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3rd Townhall Meeting High Gradient Accelerator Plasma/Laser

Plasma photocathode HEP R&D

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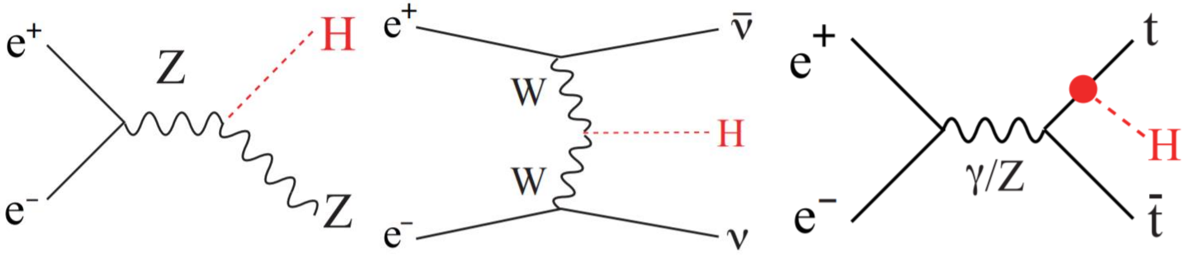
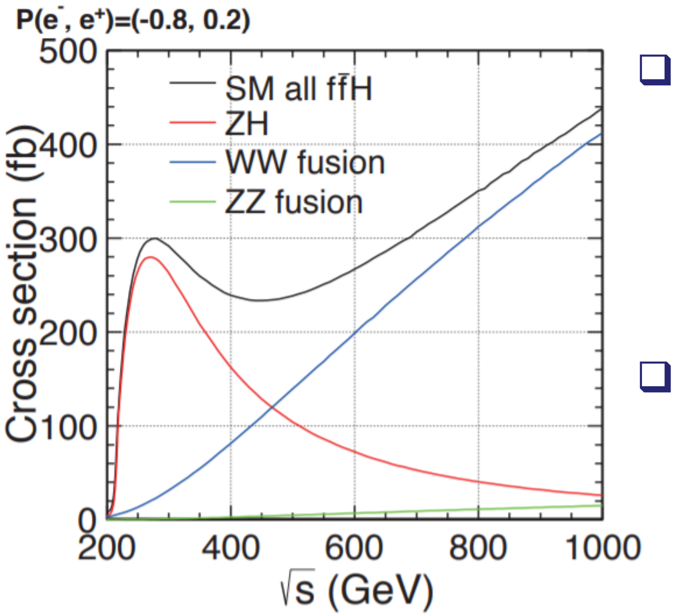
Luminosity at the Higgs factory



