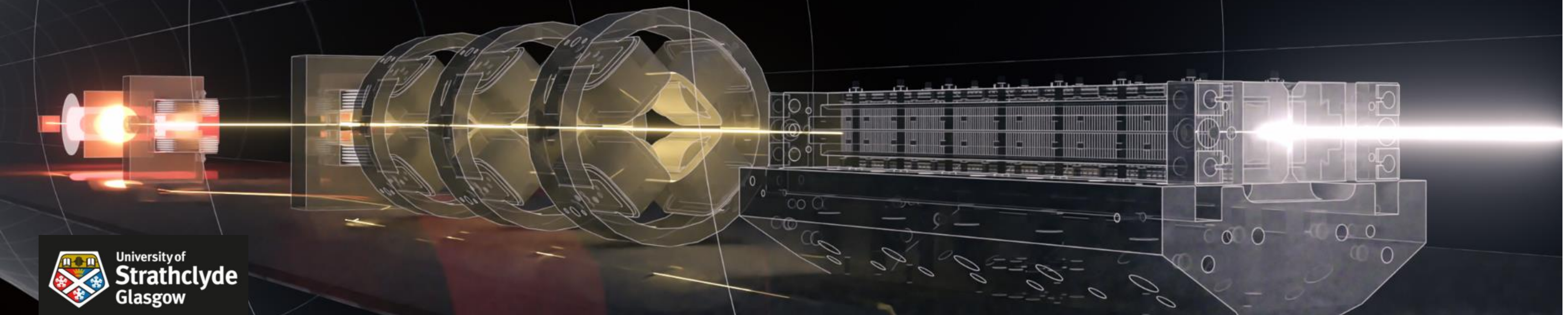
4th CLARA User Meeting
2024-12-03, Daresbury Laboratory

Fahim Habib,
Constantin Aniculaesei, Arie Irman (HZDR), Grace Manahan,
Thomas Pacey, Lewis Reid et al.

Real-time PWFA metrology



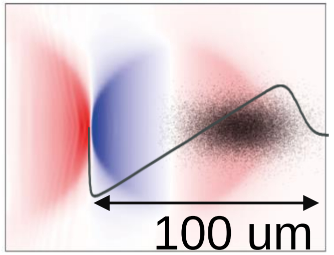
Department of Physics, University of Strathclyde
Scottish Centre for the Application of Plasma-Based Accelerators (SCAPA)
Scottish Universities Physics Alliance (SUPA)
The Cockcroft Institute

Prototyping plasma-based stages for the UK XFEL project

Leverage advanced plasma-based accleration

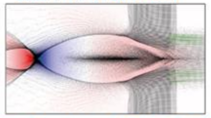
Enhance UK XFEL capabilities

Particle-driven stage
PWFA

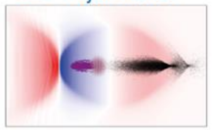


Accelerating gradient
~10-100 GV/m

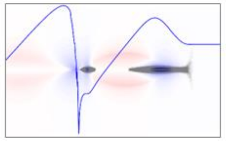
Optical downramp injection
aka Plasma torch



