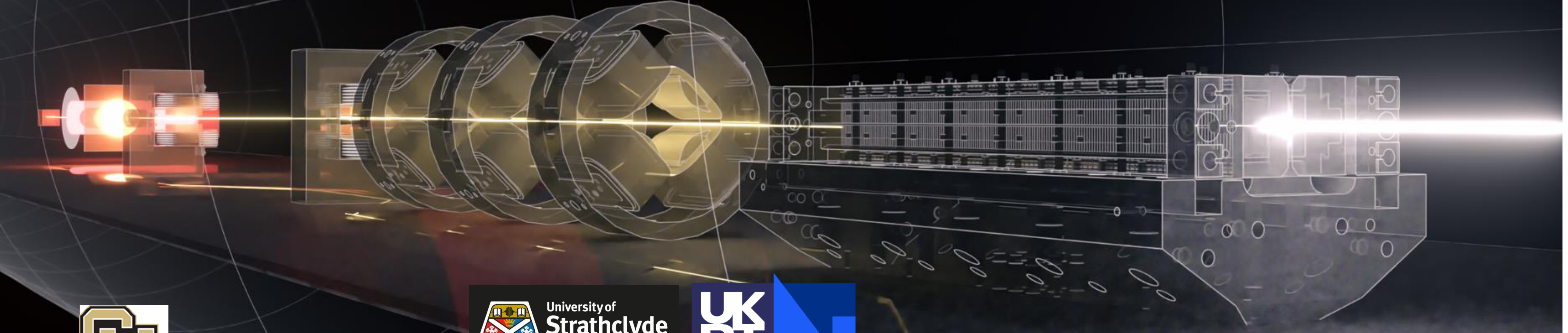
AAC Workshop 2024
2024-07-25, NIU Naperville, USA

Fahim Habib et al.

Towards ultrahigh 6D brightness electron beams from plasma wakefield accelerators

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 · UKRI · CU · Stanford University · SLAC · FACET-II Facility for Advanced Accelerator Experimental Tests · ASTeC · UCLA · SCAPA · hhu Heinrich Heine Universität Düsseldorf · The Cockcroft Institute of Accelerator Science and Technology

Snapshot of wakefield-driven X-FEL landscape

High Power Laser Science and Engineering, (2021), Vol. 9, e57, 15 pages.
doi: 10.1017/hpl.2021.39

HIGH POWER LASER SCIENCE AND ENGINEERING

REVIEW

Free electron lasers driven by plasma accelerators: status and near-term prospects

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 800 nm

INFN: M. Galletti et al. Phys. Rev. Lett. 129, 234801(2022)
→ Seeded operation at 800 nm

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

LBNL: Sam Barber, “Demonstration of a reliable, high gain laser plasma accelerator driven free electron laser”, Talk, 23 Jul 2024→ SASE at ~400 nm

Conceptual effort/upcoming programs

SLAC FACET-II: C. Emma, et al. APL Photonics 6.7 (2021), Rafi Hessami et al., Phys. Rev. Accel. Beams 27, 070701 (2024)

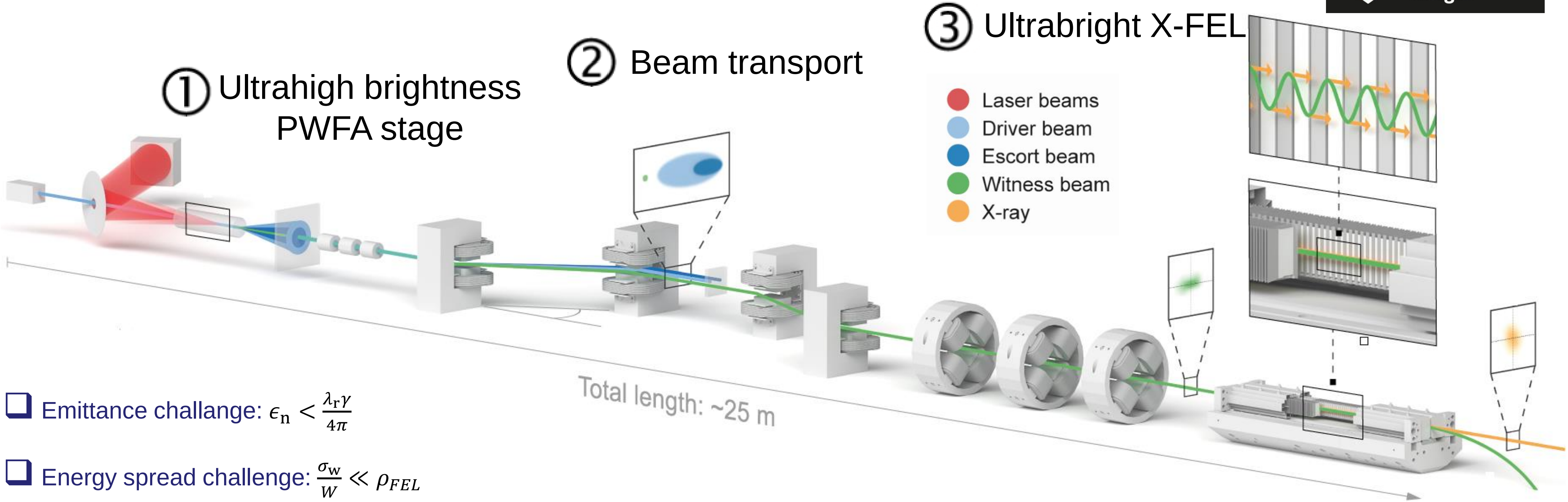
Strathclyde: A. F. Habib et al. Nat. Comm. 14, 1054, (2023)

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…

Plasma X-FEL fundamental challenges



- ❑ Emittance challange: $\epsilon_{\mathrm{n}} < \frac{\lambda_{\mathrm{r}}\gamma}{4\pi}$
- ❑ Energy spread challenge: $\frac{\sigma_{\mathrm{w}}}{W} \ll \rho_{FEL}$
- ❑ Short FEL gain length: $L_{\mathrm{g}} \propto B_{\mathrm{6D}}^{-1/3}$
- ❑ Dark current free acceleration over multi-cm→ multi-GeV energy gain
- ❑ Beam quality preservation

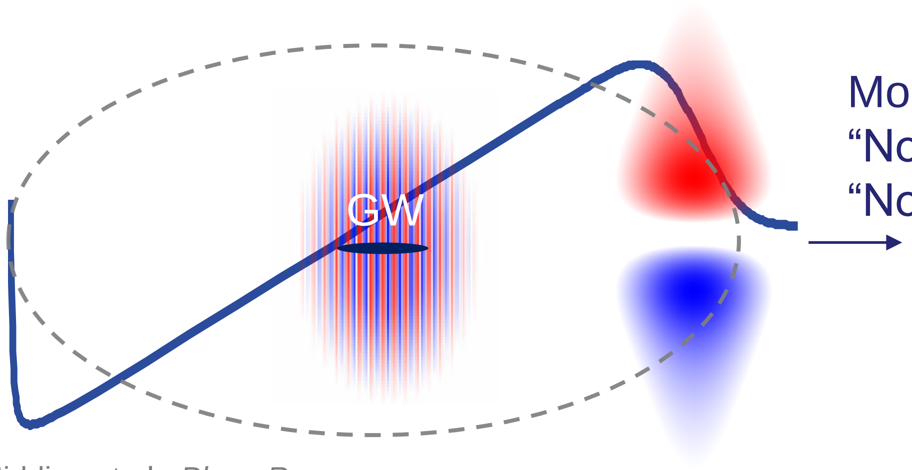
Habib, A. F., Hidding, B., Manahan, G. G., Patent App. GB1617173.8 (2016), WO2018069670A1 (2017), US Patent App. (2019): 16/341,039

- ❑ Extract and capture witness beam from the plasma stage
- ❑ Transport witness beam without quality degradation
- ❑ Separate witness beam from driver
- ❑ Match witness beam to the undulator

- ❑ Drive a XFEL at hard wavelength
- ❑ Generate radiation with fs/sub-fs duration
- ❑ Achieve saturation → coherence
- ❑ Operate in the single-spike regime to obtain fully coherent x-ray pulses ?

Emittance challenge: Plasma photocathode

Plasma photocathode



PWFA
Moderate peak fields
"No" dephasing
"No" diffraction

Hidding et al., *Phys. Rev. Letters* 108, 035001, 2012

- ❑ Injection fully decoupled from wake excitation: laser-controlled, dark current free, clean electron beam production from localized tunnel ionization e.g. of He
- ❑ Transverse residual momentum from ~10^{15} W/cm^2 laser negligible $\Rightarrow$ normalized emittance ε_n **~ nm rad scale**
- ❑ Auto-compression to kA currents *I* $\Rightarrow$ beams orders of magnitude brighter than state-of-the-art
- ❑ Test beams for staging: nm rad level emittance growth per stage observable

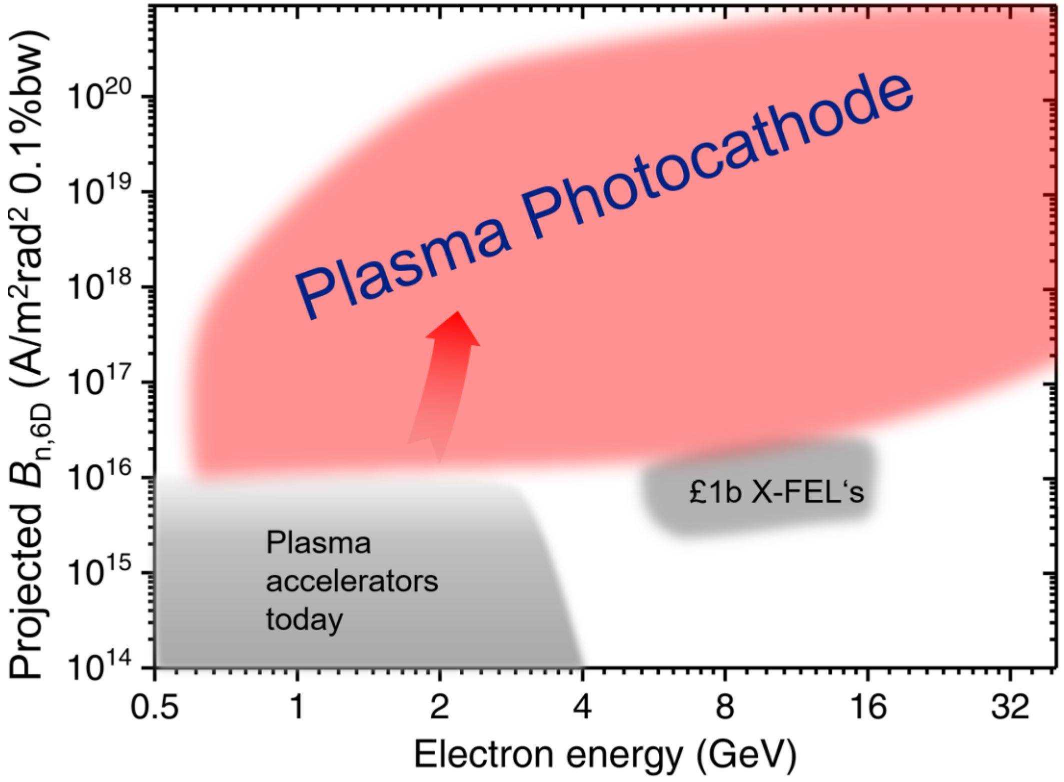
Light source and HEP applications

multi-kA current

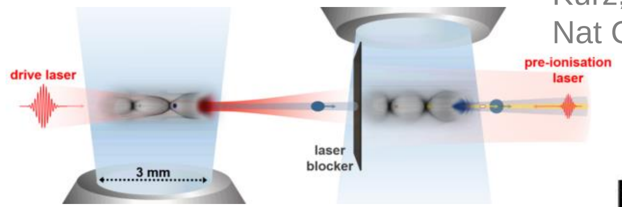
$$B_{6\mathrm{D}} = \frac{I}{\epsilon_{\mathrm{n}}^2 \cdot 0.1\%\sigma_W}$$

