2019-11-01

Bernhard Hidding, Fahim Habib, Paul Scherkl, Brian McNeil *et al.*,
Peter Williams, Jim Clarke, Deepa Angal-Kalinin *et al.*,
James Rosenzweig, Gerard Andonian *et al.*,
Mark Hogan, Vitaly Yakimenko, Erik Hemsing, Tor Raubenheimer *et al.*

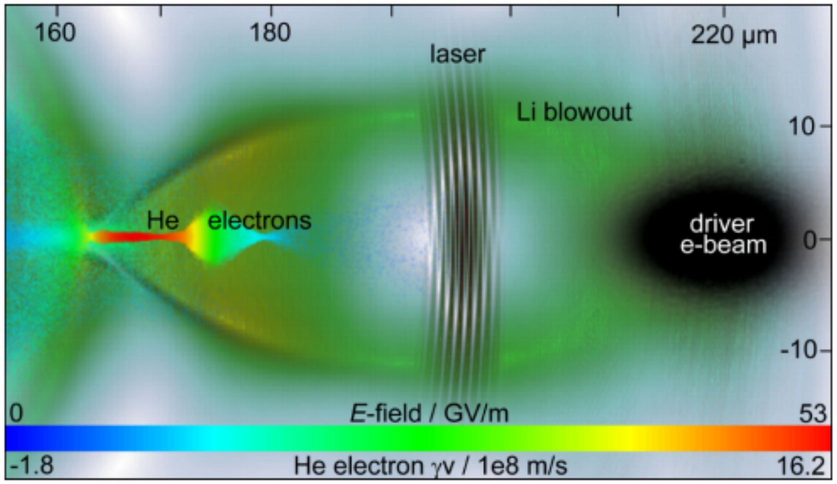
PWFA-FEL

Scottish Centre for the Application of Plasma-Based Accelerators SCAPA,
Department of Physics, University of Strathclyde,
Scottish Universities Physics Alliance SUPA, UK

Strathclyde Centre for Doctoral Training P-PALS
Plasma-based Particle and Light Sources http://ppals.phys.strath.ac.uk/

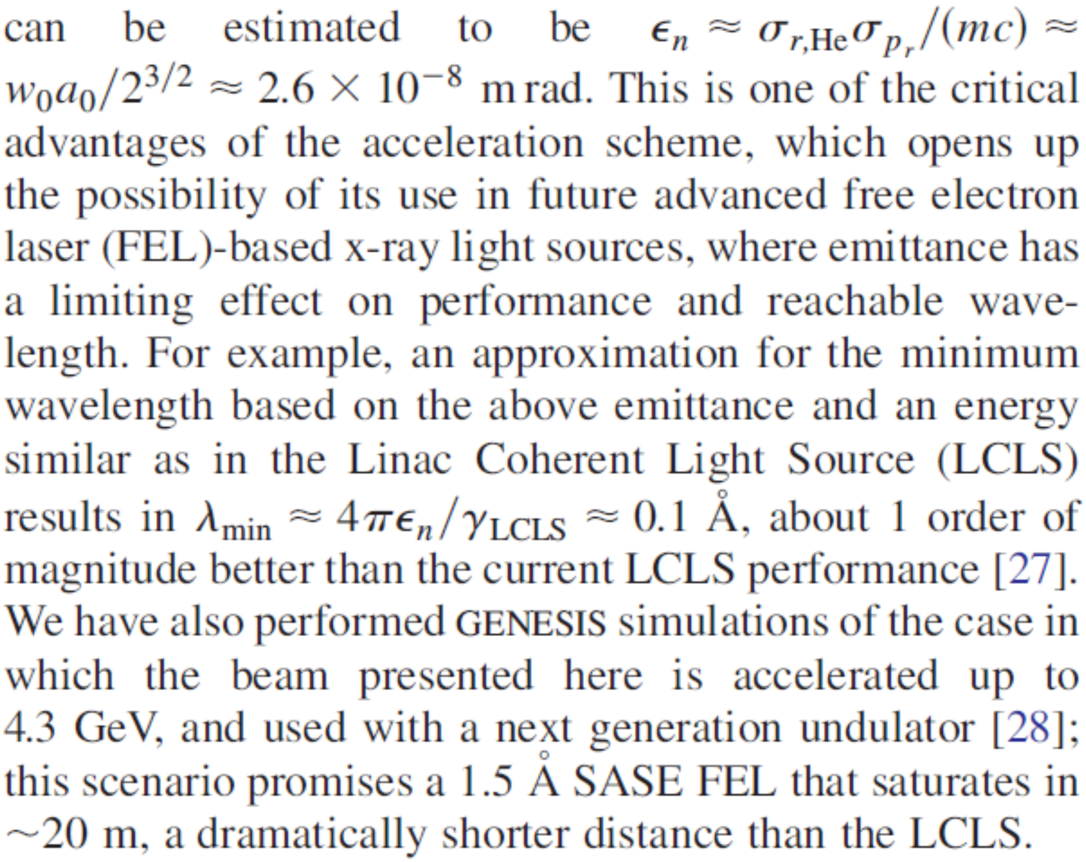
& The Cockcroft Institute

Trojan Horse plasma photocathode

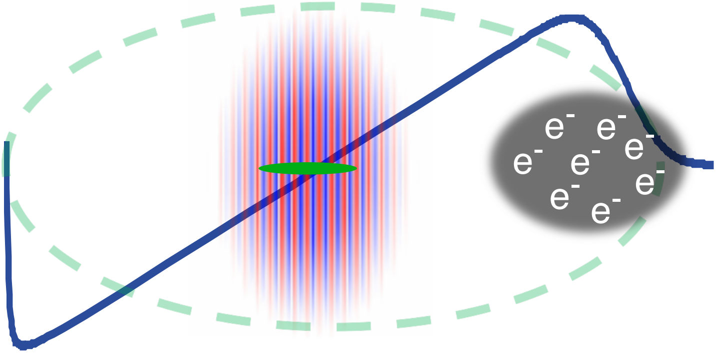


Hidding *et al.*, *Phys. Rev. Letters 108*, 035001 (2012)

- ☐ Prospect for nm rad emittance; brightness many orders of magnitude beyond even state-of-the-art X-FEL linacs



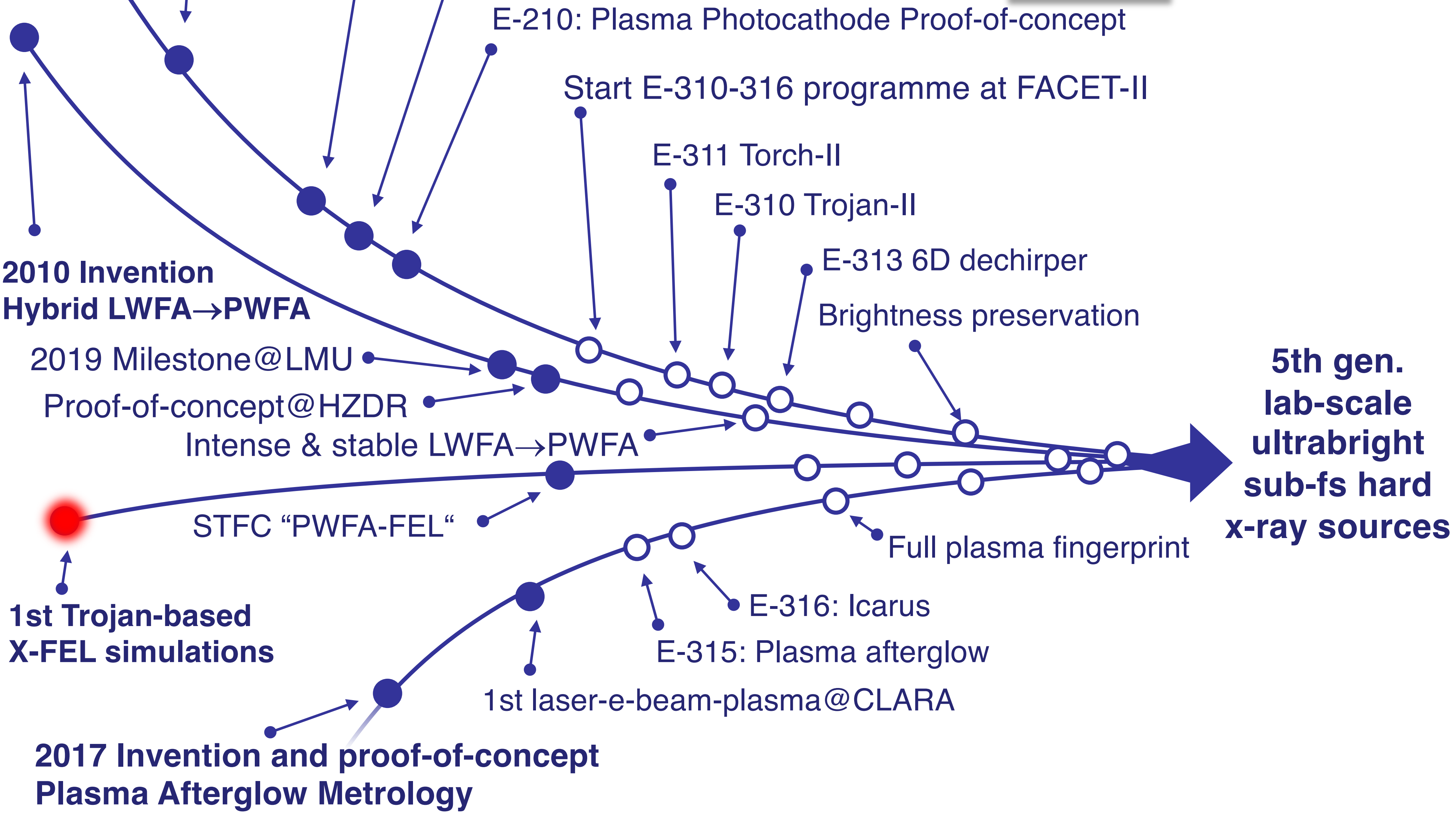
can be estimated to be $\epsilon_n \approx \sigma_{r,\mathrm{He}}\sigma_{p_r}/(mc) \approx w_0 a_0/2^{3/2} \approx 2.6 \times 10^{-8}$ m rad. This is one of the critical advantages of the acceleration scheme, which opens up the possibility of its use in future advanced free electron laser (FEL)-based x-ray light sources, where emittance has a limiting effect on performance and reachable wavelength. For example, an approximation for the minimum wavelength based on the above emittance and an energy similar as in the Linac Coherent Light Source (LCLS) results in $\lambda_{\min} \approx 4\pi\epsilon_n/\gamma_{\mathrm{LCLS}} \approx 0.1$ Å, about 1 order of magnitude better than the current LCLS performance [27]. We have also performed GENESIS simulations of the case in which the beam presented here is accelerated up to 4.3 GeV, and used with a next generation undulator [28]; this scenario promises a 1.5 Å SASE FEL that saturates in ~20 m, a dramatically shorter distance than the LCLS.



- ☐ Brightness transformer: Increase by factor up to 100000x

$$B = \frac{2I}{\epsilon_{\mathrm{n}}^2}$$

Roadmap



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E-210: Plasma Photocathode Proof-of-concept

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5th gen.
lab-scale
ultrabright
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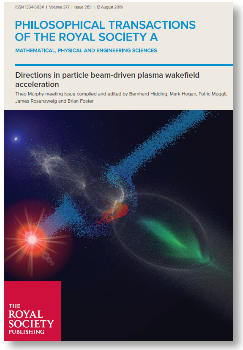

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MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

Directions in particle beam-driven plasma wakefield acceleration

Theo Murphy meeting issue compiled and edited by Bernhard Hidding, Mark Hogan, Patric Muggli, James Rosenzweig and Brian Foster

2013 - 2017

Plasma Photocathode Beam Brightness Transformer for Laser-Plasma Accelerators

Award Information

Agency:
Department of Energy

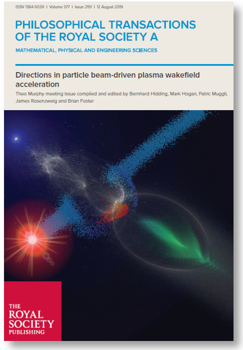
Branch:
N/A

Contract:
DE-FG02-13ER90568

Agency Tracking Number:
84148

Allowed E-210 plasma photocathode proof-of-concept, plasma torch density downramp proof-of-concept at FACET

Roadmap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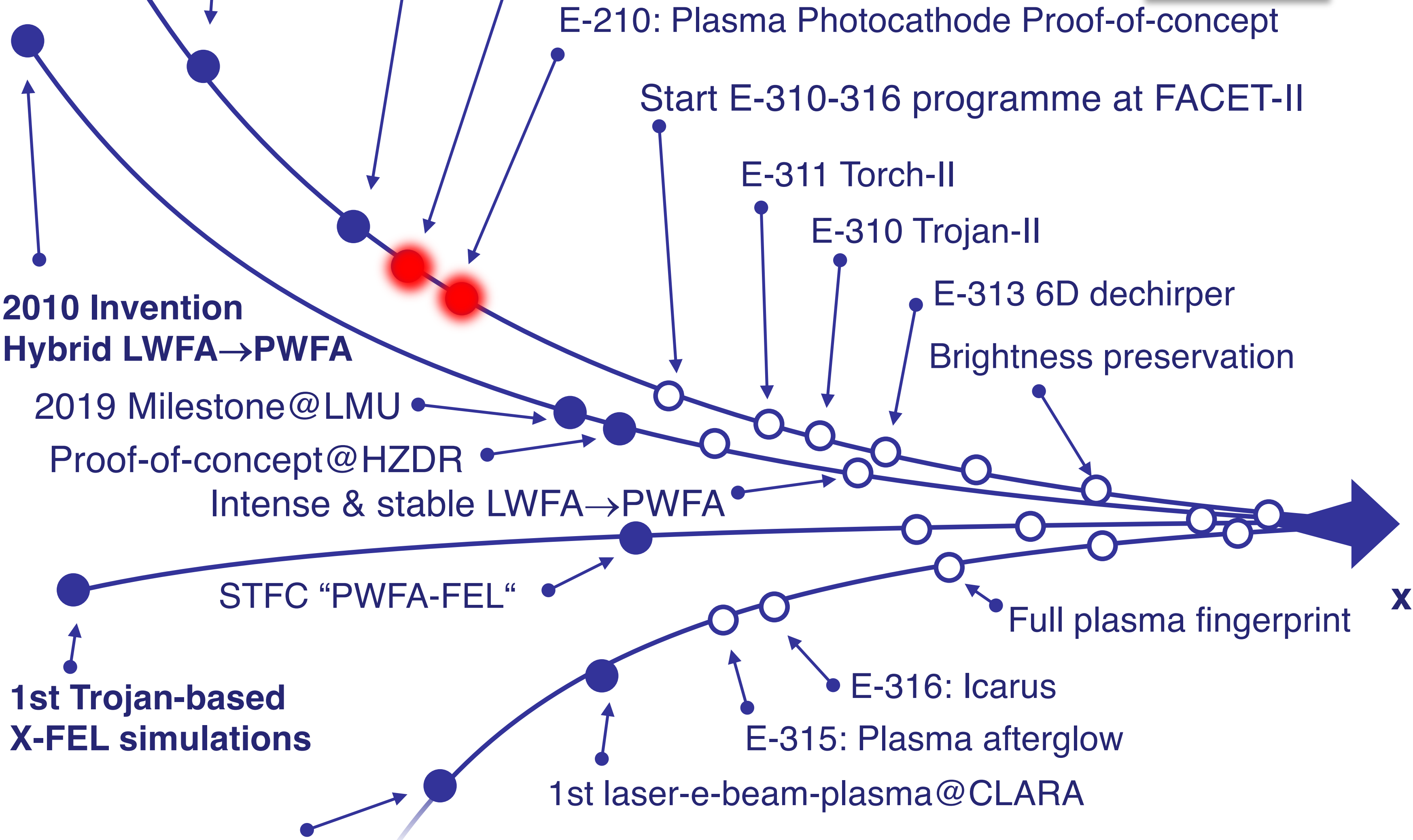
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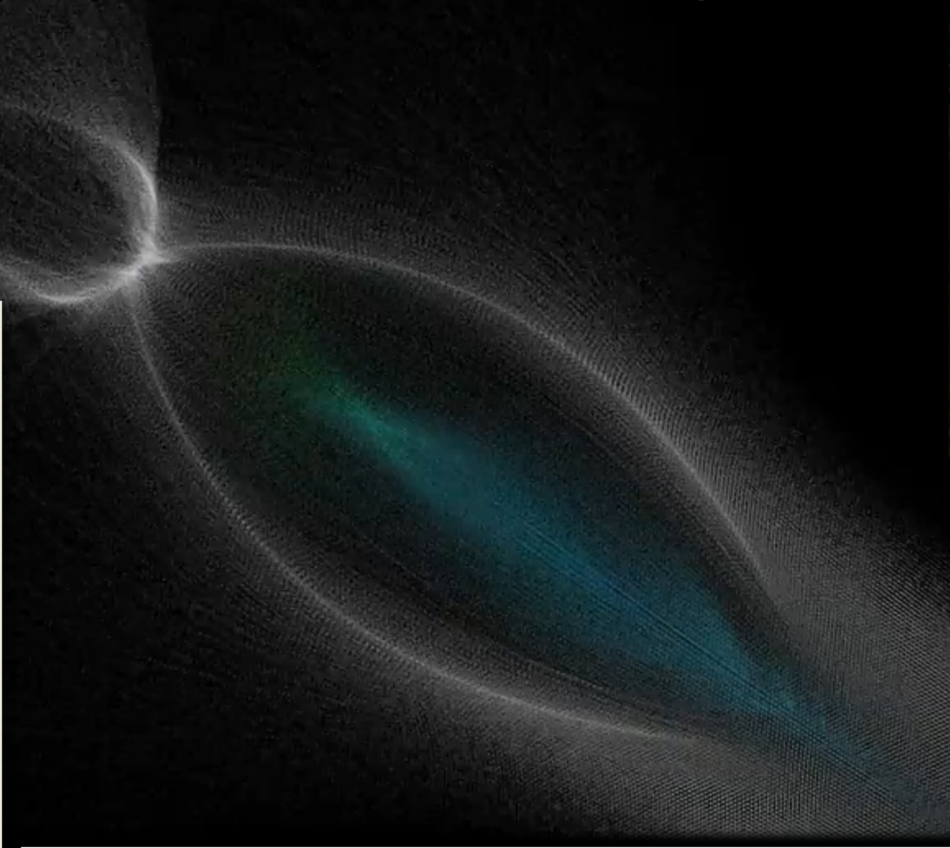
E-210: Trojan Horse
Proof-of-concept w/ 90° injector angle



