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High-energy, High-quality Plasma Wakefield Acceleration in a Laser-ionized All-optical Plasma Source

AAC 2026

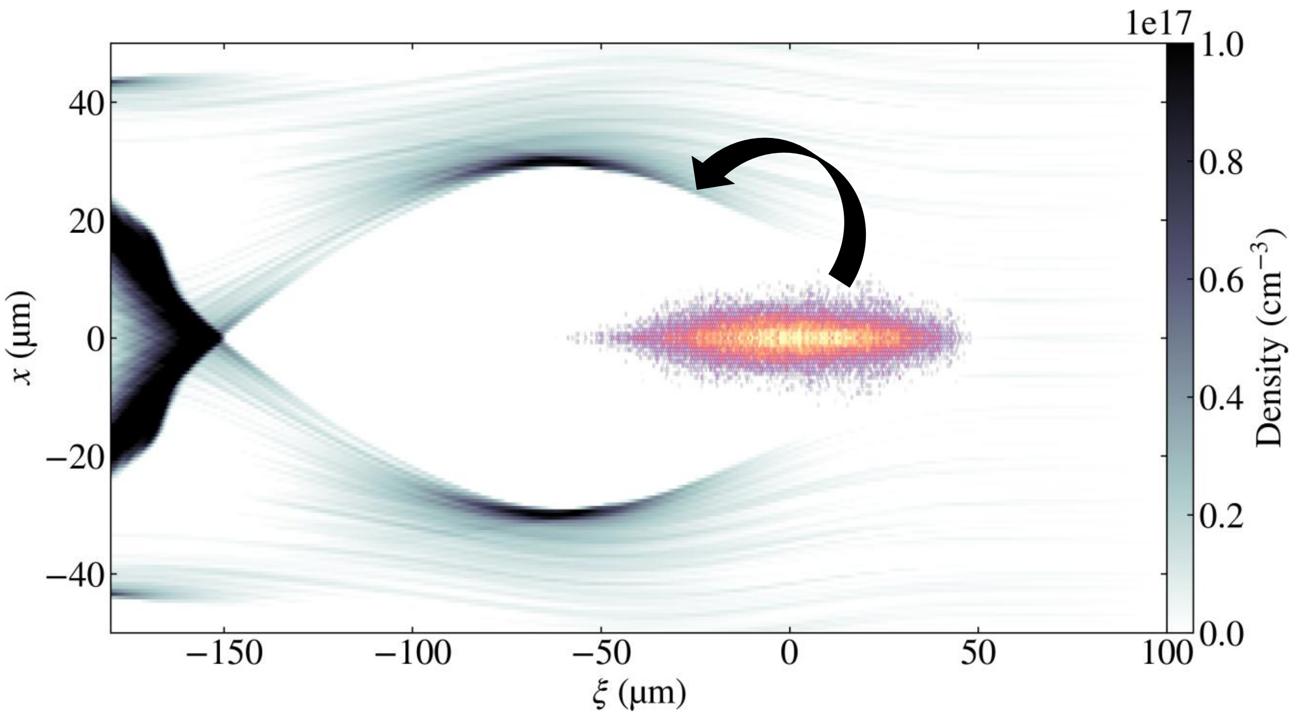
July 27, 2026

Valentina Lee

FACET-II E301 Collaboration

SLAC FACET-II

Plasma Wakefield Accelerators and Colliders Parameters



- Plasma wakefield accelerator
  - Drive beam -> wake
  - Wake -> witness
- Collider application:
  - 10-100 J of energy transferring
    - Challenge: overheating the plasma
  - Requires the ability to shape the plasma source
    - Longitudinal: emittance preservation
    - Transverse: positron PWFA in narrow plasma source

Promising solution for collider application at high rep rate and plasma density shaping:
Laser-ionized all-optical plasma source

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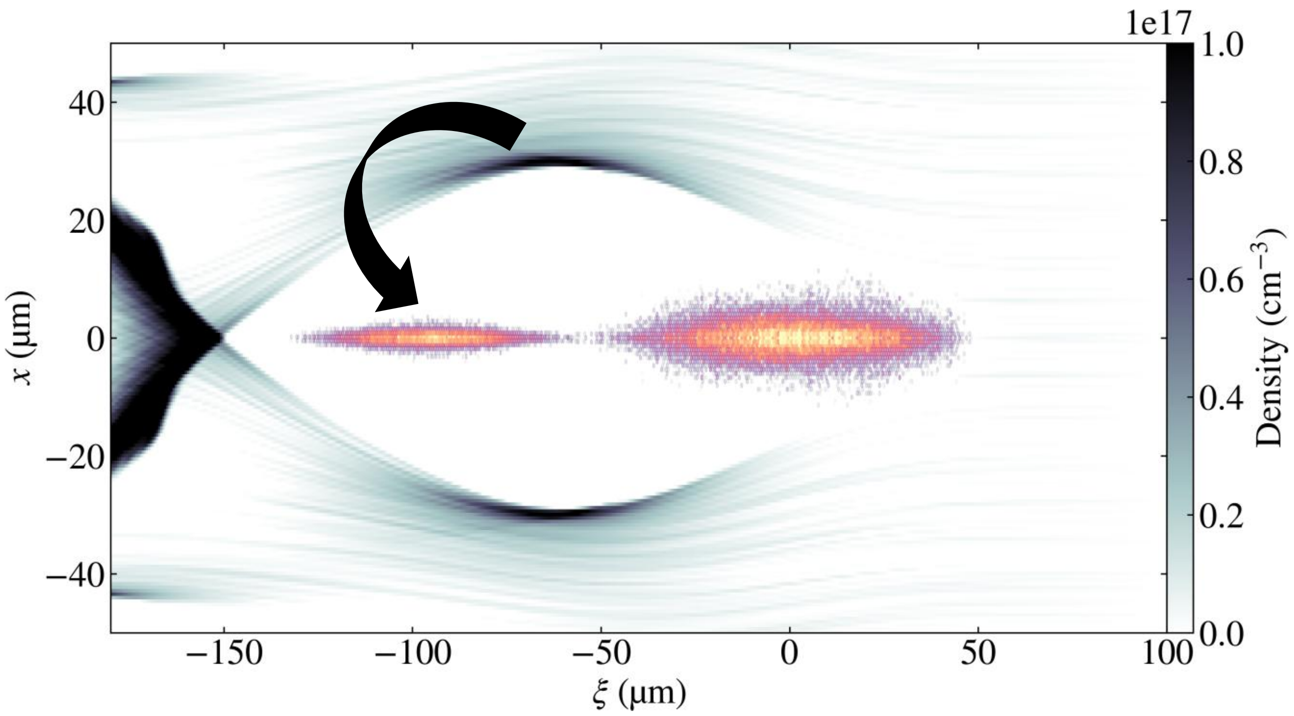

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Promising solution for collider application at high rep rate and plasma density shaping:
Laser-ionized all-optical plasma source

FACET-II at SLAC National Accelerator Laboratory

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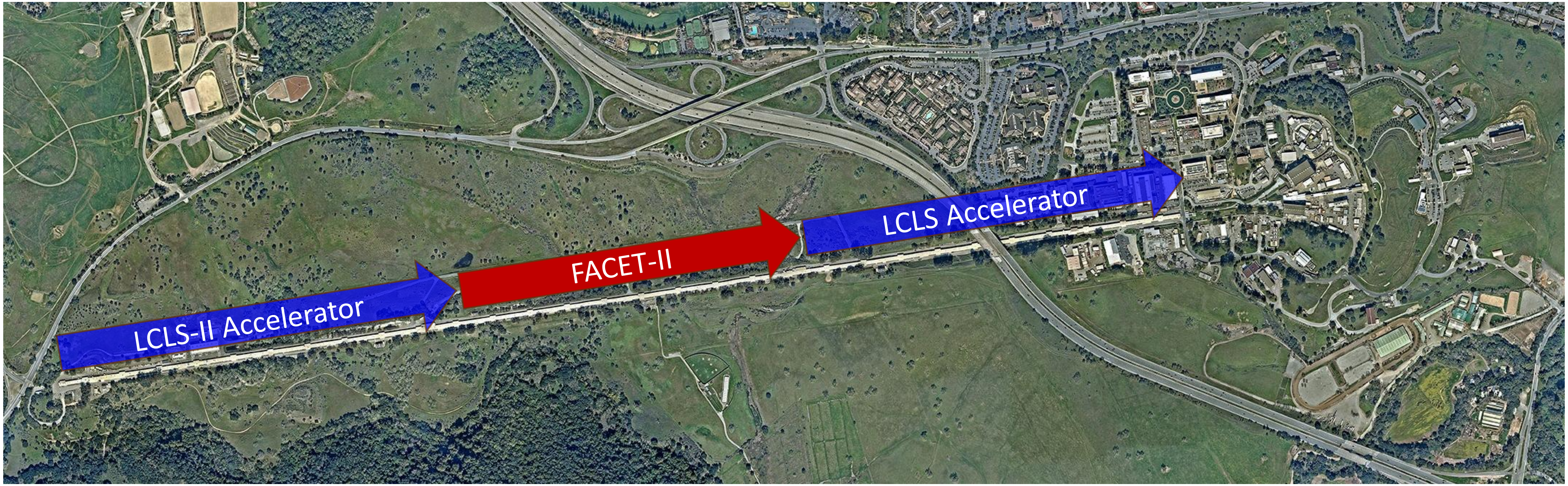
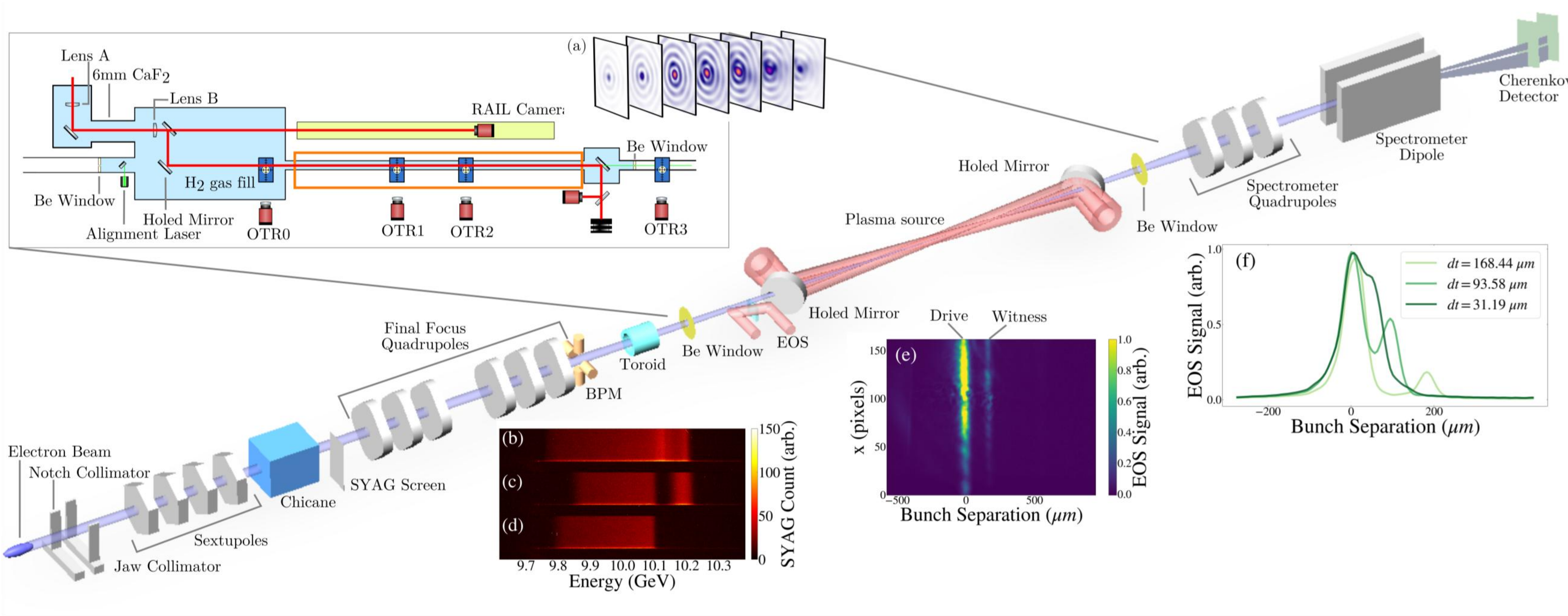
- FACET-II: Demonstrate single stage plasma wakefield acceleration at collider-relevant energy scale
  - Multi-GeV energy gain
  - ~10% energy transfer efficiency
  - Beam quality preservation
- Bonus for collider application: capability for high rep rate and plasma density shaping
  -> laser-ionized all optical plasma source



