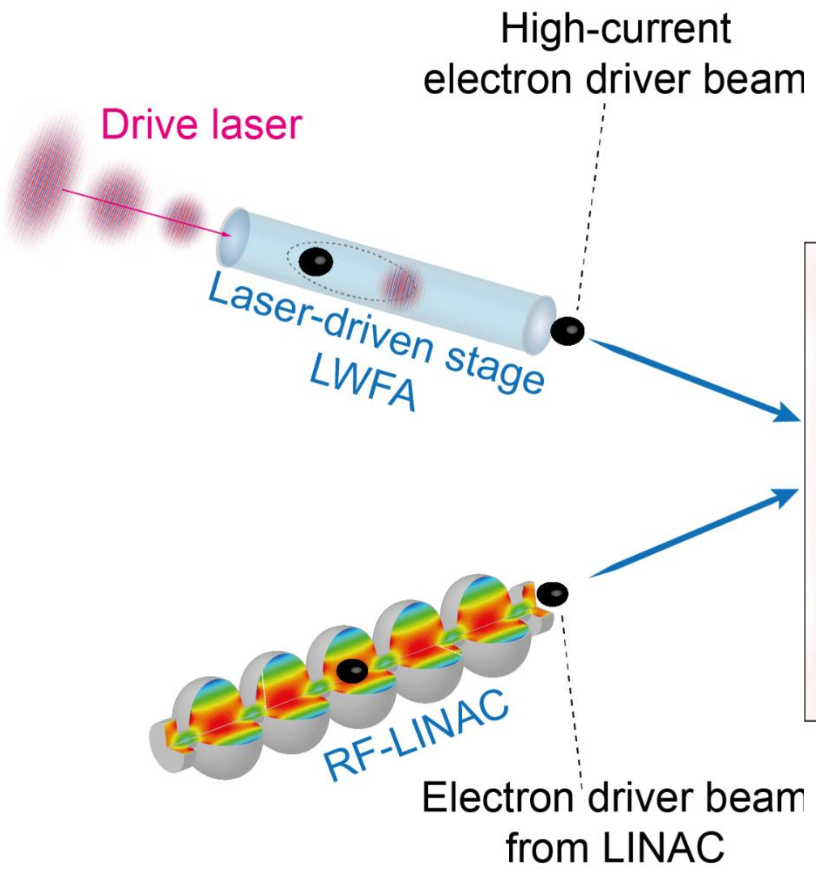
EuPraxia: Assmann, R.W. et al. Eur. Phys. J. Spec. Top. 229, 3675–4284, (2020)

Peking University: Xinlu Xu et al. Phys. Rev. Accel. Beams 27, 011301, (2024)

Many more…

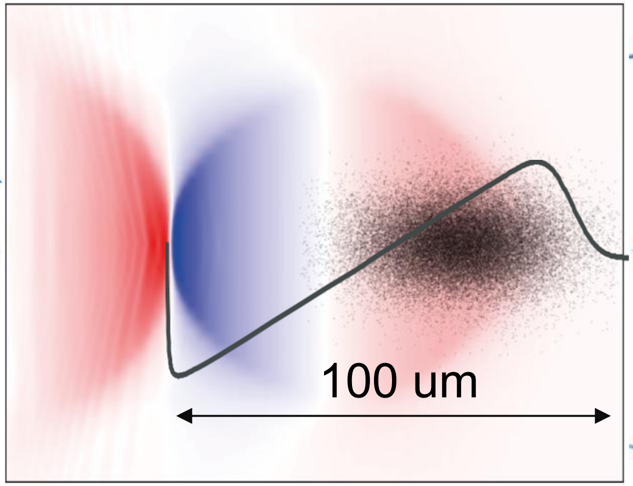
“Anatomy” of PWFA

Driver electron beam source



Accelerator cavity

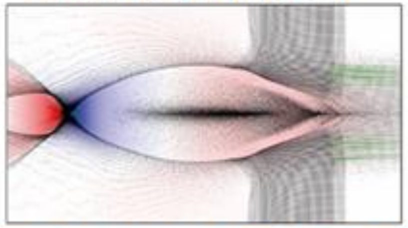
Particle-driven stage
PWFA



Accelerating gradient
~10-100 GV/m

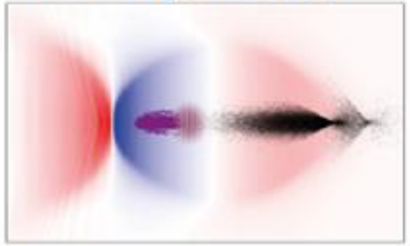
Electron Injector

Optical downramp injection
aka Plasma torch



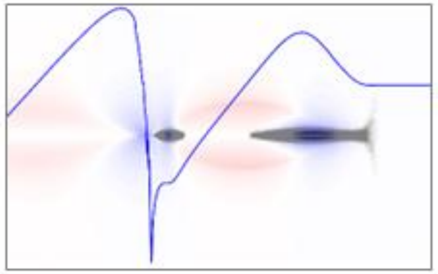
Ullmann,..,Habib et al. Phys. Rev. Research **3**, 043163, Kentch Phys. Rev. Accel. Beams **24**

Plasma photocathode injection
aka Trojan Horse



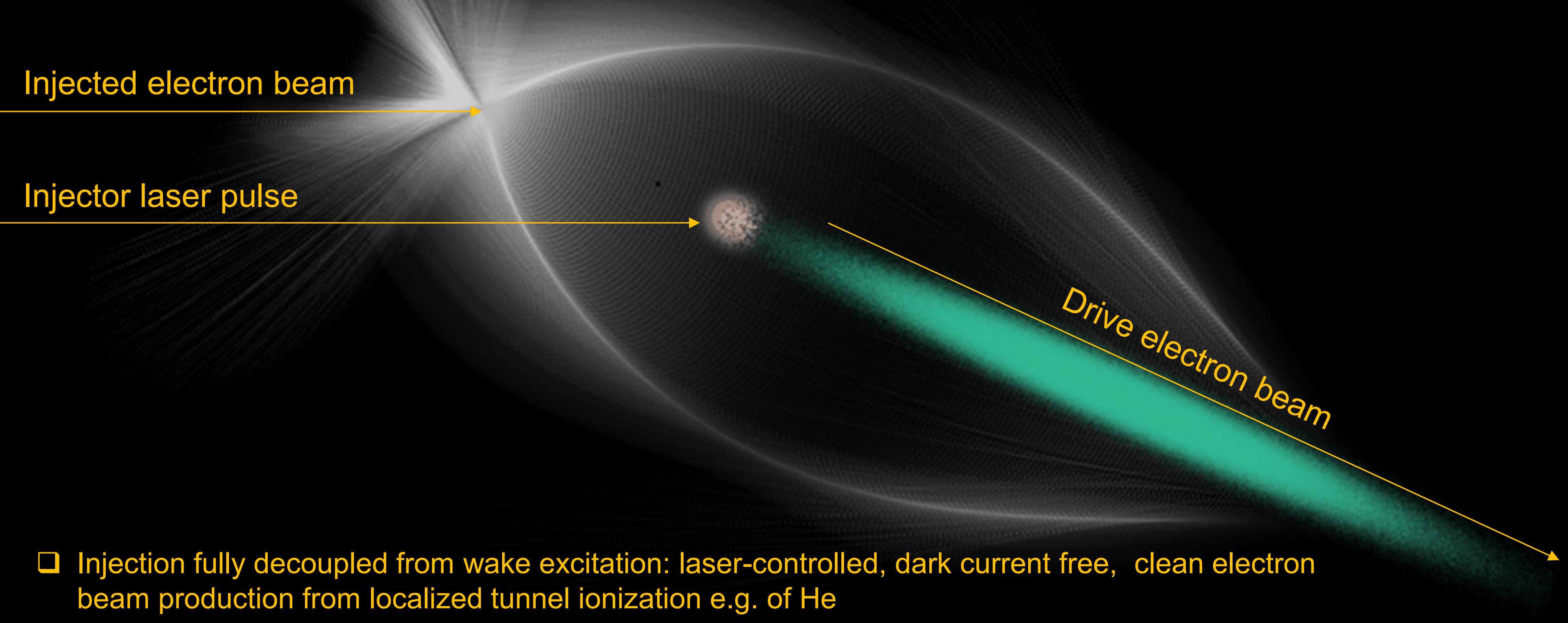
Hidding et al., *Phys. Rev. Letters* 108, 035001, 2012, G.G. Manahan/A. F. Habib *et al., Nat. Commun.* 8, 15705 (2017)

Two-bunch mode



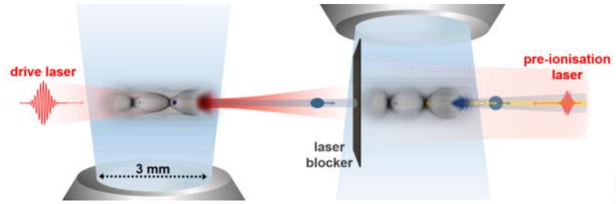
M. Litos, Nature 515, 92–95 (2014), S. Schröder et al, Nature Commun. 11, 5984 (2020)

“Anatomy” of Plasma photocathode PWFA

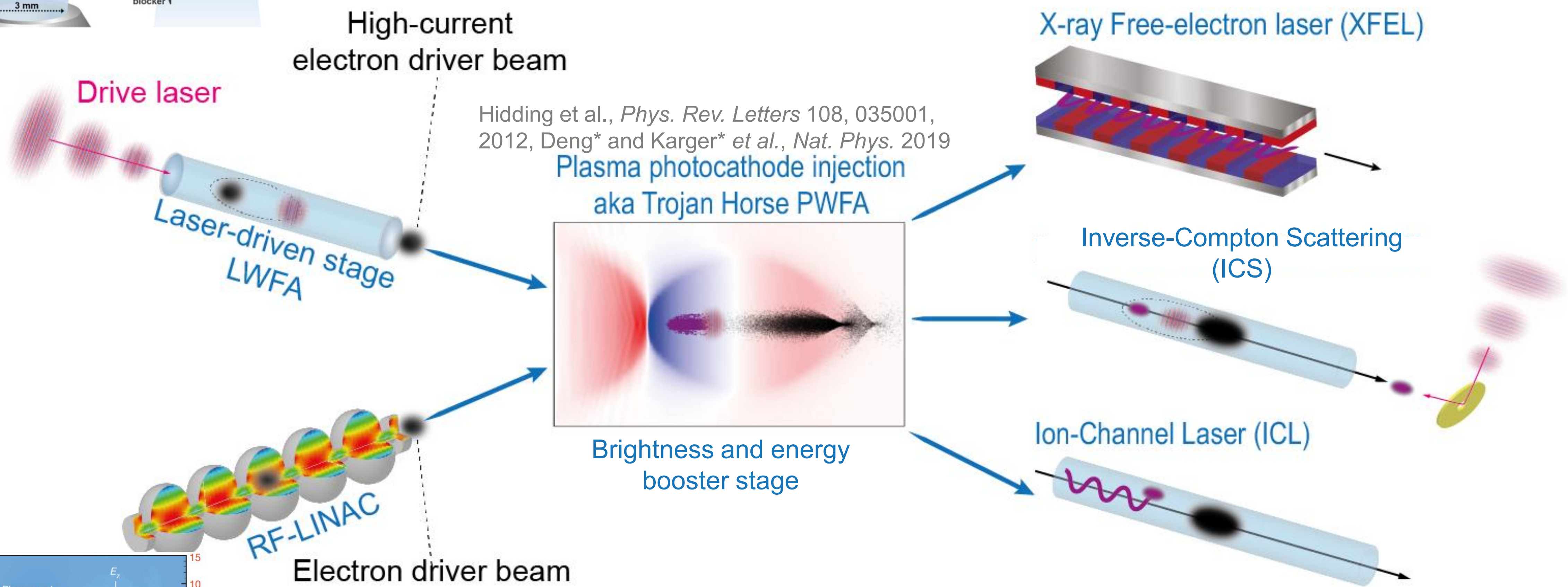


- Injection fully decoupled from wake excitation: laser-controlled, dark current free, clean electron beam production from localized tunnel ionization e.g. of He
- Normalized emittance ε_n **~ nm rad scale**
- Auto-compression to kA currents $I \Rightarrow$ beams orders of magnitude brighter than state-of-the-art
- Extreme Beams for light sources and HEP applications

