EuPRAXIA

EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

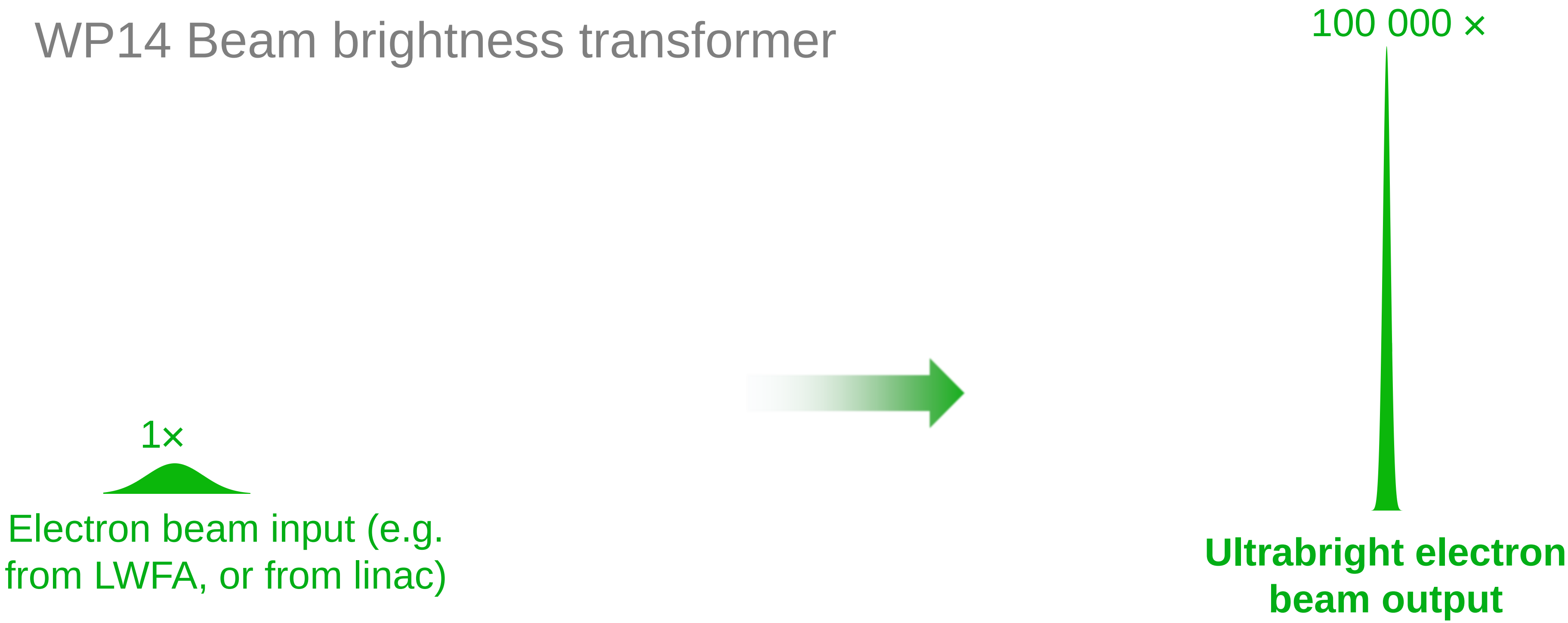
WP 14: Hybrid Laser-Electron-Beam Driven Acceleration Frascati 2018-11-20

Bernhard Hidding / Strathclyde
Alberto de la Ossa / DESY

+ SLAC + HZDR + LMU + HIJ + LOA + Uni Düsseldorf ...

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

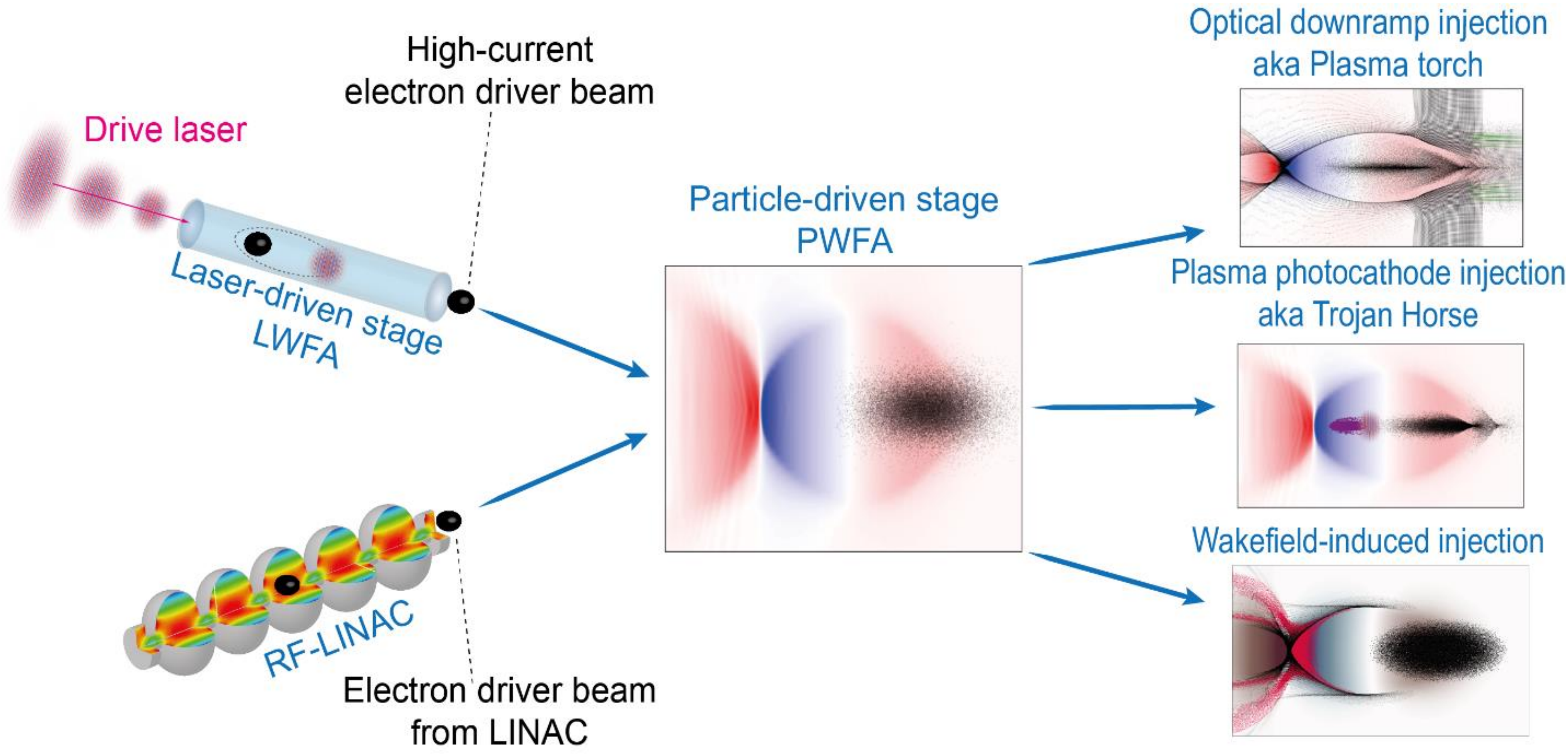
WP14 Beam brightness transformer



- ❑ Exceeds limits of LWFA or linacs, improves “intensity” of beams by factor 100 000:

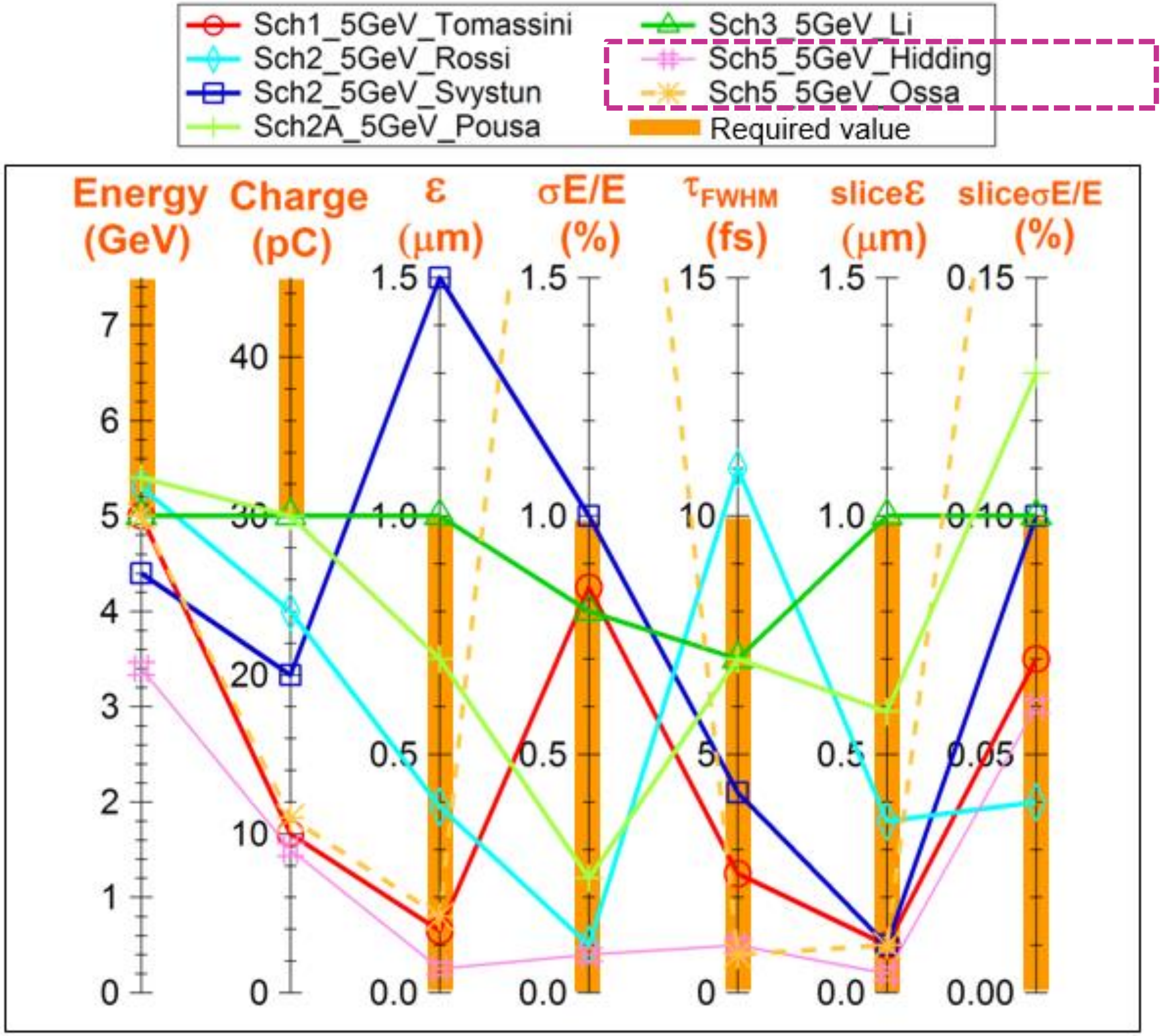
The CPA of electron beams!

Widely tunable beam brightness transformer, applicable to both LWFA and linac-driven electron beam output



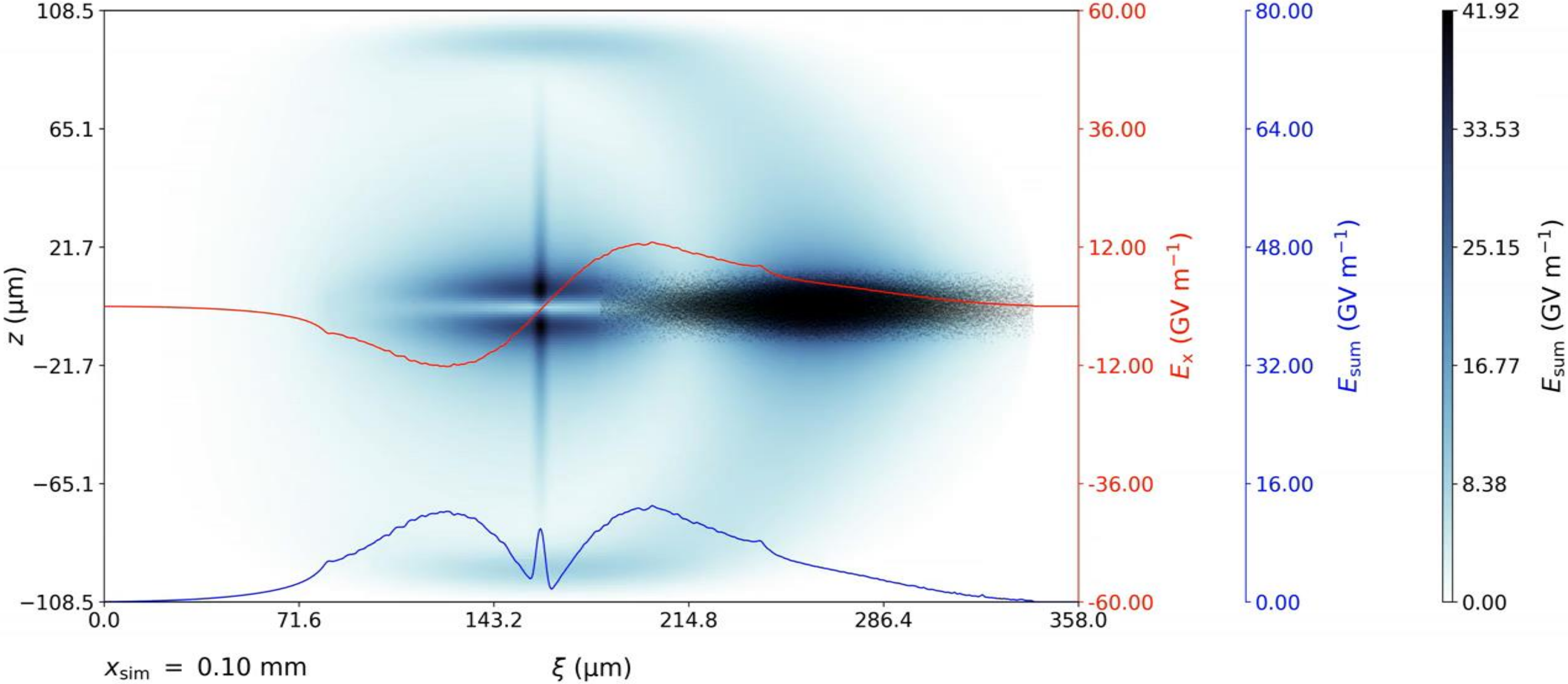
- ❑ Use lasers for ionization and to produce high current electron bunches
- ❑ Harness dephasing-free, long acceleration distances of PWFA
- ❑ Realize dark-current free, ultrahigh quality electron bunches by unique injection methods

WP14 schemes produce best beam quality:



… and are extremely tunable, as the output beam is produced in the last stage, no further staging required! This “Energy and Quality Afterburner” is applicable almost everywhere.