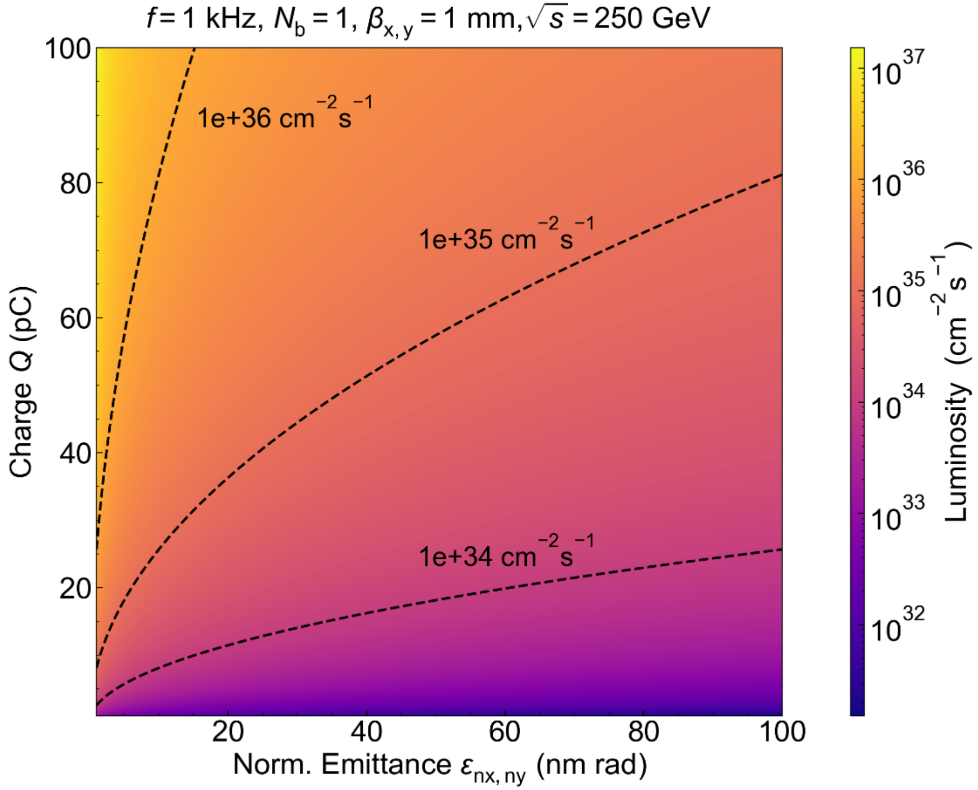


- @250 GeV dominant interaction: s-channel Higgsstrahlung process with cross section < 300 (fb)
- @1000 GeV dominat interaction: t-channel weak boson fusion process with cross section > 400 (fb) ~ 4e-37 cm^2

D.M. Asner, et. al. "ILC Higgs White Paper", arXiv:1310.0763v4, (2018)

$$\frac{dR}{dt} = \mathcal{L} \times \sigma_{e^-e^+\rightarrow f\bar{f}H}$$

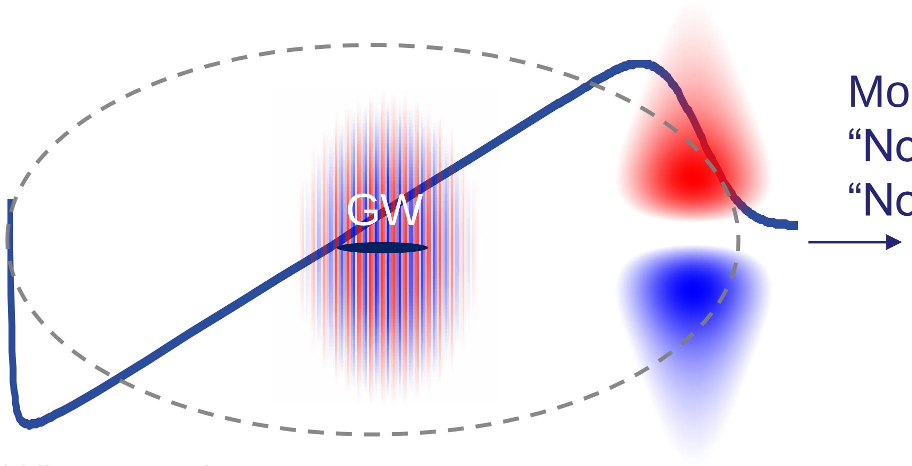
$$\mathcal{L} = \frac{\gamma f N^2}{4\pi\sqrt{\beta_x\beta_y}\sqrt{\epsilon_{nx}\epsilon_{ny}}}$$



- Cross-sections are extremely small→ high luminosity is mandatory
- @L~1e+34 cm^2 every ~5 min Higgs event

Plasma photocathode

Plasma photocathode



PWFA
Moderate peak fields
“No” dephasing
“No” diffraction

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

- Injection fully decoupled from wake excitation: laser-controlled, dark current free, clean electron beam production from localized tunnel ionization e.g. of He
- Transverse residual momentum from ~10^{15} W/cm^2 laser negligible $\Rightarrow$ normalized emittance ε_n **~ nm rad scale**
- Auto-compression to kA currents *I* ⇒ beams orders of magnitude brighter than state-of-the-art
- Test beams for staging: nm rad level emittance growth per stage observable