Experimental pathways and the vision towards PWFA-driven lights sources

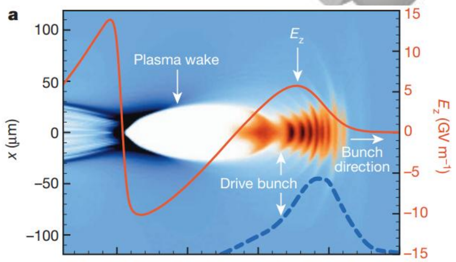


Kurz, T., Heinemann, T. et al. Nat Commun 12, 2895 (2021), F. M. Foerster et al, Phys. Rev. X 12, 041016 (2022)



Hidding et al., *Phys. Rev. Letters* 108, 035001, 2012, Deng* and Karger* *et al.*, *Nat. Phys.* 2019

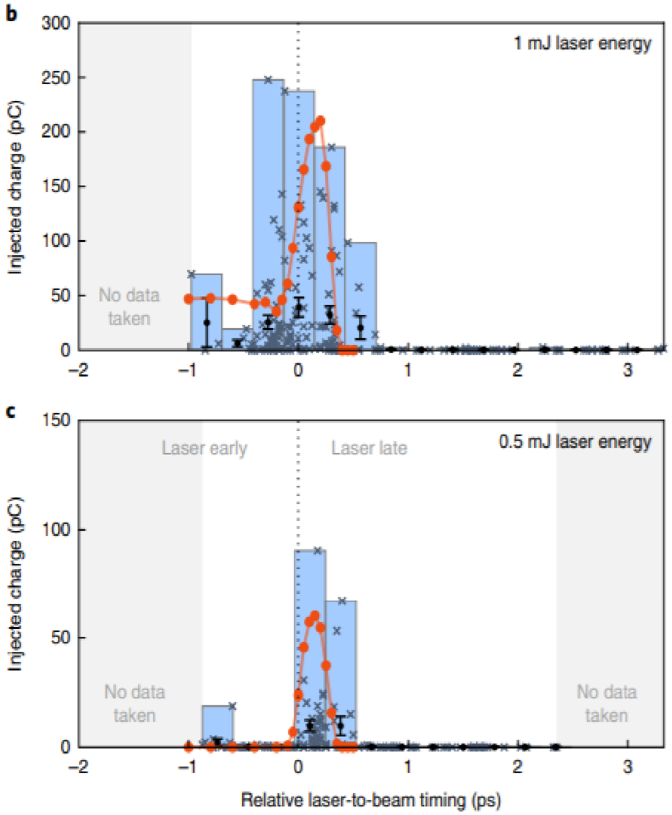
Habib et al., Proc. SPIE 11110, Advances in Laboratory-based X-Ray Sources, Optics, and Applications VII, 111100A (9 September 2019); doi: 10.1117/12.2530976



Blumenfeld Nature 445, 741–744 (2007)), M. Litos, et al., Nature 515 92-15 (2014)

Plasma photocathode experimental progress

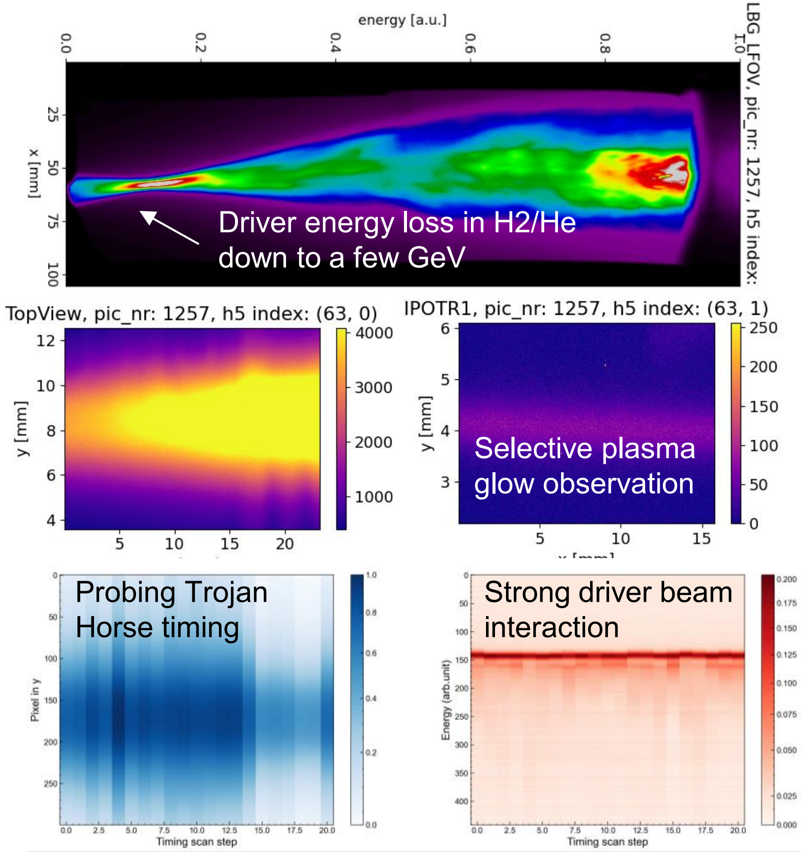
E210: Plasma photocathode injection proof-of-concept @SLAC FACET



Deng*…*et al.*, *Nat. Phys.* 2019

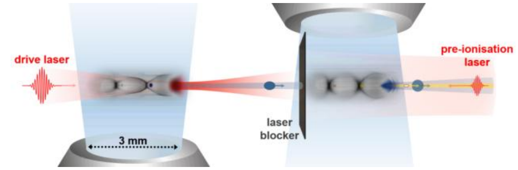
- ❑ 90° geometry version
- ❑ First demonstration of density down-ramp injection in PWFA
- ❑ Program to be continued at SLAC FACAT-II (E-310) (PI: Hidding et al.)

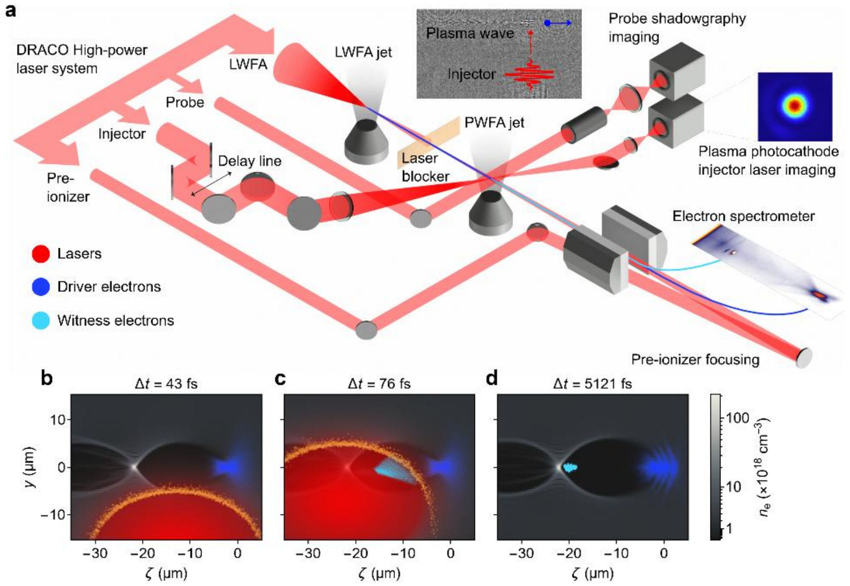
E310: First E310 experimental results in H2/He mixed gas @SLAC FACET-II



- ❑ Beam time delivered by Strathclyde (UK), SLAC (USA) and HHU (Germany) team
- ❑ Ionization tests in mixed H2/He gas
- ❑ Crucial first step towards E310 goals

