EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

WP14 Transformative Innovation Paths

Leaders: Bernhard Hidding, Stefan Karsch

LMU, HZDR, HHU, FZJ, LOA, UOXF, USTRATH,
UP, IC, UNI-ROMA2, UCLA et al.

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

Contents

- Context and new members
- TRL Status and Evolution
- Potential impact for ESFRI
- Integration options for EuPRAXIA sites
- Structures to be funded

Timeline

WP14
"Hybrid Laser-Electron-Beam Driven Acceleration"

CDR:
"Transformative Innovation Path" Cluster

WP14
"Transformative Innovation Paths"

Integration in Infrastructures

EuPRAXIA 2015-2019

EuPRAXIA-PP 2022-2026

EuPRAXIA

Objectives & deliverables
WP14 "Transformative Innovation Paths"

Funded by the European Union

Work package number	14	Lead beneficiary			USTRATH	
Work package title	Transformative Innovation Paths					
Participant number	1	6	8	12	13	14
Short name of part.	INFN	UNI-ROMA2	CNRS	FZJ	HZDR	LMU
Person months per part.:	0 (+6)	0 (+6)	0 (+6)	0 (+36)	0 (+7)	0 (+7)
Participant number	22	25	30	29		
Short name of part.	USTRATH	UOXF	IC	UCLA		
Person months per part.:	12 (+6)	0 (+6)	0 (+6)	0 (+6)		
Start month	1			End month		

Objectives
To develop R&D structures including the definition of programmatic scientific R&D, formation of excellence centres and (national and international) funding programmes and budgets to ensure the latest innovative science breakthroughs can continuously be implemented into EuPRAXIA. To develop hybrid LWFA→PWFA as a combination of and a bridge between the two main approaches of EuPRAXIA, LWFA and PWFA. To develop plasma photocathodes, multi-pulse wakefield acceleration and plasma sources for novel electron beam production. To steer scientific and technical progress of innovative, transformative approaches towards EuPRAXIA implementation.

Description of work (where appropriate, broken down into tasks), lead partner and role of participants
The WP14 is coordinated by USTRATH and LMU, supported by the collaborating institutes with their extensive experience and knowledge base. The WP develops several innovative, high gain concepts with possibly transformative potential, as specified in the CDR. Reflecting the broad range of approaches, collaborators are therefore widely spread and include groups various wider EuPRAXIA consortium members such as Universities of Oxford, Imperial, LOA. Detailed work will be performed on: Generation of low-emittance seed beams via a hybrid LWFA-PWFA approach (USTRATH, HZDR, LMU, LOA). Development of ultracold injection schemes via plasma photocathodes (USTRATH, HZDR, LMU, LOA, UOXF). Multipulse plasma wave excitation, overcoming the single-pulse energy limit of high-repetition rate few-10 fs lasers (UOXF). High repetition rate LWFA (UOXF, IC).

Part B - Page 21 of 30

Call: [INFRA-2022-DEV-02-01] — [Preparatory phase of new ESFRI research infrastructure projects]

EU Grants: Application form (HE CS

Development of tailored long plasma targets (IC). Development of spin-polarized electron beam sc
use of pre-polarized gas targets (FZJ) or plasma photocathodes (USTRATH).

Milestones
MG.1 Update of concepts for EuPRAXIA, systems status report (M24)

Deliverables (brief description and month of delivery)
D14.1 Report on structures (centres, clusters, experimental programmes) to be funded (M12)
D14.2 TRL report (M42)

- D14.1 delivered in Nov 2023. Funding pathways now crucial
- Working towards D14.2: TRL report

WP14 EuPRAXIA-PP Overview

Funded by the European Union

14.1: **Hybrid laser-particle driven wakefield acceleration (LWFA→PWFA)**

14.2: **Multipulse-driven P-MoPA** for harnessing accessible high-repetition rate laser technology

14.3: **Plasma photocathode** injectors and ultracold beams

14.4: **High-brightness prototyping** for light sources, QED and HEP

14.5: **Plasma targetry and diagnostics** for ultrabright, high rep-rate beams

Partners:

- 14.1: LMU Ludwig-Maximilians-Universität München; HZDR Helmholtz Zentrum Dresden Rossendorf; CALA; University of Strathclyde Glasgow; loa; hhu Heinrich Heine Universität Düsseldorf
- 14.2: University of Oxford; LMU Ludwig-Maximilians-Universität München; CALA
- 14.3: hhu Heinrich Heine Universität Düsseldorf; LMU Ludwig-Maximilians-Universität München; HZDR Helmholtz Zentrum Dresden Rossendorf; CALA; UCLA; University of Strathclyde Glasgow
- 14.4: hhu Heinrich Heine Universität Düsseldorf; University of Strathclyde Glasgow; UCLA; loa
- 14.5: Pécsi Tudományegyetem University of Pécs; University of Oxford; Tor Vergata Università degli Studi di Roma; hhu Heinrich Heine Universität Düsseldorf; Imperial College London; CALA

Tomorrow

17:00	**Ultracold electron sources, kHz plasma injectors and strong THz fields**	*Prof. Stefan Karsch*
	Hotel Hermitage, La Biodola Bay, Isola d'Elba, Italy	17:00 - 17:30

Funded by the European Union

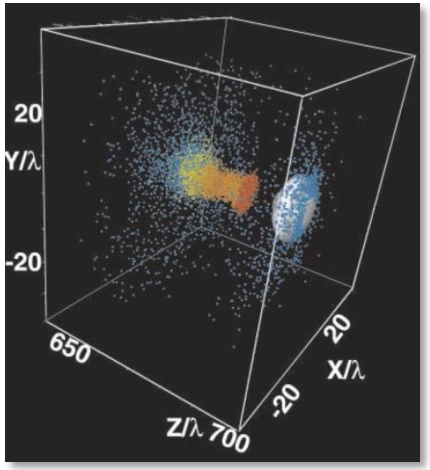
Tomorrow

17:00	**Ultracold electron sources, kHz plasma injectors and strong THz fields** *Hotel Hermitage, La Biodola Bay, Isola d'Elba, Italy*	*Prof. Stefan Karsch* 17:00 - 17:30
11:00	**Stable Beam driven wakefield in structured plasmas** *Hotel Hermitage, La Biodola Bay, Isola d'Elba, Italy*	*Alexander Pukhov* 11:00 - 11:30

Funded by the European Union

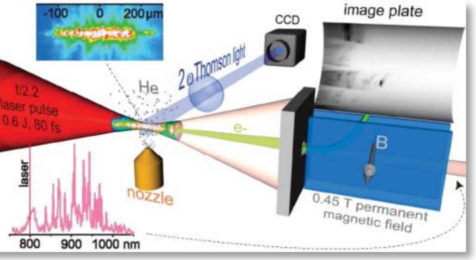
- Pioneer in LWFA and PWFA. Its researchers have collaboratively contributed to pillars EuPRAXIA builds on, such as

LWFA



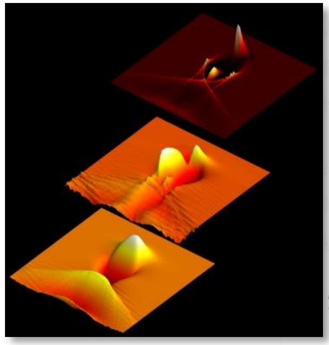
Bubble regime, Pukhov, MtV 2002

First monoenergetic LWFA, Faure .. Pukhov.. 2004

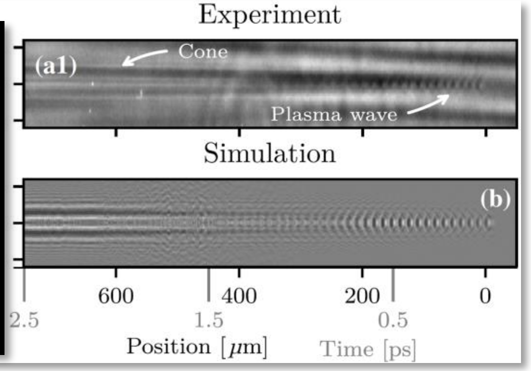


First monoenergetic LWFA in Germany, Hidding, Karsch, Pretzler et al., 2006

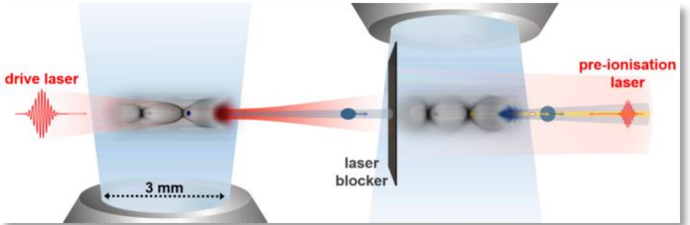
Hybrid LWFA-PWFA



Concept, Hidding, Pretzler, Karsch et al., *PRL* 2010

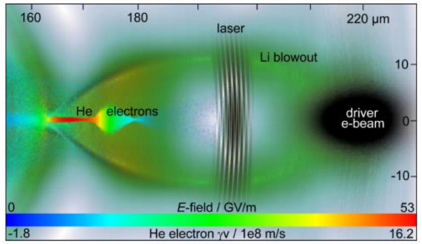


Plasma wave dynamics, Gilljohann .. Hidding, Karsch .. *PRX* 2019

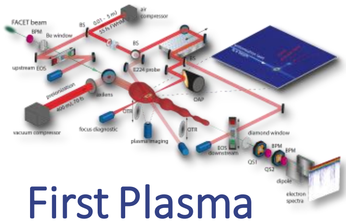


Hybrid LWFA→PWFA Platform, Kurz, Heinemann, Hidding, Karsch, Schramm, *Nat. Comm.* 2021

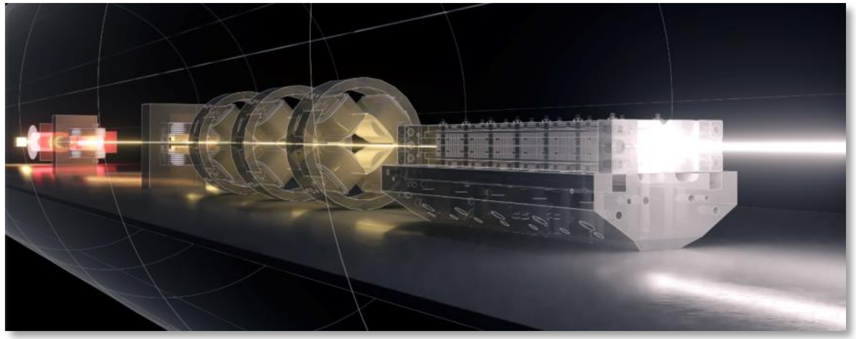
PWFA



Plasma photocathode concept, Hidding .. Pretzler et al., *PRL* 2010



First Plasma Photocathode, Deng .. Hidding, *Nat. Phys.* 2019



Hard X-FEL blueprint, Habib.. Hidding *Nat. Comm.* 2023

Heinrich Heine University Düsseldorf
A new partner in EuPRAXIA

- ARCTURUS 2x200 TW and Phaser facilities for exp. plasma wakefield acceleration
- 5 University research groups across theory, simulations and experiments

Theory & Simulation

Prof. Alexander Pukhov

Prof. Carsten Müller

Experiments

Prof. Bernhard Hidding (also University of Strathclyde Glasgow ,WP 14)

Prof. Georg Pretzler

Prof. Markus Büscher (also at JÜLICH Forschungszentrum)

HHU offers programmatic R&D resources and staffing capacities for plasma wakefield innovations, beam brightness and energy transformers, X-FEL and QED prototypes and experiments, novel diagnostics, and Training and Education

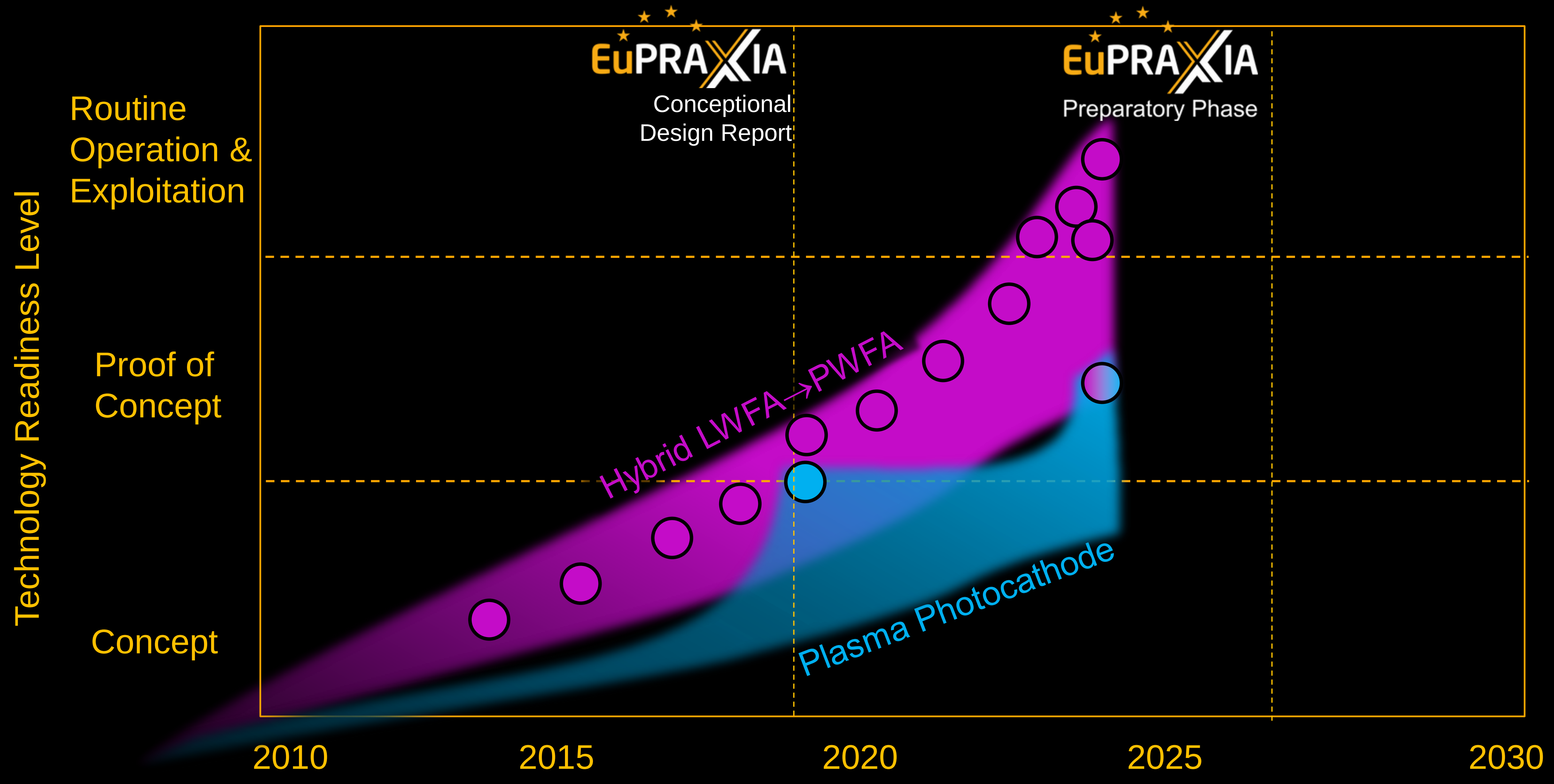
https://www.plasmaxlasers.hhu.de/
https://www.lasmat.hhu.de/

TRL evolution

Deliverables (brief description and month of delivery)
D14.1 Report on structures (centres, clusters, experimental programmes)
D14.2 TRL report (M42)

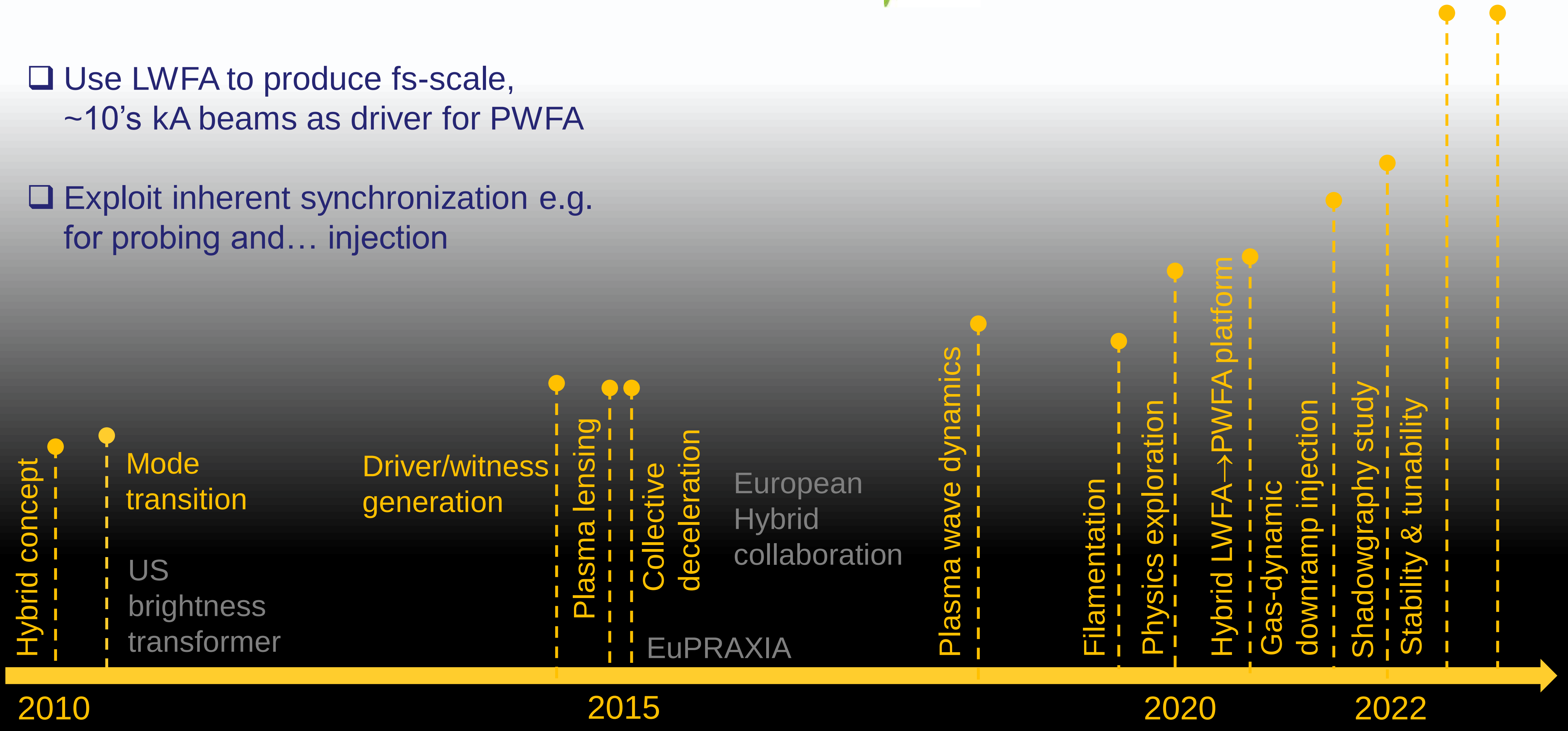
- TRL status crucial for integration into sites
- Core aim of WP is to ensure capabilities EuPRAXIA can offer to users are cutting edge *at the time user operation begins and beyond*
- Requires forward-looking R&D and implementation paths
- Innovations advanced quickly, some already at very high TRL

Concepts ⇒ Proof of Concept ⇒ Routine Operation & Exploitation
Example 14.1 and 14.3



Hybrid LWFA→PWFA

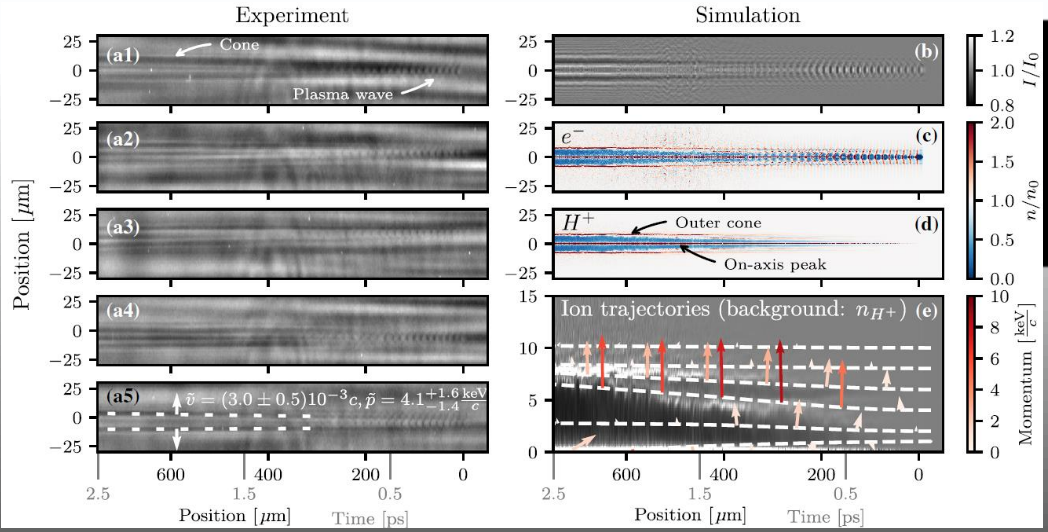
- ❑ Use LWFA to produce fs-scale, ~10’s kA beams as driver for PWFA
- ❑ Exploit inherent synchronization e.g. for probing and… injection



Progress in Hybrid Plasma Wakefield Acceleration, *Photonics* 10(2), 99 (2023)

Hybrid LWFA→PWFA

University of Strathclyde Glasgow · HZDR Helmholtz Zentrum Dresden Rossendorf · LMU · loa · DESY · hhu Heinrich Heine Universität Düsseldorf



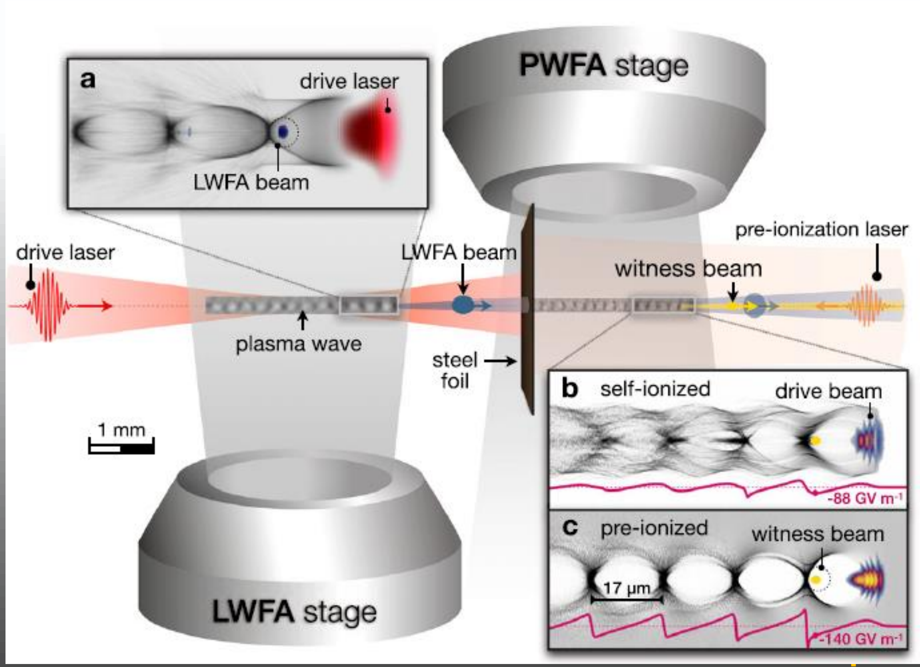
Direct Observation of Plasma Waves and Dynamics Induced by Laser-Accelerated Electron Beams
Gilljohann et al. PRX (2019)