Experimental Setup



Laser-ionized All-optical Plasma Source – Optics

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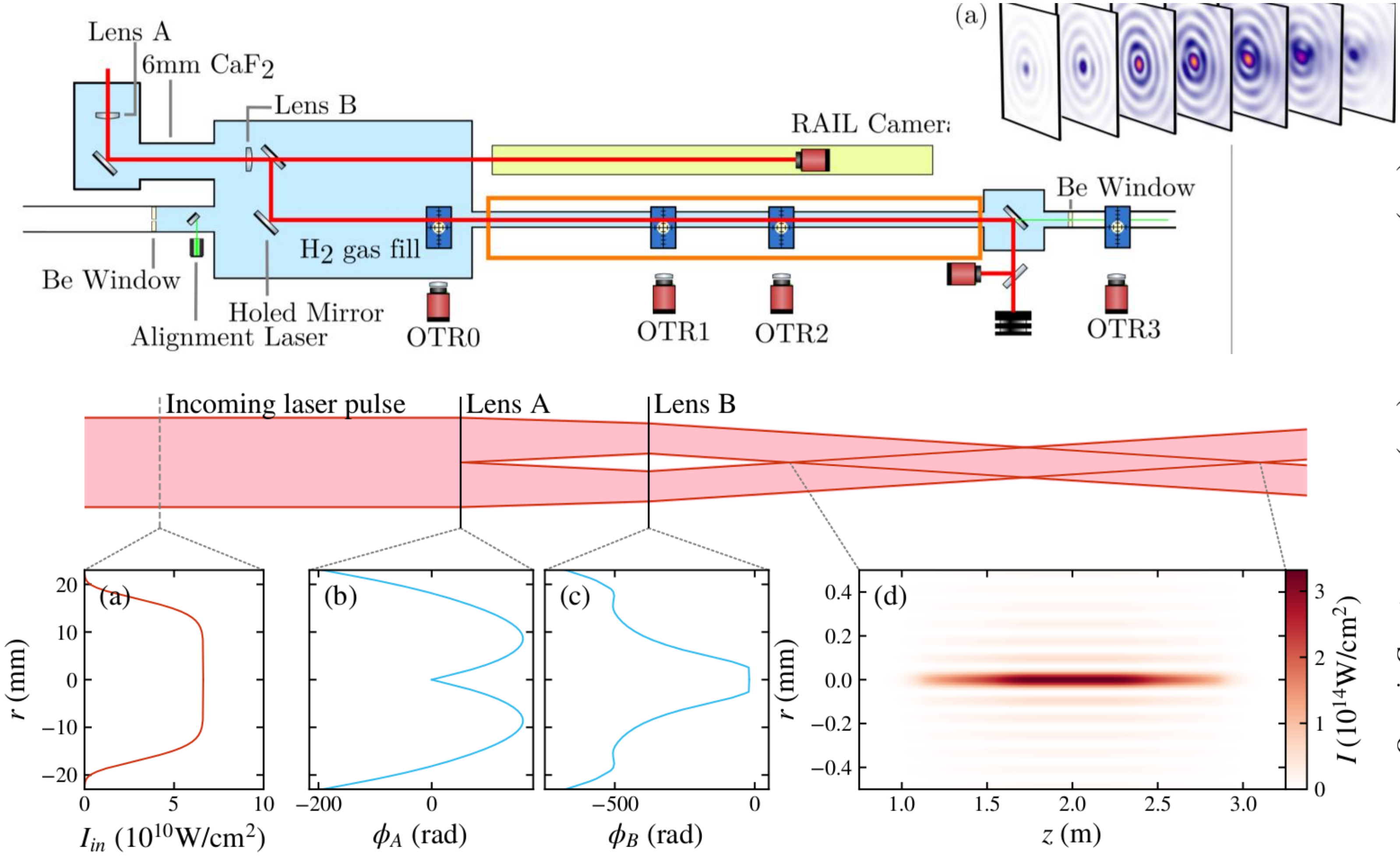

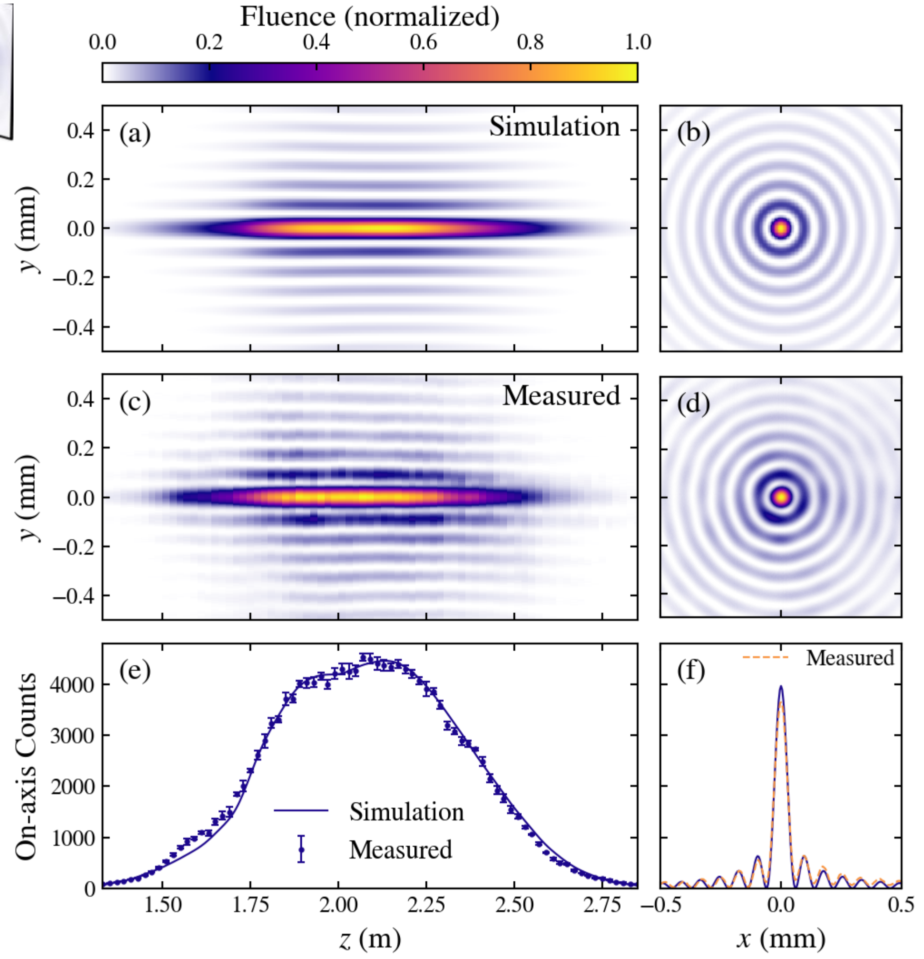

The tandem lens creates plasma in static filled H2 with on-axis density at 4.5×10^{16} cm^{-3} over 80 cm.
We measured and verified the optical performance.

Ariniello, R., V. Lee, and M. D. Litos, "Demonstration of a tandem lens for producing shaped laser-ionized plasmas for plasma wakefield acceleration" *Optics Express* 33.25 (2025): 52019-52034.

Laser-ionized All-optical Plasma Source – Plasma

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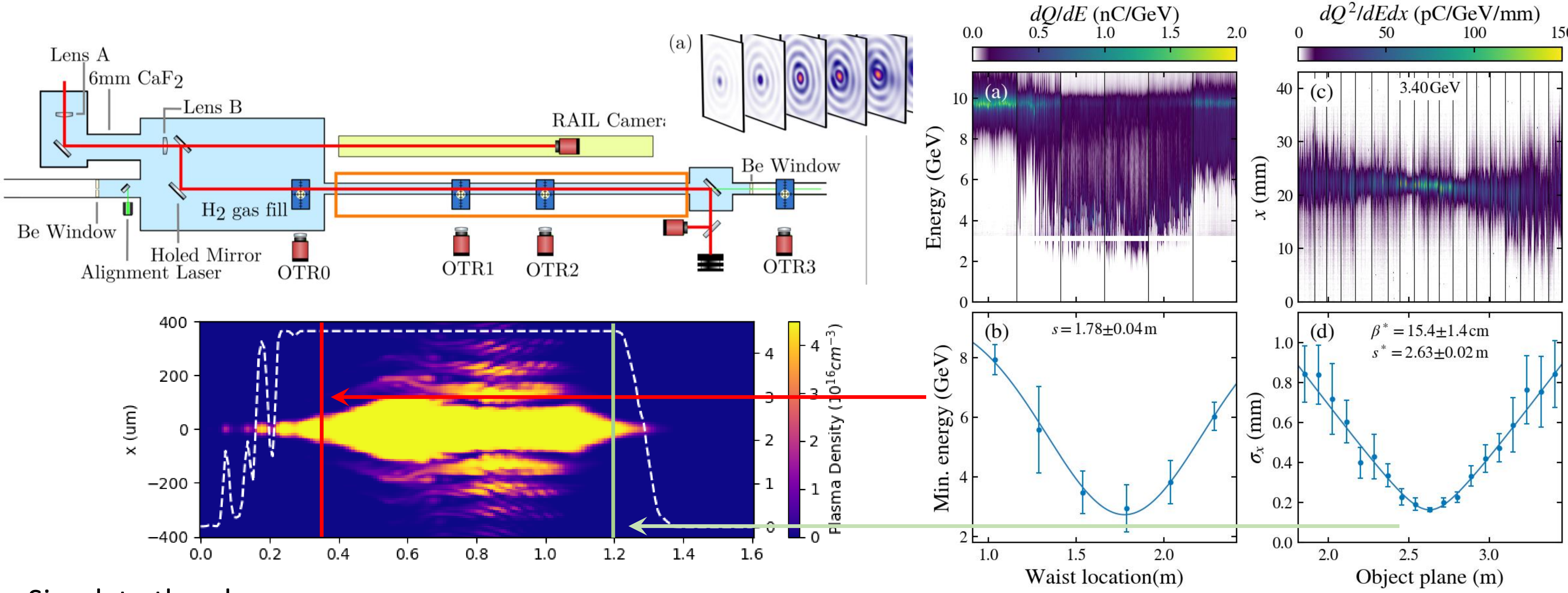
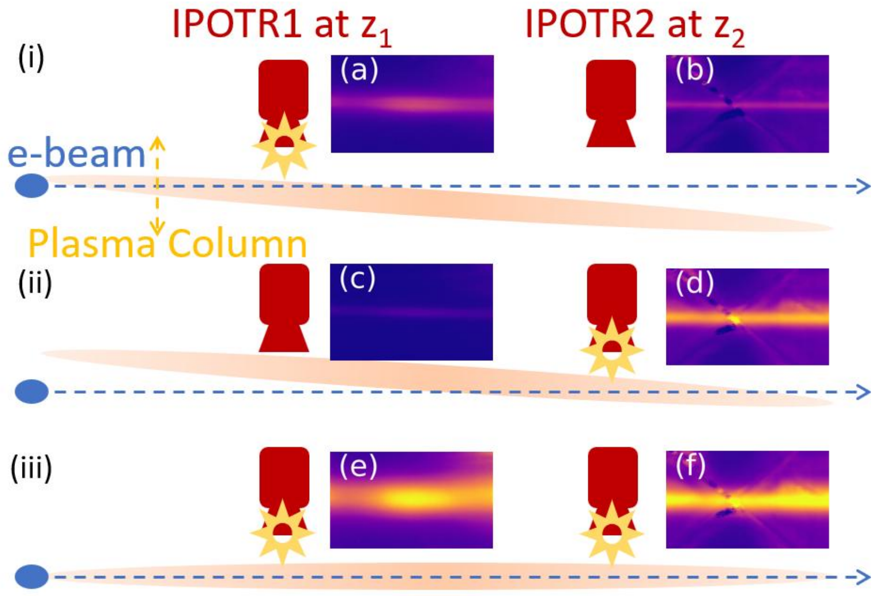


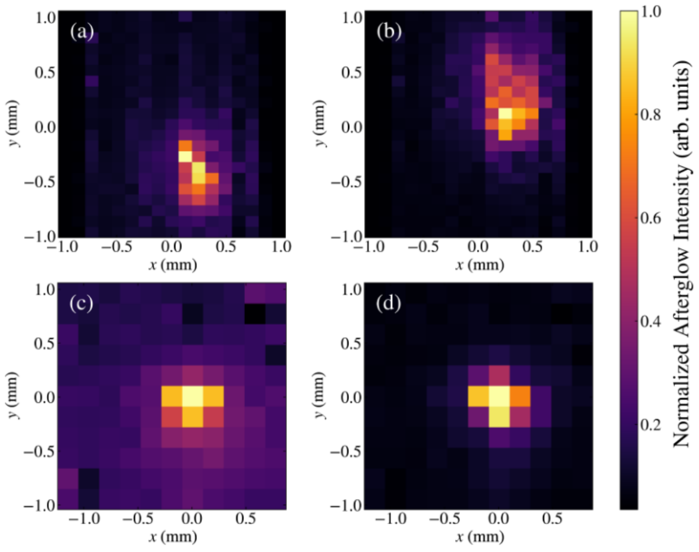
- Simulate the plasma source:
  - Verify on-axis laser intensity against data (Includes diffraction, GVD, Kerr effect, self phase modulation, and broadband chromatic effect)
  - Simulate ionization with the ADK model

