IOP Particle Accelerators and Beams Conference
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A. Fahim Habib* et al.

Ultra-compact X-ray free-electron laser near the cold beam limit

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Scottish Universities Physics Alliance (SUPA)
The Cockcroft Institute

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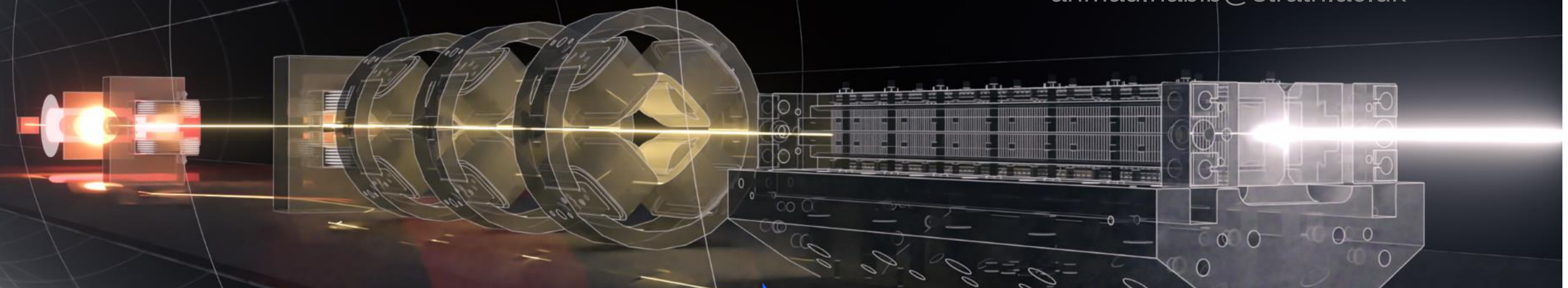

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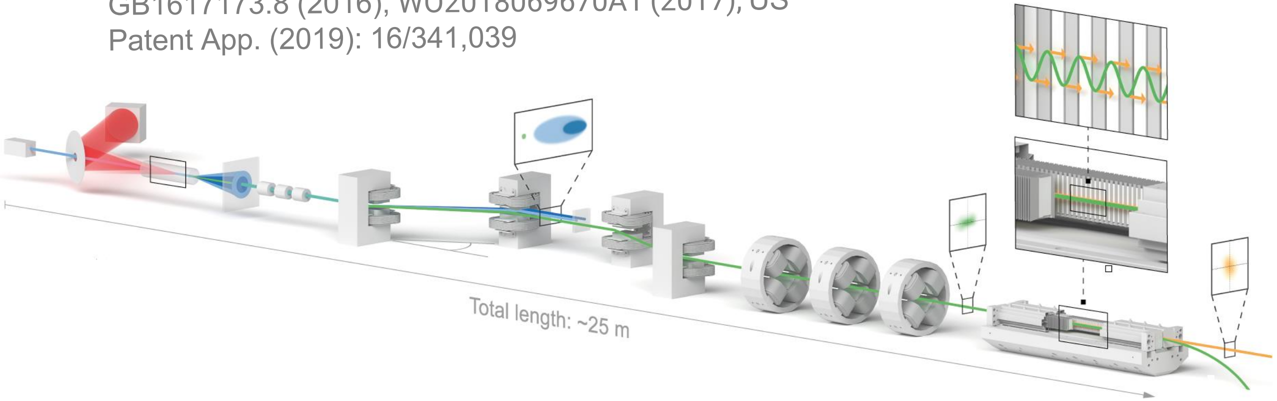
Motivation

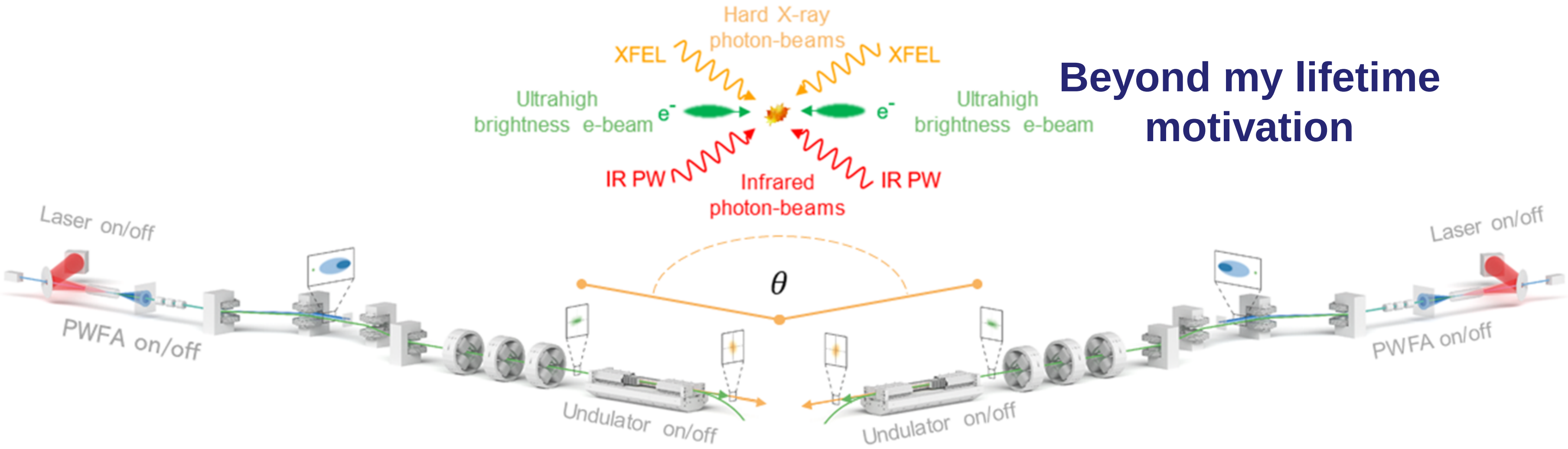
Midterm Vision

- Beam-driven plasma wakefield acceleration (PWFA) can sustain 10-100 GV/m accelerating fields
- Improve electron beam quality by many orders of magnitude
- Path to compact X-FEL
- Integrate plasam-based accelerators into existing and future XFEL facilities→ FEL afterburner?



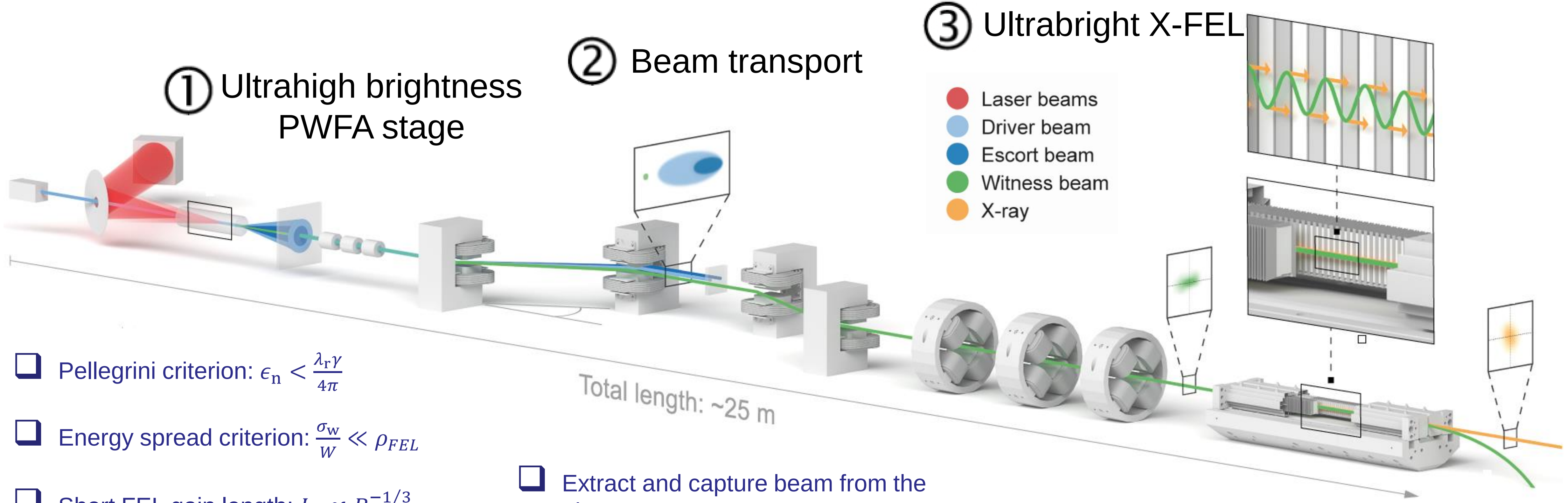
Hidding, B., Manahan, G. G., Habib, A. F., Patent App. GB1617173.8 (2016), WO2018069670A1 (2017), US Patent App. (2019): 16/341,039

Beyond my lifetime motivation



- Investigate photon-photon scattering (Not experimentally demonstrated so far)
- Single molecule tomography?

Plasma-X-FEL fundamental challenges



① Ultrahigh brightness PWFA stage

- ☐ Pellegrini criterion: $\epsilon_{\mathrm{n}} < \frac{\lambda_{\mathrm{r}}\gamma}{4\pi}$
- ☐ Energy spread criterion: $\frac{\sigma_{\mathrm{w}}}{W} \ll \rho_{FEL}$
- ☐ 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

② Beam transport

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

③ Ultrabright X-FEL

- ☐ Drive a XFEL at hard wavelength < 0.5 nm
- ☐ Generate radiation with fs/sub-fs duration
- ☐ Achieve saturation → coherence
- ☐ Operate in the single-spike regime to obtain fully coherent x-ray pulses ?