Breakthrough in Hybrids LWFA→PWFA 90° plasma photocathode realised @HZDR

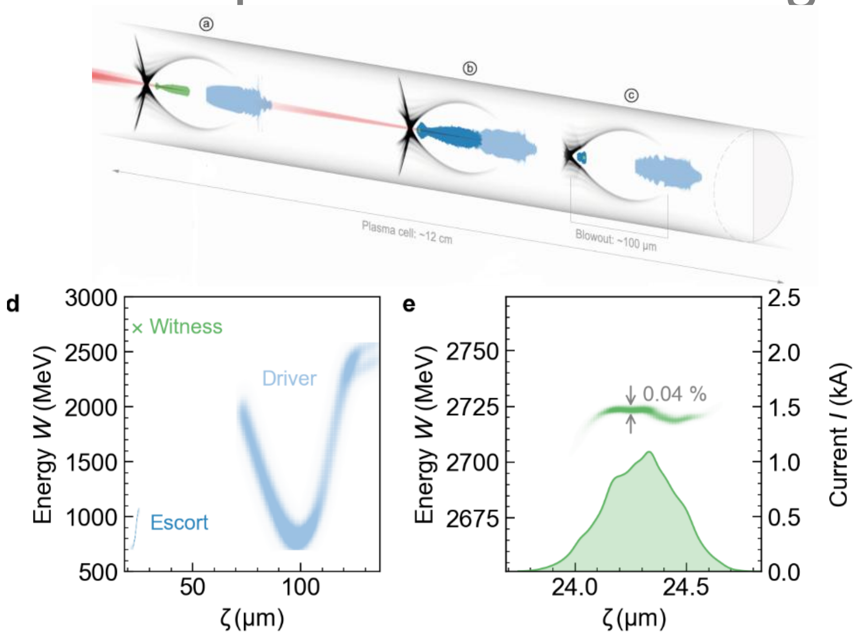


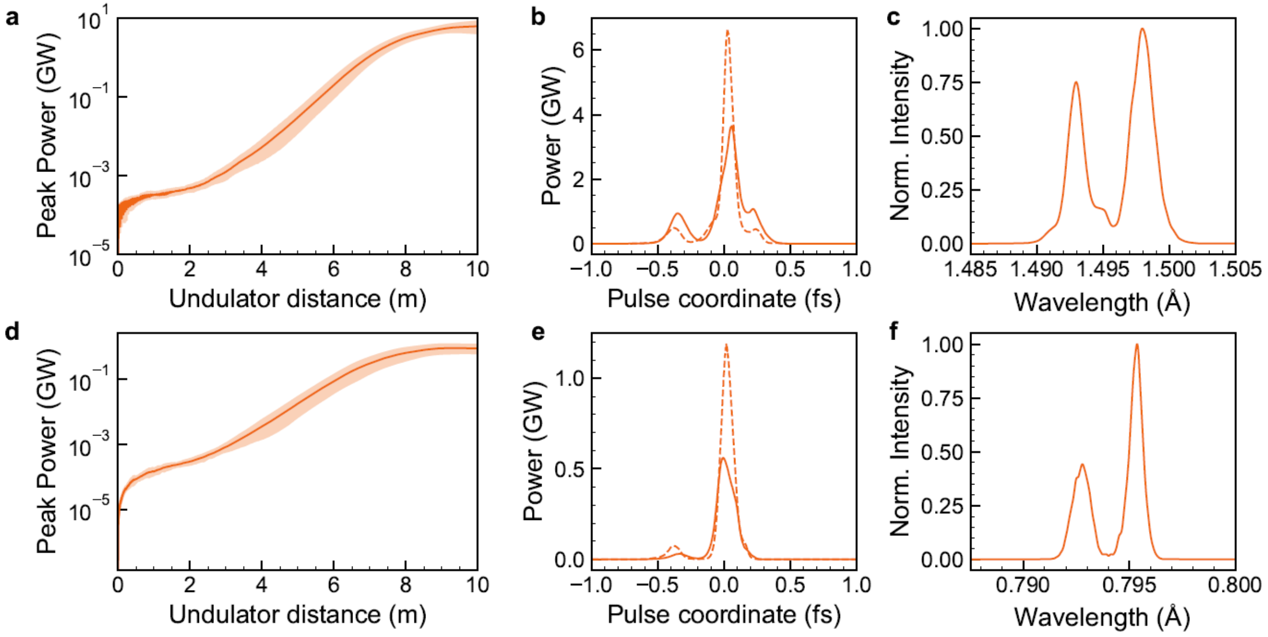


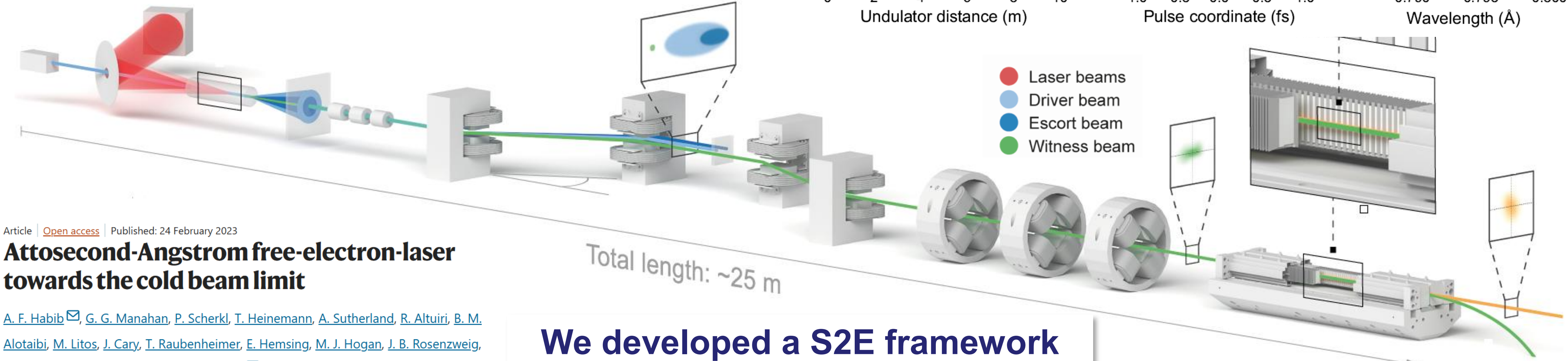
Ufer*…*et al.*, *under review*

- ❑ Realization of plasma photocathode in Hybrids LWFA→PWFA
- ❑ All-optical configuration
- ❑ Pathway towards ultra-compact and ultra-high brightness electron source

Ultra-compact attosecond-Ångstrom hard XFEL







Article | Open access | Published: 24 February 2023

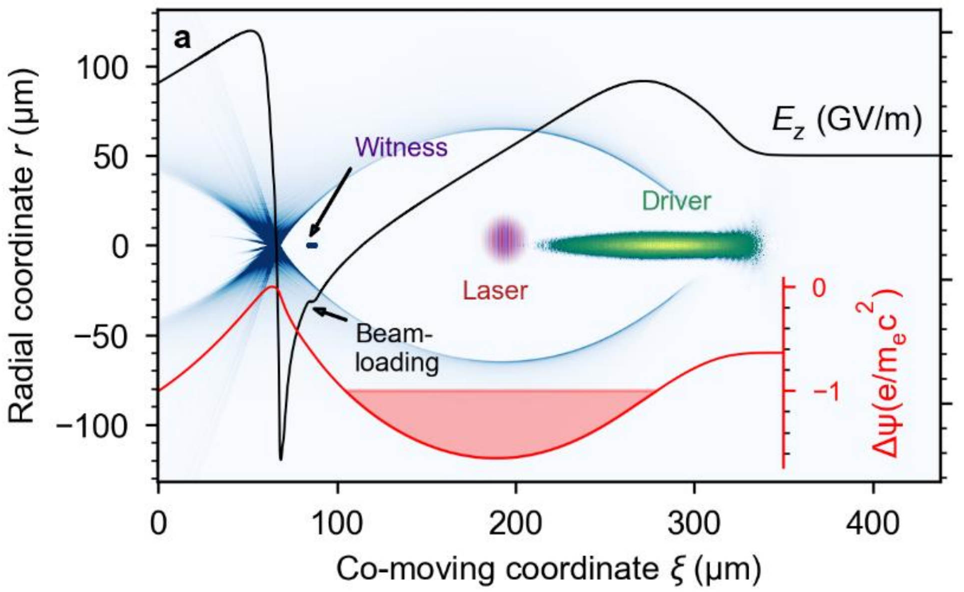
Attosecond-Angstrom free-electron-laser towards the cold beam limit

A. F. Habib, G. G. Manahan, P. Scherkl, T. Heinemann, A. Sutherland, R. Altuiri, B. M. Alotaibi, M. Litos, J. Cary, T. Raubenheimer, E. Hemsing, M. J. Hogan, J. B. Rosenzweig, P. H. Williams, B. W. J. McNeil & B. Hidding

Nature Communications **14**, Article number: 1054 (2023) | Cite this article

We developed a S2E framework for light sources

Ultra-compact water-window soft XFEL



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

arXiv > physics > arXiv:2507.06403v1

Search...
Help |

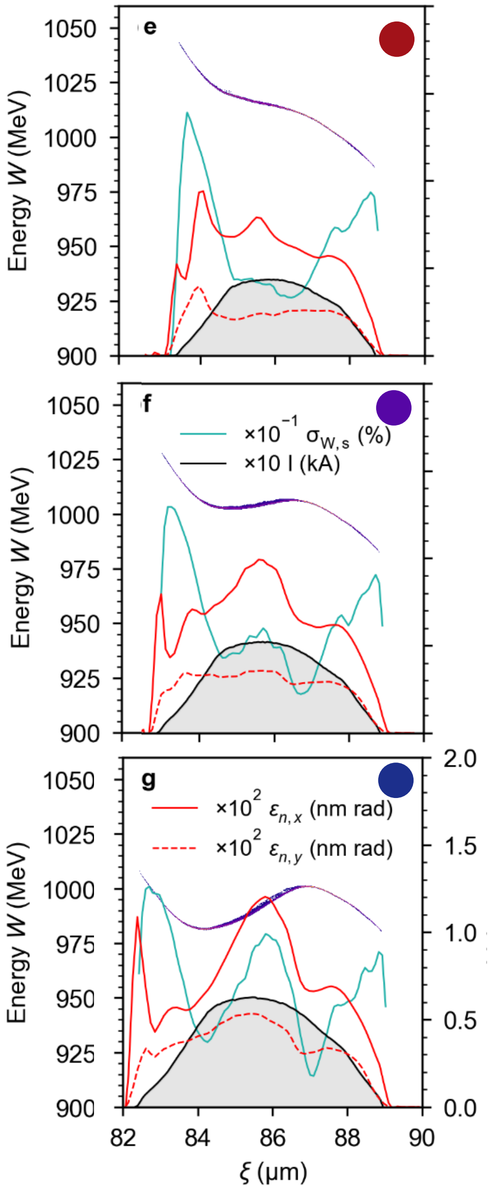
Physics > Plasma Physics

[Submitted on 8 Jul 2025]

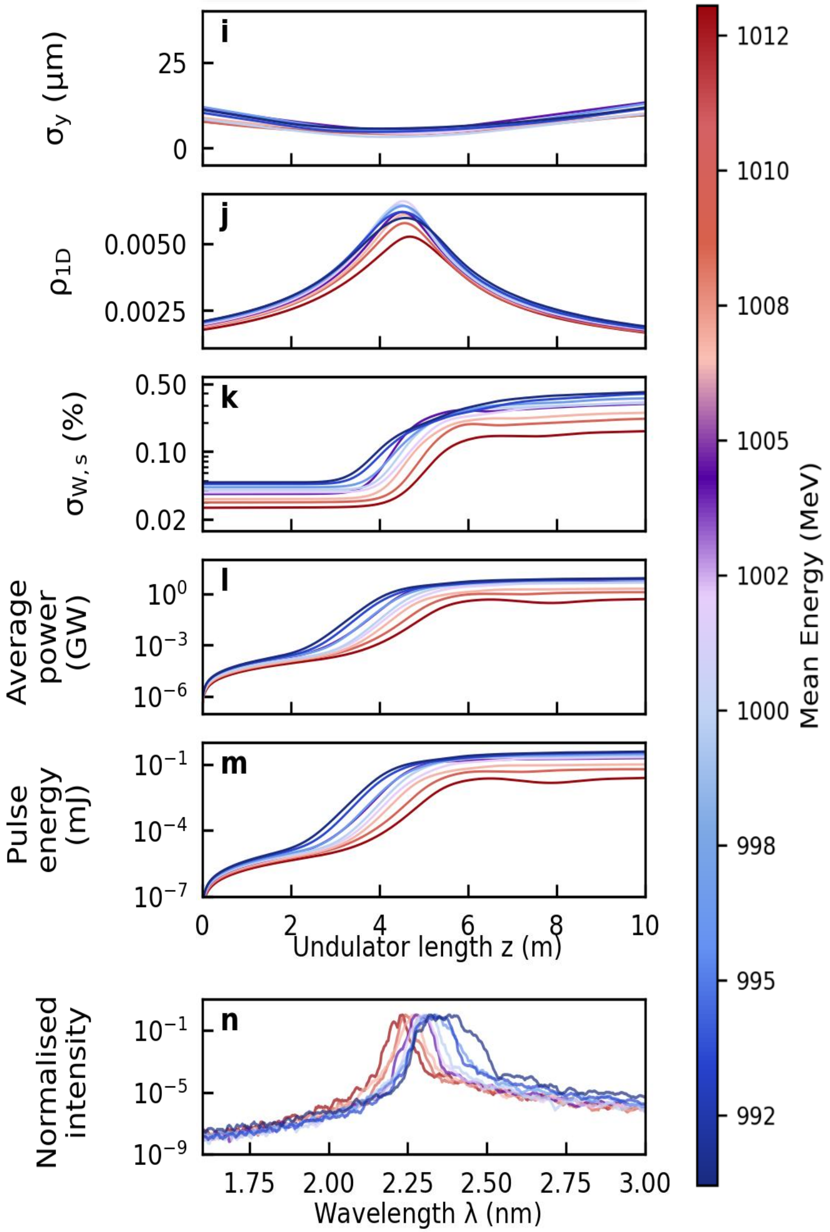
Ultra-high-gain water-window X-ray laser driven by plasma photocathode wakefield acceleration

