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

Claudio Emma, Linac Conference

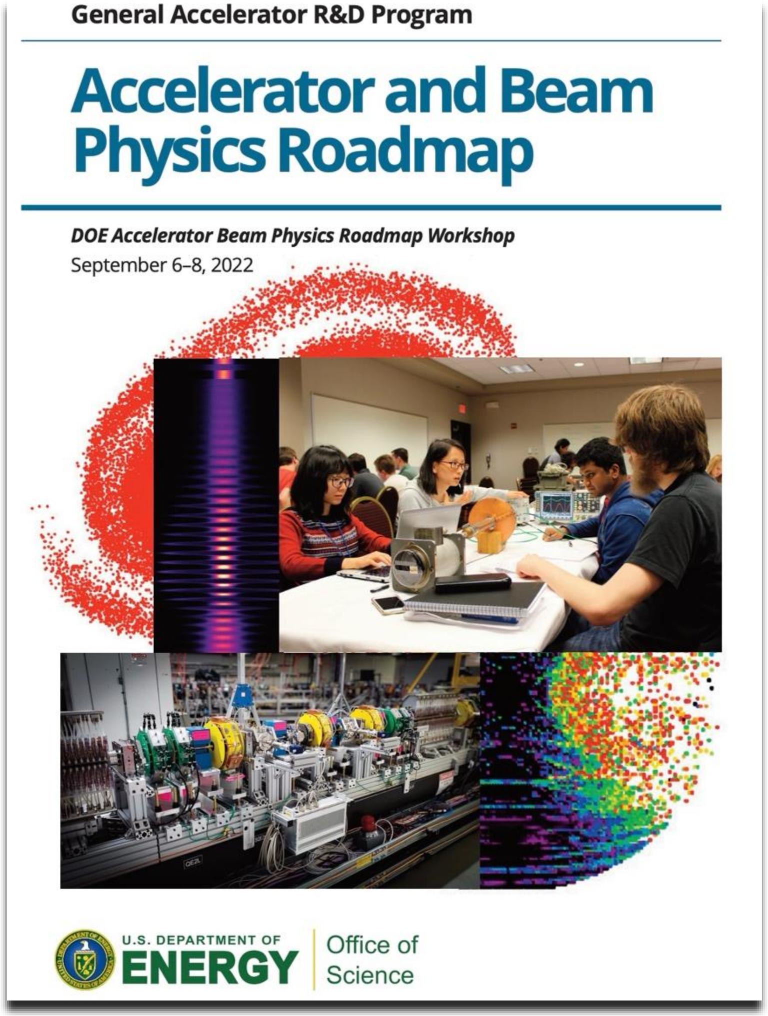
August 20th, 2026

FACET-II Facility for Advanced Accelerator Experimental Tests

Stanford University | U.S. DEPARTMENT OF ENERGY

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)

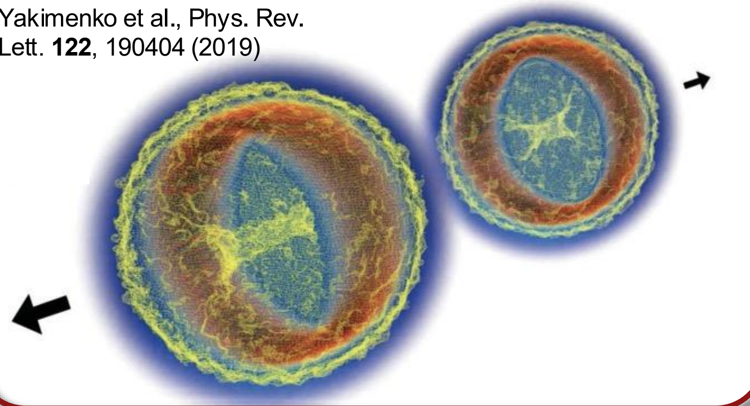
- Accelerated beams are unique probes of the natural world.
- Advances in our understanding of Nature come with improvements to beam brightness, intensity and control.
- Next generation experiments will require extreme beams with tailored properties beyond the state of the art.

Extreme beam research in line with GARD ABP roadmap

Science enabled by extreme beams

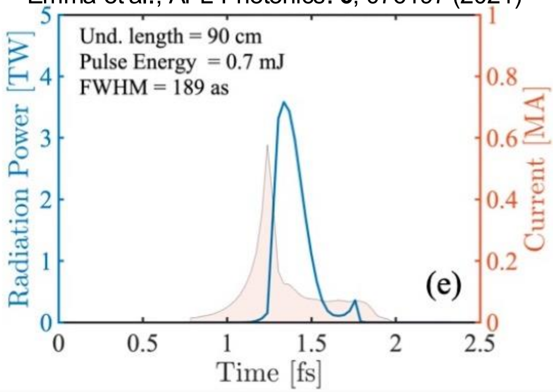
New Collider Concepts

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



Attosecond light sources

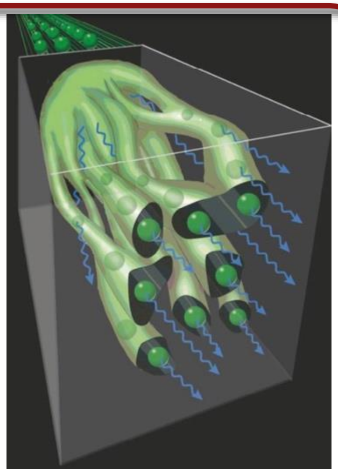
Emma et al., APL Photonics. **6**, 076197 (2021)



Laboratory Astrophysics

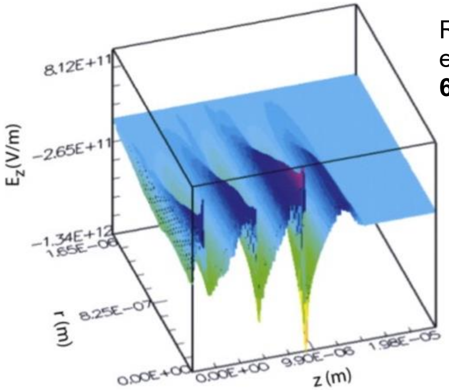
Macchi, Pegoraro, Nature Photonics **12**, 314 (2018)

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



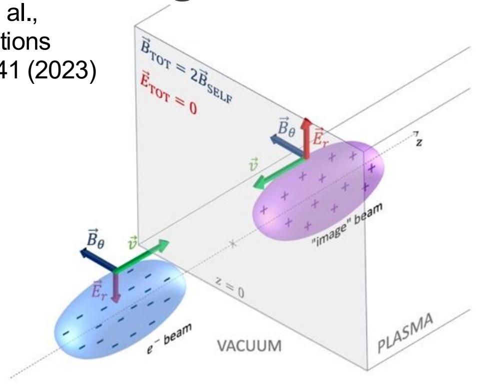
TeV/m Advanced Accelerators

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



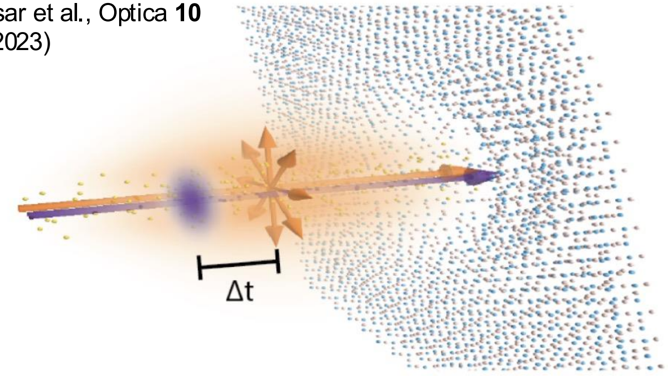
Strong field QED

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



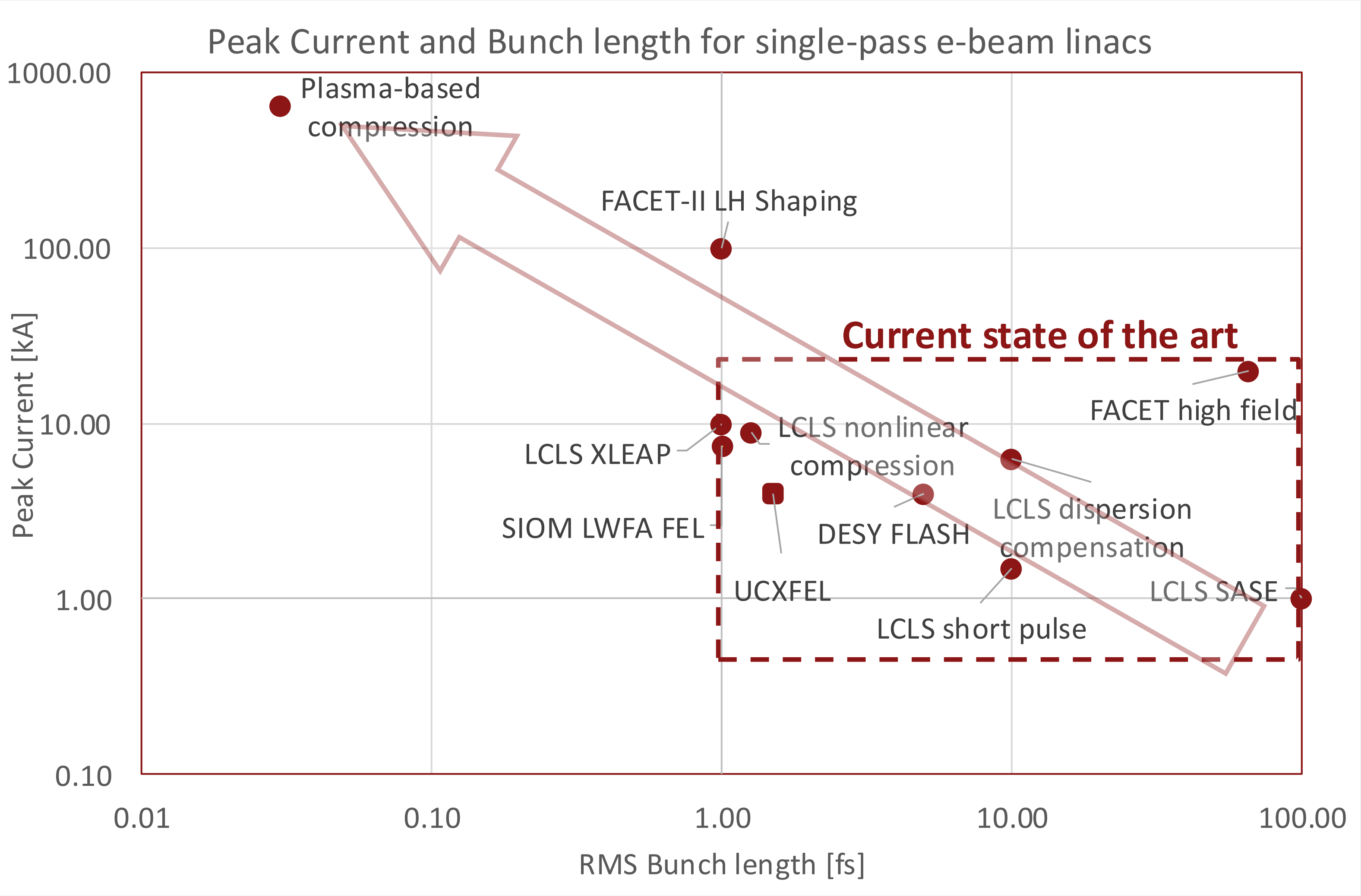
Ultrafast Quantum Dynamics

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



Extreme beams enable broad swathe of HEP and fundamental science experiments

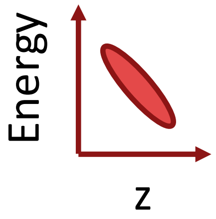
Current state of the art

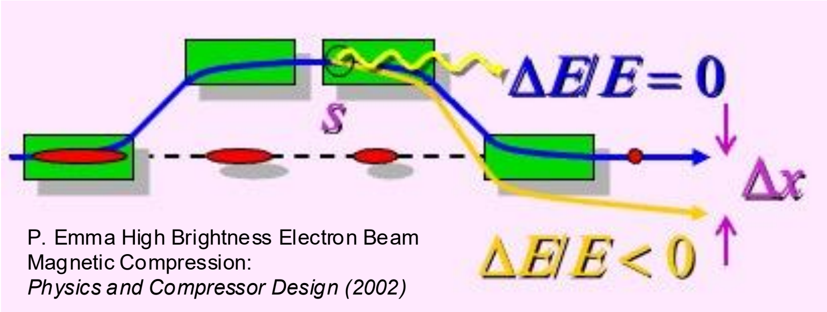


Extreme beams will be 1-2 orders of magnitude beyond state of the art

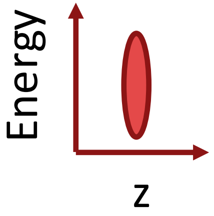
What are the challenges with extreme beams?

Extreme beams are hard to generate

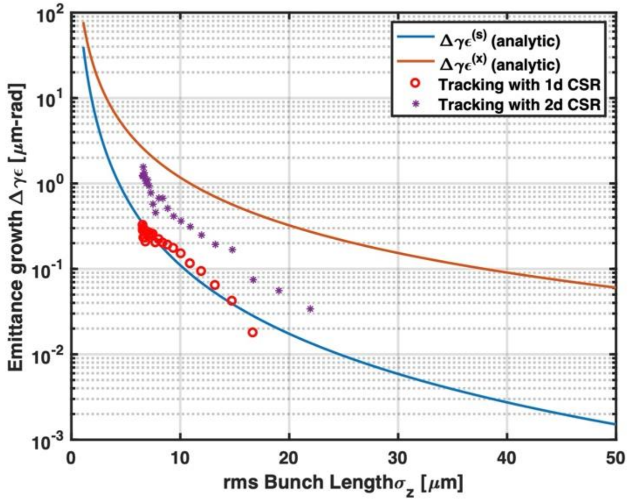


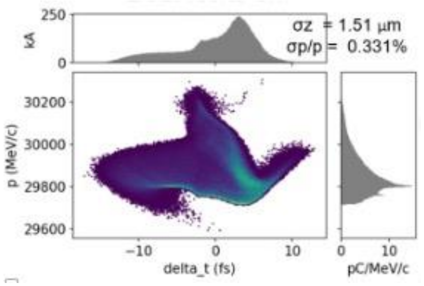


P. Emma High Brightness Electron Beam Magnetic Compression: *Physics and Compressor Design (2002)*



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





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

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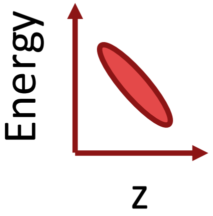

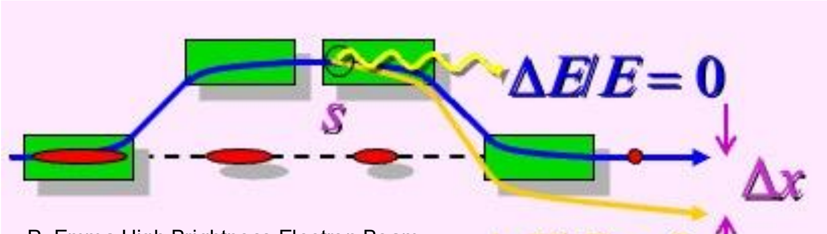

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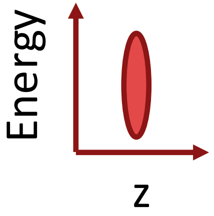