Building blocks of PWFA-X-FEL

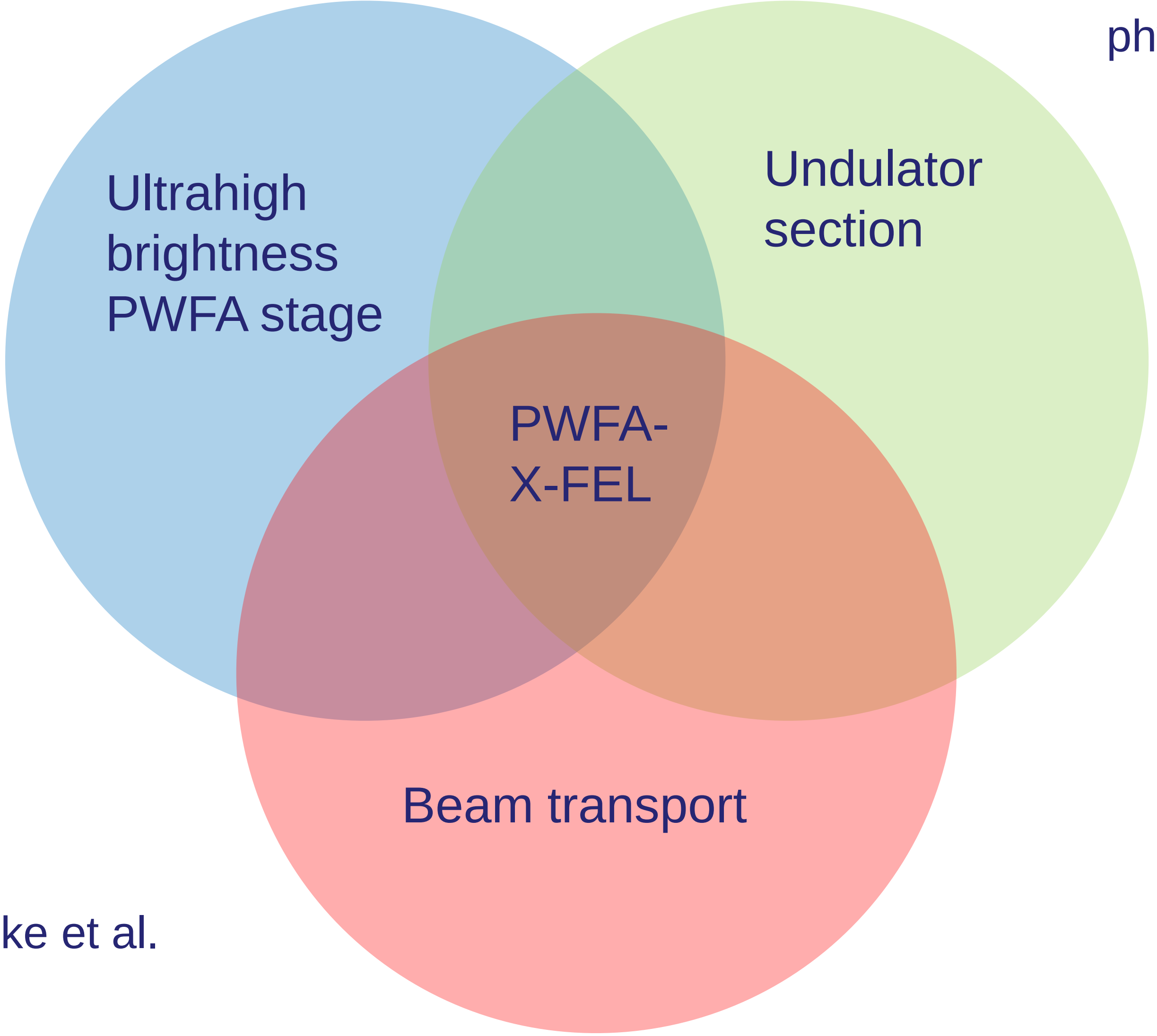
B. Hidding, McNeil, F. Habib, et al.

Rosenzweig et al.

Hogan, Raubenheimer, Hemsing et al.

Litos et al.

Williams, Clarke et al.

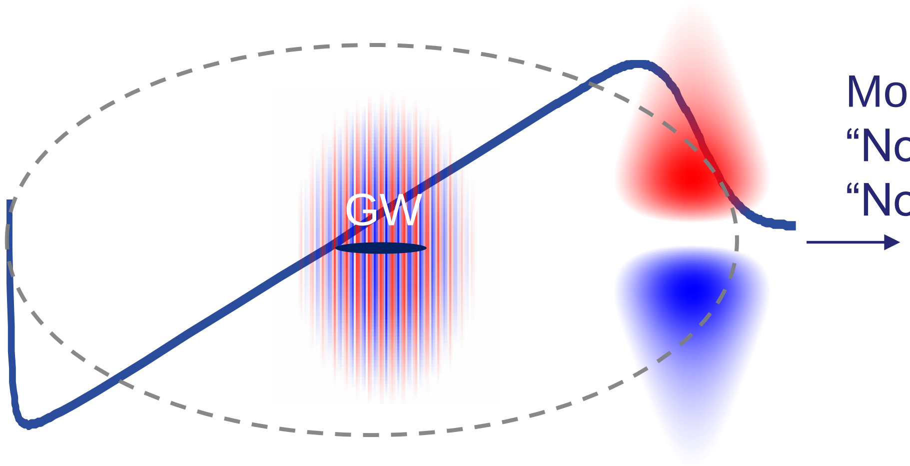


All three building blocks have their own simulation and physics challanges

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

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 clean electron beam production from localized tunnel ionization e.g. of He
- Transverse residual momentum from ~10^{15} W/cm^2 laser negligible ⇒ normalized emittance ε_n **~ nm rad scale**
- Auto-compression to kA currents I ⇒ beams orders of magnitude brighter than state-of-the-art