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

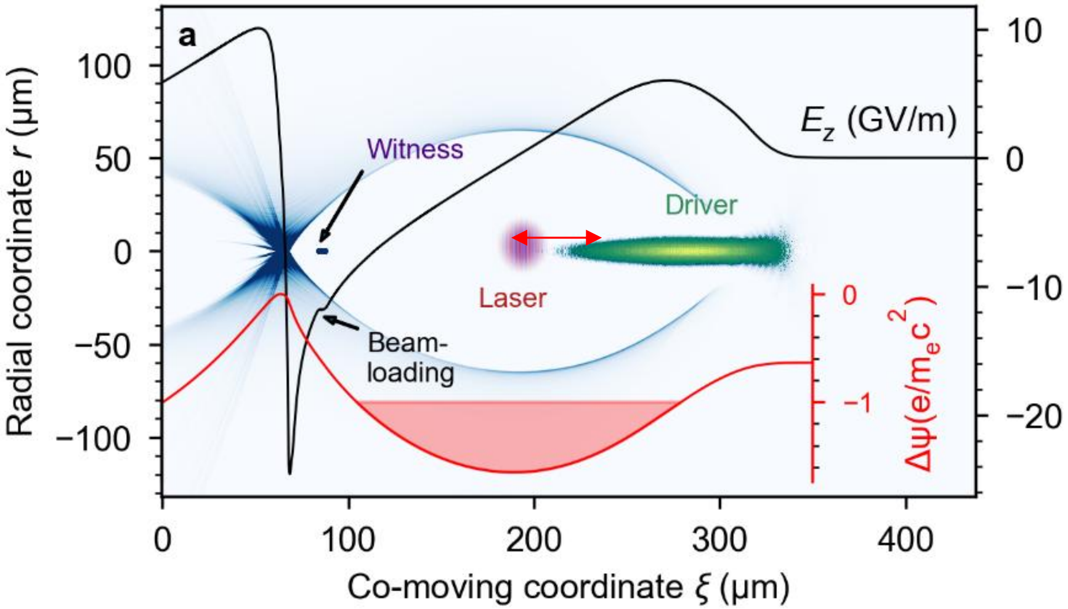
Plasma photocathode intensity tuning



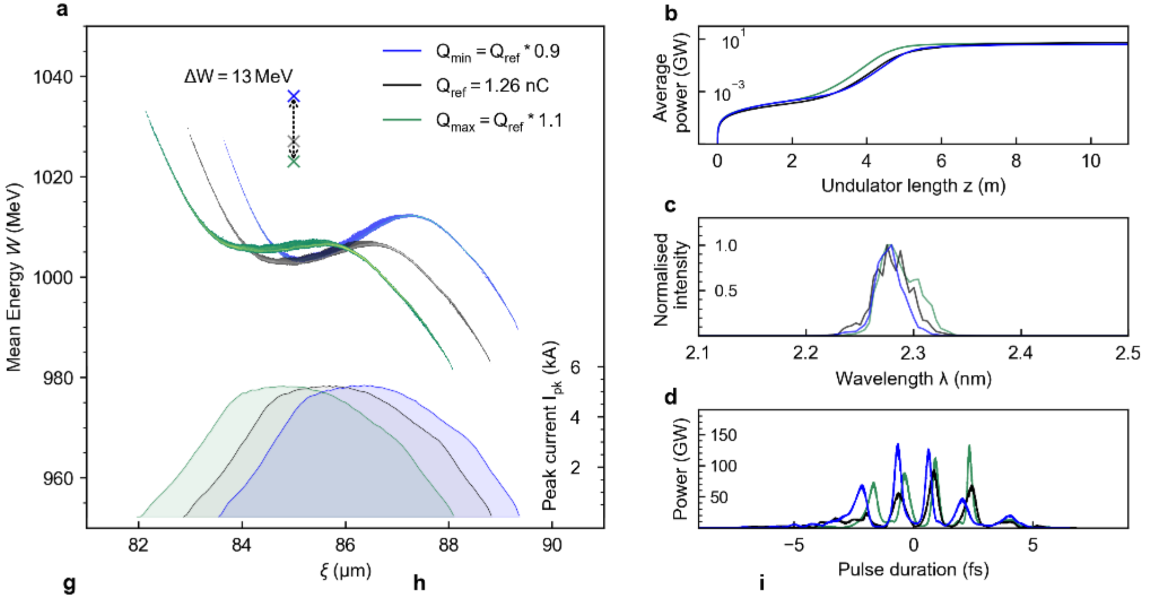
XFEL lasing



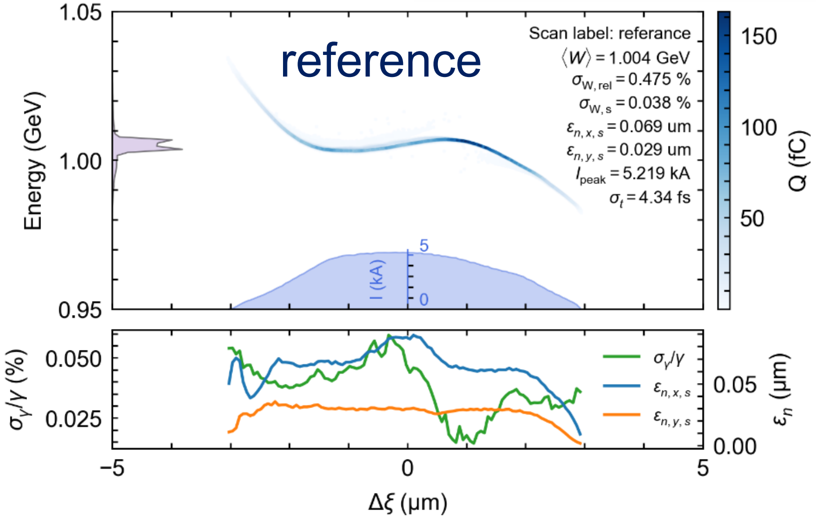
Shake the wake

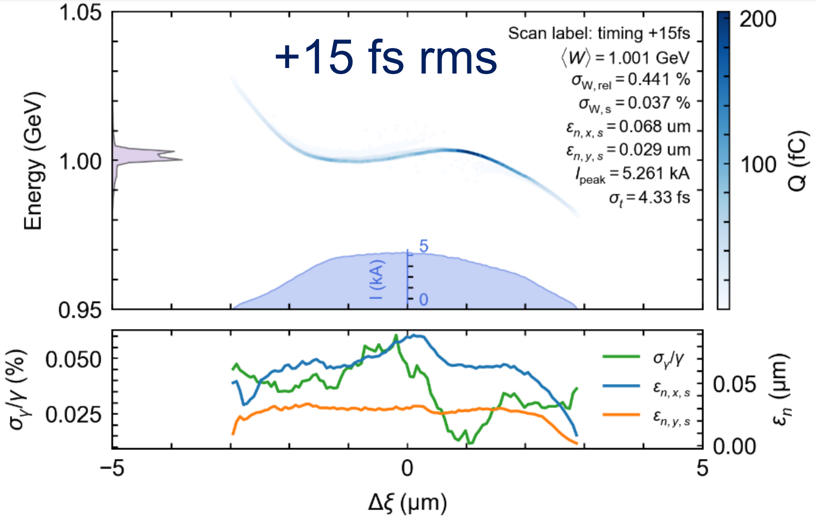


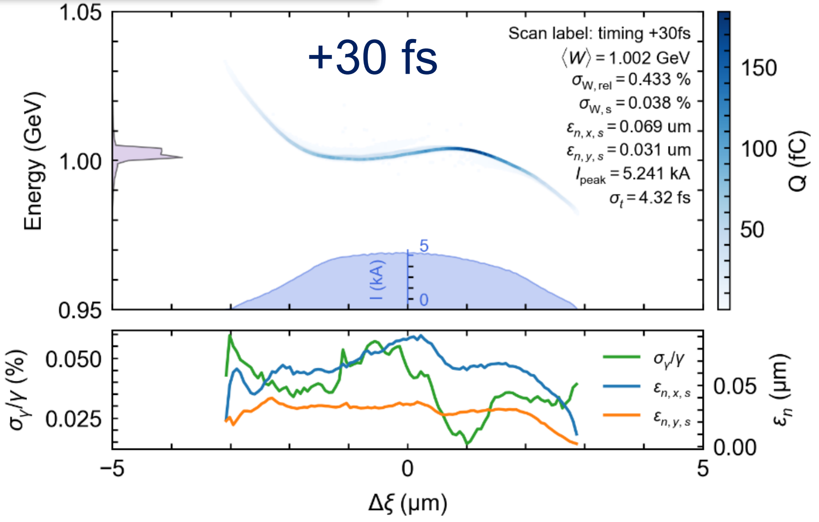
Driver charge jitter: 10 % charge jitter



Key witness beam parameter change by just few 0.01-0.1%





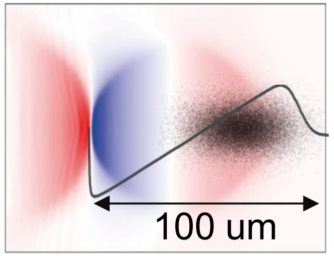


Prototyping plasma-based stages for XFEL linacs

Leverage advanced plasma-based acceleration

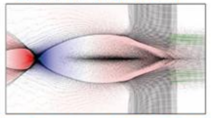
Enhance UK XFEL capabilities to meet user community requests

Particle-driven stage
PWFA

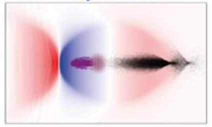


Accelerating gradient
~10-100 GV/m

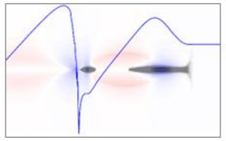
Optical downramp injection
aka Plasma torch



