# Stability analysis of plasma photocathode produced ultrahigh brightness electron beams

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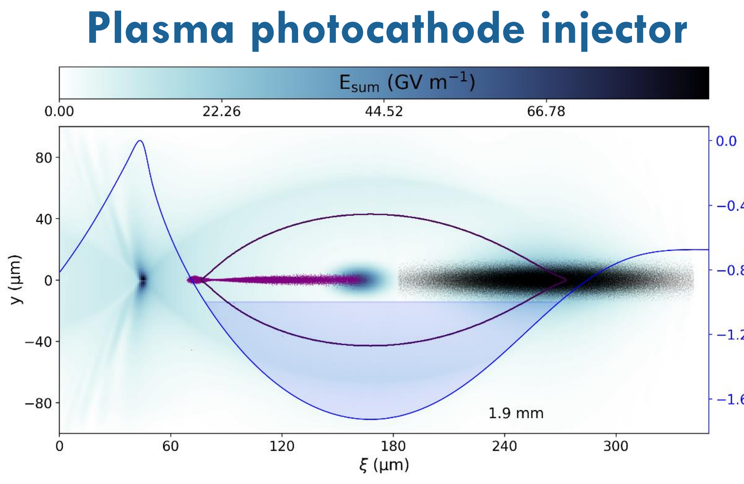
## Abstract

We report on demonstration of plasma photocathode in particle-driven Wakefield acceleration (PWFA) obtained within the "E-210: Trojan Horse PWFA" collaboration at SLAC National Accelerator Laboratory FACET. Further, we identify key experimental limitations and study them in a systematic jitter analysis utilizing 3D Particle-In-Cell (PIC) code. The results from this study indicate that the electron beam parameter shot-to-shot stability can be comparable to the state-of-the-art rf-based accelerators. These findings are very encouraging for the upcoming experimental campaigns at SLAC FACET-II: e.g. "E-310: Trojan Horse-II" and "E-313: Multibunch dechirper for ultrahigh 6D brightness beams".

## Motivation

The plasma photocathode particle-driven Wakefield accelerator (TH-PWFA) is a promising path towards electron beams with ultrahigh 6D-brightness, multi-GeV energies and sub-% energy spreads in a single PWFA acceleration stage [1,2]. This electron beams with superior quality are opening the path towards key applications such as XFEL, ICS, and HEP [2,3,4].

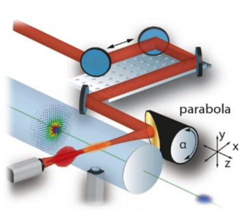
**Plasma photocathode injector**



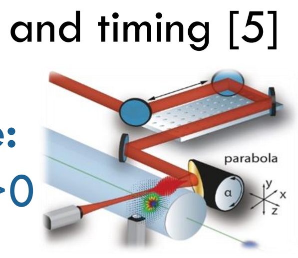

## E-210: Demonstration of 90° plasma photocathode injection

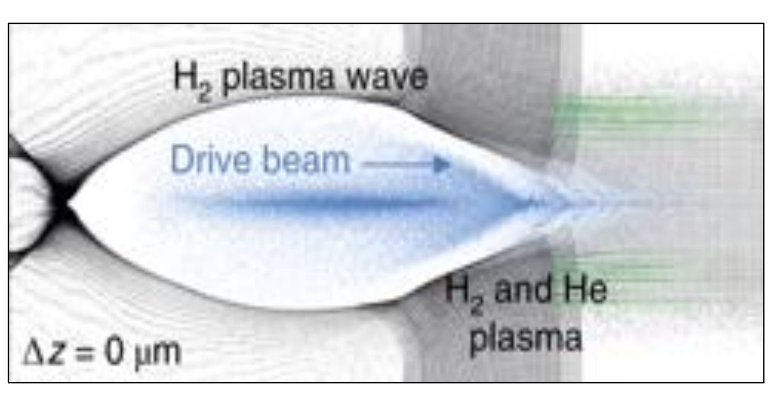
- Demonstration of two injection methods in PWFA for the first time [5]
- **Plasma torch injection:** All-optical density downramp injection
- **Trojan Horse injection:** Plasma photocathode injection in 90° geometry
- Two component noble gases (Hydrogen/Helium) are used to decouple acceleration from injection
- Both regimes accessible in the same set up by tuning laser energy and timing [5]