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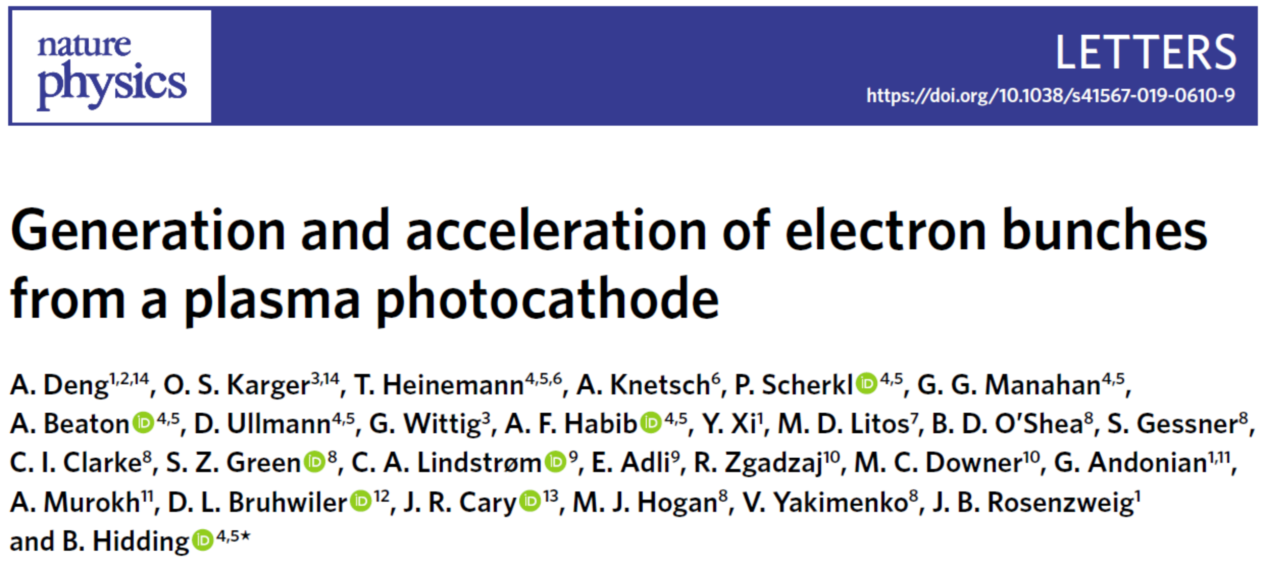


nature physics

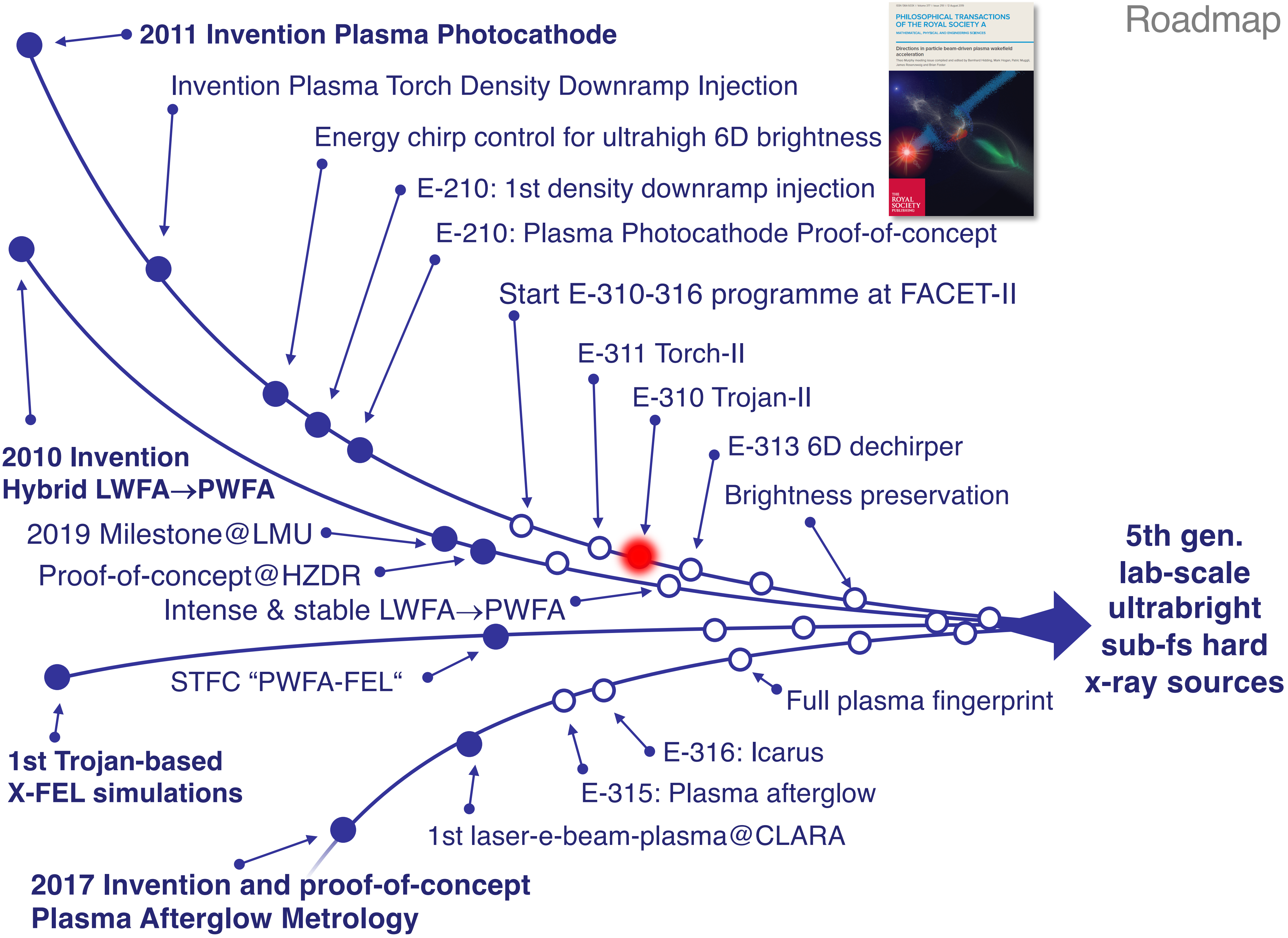
LETTERS

https://doi.org/10.1038/s41567-019-0610-9

Generation and acceleration of electron bunches from a plasma photocathode

A. Deng[1,2,14], O. S. Karger[3,14], T. Heinemann[4,5,6], A. Knetsch[6], P. Scherkl[4,5], G. G. Manahan[4,5], A. Beaton[4,5], D. Ullmann[4,5], G. Wittig[3], A. F. Habib[4,5], Y. Xi[1], M. D. Litos[7], B. D. O'Shea[8], S. Gessner[8], C. I. Clarke[8], S. Z. Green[8], C. A. Lindstrøm[9], E. Adli[9], R. Zgadzaj[10], M. C. Downer[10], G. Andonian[1,11], A. Murokh[11], D. L. Bruhwiler[12], J. R. Cary[13], M. J. Hogan[8], V. Yakimenko[8], J. B. Rosenzweig[1] and B. Hidding[4,5*]

Roadmap



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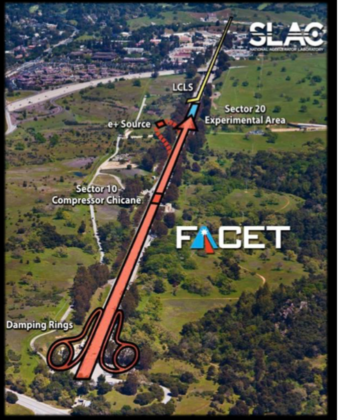
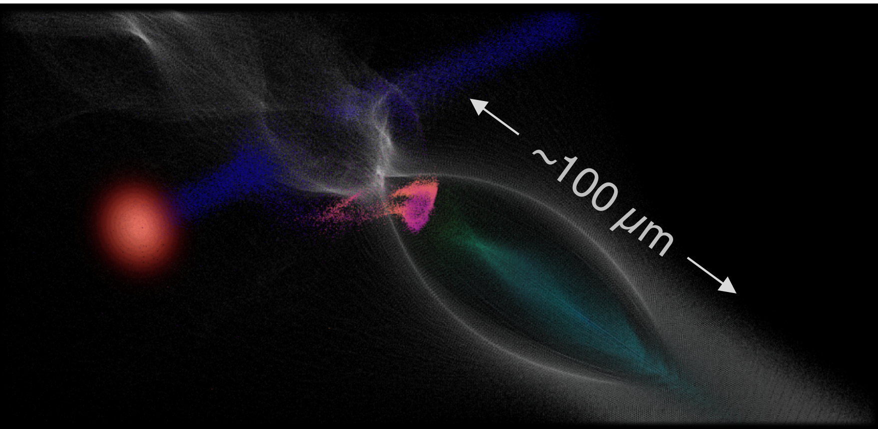
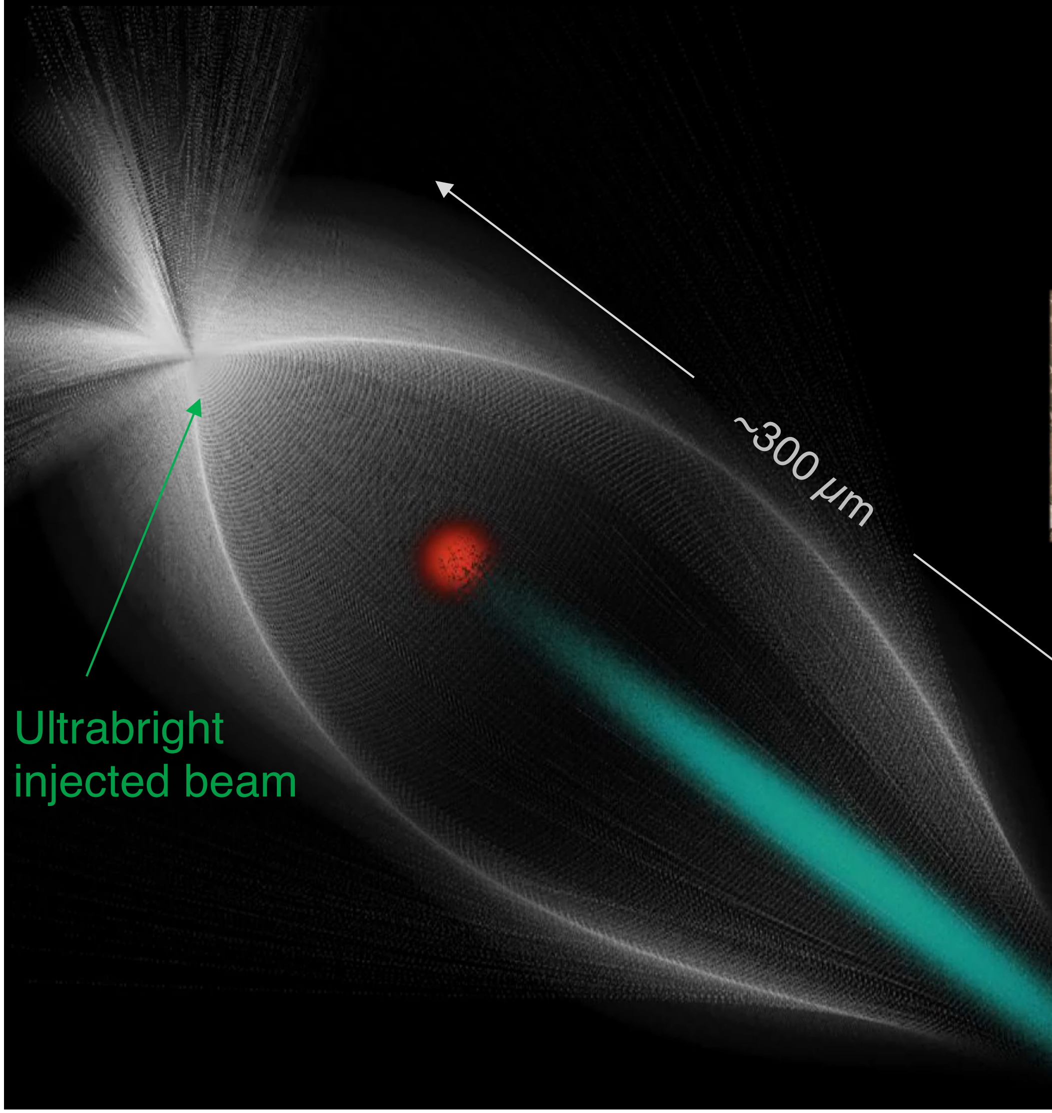
E-210: Trojan Horse at FACET



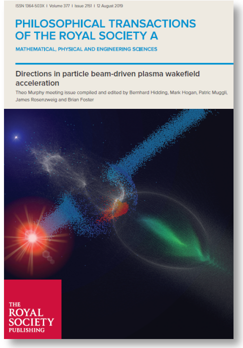




E-310: Trojan Horse-II at FACET-II

With better precision and incoming beams, in larger blowout, in collinear geometry

Roadmap



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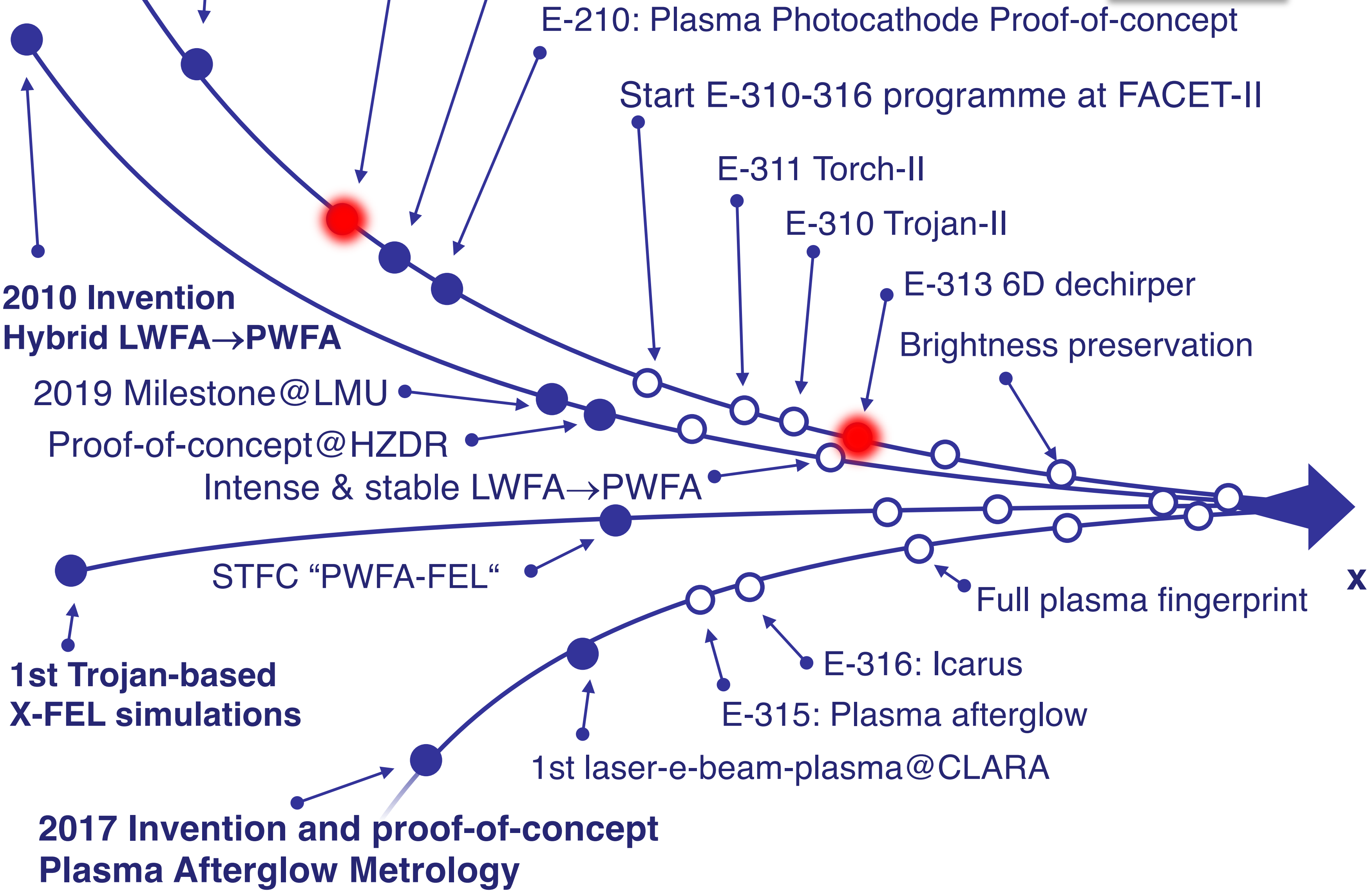

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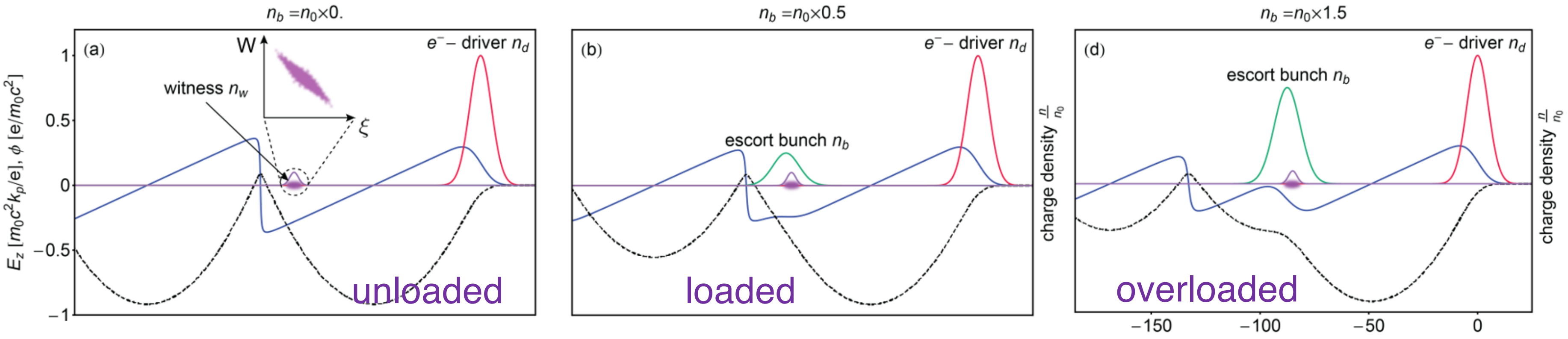
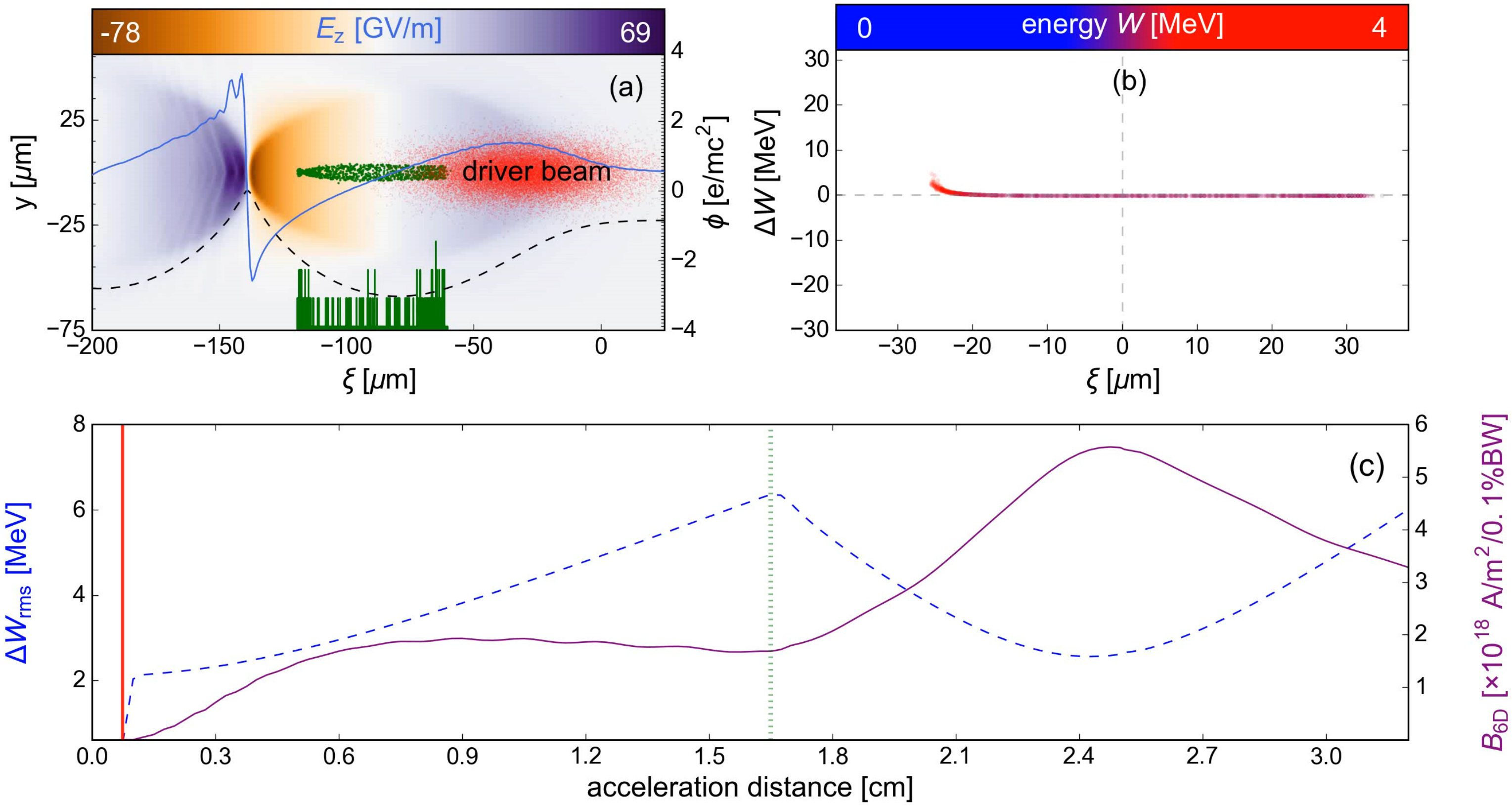
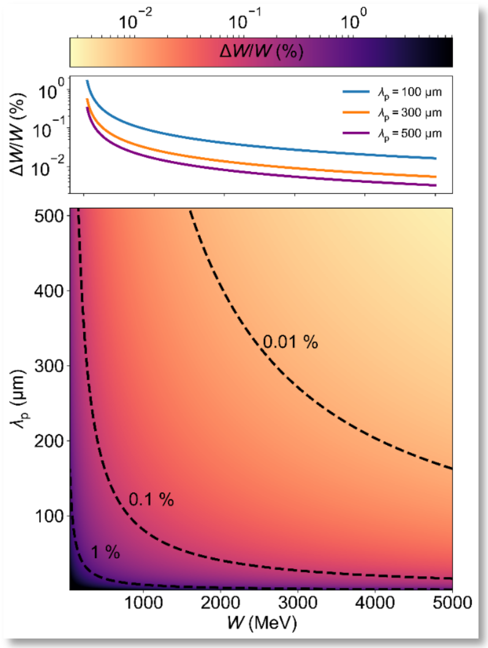
Concept of plasma photocathode-released “escort beam” for chirp control

