2019-11-13 XFEL Workshop
Imperial College

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.*

Synergies with the STFC PWFA-FEL Programme

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

Electron beam emittance and energy spread challenge

- Fundamental X-FEL thresholds:
- FEL Emittance criterion: $\epsilon_n < \lambda_r \langle\gamma\rangle / 4\pi$

  State-of-the-art ~µm rad scale normalized emittance $\varepsilon_n \Rightarrow$ multi-GeV electron energies γ required to reach hard X-ray wavelengths λ_r
- FEL Energy spread criterion: $\langle\sigma_\gamma/\gamma\rangle \ll \rho$

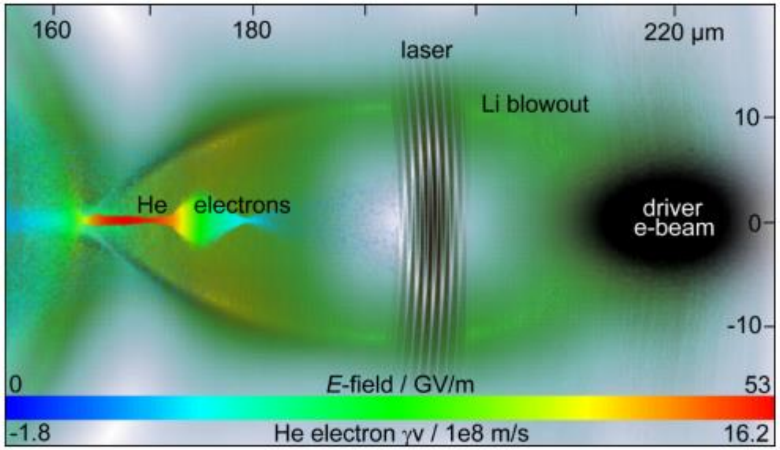
  Need <0.01% relative energy spreads to satisfy Pierce parameter ρ for hard x-ray output
- Key performance parameter is brightness, which also requires kA-level current *I*

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

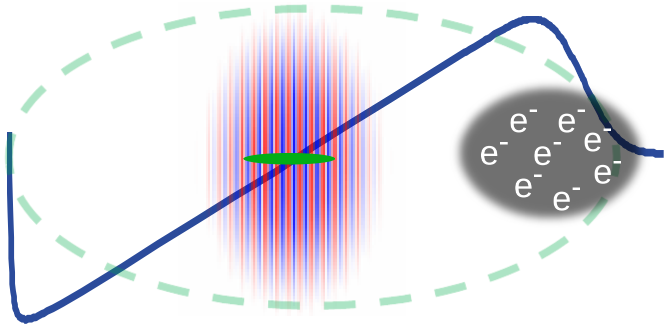
- Brightness crucial for FEL gain length: $L_{g,1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}} \propto B_e^{-1/3}$

  $\Rightarrow$ 100's m scale undulator lengths to drive photon field to saturation

Plasmas wakefield accelerators: 100 GV/m fields, great also for "plasma photocathodes" a.k.a. Trojan Horse



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



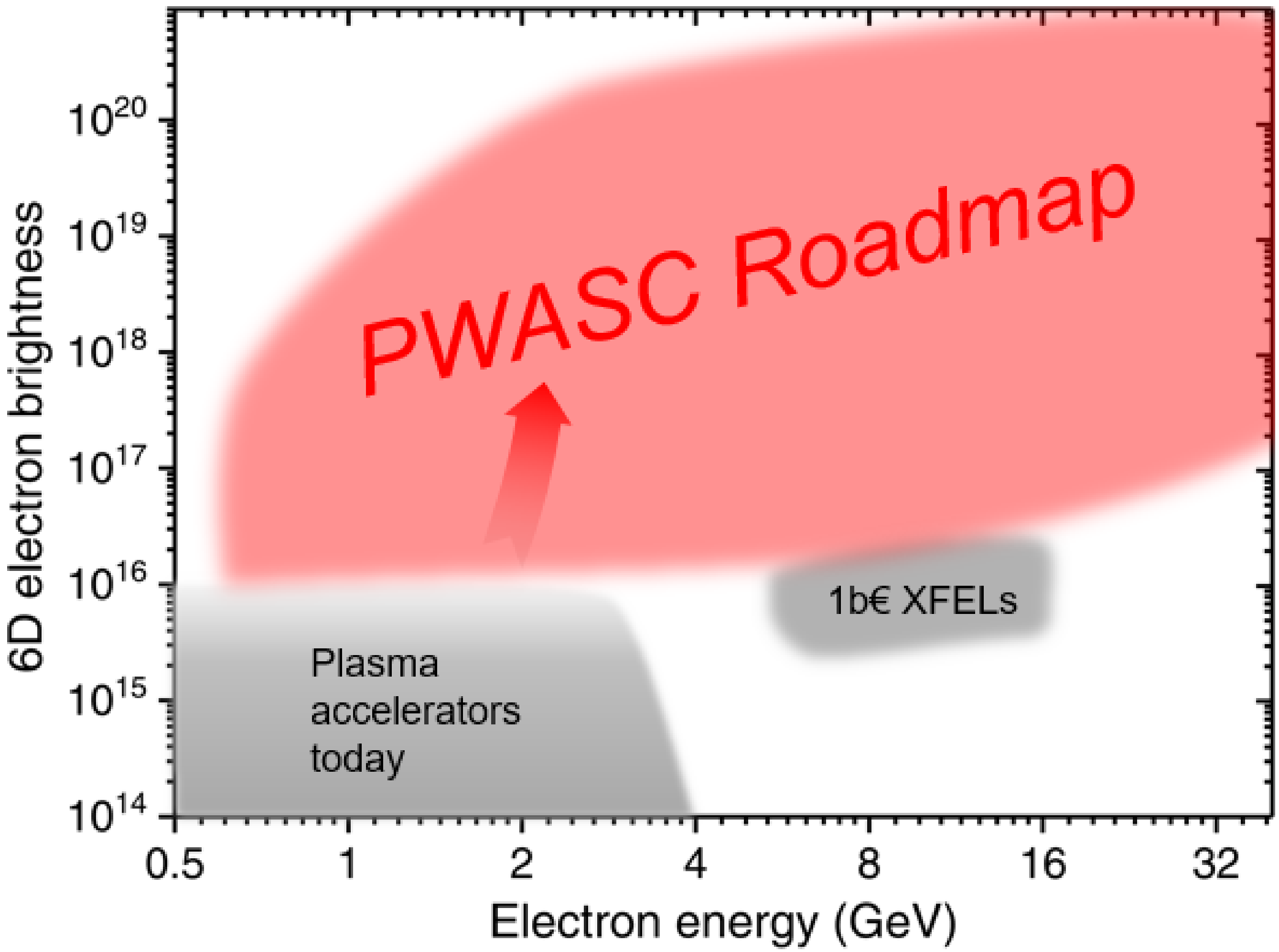
- ❑ Prospect for nm rad emittance; brightness many orders of magnitude beyond even state-of-the-art X-FEL linacs

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

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

Brightness reach of plasma photocathode



PWFA-(X)FEL may boost capabilities

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

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

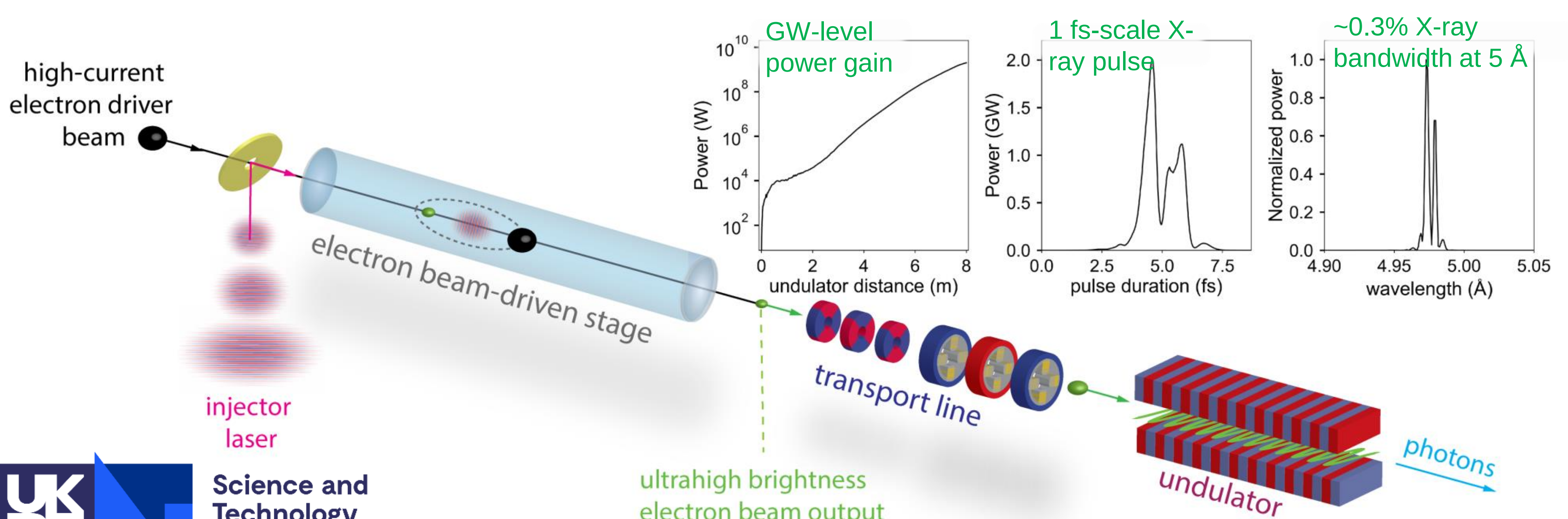
$\Rightarrow$ 10's nmrad emittance allows to push towards harder X-ray wavelengths λ_r for low electron energies γ

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

$\Rightarrow$ Energy spread (e.g. <0.01%) suffices X-FEL Pierce parameter ρ

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

$\Rightarrow$ Brightness *B* boosts gain and allows saturation of photon field in 10 m vs. 100's metres, may allow single spike sub-fs pulses



Science and Technology Facilities Council

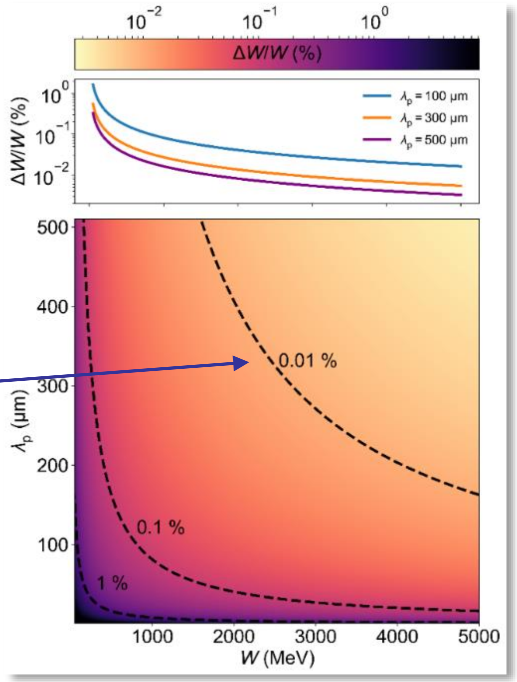
STFC "PWFA-FEL" programme:
"Exploratory Study of PWFA-FEL at CLARA" 2019-2023

- ❑ Strathclyde-ASTeC-CI-SLAC-UCLA collaboration, theory & simulation supporting exp. R&D at CLARA, SLAC, DESY etc.

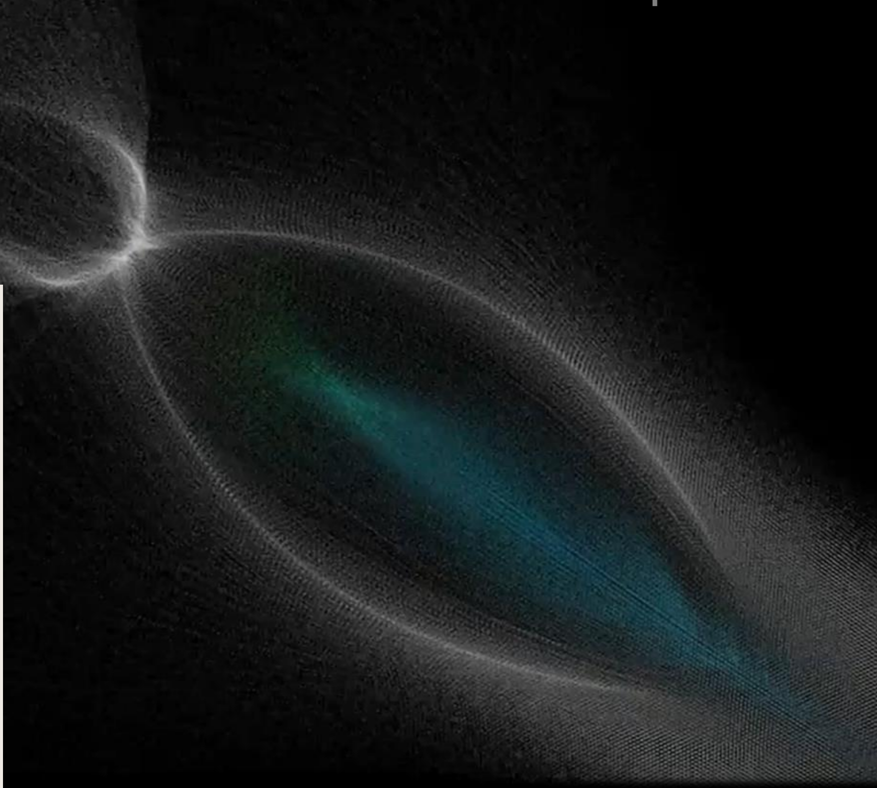
- ❑ Recent breakthroughs:

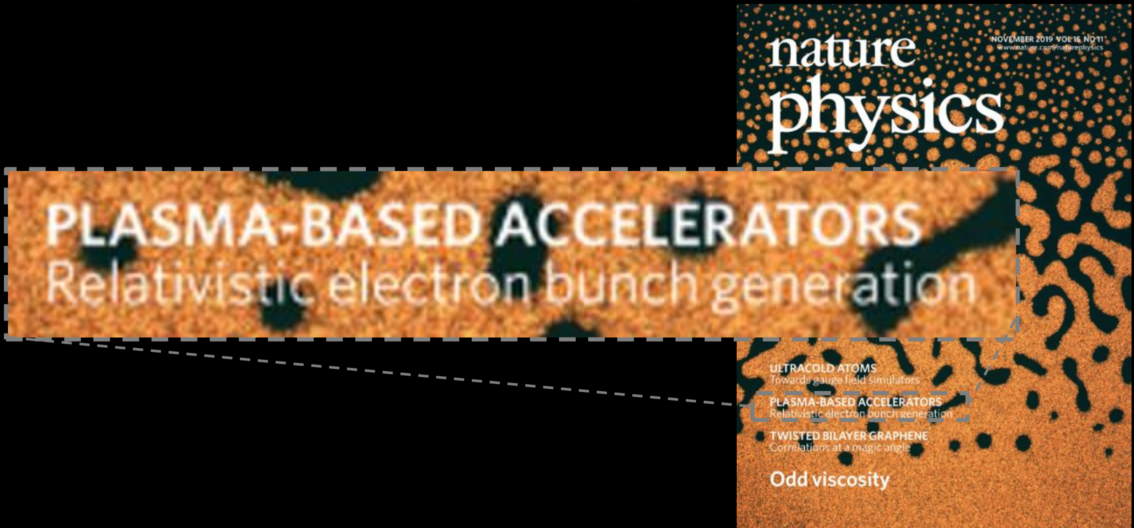
- ❑ G.G. Manahan, F. Habib *et al.*, *Nat. Comm.* 8, 15705 (2017): concept to reduce energy spread to < 0.01% levels

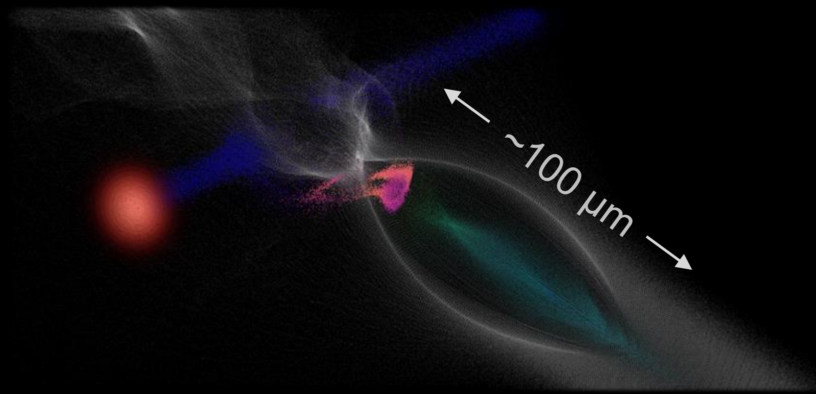
- ❑ A. Deng, O. Karger *et al., Nat. Phys.* 8, 1156–1160 (2019): proof-of-concept of plasma photocathode at SLAC FACET