Tunability via 1 mJ-class plasma photocathode laser pulse

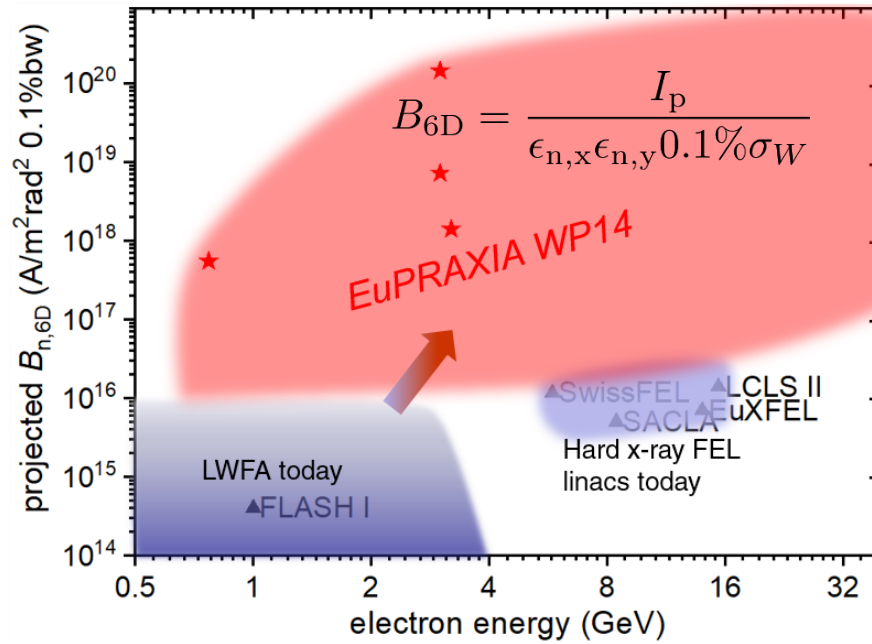


- ❑ E.g. tune charge to ~100 pC levels and beyond.. (trade-off with emittance)

Approach can be game changer for

EuPRAXIA
NOVEL FUNDAMENTAL RESEARCH
COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

- Exceeds state-of-the-art by 2-4 **orders of magnitude**, ~ 10 nmrad emittance, sub-0.01% energy spreads, 5 GeV+



EuPRAXIA Case 5 parameter table

Quantity	Range of exploration	
	Lower limit	Upper limit
Hybrid witness beam at exit of plasma 3		
Energy	1-5 GeV	
Charge	1 pC	100 pC
Bunch length	0.5 fs	10 fs
Peak current per bunch	1 - 30 kA	
Total energy spread (RMS)	0.01 %	~~3%~~
Transverse normalized emittance	10 nm rad	~~1 mm mrad~~
Transverse norm. slice emittance	tbd	tbd
Norm. 5D Brightness $B_{5D} = I / (\varepsilon_{N,x}\varepsilon_{N,y})$	10^{16} A/ m^2 /rad^2	10^{20} A/ m^2 /rad^2
Norm. 6D Brightness B_{6D} = B5D/0.1% σ_E/E	10^{16} A/ m^2 /rad^2	10^{20} A/ m^2 /rad^2
Alpha function	0	
Beta function	0.18 mm - 2 mm	
Transverse beam size (RMS)	0.02 µm	0.37 µm
Transverse divergence (RMS)	0.1 mrad	0.4 mrad
Jitter, beam to global reference (RMS)	1-30 fs	

High performance applications

- E.g., realize hard x-ray free-electron lasers at ~3 GeV with ultrahigh gain

$\langle \sigma_\gamma / \gamma \rangle \ll \rho$ ✔

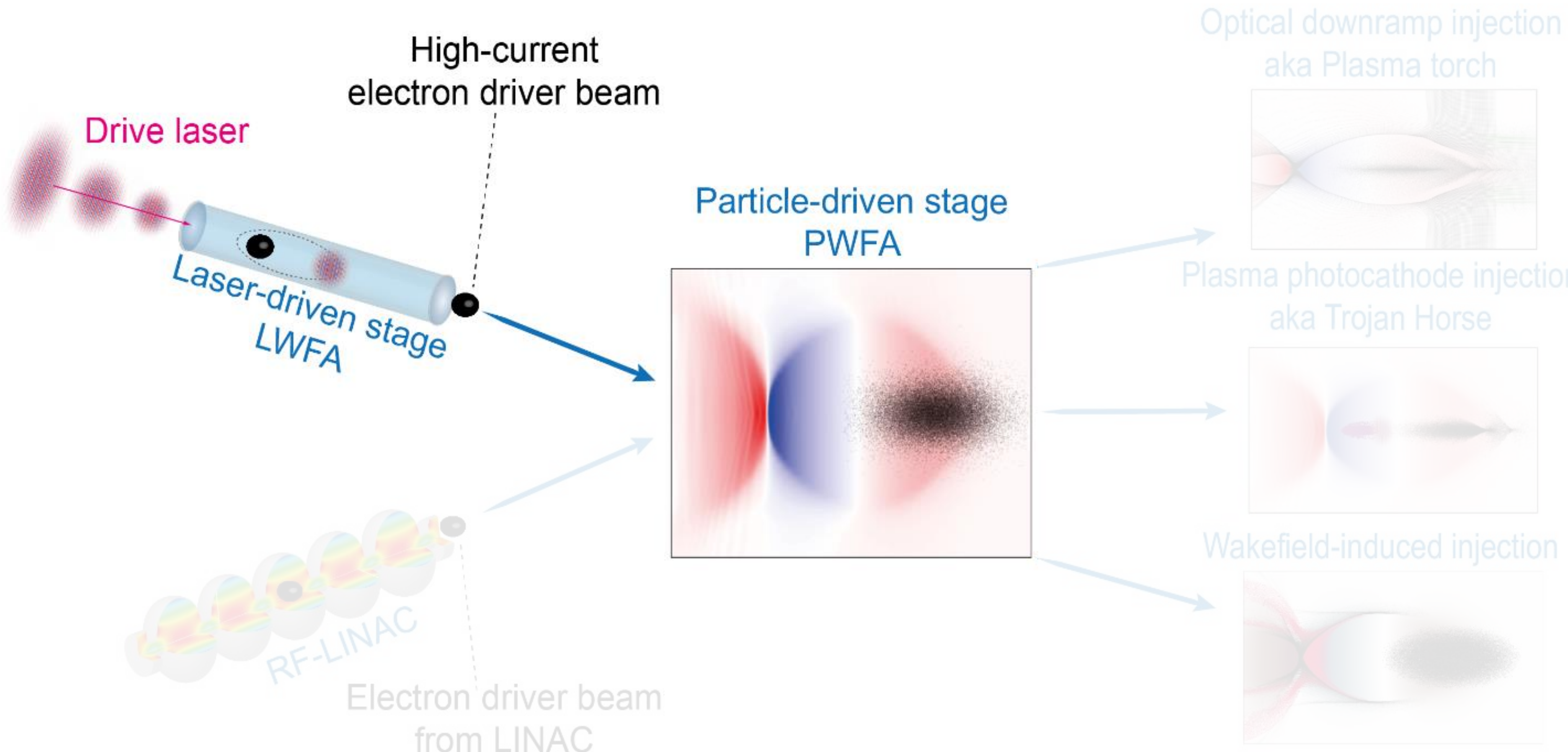
$\epsilon_n < \lambda_r \langle \gamma \rangle / 4\pi$ ✔

Pellegrini criterion

$$L_{g,1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}} \propto B_e^{-1/3}$$ ✔

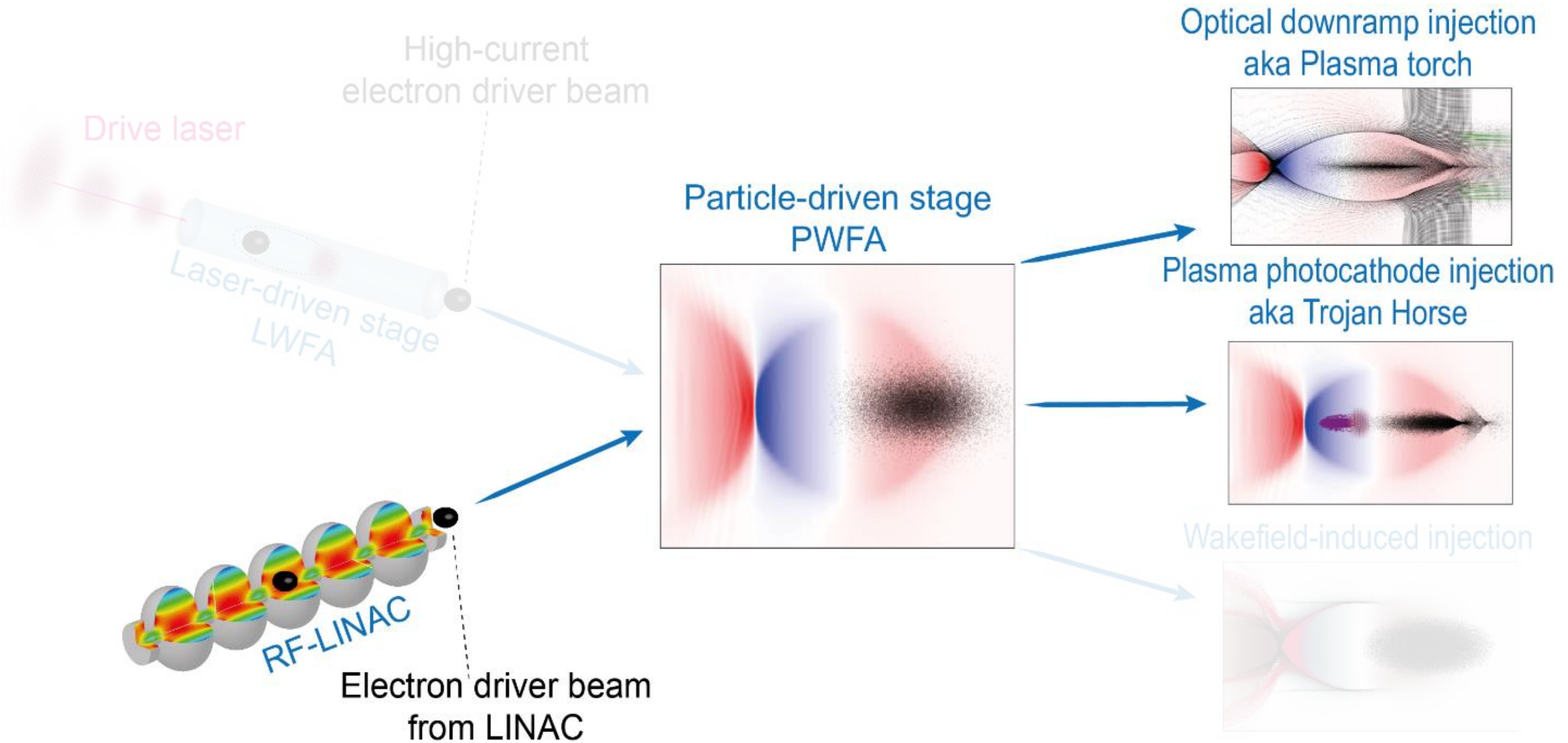
Gain length

LWFA → PWFA experimentally viable:



- ❑ Electron bunches from LWFA have high current, significant energy spread: ideal drivers for PWFA (Hidding et al., PRL 2010; Strathclyde & RadiaBeam "Beam Brightness Transformer for LWFA" SBIR Programme, DOE 2013-2017)
- ❑ Successful experiments e.g. at Jena, LMU, HZDR (to be published), see plenary by Alberto today