Plasma photocathode injection
aka Trojan Horse

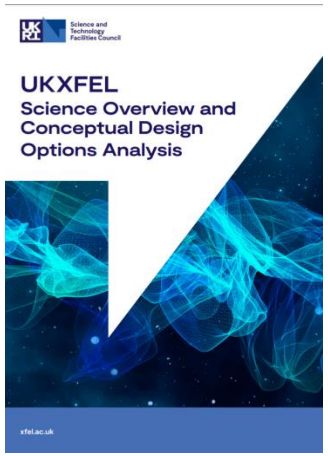


Two-bunch mode



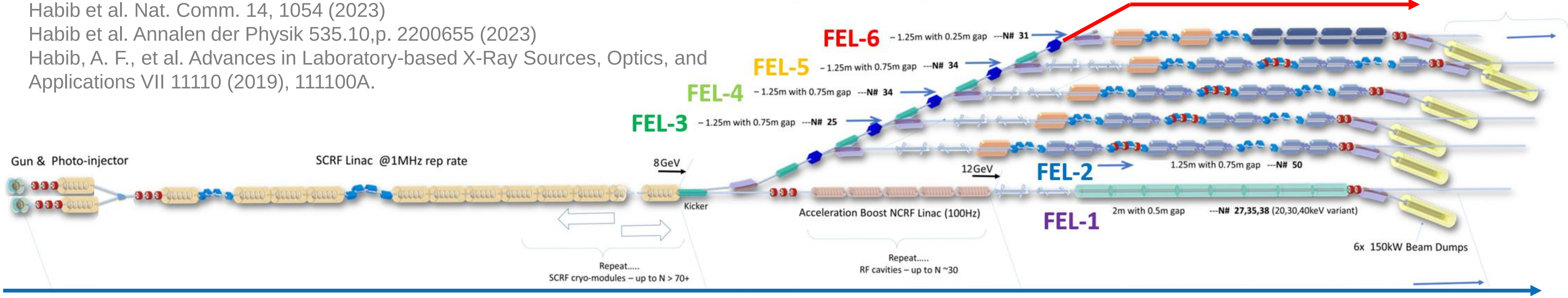
Energy boost up to x 2-3 and brightness boost up to x 100000 via PWFA stage @UK XFEL

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



Habib et al. Nat. Comm. 14, 1054 (2023)
Habib et al. Annalen der Physik 535.10,p. 2200655 (2023)
Habib, A. F., et al. Advances in Laboratory-based X-Ray Sources, Optics, and Applications VII 11110 (2019), 111100A.

Electron beamline @UK XFEL



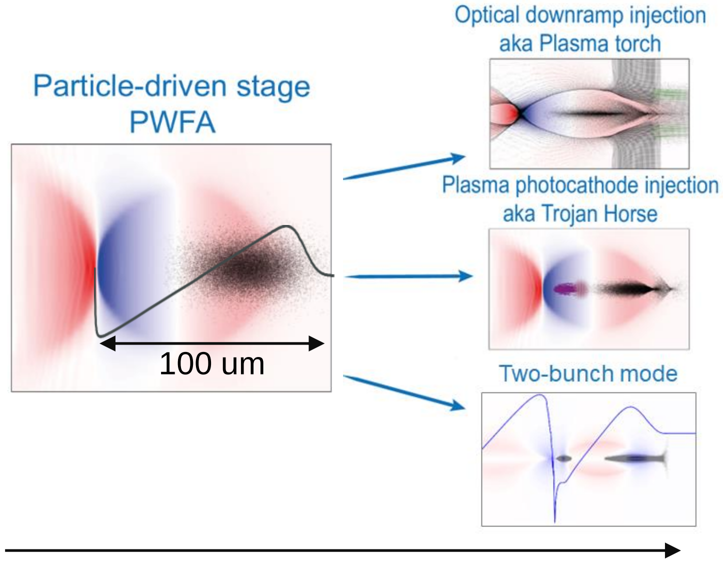
A preliminary UK XFEL layout options

Plasma-booster team:
Fahim Habib, Lily Berman, David Dunning, Brian McNeil, Ed Snedden, Peter Williams et al.

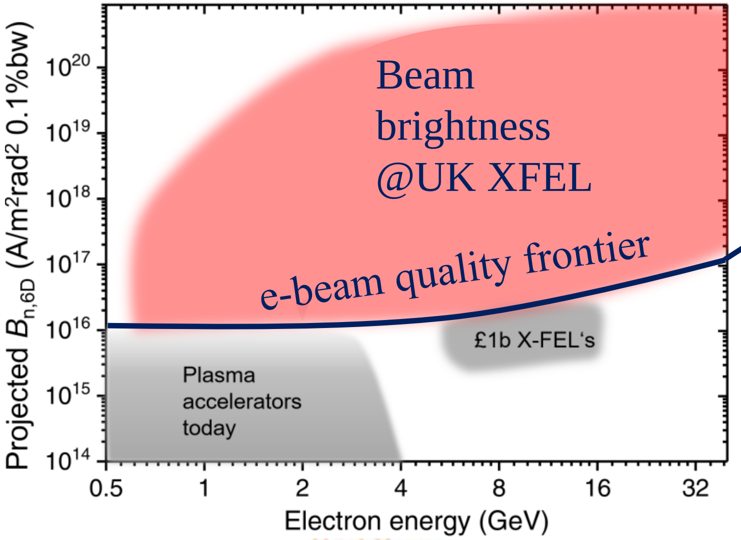
UKRI Science and Technology Facilities Council