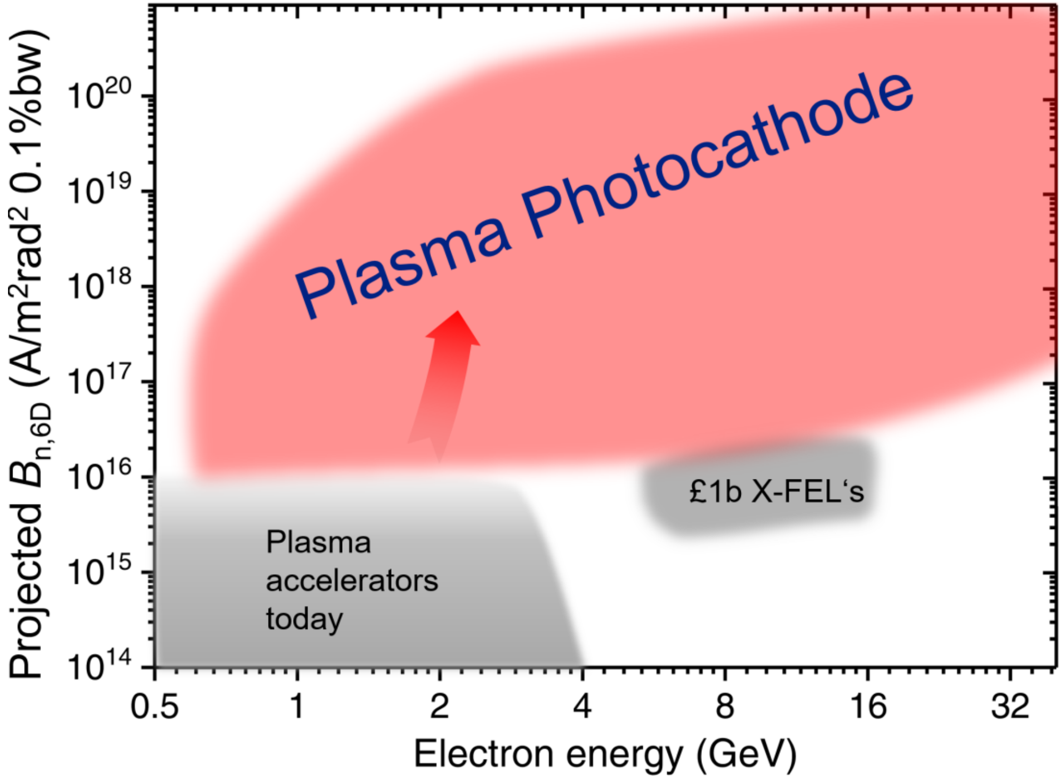
Light source and HEP applications

multi-kA current

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

energy spread <0.01%

nm rad emittance



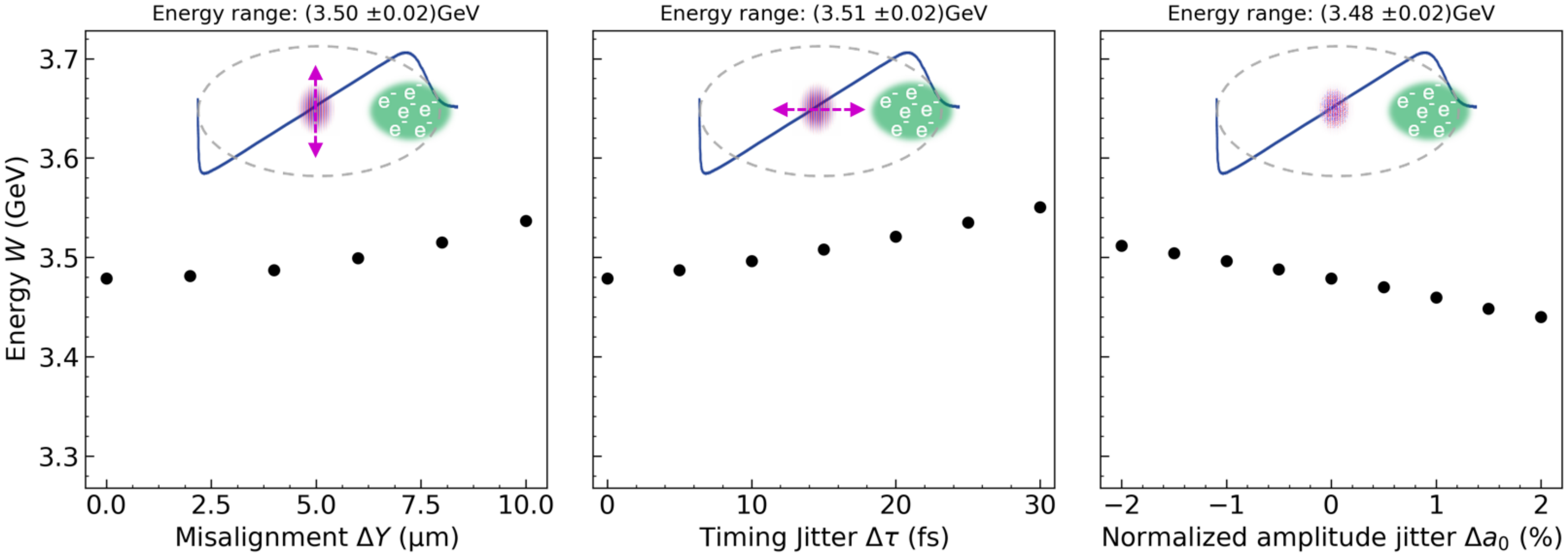
Stability analysis

Conservative jitter parameters

- Temporal offset: 0-30 fs
- Transverse offset: 0-10 µm
- Focus laser intensity a_0: 0-2%

Beam parameter stability

- Key properties show % to sub-% level stability
- Path towards stability levels for FEL and HEP applications
- Beam energy stability within beam transport tolerances
- Huge improvment potential considering state-of-the-art synchronization limits
- Deliberately misaligning injector laser for flat beams