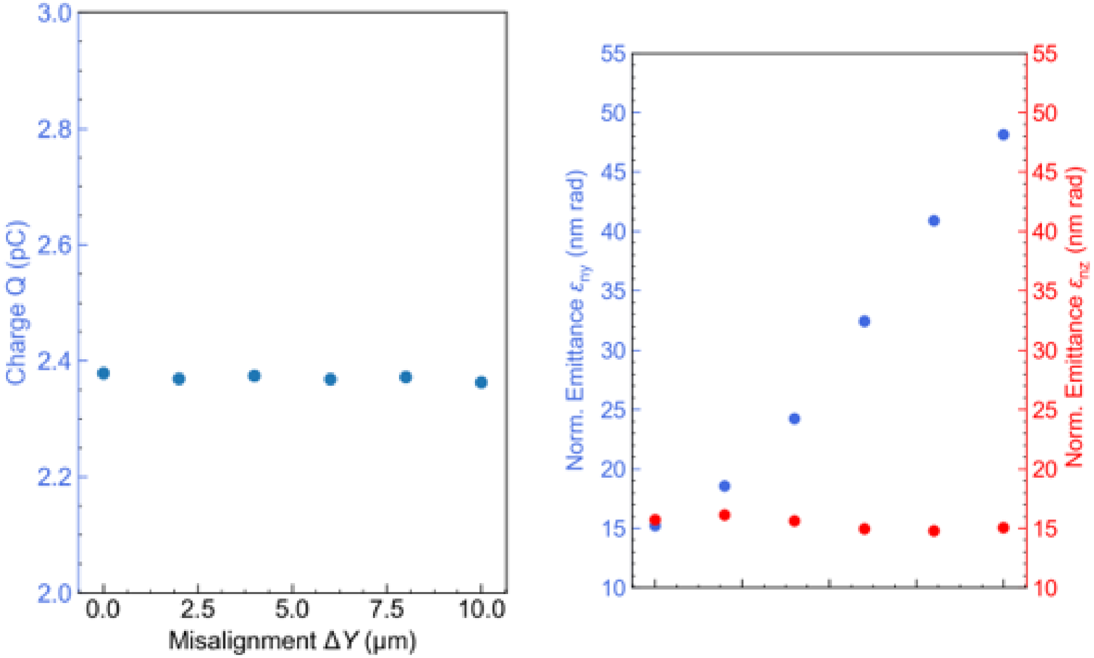
LINAC→PWFA experimentally viable



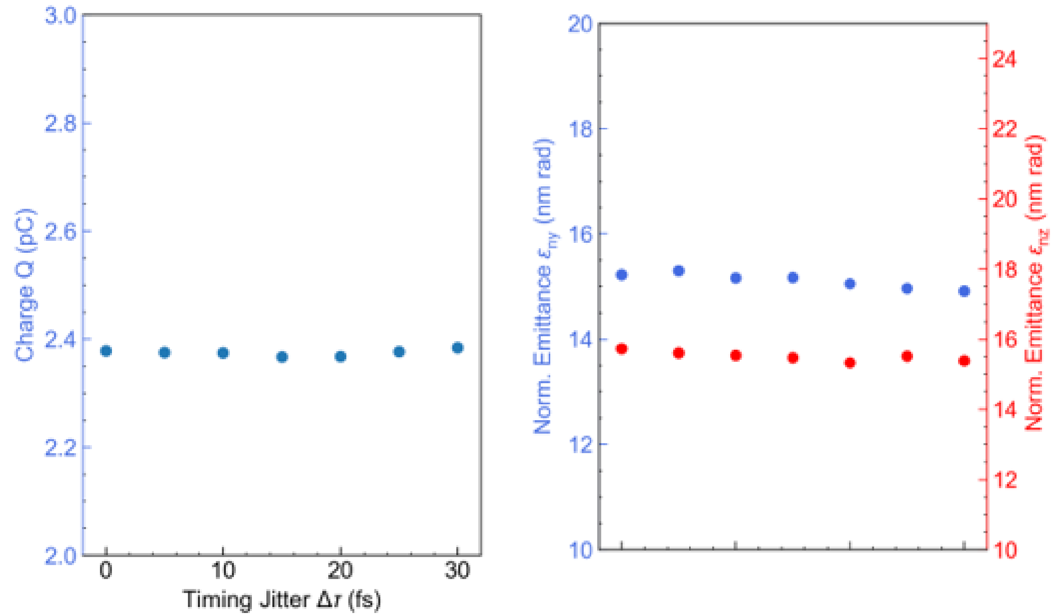
- Successful experiments at FACET e.g. in the E210: Trojan Horse programme (publications under review): First demonstration of PWFA downramp injection, first demonstration of plasma photocathode injection
- Experiments at FLASHforward, INFN, CLARA to come
- Trojan Horse-II at FACET-II: proposal ranked “excellent“

Trojan Horse plasma photocathode very robust: sensitivity study

- ❑ E.g. Transverse misalignment in 250 µm long blowout

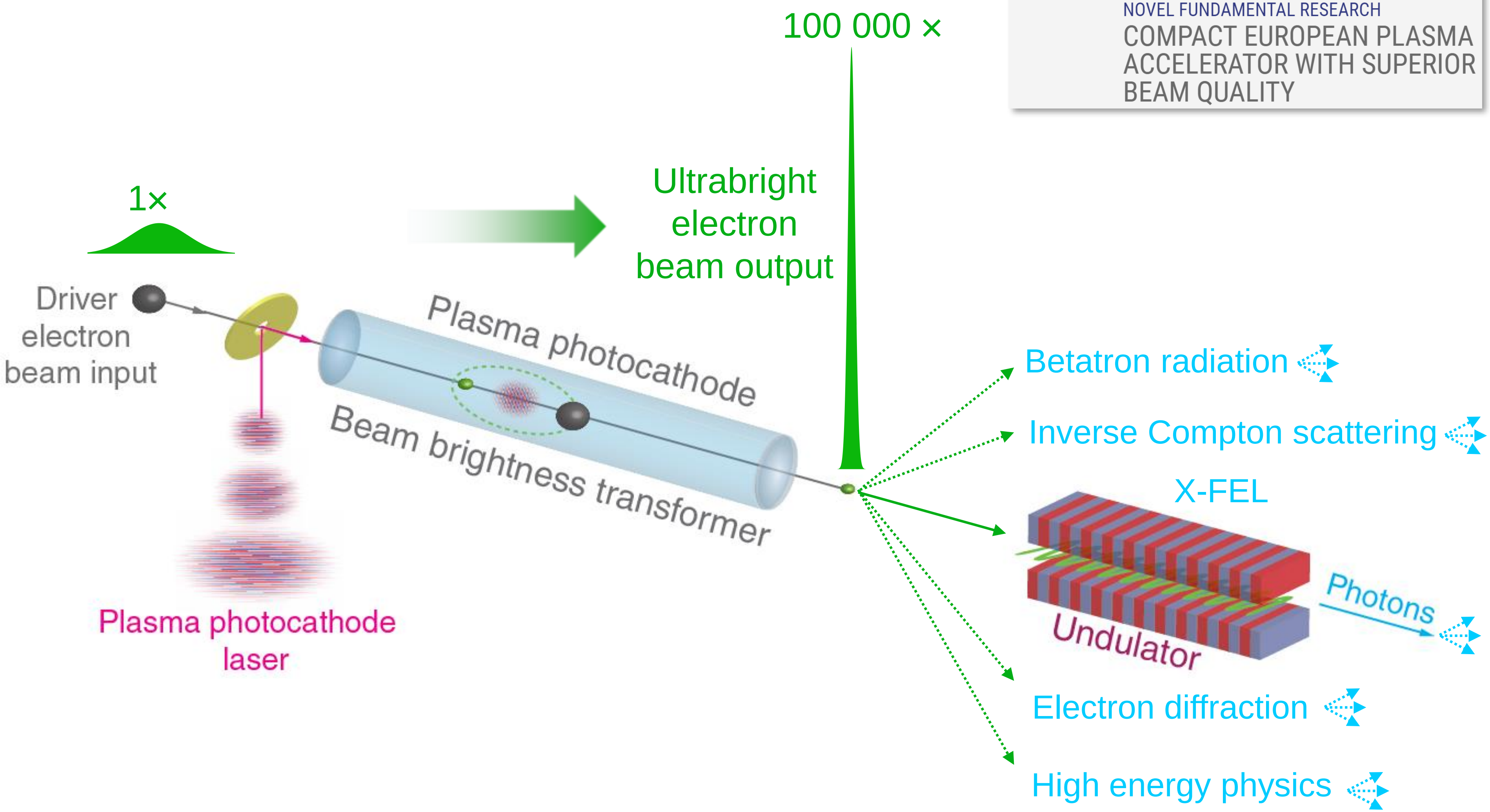


- ❑ E.g. Timing jitter:



- ❑ See plenary Hidding tomorrow

Impact



EuPRAXIA
NOVEL FUNDAMENTAL RESEARCH
COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

THE ROYAL SOCIETY

Directions in particle beam-driven plasma wakefield acceleration

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

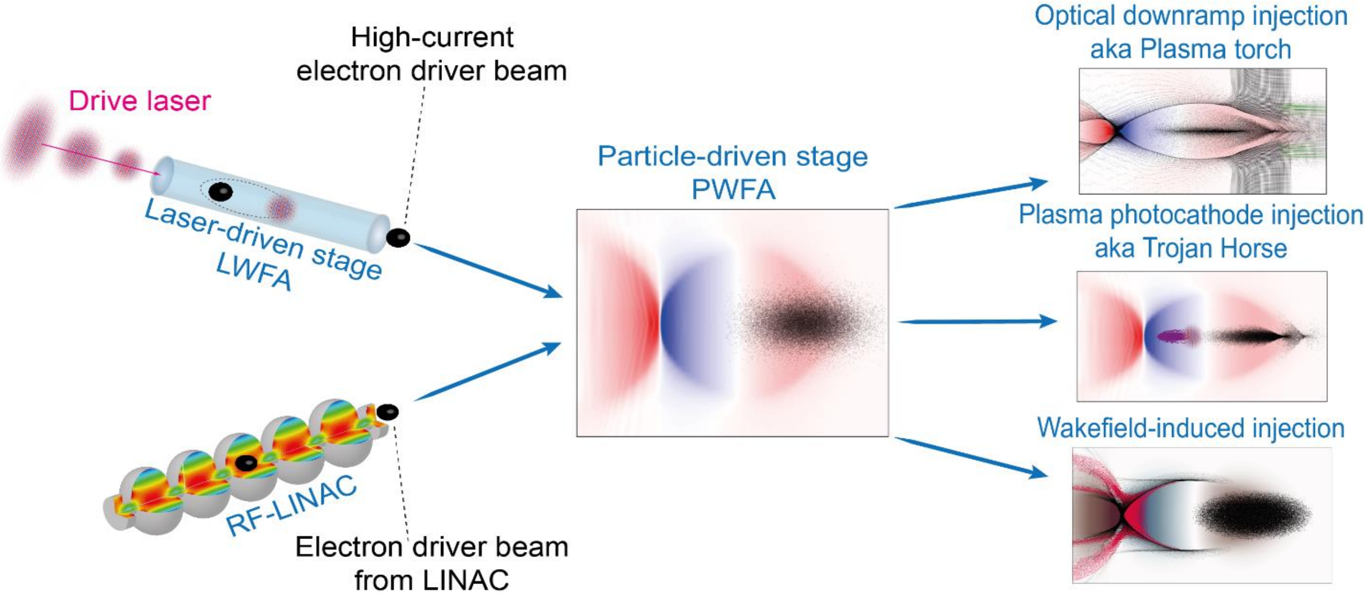
04 June

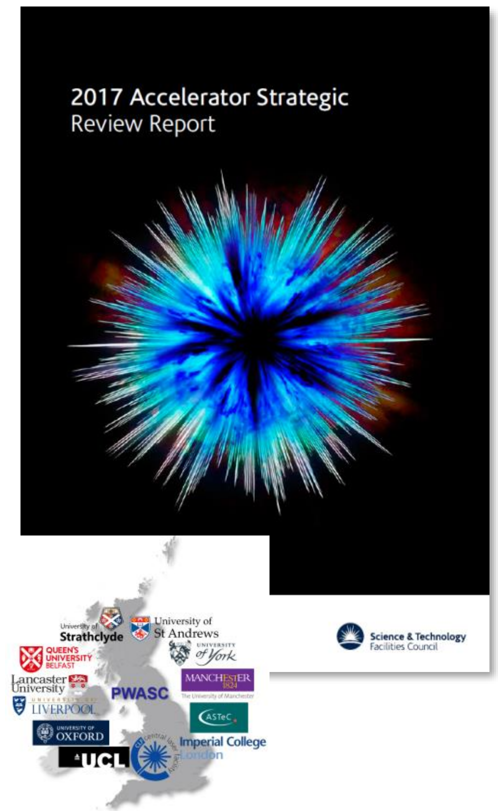
Session 1	09:00-12:50	Linac-driven electron PWFA
Session 2	13:40-17:00	Hybrid LWFA-driven PWFA

05 June

Session 3	09:00-12:30	Positron and proton PWFA
Session 4	13:20-17:00	PWFA applications

- ❑ Quality booster schemes are combinable with both main EuPRAXIA approaches (sites?), LWFA-driven as well as rf-linac-driven

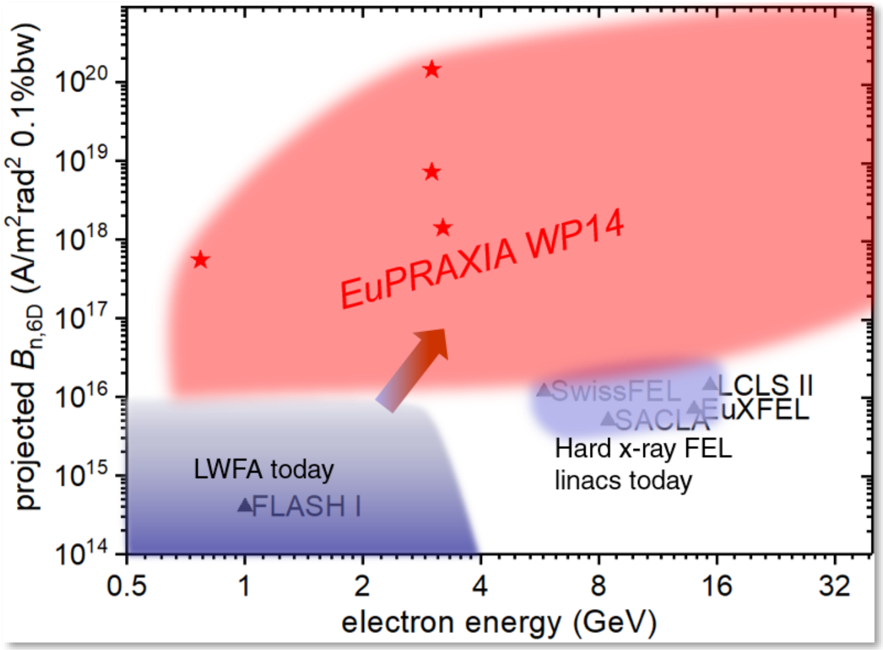




“Hybrid“ topic picks up steam, additional collaborators now FSU (Zepf et al.), HZDR (Irman, Schramm et al.), LMU (Karsch et al.), LOA (Corde et al.) – more welcome

Summary

- ❑ Hybrid plasma acceleration substantiates delivery of “superior beam quality“



EuPRAXIA

NOVEL FUNDAMENTAL RESEARCH
COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

- ❑ Pathways are experimentally viable and comparaly high TRL
- ❑ Full realization expected over next years
- ❑ Applcable for both LWFA and PWFA-centred EuPRAXIAs
- ❑ Should be major research thrust of (future) EuPRAXIA

SAC comments

WP14: Hybrid Laser-Electron-Beam Driven Acceleration

In the presentation of WP 14 its leaders presented a hybrid approach where the initial seeder beam is generated in a laser wakefield accelerator (LWFA) and the resulting beam is used to drive a plasma wakefield accelerator. LWFA typically exhibit much larger charge/bunch but at reduced beam quality compared to RF accelerators. The hybrid approach would allow overcoming some of the known bottlenecks of current LWFA, specifically the limited beam quality and energy spread. Early results from experiments on existing laser user facilities are promising. The group expects that the beam brightness could exceed 2-4x of those at current FELs and meets the superior beam quality requirement set forth EuPRAXIA.