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



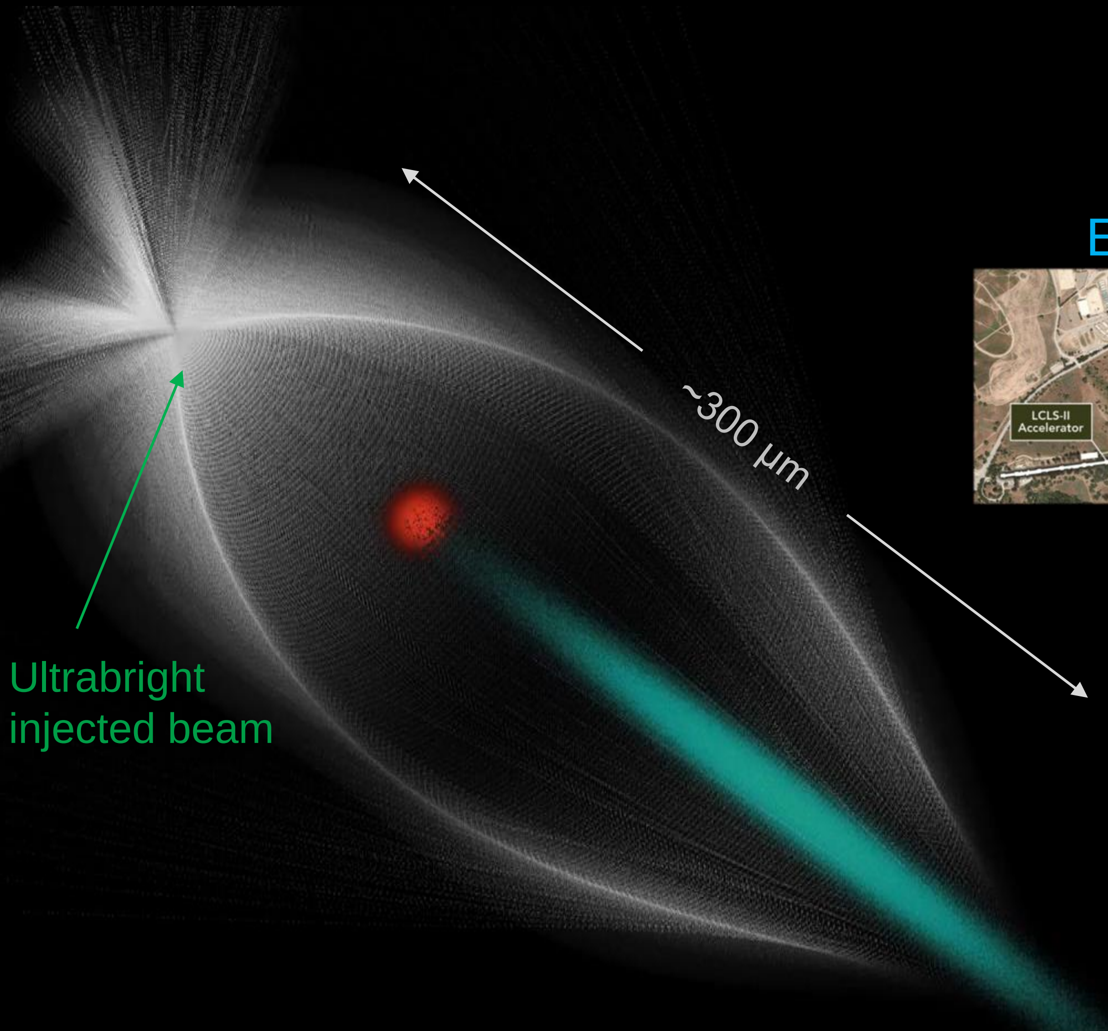


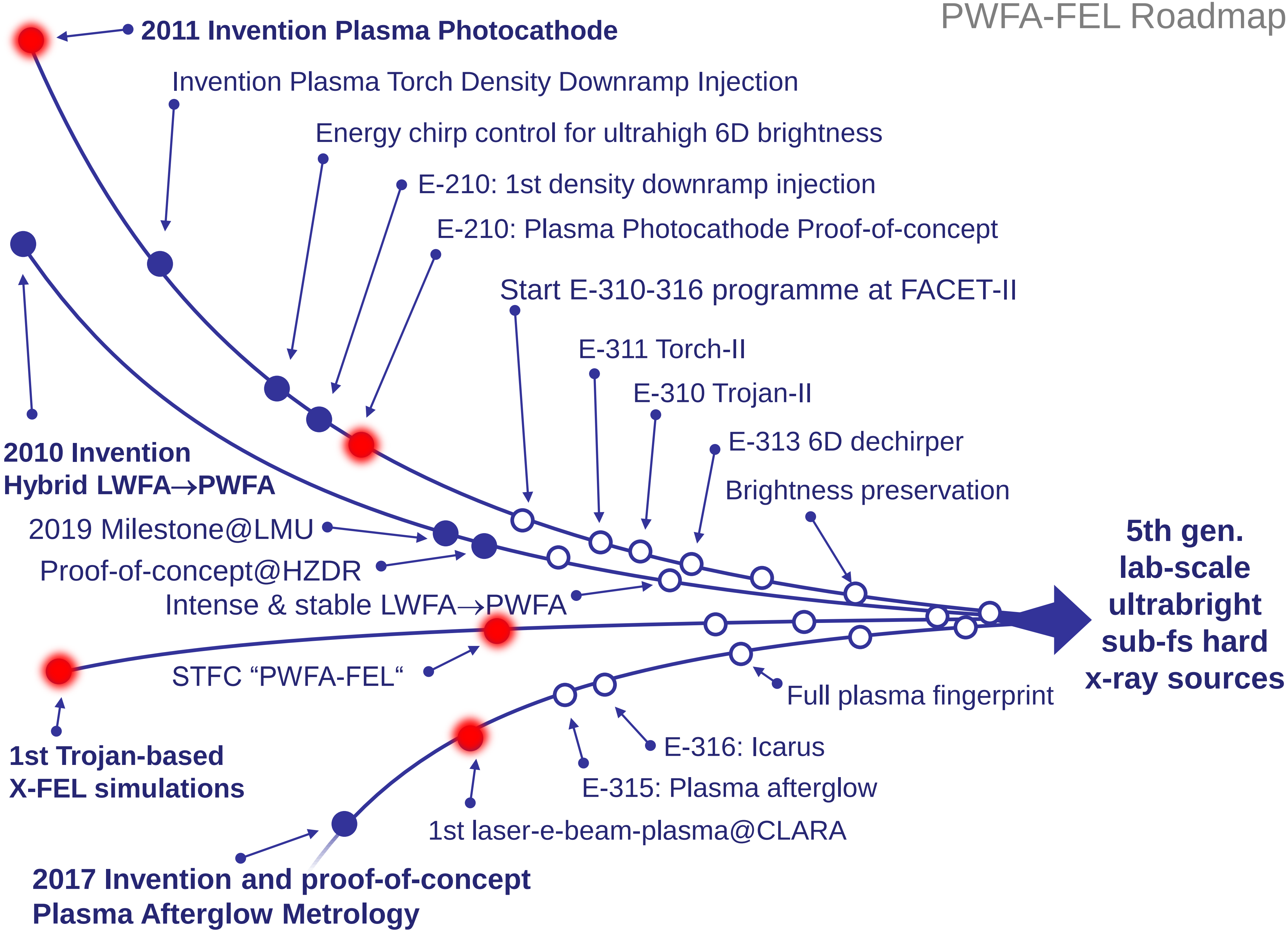


E-210: Trojan Horse at FACET

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

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

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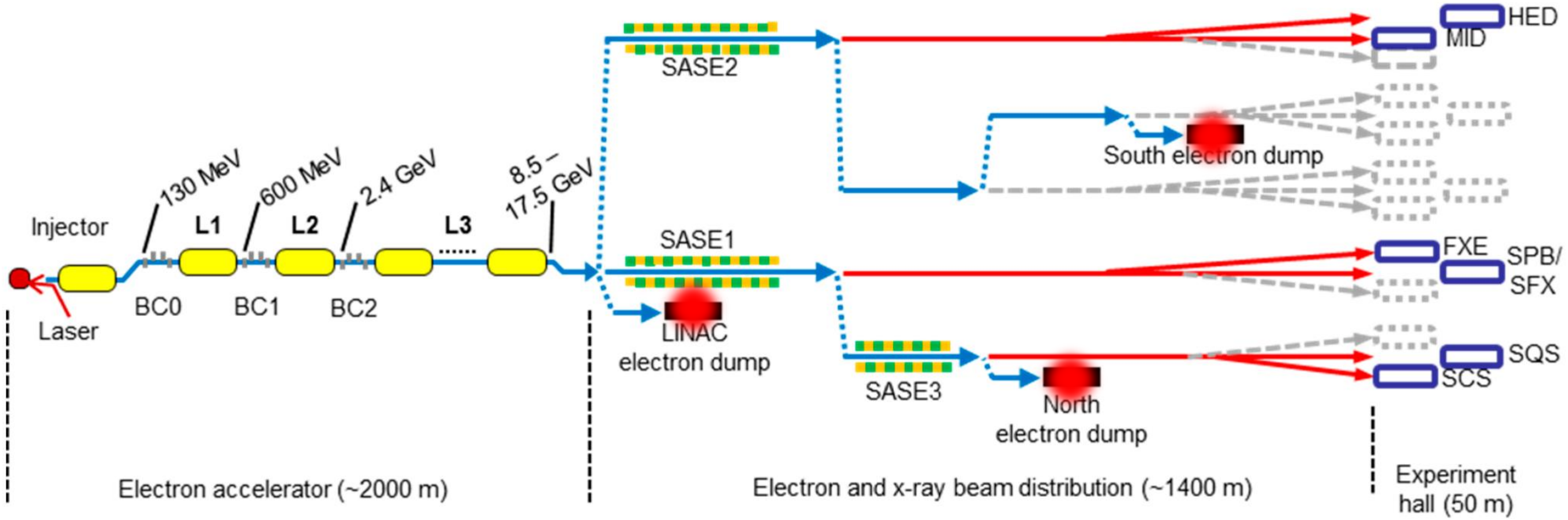
Options to integrate future PWFA-(X)FEL into the UK X-FEL?

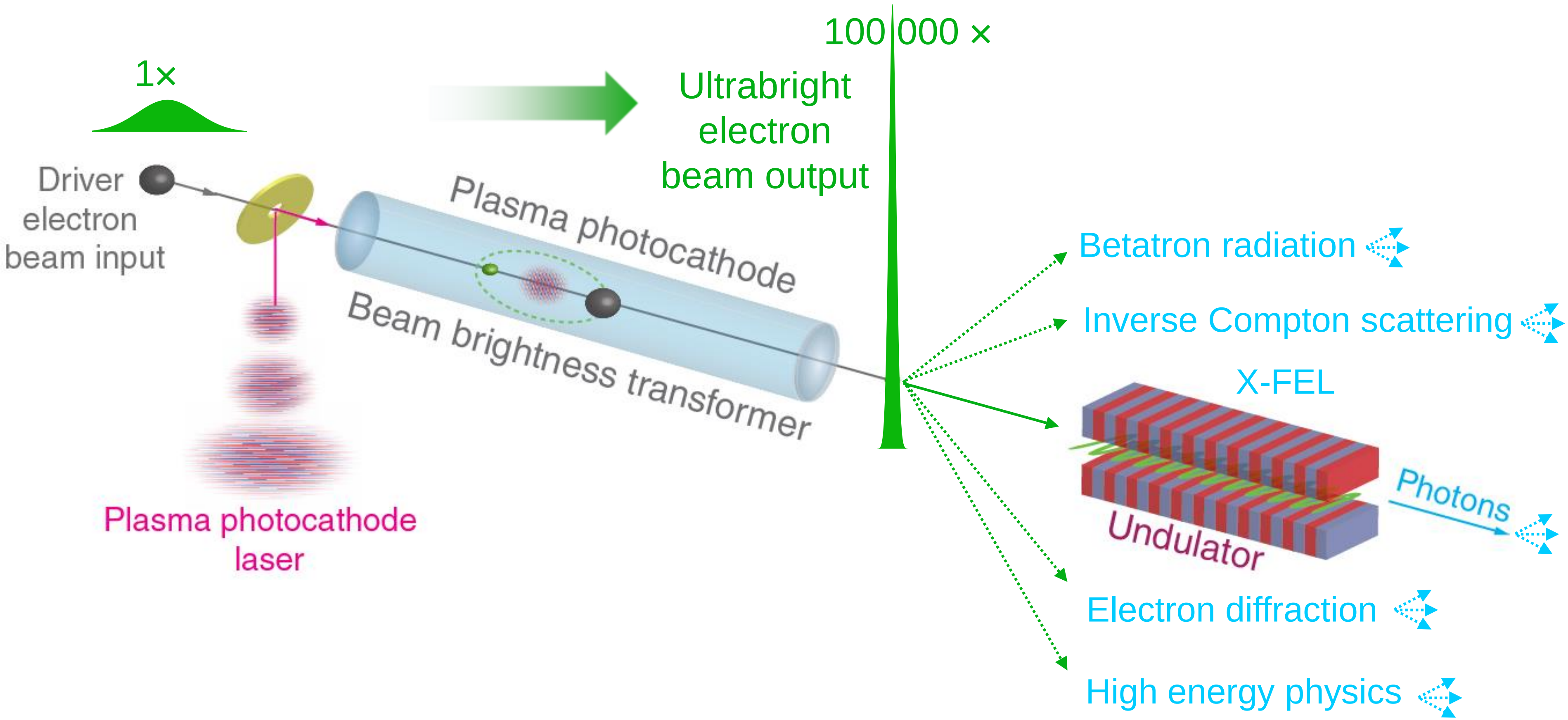
- Add-on as ~10 metre-scale energy & brightness transformer:



- E.g. ~3 GeV, ~5 kA, ~10 µmrad ε_n, 20 fs **in** (can have 10's % energy spread)

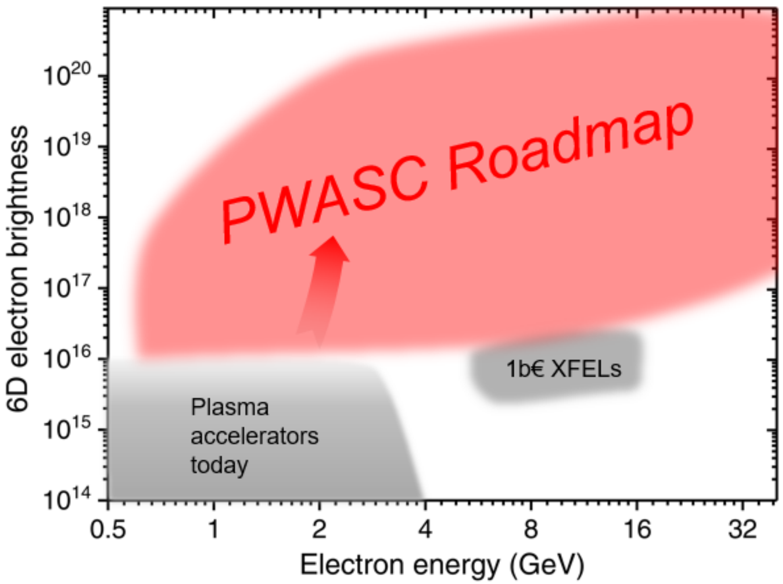
→ ~6 GeV, ~1 kA, ~10 nmrad ε_n, sub-fs **out**

Ultralow emittance, ultrahigh brightness electron beams useful for various applications

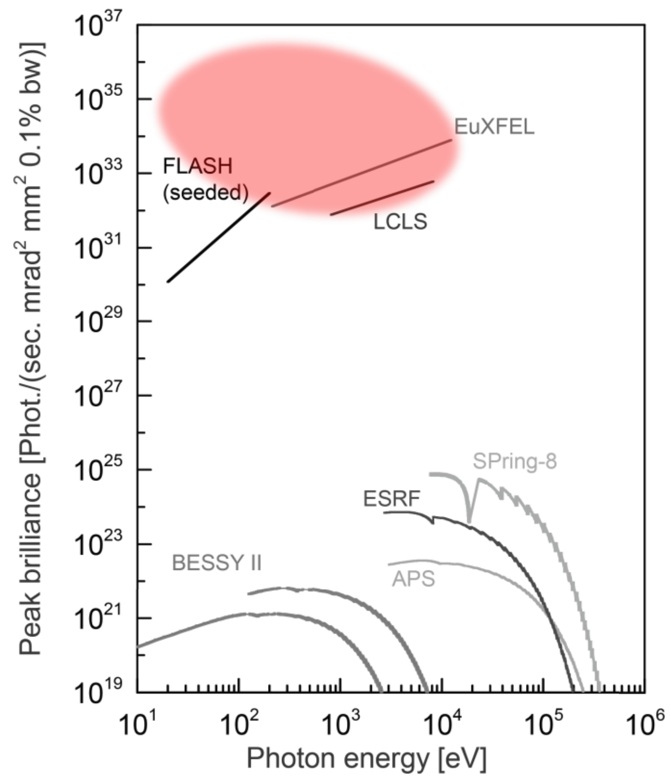


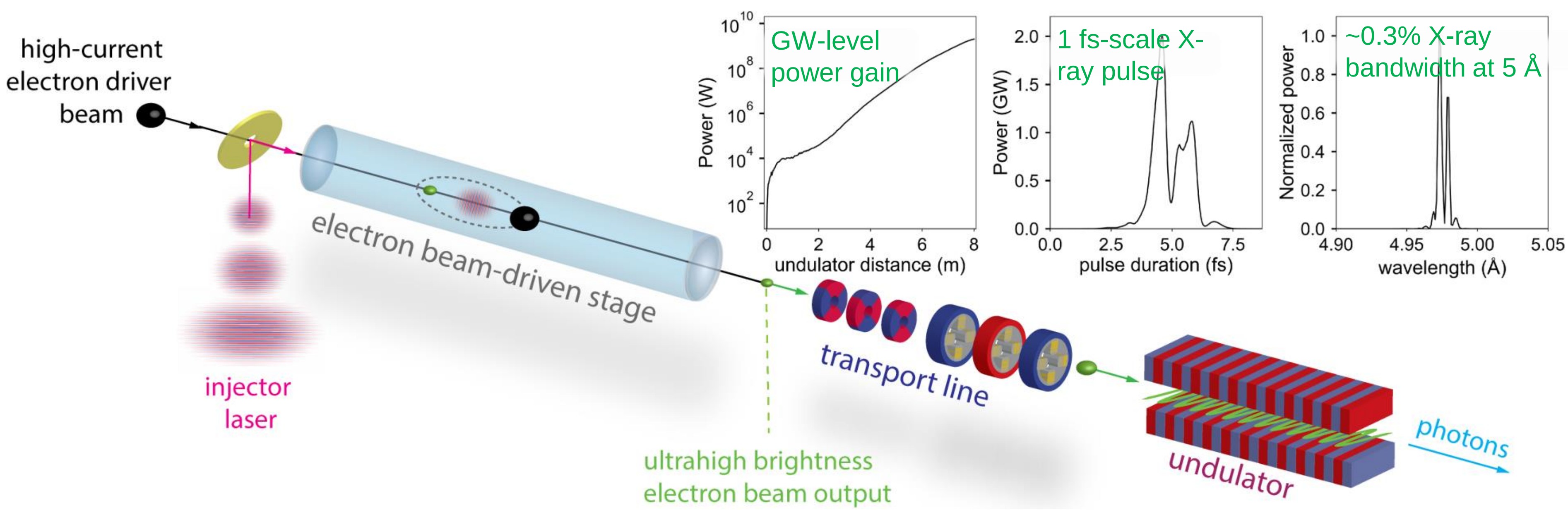
STFC "PWFA-FEL" programme 2019-2023

Workshops planned across (plasma) accelerator & photon science

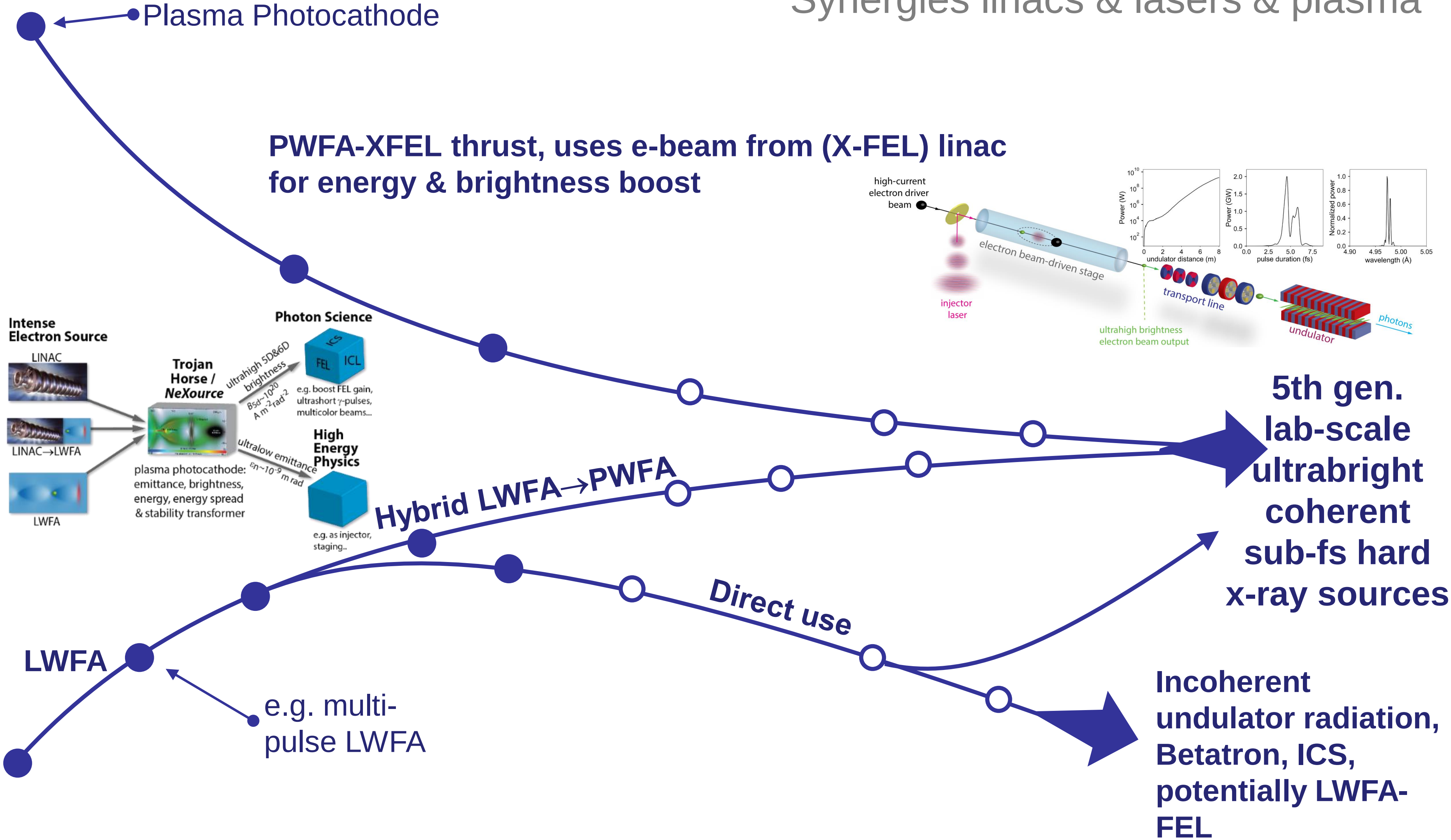


Sub-fs pulses?
Harder x-rays?
Extreme tunability?
Multicolor beams?
...





