FACET-II

Facility for Advanced Accelerator Experimental Tests

Beam-Driven Plasma Wakefield Experiments at FACET-II…and friends

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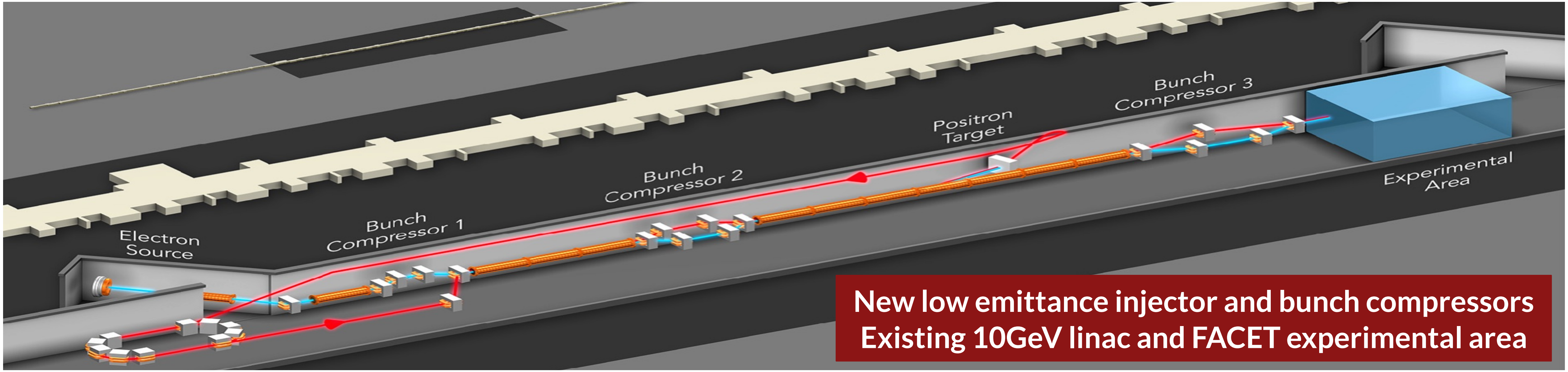
September 22, 2025

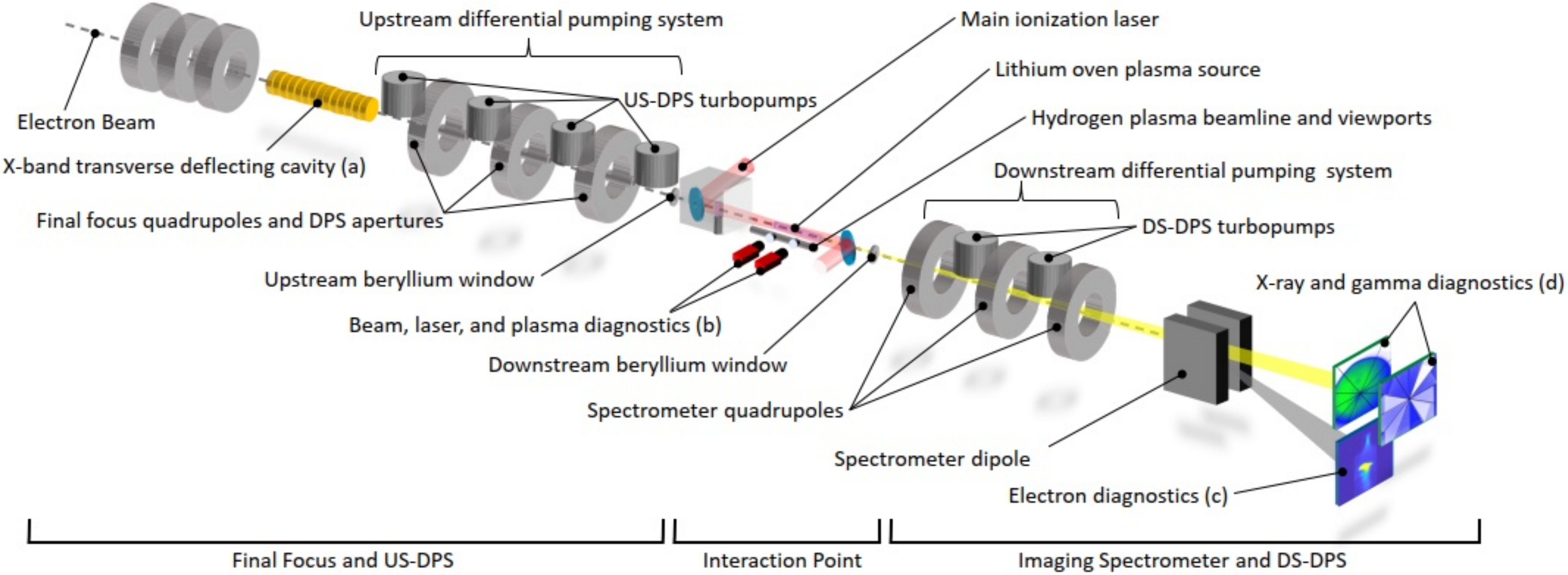
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