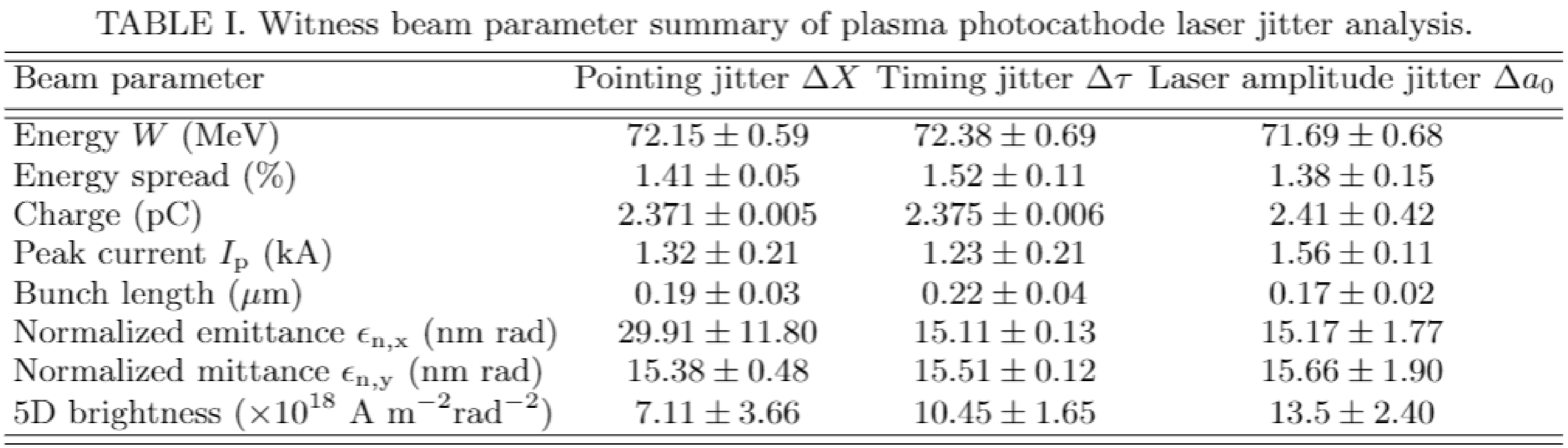


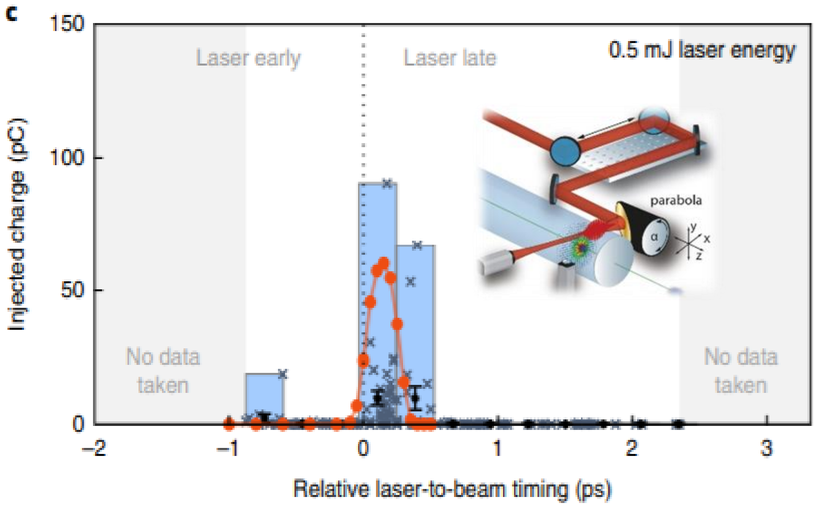
TABLE I. Witness beam parameter summary of plasma photocathode laser jitter analysis.

Beam parameter	Pointing jitter ΔX	Timing jitter $\Delta\tau$	Laser amplitude jitter Δa_0
Energy W (MeV)	72.15 ± 0.59	72.38 ± 0.69	71.69 ± 0.68
Energy spread (%)	1.41 ± 0.05	1.52 ± 0.11	1.38 ± 0.15
Charge (pC)	2.371 ± 0.005	2.375 ± 0.006	2.41 ± 0.42
Peak current I_p (kA)	1.32 ± 0.21	1.23 ± 0.21	1.56 ± 0.11