Plasma photocathode injection
aka Trojan Horse

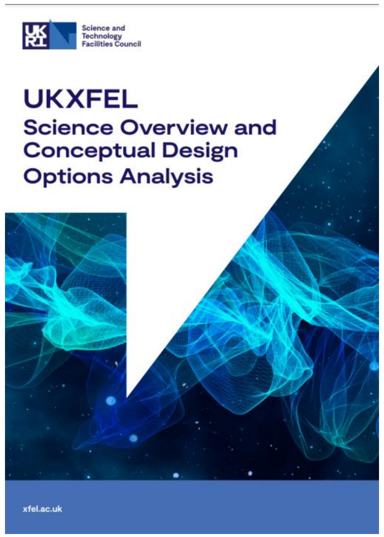


Two-bunch mode



Energy boost up to x 2-3 and brightness boost up to x 100000 via PWFA stage @UK XFEL

A pathway towards energy and brightness booster for the next generation of XFEL



Paper

9 September 2019

Plasma accelerator-based ultrabright x-ray beams from ultrabright electron beams

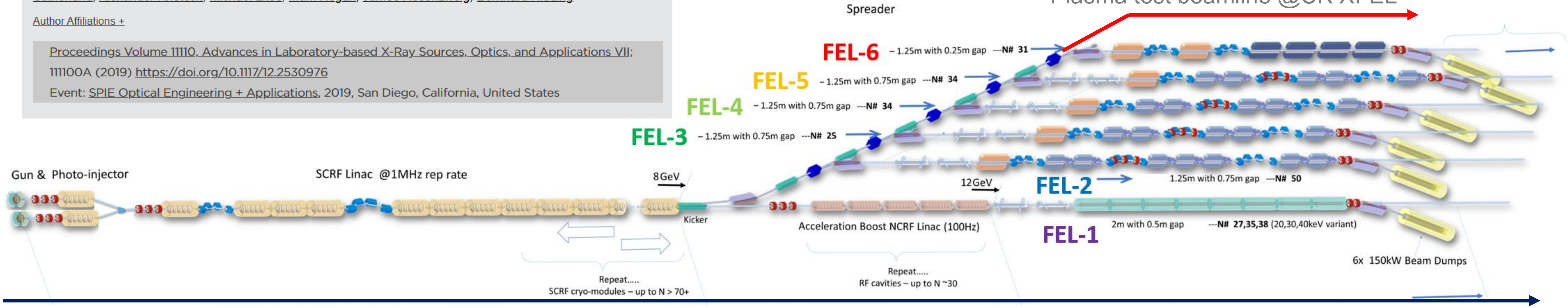
Ahmad Fahim Habib, Paul Scherkl, Grace Gloria Manahan, Thomas Heinemann, Daniel Ullmann, Andrew Sutherland, Alexander Knetsch, Michael Litos, Mark Hogan, James Rosenzweig, Bernhard Hidding

Author Affiliations +

Proceedings Volume 11110, Advances in Laboratory-based X-Ray Sources, Optics, and Applications VII; 111100A (2019) https://doi.org/10.1117/12.2530976

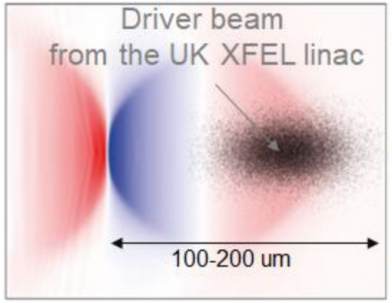
Event: SPIE Optical Engineering + Applications, 2019, San Diego, California, United States

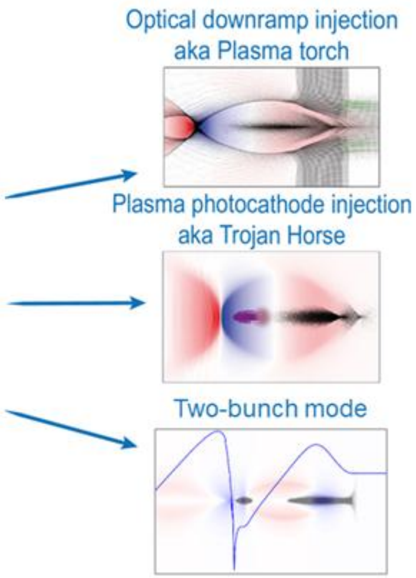
Plasma test beamline @UK XFEL



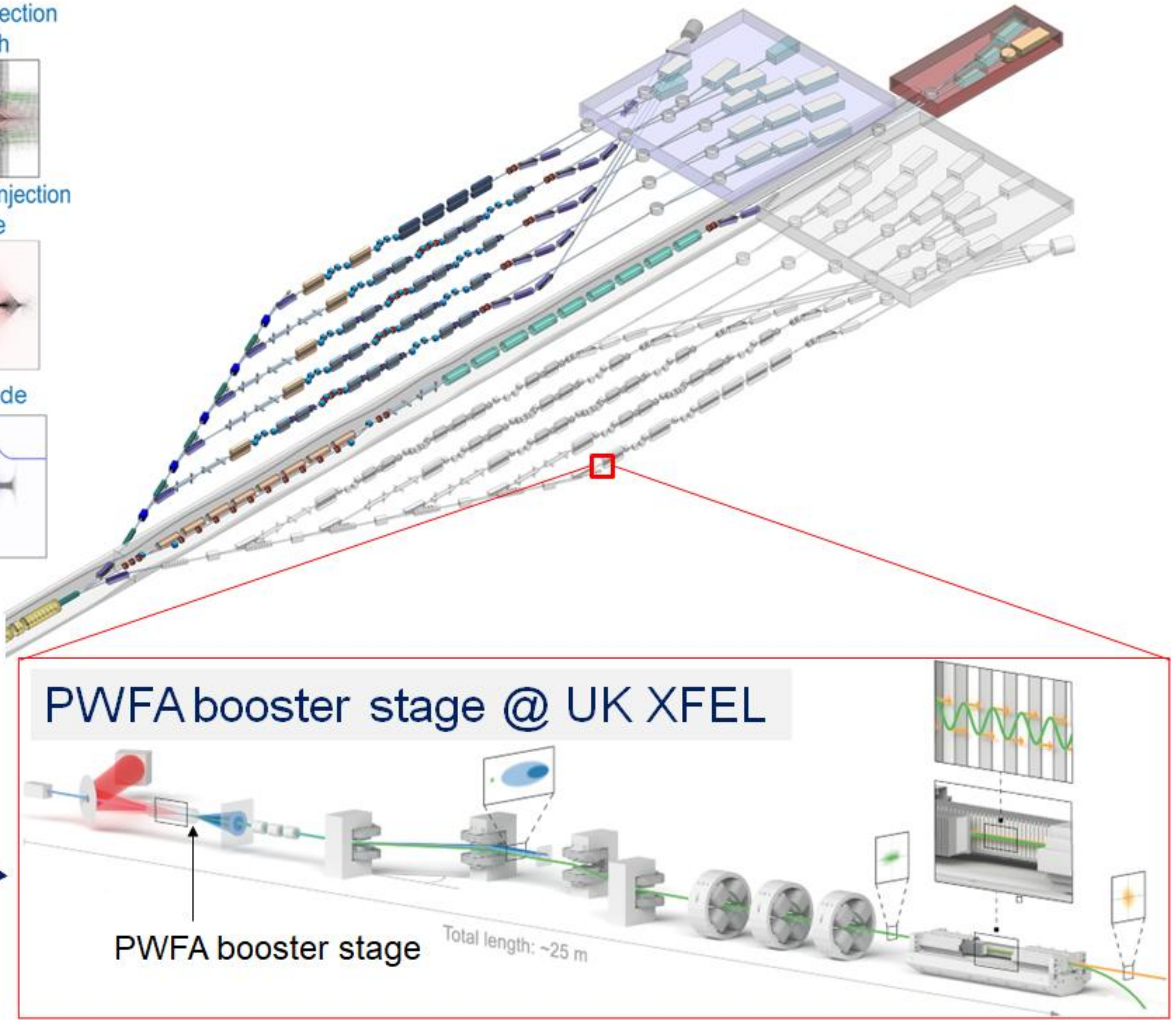
Plasma capabilities part of next-generation XFEL

Particle-driven stage
PWFA





PWFA energy and brightness booster stage



Plasma booster “dream” beam team: Fahim Habib, Lily Berman (CI Phd student), Alex Brynes, Dave Dunning, Brian McNeil, Deepa Angal-Kalinin,, Peter Williams, Ed Snedden et al.

Project Sponsor: John Collier
Science Lead: Jon Marangos
Technical Lead: Jim Clarke
Project Manager: Paul Aden

Science and Technology Facilities Council

Novel simulation framework for boosted plasma simulations

Future task: Bayesian optimisation of simulations, feedback loops and machine learning

x100 speed-up of optimization

Injection and acceleration phase

Fully explicit PIC codes: fbpic, VSim, WarpX

Acceleration phase

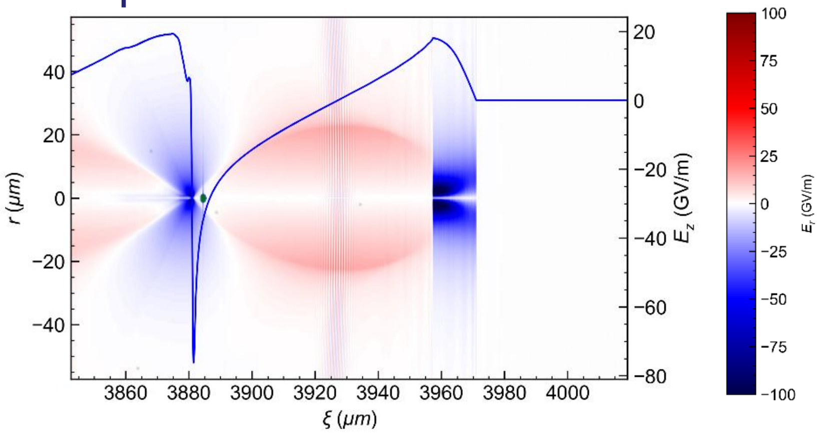
Reduced models (RM) with quasi-static approximation→ x100 speed-up

other codes

Beam transport, radiation modelling, FEL modelling, etc

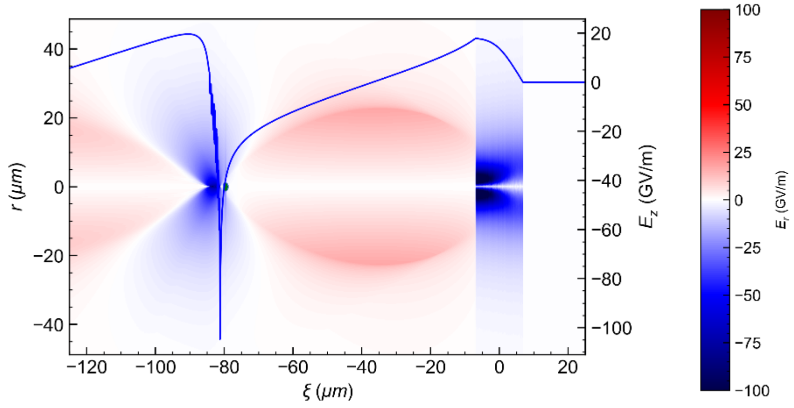
Current approach (PWFA XFEL paper Nat.Comm. 2023)
Viable approach for selected cases