FACET-II @ SLAC: km-long electron linac delivering 10GeV beams

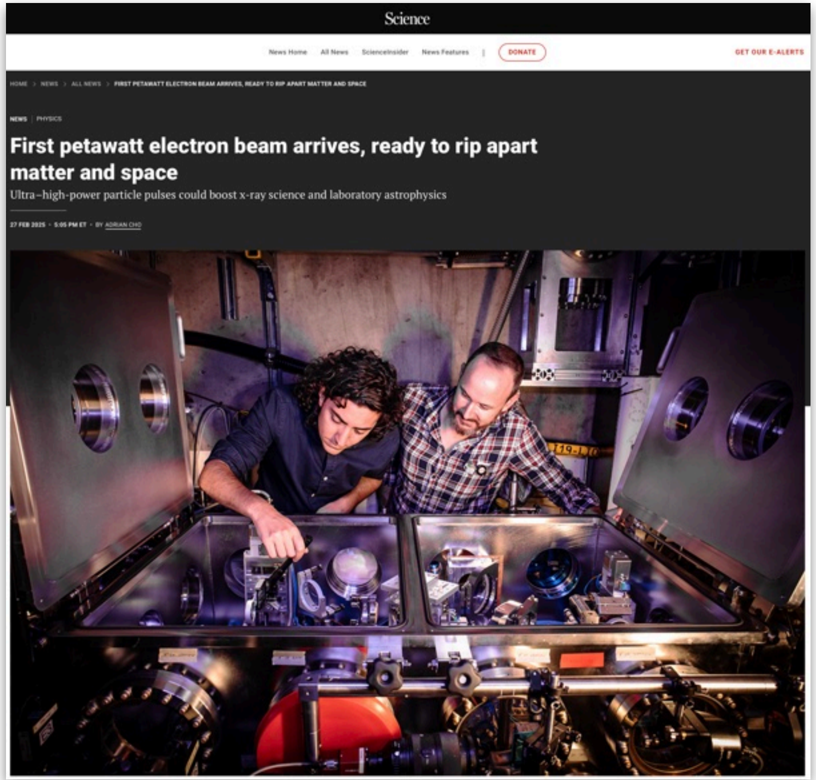


FACET-II Experimental Area Overview



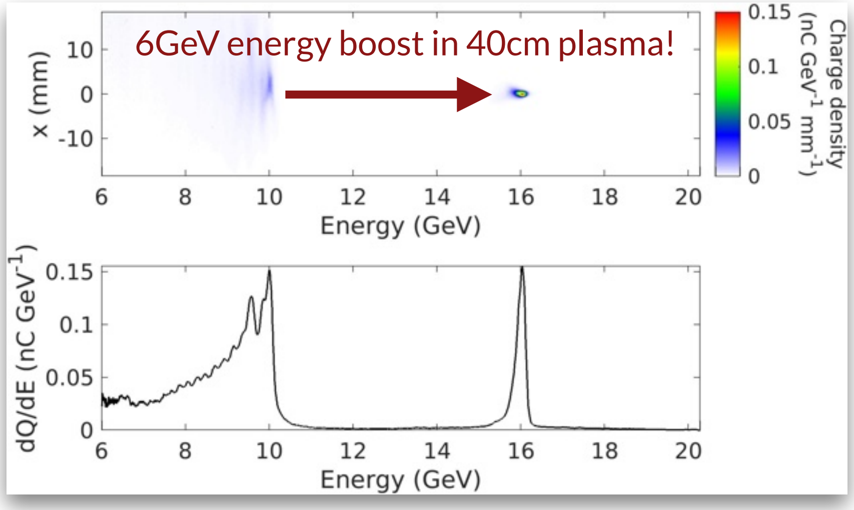
FACET-II: A National User Facility with a Broad User Program Based on 10GeV Beams and Their Interaction with Lasers, Materials and Plasma