Bunch length (μm)	0.19 ± 0.03	0.22 ± 0.04	0.17 ± 0.02
Normalized emittance $\epsilon_{\mathrm{n,x}}$ (nm rad)	29.91 ± 11.80	15.11 ± 0.13	15.17 ± 1.77
Normalized mittance $\epsilon_{\mathrm{n,y}}$ (nm rad)	15.38 ± 0.48	15.51 ± 0.12	15.66 ± 1.90
5D brightness ($\times 10^{18}$ A m^{-2}rad^{-2})	7.11 ± 3.66	10.45 ± 1.65	13.5 ± 2.40

A.F. Habib *et al.*, (2021), in prep

Conceptual and experimental milestones

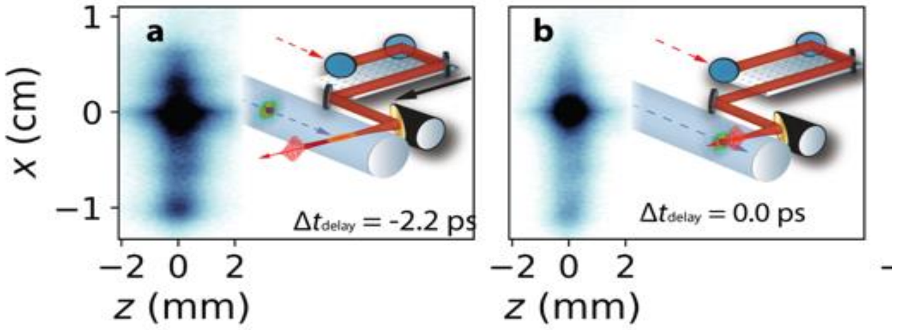
Plasma photocathode injection proof-of-concept @SLAC FACET