fbpic simulation

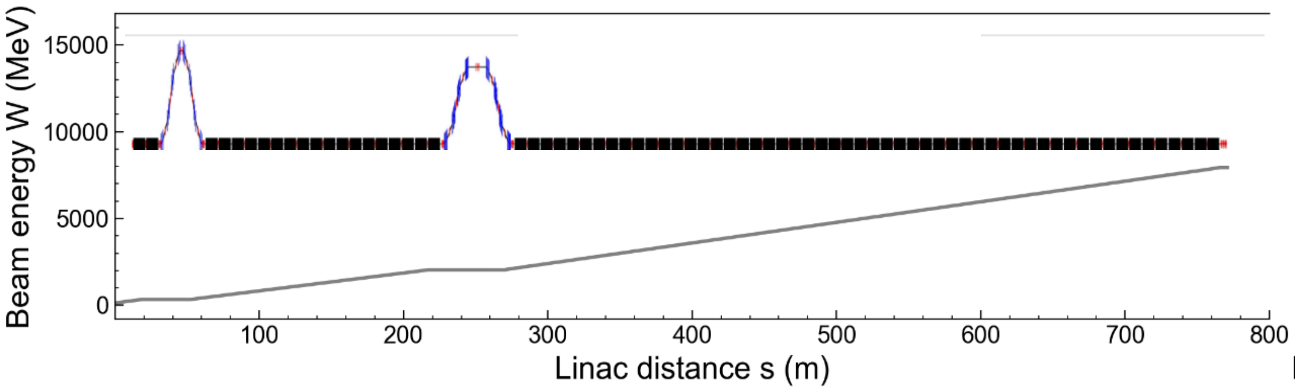


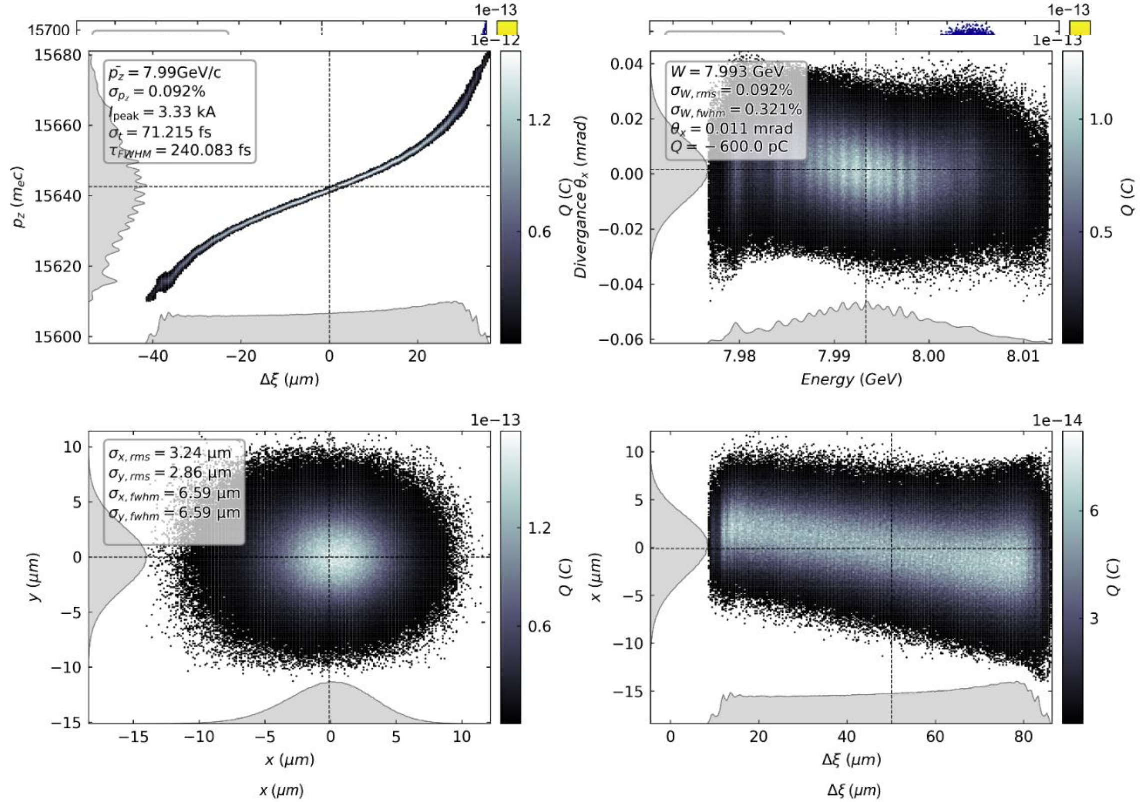
handshake

Wake-T simulation

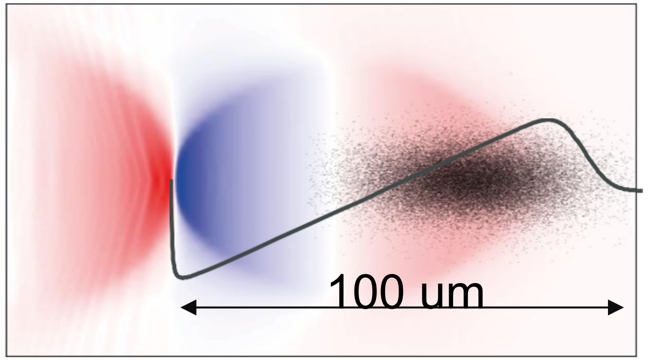


Exploring XFEL linac operation point for PWFA





Particle-driven stage
PWFA



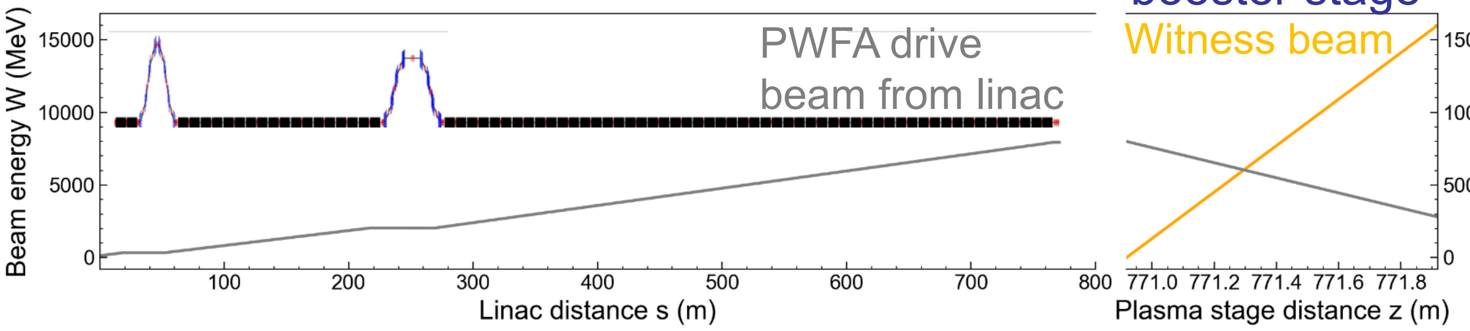
Accelerating gradient
~10-100 GV/m

- ❑ Electron beams from realistic linac simulation give great inside into the plasma response and PWFA stage
- ❑ Controlling spatiotemporal correlations in the beam is very challenging but has a huge impact on the PWFA stage
- ❑ Key contribution to the spatiotemporal correlations in the beam is CSR kicks in the chicanes

Plasma booster stages for UK XFEL

8 GeV UK XFEL linac

PWFA booster stage

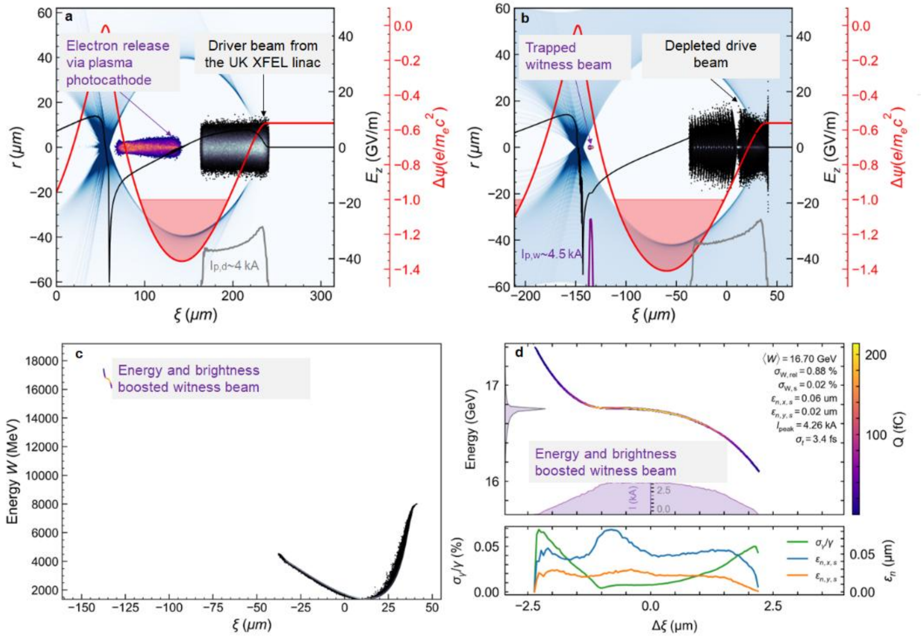


~1 m

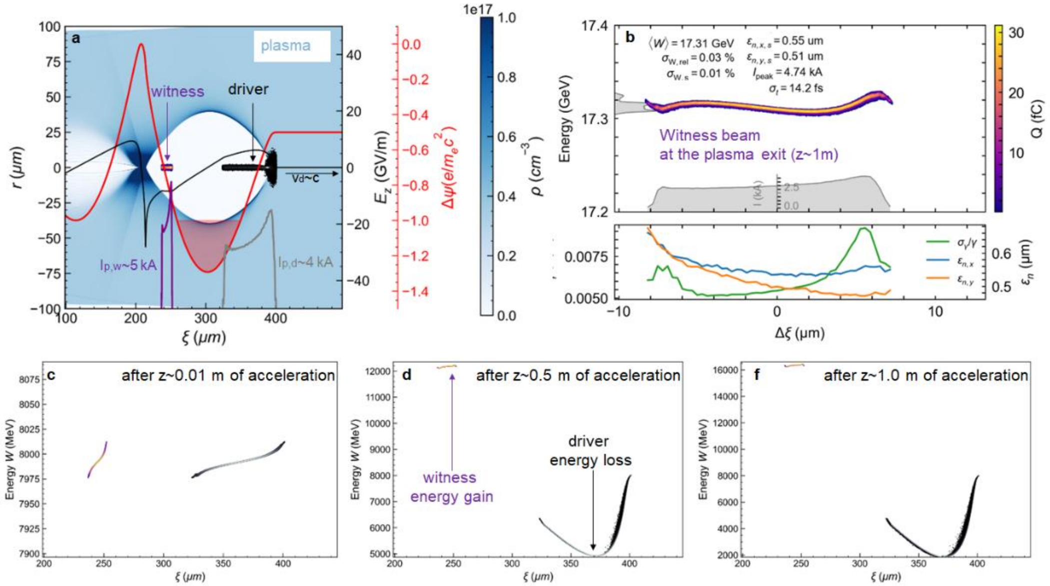
Linac simulations credit: **Alex Brynes** & Peter Williams et al.