Tailored beam loading via escort bunch allows chirp control:



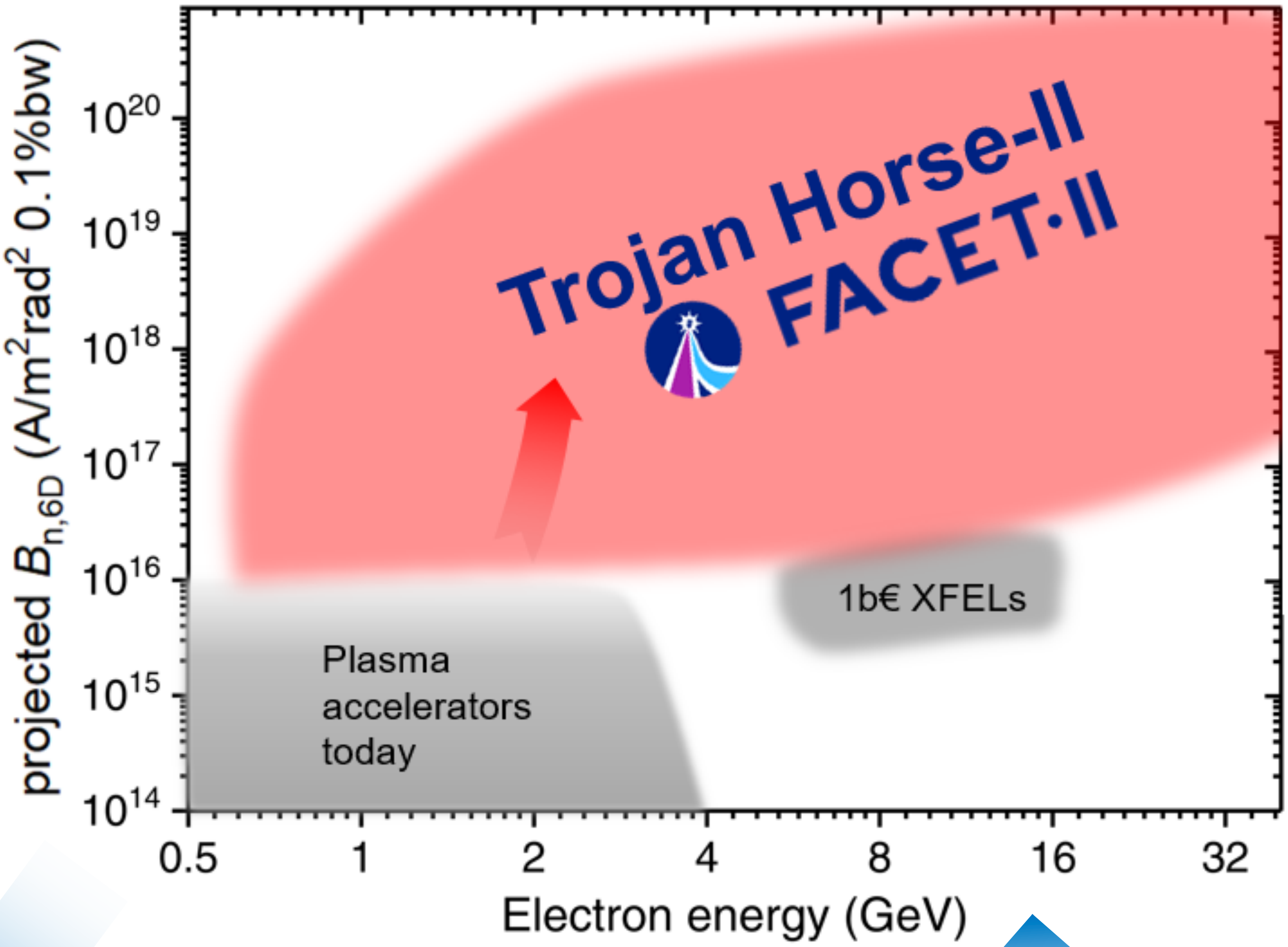




G.G. Manahan, F. Habib et al., *Nat. Comm.* 8, 15705 (2017)

E-310: Trojan Horse-II

In combination with
E-311: Plasma Torch
E-312: Dragon Tail
E-313: Multibunch Dechirper
E-314: Ion Collapse
E-315: Plasma Afterglow
E-316: Icarus



❑ Ultralow emittance beams for HEP

❑ Ultrabright beams for photon science (UK-US STFC “PWFA-FEL“ project)

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%

Manahan &Habib *et al.*, *Nat. Comm.* 8, 15705 (2017)

FACET-II PAC, 2018-10-10

Bernhard Hidding, Fahim Ahmad Habib *et al.*

Plasma-based hard X-Ray FEL with ultrahigh gain and sub-fs capability

Scottish Centre for the Application of Plasma-Based Accelerators SCAPA,
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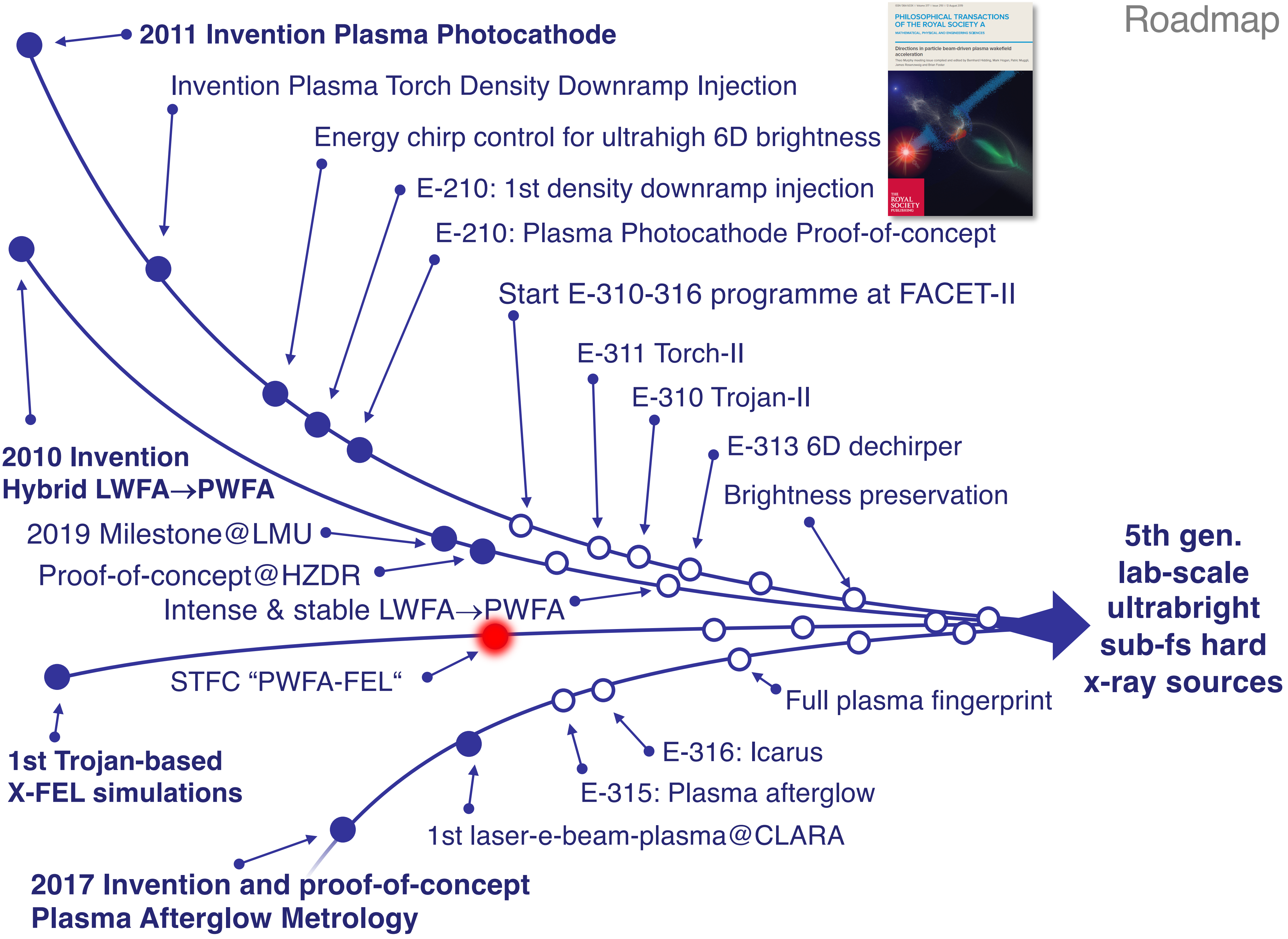
Plasma-based Particle and Light Sources http://ppals.phys.strath.ac.uk/

& The Cockcroft Institute

“Proposal ahead of its time” – resubmission encouraged

Roadmap



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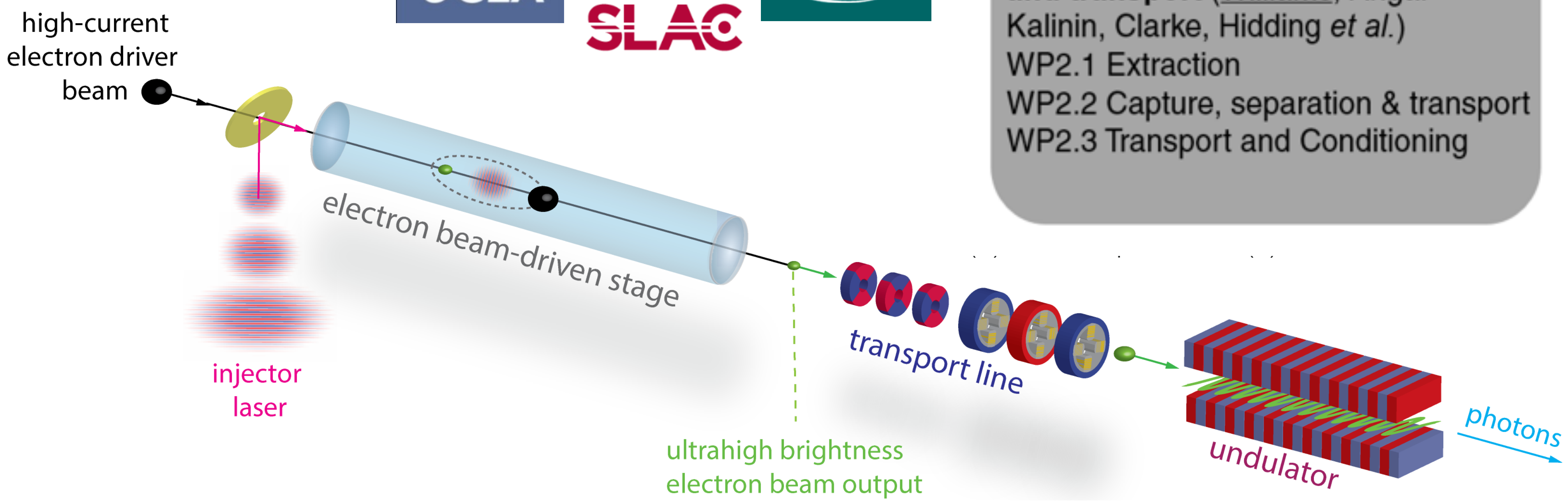
“Exploratory Study of PWFA-FEL at CLARA”

UKRI Science and Technology Facilities Council

- ❑ STFC funded 2019-2023

UCLA University of Strathclyde Glasgow SLAC ASTeC

WP2: Beam extraction, dynamics and transport (Williams, Angal-Kalinin, Clarke, Hidding *et al.*)
WP2.1 Extraction
WP2.2 Capture, separation & transport
WP2.3 Transport and Conditioning



WP1: Plasma photocathode PWFA (Hidding, Rosenzweig, Hogan, Yakimenko *et al.*)
WP1.1 Preionization
WP1.2 Plasma Photocathode 5D Brightness
WP1.3 Dechirping 6D Brightness

WP3: FEL Beam-by-design simulations (McNeil, Raubenheimer, Hemsing, Habib *et al.*)
WP3.1 Unconditioned FEL estimates
WP3.2 FEL@5D Brightness
WP3.3 FEL@6D Brightness
WP3.4 Advanced FEL options

Spatiotemporal injection accuracy

- ❑ Recipes: a) measure & minimize absolute jitter of incoming pulses; b) increase blowout size (Deng, Karger *et al.*, *Nat. Phys.* 2019, supplemental discussion)

Small blowout, large jitter:
Poor injection precision

Large blowout, small jitter:
Excellent injection precision (sub-%), and tunability?

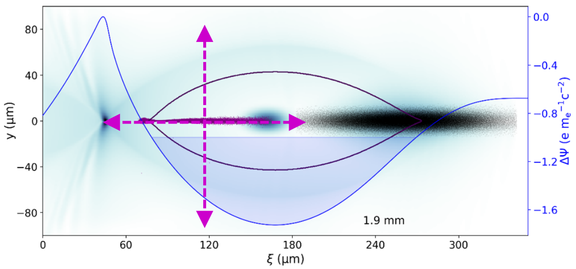
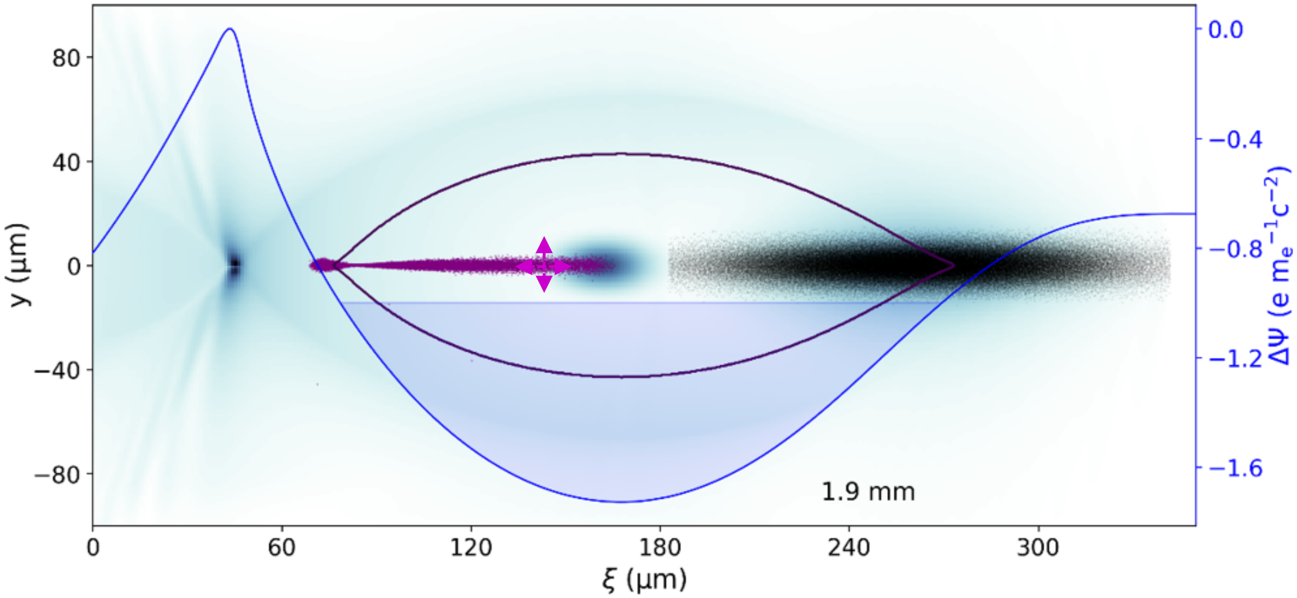


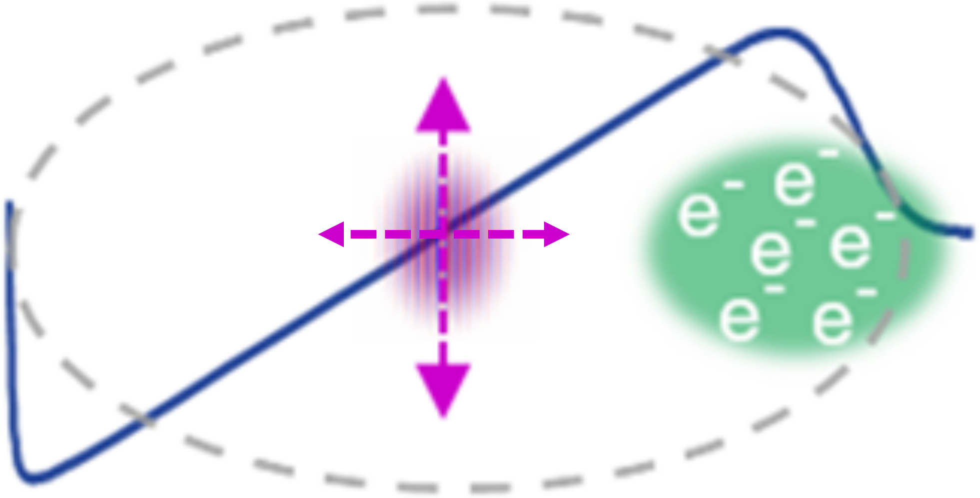
Figure of merit χ:
laser precision/(λ_p)
33% at FACET



- ❑ Bonus: operation at lower plasma densities reduces residual energy spread (Manahan & Habib *et al.*, *Nat. Comm.* 8, 15705, 2017), and reduces requirements on driver beam (can in turn realize kickback by further increasing stability?)

How precise does the spatiotemporal injection need to be?

