FACET-II

Facility for Advanced
Accelerator Experimental Tests

Recent Advances in Plasma Wakefield Acceleration at FACET-II

Advanced Accelerator Concepts 2026

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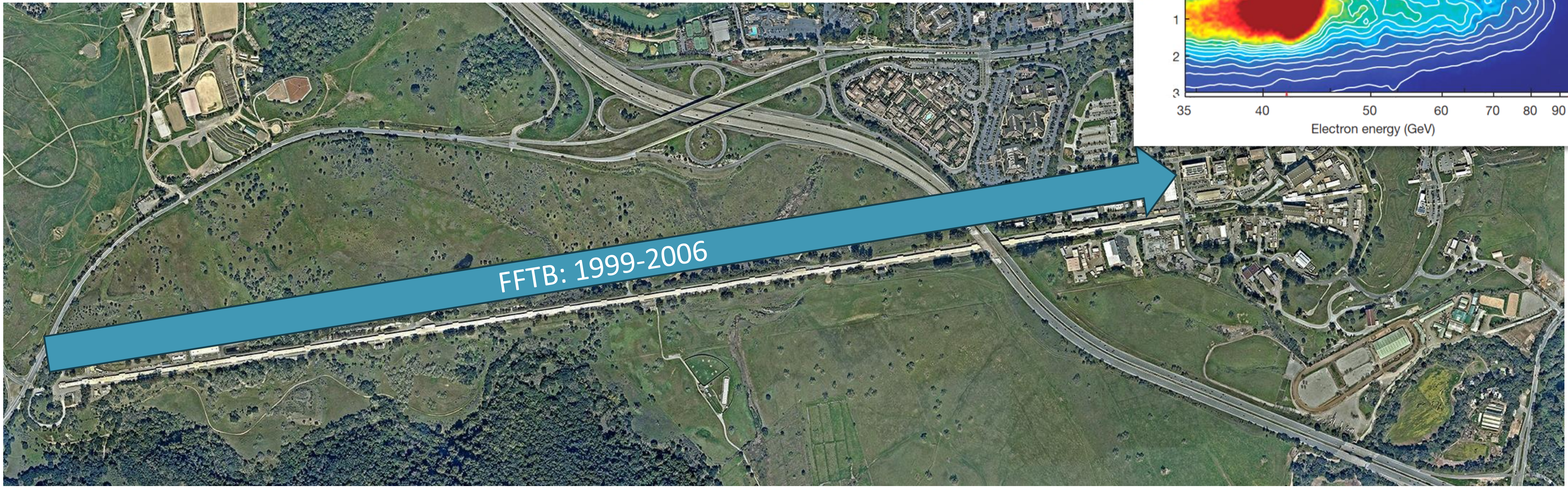
SLAC NATIONAL ACCELERATOR LABORATORY

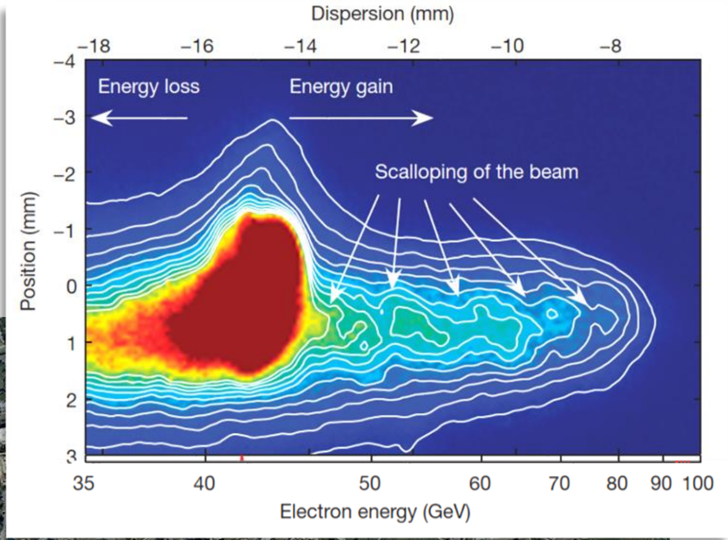
Stanford University | U.S. DEPARTMENT OF ENERGY

Beam driven PWFA at SLAC - FFTB

Blumenfeld *et al.*, Nature 445, 741 (2007)

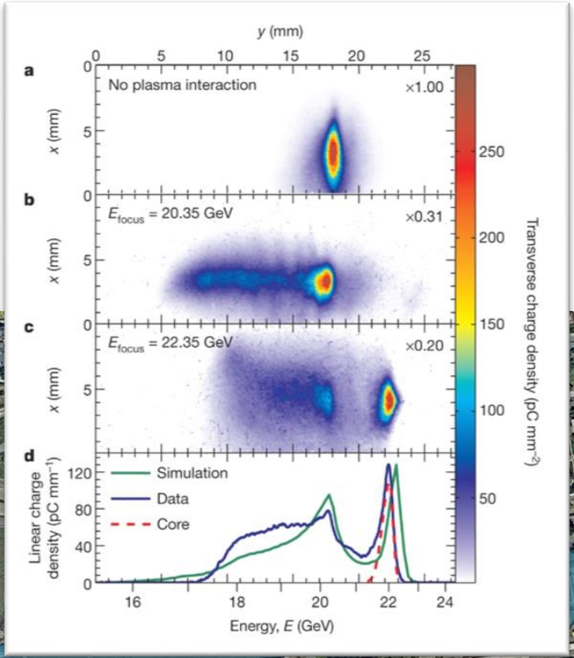
- Energy doubling of 42 GeV electrons in the SLAC linear accelerator
- High energy gain - but not a discrete bunch





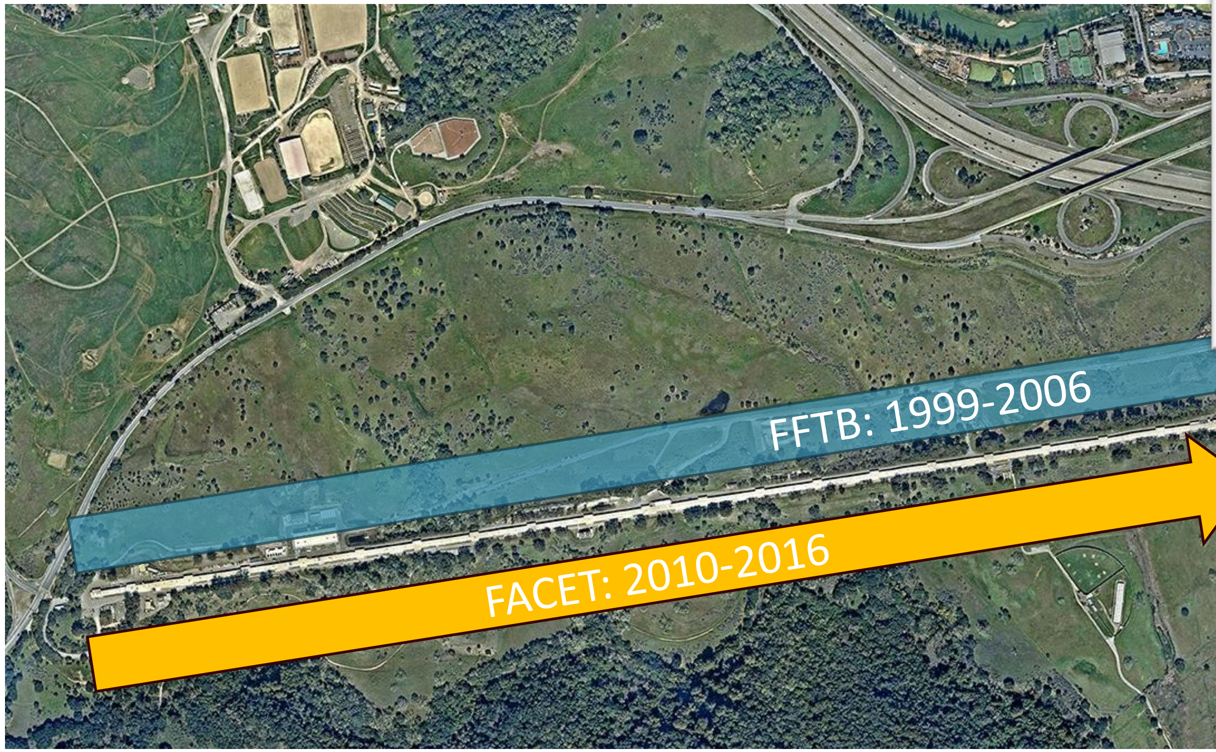
Beam driven PWFA at SLAC - FACET

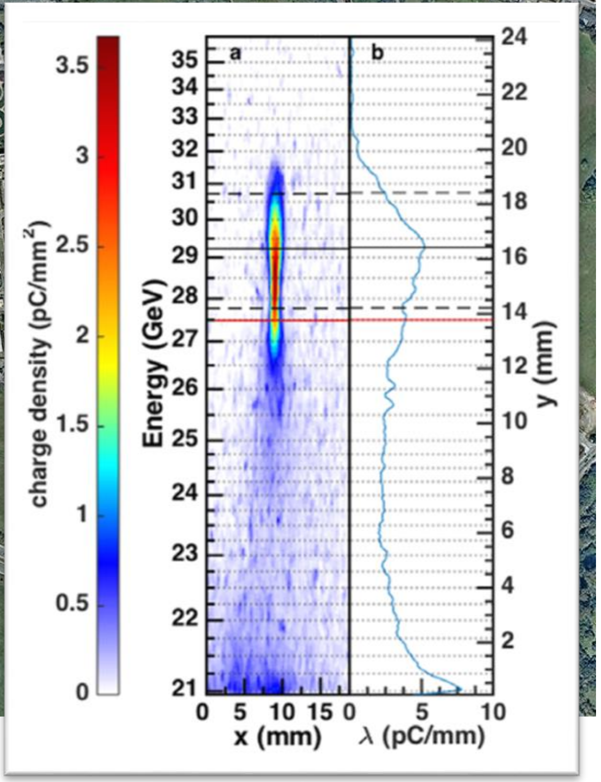
- Two bunch PWFA
- Multi-GeV energy gain, few-% transfer eff.



Litos, et al., Nature 515, 92 (2014)

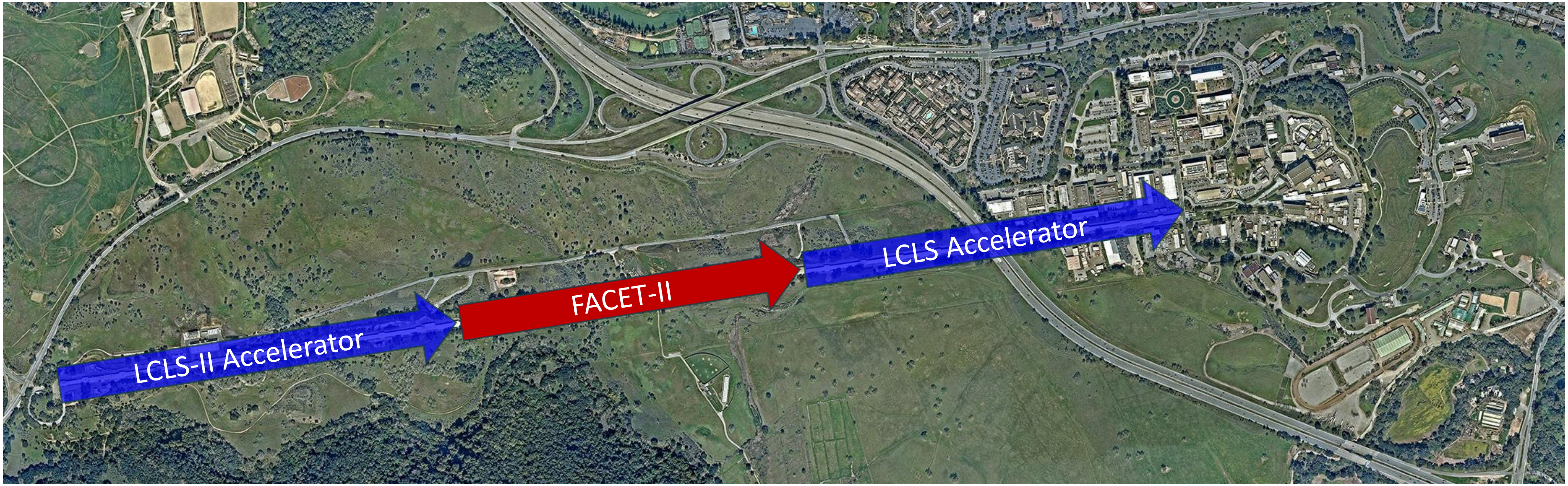
Litos, et al., PPCF 58, (2016)



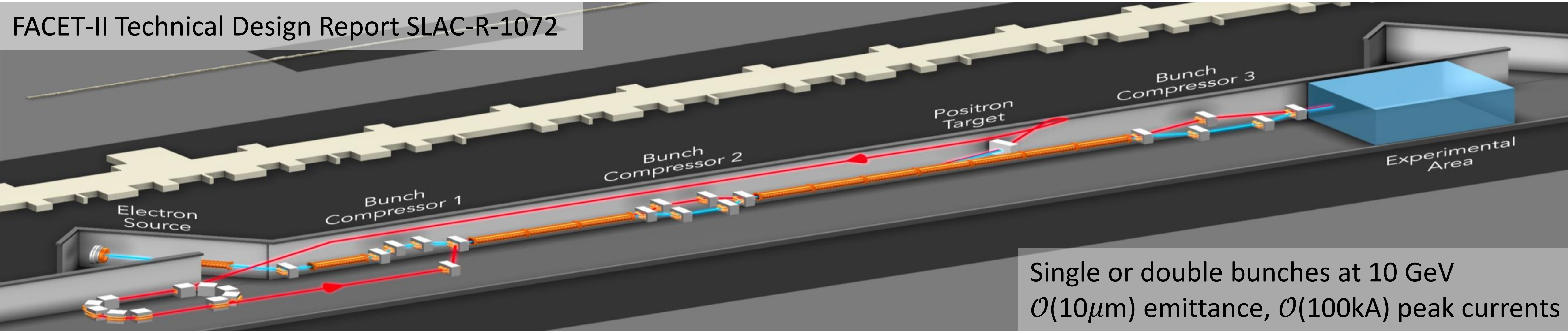


FACET-II – A facility for precision PWFA studies

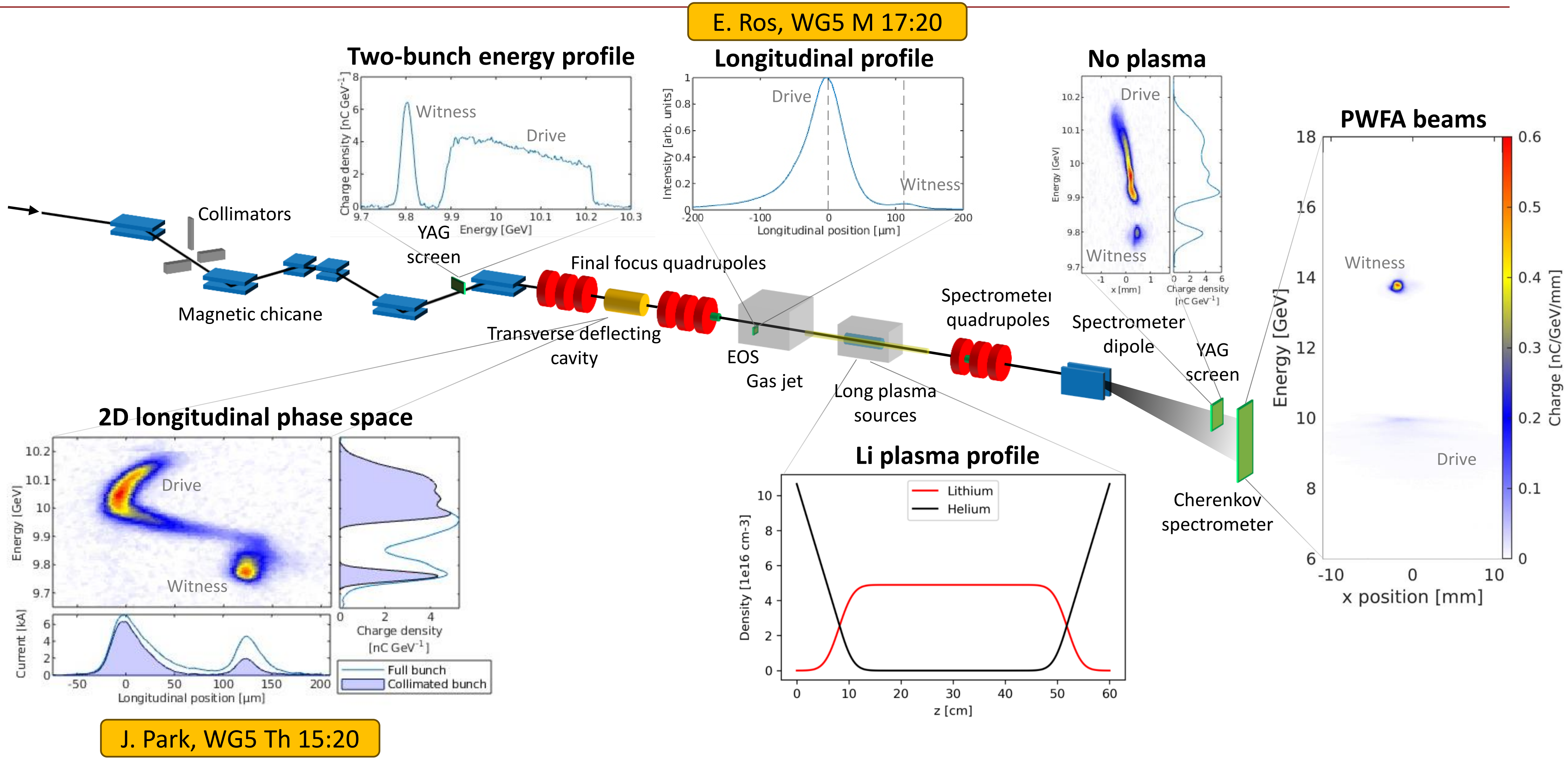
- SLAC linac further divided
- FACET-II: Demonstrate single stage plasma wakefield acceleration at collider-relevant energy scale
  - Single or double bunches from a new RF photo-injector
  - RF linac and bunch compressors for precise control of longitudinal phase space



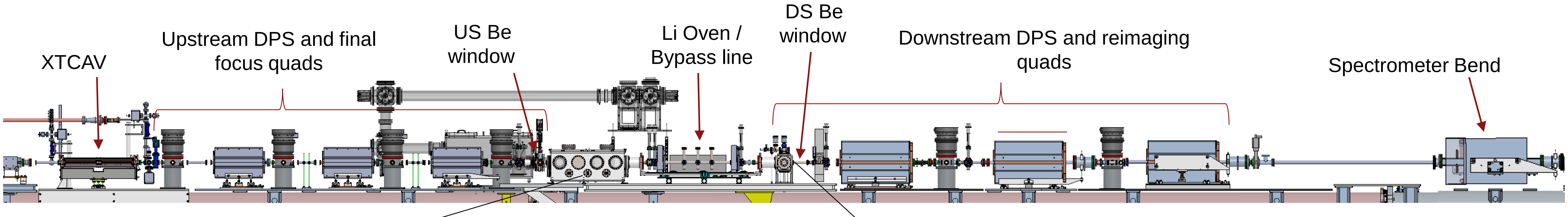
FACET-II provides 10 GeV beams for PWFA studies