Combining extreme beams (>100kA) and plasma to make high-gradient energy and brightness booster…



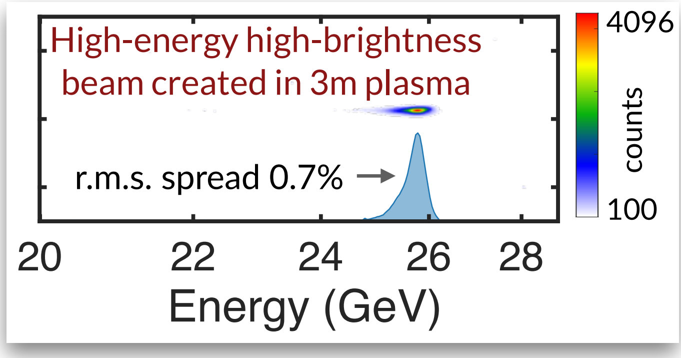
Plasma wakefield acceleration

Developing plasma accelerators as multi-GeV/m accelerator technology aligned with HEP roadmaps



PWFA Applications

Brightness booster, Attosecond X-ray pulses as near term (pre-collider) demonstration applications



…while also using these unique beams for a variety of User programs focused on:

Strong Field Quantum Electrodynamics

Stable high-energy beams and multi-TW laser for precision probing of SFQED

High-field Physics

Beam fields > 1V/Å enable unique studies in astrophysics, material science and beam physics

AIML & Beam Physics

Harnessing new initiatives in AIML to diagnose and control beams with unprecedented intensities aligned with GARD ABP roadmaps

Outline for the remainder of the presentation

Recent progress at FACET-II

- Highlight #1: extreme currents, compression and brightnesses
- Highlight #2: high-field, efficient and uniform acceleration in plasma
- Highlight #3: extreme focusing of high-energy beams
- Highlight #4: strong field QED and quantum radiation reaction

FACET-II highlight #1: extreme currents, compression and brightnesses

- Generate 100-kA-scale currents with laser heater

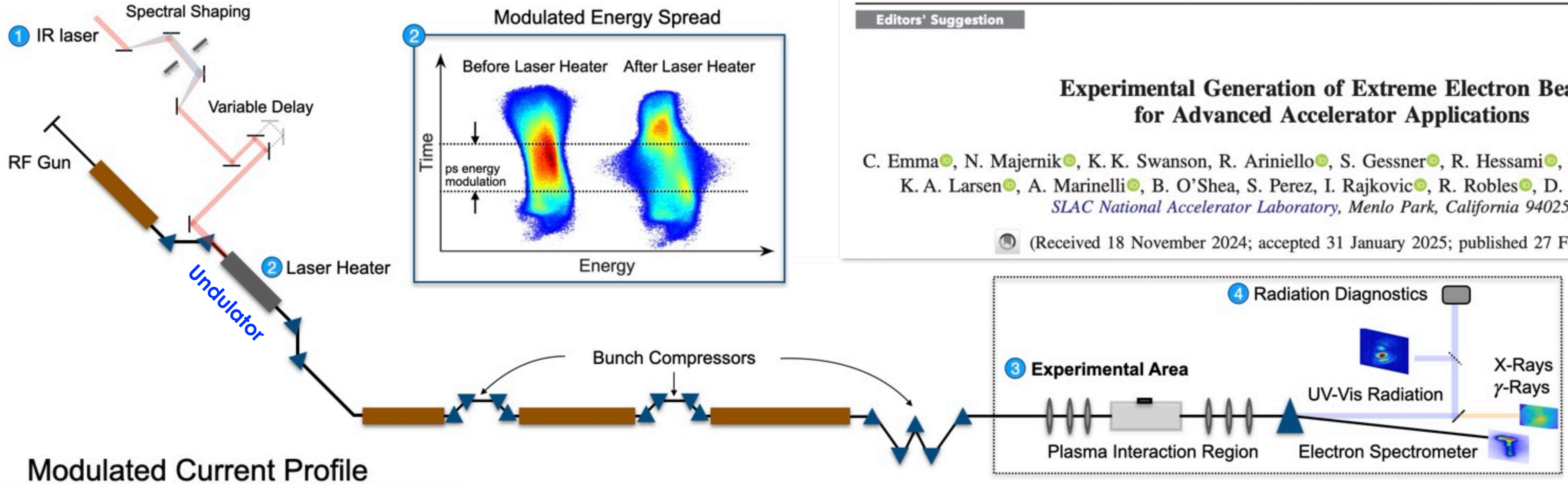
PHYSICAL REVIEW LETTERS **134**, 085001 (2025)

