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# From spatiotemporal plasma-based diagnostics to high rep-rate PWFA at IOTA/FAST

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Strathclyde Centre for Doctoral Training P-PALS
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Strathclyde Space Institute

& The Cockcroft Institute

HEP: Need high luminosity for high event rate

Need high rep rate & charge:
FAST (MHz, nC scale)

$$L = \frac{fN^2}{4\pi\sigma_x\sigma_y}$$

Need low emittance & energy spread for small final focus size:
Advanced PWFA (beam-loaded Trojan Horse: nmrad, <0.01%)

Light sources: Need high brightness, low emittance, low energy spread, high rep rate

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

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

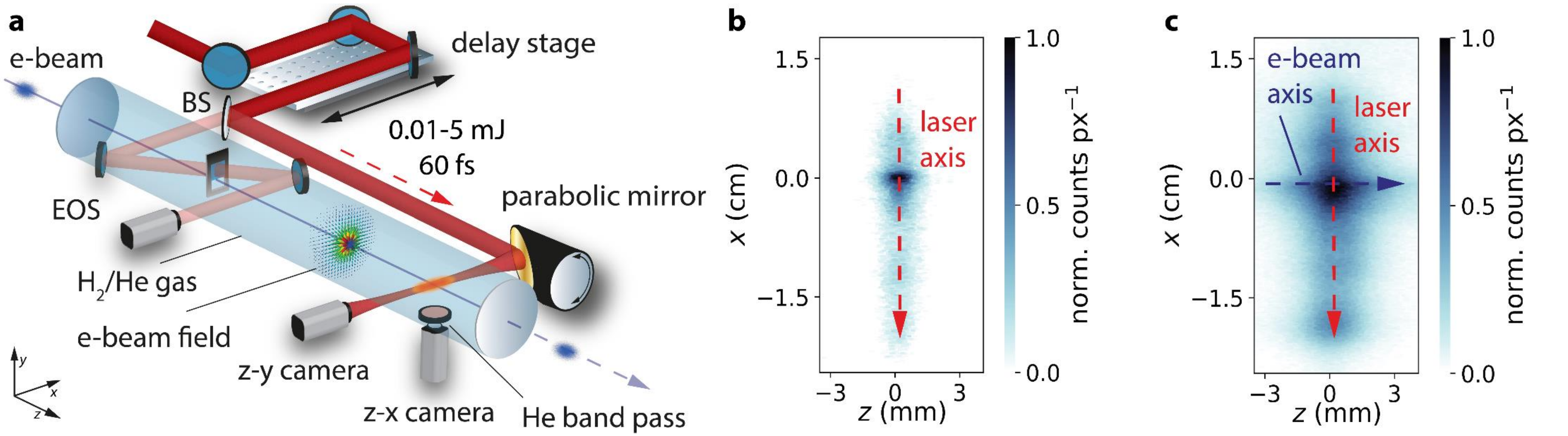
6D brightness: $B_{\mathrm{n,6D}} = \frac{I_{\mathrm{p}}}{\epsilon_{\mathrm{n,x}}\epsilon_{\mathrm{n,y}} 0.1\% \sigma_{\mathrm{W}}}$

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

# Spatiotemporal synchronization & alignment, and multi-purpose diagnostics

- Various aspects of PWFA (injection, plasma photocathode, tailored preionization, staging..) need fs-µm-scale synchronization and alignment
- fs-µm-scale effects naturally difficult to diagnose
- Plasma-photonic spatiotemporal alignment: a magnifying glass, which transforms fs-µm-scale interaction signatures to observables on µs-mm-scale
- Highlights importance of intermediate timescale and effect: plasma electron-based collisional ionization
- Has huge development potential in particular for high rep rate interaction and diagnostics
- Requires very small gas/plasma volume (better not go full plasma for first experiments in SC environment) and could be candidate for first plasma experiment at FAST

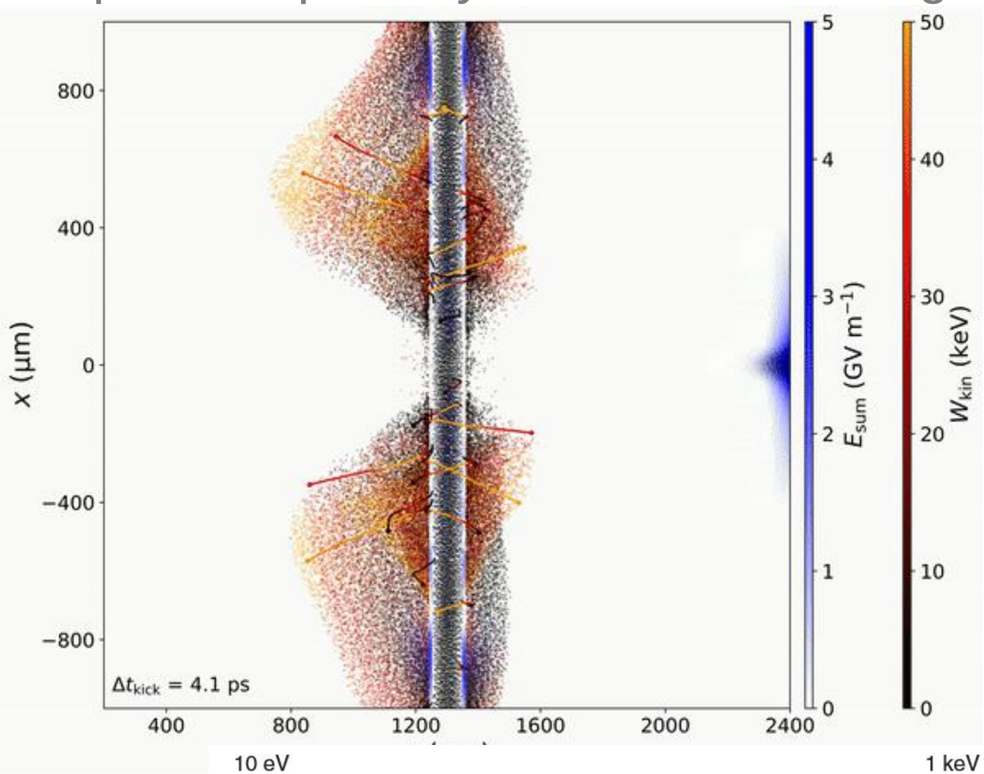
# Spatiotemporal synchronization & alignment on fs-µm scale