Deng*, Karger* *et al.*, *Nat. Phys.* 2019
D. Ullmann *et al.*, arXiv:2007.12634

- ❑ 90° geometry version
- ❑ First demonstration of density down-ramp injection in PWFA
- ❑ Program to be continued at SLAC FACAT-II (E-31x)

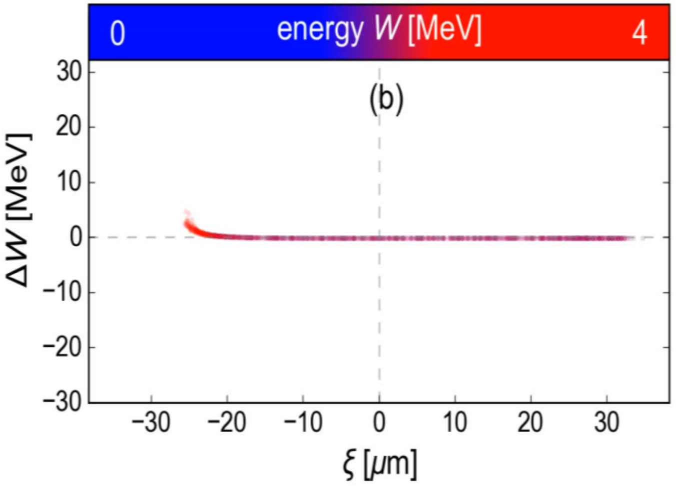
Plasma afterglow beam metrology



P. Scherkl *et al.*, arXiv:1908.09263
A. Sutherland *et al.*, (2021), in prep

- ❑ Plasma based spatial temporal synchronization diagnostic pioneered at SLAC FACET. Already utilized at many other labs worldwide
- ❑ Opens the path towards plasma-based beam diagnostics

Energy chirp control of nm rad emittance beams in a single stage



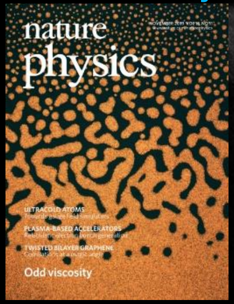
Manahan*, Habib* *et al.*, *Nat. Comm.* 8, 15705 (2017)

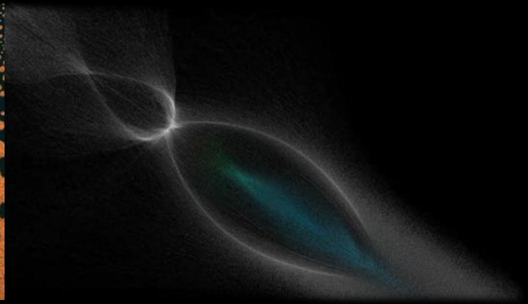
- ❑ Theory and simulations predict energy spreads < 0.01% at few GeV energies
- ❑ E-313 experiment at FACET-II and X-19 at DESY (PIs: Habib/Hidding)