Synergies linacs & lasers & plasma



- ❑ Lasers required at all ends: for preionization of PWFA stage, plasma photocathode(s), pump-probe, WDM, diagnostics
- ❑ Laser-plasma-based diagnostics novel promising additions for beam metrology
- ❑ Co-location highly profitable

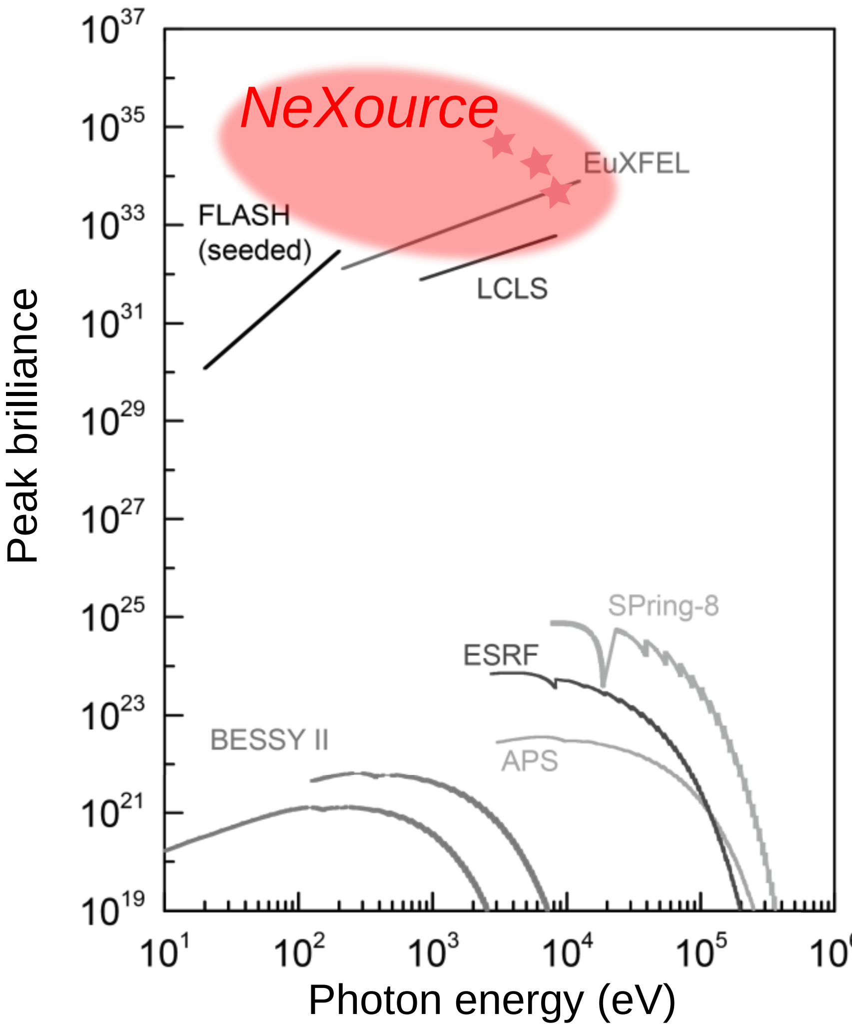
Summary

- PWFA and plasma photocathode may extend electron energy (factor 2-6) and brightness (4-5 orders of magnitude) in linac afterburner add-on configurations
- UK-led experimental R&D programmes at on Trojan-PWFA at FACET-II, CLARA, DESY
- STFC “PWFA-FEL“ programme forward-looking support on theory and simulations
- By boosting electron energy and brightness, the X-FEL range could be substantially expanded
- It may be prudent to add PWFA-FEL as a competitive edge for the UK X-FEL, anticipating that the brightness boost can be demonstrated
- In such anticipation, we are also looking into where at SLAC a PWFA-XFEL booster could be added/realized
- Hybrid LWFA→PWFA could provide lab-scale solutions, LWFA e.g. via multi-pulse may provide direct pathways to FEL, already produces supportive light sources
- Strong synergies between e-beams and lasers, R&D e.g. at CLF, SCAPA can support the UK X-FEL mothership
- R&D aligned with Plasma Wakefield Accelerator Steering Committee (PWASC) roadmap

Electron brightness begets photon brightness

- 6D electron brightness 100000× better ⇒ light sources with ultrahigh performance

- *E.g.* hard x-ray free-electron laser:
  - Ultrahigh gain in undulator, ~10 metre saturation length vs. 100's of metres
  - Improve peak photon brilliance by at least two orders of magnitude
  - Push towards higher photon energies
  - Attosecond photon beams: visualize electron motion in molecules on natural timescale



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Plasma Photocathode Beam Brightness Transformer for Laser-Plasma Accelerators

radiabeam TECHNOLOGIES University of Strathclyde Glasgow UCLA SLAC

Print

Award Information

Agency:
Department of Energy

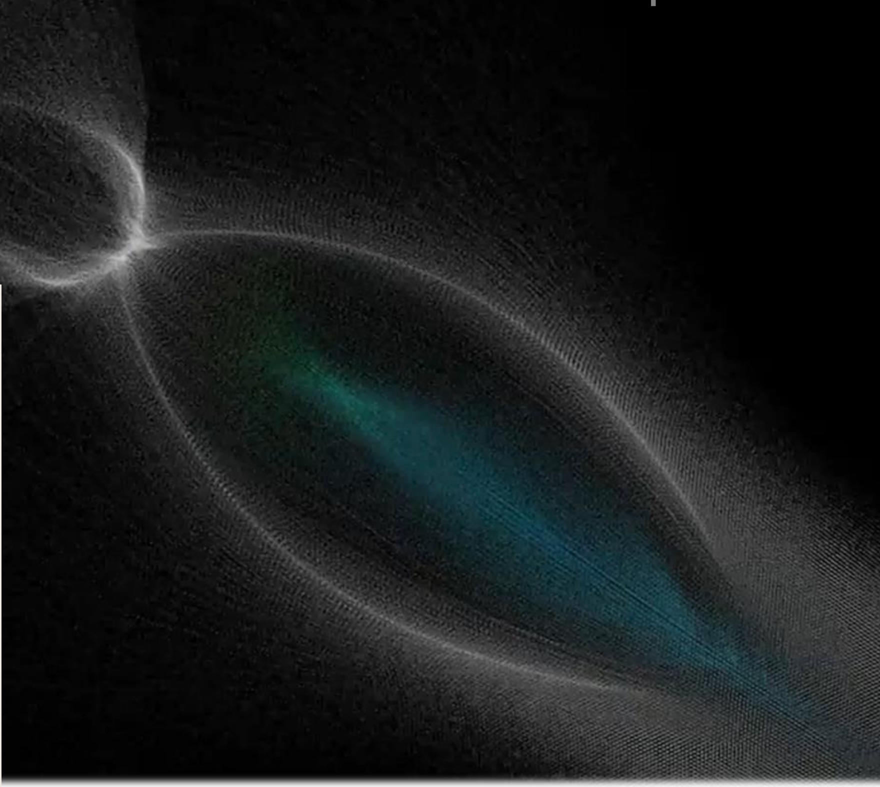
Branch:
N/A

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

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

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

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

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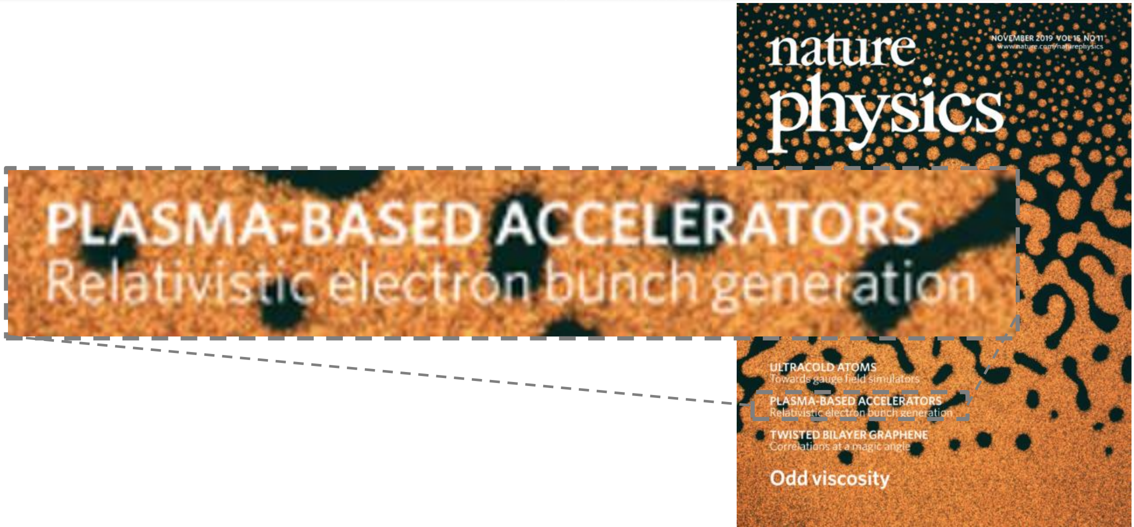

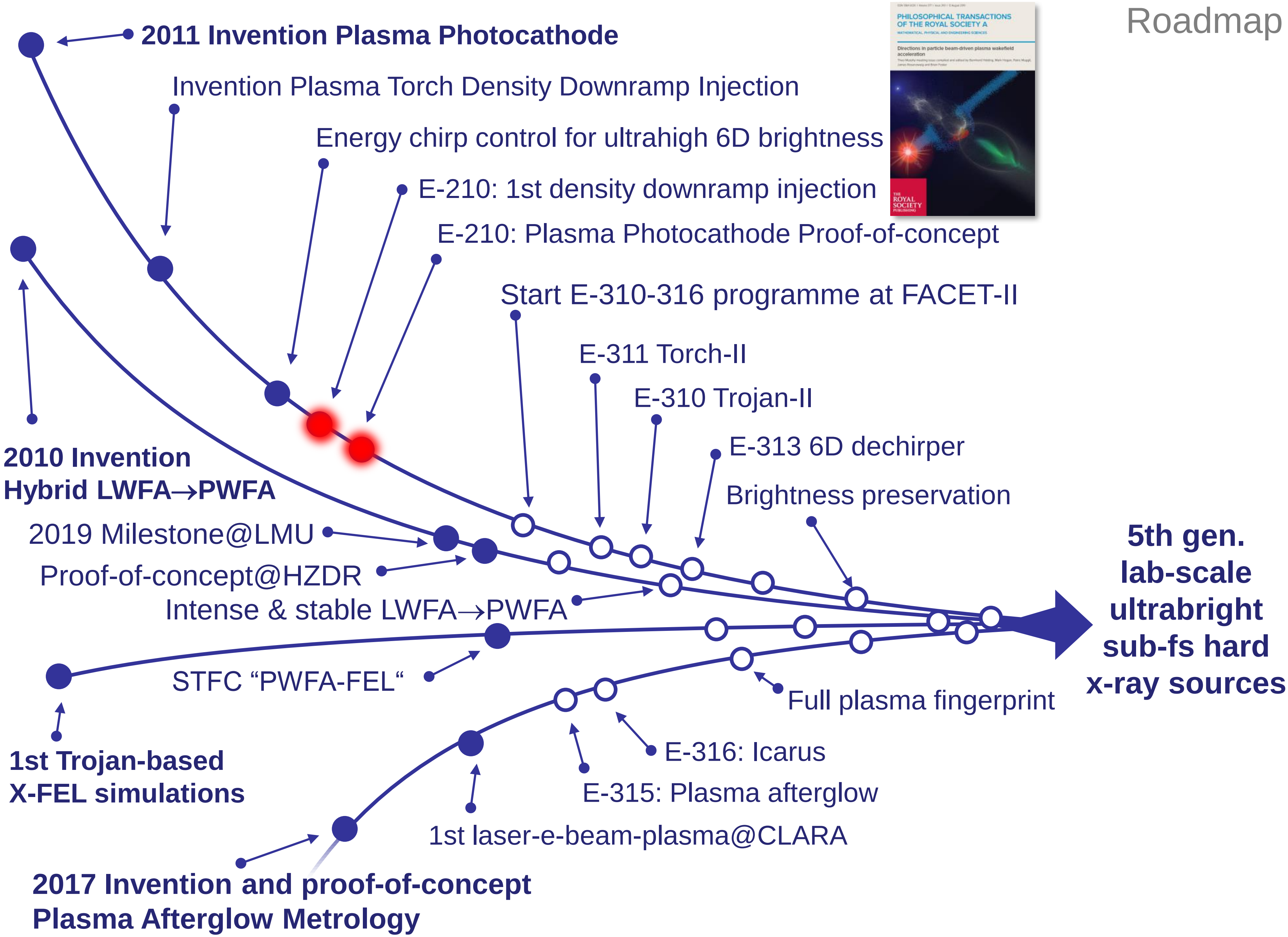
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lab-scale
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Directions in particle beam-driven plasma wakefield acceleration
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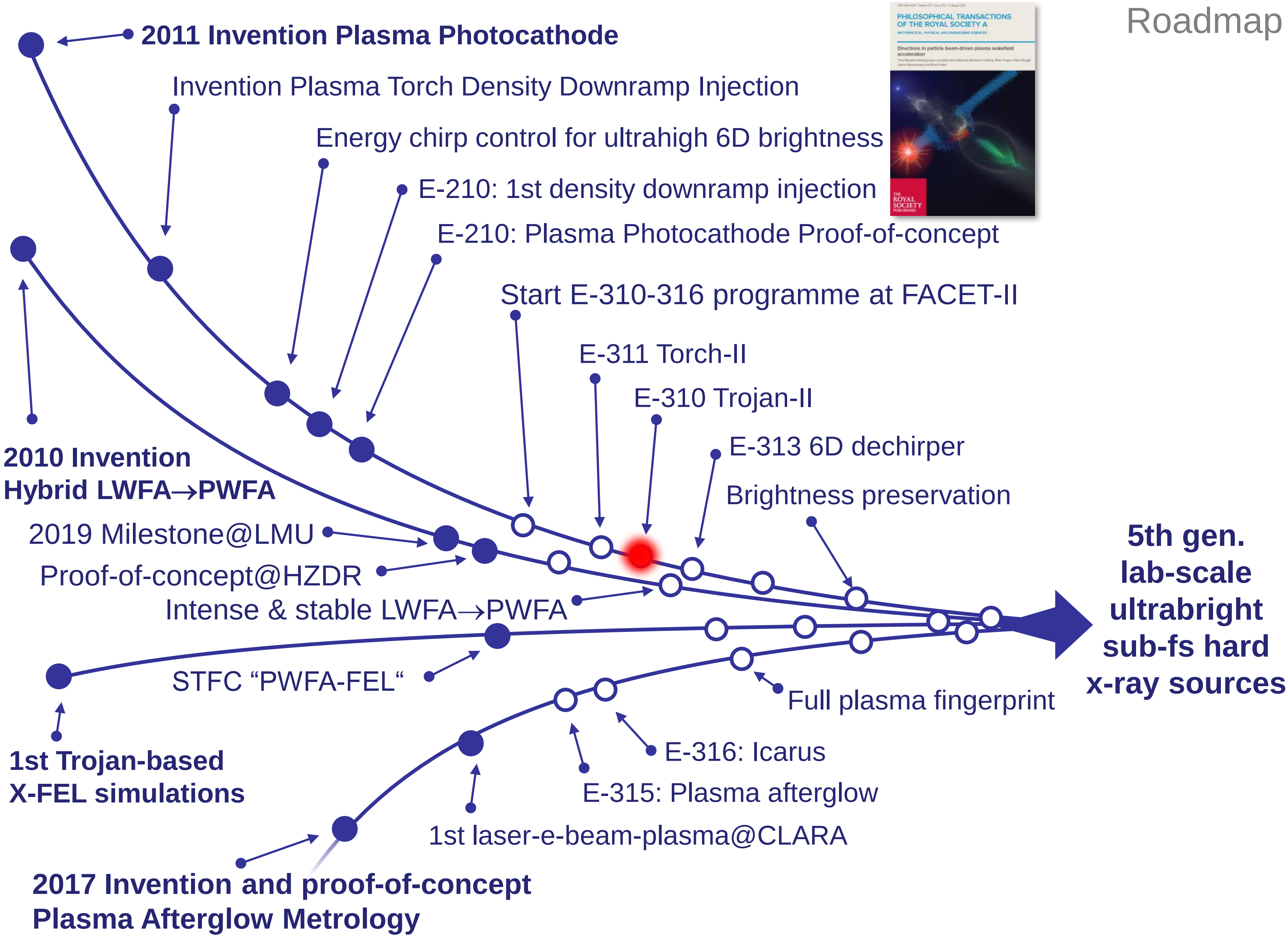
Roadmap



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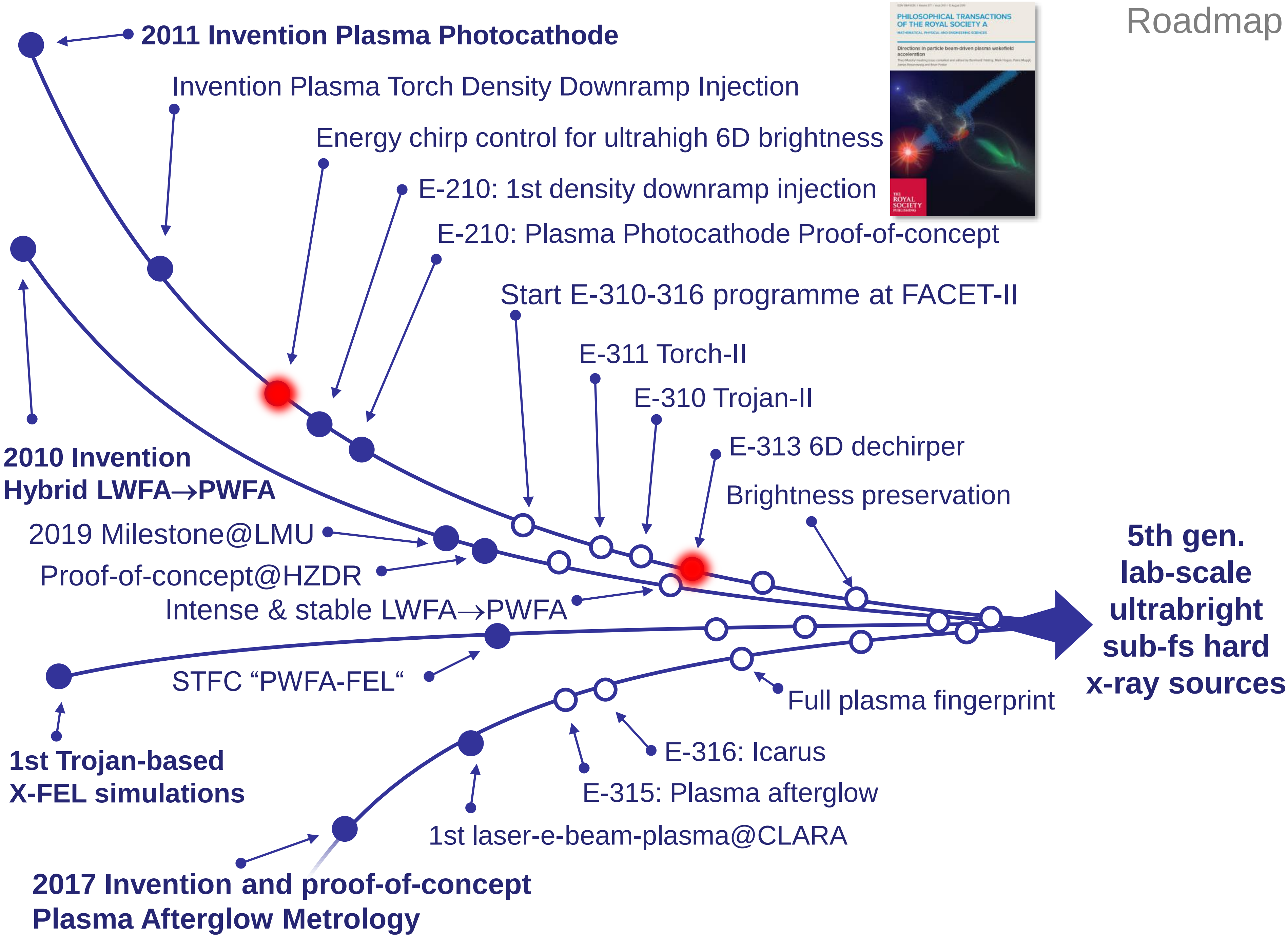