- 2010 — Hybrid concept
- Mode transition
- US brightness transformer
- Driver/witness generation
- Plasma lensing
- 2015 — Collective deceleration
- European Hybrid collaboration
- EuPRAXIA
- Plasma wave dynamics
- Filamentation
- 2020 — Physics exploration
- Hybrid LWFA→PWFA platform
- Gas-dynamic downramp injection
- Shadowgraphy study
- 2022 — Stability & tunability

Progress in Hybrid Plasma Wakefield Acceleration, *Photonics* 10(2), 99 (2023)

Hybrid LWFA→PWFA

University of Strathclyde Glasgow · HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF · LMU · loa · DESY. · hhu Heinrich Heine Universität Düsseldorf



Demonstration of a compact plasma accelerator powered by laser-accelerated electron beams
Kurz, Heinemann et al.
Nat. Comm. (2021)

Hybrid concept

Mode transition

US brightness transformer

Driver/witness generation

Plasma lensing

Collective deceleration

European Hybrid collaboration

EuPRAXIA

Plasma wave dynamics

Filamentation

Physics exploration

Hybrid LWFA→PWFA platform

Gas-dynamic downramp injection

Shadowgraphy study

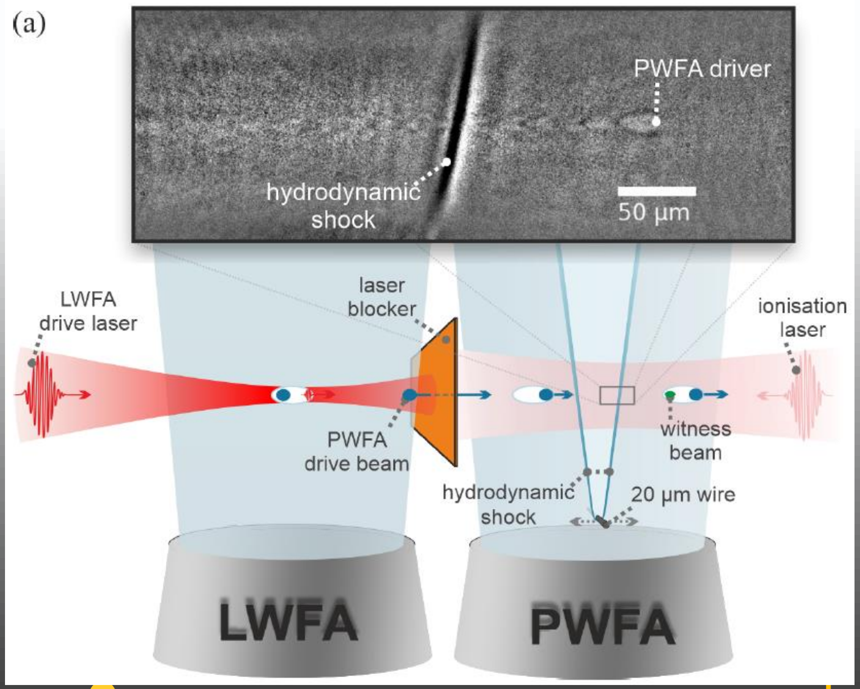
Stability & tunability

2010 · 2015 · 2020 · 2022

Progress in Hybrid Plasma Wakefield Acceleration, *Photonics* 10(2), 99 (2023)

Hybrid LWFA→PWFA

University of Strathclyde Glasgow · HZDR Helmholtz Zentrum Dresden Rossendorf · LMU · loa · DESY · hhu Heinrich Heine Universität Düsseldorf



Gas-dynamic density downramp injection in a beam-driven plasma wakefield accelerator
Couperus Cabadağ et al.
Phys Rev. Res. (2021)

Hybrid concept

Mode transition

US brightness transformer

Driver/witness generation

Plasma lensing

Collective deceleration

European Hybrid collaboration

EuPRAXIA

Plasma wave dynamics

Filamentation

Physics exploration

Hybrid LWFA→PWFA platform

Gas-dynamic downramp injection

Shadowgraphy study

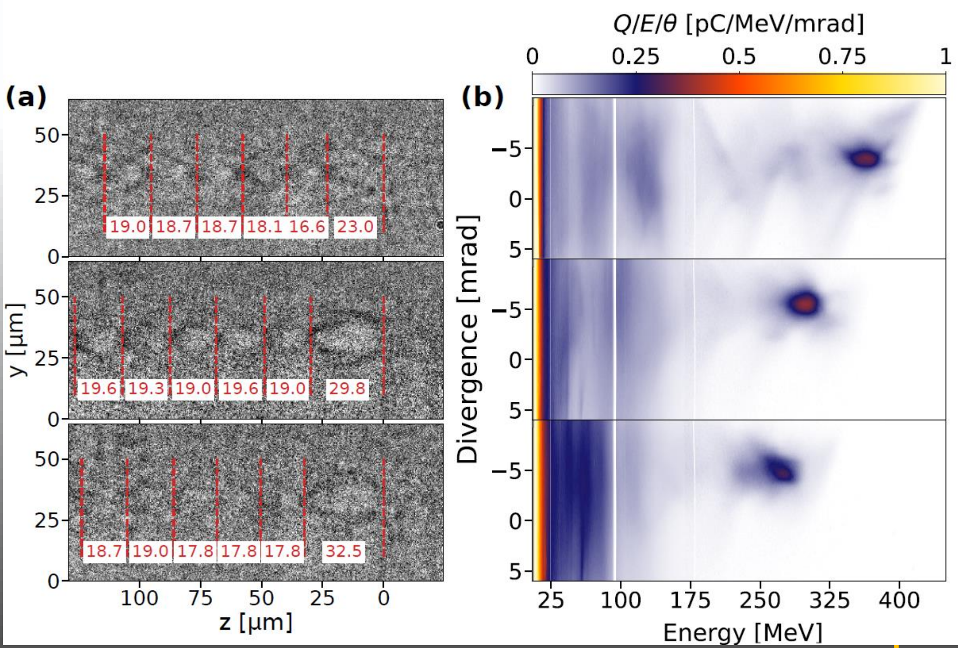
Stability & tunability

2010 2015 2020 2022

Progress in Hybrid Plasma Wakefield Acceleration, *Photonics* 10(2), 99 (2023)

Hybrid LWFA→PWFA

University of Strathclyde Glasgow
HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF
LMU
loa
DESY.
hhu Heinrich Heine Universität Düsseldorf



Effect of driver charge on wakefield characteristics in a plasma accelerator probed by femtosecond shadowgraphy
Schoebel et al. NJP (2022)

- 2010: Hybrid concept
- Mode transition
- US brightness transformer
- Driver/witness generation
- Plasma lensing
- 2015: Collective deceleration
- European Hybrid collaboration
- EuPRAXIA
- Plasma wave dynamics
- Filamentation
- 2020: Physics exploration
- Hybrid LWFA→PWFA platform
- Gas-dynamic downramp injection
- Shadowgraphy study
- 2022: Stability & tunability

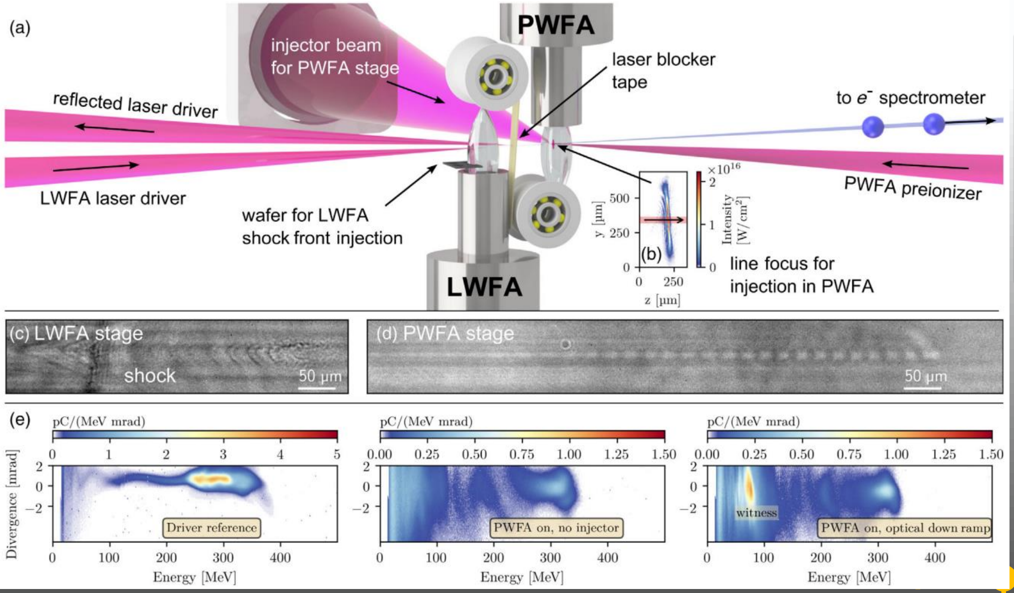
Progress in Hybrid Plasma Wakefield Acceleration, *Photonics* 10(2), 99 (2023)

Hybrid LWFA→PWFA

University of Strathclyde Glasgow

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Heinrich Heine Universität Düsseldorf



Stable and High-Quality Electron Beams from Staged Laser and Plasma Wakefield Accelerators
Foerster et al. PRX (2022)

2010
- Hybrid concept
- Mode transition
- US brightness transformer
- Driver/witness generation

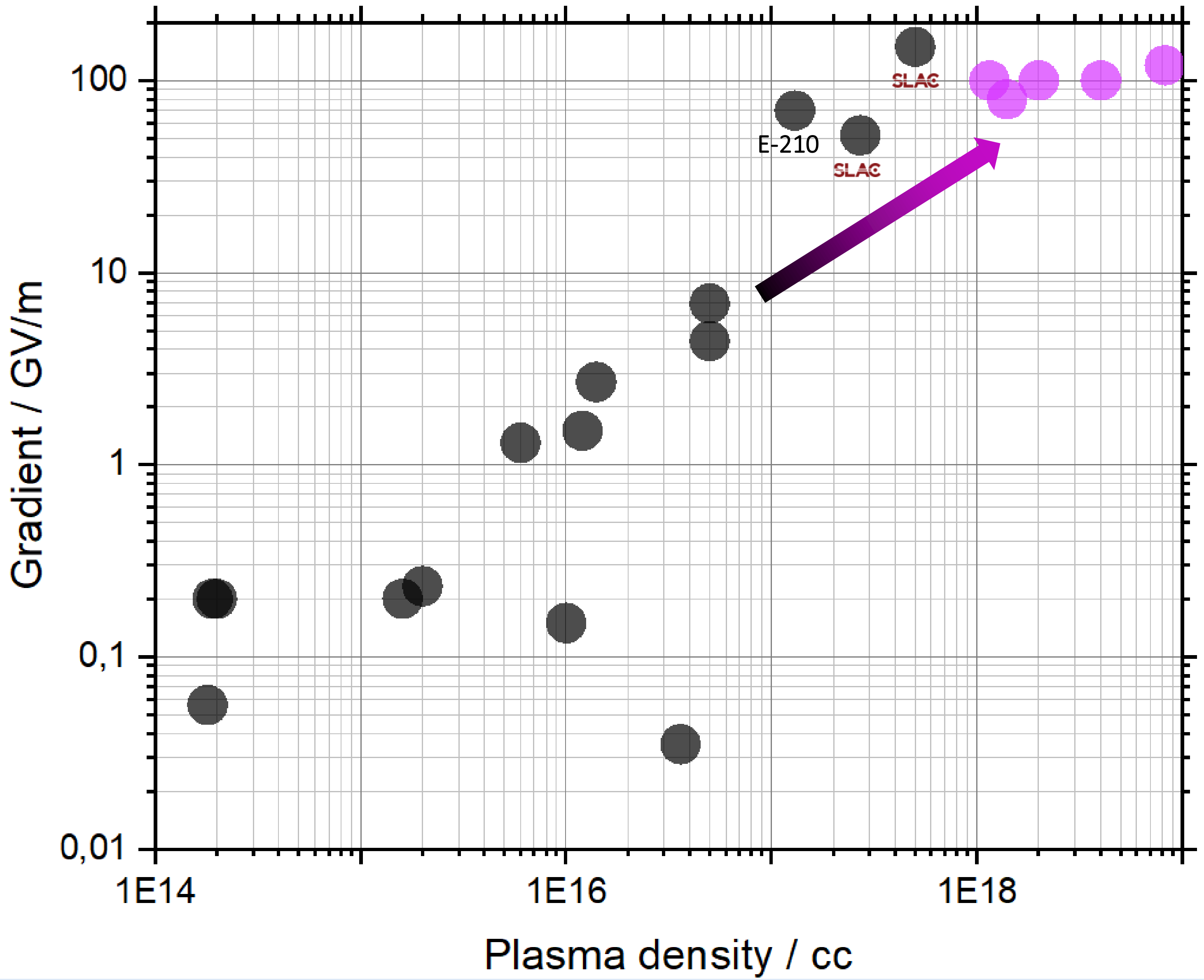
2015
- Plasma lensing
- Collective deceleration
- European Hybrid collaboration
- EuPRAXIA
- Plasma wave dynamics

2020
- Filamentation
- Physics exploration
- Hybrid LWFA→PWFA platform
- Gas-dynamic downramp injection

2022
- Shadowgraphy study
- Stability & tunability

Progress in Hybrid Plasma Wakefield Acceleration, *Photonics* 10(2), 99 (2023)

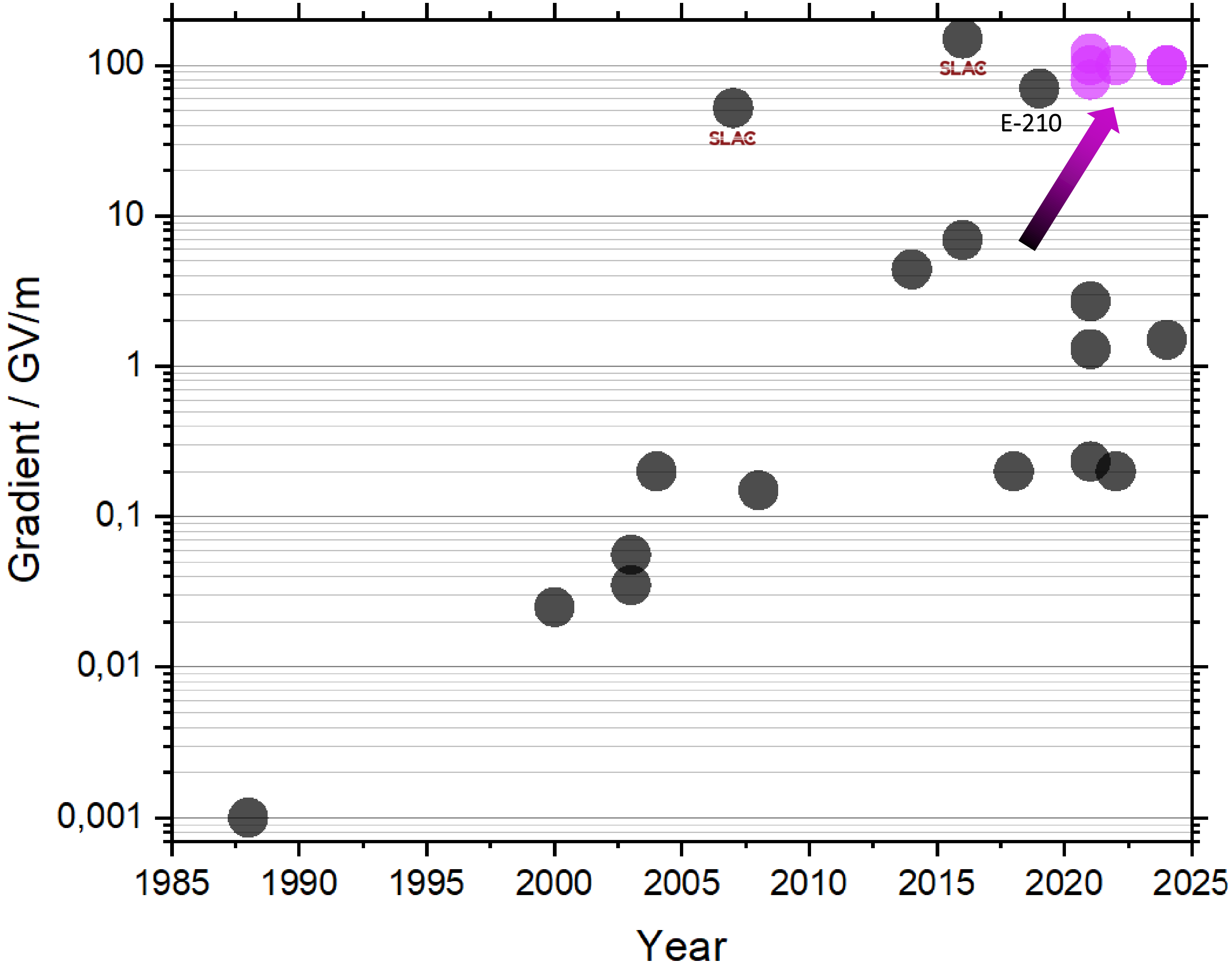
Hybrids enable resonant Strong Field-PWFA operation at 100 GV /m scale



Extends EuPRAXIA PWFA operation range by two orders of magnitude

- Linac-driven PWFA
- Hybrid LWFA→PWFA

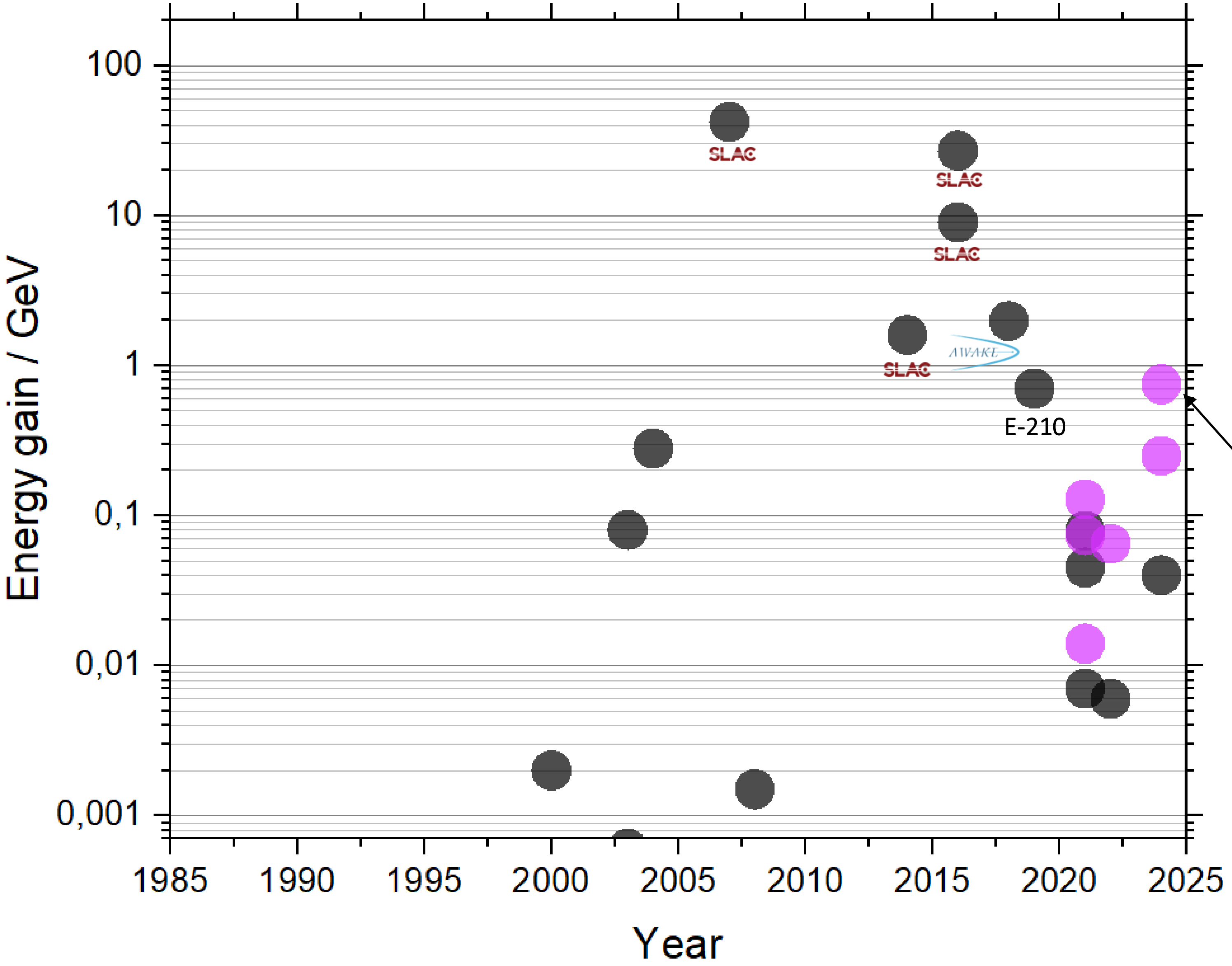
Hybrid enables resonant PWFA operation at 100 GV /m scale



Post-CDR successes

- Linac-driven PWFA
- Hybrid LWFA→PWFA

Hybrid (currently) extends energy gain by 2 orders of magnitude



Also leading energy gain results (discounting multi-km SLAC and CERN)

- Linac-driven PWFA
- Hybrid LWFA→PWFA

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

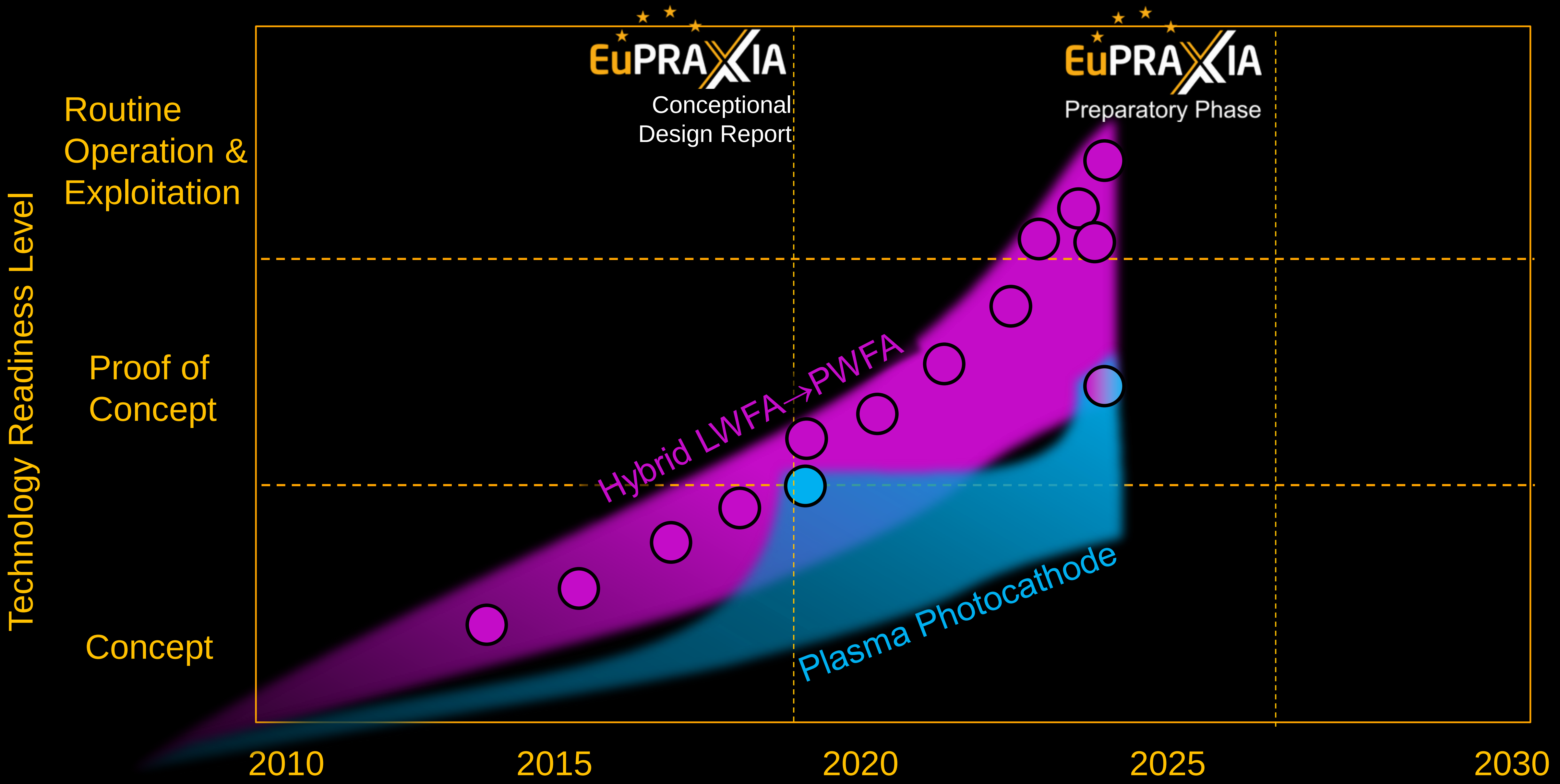
CALA

Newest energy gain record: See Stefan's talk tomorrow!