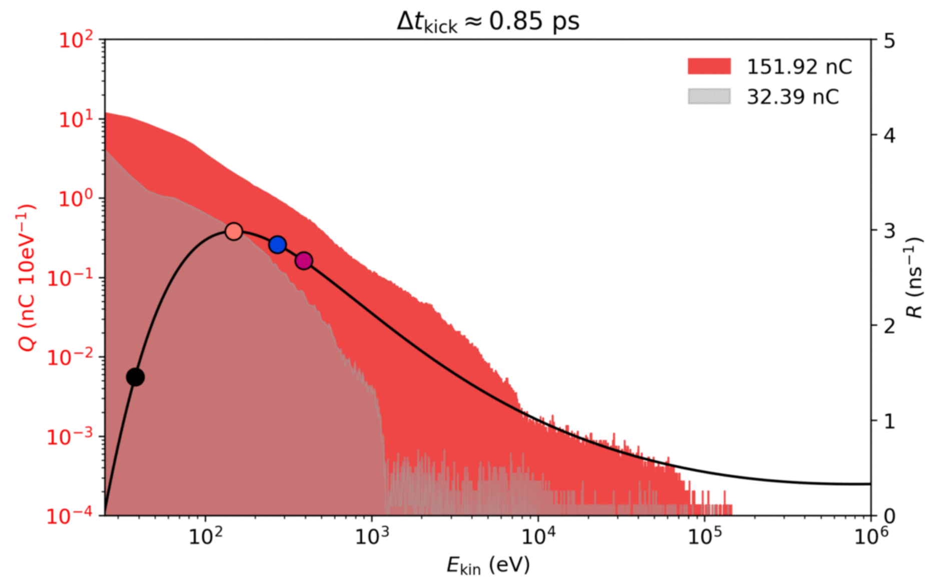


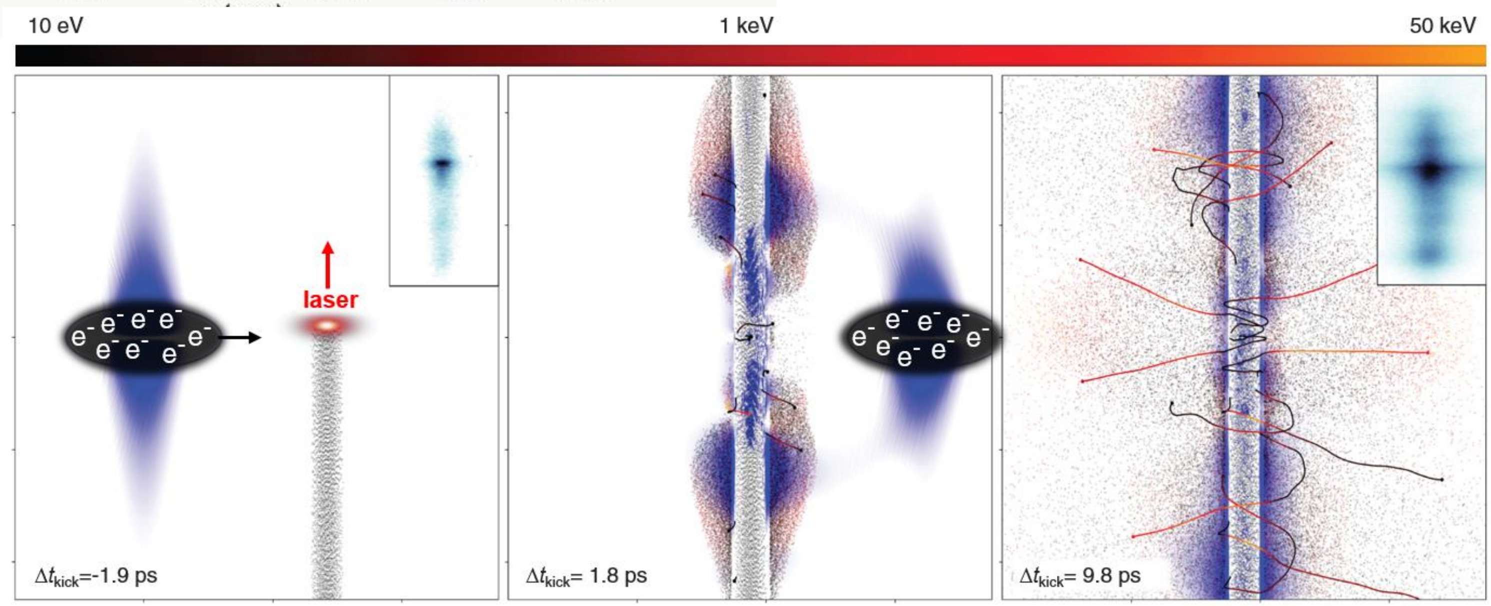

- Relativistic electron beam propagates through gas volume, e.g. H2/He or else
- Due to low impact ionization cross sections, no significant plasma is generated
- Sub-mJ, ~60 fs Ti:Sapphire laser pulse generates ~50 µm diameter plasma torch, e.g. in 90° geometry
- A simple integrating CCD observes the plasma afterglow: if laser is misaligned or comes later, the pure laser-generated plasma afterglow is observed (**b**)
- If laser is aligned and overlaps with electron beam trajectory, and generates plasma torch before electron beam arrival, a substantially enhanced plasma afterglow is observed (**c**)!

P. Scherkl et al., under review

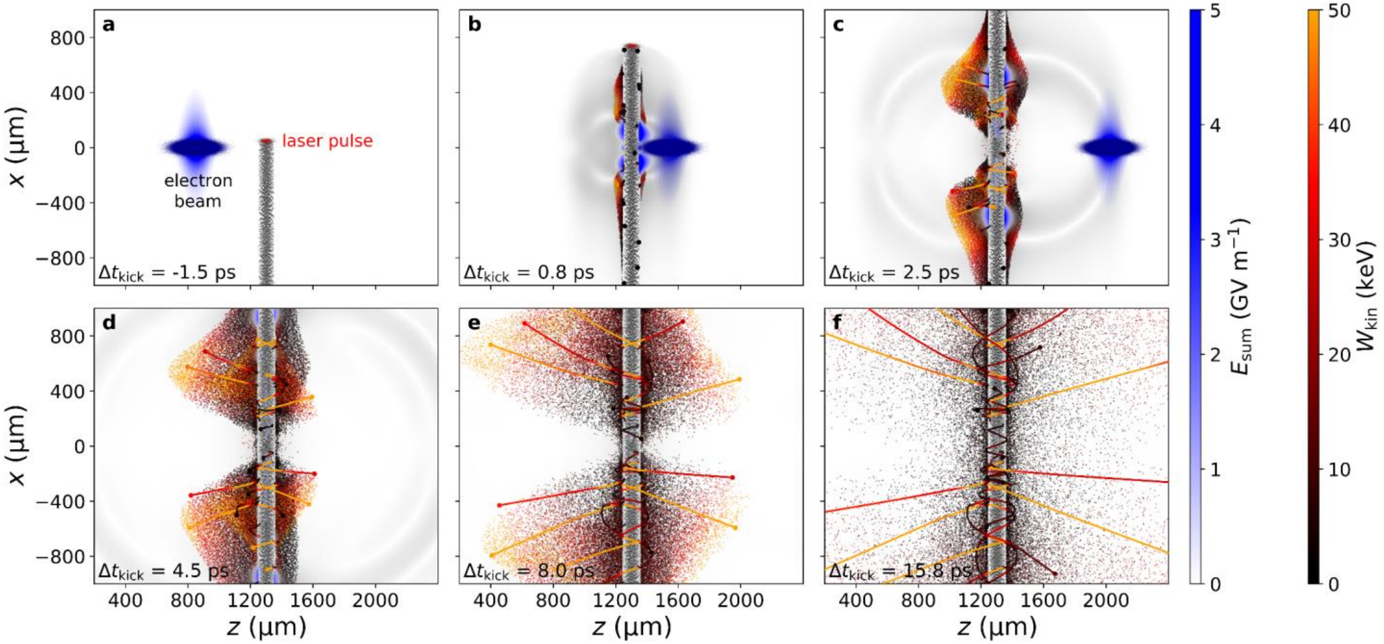
# Spatiotemporal synchronization & alignment on fs-µm scale