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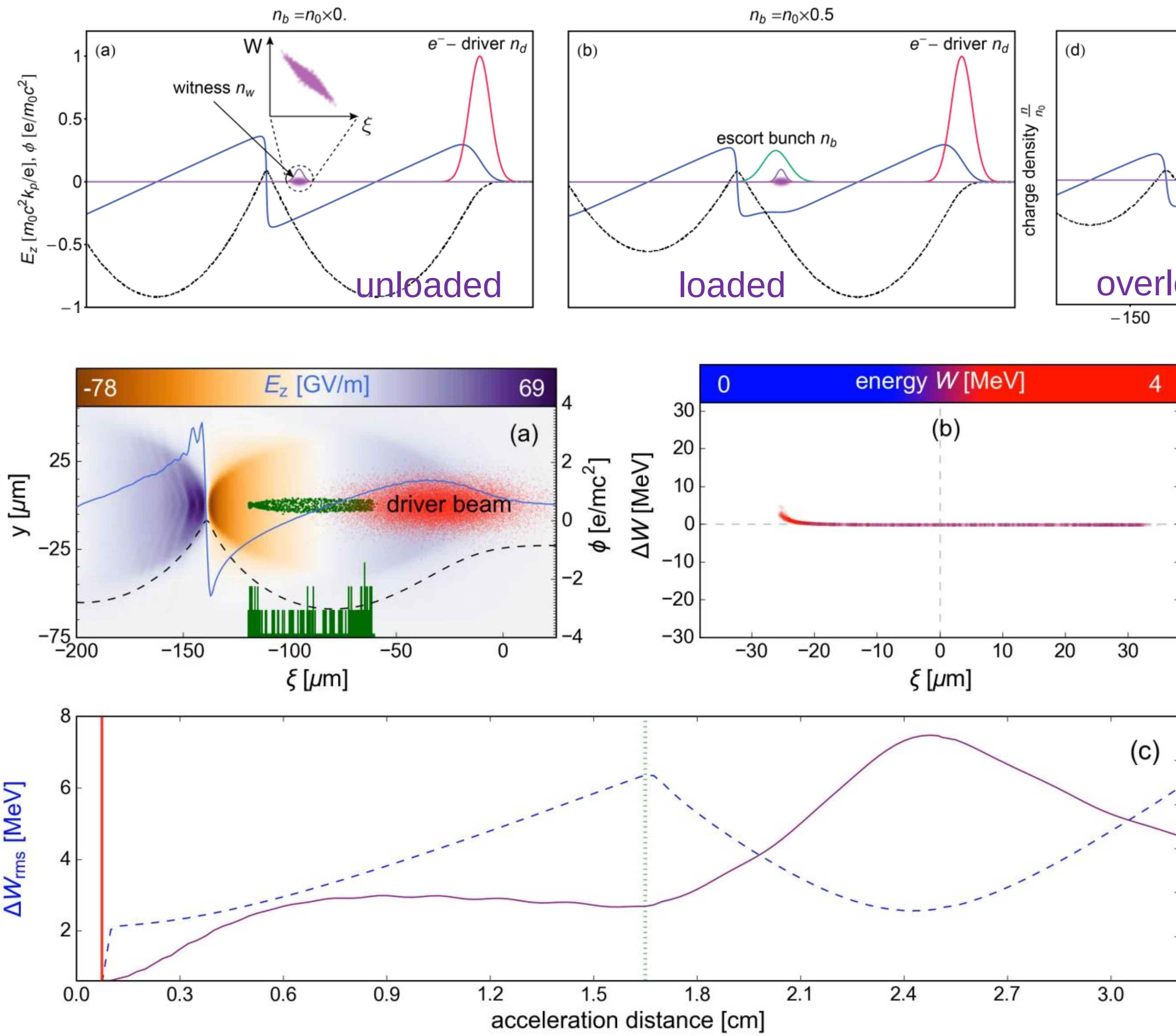
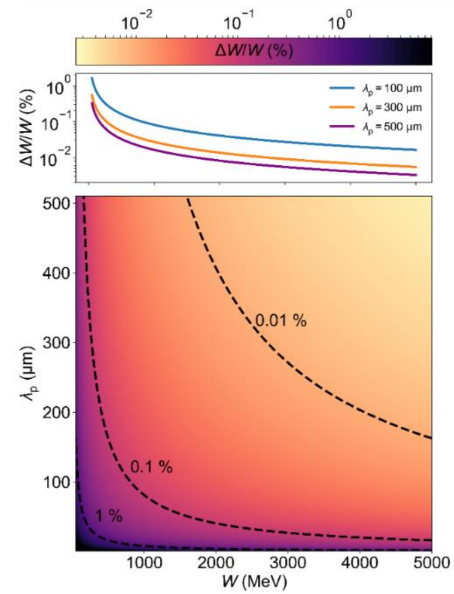
Concept of plasma photocathode-released "escort beam" for chirp control

Tailored beam loading via escort bunch allows chirp control:

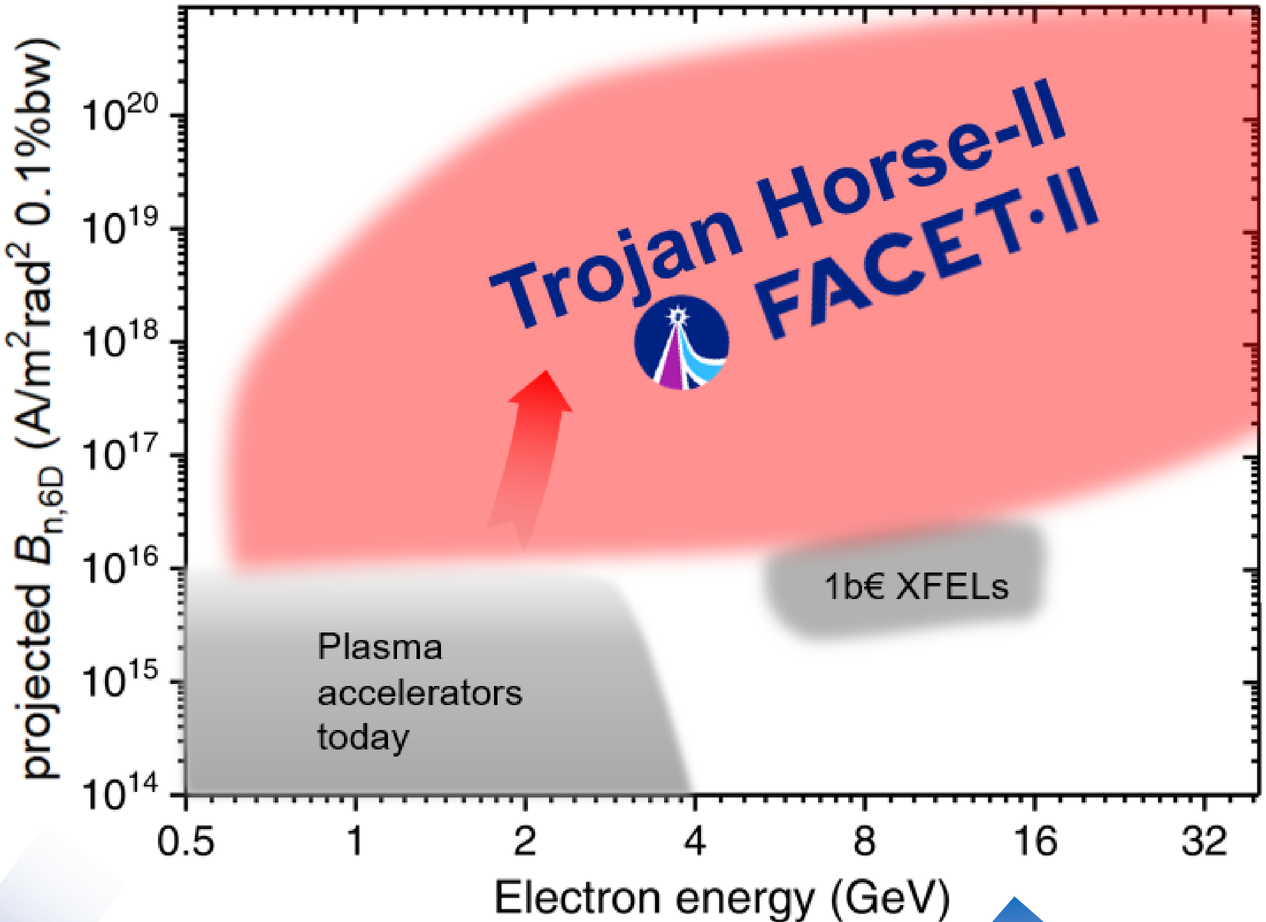




G.G. Manahan, F. Habib et al., *Nat. Comm.* 8, 15705 (2017)

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

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

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,
Department of Physics, University of Strathclyde
Scottish Universities Physics Alliance SUPA, UK

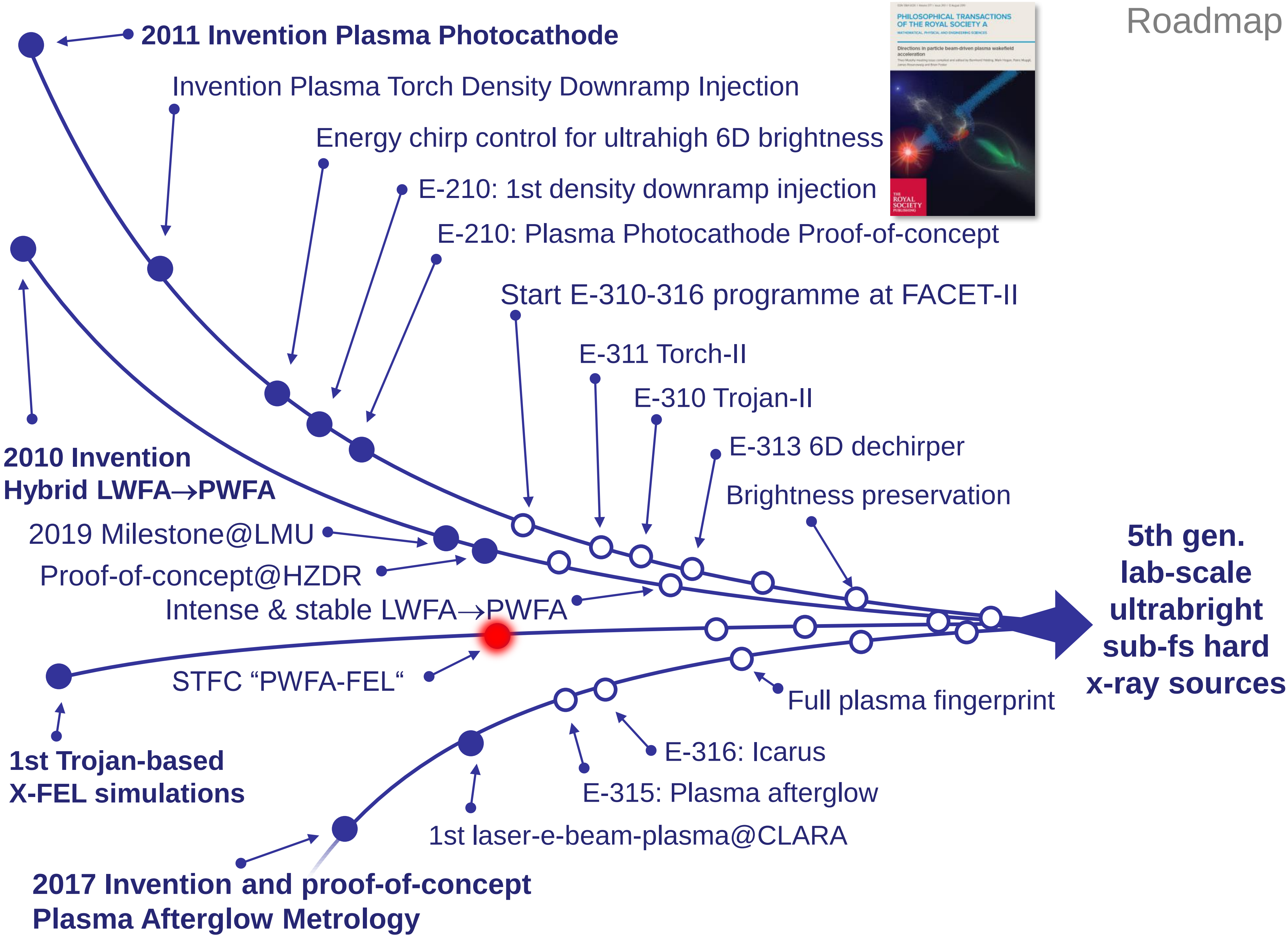
Strathclyde Centre for Doctoral Training P-PALS
Plasma-based Particle and Light Sources http://ppals.phys.strath.ac.uk/

& The Cockcroft Institute

"Proposal ahead of its time" – resubmission encouraged

FACET-II
Facility for Advanced Accelerator Experimental Tests

Roadmap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- STFC funded 2019-2023

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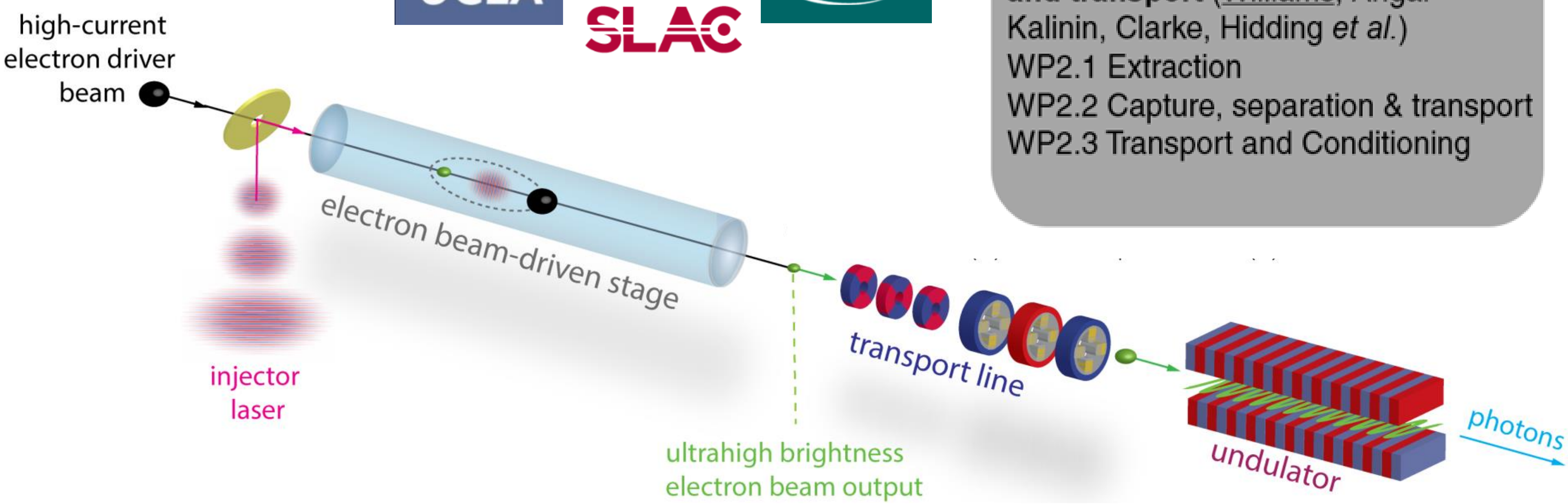
SLAC
ASTeC



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

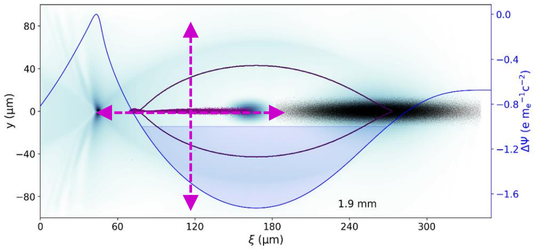
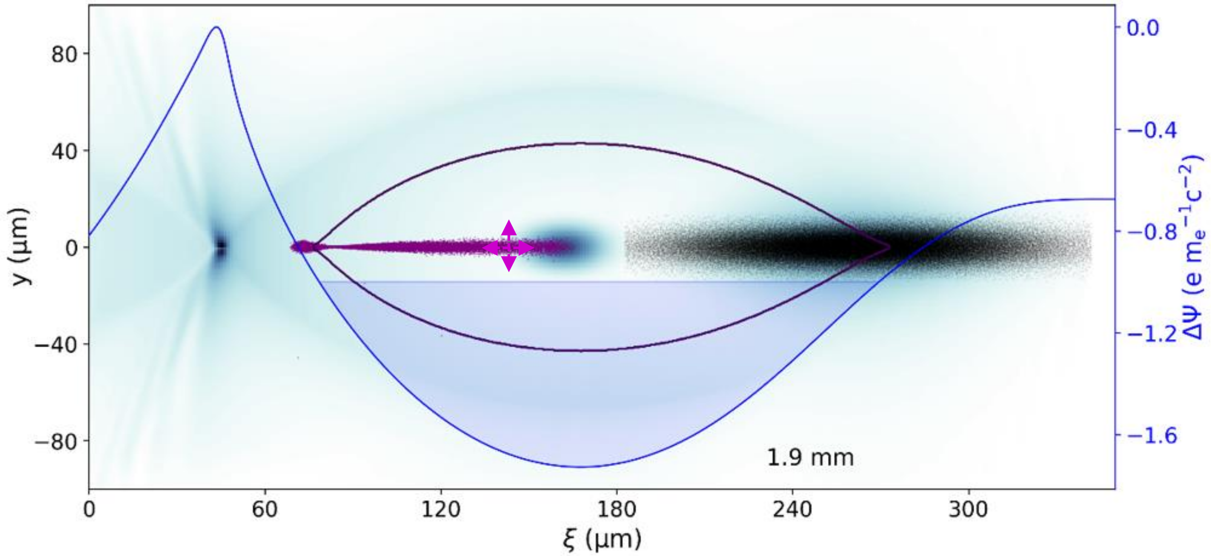


Figure of merit χ:
laser precision/(λ_p)
33% at FACET

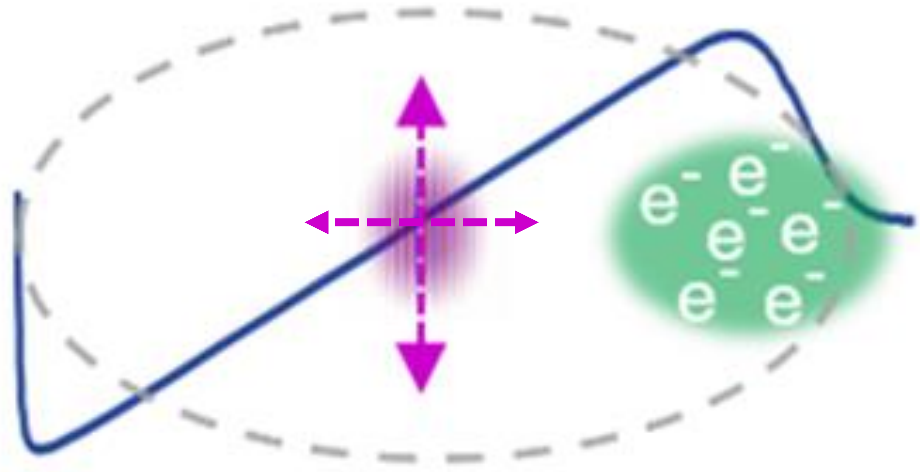
Large blowout, small jitter:
Excellent injection precision (sub-%), and tunability?