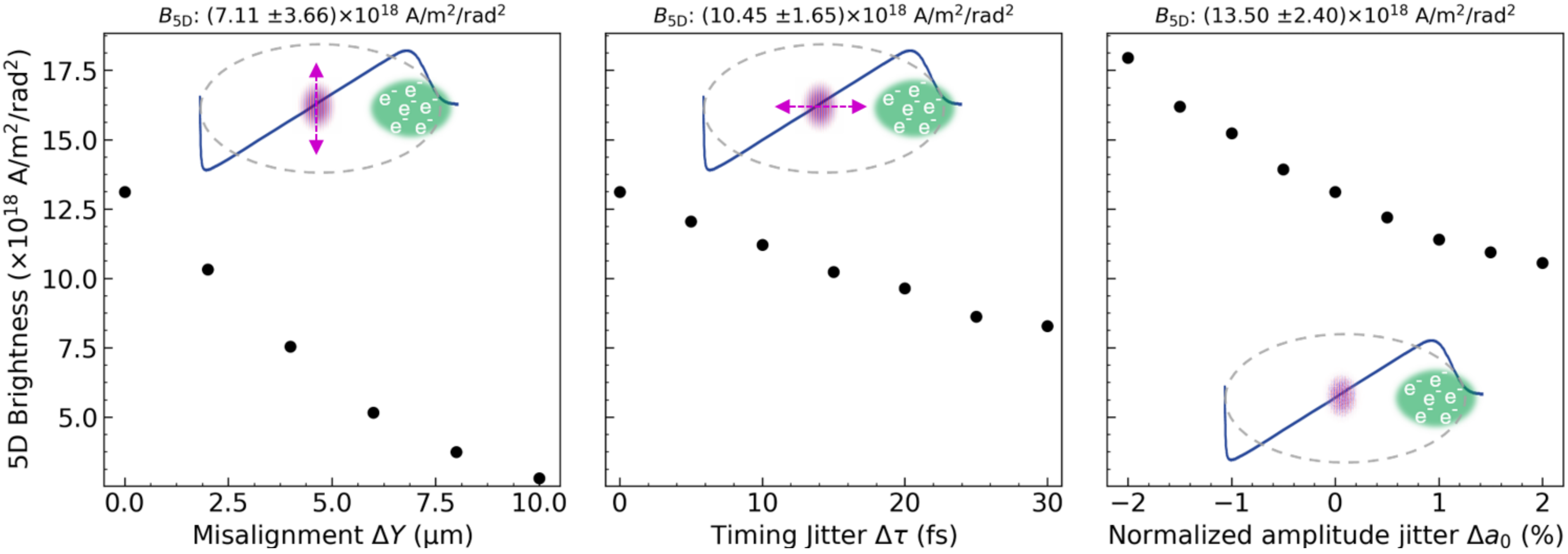
- Once absolute spatiotemporal injection precision is known:
- Injection precision is dependent on size of the plasma wave, and absolute jitter of incoming laser and delectron beam ⇒ work at lower plasma densities
- E.g. 500 μm plasma wavelength, with 30 fs r.m.s. timing jitter (LCLS aims at <10 fs) and similar pointing accuracy, an injection precision of ~1% can be achieved



Follow up: What does this mean for obtainable beam quality and stability (5D)?

- Sensitivity analysis done for 250 μm plasma wavelength: vary temporal desync. from 0-30 fs, misalignment from 0-10 μm, laser intensity a_0 0-2%

Resulting 5D brightness: $B_{5\mathrm{D}} = \dfrac{2I_\mathrm{p}}{\epsilon_{\mathrm{n,x}}\,\epsilon_{\mathrm{n,y}}}$



Note: X-FEL 5D brightness is at 1e12 level

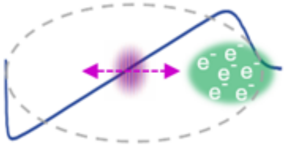
❑ Timing varied up to 30 fs in ~250 μm blowout ($\chi \approx 4\%$): **excellent output beam stability!**

Energy Stability: (72.38±0.69) MeV

Emittance Y Stability: (15.11±0.13) nm rad

Emittance Z Stability: (15.51±0.12) nm rad

Bunch Length Stability: (0.22±0.04) μm

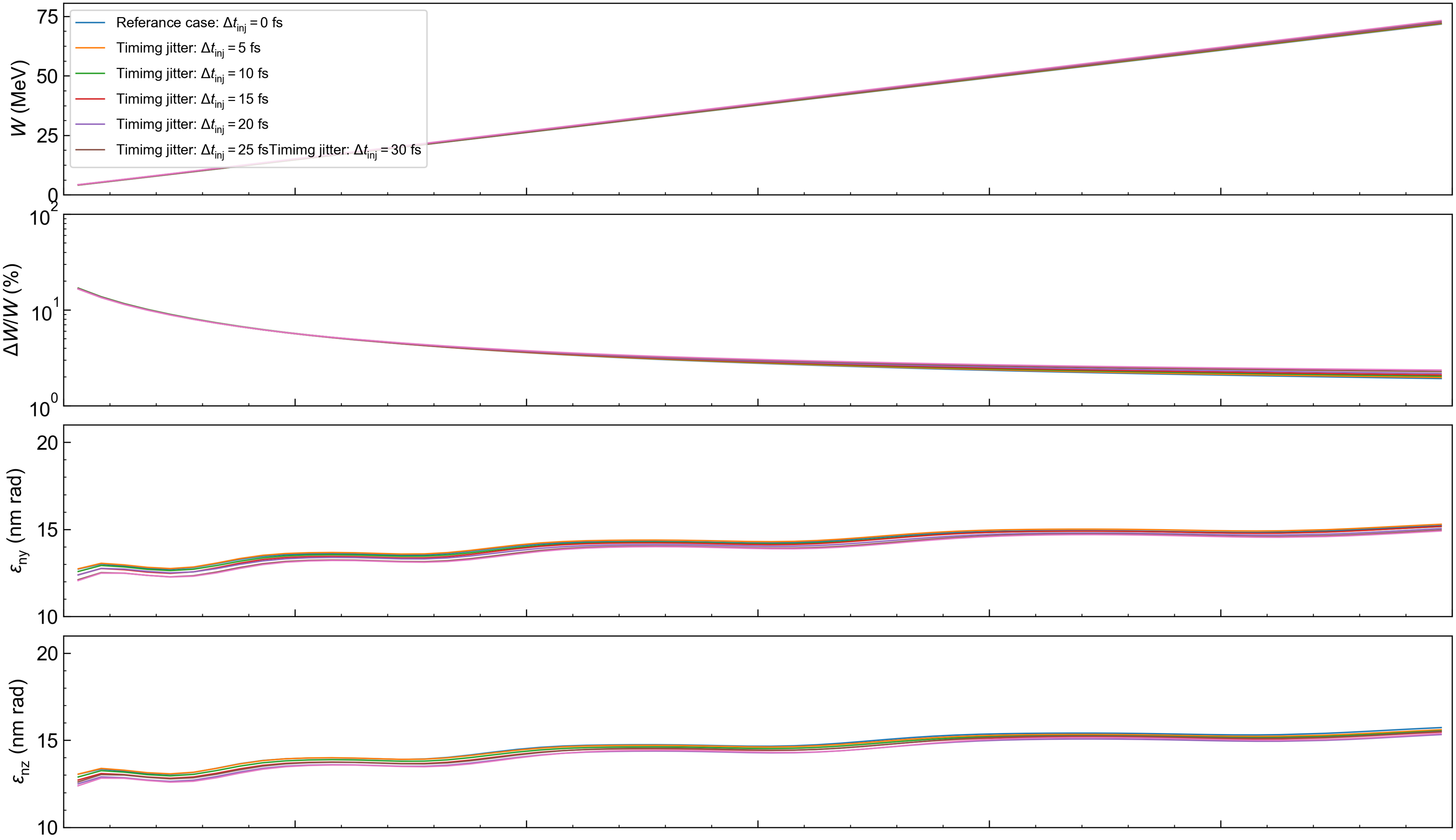


Charge Stability: (2.375 ±0.006) pC

Rel. Energy Spread Stability: (1.52±0.11) %

5D Brightness Stability: $(10.45\pm1.65)\times10^{18}$ A nm^{-2} rad^{-2}

Peak Current Stability: (1.23±0.21) kA



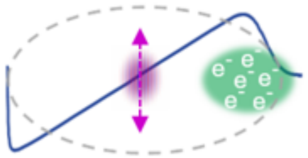
Transverse plasma photocathode release laser offset jitter study in 250 μm length blowout

Energy Stability: (72.15±0.59) MeV

Emittance Y Stability: (29.91±11.8) nm rad

Emittance Z Stability: (15.38±0.48) nm rad

Bunch Length Stability: (0.19±0.03) μm

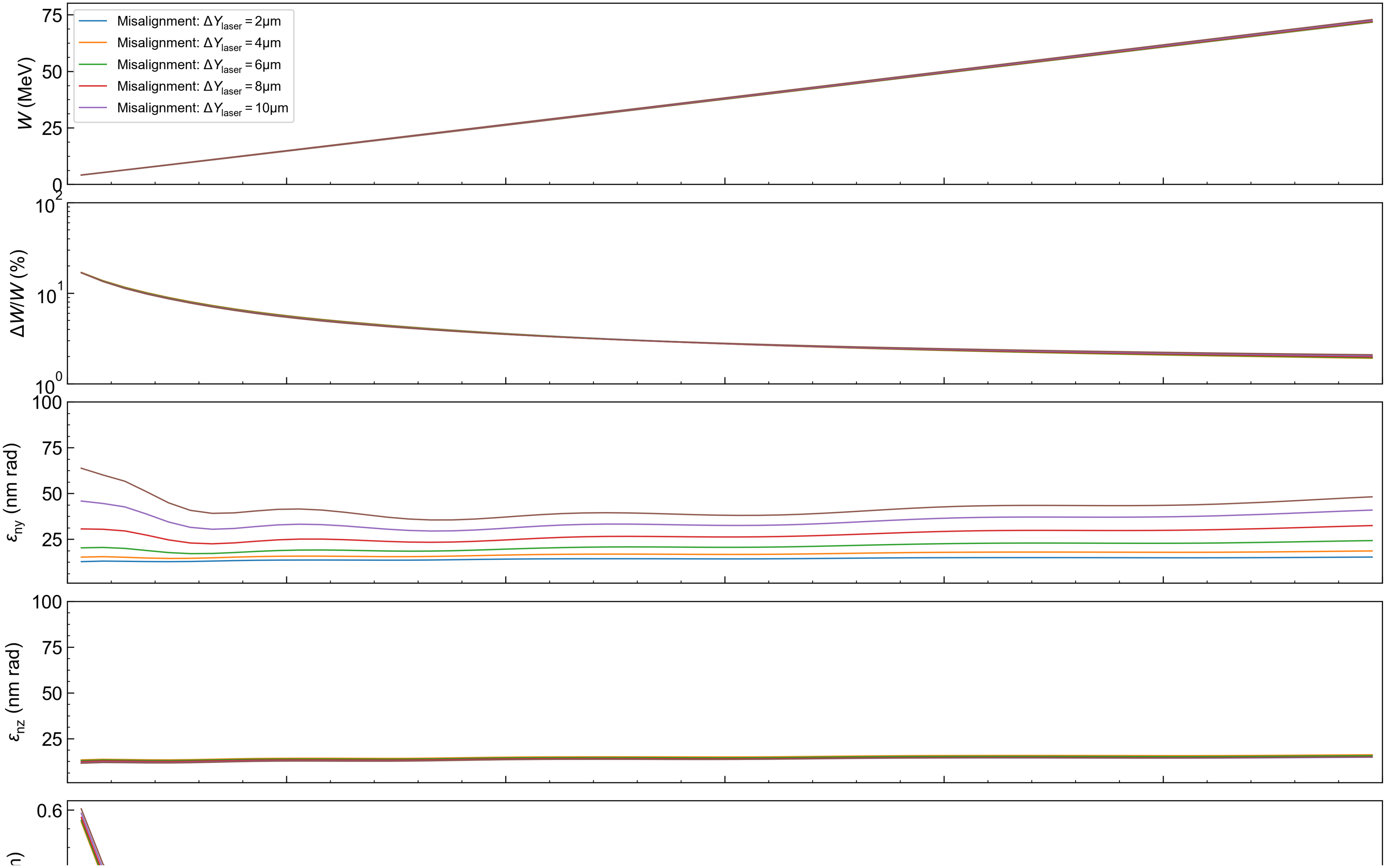


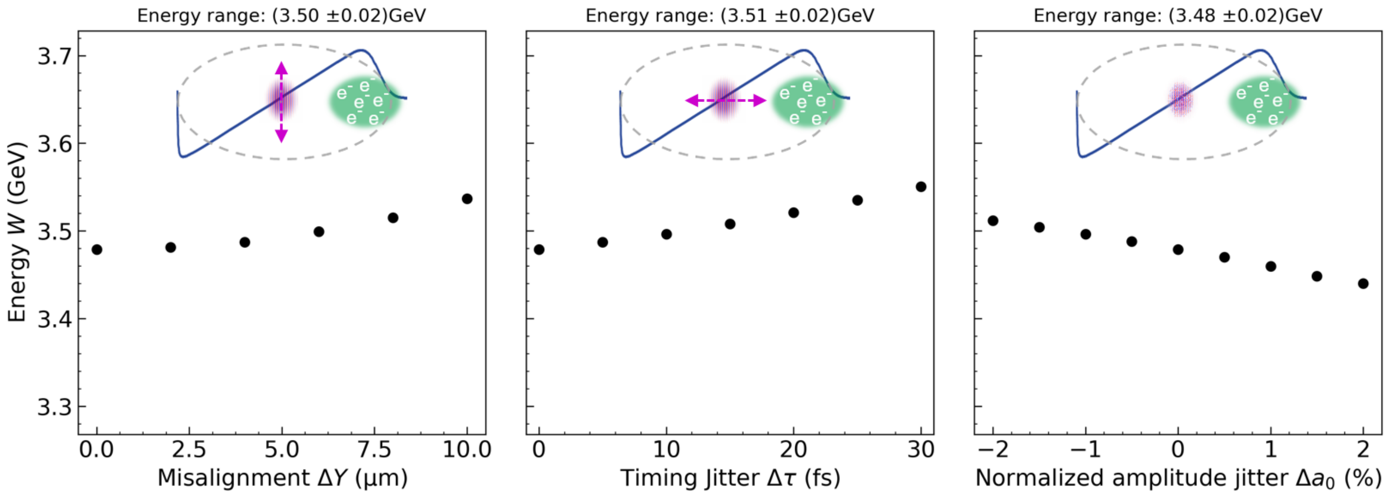
Charge Stability: (2.371 ±0.005) pC

Rel. Energy Spread Stability: (1.41±0.05) %

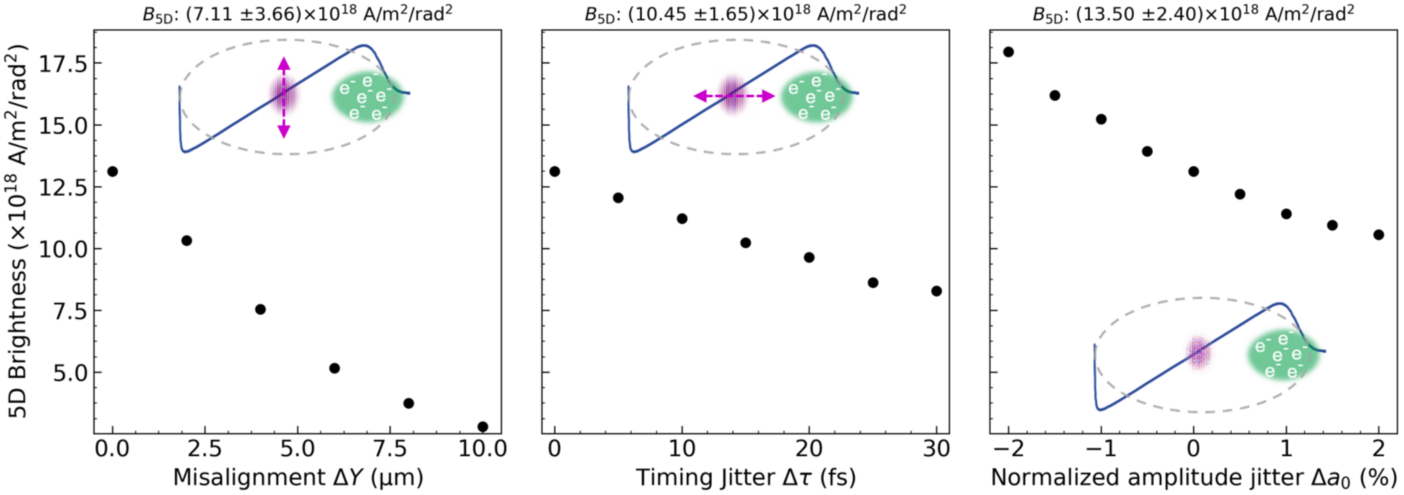
5D Brightness Stability: $(7.11\pm3.66)\times10^{18}$ A nm^{-2} rad^{-2}

Peak Current Stability: (1.32±0.21) kA

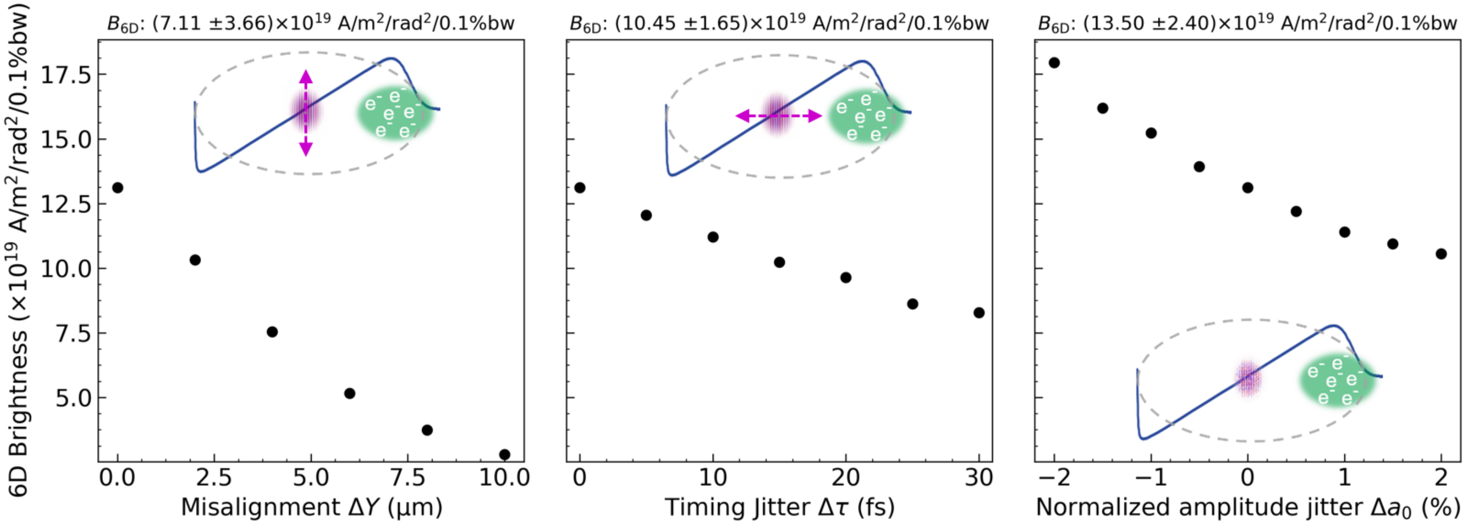




Output beam energy stability better than 1% (linac level)