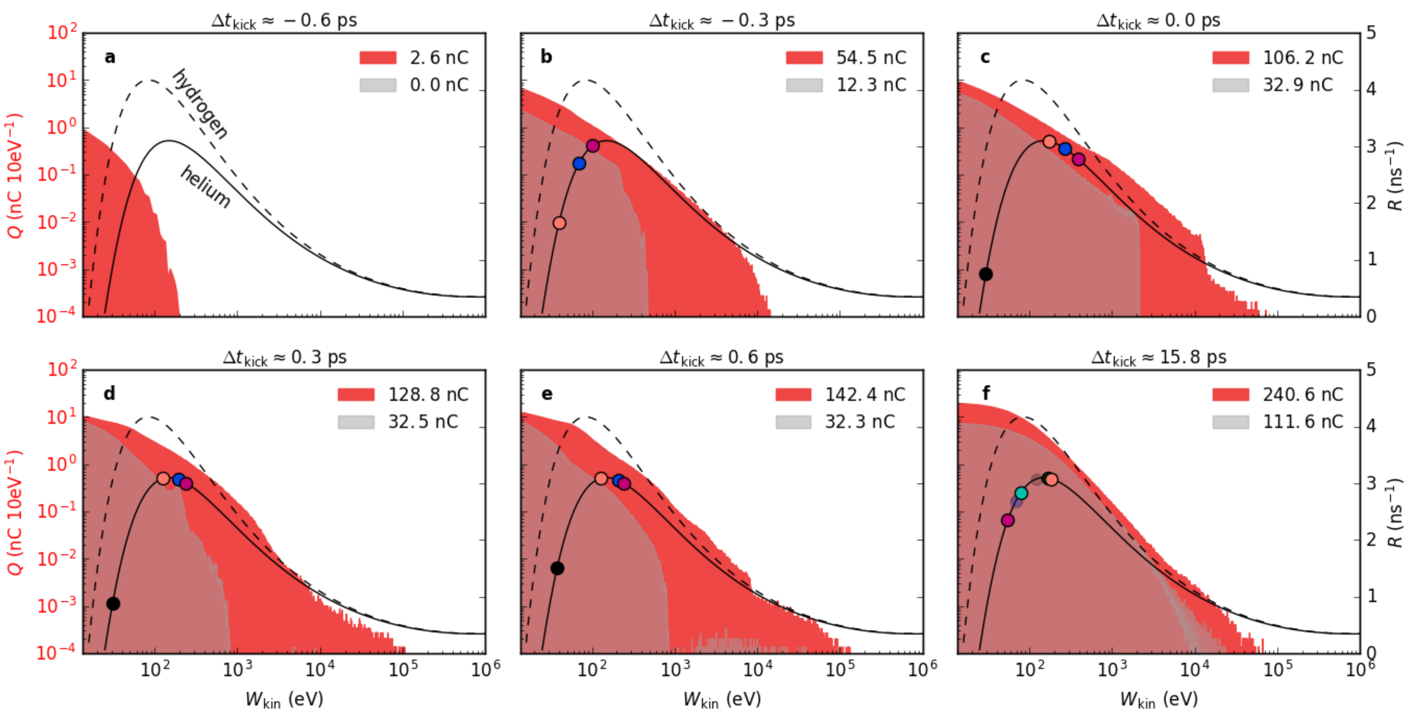




P. Scherkl et al., under review

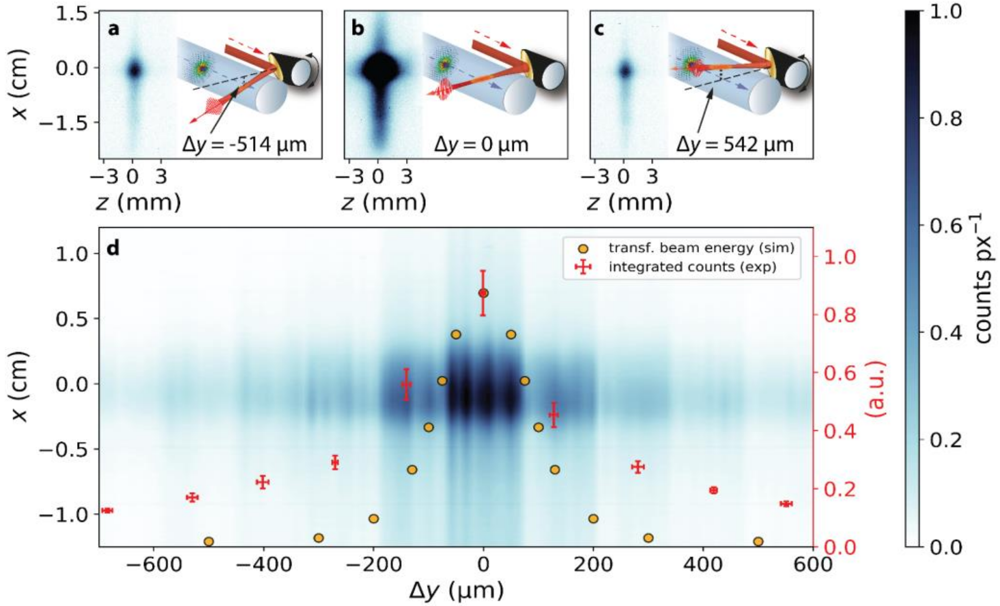



- Seed plasma electrons heated to keV energies, where impact ionization cross sections in neutral gas are highest

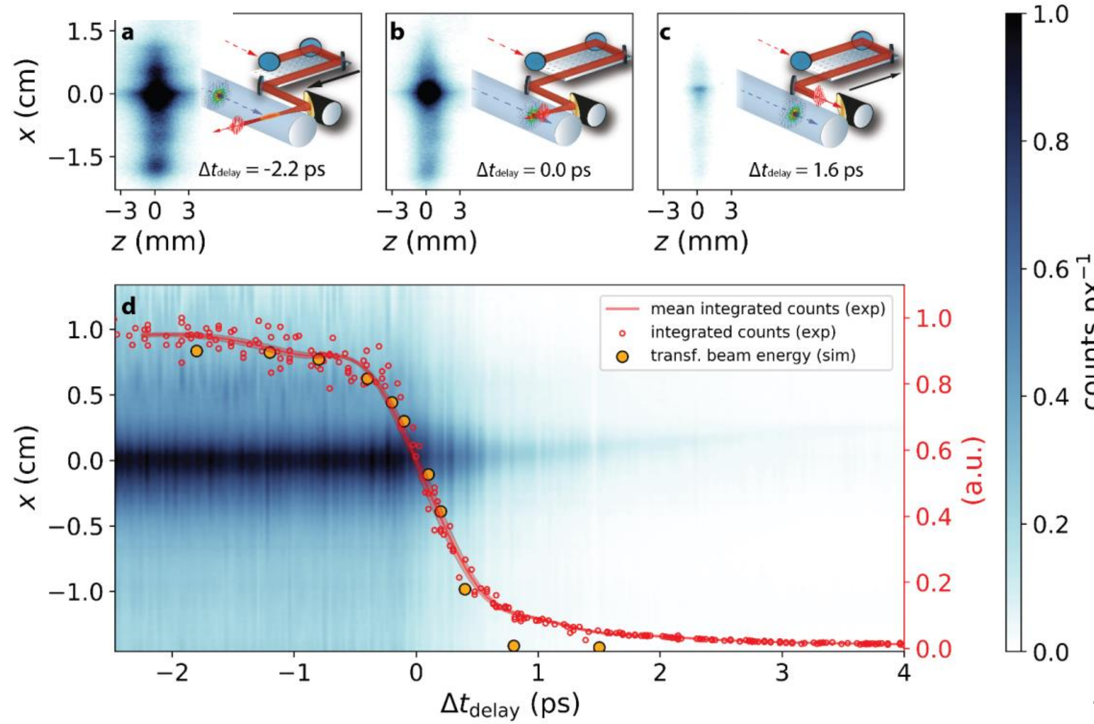



- Seed plasma electrons oscillate around core plasma, impact ionize further surrounding gas
- Additional plasma production over extended time and spatial scales due to surface plasma waves