Conclusion: Hybrid LWFA→PWFA is proven technology, adds very significant capabilities

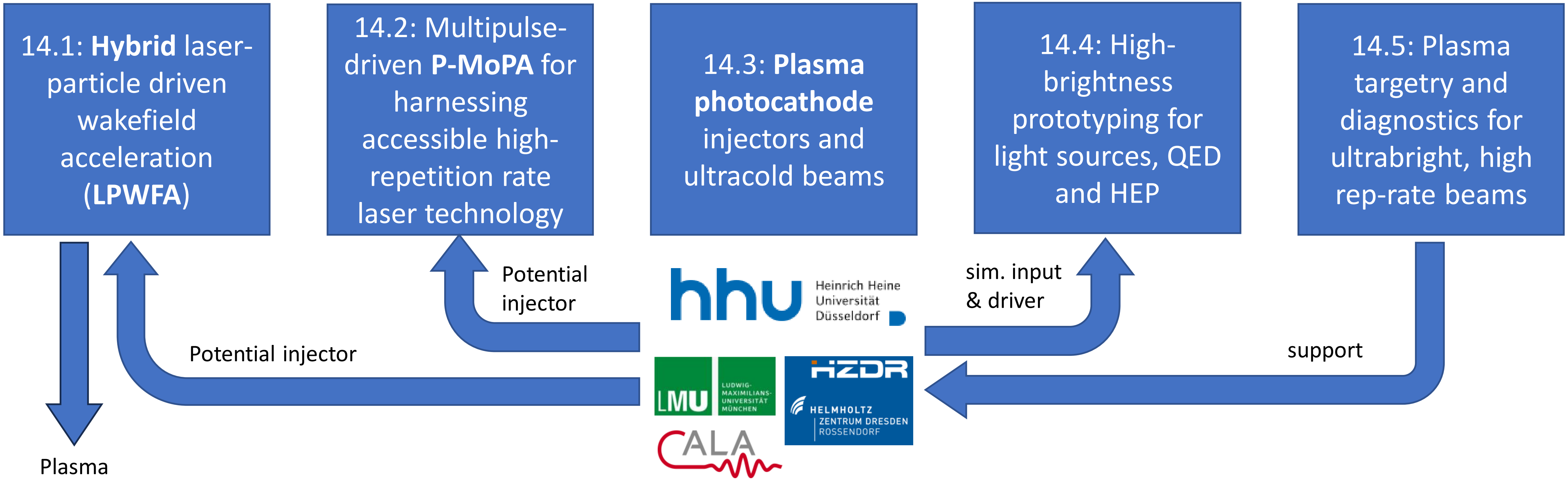
- Highest TRL obtained: routine operation
- Already enabled cutting edge PWFA (gradient, energy gain, shadowgraphy, ion motion, laser-triggered injection…)
- Extends EuPRAXIA PWFA gradient by two orders of magnitude
- Could be implemented at PWFA site
- Also relevant for LWFA site: enables dephasing-free plasma wakefield acceleration and ultracold injection schemes

Availability of strong-field PWFA outwith SLAC boosts plasma photocathode R&D



Cross-links 14.3: plasma photocathode

Funded by the European Union



Plasma photocathode
+
Hybrid
=
ultracold injector for PWFA

“plasma photocathode + hybrid as key ultracold injector technology for PWFA”

Plasma torch injection in a hybrid plasma accelerator

Facility

HZDR

Project ID

HZDR002800

Applicant Name

Bernhard Hidding

Home Institute

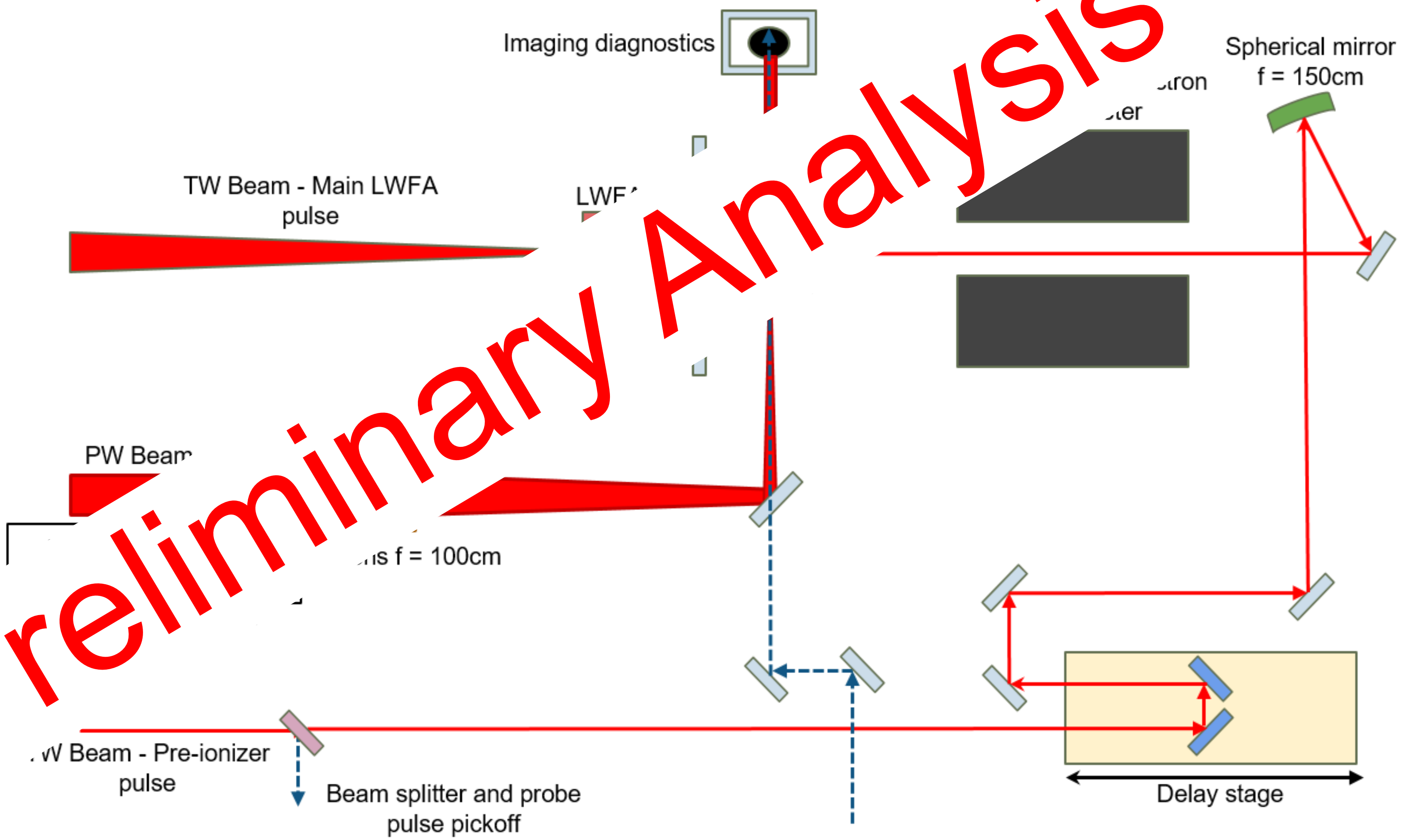
University of Strathclyde

Country

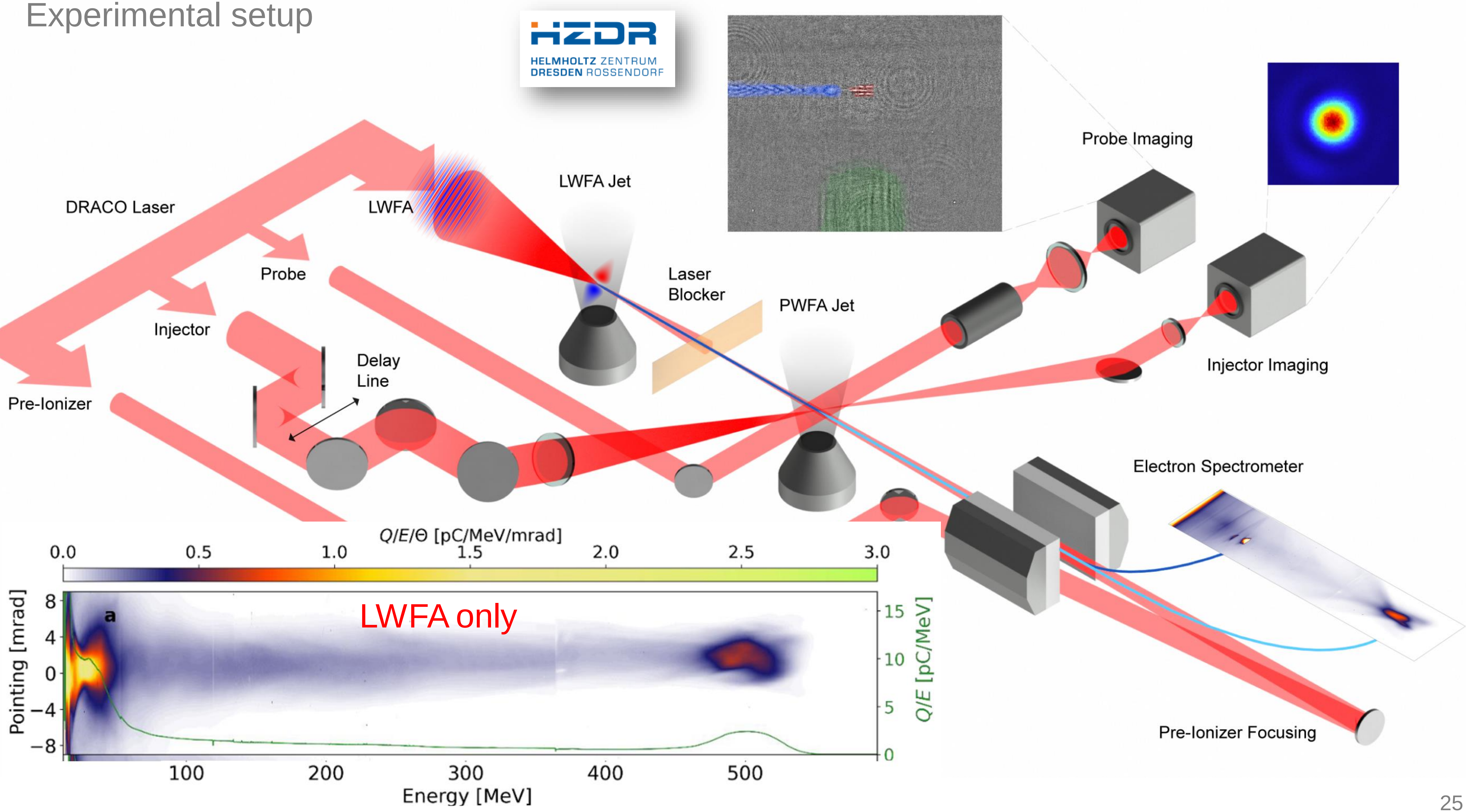
UK

year

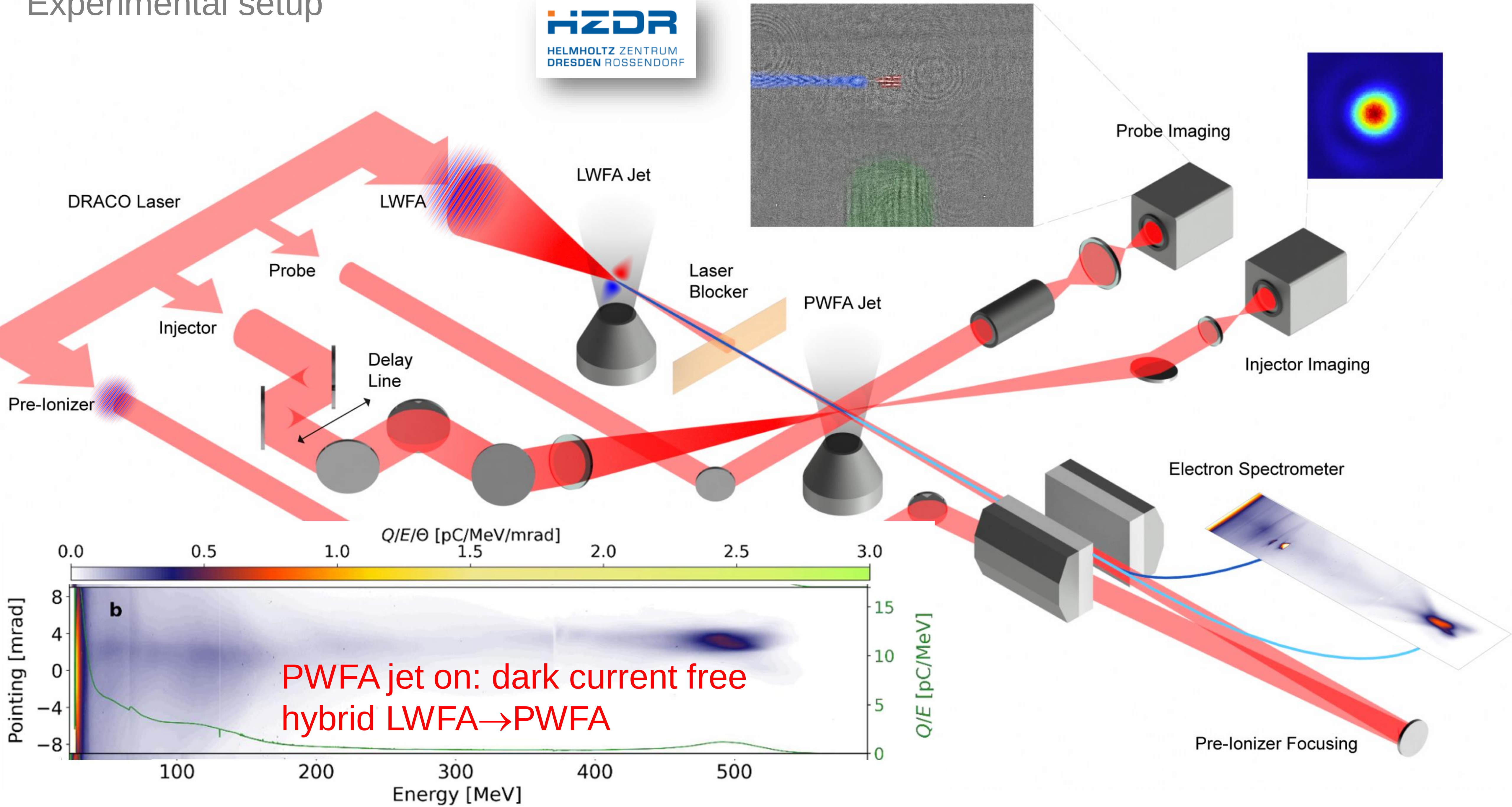
2021



Experimental setup

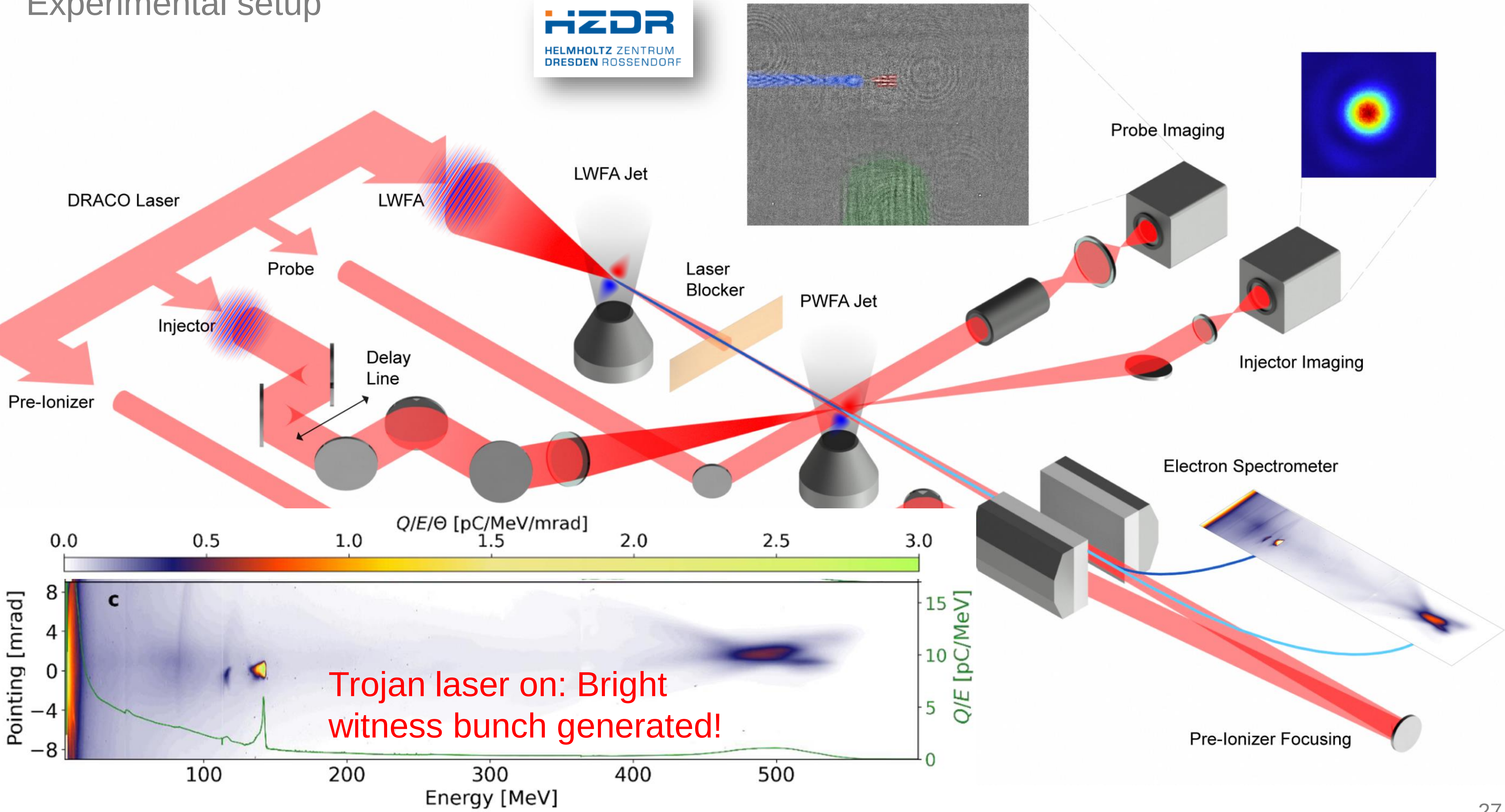


Experimental setup

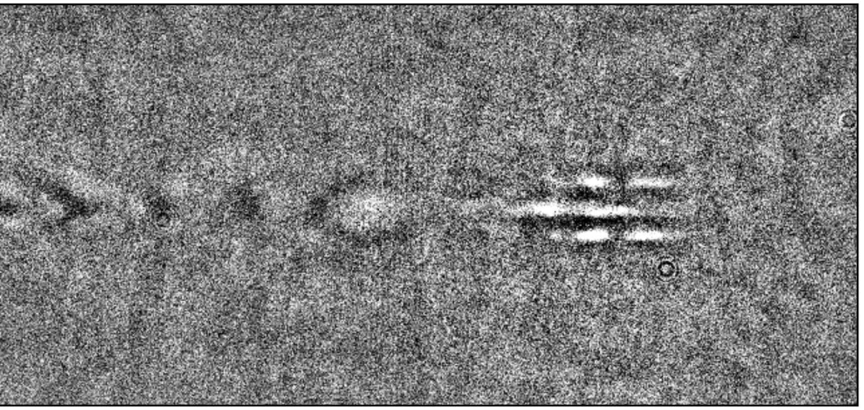


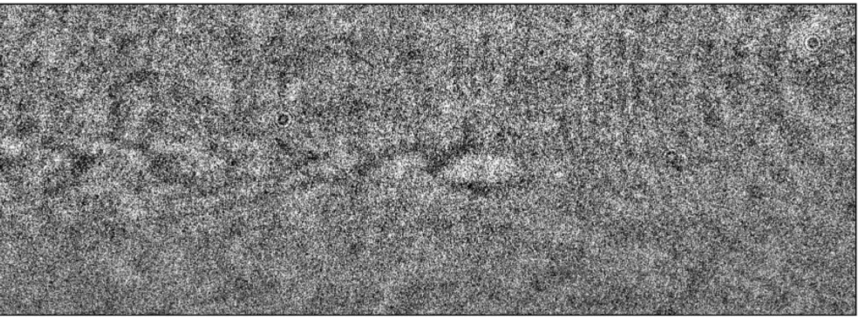
PWFA jet on: dark current free hybrid LWFA→PWFA