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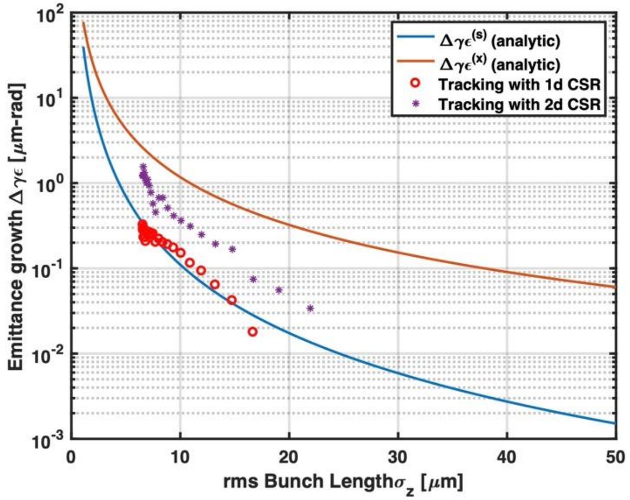
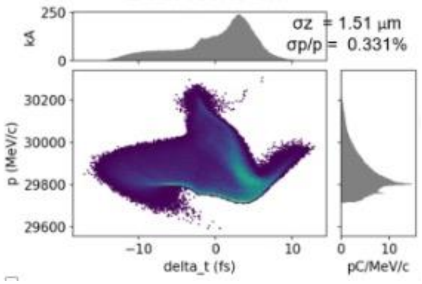
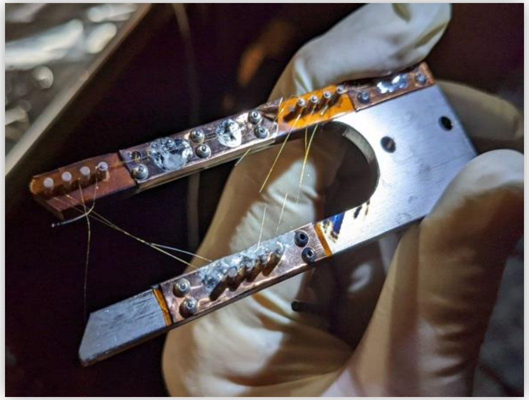


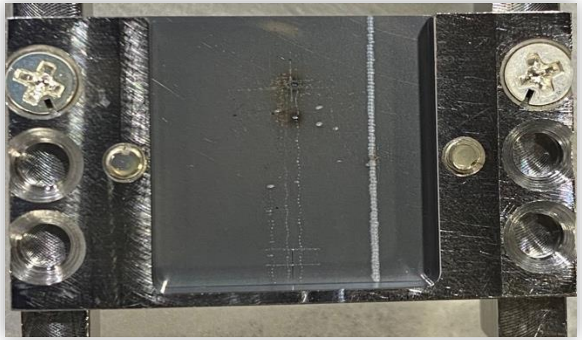


W. Lou, Y. Cai, C. Mayes, G. White Proc IPAC 2021 WEPAB234

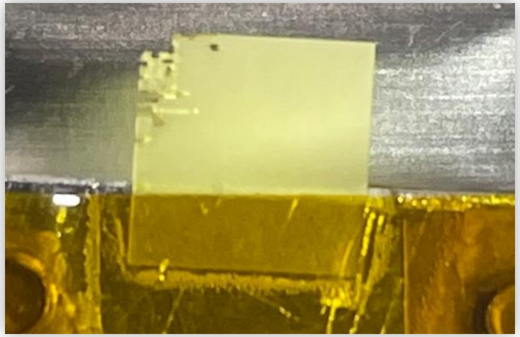
Extreme beams are hard to measure



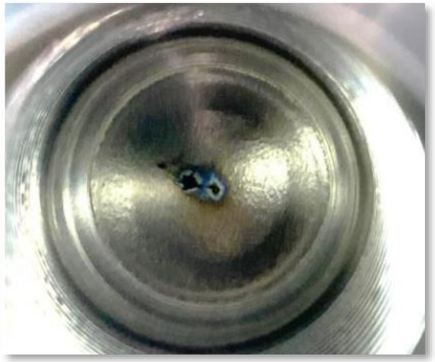
Wire scanner… shredded



Metal foil… drilled



YAG crystal… swiss-cheesed



Be window… opened

How can we address these challenges?

Laser-based compression

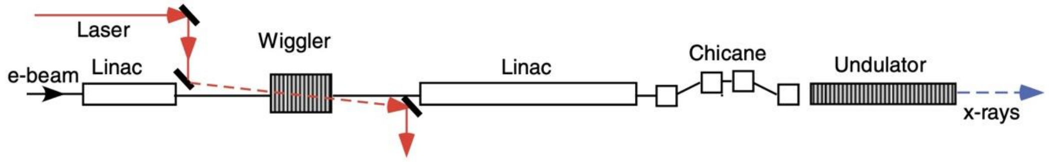
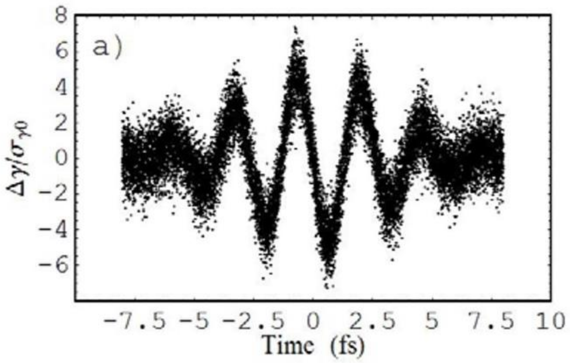
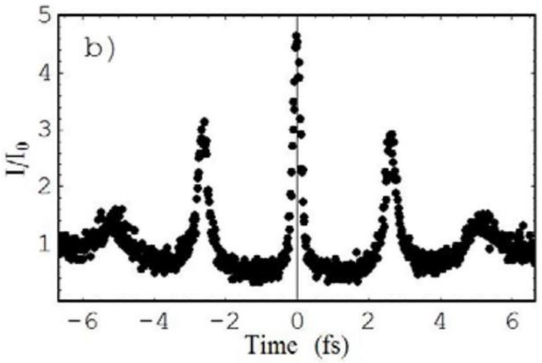


FIG. 1. (Color) A schematic of ESASE x-ray FEL.

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





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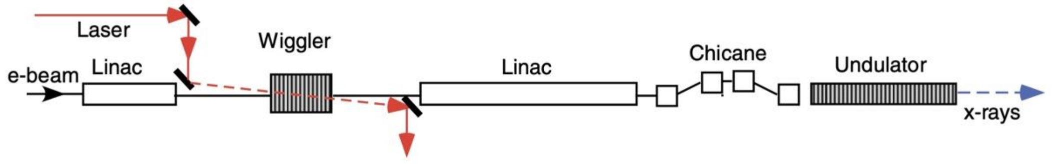

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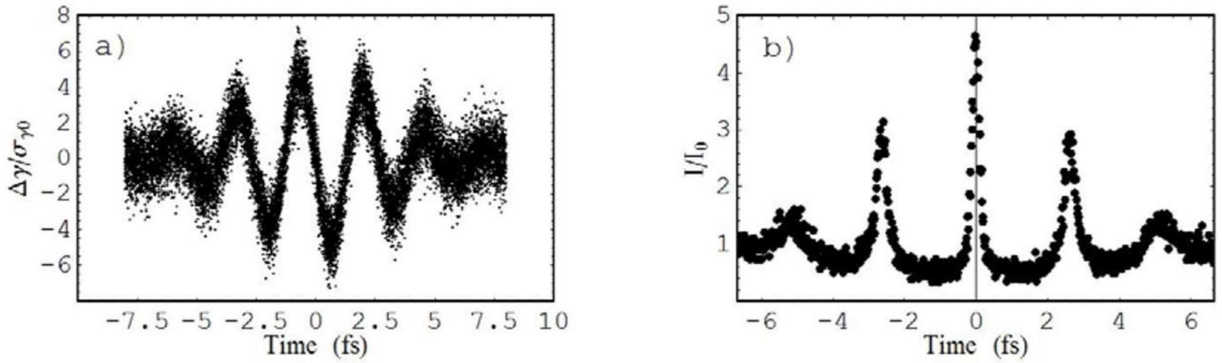
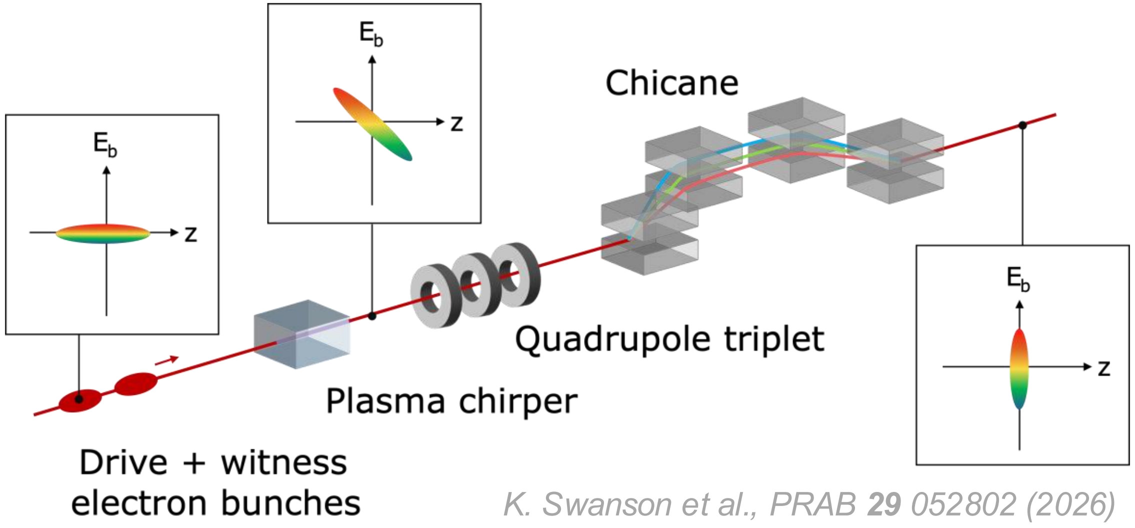


Plasma-based compression



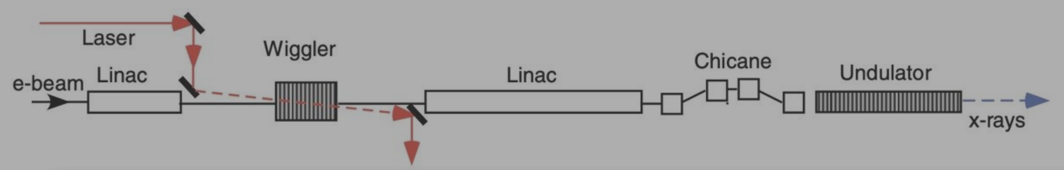
K. Swanson et al., PRAB **29** 052802 (2026)

Ideal for extreme compression

- Large fields → large chirps → small bend angles → less CSR
- Small slice energy spread → small final bunch length

How can we address these challenges?

Laser-based compression



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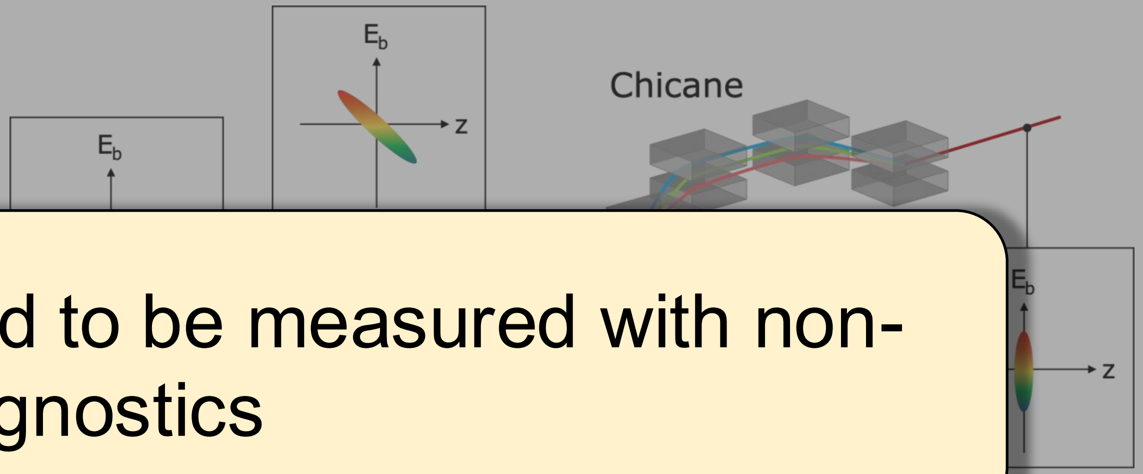

Extremely compressed beams need to be measured with non-intercepting diagnostics

current while preserving beam brightness

in PRAB

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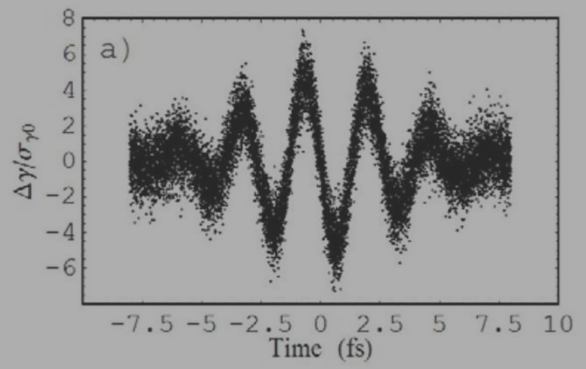
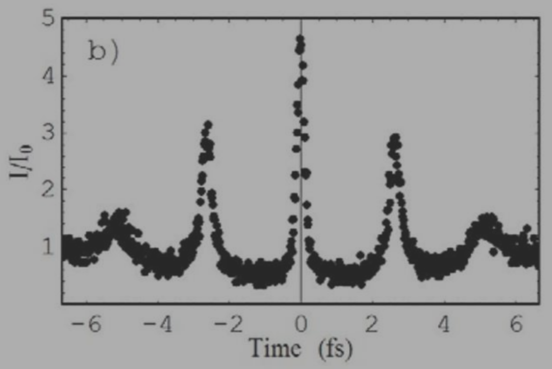
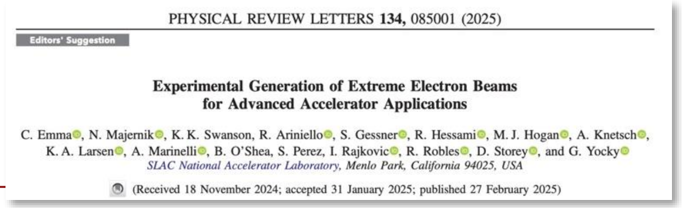




Laser based compression for 100 kA beam generation at FACET-II

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

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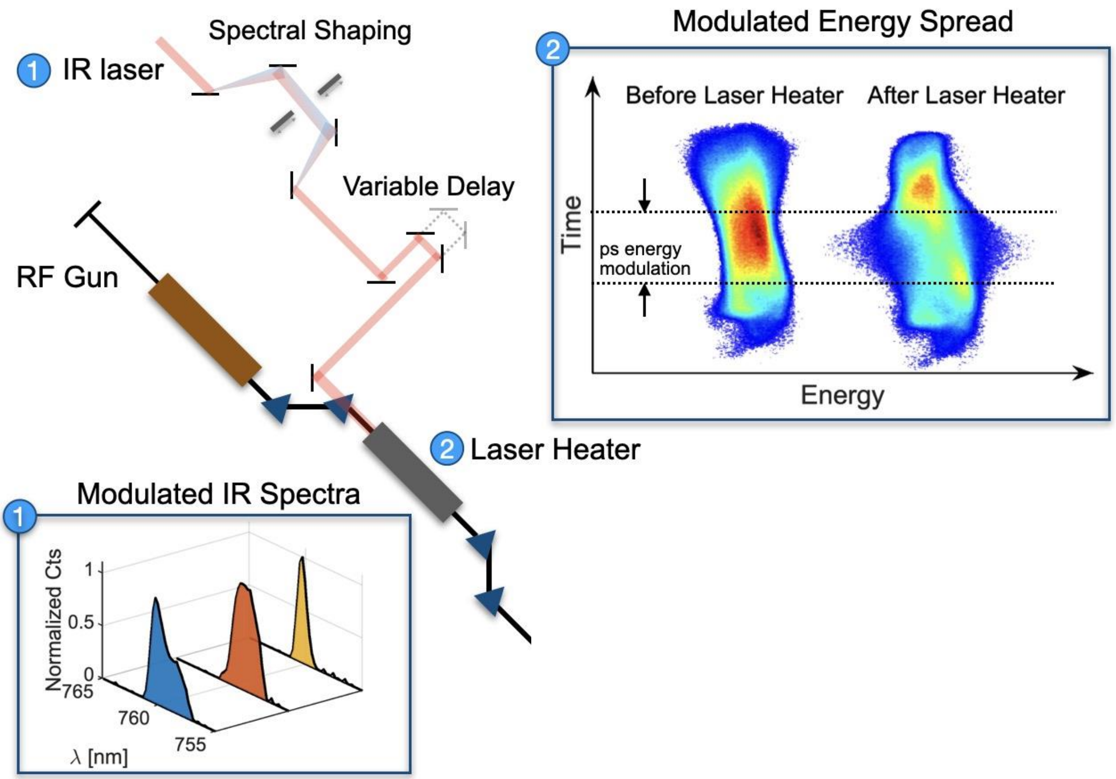