nm rad emittance

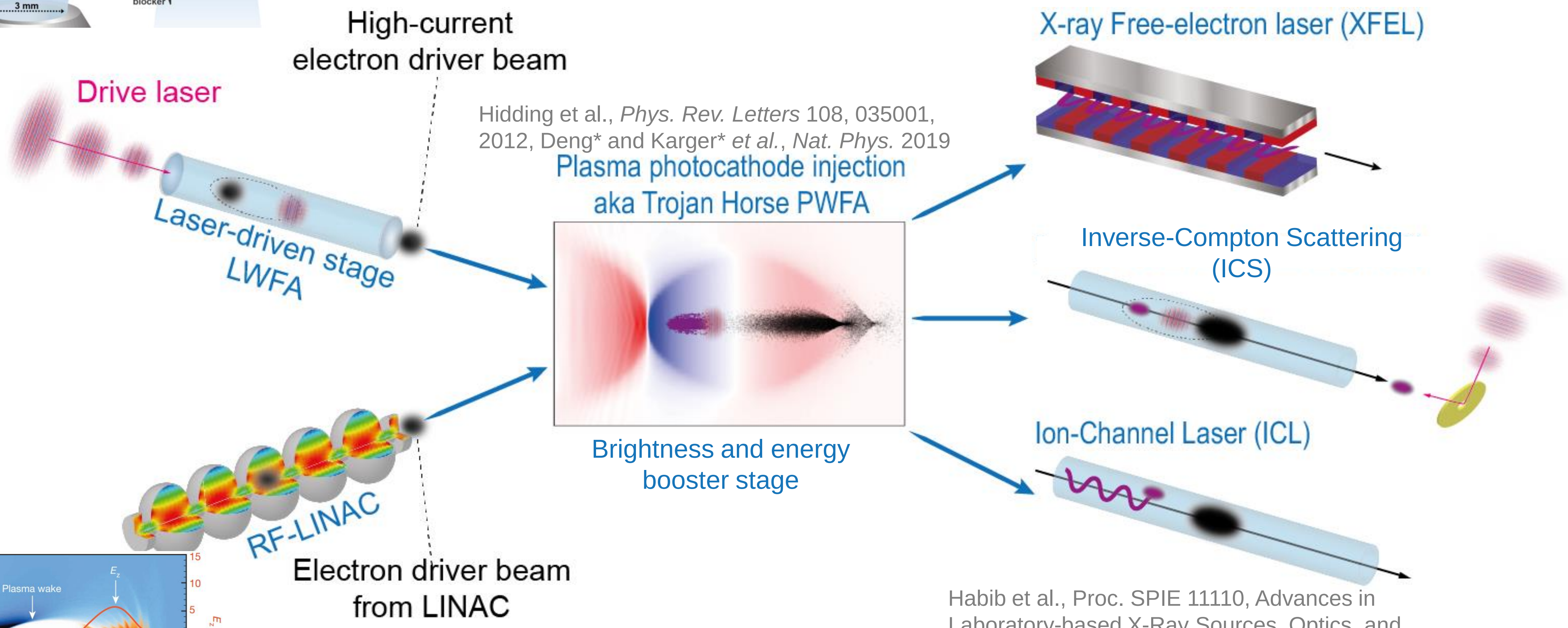
energy spread <0.01%



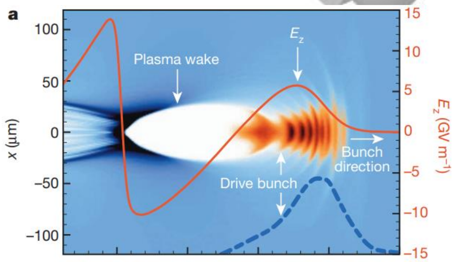
Experimental pathways towards PWFA based light sources



Kurz, T., Heinemann, T. et al.
Nat Commun 12, 2895 (2021).



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

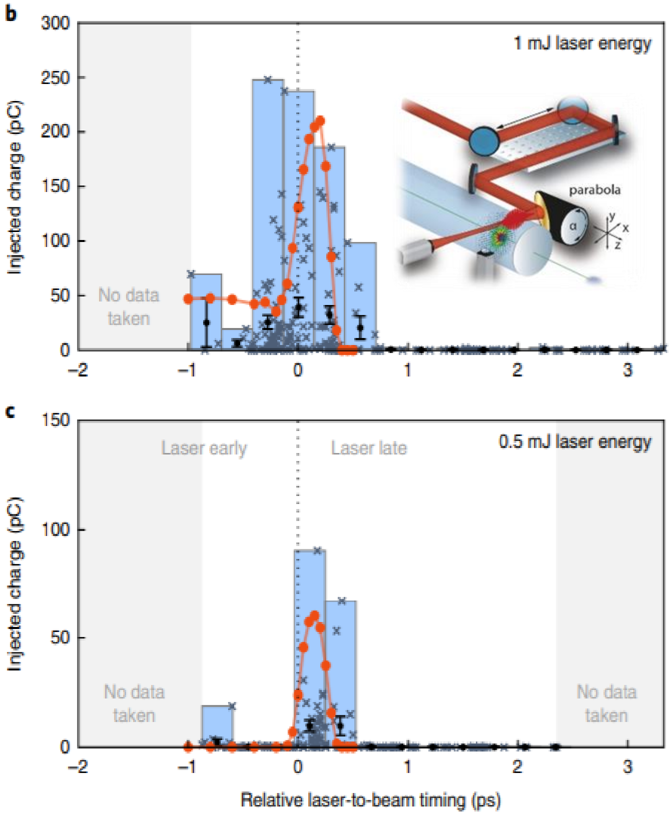


M. Litos, et al., Nature 515 92-15 (2014)

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

Plasma photocathode experimental progress

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



Deng* and Karger* *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

Publication embargo

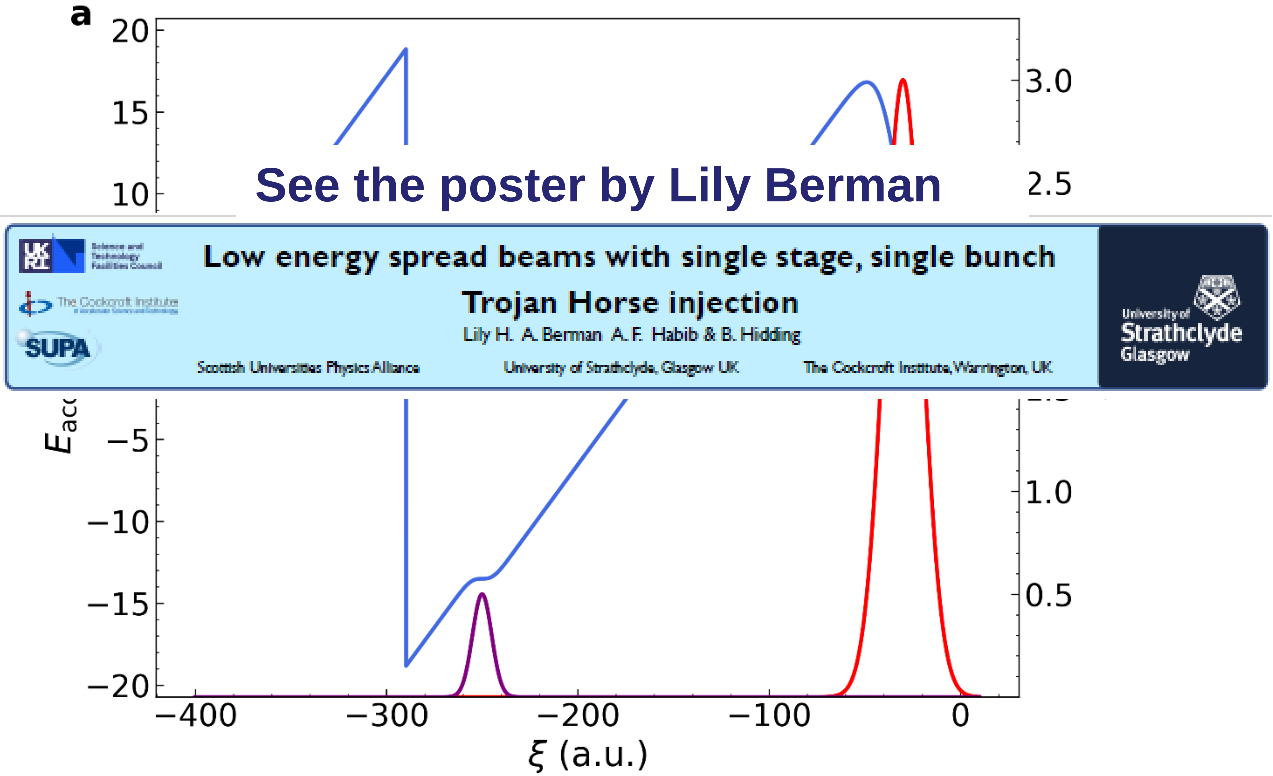
- ❑ Beam time delivered by Strathclyde (UK), SLAC (USA) and HHU (Germany) team
- ❑ Ionization tests in mixed H2/He gas
- ❑ Crucial first step towards E310 goals

