Experimental generation of petawatt power electron beams via laser heater shaping at FACET-II

Claudio Emma, European Advanced Accelerator Conference

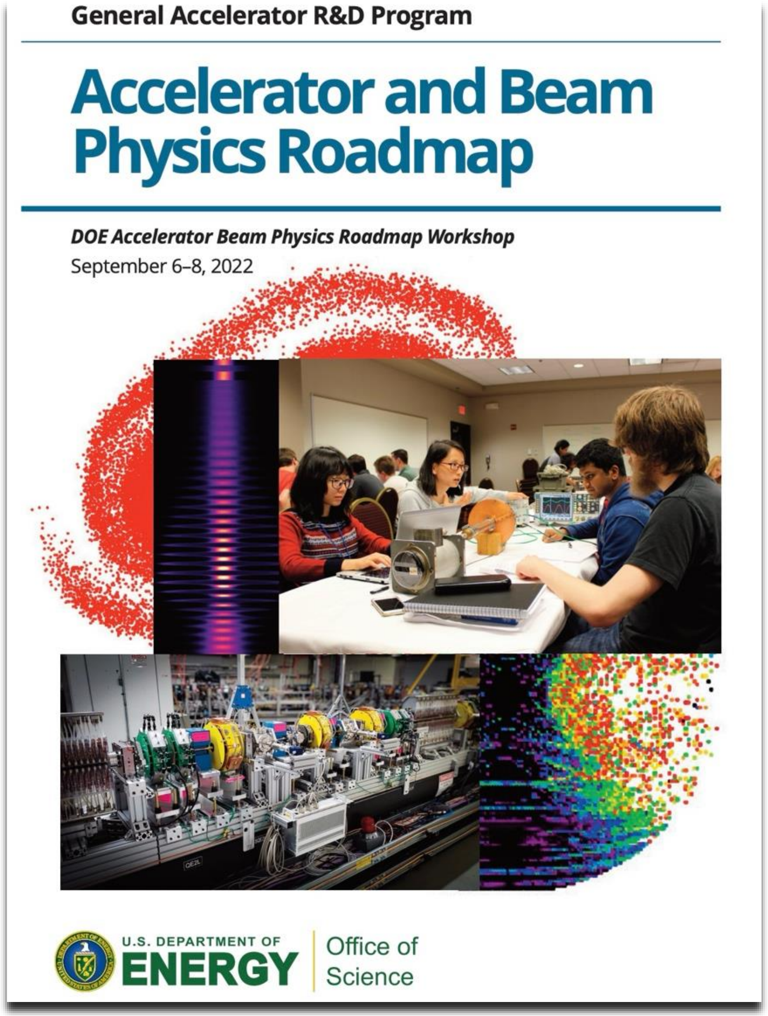
September 23rd, 2025

Stanford University | U.S. DEPARTMENT OF ENERGY

FACET-II Facility for Advanced Accelerator Experimental Tests

SLAC NATIONAL ACCELERATOR LABORATORY

Why extreme particle beams?



4 Grand Challenge Two

Beam Quality: How do we increase beam phase-space density by orders of magnitude, towards the quantum degeneracy limit?

"Quality" Grand Challenge Roadmap

YEAR 1	2	3	4	5	6	7	8	9	10

High-brightness beam generation and preservation

High-peak current (100kA-class e-) beams generation and characterization, benchmark with CSR simulations	Ultrahigh-peak current bright e-beams by mitigating CSR emittance growth (MA current, 0.1 um bunch length)

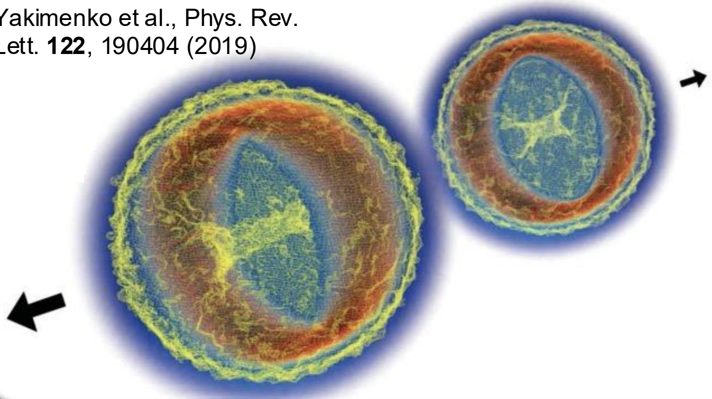
- Accelerated beams are unique probes of the natural world.
- Advances in our understanding of Nature come with improvements to beam brightness, intensity and control.
- Next generation experiments will require extreme beams with tailored properties beyond the state of the art.

Extreme beam research in line with GARD ABP roadmap

Science enabled by extreme beams

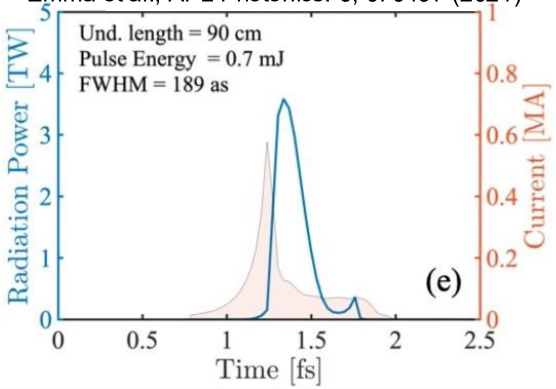
New Collider Concepts

Yakimenko et al., Phys. Rev. Lett. **122**, 190404 (2019)



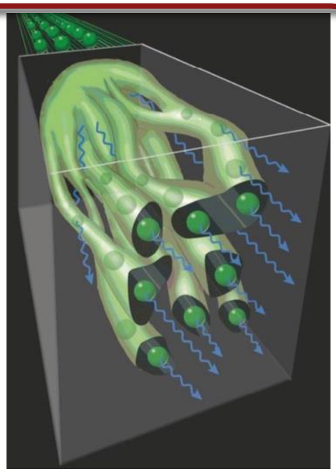
Attosecond light sources

Emma et al., APL Photonics. **6**, 076197 (2021)



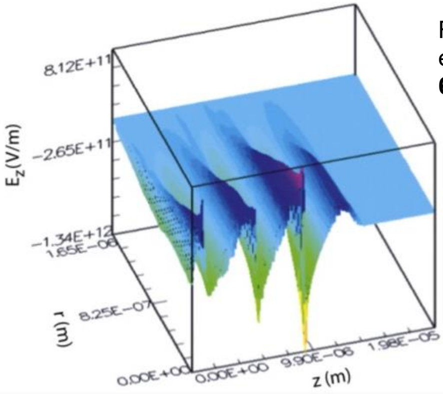
Laboratory Astrophysics

Macchi, Pegoraro, Nature Photonics **12**, 314 (2018)
Benedetti, Tamburini, Keitel, Nature Photonics **12**, 319 (2018)



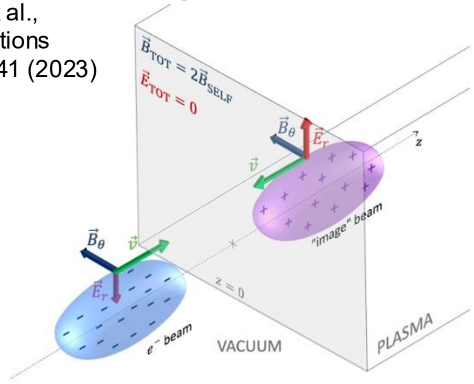
TeV/m Advanced Accelerators

Rosenzweig et al., NIMA **653** 11 (2011)



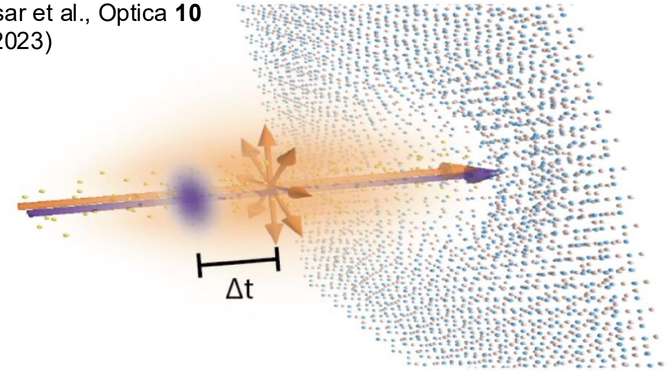
Strong field QED

Matheron et al., Communications Physics **6** 141 (2023)



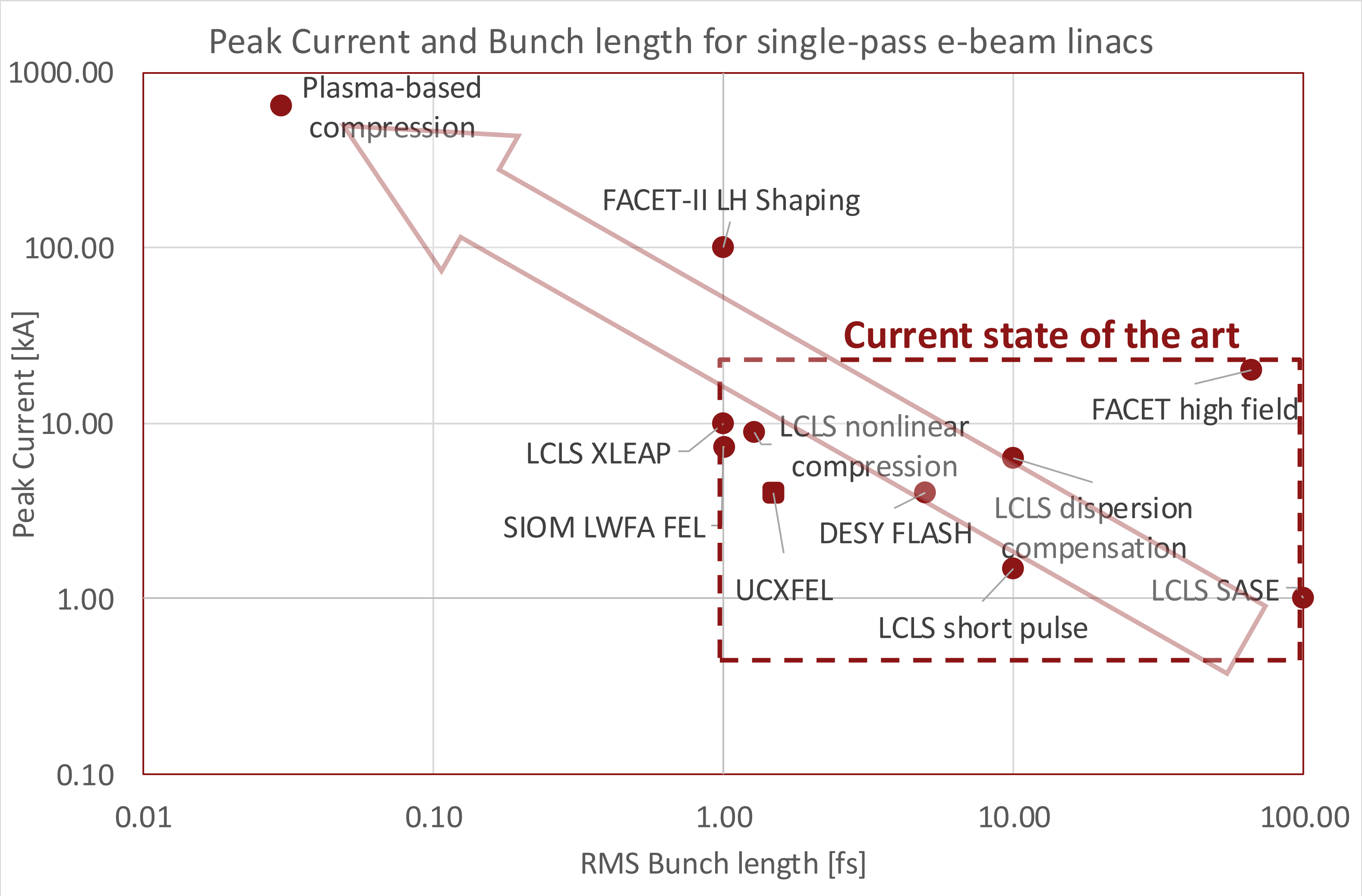
Ultrafast Quantum Dynamics

Cesar et al., Optica **10** 1 (2023)