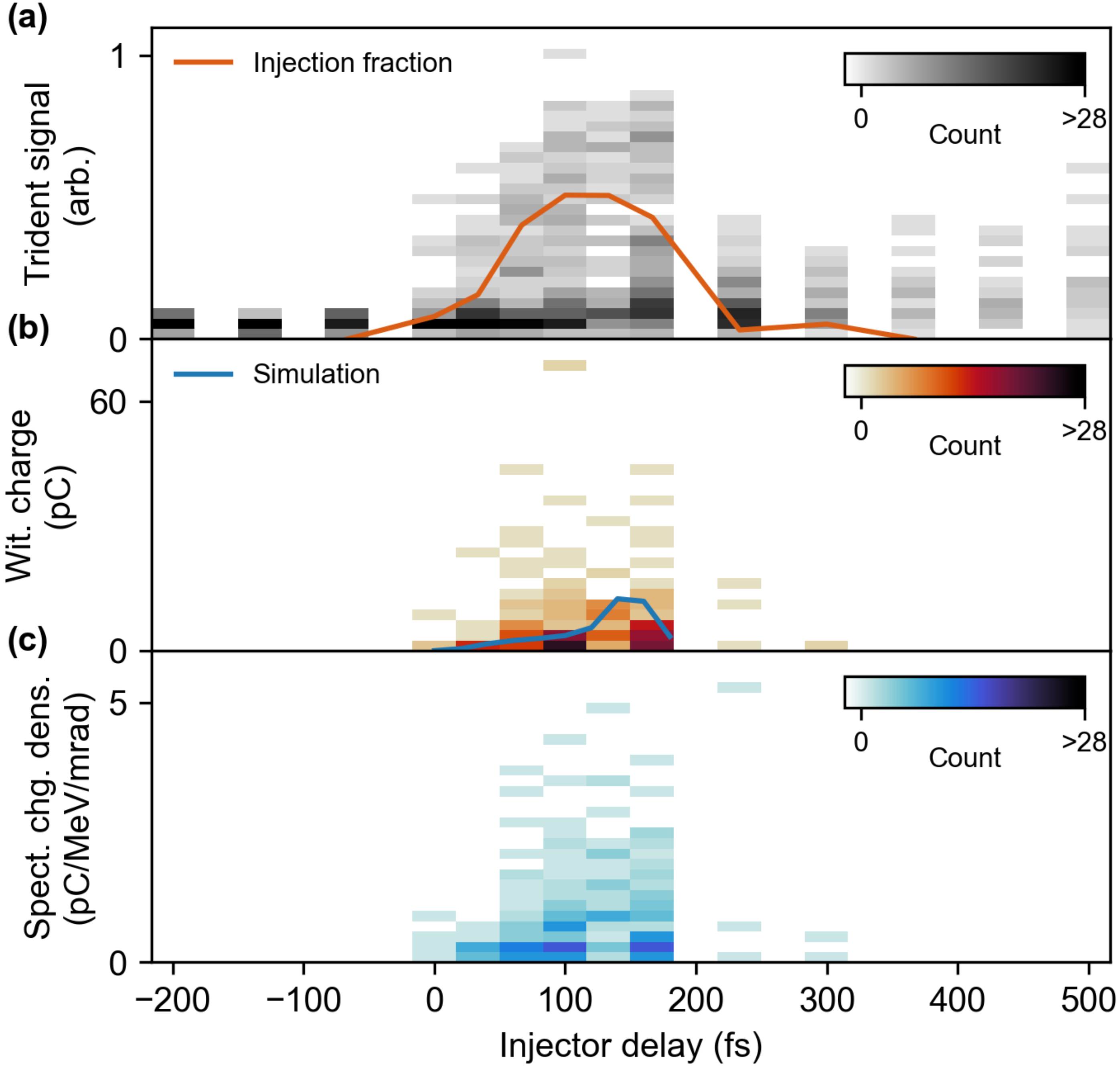
Experimental setup



Isolation and visualization of plasma photocathode

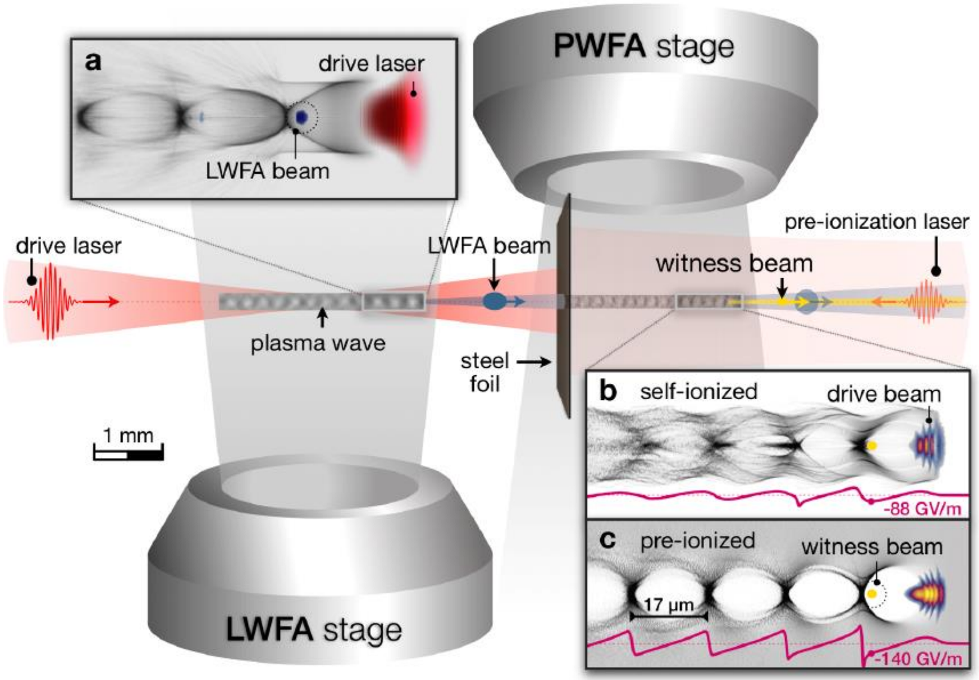


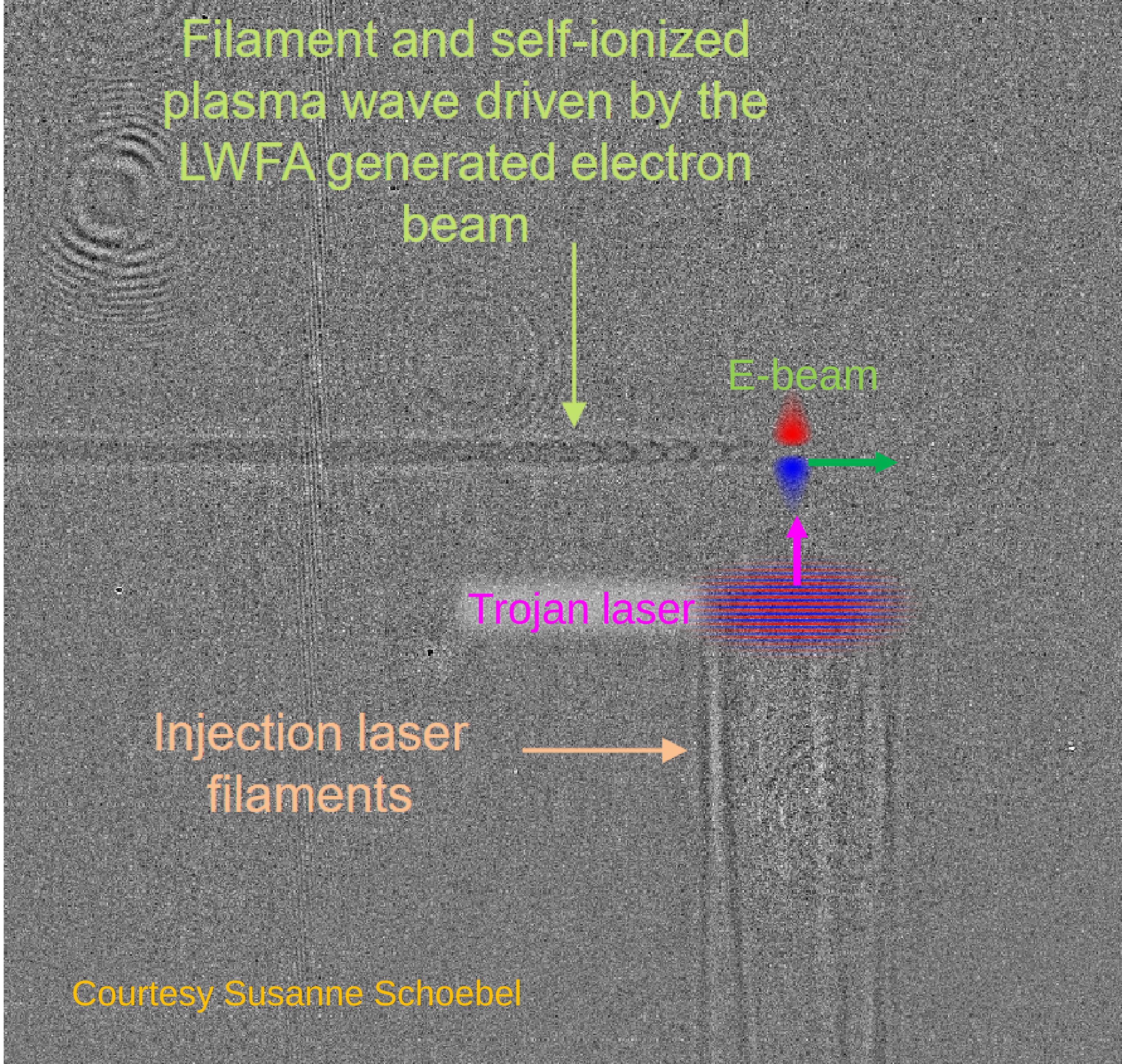




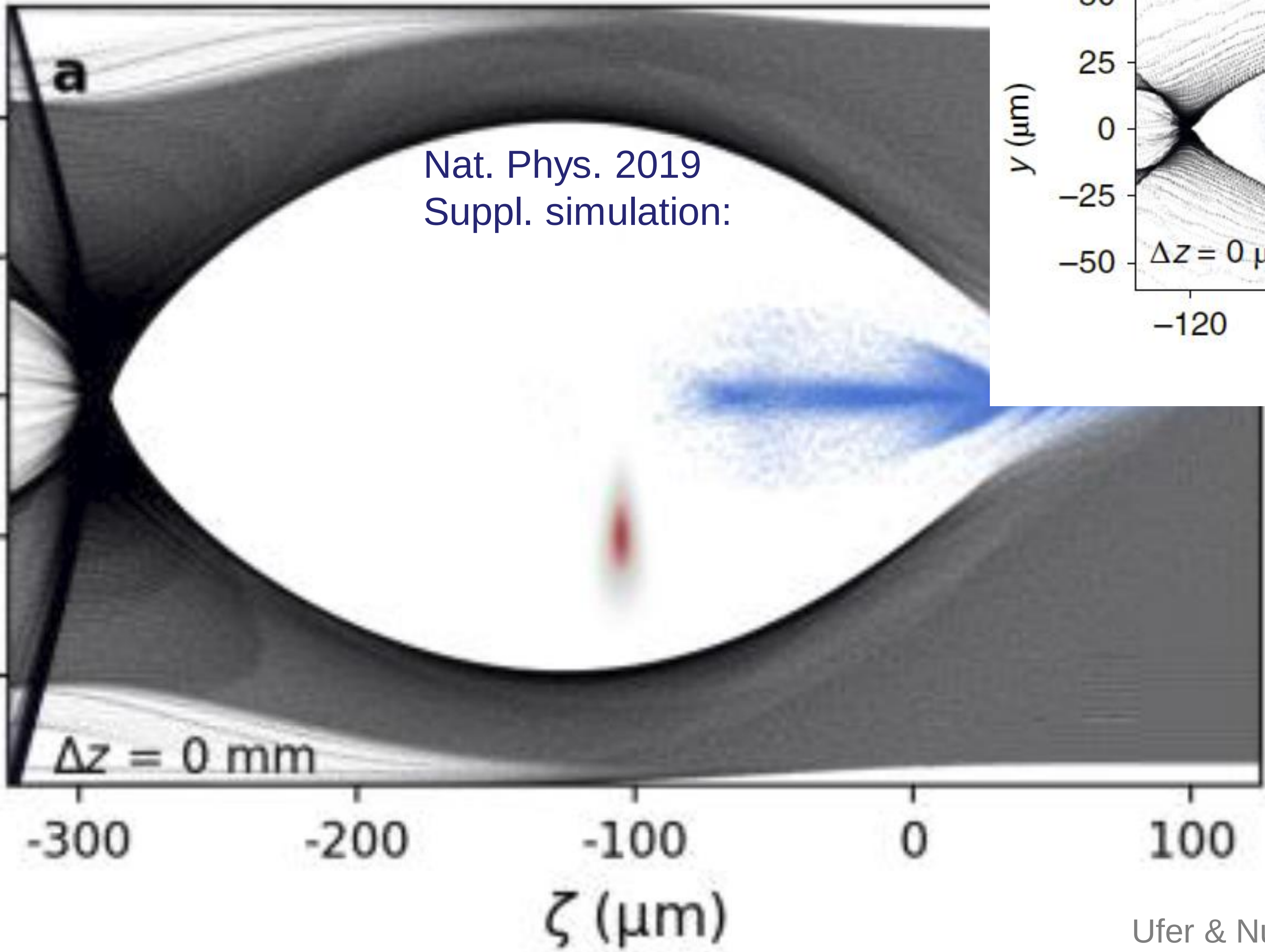
Spatiotemporal overlap

- ❑ Shadowgraphy works well at high plasma densities
- ❑ Exploits inherent "perfect" synchronization
- ❑ Allows observation of ionizing injection laser on collision course with e-beam driven wake

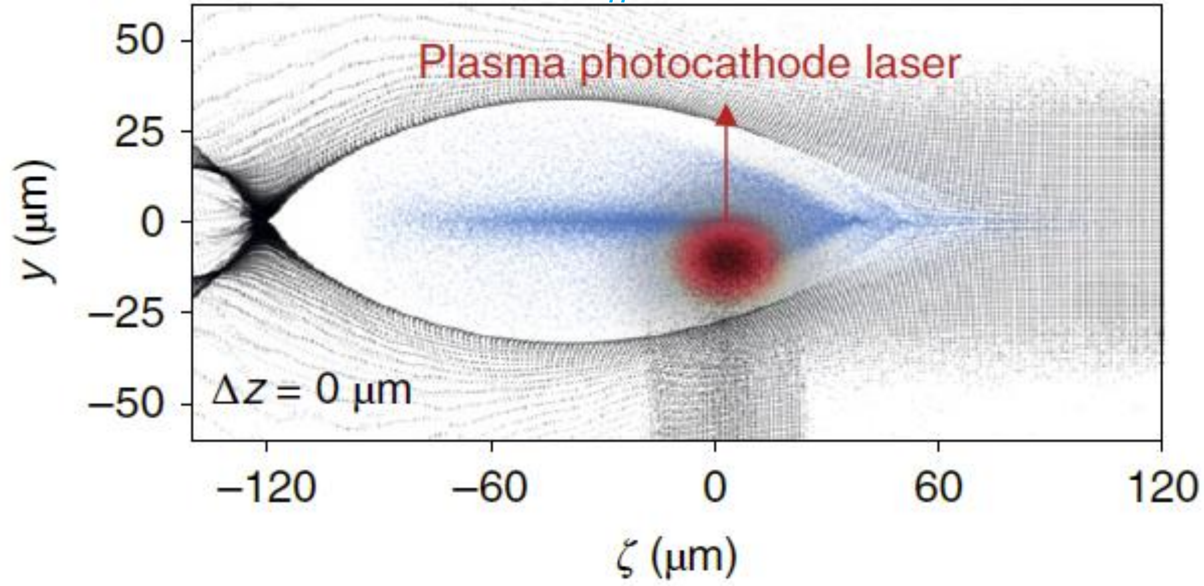




Nat. Phys. 2019
Suppl. simulation:



FACET 2017: ε_n ~1 mm mrad

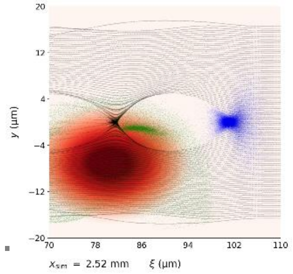


Now:

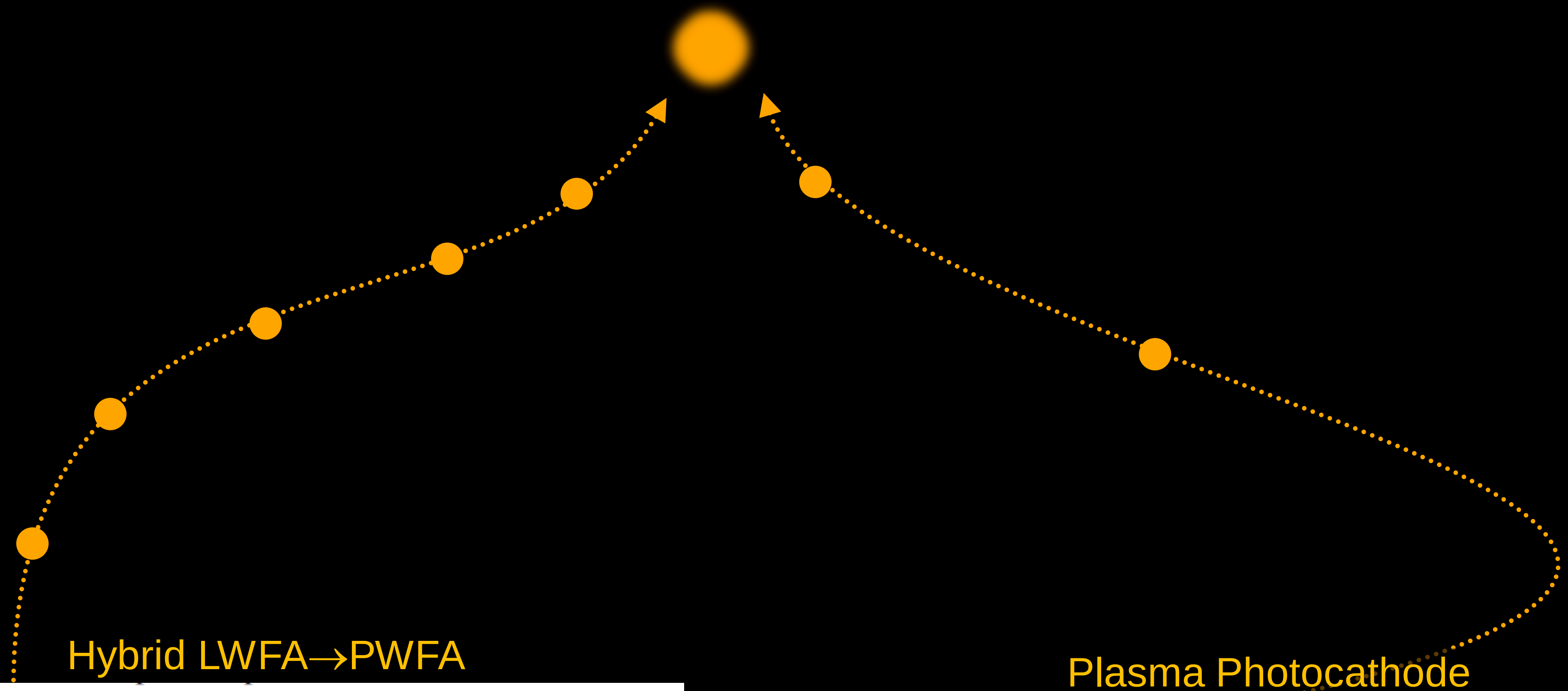
“Ultracompact plasma photocathode”

Fascinating prospects for emittance, energy spread / brightness..

Ufer & Nutter et al., in prep.



Hybrid Plasma Photocathode Wakefield Acceleration



Hybrid LWFA→PWFA

To overcome this dilemma, we propose a hybrid acceleration scheme which combines the best of both worlds. [redacted] This is the first plasma wakefield acceleration scheme which (a) provides wakefields of $E_z > 100$ GV/m, [redacted] This could strongly relax the requirements for future hybrid PWFA experiments, and still would enable to harvest the advantages of ultrashort LWFA-generated witness bunches.