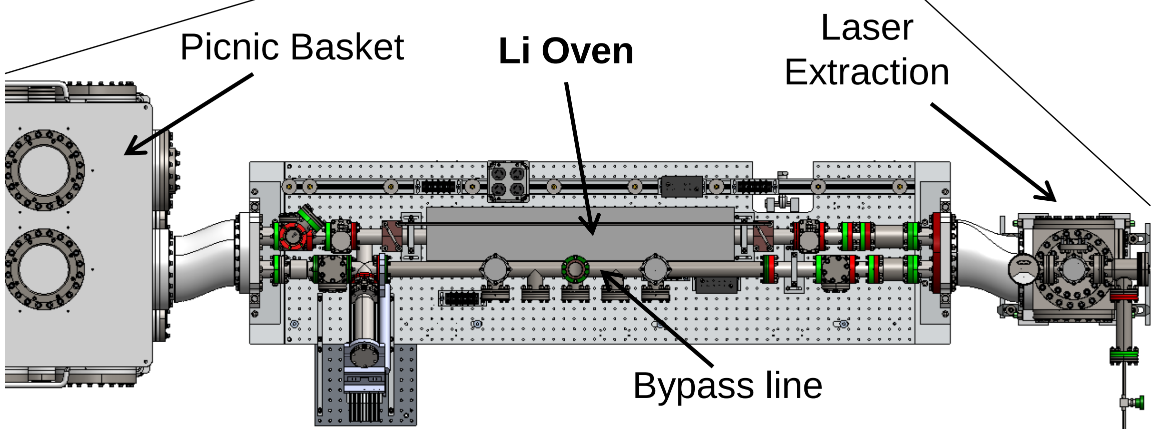


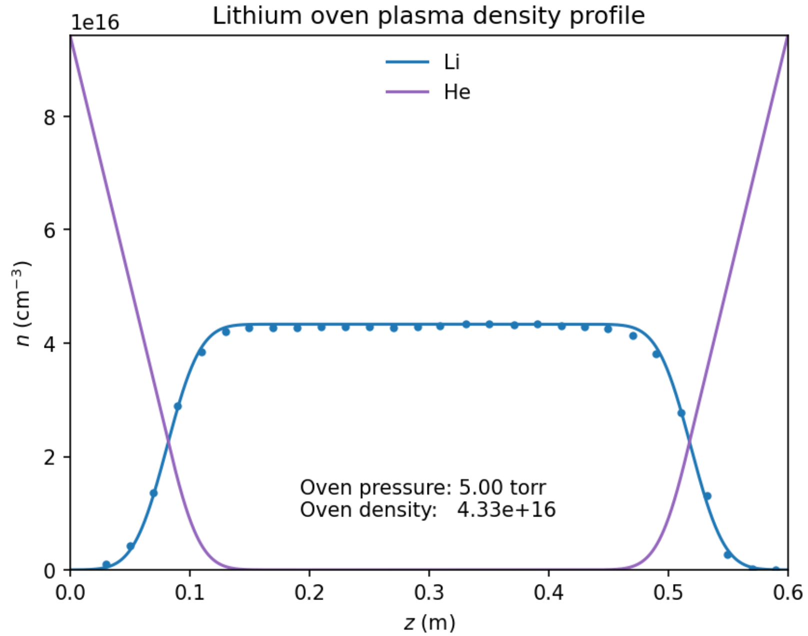
FACET-II experimental area



Plasma sources at FACET-II: **Li oven plasma source**



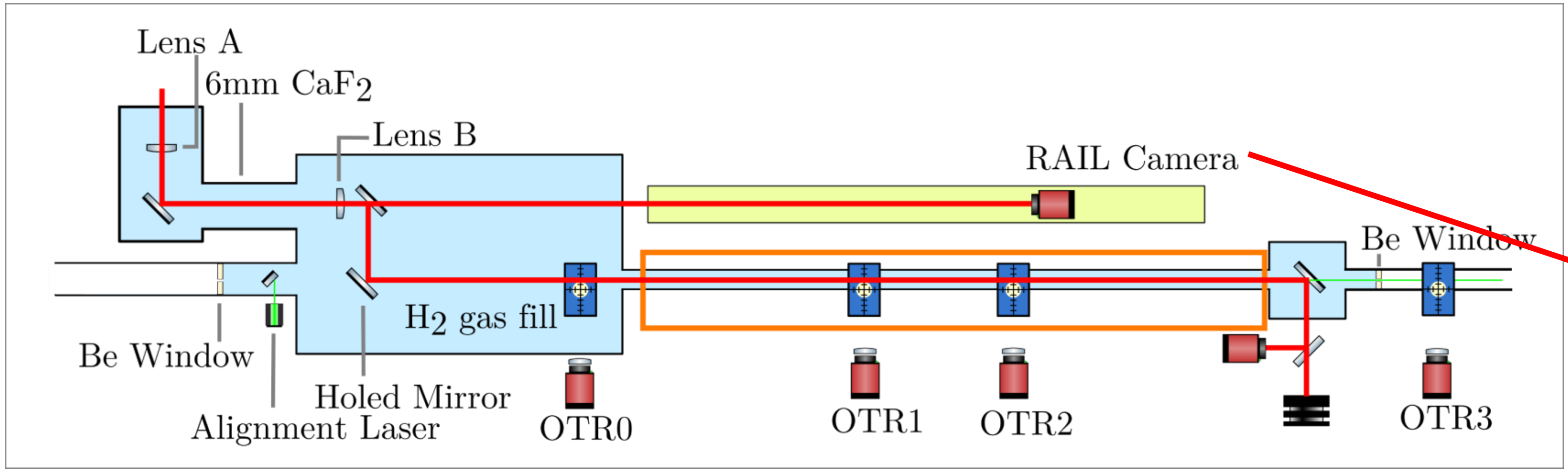


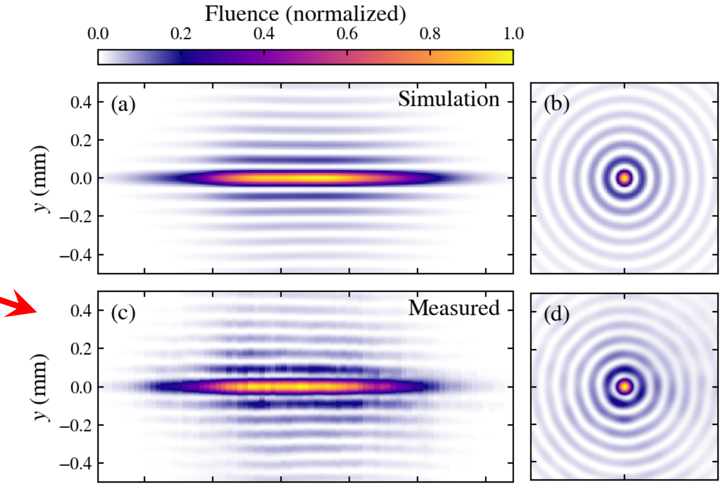


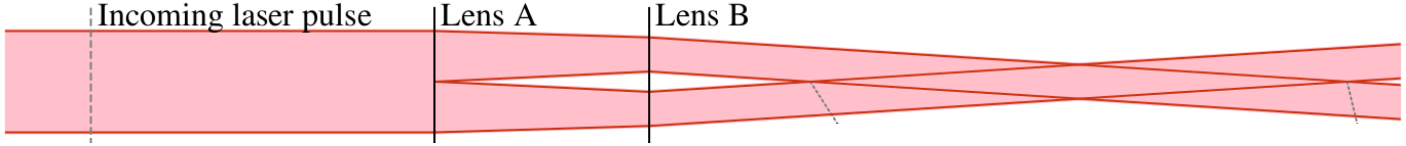
Lithium oven vapor source:

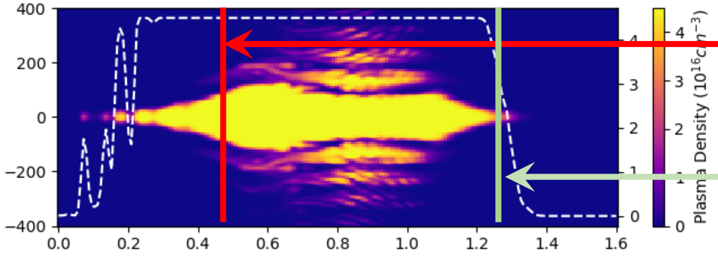
- Beam or laser ionized plasma source
- Nominal plasma density of 4×10^{16} cm^{-3} over 40cm length
- ~10 cm density ramps defined by Li/He boundary

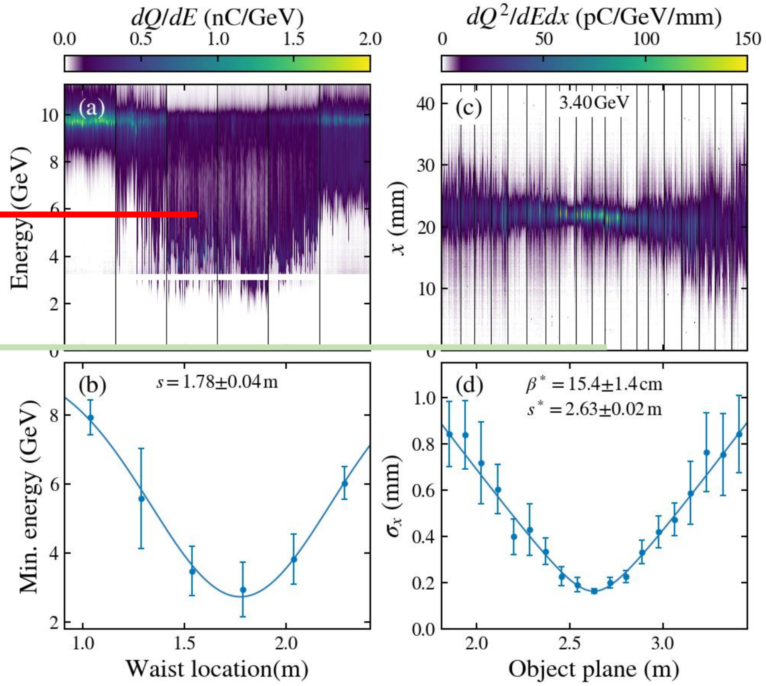
Plasma sources at FACET-II: **Laser ionized hydrogen plasma**











- Laser-ionized unconfined H2 gas
- Tandem lens shapes intensity and phase
- On-axis density at 5×10^{16} cm^{-3} over 80 cm
- Longitudinal laser intensity measurement confirms lens design and beam-based measurement confirms plasma length

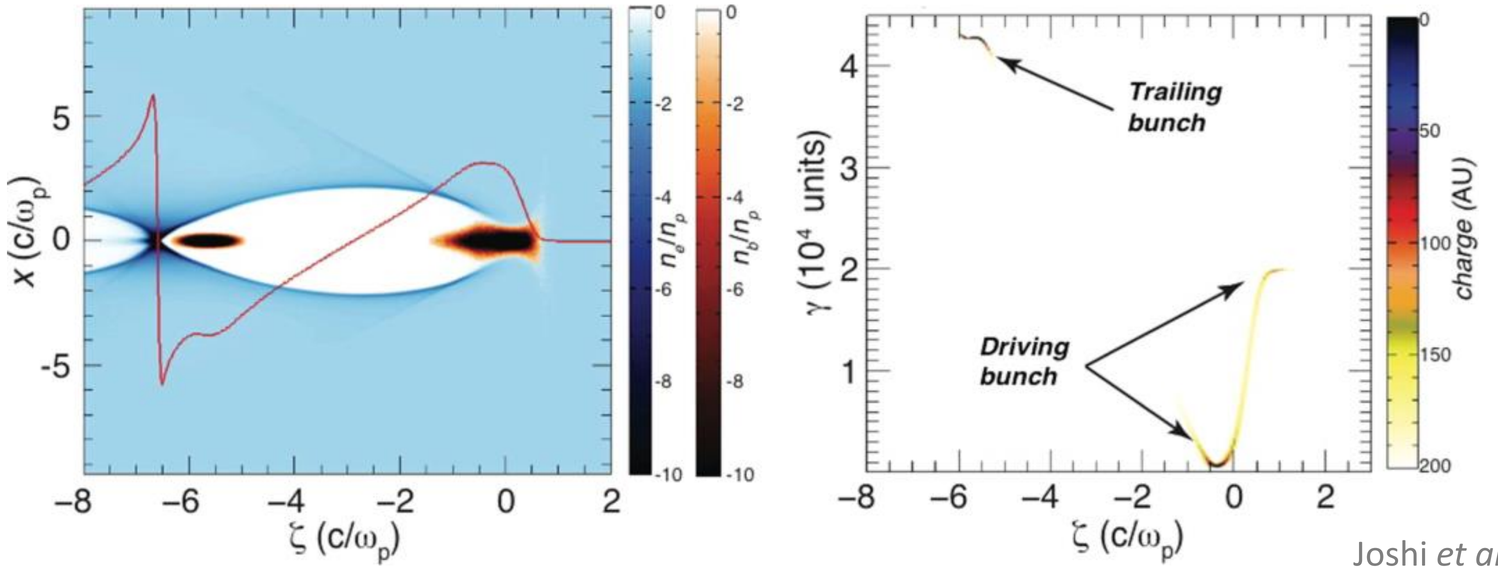
Ariniello, R., V. Lee, and M. D. Litos, *Optics Express* 33.25 (2025): 52019-52034.

Topic #1

Multi-GeV PWFA with high beam quality and efficiency

FACET-II Goal: PWFA with high efficiency and high beam quality

- Multi-GeV energy gain, **with** 10's-% energy transfer efficiency, **and** beam quality preservation

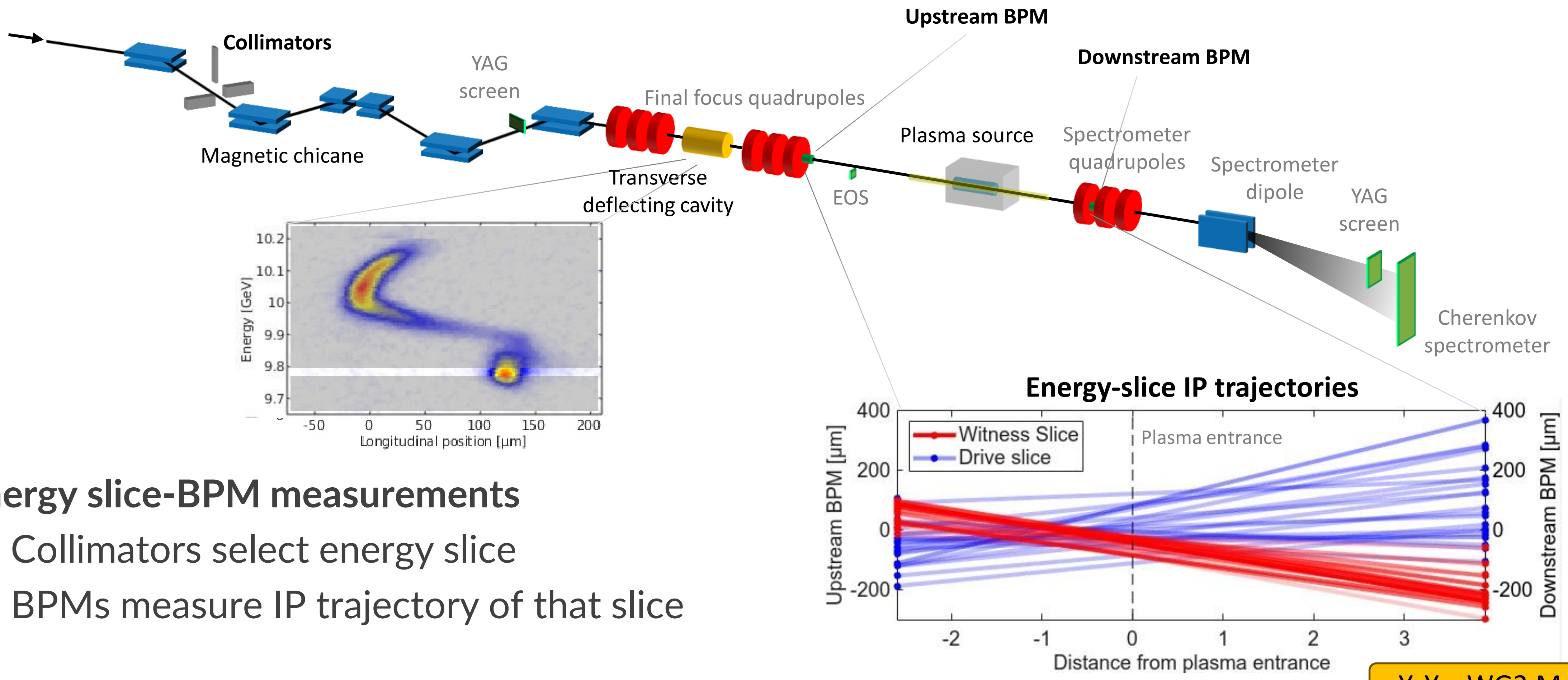


Joshi *et al.*, PPCF **60**, 034001 (2018)

What do we need to achieve this goal?

- Peak current of drive and witness bunches $\mathcal{O}$(10 kA)
- Witness (and drive) bunches matched to the plasma density
- Drive and witness transversely aligned, and with the correct bunch separation

The beam alignment problem – *How do you measure it?*



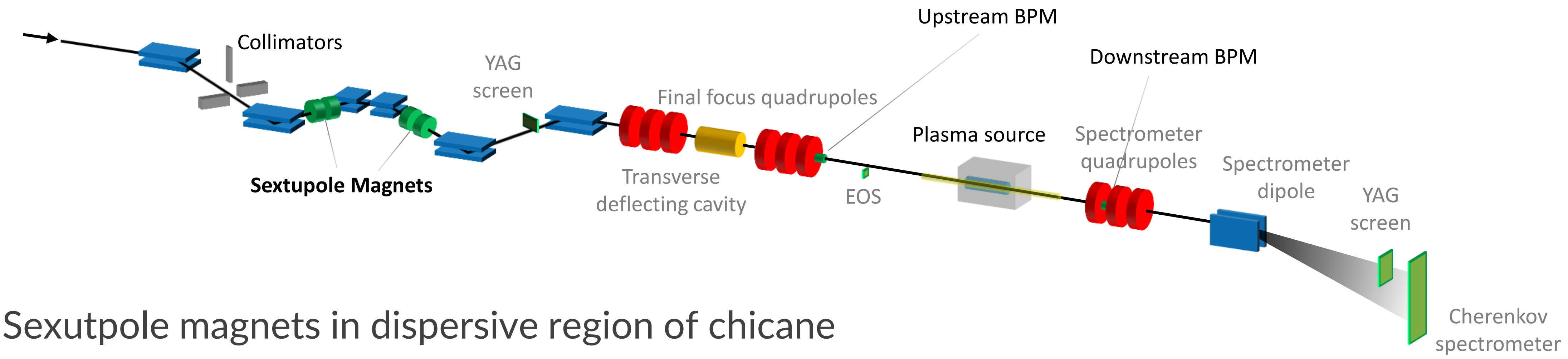
Energy slice-BPM measurements

- Collimators select energy slice
- BPMs measure IP trajectory of that slice

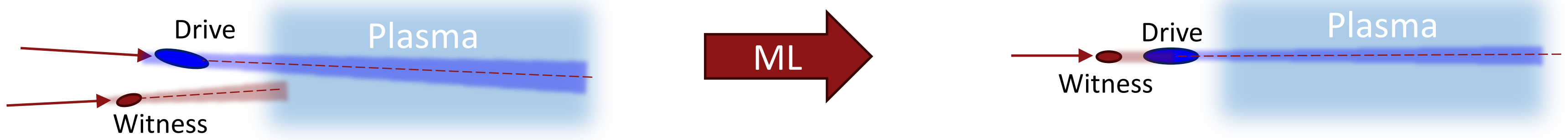
Y. Ye, WG3 M 14:50

Novel slice BPM dispersion measurement allows for measurement and optimization of critical beam properties

The beam alignment problem – *How do you fix it!*



- Sexutpole magnets in dispersive region of chicane
- Adjust sextupole **strength** and **position** to align energy slices
  - 12 degrees of freedom to tune!