Breakthrough in Hybrids LWFA→PWFA 90° plasma photocathode realized

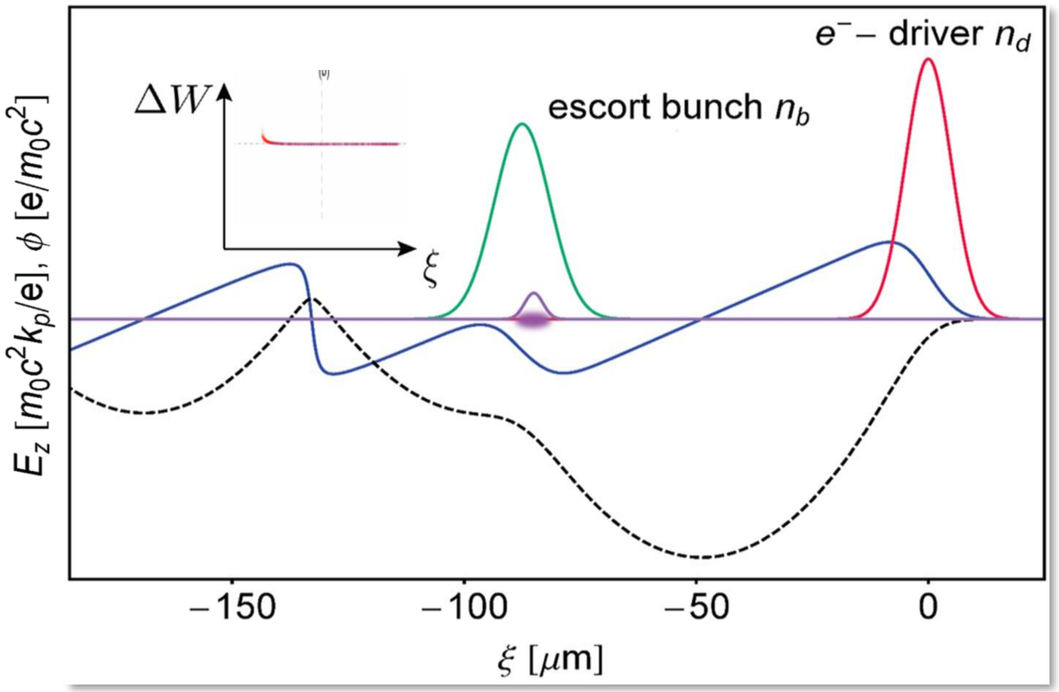
Publication embargo

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

Energy spread challenge



L. Berman, A. F. Habib *et al., paper in prep* (2024)

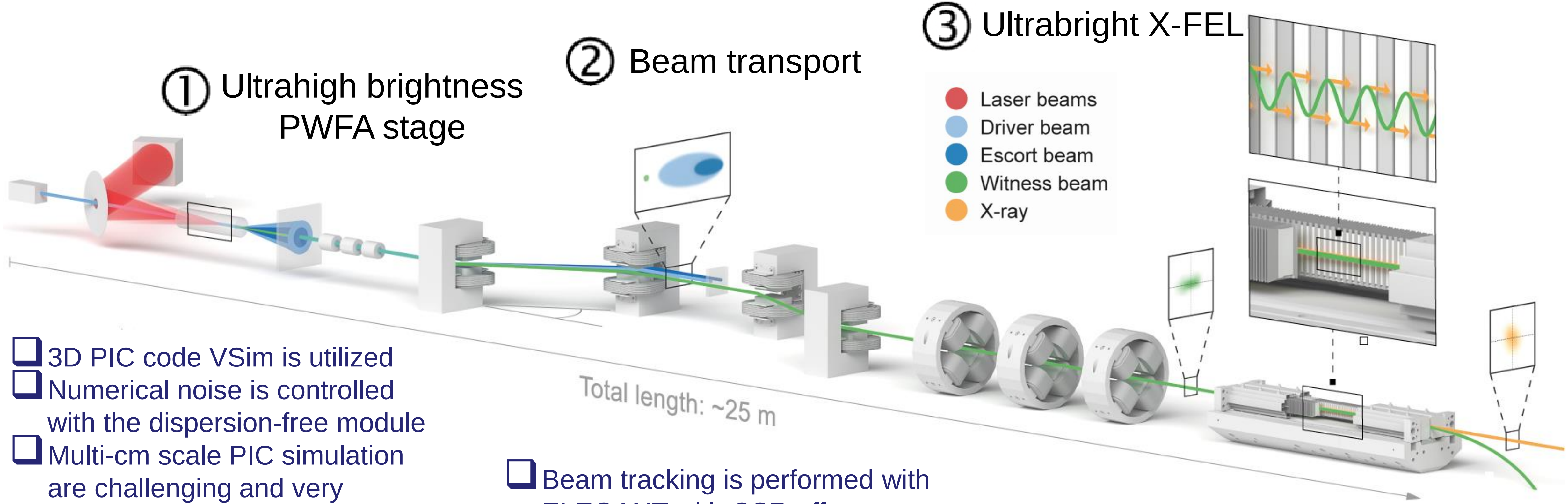


G.G. Manahan*, A. F. Habib* *et al., Nat. Comm.* 8, 15705 (2017)

- Straightforward way: take advantage of beam loading via tailored plasma photocathode injector
- Requires multi-kA beams to load the wakefield
- May spoil spoils norm. emittance due to space charge

- Exploit tailored beam loading via “escort beams“to flip the accelerating field locally
- Reduced the energy spread down to ~ 0.01% at few GeV beam energy may be possible
- E-313 experiment at SLAC FACET-II (PIs: Habib/Hidding)

High-fidelity start-to-end-simulation framework



- 3D PIC code VSim is utilized
- Numerical noise is controlled with the dispersion-free module
- Multi-cm scale PIC simulation are challenging and very expensive

VSim

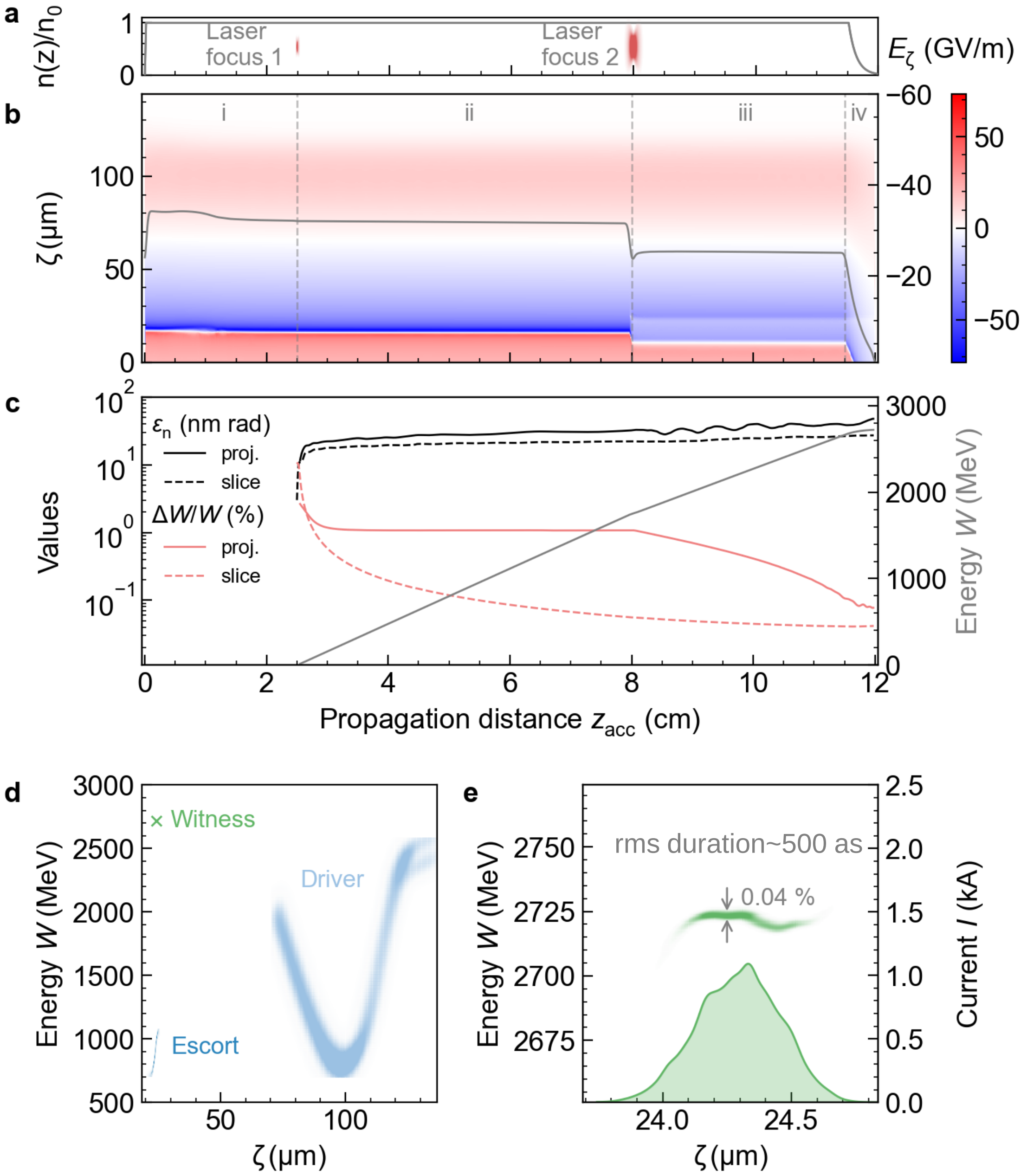
- Beam tracking is performed with ELEGANT with CSR effects
- Complete 6D phase space of the witness, drive, and escort beam are considered

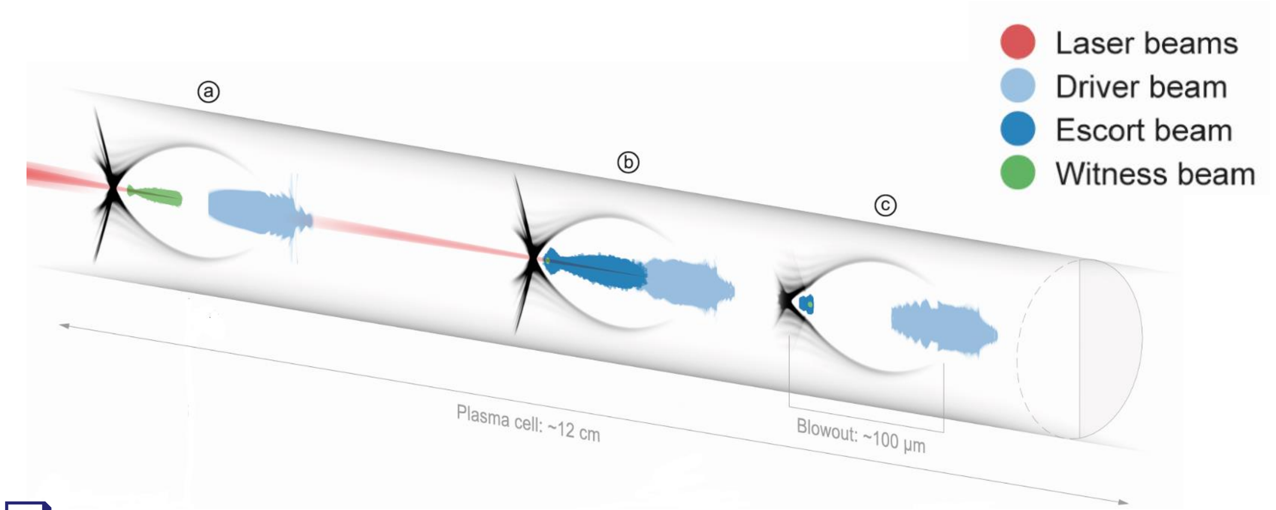
- We use the unaveraged 3D FEL code Puffin developed in Strathclyde
- We introduce proper Poisson ‘shot-noise’ to the electron beam (McNeil and Robb, J. Phys. D: Appl. Phys. 30 567,(1997))
- The undulator B-fields are implemented in 3D

Magnet and undulator calculations with Sirepo radiasoft

Magnet and undulator models from RadiaBeam RadiaBeam

Ultrahigh brightness PWFA stage



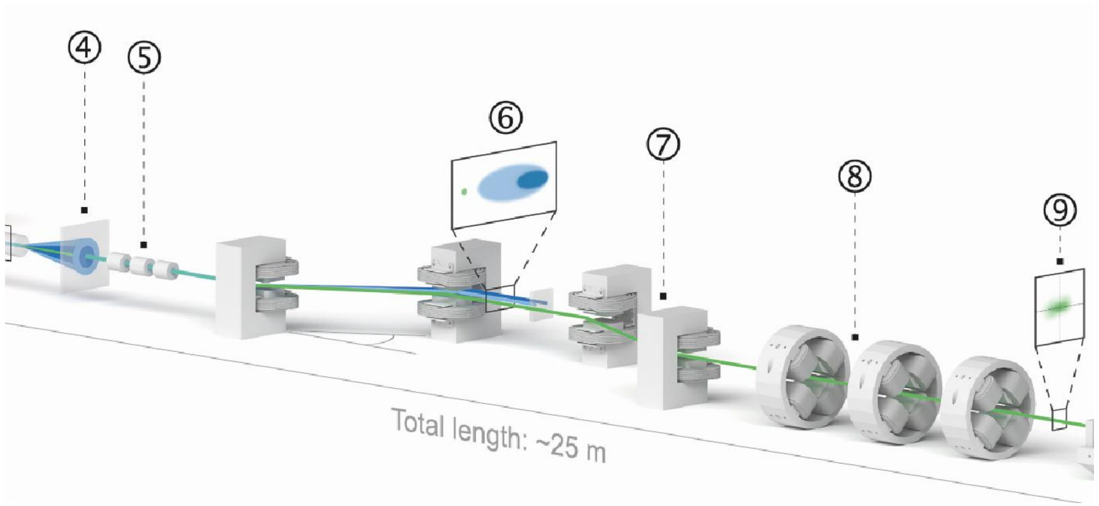


- High- fidelity 3D PIC simulation of the PWFA-stage
- High quality witness beam is produced, accelerator, dechirped and extracted without quality degradation in the same PWFA stage!