Laser shaping for PW beam generation at FACET-II


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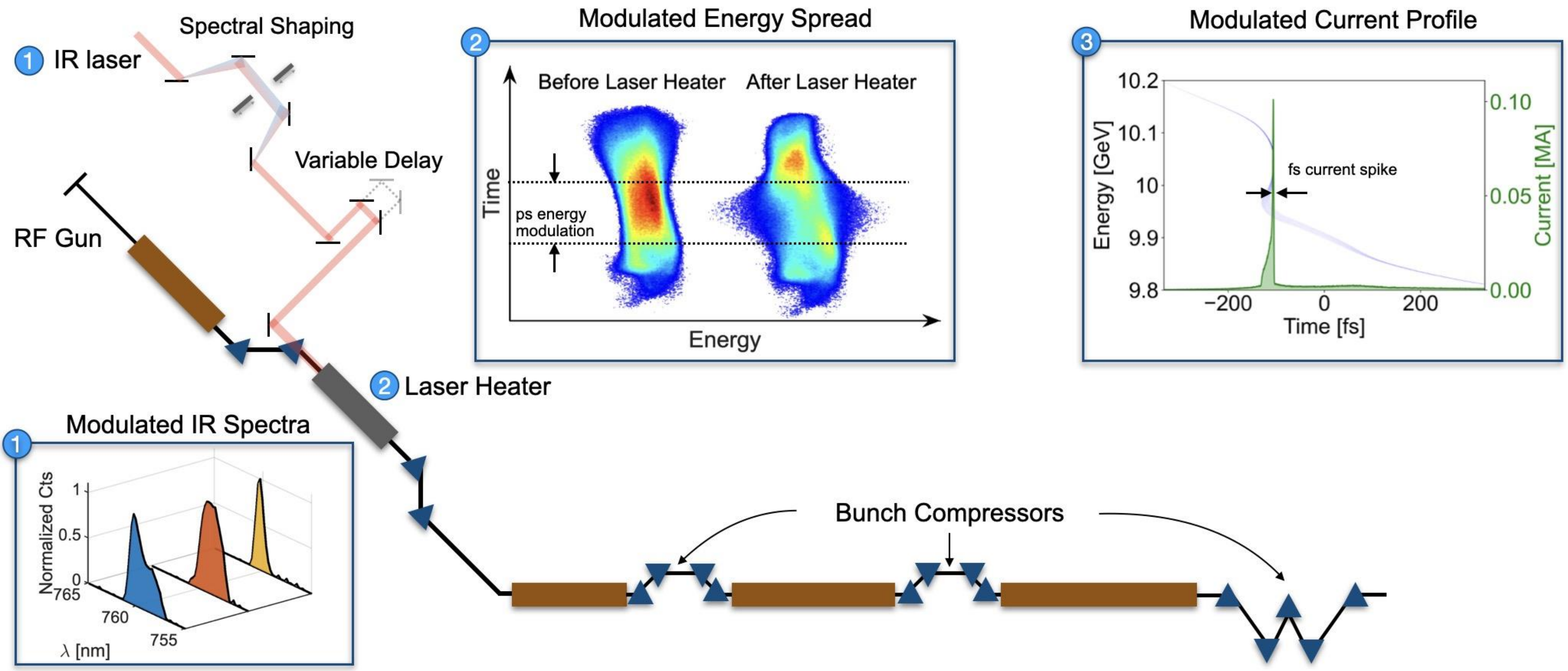

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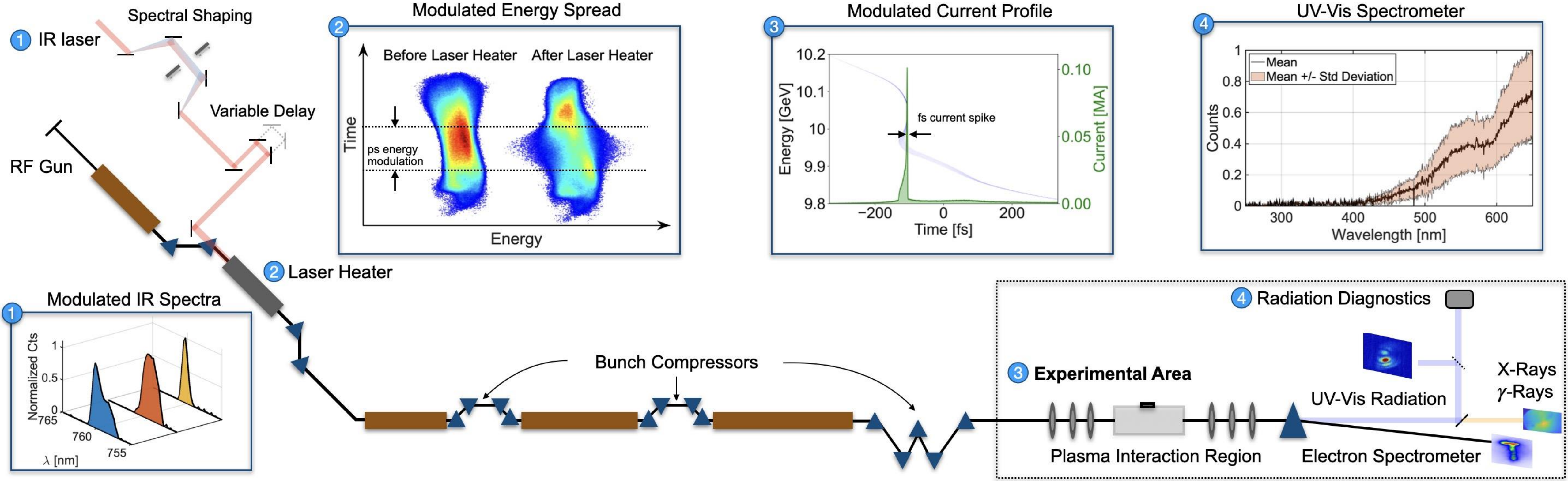

Original work done on LH Shaping experiments/sims at LCLS/LCLS-II: Marinelli et al., PRL (2016), D. Cesar et al PRAB (2021), S. Li et al APL (2024)

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

Estimating the spike duration


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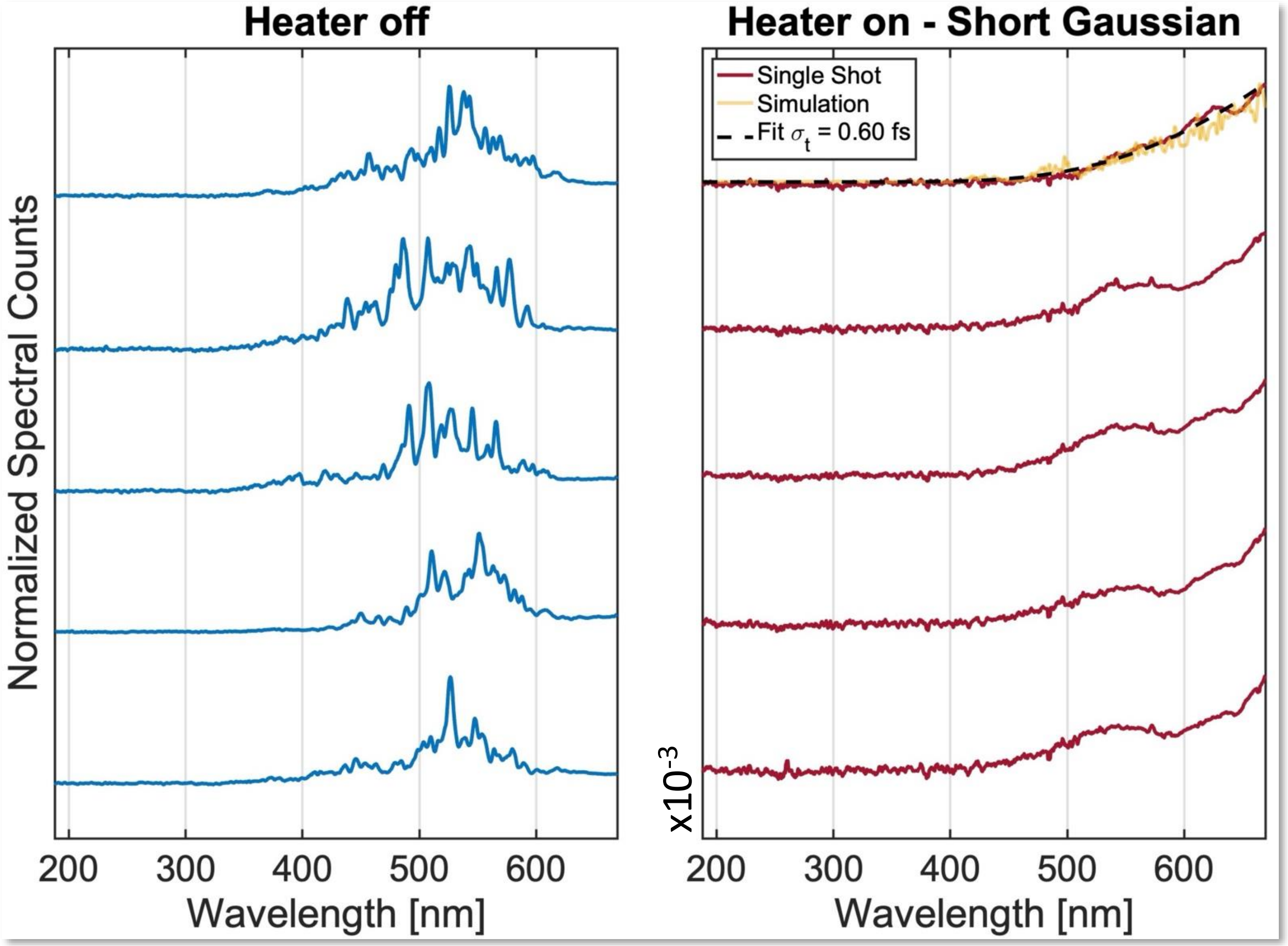

CSR spectra reveal RMS bunch length of LH seeded current spike O(1fs)

Using the current spike to ionize He


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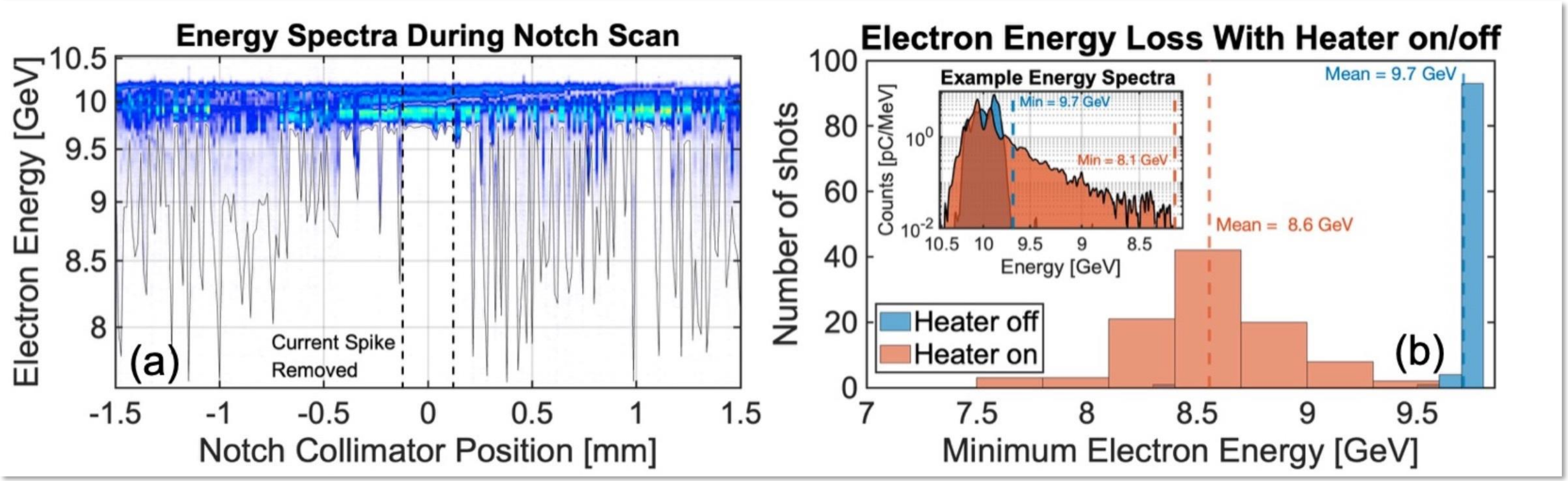
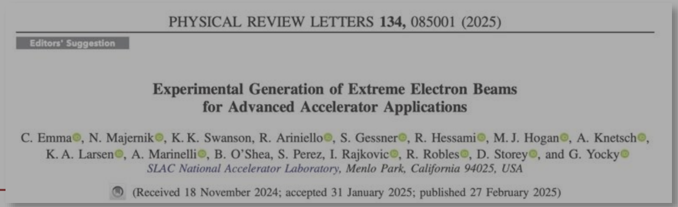


Current spikes enable controlled ionization of gas targets relevant to AAC applications

Using the current spike to ionize He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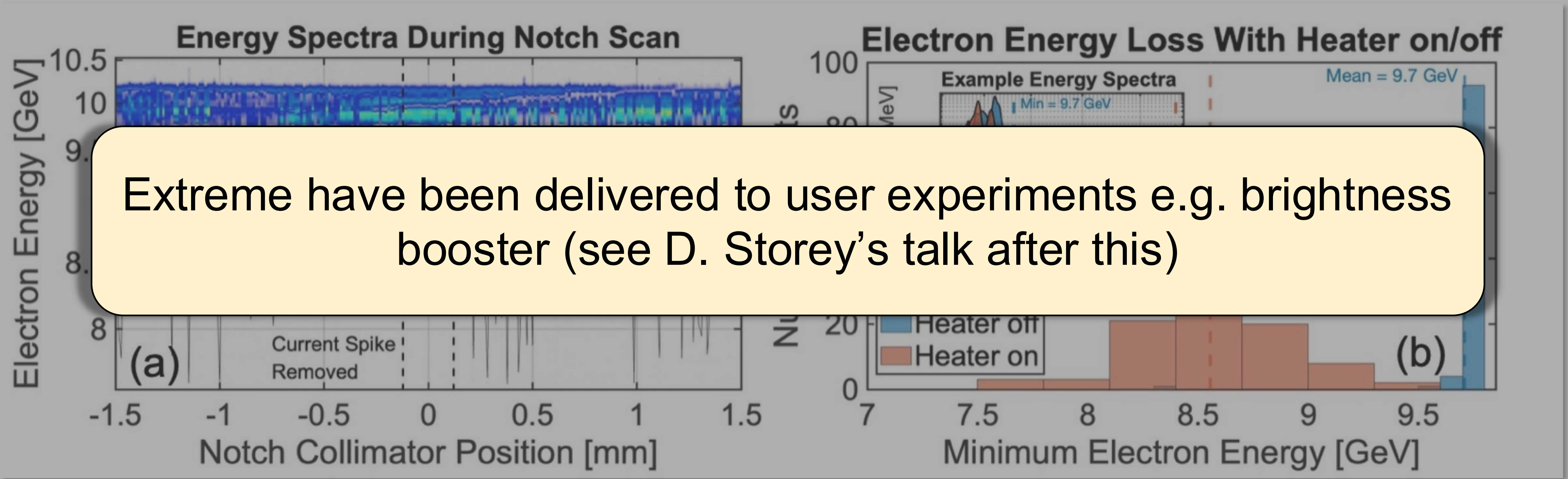
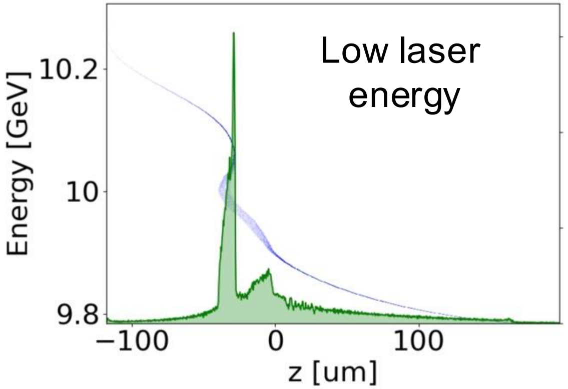


