FACET-II

Facility for Advanced
Accelerator Experimental Tests

Simultaneous boost of electron beam energy and brightness in a plasma wakefield accelerator

LINAC2026 - 33rd Linear Accelerator Conference

Doug Storey | FACET-II | SLAC National Accelerator Laboratory

August 20, 2025

Downramp trapping in PWFA for generating low emittance beams

- E304 experiment at FACET-II, SLAC National Accelerator Laboratory

- Goals:
  - Generating low-emittance beams using density downramp injection in a plasma wakefield accelerator

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Article https://doi.org/10.1038/s41467-025-65742-8

Plasma-wakefield accelerator simultaneously boosts electron beam energy and brightness

Received: 2 July 2025

Accepted: 21 October 2025

Published online: 28 November 2025

Check for updates

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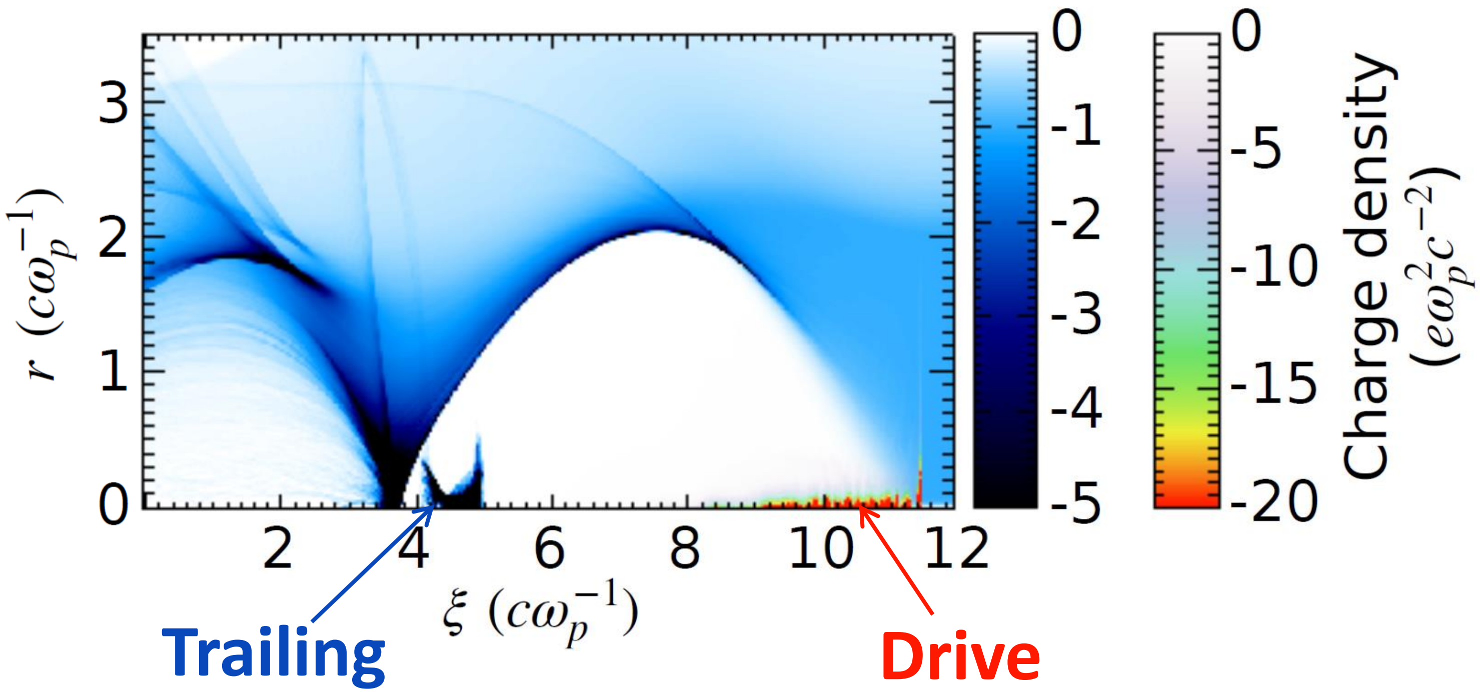
Zhang *et al.*, Nat. Comms. ***16***, 10719 (2025)

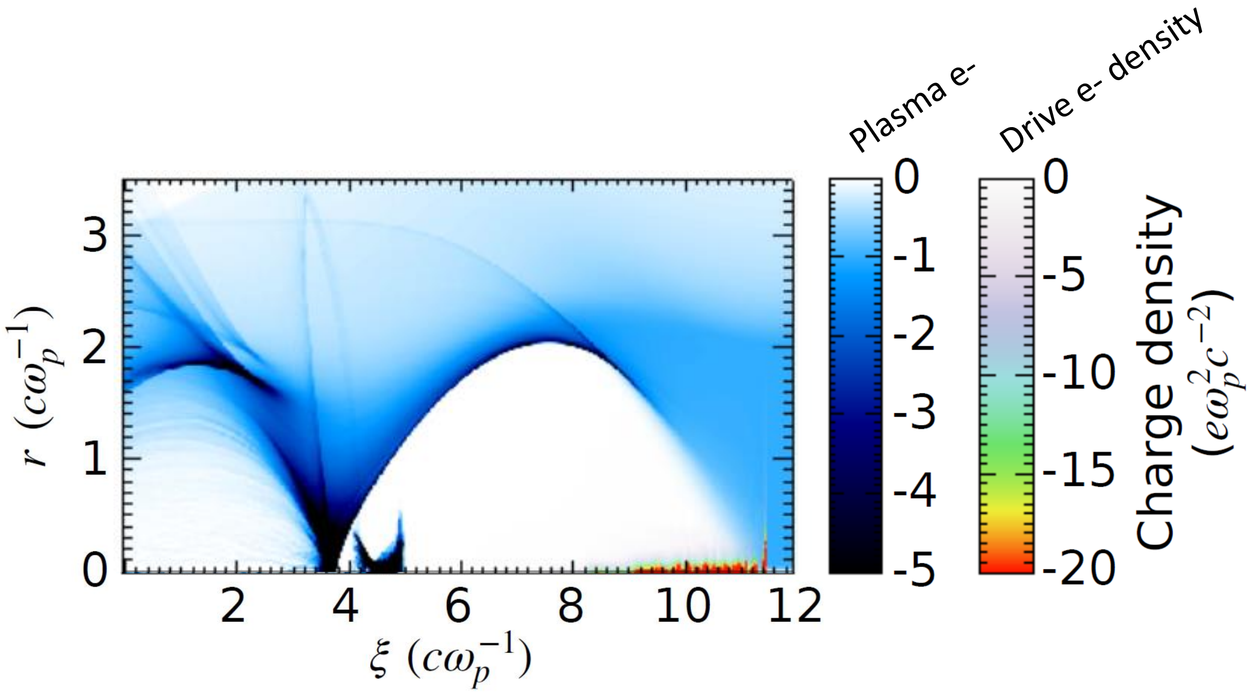
Energy Booster – Plasma Wakefield Acceleration (PWFA)

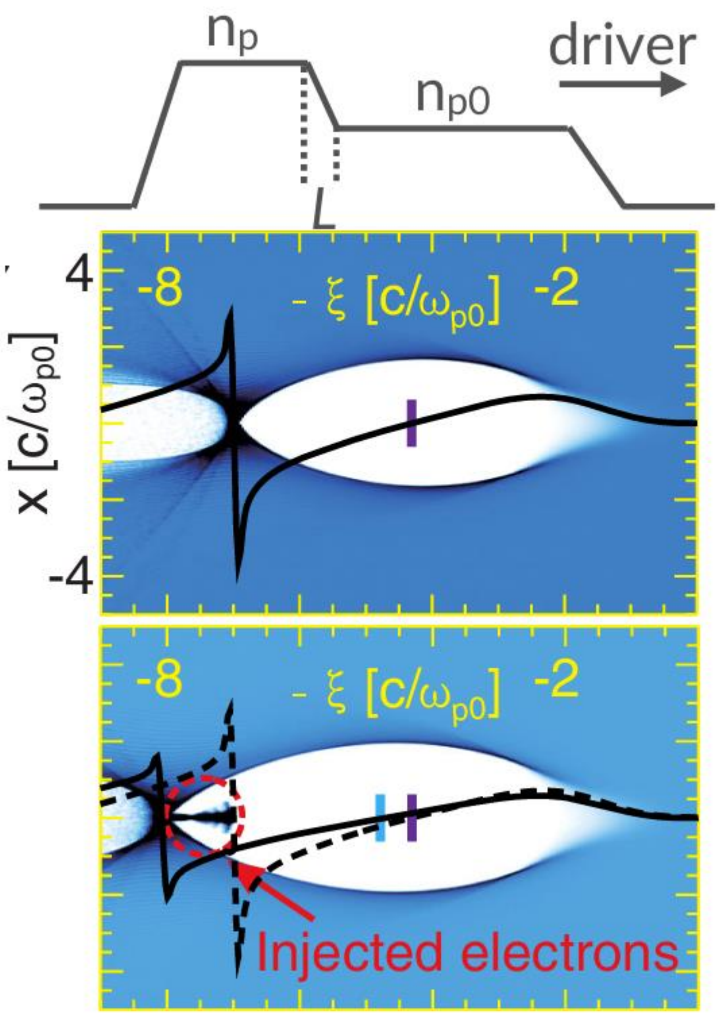
- PWFA in the non-linear blowout regime
  - Drive bunch → expels plasma e- and transfers energy to wake
  - Trailing bunch → e- bunch located at back of the bubble are both focused and accelerated
  - Accelerating gradients ~10's to 100's GV/m
  - Strong focusing force for e-
- Energy transformer from drive to trailing bunch



Brightness Booster – Density Downramp Injection

- Injection of high-quality electron bunches through tailored plasma density profile
  - Injected with dimensions << plasma wavelength
  - Accelerated to relativistic energy very quickly