- ❑ UK XFEL linac produces electron beams suitable for PWFA
- ❑ High-gradient PWFA stages for double-bunch and plasma photocathode injections are possible
- ❑ Energy and brightness booster stages explored

Plasma photocathode PWFA stage

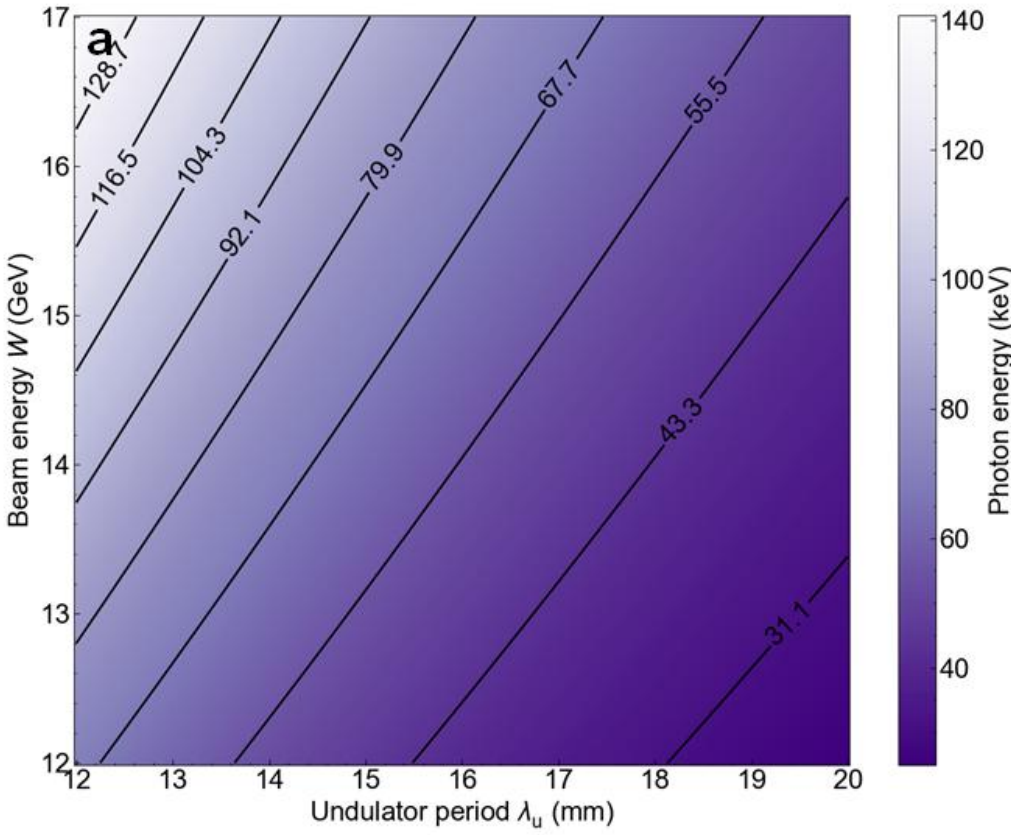


Double bunch PWFA stage

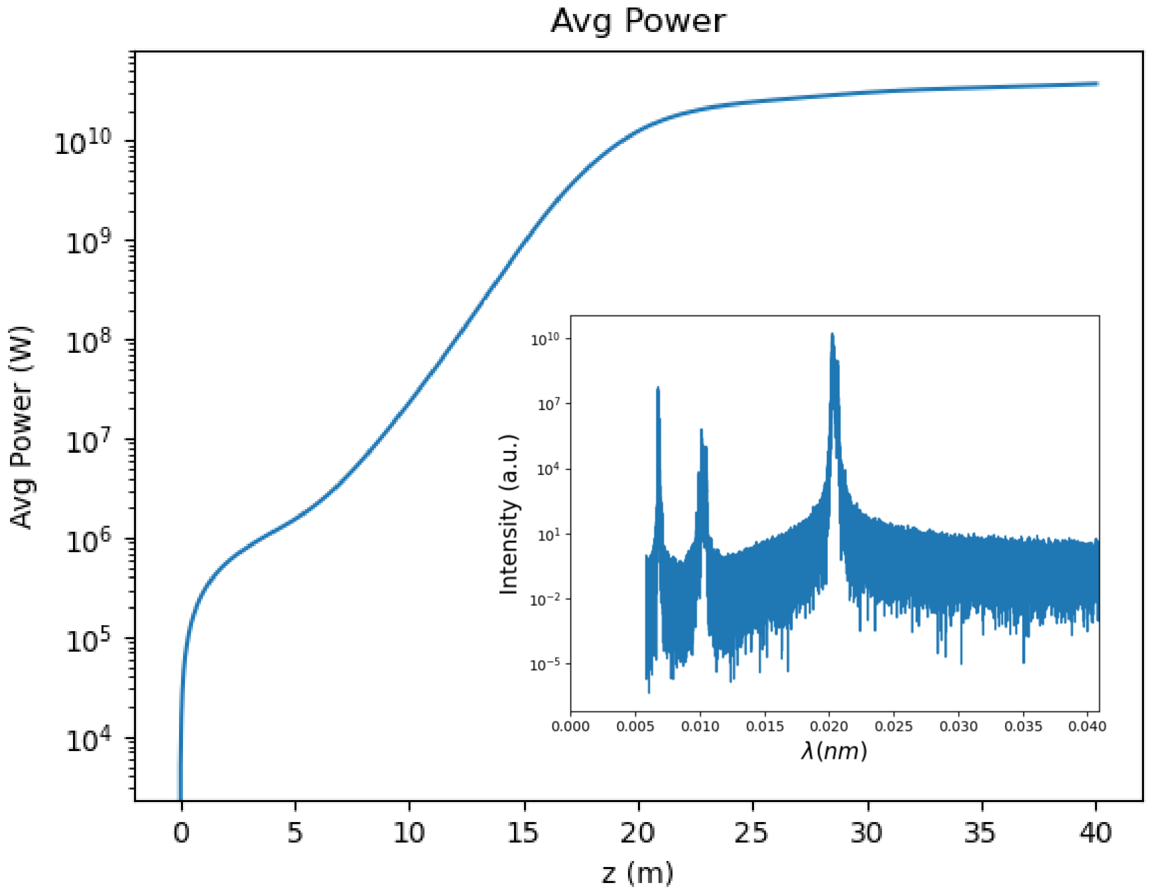


Lasing at very hard photon energies and beyond

60 keV photon energy lasing and saturation! Higher harmonics up to 180 keV

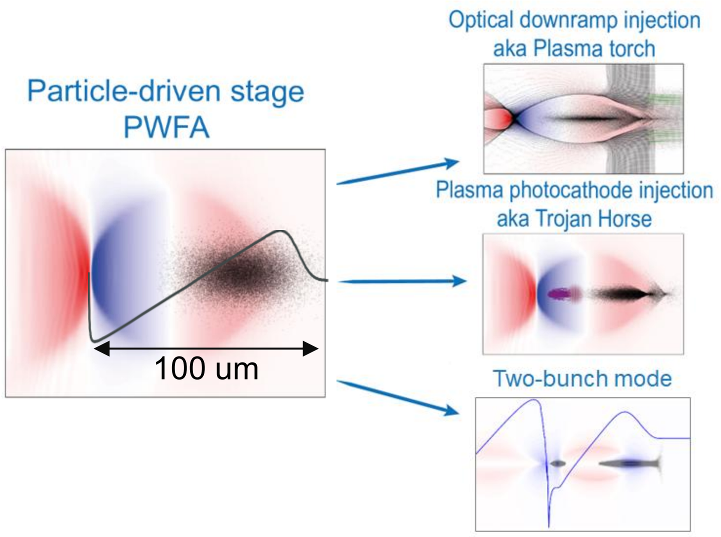


Habib et al. Nat. Comm. 14, 1054 (2023)
Habib et al. Annalen der Physik 535.10,p. 2200655 (2023)

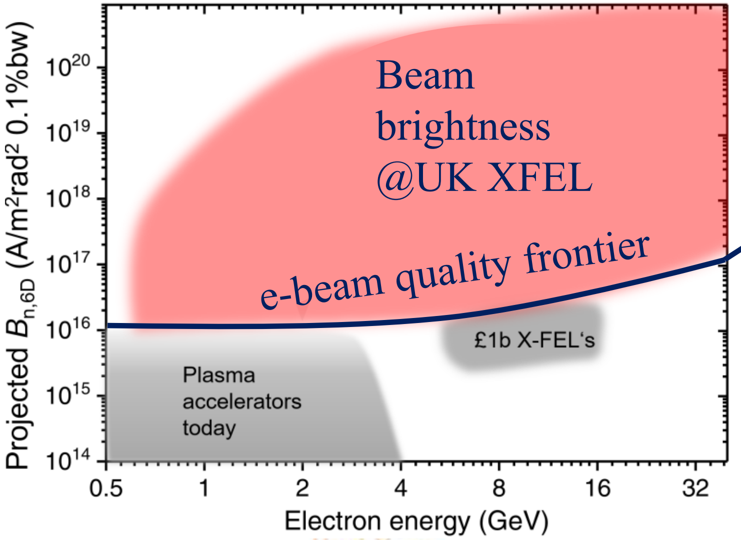


A. F. Habib, L. Berman, *et al., paper in prep (*2025)

Application of next-generation extreme electron beams

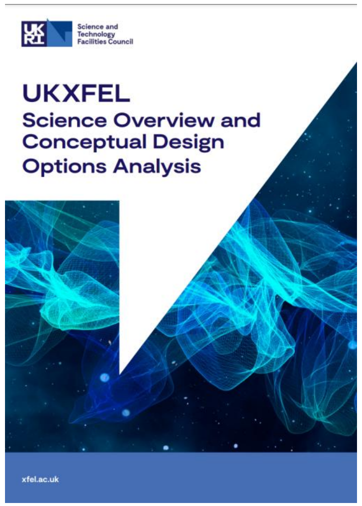


Beam brightness and energy booster stage

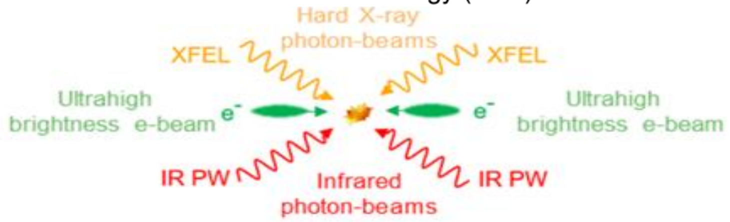


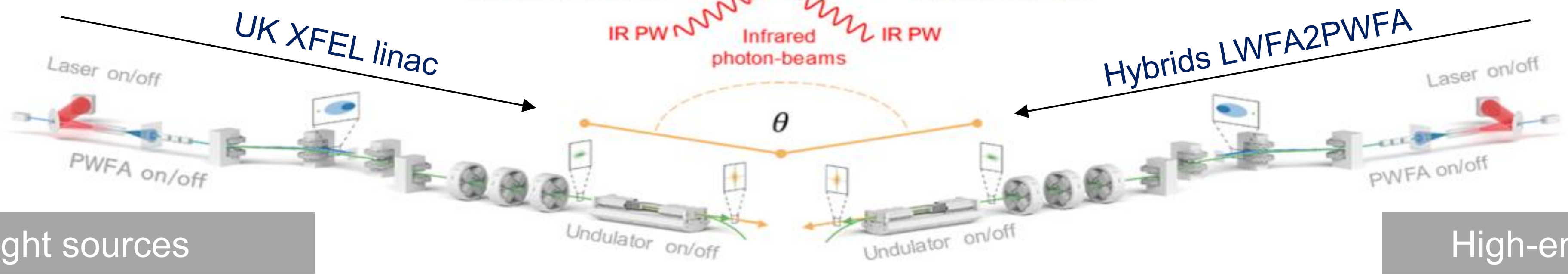
Energy boost up to x 2-3 and brightness boost up to x 100000 via PWFA stage @UK XFEL