# Realized within E210 at SLAC FACET: spatiotemporal sync. & alignment



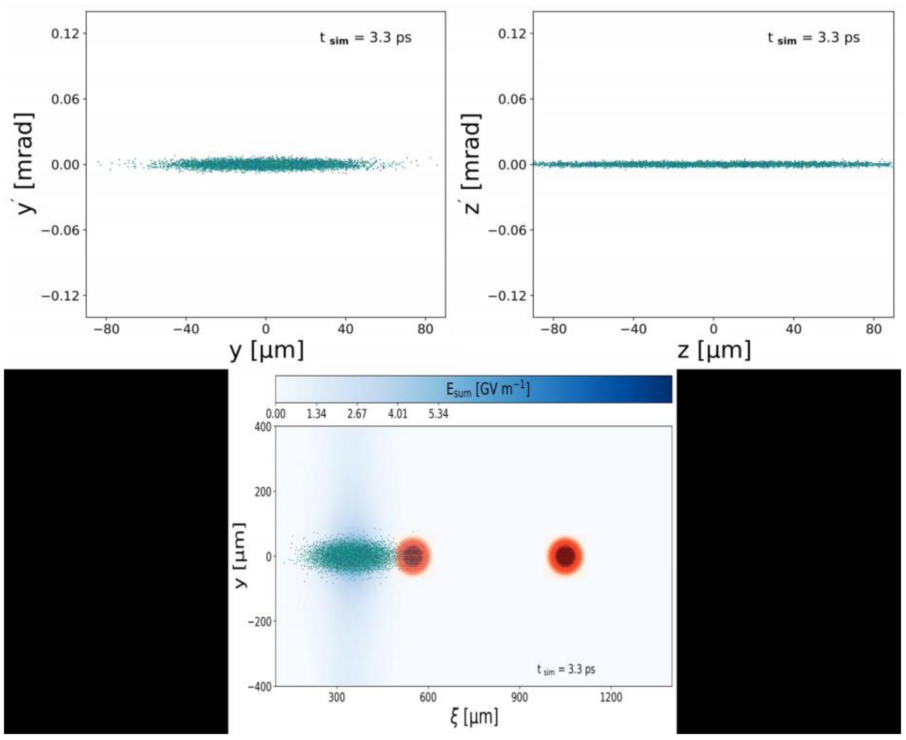

- Alignment scan for laser early case (~50 ps) allows robust online alignment




- Timing scan for aligned case allows time-of-arrival measurement
- Unique method which works with focused, intense beams

# Huge development potential of method, in particular with high rep rate

- Fundamental question: what happens in a PWFA plasma over ps-ns and mm-cm scales?
- In E210 at FACET, plasma afterglow was observed only at one wavelength (H2/He), integrated over ms
- Next steps: explore effect spatially, temporally (streak camera?), and spectrally resolved..
- Investigate surface waves, radiation production
- Explore with different angles than 90°
- Explore with multi-torches
- Explore plasma kicker
- Machine learning of afterglow signature?
- **Ultra-versatile bunch diagnostics**



# Requirements and future steps

- mJ-class laser system which is capable to ionize small seed plasma filament
- Gas volume
- Next steps: increase plasma volume to go to plasma lensing and then PWFA..
- Lase upgrade: mJ $\rightarrow$ Joule-class laser system for preionization of larger volume, which is required for PWFA. Optically generated plasma is the superior method plasma generation!
- Explore optical downramp (plasma torch injection) and plasma photocathode at high rep rate (emittance growth test bed requires novel diagnostic methods): If emittance preservation during staging can be shown to the e.g. 1 µm rad level, who knows if it will work to the nm rad level? Will you see this only after having built 100 stages and emittance growth has accumulated?

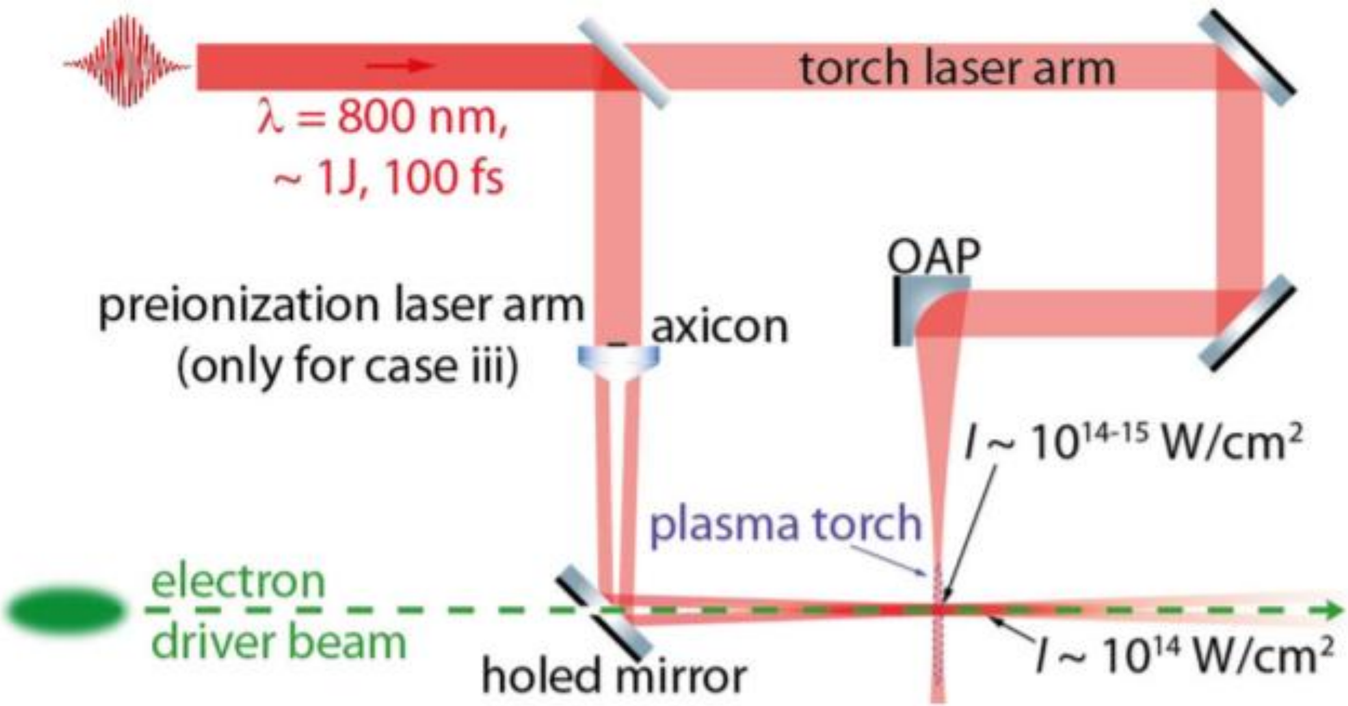
# Optical density downramp injection: Plasma torch

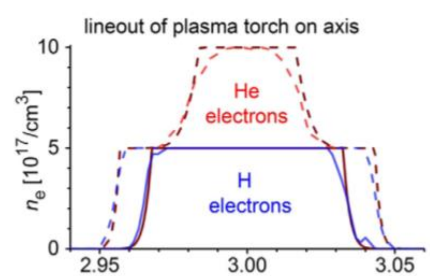
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **18,** 081304 (2015)