Extreme beams enable broad swathe of HEP and fundamental science experiments

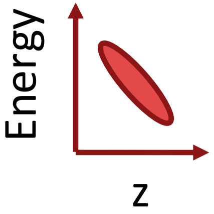
Current state of the art

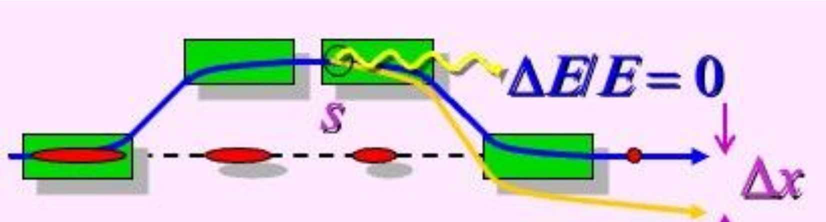


Extreme beams will be 1-2 orders of magnitude beyond state of the art

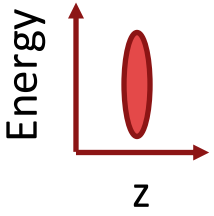
What are the challenges with extreme beams?

Extreme beams are hard to generate

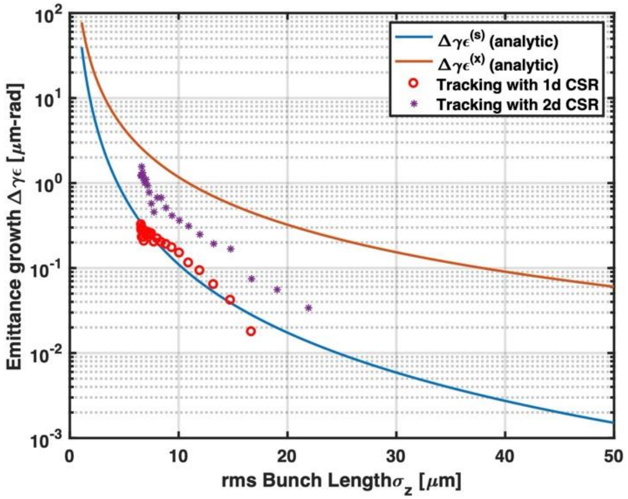


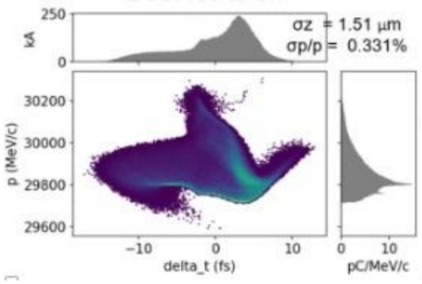


P. Emma High Brightness Electron Beam Magnetic Compression: *Physics and Compressor Design (2002)*



- Radiation during bunch compression can spoil beam quality in traditional compressor designs

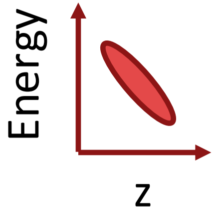


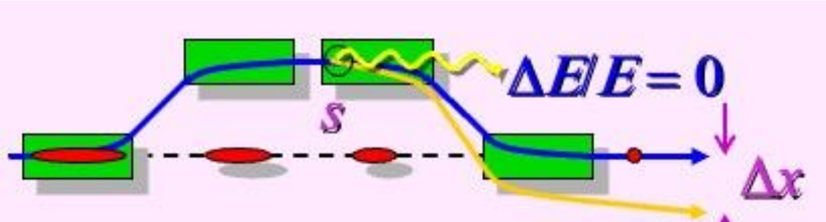


W. Lou, Y. Cai, C. Mayes, G. White Proc IPAC 2021 WEPAB234

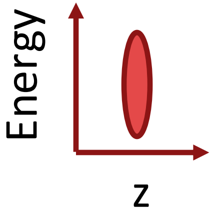
What are the challenges with extreme beams?

Extreme beams are hard to generate

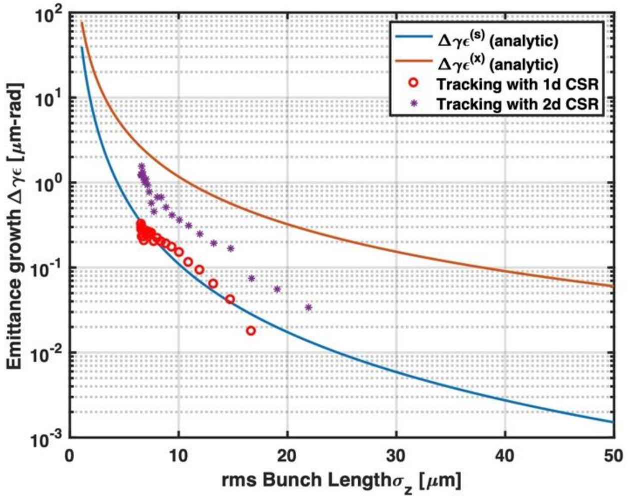


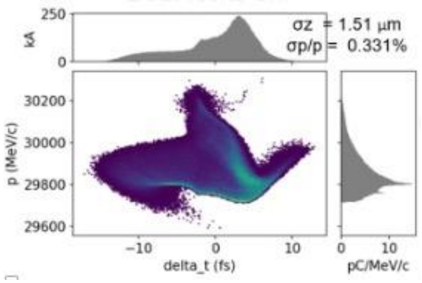


P. Emma High Brightness Electron Beam Magnetic Compression: *Physics and Compressor Design (2002)*



- Radiation during bunch compression can spoil beam quality in traditional compressor designs





W. Lou, Y. Cai, C. Mayes, G. White Proc IPAC 2021 WEPAB234

Laser-based chirping

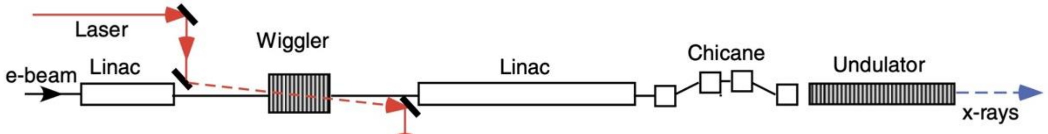
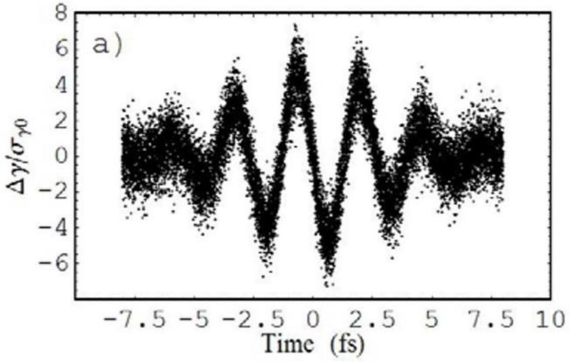
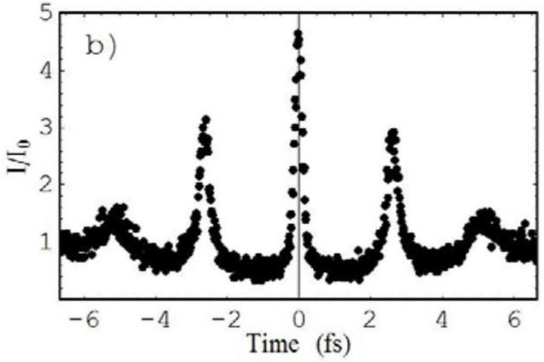


FIG. 1. (Color) A schematic of ESASE x-ray FEL.

A. Zholents, PRSTAB **8** 040701 (2005)

- Lasers can impart localized chirp to e-beam
- Chirp can be compressed to increase the current while preserving beam brightness





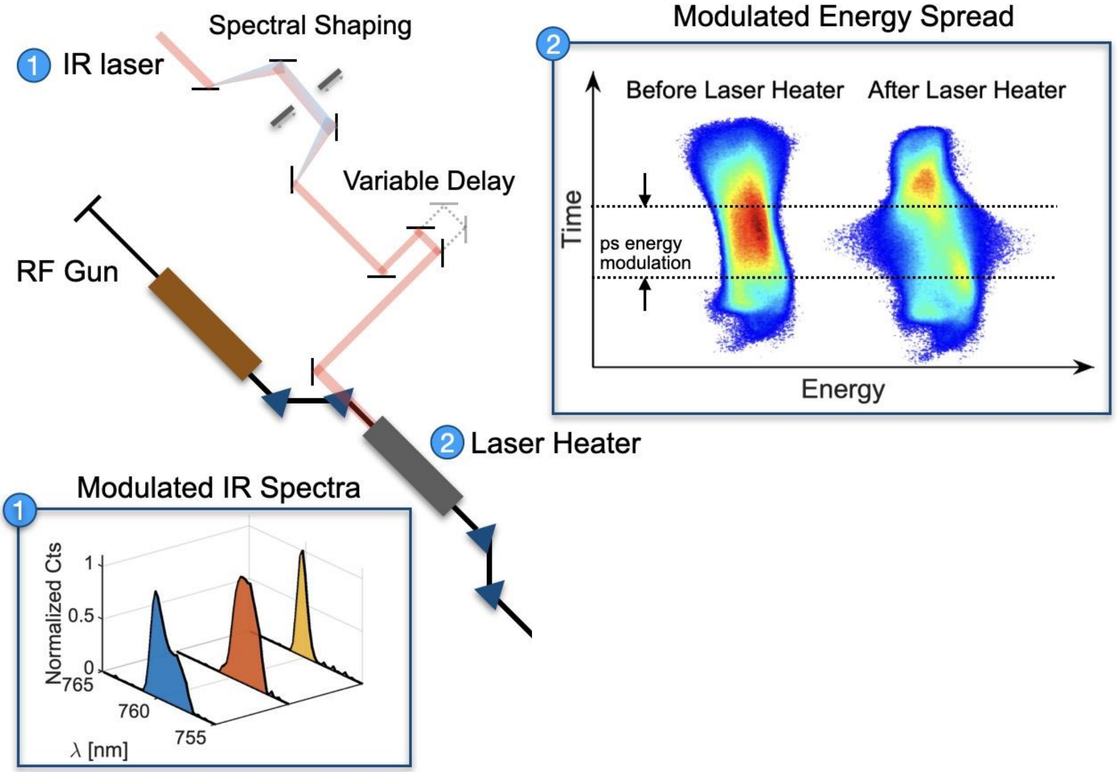
Laser shaping for PW beam generation at FACET-II