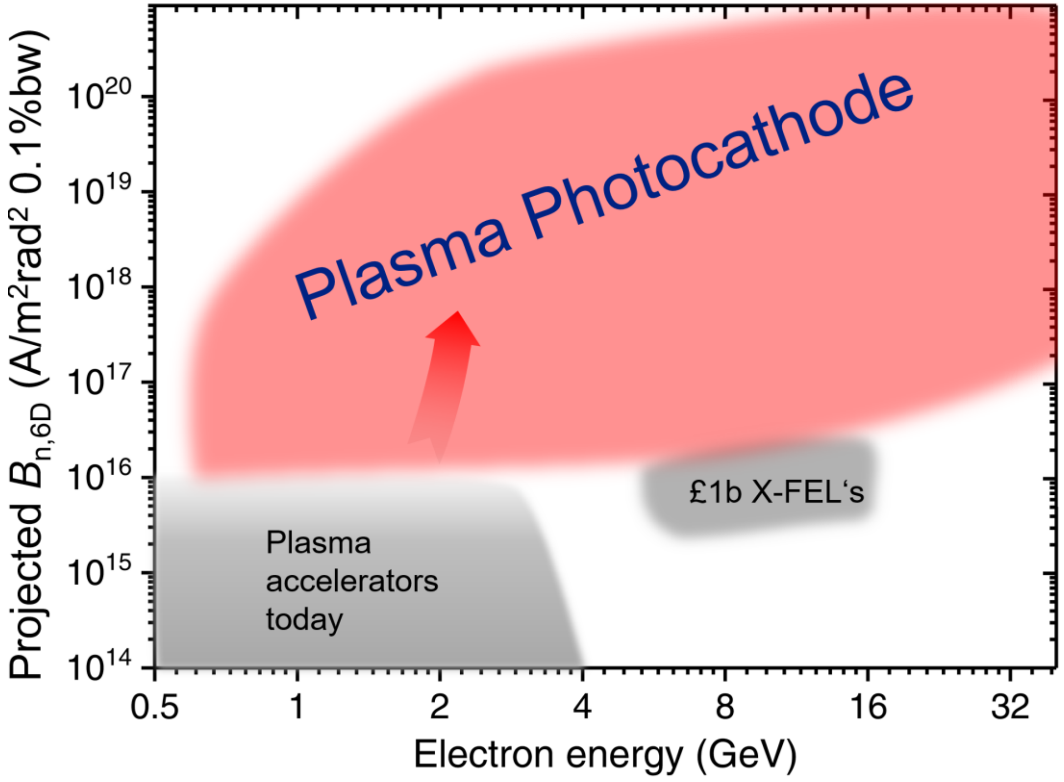
Light source and HEP applications

multi-kA current

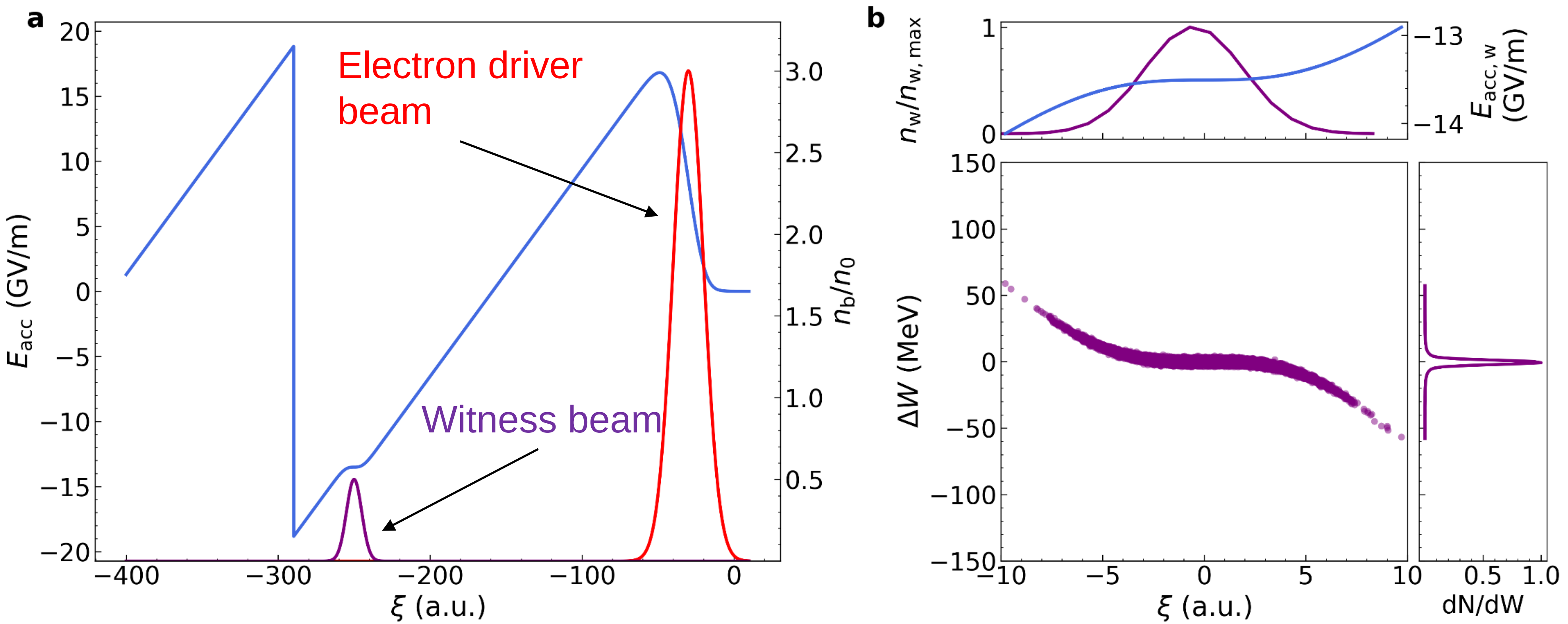
$$B_{6D} = \frac{I}{\epsilon_n^2 \cdot 0.1\% \sigma_W}$$

energy spread <0.01%

nm rad emittance

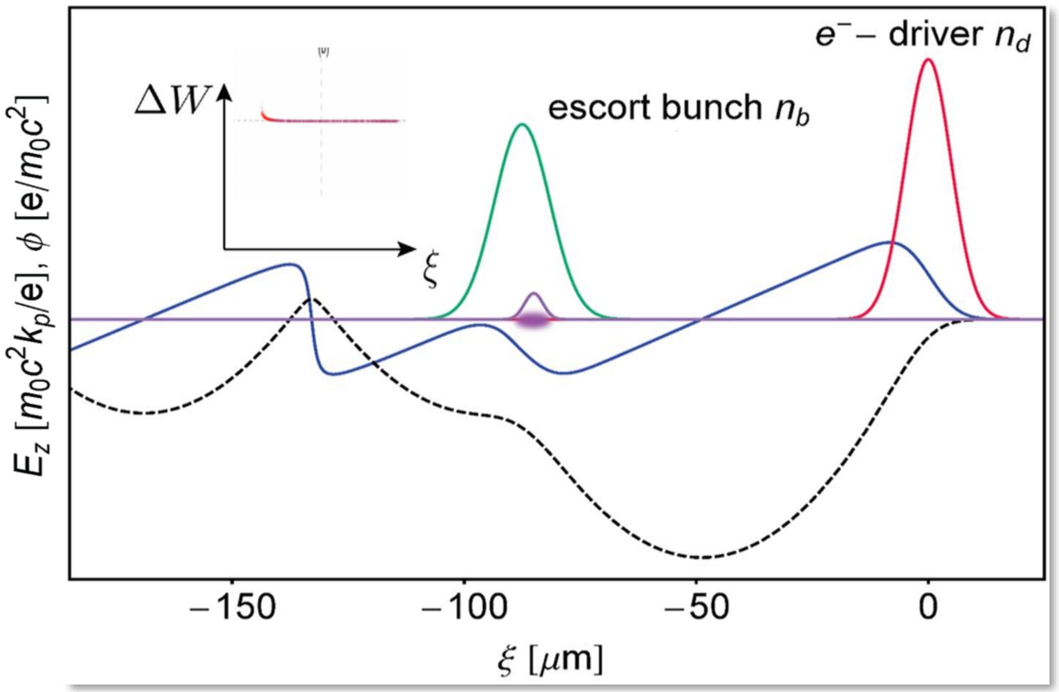


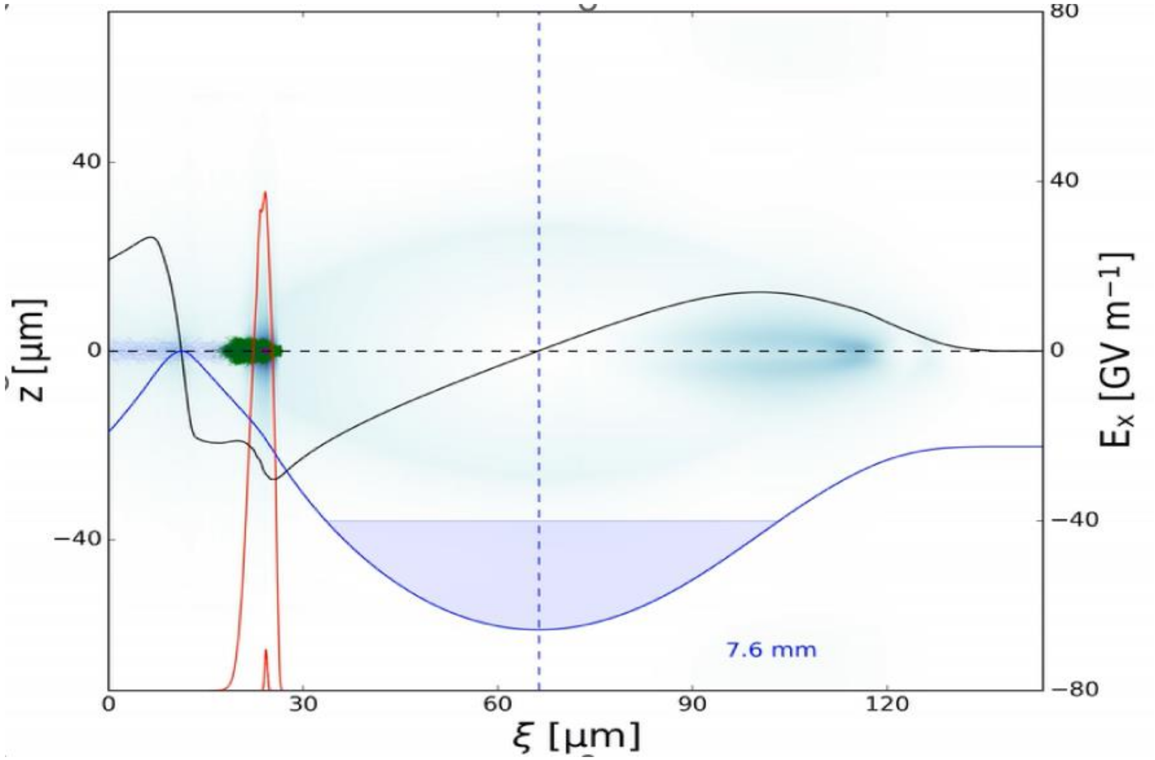
Energy spread/chirp challenge: direct beam loading



- ❑ Straightforward way→ Take advantage of direct beam loading
- ❑ Requires multi-kA witness beams to load the wakefield
- ❑ **Problem:** Space charge effects degrades beam emittance ~100 nm rad level→ reduced 6D brightness
- ❑ **See poster by Lily Berman on soft X-ray FEL (Poster Session)**