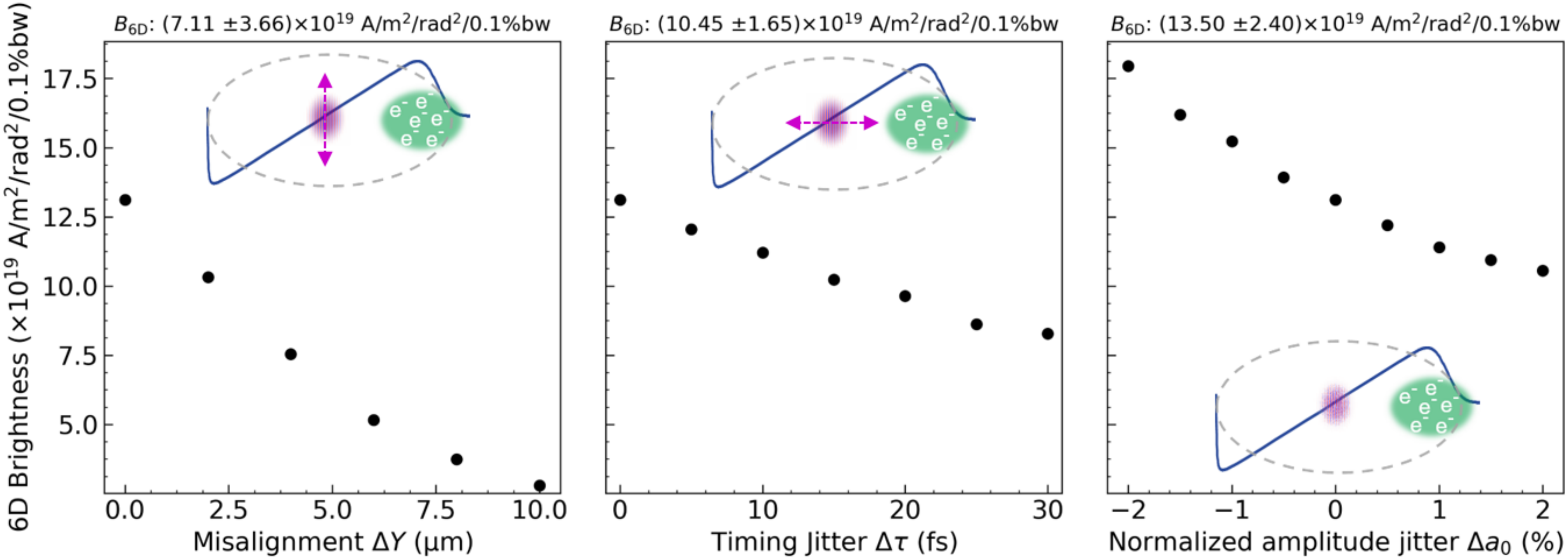


5D brightness orders of magnitude better than today‘s X-FEL‘s



6D brightness orders of magnitude better than today‘s X-FEL‘s (estimated)

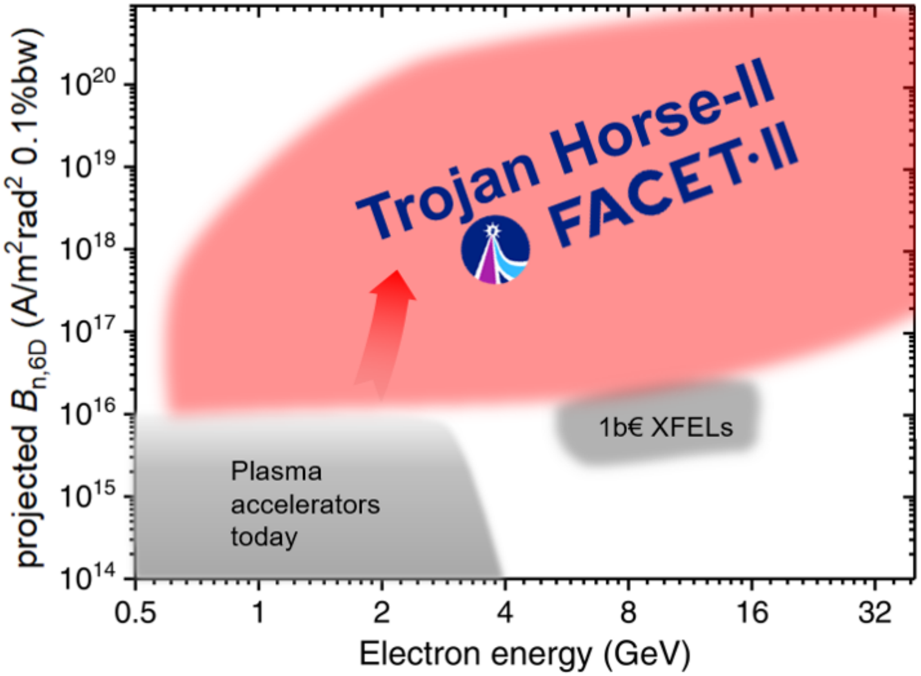
What does this mean for obtainable beam quality and stability (6D)?



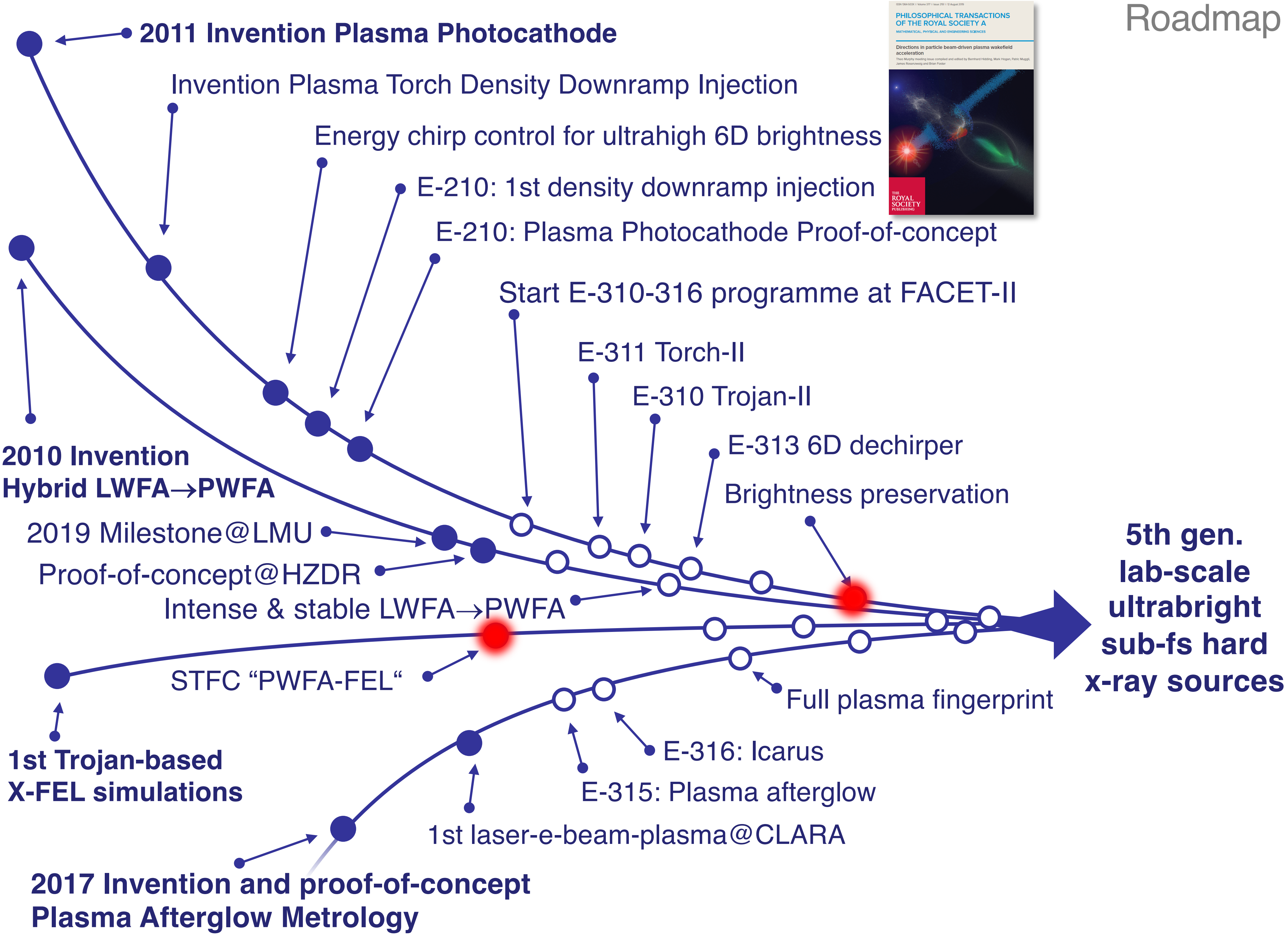
Resulting 6D brightness:

$$B_{6D} = \frac{I_p}{\epsilon_{n,x}\,\epsilon_{n,y} 0.1\%BW}$$

Note: LCLS 6D brightness is at 1e16 level



Roadmap



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Invention Plasma Torch Density Downramp Injection

Energy chirp control for ultrahigh 6D brightness

E-210: 1st density downramp injection

E-210: Plasma Photocathode Proof-of-concept

Start E-310-316 programme at FACET-II

E-311 Torch-II

E-310 Trojan-II

E-313 6D dechirper

Brightness preservation

2010 Invention
Hybrid LWFA→PWFA

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Proof-of-concept@HZDR

Intense & stable LWFA→PWFA

5th gen.
lab-scale
ultrabright
sub-fs hard
x-ray sources

STFC “PWFA-FEL“

Full plasma fingerprint

1st Trojan-based
X-FEL simulations

E-316: Icarus

E-315: Plasma afterglow

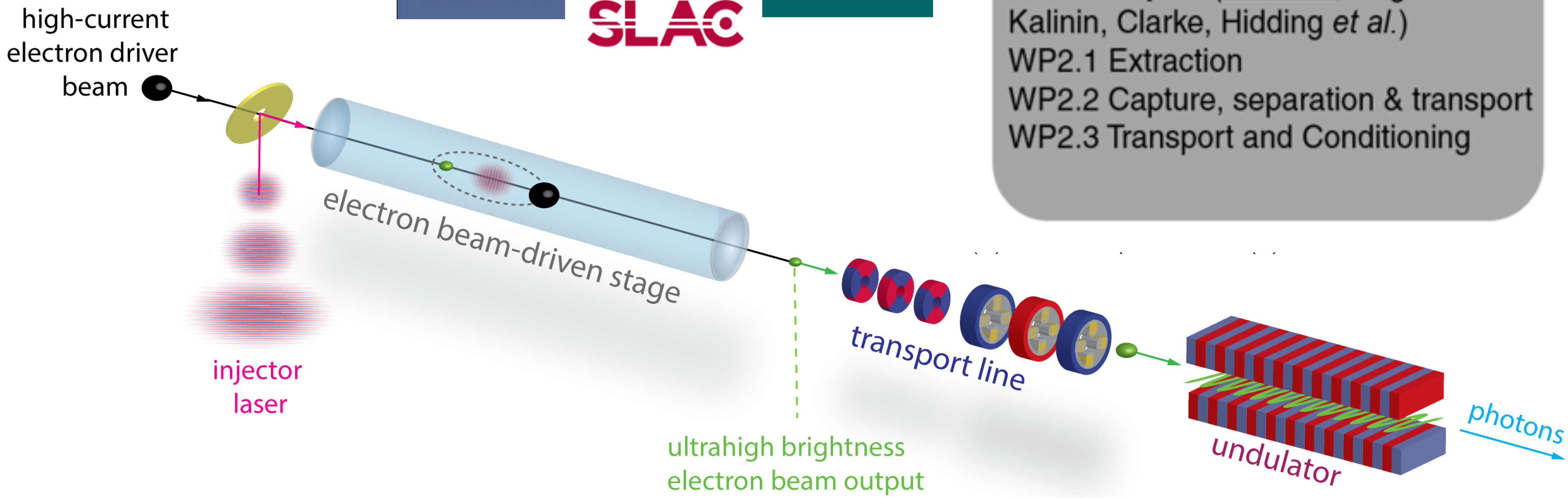
1st laser-e-beam-plasma@CLARA

2017 Invention and proof-of-concept
Plasma Afterglow Metrology

PWFA-FEL

- ❑ STFC funded 2019-2023

WP2: Beam extraction, dynamics and transport (Williams, Angal-Kalinin, Clarke, Hidding *et al.*)
WP2.1 Extraction
WP2.2 Capture, separation & transport
WP2.3 Transport and Conditioning



WP1: Plasma photocathode PWFA (Hidding, Rosenzweig, Hogan, Yakimenko *et al.*)
WP1.1 Preionization
WP1.2 Plasma Photocathode 5D Brightness
WP1.3 Dechirping 6D Brightness

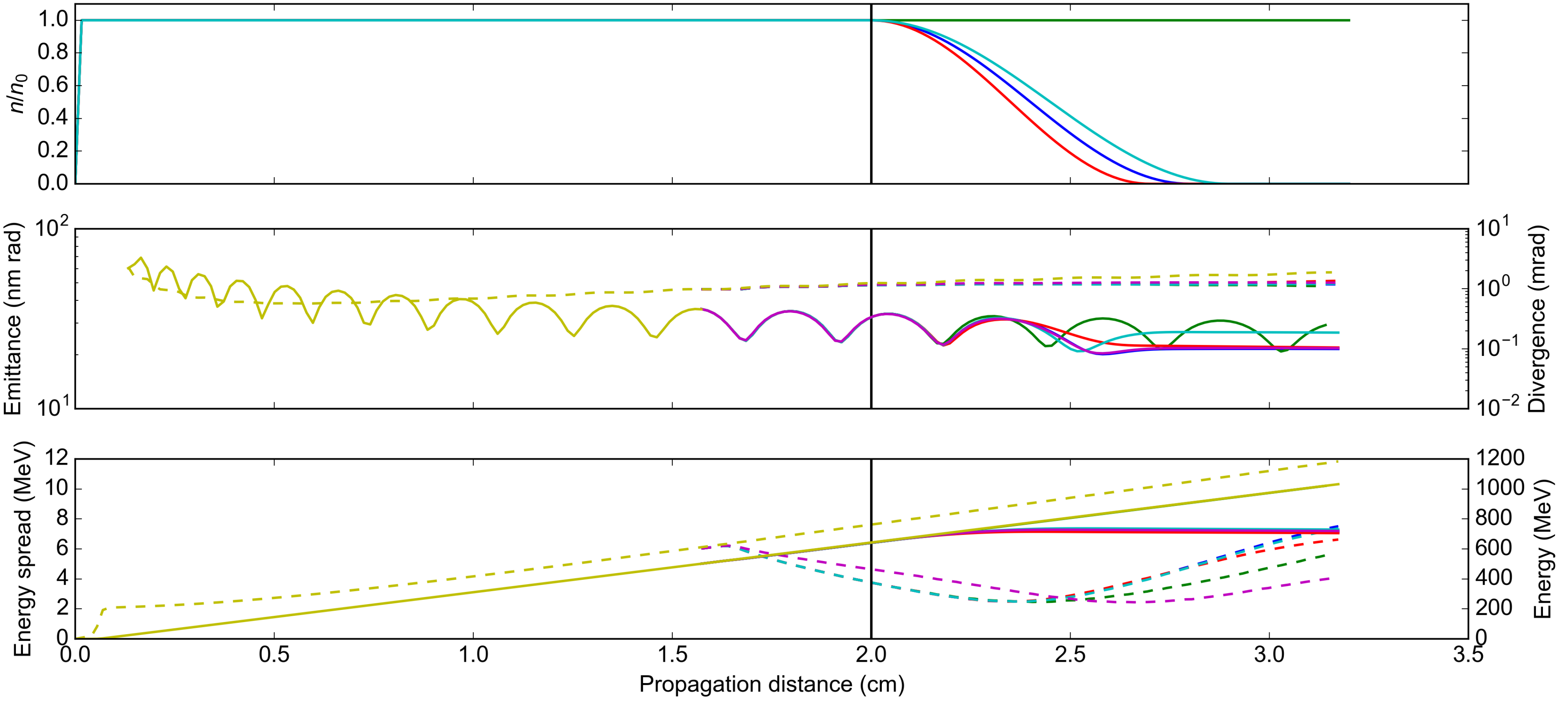
WP3: FEL Beam-by-design simulations (McNeil, Raubenheimer, Hemsing, Habib *et al.*)
WP3.1 Unconditioned FEL estimates
WP3.2 FEL@5D Brightness
WP3.3 FEL@6D Brightness
WP3.4 Advanced FEL options

WP 2: Preliminary witness beam extraction

☐ Tailored plasma density at the exit

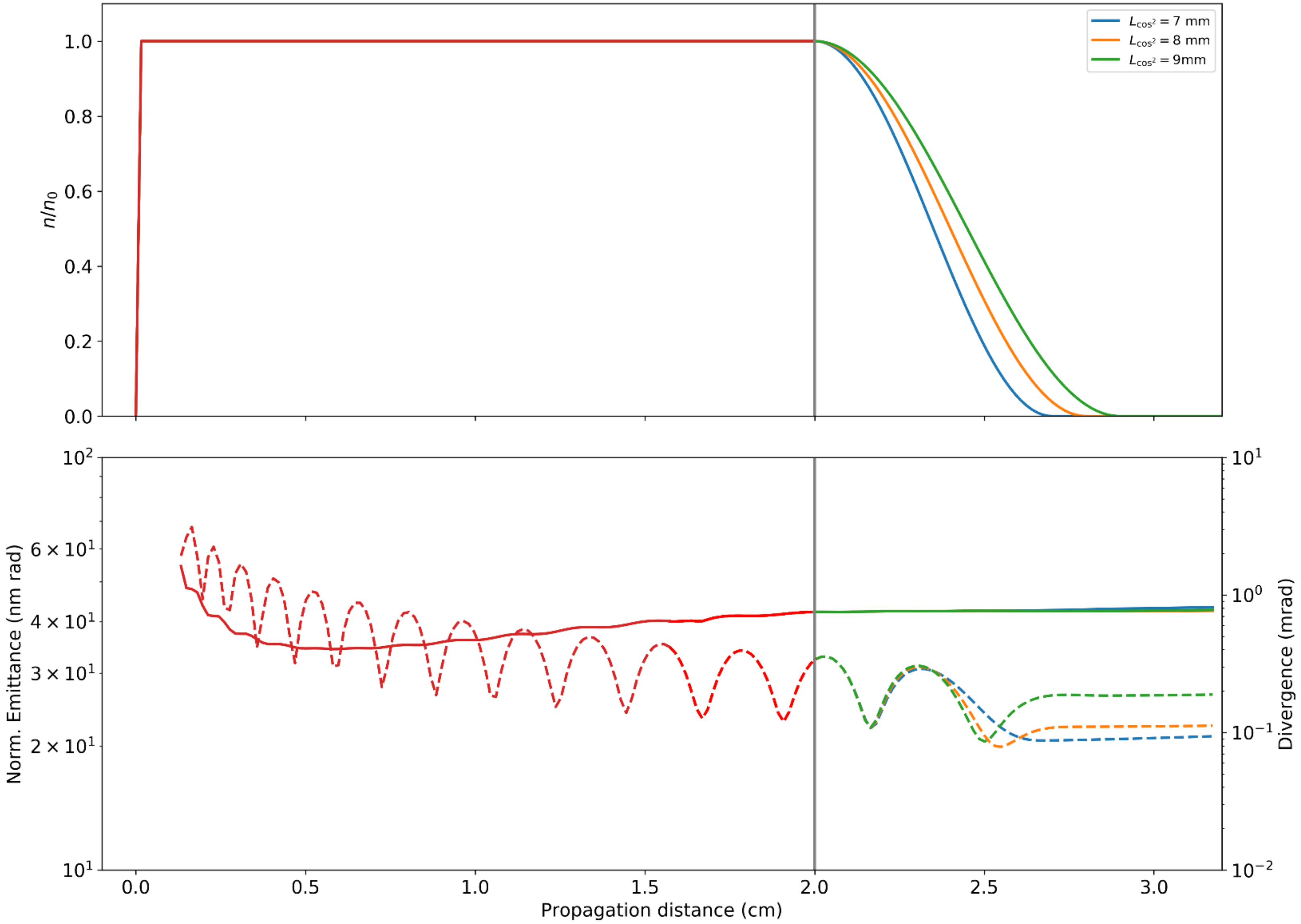
☐ “escort”-bunch dechirping

☐ Emittance is preserved at the exit



Emittance preservation during extraction

- Decreasing plasma density at the exit
- With “escort”-bunch dechirping
- Emittance is preserved!