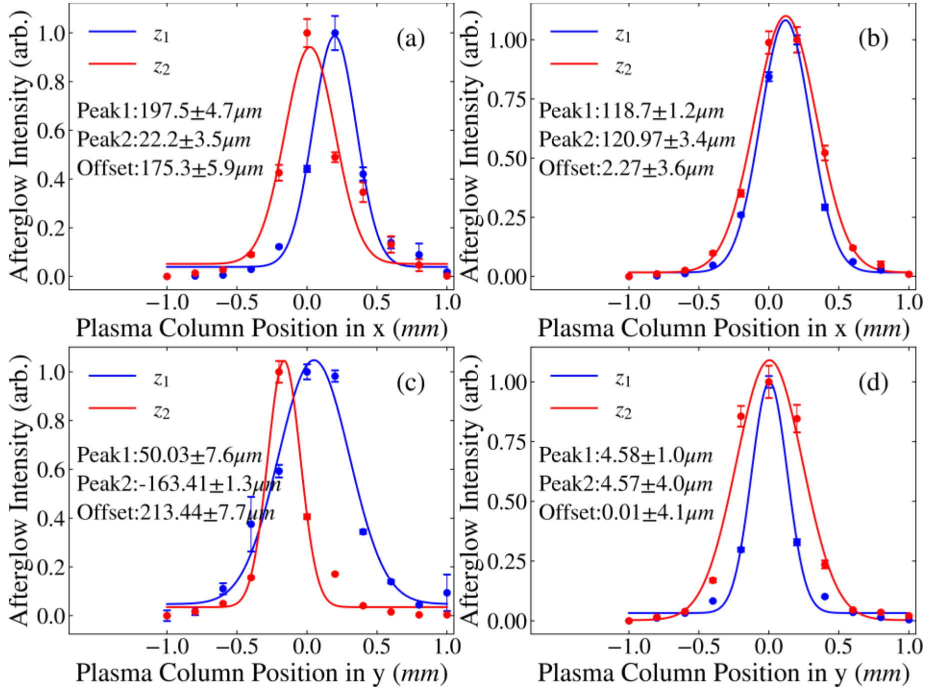
A beam-based measurement confirms plasma length.

Ariniello, R., V. Lee, et. al., "Drive beam depletion with multi-Joule energy transfer in a plasma wakefield accelerator" submitting to PRAB, arXiv:2511.15143 (2025).

Challenge 1: Plasma & e-beam Alignment





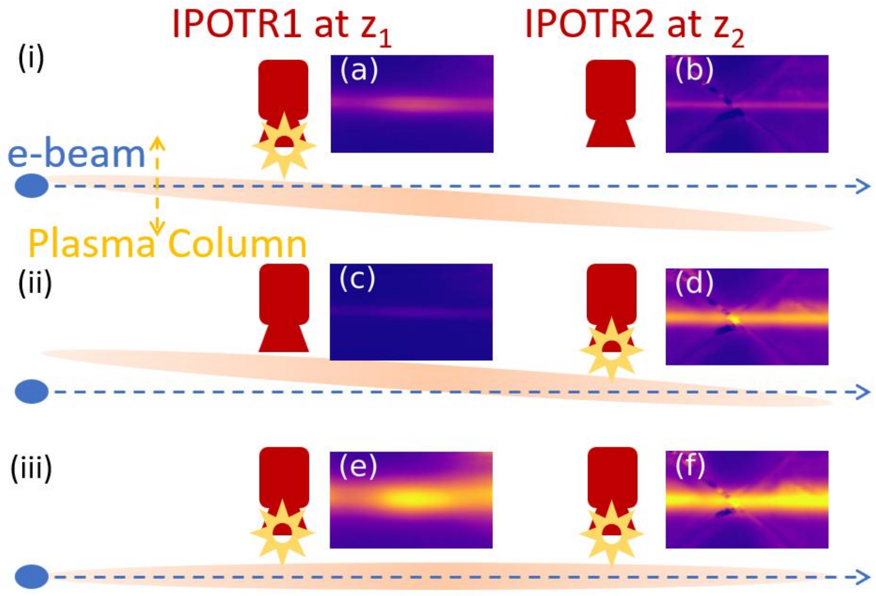


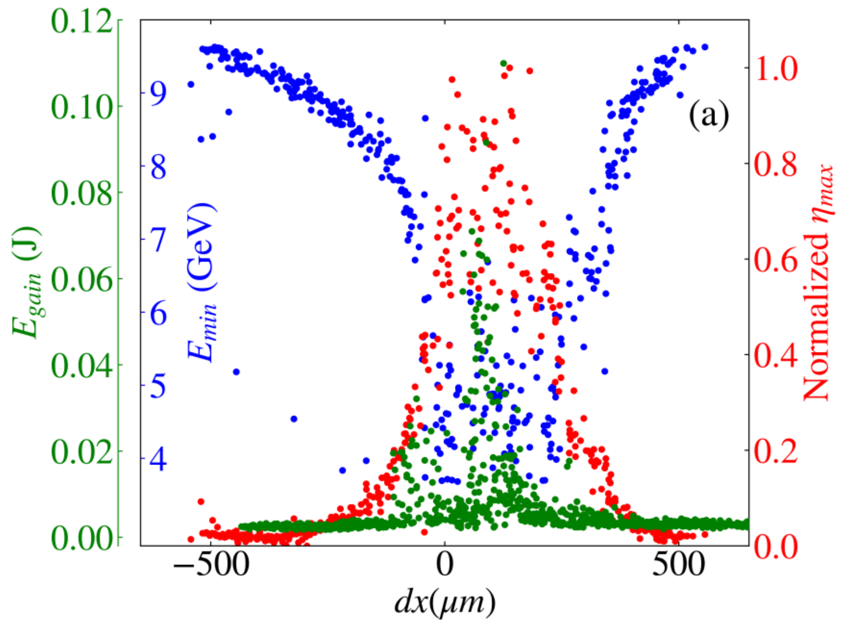
- Conventional OTR-based alignment is limited by COTR at high current with only ~200 µm, 200 µrad precision
- The technique relies on analyzing plasma afterglow light at two longitudinal position.
- The automation of the technique reduces the alignment time from 12h to ~1h

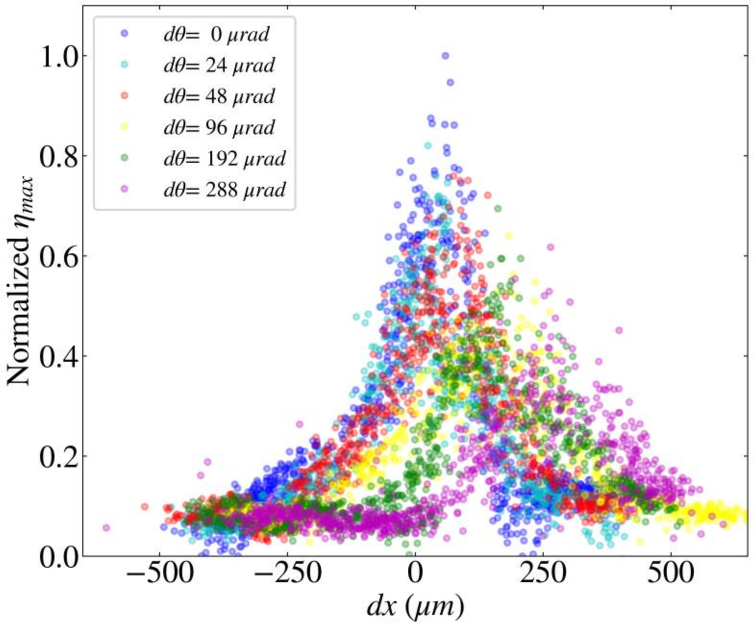
Using this method, we aligned an 80-cm plasma source to a 10 GeV electron beam with better than **10 µm** transverse offset and **10 µrad** angular error.

Lee, Valentina, et al. "Precision alignment and tolerance of a plasma wakefield accelerator in a laser-ionized plasma source." *Physical Review Accelerators and Beams* 29.4 (2026): 041001.

Challenge 1: Plasma & e-beam Alignment







We determined the alignment tolerances requirement, which is useful for staging design study.

Lee, Valentina, et al. "Precision alignment and tolerance of a plasma wakefield accelerator in a laser-ionized plasma source." *Physical Review Accelerators and Beams* 29.4 (2026): 041001.

Challenge 2: Drive-witness Beam Alignment

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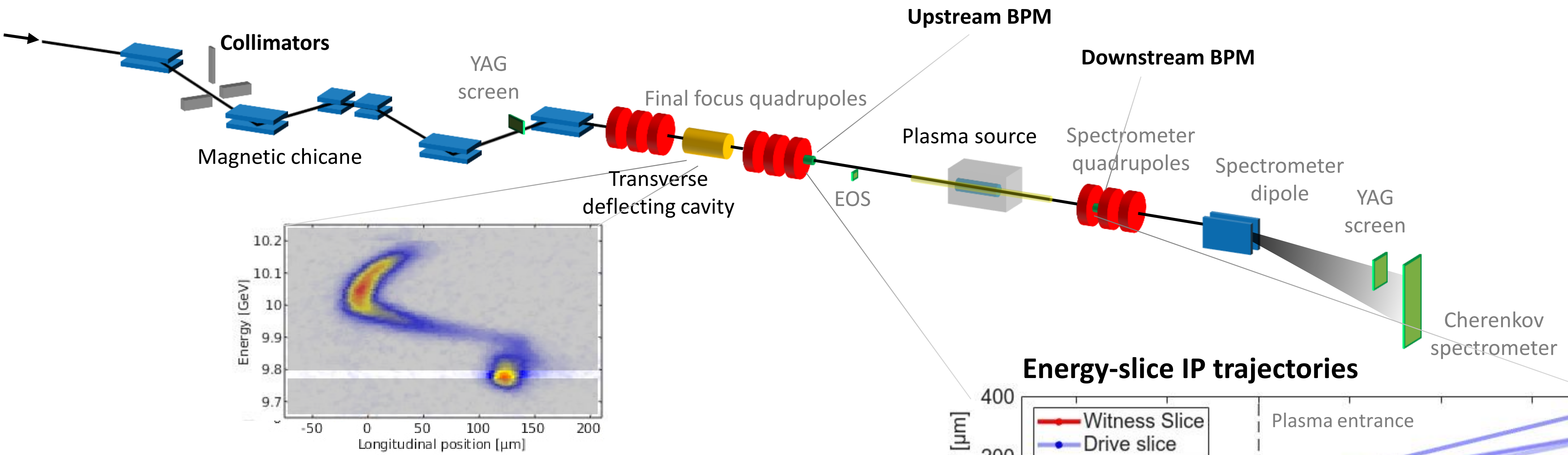
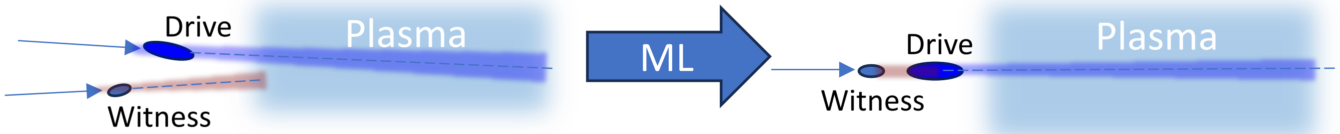
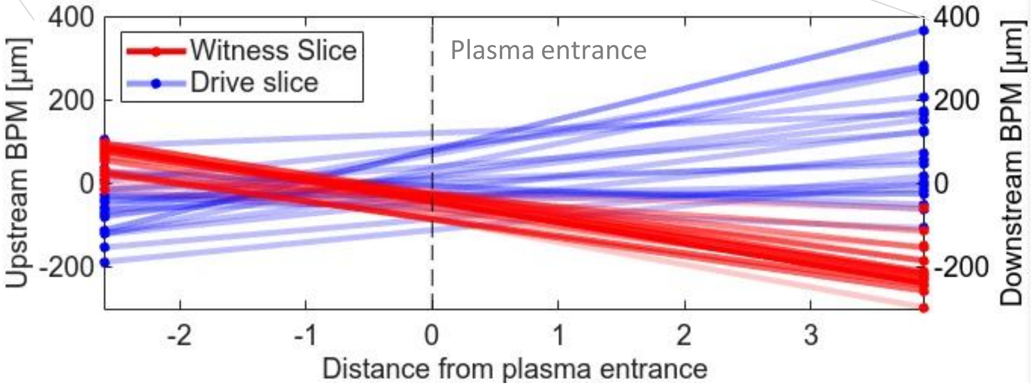




Energy-slice IP trajectories



Slice BPM measures beam dispersion and ML tool optimizes PWFA interaction while reducing dispersion, enabling faster, repeatable PWFA operation.