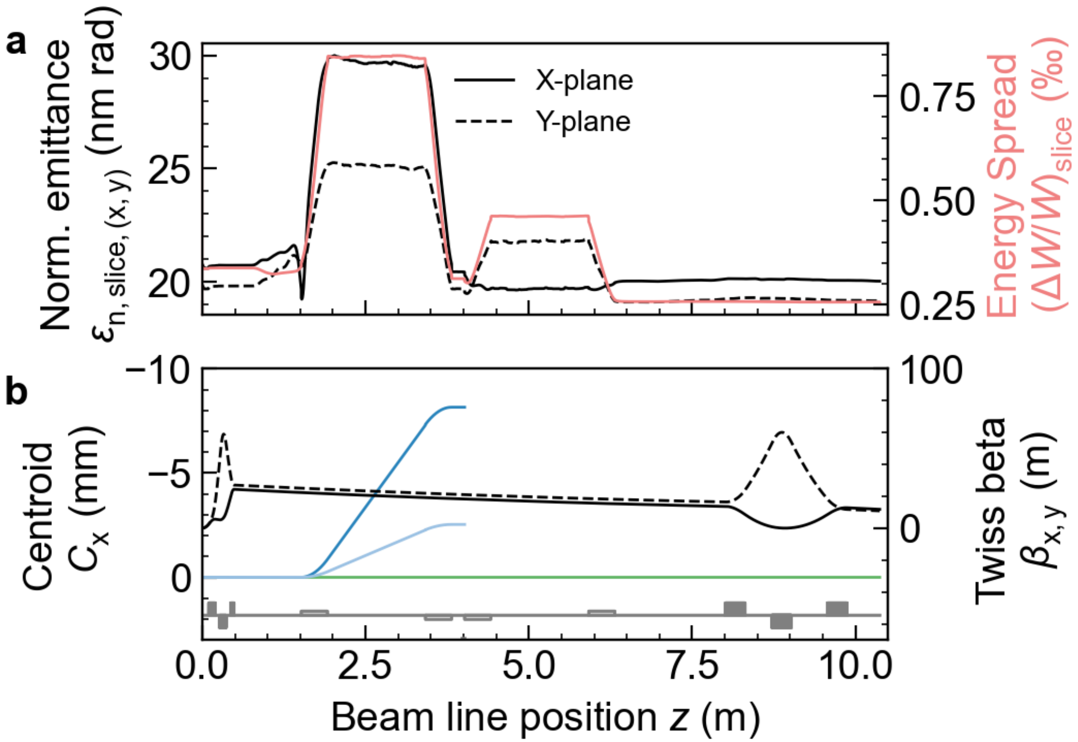
Witness beam at the plasma stage exit

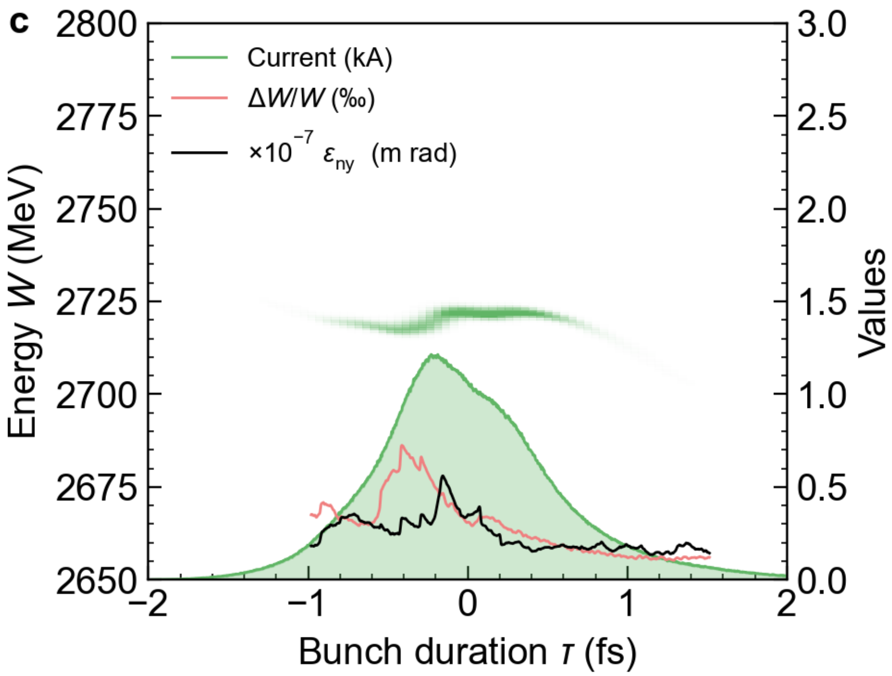
- Energy~2.7 GeV, slice norm. emittance ~20 nm rad, slice energy spread~ 0.04%, peak current~ 1.2 kA, 6D brightness~10^{18} A m^{-2} rad^{-2}/0.1%bw.
- Witness beam energy is larger than driver and escort beam energy

Beam transport line

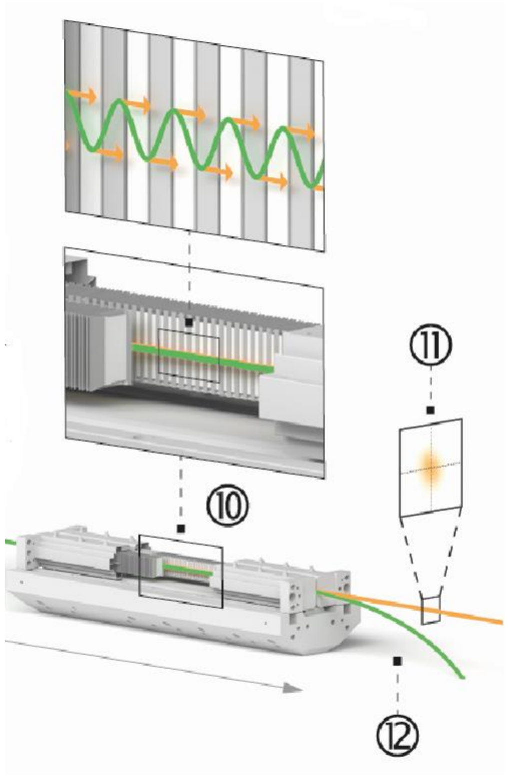


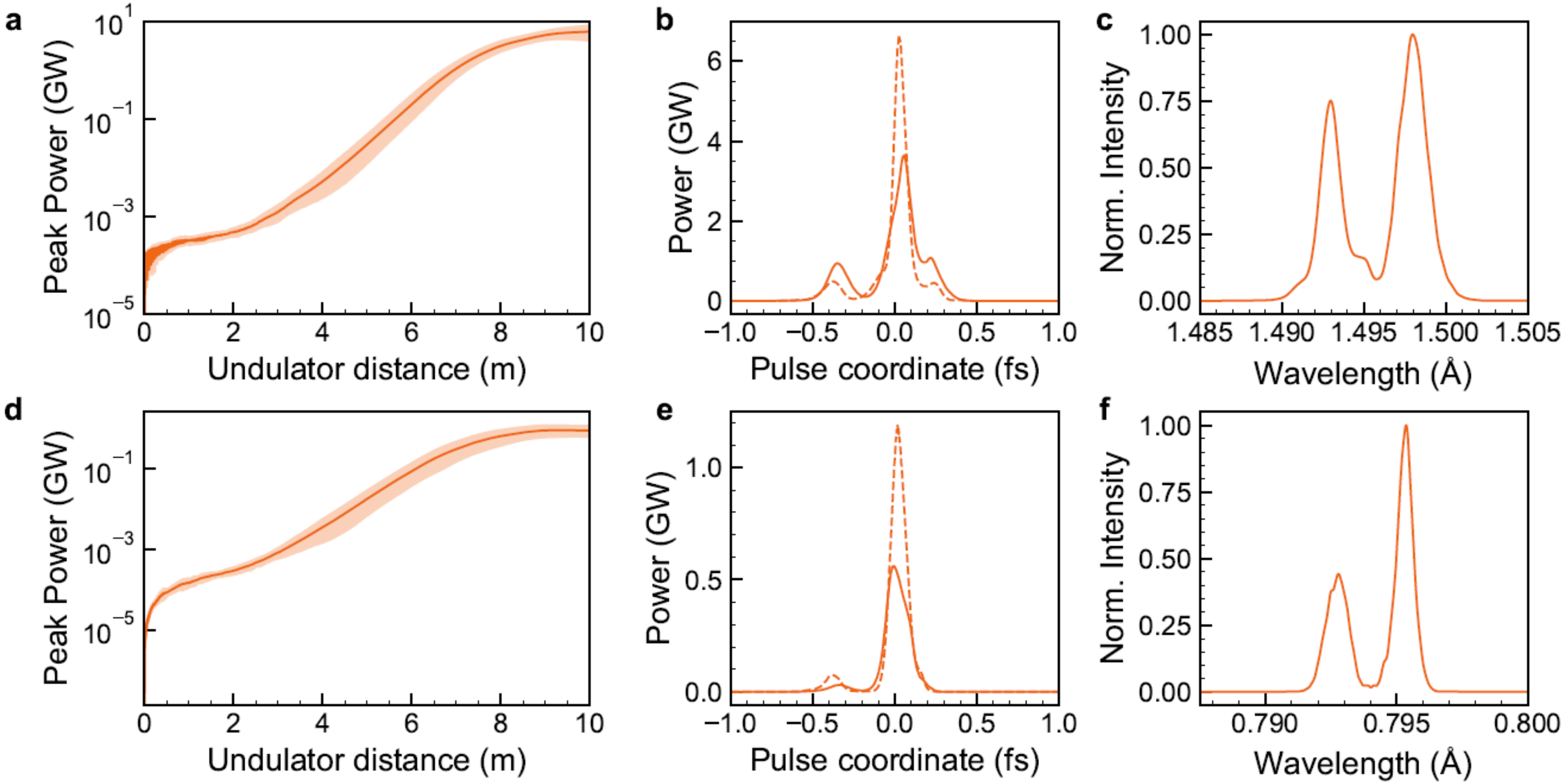
- Witness beam is captured, separated and matched to the undulator section
- CSR effects do not compromise beam quality
- Slice and projected witness beam properties in terms of emittance, energy spread and current are preserved
- Slice energy spread is slightly reduced due to decompression in the chicane to 0.026 %
- Projected (slice) brightness at the undulator entrance $B_{6D} \approx 1.3 \times 10^{18}$ (1.1×10^{19}) A m^{-2} rad^{-2}/0.1%bw.