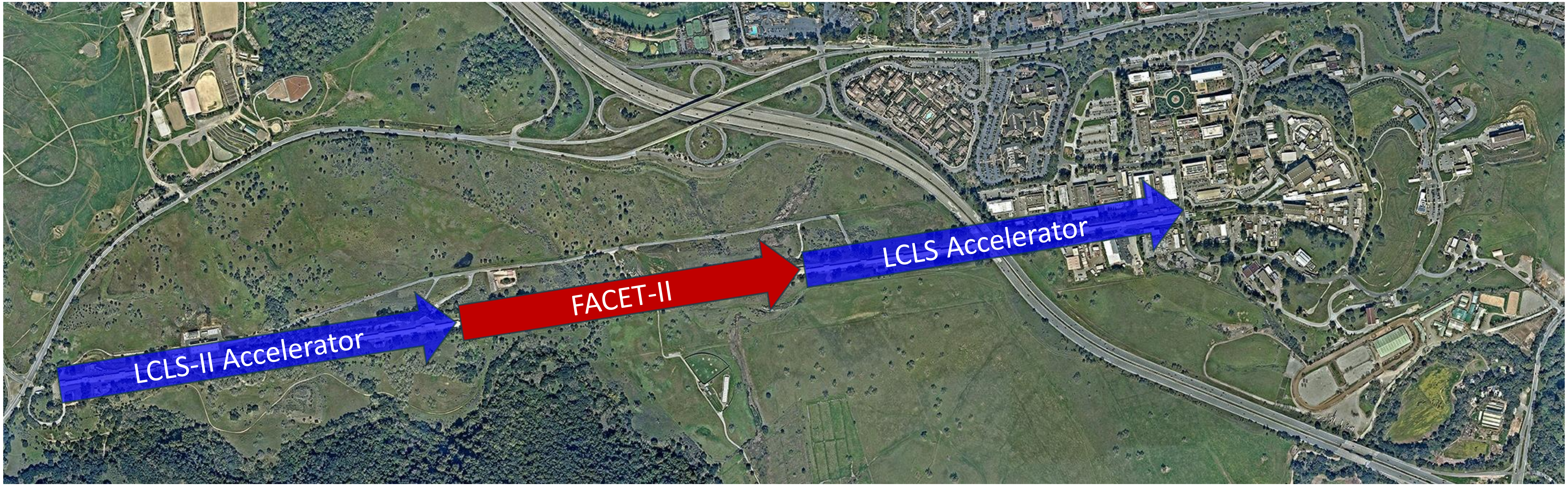




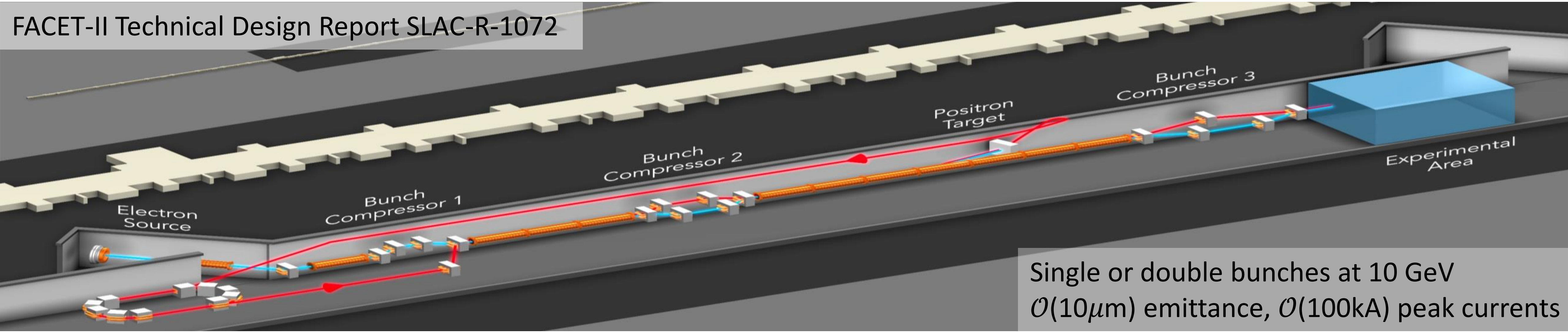
Xu *et al.*, PRAB **20**, 111303 (2017)

FACET-II – A facility for precision PWFA studies

- Experiments performed at the FACET-II National User Facility
- 10 GeV linac for PWFA studies
  - Single or double bunches from a new RF photo-injector
  - RF linac and bunch compressors for precise control of longitudinal phase space

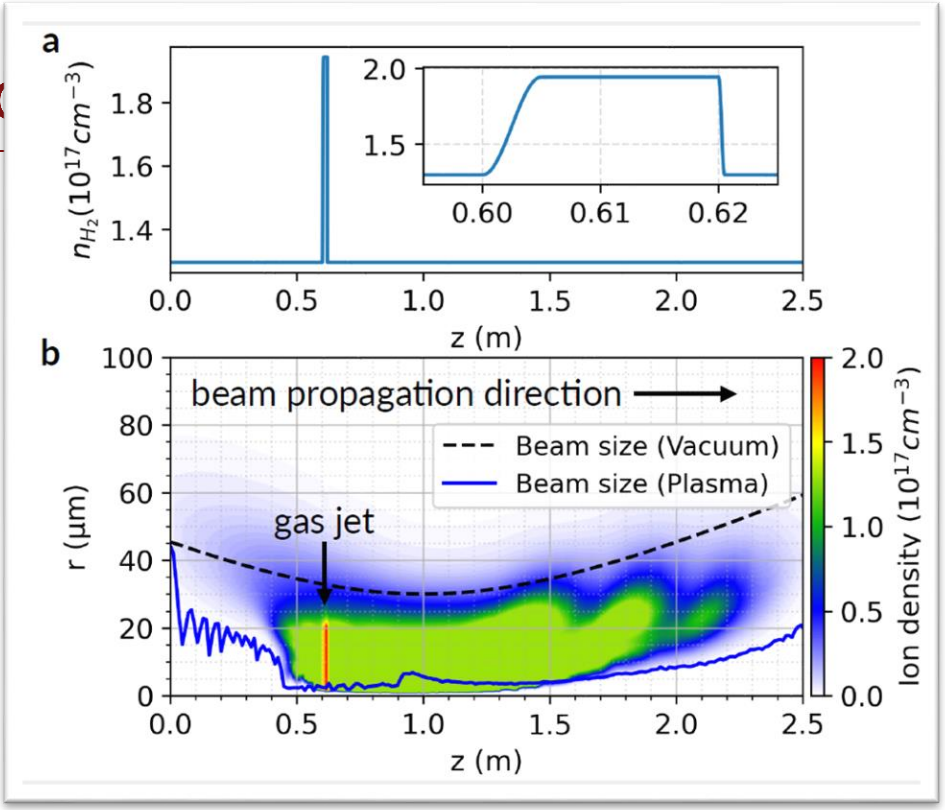


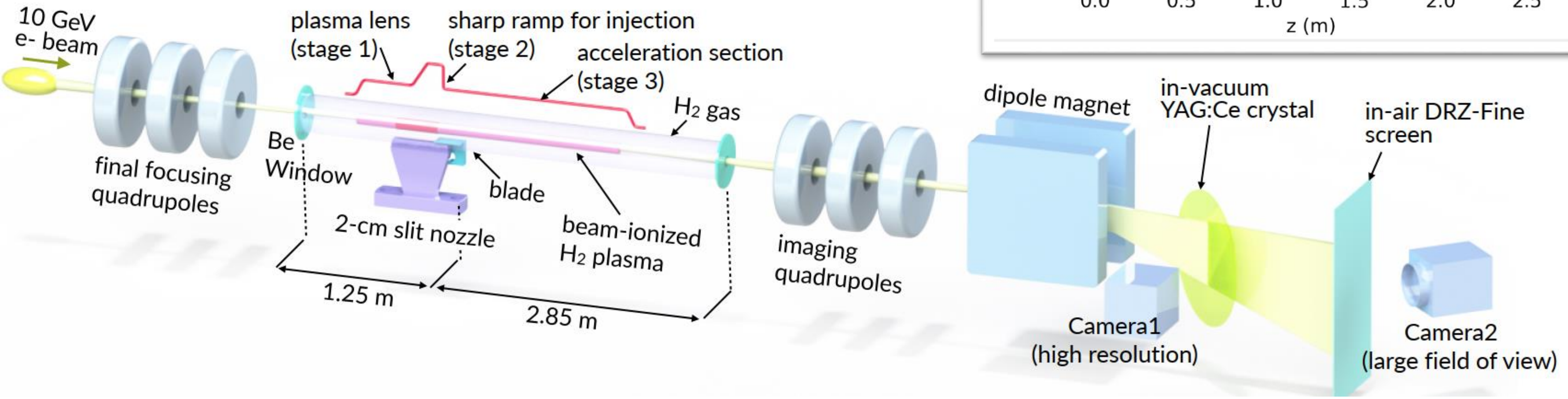
FACET-II provides 10 GeV beams for PWFA studies



Plasma-wakefield energy and brightness boo

- Meter-scale static fill H2 gas, with H2 gas jet
- 10 GeV driver, 1.6 nC
- **Three stage brightness booster:**
  - Stage 1: Plasma lens
  - Stage 2: Density downramp injection
  - Stage 3: Plasma Accelerator





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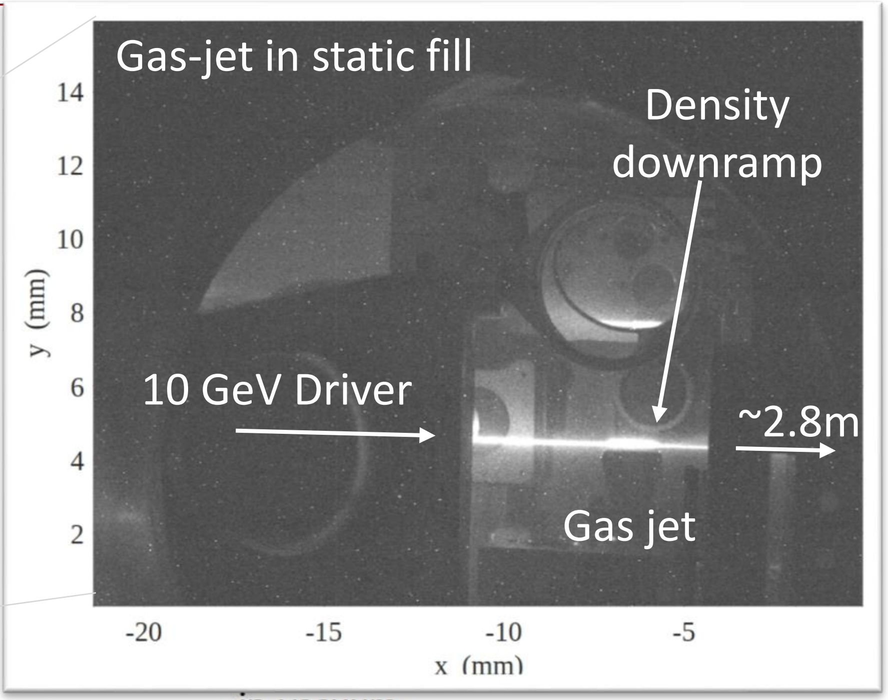