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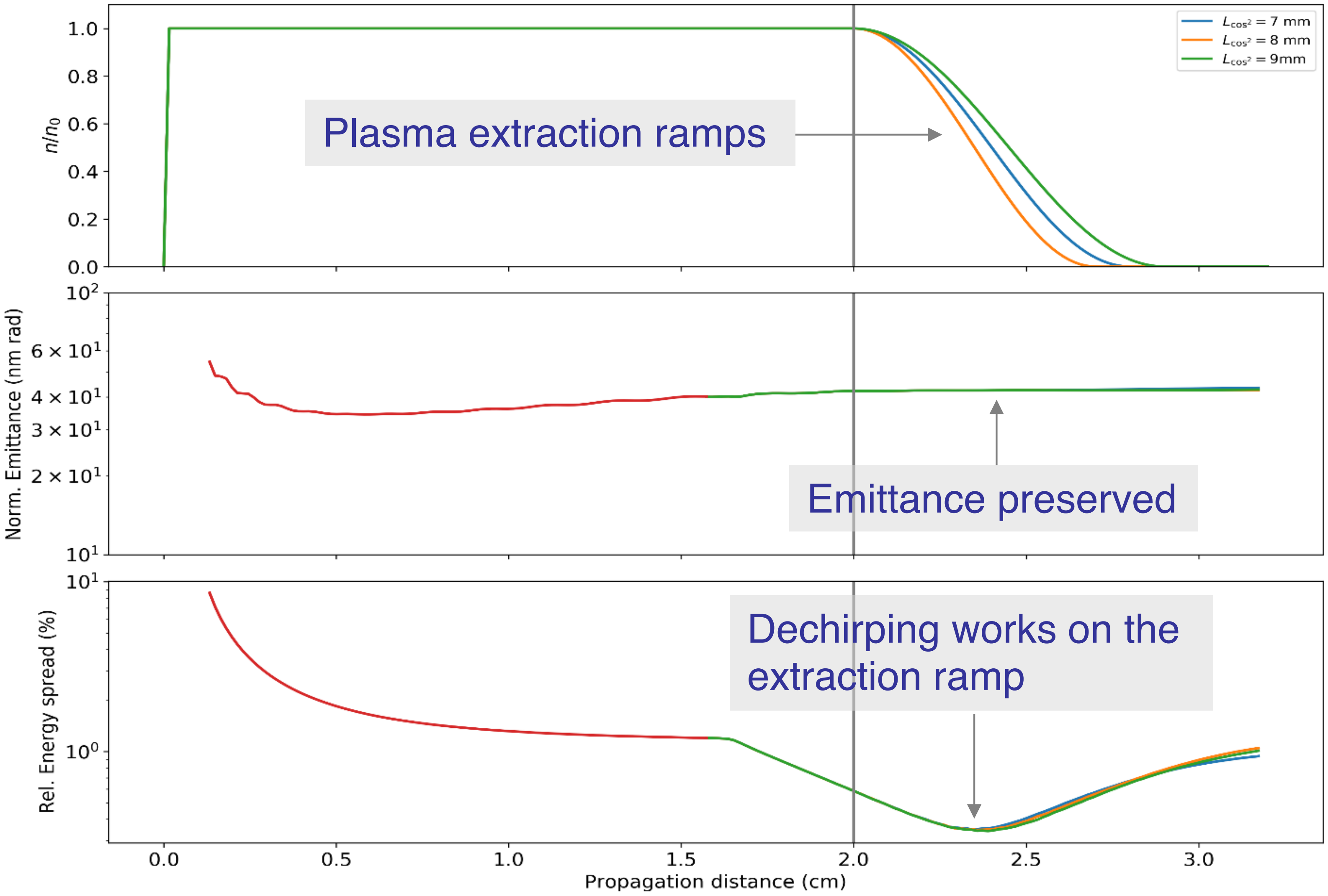
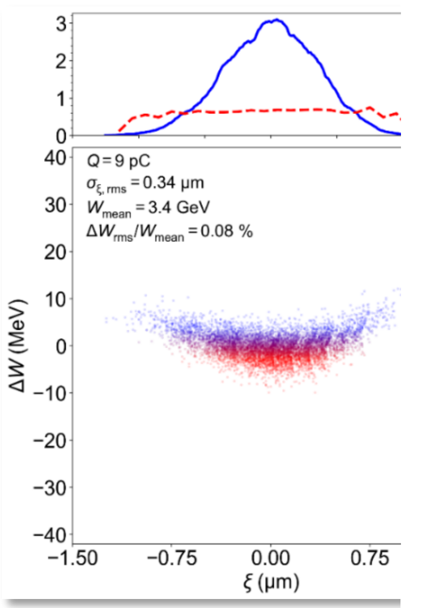


Plasma extraction ramps

Emittance preserved

Dechirping works on the extraction ramp

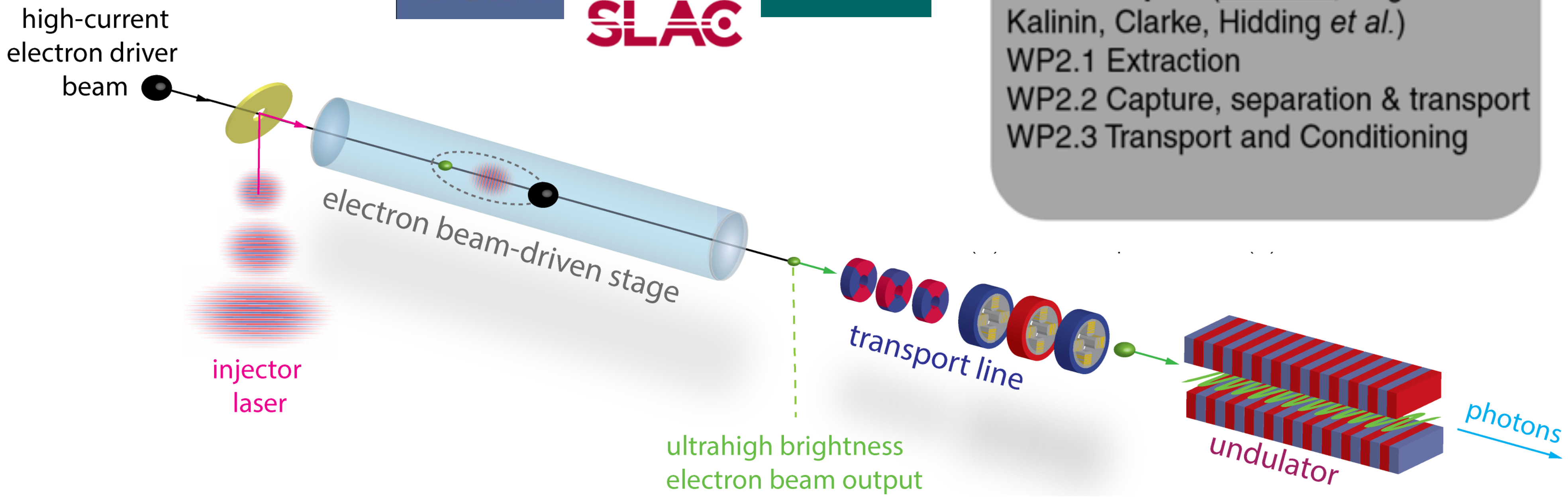


Q = 9 pC
$\sigma_{\xi,\mathrm{rms}} = 0.34$ μm
$W_{\mathrm{mean}} = 3.4$ GeV
$\Delta W_{\mathrm{rms}}/W_{\mathrm{mean}} = 0.08$ %

- ☐ Tailored plasma density at the exit
- ☐ “escort”-bunch dechirping works with extraction ramp
- ☐ Emittance is preserved at the exit

PWFA-FEL

- ❑ STFC funded 2019-2023



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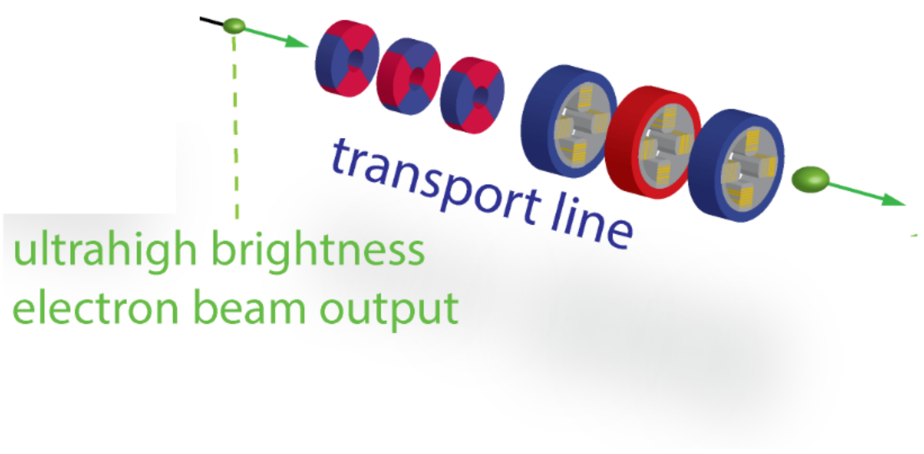
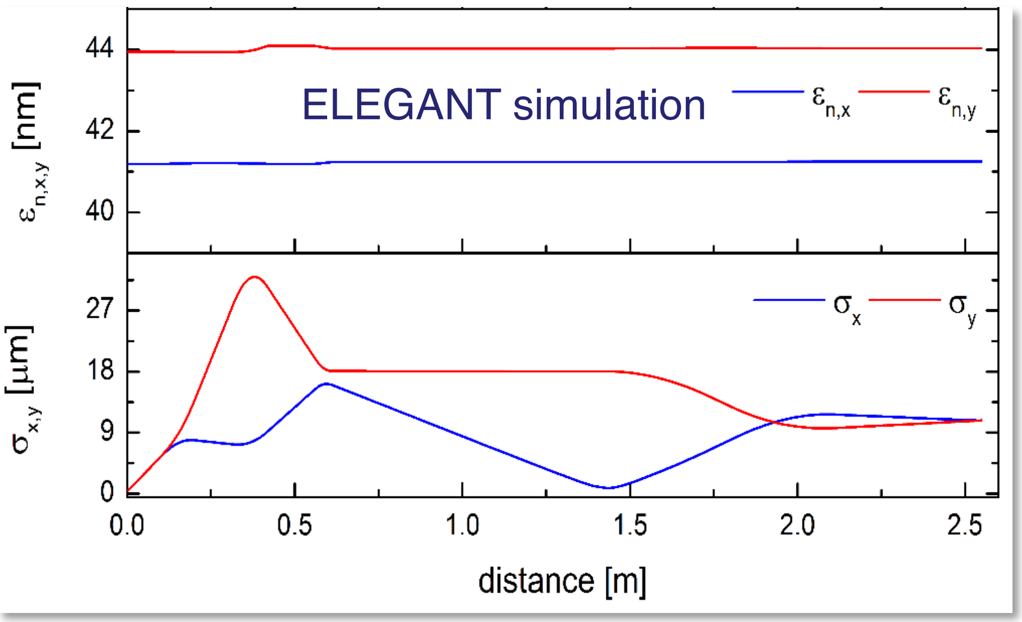
WP 2: Preliminary transport line design

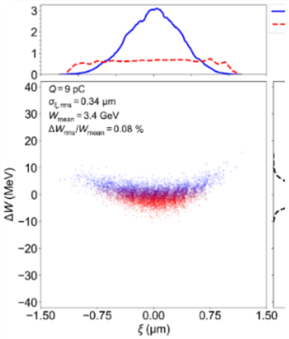
Double triple beam transport line





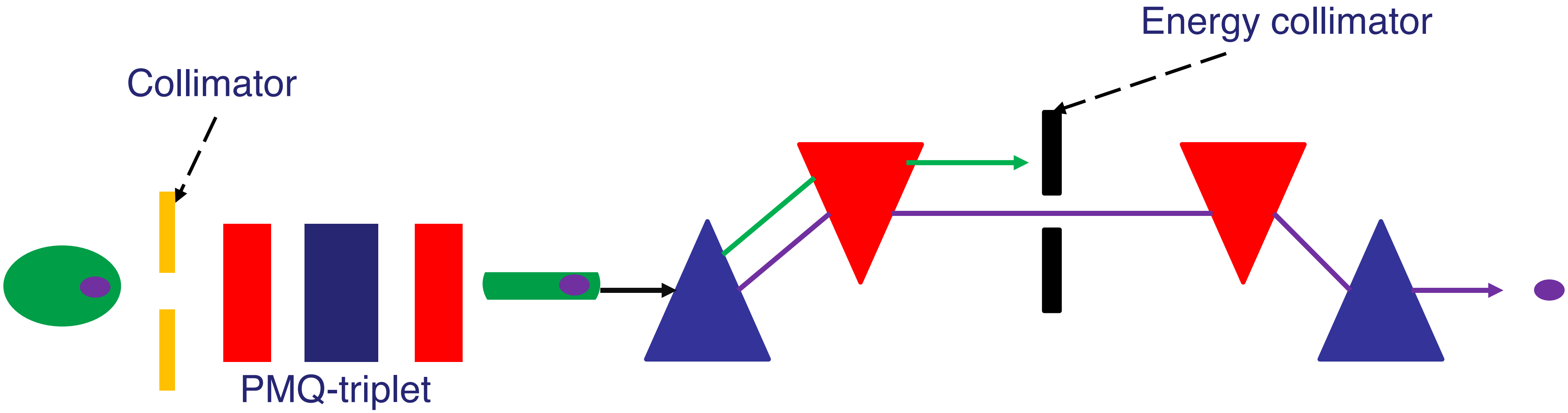
- ☐ First triplet: permanent magnet quadrupoles (PMQs) 700 T/m
- ☐ Plasma lenses?
- ☐ 10 cm distance until 1st PMQ
- ☐ 6D-bright witness. 9 pC, duration 0.34 *µm*
- ☐ Second triplet: electromagnet quadrupoles
- ☐ Elegant: CSR not problem.

- ☐ 6D phase space from the PIC-simulation is considered
- ☐ Witness beam is captured and matched
- ☐ No witness beam emittance growth→6D brightness is preserved



WP2: Escort and witness beam separation

- ☐ Beam energy of the escort bunch is significantly lower than witness beam energy
- ☐ Use dispersion elements such as dipoles to separate escort and witness bunch
- ☐ For example: A chicane/ by-pass line with energy collimator after the second dipole
- ☐ Simulations indicate that the escort bunch diffracts quickly after the plasma stage



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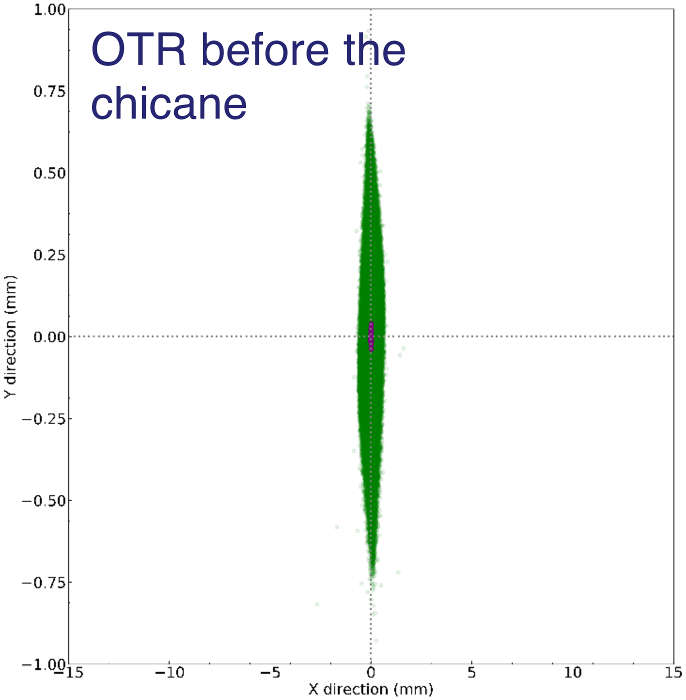
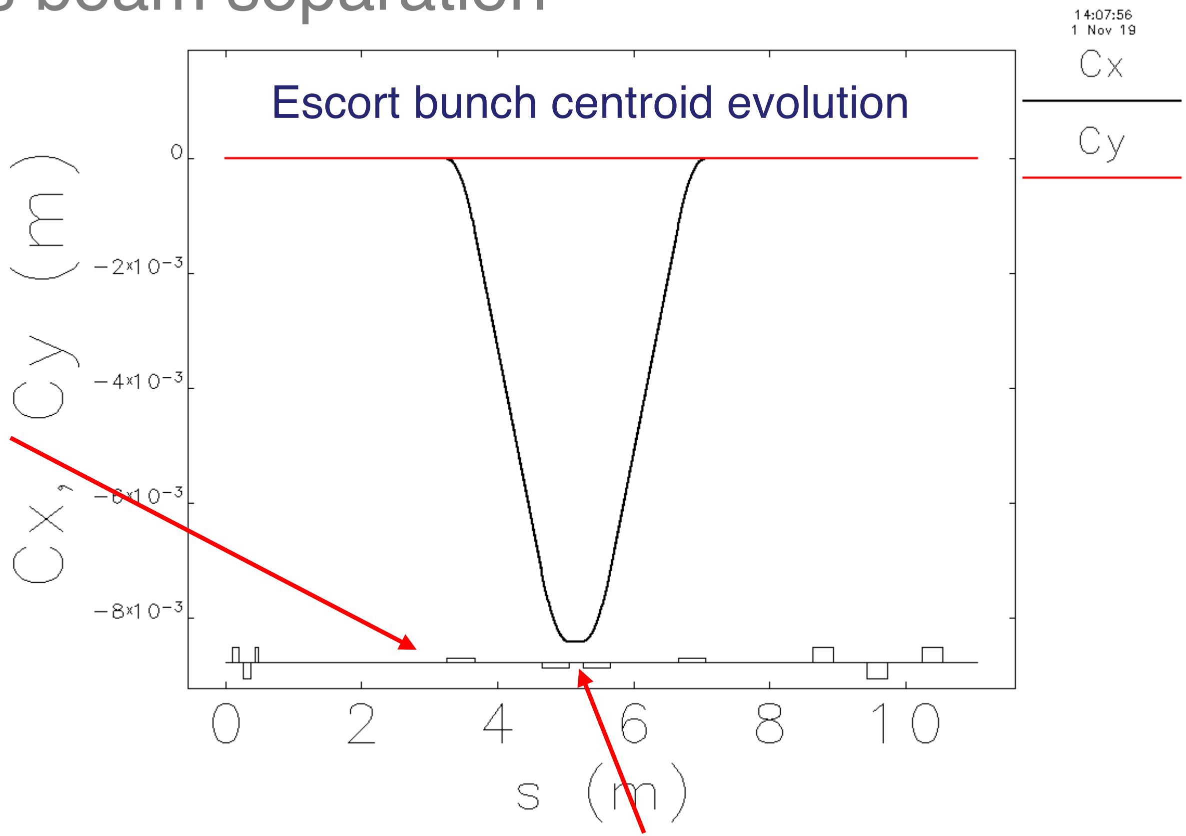
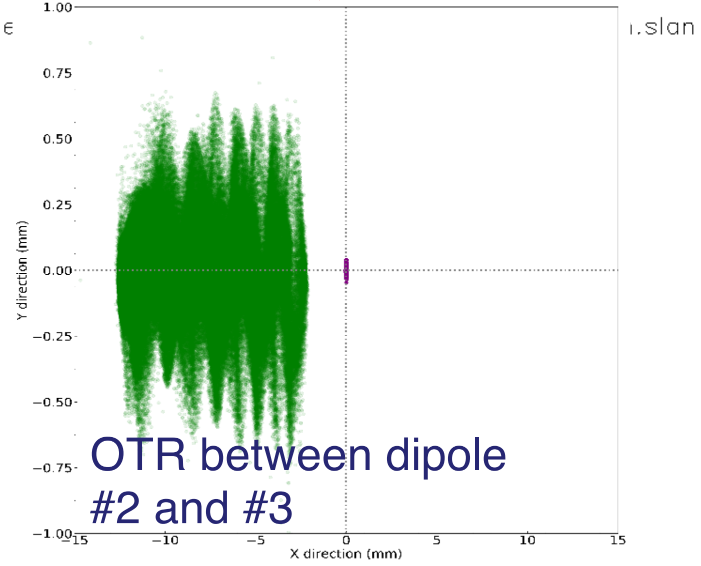