Energy spread/chirp challenge: escort





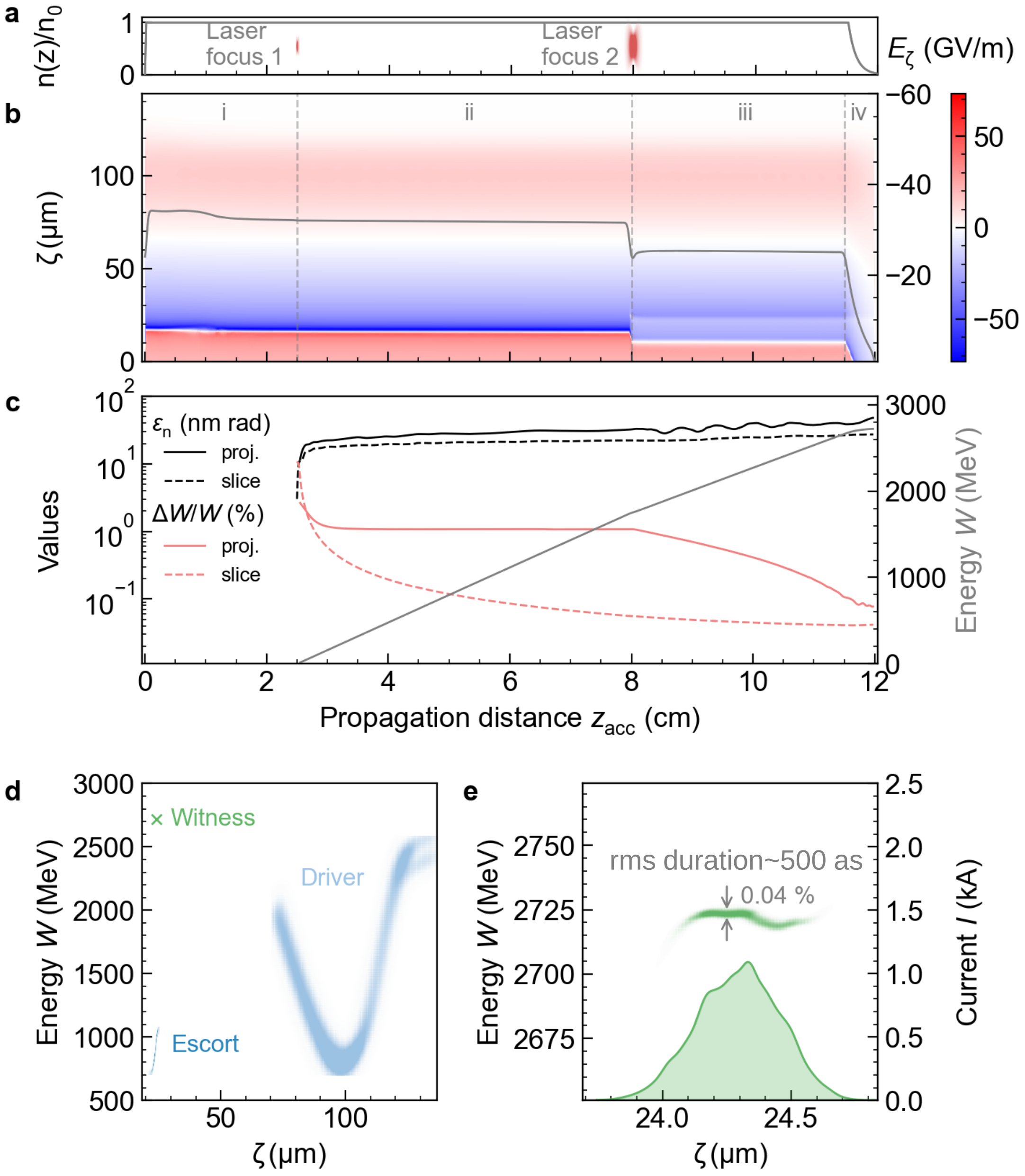
G.G. Manahan/A. F. Habib *et al., Nat. Comm.* 8, 15705 *(*2017)

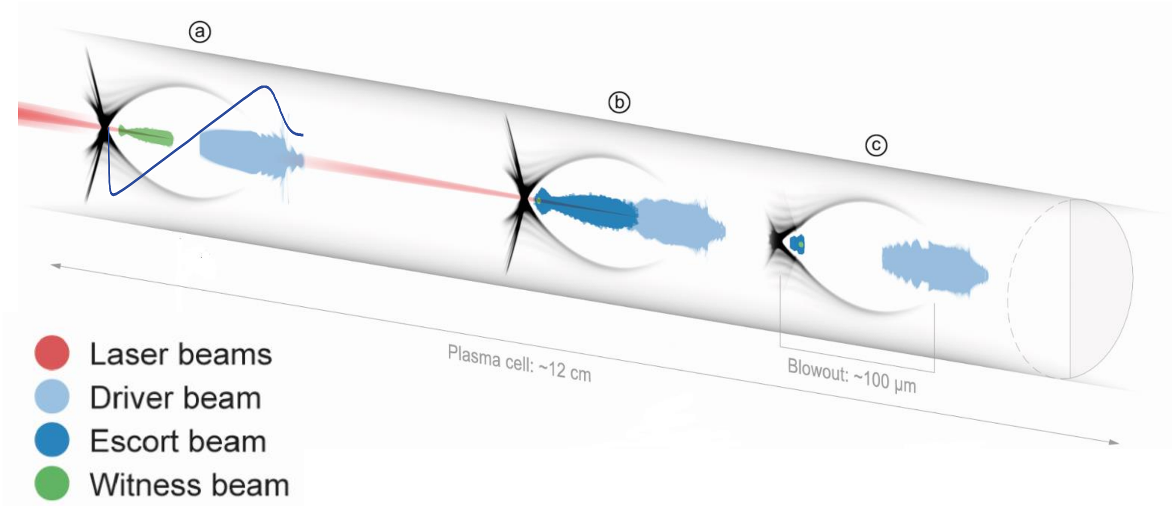
- Decouple witness beam production from dechirping →Exploit tailored beam loading via a second “escort“ beam“approach→ locally flip field gradient at the witness position

- Reduced the energy spread down to ~ 0.3% at approx. 700 MeV

- E-313 experiment at FACET-II (PIs: Habib/Hidding)

Ultrahigh brightness PWFA stage



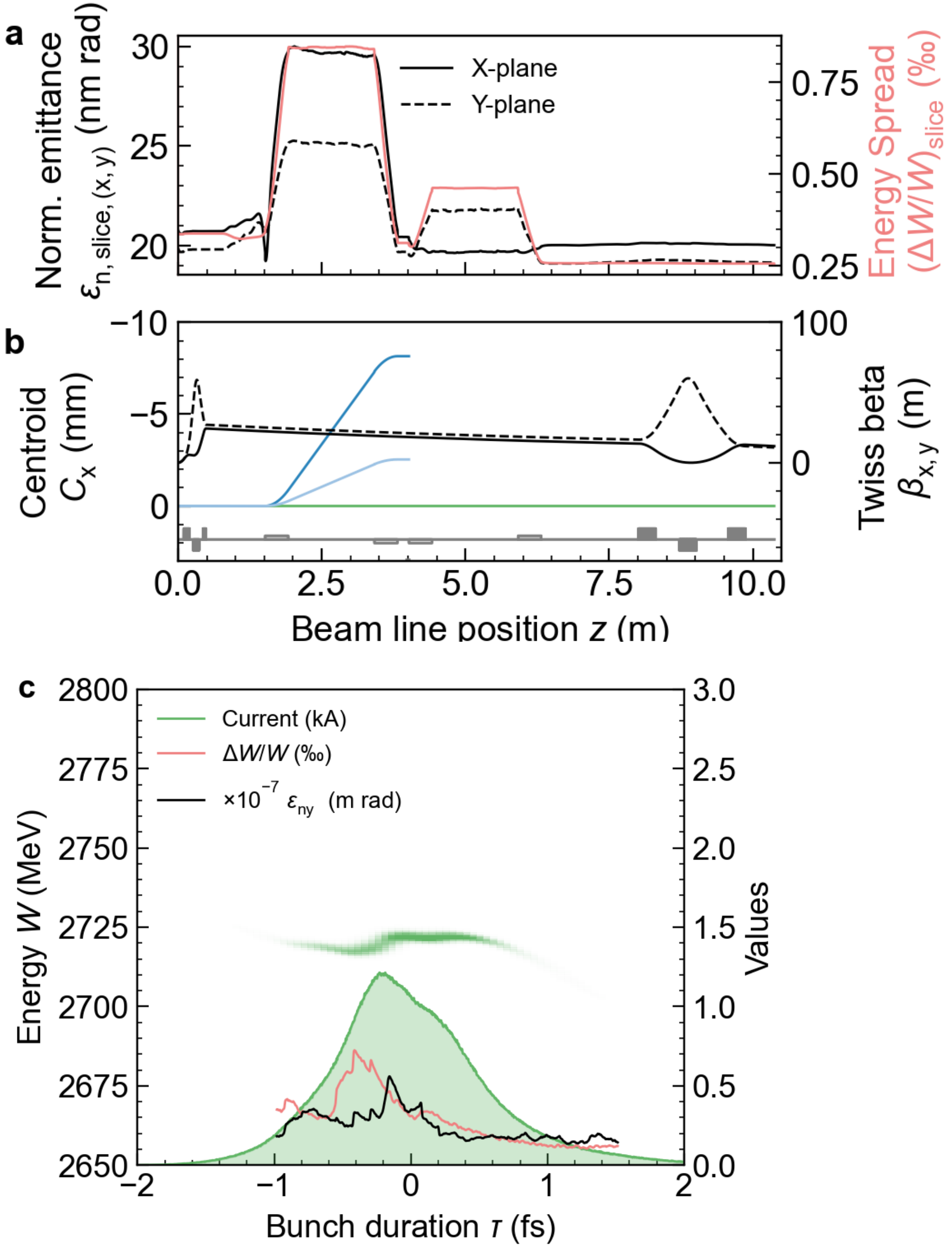


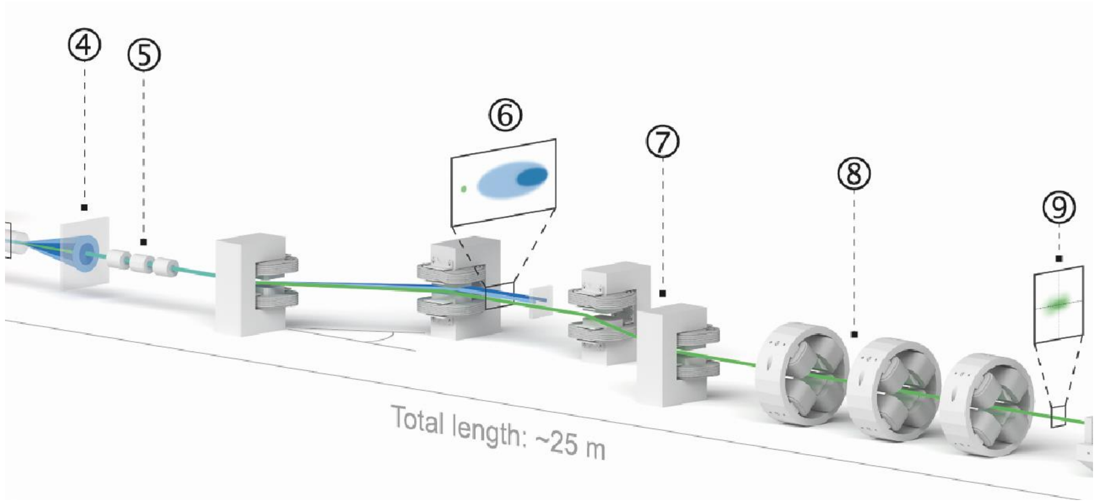
☐ High quality witness beam is produced, accelerator, dechirped and extracted without quality degradation in the same PWFA stage!