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

Application of next-generation of electron beams @UK XFEL



Beam brightness and energy booster stage



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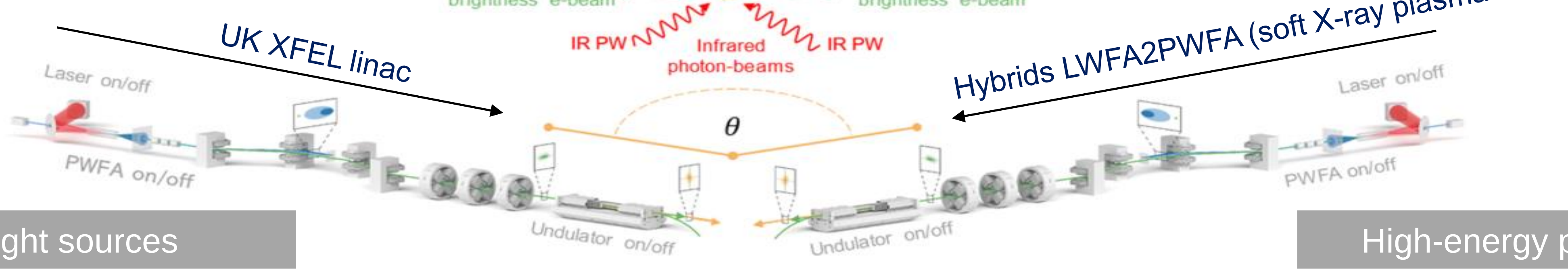


Light sources

- 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

Receipt for a high-brightness PWFA stage

Prototyping high brightness PWFA stage @ CLARA FEBE?

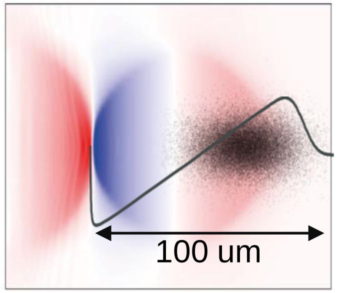
What are the key ingredients for a high-brightness PWFA stage?

Parameter	High charge
Energy [MeV]	250
Charge [pC]	250
RMS t [fs]	100
σ_E/E [%]	<5
RMS x [µm]	100
RMS y [µm]	100
ε_N x [µm]	5
ε_N y [µm]	5

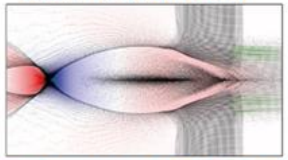
At compressor exit	
wavelength	807 nm
Peak Power	122 TW
Energy	2.8 J
τ_{FWHM}	23 fs
Rep Rate	5 Hz
w_{FWHM}	73 mm
Strehl ratio	0.90
Pointing stability	3 µrad
Energy stability	1%

How to get there?

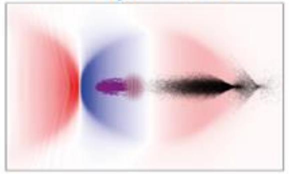
Particle-driven stage PWFA



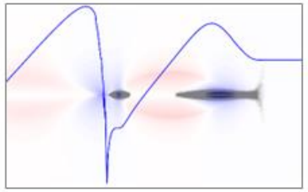
Optical downramp injection aka Plasma torch