A pathway towards energy and brightness booster for the next generation of XFEL



Habib et al. Nat. Comm. 14, 1054 (2023)
Habib et al. Annalen der Physik 535.10,p. 2200655 (2023)





Light sources

- ❑ Plasma-XFEL and QFEL for coherent photons at >20 keV
- ❑ ICS incoherent MeV photons
- ❑ Novel modalities in life science
- ❑ and more…

High-Field physics

- ❑ Extreme electron beam densities
- ❑ Strong-field/nonlinear QED
- ❑ Investigation of Photon-Photon physics (colliding photons)

High-energy physics

- ❑ PWFA staging R&D towards plasma-based linear collider
- ❑ Use nm-rad emittances beams as emittance growth probes

Take home messages

- UK community has strategically developed recipes for ultrahigh beam production
- UK XFEL CDR-OA: R&D for plasma wakefield acceleration, and in turn potential plasma-based capability boosts foreseen
- We reached key milestones modelling soft X-ray, attosecond-Ångstrom and very hard X-FEL: Foreseen decision point reached to escalate to larger R&D project
- Experimental efforts on realizing the full potential of plasma photocathodes in PWFA takes momentum at FACET-II (E31x collaboration)
- Pathway towards gamma-ray FEL becomes increasingly tangible

University of Strathclyde Glasgow

Thanks

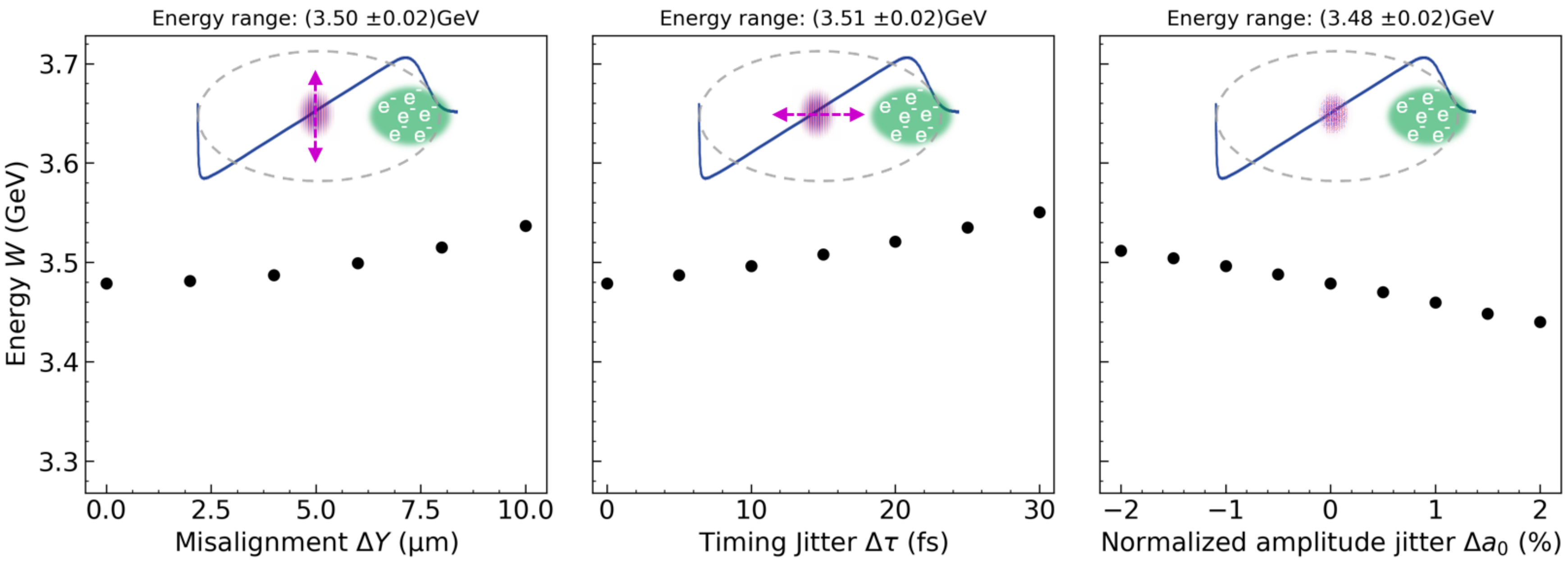
Have a bright EAAC

UKRI Science and Technology Facilities Council

UKRI Science and Technology Facilities Council ASTeC

The Cockcroft Institute of Accelerator Science and Technology

Stability analysis



Conservative jitter parameters

- Temporal offset: 0-30 fs
- Transverse offset: 0-10 μm
- Focus laser intensity a_0: 0-2%

Beam parameter stability

- Key propartíes show % to sub-% level stability
- Path towards stability levels for FEL and HEP applications
- Beam energy stability within beam transport tolerances
- Huge improvment potential considering state-of-the-art synchronization limits
- Deliberately misaligning injector laser for flat beams

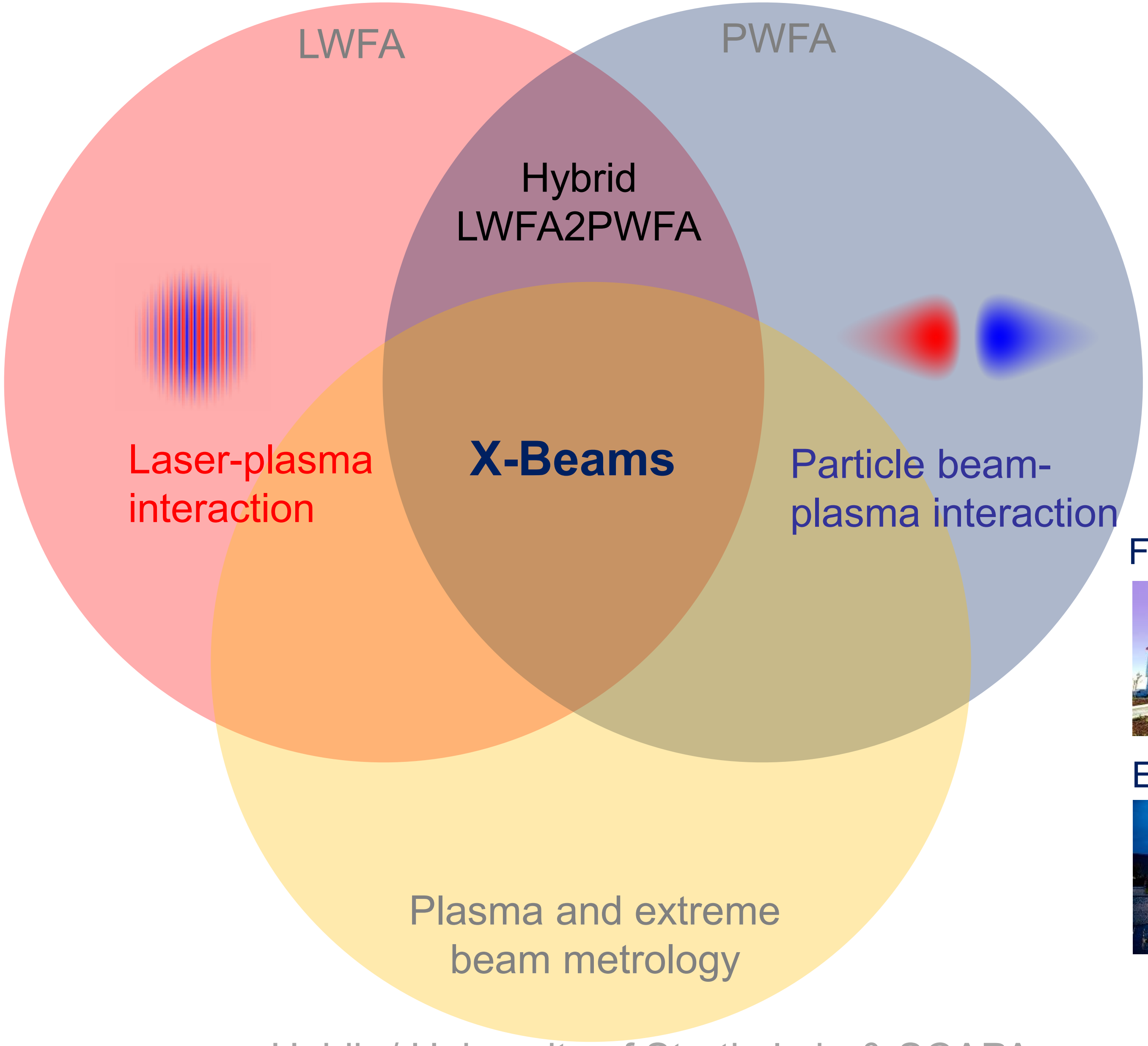
TABLE I. Witness beam parameter summary of plasma photocathode laser jitter analysis.

Beam parameter	Pointing jitter ΔX	Timing jitter $\Delta\tau$	Laser amplitude jitter Δa_0
Energy W (MeV)	72.15 ± 0.59	72.38 ± 0.69	71.69 ± 0.68
Energy spread (%)	1.41 ± 0.05	1.52 ± 0.11	1.38 ± 0.15
Charge (pC)	2.371 ± 0.005	2.375 ± 0.006	2.41 ± 0.42
Peak current I_p (kA)	1.32 ± 0.21	1.23 ± 0.21	1.56 ± 0.11
Bunch length (μm)	0.19 ± 0.03	0.22 ± 0.04	0.17 ± 0.02
Normalized emittance $\epsilon_{n,x}$ (nm rad)	29.91 ± 11.80	15.11 ± 0.13	15.17 ± 1.77
Normalized mittance $\epsilon_{n,y}$ (nm rad)	15.38 ± 0.48	15.51 ± 0.12	15.66 ± 1.90
5D brightness ($\times 10^{18}$ A m^{-2}rad^{-2})	7.11 ± 3.66	10.45 ± 1.65	13.5 ± 2.40

X-Beams - eXtreme beams for fundamental science & applications
Realization of X-Beams @national facilities

CLF EPAC @RAL

SCAPA lab @Strathclyde



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Strong International links