Y. Ye, WG3 M 14:50

S. Rego, Ecole Polytechnique

Drive Beam Depletion with Multi-J Energy Transfer

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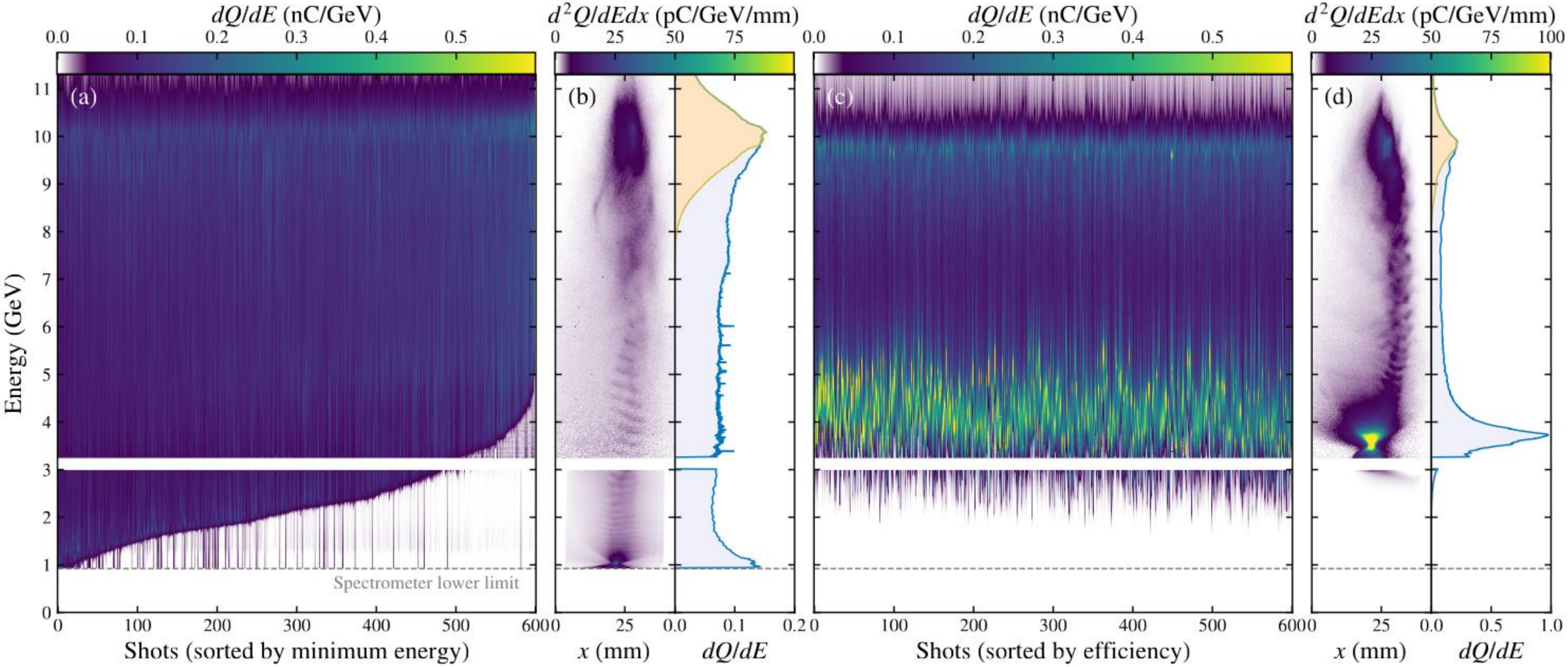


- Energy depletion of the electron beam showing significant charge below the spectrometer's lower limit of 0.93 GeV with up to 90% of the charge participating in the interaction.
- Transferred **at least 5.6 J** from a 1.52 nC, 10 GeV electron beam to a 4.5×10^{16} cm^{-3} hydrogen plasma while achieving at least **37 ± 3% drive-to-wake energy transfer efficiency**.

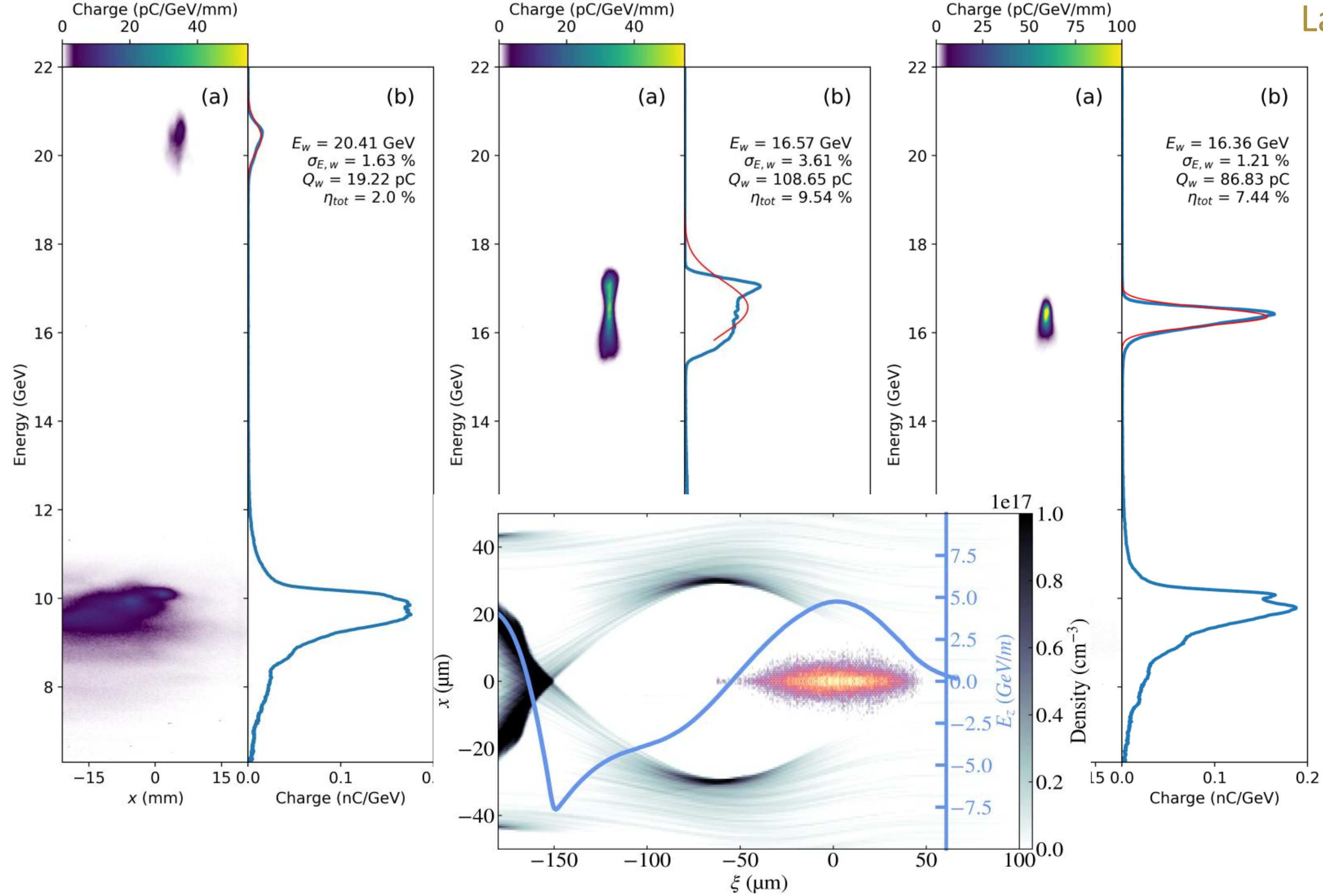
Ariniello, R., V. Lee, et. al., "Drive beam depletion with multi-Joule energy transfer in a plasma wakefield accelerator" submitting to PRAB, arXiv:2511.15143 (2025).

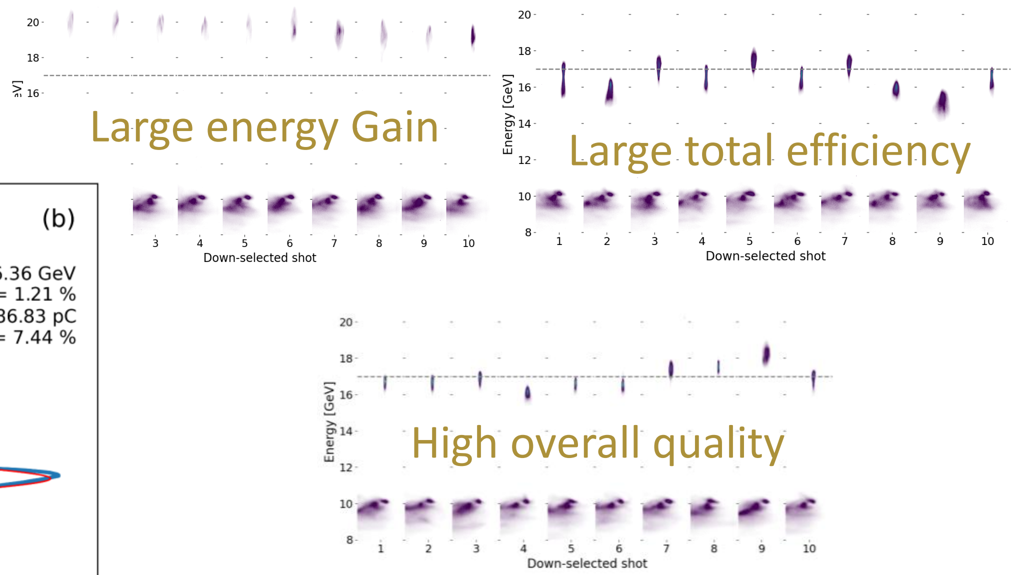
High-performance PWFA in Laser-ionized All-optical Plasma

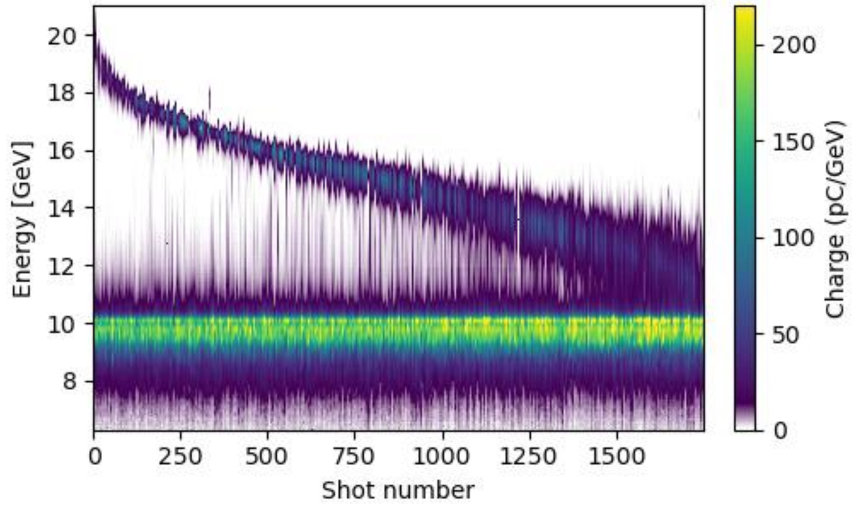
Large energy Gain

Large total efficiency

High overall quality







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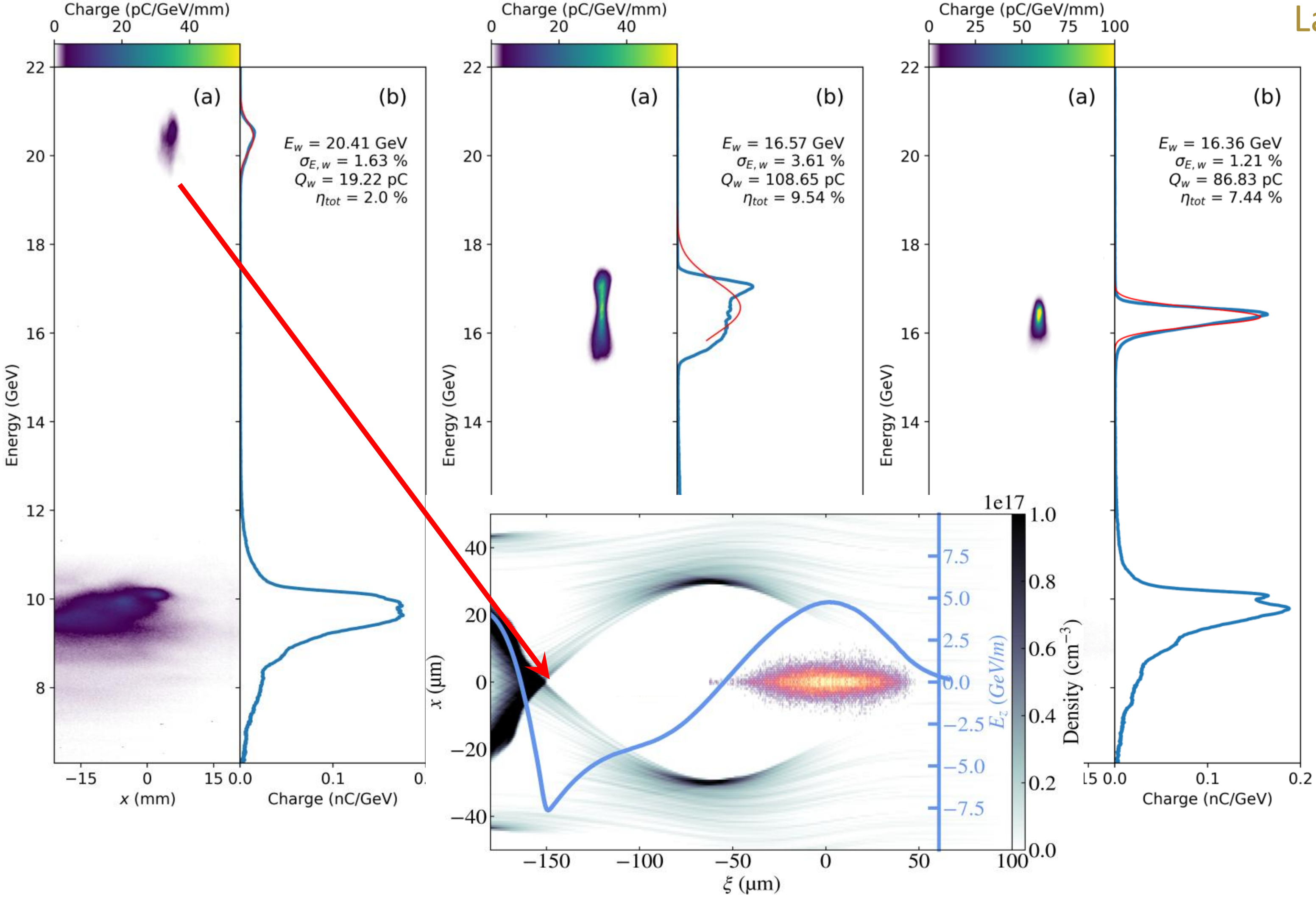