OTR before the chicane



Escort bunch centroid evolution



OTR between dipole #2 and #3

- Green: escort; purple witness
- Chicane between PMQ and EMQ triplet for escort-witness beam separation
- 1D CSR effects included
- Chicane acts as a by-pass line for the 3.4 GeV witness beam (0.08% energy spread, no chromatic issues)→ bunch duration, emittance and charge stays constant after chicane (escort ~ 1 GeV)

“PWFA-FEL” project: Strathclyde-STFC-SLAC-UCLA 2019-2023

❑ Explore capability of Trojan Horse-generated ultrahigh brightness beams for X-FEL

❑ FEL Emittance criterion: $\epsilon_n < \lambda_r \langle\gamma\rangle / 4\pi$ ✔

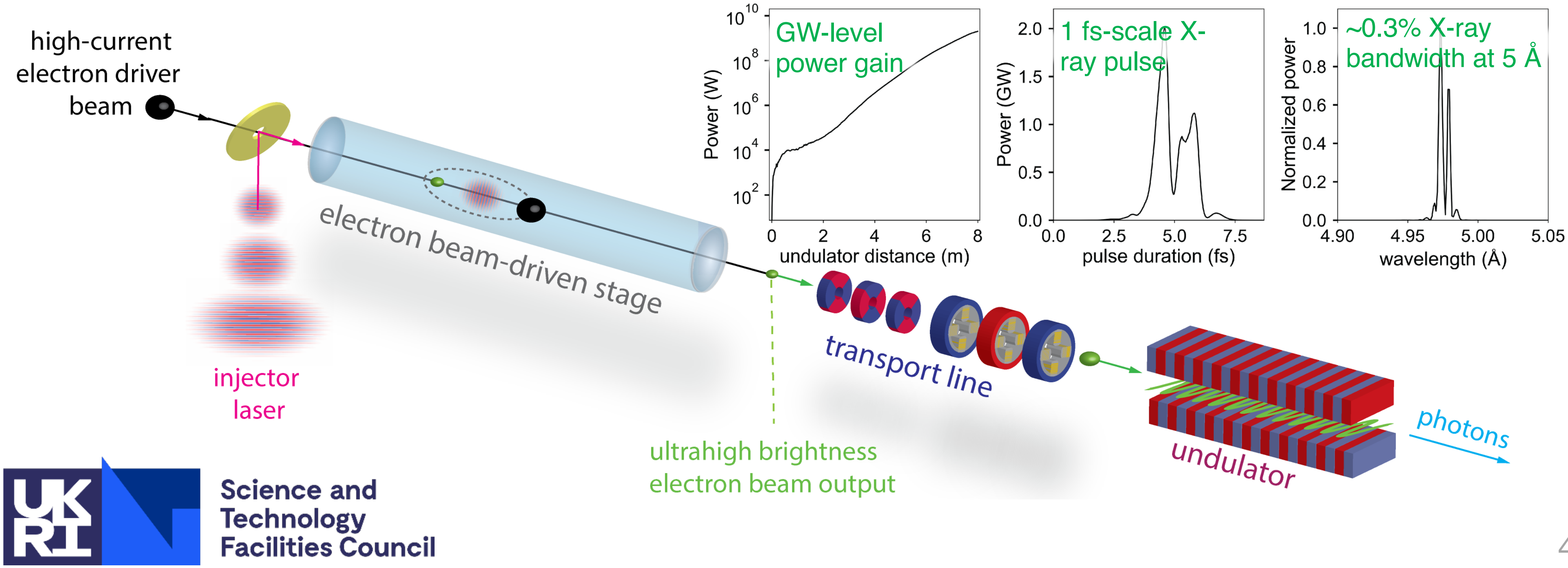
⇒ 10‘s nmrad emittance allows to push towards harder X-ray wavelengths λ_r for electron energies γ

❑ FEL Energy spread criterion: $\langle\sigma_\gamma/\gamma\rangle \ll \rho$ ✔

⇒ breakthrough: electron energy spread (e.g. <0.01% suffices X-FEL Pierce parameter ρ)

❑ FEL gain length: $L_{g,1D} = \dfrac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}} \propto B_e^{-1/3}$

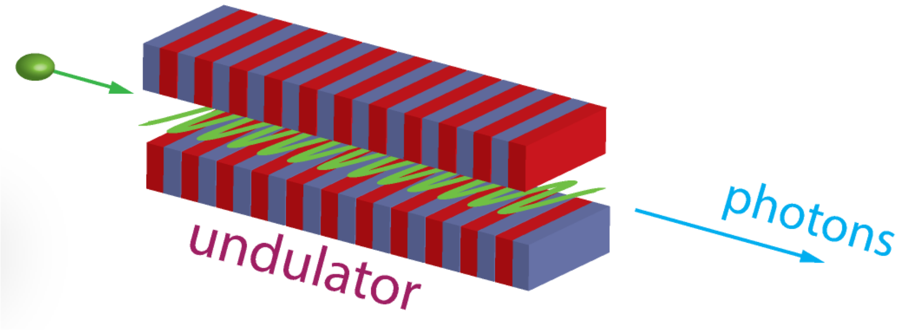
⇒ Brightness *B* boosts gain and allows saturation of photon field in 10 m vs. 100‘s metres



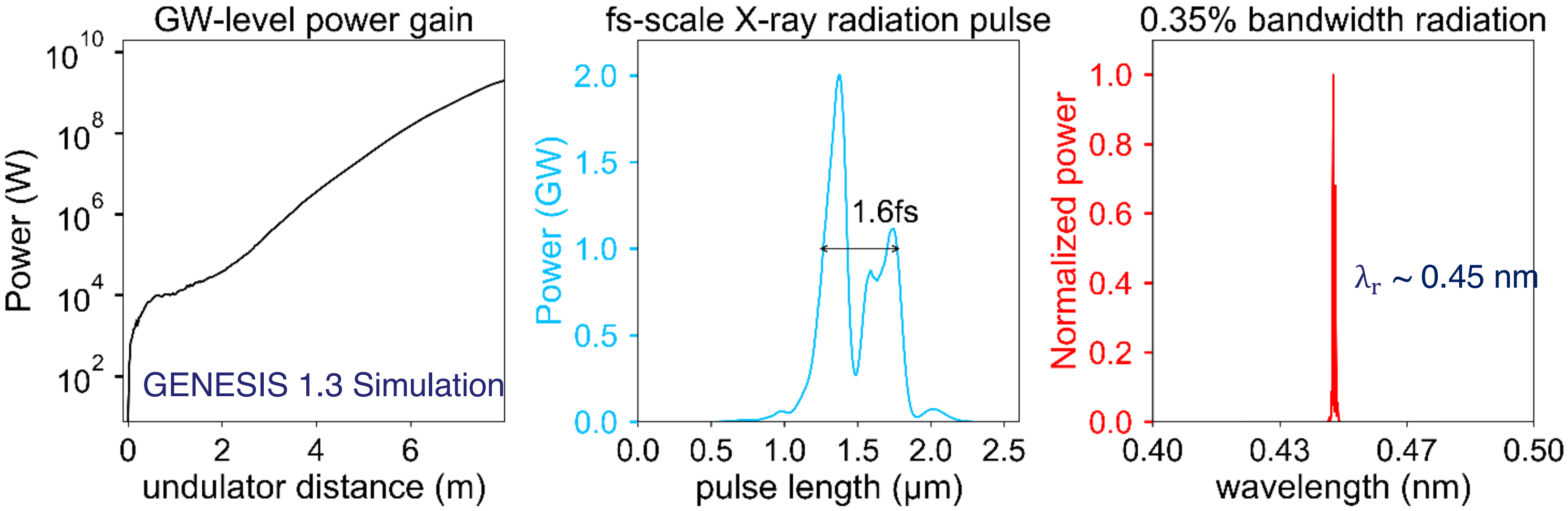
Science and
Technology
Facilities Council

WP 3: XFEL Beam-by-design simulation

A. F. Habib et.al., publication in preparation



- ☐ State-of-the-art NdFeB undulator
- ☐ Undulator period: λ_u = 1.5 cm
- ☐ Undulater parameter: K ~ 1.8
- ☐ Resonace wavelength: λ_r = 0.45 nm



GENESIS 1.3 Simulation

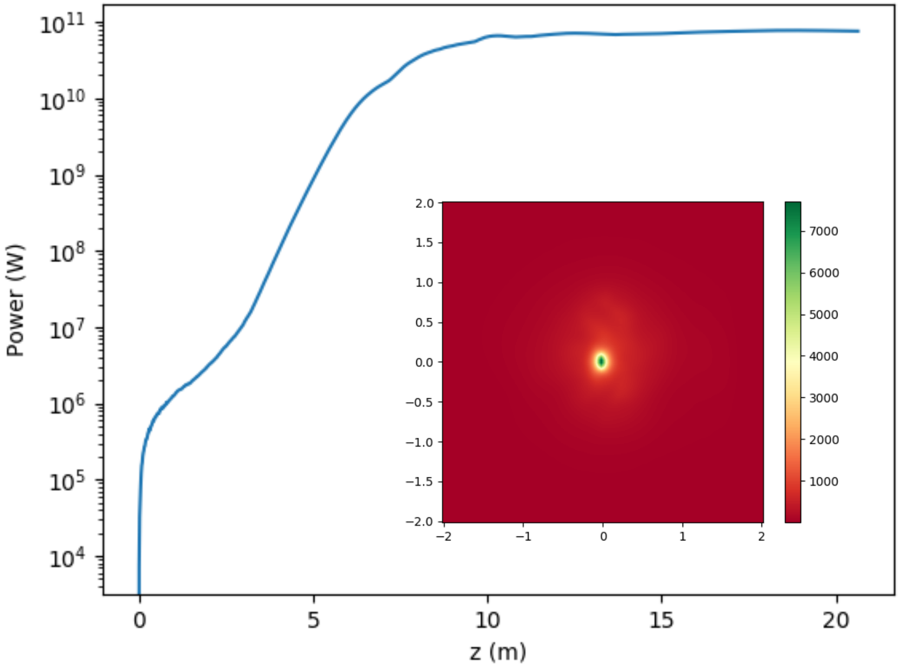
- ☐ Radiation wavelength: λ_r ~ 0.45 nm
- ☐ Radiation bandwidth: ~0.1-0.35%
- ☐ Saturation power: ~ GW-level
- ☐ Radiation pulse duration: ~fs → Potential for sub-fs pulses
- ☐ Saturation length: ~ 8-10 m

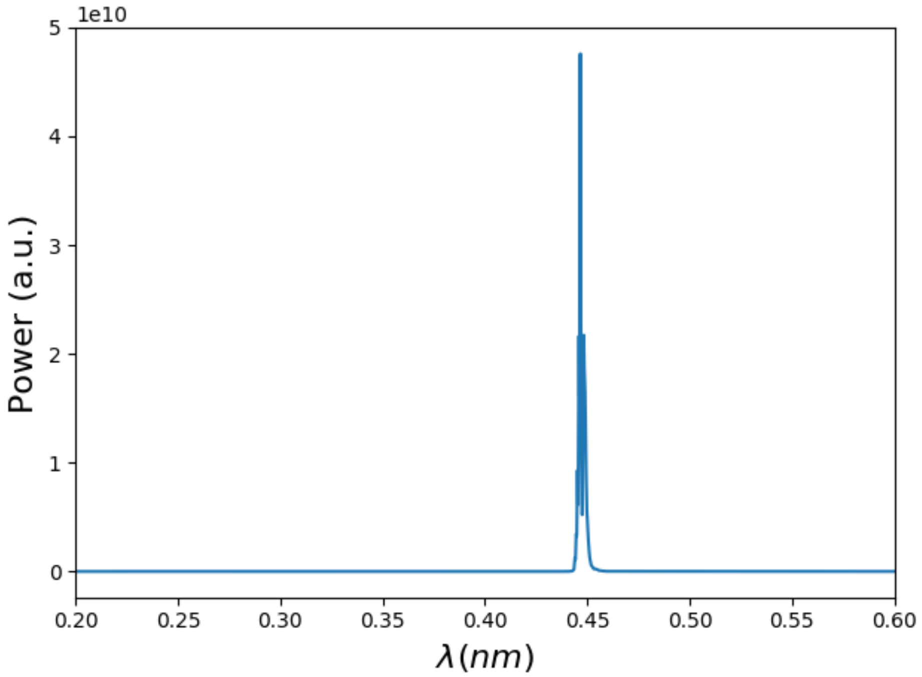
Preliminary X-ray free-electron laser results

Benchmark with unaveraged FEL code Puffin (Parallel Unaveraged Fel INtegrator)

LT Campbell and BWJ McNeil, Physics of Plasmas 19, 093119 (2012)

- ‘’Unaveraged’’ FEL code
- Not slowly varying envelope approximation (SVEA) and wiggler period averaging approximations.
- CSR is taken into account
- **Puffin results show excellent agreement with genesis simulation**
- **Puffin results indicates sub-fs hard X-ray pulses→ single spike XFEL ?**





Summary

- Relative energy spread is reduced down to $\Delta W_{\mathrm{rms}}/W = $ 0.08 % and can be potetially decreased further to $\Delta W_{\mathrm{rms}}/W <$ 0.01 %

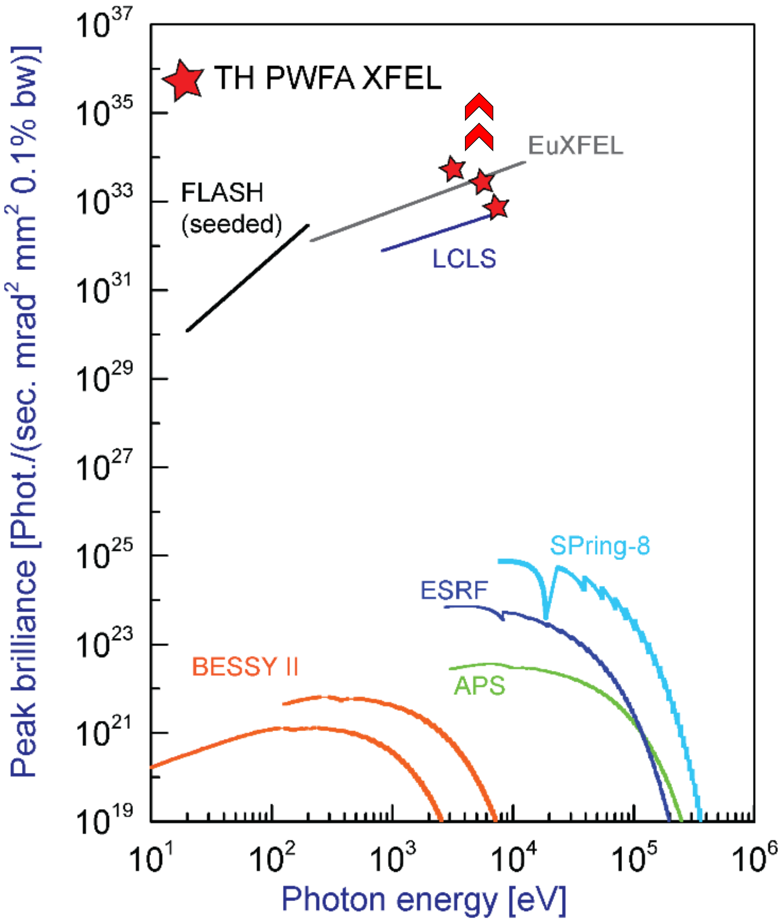
- Unprecedented ultrahigh 6D-brightness beams are produced

- 6D-brightness technique potentially game-changing for light sources and applications

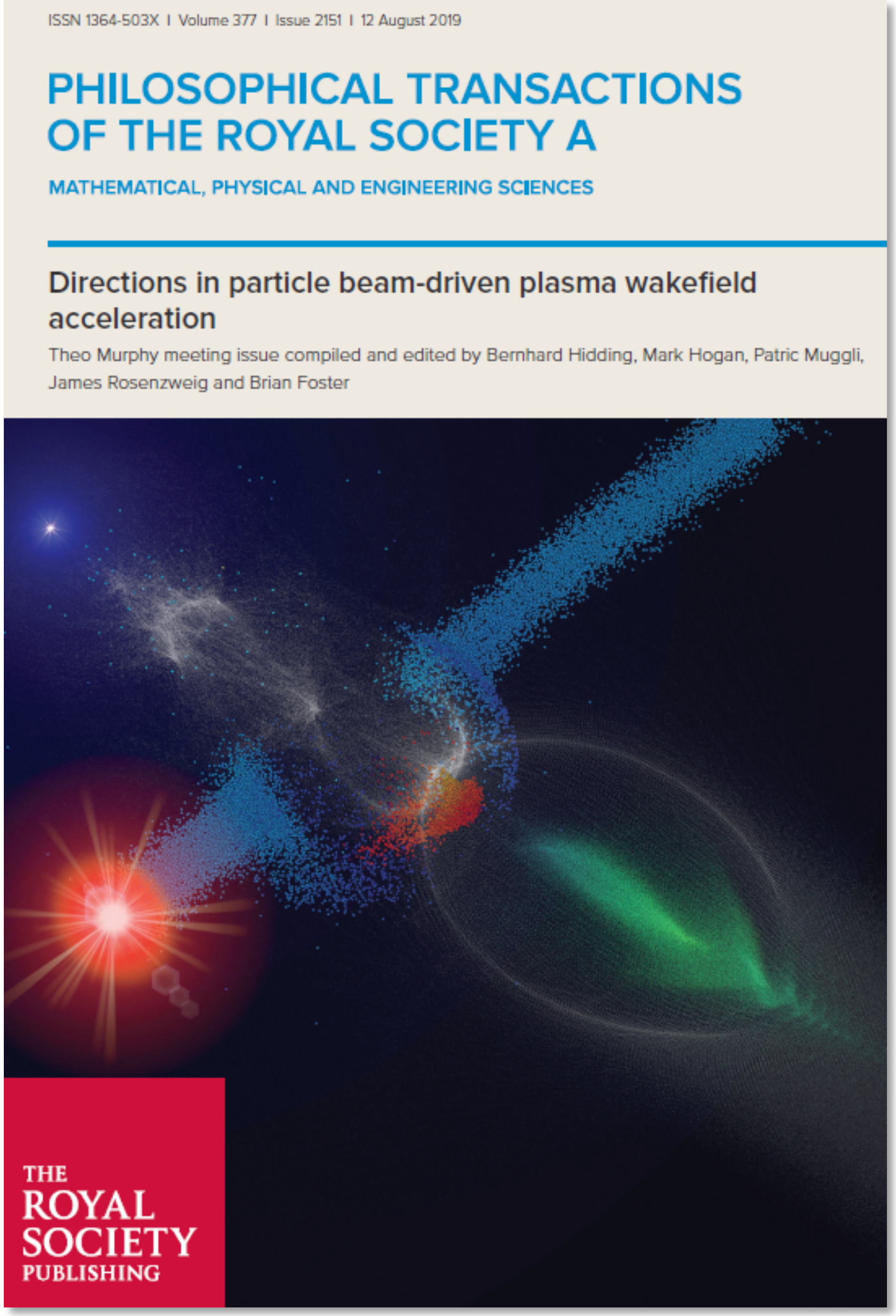
- Electron beam 6D-brightness remains preserved during the extraction from the plasma stage and trasnport towards the undulator