Machine learning enables more efficient bunch alignment in this high-dimensional search space

Maximizing drive-to-wake energy transfer with ML beam tuning

- **ML-tuning achieved up to η_{dw}~50%**
  - Single bunch: 1.6 nC @ 10 GeV
  - 7.7 J energy transferred to the plasma

Credit: S. Rego, Ecole Polytechnique

- Statistics across subset of dataset with same compression:
  - E_{loss} = 6.1 ± 0.5 J and η_{dw} = 38 ± 3%
  - $E_{min} \sim 2$ GeV

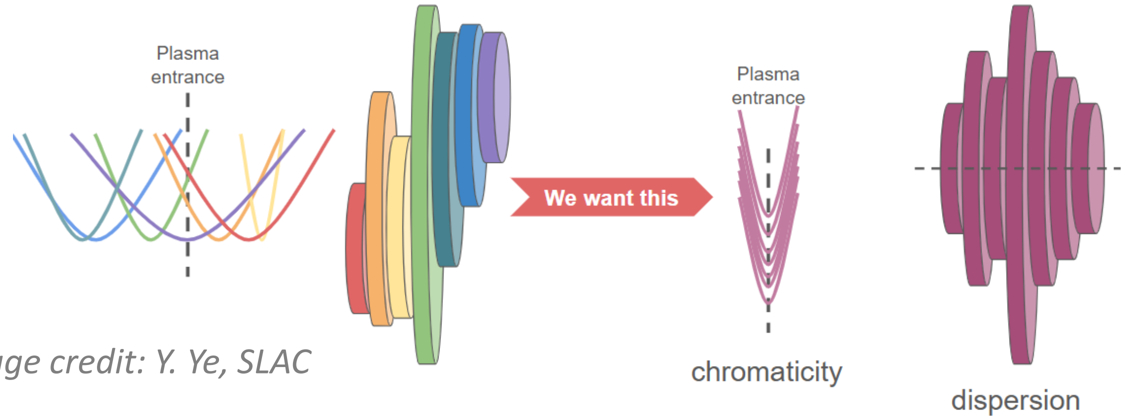
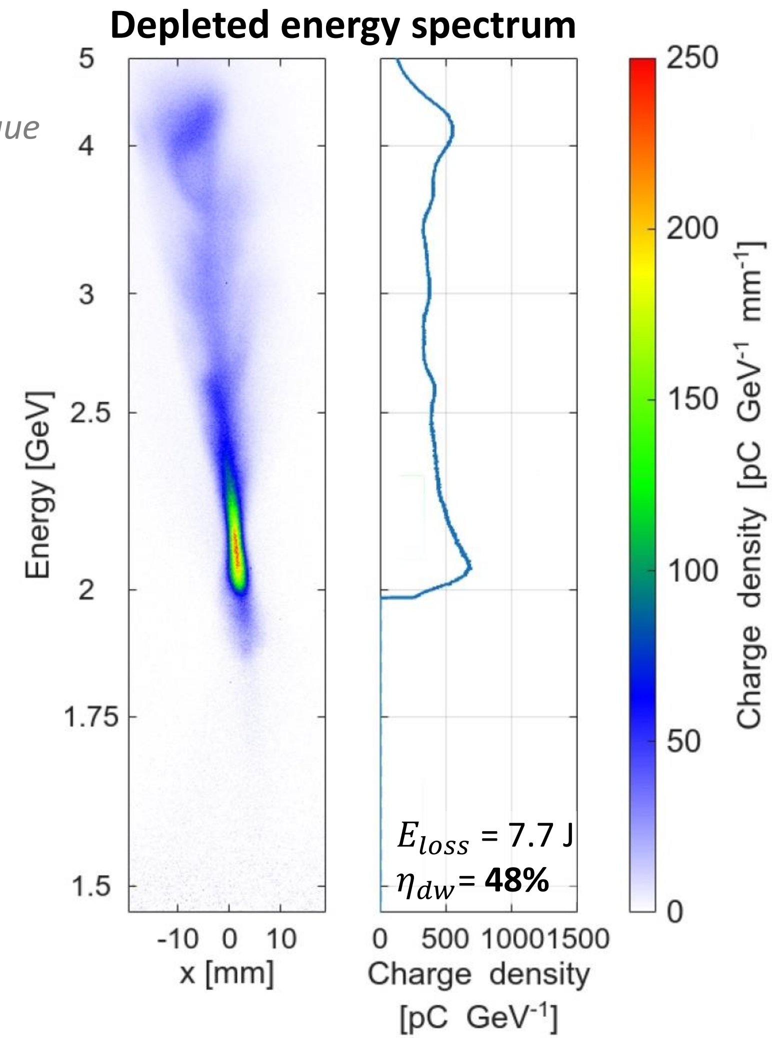


Image credit: Y. Ye, SLAC



Approaching the energy-transfer scale required for efficient staging applications

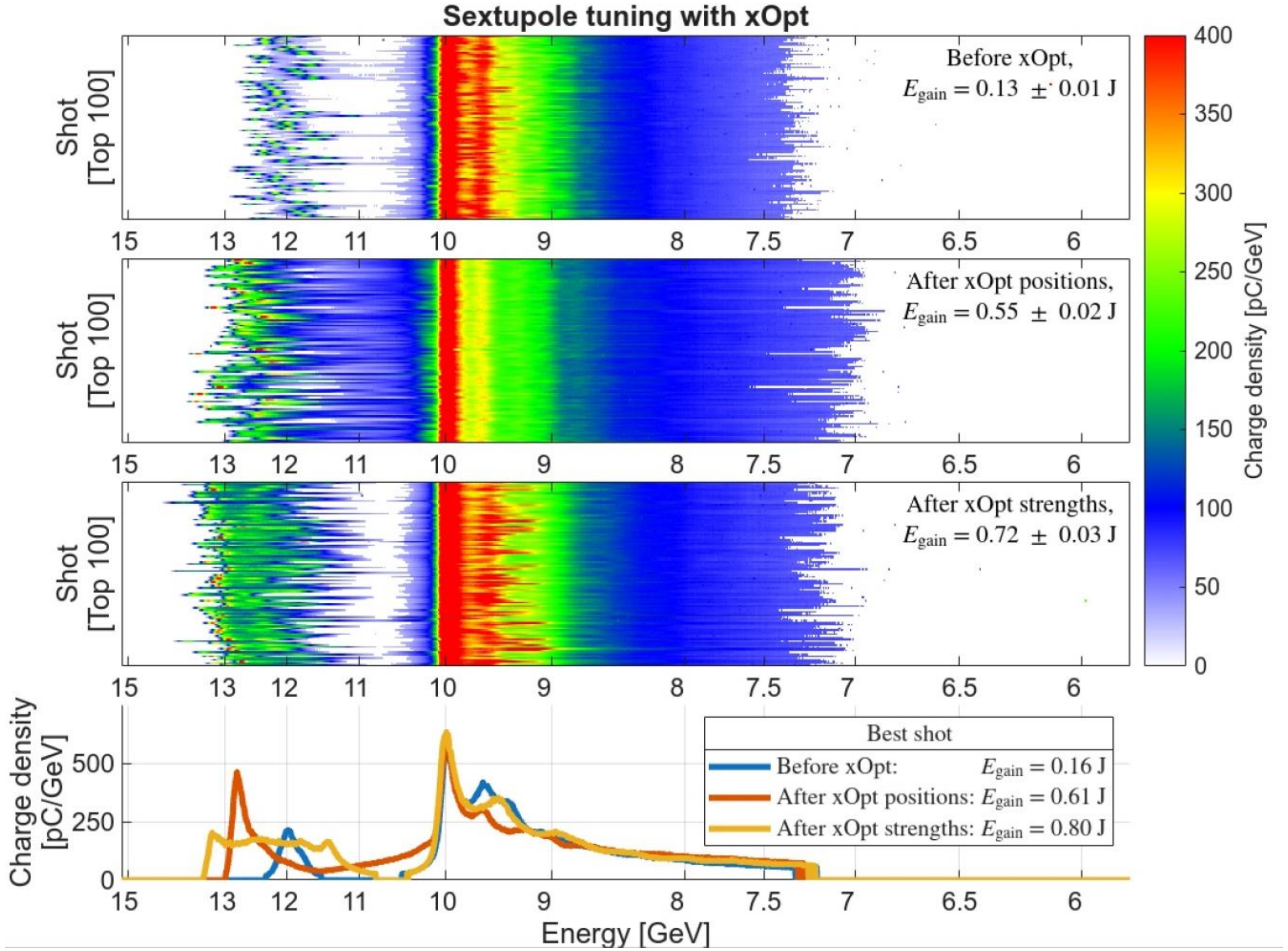
Plasma-based ML optimization of two bunch PWFA

- ML tuning on PWFA performance:
  - **Objective:** Maximize total energy transfer efficiency *(drive → witness)*

$$\eta_{tot} = \frac{Q_w \Delta E_w}{Q_d E_{d,0}}$$

- Result: **5x improvement in $\boldsymbol{\eta_{tot}}$**

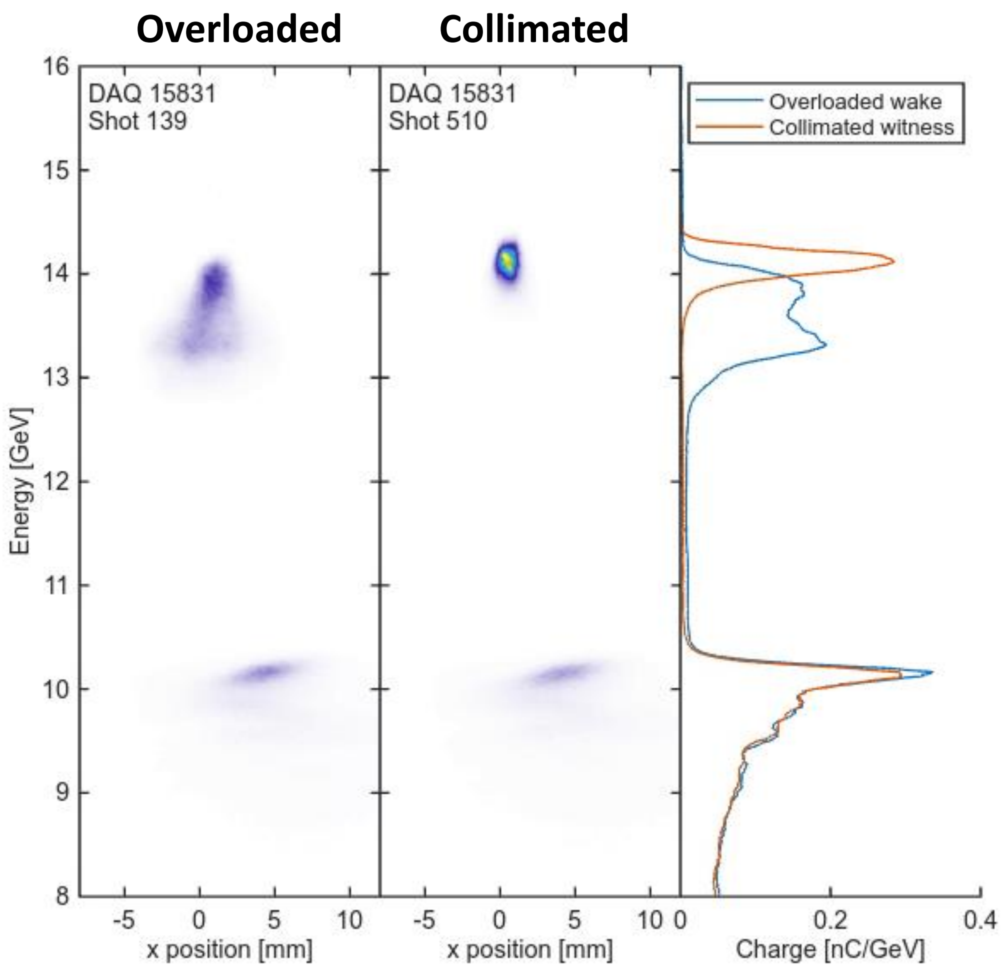
- Next steps to improve performance
  - Include additional linac settings as model inputs (phase, BPM readings, etc)
  - Expand actuators (DOFs): sextupoles + FF quads + correctors



Credit: S. Rego, Ecole Polytechnique

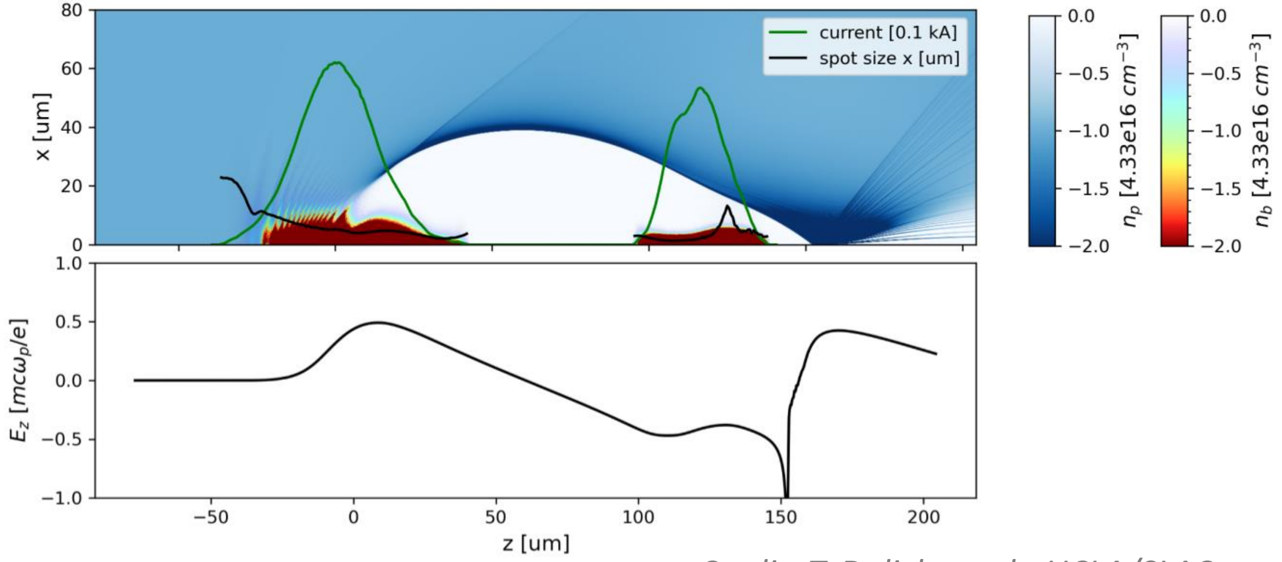
ML optimization is now part of routine PWFA tuning, enabling faster, repeatable operation

Optimizing beam loading to reduce energy spread



- Next step – use collimators to shape the witness profile to optimize beam loading
  - By flattening the wake: $\sigma_E \sim 5\% \rightarrow < 1\%$

Overloading in QPAD simulation

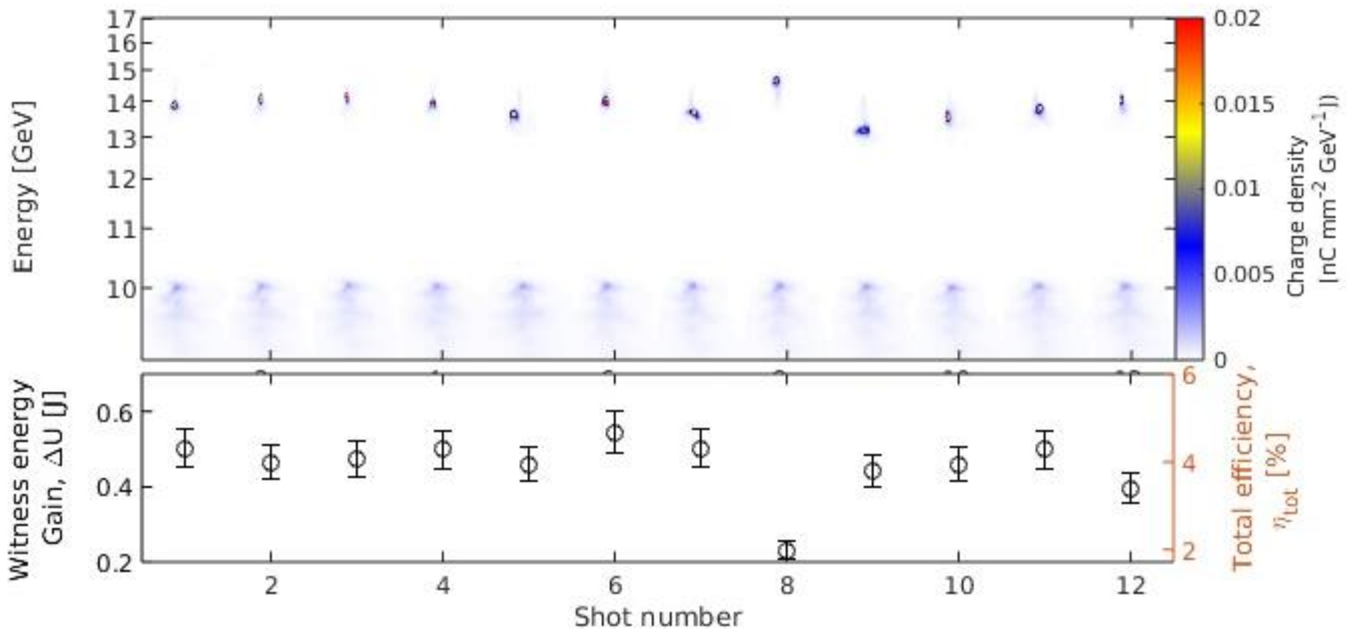


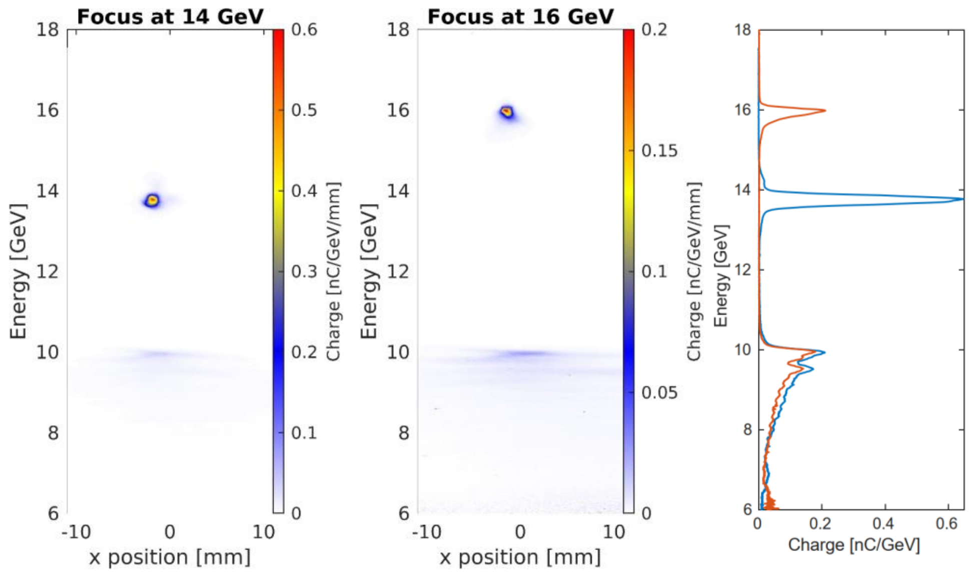
Credit: T. Dalichaouch, UCLA/SLAC

Can achieve <1% energy spread on witness after proper bunch shaping

Multi-GeV acceleration with high field-uniformity and efficiency

- Stable witness acceleration across shots with comparable incoming beam parameters
  - Driver: 1.2 nC, 6-8 kA, Witness: ~250 pC
  - Plasma: 40cm long lithium plasma, 4e16 cm^{-3}