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, projected (slice) brightness $\sim B_{6D} \approx 1.3 \times 10^{18}$ (7.5×10^{18}) A m^{-2} rad^{-2}/0.1%bw.

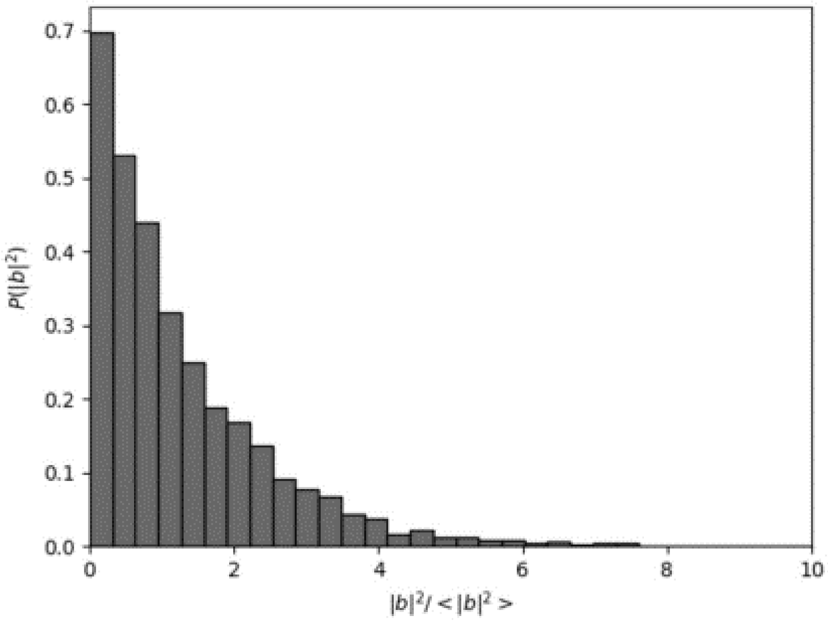
Beam transport line





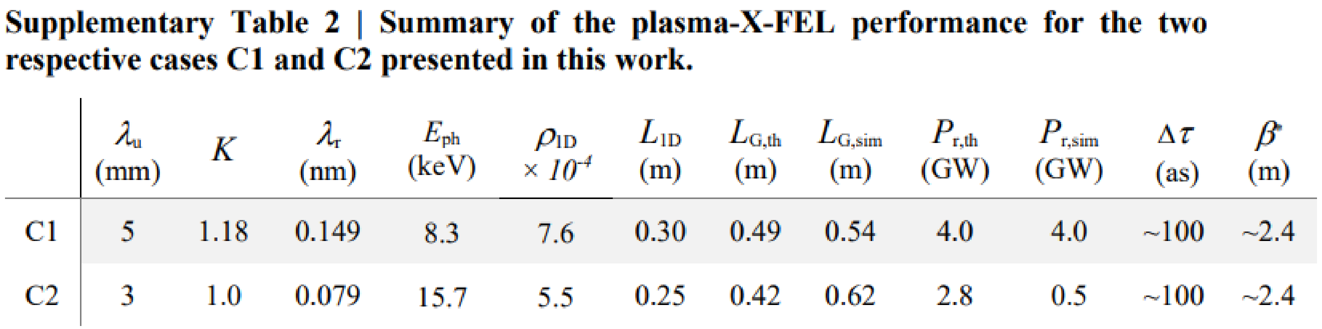
- Slice normalized emittance: 20 nm rad
- Slice energy spread~0.026 %
- Bunch rms duration: 500 atto-sec
- Projected (slice) brightness at the undulator entrance $B_{6D} \approx 1.3 \times 10^{18}$ (1.1×10^{19}) A m^{-2} rad^{-2}/0.1%bw.

Fixing the shot-noise and undulator considerations



Traczykowski, P. et al. Computer Physics Communications, 108661 (2023).

- 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



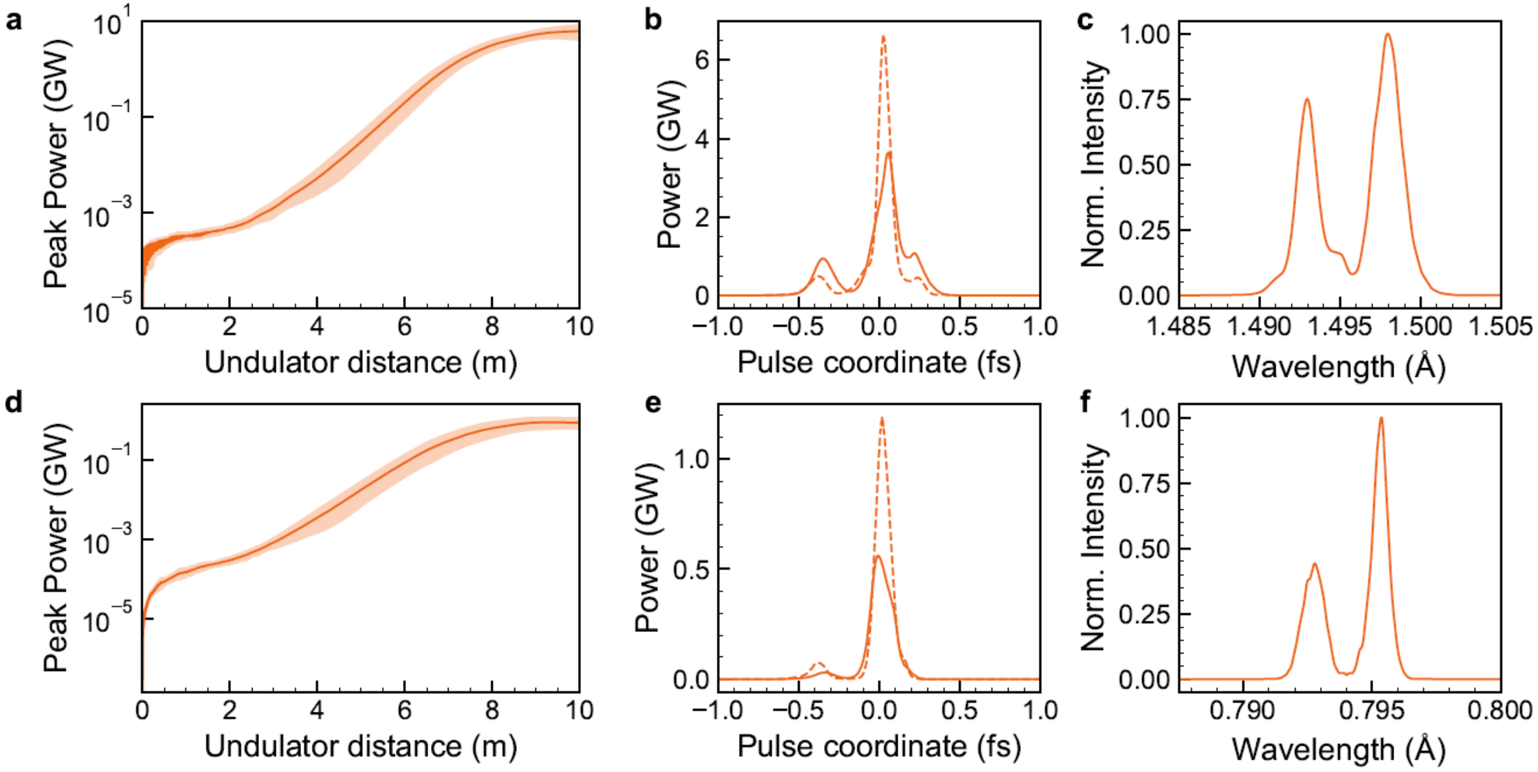
Supplementary Table 2 | Summary of the plasma-X-FEL performance for the two respective cases C1 and C2 presented in this work.

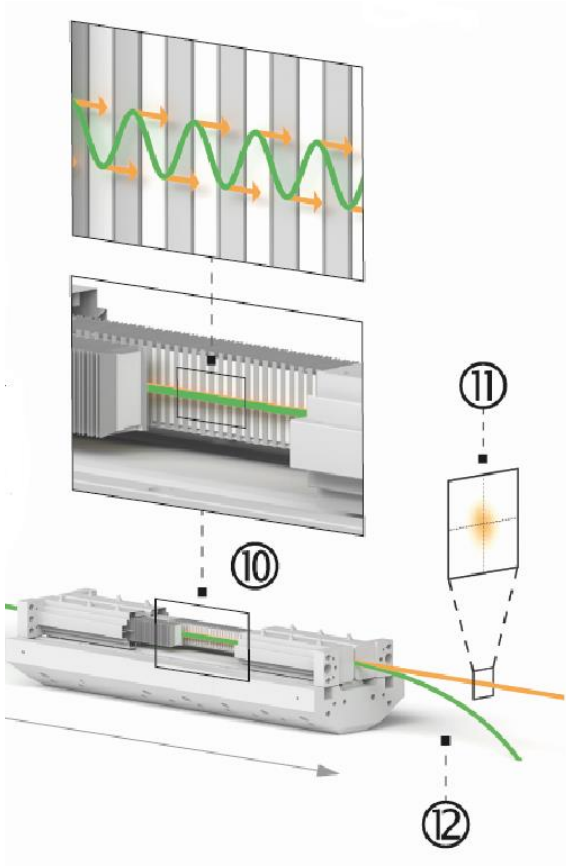
	λ_u (mm)	K	λ_r (nm)	E_{ph} (keV)	ρ_{1D} $\times 10^{-4}$	L_{1D} (m)	$L_{G,th}$ (m)	$L_{G,sim}$ (m)	$P_{r,th}$ (GW)	$P_{r,sim}$ (GW)	$\Delta\tau$ (as)	β^* (m)
C1	5	1.18	0.149	8.3	7.6	0.30	0.49	0.54	4.0	4.0	~100	~2.4
C2	3	1.0	0.079	15.7	5.5	0.25	0.42	0.62	2.8	0.5	~100	~2.4

- 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).