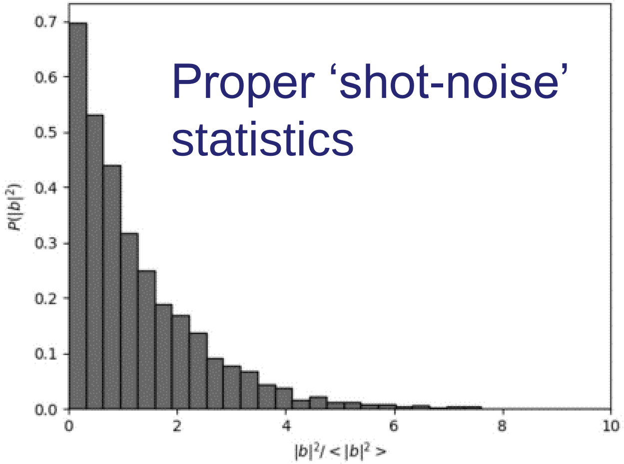


Hard X-ray FEL section

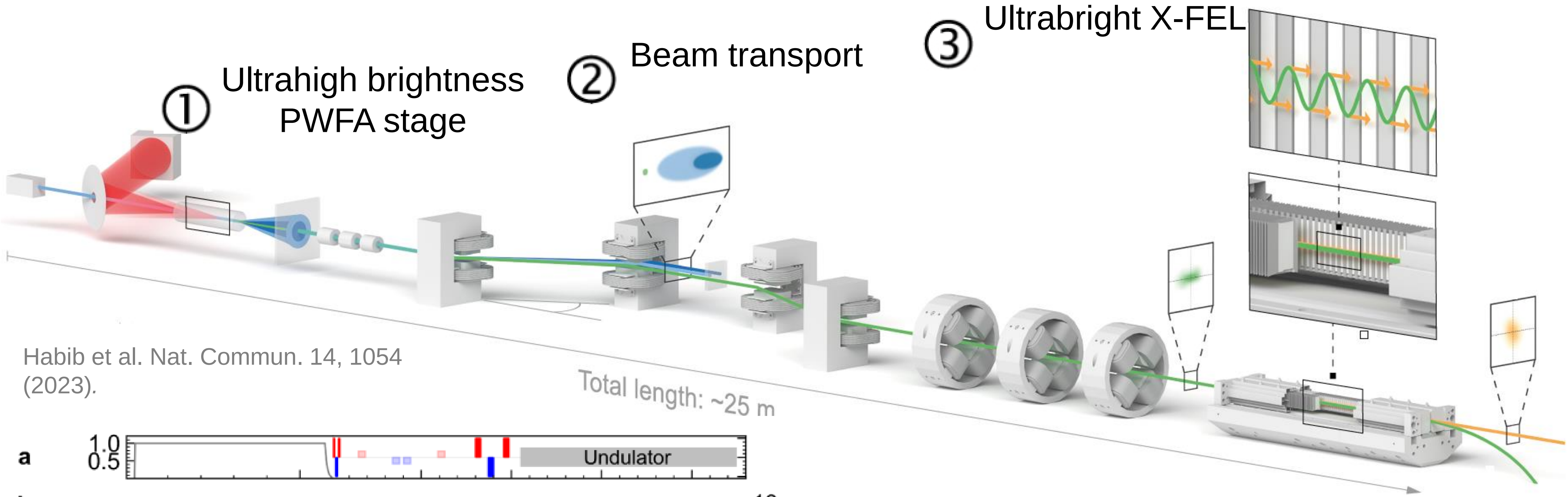




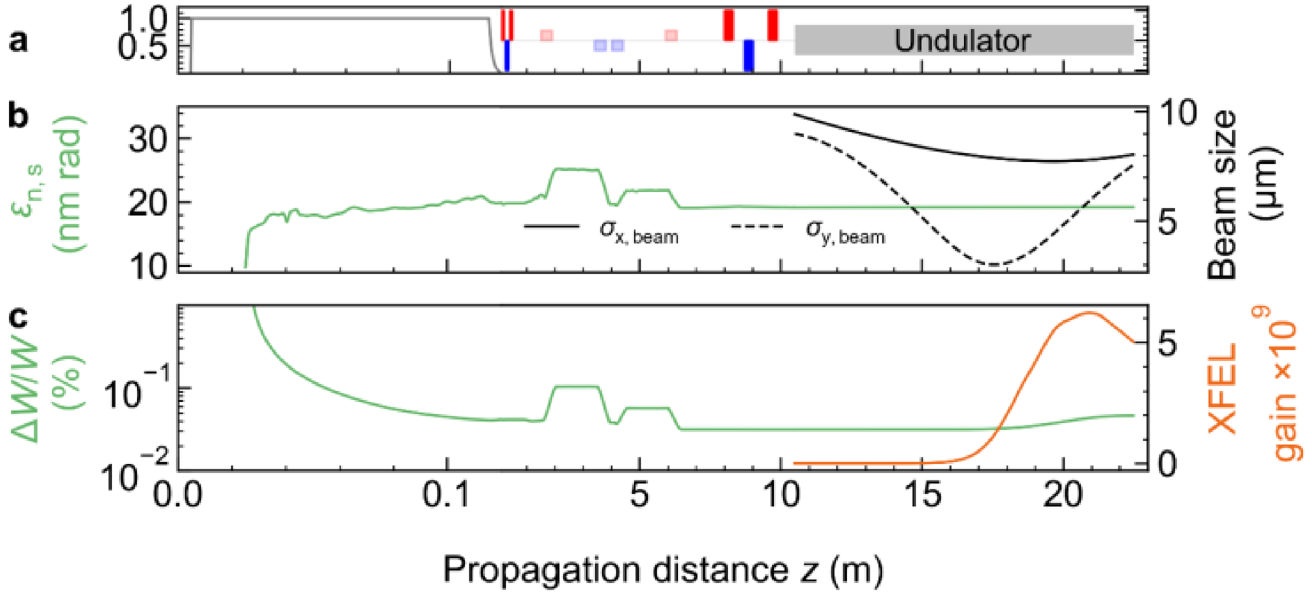
- **SASE Hard X-ray FEL:** ~1.5 Å and **Sub-Ångström** ~0.8 Å
- Saturation below 10 m undulator length → GW power levels
- Radiation pulses are of atto-second pulse duration ~100 as
- High gain and short bunch duration few modes are amplified→ near longitudinal coherence
- ΔνΔτ ≈ 1.8 indicates that further improvements may yield Fourier transform limited X-FEL
- Note 3D gain length is very close to the theoretical 1D gain length→ cold beam limit



Summary PWFA-X-FEL

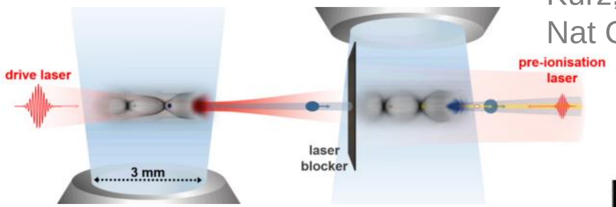


Habib et al. Nat. Commun. 14, 1054 (2023).



- Ultra-high 6D brightness witness beams are produced in PWFA via plasma photocathode
- Witness beam is extracted from the PWFA, captured, isolated and refocused into the undulator
- Beam quality is preserved across the building blocks
- GW power attosecond pulses at ~1.5 Å and ~0.8 Å

Experimental pathways towards PWFA based light sources



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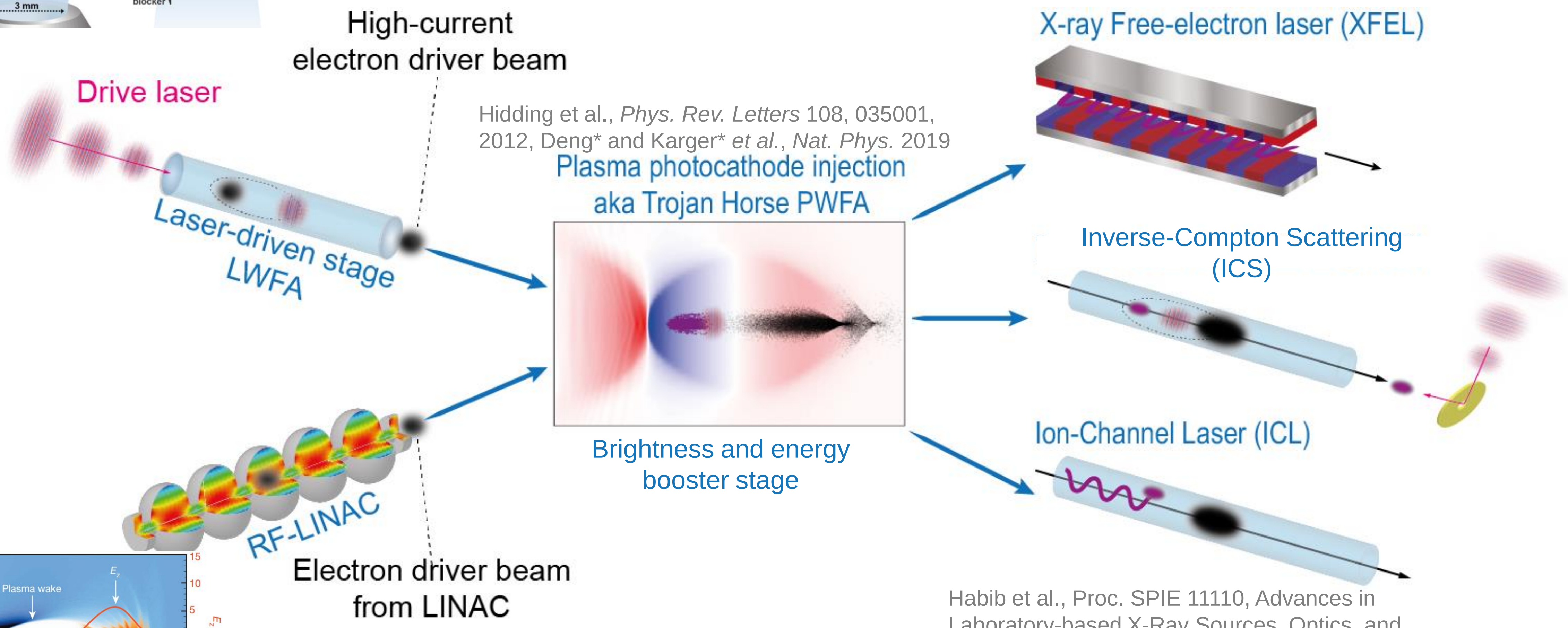
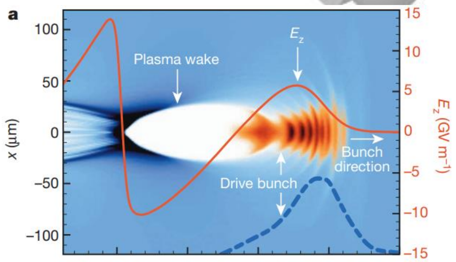