- 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?

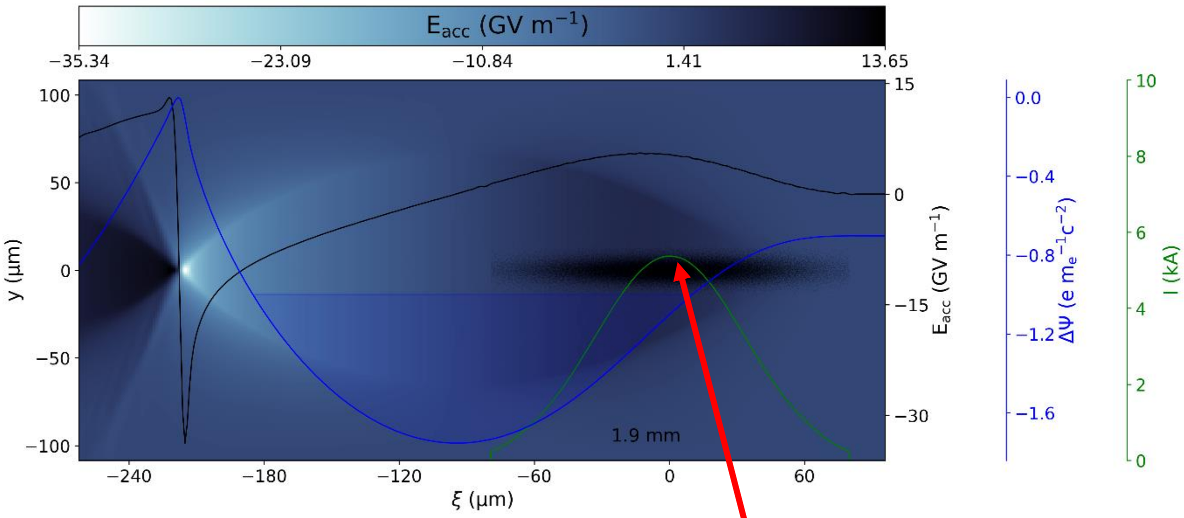
- Once absolute spatiotemporal injection precision is known:
- Injection precision is dependent on size of the plasma wave, and absolute jitter of incoming laser and delectron beam ⇒ work at lower plasma densities
- E.g. 500 µm plasma wavelength, with 30 fs r.m.s. timing jitter (LCLS aims at <10 fs)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



FACET-II driver beam baseline parameters

FACET-II driver beam parameters at the IP (BP or further downstream):

Charge = 1.5 nC
Beam length rms = 30 um
Beam length max = 160 um
Beam peak current ~ 5.0 kA
Beam density= 9.3e+23 m^(-3)
Qtilde= 8.3
Mean Energy= 10 GeV
Energy deviation rms = 500 MeV
Energy spread rms = 5 %
Beam width Y rms = 4.4 um
Beam width Z rms = 4.4 um
Beam normalized emittance Y rms = 50 mu rad
Beam normalized emittance Z rms = 50 mu rad
Beam beta*~ 7.5 mm?

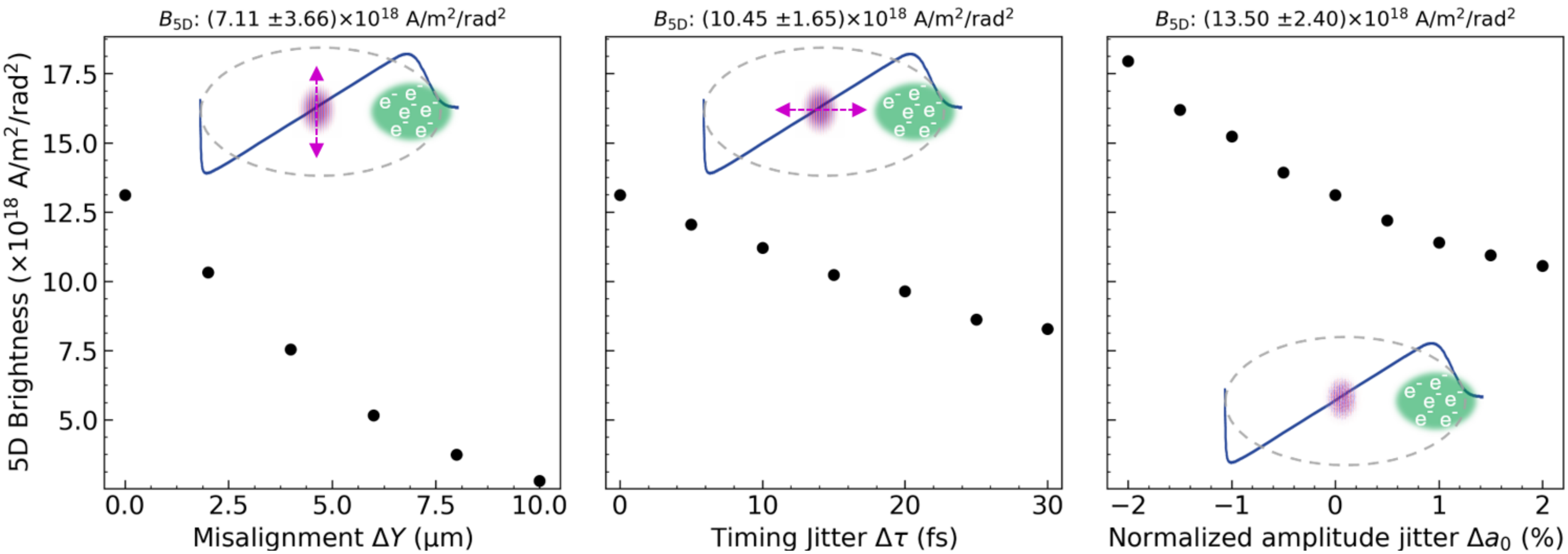


FACET-II driver

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: $$B_{5D} = \frac{2I_p}{\epsilon_{n,x}\,\epsilon_{n,y}}$$



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

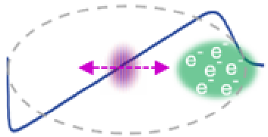
❑ Timing varied up to 30 fs in ~250 μm blowout ($\chi \approx 4\%$): **excellent output beam stability!**

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

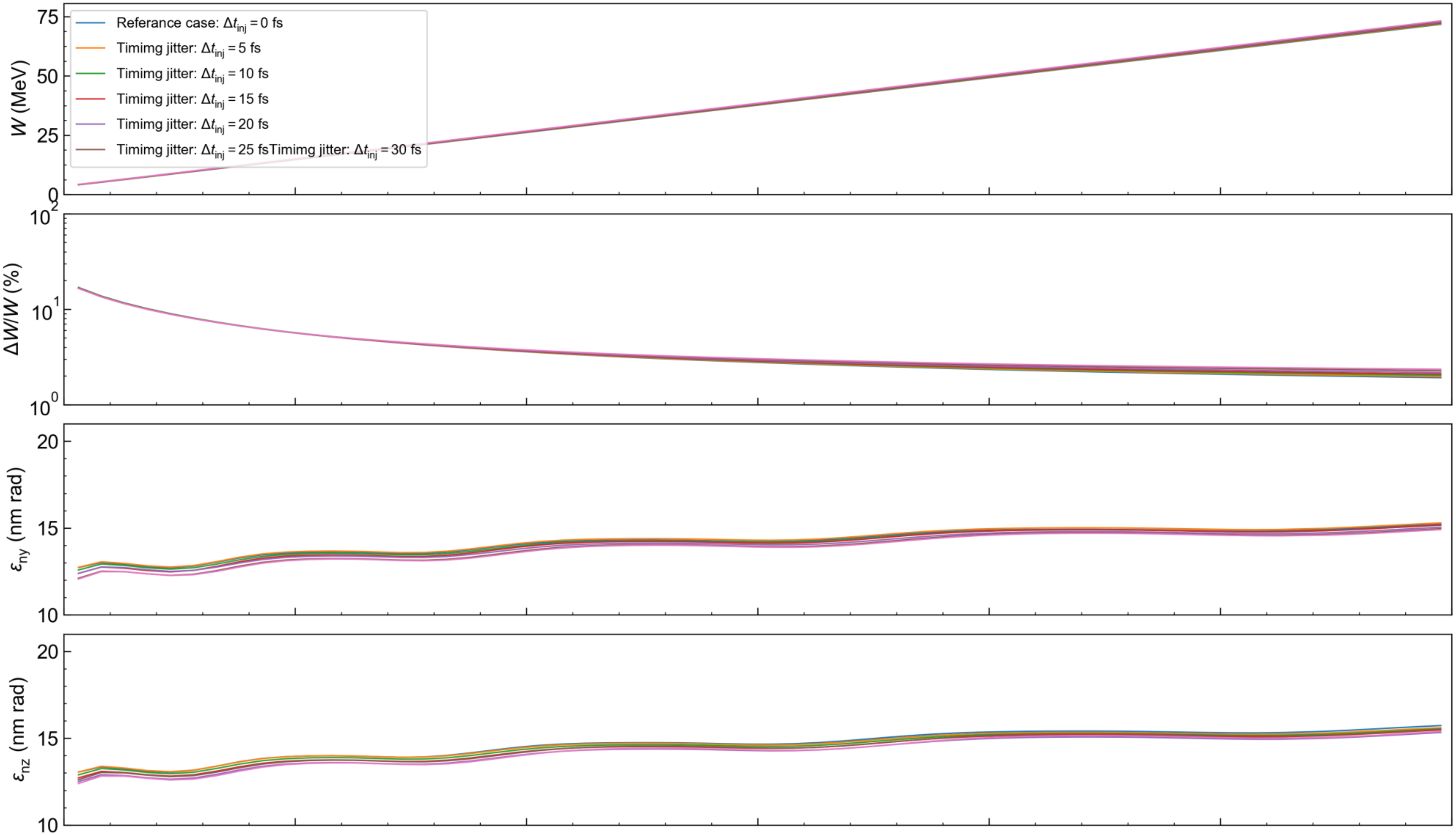


Charge Stability: (2.375 ±0.006) pC

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



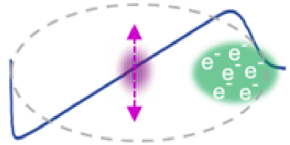
Transverse plasma photocathode release laser offset jitter study in 250 μm length blowout

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

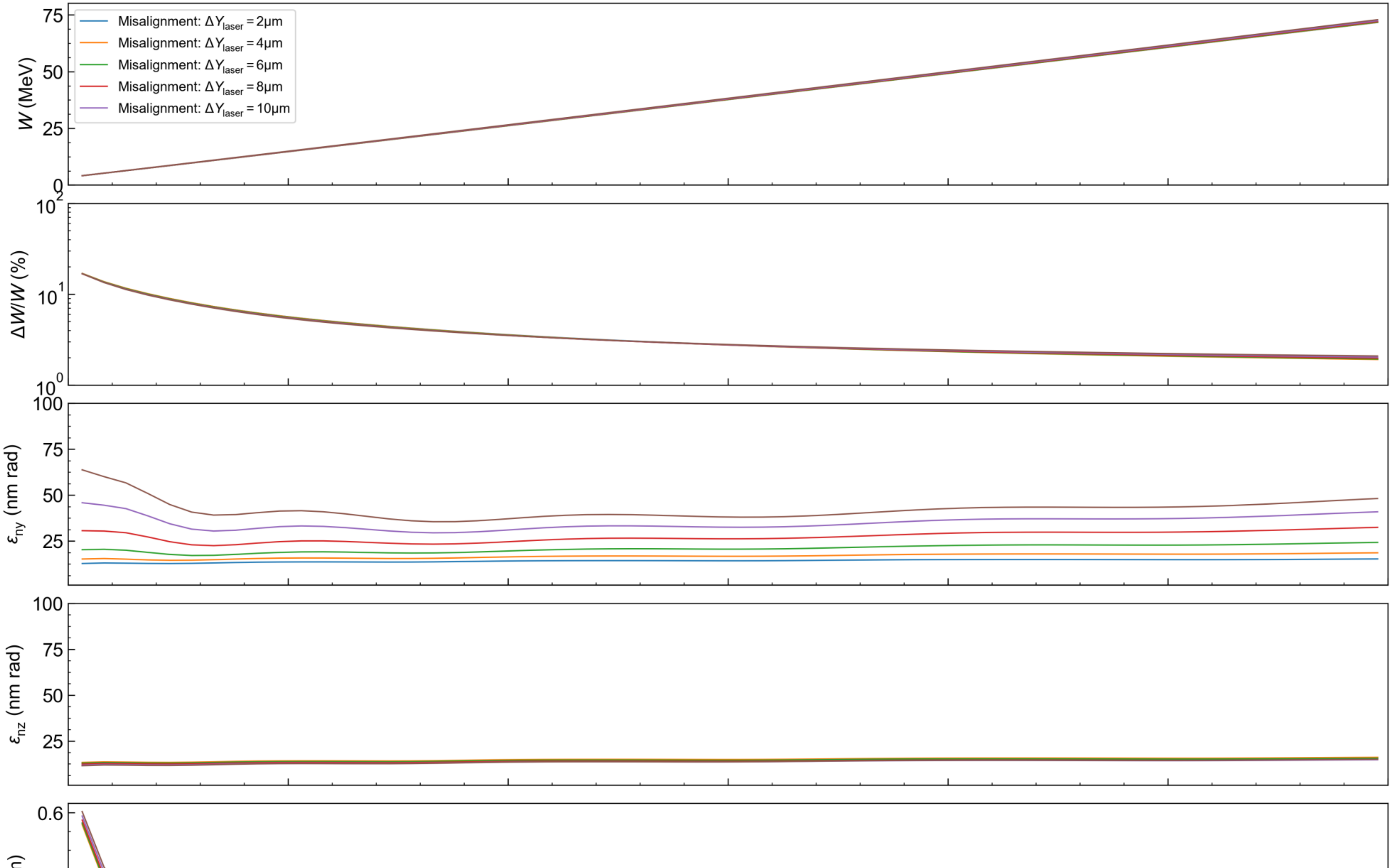


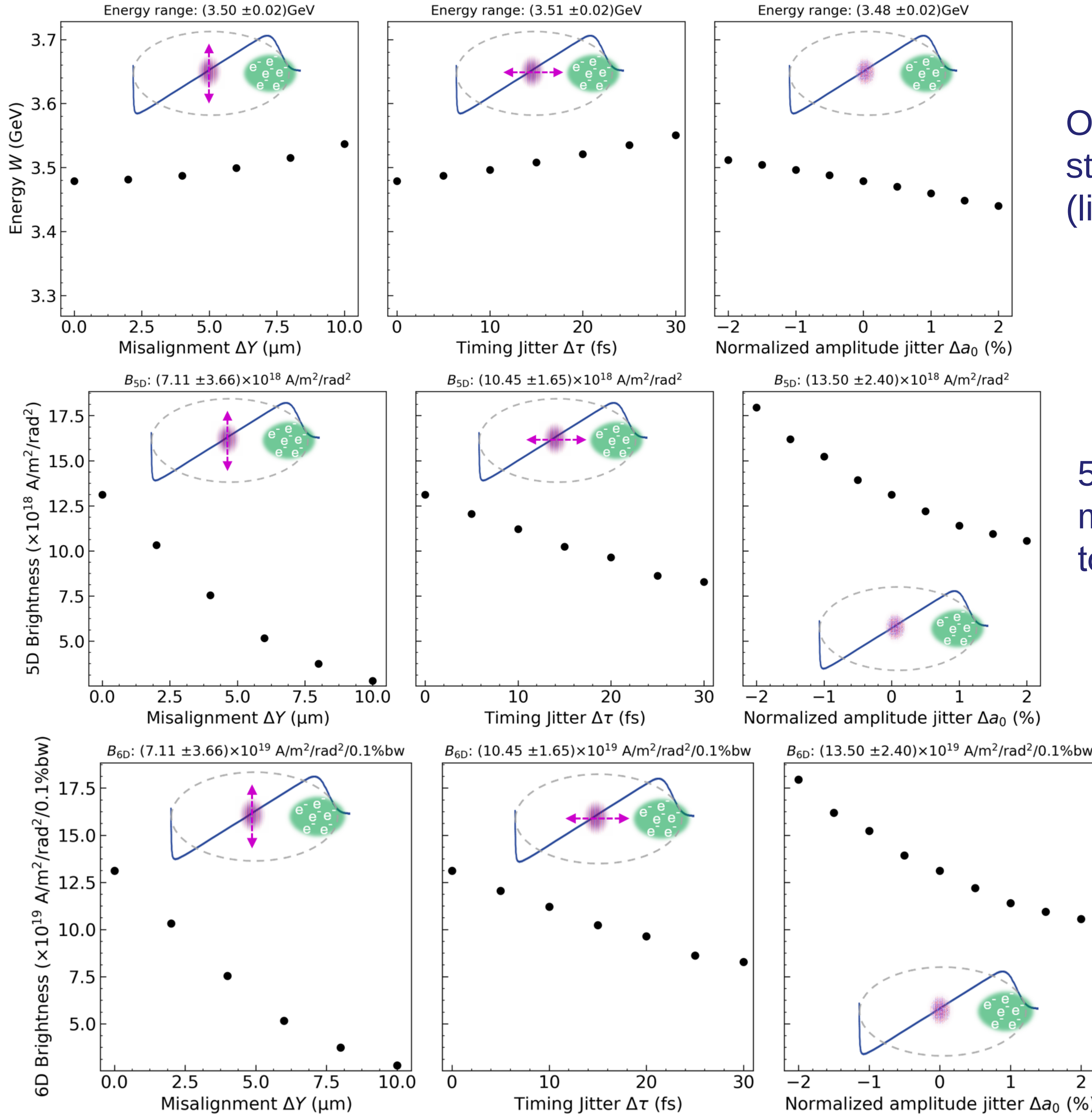
Charge Stability: (2.371 ±0.005) pC

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



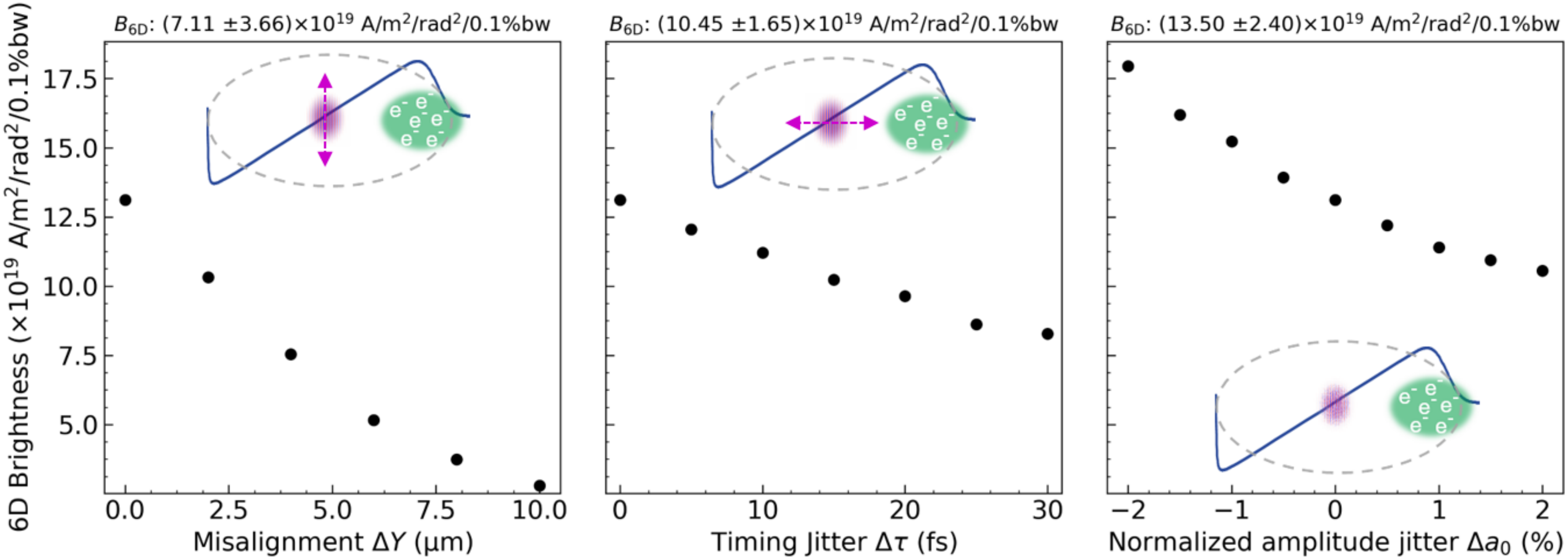


Output beam energy stability better than 1% (linac level)