PHYSICAL REVIEW LETTERS 134, 085001 (2025)
Editors' Suggestion

Experimental Generation of Extreme Electron Beams for Advanced Accelerator Applications

C. Emma, N. Majernik, K. K. Swanson, R. Ariniello, S. Gessner, R. Hessami, M. J. Hogan, A. Knetsch, K. A. Larsen, A. Marinelli, B. O'Shea, S. Perez, I. Rajkovic, R. Robles, D. Storey, and G. Yocky
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

(Received 18 November 2024; accepted 31 January 2025; published 27 February 2025)



Laser shaping for PW beam generation at FACET-II

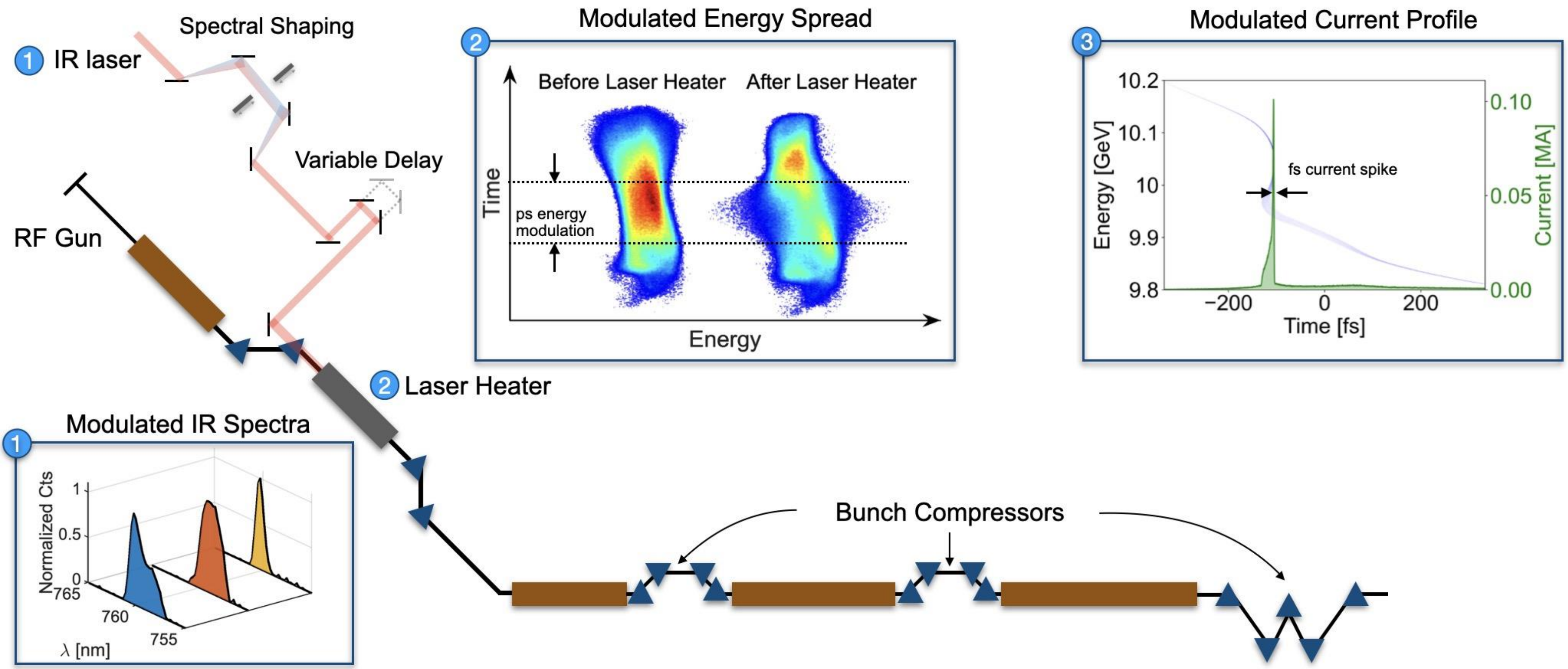

PHYSICAL REVIEW LETTERS **134,** 085001 (2025)

Editors' Suggestion

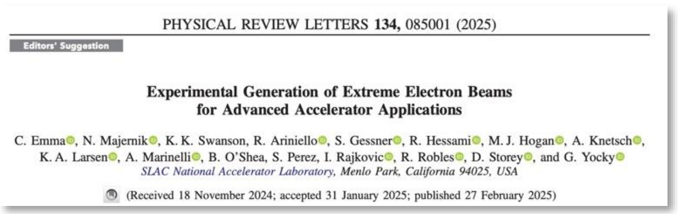
Experimental Generation of Extreme Electron Beams for Advanced Accelerator Applications

C. Emma, N. Majernik, K. K. Swanson, R. Ariniello, S. Gessner, R. Hessami, M. J. Hogan, A. Knetsch, K. A. Larsen, A. Marinelli, B. O'Shea, S. Perez, I. Rajkovic, R. Robles, D. Storey, and G. Yocky
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

(Received 18 November 2024; accepted 31 January 2025; published 27 February 2025)



Laser shaping for PW beam generation at FACET-II


PHYSICAL REVIEW LETTERS 134, 085001 (2025)

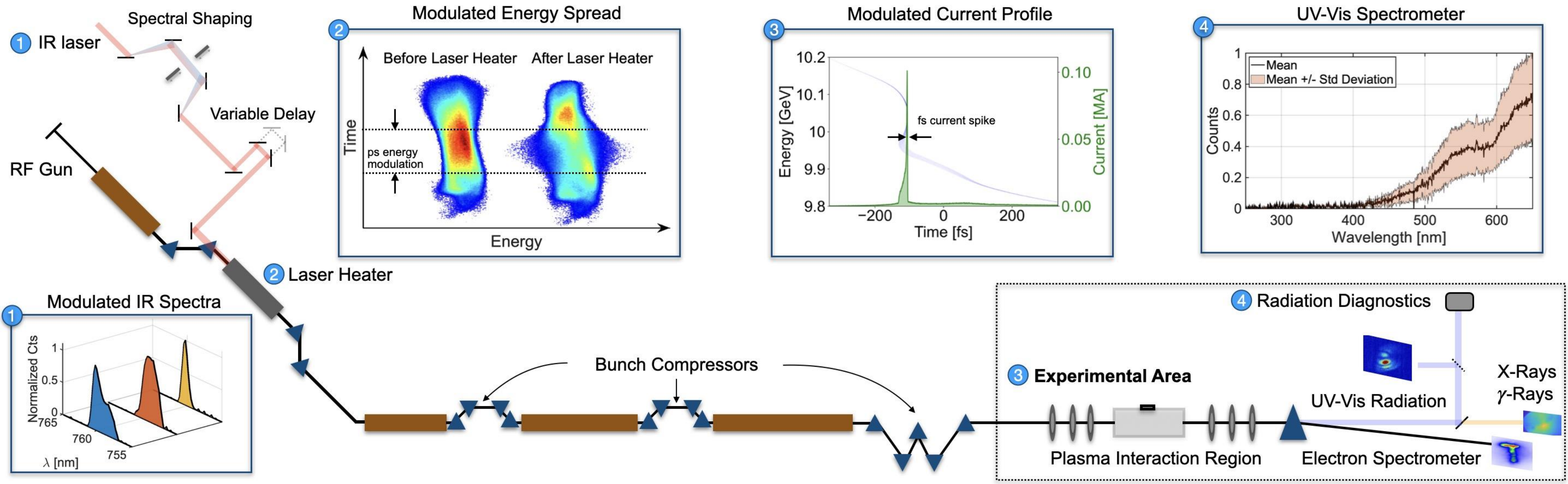
Editors' Suggestion

Experimental Generation of Extreme Electron Beams for Advanced Accelerator Applications

C. Emma, N. Majernik, K. K. Swanson, R. Ariniello, S. Gessner, R. Hessami, M. J. Hogan, A. Knetsch, K. A. Larsen, A. Marinelli, B. O'Shea, S. Perez, I. Rajkovic, R. Robles, D. Storey, and G. Yocky

SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

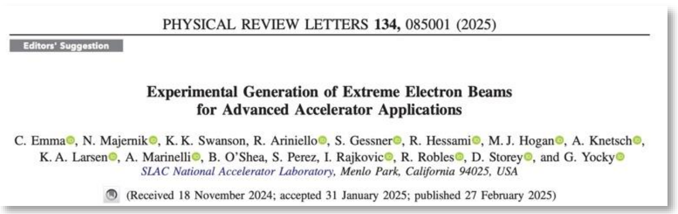
(Received 18 November 2024; accepted 31 January 2025; published 27 February 2025)



Original work done on LH Shaping experiments/sims at LCLS/LCLS-II: Marinelli et al., PRL (2016), D. Cesar et al PRAB (2021), S. Li et al APL (2024)