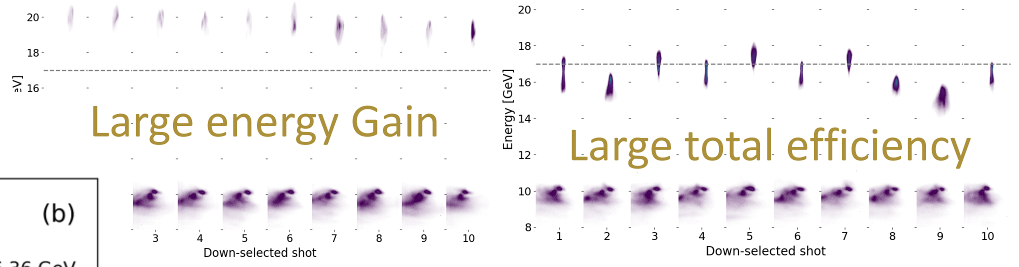

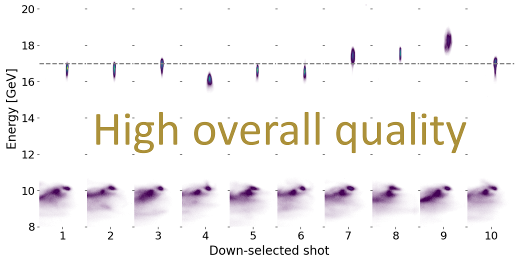

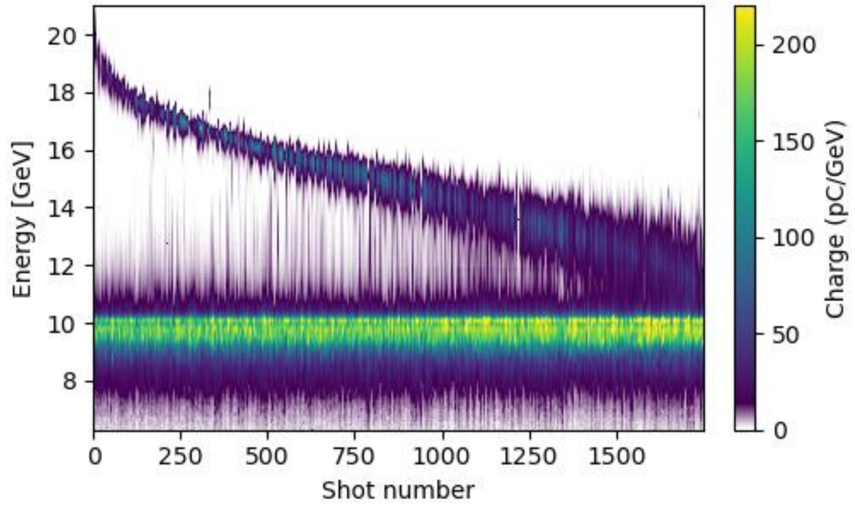

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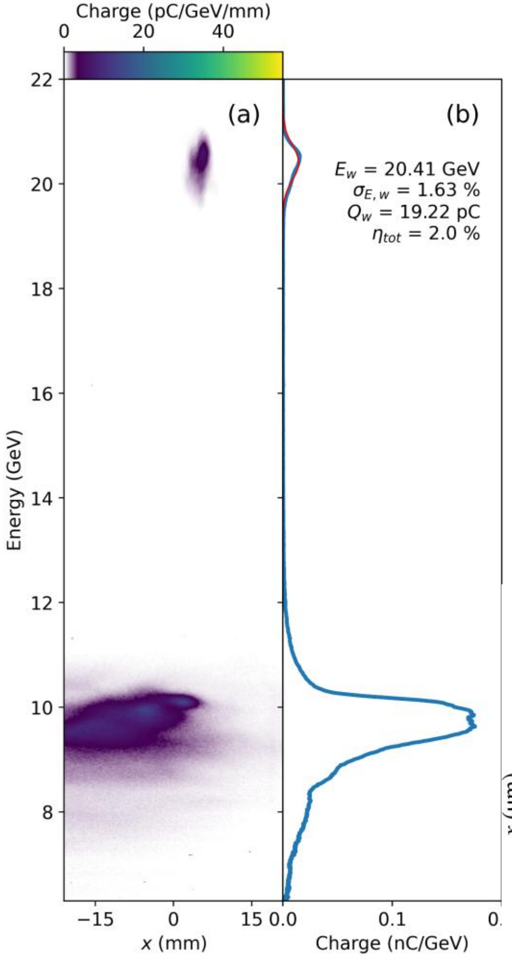
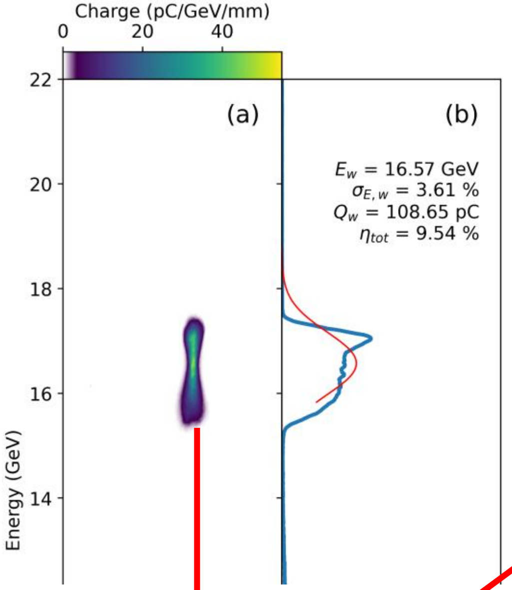
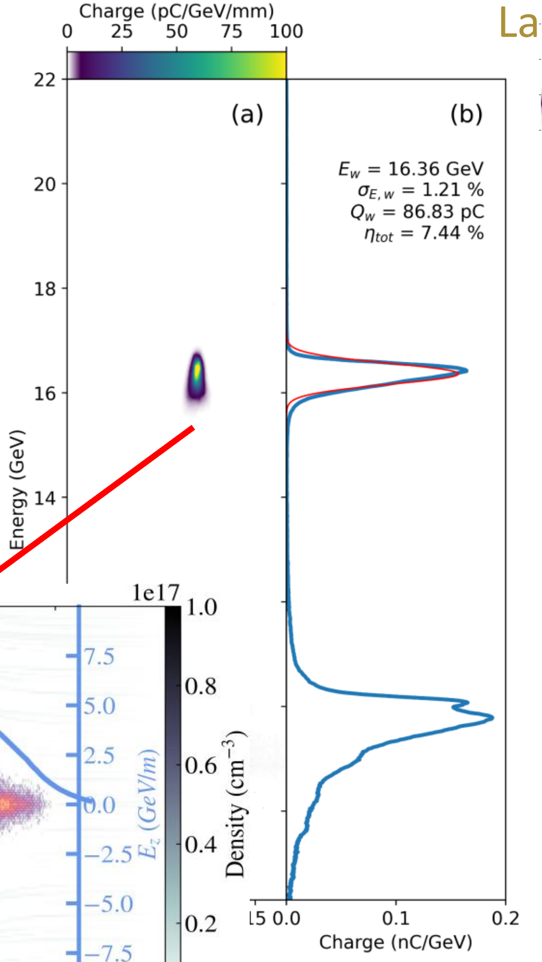
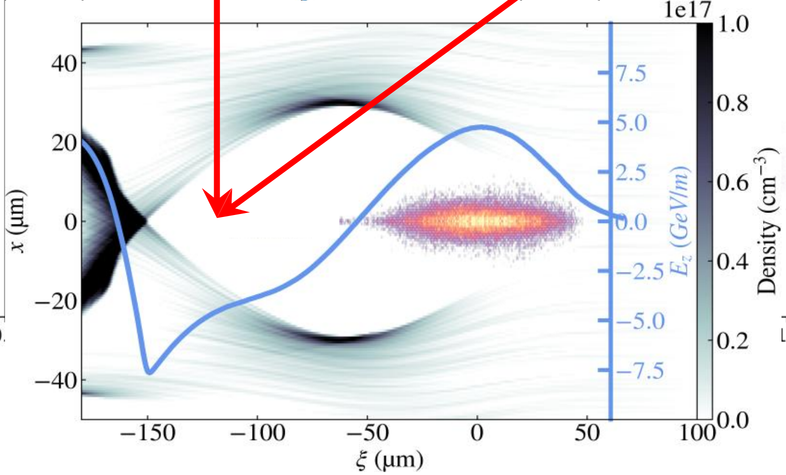