**Plasma Torch:**
time-of-arrival (TOA)<0

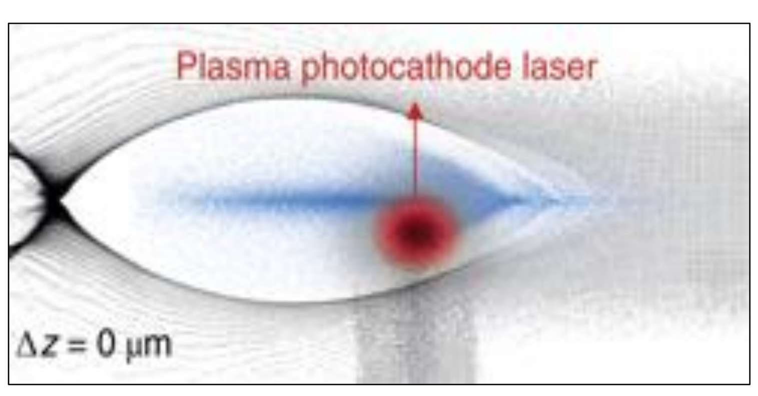


**Plasma Photocathode:**
time-of-arrival (TOA)>0

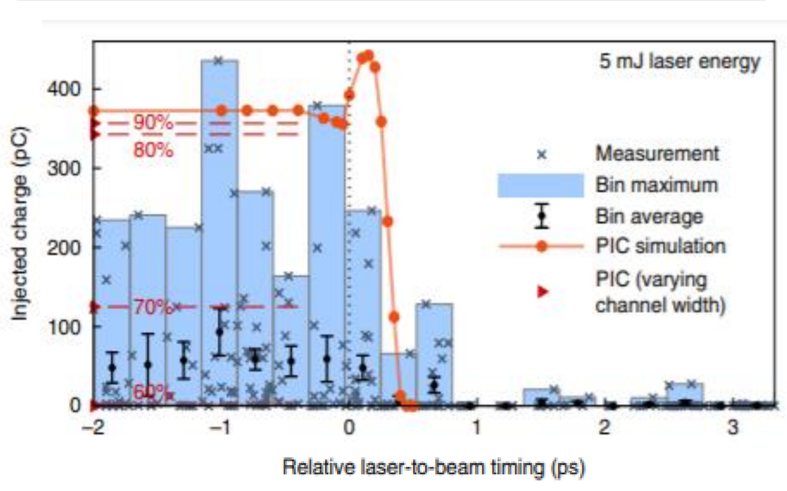




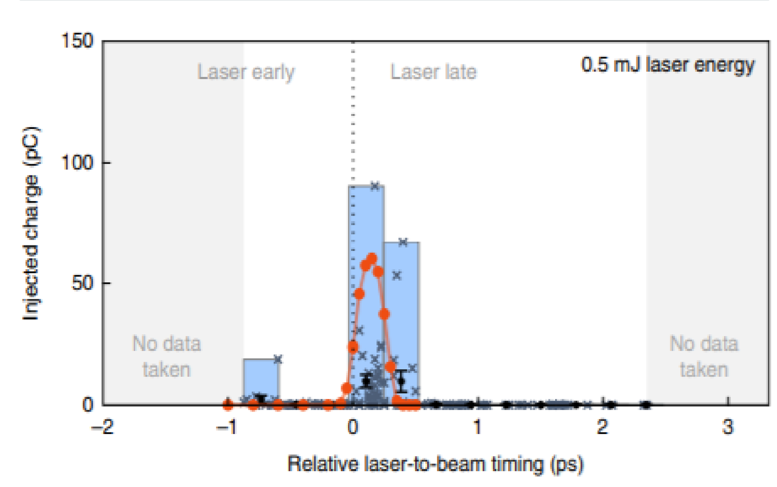

3D PIC simulation of plasma torch injection




3D PIC simulation of 90 plasma photocathode injection

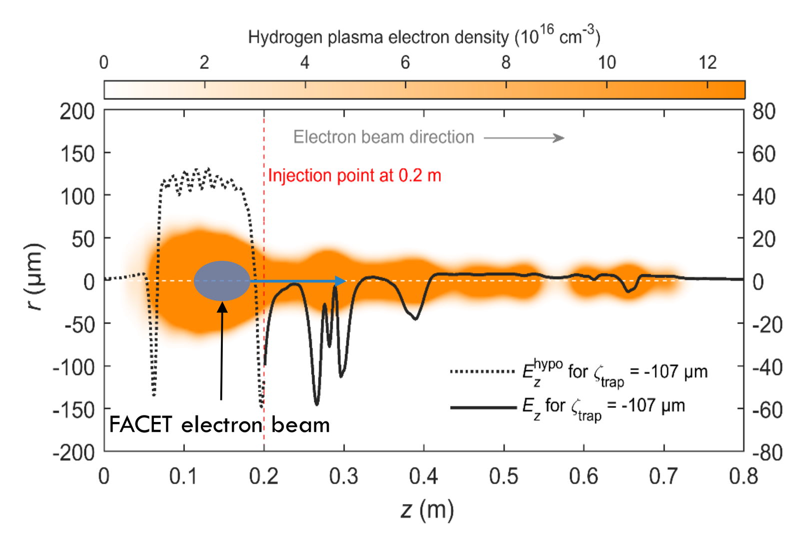



Laser timing scan at 5mJ injector laser energy

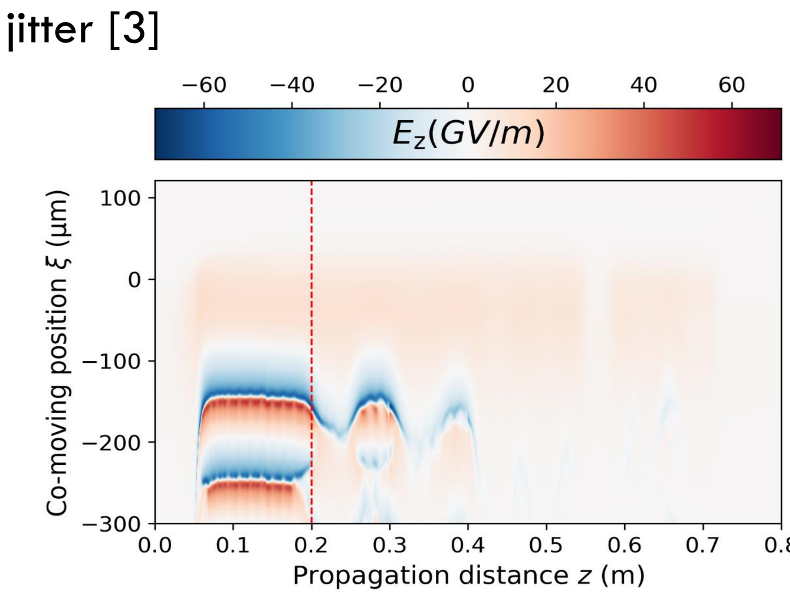



Laser timing scan at 0.5mJ injector laser energy