Plasma photocathode injection aka Trojan Horse



Two-bunch mode



Reliable electron driver beam

Plasma source

Computational methods

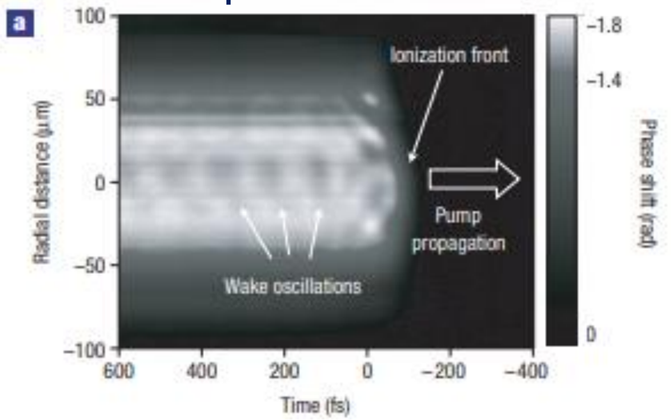
High-power laser system

Electron beam and plasma diagnostics

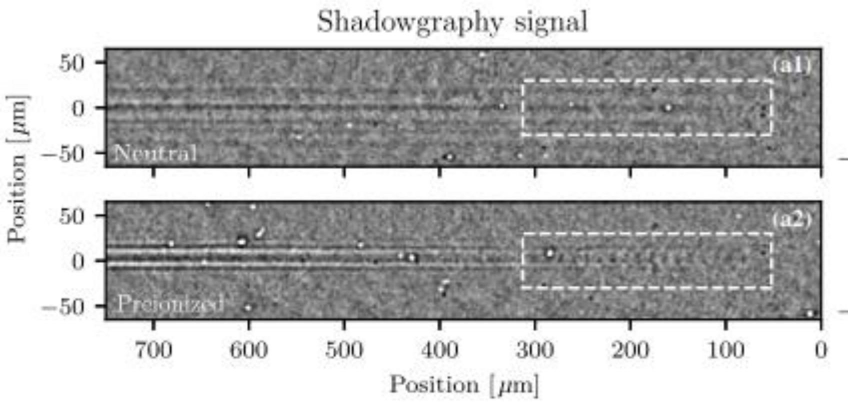
We need real-time PWFA metrology

What diagnostics do we have for PWFA metrology?

Few cycle laser pulse-based shadowgraph
Effective at plasma densities >1.0 × 10^{18} cm^{-3}

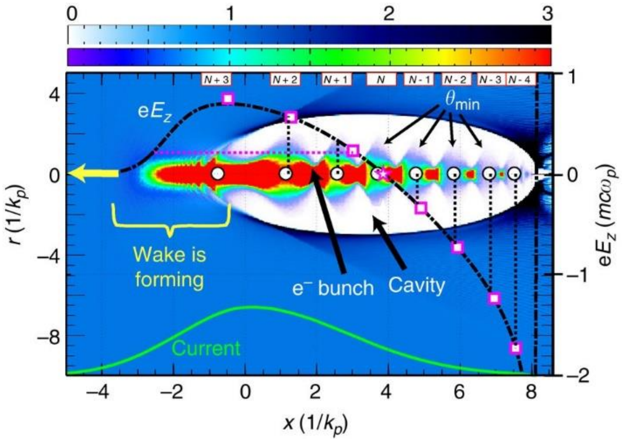


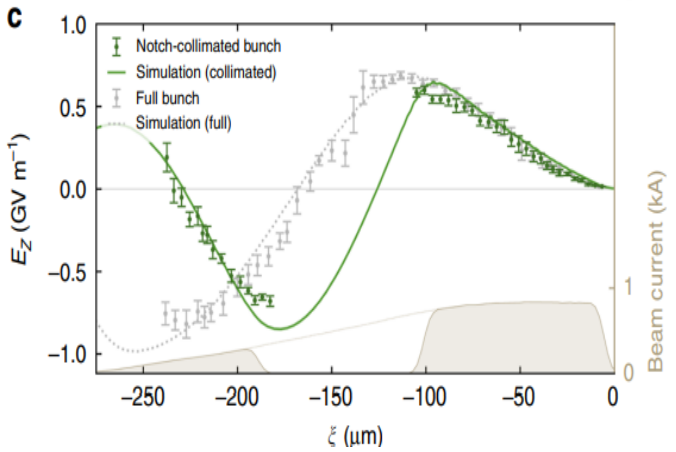
Matlis, N., et al. Nature Phys **2**, 749–753 (2006)
Buck, M. et al . Nat. Phys. 7, 543–548 (2011)
Sävert, A et al.Phys. Rev. Lett. 115, 055002 (2015)



Gilljohann, M. F., et al. *Physical Review X* 9.1 (2019): 011046.