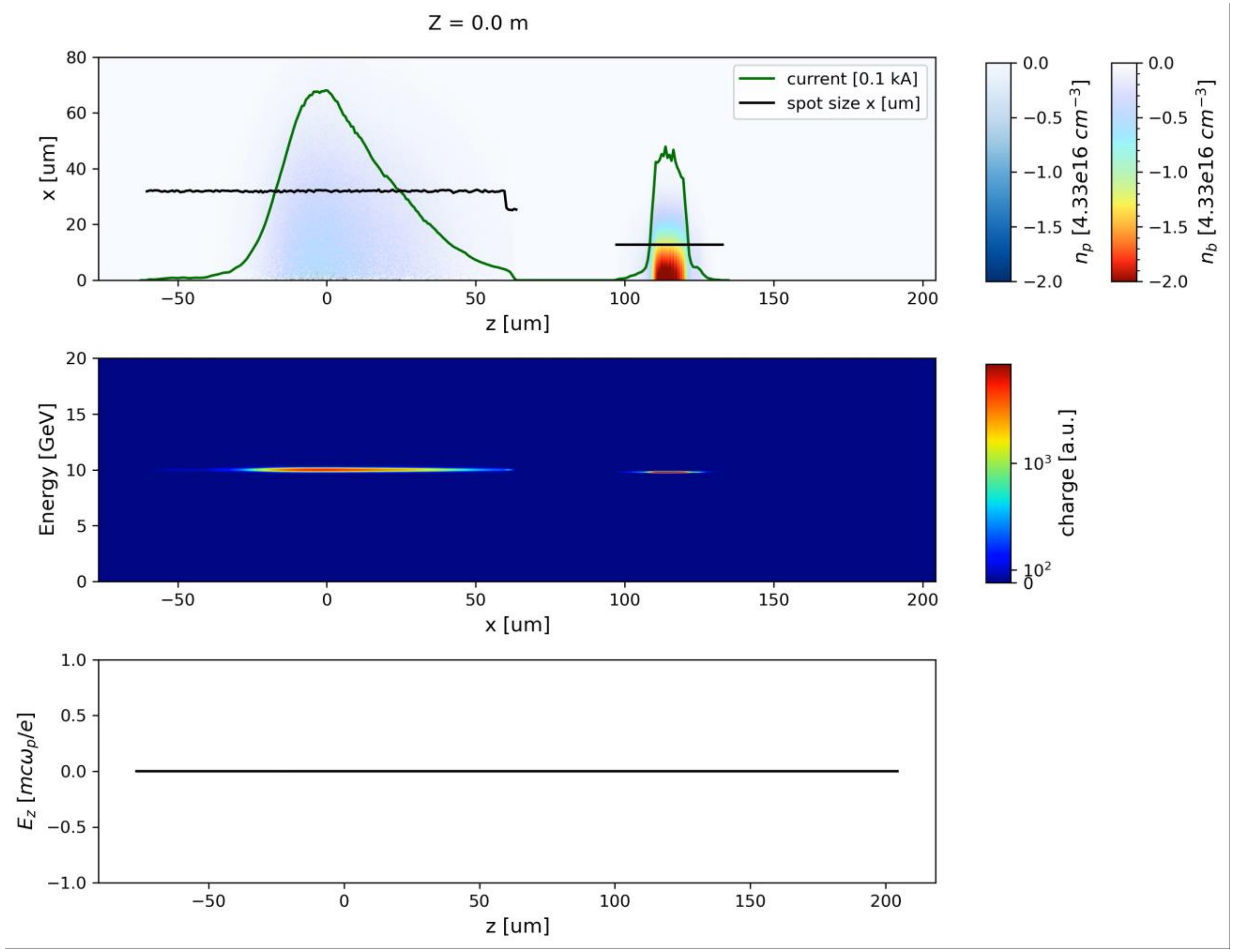




Energy gain, ΔE_w	**(4.1 ± 0.3) GeV**
Gradient, $\Delta E_w/L_p$	(10 ± 1.0) GeV/m
Energy spread	**(0.58 ± 0.06) %**
Field uniformity, $\sigma_{E_w}/\Delta E$	**(2.0 ± 0.2) %**
Instantaneous efficiency, $\eta_{inst.}$	~20-30 %
Total efficiency, η_{tot}	**(4.9 ± 0.5) %**

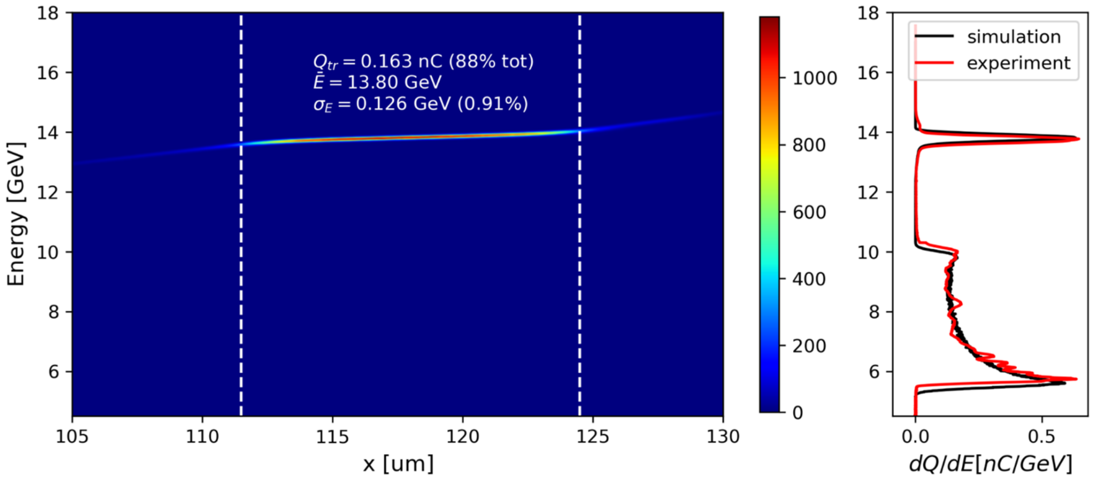
Precision PWFA studies at collider-relevant energy scale

PIC simulations are guiding future progress



Credit: T. Dalichaouch, UCLA/SLAC

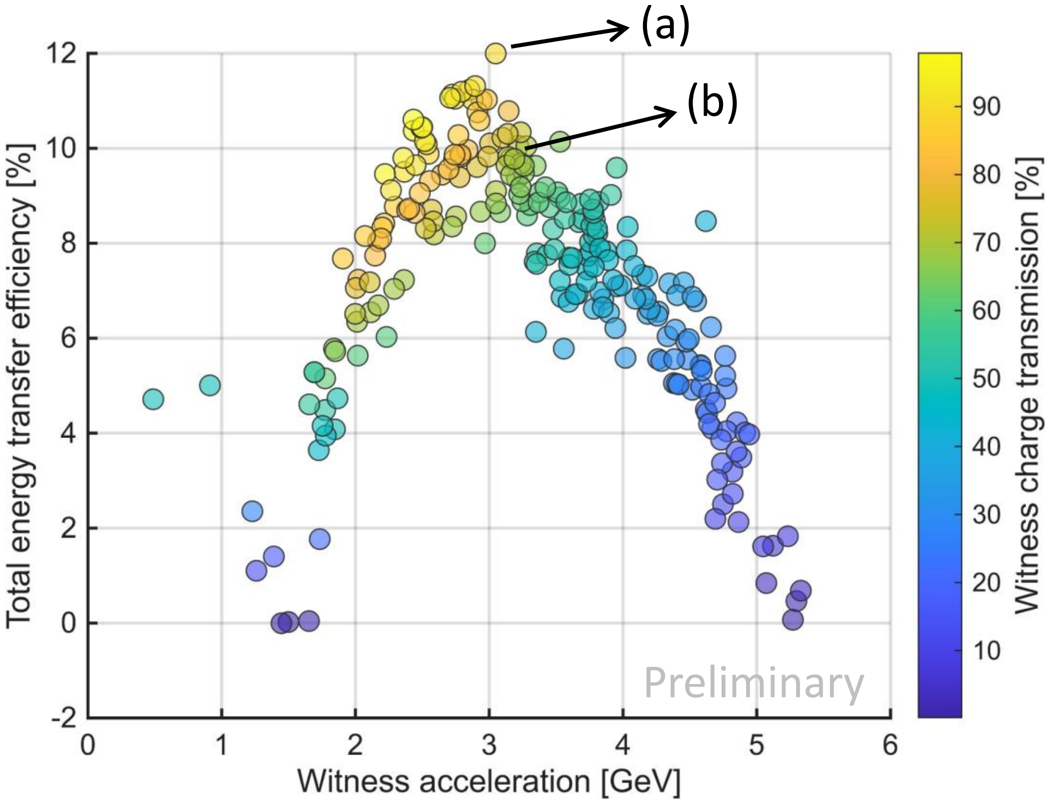
- QPAD simulations used to better understand loading, matching, etc
  - Performed by T. Dalichaouch (UCLA/SLAC)
- Simulation matches experimental setup
  - With plasma density ramps
  - Similar LPS and emittances, but with azimuthal symmetry

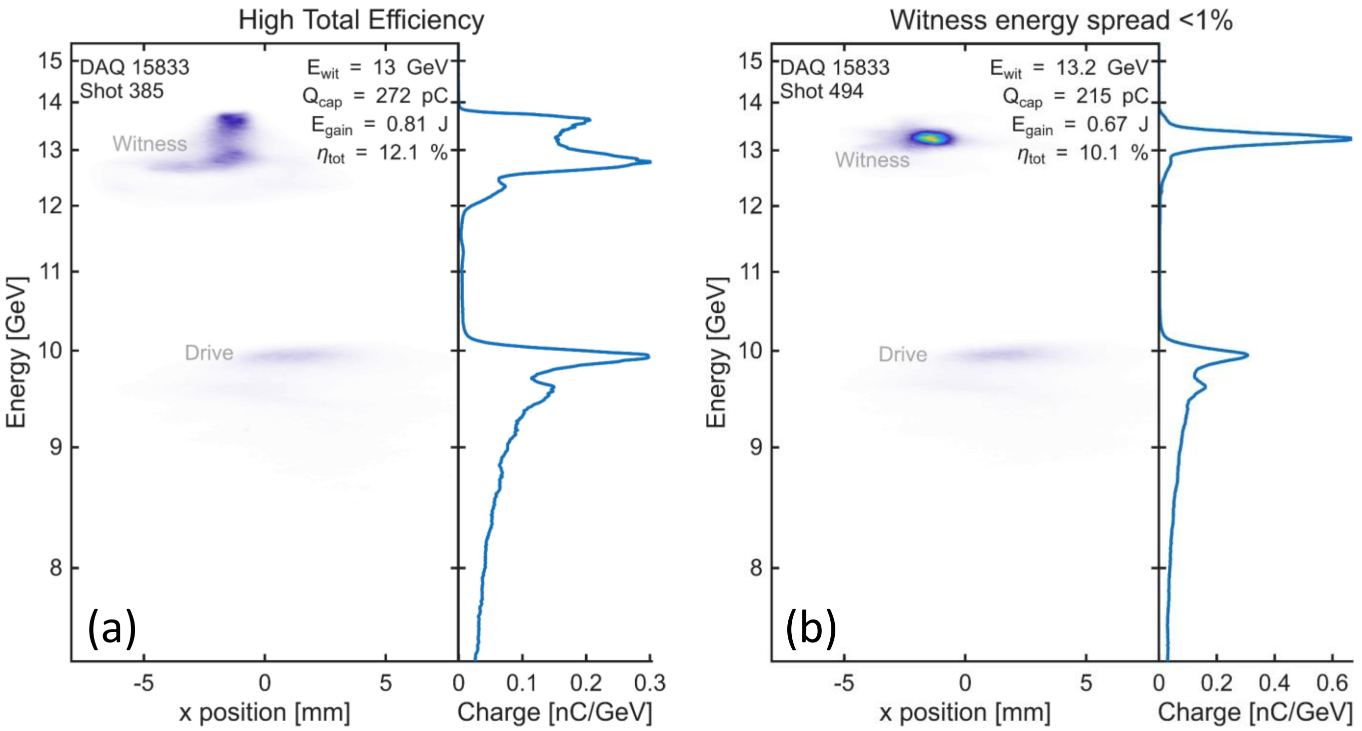


Excellent agreement between PIC sims and experimental results

Pushing the energy-transfer efficiency beyond $\eta_{tot} = 10\%$

- New tools have pushed our total efficiency to ~10% while maintaing sub percent energy spread



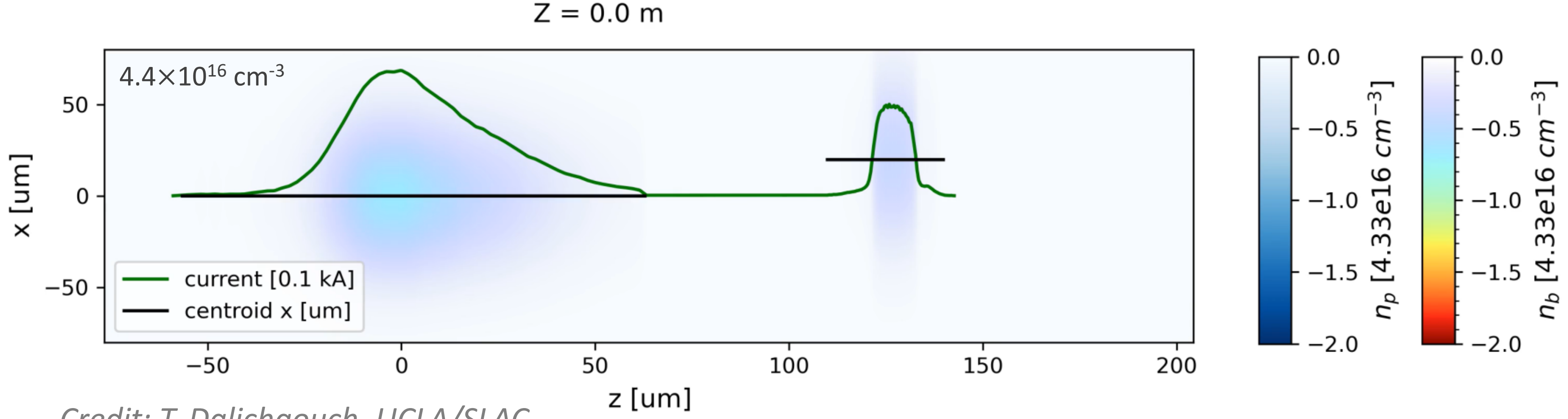


Pushing the bounds of energy transfer efficiency, while maintaining high quality acceleration

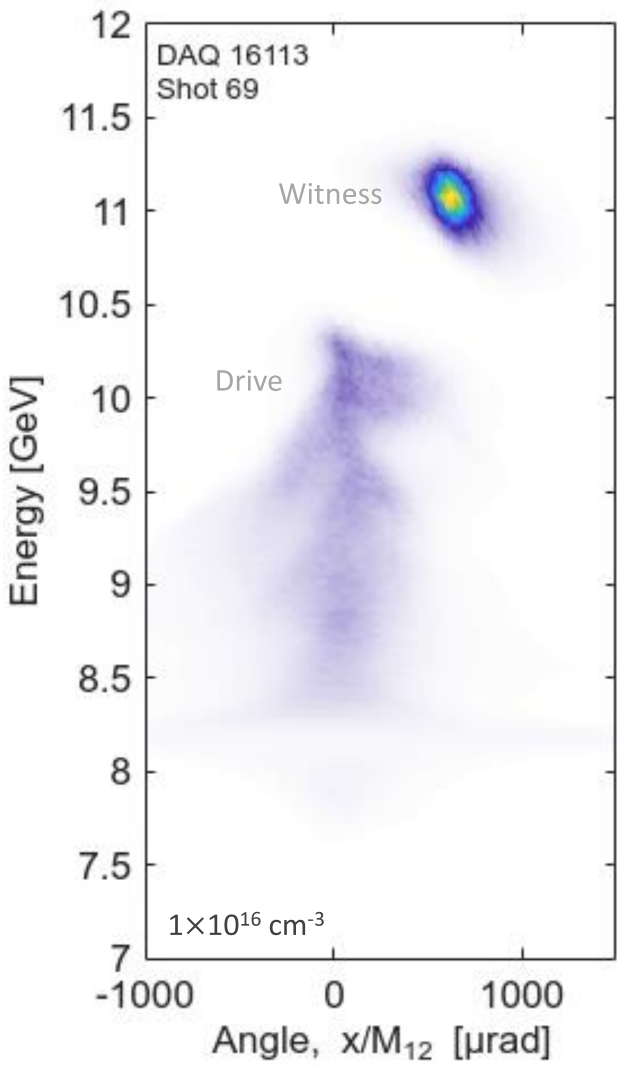
Work towards matching and emittance preservation

Y. Ye, WG3 M 14:50

20 µm transverse offset of the witness



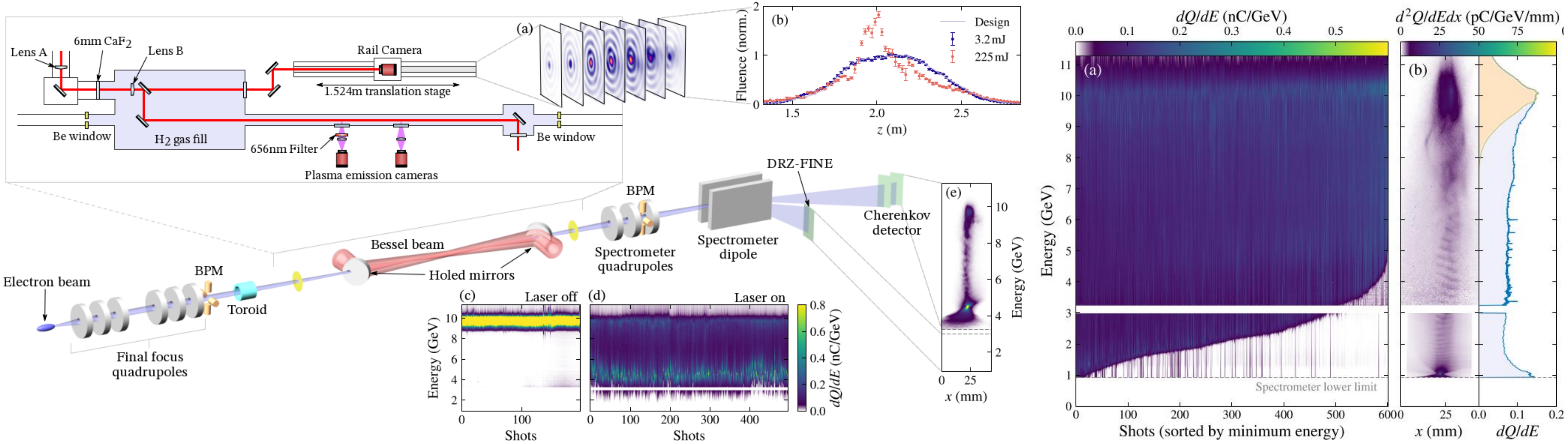
Credit: T. Dalichaouch, UCLA/SLAC



- Transverse offset of the witness bunch leads to emittance growth
  - PWFA studies at 1×10^{16} cm^{-3} (λ_p goes from 160 µm to ~300 µm)

- At this reduced plasma density:
  - Witness energy gain of 1.2 GeV
  - Beam divergence increased to $\sigma_{x'}$ ~ 100 µrad (factor of 5 over incoming)

Drive beam depletion in laser-ionized hydrogen plasma source



Ariniello *et al.*, arXiv:2511.15143 (2025)

Lee *et al.*, PRAB **29**, 041001 (2026)

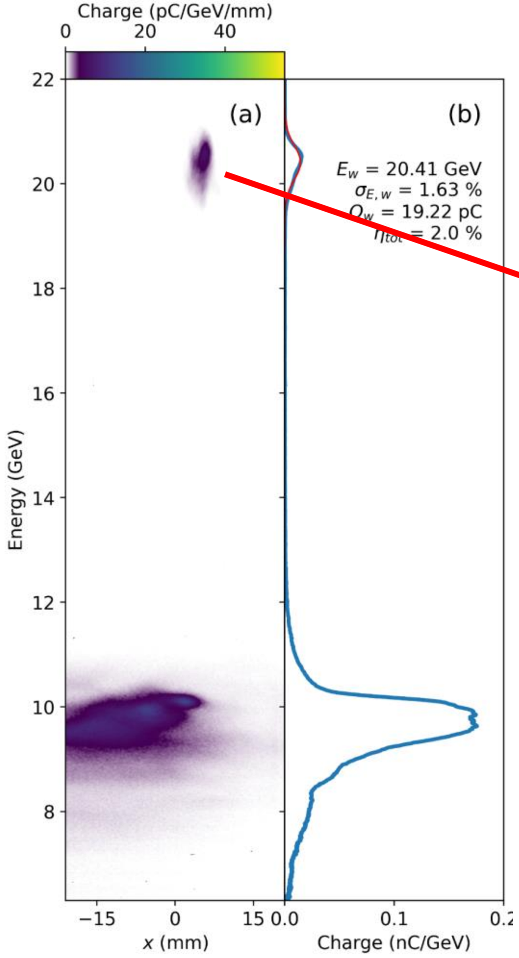
- E_{Wake} 5.6 J and η_{dw} = 37 ± 3% in an all-optical plasma source
- Energy depletion of particles to below 1 GeV

Multi-joule energy transfer demonstrated in the laser ionized plasma source

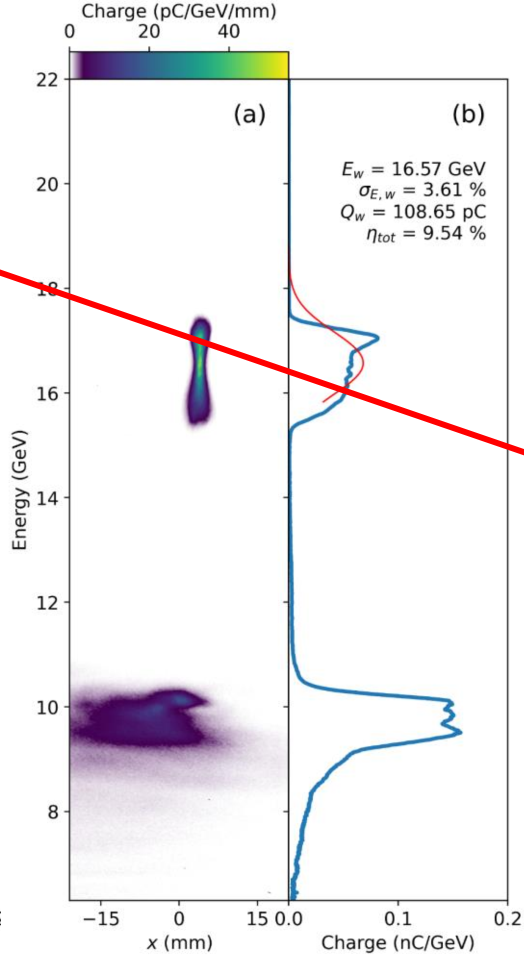
High-performance PWFA in laser-ionized hydrogen plasma