**Optical plasma torch electron bunch generation in plasma wakefield accelerators**

G. Wittig,[1] O. Karger,[1] A. Knetsch,[1] Y. Xi,[2] A. Deng,[2] J. B. Rosenzweig,[2] D. L. Bruhwiler,[3,4] J. Smith,[5] G. G. Manahan,[6] Z.-M. Sheng,[6] D. A. Jaroszynski,[6] and B. Hidding[1,2,6]

- Problem with density downramp schemes: how to shape and reliably produce density downramps?
- Approach: use laser to produce density spike via ionization of higher ionization threshold medium



# Optical density downramp injection: Plasma torch

- Proposed this as part of FACET Trojan Horse proposal in 2011

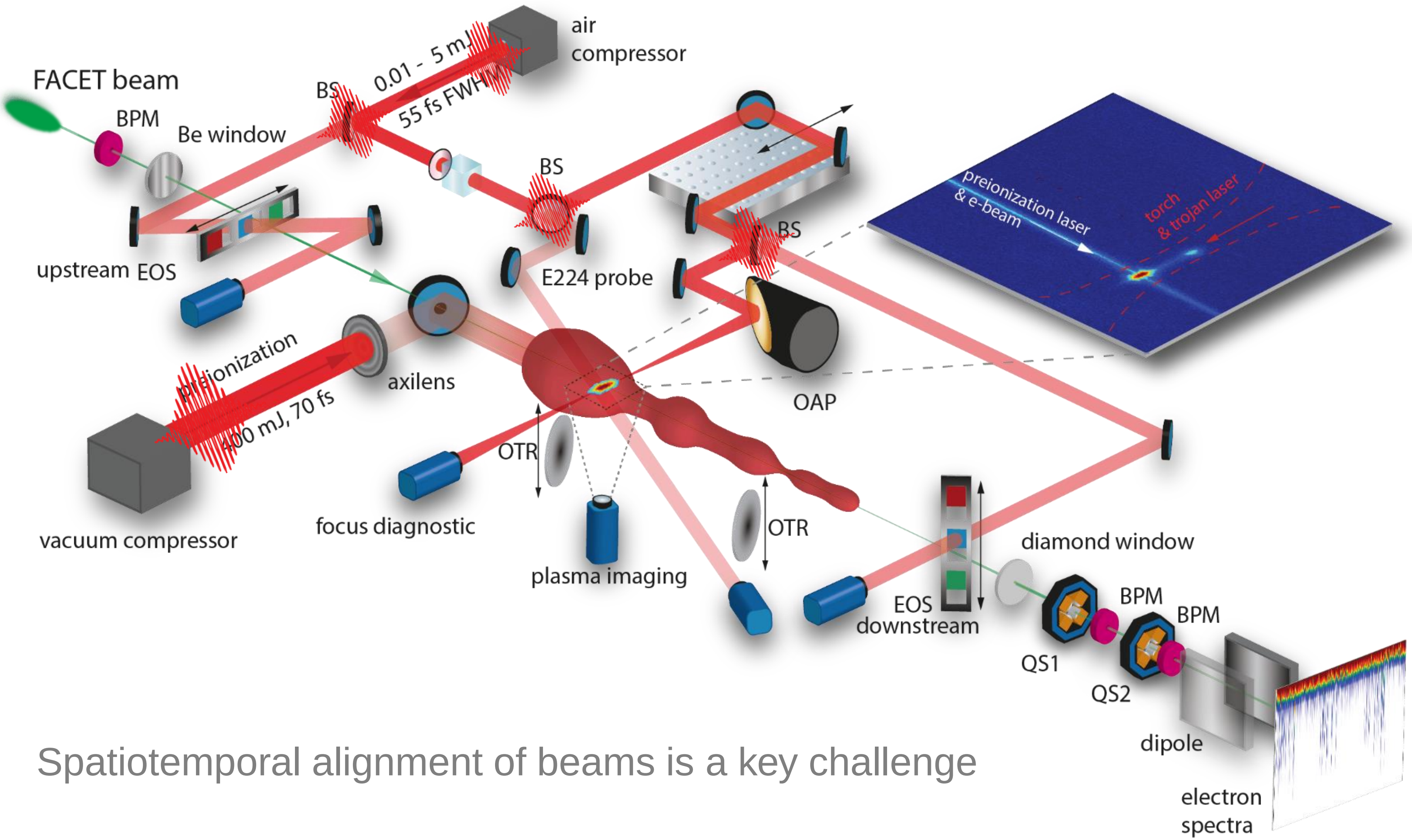
- Realized this 2016/17 at SLAC FACET

all types of experiments at FACET, enabling ultrafast pump-probe type experiments, for example.

Until the sub-100-fs, synchronized LCLS probe laser can be used, we propose to use a green 532 nm laser system (multi-J, ns-class, already planned to be used to pre-ionize Cs or Rb oven) for initial and necessary preparatory studies of the scheme. To this end, the laser pulse has to be focused tightly to intensities at the ionization threshold of the high-ionization threshold gas component (He/Cs+/Rb+). Just as in the fully evolved Trojan Horse scheme, it will release electrons in the beam's path. However, since it is a few nanoseconds long, it will be ionizing already before the electron beam arrives. Both the electrons as well as the ions are quasistationary at these intensities and on this timescale. This will generate a standing plasma torch. The difference to the way this laser is planned to be used to pre-ionize Cs is: a) the focusing is much tighter, aiming at a very small, micron-sized focal spot instead of soft-focusing and a long ionized track, and b) the focal intensity shall be higher, because here, Cs+ must also be ionized in the focal spot, not only Cs. The central region of ionized volume will be filled with Cs++ ions and both the Cs+ and the Cs++ electrons, being flanked by a region where only the 1st ionization level of Cs is ionized by the focusing/defocusing laser pulse. When the driver beam arrives, it will see the local electron density spike, and the blowout will be perturbed. It is known that a local density spike leads to increased self-injection [12,13]. The locally increased charge will be accelerated and will be visible on the beam viewer behind the spectrometer as an intensity spike at a certain sharp energy. The energy correlates approximately linearly with the position of the plasma torch. By moving the position of

Trojan Horse Facet Proposal 2011 (long version)