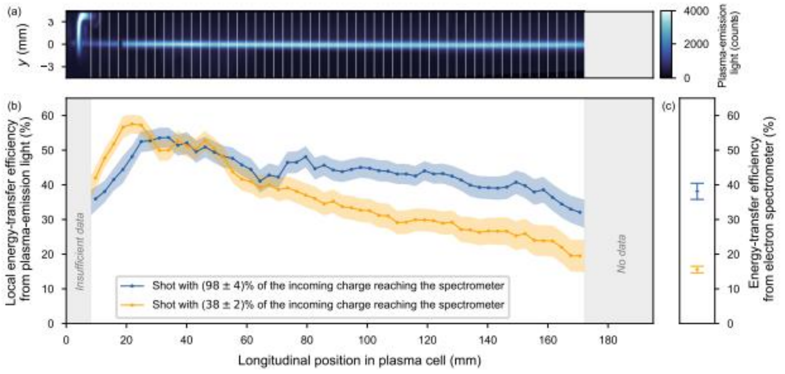
Methods based on trailing bunch probing





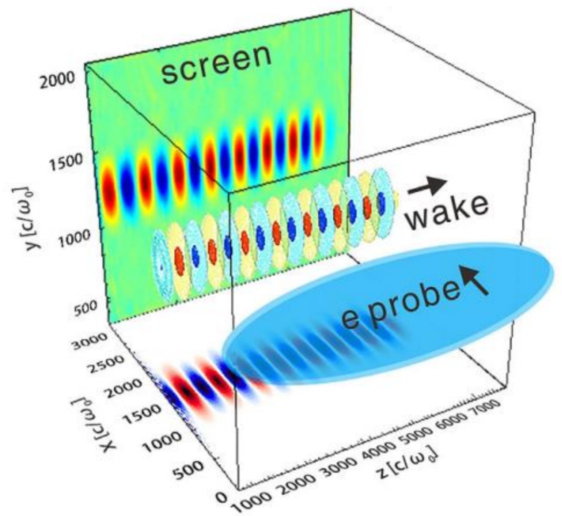
Litos, M., et al. Nature 515, 92–95 (2014)
Clayton, C. E. et al. Nature communications 7, 12483 (2016)
Schröder, S., Lindstrøm, C.A., Bohlen, S. et al. Nat Commun 11, 5984 (2020)

Using the plasma glow as plasma stage diagnostics



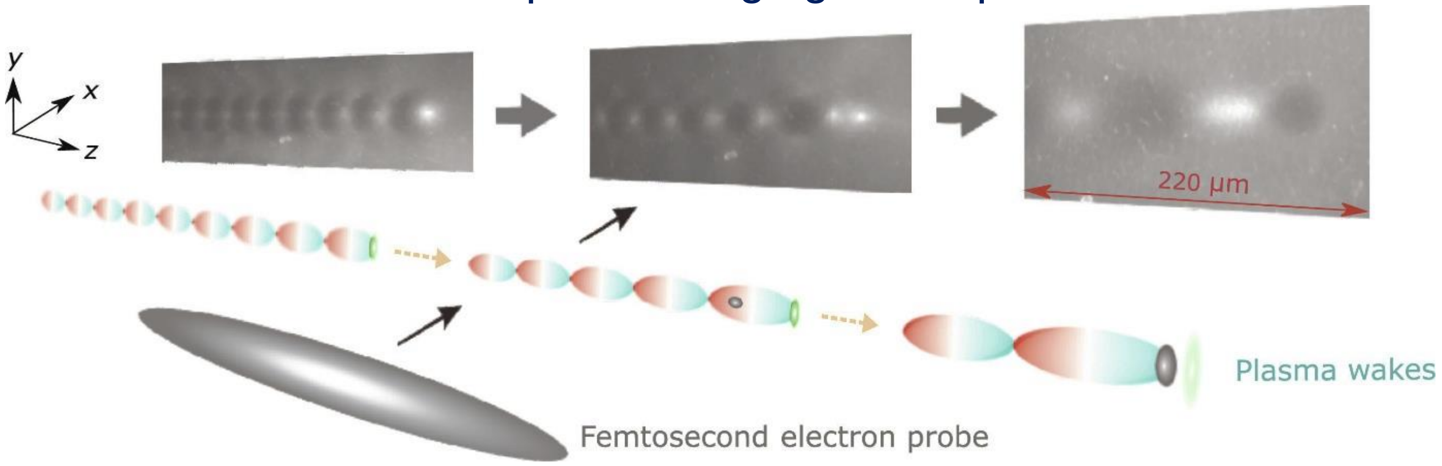
E. Oz *et al*., "Plasma Light diagnostic for PWFA at SLAC," *The 31st IEEE International Conference on Plasma Science, 2004. ICOPS (2004)*
Scherkl, P. et al.. Phys. Rev. Accel. Beams 25, 052803 (2022)
L. Boulton *et al.* arXiv:2209.06690v1 (2022)