Hidding et al., *Phys. Rev. Letters* 108, 035001, 2012, Deng* and Karger* *et al.*, *Nat. Phys.* 2019



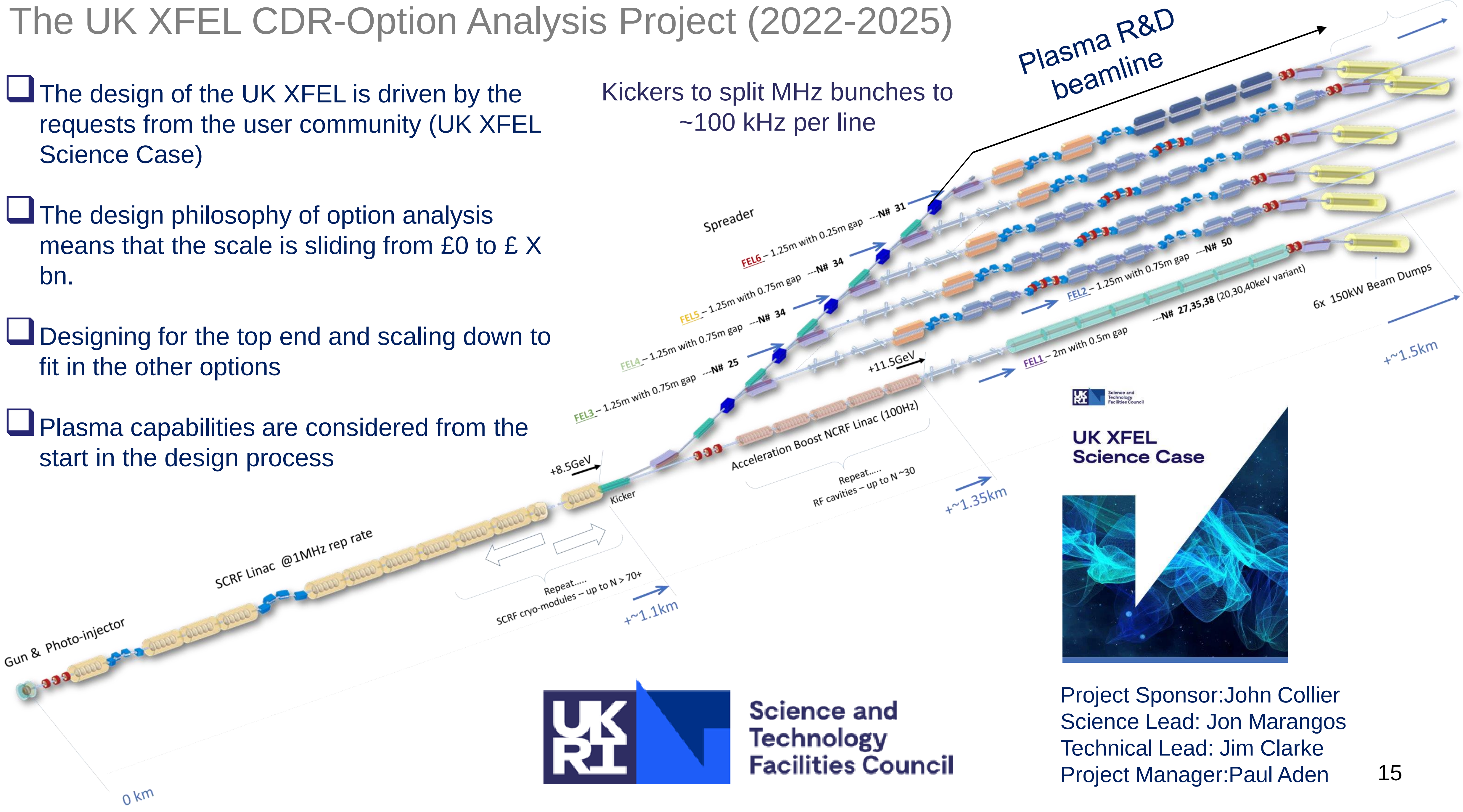
M. Litos, et al., Nature
515 92-15 (2014)

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

The UK XFEL CDR-Option Analysis Project (2022-2025)

- The design of the UK XFEL is driven by the requests from the user community (UK XFEL Science Case)
- The design philosophy of option analysis means that the scale is sliding from £0 to £ X bn.
- Designing for the top end and scaling down to fit in the other options
- Plasma capabilities are considered from the start in the design process

Kickers to split MHz bunches to ~100 kHz per line



Science and Technology Facilities Council

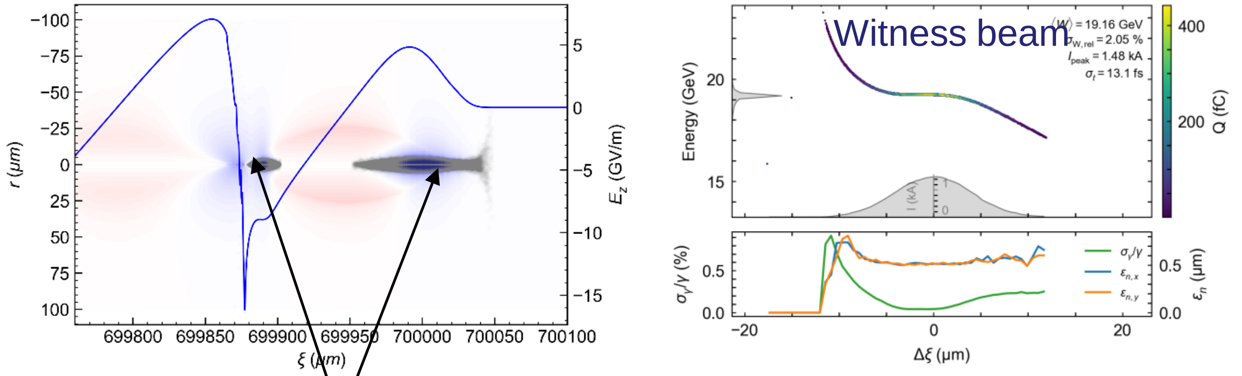
Project Sponsor:John Collier
Science Lead: Jon Marangos
Technical Lead: Jim Clarke
Project Manager:Paul Aden

PWFA-booster station @ UK XFEL

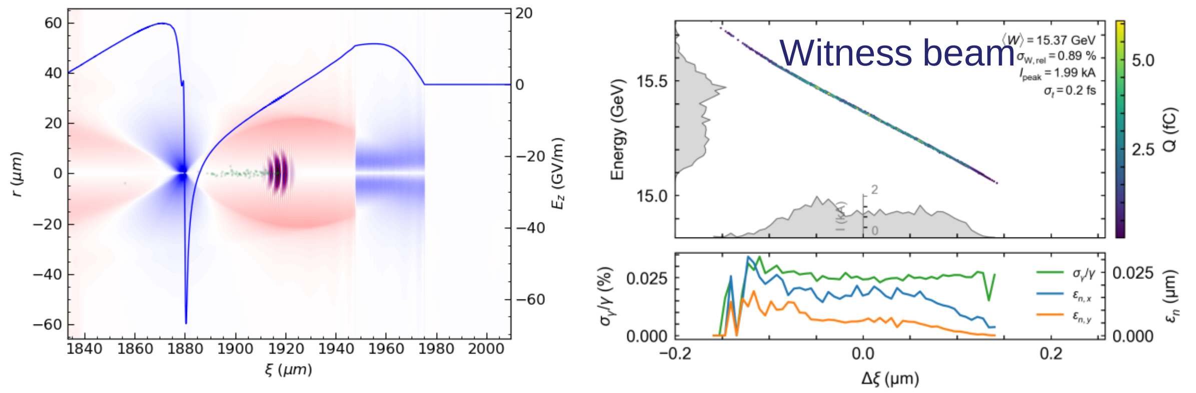
- ❑ Feasibility study of extending FEL photon energy beyond nominal 20 keV through the PWFA-booster station
- ❑ Consideration of the best strategy for integration into wider facility
- ❑ Sponsored/founded by the UK XFEL CDR- Option Analysis project

AAC 2018 poster on energy and brightness booster for linac-driven XFELs

1. Energy boost to 19-20 GeV
Via two bunch configuration from UK XFEL linac

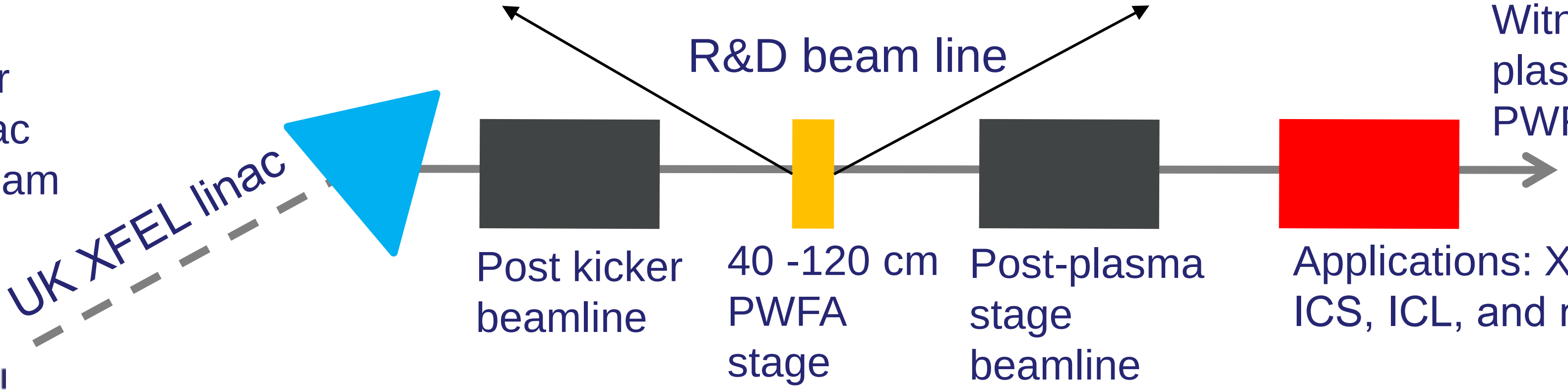


2. Brightness boost to 20-50 nm rad norm. emittance
Via plasma photocathode injection into PWFA



Driver-witness pair from UK XFEL linac @ 8 GeV initial beam energy

Witness beam injected via plasma photocathode in PWFA

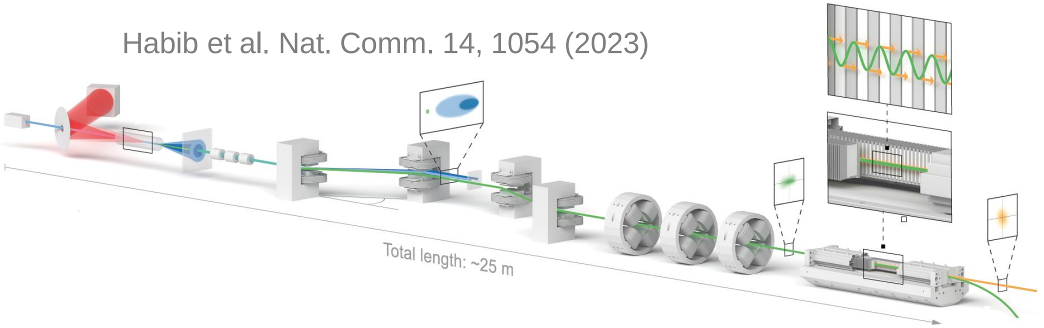


Science and Technology Facilities Council

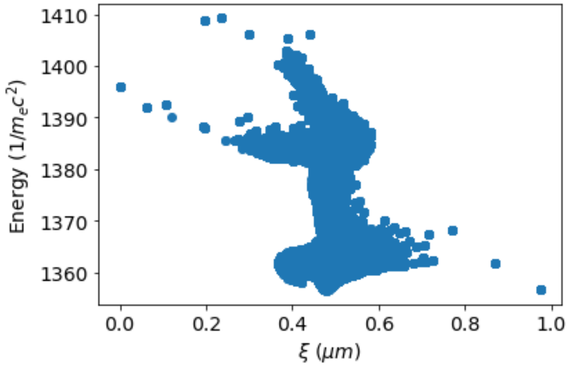
Selected applications of plasma-based electron beams