Hard X-ray FEL section





- **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 atto sec
- High gain and short bunch duration few modes are amplified→ near longitudinal coherence
- $\Delta\nu\Delta\tau \approx 1.8$ 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

Experimental pathways toward bright light sources

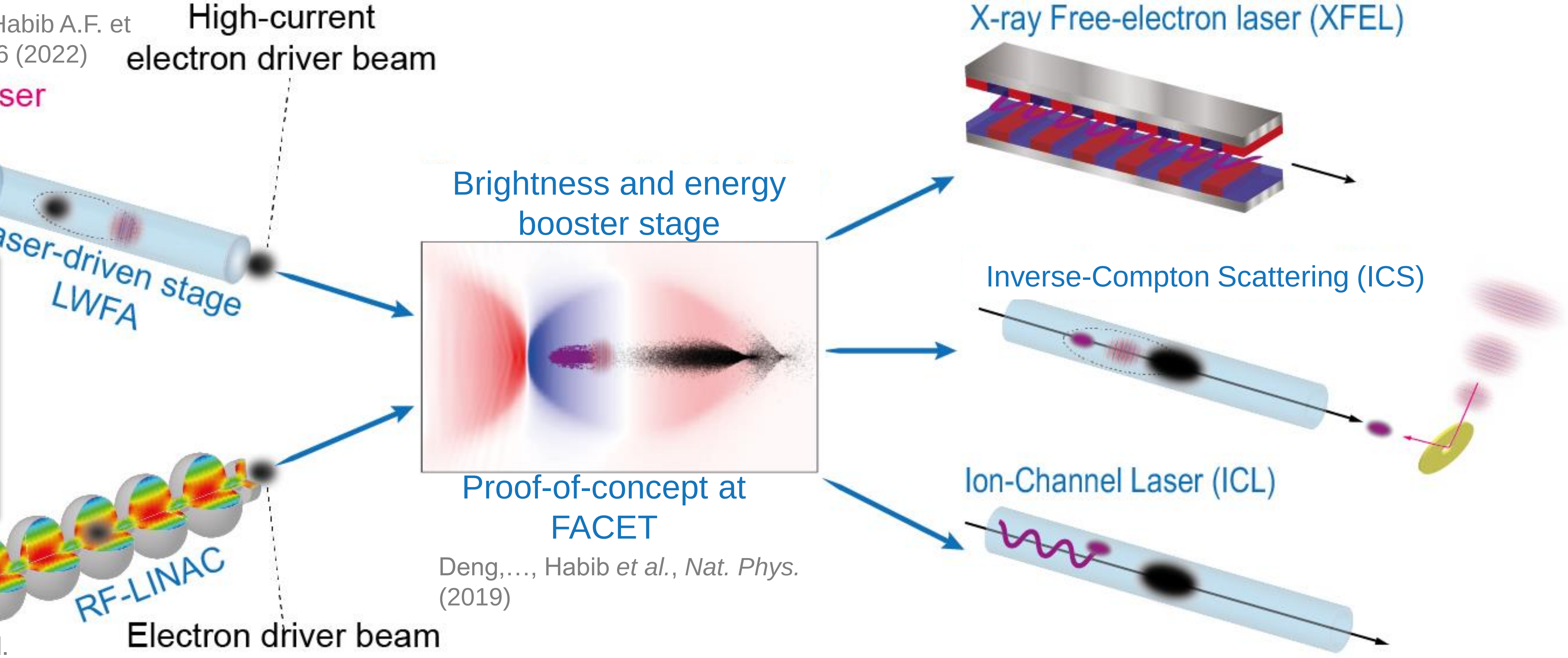
Giljohann, M. F. et al. PRX 9, 011046 (2019)

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

Foerster F.M., ..., Habib A.F. et al. PRX 12, 041016 (2022)

More high-power laser systems for LWFA, i.e in SCAPA, EPAC, HZDR, CALA, HHU and more

Plasma photocathode may enable novel applications in light sources, high field physics (QED) and HEP



Brightness and energy booster stage

Proof-of-concept at FACET

Deng,…, Habib *et al.*, *Nat. Phys.* (2019)

Habib, A. F. et al., Proc. SPIE 11110 (2019)

Blumenfeld, I. et al. Nature 445, 741–744 (2007)

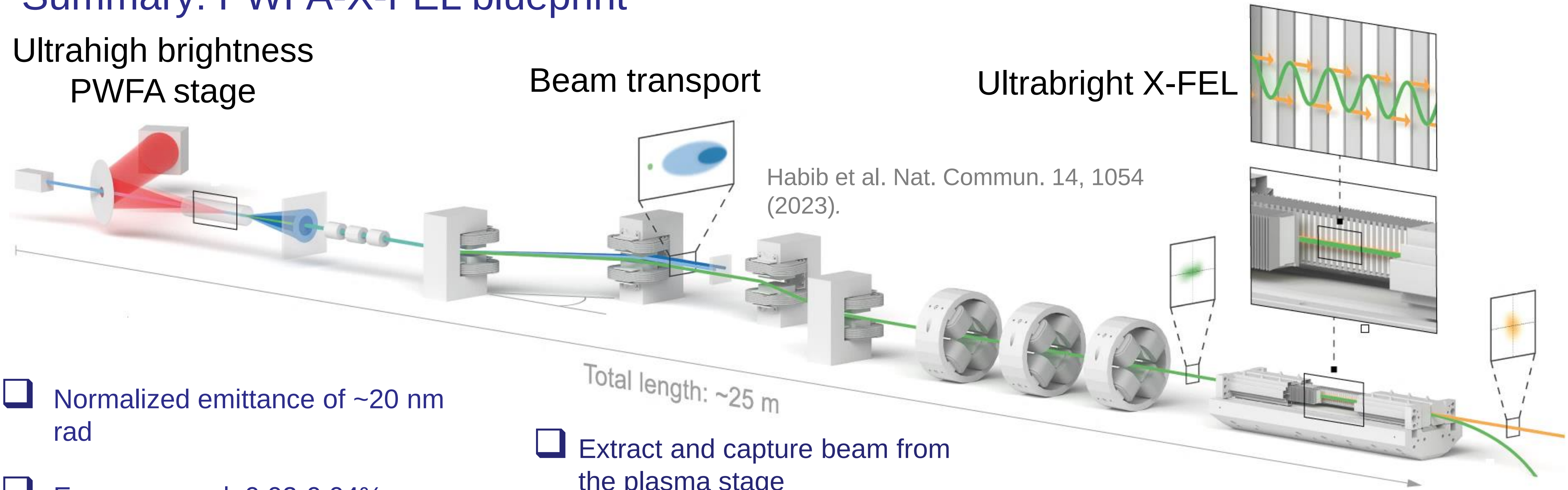
M. Litos, et al., Nature 515 92-15 (2014)

Deng,…, Habib *et al.*, *Nat. Phys.* (2019)

RF-facilities for PWFA

i.e FACET-II, LCLS, CLARA, PSI, DESY and more

Summary: PWFA-X-FEL blueprint



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

Ultrahigh brightness PWFA stage

- ☐ Normalized emittance of ~20 nm rad
- ☐ Energy spread: 0.02-0.04%
- ☐ Ultrahigh 6D brightness beams
- ☐ Dark current free acceleration over multi-cm→ multi-GeV energy gain
- ☐ Beam quality preservation

Beam transport

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

Ultrabright X-FEL

- ☐ Dramatically improved: ~1.5 Å and ~0.8 Å
- ☐ Generate radiation pulse ~100 as duration
- ☐ Near single-spike regime→ $\Delta\nu\Delta\tau \approx 1.8$ close to Fourier transform limited X-FEL pulse
- ☐ 3D gain length is very close to the 1D gain length→ **cold beam limit**