PWFA metrology via electron beam probes

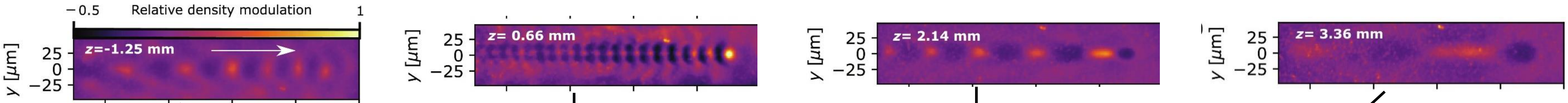


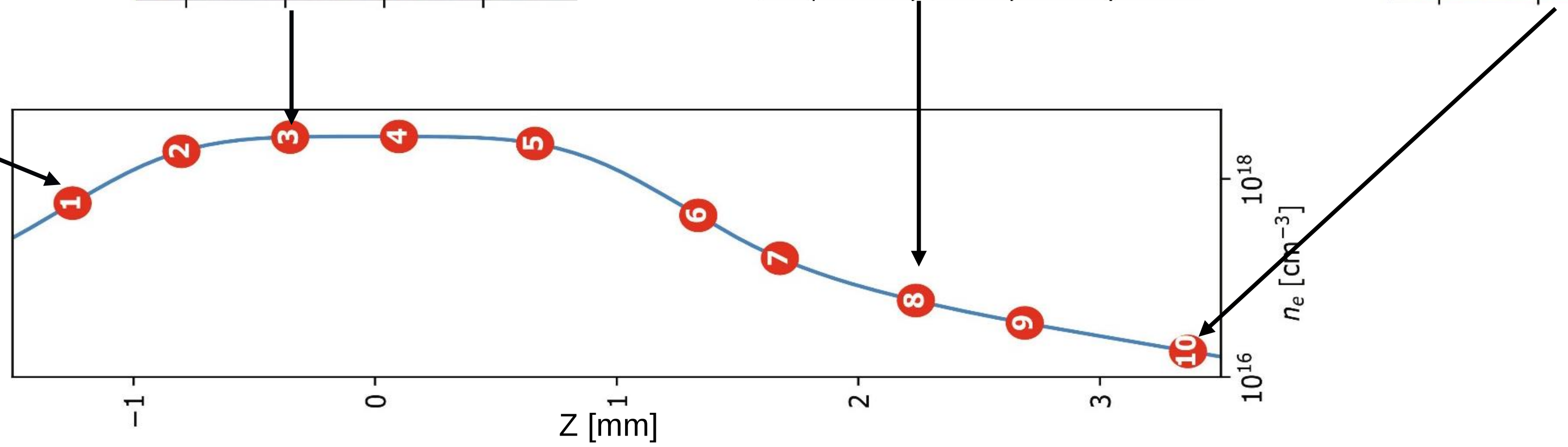
Zhang, C., Hua, J., Xu, X. et al. Sci Rep **6**, 29485 (2016)
Zhang, C, Phys. Rev. Lett. **119**, 064801 (**2017)**