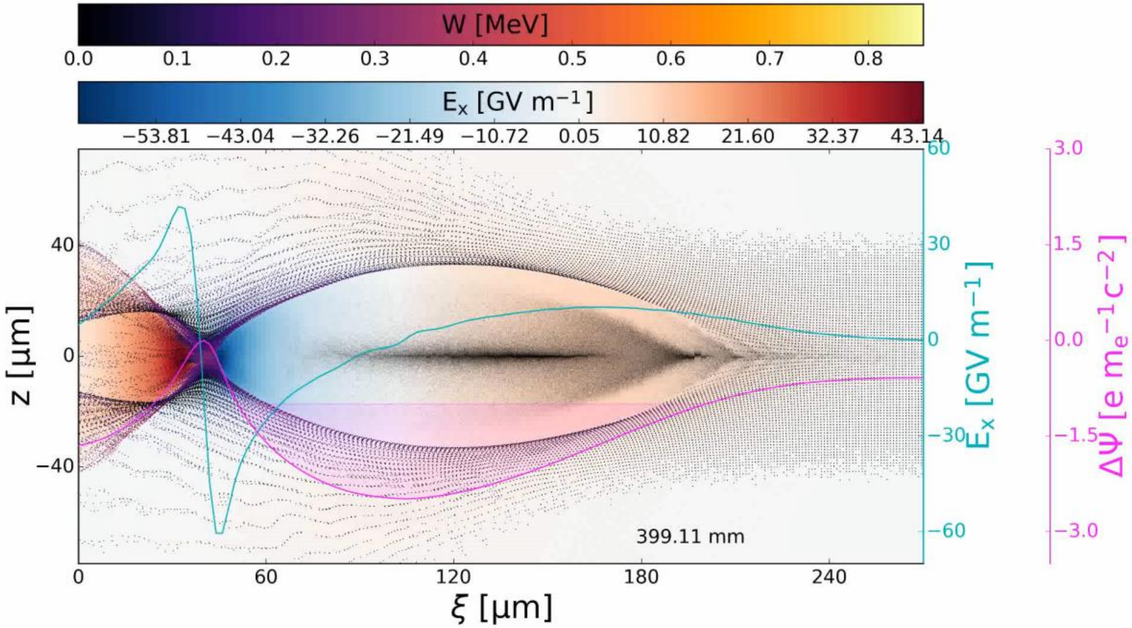
2016: Full E210 setup with two independently tunable main laser arms, up to 5 laser beams (1 preionization, 2 EOS, 1 Trojan photocathode, 1 E224 probing) from vacuum and air compressor, and SLAC linac electron beam