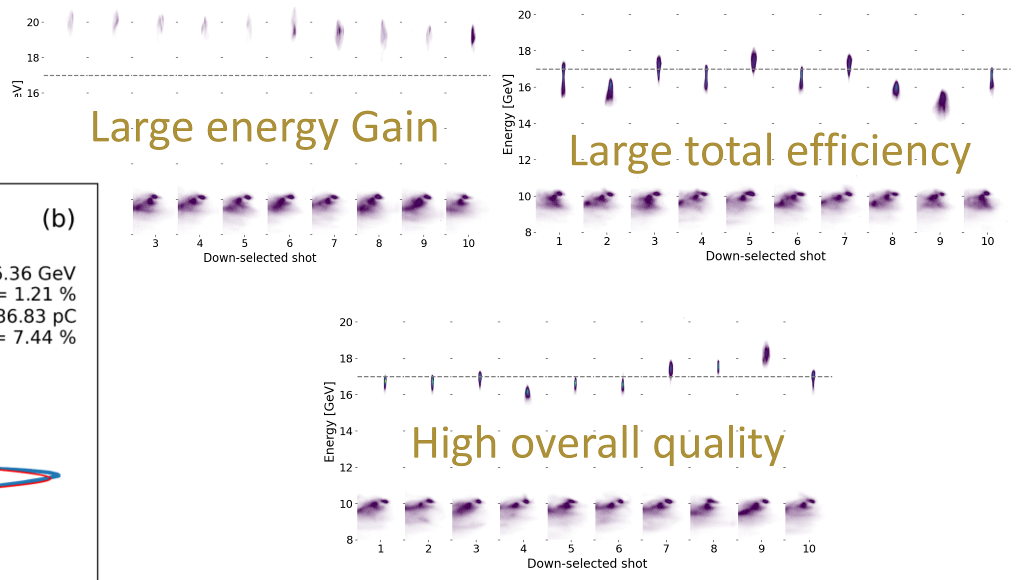
Large total efficiency

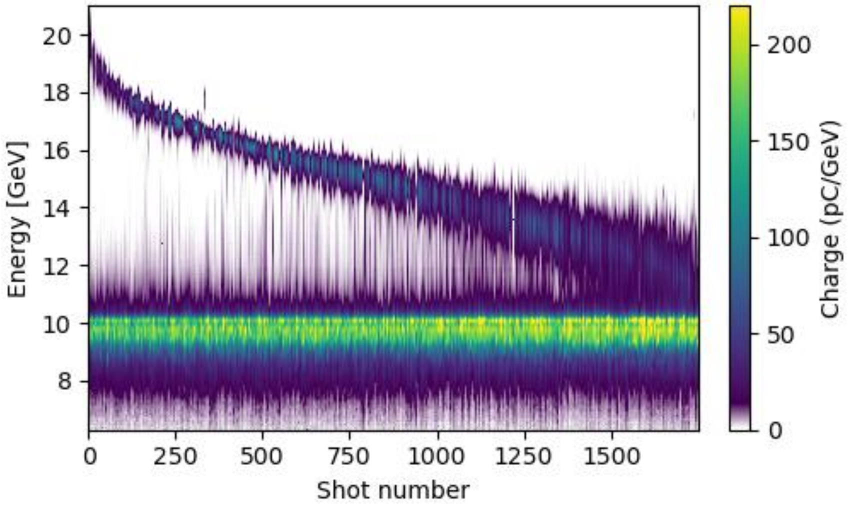


High overall quality









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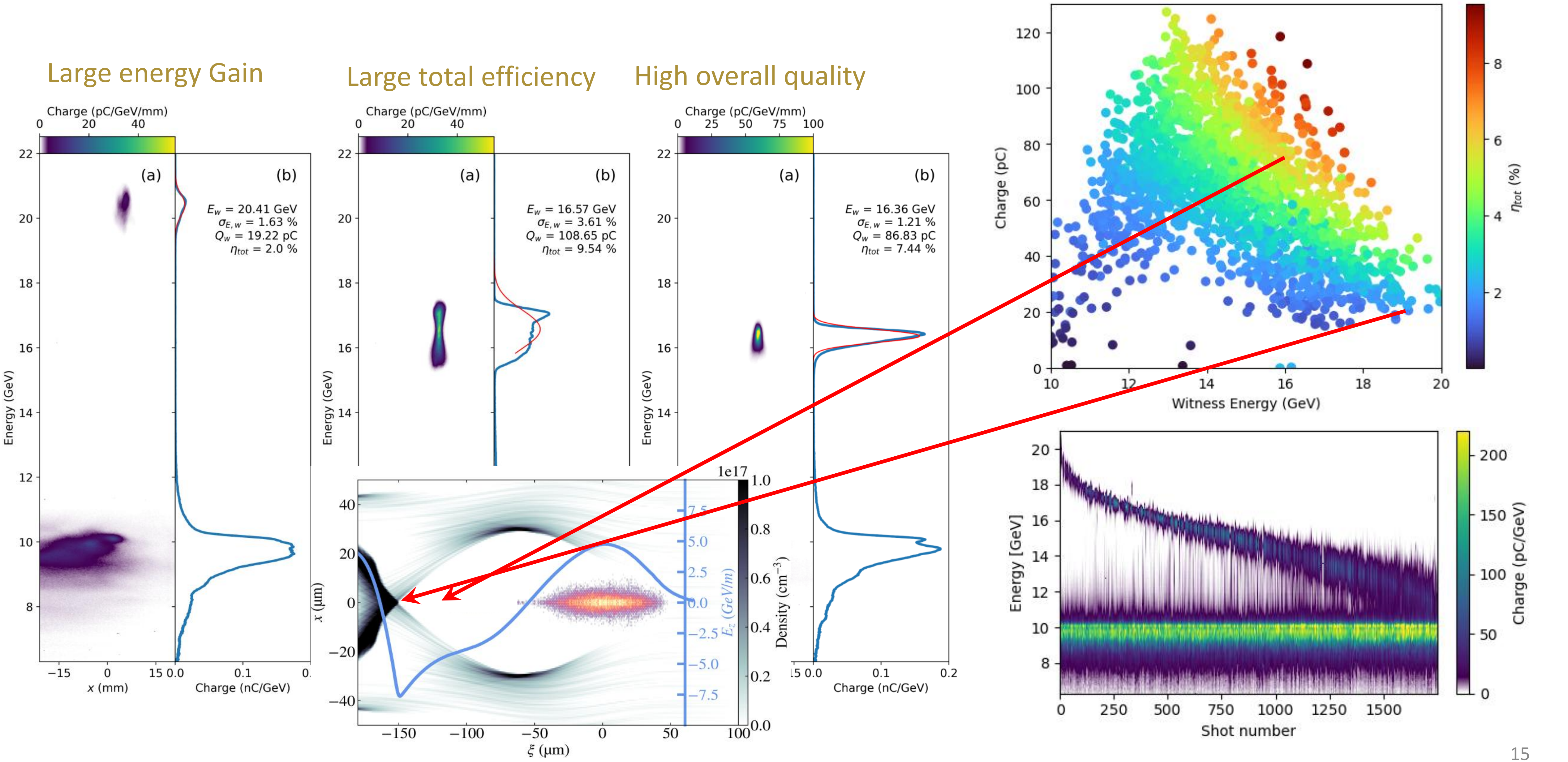

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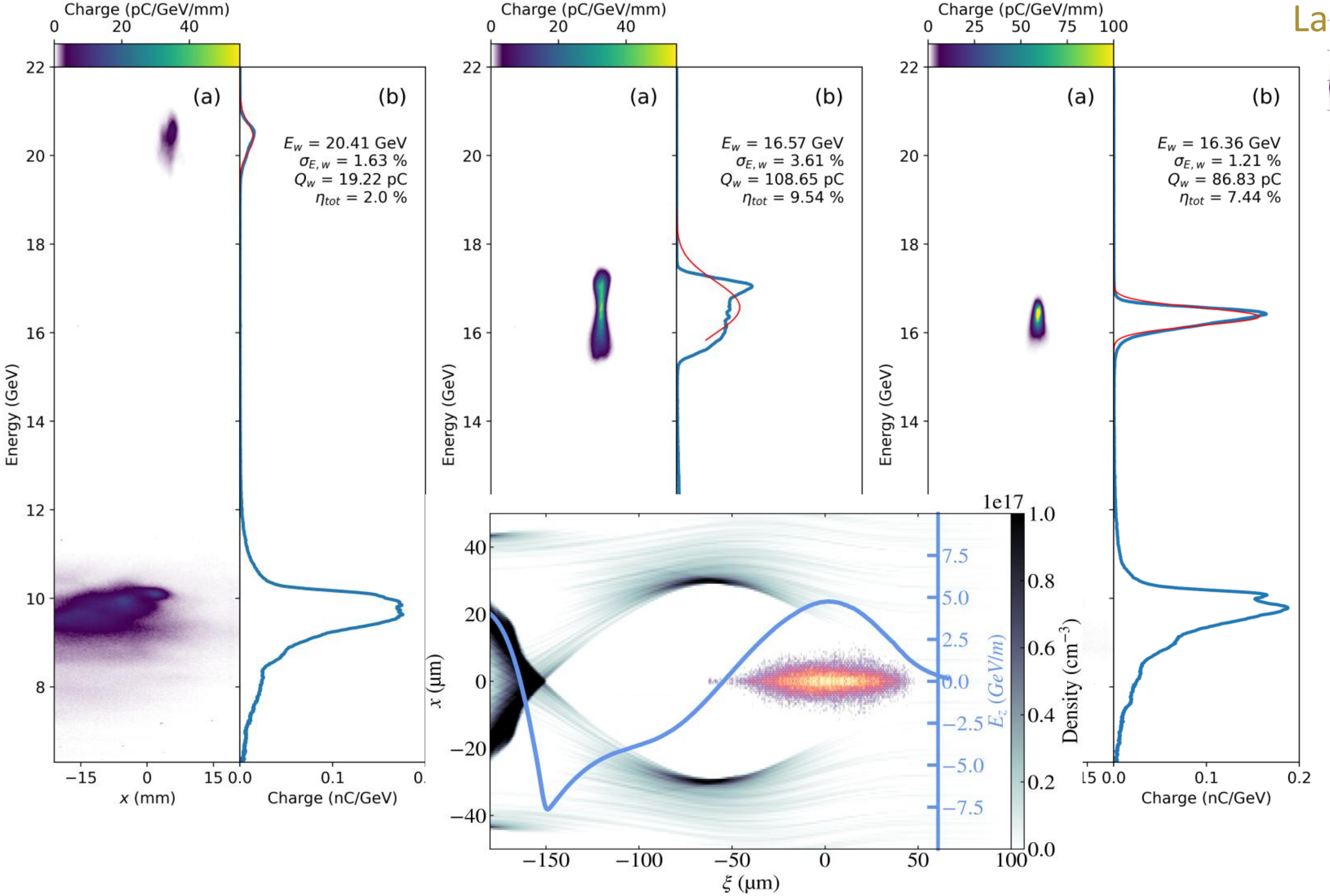