Experiments at FACET-II generate ~fs-duration ~0.1 MA current

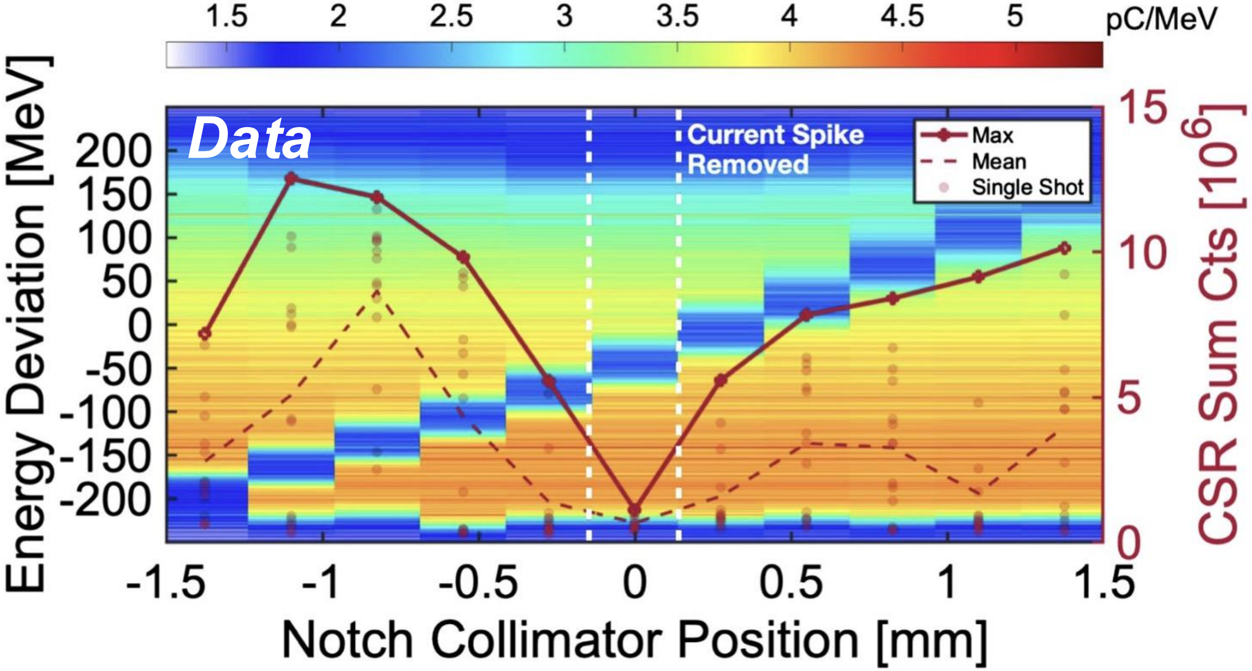
Localizing the current spike in the beam

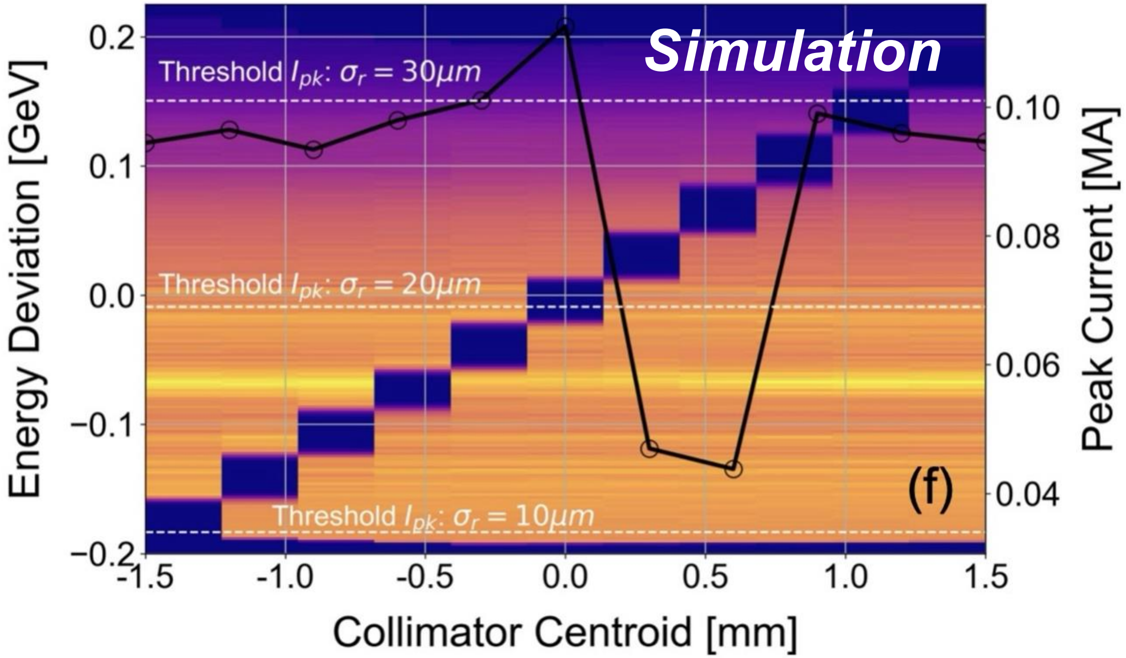

PHYSICAL REVIEW LETTERS 134, 085001 (2025)
Editors' Suggestion

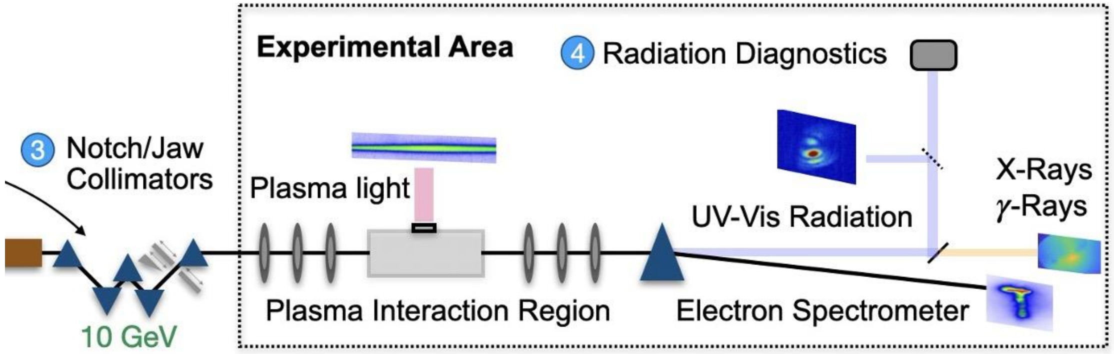
Experimental Generation of Extreme Electron Beams for Advanced Accelerator Applications

C. Emma, N. Majernik, K. K. Swanson, R. Ariniello, S. Gessner, R. Hessami, M. J. Hogan, A. Knetsch, K. A. Larsen, A. Marinelli, B. O'Shea, S. Perez, I. Rajkovic, R. Robles, D. Storey, and G. Yocky
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

(Received 18 November 2024; accepted 31 January 2025; published 27 February 2025)

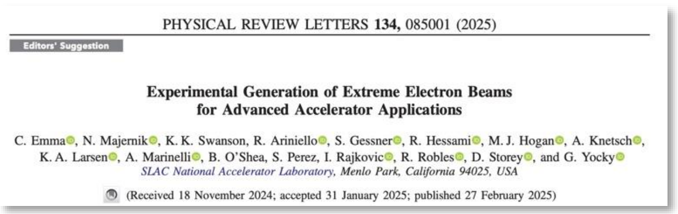






Reduction in CSR reveals current spike is highly localized in energy and time

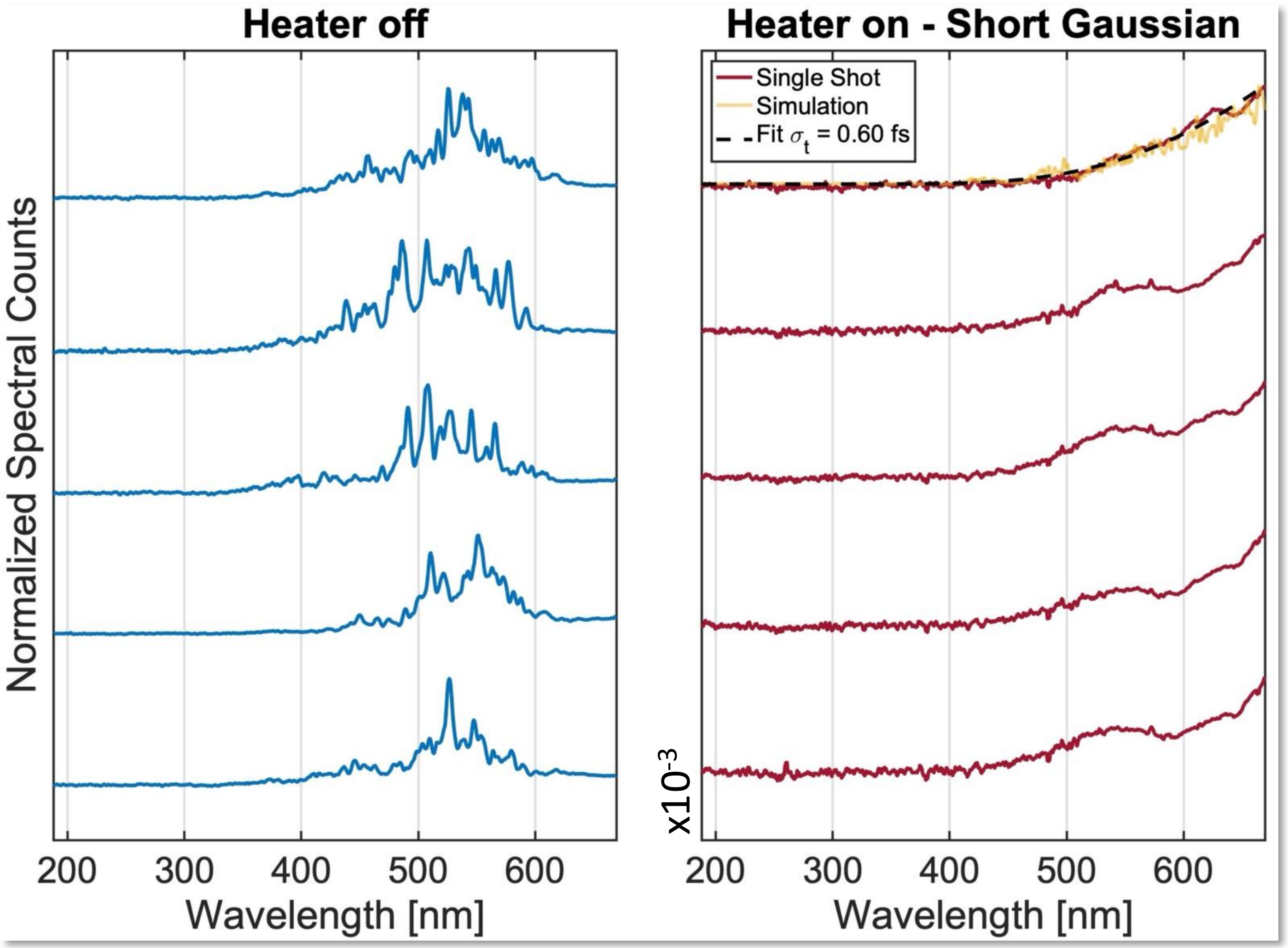
Estimating the spike duration


PHYSICAL REVIEW LETTERS 134, 085001 (2025)
Editors' Suggestion

Experimental Generation of Extreme Electron Beams for Advanced Accelerator Applications