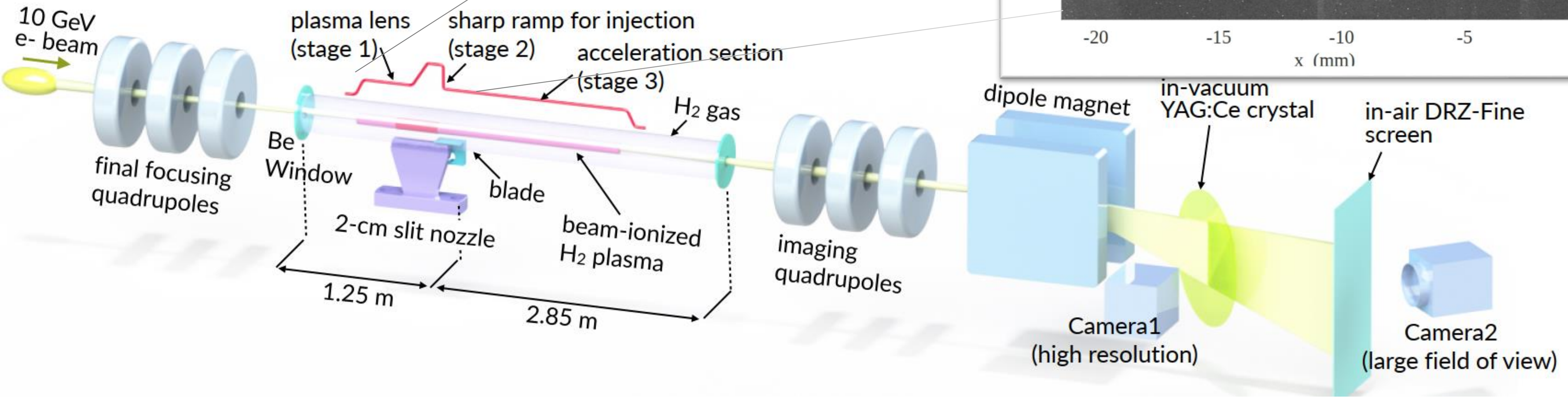

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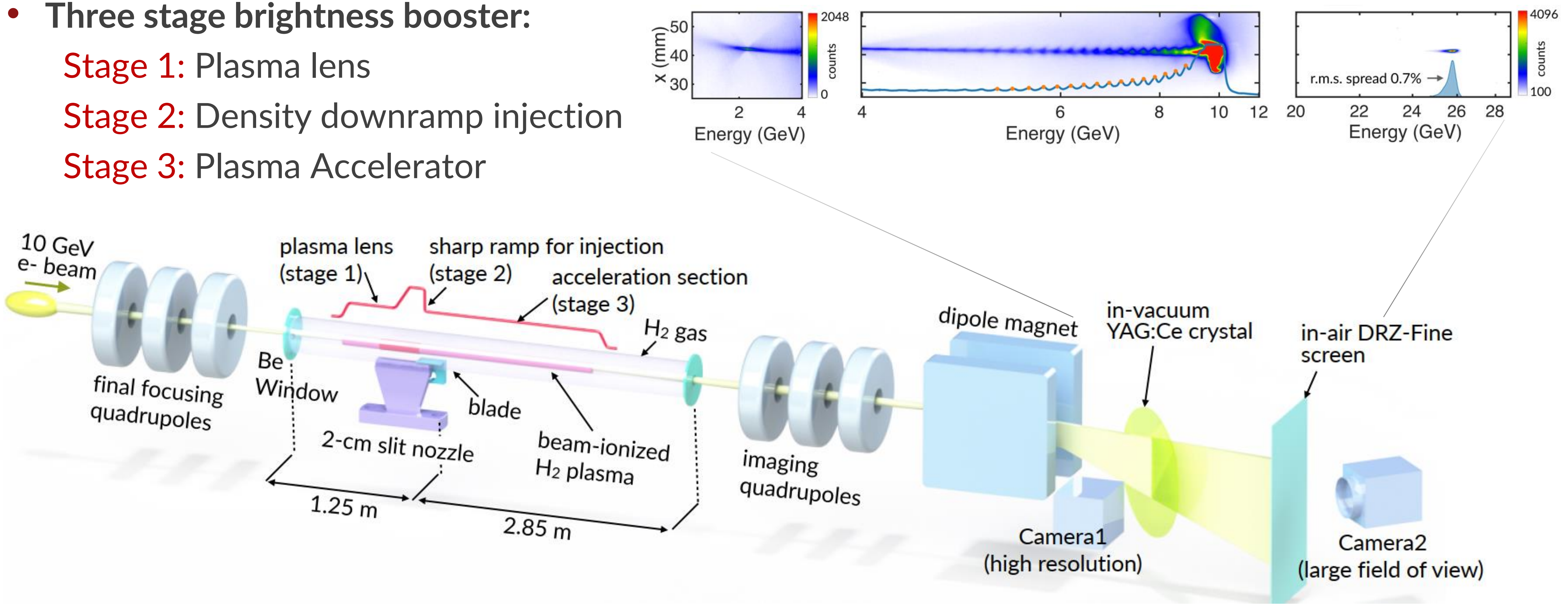
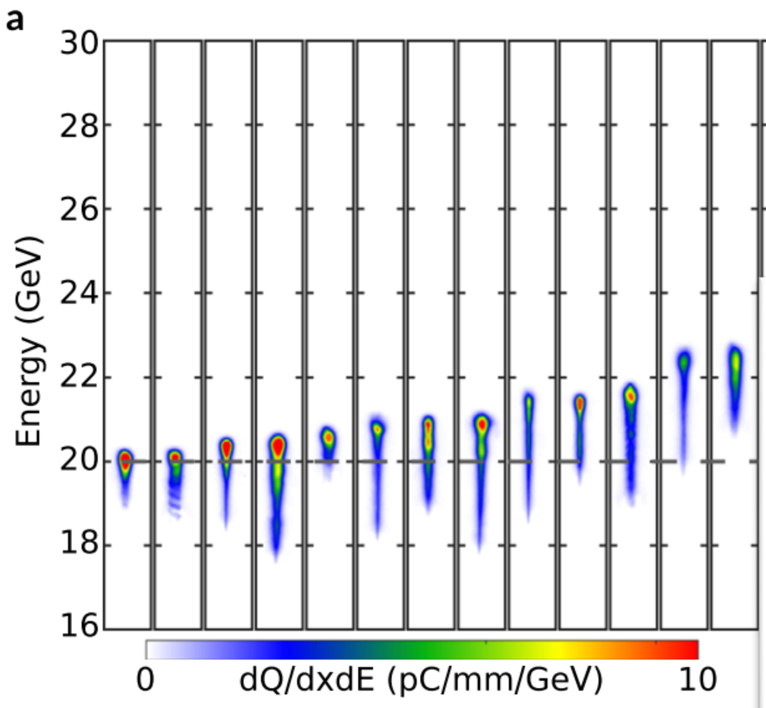
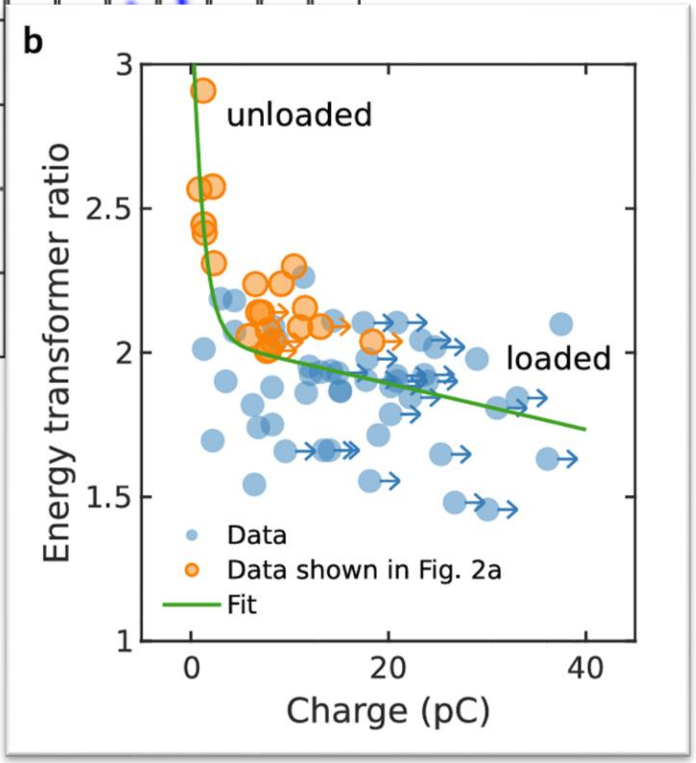


High transformer ratio acceleration of the injected bunch

- **10 GeV incoming electron bunch**
  - Charge: $Q_D = 1.6$ nC
  - Emittance: $\epsilon_{n,x} = 23$ mm mrad
  - Energy spread: $\sigma_E = 0.5\%$
  - Current: $I_{peak} \sim 8$ kA

- **Outgoing beams:**
  - Injected charge: Q_W up to ~40 pC
  - Accelerated to 20 to 30 GeV