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)

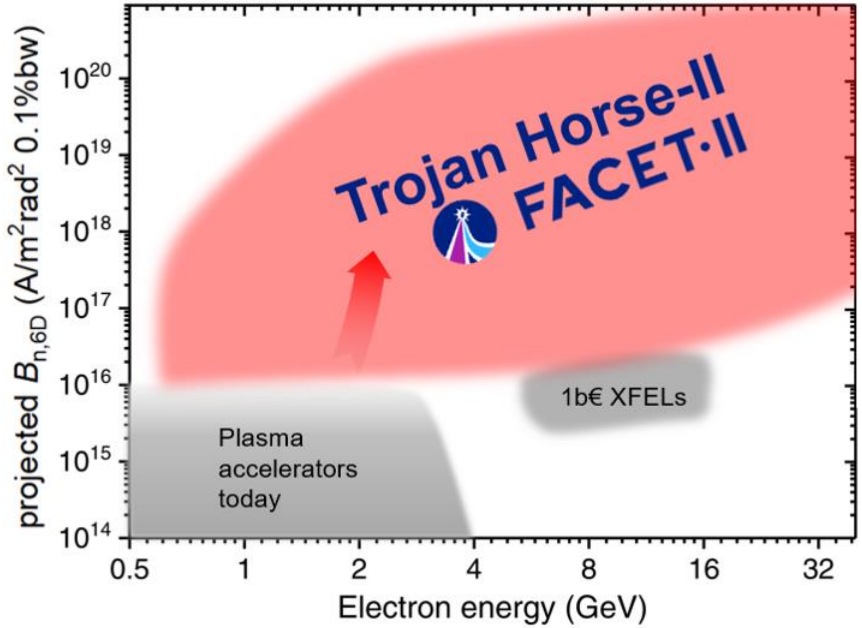
What does this mean for obtainable beam quality and stability (6D)?



Resulting 6D brightness:

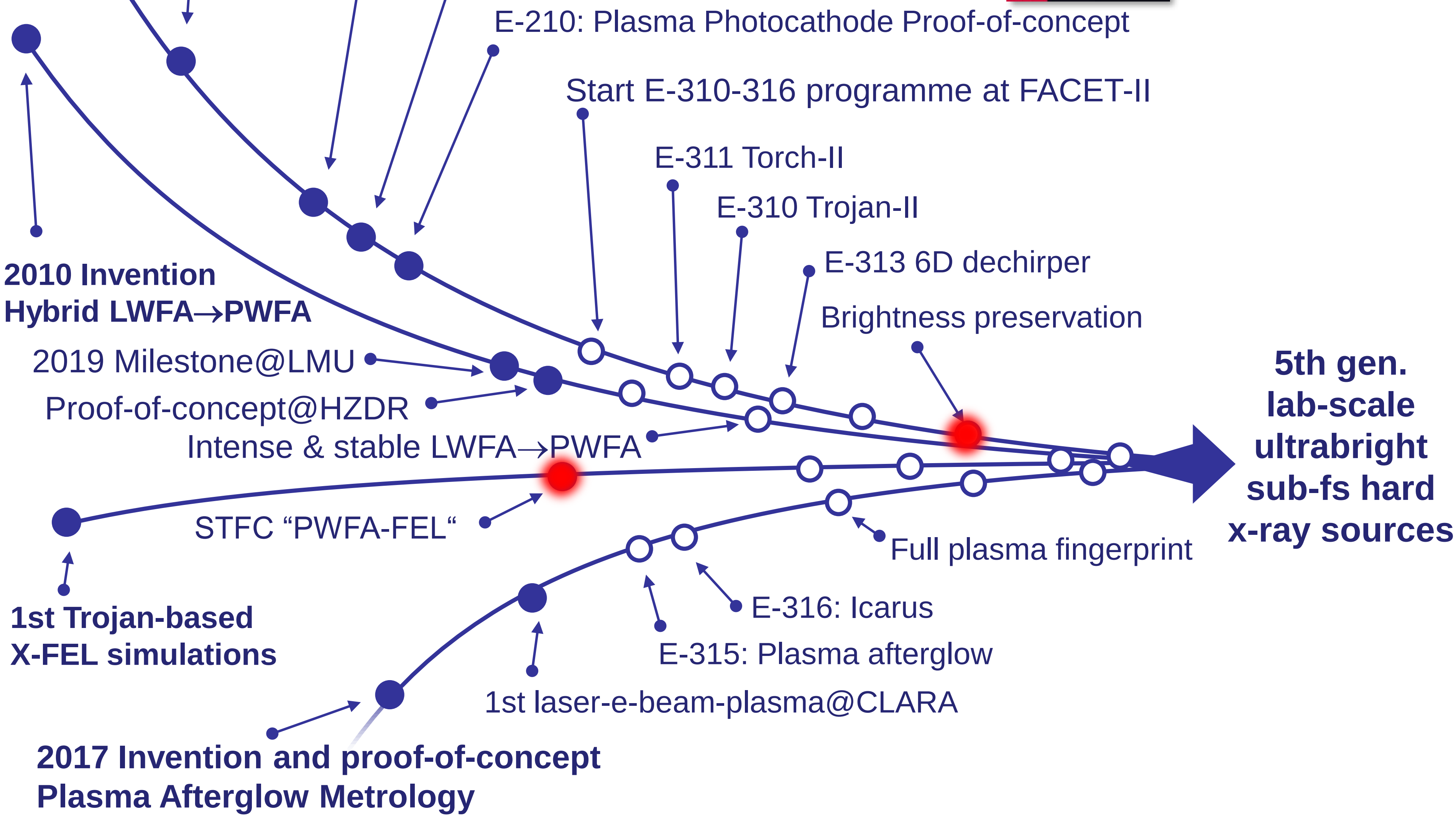
$$\mathrm{B}_{6\mathrm{D}} = \frac{I_{\mathrm{p}}}{\epsilon_{\mathrm{n,x}}\,\epsilon_{\mathrm{n,y}} 0.1\%\mathrm{BW}}$$

Note: LCLS 6D brightness is at 1e16 level



Roadmap


PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES
Directions in particle beam-driven plasma wakefield acceleration
THE ROYAL SOCIETY PUBLISHING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Invention Plasma Torch Density Downramp Injection
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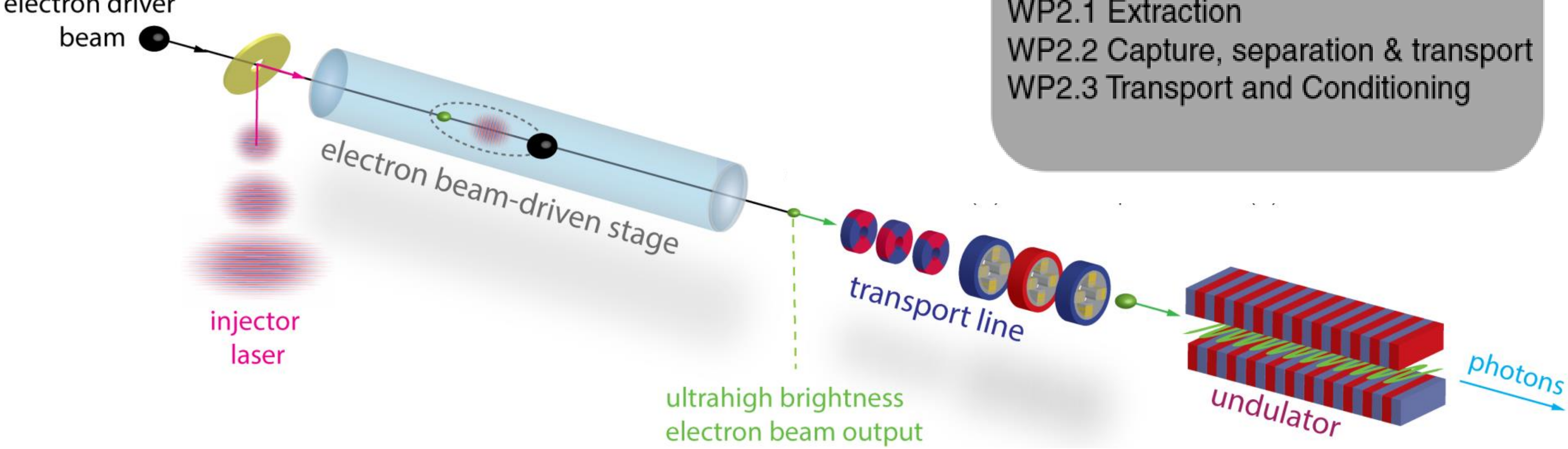
E-210: 1st density downramp injection
E-210: Plasma Photocathode Proof-of-concept
Start E-310-316 programme at FACET-II
E-311 Torch-II
E-310 Trojan-II
E-313 6D dechirper
Brightness preservation
2010 Invention
Hybrid LWFA→PWFA
2019 Milestone@LMU
Proof-of-concept@HZDR
Intense & stable LWFA→PWFA
STFC "PWFA-FEL"
Full plasma fingerprint
5th gen.
lab-scale
ultrabright
sub-fs hard
x-ray sources
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



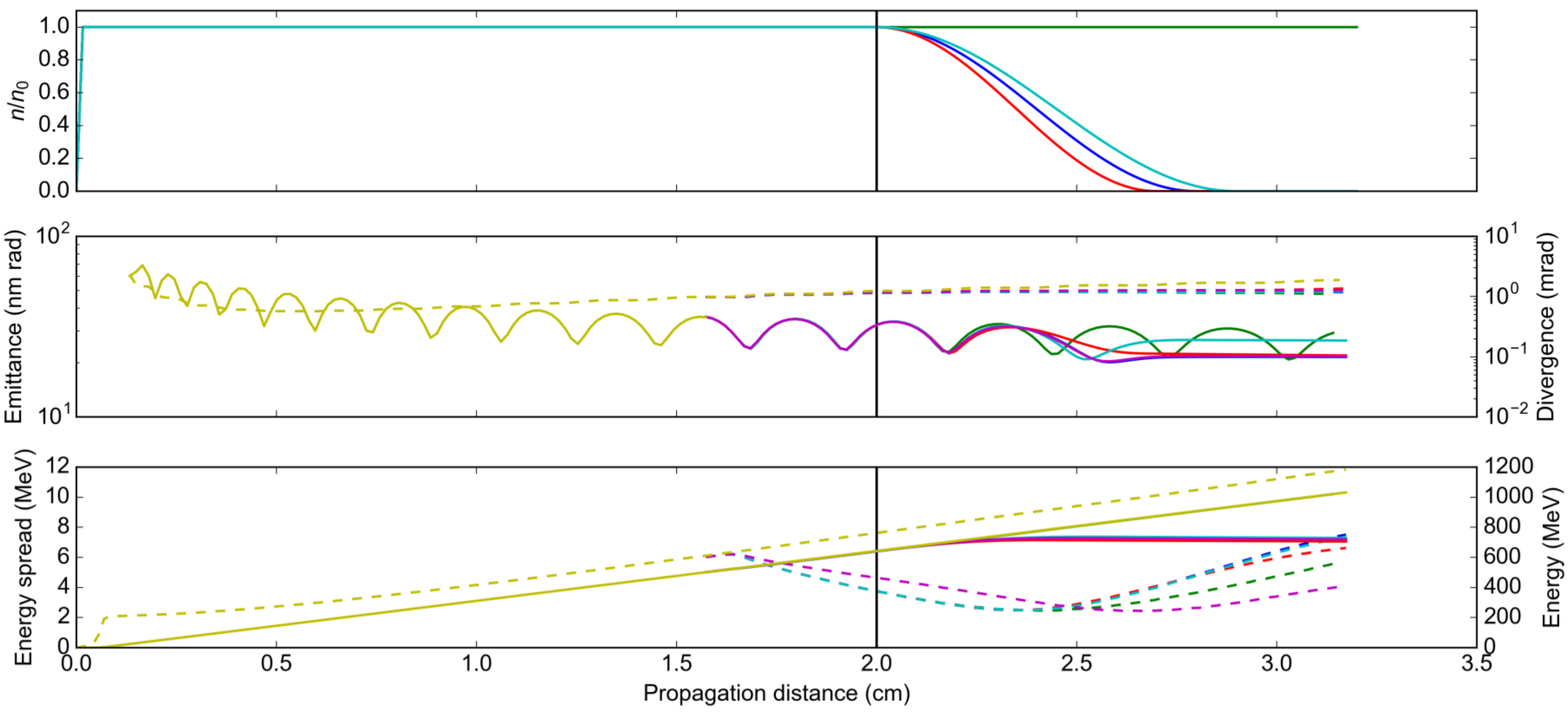
WP2: Beam extraction, dynamics and transport (Williams, Angal-Kalinin, Clarke, Hidding *et al.*)
WP2.1 Extraction
WP2.2 Capture, separation & transport
WP2.3 Transport and Conditioning

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

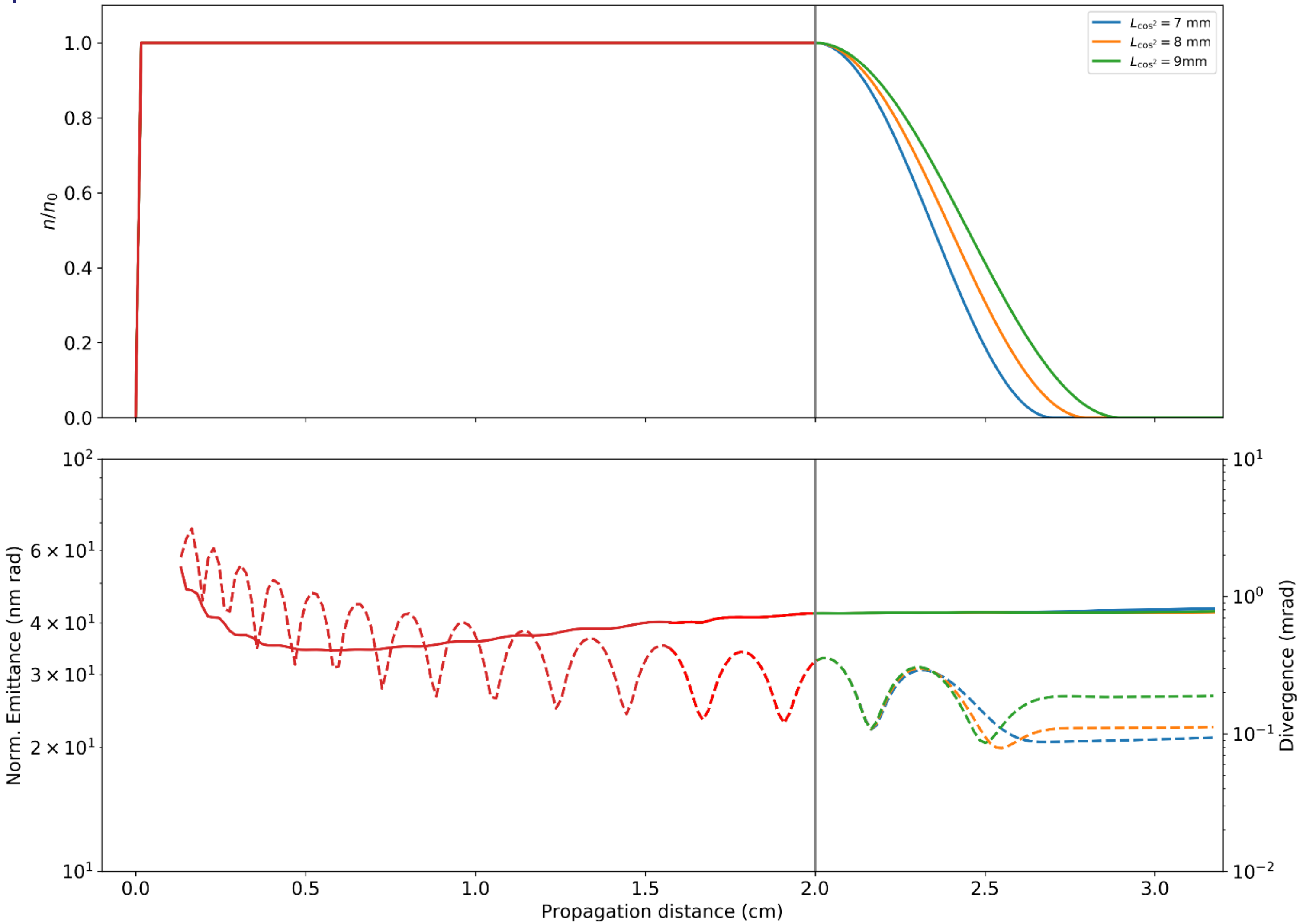
WP 2: Preliminary witness beam extraction