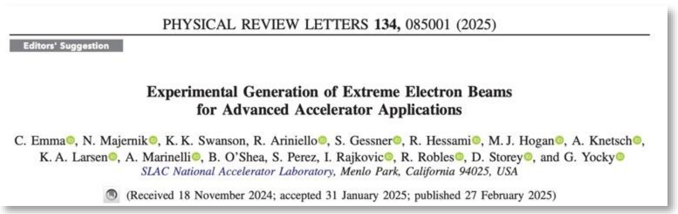
C. Emma, N. Majernik, K. K. Swanson, R. Ariniello, S. Gessner, R. Hessami, M. J. Hogan, A. Knetsch, K. A. Larsen, A. Marinelli, B. O'Shea, S. Perez, I. Rajkovic, R. Robles, D. Storey, and G. Yocky
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

(Received 18 November 2024; accepted 31 January 2025; published 27 February 2025)



CSR spectra reveal RMS bunch length of LH seeded current spike O(1fs)

Using the current spike to ionize He

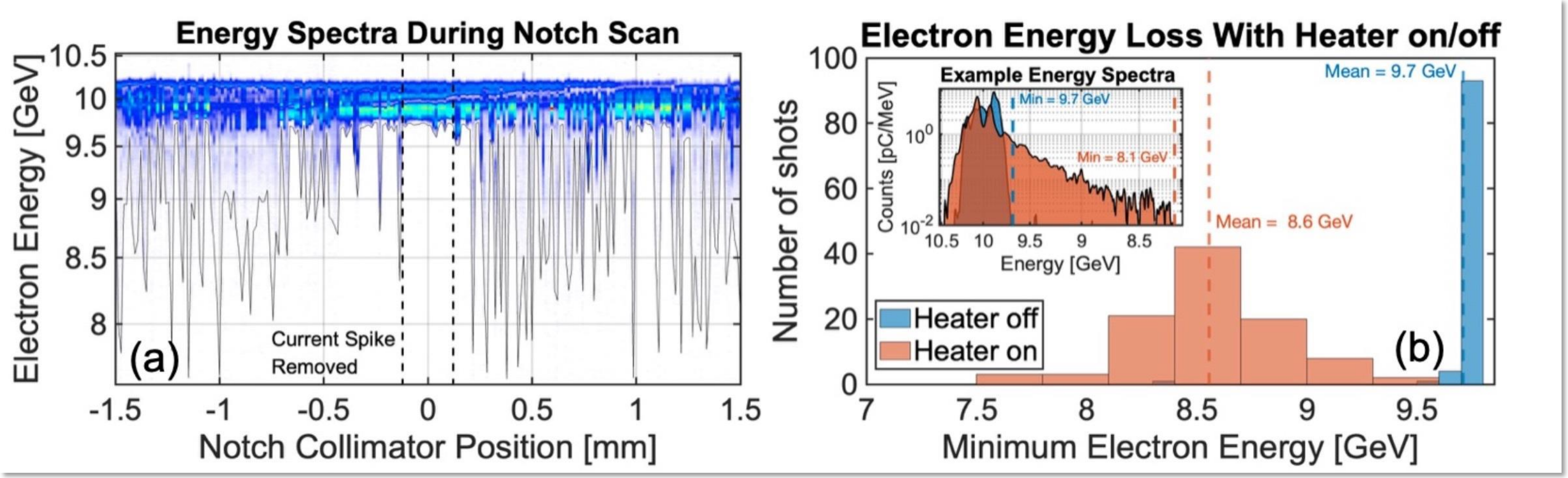

PHYSICAL REVIEW LETTERS 134, 085001 (2025)

Editors' Suggestion

Experimental Generation of Extreme Electron Beams for Advanced Accelerator Applications

C. Emma, N. Majernik, K. K. Swanson, R. Ariniello, S. Gessner, R. Hessami, M. J. Hogan, A. Knetsch, K. A. Larsen, A. Marinelli, B. O'Shea, S. Perez, I. Rajkovic, R. Robles, D. Storey, and G. Yocky
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

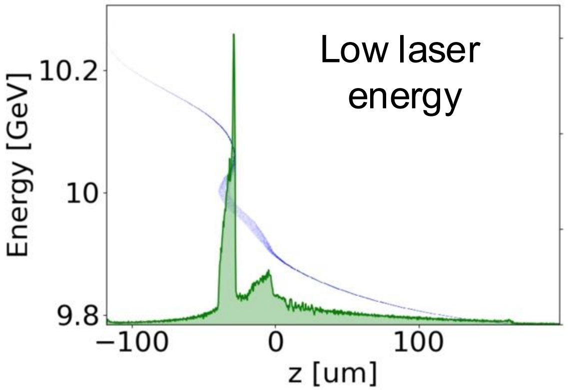
(Received 18 November 2024; accepted 31 January 2025; published 27 February 2025)

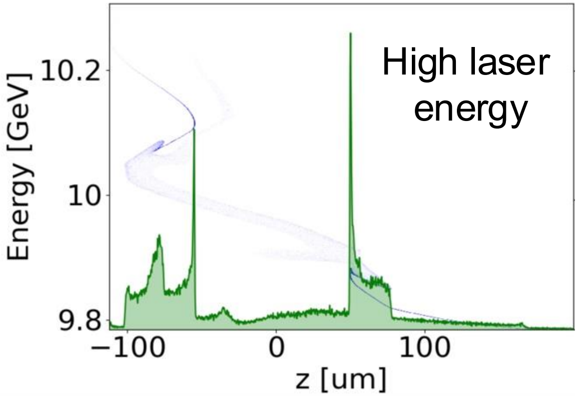


Current spikes enable controlled ionization of gas targets relevant to AAC applications

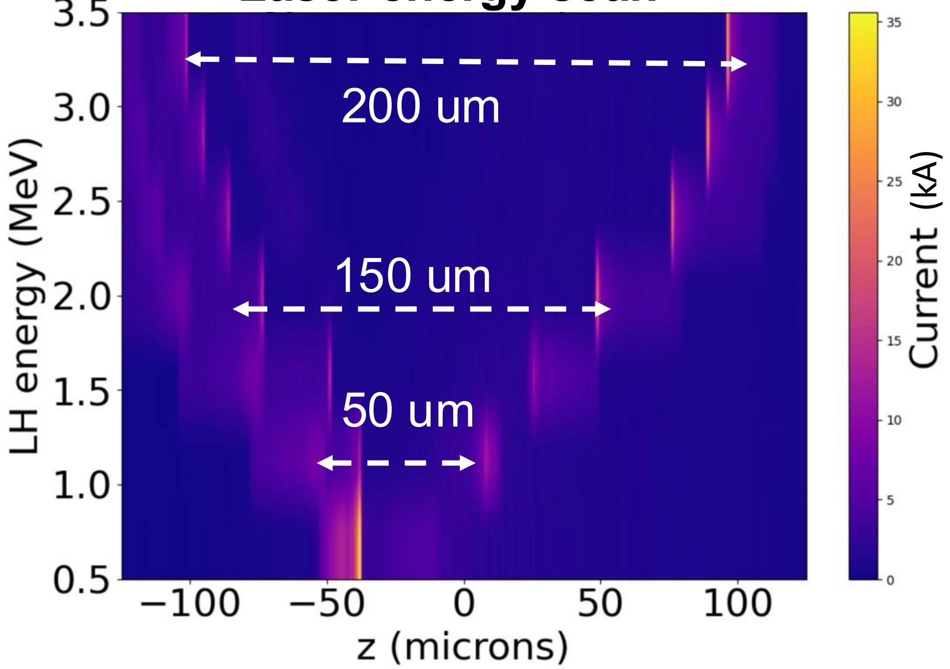
Next steps - advanced heater shaping modes