- XFEL saturations after ~10 m, radiation wavelength of $\lambda_r \sim$ 0.45 nm

- X-ray pulse of fs/sub-fs duration with GW-level peak power



Vision and roadmap



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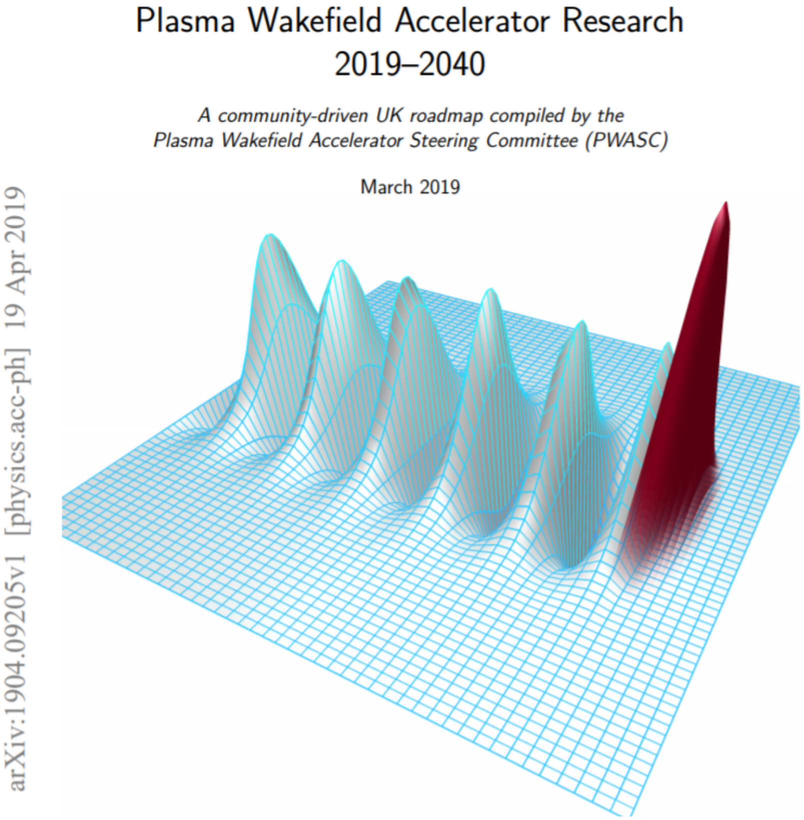
Fully synergistic with UK Plasma Wakefield Accelerator Research Roadmap 2019-2040 and with US roadmap



Plasma Wakefield Accelerator Research 2019–2040

A community-driven UK roadmap compiled by the Plasma Wakefield Accelerator Steering Committee (PWASC)

March 2019

arXiv:1904.09205v1 [physics.acc-ph] 19 Apr 2019

XFEL Roadmap

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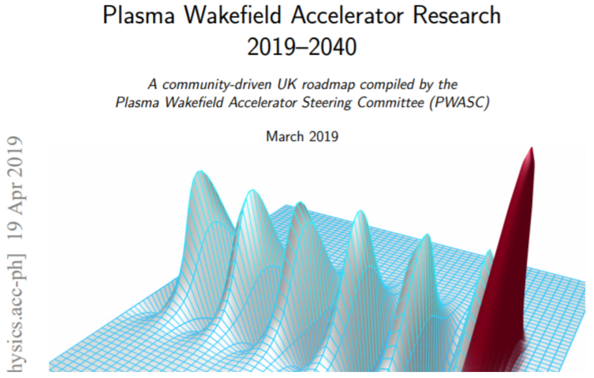

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2019–2040

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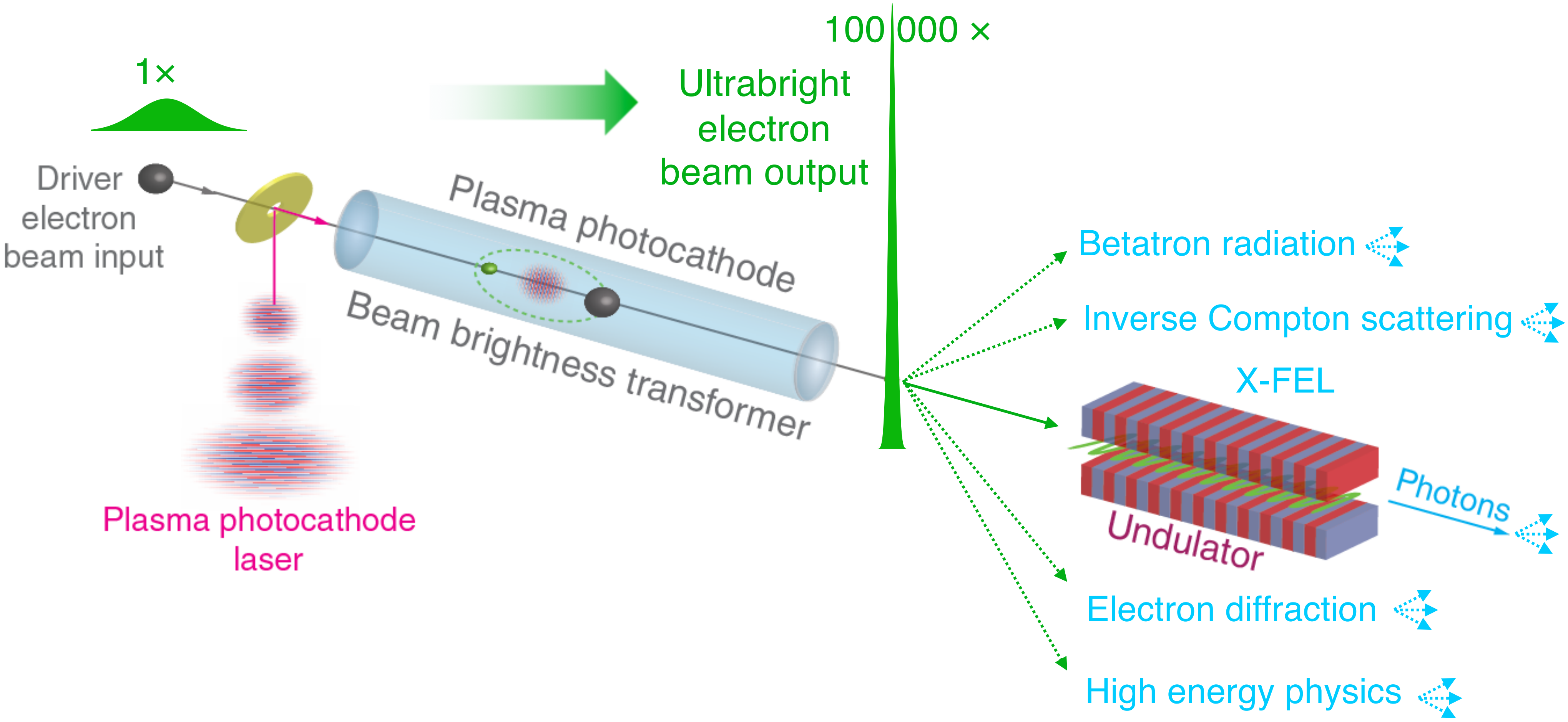
March 2019

hysics.acc-ph] 19 Apr 2019

Mission

- ❑ Much higher beam quality than state-of-the art, supported by novel enabling plasma sources and plasma-based diagnostics, will allow to realize advanced applications



Proj

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WP1.
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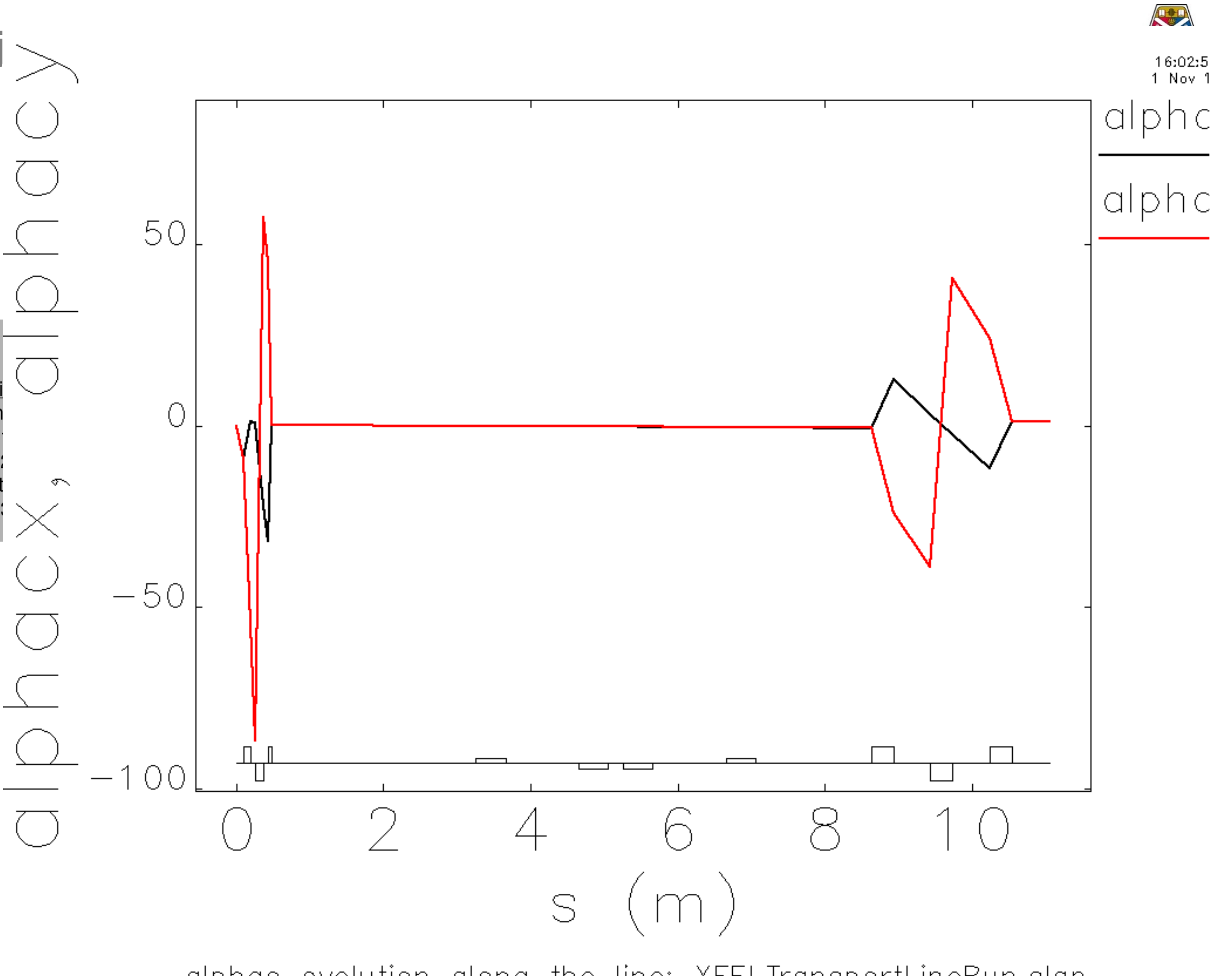
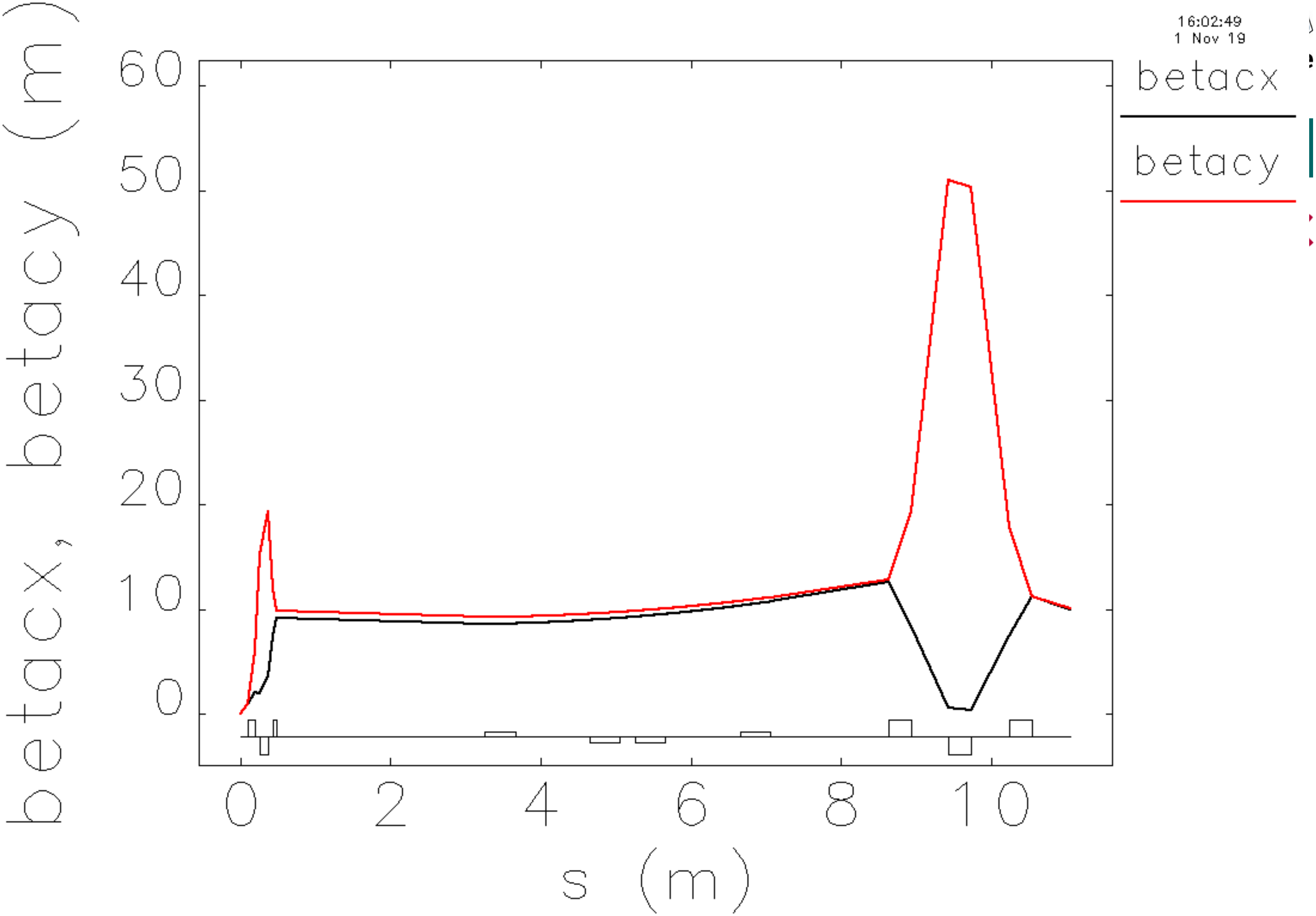
WP1.

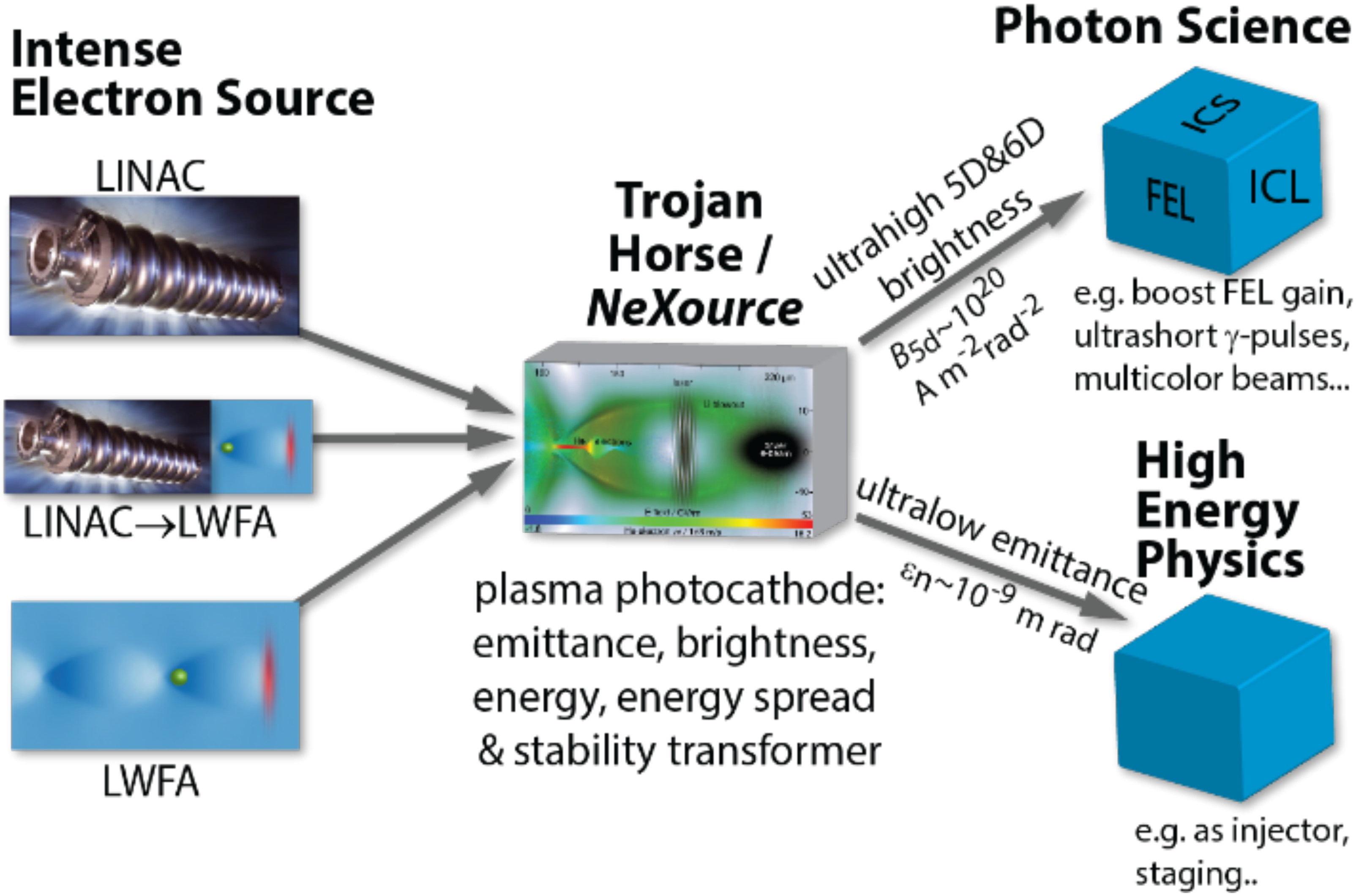




betac evolution along the line: XFELTransportLineRun.slan

WP 14 Beam Quality Transformer

Trojan Horse plasma photocathode



Intense Electron Source

LINAC

LINAC→LWFA

LWFA

Trojan Horse / *NeXource*

plasma photocathode:
emittance, brightness,
energy, energy spread
& stability transformer

ultrahigh 5D&6D brightness

$B_{5d} \sim 10^{20}$ A m^{-2} rad^{-2}

ultralow emittance

$\varepsilon_n \sim 10^{-9}$ m rad

Photon Science

ICS

FEL

ICL

e.g. boost FEL gain,
ultrashort γ-pulses,
multicolor beams...

High Energy Physics

e.g. as injector,
staging..