Electron beam probe imaging of the plasma wave



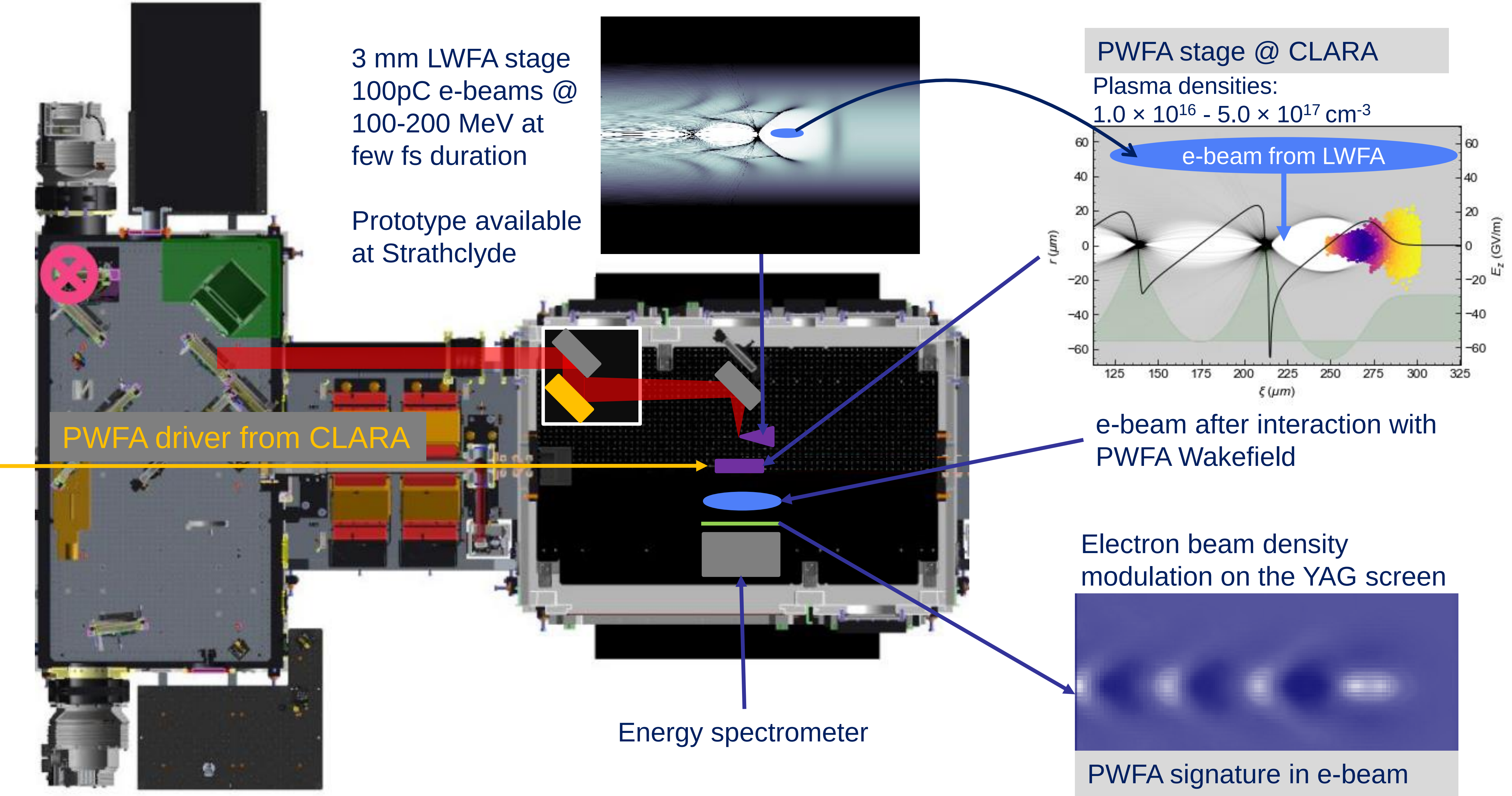
Wan, Y., Seemann, O., Tata, S. et al. Nat. Phys. ***18****, 1186–1190 (2022)*
*Wan, Y. et al. Sci. Adv.****10****, eadj3595 (2024)*





Electron beams allow probing of the plasma waves across a large range of plasma densities at excellent time resultion

Electron beam probing @CLARA FEBE



Proposal: Real-time PWFA metrology

- State-of-the-art linac producing 250 MeV dense electron beam + 120 TW high-power laser system

- Leverage these unique capabilities and hardware @ CLARA FEBE for science not possible elsewhere

- Electron beam-based metrology of plasma waves and electron beams leverages the unique combination of hardware available at CLARA FEBE