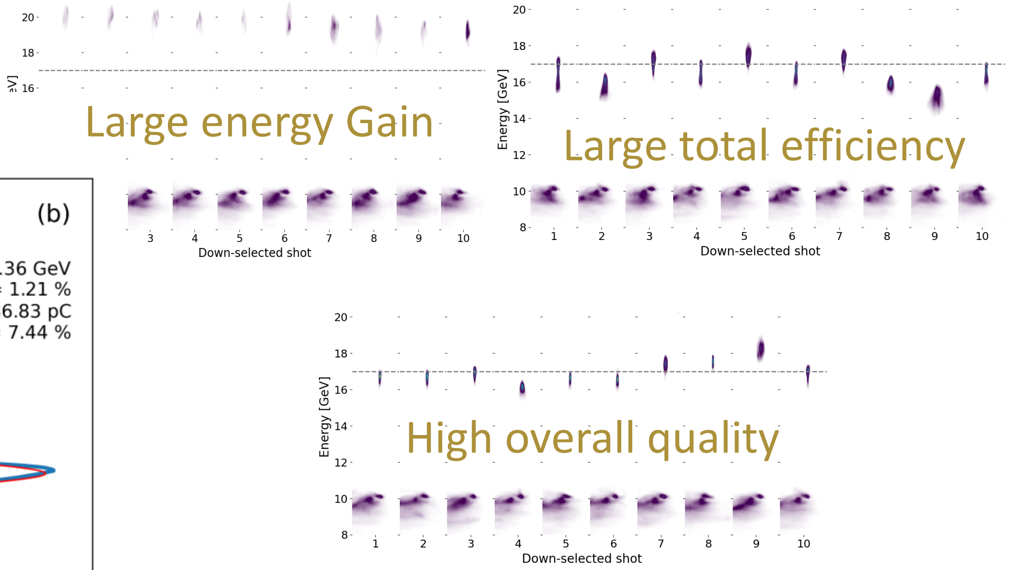

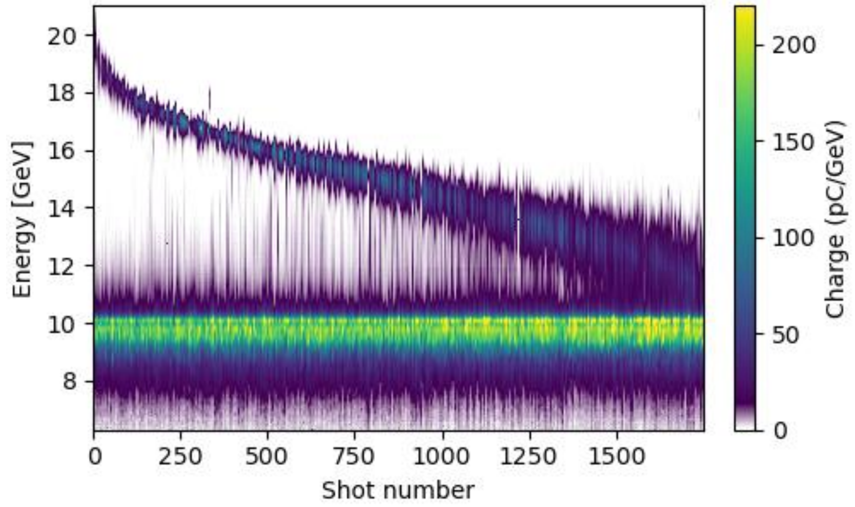

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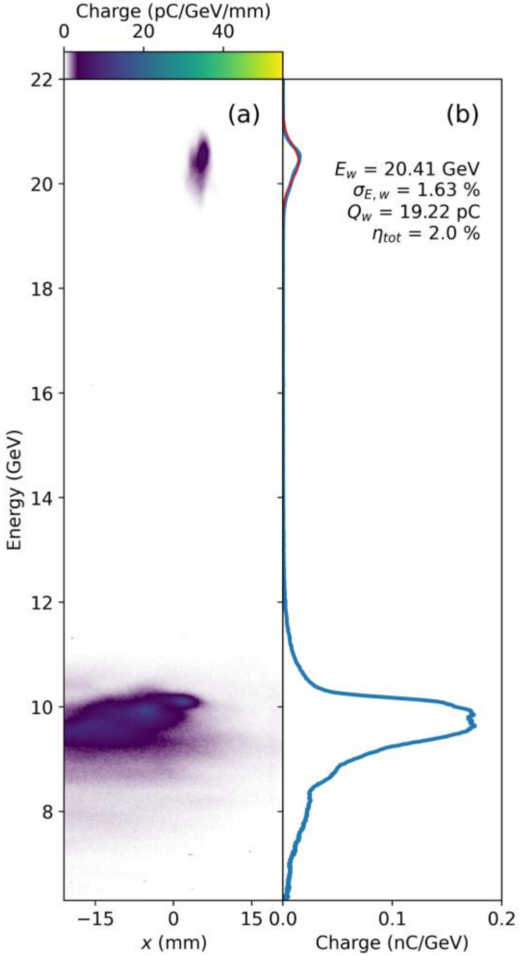
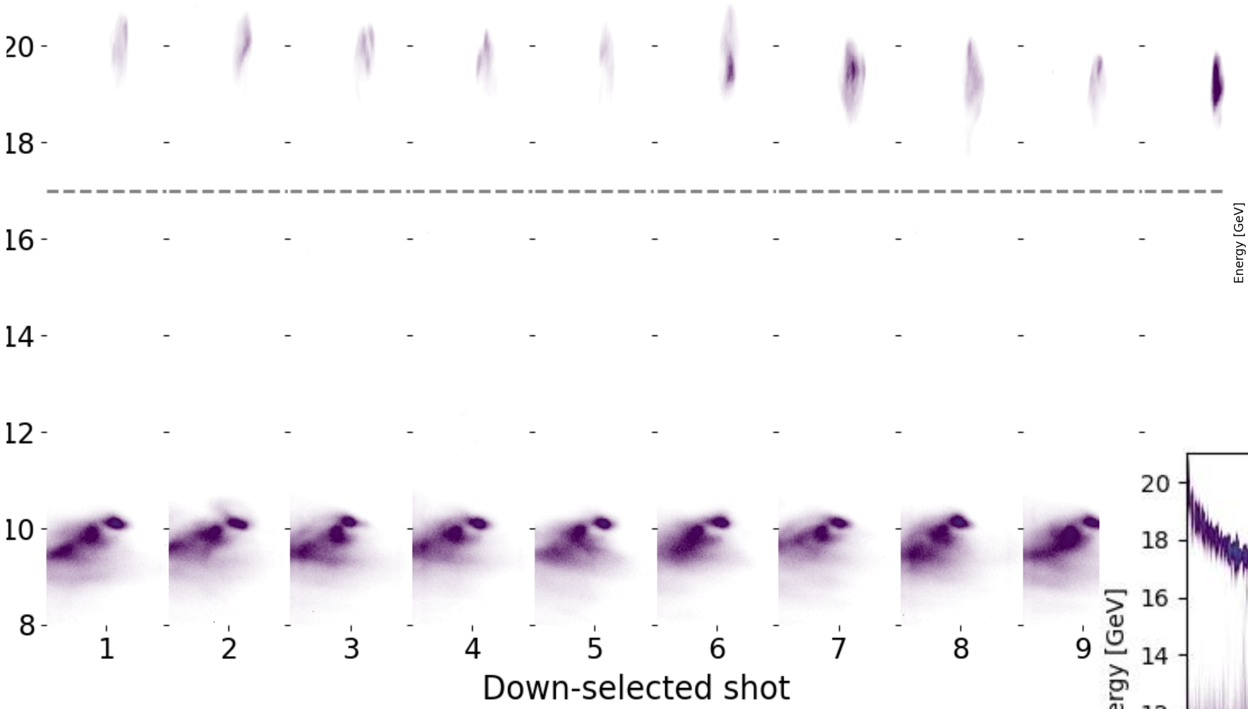
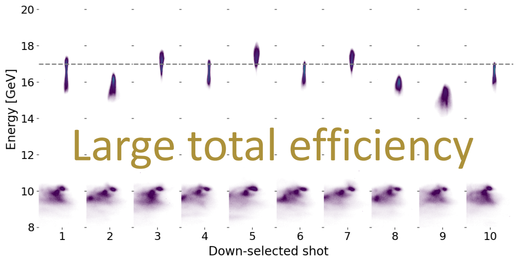


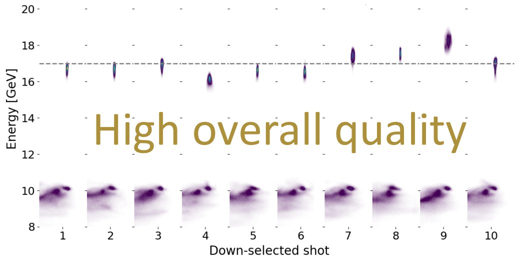


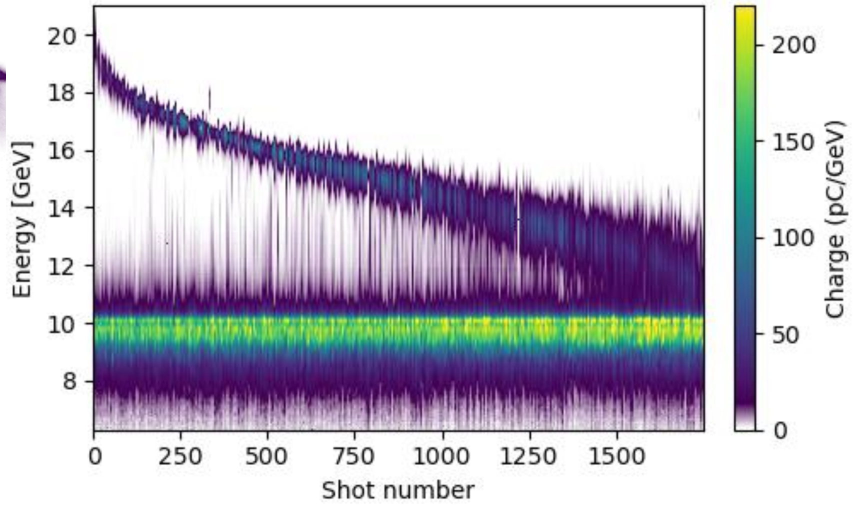
$$E_w = 20.41\ \text{GeV}$$
$$\sigma_{E,w} = 1.63\ \%$$
$$Q_w = 19.22\ \text{pC}$$
$$\eta_{tot} = 2.0\ \%$$

Large total efficiency



High overall quality





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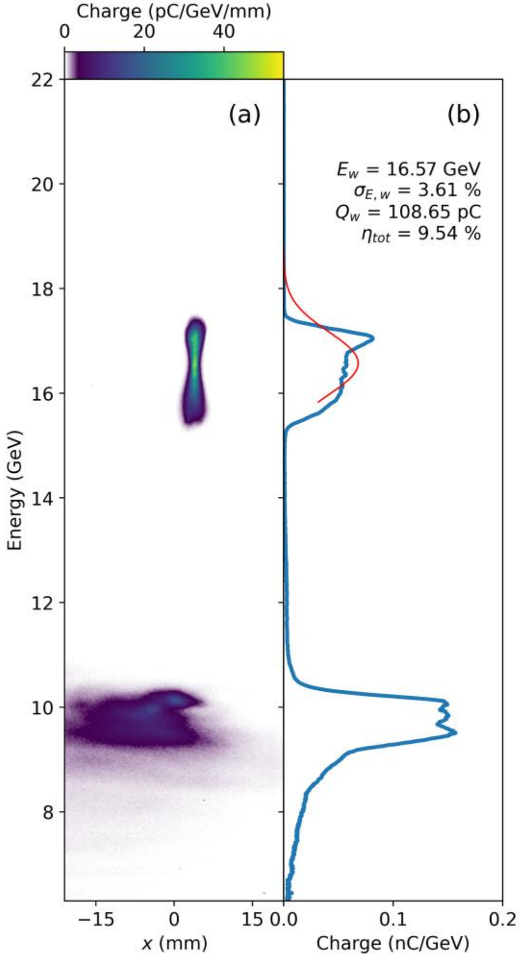
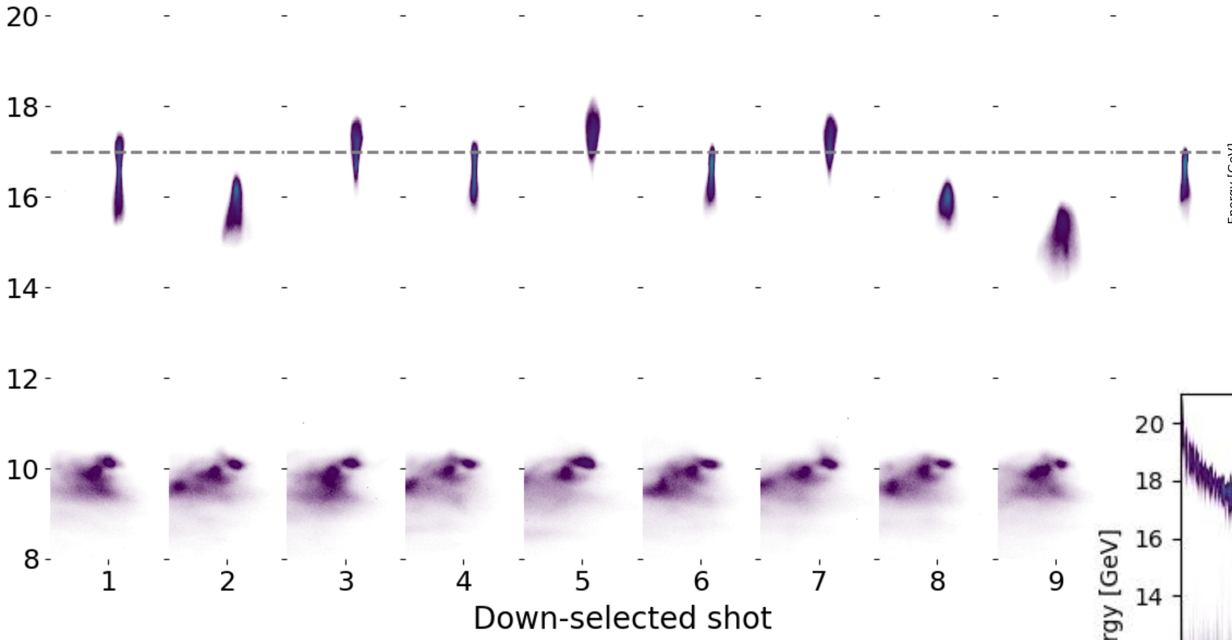
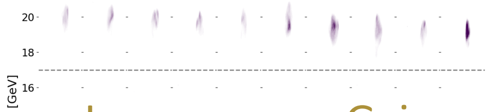
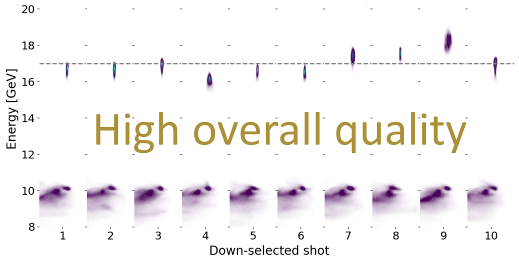




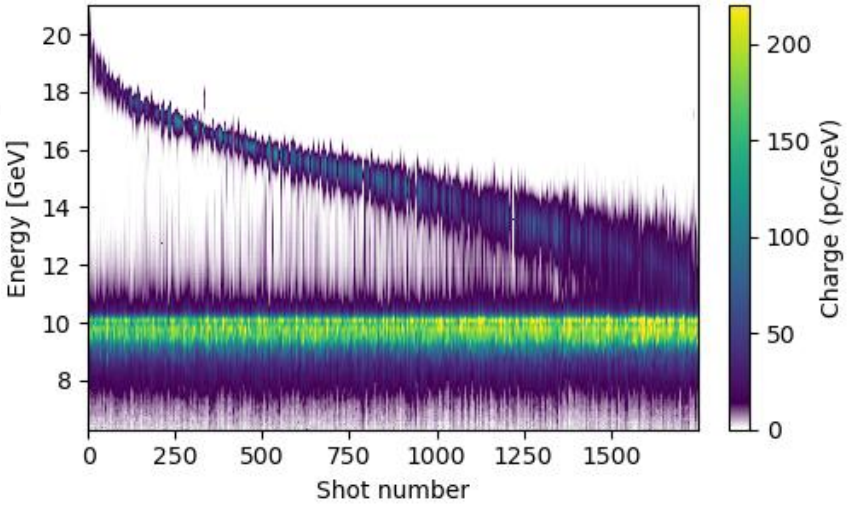
$$E_w = 16.57\text{ GeV}$$
$$\sigma_{E,w} = 3.61\ \%$$
$$Q_w = 108.65\text{ pC}$$
$$\eta_{tot} = 9.54\ \%$$