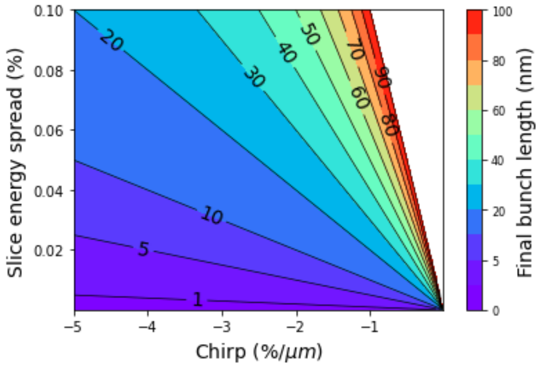
Attosecond-angstrom class XFEL photon pulses module

Habib et al. Nat. Comm. 14, 1054 (2023)

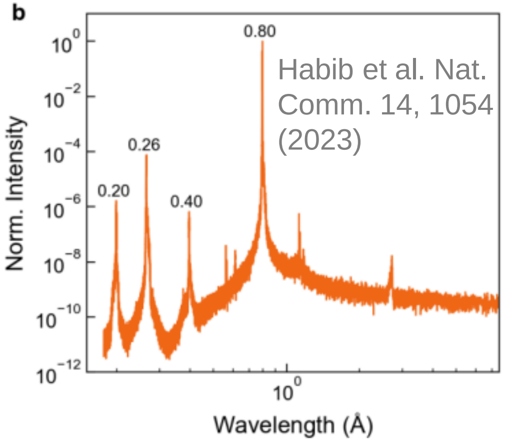


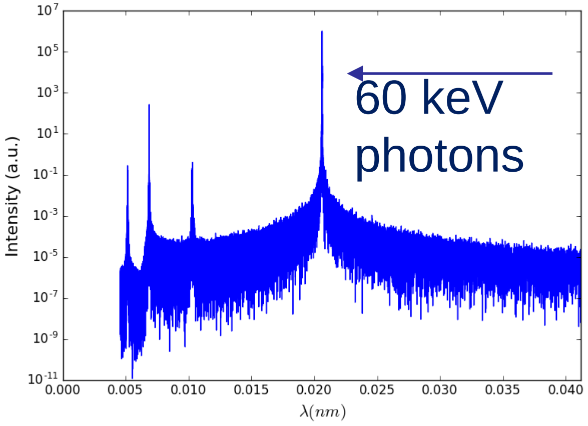
Attosecond-electron beams via extreme compression in post-plasma beamline (PAX)- Courtesy of Lily Berman





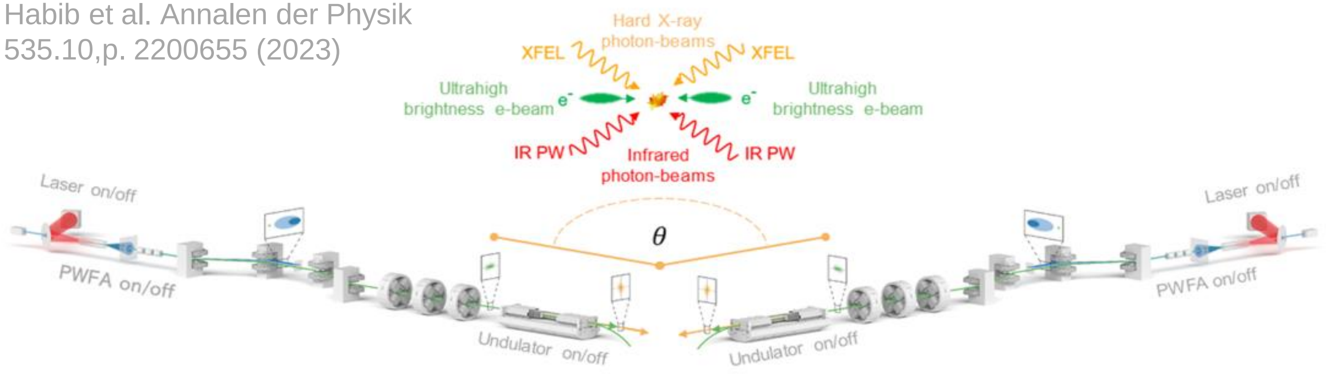
XFEL photon energies > 20 keV maybe possible





Pathways to novel electron and photon modalities towards QED, HEP and High-Field Physics.

Habib et al. Annalen der Physik 535.10,p. 2200655 (2023)



Many more applications such as ICS, ICL and betatron radiation in combination with XFEL pulses…→ Pathway to new science?

Habib, Hidding, McNeil, Berman, et al.

University of Strathclyde Glasgow

hhu Heinrich Heine Universität Düsseldorf

UCLA

Rosenzweig et al.

SLAC

Hogan, Raubenheimer, Hemsing et al.

CU Boulder

Litos et al.

The Cockcroft Institute of Accelerator Science and Technology

Dunnig, Snedden, Williams, Clarke et al.

Industrial partners:
RadiaBeam (Andonian, Murokh et al.),
Tech-X (Cary et al.),
RadiaSoft (Bruhwiler et al.)

TECH-X

radiasoft

radiabeam TECHNOLOGIES

Thanks

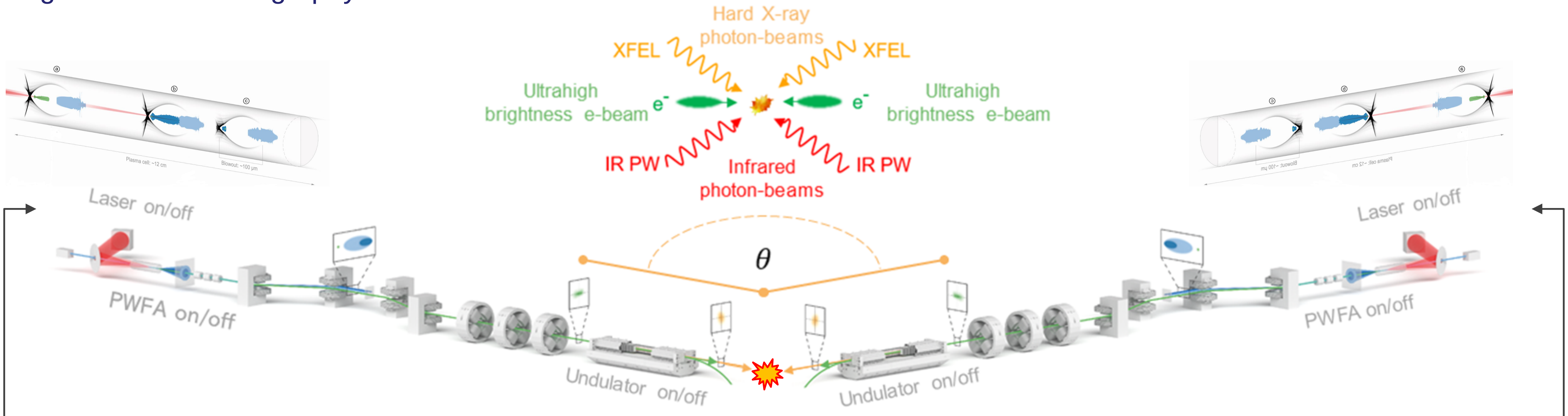
Have a bright AAC 2024

UKRI

University of Strathclyde Glasgow

Outlook: prospects of PWFA-X-FEL

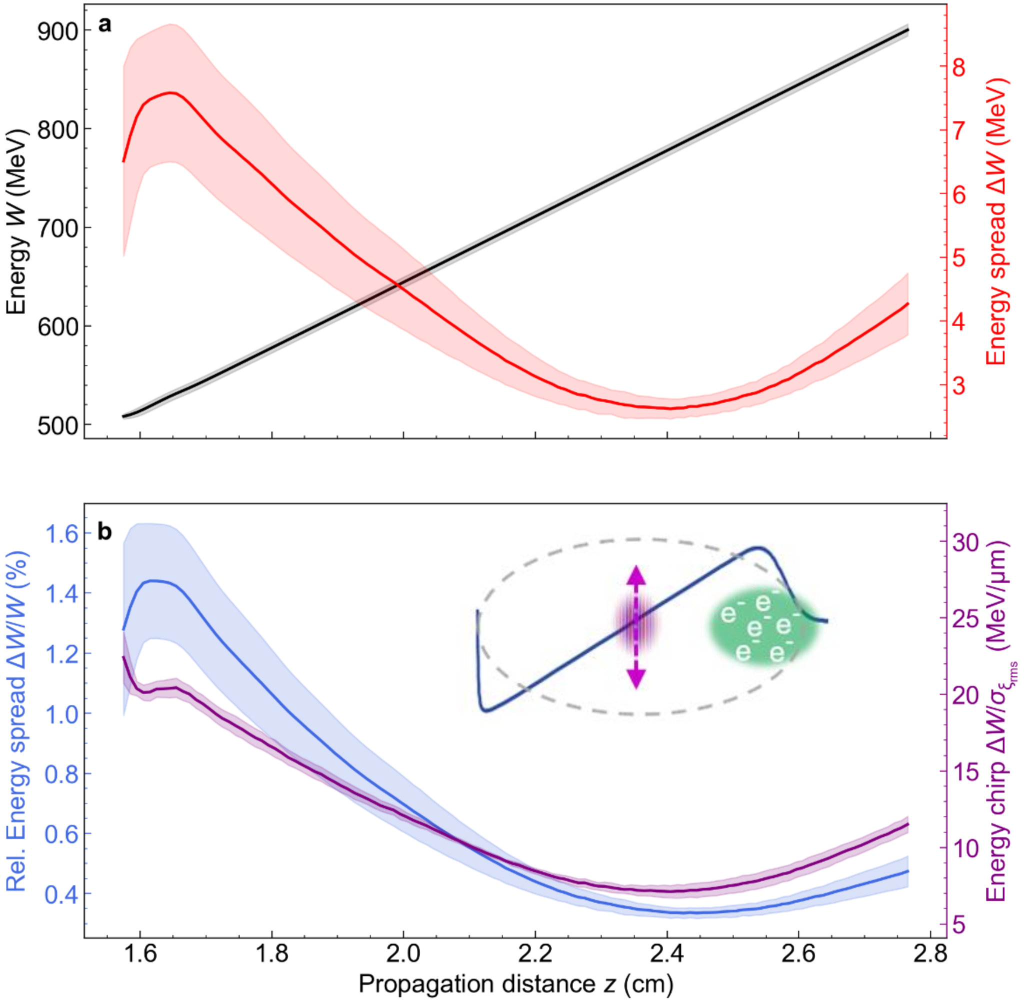
- Colliding photon and ultra-high brightness electron beams with arbitrary permutation
- Enables novel electron and photon beams modalities
- Investigate photon-photon scattering (Not experimentally demonstrated so far)
- QED and basic science studies with a new set of tools
- Single molecule tomography?