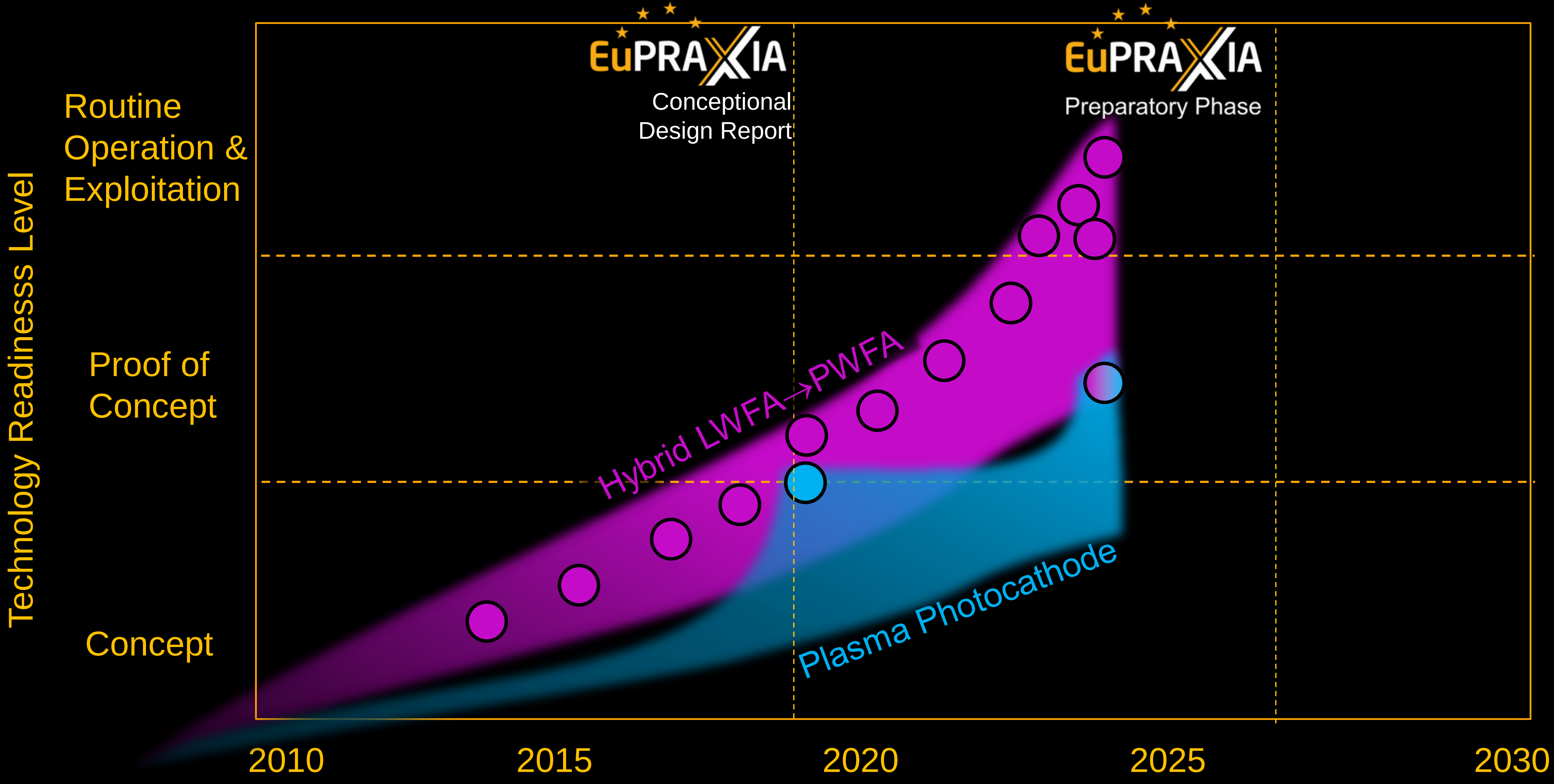
Phys. Rev. Letters 2010

Plasma Photocathode

LWFA facilities have the potential to produce all-optical versions of the presented scheme, where the main laser pulse would be used to produce the higher charge, lower phase space quality electron beam driver, and a small, inherently synchronized split-off laser pulse would be subsequently used for electron release into the blowout.

Phys. Rev. Letters 2012

Now proven ability of Hybrid LWFA→PWFA systems to host plasma photocathodes removes host bottleneck, and will accelerate progress further



14.3: Plasma photocathode injectors

Funded by the European Union

Two pathways established:
1. Linac-PWFA
2. Hybrid LWFA→PWFA

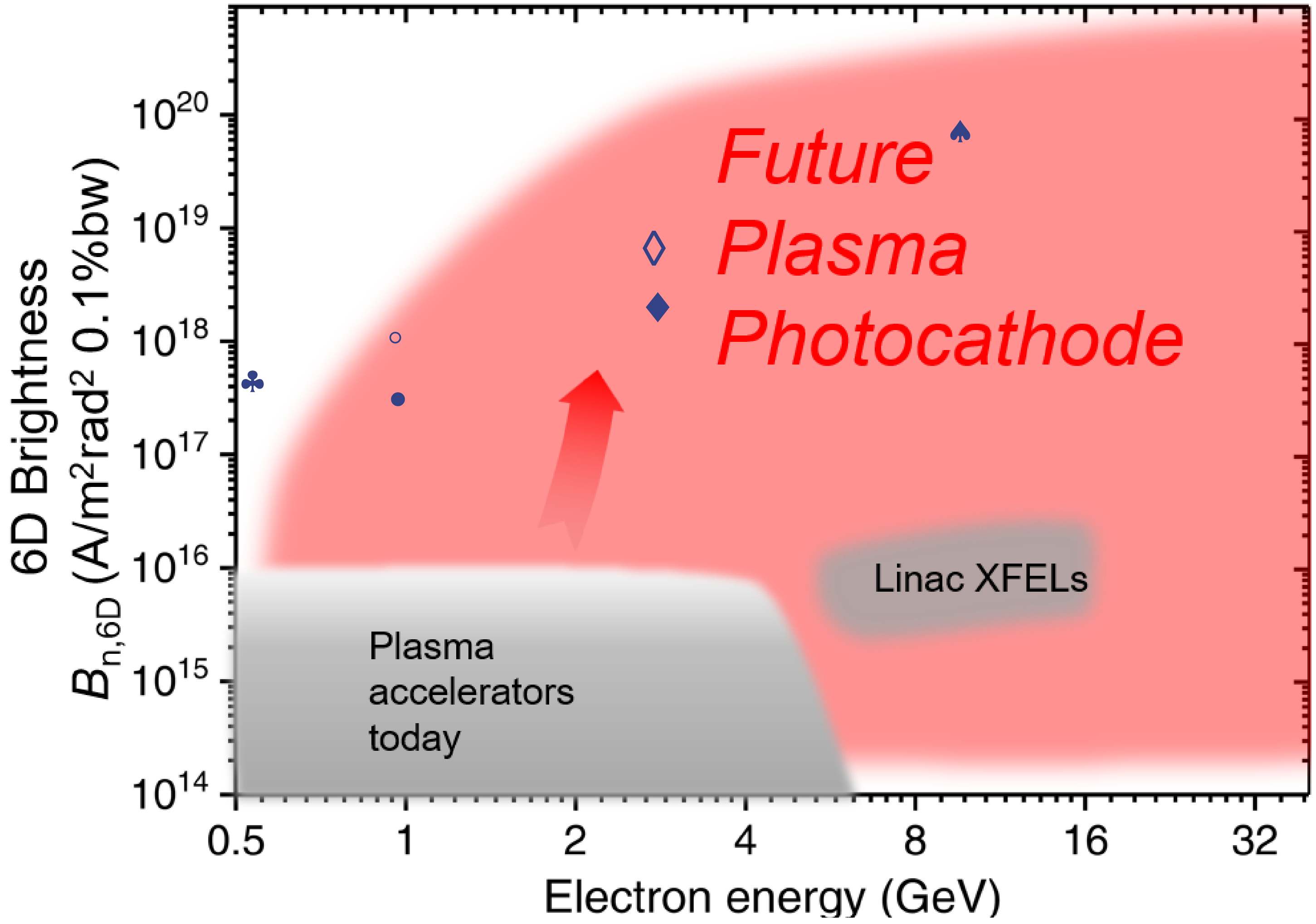
Now evidence that both can host plasma photocathodes
(i.e. relevant for both sites – strong synergies!)

♦ projected and ◊ average slice norm. 6D-brightness (Habib *et al.*, *Nat. Comm.* 2023 S2E, collinear plasma photocathode)

♣ slice brightness within reach of recently realized hybrid 90° setup

• projected and ◦ slice brightness for directly beam loaded soft X-FEL 2.3 nm

♠ projected slice norm. brightness (Habib *et al.*, Plasma Photocathodes, Annalen Physik 2023, collinear extrapolated)



Electron beam energy, and quality determines X-FEL reach and capabilities

- Electron beam 6D brightness: amalgamation of electron beam quality

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

Current

Normalized emittance

Relative energy spread

- Electron beam energy:

$$\gamma = \frac{E_{\mathrm{kin}}}{E_0} + 1$$

- Emittance and energy determine coherent photon energy

$$\epsilon_{\mathrm{n}} < \lambda_r \langle \gamma \rangle / 4\pi$$

Resonant FEL wavelength

- Brightness determines gain

$$L_{\mathrm{gain}} \propto B_{6\mathrm{D}}^{-1/3}$$

At given emittance, increasing the beam energy can give you harder photons

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

J. Rossbach, J.R. Schneider and W. Wurth / Physics Reports 808 (2019) 1–74 11

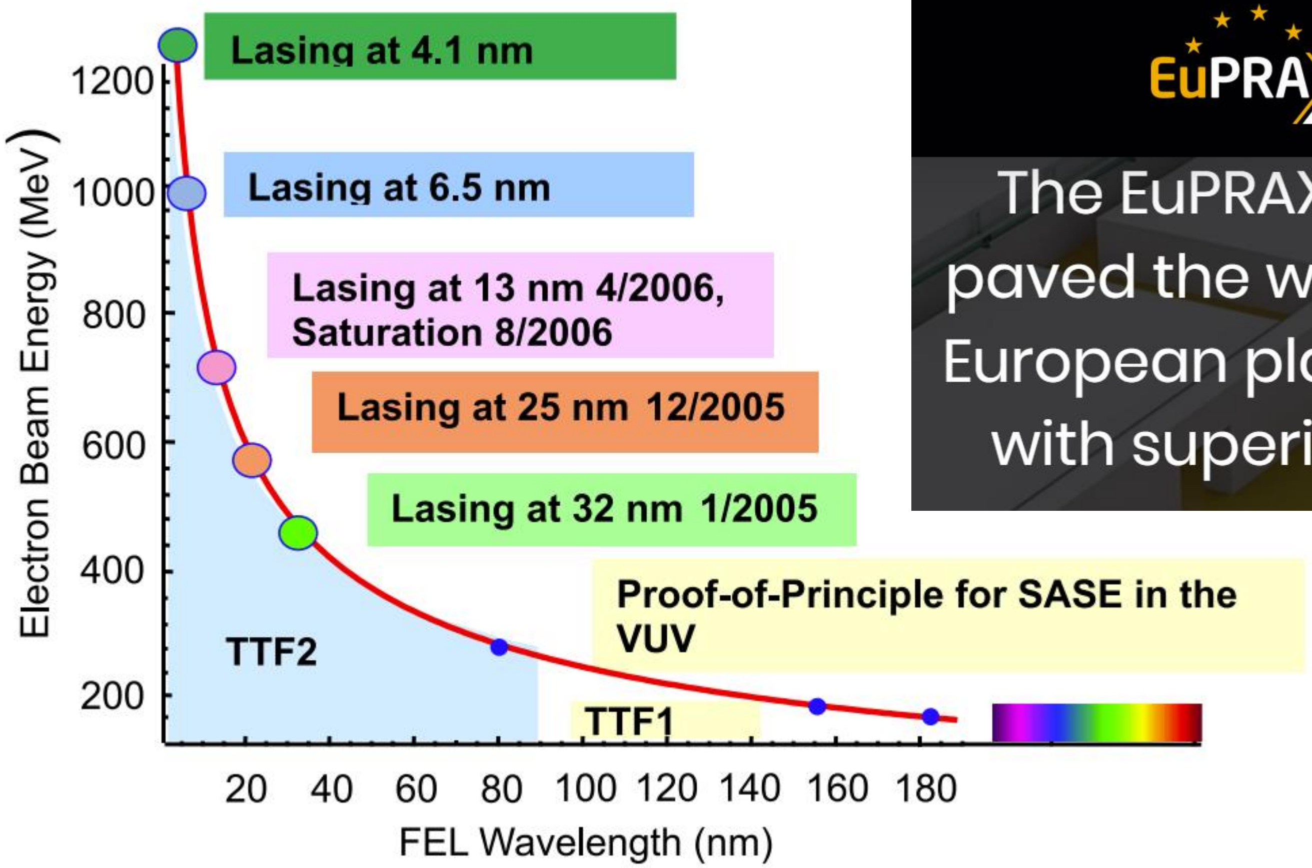
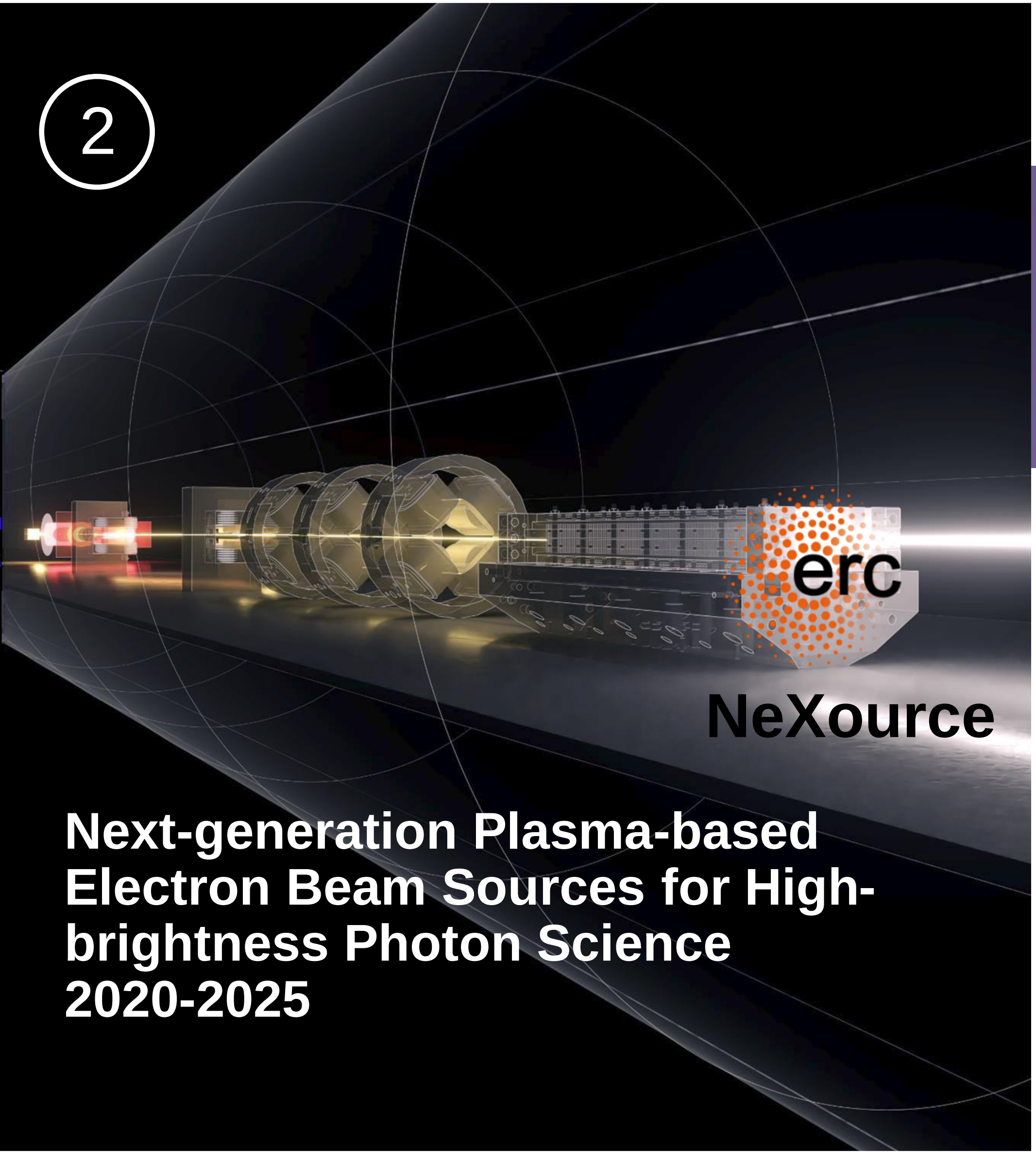


Fig. 9. History of world record demonstrations of FEL gain at shorter and shorter wavelengths at FLASH. In all cases, FEL saturation was achieved and agreement with FEL theory could be proven.

14.4: High-brightness prototyping for Light Sources, e.g. (X)FEL driven by plasma photocathode beams

Funded by the European Union



UK RI Science and Technology Facilities Council

PWFA-FEL 2019-2024

1

Plasma wakefield, beam transport and X-FEL experts in the UK (Strathclyde & Daresbury) and the US (SLAC and UCLA) team up to explore and develop Trojan Horse and other PWFA-based ultrabright future X-FEL sources in a project called **Exploratory Study of PWFA-driven FEL at CLARA** funded by the UK Sciene and Technologies Facilities Council (STFC) 2019-2023.

First large XFEL project that considers plasma as brightness and/or energy boosters right from the onset

Hard XFEL S2E Showcase

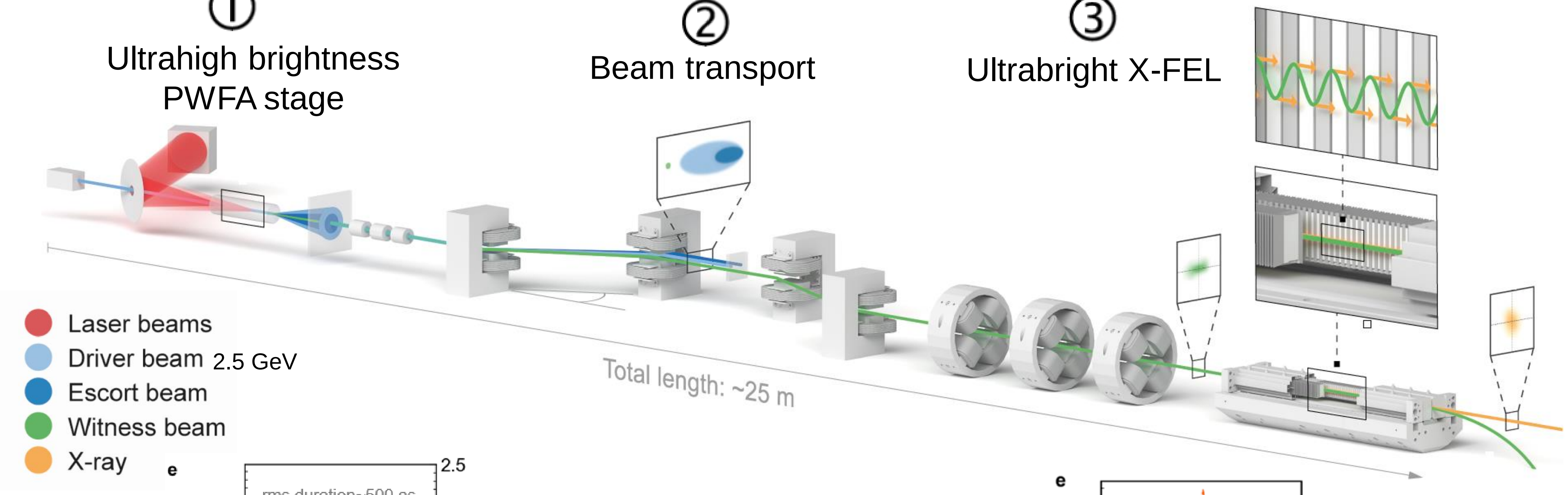
Attosecond-Angstrom free-electron-laser towards the cold beam limit, F. Habib et al, Nat. Comm. 2023

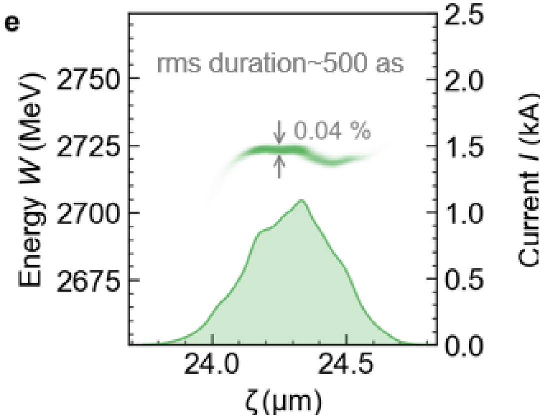
Funded by the European Union

① Ultrahigh brightness PWFA stage

② Beam transport

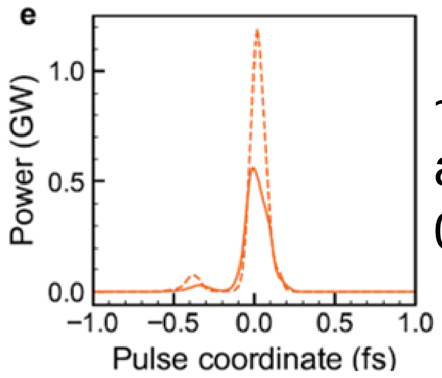
③ Ultrabright X-FEL





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

20 nmrad | 0.8 Å | 2.7 GeV

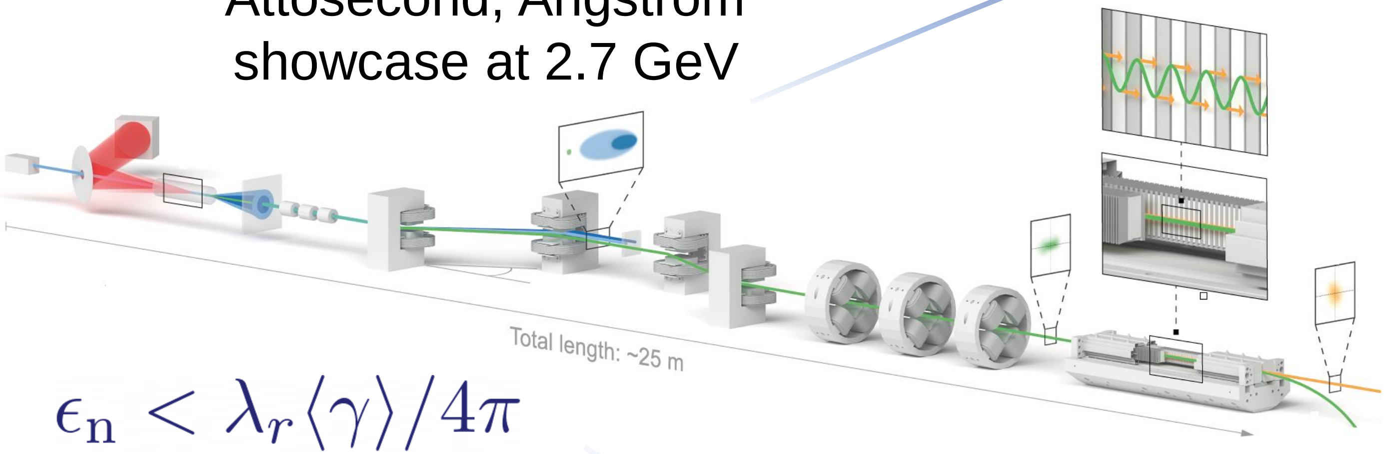


~100 attoseconds, 0.8 Å

Examples for further developments

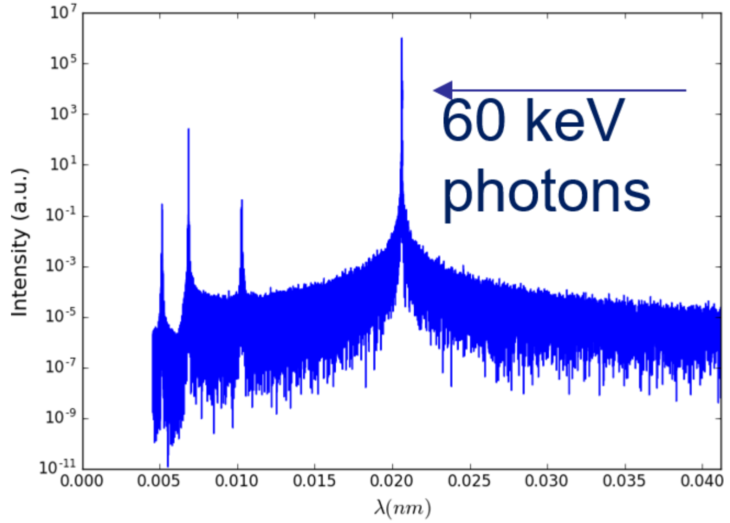
UK XFEL CDR-Option Analysis Project (2022-2025)