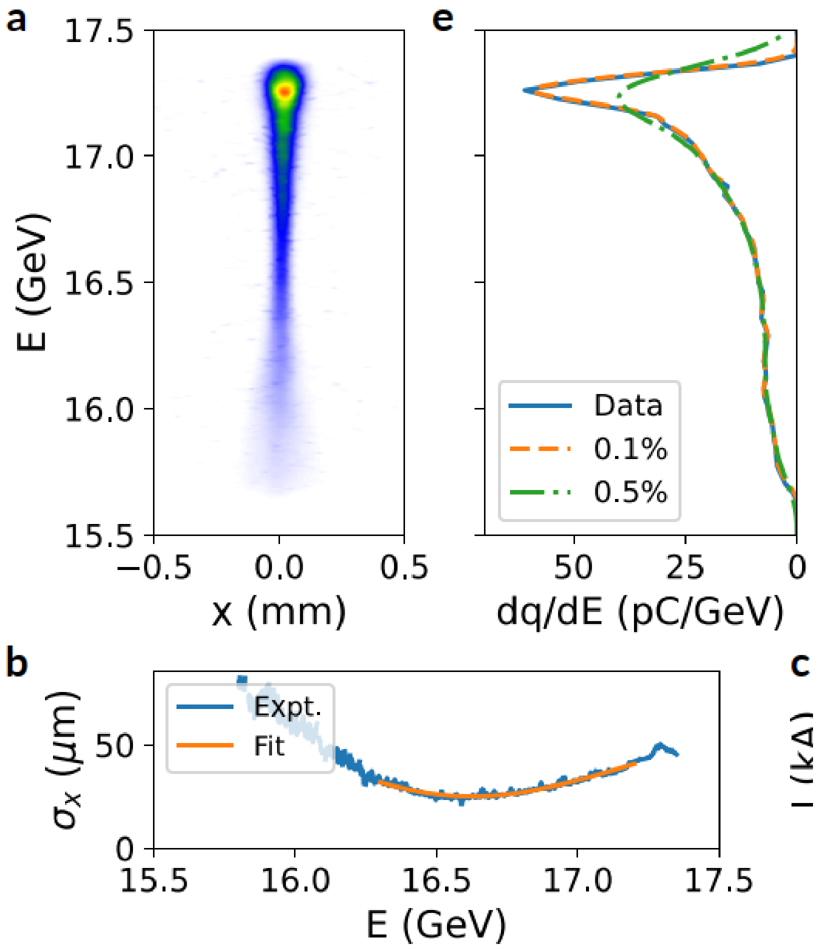
Plasma injected bunches accelerated up to 30 GeV with transformer ratio greater than 2

Direct measurement of emittance and energy spectra

- **Outgoing beams:**
  - Injected charge: Q_W up to ~40 pC
  - Accelerated to 20 to 30 GeV
  - Projected emittance: $\epsilon_{n,x} < \sim 2$ mm mrad

  - Low divergence, but resolution limited emittance measurement

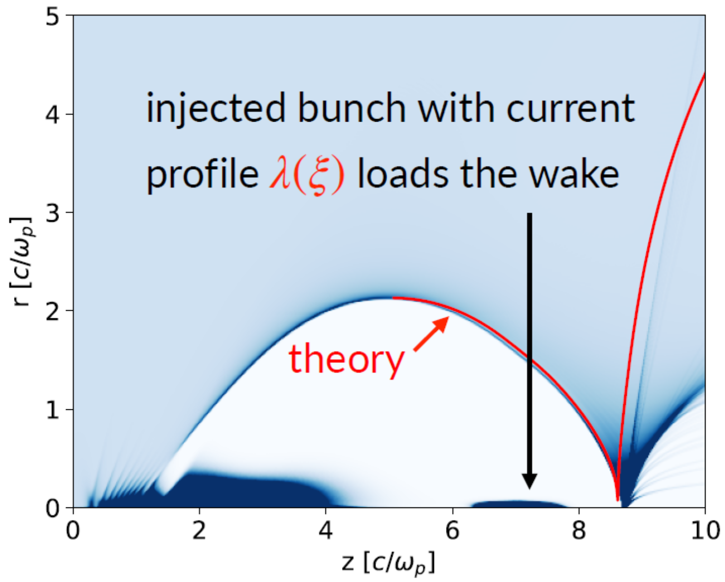
- No direct measurement of beam current

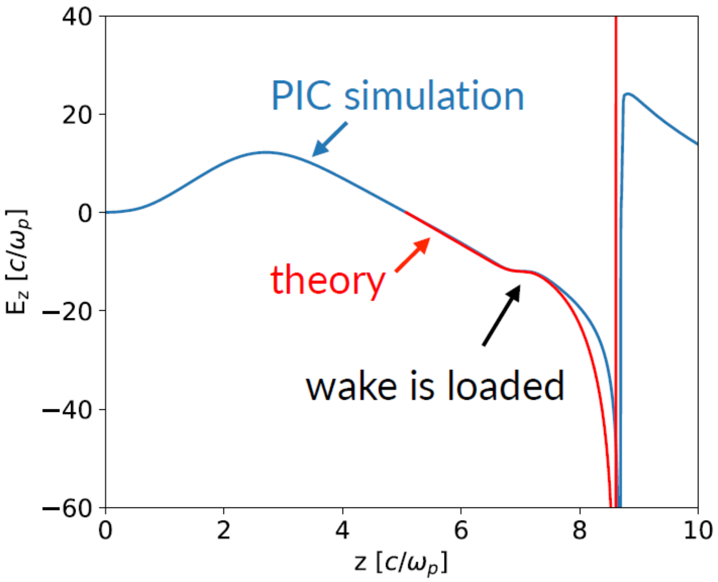


Reconstructing longitudinal phase space from measured energy spectra

- A precise model for PWFA enables the reconstruction of the injected bunch's current profile:

for a given injected bunch with current profile $\lambda(\xi)$ → solving an ODE $A'(r_b)\frac{d^2 r_b}{d\xi^2} + B'(r_b) r_b (\frac{dr_b}{d\xi})^2 + C'(r_b) r_b = \frac{\lambda(\xi)}{r_b}$ to get r_b and the accelerating field E_z → energy spectrum determined by $\lambda(\xi)$ and $E_z(\xi)$



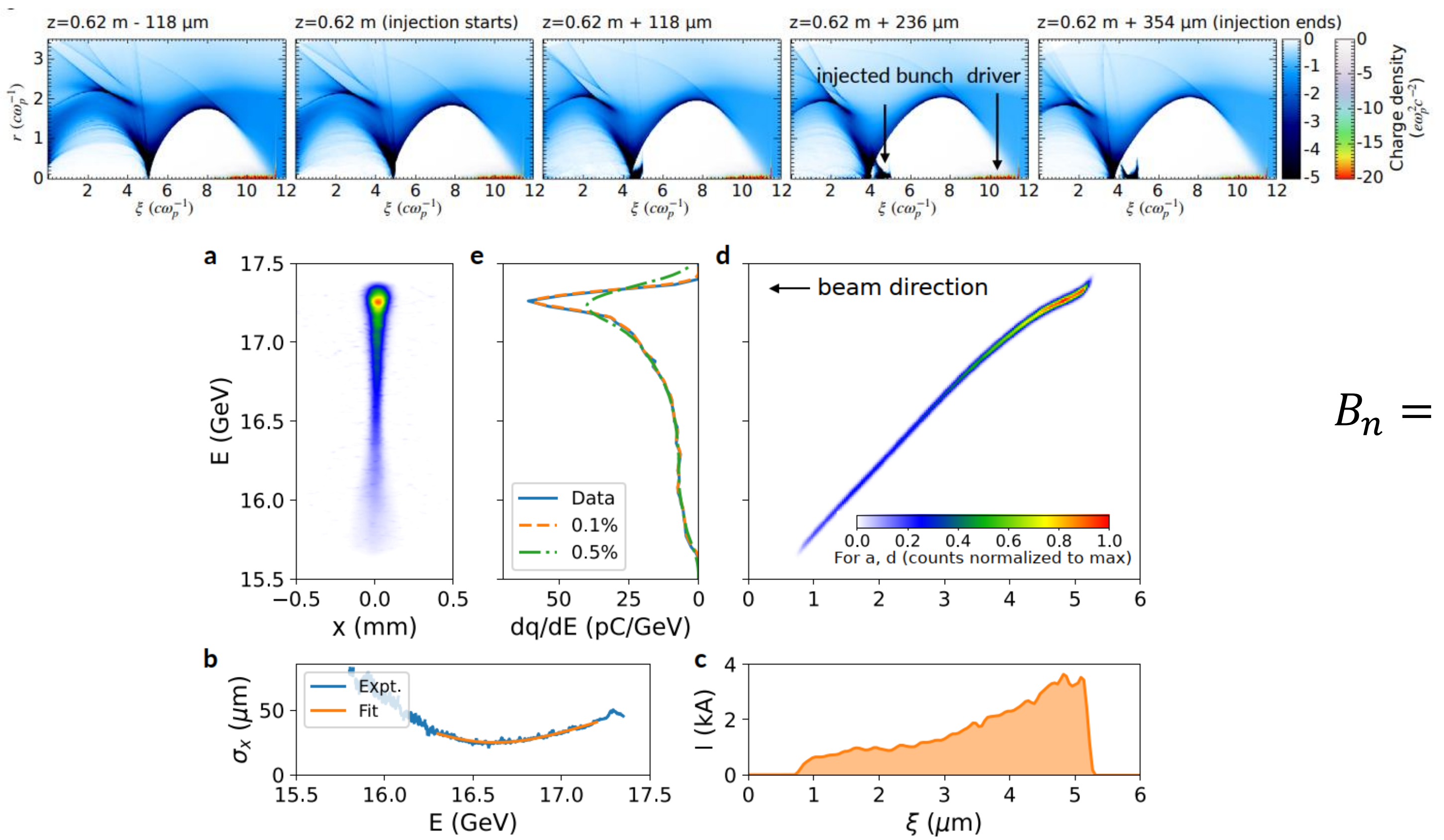


Lu *et al.*, PRST-AB (2007)
Dalichaouch *et al.*, Phys. Plasmas (2021)