Rec35. Communicate idea to other WP leaders more broadly and establish peer review of the idea within EuPRAXIA to gain support.

Rec36. Develop clear understanding of bottlenecks and risks, specifically which challenges have to be overcome to establish this idea at eye-height with the other approaches.

Rec37. Establish a clear understanding of laser and interface requirements.

Rec38. Continue to build trust in the approach by experimental and modeling effort – request support from EuPRAXIA leadership on gaining timely access to user facilities.

4 orders of magnitude!!

WP14: Hybrid Laser-Electron-Beam Driven Acceleration

he presentation of WP 14 its leaders presented a hybrid approach where the initial see
m is generated in a laser wakefield accelerator (LWFA) and the resulting beam is use
ve a plasma wakefield accelerator. LWFA typically exhibit much larger charge/bunch
reduced beam quality compared to RF accelerators. The hybrid approach would al
rcoming some of the known bottlenecks of current LWFA, specifically the limited be
lity and energy spread. Early results from experiments on existing laser user facilities
mising. The group expects that the beam brightness could exceed 2-4x of those at cur
Ls and meets the superior beam quality requirement set forth EuPRAXIA.

c35. Communicate idea to other WP leaders more broadly and establish peer review of
a within EuPRAXIA to gain support.

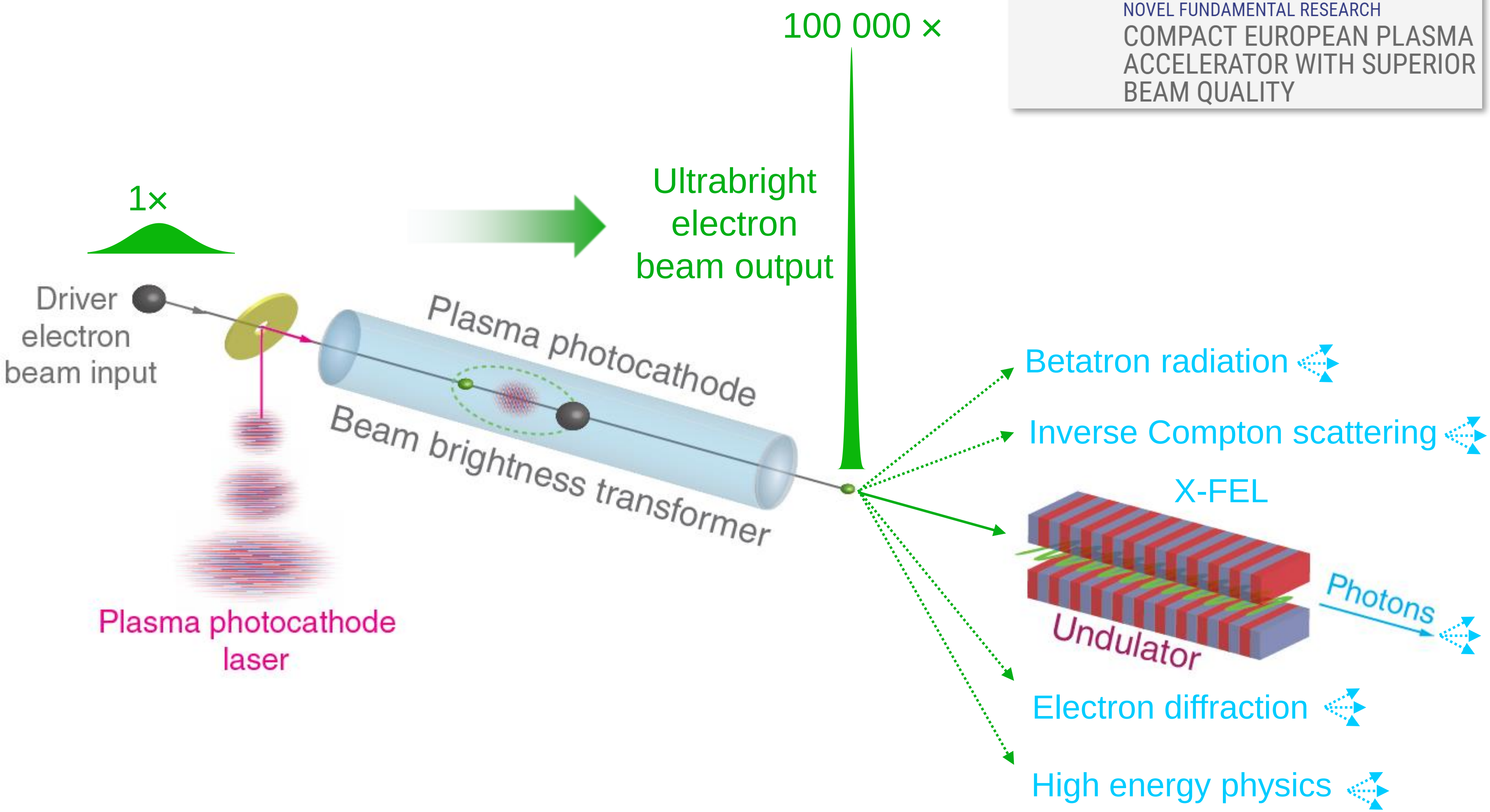
c36. Develop clear understanding of bottlenecks and risks, specifically which challen
e to be overcome to establish this idea at eye-height with the other approaches.

c37. Establish a clear understanding of laser and interface requirements.

c38. Continue to build trust in the approach by experimental and modeling effort – req
port from EuPRAXIA leadership on gaining timely access to user facilities.

Impact

NOVEL FUNDAMENTAL RESEARCH
COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

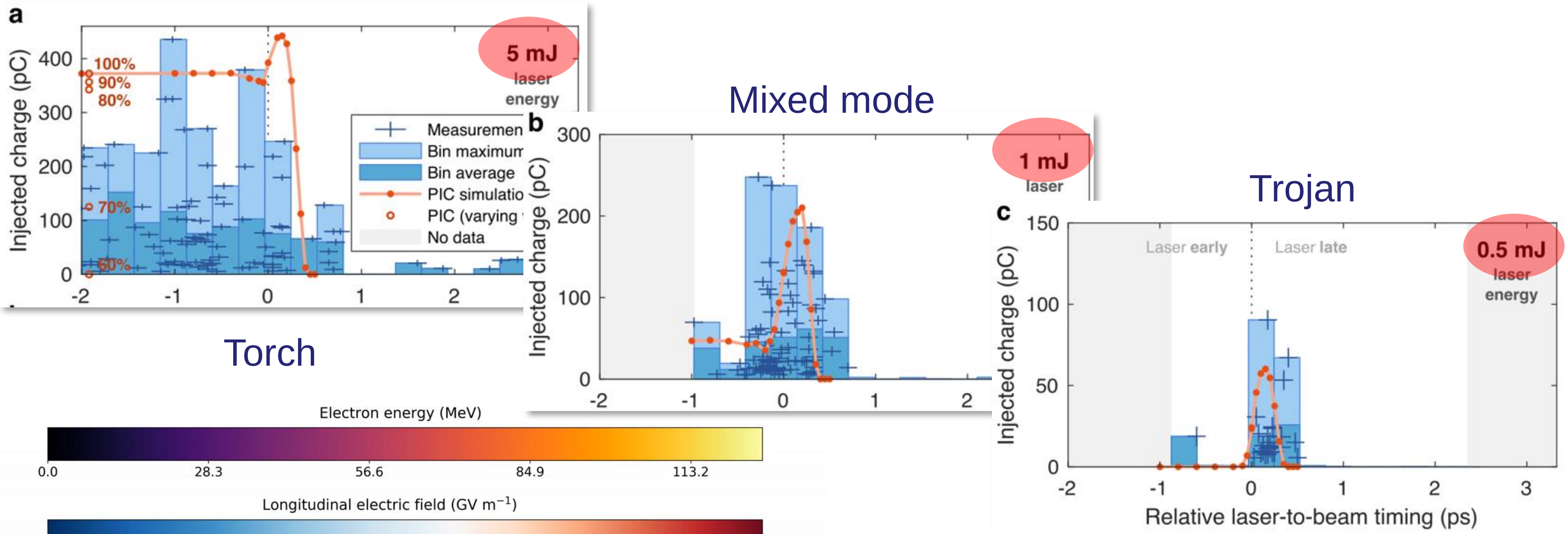


E210 Trojan Horse at SLAC FACET

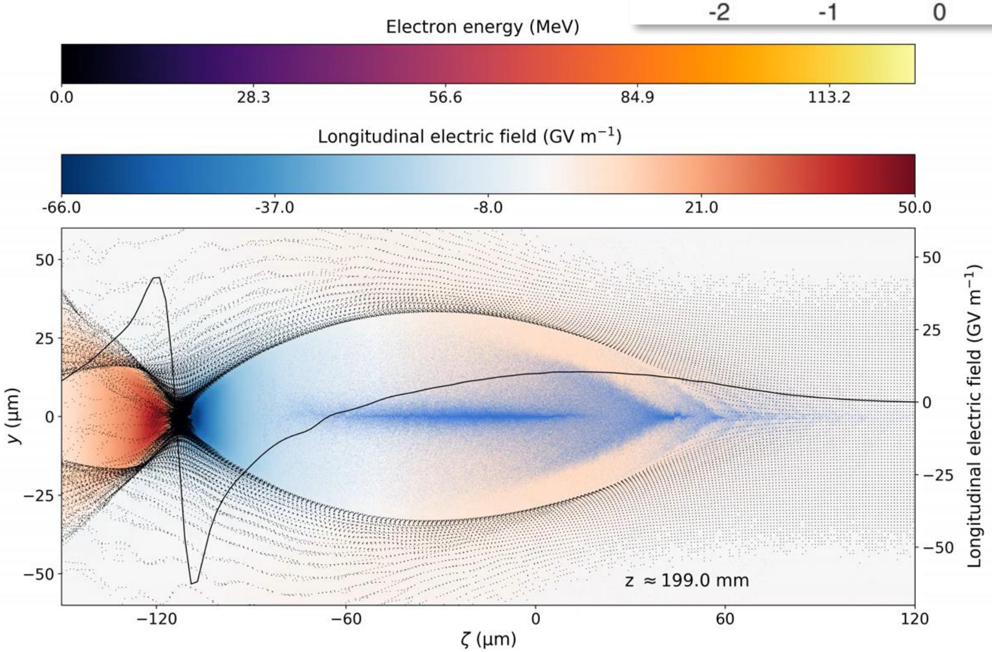
Experimental data

Mixed mode

Trojan



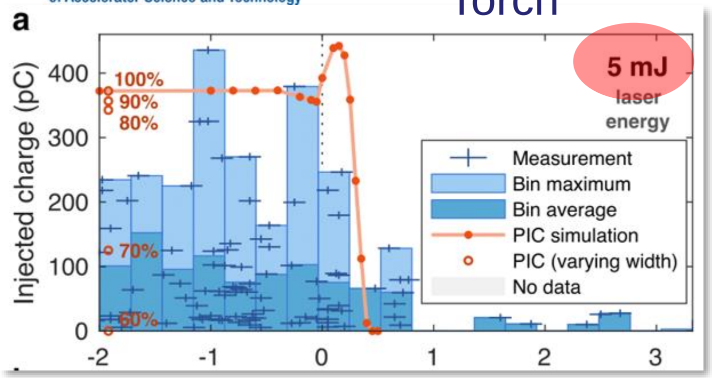
Torch



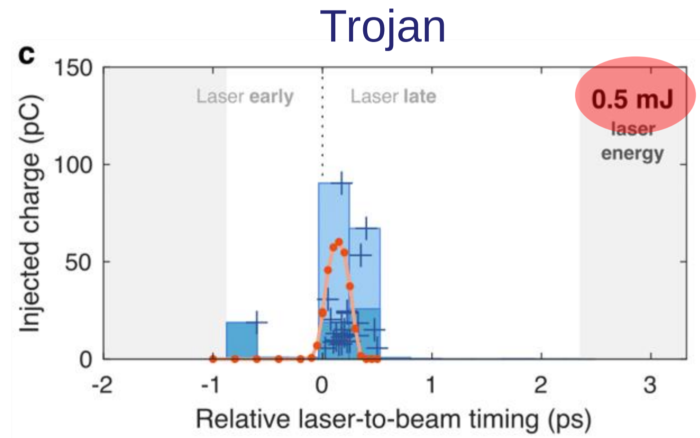
- ❑ Jitter of incoming laser and electron beams reflected by output beam jitter