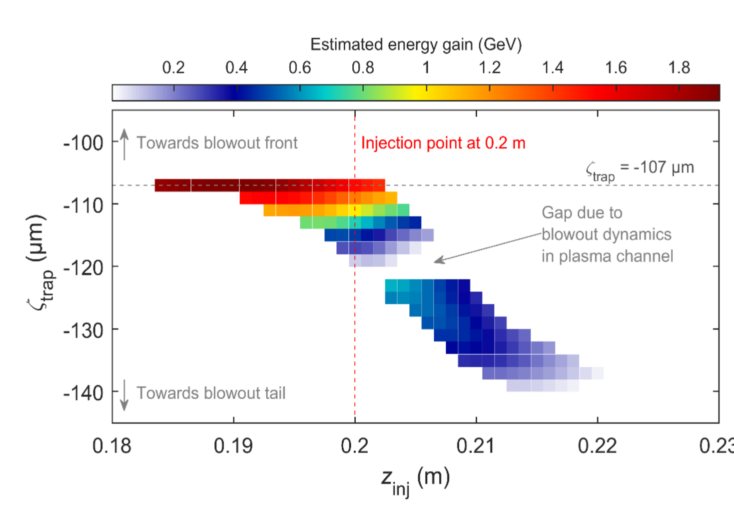
- Hydrogen plasma channel width limits PWFA operation point ($\lambda_p = 98\ \mu m$)
- Plasma channel radius $r_c$ is smaller than the blowout radius $R_b$ in some parts
- Wakefield evolves because of plasma channel width variation
- Wakefield changes from accelerating to deaccelerating phase at the witness beam trapping position → Limits witness beam energy gain [5]
- Technical limitations: Driver beam, plasma channel and injection laser jitter contribute to witness beam parameter jitter [3]