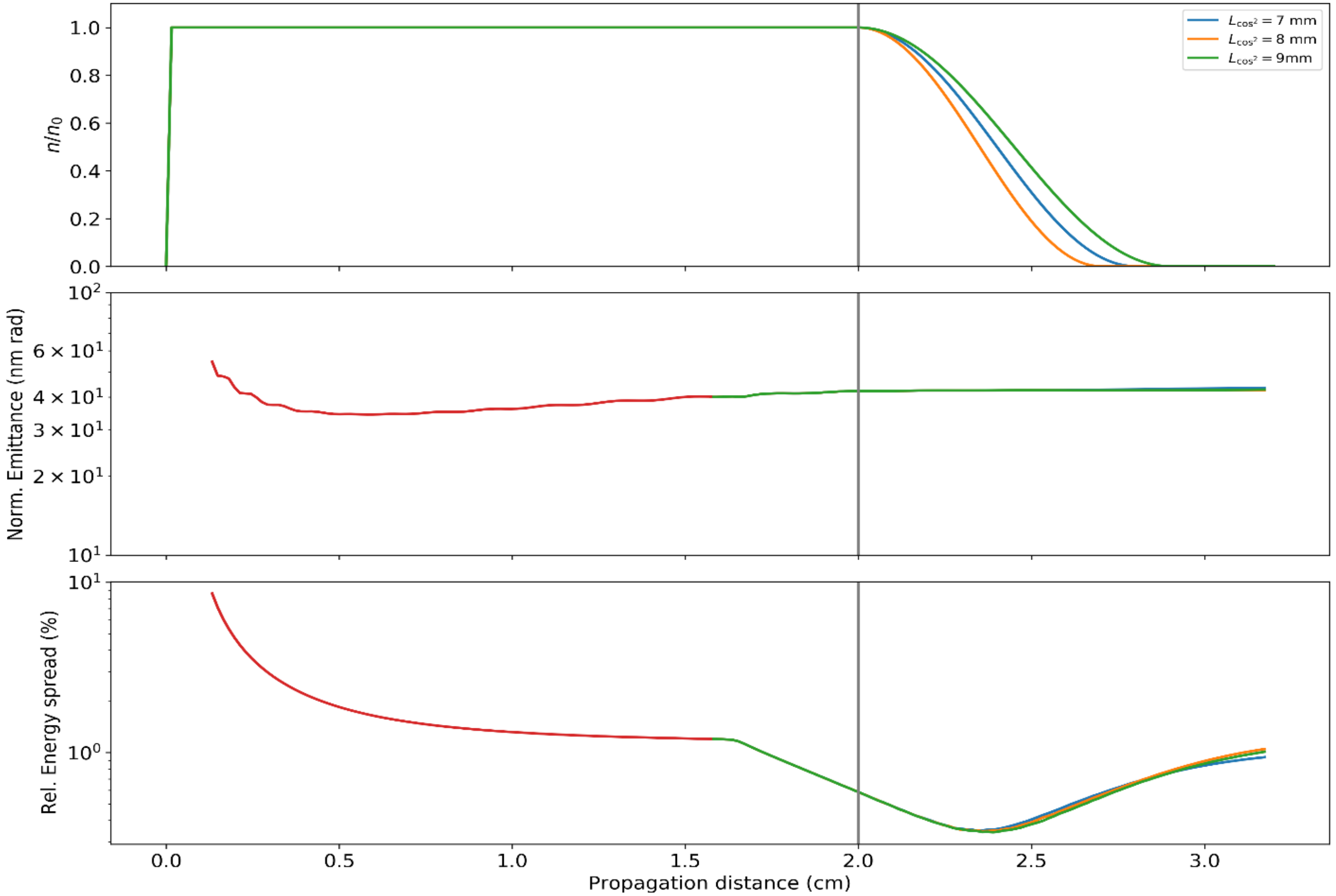


New Science?

Driver beam may come from RF-Linac or Hybrid LWFA2PWFA

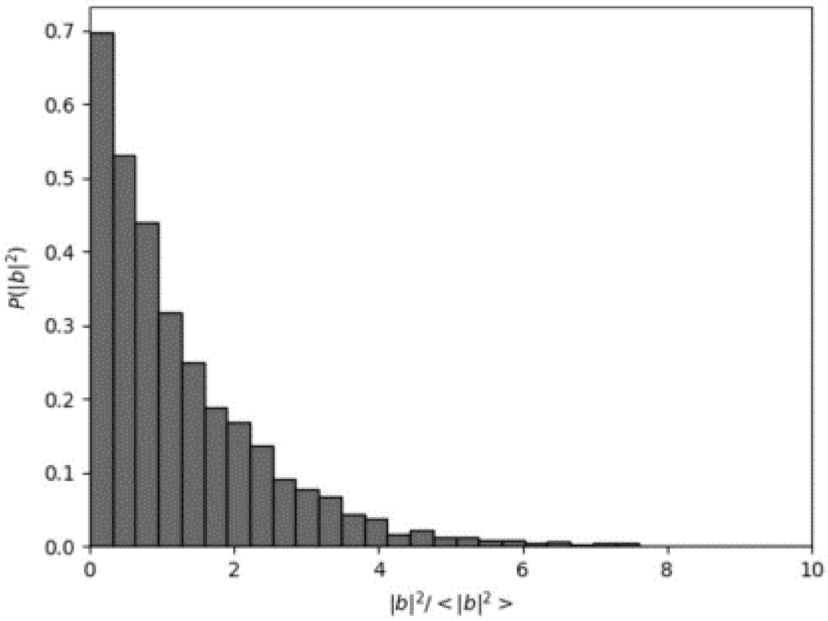
Stability of energy spread and extraction





- ❑ Witness beam injector laser misaligment does not have a dramatic impact on dechirping
- ❑ Witness beam can be extracted from the plasam stage without quality degradation

Fixing the shot-noise and undulator considerations



Supplementary Table 2 | Summary of the plasma-X-FEL performance for the two respective cases C1 and C2 presented in this work.

	λ_u (mm)	K	λ_r (nm)	E_{ph} (keV)	ρ_{1D} × 10^{-4}	L_{1D} (m)	$L_{G,th}$ (m)	$L_{G,sim}$ (m)	$P_{r,th}$ (GW)	$P_{r,sim}$ (GW)	$\Delta\tau$ (as)	β^* (m)
C1	5	1.18	0.149	8.3	7.6	0.30	0.49	0.54	4.0	4.0	~100	~2.4
C2	3	1.0	0.079	15.7	5.5	0.25	0.42	0.62	2.8	0.5	~100	~2.4

- We use advanced undulator similar presented in the UC-XFEL configuration
- Low electron energy, low emittance and short period undulators belong together
- We pushed towards the cold beam regime

Rosenzweig, J.B. et al. An ultra-compact x-ray free-electron laser. New J. Phys. 22, 093067 (2020).

- We need to carefully up-sampling the total number of particles for the FEL code
- Electron beams from PIC-codes have the "wrong" shot-noise statistics.
- Very important! Introduce proper Poissonian 'shot-noise' to the up-sampled distribution

Beam quality 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 properties 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

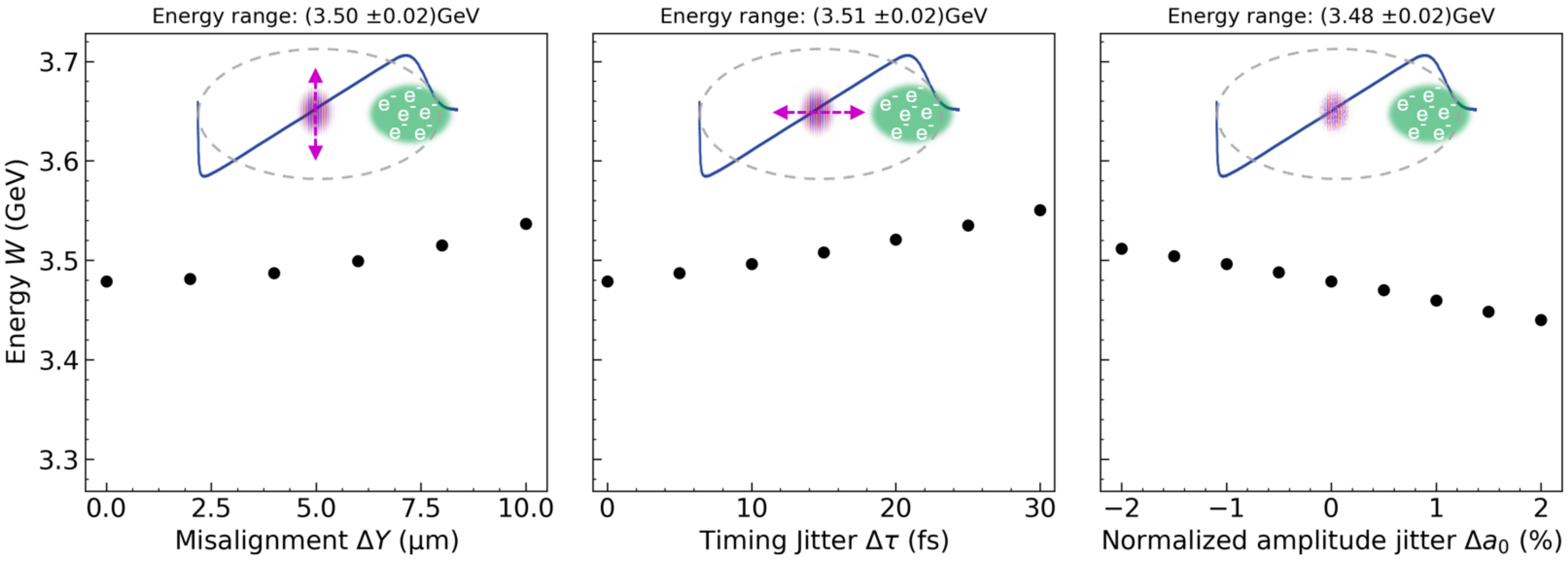


TABLE I. Witness beam parameter summary of plasma photocathode laser jitter analysis.

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

Habib, F. A. et al. Ultrahigh brightness beams from plasma photoguns. Preprint at https://arxiv.org/abs/2111.01502 (2021).