E210 Trojan Horse at SLAC FACET

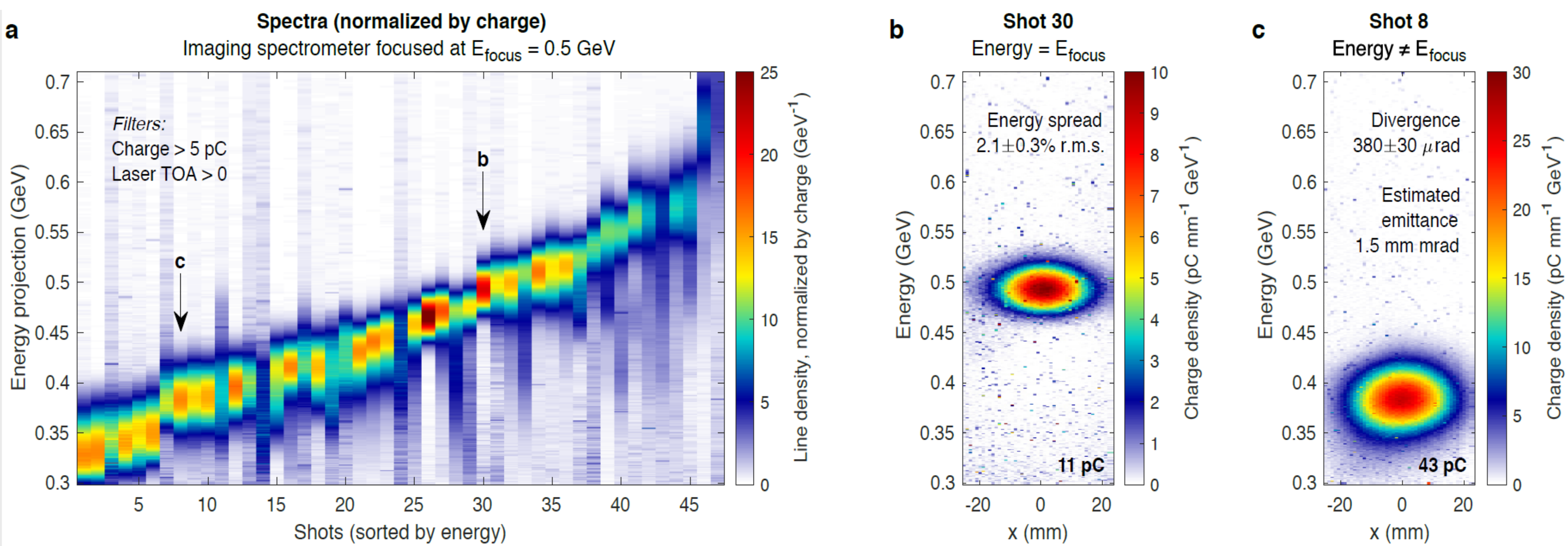
The Cockcroft Institute of Accelerator Science and Technology



- ❑ Jitter of incoming laser and electron beams reflected by output beam jitter

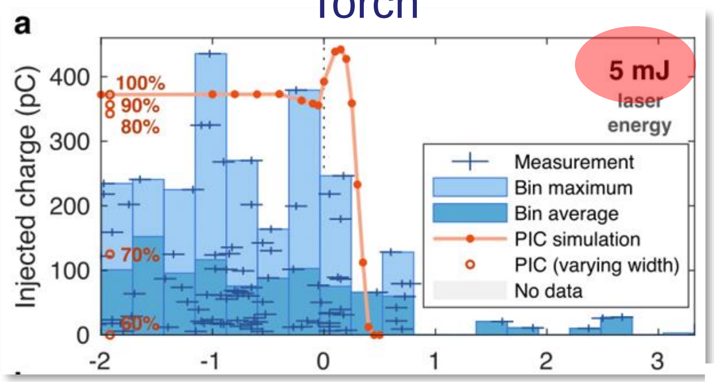


- ❑ Range of observed range of output beam charges, energies etc. in agreement with simulations
- ❑ Observed range of output beams is a passive parameter scan

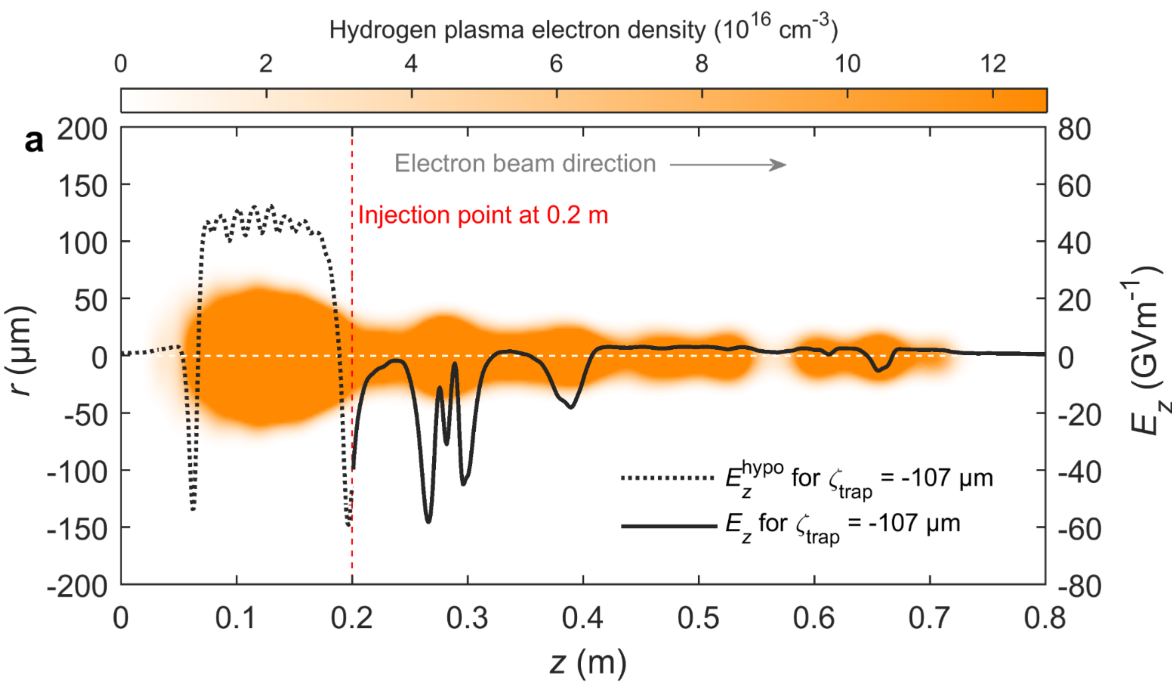


E210 Trojan Horse at SLAC FACET

Torch

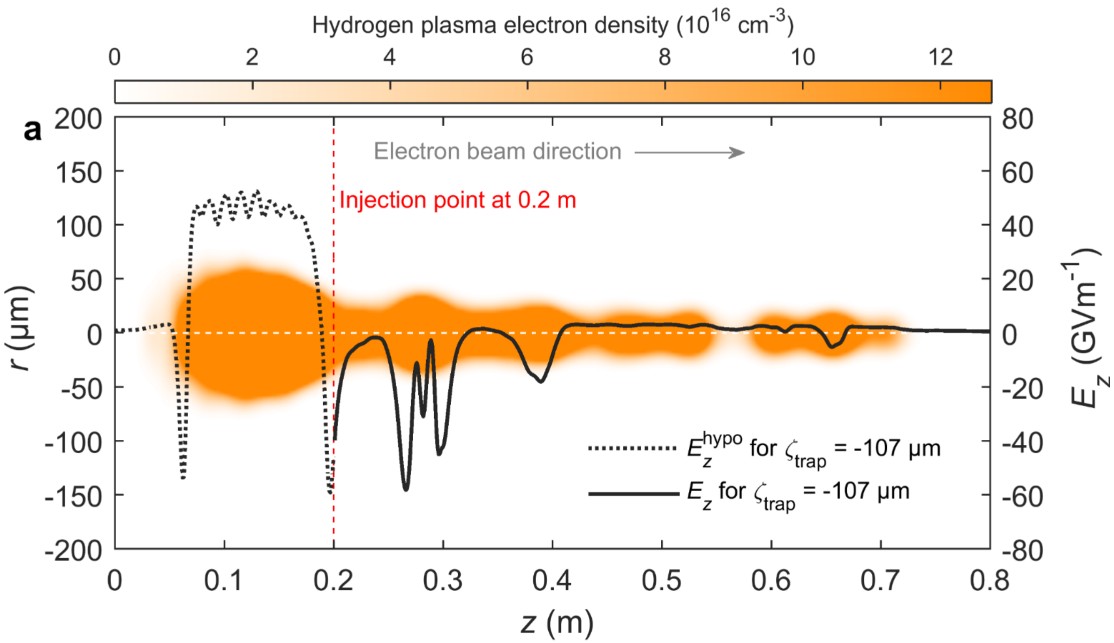


- Even in the torch (laser-early, not timing-dependent) mode, there is substantial jitter of output beams
- The jitter can be reproduced by jitter of the preionized channel width



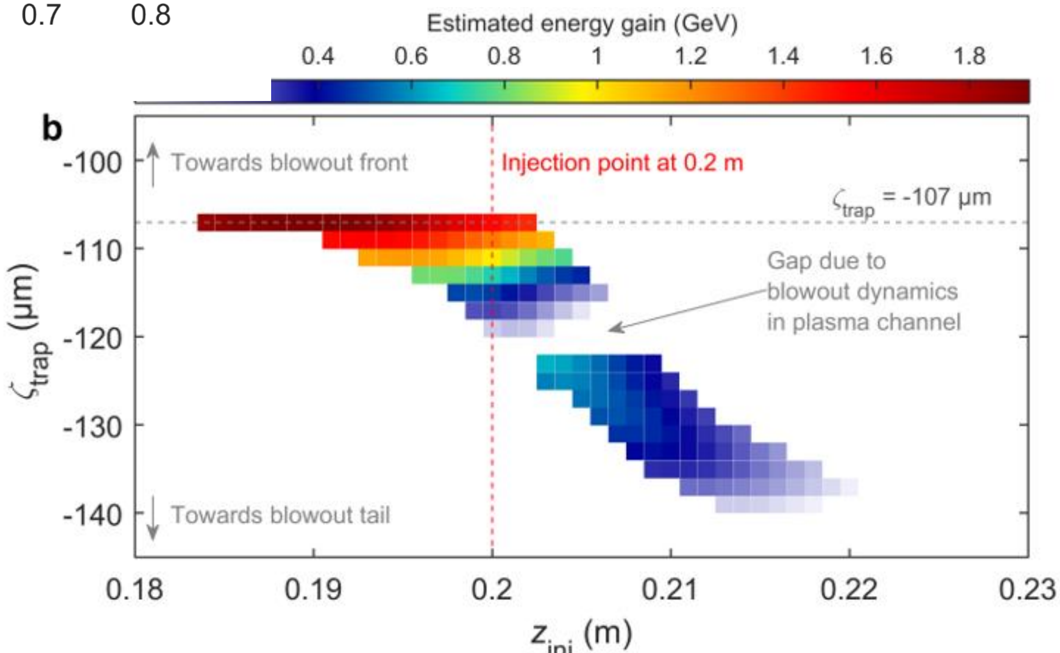
- Narrow preionized plasma channel width: forces to small blowouts ~100 µm to fit into channel
- Even then, electric field seen by the injected electrons is only accelerating over small distance, then even decelerating

E210 Trojan Horse at SLAC FACET



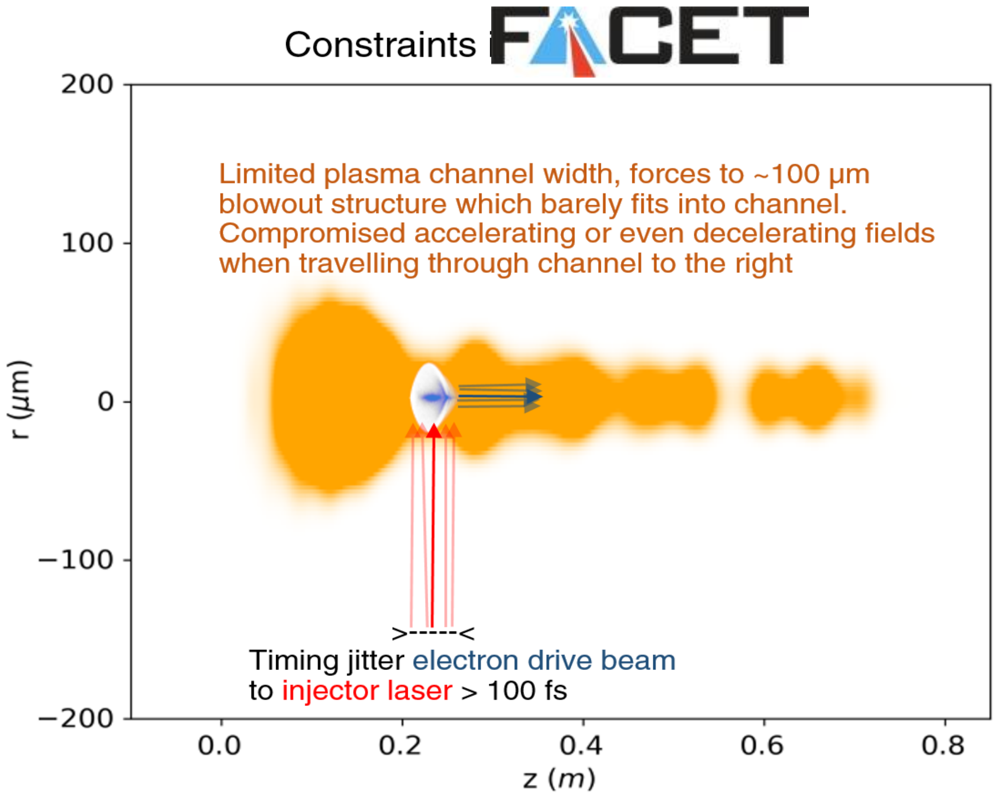
- Electric field for one trapping position in blowout frame