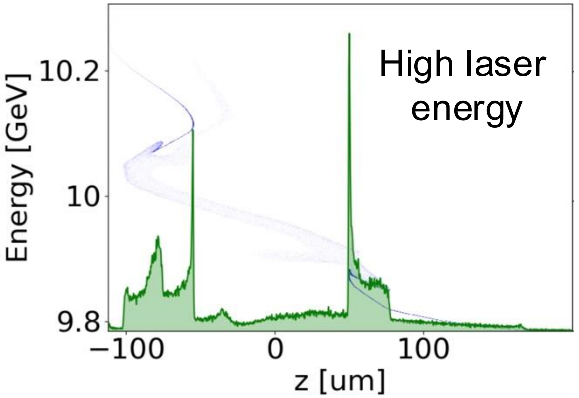
Extreme have been delivered to user experiments e.g. brightness booster (see D. Storey's talk after this)

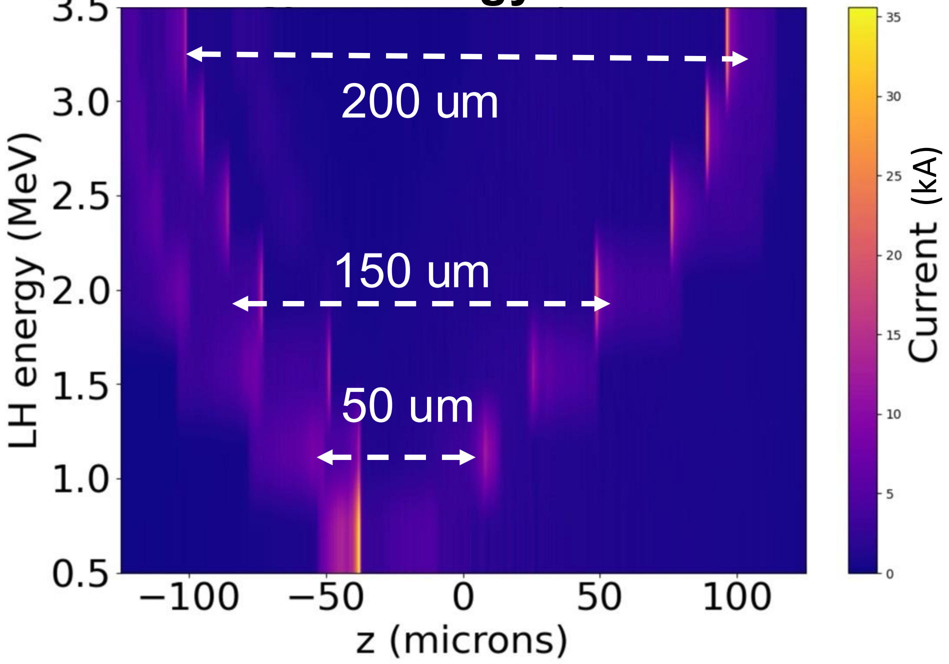
Current spikes enable controlled ionization of gas targets relevant to AAC applications

Next steps - advanced heater shaping modes

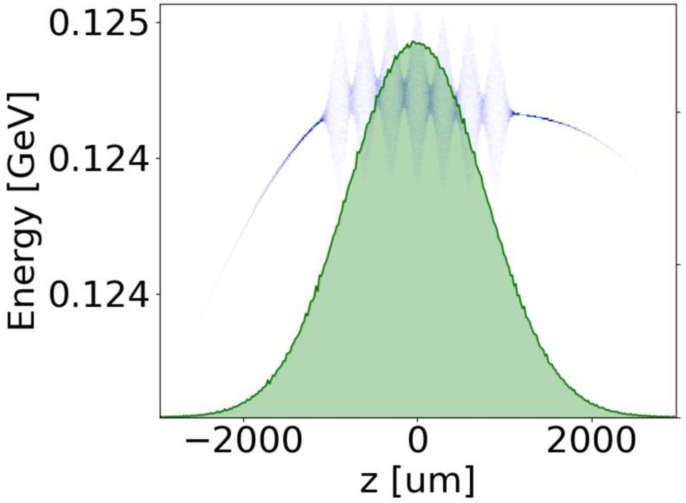
- Two bunches with variable spacing







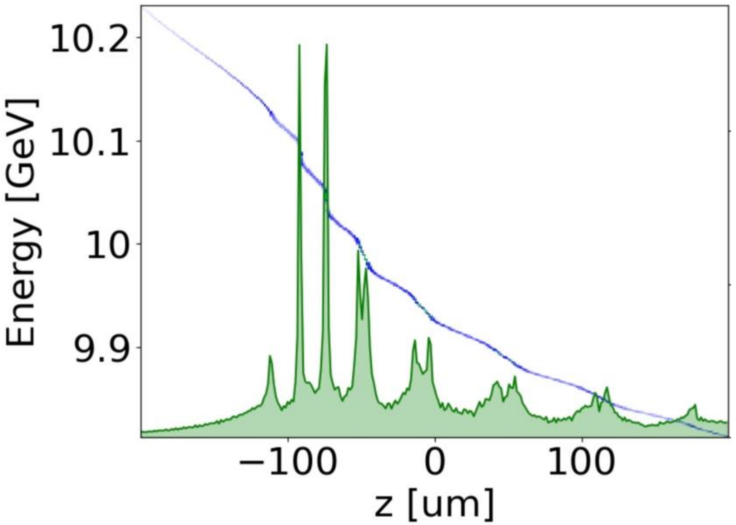
- Multi-spike for resonant PWFA



At Laser Heater

Collaboration with INFN

See e.g. L. Verra, M. Galletti et al PRE 112, 045205 (2025)



At Experiment

Next steps - advanced heater shaping modes

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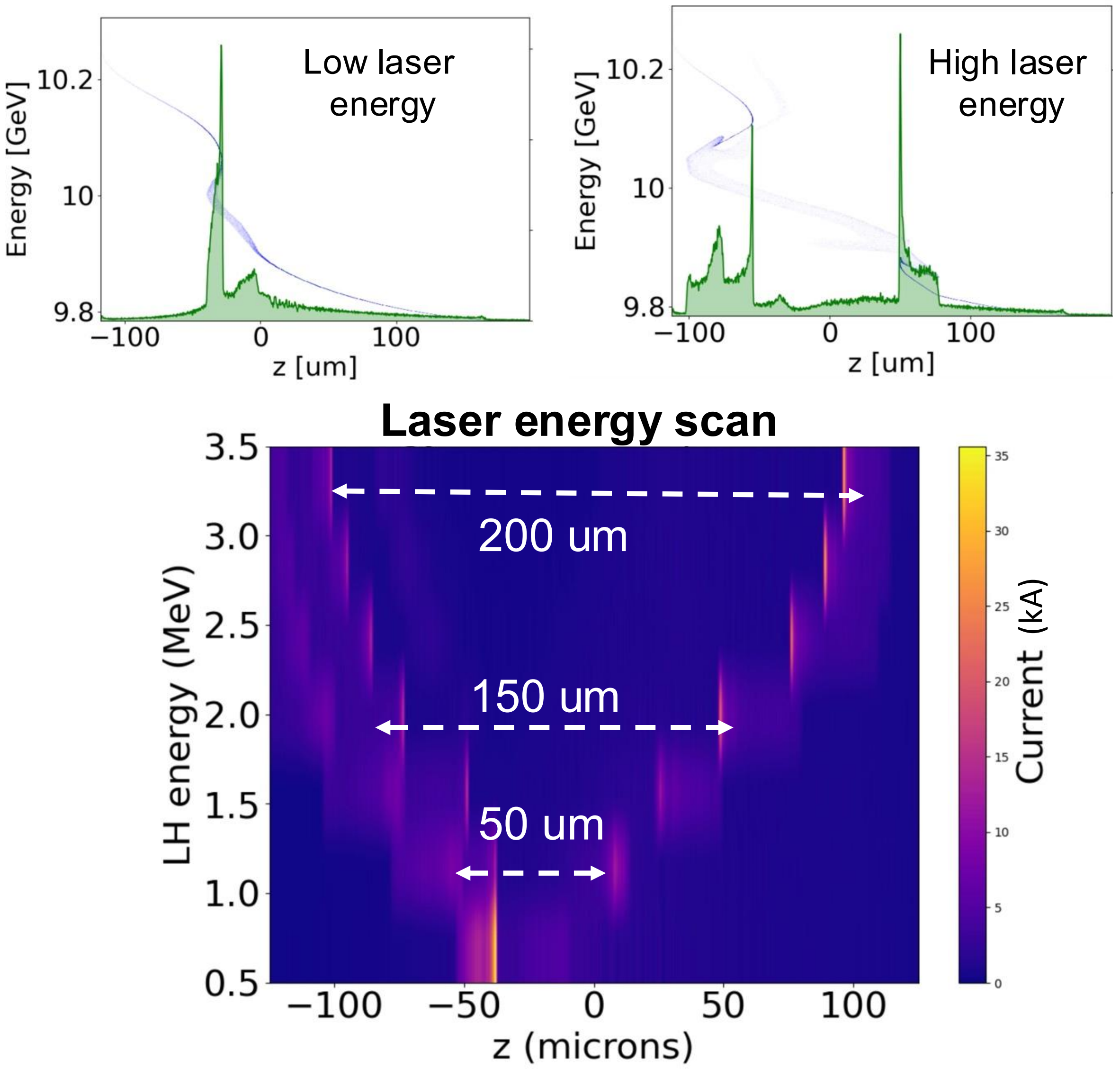
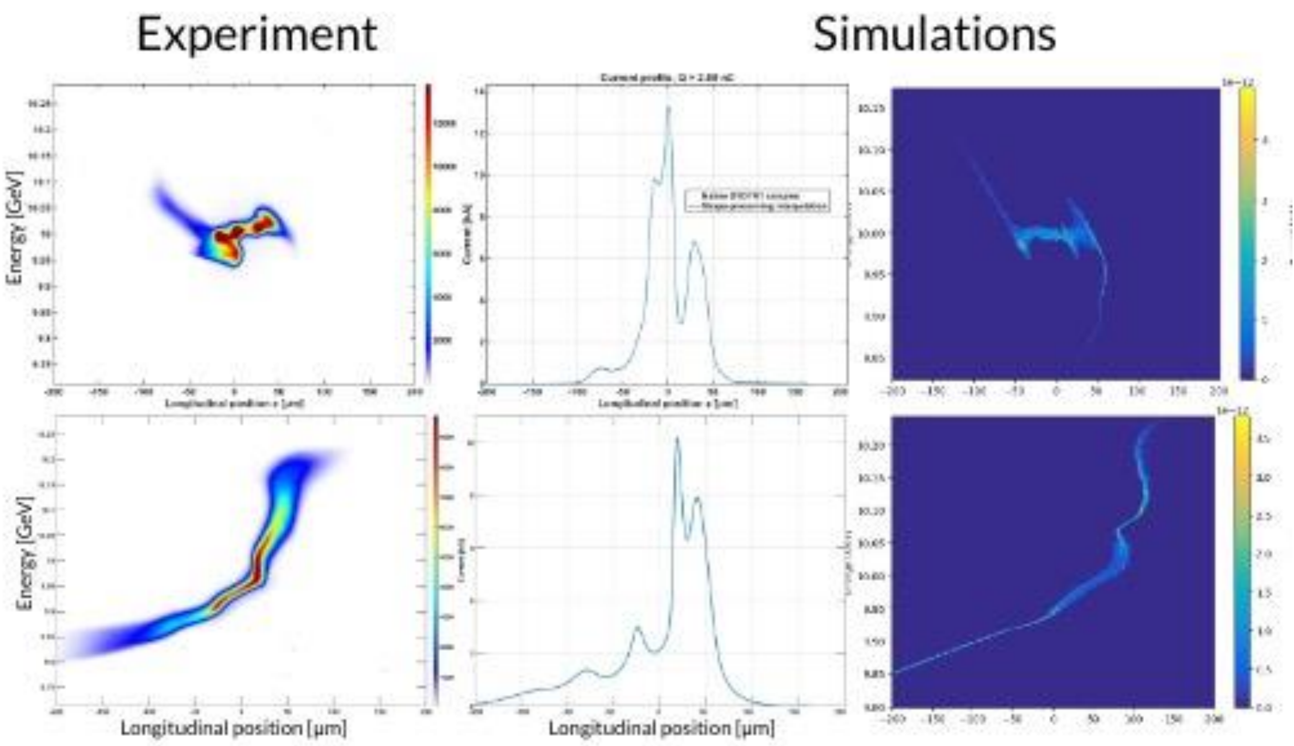


- Multi-spike for resonant PWFA

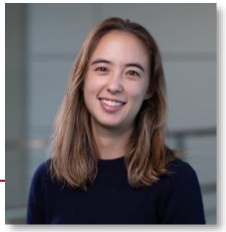
Preliminary experimental data from FACET-II 6/2026