Attosecond, Angstrom showcase at 2.7 GeV



$$\epsilon_{\mathrm{n}} < \lambda_r \langle\gamma\rangle / 4\pi$$

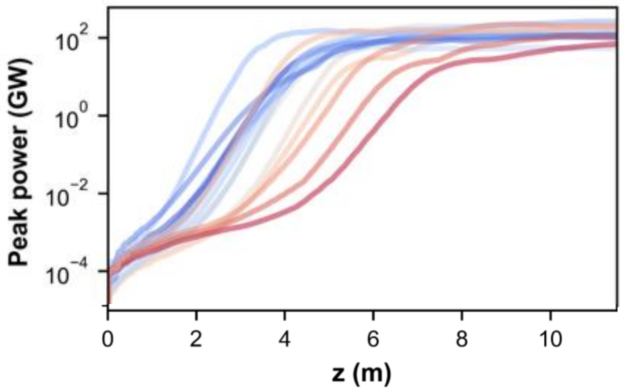
E.g. Towards higher photon energies



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

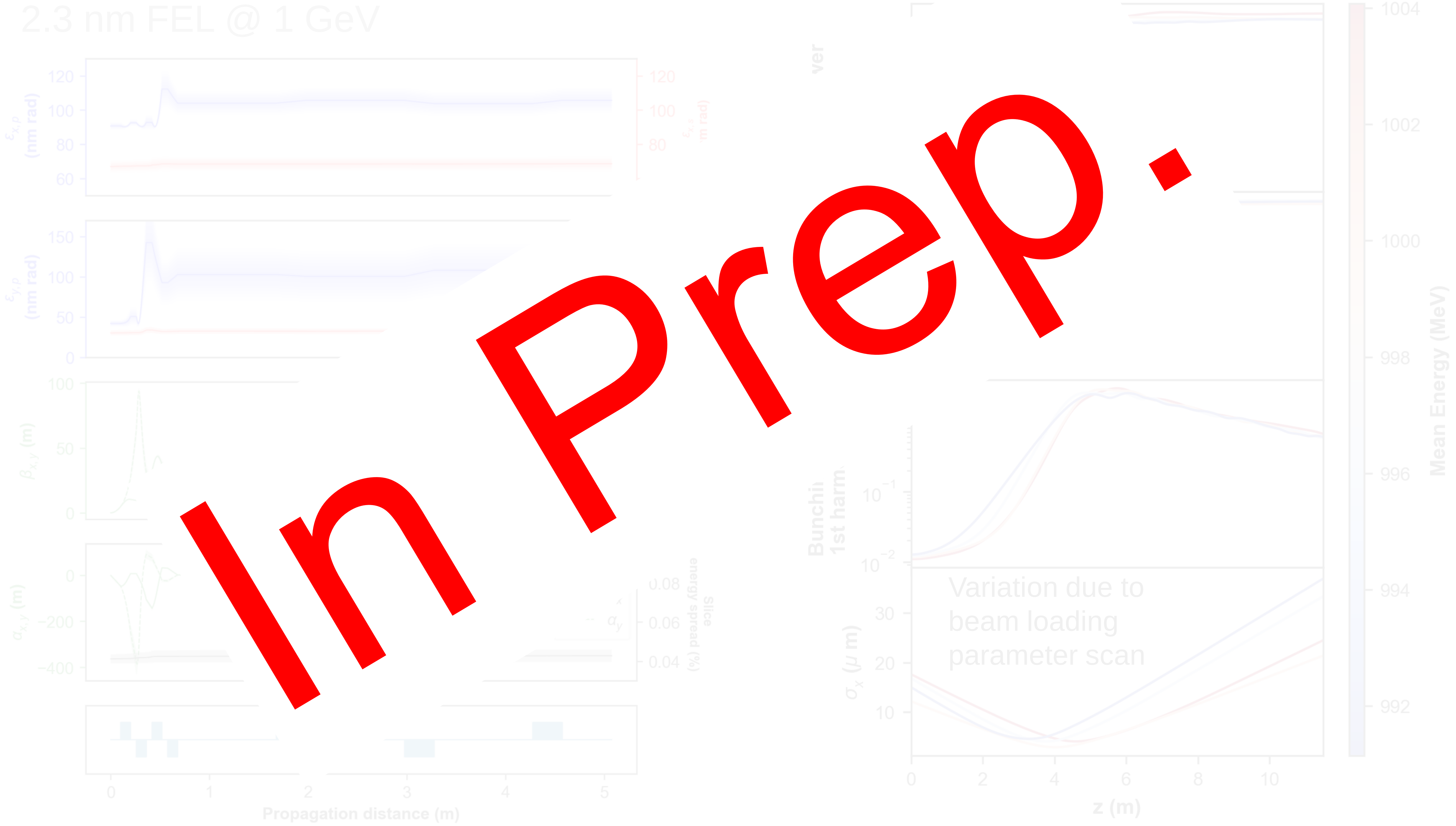
2.3 nm FEL at ~1 GeV: Direct beam-loading, standard undulator, reduced & shorter setup

L. Berman et al., in prep.



Many 10s pC,
Sub-100/50 nm slice emittances
robust & efficient

2.3 nm FEL @ 1 GeV



Contents

- Context and new members
- TRL Status and Evolution
- Potential impact for ESFRI
- Integration options for EuPRAXIA sites
- Structures to be funded

Deliverables / Structures to be funded

- 2^{nd} generation hybrid LWFA→PWFA beamline.
  Dual Use:
  1. Expand PWFA capabilities at INFN (e.g. 1 GV/m→100GV/m)
  2. Implement PWFA capabilities at LWFA site

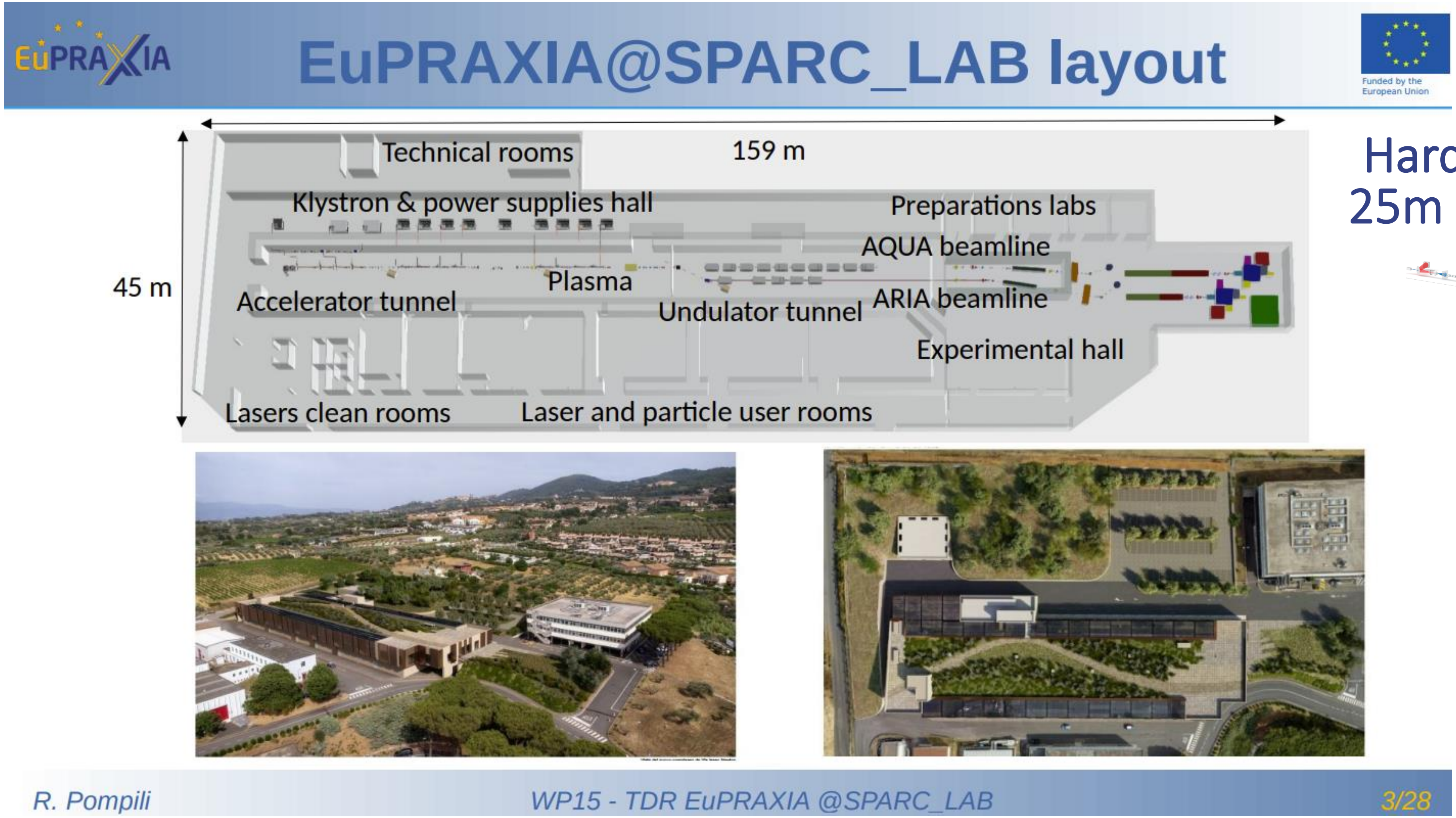
- Ultrabright photon sources (UPS) based on ultracold sources such as plasma photocathode, driven by linac, hybrid or multi-pulse LWFA.
  Enhance beam brightness by orders of magnitude & harness for light sources

- Doctoral Training Centre

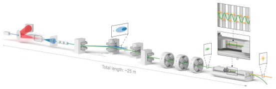
- Junior Research Groups

Backup

Footprint?



Hard XFEL S2E:
25m (excl. laser)



Energy spread control *inside the plasma*

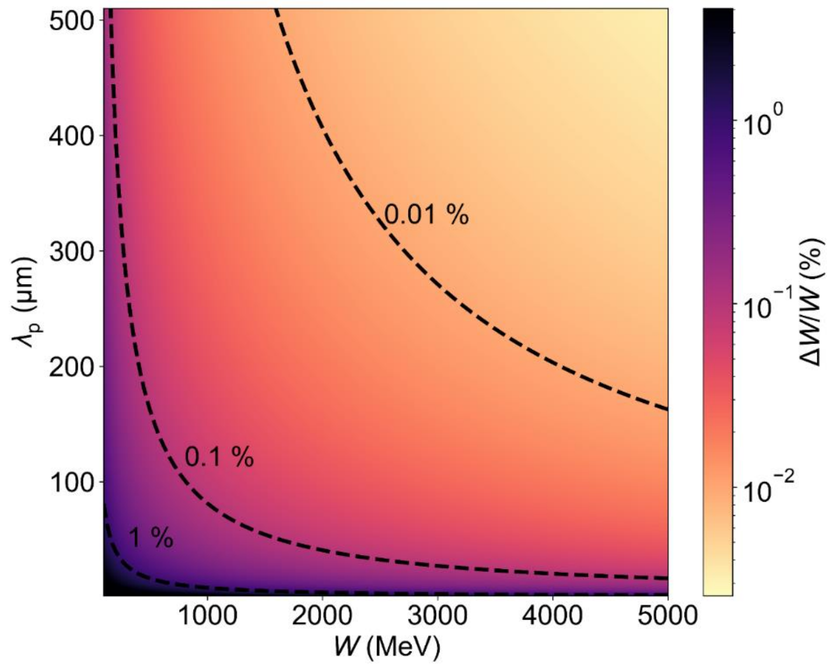
nature COMMUNICATIONS

ARTICLE

Received 16 Dec 2016 | Accepted 21 Apr 2017 | Published 5 Jun 2017 DOI: 10.1038/ncomms15705 OPEN

Single-stage plasma-based correlated energy spread compensation for ultrahigh 6D brightness electron beams

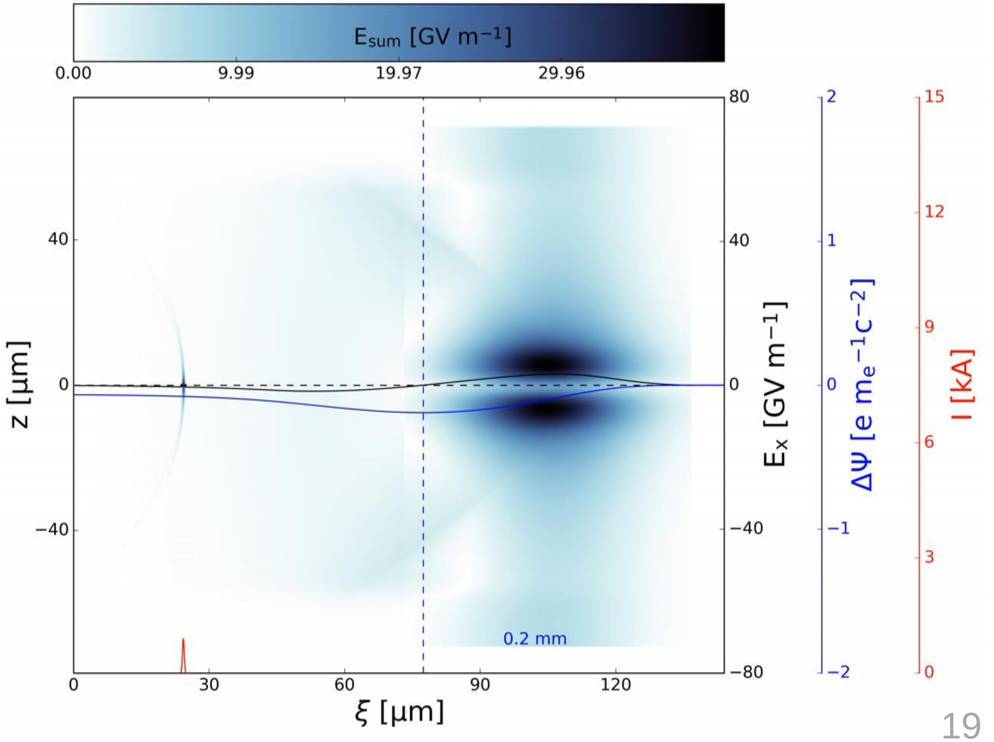
G.G. Manahan[1,2], A.F. Habib[1,2,3], P. Scherkl[1,2], P. Delinikolas[1,2], A. Beaton[1,2], A. Knetsch[3], O. Karger[3], G. Wittig[3], T. Heinemann[1,2,3,4], Z.M. Sheng[1,2,5], J.R. Cary[6], D.L. Bruhwiler[7], J.B. Rosenzweig[8] & B. Hidding[1,2]



- Exploit tailored beam loading via “escort beams“ to locally flip field accelerating field gradient

- Full head-to-tail chirp compensation

- Operation at low plasma density minimizes residual energy spread, and e.g. energy spreads < 0.01% can be reached at few GeV energies ⇒ 6D brightness orders of magnitude better than state-of-the-art of even the finest linacs



Article nature communications https://doi.org/10.1038/s41467-023-36592-z

Attosecond-Angstrom free-electron-laser towards the cold beam limit

Received: 30 March 2022

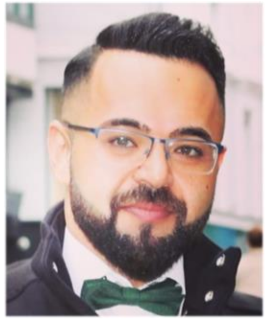
Accepted: 8 February 2023

Published online: 24 February 2023

A. F. Habib[1,2], G. G. Manahan[1,2], P. Scherkl[1,2,3], T. Heinemann[1,2], A. Sutherland[1,2], R. Altuiri[1,4], B. M. Alotaibi[1,4], M. Litos[5], J. Cary[5,6], T. Raubenheimer[7], E. Hemsing[7], M. J. Hogan[7], J. B. Rosenzweig[8], P. H. Williams[2,9], B. W. J. McNeil[1,2] & B. Hidding[1,2,10]

Electron beam quality is paramount for X-ray pulse production in free-electron-lasers (FELs). State-of-the-art linear accelerators (linacs) can deliver multi-GeV electron beams with sufficient quality for hard X-ray-FELs, albeit requiring km-scale setups, whereas plasma-based accelerators can produce multi-GeV electron beams on metre-scale distances, and begin to reach beam qualities sufficient for EUV FELs. Here we show, that electron beams from plasma photocathodes many orders of magnitude brighter than state-of-the-art can be generated in plasma wakefield accelerators (PWFAs), and then extracted, captured, transported and injected into undulators without significant quality loss. These ultrabright, sub-femtosecond electron beams can drive hard X-FELs near the cold beam limit to generate coherent X-ray pulses of attosecond-Angstrom class, reaching saturation after only 10 metres of undulator. This plasma-X-FEL opens pathways for advanced photon science capabilities, such as unperturbed observation of electronic motion inside atoms at their natural time and length scale, and towards higher photon energies.

Output of the STFC-funded UK-US collaborative project on “PWFA-FEL“ 2019-2024



Fahim Habib

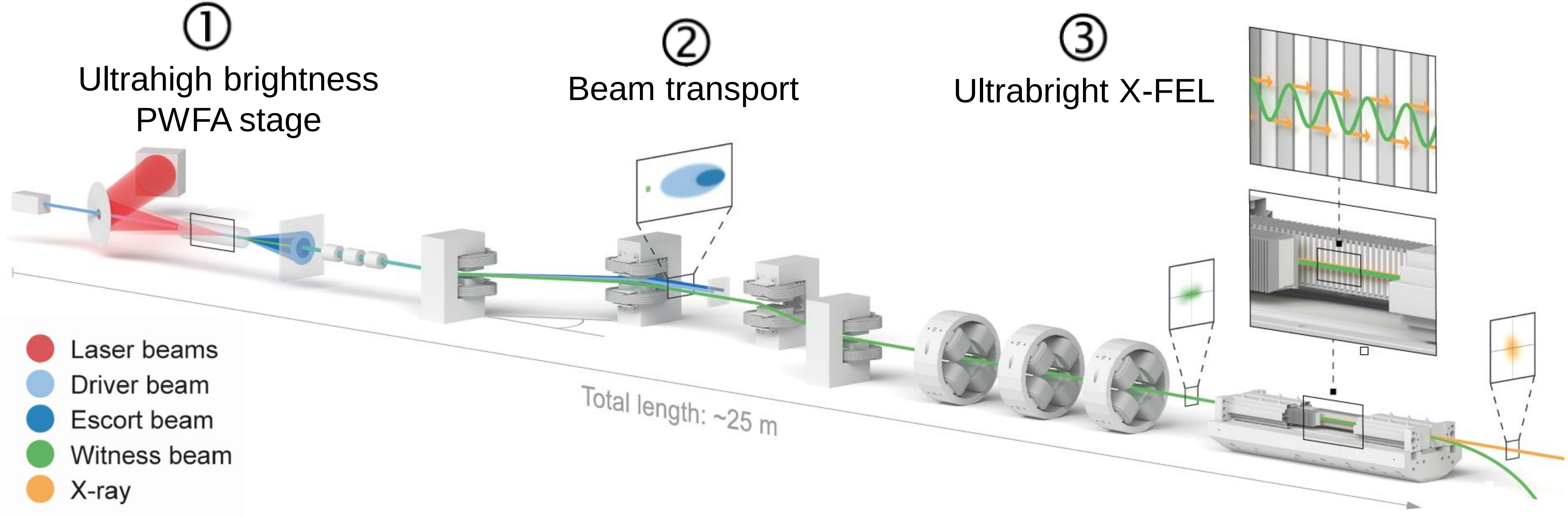
University of Strathclyde Glasgow

UKRI Science and Technology Facilities Council

UCLA SLAC

http://pwfa-fel.phys.strath.ac.uk/

High-fidelity start-to-end-simulation framework

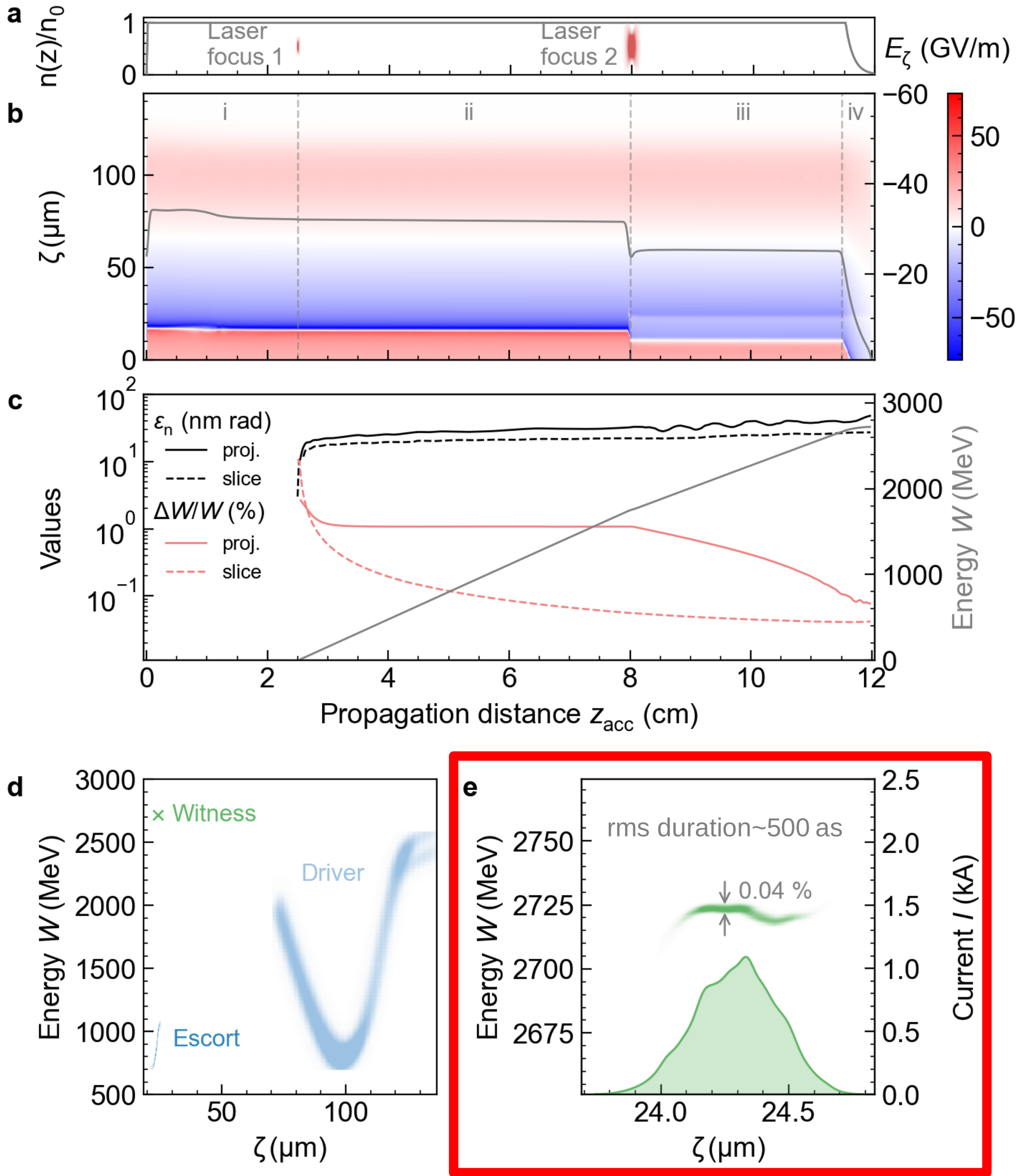


- ❑ Multi-cm scale PIC with of nmrad-scale beams is very challenging and expensive
- ❑ 3D PIC code VSim
- ❑ Numerical noise controlled with dispersion-free module