- In vivo probing of PWFA, LWFA and electron beams provides real-time monitoring of conditions→ essential for optimization and stability of the plasma stages

- We will be able to study the impact of ramps on the in and out-coupling of the driver and witness beams→ pathway to PWFA or LWFA staging

- Electron beam probing would be first time in the UK and linac-based PWFA facility→ Pioneer the technology and lead the community worldwide

- Pathway towards PWFA stage supporting high-brightness electron beam injection

Synergies with other activities:

- External injection programme at CLARA FEBE
- Strong synergies with the activities at RUEDI
- UK XFEL plasma booster project

PWFA-prototyping @CLARA FEBE for UK XFEL

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RMS t [fs]	100
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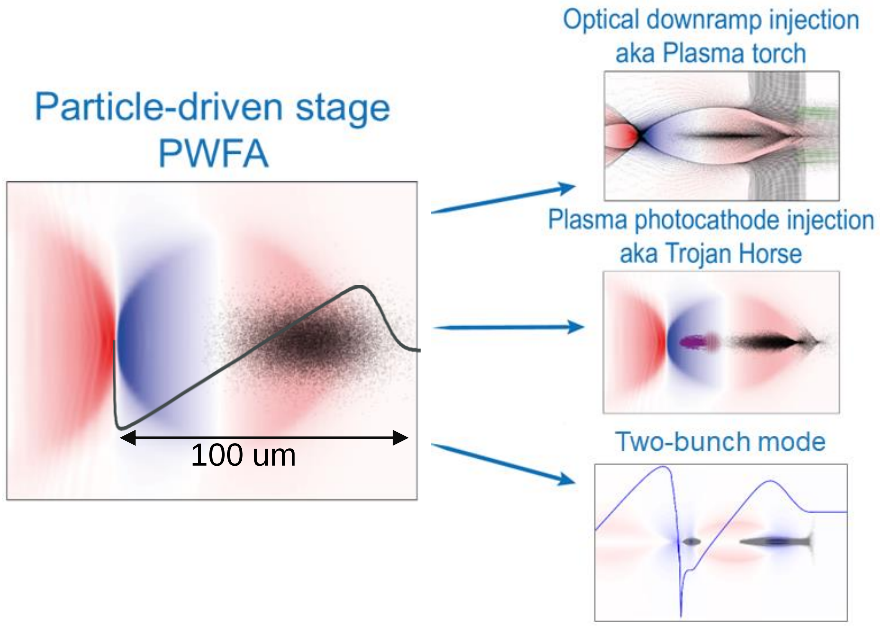
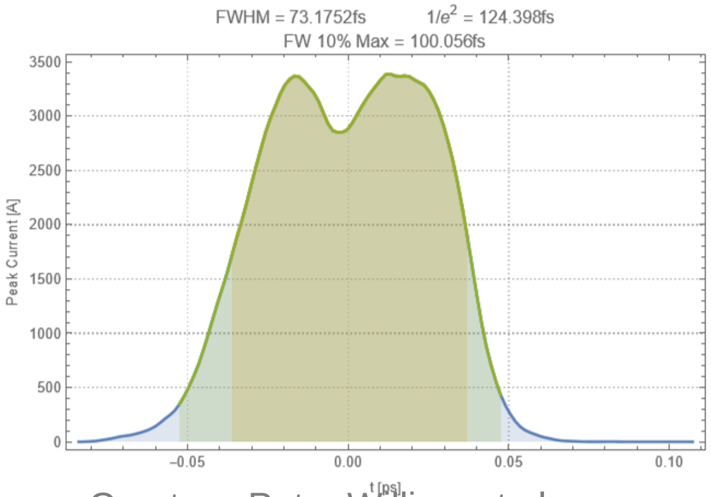
Energy	2.8 J
τ_{FWHM}	23 fs
Rep Rate	5 Hz
w_{FWHM}	73 mm
Strehl ratio	0.90
Pointing stability	3 µrad
Energy stability	1%

What is the pathway towards PWFA in the blowout regime?



- ❑ Increase electron beam density → Stronger compression
- ❑ Increase electron beam density → Stronger focusing via plasma lenses



Courtesy Peter Willims et al.