V. Lee, WG3 Tu 14:10

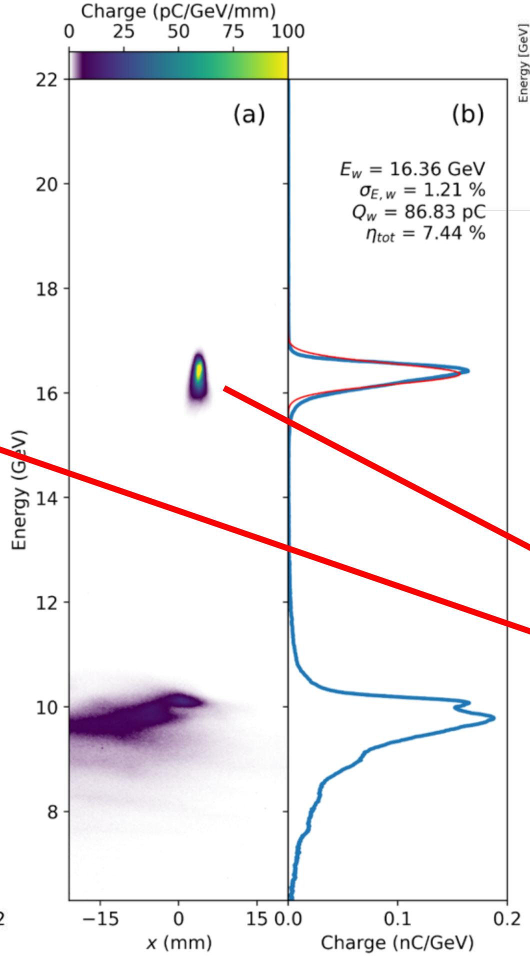
Large energy gain

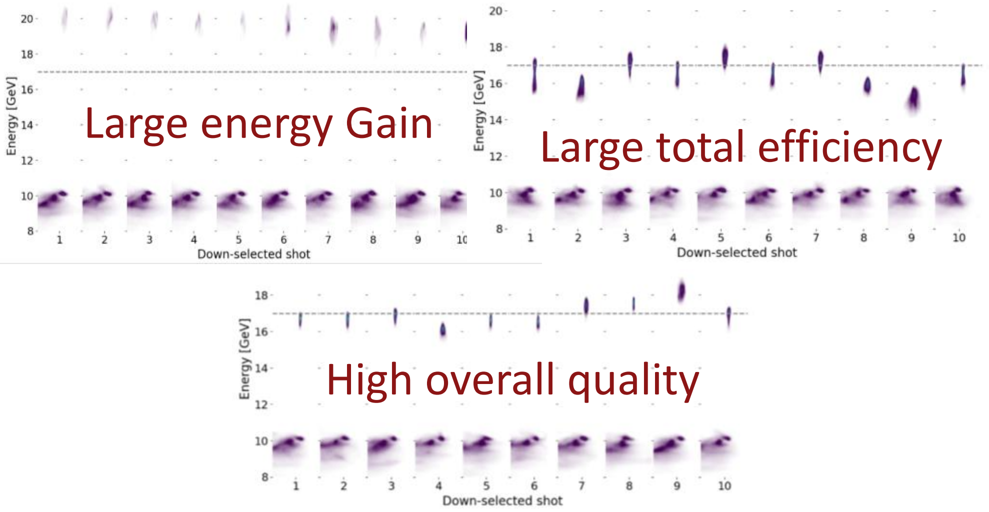


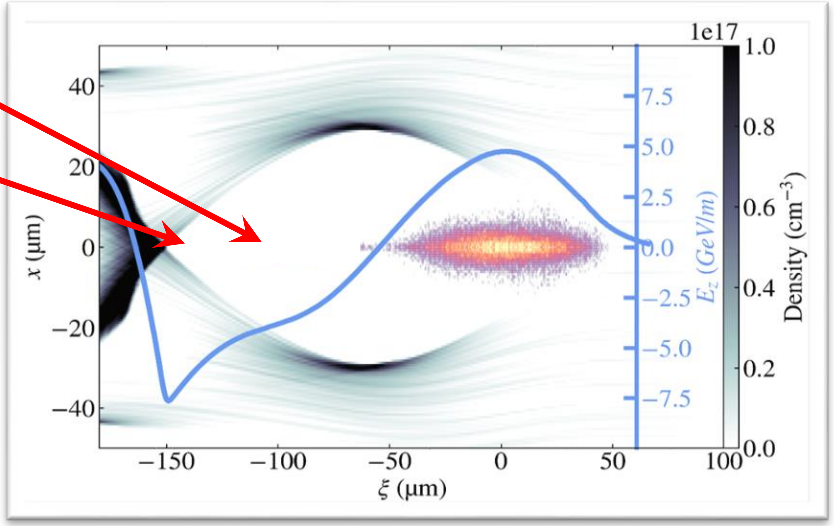
Large total efficiency



High overall quality



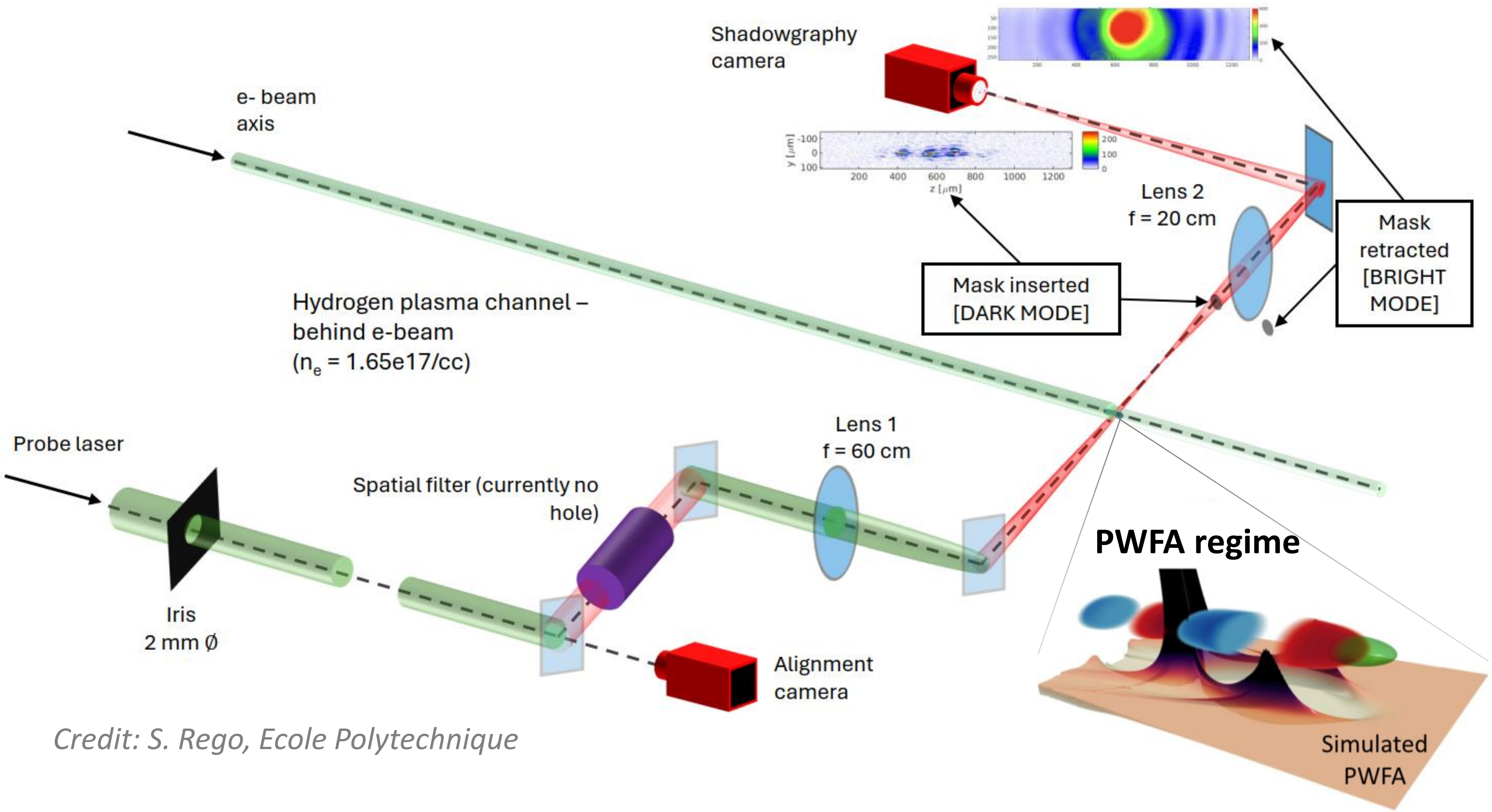




High quality and high efficiency witness acceleration in an application-relevant plasma source

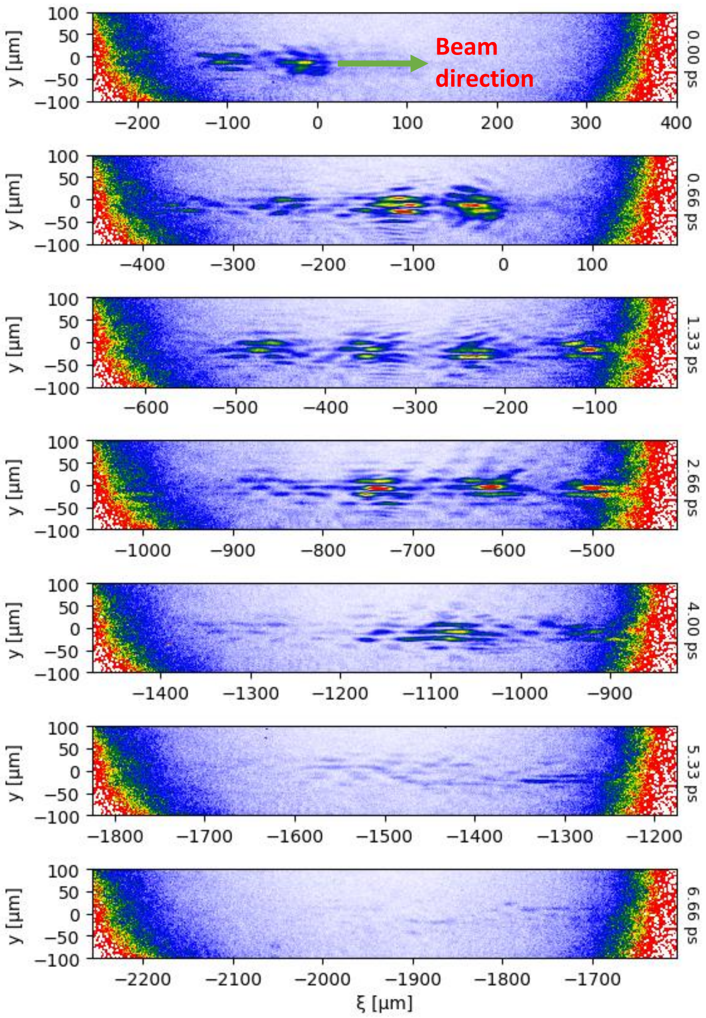
Optical probing of plasma wakes via dark field shadowgraphy

- Observation of plasma wakes to diagnose wake structures in **PWFA** and exotic regimes



Credit: S. Rego, Ecole Polytechnique

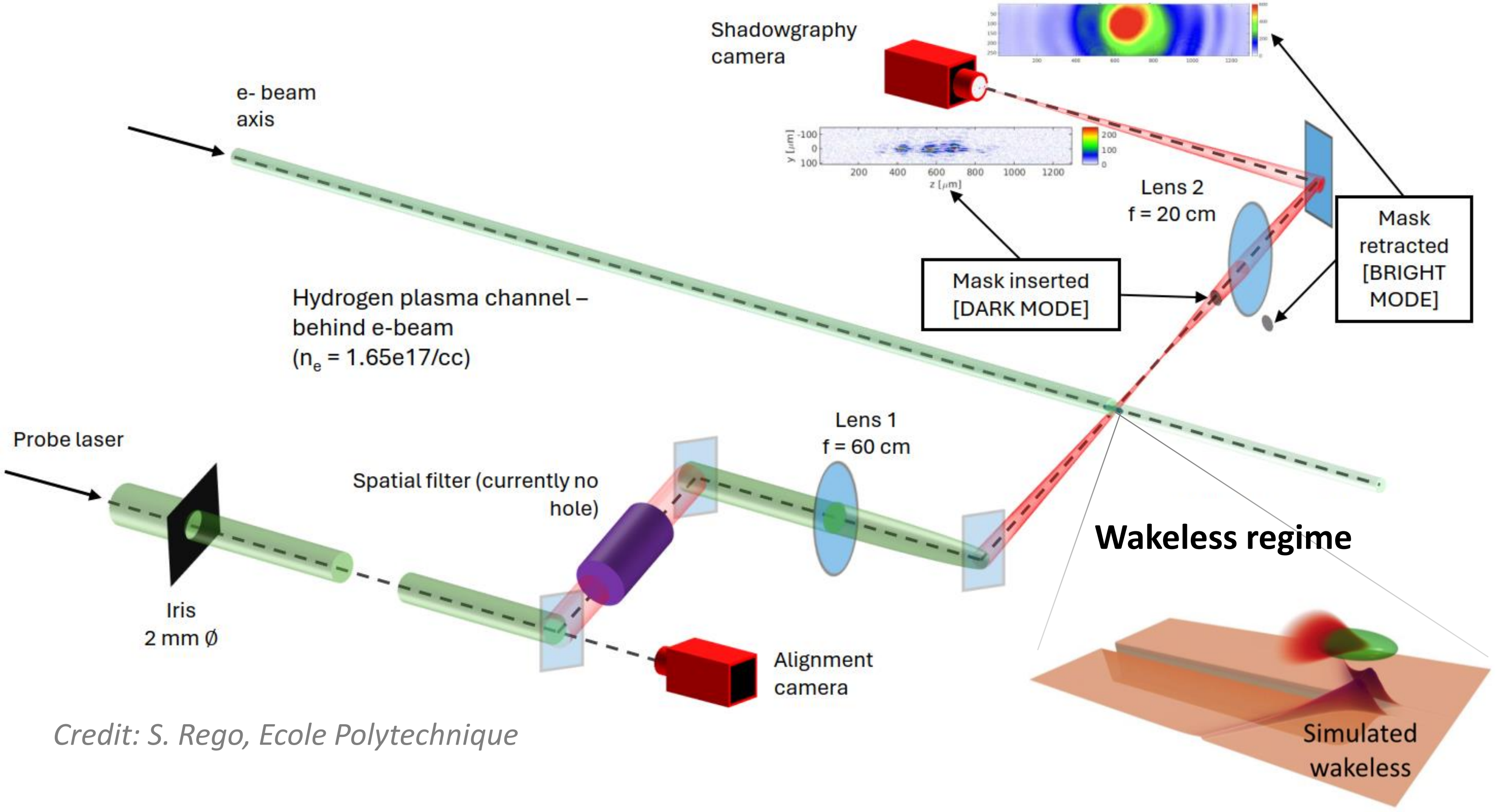
PWFA regime



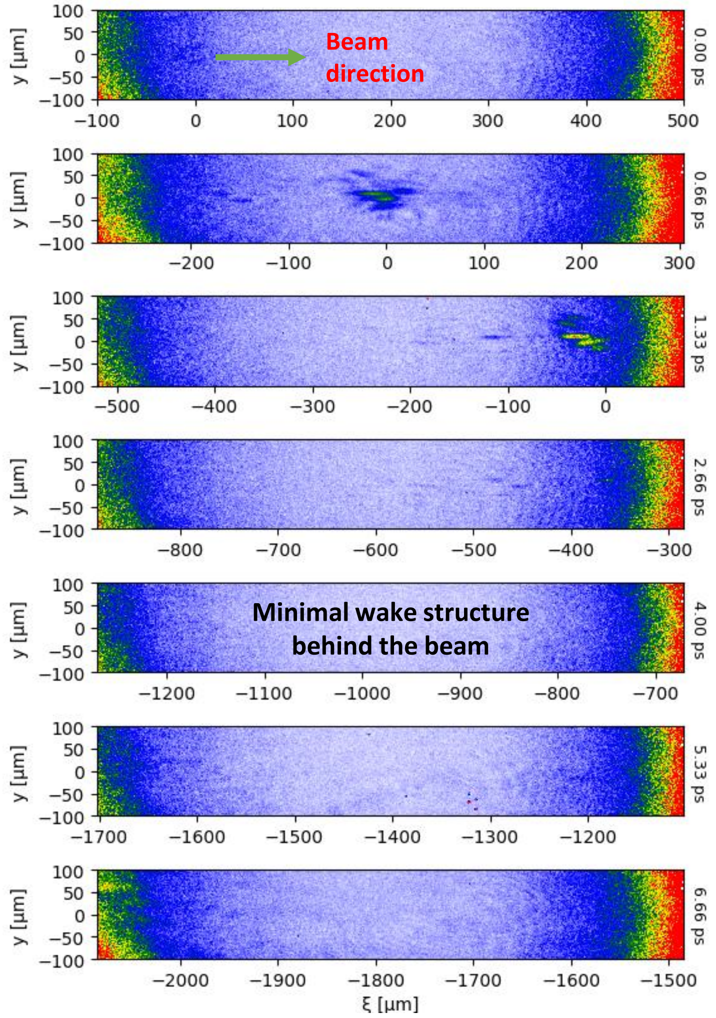
H. Zhang, WG3 Th 14:50

Optical probing of plasma wakes via dark field shadowgraphy

- Observation of plasma wakes to diagnose wake structures in PWFA and **exotic regimes**