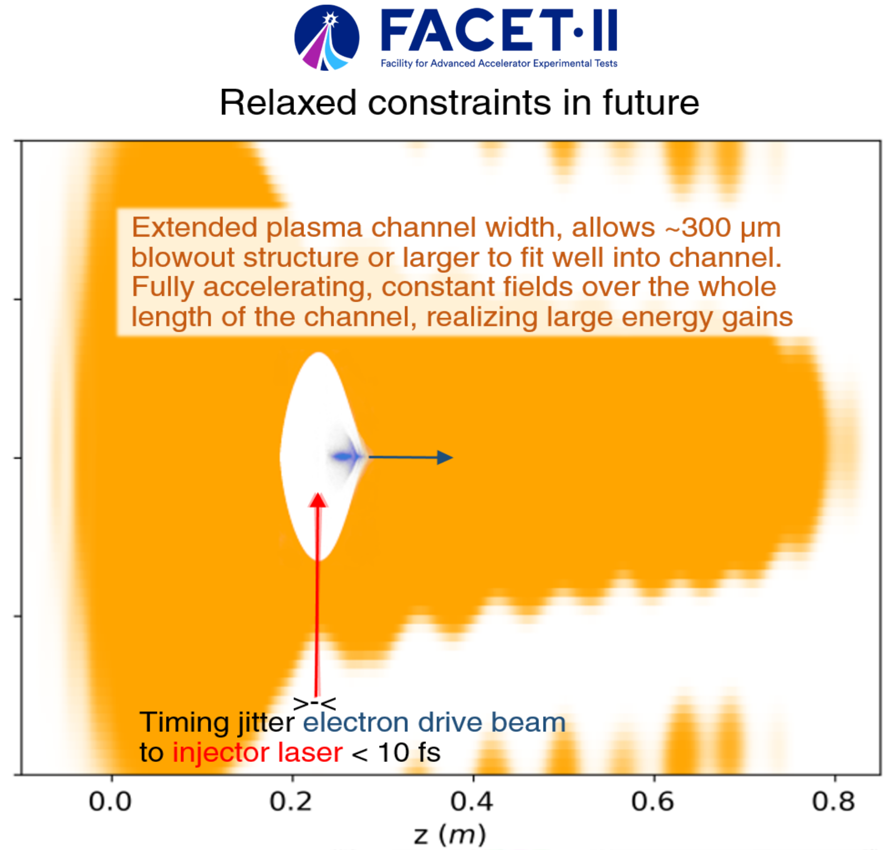
- Expected energy gains when trapping positions change due to timing jitter



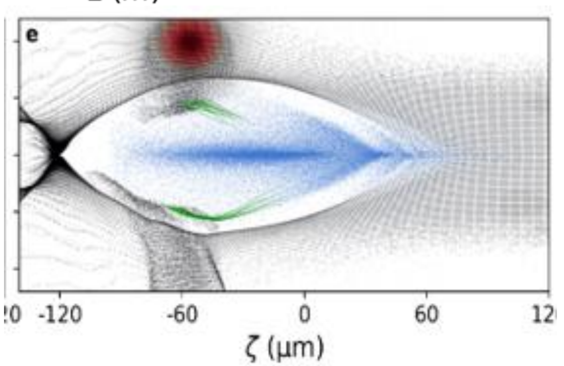
Elimination of constraints at FACET-II

- ❑ Wider channels ⇒ can work at reduced plasma density, larger blowouts!
- ❑ Reduced jitter!





- ❑ Realize precision injection: 500 µm plasma blowout, *e.g.* 15 fs jitter means we will release with **1% precision shot-by-shot** in centre of plasma wave
- ❑ Transverse kick by drive beam eliminated
- ❑ Lower plasma densities also better for residual energy spread (Manahan, Habib *et al.*, *Nat. Comm.* 8, 15705, 2017), and preclude hot spots



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

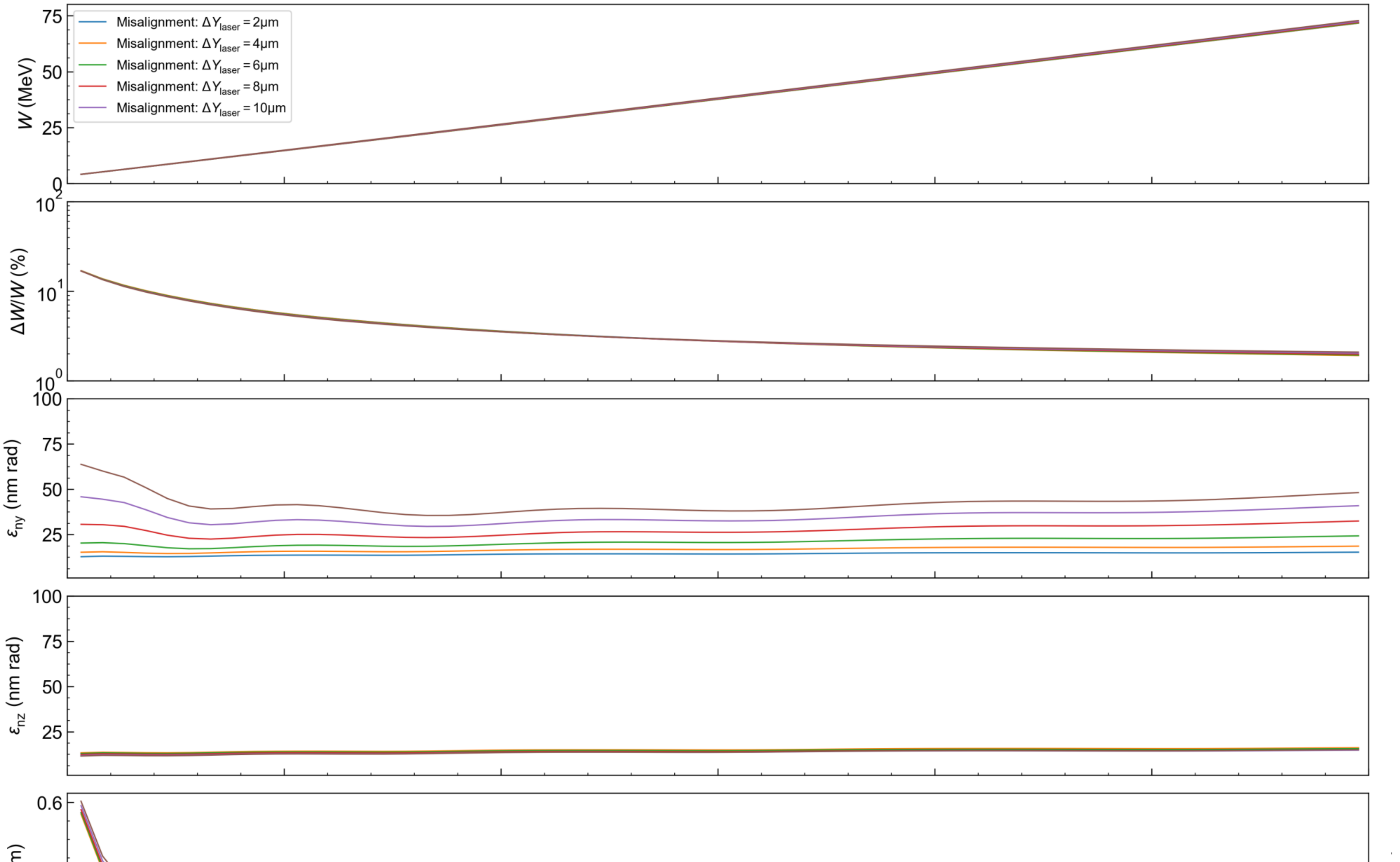
Bunch Length Stability: (0.19±0.03) μm

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}

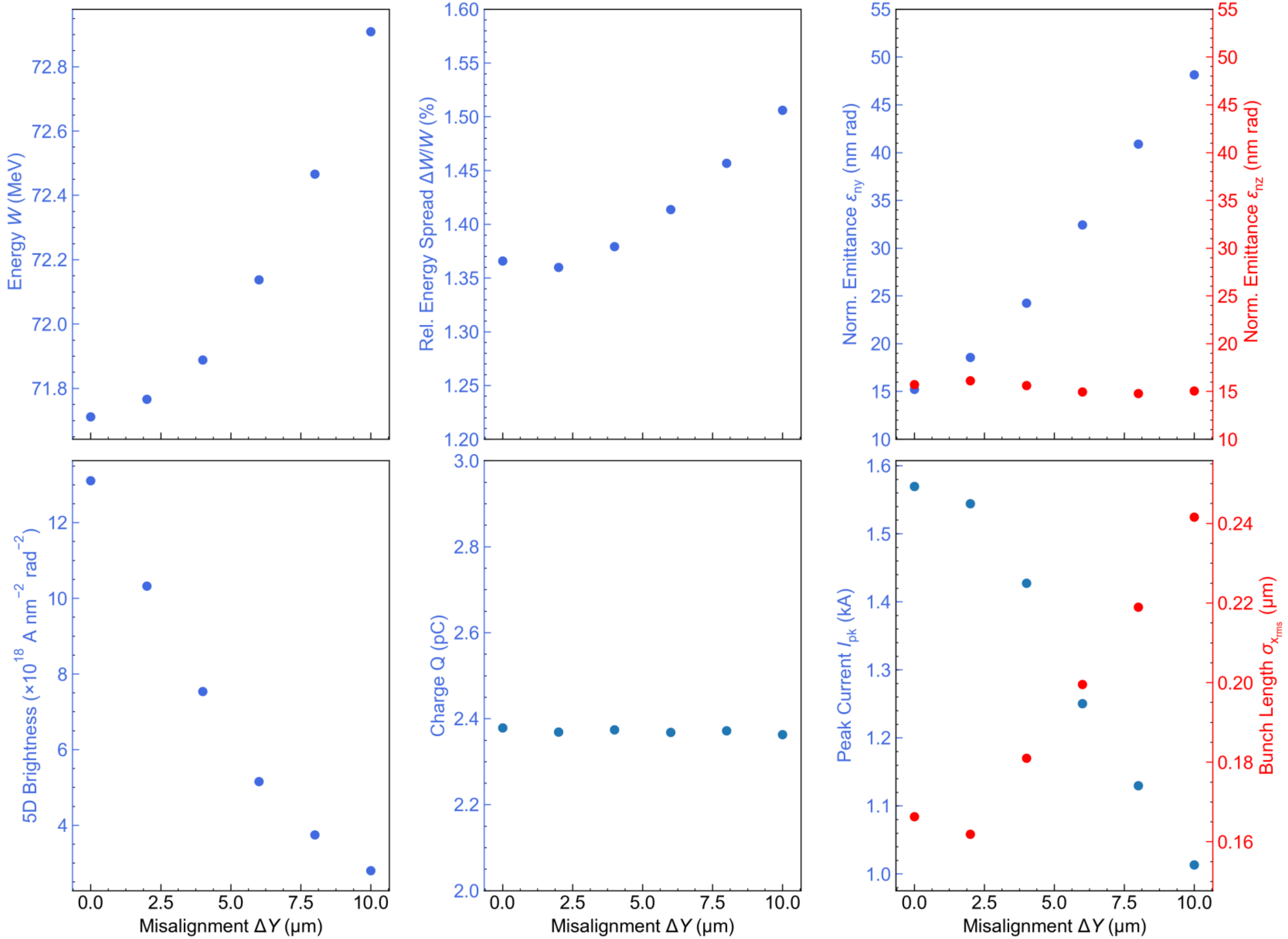
Peak Current Stability: (1.32±0.21) kA



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

Energy Stability: (72.15±0.59) MeV
Rel. Energy Spread Stability: (1.41±0.05) %
Emittance Y Stability: (29.91±11.8) nm rad
Emittance Z Stability: (15.38±0.48) nm rad

5D Brightness Stability: $(7.11\pm3.66)\times10^{18}$ A nm^{-2} rad^{-2}
Charge Stability: (2.371 ±0.005) pC
Peak Current Stability: (1.32±0.21) kA
Bunch Length Stability: (0.19±0.03) μm