Strathclyde Hidding Group Roadmap

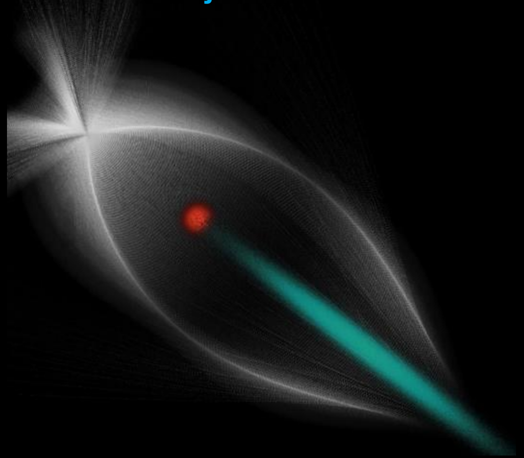
Plasma Photocathodes

E-210: Trojan Horse at FACET

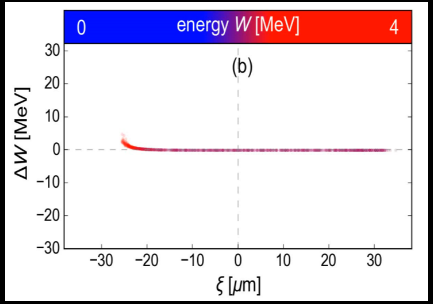




E-310: Trojan Horse-II at FACET-II



E-313: Energy spread



Hybrid
LWFA→PWFA

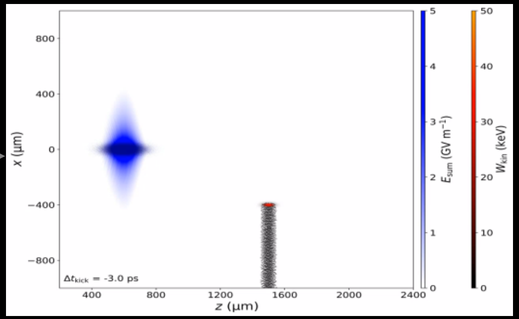
NeXource

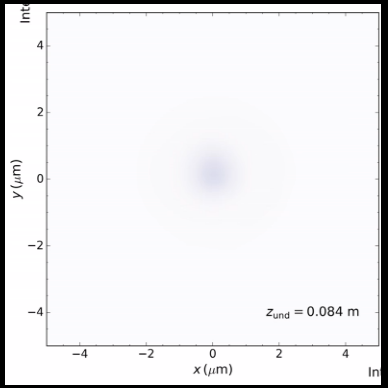
PWFA XFEL

Plasma
afterglow metrology

Hard X-ray FEL

Plasma afterglow





Light source &
HEP applications

Plasma photocathode HEP R&D @national/international facilities

SCAPA @Strathclyde

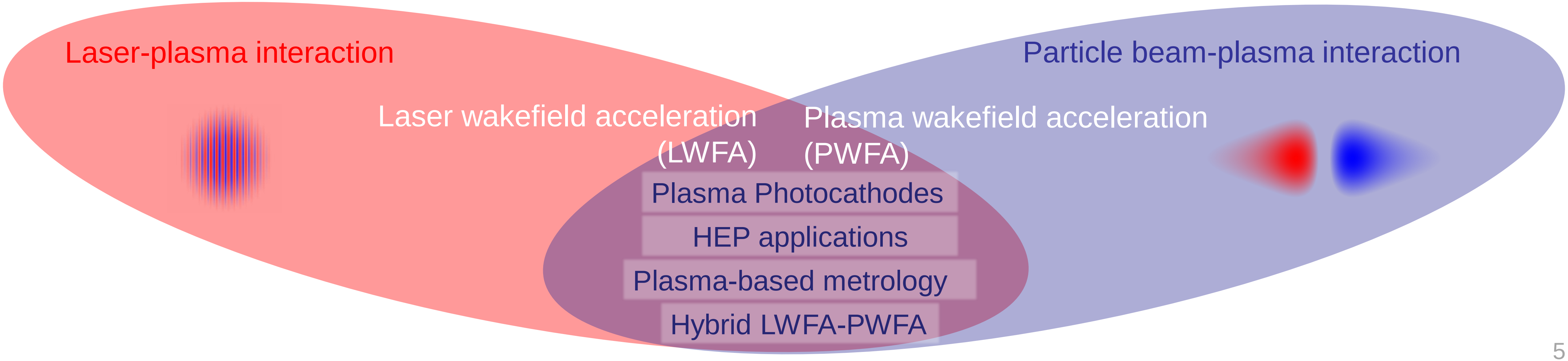
FACET-II @SLAC

CLARA FEBE @Daresbury

FF@DESY

HZDR&LMU&LOA

Plasma photocathode R&D ecosystem



Laser-plasma interaction

Particle beam-plasma interaction

Laser wakefield acceleration (LWFA)

Plasma wakefield acceleration (PWFA)

Plasma Photocathodes

HEP applications

Plasma-based metrology

Hybrid LWFA-PWFA

Questions from the Expert Panel: Part I

1) Where do you see HEP applications of advanced accelerators in 30 years?