Credit: S. Rego, Ecole Polytechnique



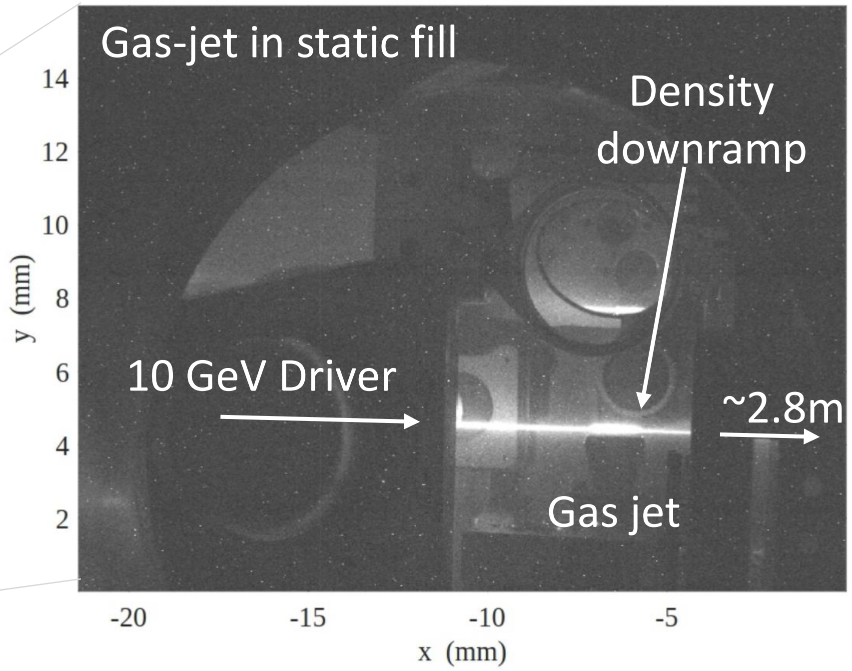
H. Zhang, WG3 Th 14:50

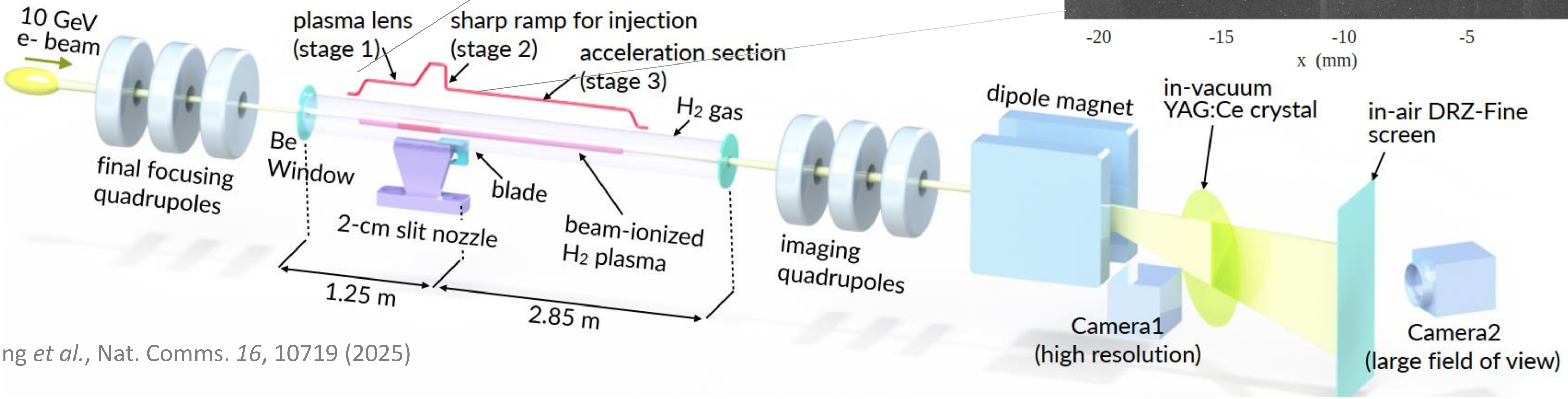
Topic #2

Ultra-high brightness plasma injectors and brightness transformers

Plasma-wakefield injector boosts energy and brightness

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

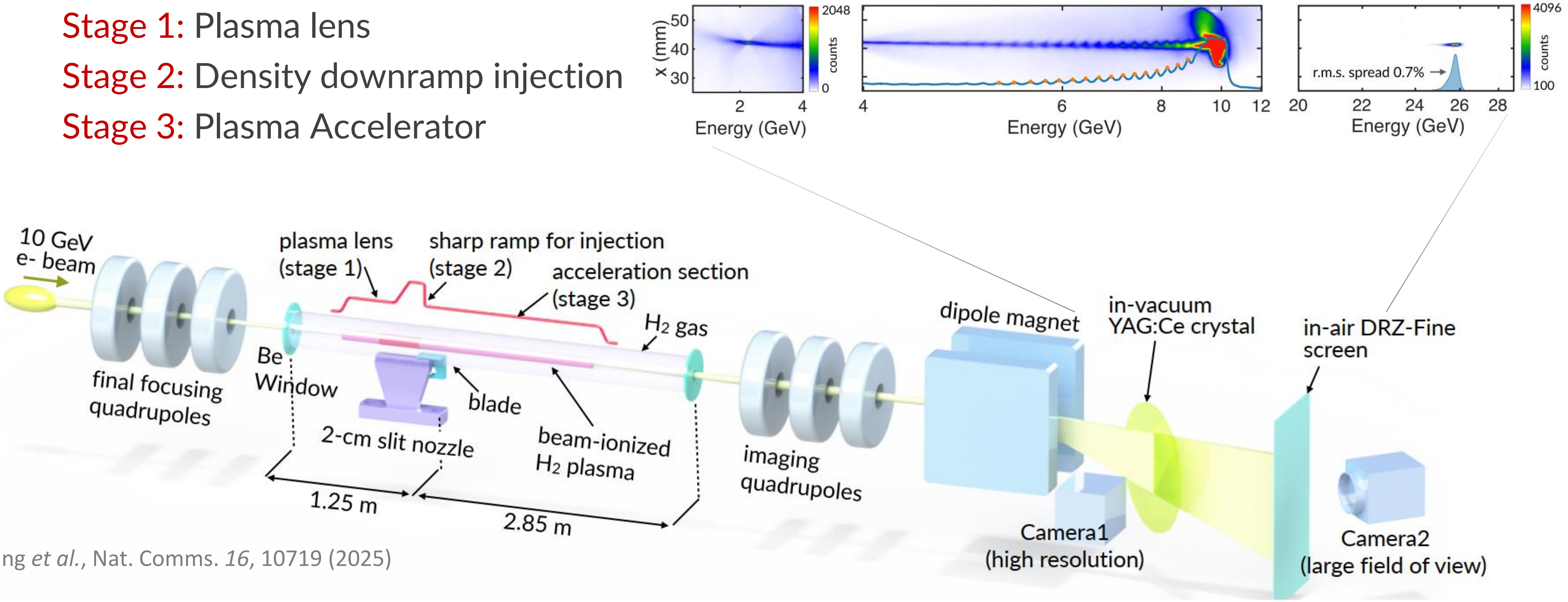




Zhang *et al.*, Nat. Comms. *16*, 10719 (2025)

Plasma-wakefield energy and brightness booster

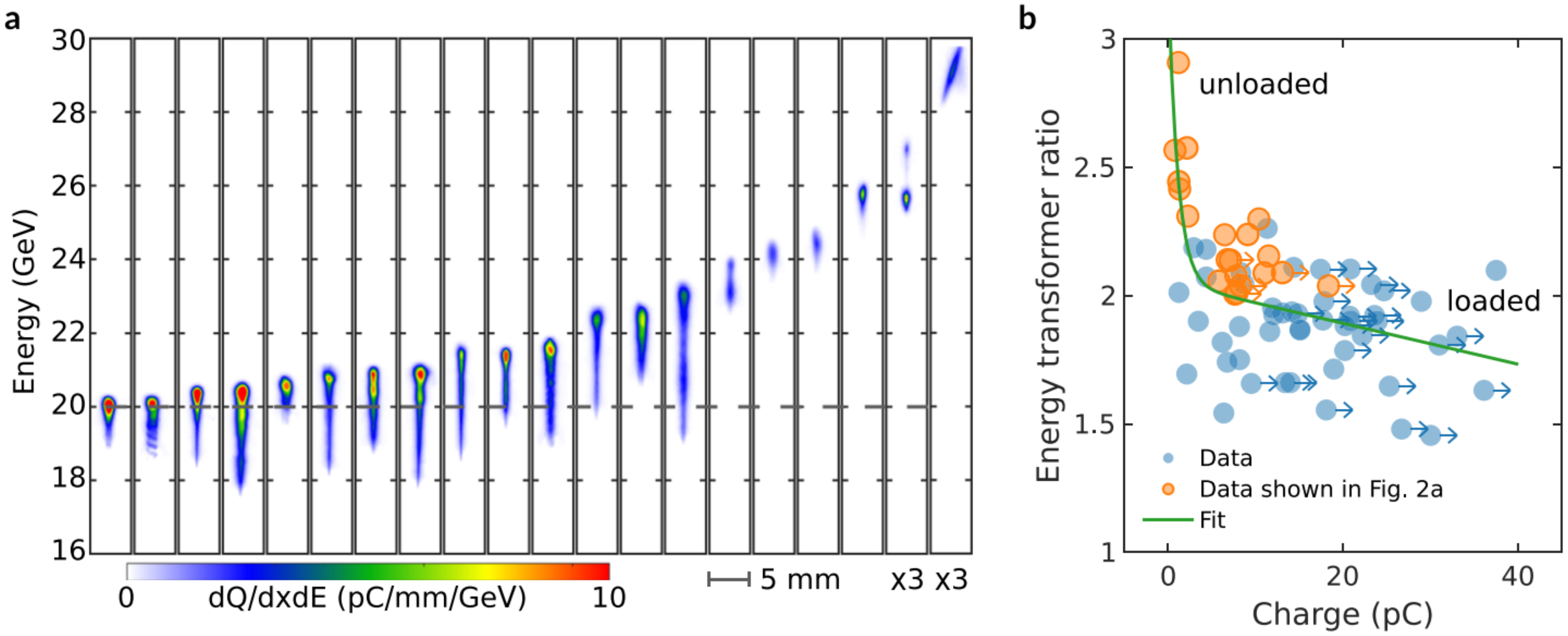
- Meter-scale static fill H2 gas, with H2 gas jet
- **Three stage brightness booster:**
  - Stage 1: Plasma lens
  - Stage 2: Density downramp injection
  - Stage 3: Plasma Accelerator



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

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
  - Emittance: $\epsilon_{n,x} < \sim 2$ mm mrad
  - Energy spread: $\sigma_{E,W} \sim 1\%$
  - Current: ??



- Extension of this idea:
  - TeV electron beams from Plasma Acceleration via Regenerative Cascading

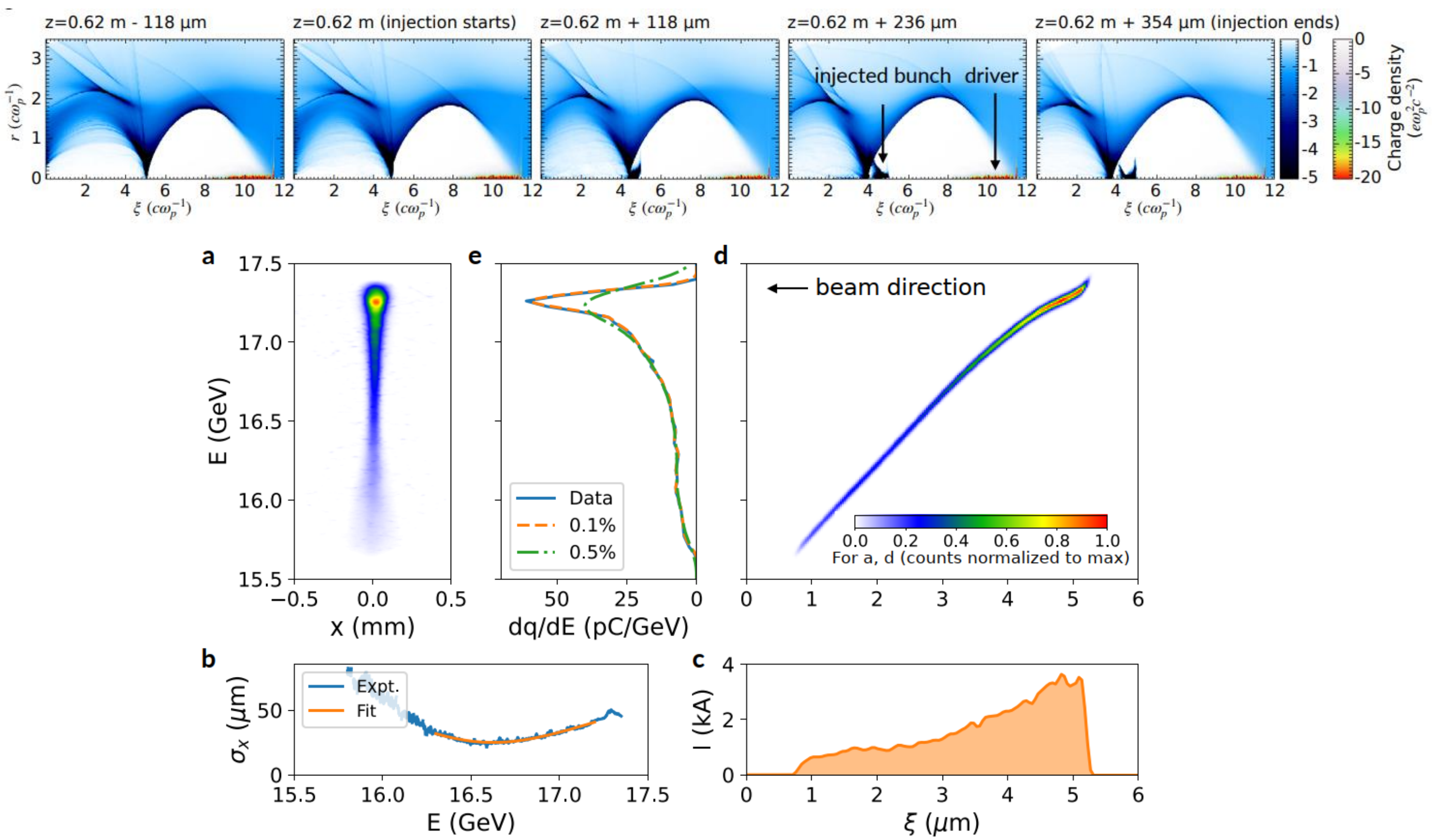
Zhang and Joshi , arXiv:2607.07979 (2026)

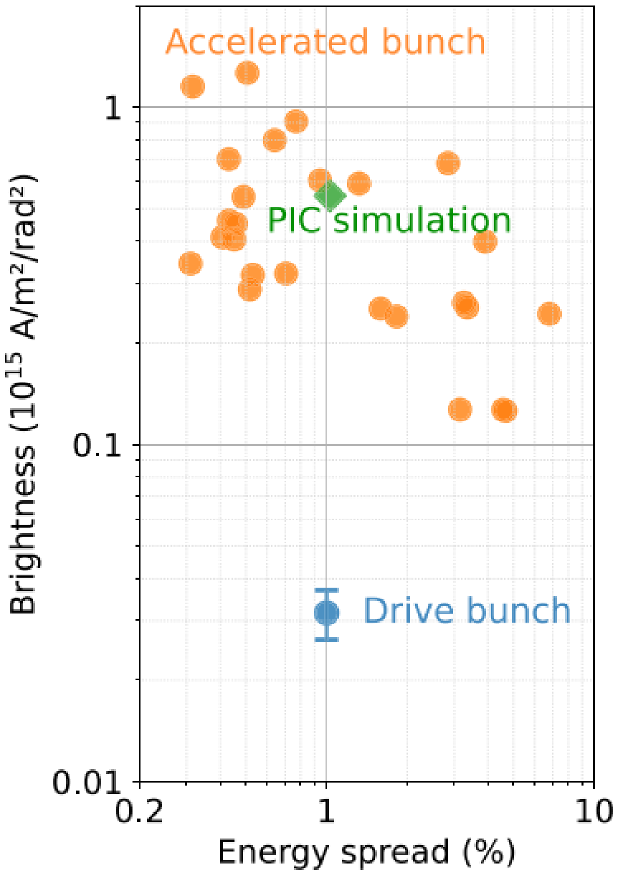
C. Zhang, WG3 Tu 13:30

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

Brightness transformer with high conversion efficiency

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



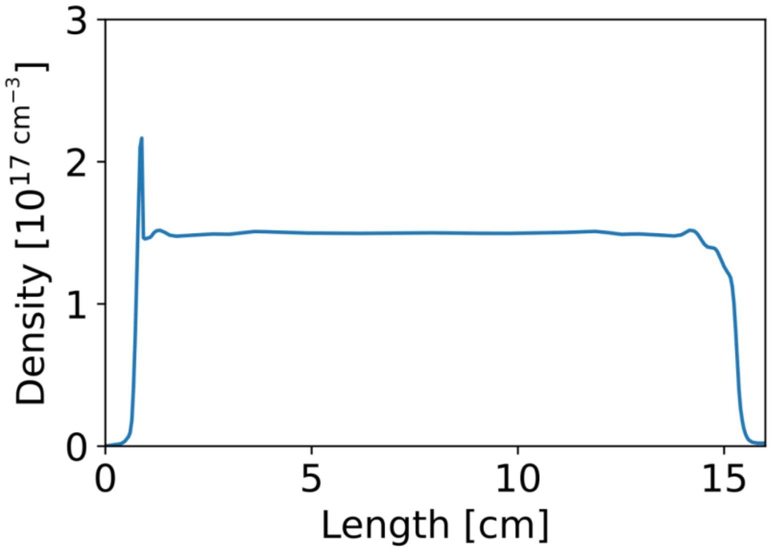


Zhang *et al.*, Nat. Comms. *16*, 10719 (2025)

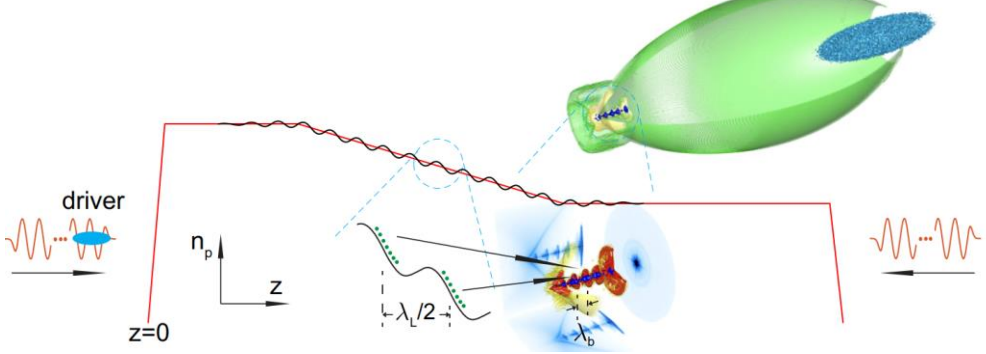
Brightness of injected beams up to 38x brighter than incoming bunch