Large energy Gain



High overall quality



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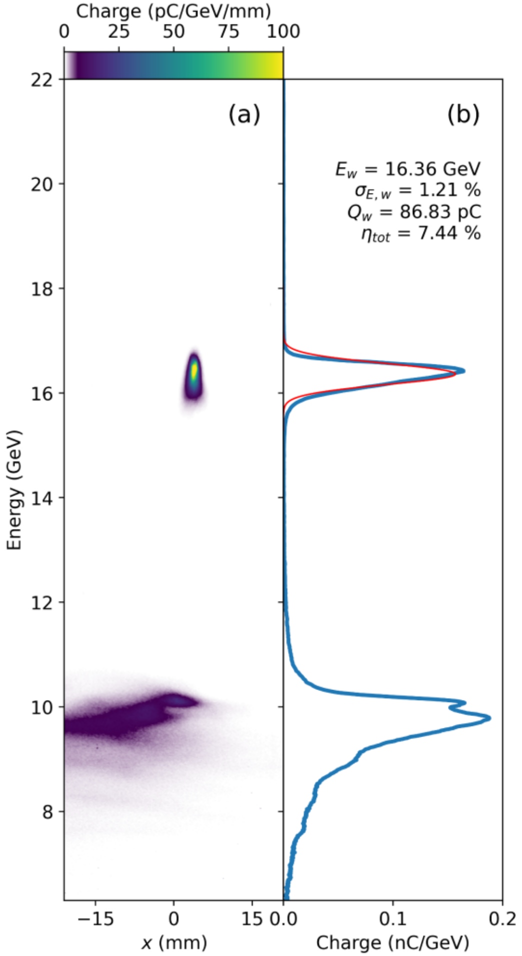
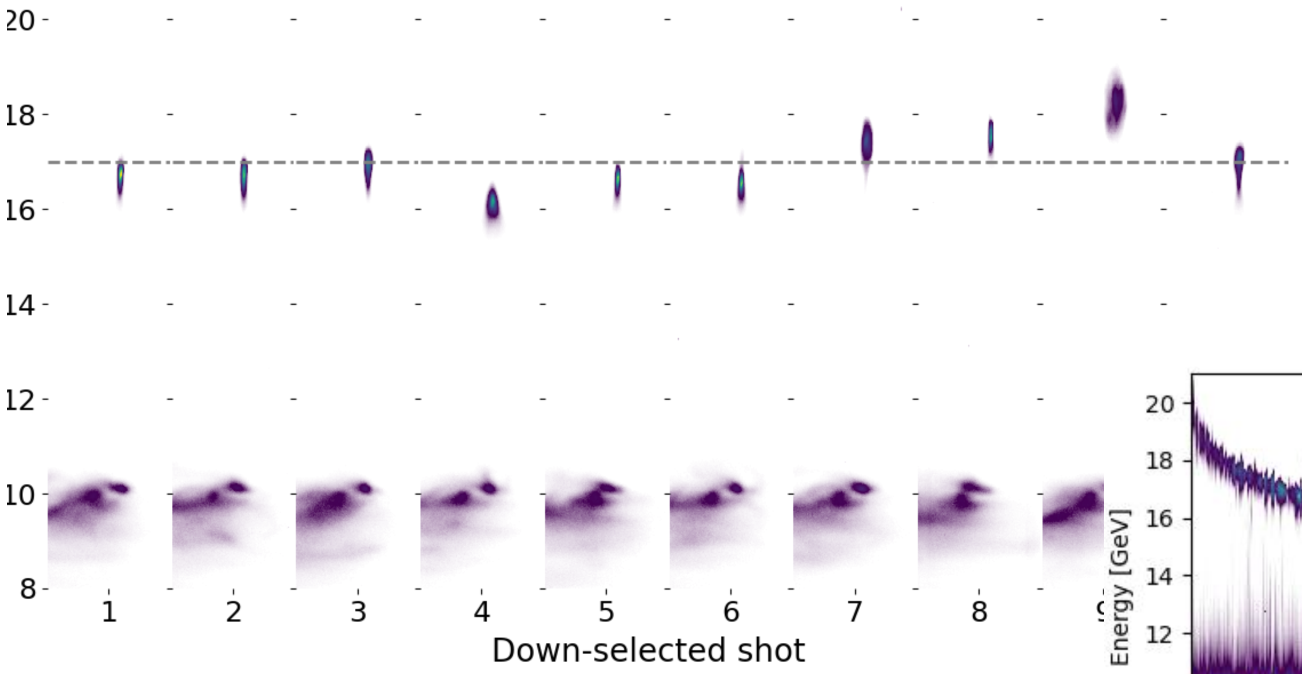
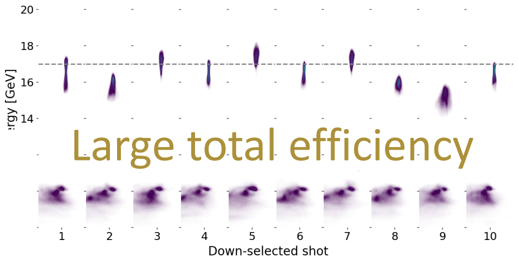
High overall quality



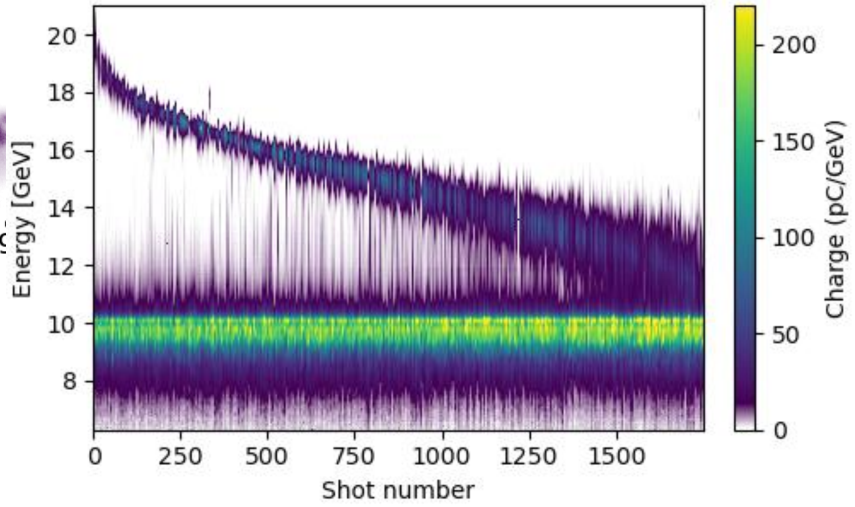


$$E_w = 16.36 \text{ GeV}$$
$$\sigma_{E,w} = 1.21 \text{ \%}$$
$$Q_w = 86.83 \text{ pC}$$
$$\eta_{tot} = 7.44 \text{ \%}$$

Large energy Gain

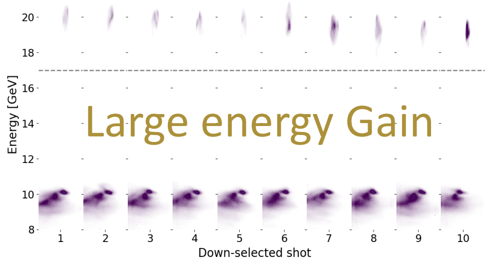


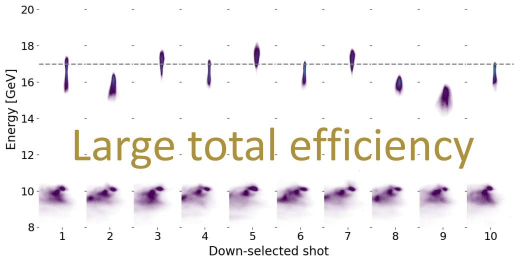
Large total efficiency

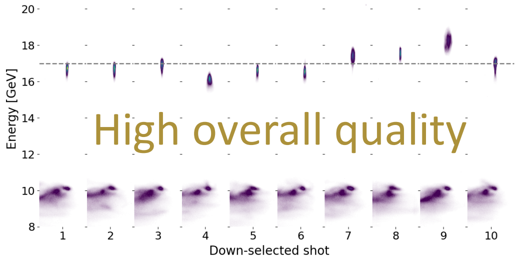


Performance Comparison

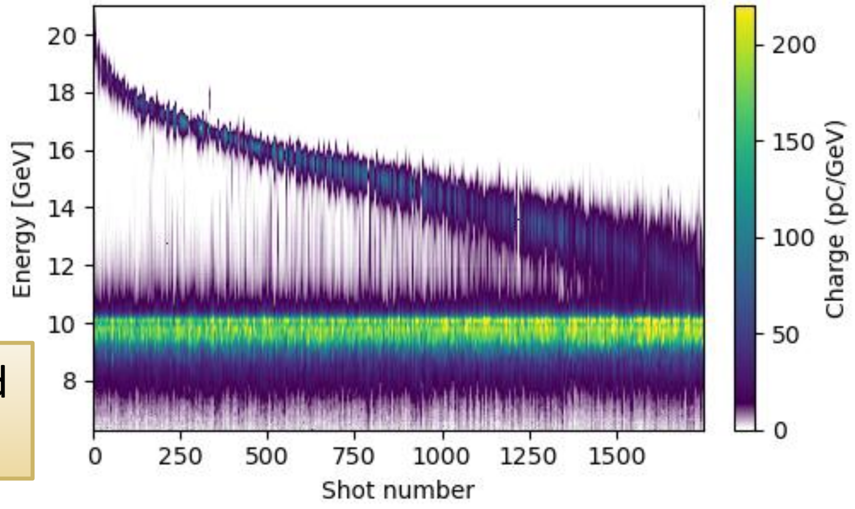
	FACET 2016	FLASH 2024	FACET-II All-optical	HALHF
Energy transferred (J)	0.6	0.0016	0.55	12.5
Energy gain, ΔE_w (GeV)	9	0.04	6.4	7.8
Energy spread	5%	0.09%	1.2%	0.15%
Field uniformity, $\sigma_{E_w}/\Delta E$	10.5%	2.4%	3.1%	0.2%
Total efficiency, η_{tot}	2%	3.6%	7.4%	40%







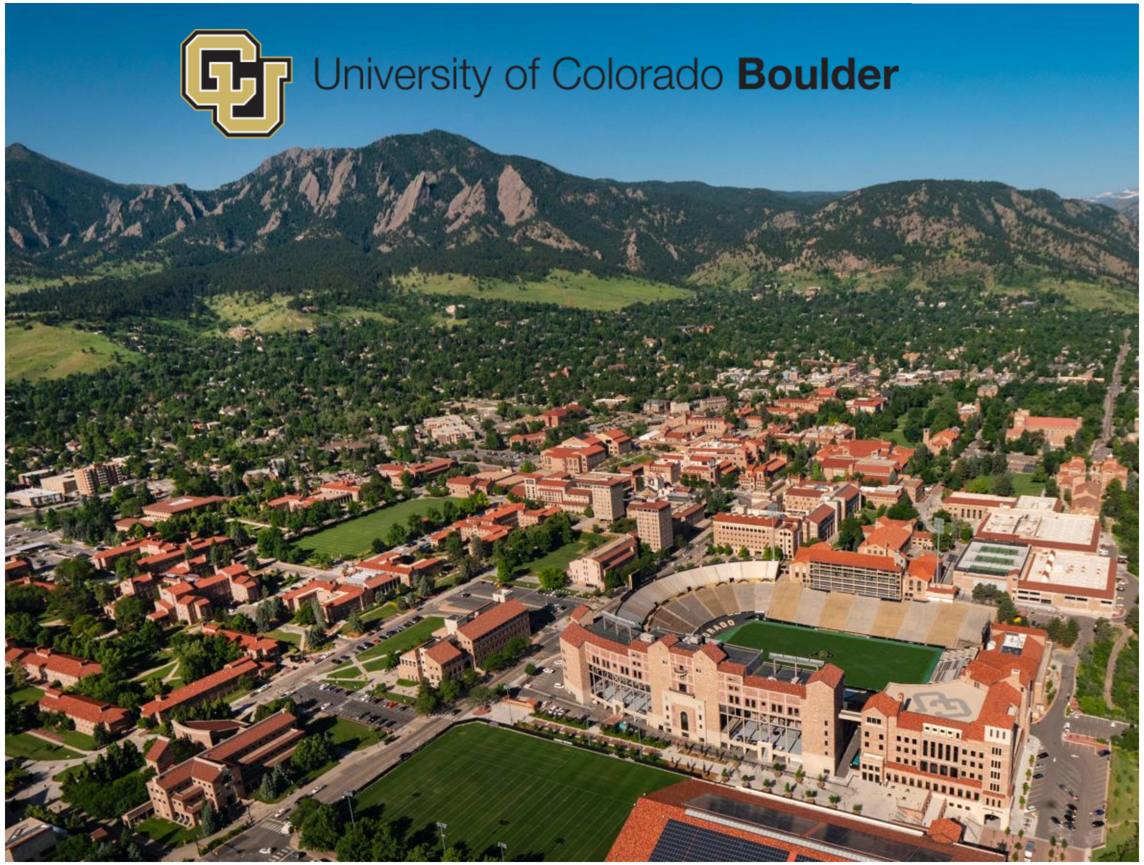
Future work
-Matching with long ramp (new lens)
-PWFA+ passive plasma lens



Demonstration of high quality PWFA at collider-relevant energy in a laser-ionized all-optical plasma source, suitable for high rep-rate and plasma density shaping

Thank You for Your Attention! Questions?

FACET-II SLAC



This work was funded by the U.S. DOE Office of Science award No. DE-SC0017906, DoE Contract No. DE-AC02- 19 76SF00515, and NSF Award Number PHY-1806053.