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

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

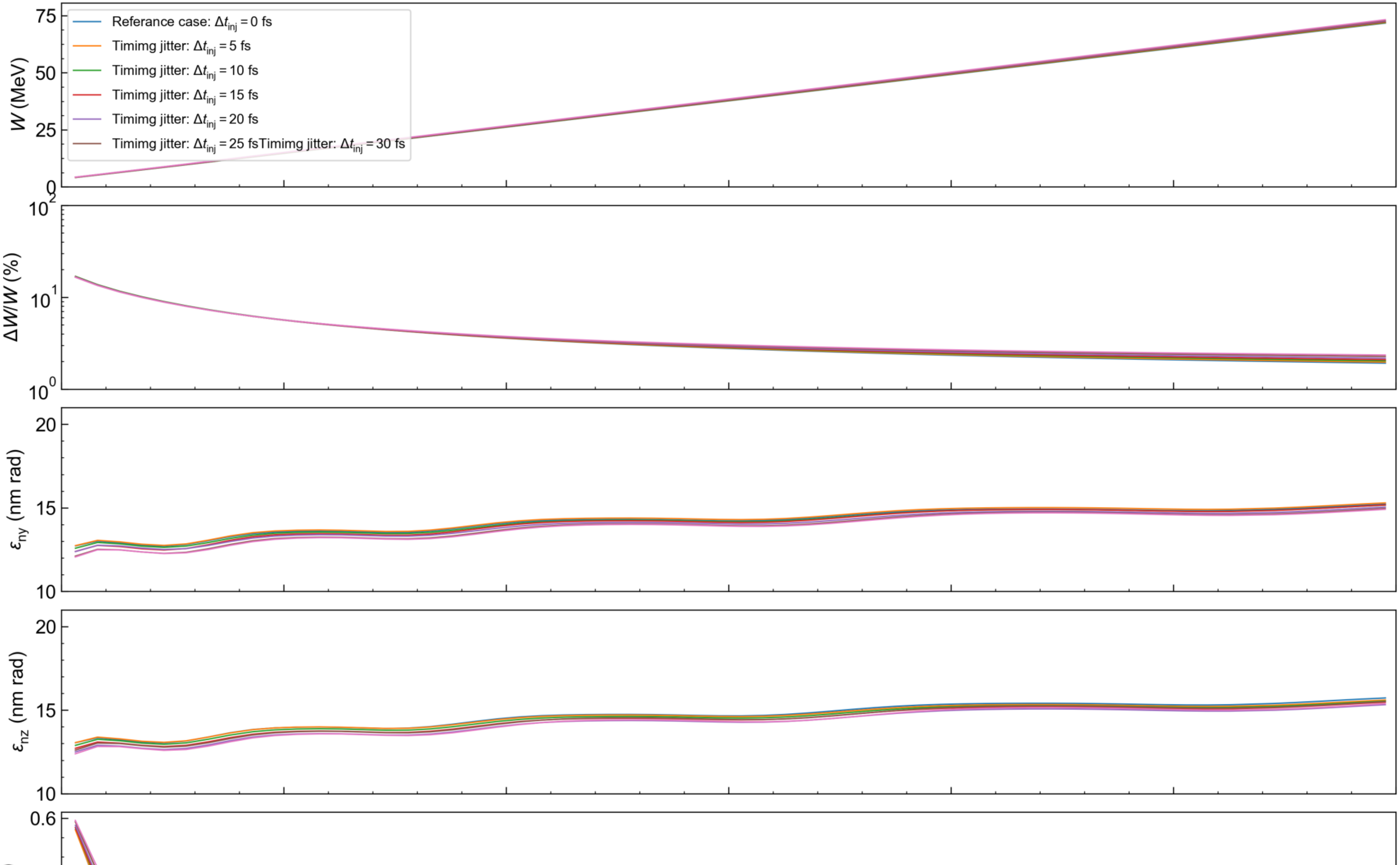
Bunch Length Stability: (0.22±0.04) μm

Charge Stability: (2.375 ±0.006) pC

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

5D Brightness Stability: (10.45±1.65)×10^{18} A nm^{-2} rad^{-2}

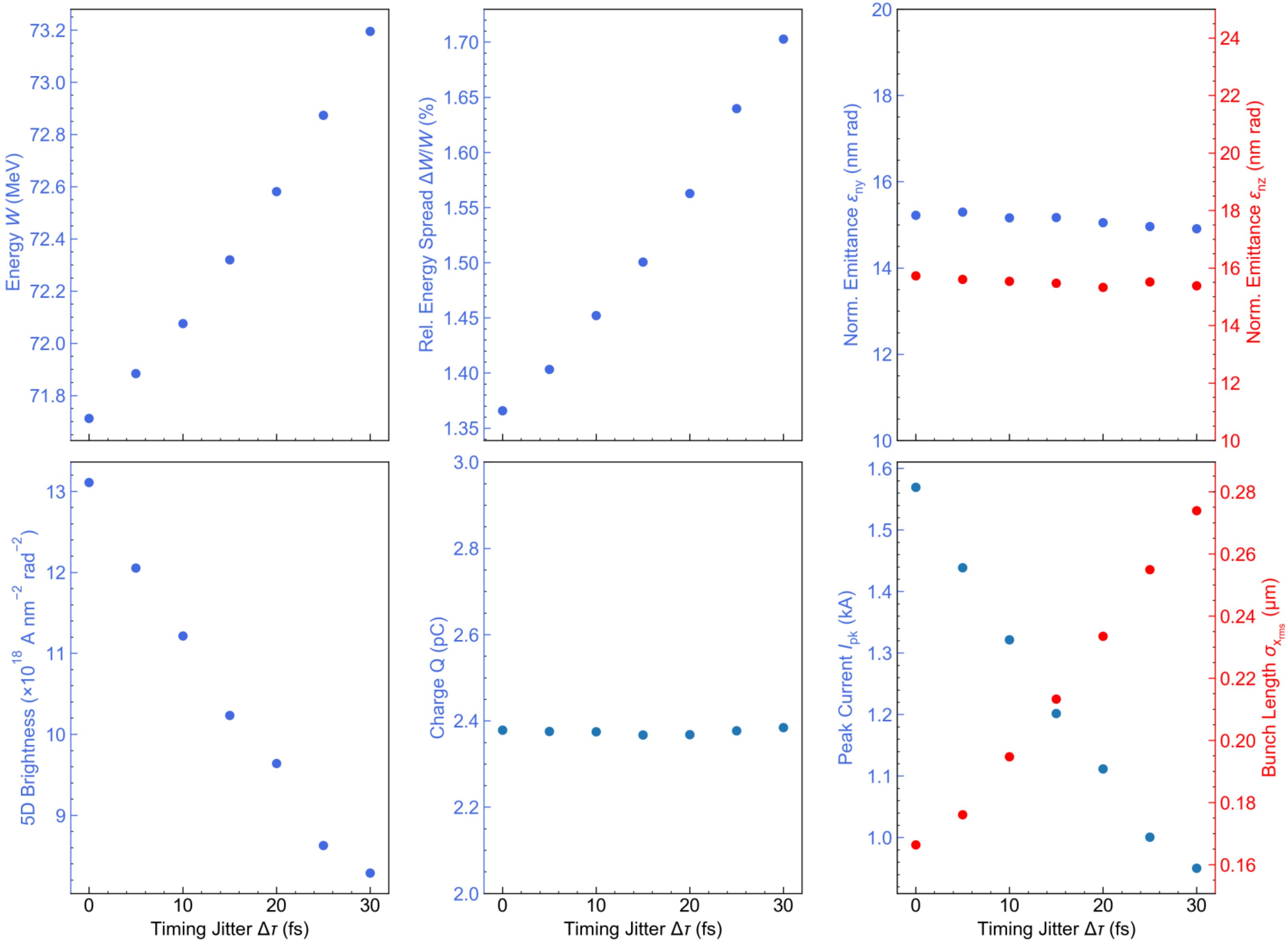
Peak Current Stability: (1.23±0.21) kA



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

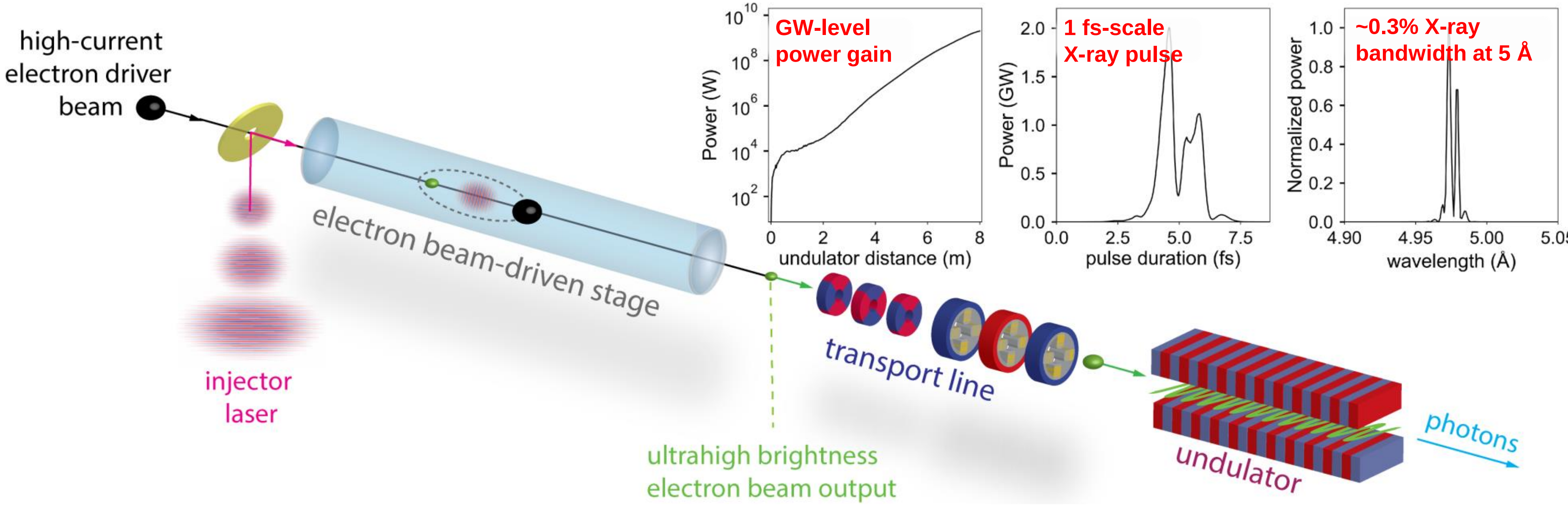
Energy Stability: (72.38±0.69) MeV
Rel. Energy Spread Stability: (1.52±0.11) %
Emittance Y Stability: (15.11±0.13) nm rad
Emittance Z Stability: (15.51±0.12) nm rad

5D Brightness Stability: $(10.45\pm1.65)\times10^{18}$ A nm^{-2} rad^{-2}
Charge Stability: (2.375 ±0.006) pC
Peak Current Stability: (1.23±0.21) kA
Bunch Length Stability: (0.22±0.04) µm



All scans done for 250 µm plasma wavelength, plasma photoacthode laser a0= 0.018, w0 = 7 µm, laser duration 50 fs

Preliminary FEL simulations, including extraction, capture, transport, conditioning: hard x-ray-FEL with ultrahigh gain (10 m undulator):



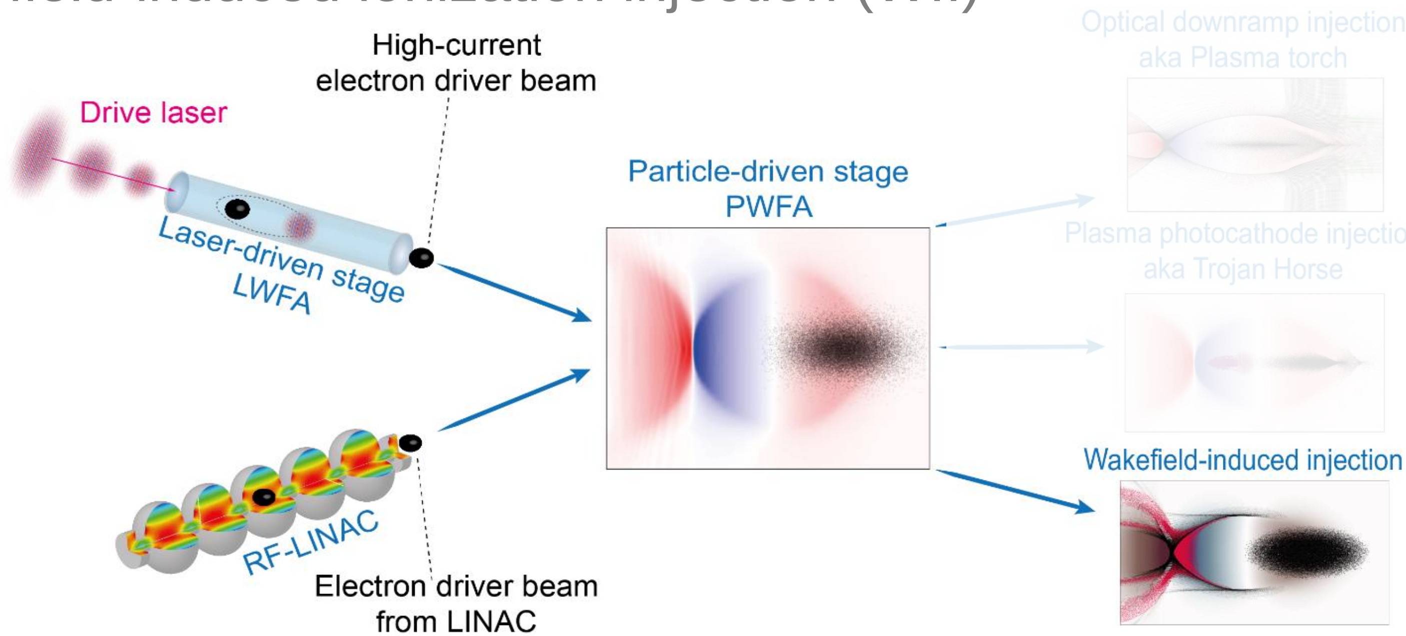
3 lasers, including 350 TW, 5 Hz flagship, 3 shielded bunkers, up to 7 beamlines