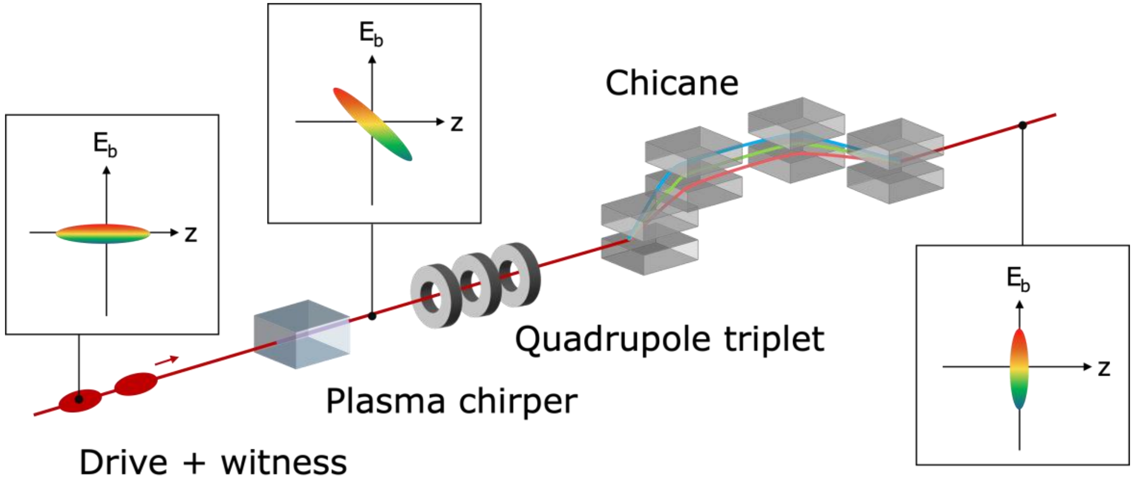


A. Kinderman

Plasma based compression for MA beams and attosecond X-rays

Plasma-based compression for MA beams

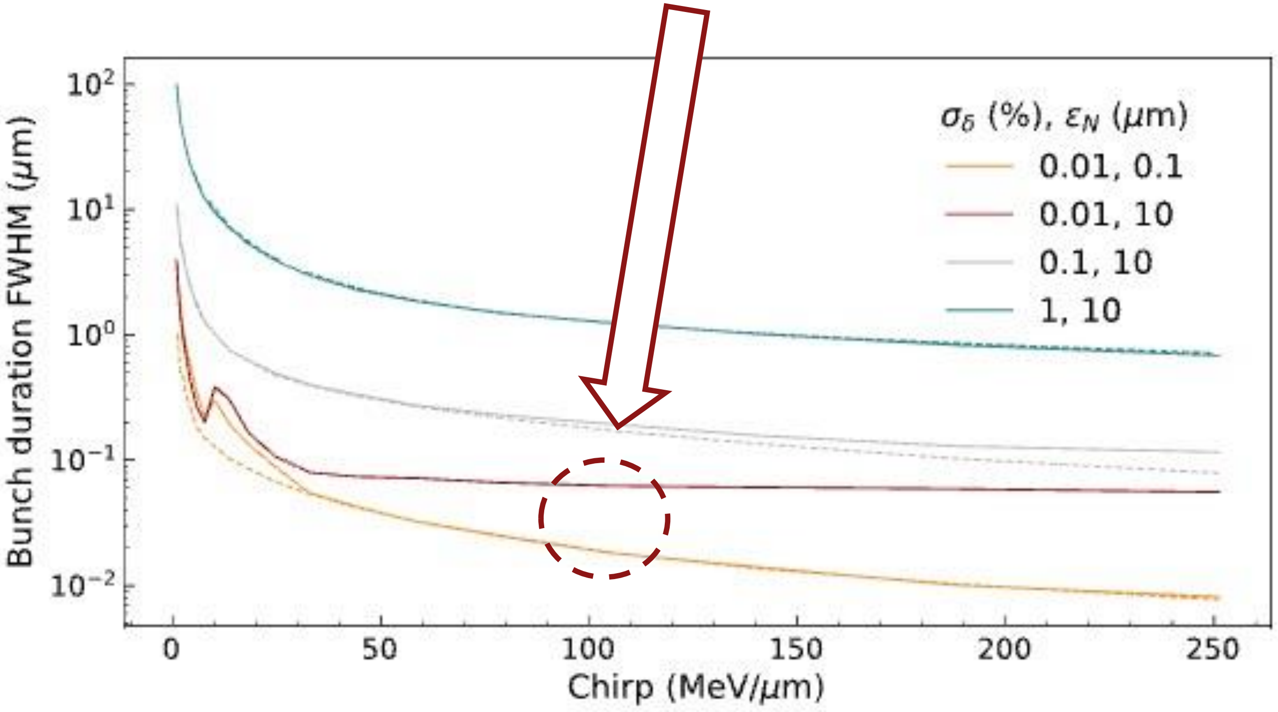




K. Swanson et al., PRAB **29** 052802 (2026)

Chirps of 100 MeV/um measured at FACET-II

Compression down to 10s-100 nm possible



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

PAX: a Plasma-driven Attosecond X-ray Source

Large plasma fields impart large energy chirp

↓

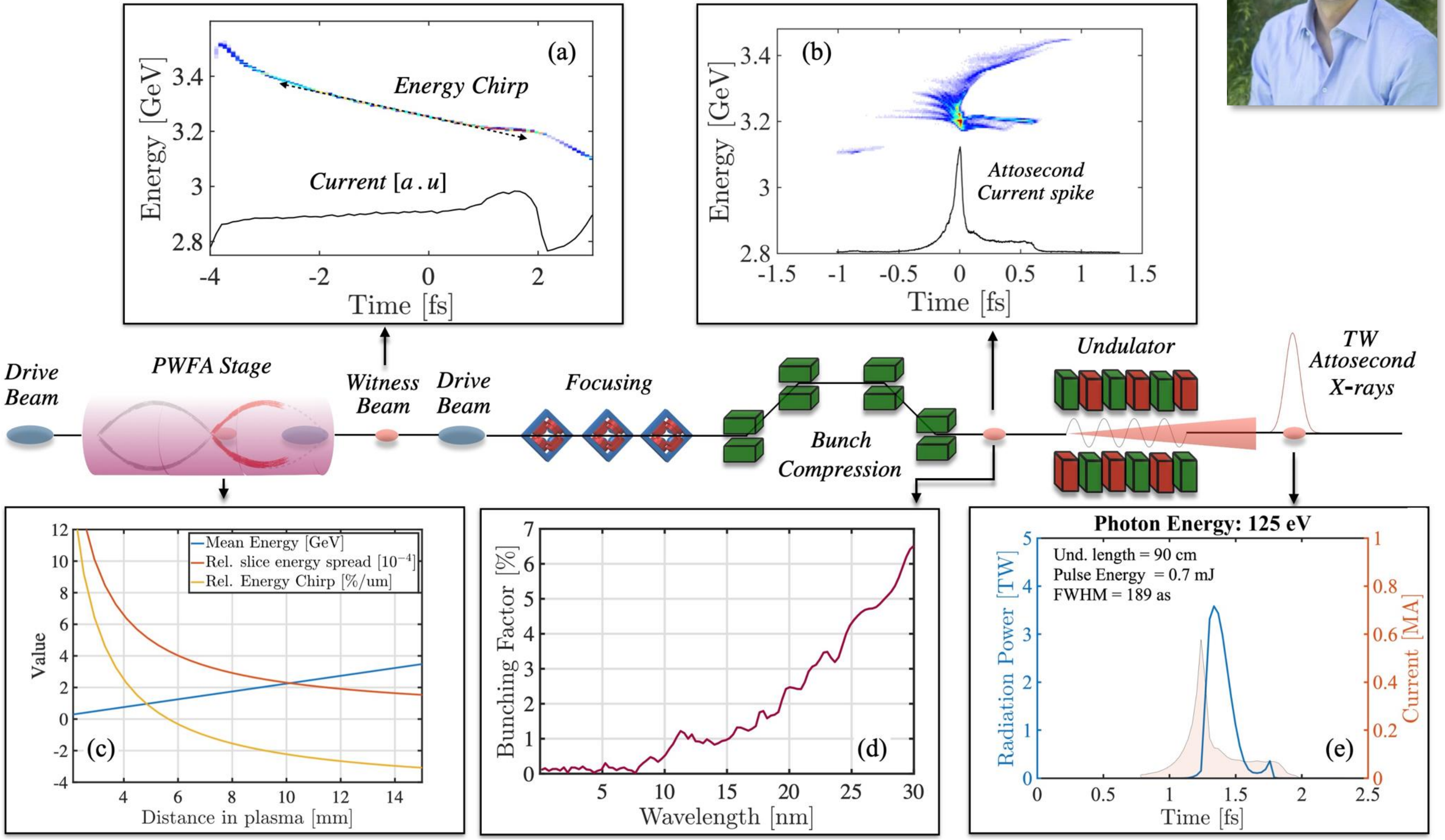
Weak chicane compresses e-beam to as-duration

↓

Beam is bunched at soft X-ray wavelengths

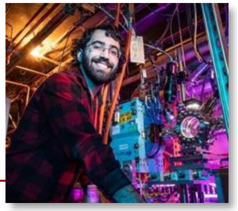
↓

Pre-bunching relaxes tolerance on energy spread, emittance, pointing stability



PAX combines benefit of HHG sources and attosecond XFELs – complementary to LCLS

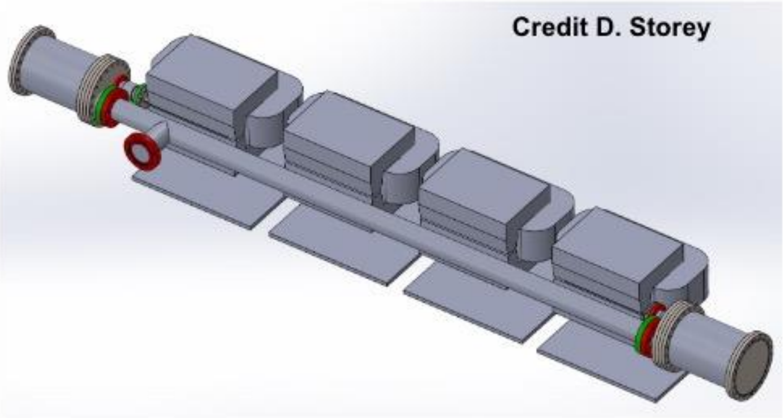
Plasma-based compression experiment at FACET-II



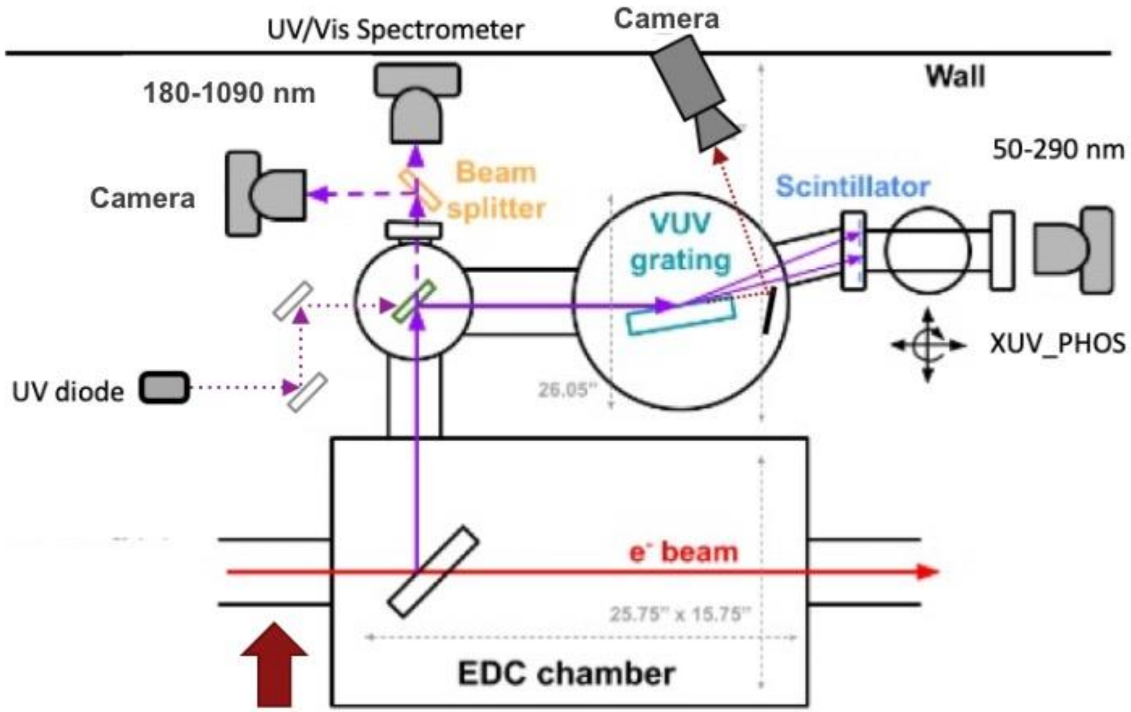
Plasma Sources

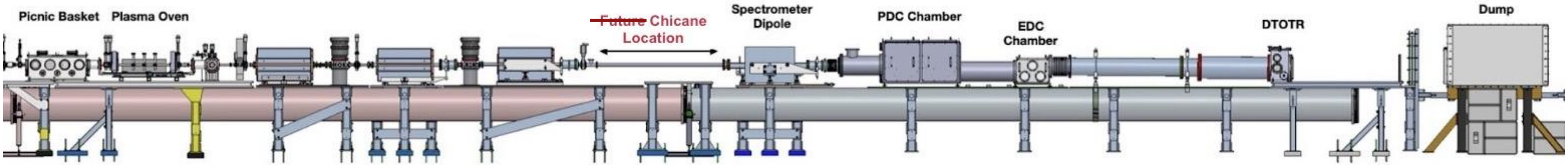
- Gas Jet
  $n_e = 10^{18} – 10^{20}$ cm^{-3}
- Li Oven
  ne = $10^{16} – 10^{27}$ cm^{-3}
- Static fill

Chicane + bypass line



Spectral Measurement Setup





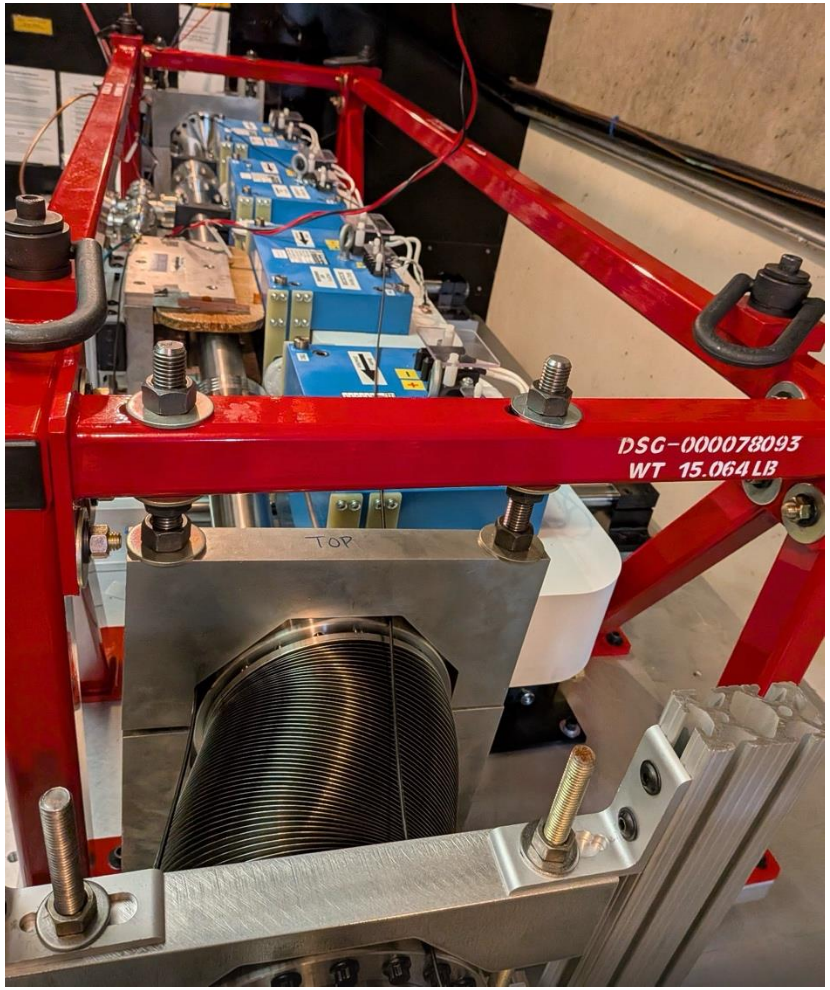
Planned experiments at FACET-II to explore extreme compression in upcoming run

Hardware installation

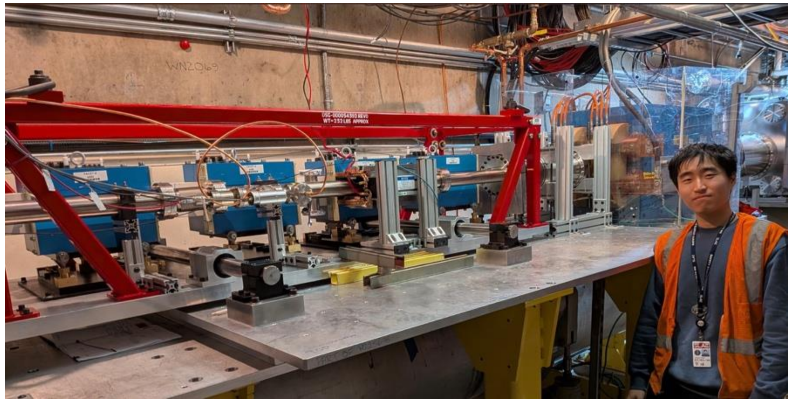
Magnets + mover bench tested (Oct 2025)

Big empty space in beamline waiting for chicane…

Chicane + mover installed on beamline (Feb 2026)



Happy faces!