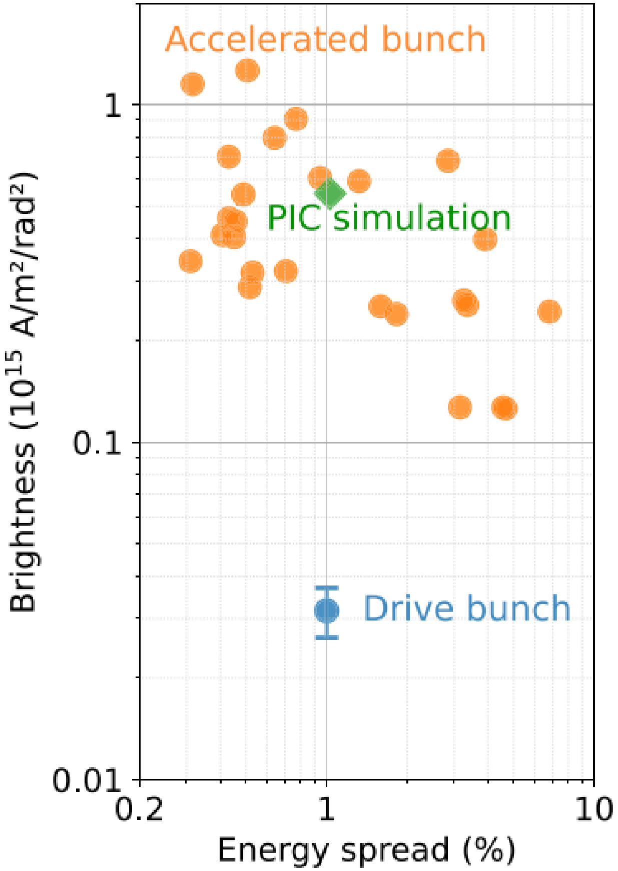
The injected charge must be distributed to load the wake such that the resulting energy spectrum matches the measured one

Indirect reconstruction of the longitudinal phase space

- Use the measured *energy spectrum* to infer the *current profile* from a physics informed model of the plasma acceleration process



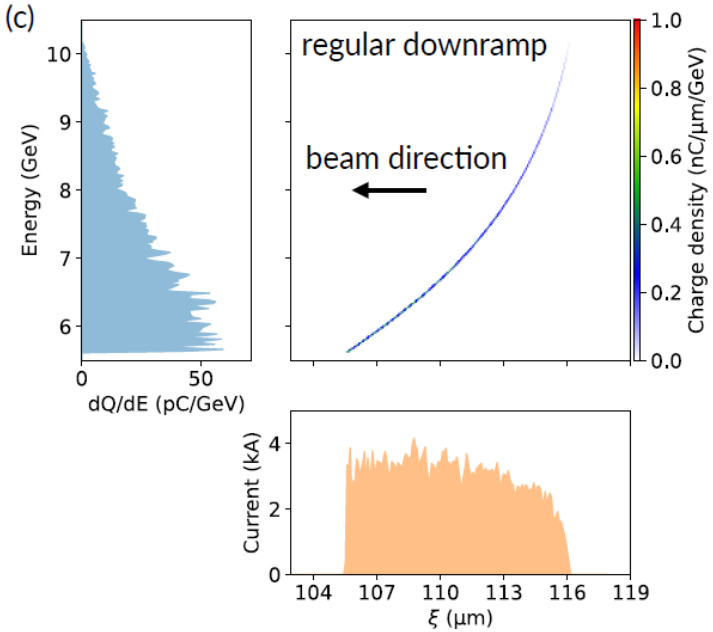
$$B_n = \frac{2I_{peak}}{\epsilon_n^2}$$

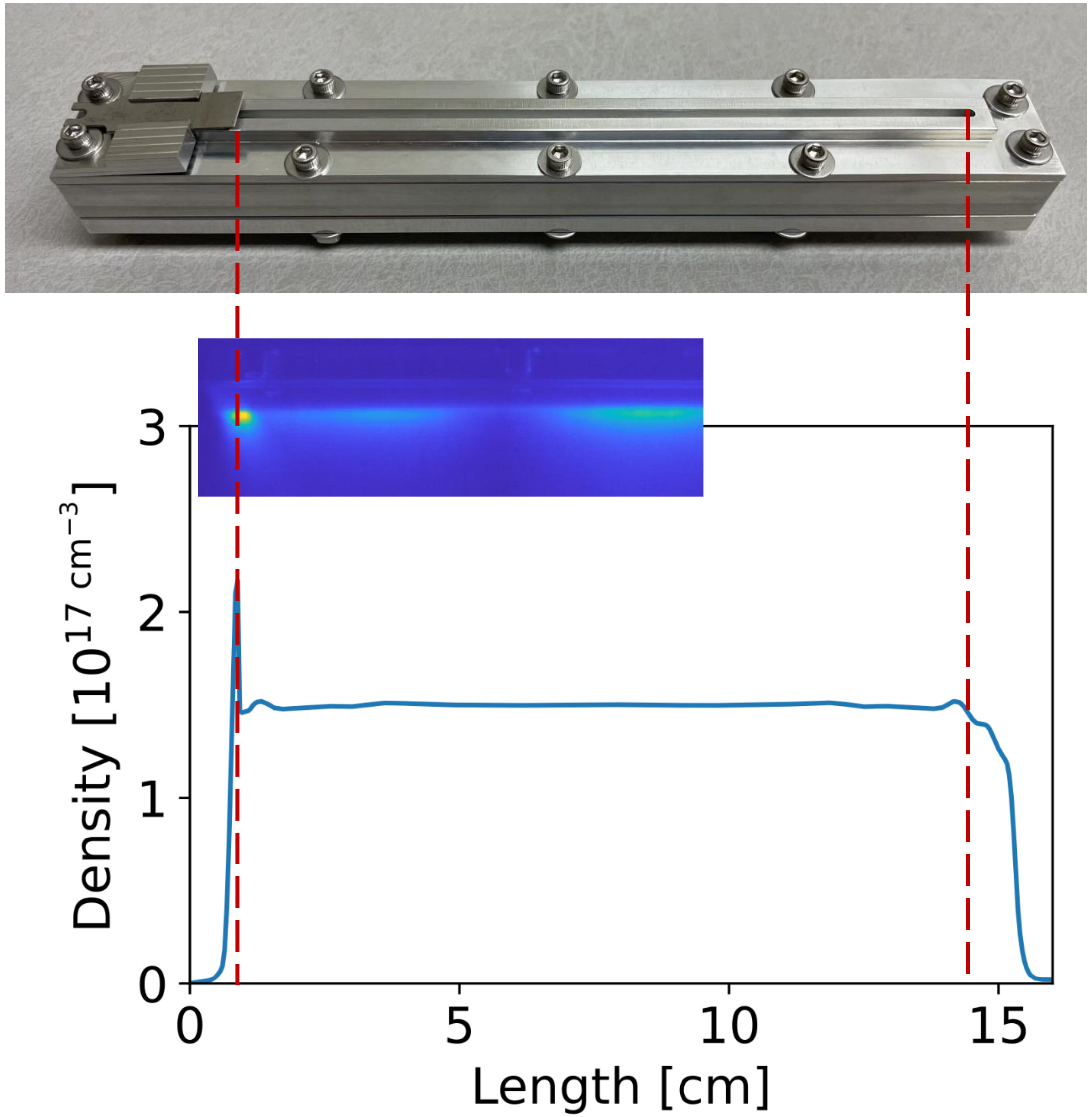


Brightness of injected bunches boosted by greater than an order of magnitude over the incoming bunch

Increasing the stability and control of injection

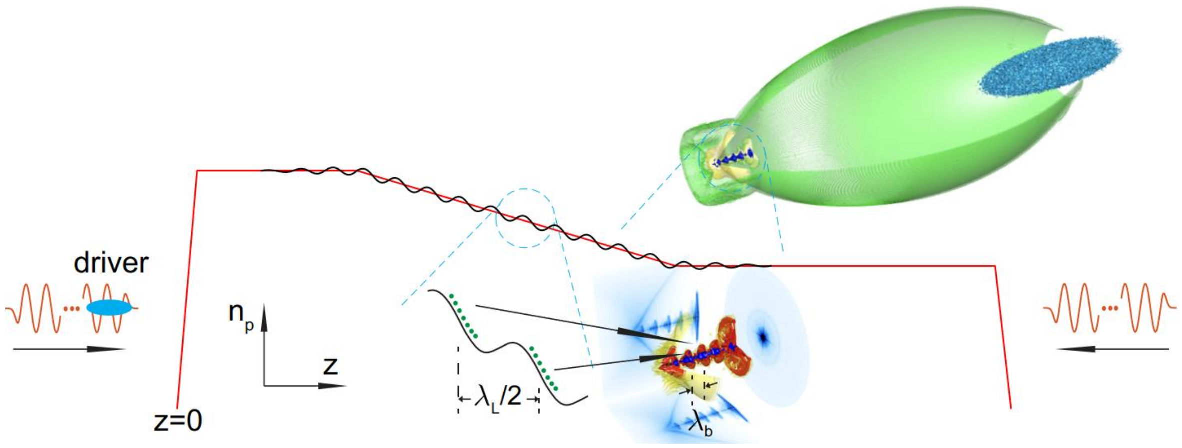
- Replace meter-scale plasma with a 15cm gas jet
  - Controlled acceleration length
  - Does not rely on pre-plasma lens section
  - Multi-GeV acceleration