- 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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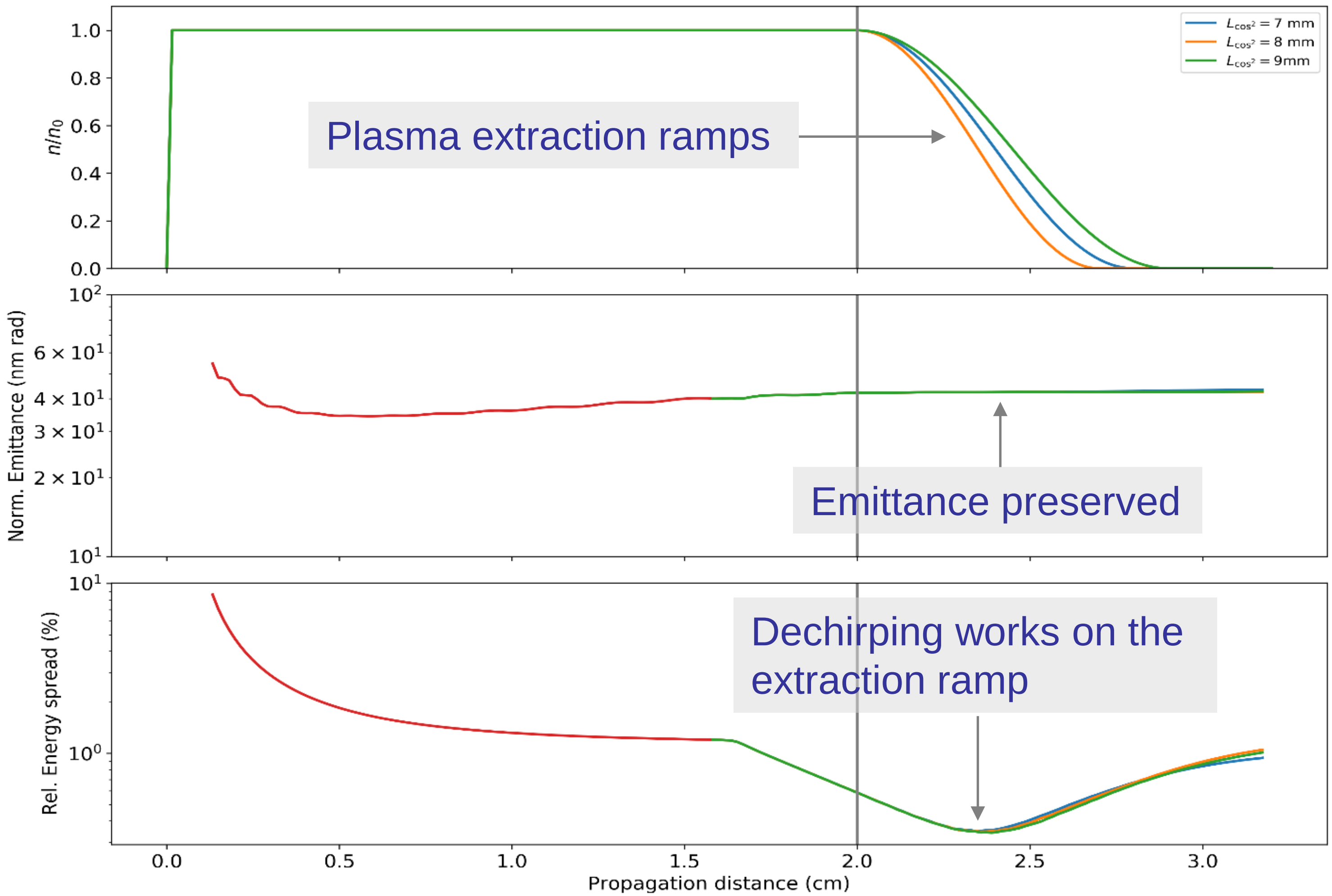
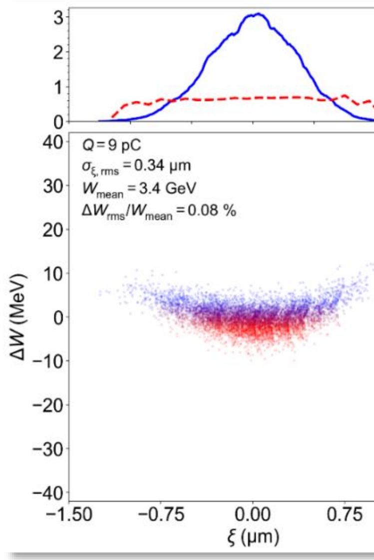
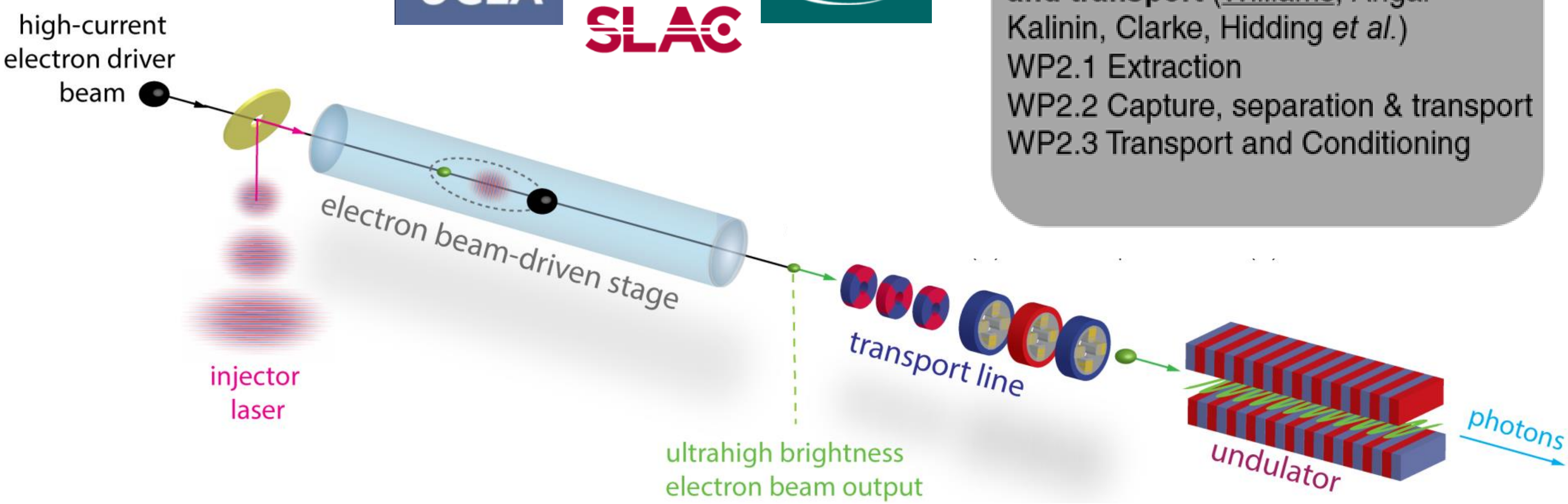




- ❑ Tailored plasma density at the exit
- ❑ “escort”-bunch dechirping works with extraction ramp
- ❑ Emittance is preserved at the exit

PWFA-FEL

- STFC funded 2019-2023



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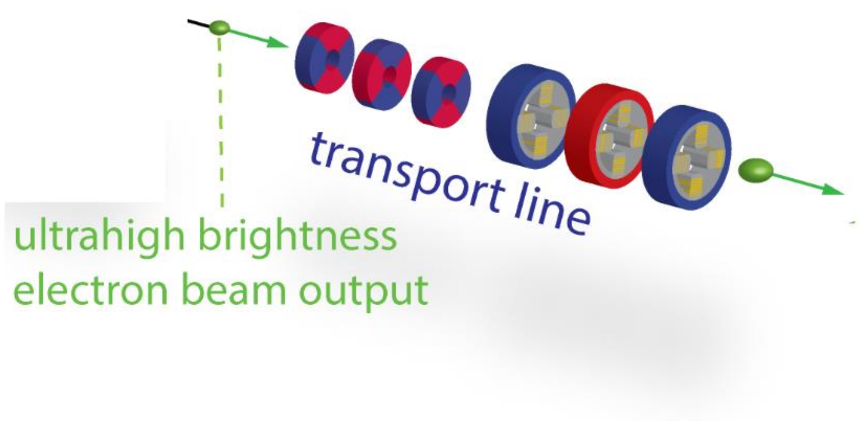
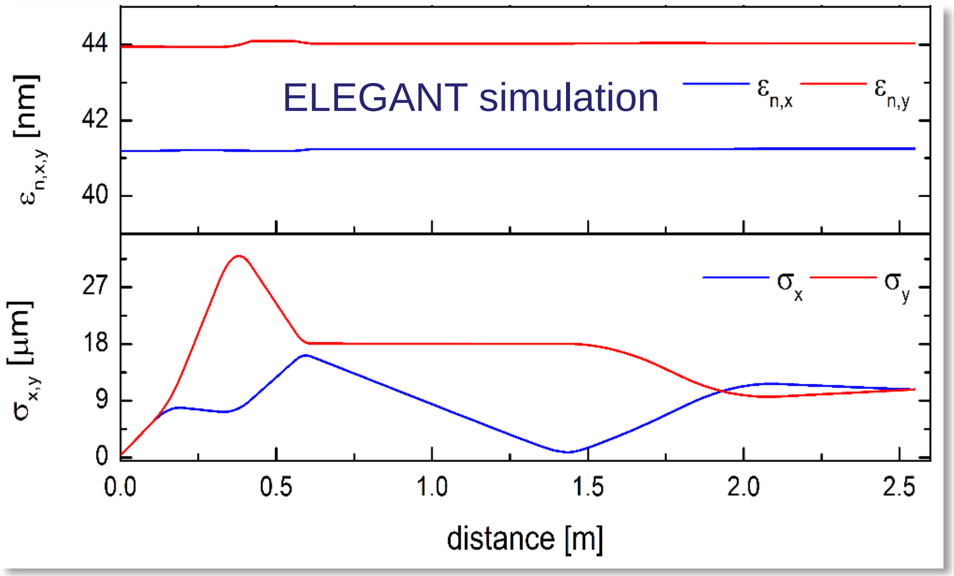
WP 2: Preliminary transport line design

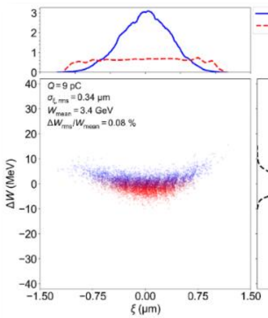
Double triple beam transport line





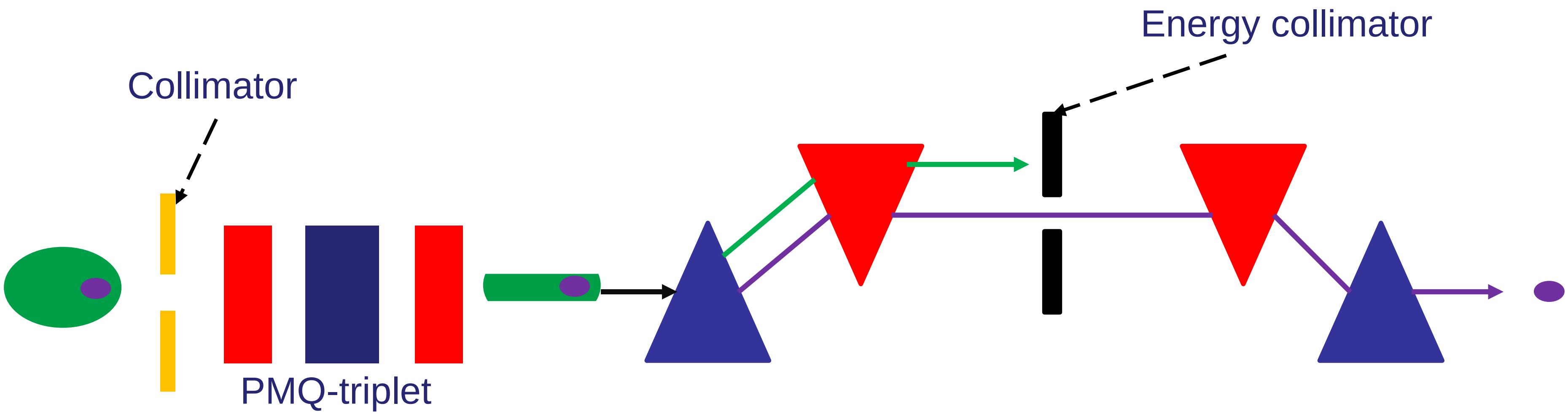
- ❑ First triplet: permanent magnet quadrupoles (PMQs) 700 T/m
- ❑ Plasma lenses?
- ❑ 10 cm distance until 1st PMQ
- ❑ 6D-bright witness. 9 pC, duration 0.34 µm
- ❑ Second triplet: electromagnet quadrupoles
- ❑ Elegant: CSR not problem.

- ❑ 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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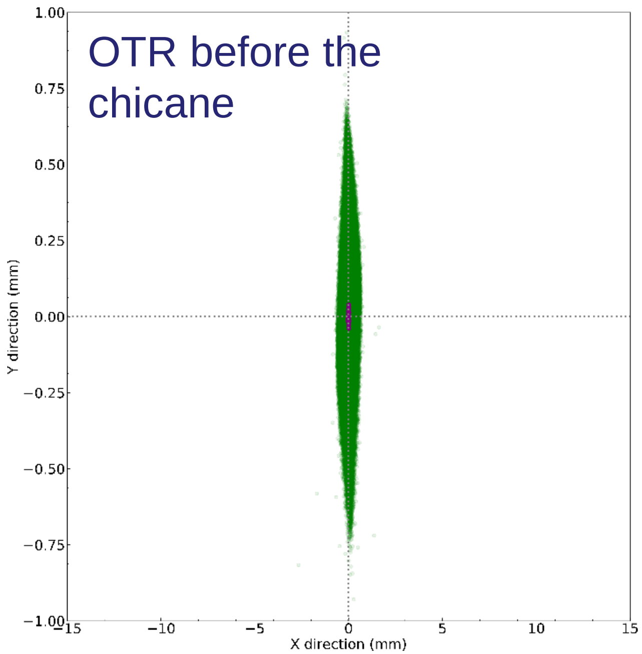
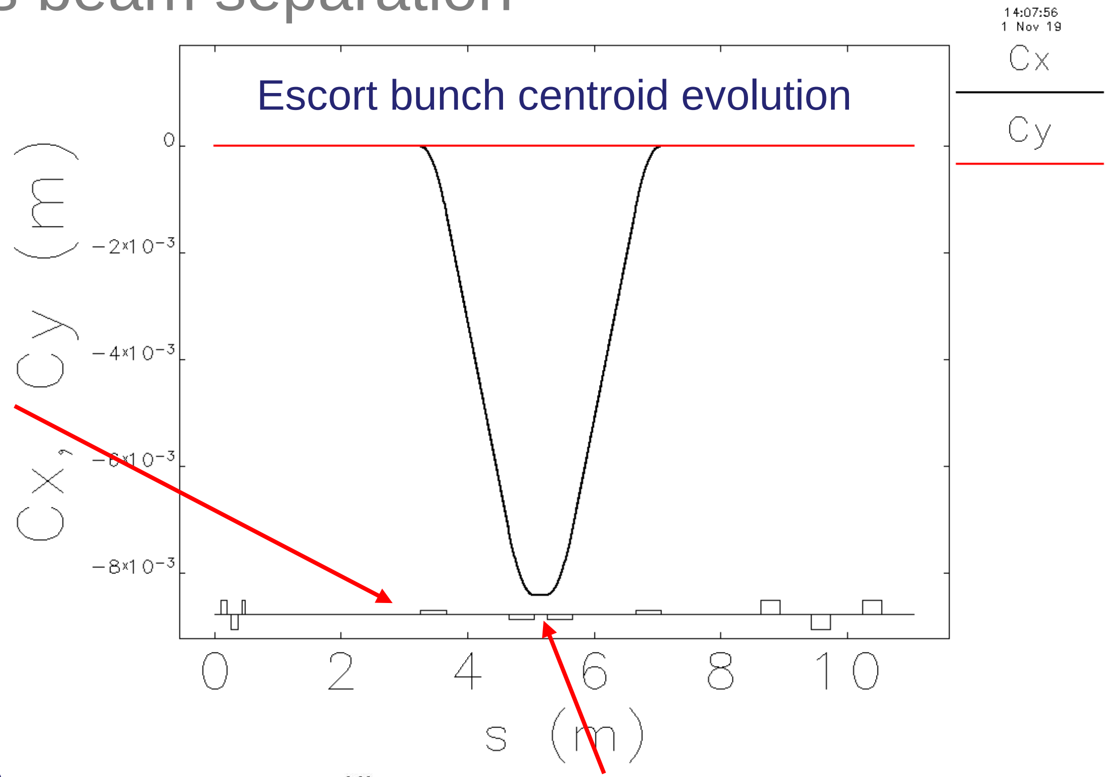
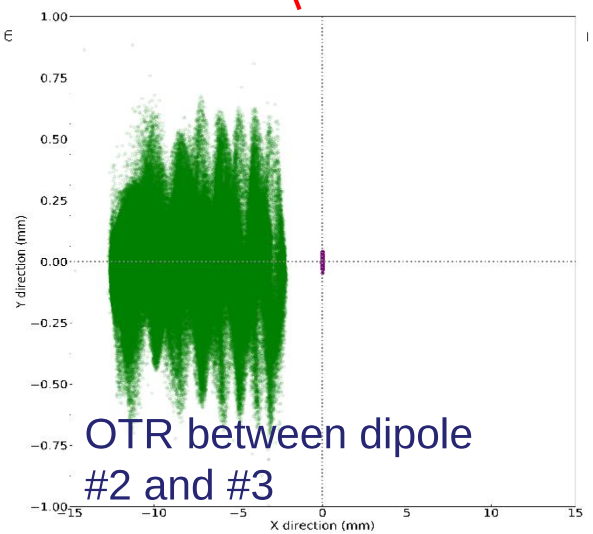


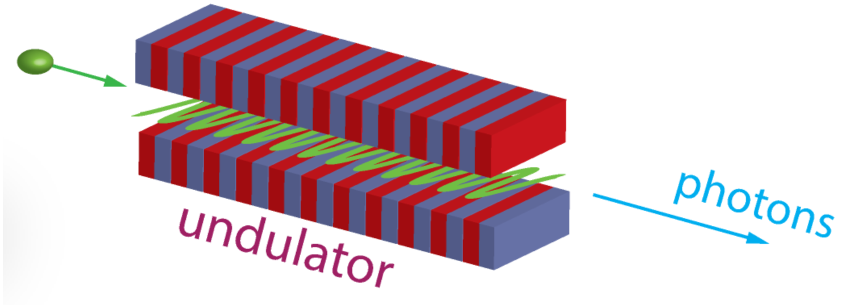




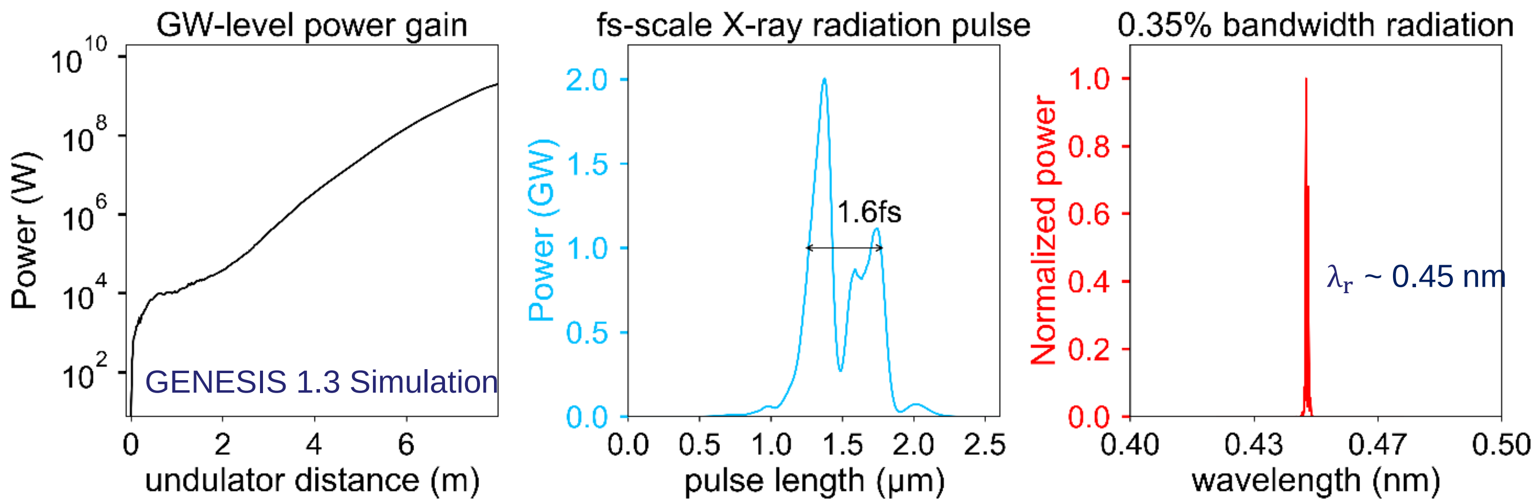
- Green: escort; purple witness
- Chicane between PMQ and EMQ triplet for escort-witness beam separation
- 1D CSR effects included
- Chicane acts as a by-pass line for the 3.4 GeV witness beam (0.08% energy spread, no chromatic issues)→ bunch duration, emittance and charge stays constant after chicane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