UKRI Science and Technology Facilities Council

Thanks
Have a bright PAB

University of Strathclyde Glasgow

Industrial partners:

radiasoft

TECH-X

radiabeam TECHNOLOGIES

Stanford University

SLAC

FACET-II Facility for Advanced Accelerator Experimental Tests

ASTeC

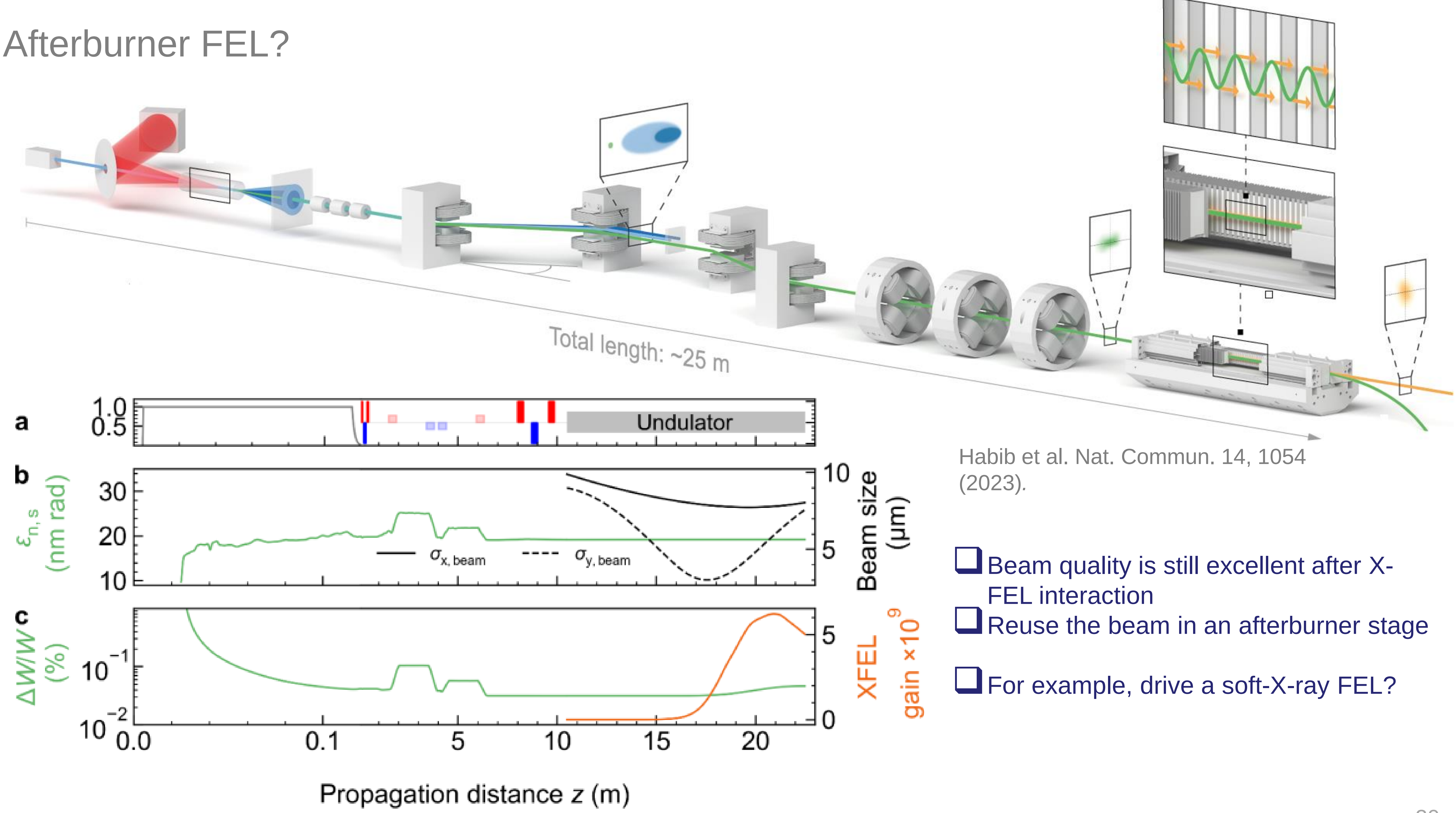
UCLA

SCAPA

hhu Heinrich Heine Universität Düsseldorf

Back up

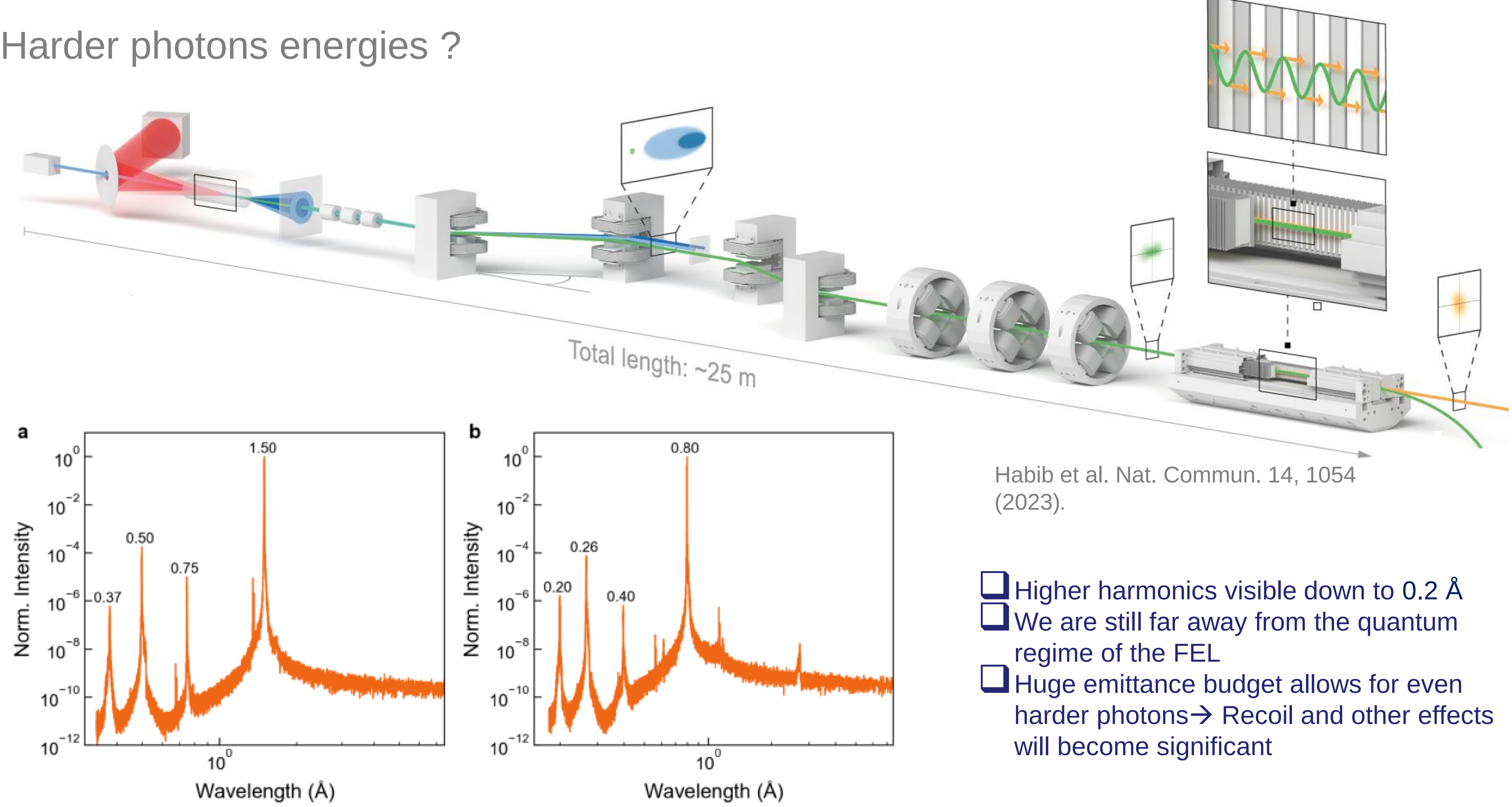
Afterburner FEL?



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

- Beam quality is still excellent after X-FEL interaction
- Reuse the beam in an afterburner stage
- For example, drive a soft-X-ray FEL?

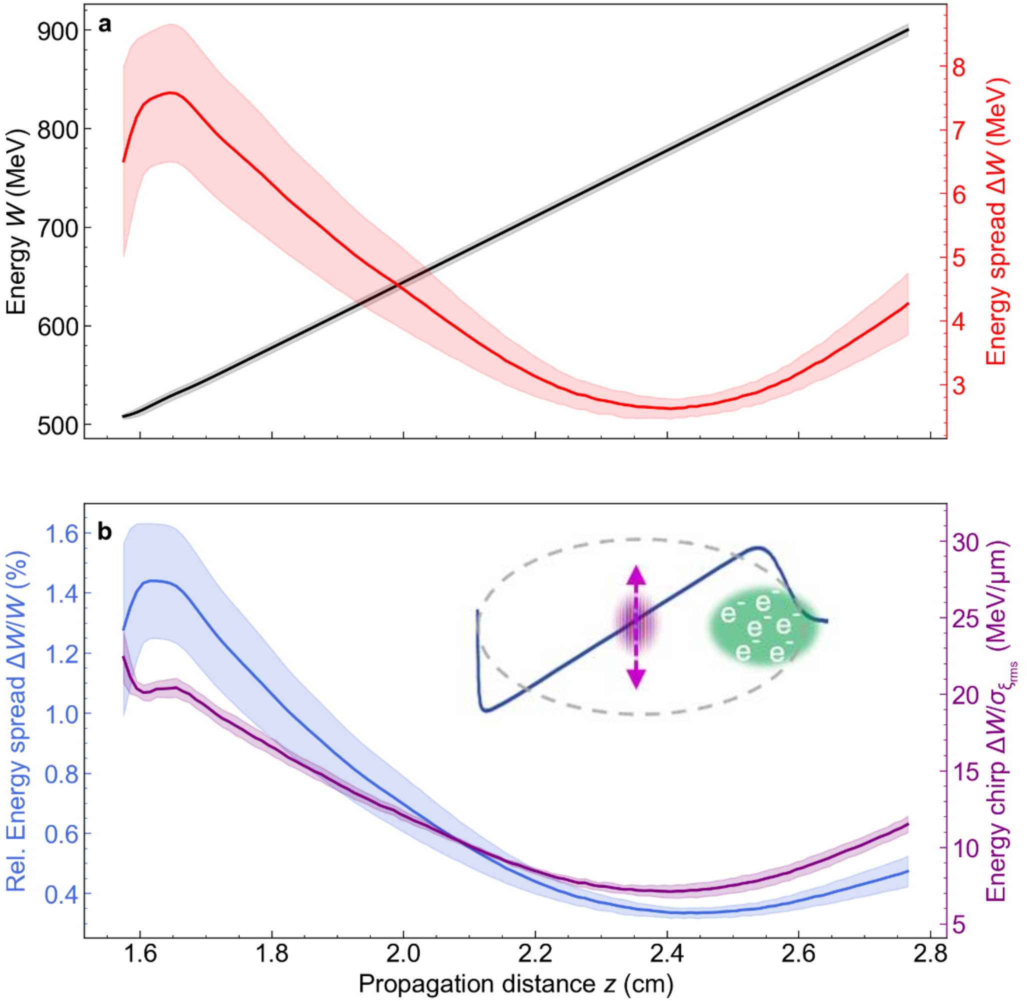
Harder photons energies ?