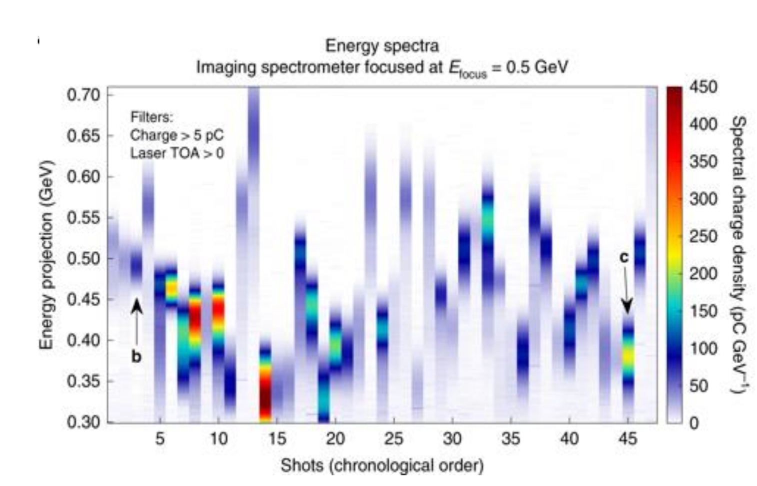

Axilens generated plasma channel




On-axis Wakefield evolution



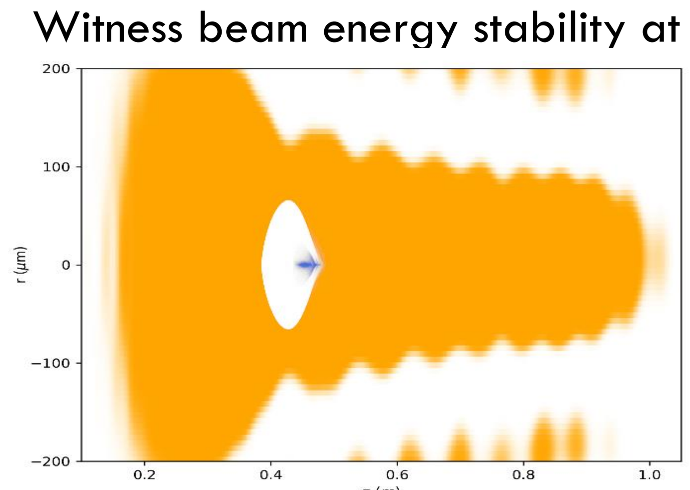

Witness beam energy estimates



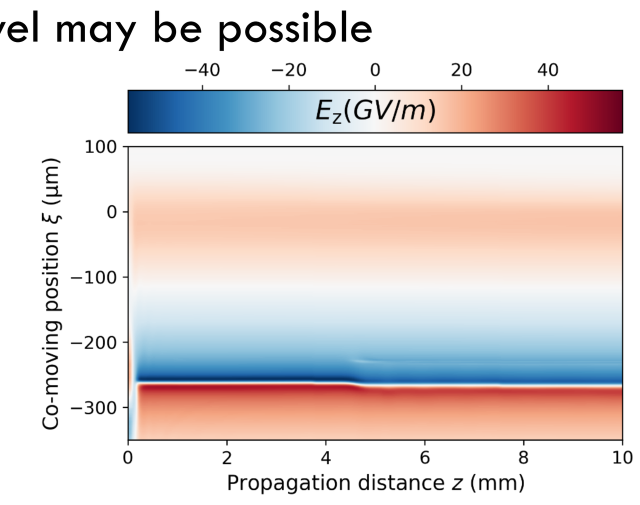

Witness beam energy measurements

## Stability analysis of plasma photocathode towards FACET-II experiments and beyond

- Wide plasma channel (e.g. channel radius $r_c \geq 2 \times R_b$ ) allows stabile PWFA operation at longer plasma wavelength (e.g. $\lambda_p \geq 250\ \mu m$) [3]
- Stabile witness beam acceleration over meter distances→ multi-GeV beams
- Longer plasma wavelength relaxes alignment and timing requirements
  → Impact on witness beam properties is significantly reduced
- Witness beam energy stability at sub-% level may be possible



Wide plasma channel




Wakefield evolution in a wide plasma channel

Publication embargo

TH-PWFA witness beam energy stability considering various jitter contributions

- Generous injection laser jitter values are assumed; Misalignment: $\pm 10\mu m$, Timing jitter: ±30 fs, normalized laser amplitude jitter: ±2%
- For simplicity an uniform statistical probability is considered
  → A Gaussian statistical probability is a better approximation
- The 6D-brightness combines key beam properties such as: beam peak current, normalized emittance and energy spread

$$B_{6D} = \frac{I_p}{\epsilon_{n,x}\,\epsilon_{n,y} 0.1\%BW}$$

Publication embargo

TH-PWFA witness beam 6D brightness stability considering various jitter contributions

- Ultra-high 6D brightness jitter of the witness beam is comparable to modern LINACs [6]→ Promising for key applications such as XFEL, ICS and HEP.
- Technical improvement will further enhance electron output stability
- Results are encouraging towards FACET-II and future experiments

## Conclusion

- **Plasma torch** and **Plasma photocathode injection** work in PWFA even under sub-optimal conditions→ Path towards ultra-high quality electron beams
- Plasma channel width limits energy gain and witness beam parameter stability
- Wider plasma channels allow stable acceleration over meter distance
- Longer plasma wavelength may enable sub-% energy spread beams with nm rad normalized emittances [2] and reduces alignment and timing requirements
- Witness beam parameter stability is comparable with rf-based accelerators
- Results are promising towards applications such as XFEL, ICS and HEP

## References & Acknowledgment

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