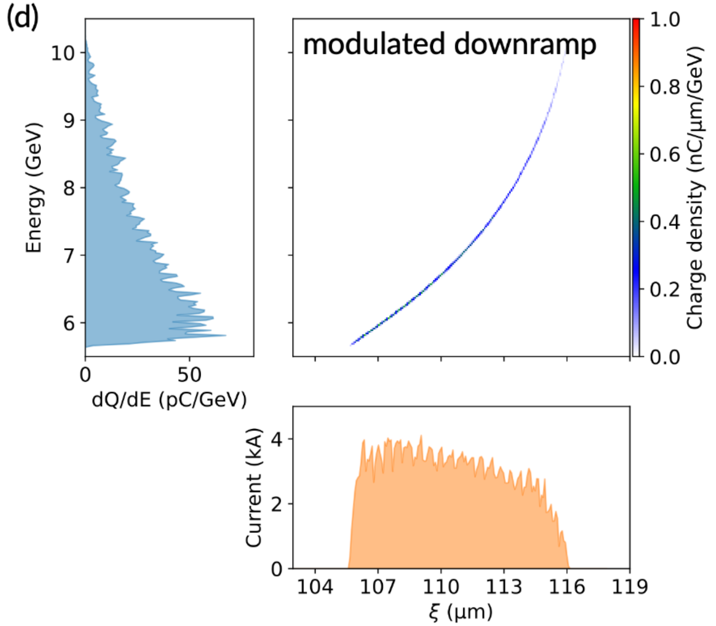


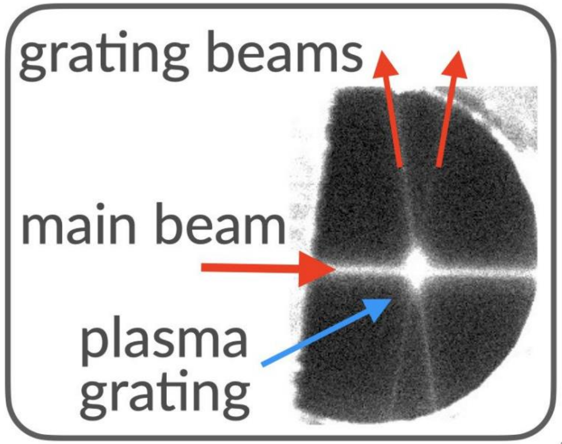
Generation of pre-bunched beams via modulated density downramp

- Use laser ionization induced plasma grating to modulate the density downramp
- Injected beam bunches at ~500 nm spacing



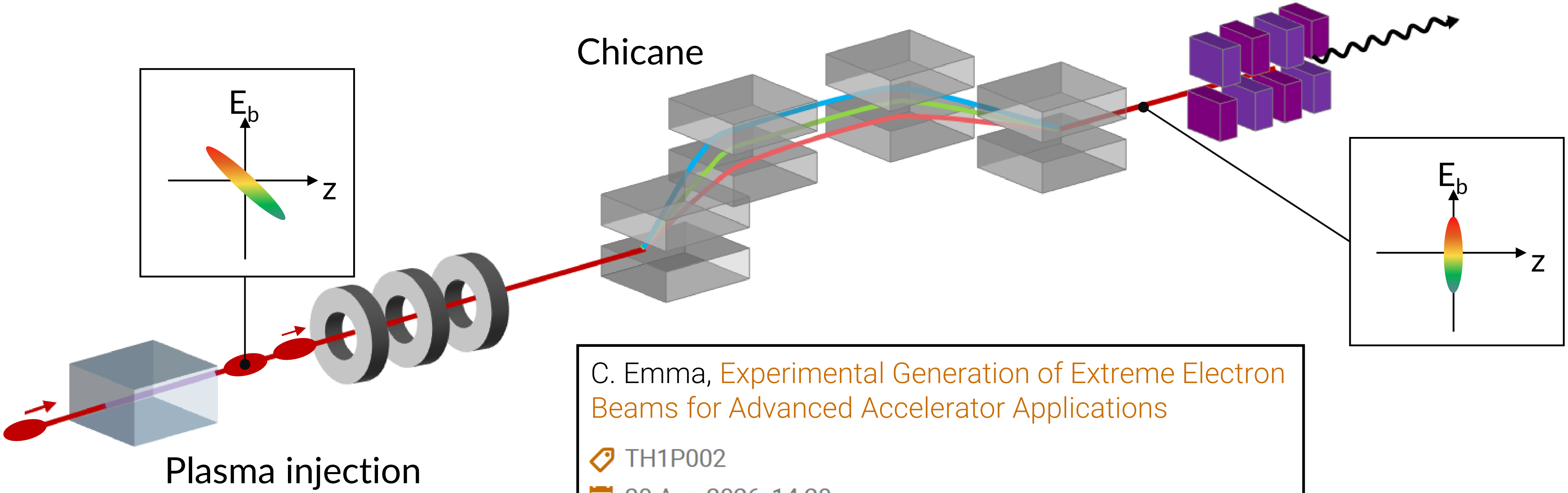
Xu *et al.*, Nat. Comms. *13*, 3364 (2022)





Application 1 - Brightness booster for light sources

- Brightness boosted beams can be used directly for light source applications
- Further bunch compression of chirped injected bunch → attosecond-scale bunch lengths
  - Generate attosecond x-ray pulses with mJ energies in shorter undulators



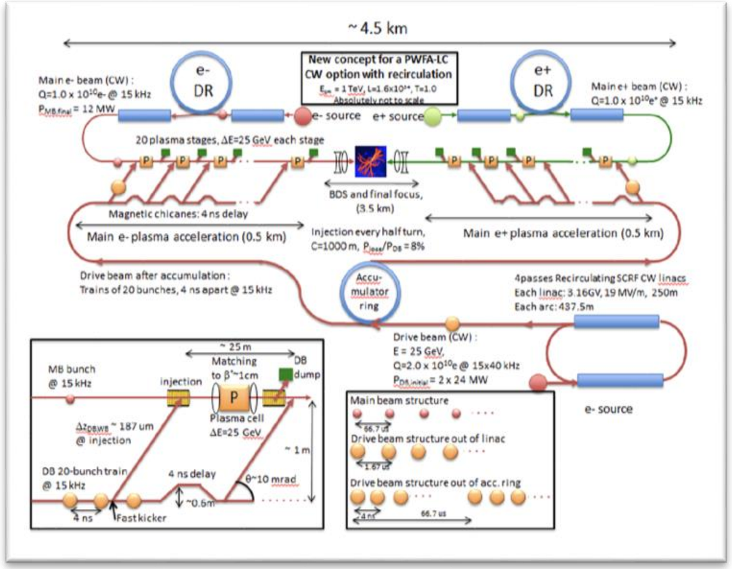
C. Emma, Experimental Generation of Extreme Electron Beams for Advanced Accelerator Applications

TH1P002

20 Aug 2026, 14:20

Application 2 - Plasma Acceleration via Regenerative Cascading

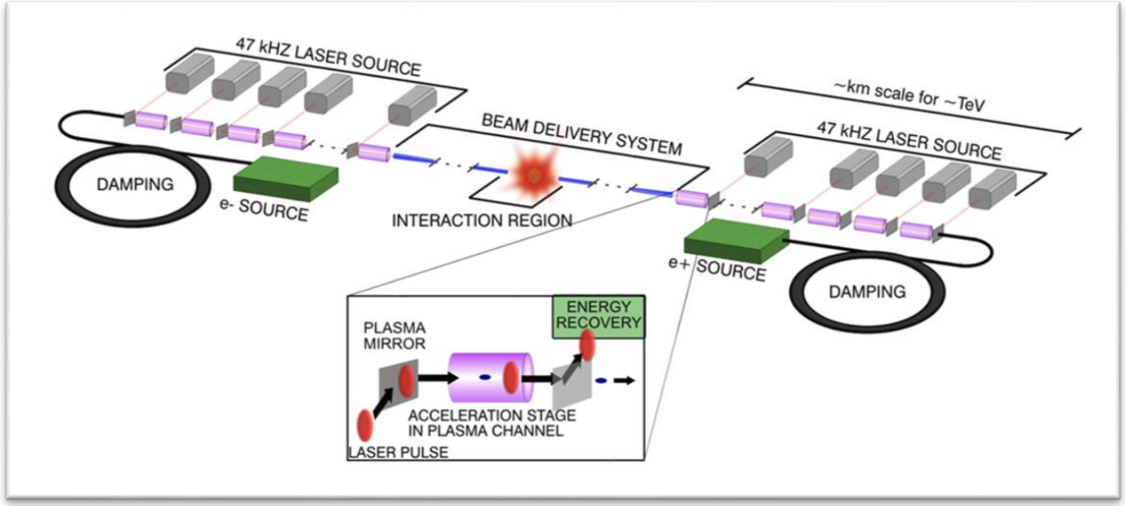
- TeV-scale PWFA-based linacs require many (10's to 100's) of stages



Adli *et al.*, Snowmass (2013)