- Two bunches with variable spacing

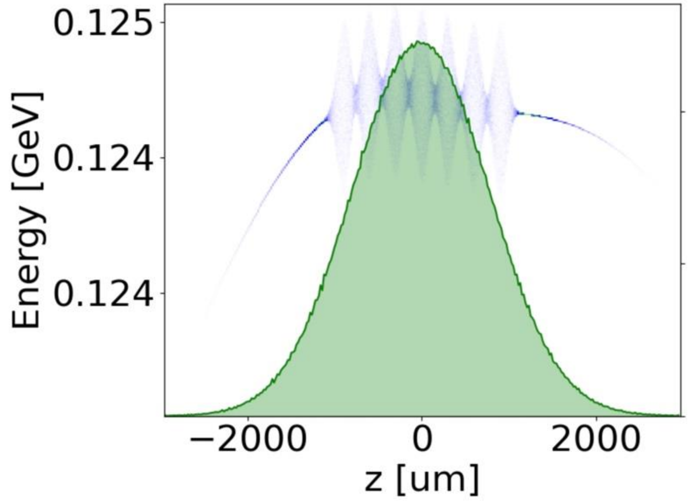




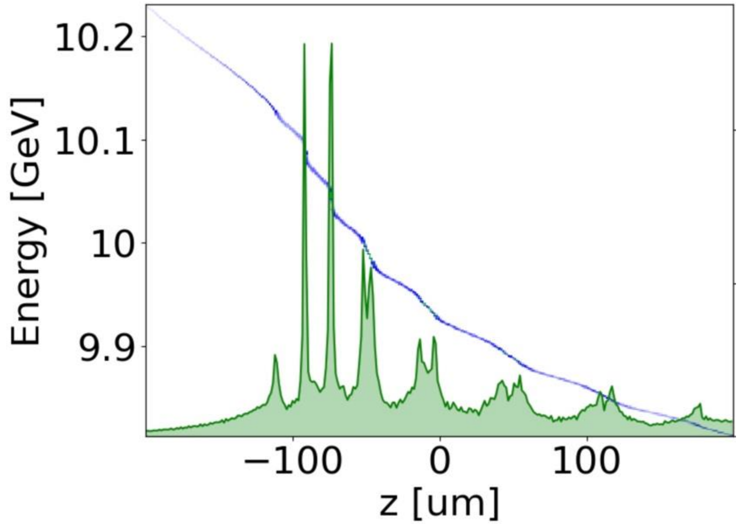
Laser energy scan



- Multi-spike for resonant PWFA



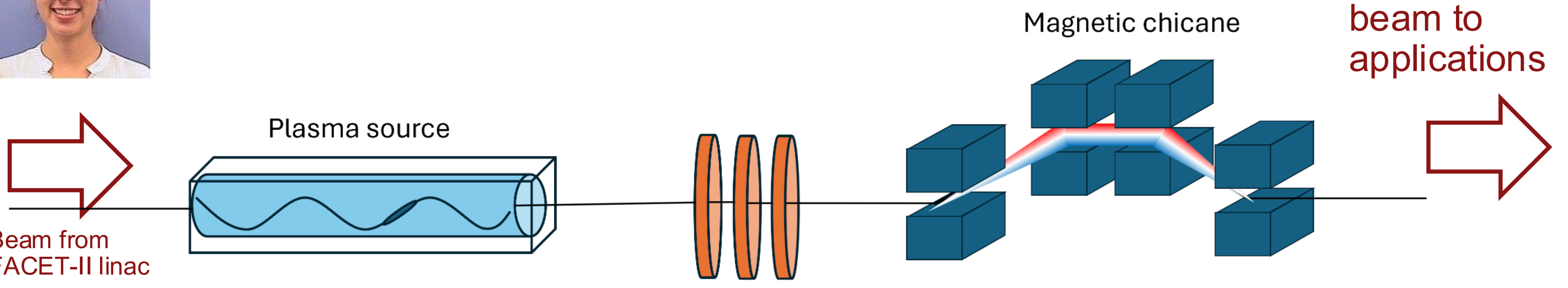
At Laser Heater

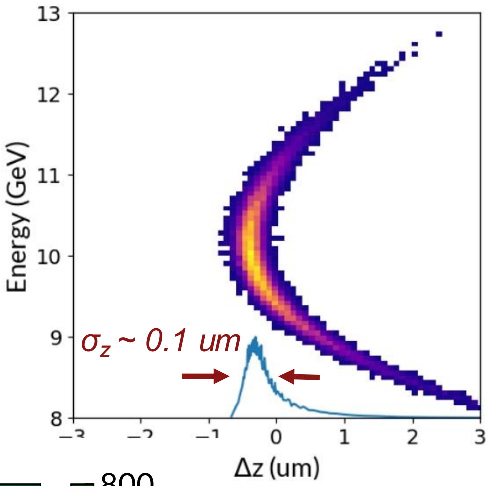


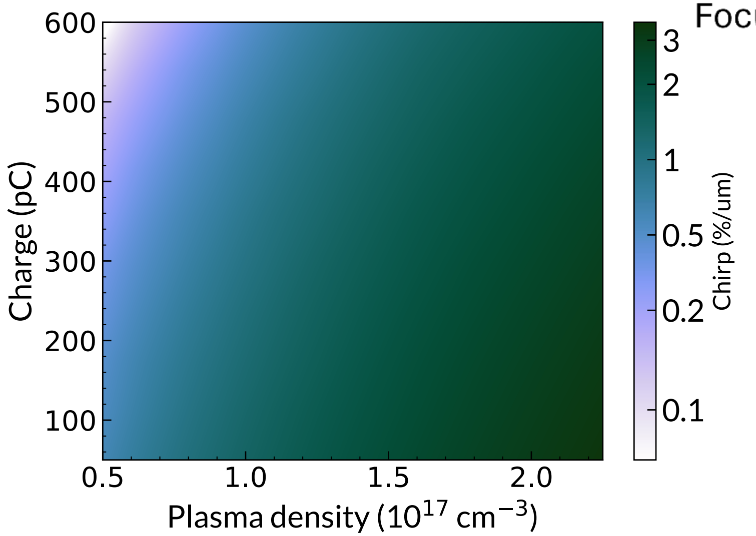
At Experiment

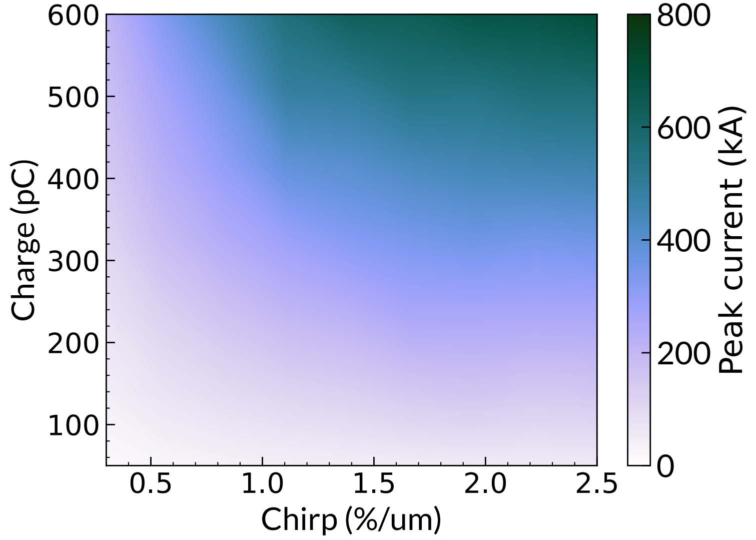
Next next steps – plasma-based compression for MA beams

K. Swanson
In preparation









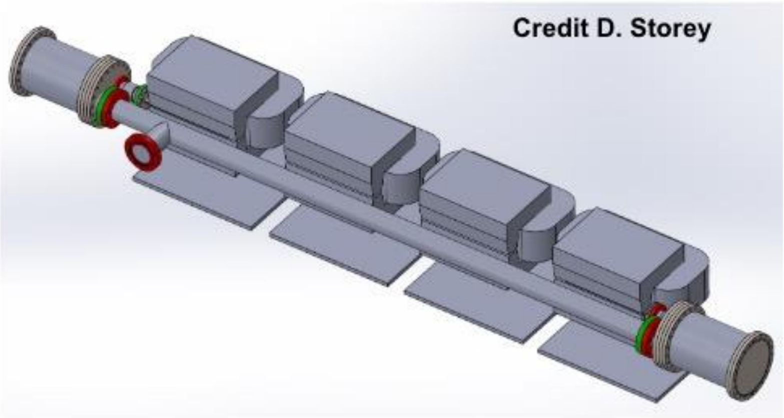
Simulations explore extreme beam parameter space and reveal trade-offs for different applications

Next next steps – plasma-based compression for MA beams

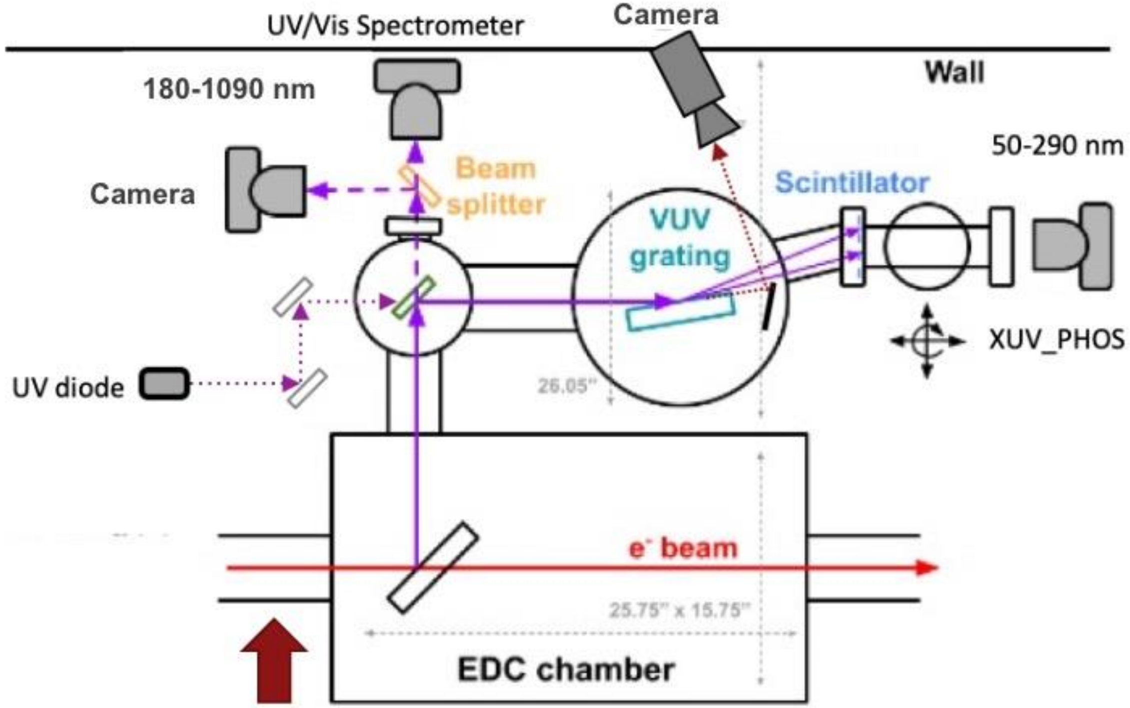
Plasma Sources

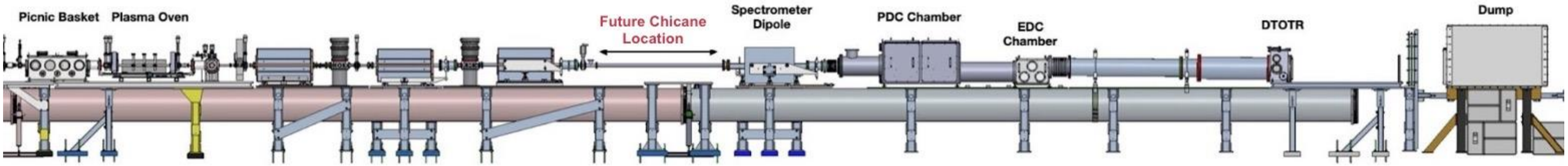
- Gas Jet
  $n_e = 10^{18} – 10^{20}$ cm^{-3}
- Li Oven
  ne = $10^{16} – 10^{27}$ cm^{-3}
- Static fill

Chicane + bypass line



Spectral Measurement Setup





Planned experiments at FACET-II to explore extreme compression in upcoming run

Summary

- We generated e- beams with 0.1 MA peak current and PW peak power at FACET-II using laser-based beam shaping.
- We characterized the properties of these beams via UV-vis spectroscopy, simulations and beam-plasma interaction measurements.
- We delivered these beams to user experiments studying PWFA regimes (wakeless vs blowout) and plasma-based injection (density downramp).
- Future Improvements may include transverse shaping/better longitudinal shaping to create custom profiles (spike trains, ramps etc.).
- Next next steps is to go from 0.1 MA to 1 MA, and beyond…?