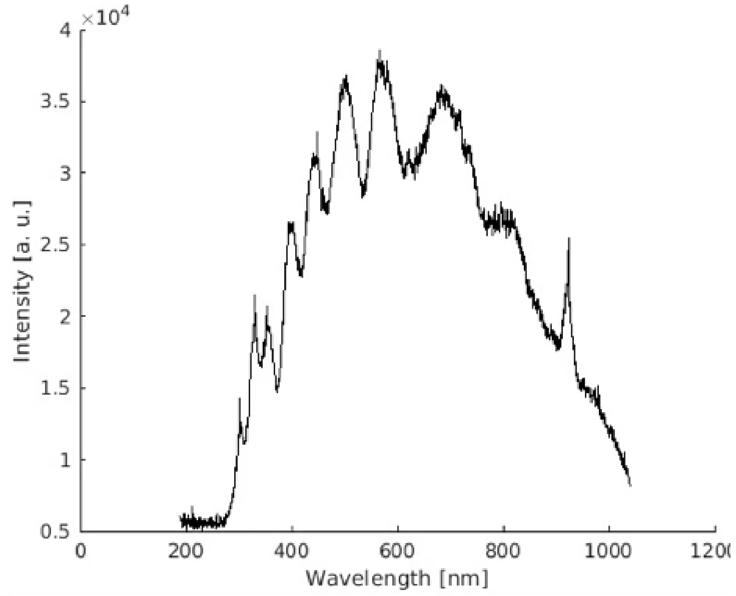
Magnets and mover installed and commissioned with beam

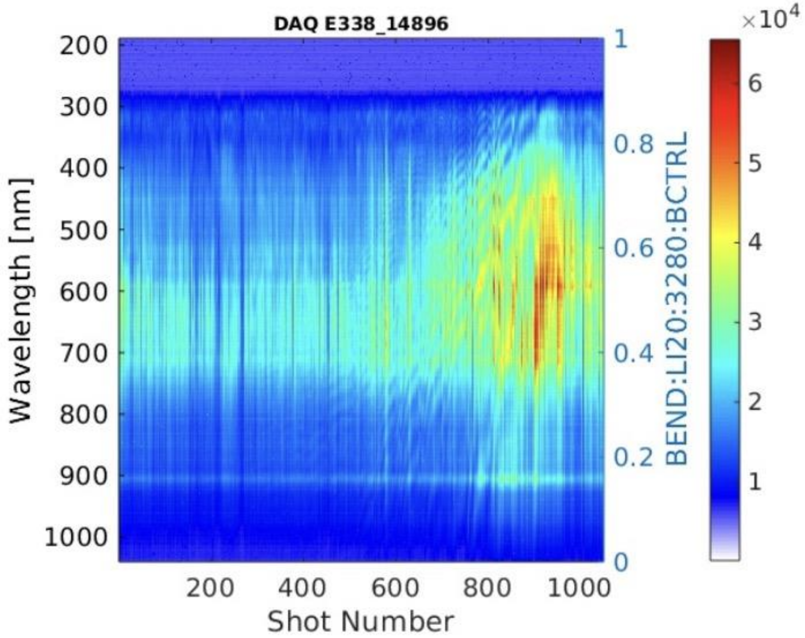
First plasma + chicane results

Preliminary

Lithium oven plasma

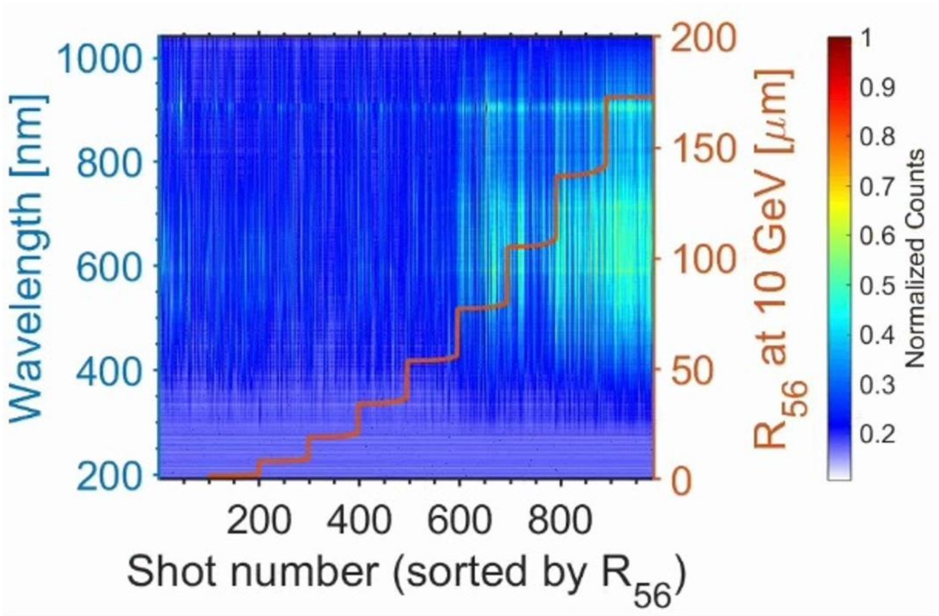
Interference observed between two magnets - fringe spacing controlled with dipole field





Hydrogen plasma

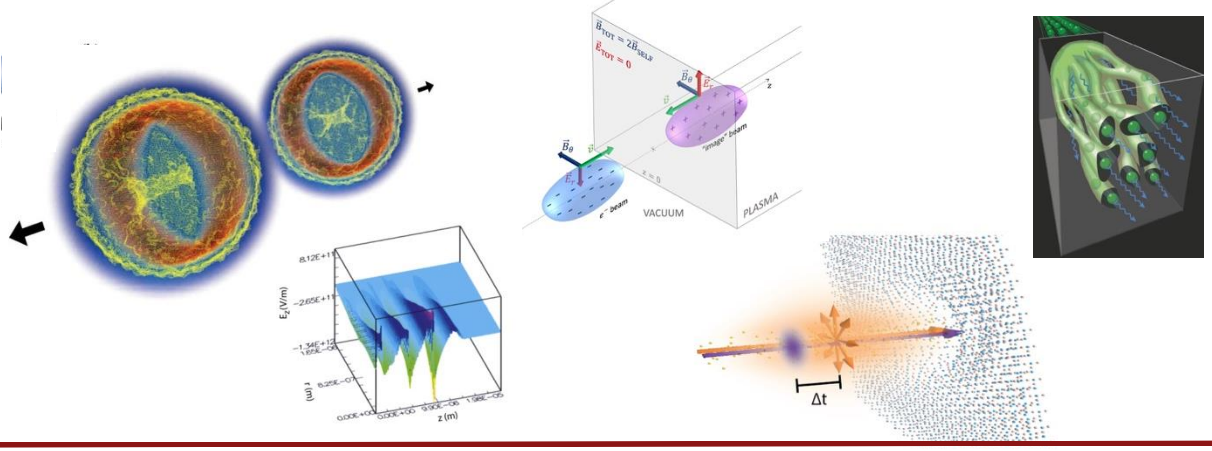
Evidence of beam compression with increasing magnetic field



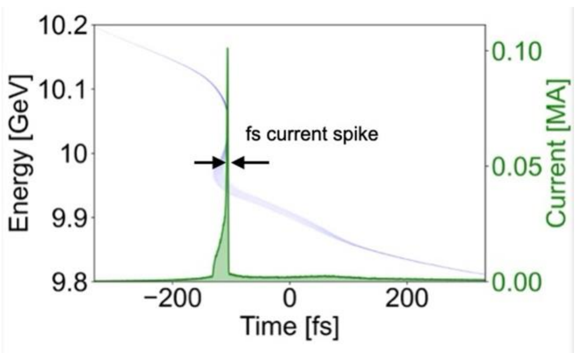
First experiments observe coherent emission from beam after plasma exit

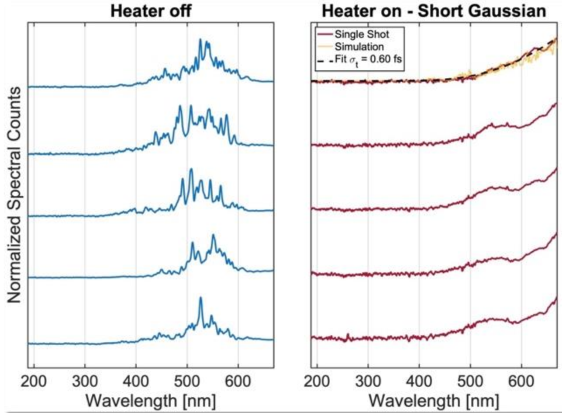
Summary and outlook

Extreme electron beams will be the beams of the future, serving experiments across scientific domains.

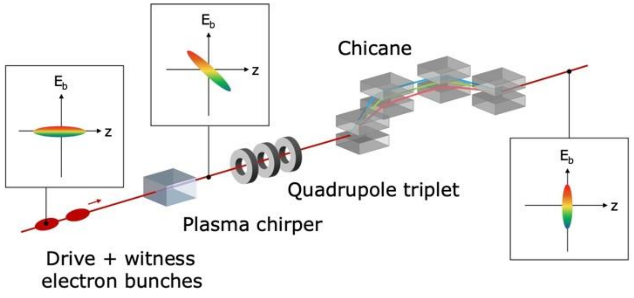


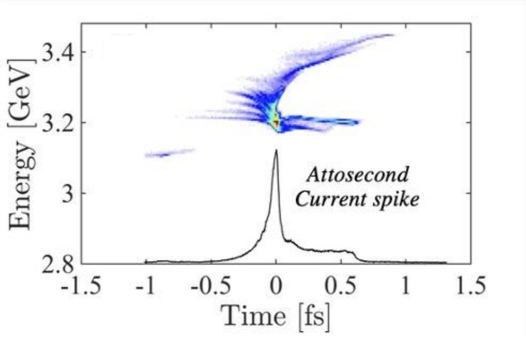
At FACET-II we have started generating, characterizing these beams and delivering them to users.



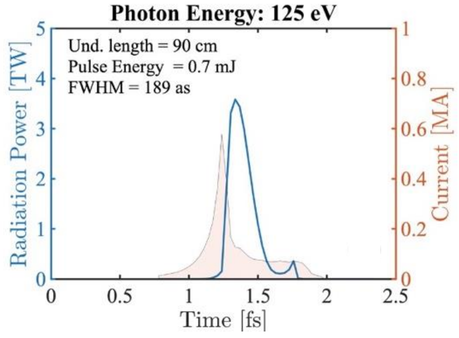


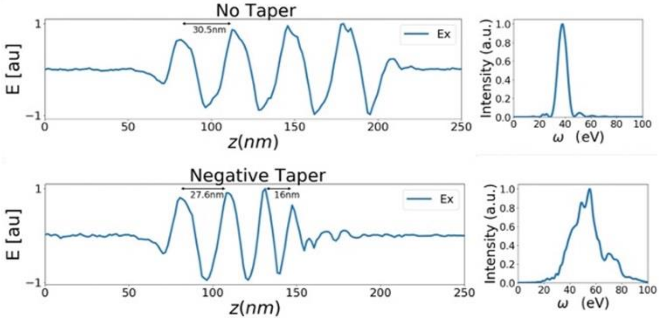
Plasma-based compression will further push currents from 0.1 to 1 MA and bunch length from fs to as





A dedicated program exists to exploit extreme beams for attosecond XUV/X-ray generation.





FACET-II is pursuing extreme particle and photon beam science

Acknowledgments

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

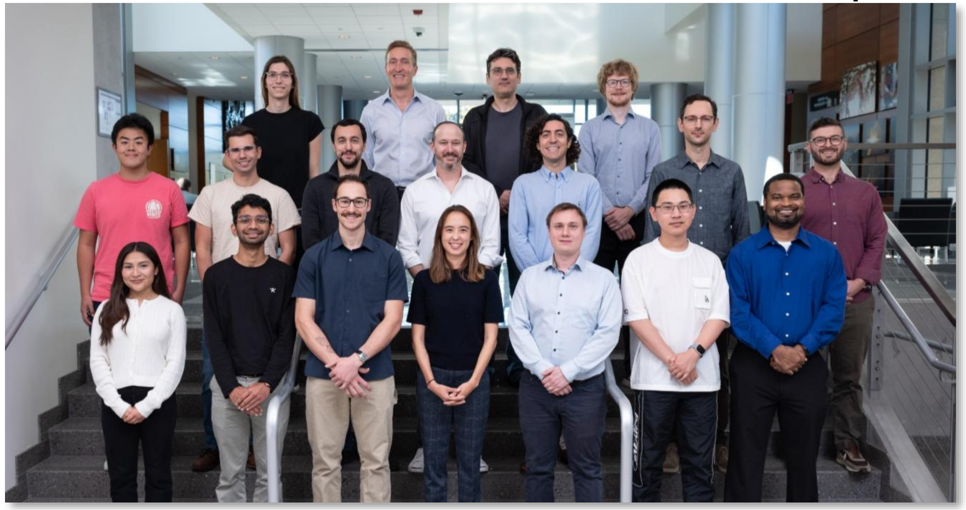
- FACET-II Scientific User Program, in particular E338, E300, E304 collaborations

- 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

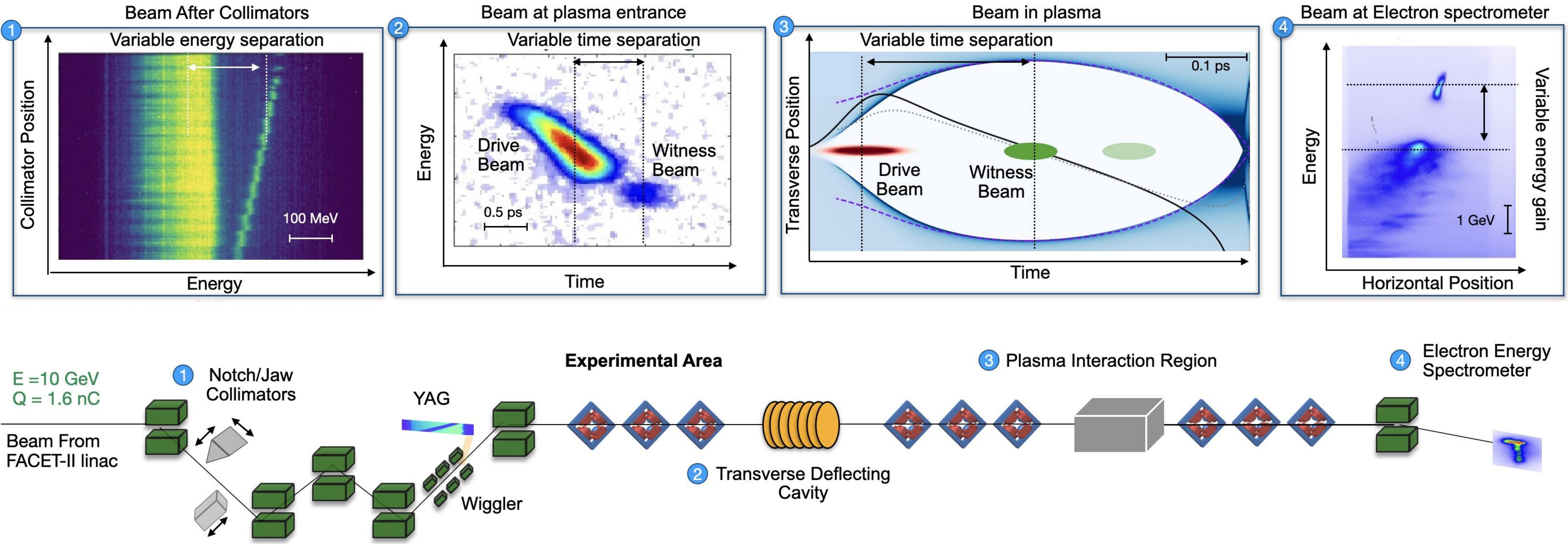
PAX group

Advanced Accelerator Research Dept



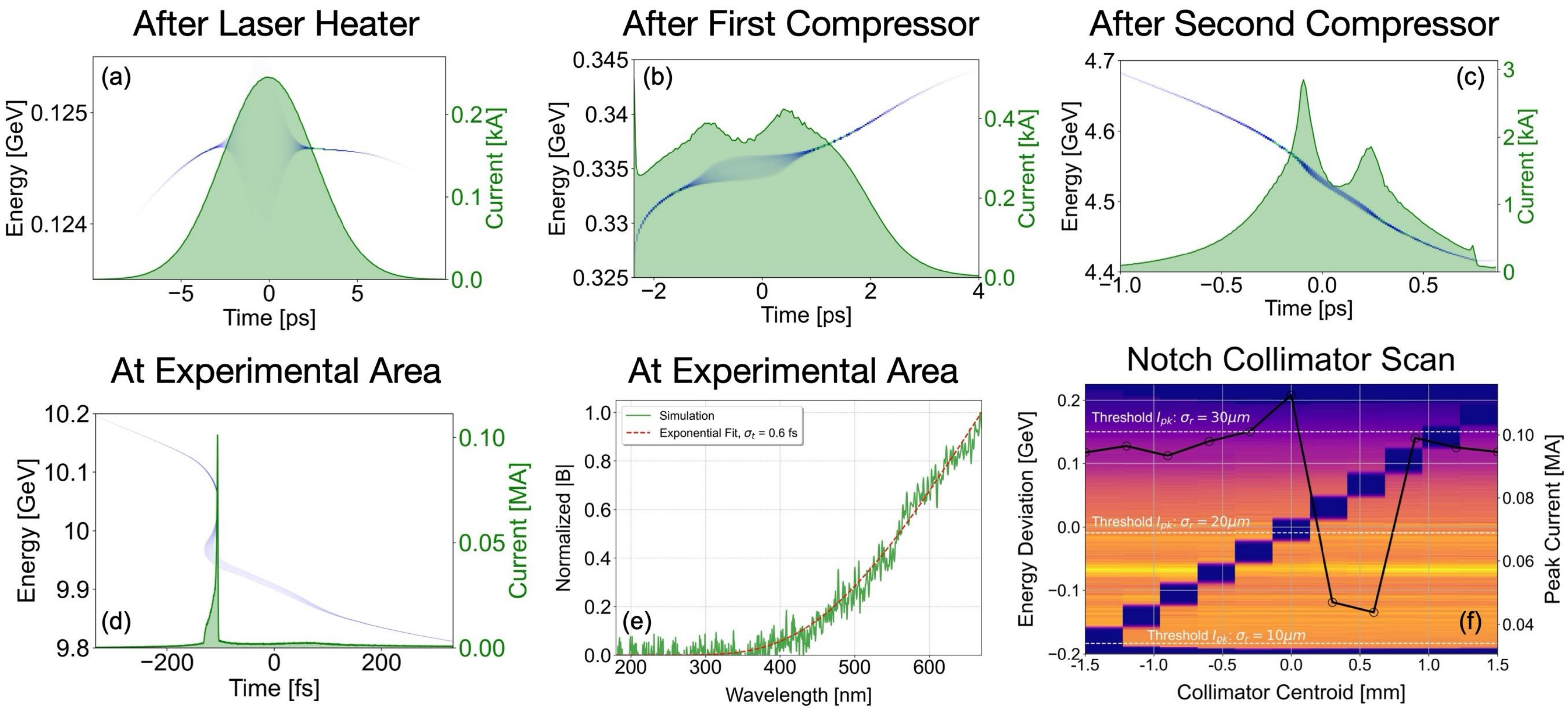
Backup slides

External injection experiments at FACET-II



Wakefield mapping with external injection enables controlled chirp measurements

Particle tracking simulations of the spike generation



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


PHYSICAL REVIEW LETTERS 134, 085001 (2025)