-

2) What intermediate physics applications/steps do you see until a HEP linear collider?

- Very clearly, as stated by various roadmaps, demonstration of FEL. Saturation and ability to drive hard X-ray FEL are key milestones, as these are acid tests for sufficient beam quality for HEP
- Various lights sources: Betatron radiation, ion channel laser, ICS e.g. Litos *et al.*, AAC 2018, 10.1109/AAC.2018.8659422, Habib *et al.*, SPIE 2019, 10.1117/12.2530976
- Demonstration of ultra-low emittance beams from plasma photocathodes for staging, diagnostics and beam sources
- High-Field physics experiments, where quality of beams can be harnessed for novel modalities Yakimenko *et al.*, *PRL* 122, 190404 (2019)
- γ-rays from ultradense e-beam-matter interaction e.g. Benedetti *et al.*, *Nat. Phot.* 12, 319 (2018)
- Fixed target high luminosity experiments (radiation hardness, secondary beams such as positrons, muons)

3) What is the synergy with related fields?

- Beam emittance preservation in staging is a key part of plasma-based collider concepts. Even nm rad emittance growth per stage can have dramatic impact on the capabilities at the IP. Therefore, ultra-low emittance beams are ideal candidates to test even nm rad emittance growth in single stage.

- Diagnostics of ultralow emittance beams from plasmas, including spatiotemporal alignment and synchronization

- Fundamental physics issues of plasma accelerators that take place on nm rad scale emittance levels

4) What is the role of your work here?

- Enabling tunable ultralow emittance beams for HEP building block development, test and as beam source without damping rings
- Enabling other applications that profit from ultralow emittance / ultrahigh brightness beams
- Development of plasma-based diagnostics towards beam metrology

Questions from the Expert Panel: Part II

1) What are the important milestones for the next 10 years to get there from today?

- Demonstration of emittance and brightness boost by factor 10 to 10000 compared to what is within reach of plasma accelerators today
- Energy spread control and charge and current tuning

2) What additional support is needed to achieve these?

- Dedicated funding for plasma photocathodes development for HEP applications and from HEP perspective
- Beamtime with dedicated setups to test and demonstrate the full functionality of plasma photocathodes

3) What should be proposed as deliverables until 2026? Please list in order of priority.

- Demonstration of ultralow emittance beam operation of a plasma photocathode
- Energy chirp control of plasma photocathodes
- Demonstration of inherent stability of plasma photocathodes vs. jitter of incoming beams
- S2E simulations of hard XFEL light sources (or similar) based on beams from plasma photocathodes

4) Is the R&D work for each of those deliverables already funded and, if not, what additional resources / support would be needed?

- Funding is required

Questions from the Expert Panel: Part III

1) What key R&D needs can be achieved in existing R&D facilities?

- FACET-II is expected to have sufficient beam current (>6 kA) to allow straightforward Trojan Horse
- Other linac-based and FEL facilities have the potential to host plasma photocathode injection. However, will require peak current upgrades
- LWFA->PWFA is a university-lab compatible approach that allows production of sufficient beam currents
- Synchronization of laser to electron beam at linac-based facilities
- Continues development of plasma afterglow diagnostic approach

2) What is the role of the already planned future facilities in Europe and world-wide?

- INFN EuPRAXIA needs ultrabright beams to generate a step change in capabilities

3) What can be done with the existing and planned funding base?

- Existing funding base covers only parts of the R&D program. However, for HEP focused objectives more dictated funding programs are required

4) Is a completely new facility needed?

- No. not necessarily

5) Are additional structures needed beyond existing networks and projects, e.g. a design study for a collider or an advanced accelerator stage?

- N/A

Thanks