Stable density downramp injection – next steps

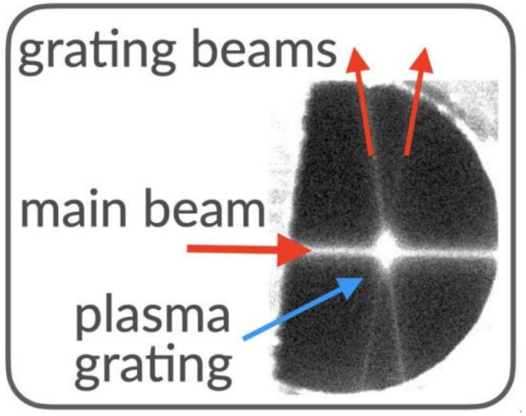
- New fixed length plasma source tested

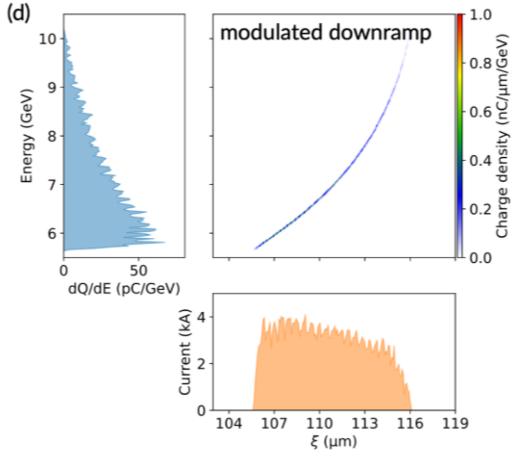


- Modulated downramp injection



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

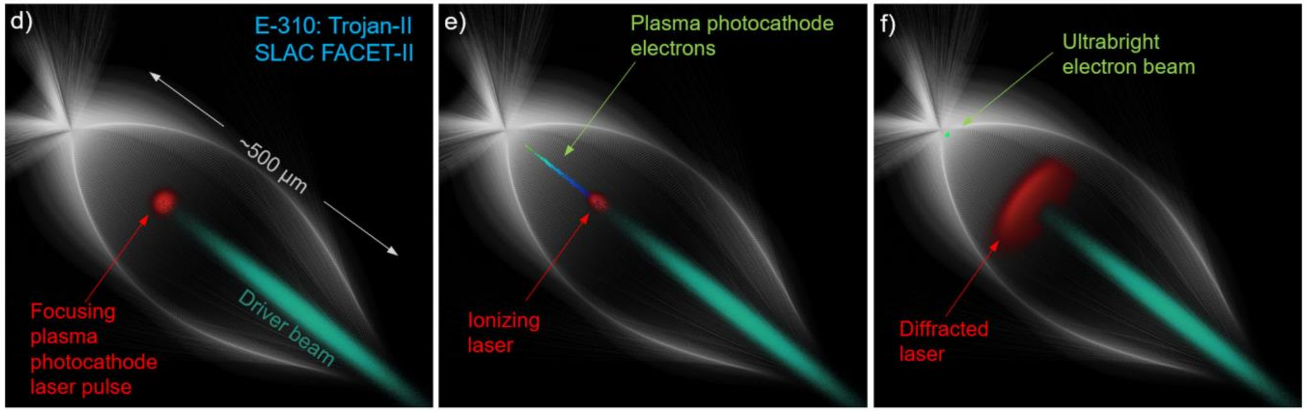




Credit: C. Zhang, UCLA

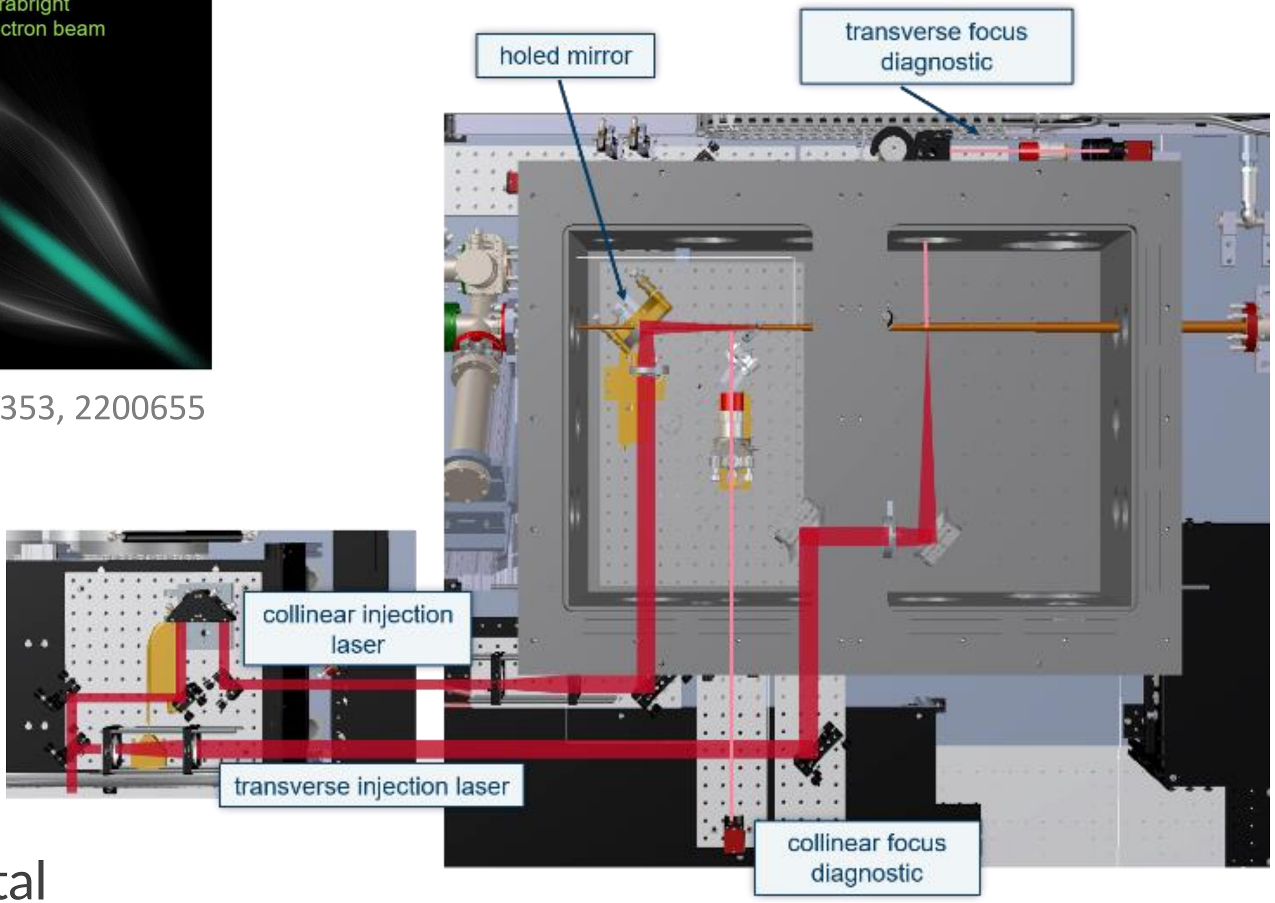
Generating stable, low-emittance, pre-bunched beams in a plasma wakefield accelerator

Trojan Horse injection for ultra-bright electron beams



Habib and Heinemann, *et al.*, Ann. Phys. **2023**, 353, 2200655

New FACET IP layout



- Collinear Trojan Horse injection
  - nm rad-scale emittance
  - Application towards future light sources

  Habib *et al.*, Nat. Comms. **14**, 1054 (2023)

B. Hidding, WG6 M 16:40, WG3 Th 14:30, …

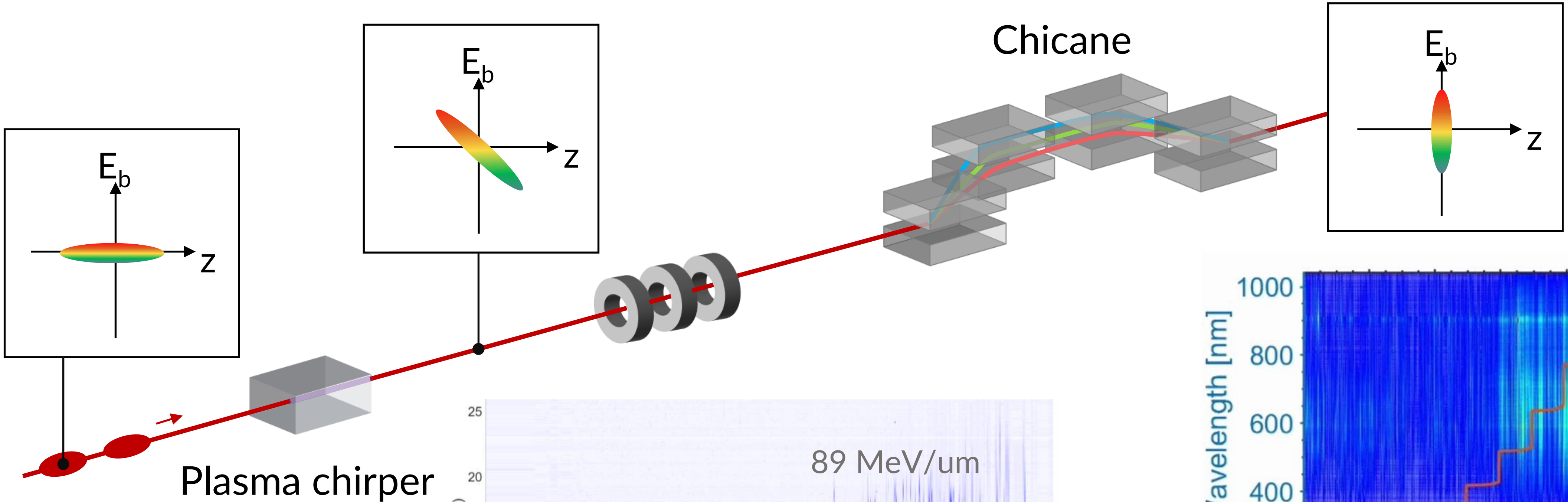
- Reconfiguration of the FACET-II experimental area underway!

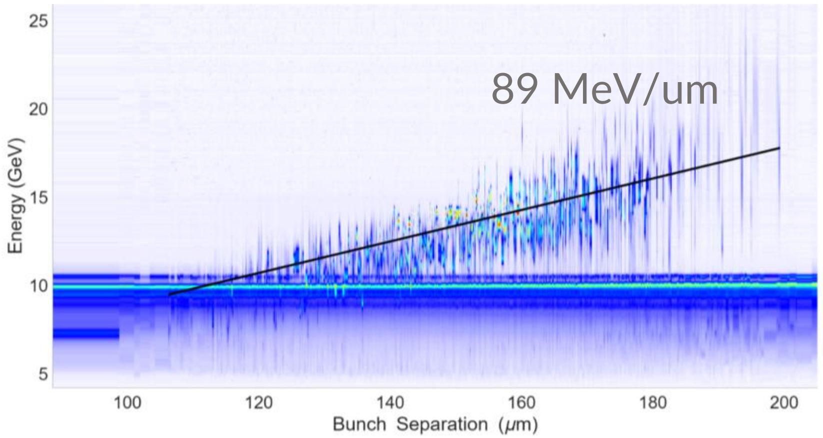
N. Thomas, WG3 M 13:50

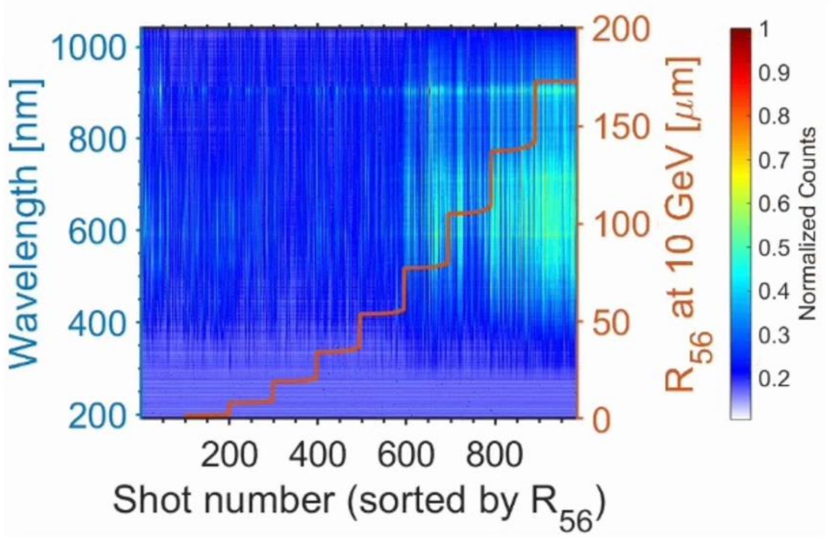
E. Hartmann, WG5 M 14:50

First collinear Trojan Horse injection experiments will take place this fall

Energy chirp in PWFA beams enable compression to <100 nm duration







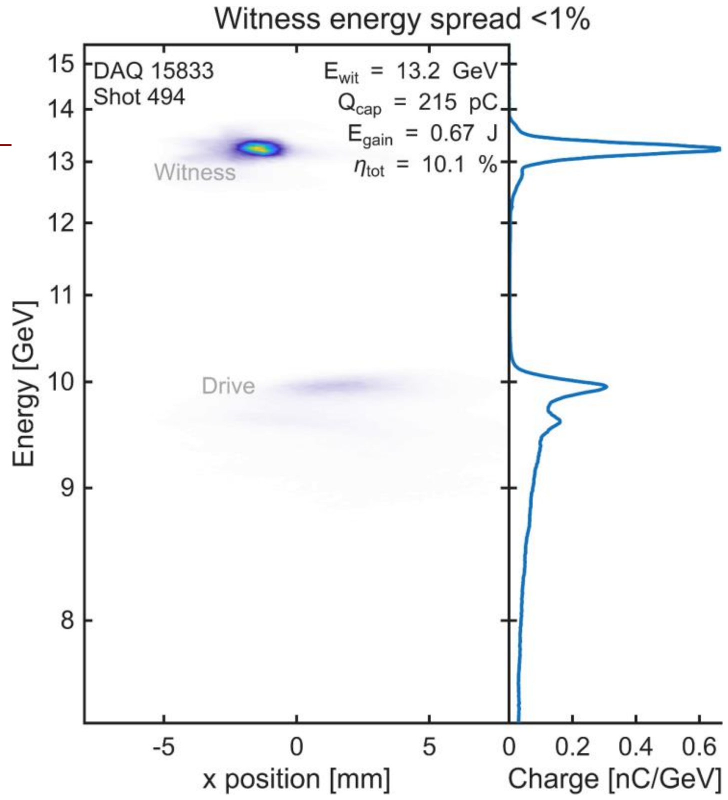
R. Hessami, WG6 M 16:00

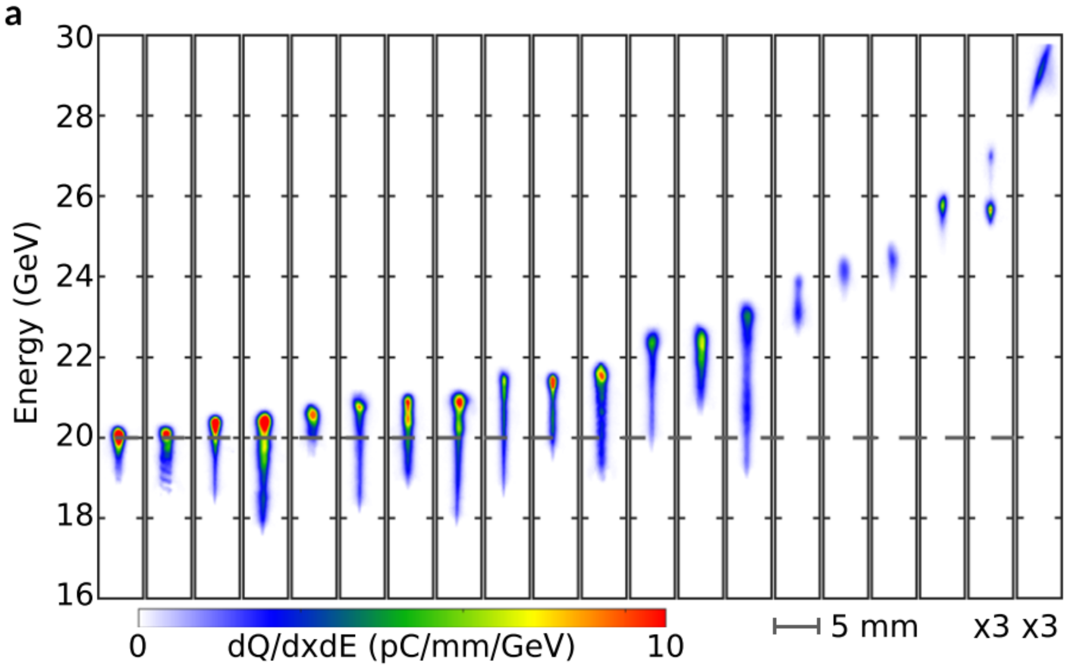
Compression of plasma-chirped witness beams → increased CSR emission as compression is increased

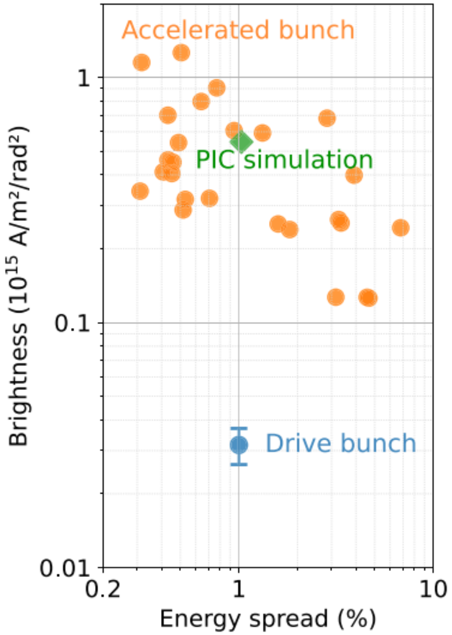
Plenary: K. Swanson, Th 10:45

PWFA studies at FACET-II

- **Multi-GeV acceleration with high beam quality and efficiency at collider-relevant energy scales**
  - ~10% energy efficiency with sub percent energy spread
  - Next step – emittance preservation!







- **Ultra-high brightness plasma injectors and brightness transformers**
  - Transformer ratios >2
  - >38x brightness boost

Many thanks to all my collaborators

- SLAC Advanced Acceleration Research Department team:
  - S. Crisp, T. Dalichaouch, K. Downham, A. Edelen, C. Emma, S. Gessner, C. Hast, J.P. Gonzalez Aguilera, M. Hogan, P. Kicsiny, A. Kinderman, A. Knetsch, C. Lin, J. Park, S. Perez, I. Rajkovic, D. Storey, K. Swanson, Y. Ye, J. Wang, B. O'Shea
  - Z. Buschmann, R. Loney, M. Parker, G. Yocky

Plus many more contributions:

FACET-II is supported in part by the U.S. Department of Energy under contract number DE-AC02-76SF00515

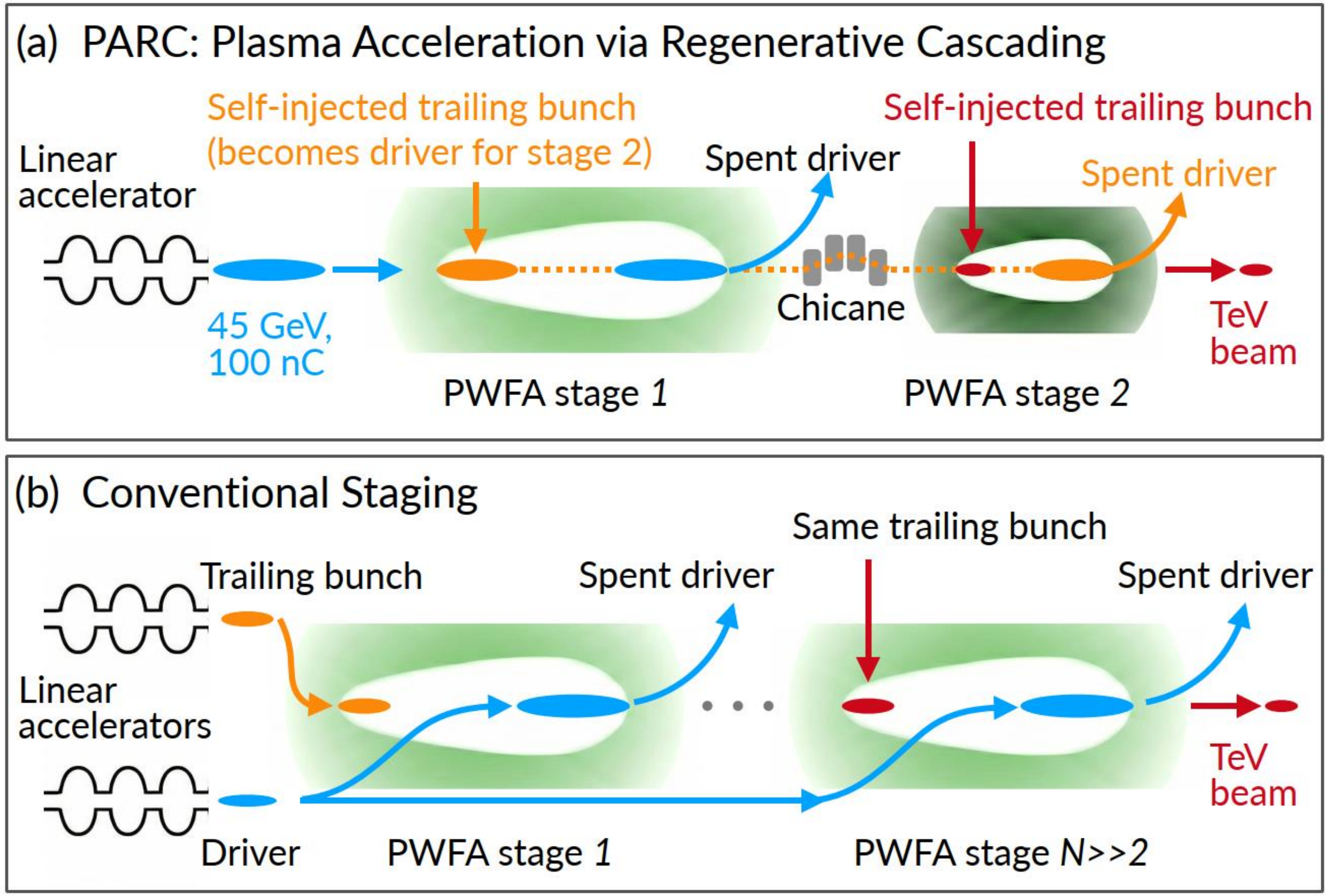
Thank you!

Questions?