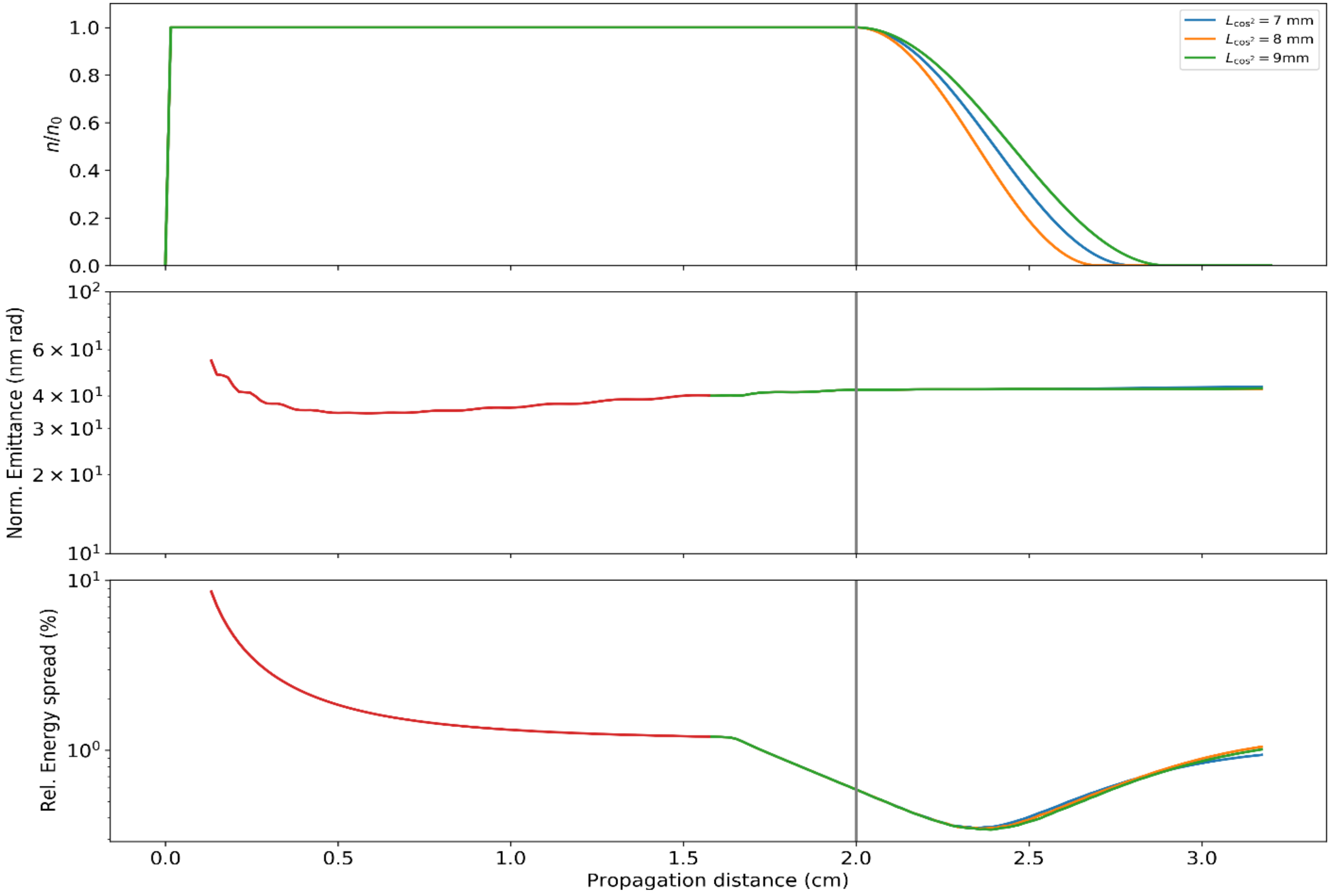


Habib et al. Nat. Commun. 14, 1054 (2023).

- ☐ Higher harmonics visible down to 0.2 Å
- ☐ We are still far away from the quantum regime of the FEL
- ☐ Huge emittance budget allows for even harder photons→ Recoil and other effects will become significant

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

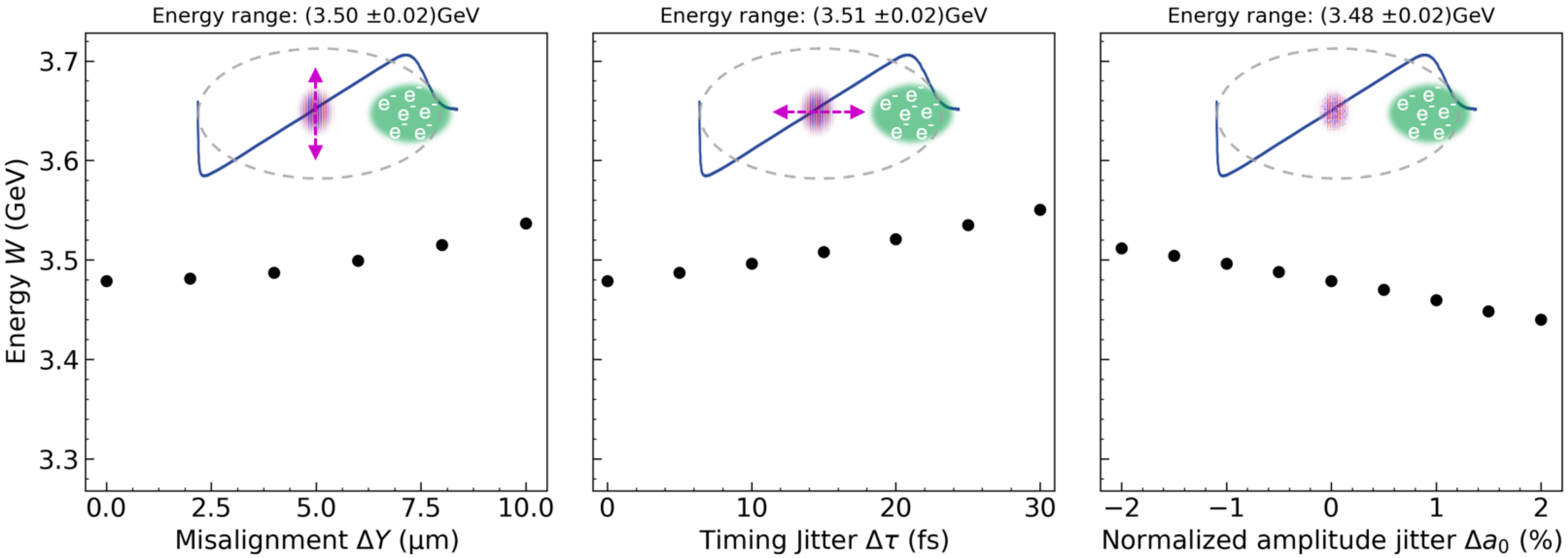
Beam quality stability analysis

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



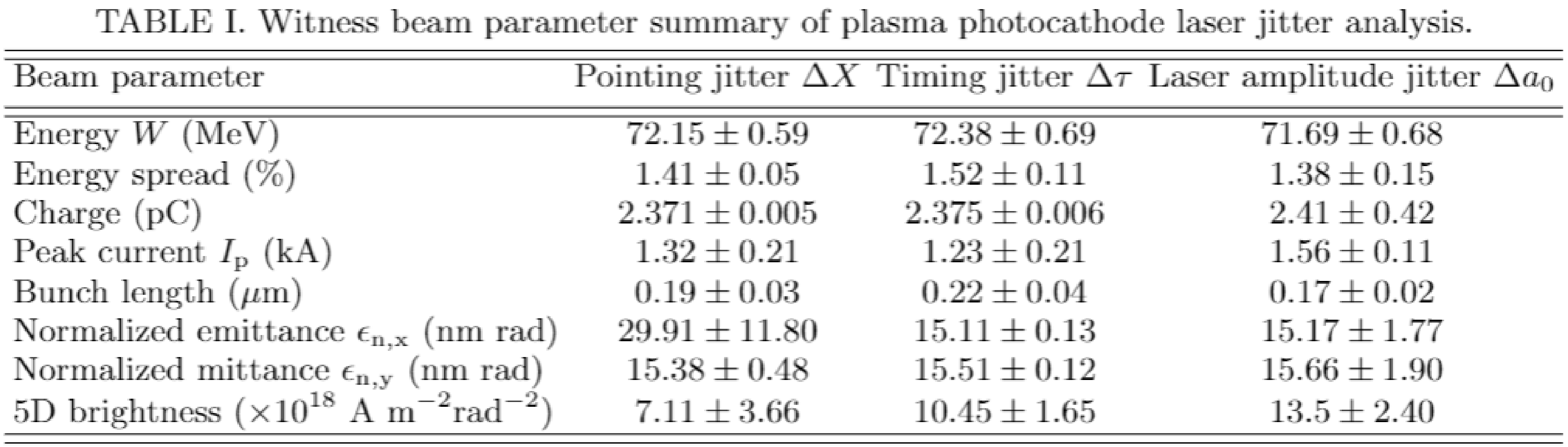


TABLE I. Witness beam parameter summary of plasma photocathode laser jitter analysis.

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).