EuPRAXIA @ SCAPA

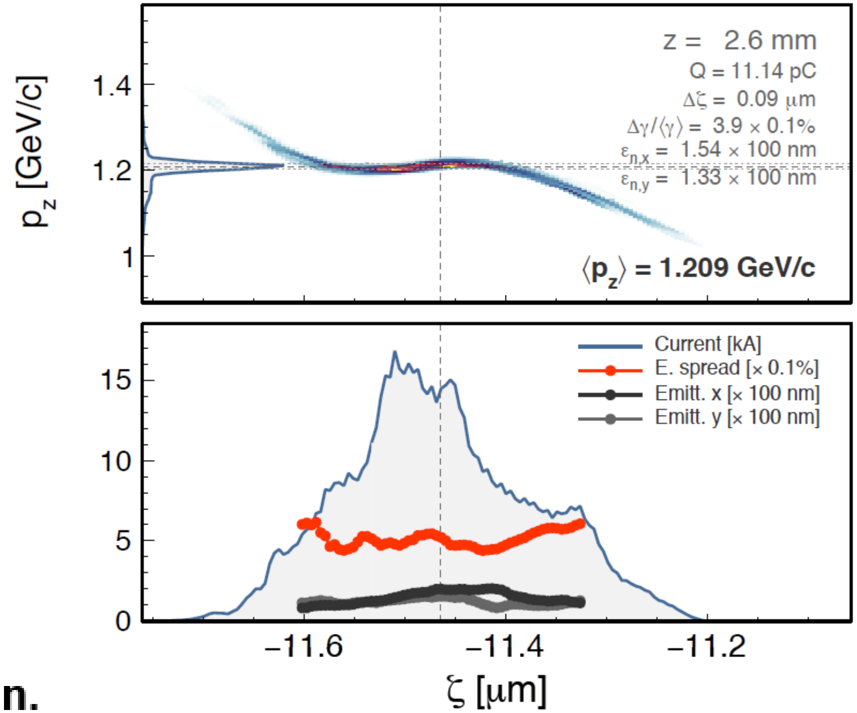
BEAMLINE

Scottish Centre for the **Application** of Plasma-based Accelerators (fits well to multi-site approach and industry applications

Wakefield-induced ionization injection (WII)



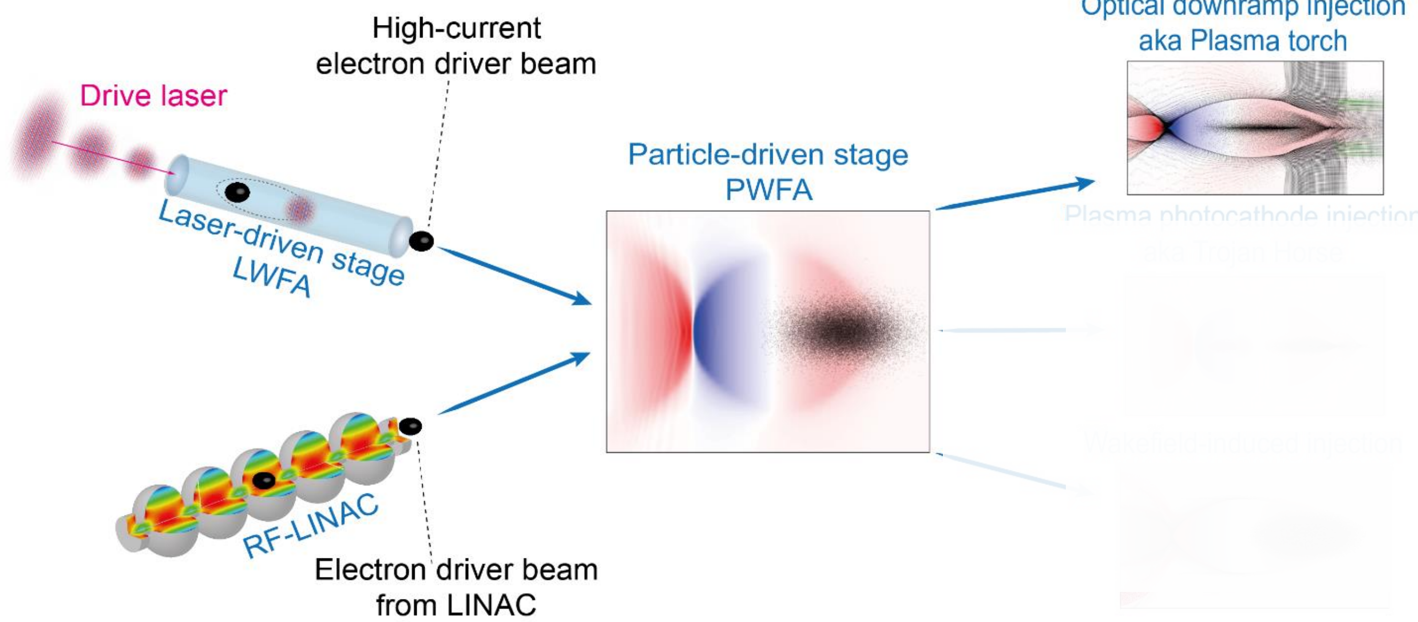
- ❑ Hydrodynamically localized He dopant ionized by wakefield, laser required only for preionization of hydrogen fraction
- ❑ Can produce beautiful bunch with ~100 nm emittance, sub-% energy spread



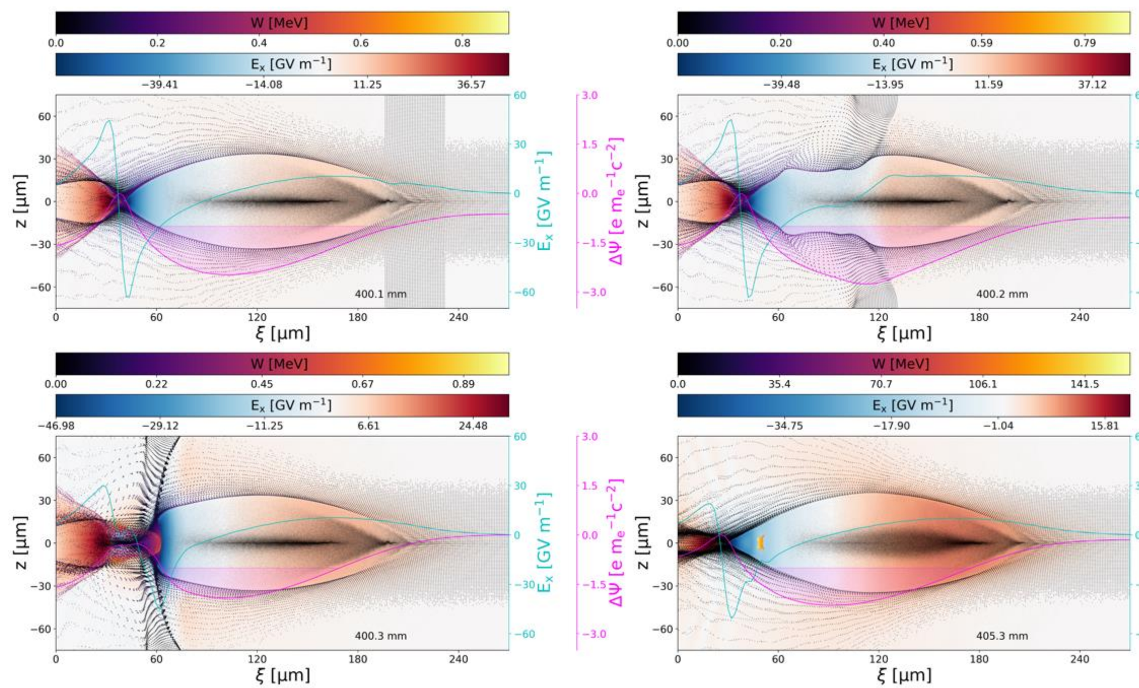
A. Martinez de la Ossa et al., Phys. Rev. Lett. 111, 245003 (2013); Phys. Plasmas 22, 093107 (2015)

Task 14.3. Wakefield-induced ionisation injection.

Plasma torch injection – optical density downramp

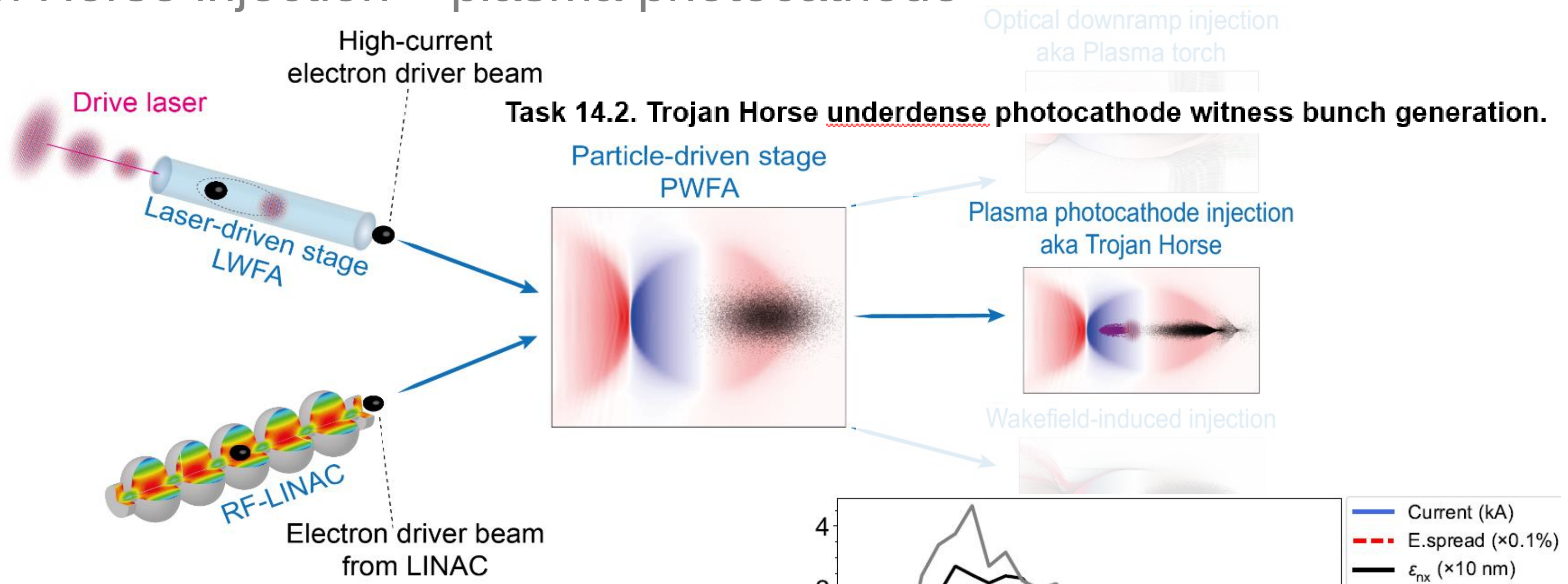


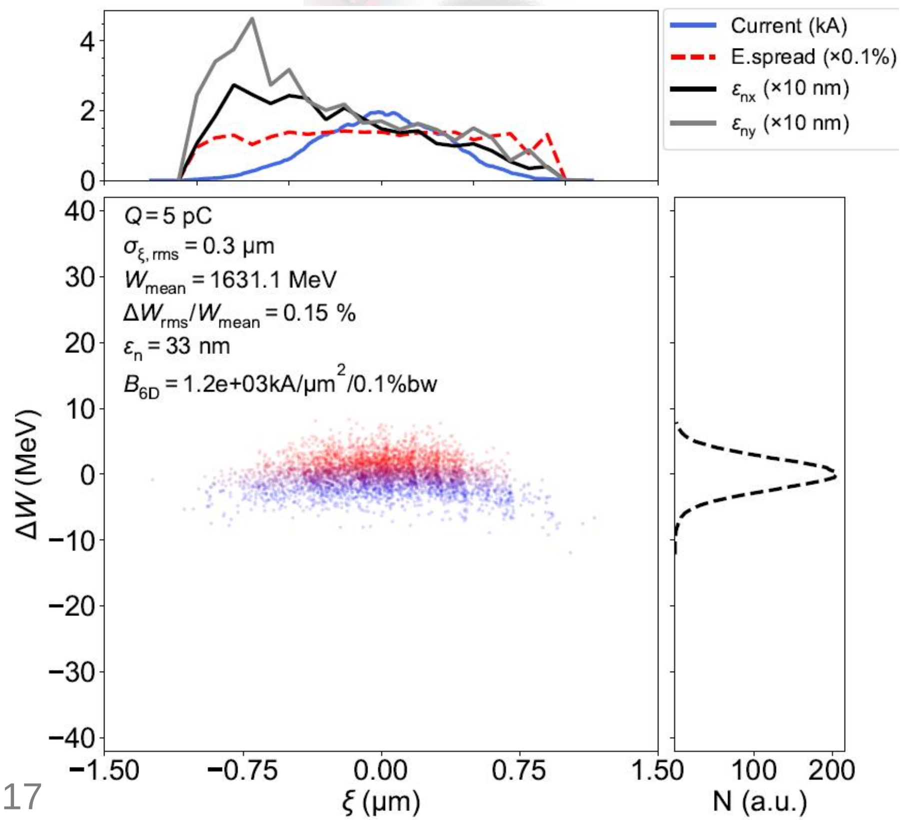
- ❑ Laser produces He density spike, optically tailored downramp facilitates injection
- ❑ Realize ultrahigh quality of density downramp schemes, high tunability
- ❑ (Optical) density downramp injection shown for the first time at FACET in E210 programme



D. Ullmann et al,, to be published

Trojan Horse injection – plasma photocathode





- ❑ Laser releases utracold He electrons directly within H blowout
- ❑ Experimental culmination of FACET E210 programme
- ❑ Tailored beam loading via escort bunch allows reduction of energy spread of ~30 nm rad witness bunch to ~0.01% level at 5 GeV
- ❑ Path to brightest electron beams of the world
  http://www.eupraxia-project.eu/the-brightest-electron-beams-of-the-world.html

A. Deng, O. Karger et al,, to be published
G.G. Manahan, F. A. Habib et al., Nat. Comm. 8, 15705, 2017