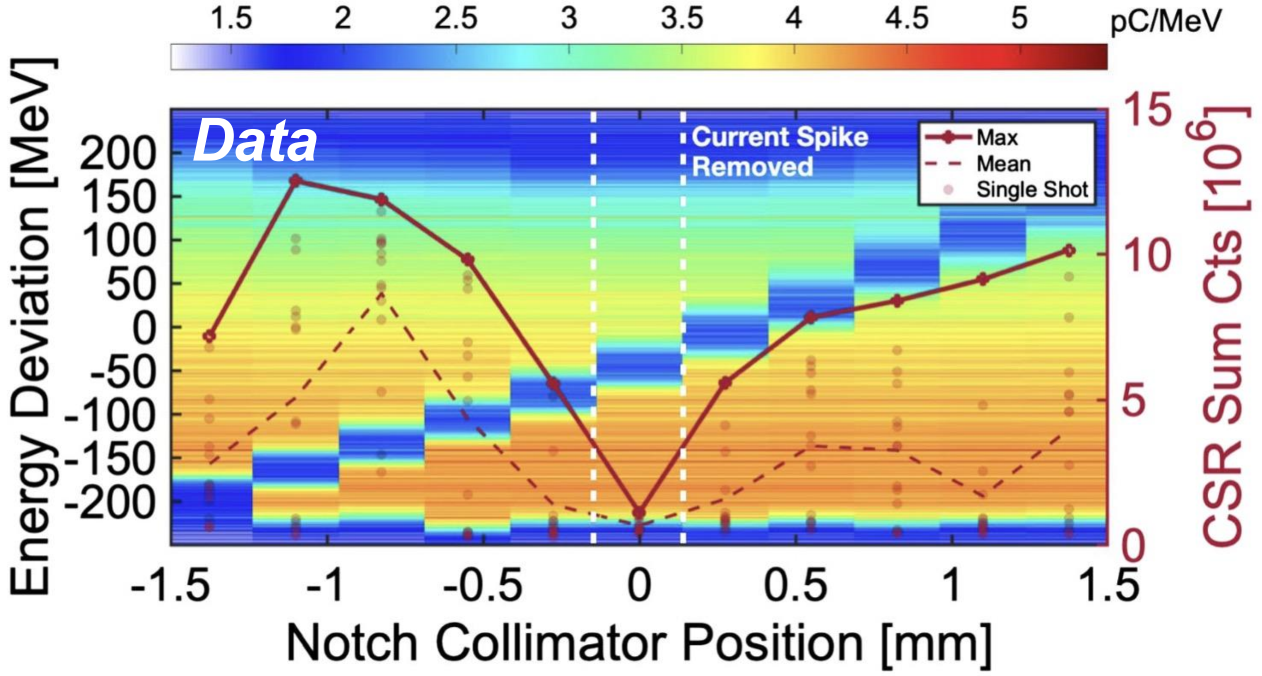
Editors' Suggestion

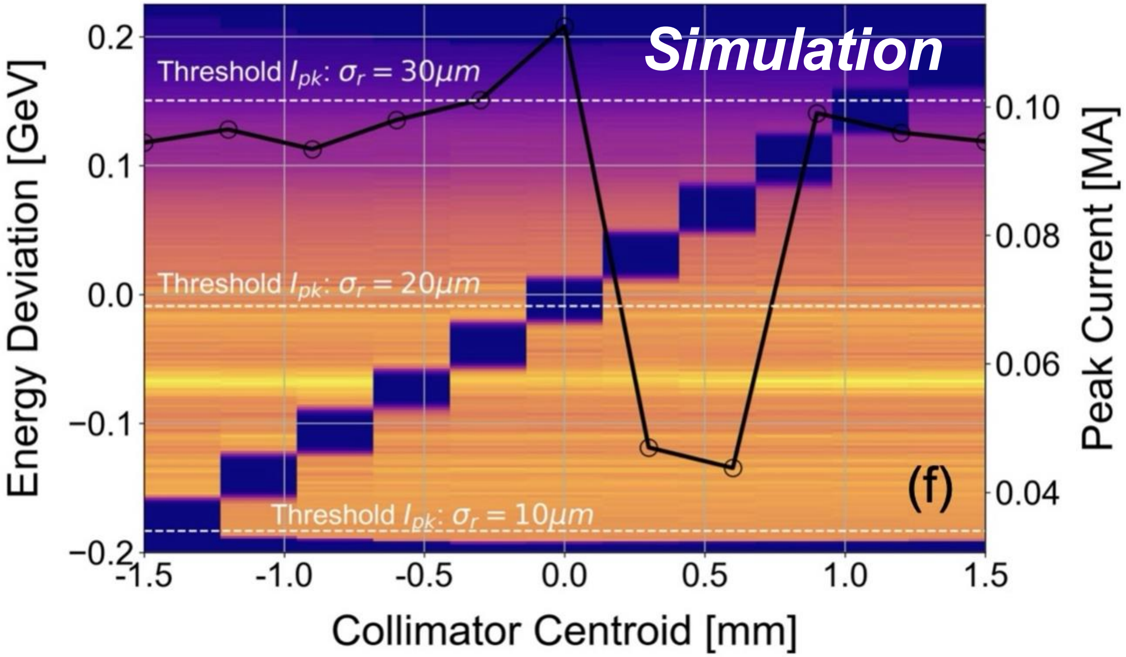
Experimental Generation of Extreme Electron Beams for Advanced Accelerator Applications

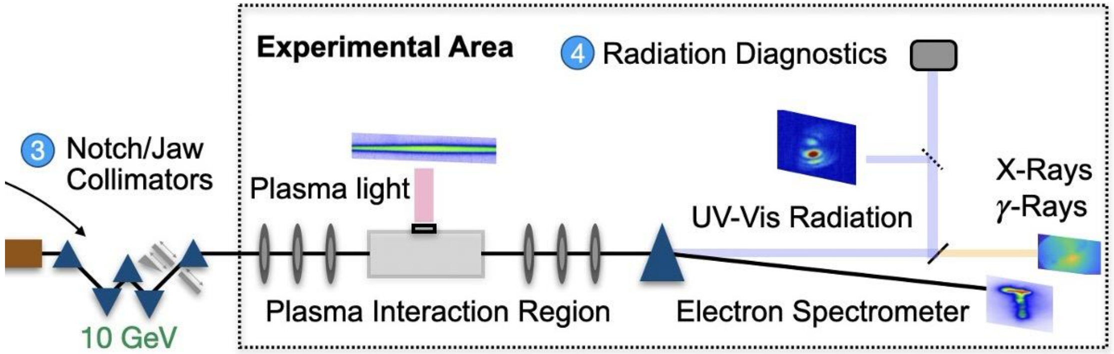
C. Emma, N. Majernik, K. K. Swanson, R. Ariniello, S. Gessner, R. Hessami, M. J. Hogan, A. Knetsch, K. A. Larsen, A. Marinelli, B. O'Shea, S. Perez, I. Rajkovic, R. Robles, D. Storey, and G. Yocky
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

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

Localizing the current spike in the beam



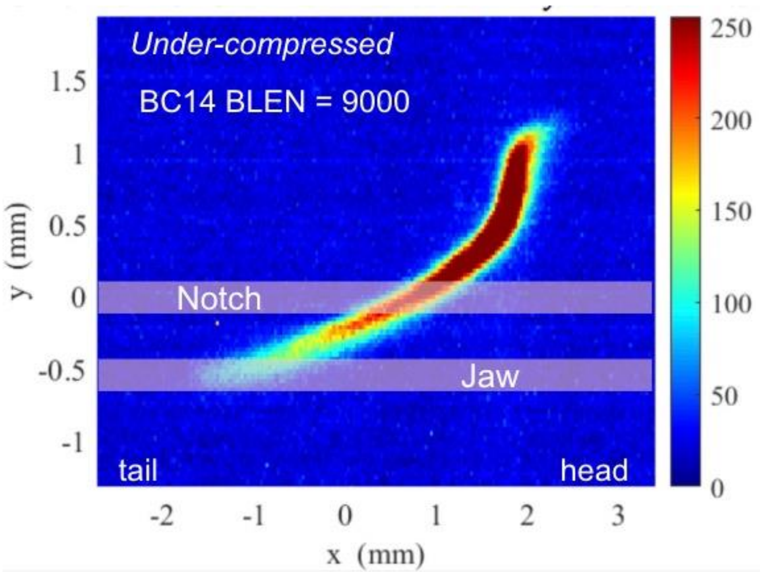


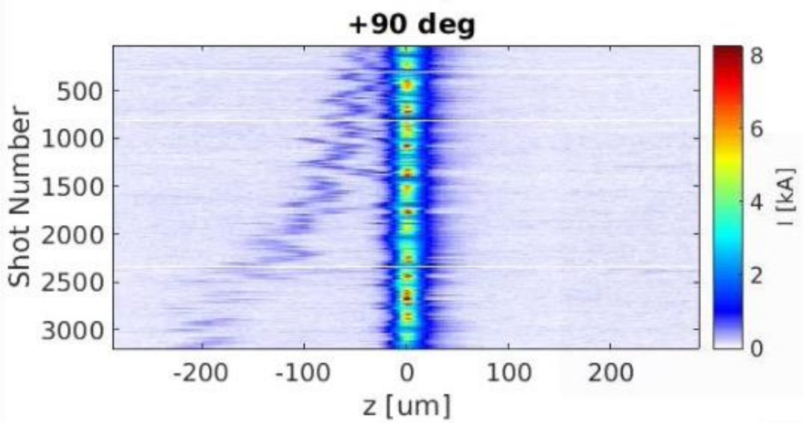


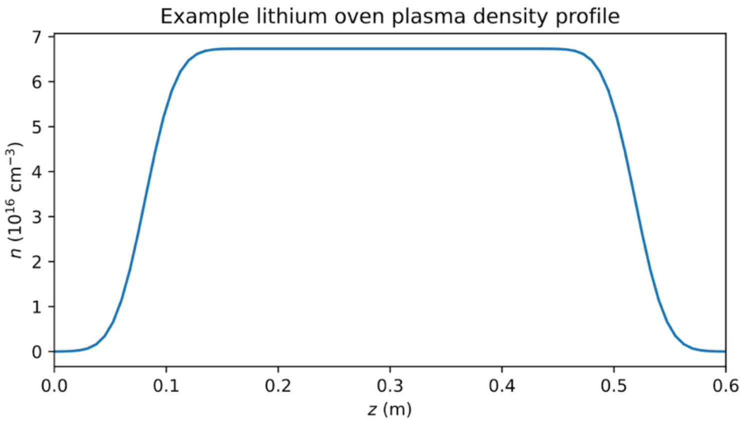
Reduction in CSR reveals current spike is highly localized in energy and time