Acknowledgments

- FACET-II AARD, Beam Physics and Operations, Test Facilities

- FACET-II Scientific User Program, in particular E338, E300, E304 collaborations

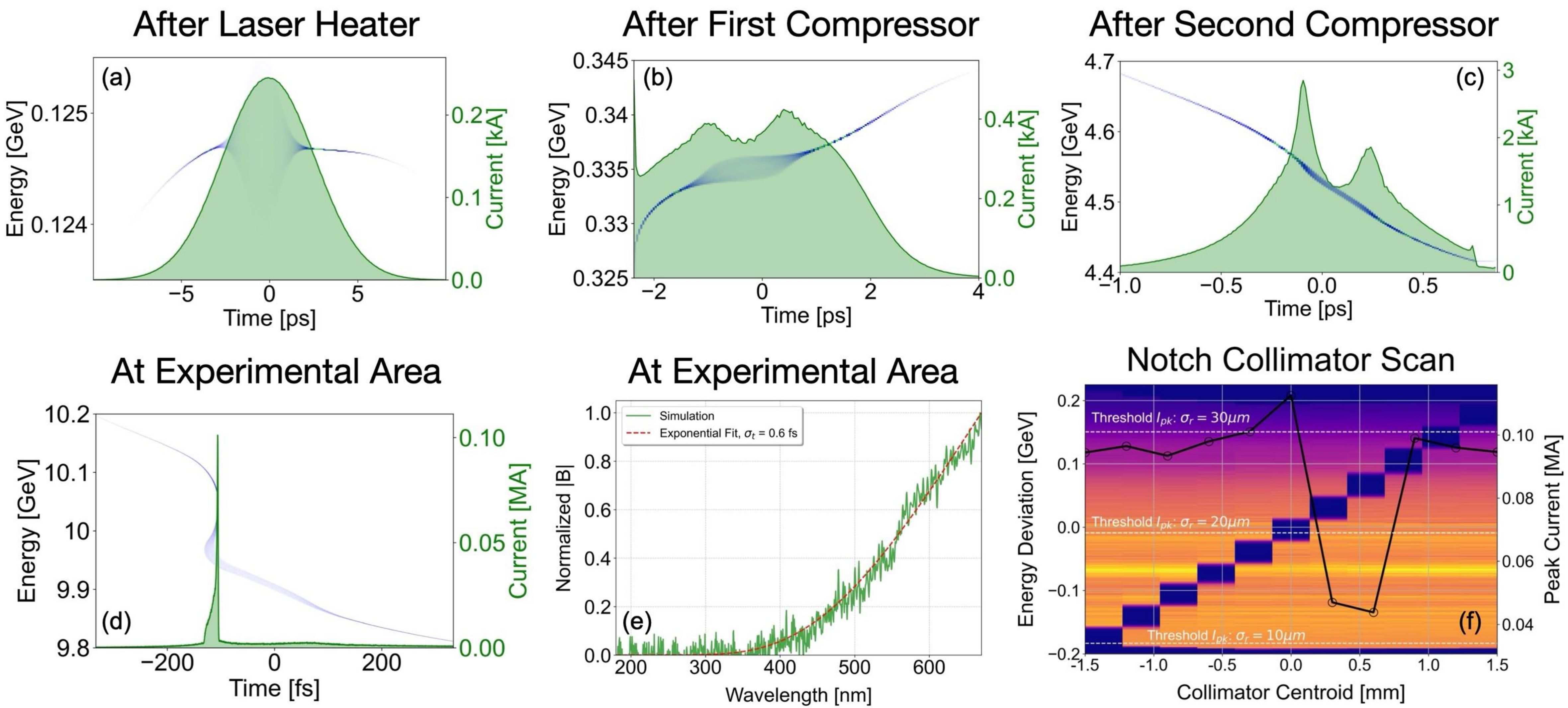
- This work was supported by the U.S. Department of Energy under contract number DE-AC01-76SF00515. C. Emma and K. Swanson acknowledge support from the Department of Energy Early Career Research Program.

Thank you for your attention

Questions?

Bonus slides

Particle tracking simulations of the spike generation

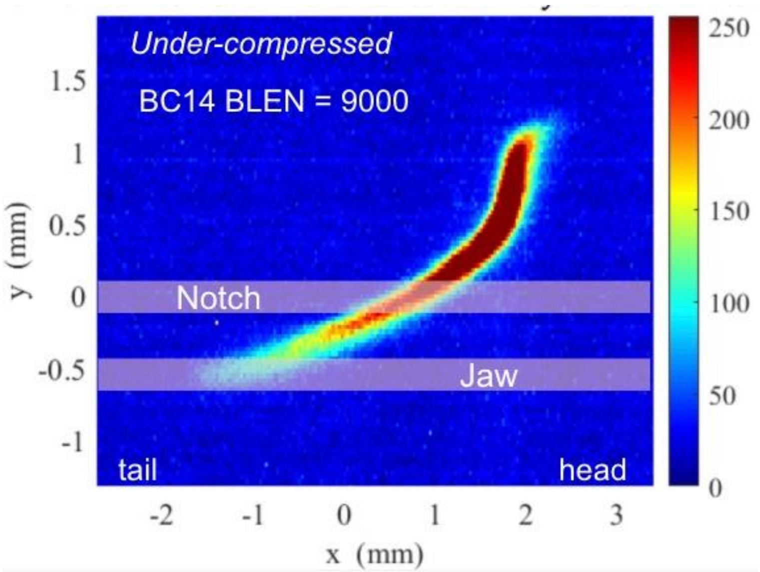


Simulations show generation of a fs-long 0.1 MA spike consistent with measured CSR spectra

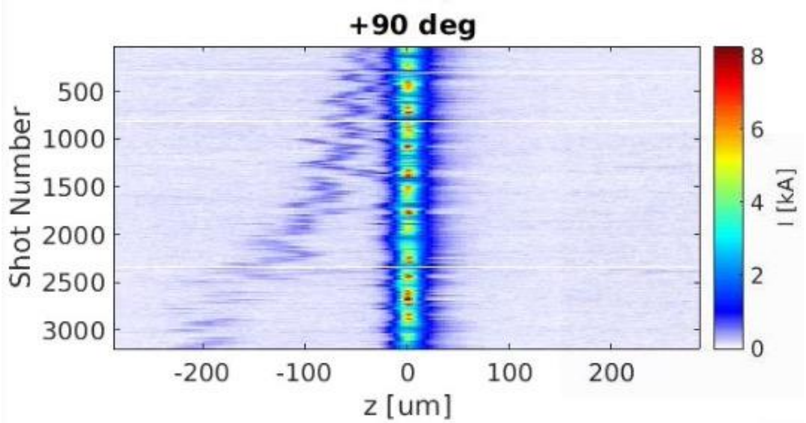
Initial wakefield mapping measurements

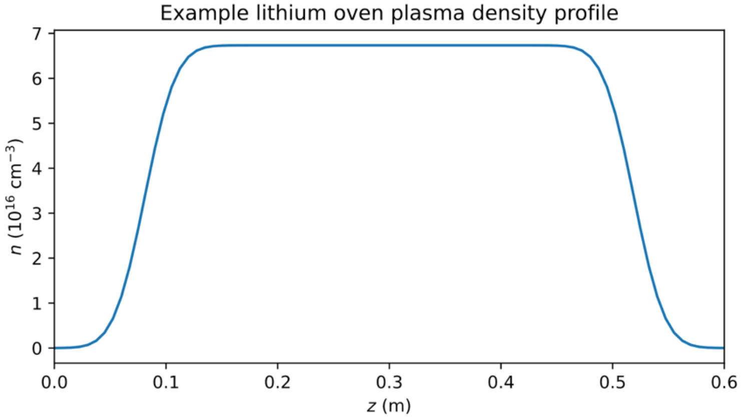
Preliminary

Longitudinal phase space
At plasma entrance

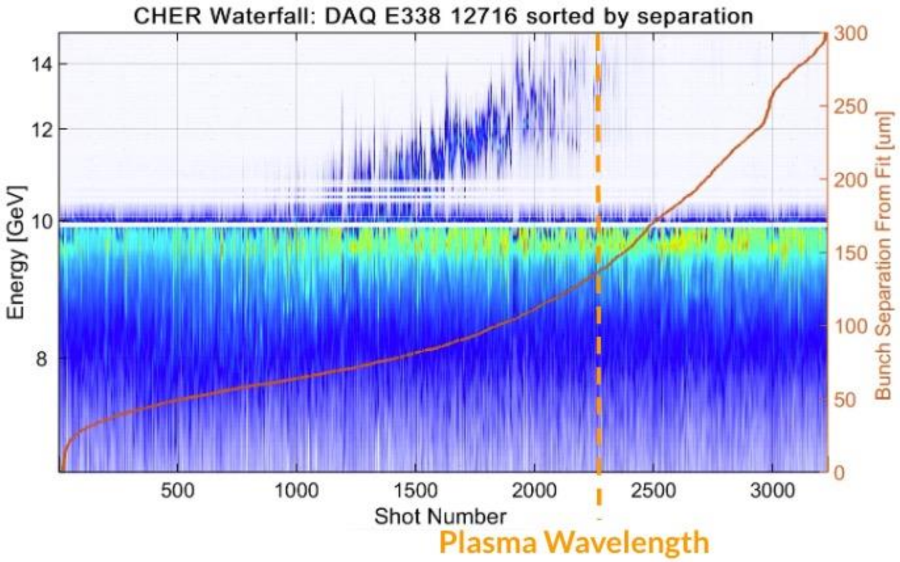


Current profile at variable bunch spacing
(notch + jaw collimators)