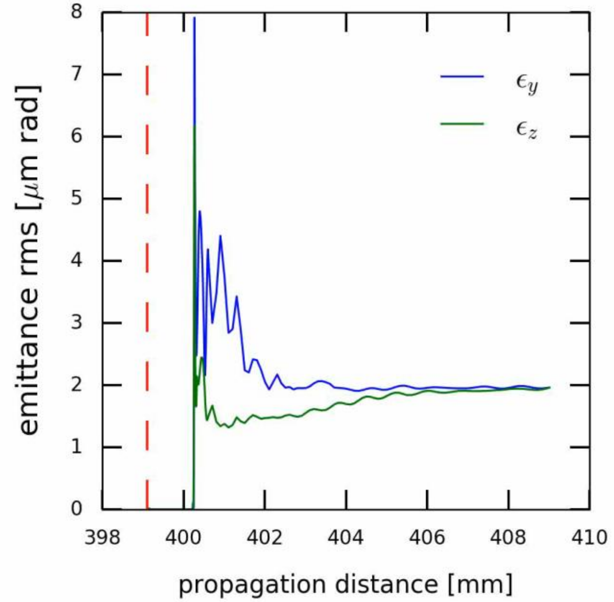


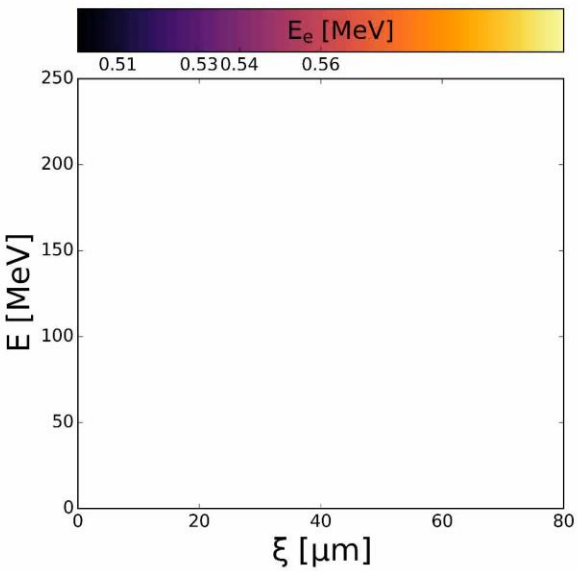

Spatiotemporal alignment of beams is a key challenge

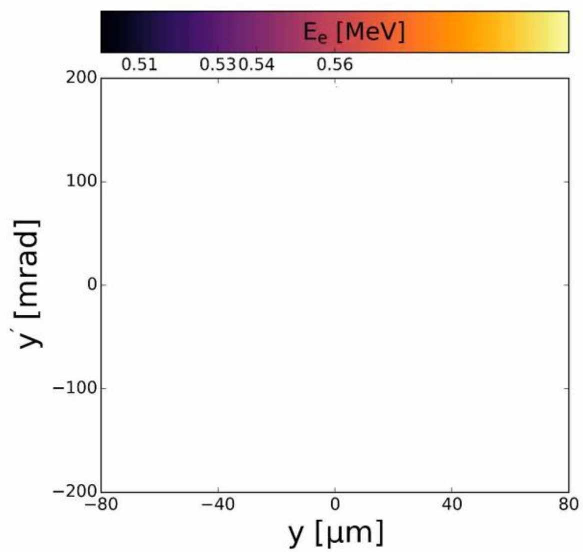
# Plasma Torch injection @5 mJ

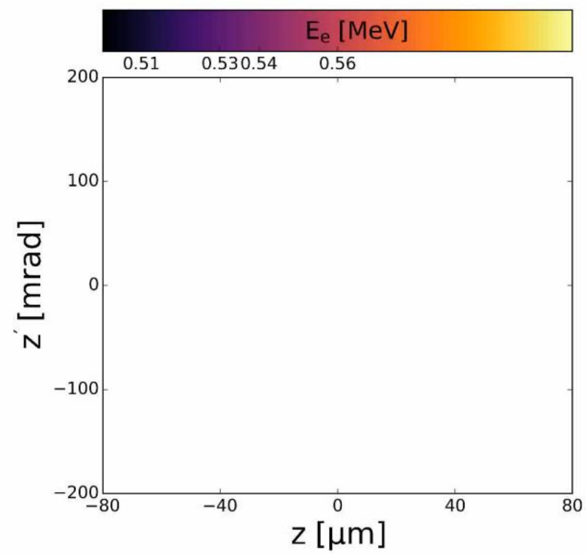
simulation with Tech-X VSim & PicViz



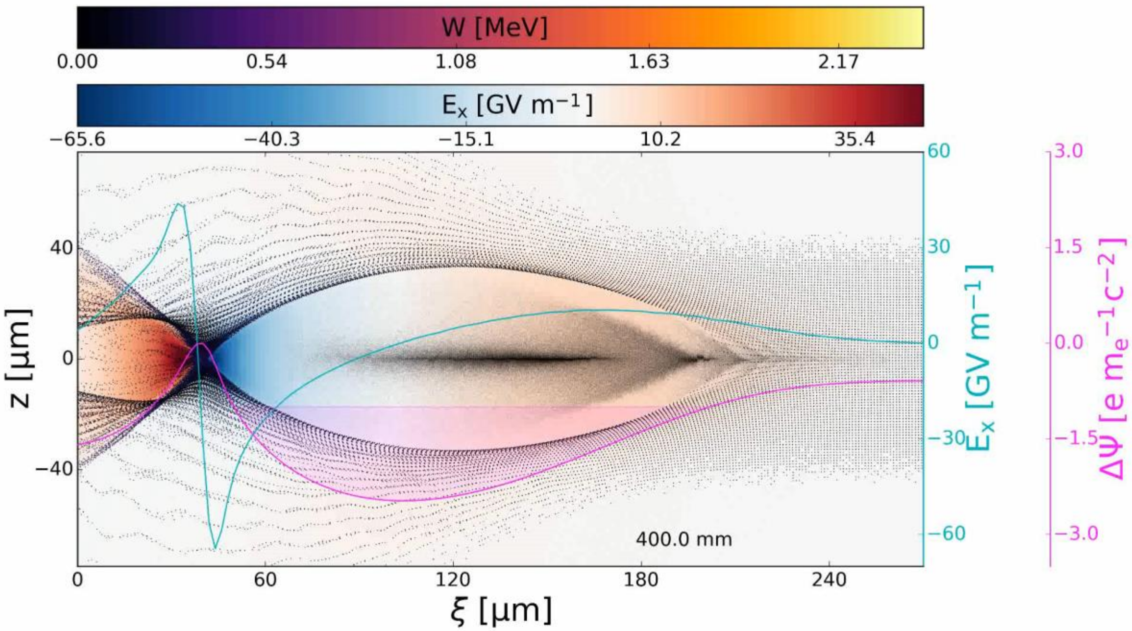



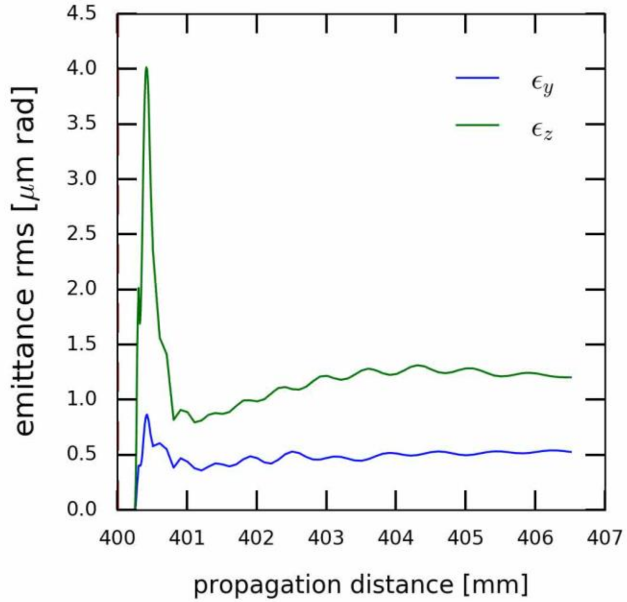



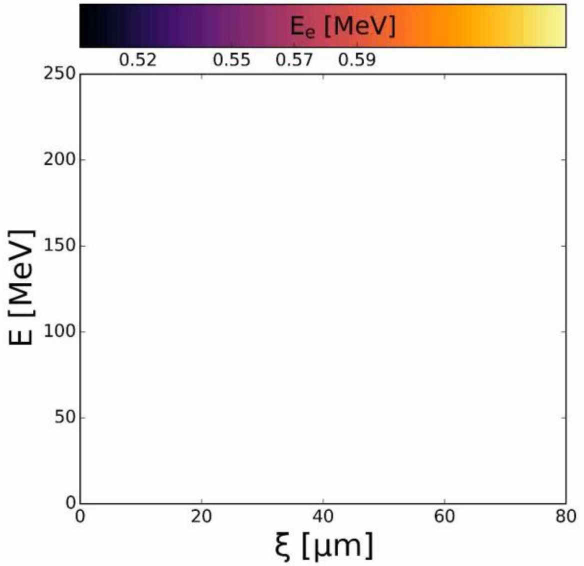



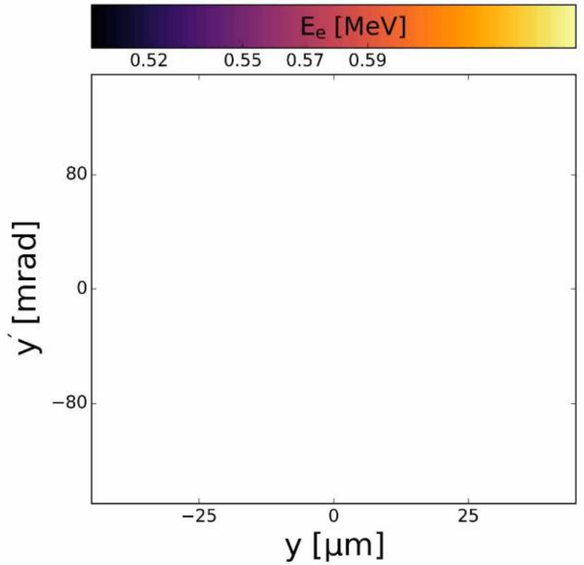
# Trojan Horse injection @0.5 mJ

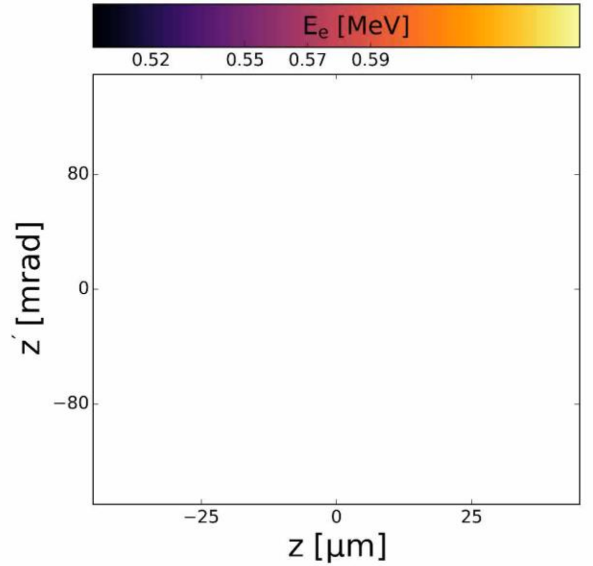
simulation with Tech-X VSim & PicViz



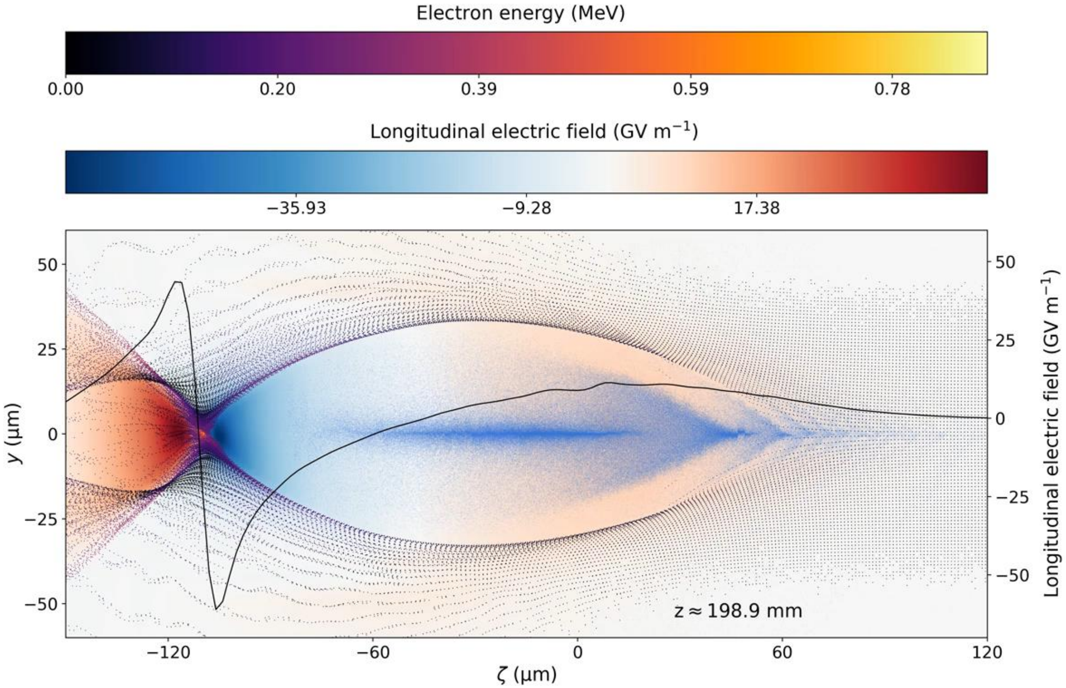



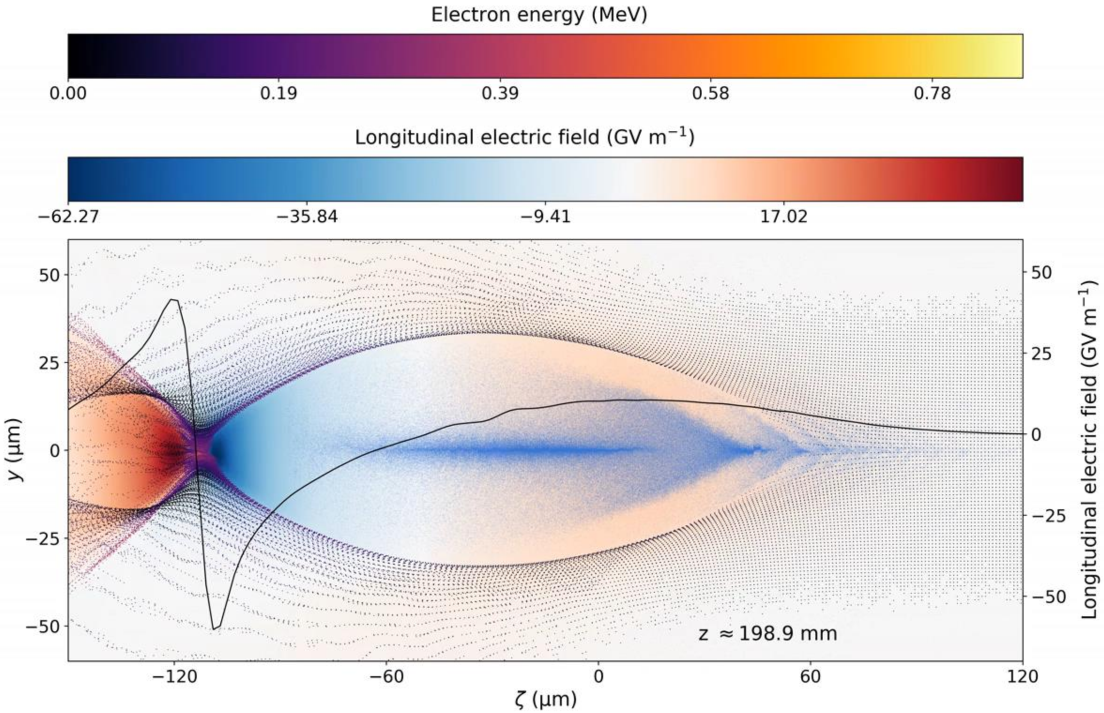



Torch

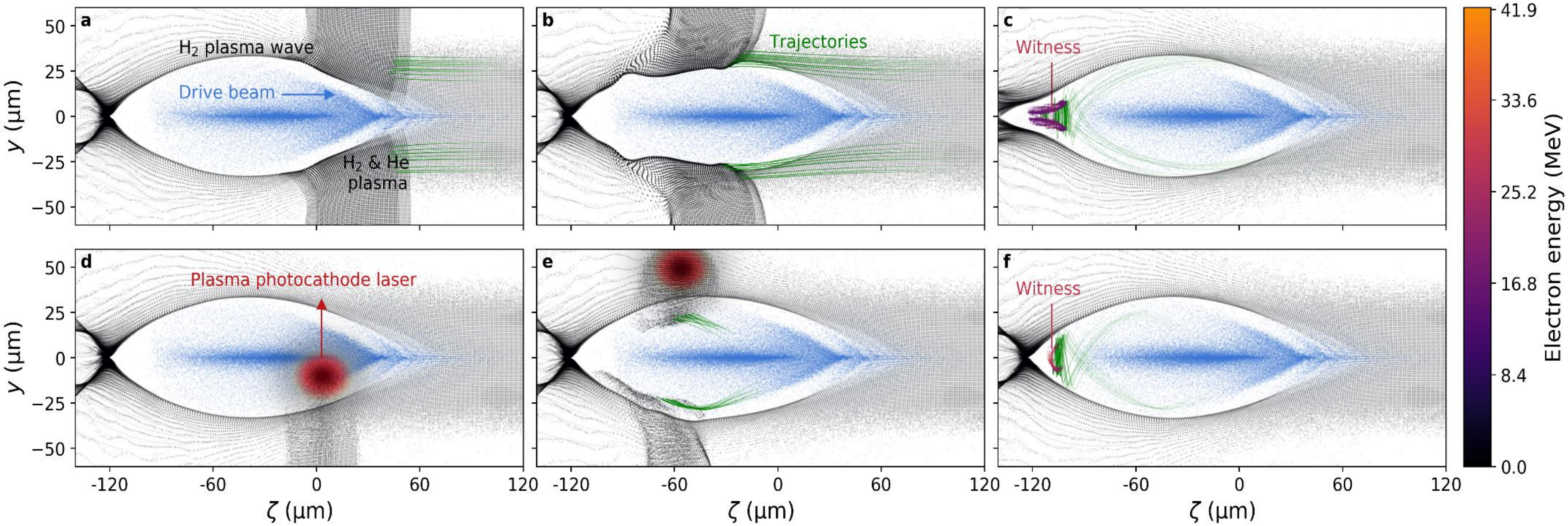



vs.

Trojan



Torch




Trojan

# Exploration potential

- Investigate plasma torch and Trojan at high rep rate – plasma heating and shaping effects including impact ionization and surface waves important?
- Ion motion?
- Instability studies: use plasma photocathode to shape beams in form and chirp?

  via tailored beam loading G.G. Manahan, F. Habib, *Nat. Comms. 8, 15705*, 2017
- Show nm emittances by using larger blowout and non-90° geometry
- Show nm-level emittance preservation during staging?
- Realize radiation sources based on tiny emittances, spot sizes and high 6D brightness?
- .....

# UK STFC Accelerator Review Report


- ❑ Just released (including UK version of "Novel Acceleration" roadmap)

Exec. Summary: "Novel Acceleration is a priority for the future of the accelerator programme" .. "Novel acceleration research is centred on CLF and the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA)"

**Recommendation 1** – Expeditious investment in novel acceleration over a 5-10 year timescale is recommended to support accelerator applications development in collaboration with industry.

**Recommendation 2** – Investment to complete development of CLARA and support its exploitation is recommended to enable:

- Research and development for FELs as a European test-bed facility;
- Novel acceleration development;
- A test-bed for industrial applications.

**Recommendation 6** - Collaboration with international partners on facility development and accelerator research activities is recommended, where appropriate.

# UK Plasma Wakefield Accelerator Steering Committee PWASC

- ❑ Upcoming PWASC roadmap will also emphasize PWFA and intn‘l collaboration


www.pwasc.info

# Summary and conclusions

- High interest to engage in beam-laser-plasma-interaction at FAST at Strathclyde & the UK
- Novel versatile plasma-photonic regime found which is of large interest to high rep-rate setups, and needs only very limited gas/plasma load
- Ionizing laser needed!
- Straightforward path to develop this seed experimental setup to advanced PWFA
- Momentum is increasing to develop this as part of a US-UK collaboration