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

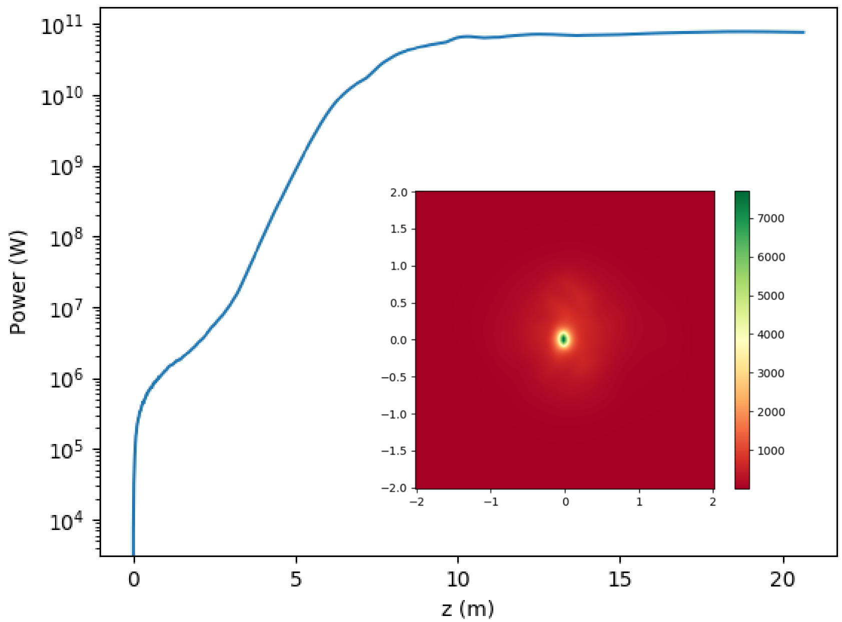
- Radiation wavelength: λ_r ~ 0.45 nm
- Radiation bandwidth: ~0.1-0.35%
- Saturation power: ~ GW-level
- Radiation pulse duration: ~fs → Potential for sub-fs pulses
- Saturation length: ~ 8-10 m

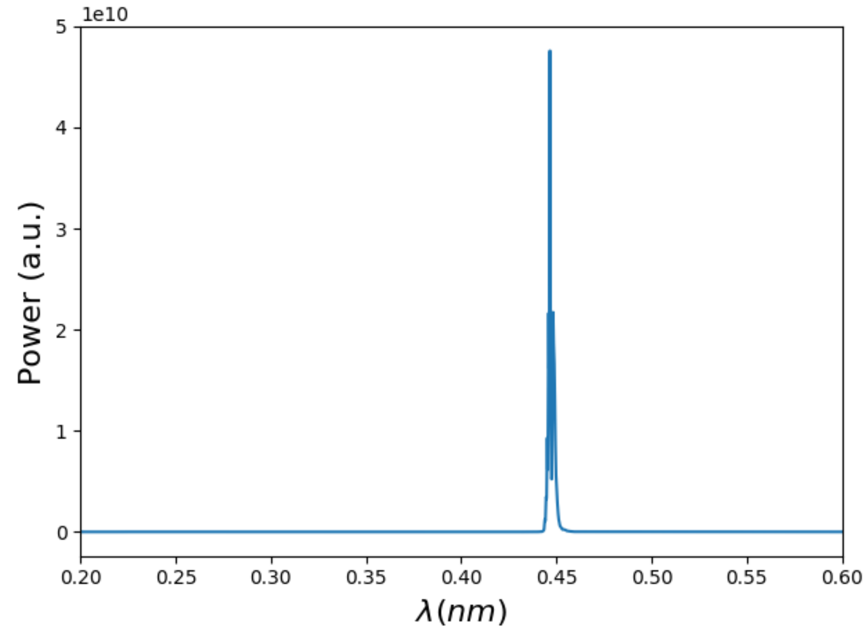
Preliminary X-ray free-electron laser results

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

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

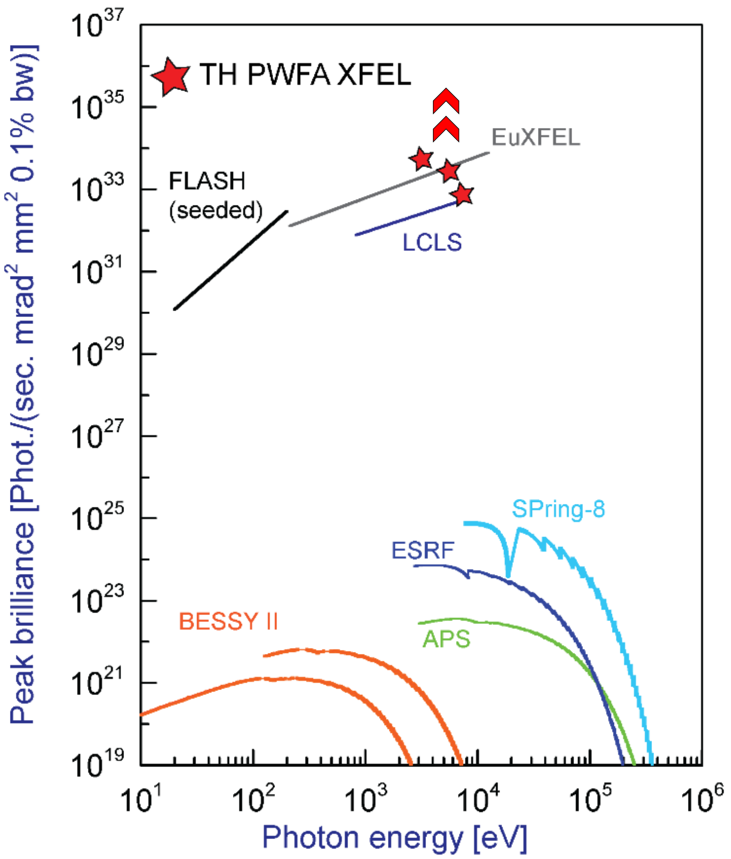
- ‘’Unaveraged’’ FEL code
- Not slowly varying envelope approximation (SVEA) and wiggler period averaging approximations.
- CSR is taken into account
- **Puffin results show excellent agreement with genesis simulation**
- **Puffin results indicates sub-fs hard X-ray pulses→ single spike XFEL ?**





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 λ_r ~ 0.45 nm
- X-ray pulse of fs/sub-fs duration with GW-level peak power



Vision and roadmap


ISSN 1364-503X I Volume 377 I Issue 2151 I 12 August 2019

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

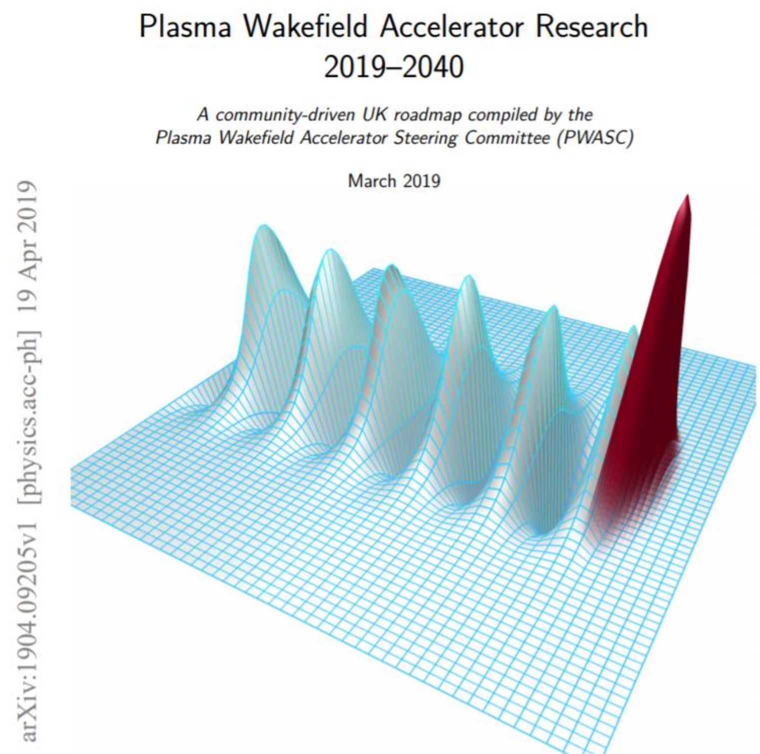
MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

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

THE ROYAL SOCIETY PUBLISHING

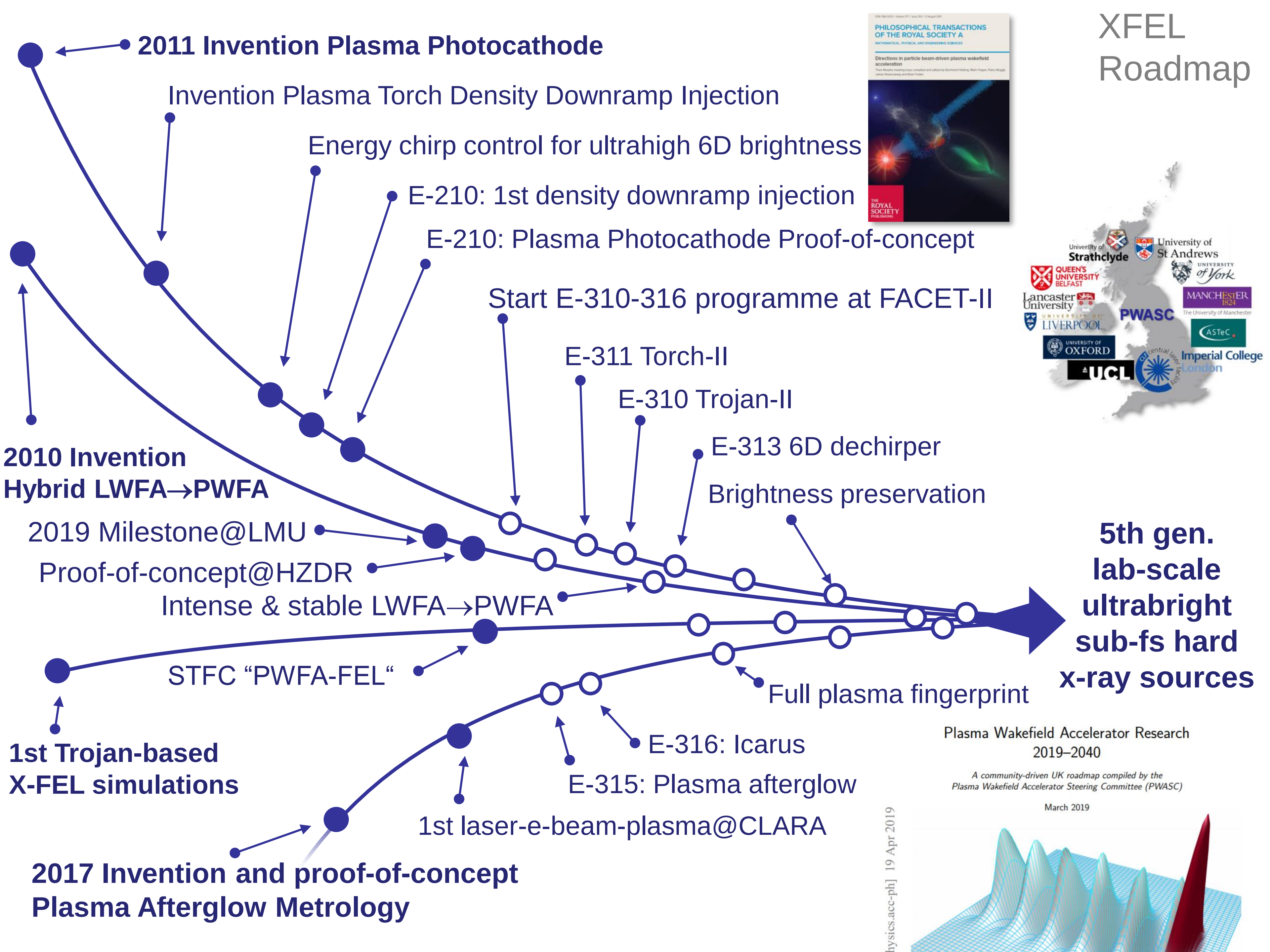
Fully synergistic with UK Plasma Wakefield Accelerator Research Roadmap 2019-2040 and with US roadmap


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
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Queen's University Belfast
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Lancaster University
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PWASC
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University of Oxford
Imperial College London
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central laser facility
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WP1:
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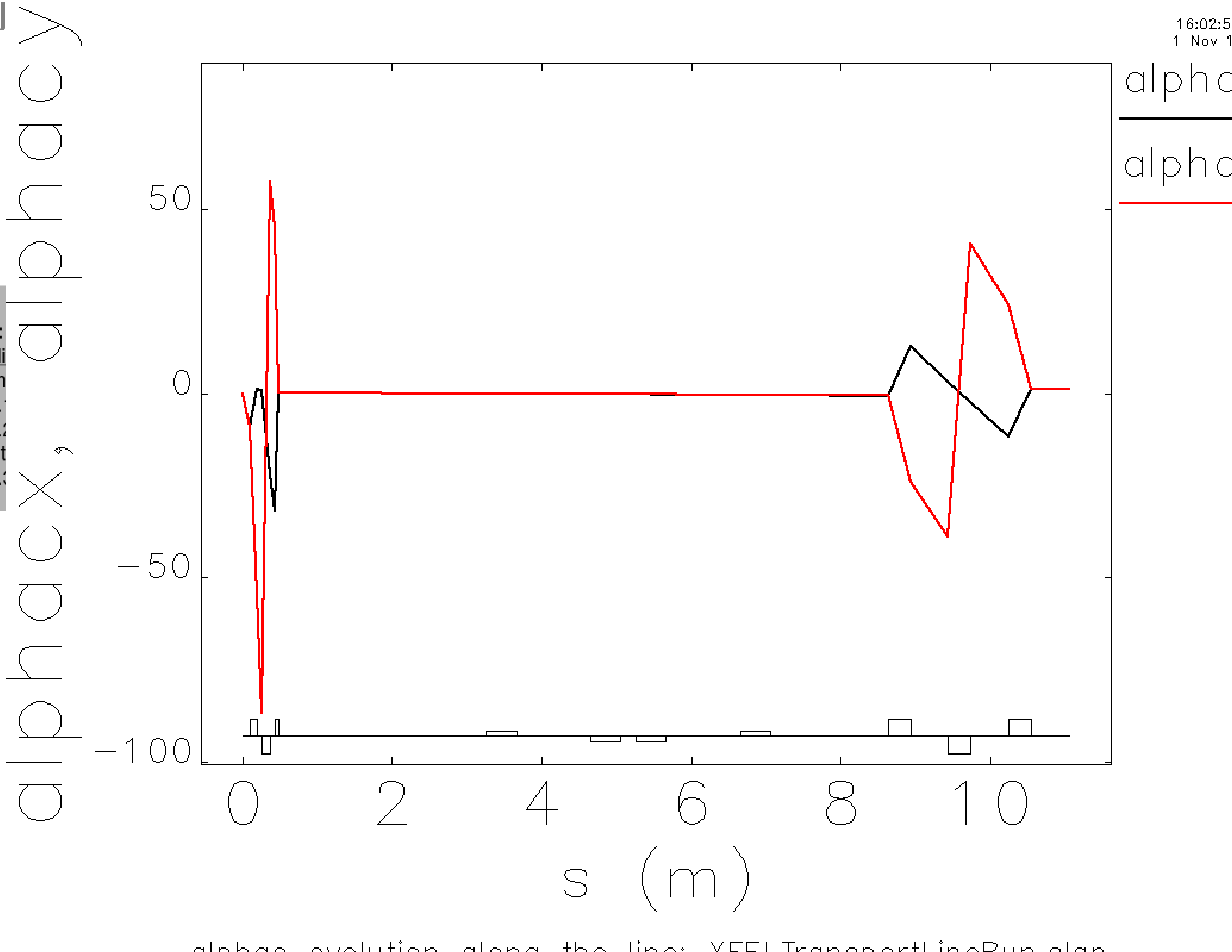
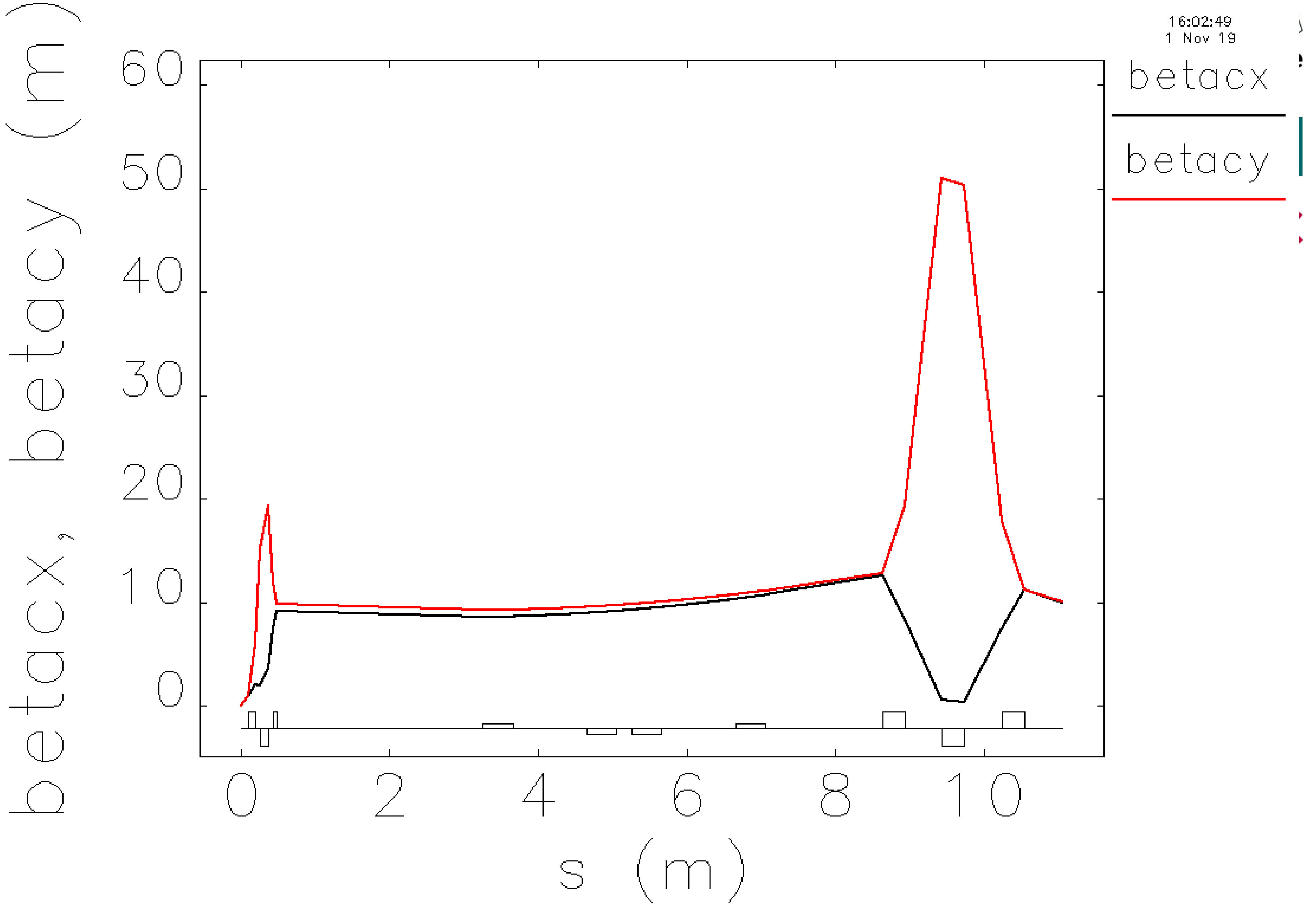
Yakim
WP1.1
WP1.2
Bright
WP1.3





betac evolution along the line: XFELTransportLineRun.slan

WP 14 Beam Quality Transformer

Trojan Horse plasma photocathode