Energy spectra after plasma
during separation scan

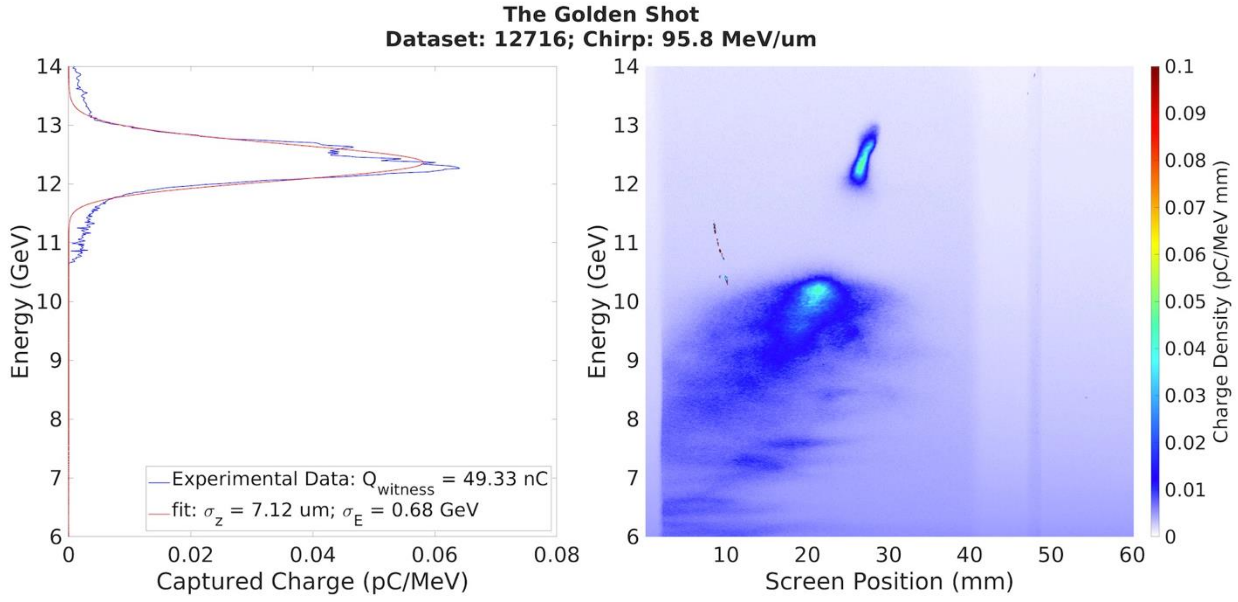


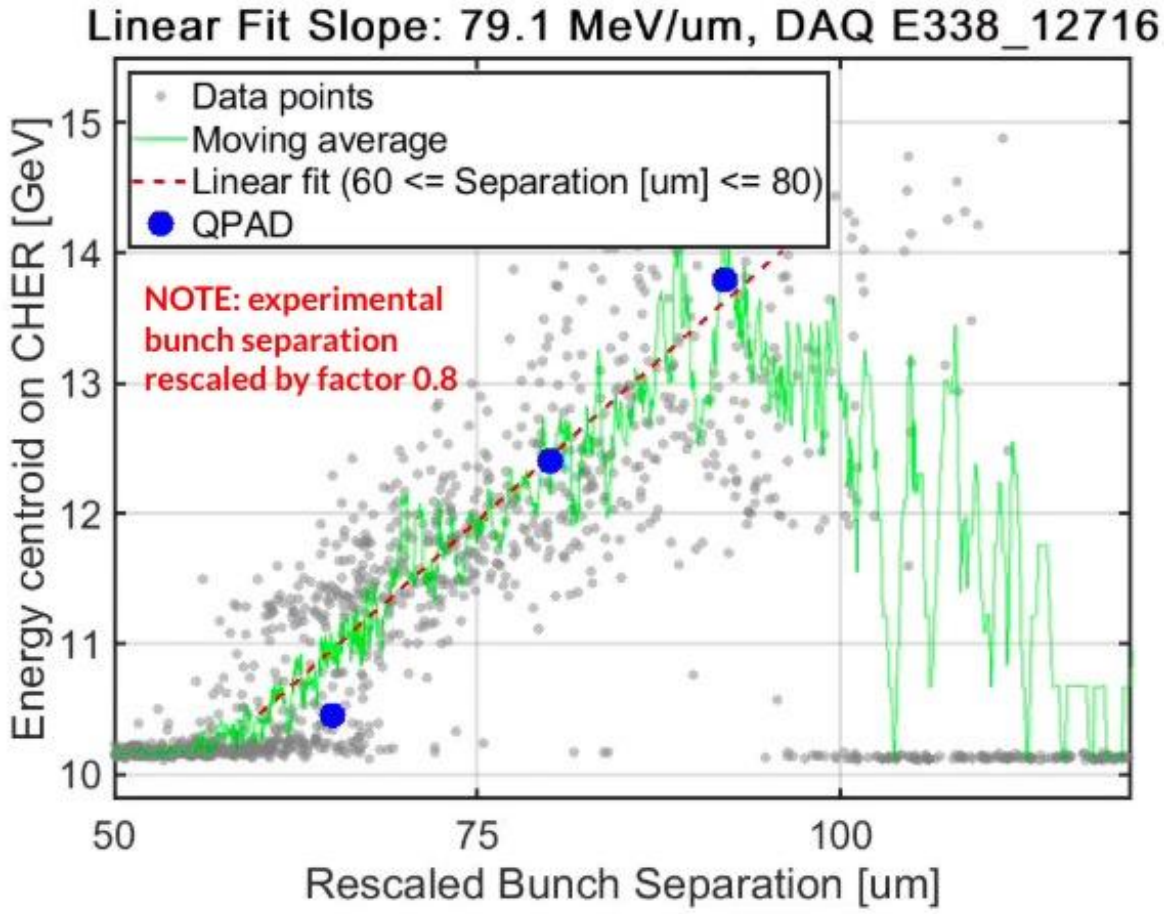
Plasma-induced chirp measured on FACET-II beam with notched two-bunch beam

Chirp calculation results

Preliminary

Lithium Oven at 8 Torr, n_p = 6.7e16

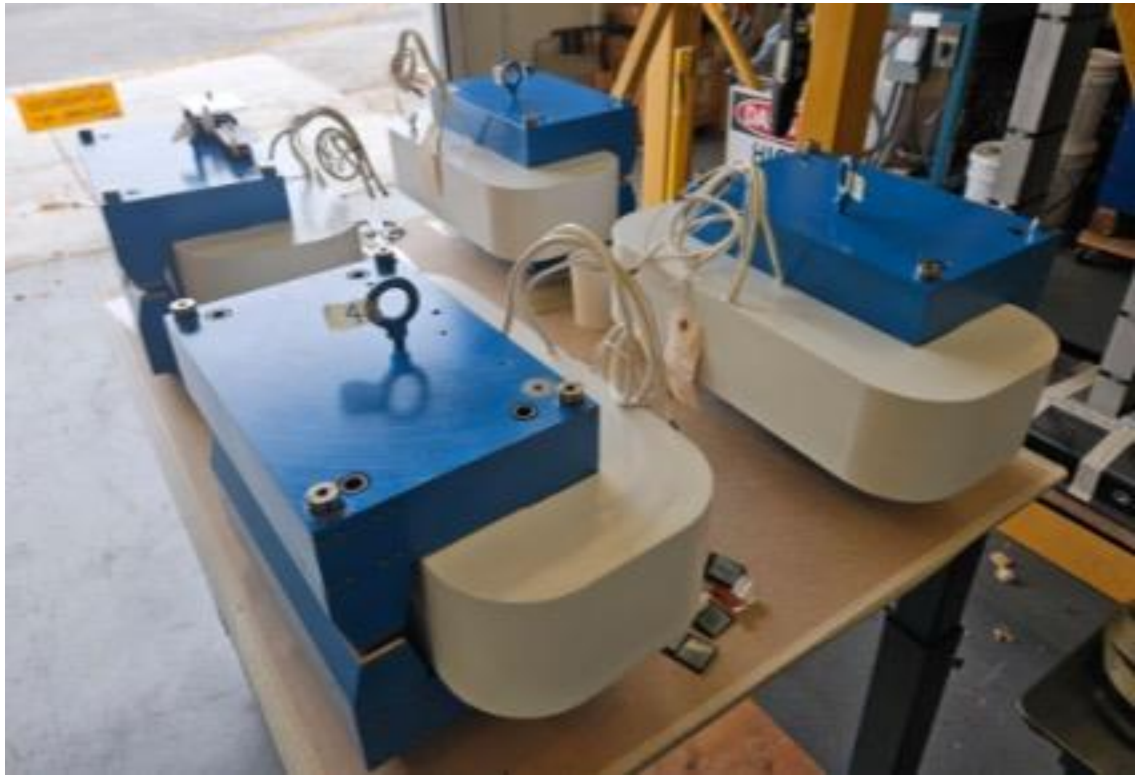




- QPAD simulations in agreement with data for chirp and witness energy gain. Rescaling of experimental bunch separation due to uncertain TCAV calibration.

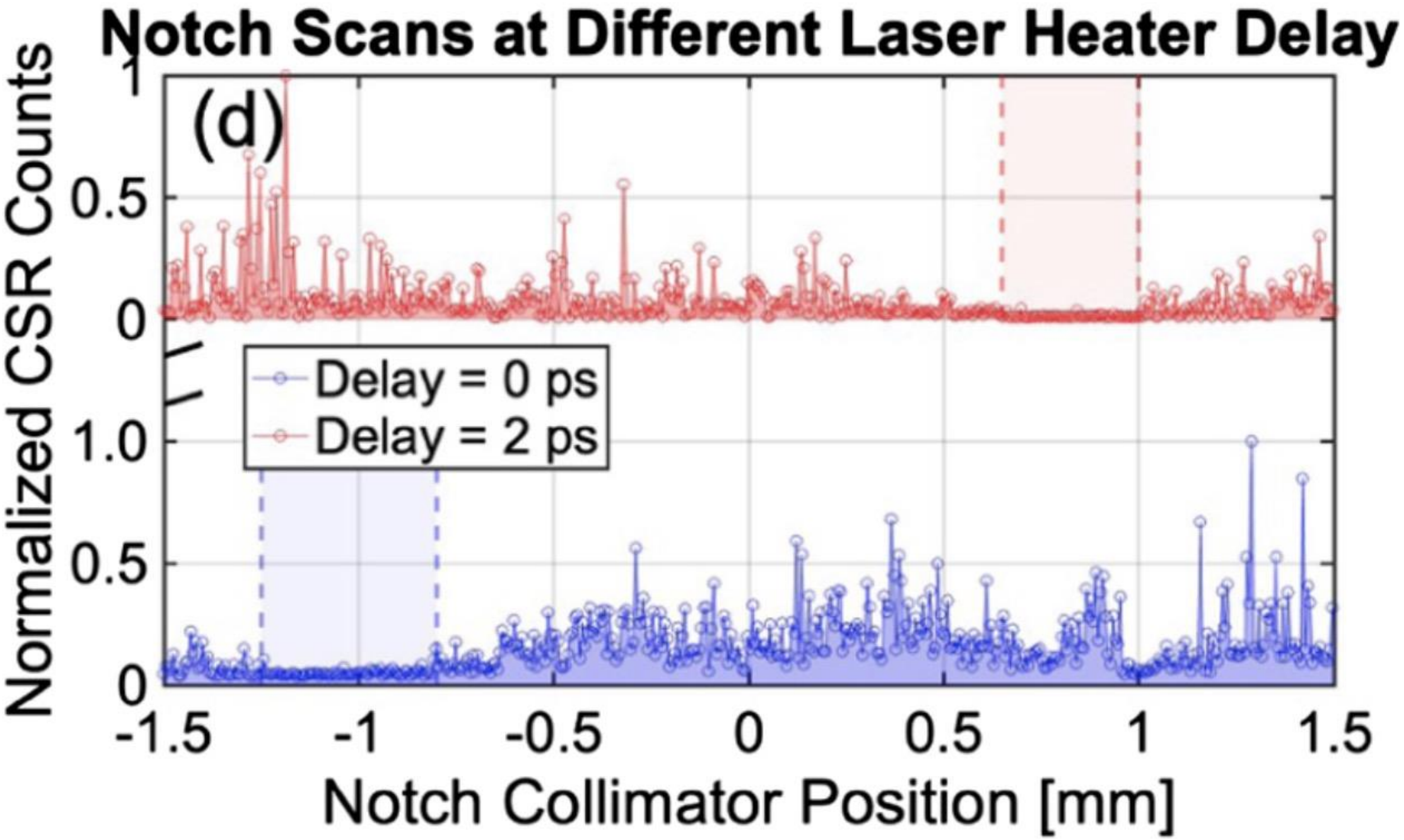
Chirped beams generated with Li oven sufficient for full compression in post-plasma chicane

Chicane installation status and plans



Magnets and mover built, currently testing, beamline installation planned for Oct-Nov

Controlling the spike position using laser heater delay



High current spike can be moved to head/tail of the bunch by changing laser delay