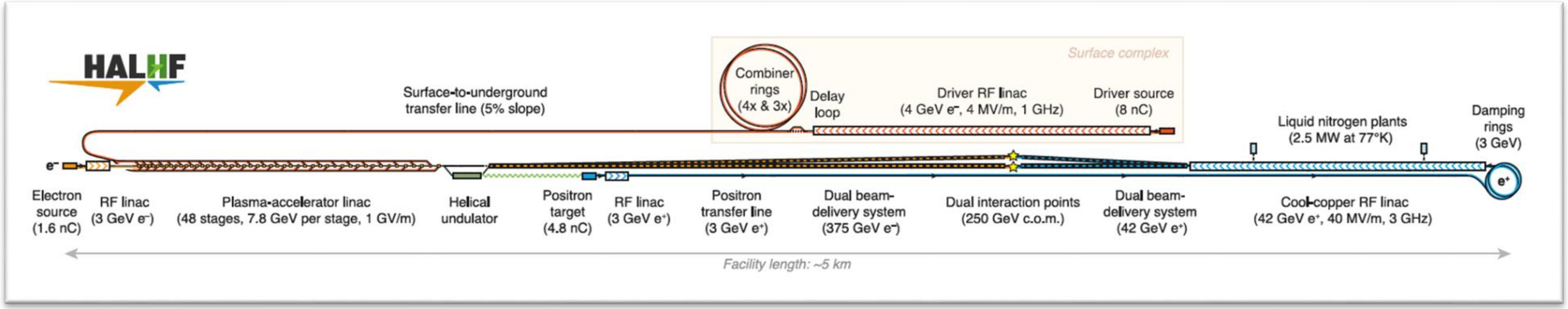
◀ Beam-driven PWFA collider

▼ Laser-driven LWFA collider



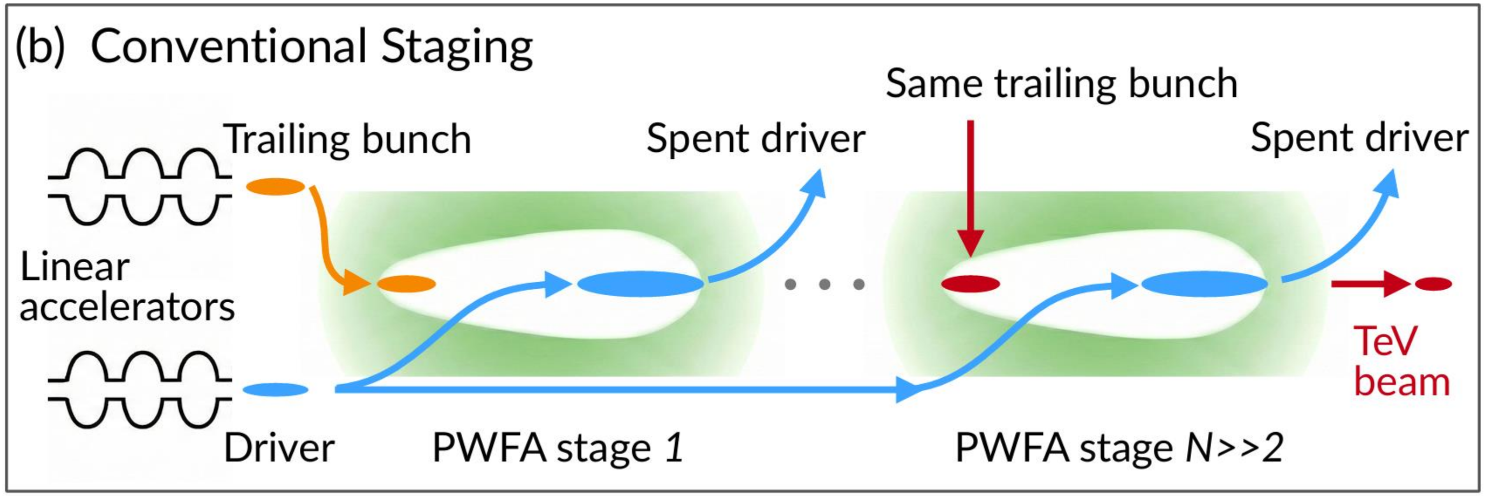
Schroeder *et al.*, JINST **18**, T06001 (2023)

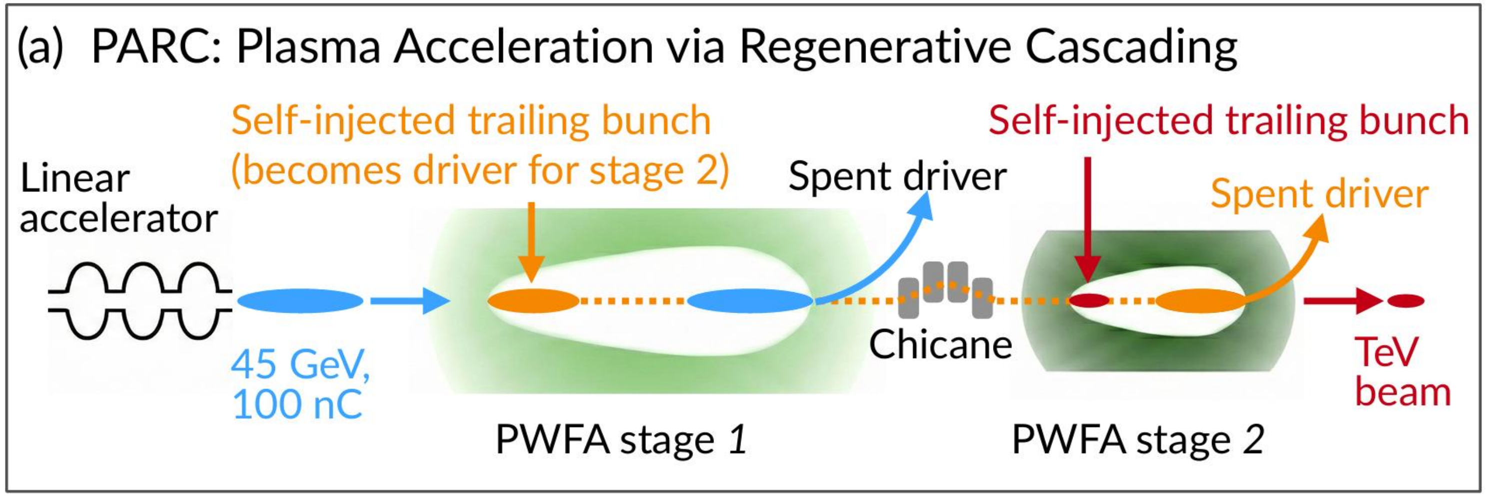
HALHF – Hybrid Asymmetric Linear Higgs Facility ▶



Foster *et al.*, Phys. Open **23**, 100261 (2025)

Staging for high energy plasma accelerators





- Conventional staging
  - Same witness transported and accelerated in many stages
  - Challenges:
    - Alignment, synchronization
    - Emittance degradation
  - ***Energy scaling: Linear addition***
- Plasma Acceleration via Regenerative Cascading
  - Self-injected witness in each stage
  - Brightness boosted
  - ***Energy scaling: Multiplicative***

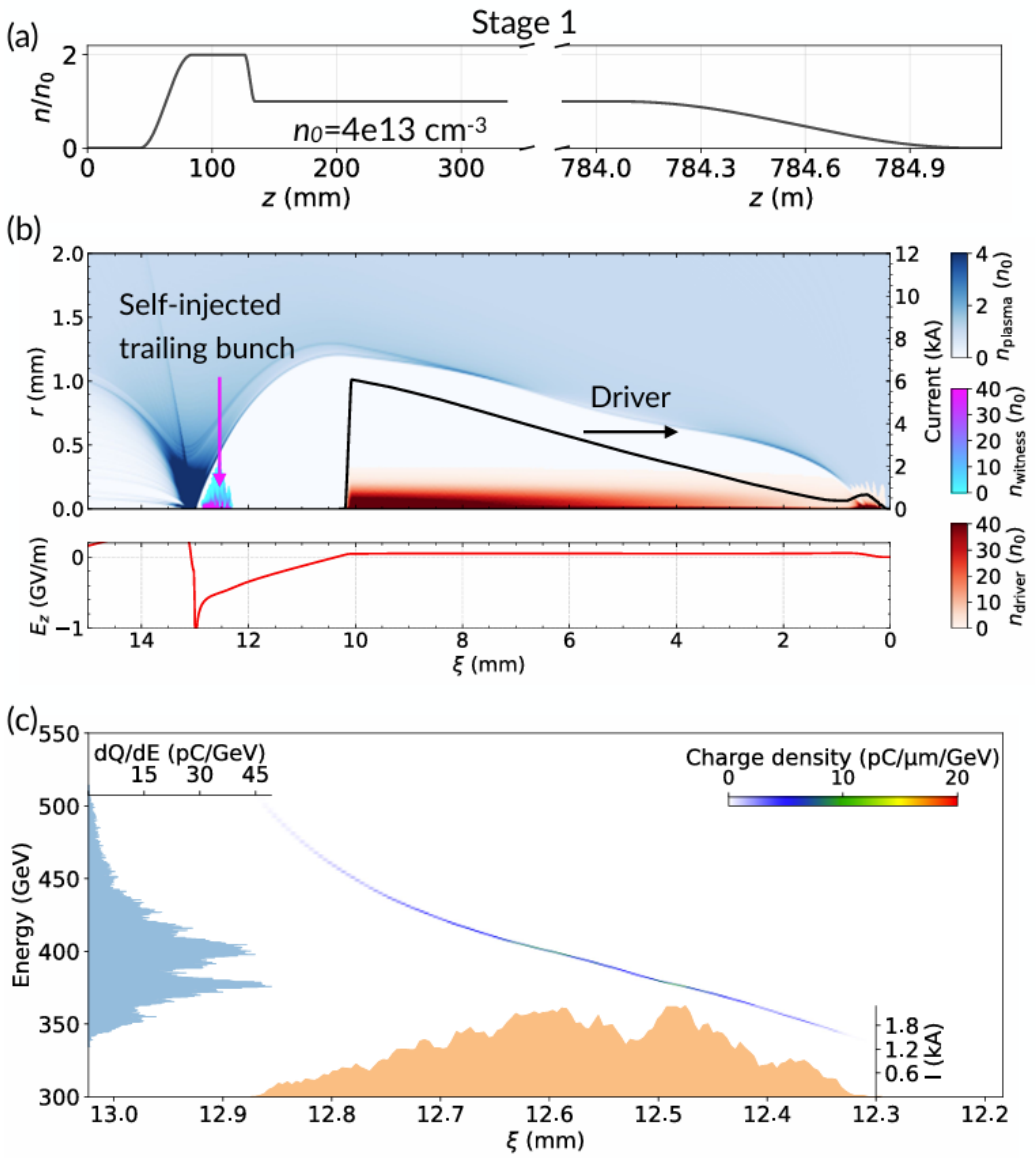
Zhang and Joshi, arXiv:2607.07979v1 (2026)