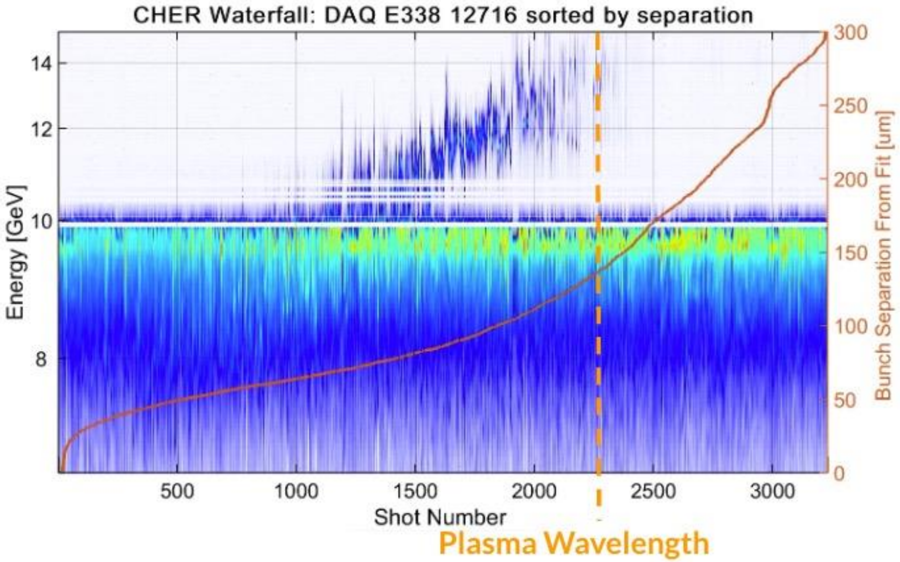
Initial wakefield mapping measurements

Preliminary







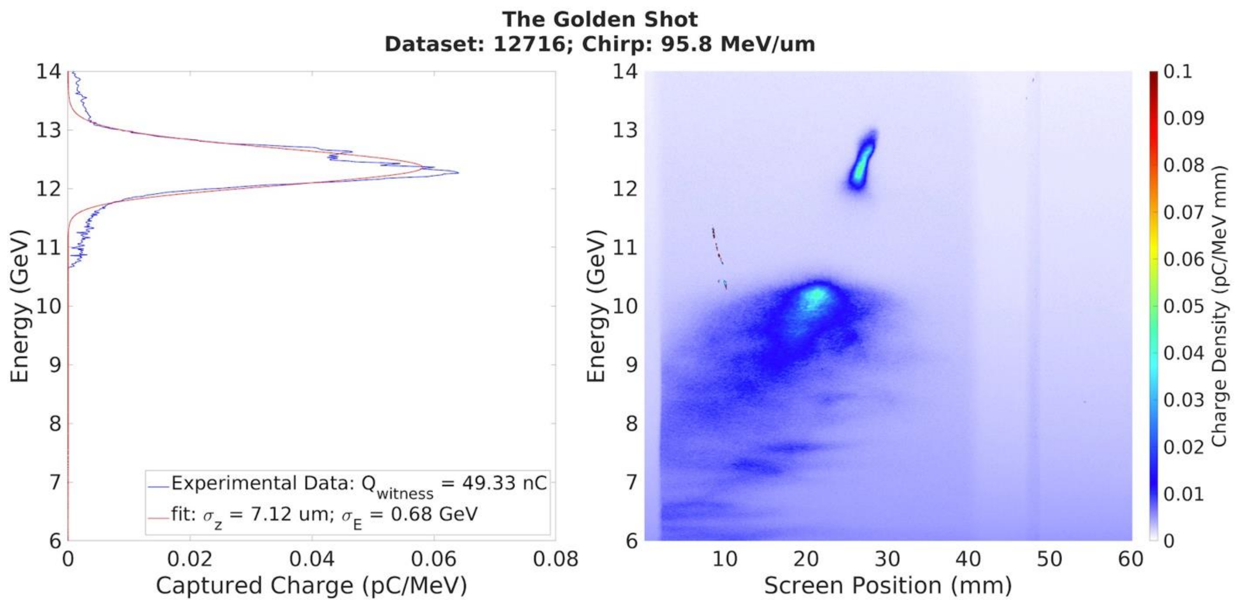


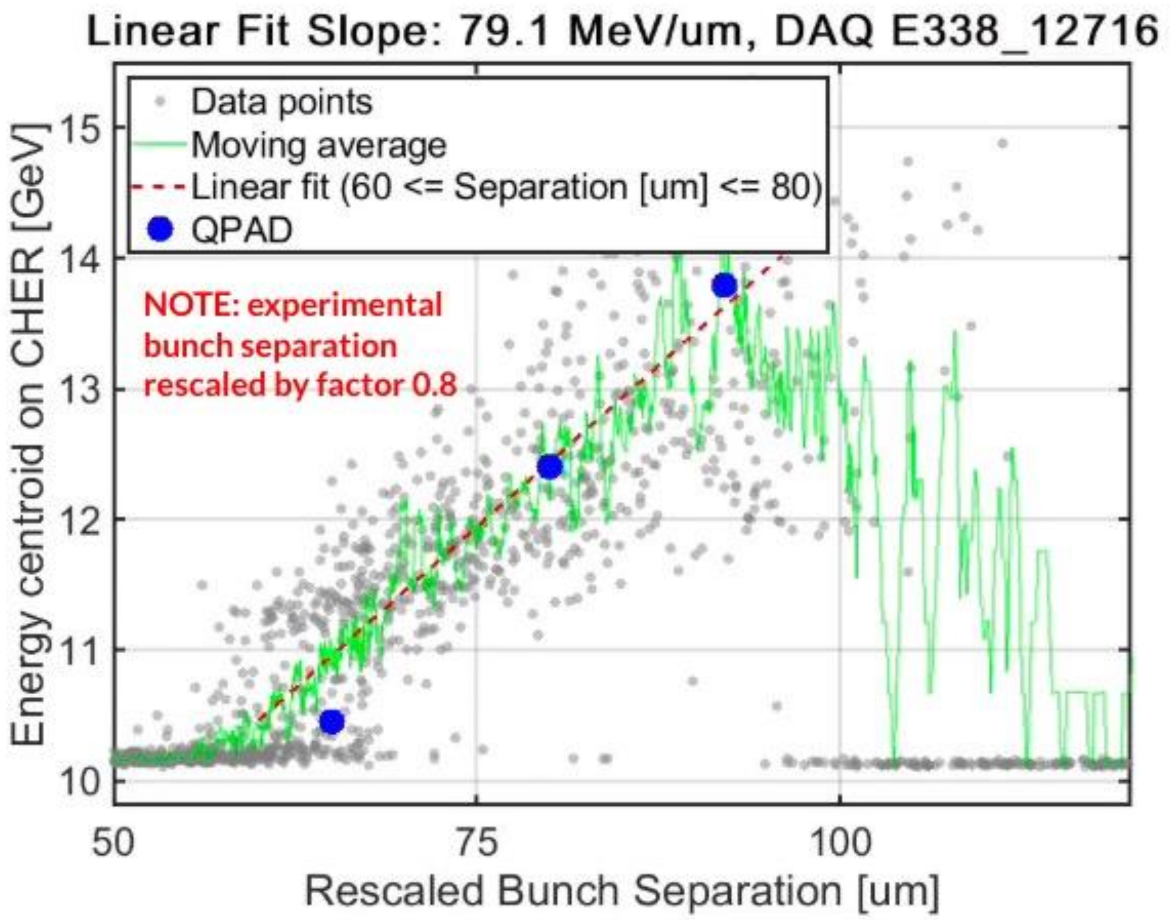
Plasma-induced chirp measured on FACET-II beam with notched two-bunch beam

Chirp calculation results

Preliminary

Lithium Oven at 8 Torr, n_p = 6.7e16

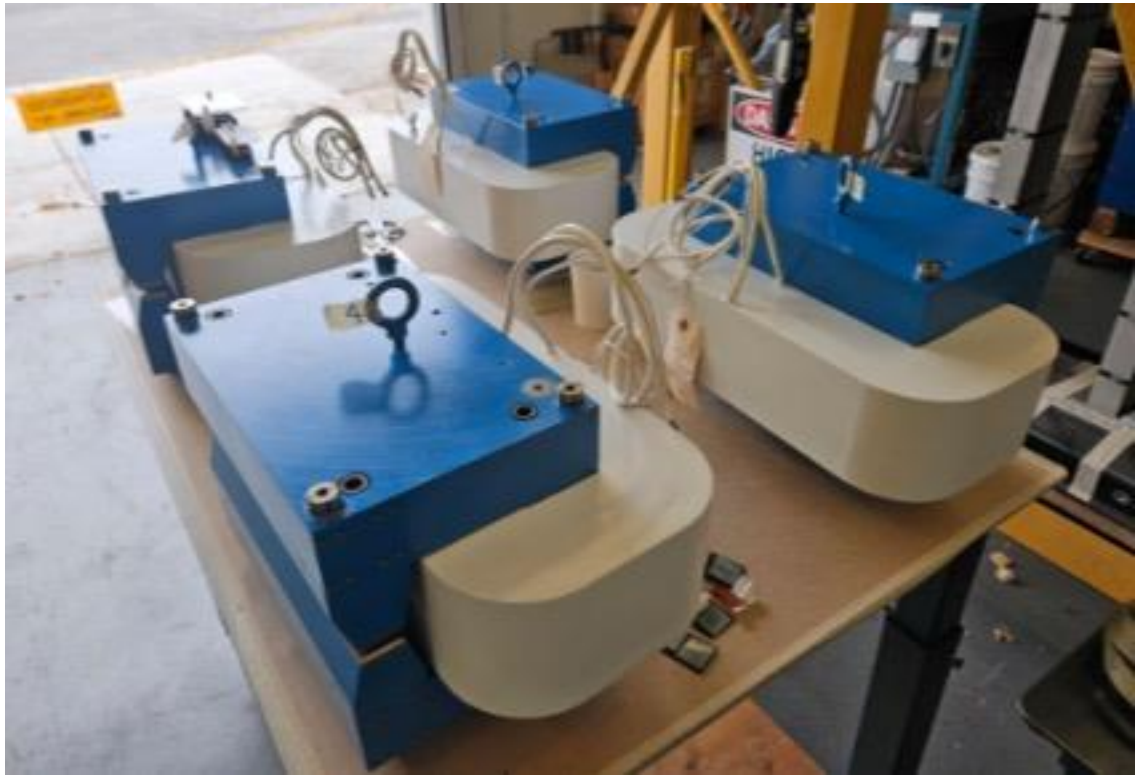




- QPAD simulations in agreement with data for chirp and witness energy gain. Rescaling of experimental bunch separation due to uncertain TCAV calibration.

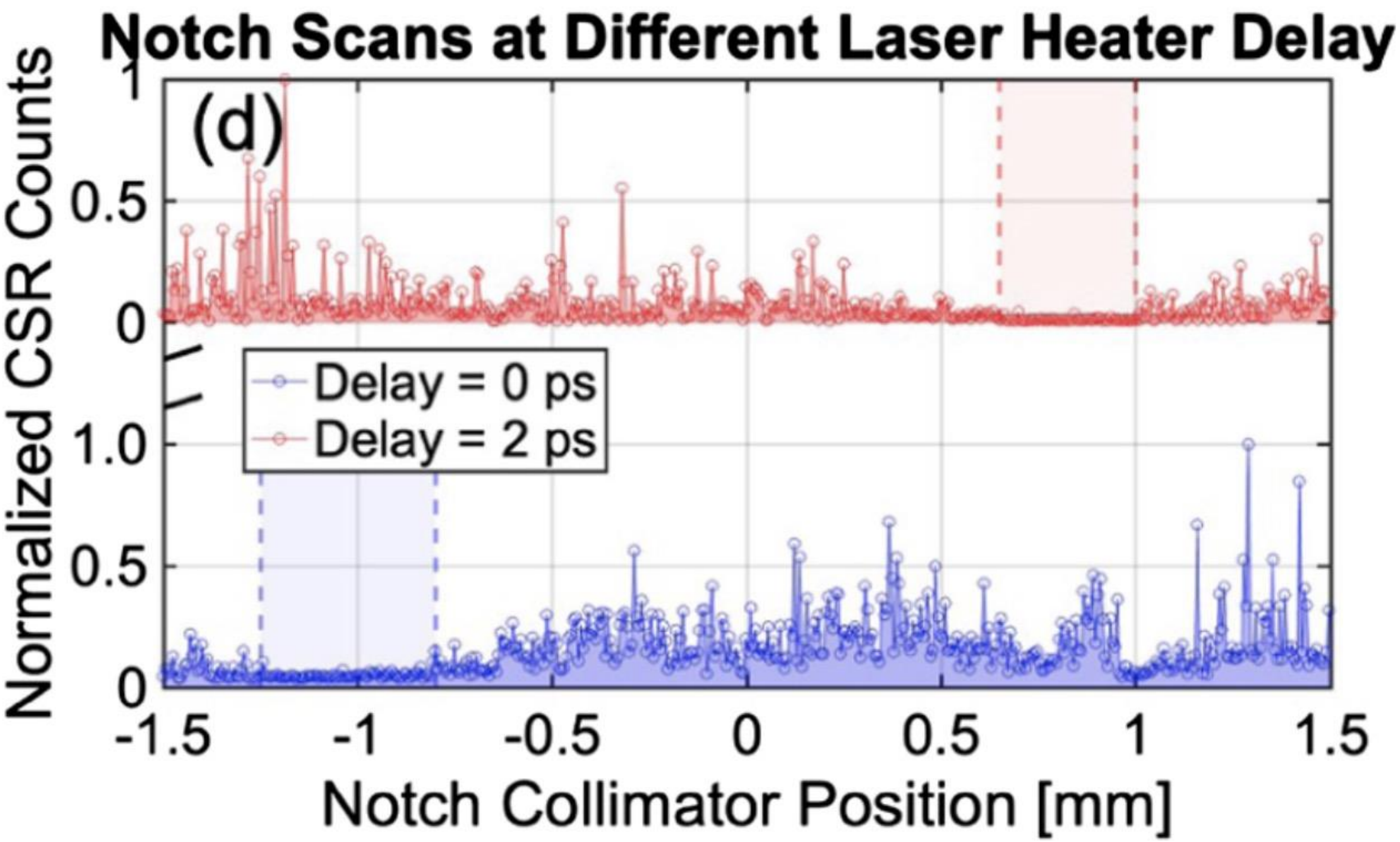
Chirped beams generated with Li oven sufficient for full compression in post-plasma chicane

Chicane installation status and plans



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

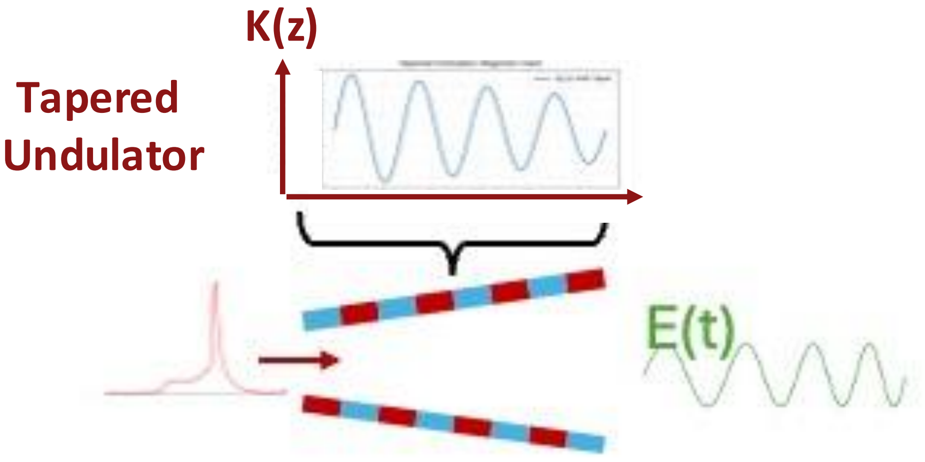
Controlling the spike position using laser heater delay

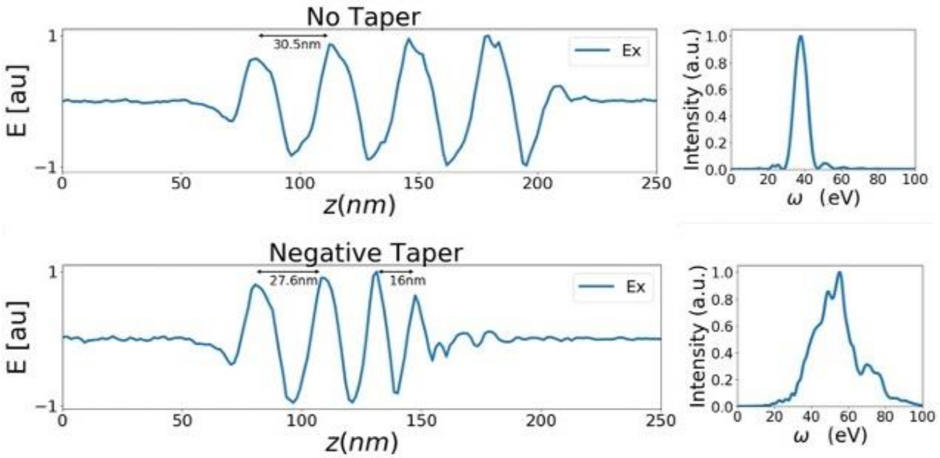


High current spike can be moved to head/tail of the bunch by changing laser delay

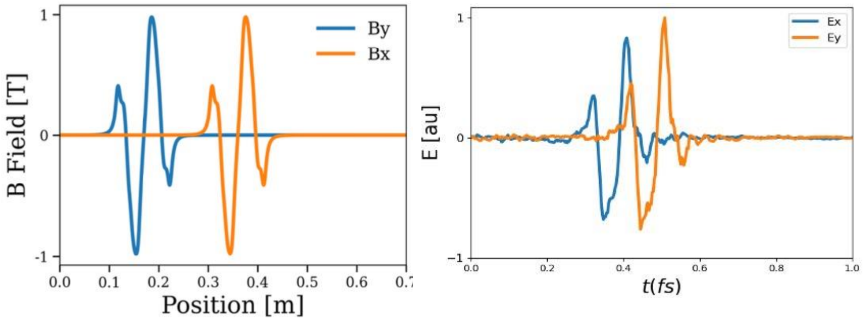
PAX for coherent control of X-ray waveforms

Frequency Chirped X-rays



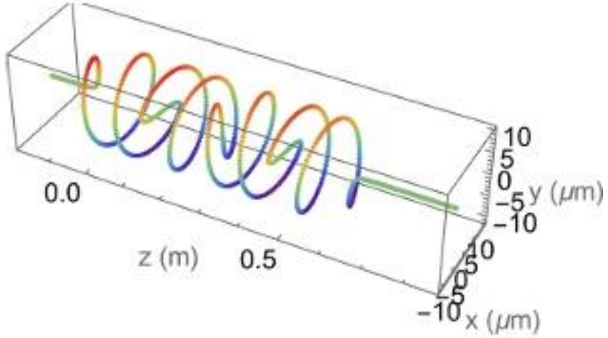


Alternating polarization

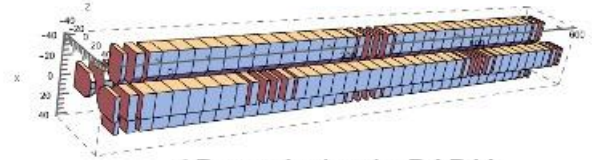


3D plot of the on-axis electric field vector

Undulator gymnastics



RADIA simulations N. Sudar



3D rendering in RADIA

Circular polarization with multiple helicity flips

Photon beam properties can be manipulated by shaping undulator magnetic field