- ❑ Beam tracking performed with ELEGANT
- ❑ Complete 6D phase space of the witness, drive and escort beams are considered

- ❑ Unaveraged 3D FEL code Puffin developed by Strathclyde
- ❑ Introduced proper Poissonian ‘shot-noise’ to the electron beam
- ❑ Undulator B-fields implemented in 3D

Ultrahigh brightness PWFA stage

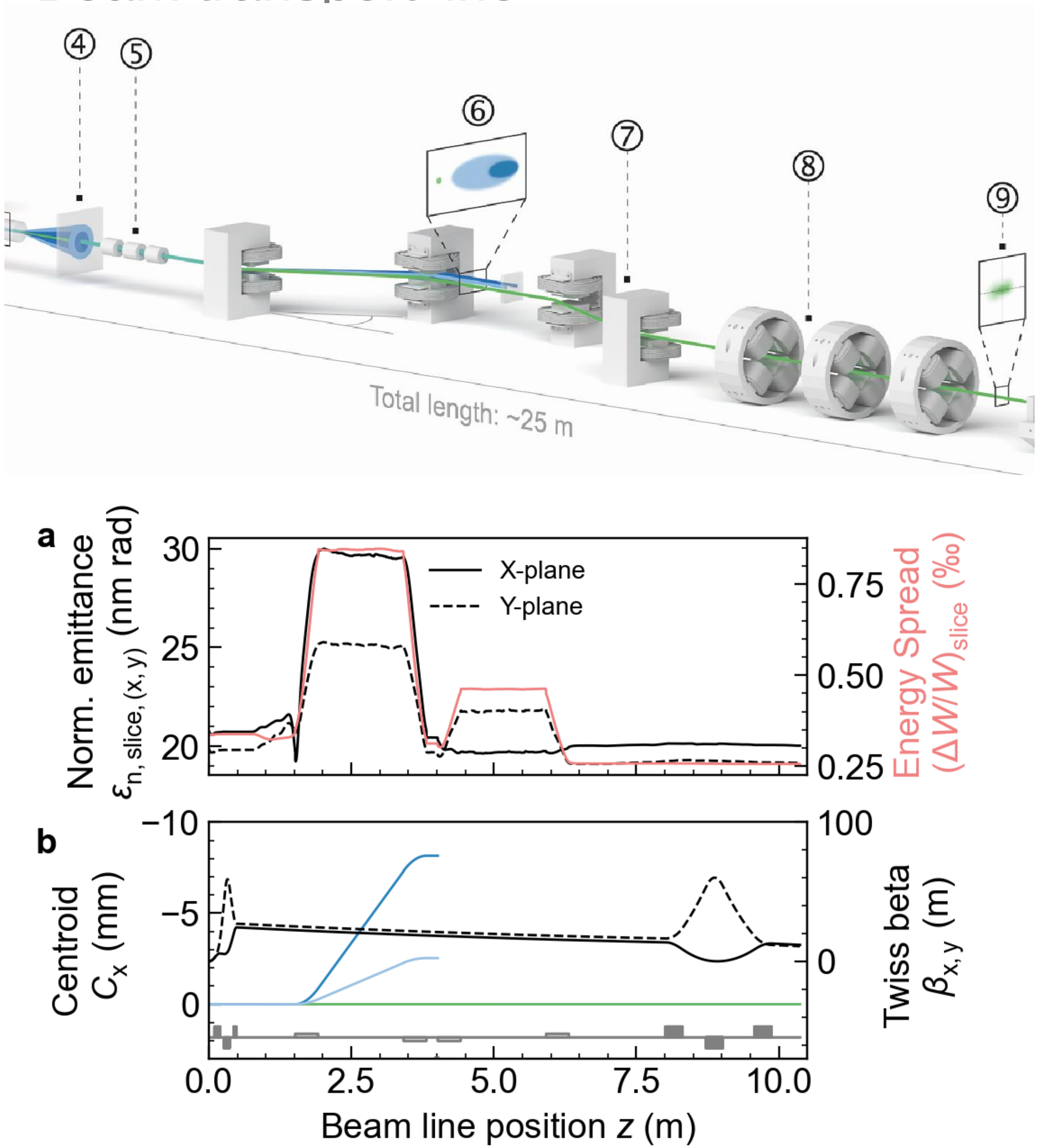


- ❑ 2.5 GeV, high current driver beam drives strong PWFA
- ❑ High quality witness beam is produced, accelerated, dechirped and extracted without quality degradation in single plasma stage

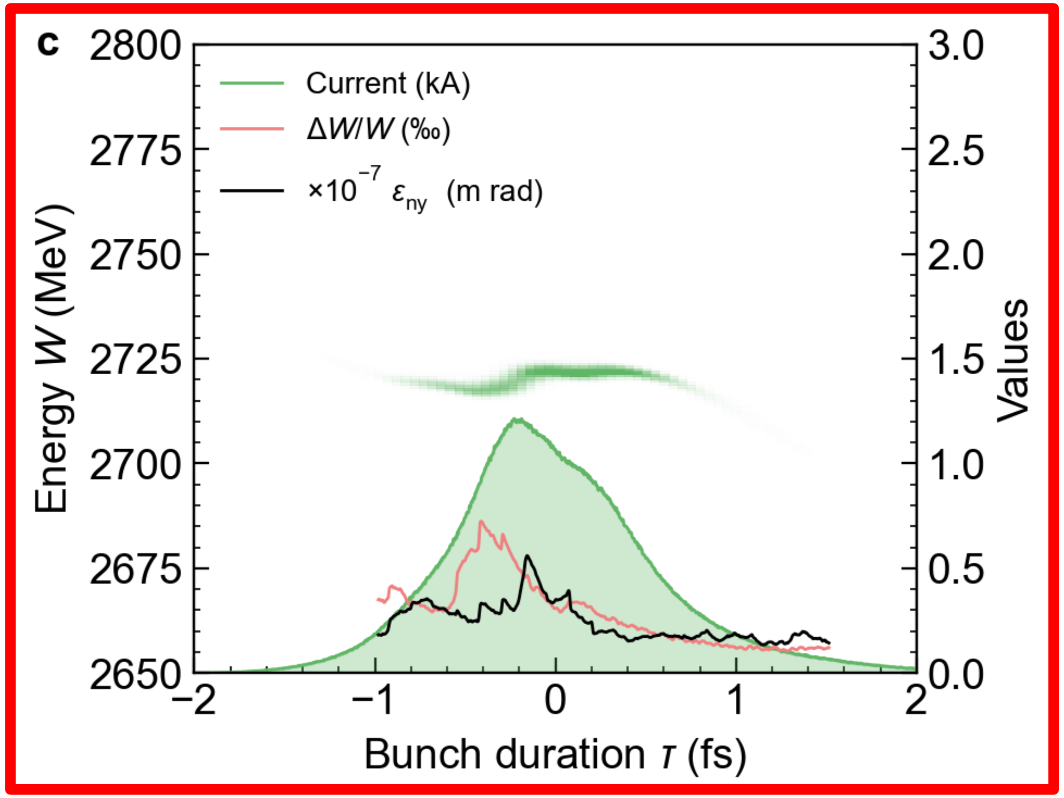
Witness beam at plasma stage exit:

- ❑ ~2.7 GeV (significantly larger than driver and escort beam)
- ❑ Norm. slice emittance ~20 nm rad (projected emittance similar)
- ❑ Slice energy spread~ 0.04%
- ❑ Bunch duration 500 attoseconds
- ❑ Peak current~ 1.2 kA

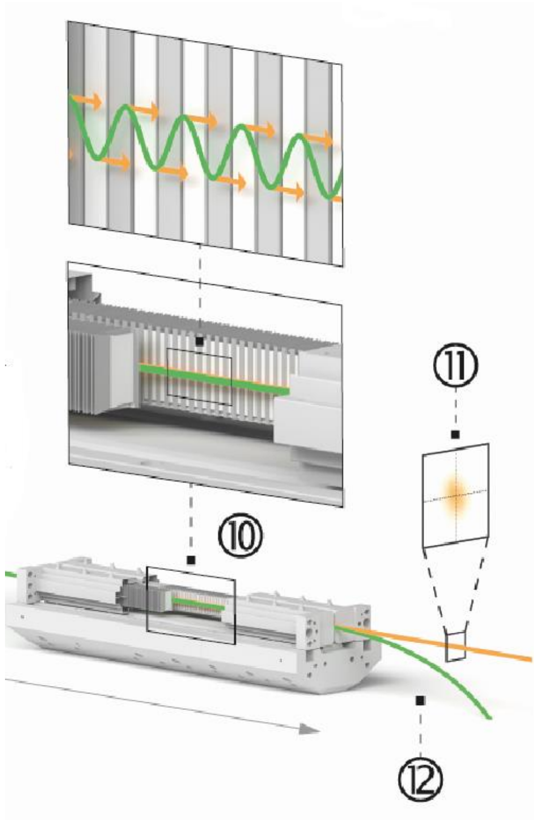
Beam transport line

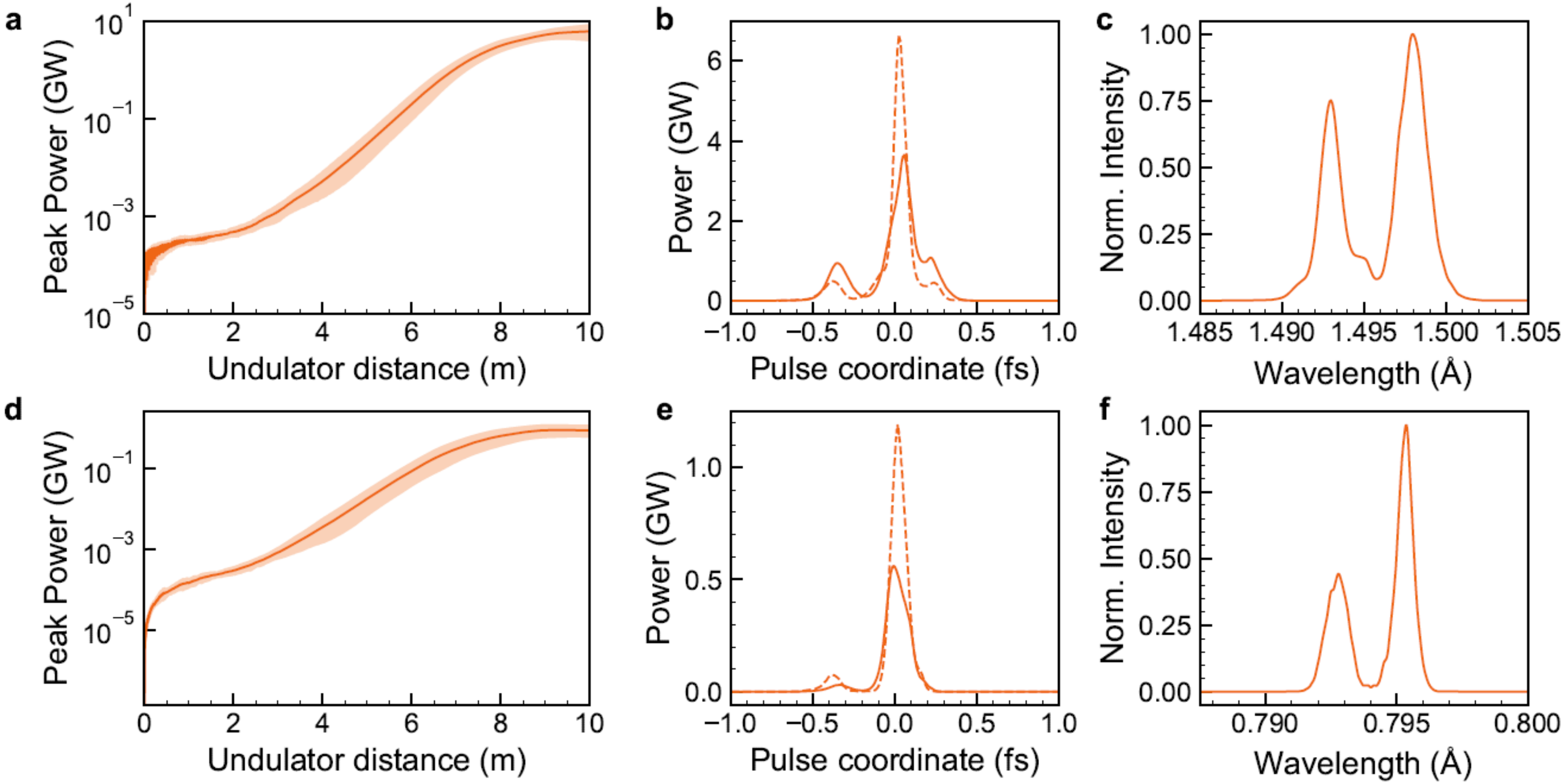


- ❑ No emittance growth during extraction and capture: there are simply no achromaticities to worry about
- ❑ No deleterious CSR
- ❑ Slice and projected emittance, energy spread and current are fully preserved



Hard X-ray FEL section





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

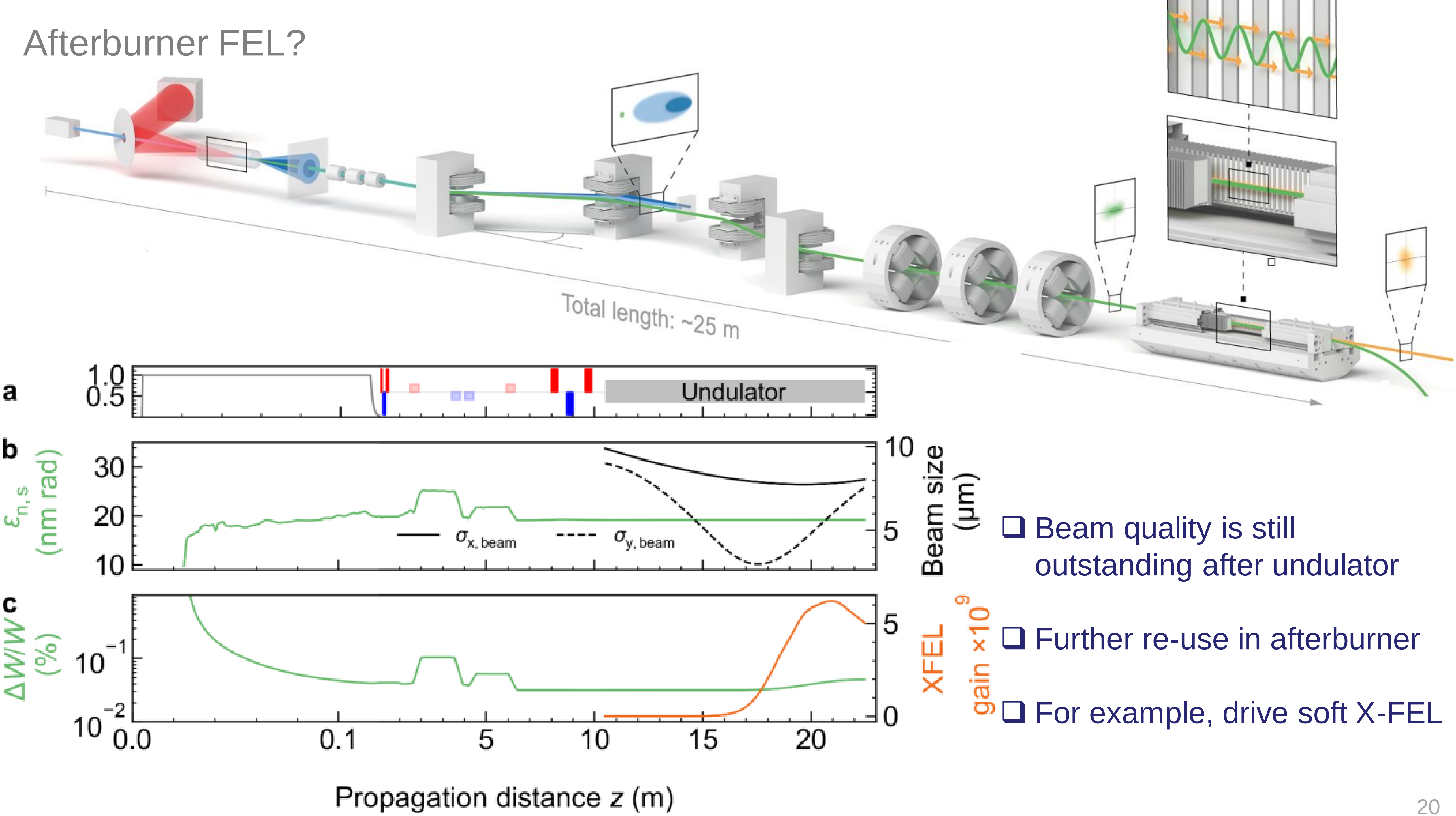
20 nmrad 0.8 Å 2.8 GeV

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

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

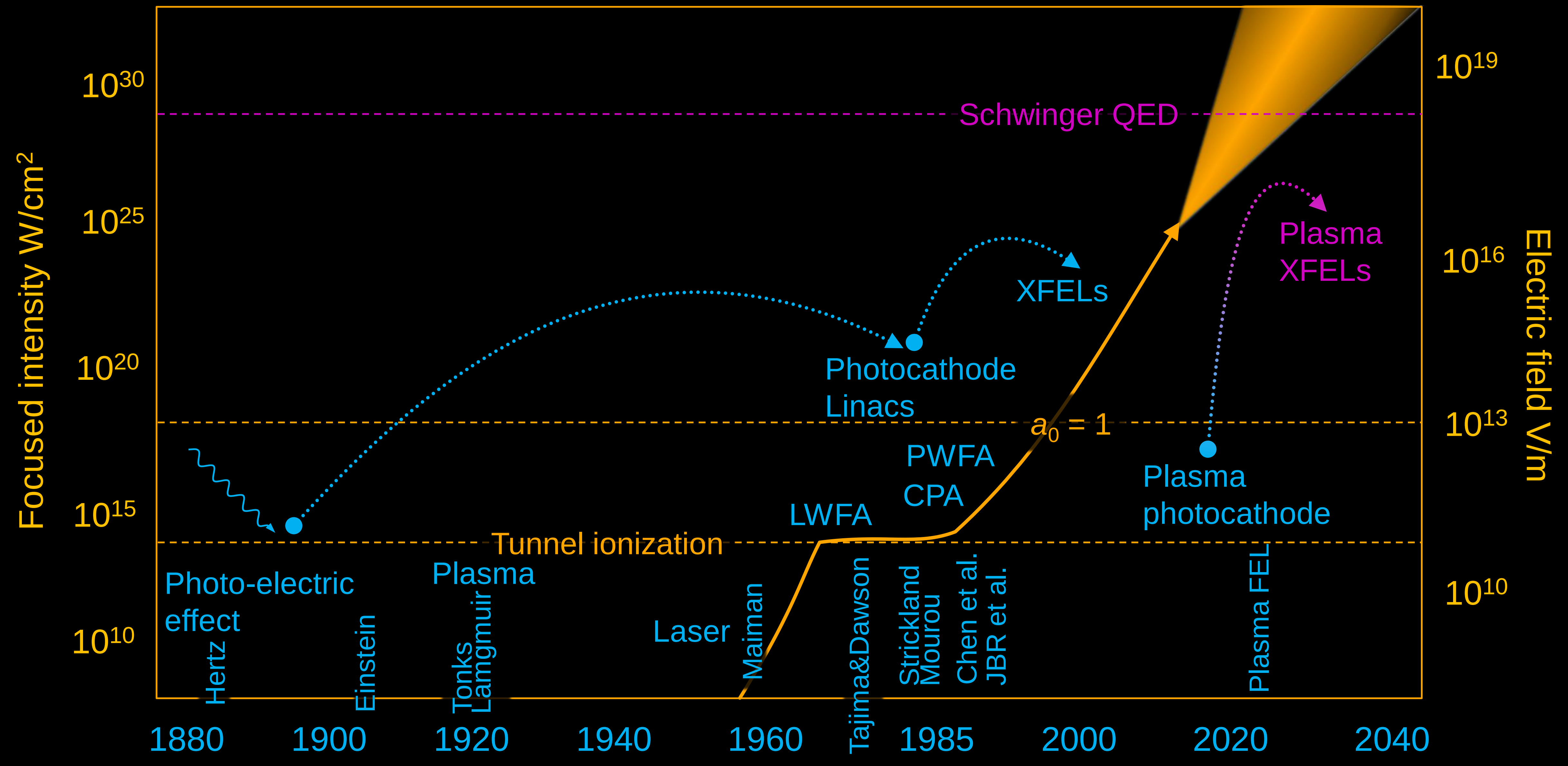
- ❑ Ice-cold beam: 3D gain near 1D gain, the cold beam limit
- ❑ Ultrastrong gain in advanced undulators: saturation after 10m; longitudinal coherence, near single spike mode
- ❑ 100 Attosecond pulse duration
- ❑ Two showcases: Hard SASE X-FEL with ~1.5 Å and ~0.8 Å

Afterburner FEL?