FACET-II | Facility for Advanced Accelerator Experimental Tests

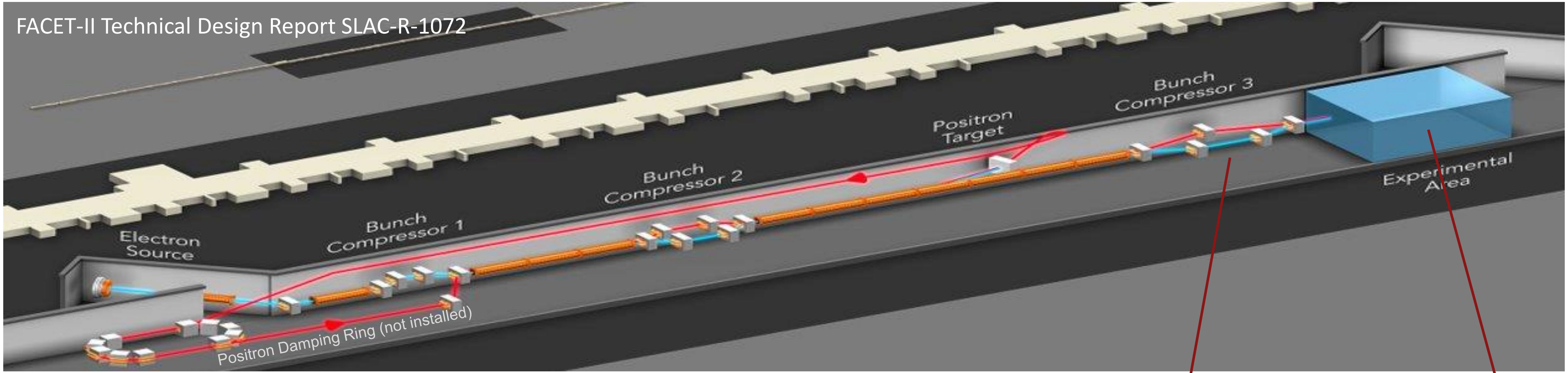
Extra materials

TeV electron beams from Plasma Acceleration via Regenerative Cascading



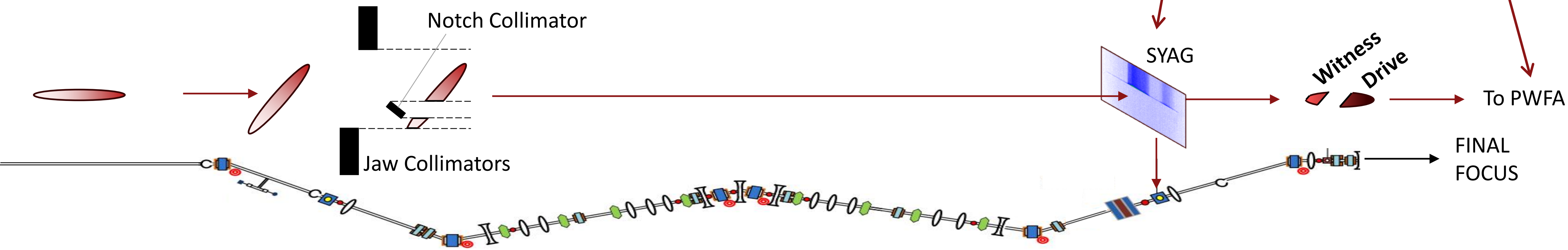
TeV beams from a two-stage sub-kilometer plasma accelerator

FACET-II provides 10 GeV beams for PWFA studies

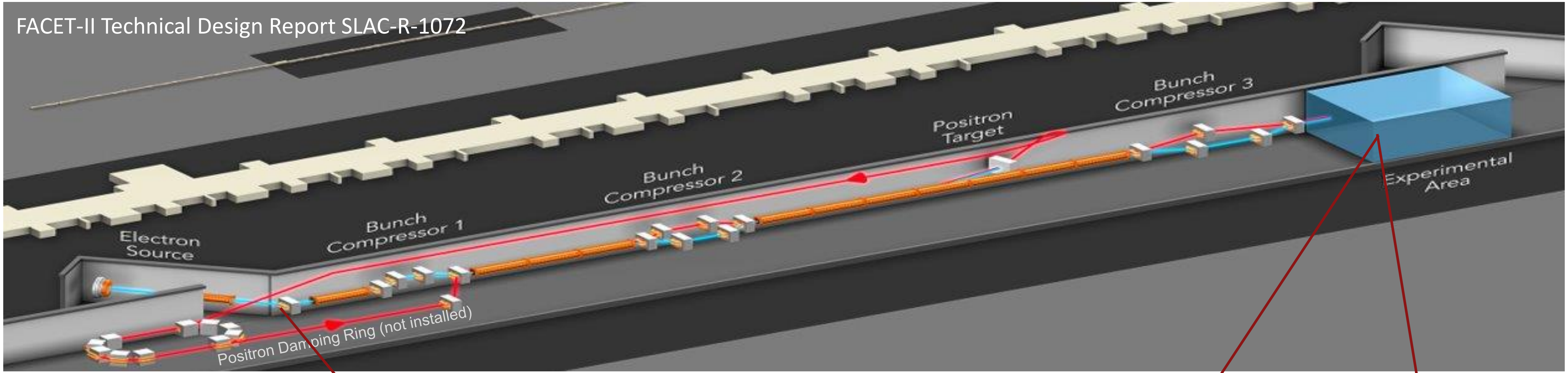


Two ways to produce 2 bunches at the experimental area for PWFA studies:

1) Single chirped long bunch, collimated to produce lower current drive and witness

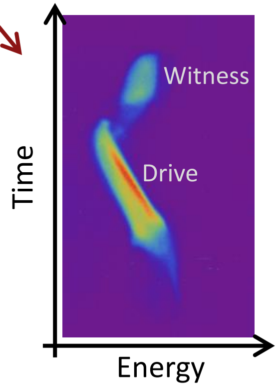


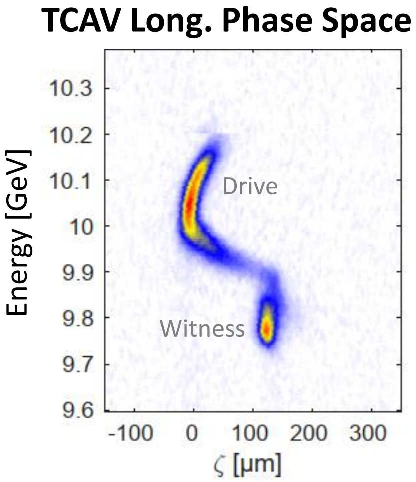
FACET-II provides 10 GeV beams for PWFA studies

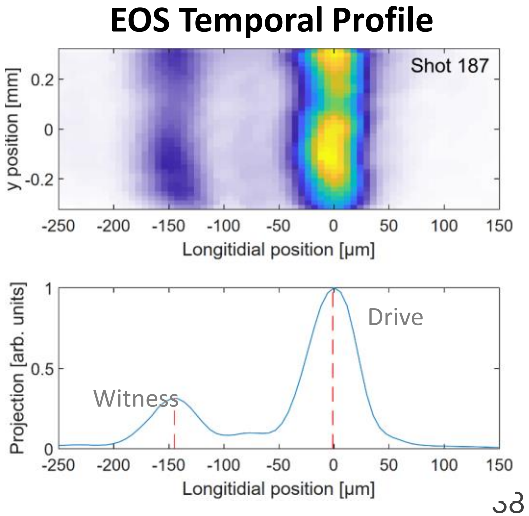


Two ways to produce 2 bunches at the experimental area for PWFA studies:

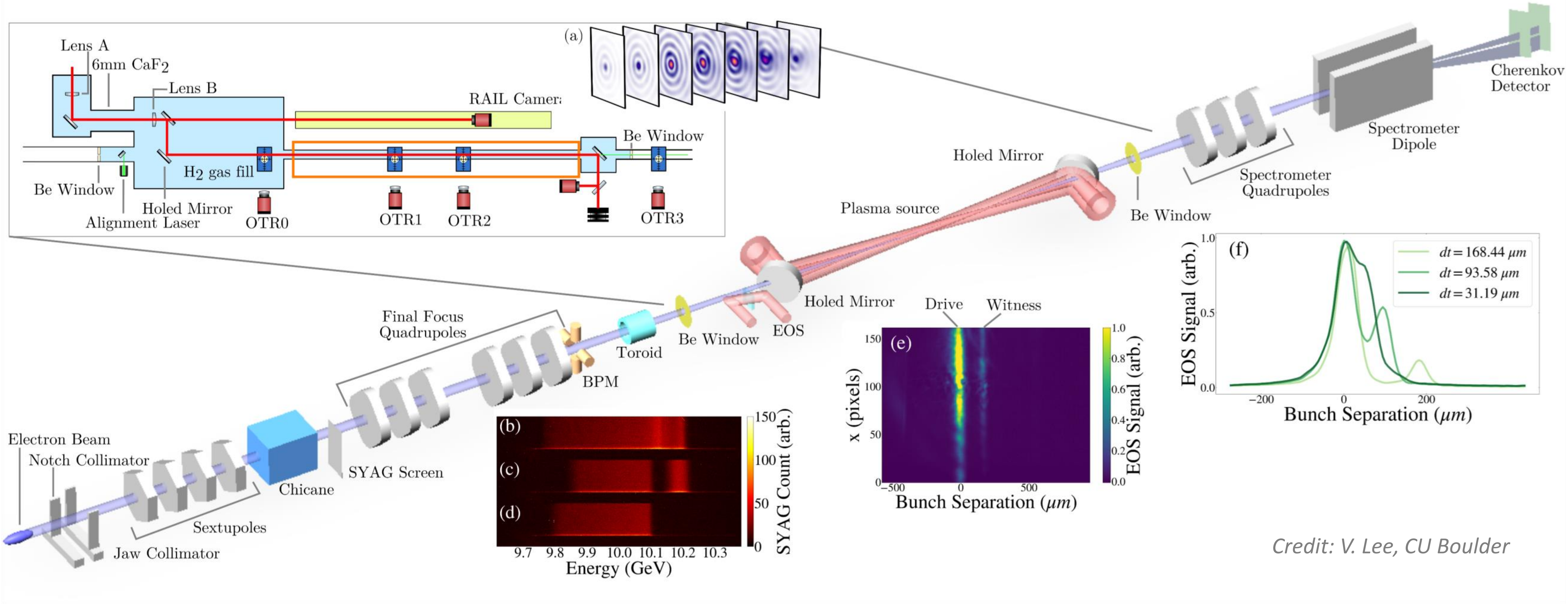
2) Two bunches off the photo cathode, co-accelerated through the linac







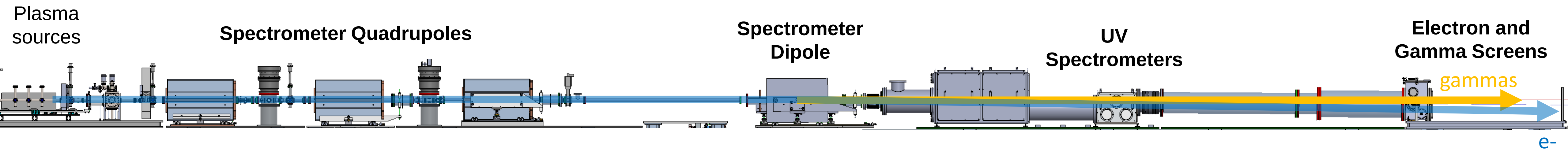
PWFA in the laser-ionized hydrogen plasma source



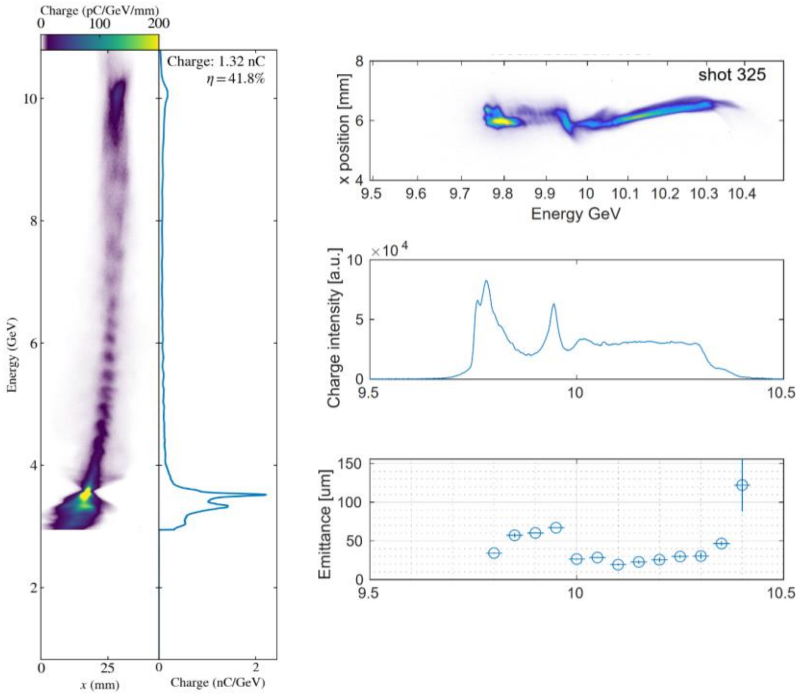
Credit: V. Lee, CU Boulder

5×10^{16} cm^{-3} laser ionized plasma, 80 cm length

Post plasma diagnostics

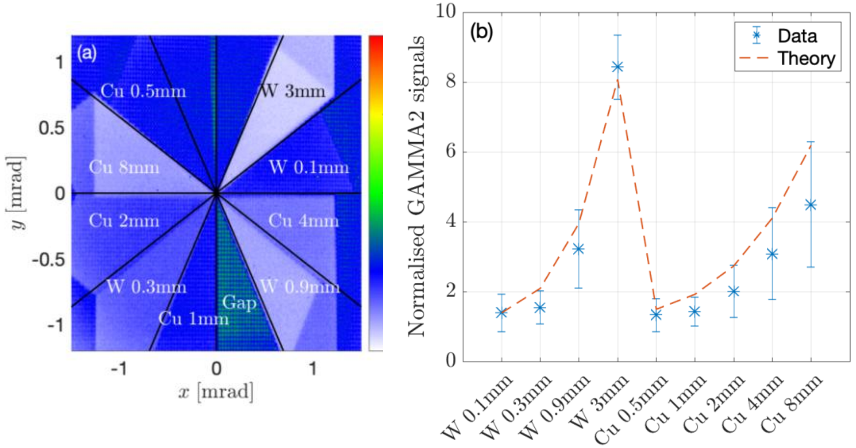


Imaging electron spectrometer



D. Storey et al., PRAB **27** 051302 (2024)

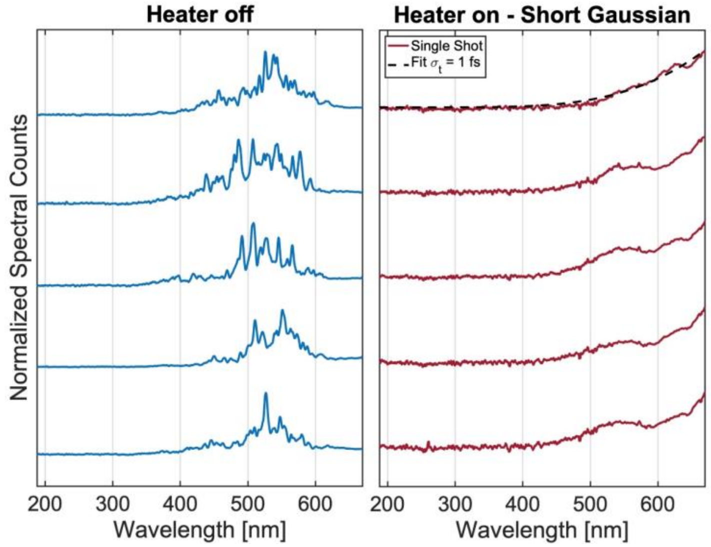
Betatron radiation diagnostics



P. San Miguel Claveria et al., AAC (2022)

- Compton Spectrometer upcoming, covering a range of 180 keV-28 MeV

UV and XUV spectrometers

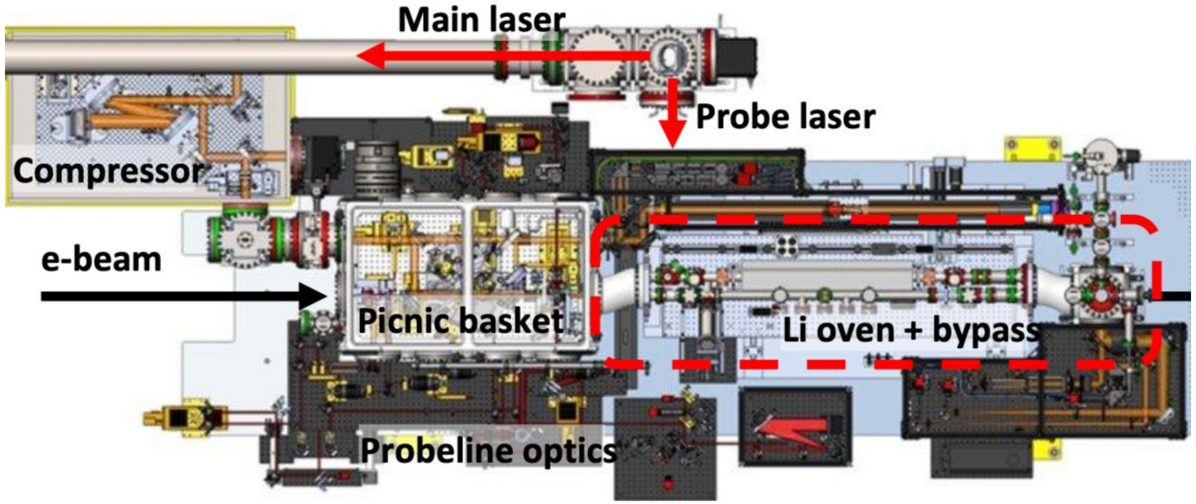


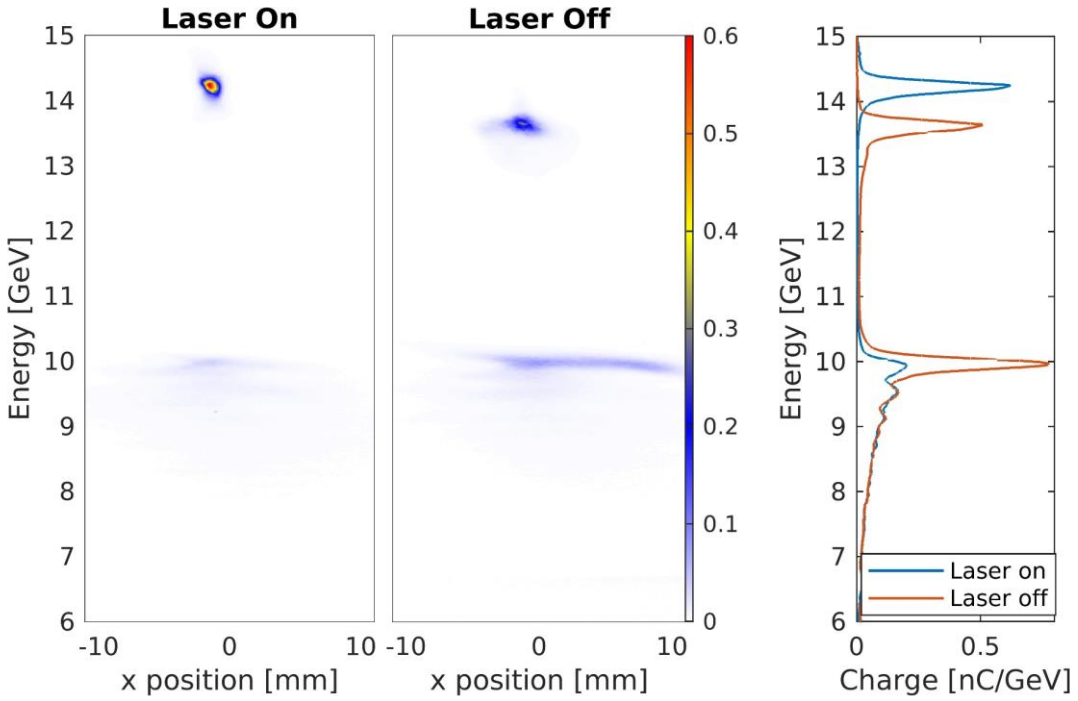
C. Emma et al., PRL **134**, 085001 (2025)

SLAC

Laser pre-ionization of Lithium plasma

- Pre-ionization increases PWFA performance over relying on beam ionization
  - ~1 mm wide plasma channel
  - Increased participating drive charge
  - Increased witness acceleration and total efficiency





	Laser Ionized	Beam Ionized
Energy gain, ΔE_w	(4.0 ± 0.2) GeV	(3.7 ± 0.2) GeV
Field uniformity, $\sigma_{E_w}/\Delta E$	(2.3 ± 0.2) %	(3.4 ± 0.6) %
Total efficiency, η_{tot}	**(5.5 ± 0.5) %**	**(4.6 ± 0.3) %**
Witness charge capture, $\mathrm{Q_w}$	(68 ± 6) %	(64 ± 4) %

Longitudinal Phase Space delivered to the plasma

- Control of the LPS is critical for:
  - Ensuring proper bunch spacing
  - Optimizing driver intensity for efficient energy transfer
  - Beam loading of the wake for minimizing witness energy spread

- Achieved through combination of RF phases, collimators, cathode laser pulse separation

- LPS measured via transverse deflecting cavity before the plasma

Range of Longitudinal Phase Space Profiles