TeV beams in two stages – **Stage 1**: 45 GeV → 400 GeV

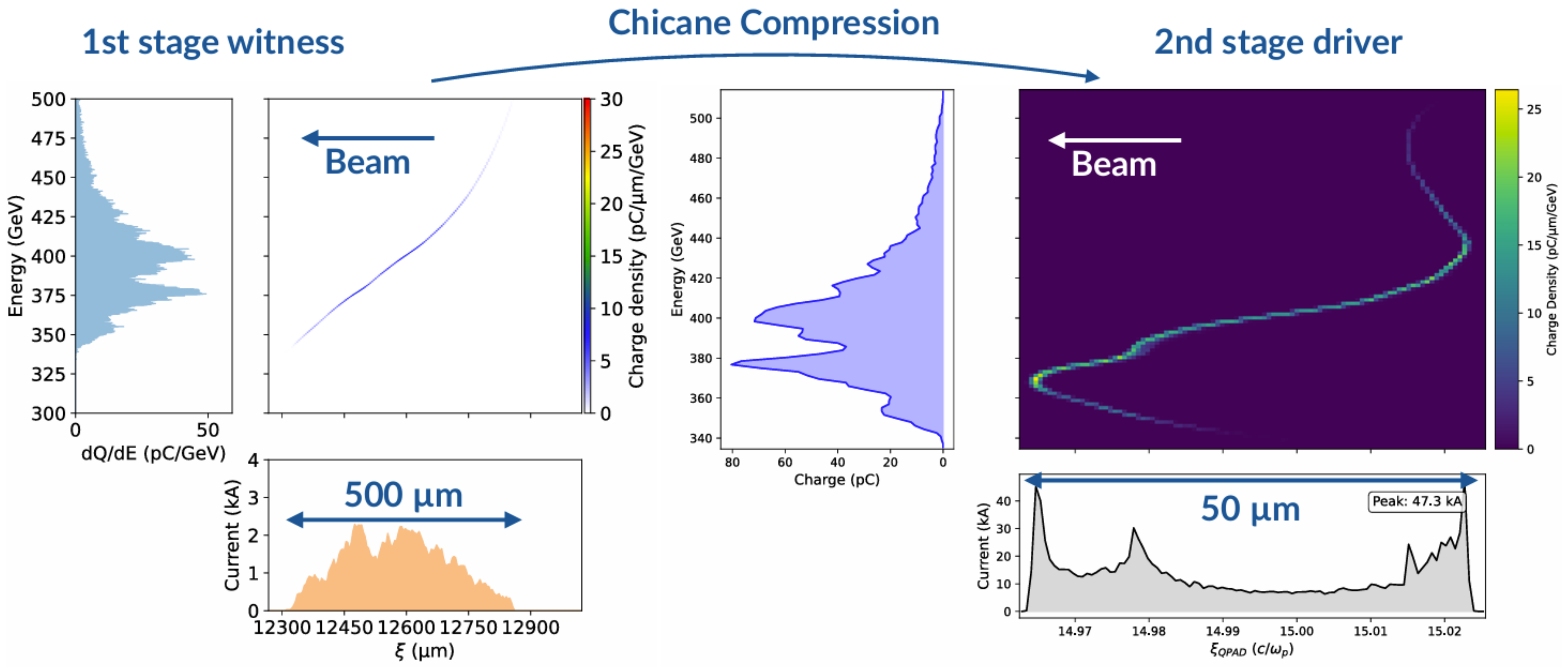
- Start-to-end PIC simulation
  - Modelled using OSIRIS (injection) and QPAD (acceleration)

- Stage 1:
  - 45 GeV, 100 nC drive bunch
  - Current profile shaped for high transformer ratio
  - 785m long 4×10^{13} cm^{-3} plasma with a density downramp

- Output:
  - 400 GeV, 2.3 nC, 2.4 kA witness beam
  - Transformer ratio of 10



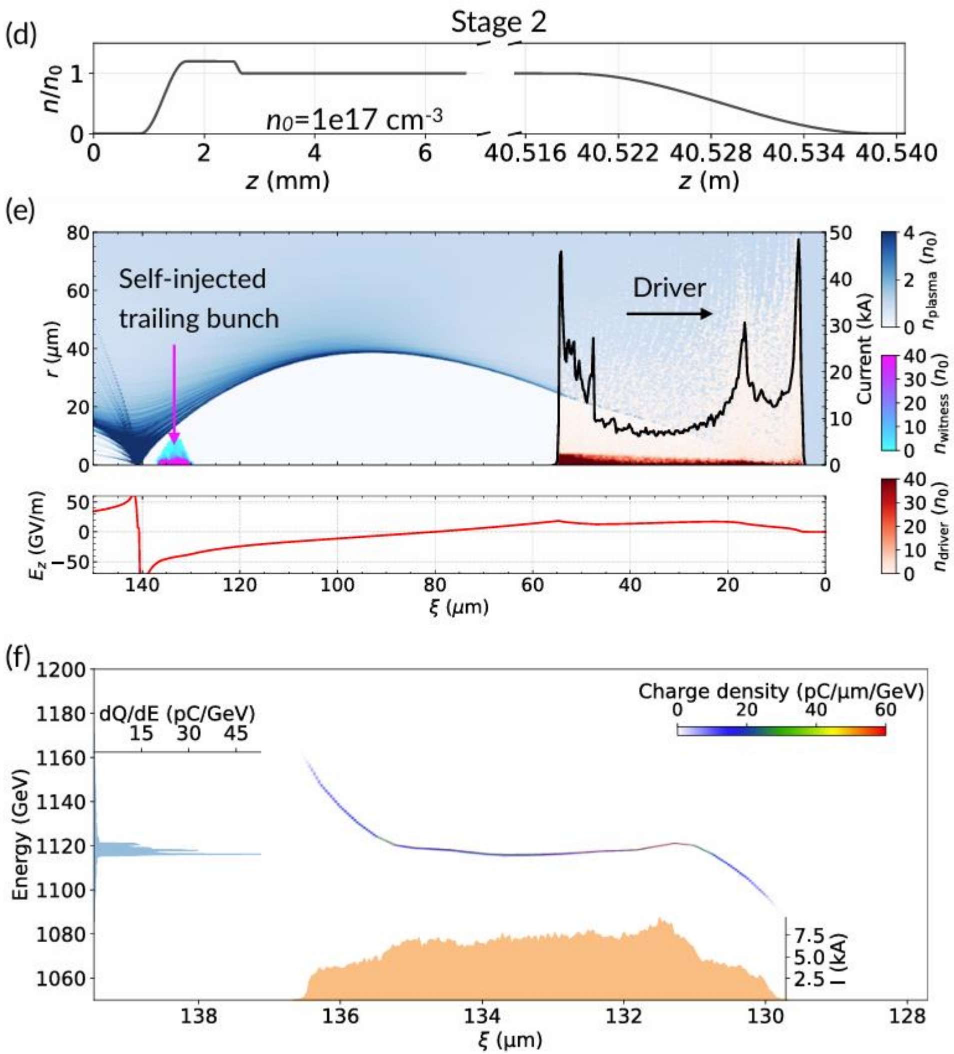
Interstage compression of the stage 1 injected bunch



- Large energy chirp of injected bunch
  - Compression to 50 µm with negligible emittance growth

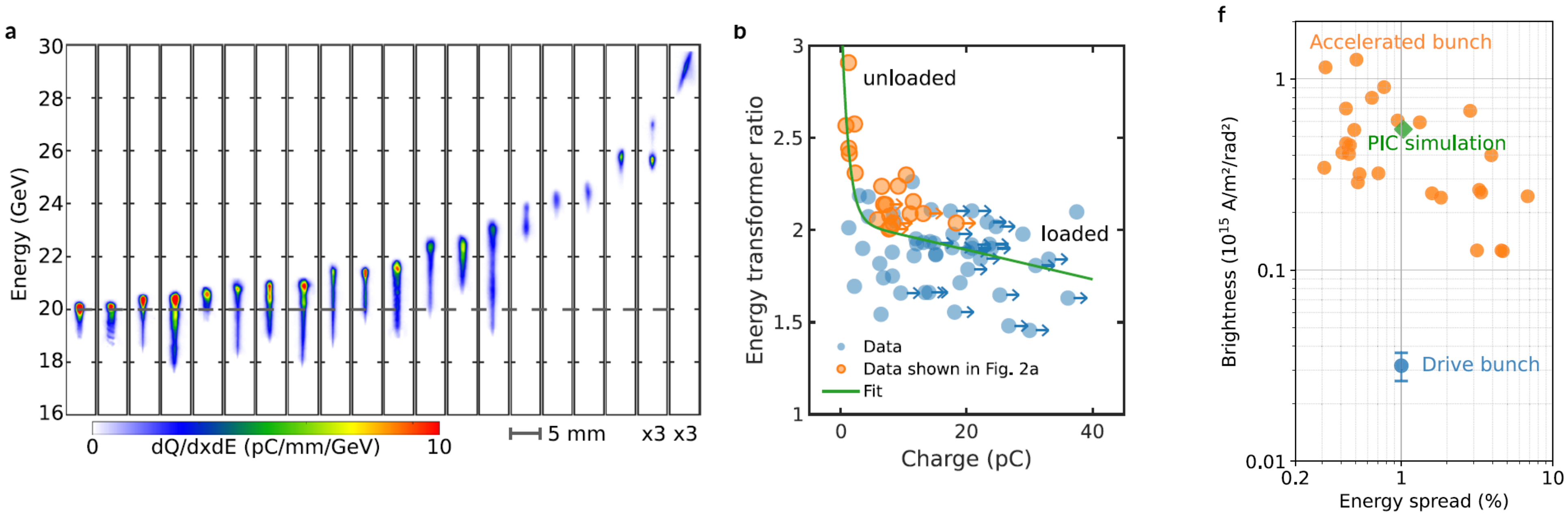
TeV beams in two stages – **Stage 2**: 400 GeV → 1 TeV

- Start-to-end PIC simulation
  - Modelled using OSIRIS (injection) and QPAD (acceleration)
- Stage 2:
  - 400 GeV, 2.3 nC, 47kA drive bunch
  - 40m long 1e17 cm-3 plasma with density downramp
- Output:
  - 1.1 TeV, 0.12 nC beam with 0.3% energy spread
  - Low energy spread due to wake evolution
  - Transformer ratio of ~3



Summary

- Demonstration of a PWFA beam brightness and energy booster
- Brightness boosted by over an order of magnitude
- Future work:
  - Focus on stability and control of the injection and acceleration process
  - Measurement of sub-µm emittance
  - Production of pre-bunched beams via modulated density downramp injection



Acknowledgments

Special thanks to Chaojie Zhang, UCLA

Acknowledgements

The FACET-II E300 and E304 plasma wakefield acceleration experiments were built and operated with funding from the U.S. Department of Energy under Contract No. DE-AC02-76SF00515. This work was supported at UCLA by the U.S. Department of Energy through Grant No. DE-SC0010064. Simulations were performed using resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility located at Lawrence Berkeley National Laboratory, operated under Contract No. DE-AC0205CH11231 using NERSC Award HEP-ERCAP-MP113. S.C. was supported by the ANR (UnRIP project, Grant No. ANR-20-CE30-0030).

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https://doi.org/10.1038/s41467-025-65742-8

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TeV Electron Beams from Plasma Acceleration via Regenerative Cascading

Chaojie Zhang[1,*] and Chan Joshi[1]

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(Dated: July 10, 2026)

arXiv:2607.07979v1 [physics.acc-ph] 8 Jul 2026