- ❑ Beam quality is still outstanding after undulator
- ❑ Further re-use in afterburner
- ❑ For example, drive soft X-FEL

Plasma X-FELs driven by ultrabright e-beams



UK XFEL Science Case 2020: PWFA afterburner

A3.2 Plasma and laser wakefield acceleration

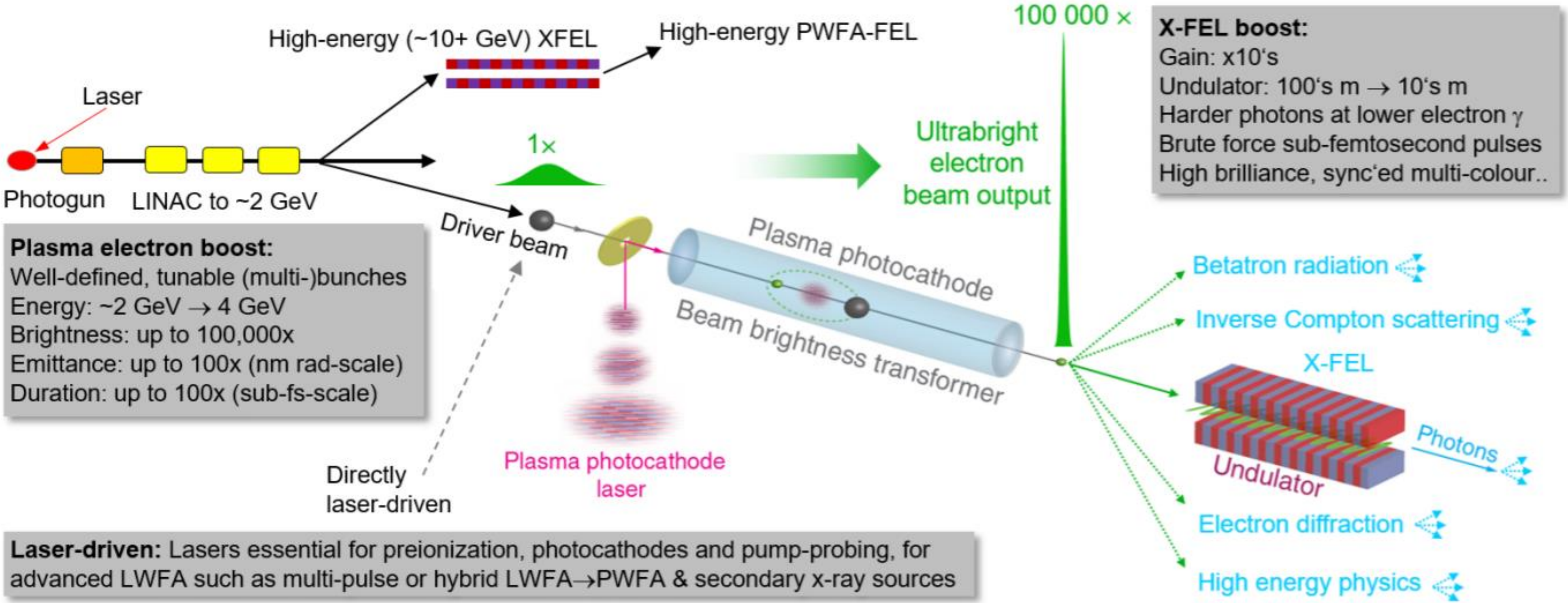
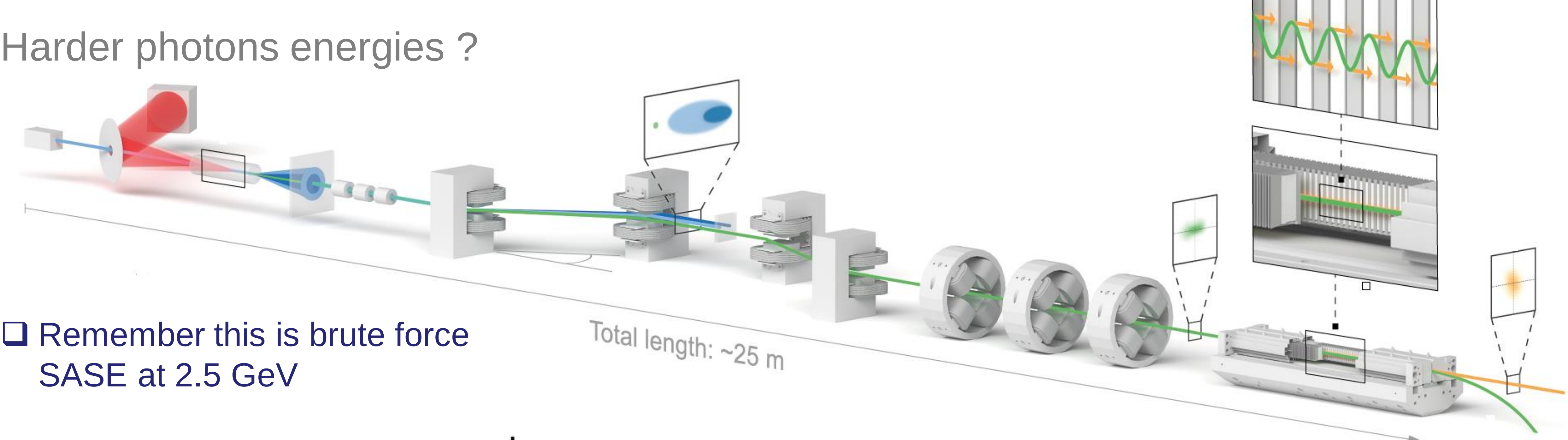
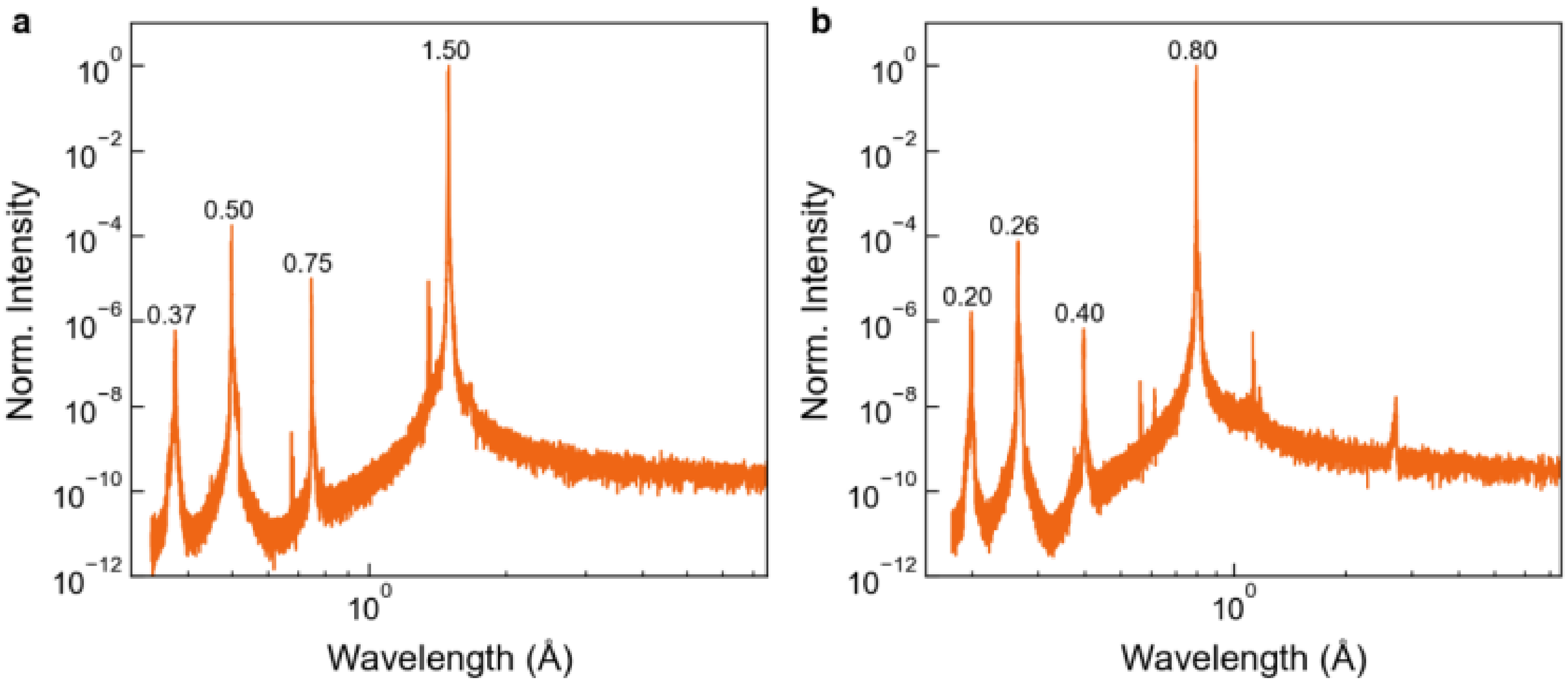


Figure A3.1: Schematic diagram of the capabilities enabled by combining XFEL beamlines and plasma accelerators

Harder photons energies ?



- ❑ Remember this is brute force SASE at 2.5 GeV

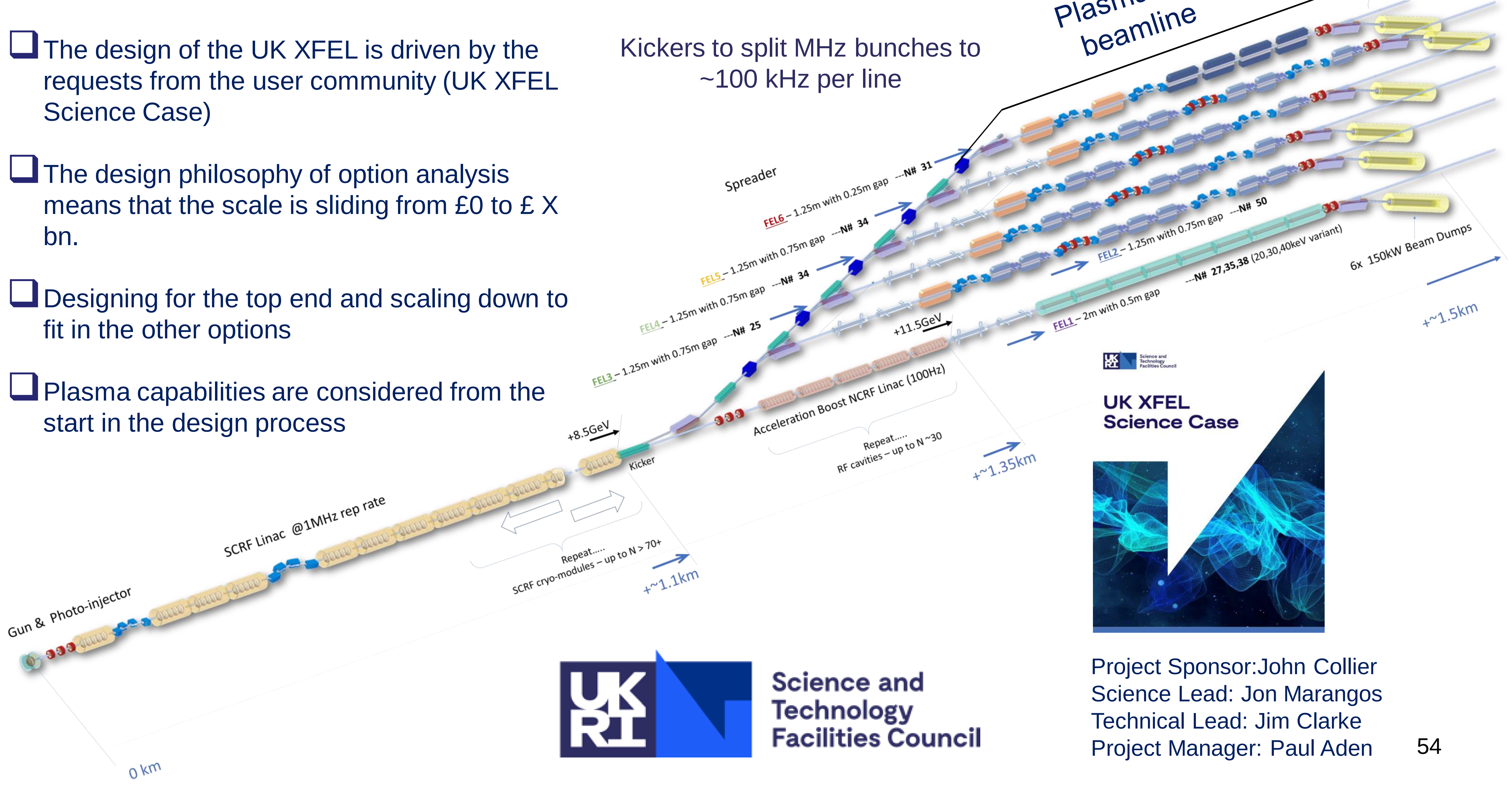


- ❑ Higher harmonics visible down to 0.2 Å
- ❑ Still far away from quantum regime of the FEL
- ❑ Huge emittance budget allows for even harder photons. Recoil and other effects will become significant at some point

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

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

Kickers to split MHz bunches to ~100 kHz per line

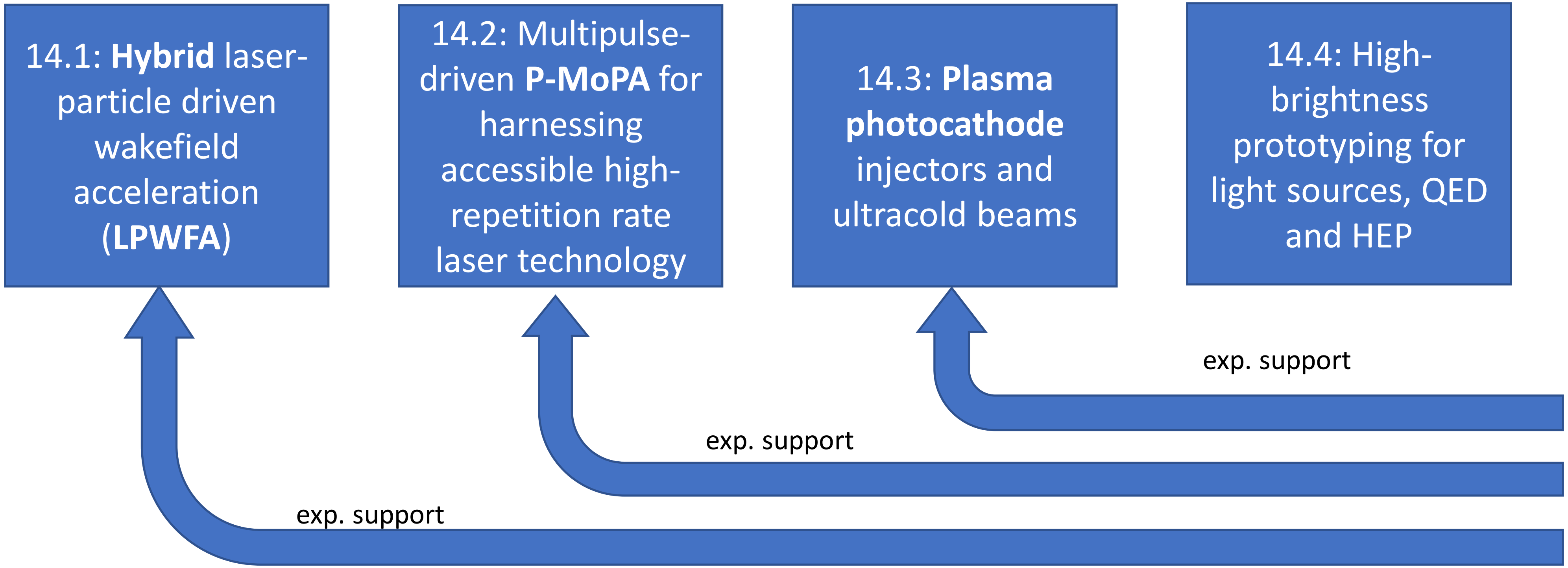


Science and Technology Facilities Council

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

Cross-links 14.5: targetry and diagnostics

Funded by the European Union



PÉCSI TUDOMÁNYEGYETEM UNIVERSITY OF PÉCS

UNIVERSITY OF OXFORD

TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA

hhu Heinrich Heine Universität Düsseldorf

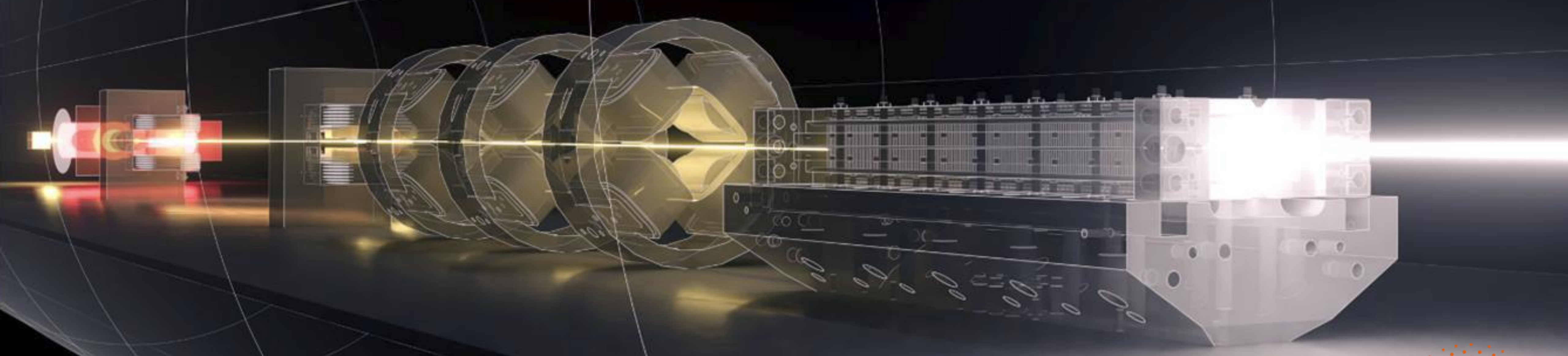
Imperial College London

CALA

"Bespoke targetry and diagnostics are vital for exp. success"

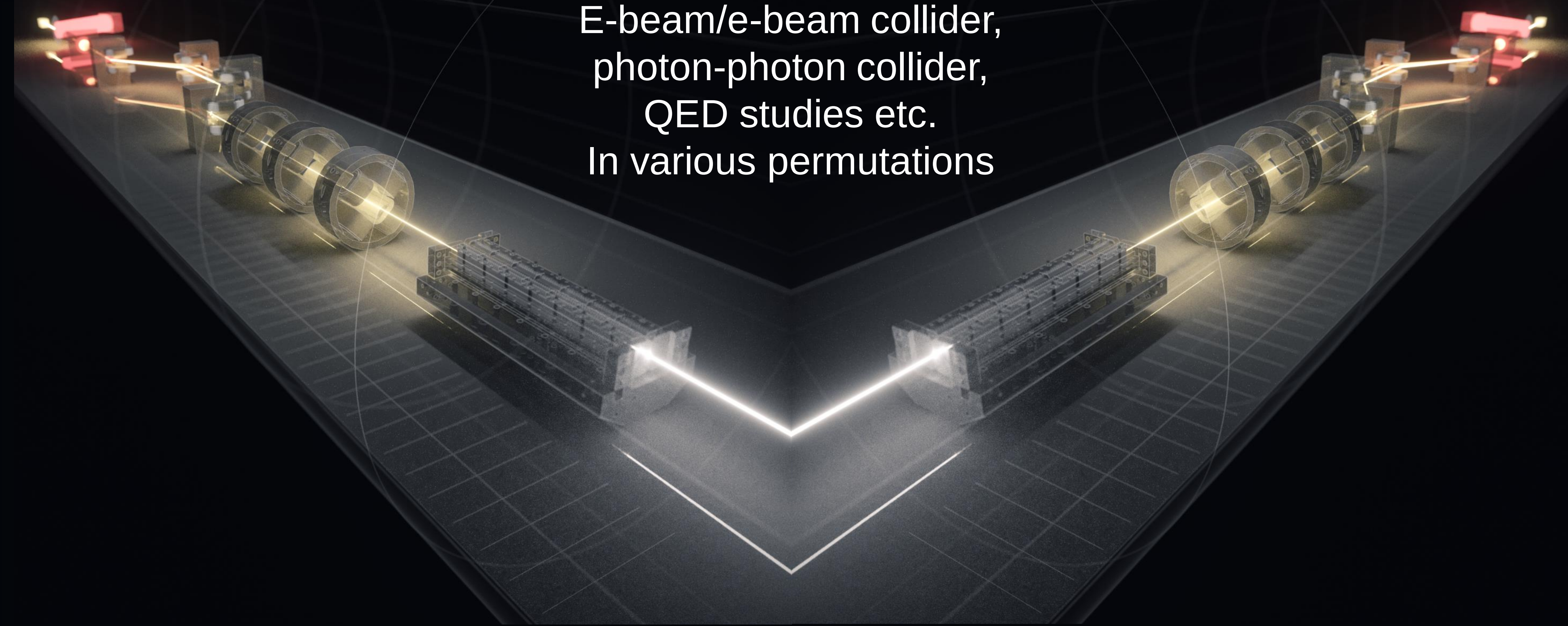
Heinrich Heine University Düsseldorf

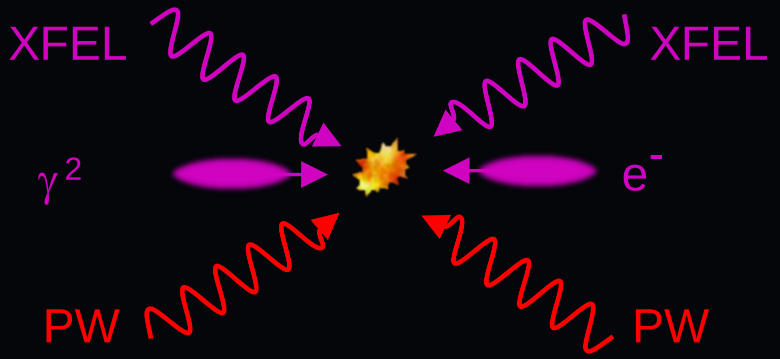
- ❑ Potential HHU main deliverable #1: hybrid LWFA-PWFA-X-FEL beamline for INFN (PWFA site) and LWFA site(s), fully developed, tested and commissioned at HHU ARCTURUS
  - ❑ Following blueprint developed through “PWFA-FEL” project USTRATH-SLAC-STFC-UCLA, presented in Habib et al., Attosecond-Angstrom free-electron-laser towards the cold beam limit, *Nat. Comm.* 14, 1054 (2023)



- ❑ EuPRAXIA benefit: beam brightness improved by orders of magnitude, strongly boosted capacities and capabilities at PWFA and LWFA sites, thus fulfilling the WP14 thrust

E-beam/e-beam collider,
photon-photon collider,
QED studies etc.
In various permutations





EuPRAXIA-PP Consortium

Funded by the European Union

Coordinator

INFN
Istituto Nazionale di Fisica Nucleare

Consiglio Nazionale delle Ricerche

Elettra Sincrotrone Trieste

ENEA
Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

SAPIENZA Università di Roma

Università di Roma Tor Vergata

Imperial College London

Queen's University Belfast

UK Research and Innovation

University of Liverpool

University of Oxford

University of Strathclyde Glasgow

CERN

DESY.

Leibniz Ferdinand Braun Institut

Fraunhofer ILT

GSI

hhu Heinrich Heine Universität Düsseldorf

HZDR Helmholtz Zentrum Dresden Rossendorf

Jülich Forschungszentrum

LMU Ludwig-Maximilians-Universität München

Amplitude

cea

cnrs

THALES

eli

Técnico Lisboa

ALBA

CLPU Centro de Láseres Pulsados

Empa Materials Science and Technology

EPFL

Paul Scherrer Institut PSI

The Hebrew University of Jerusalem

IASA

Pécsi Tudományegyetem University of Pécs

SZTE University of Szeged

Wigner

The University of California UCLA