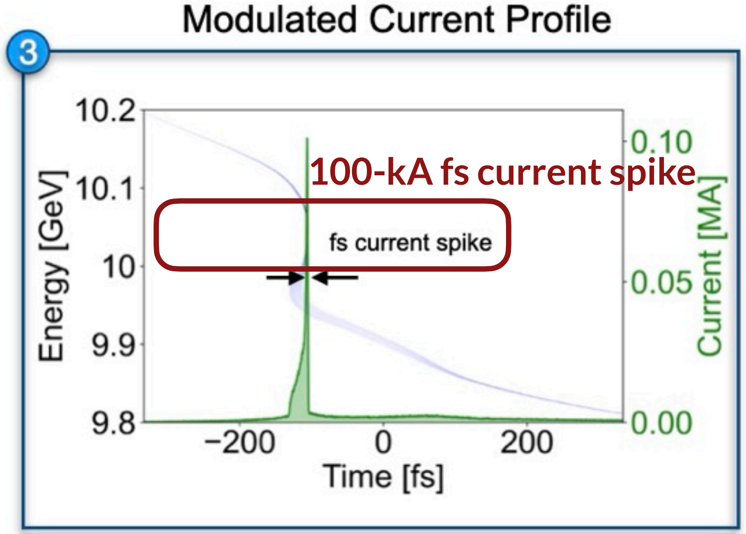
Editors' Suggestion

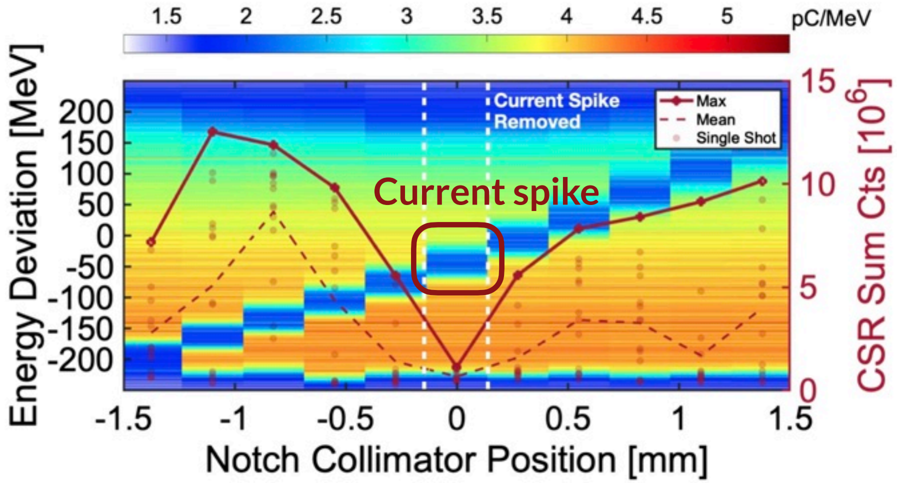
Experimental Generation of Extreme Electron Beams for Advanced Accelerator Applications

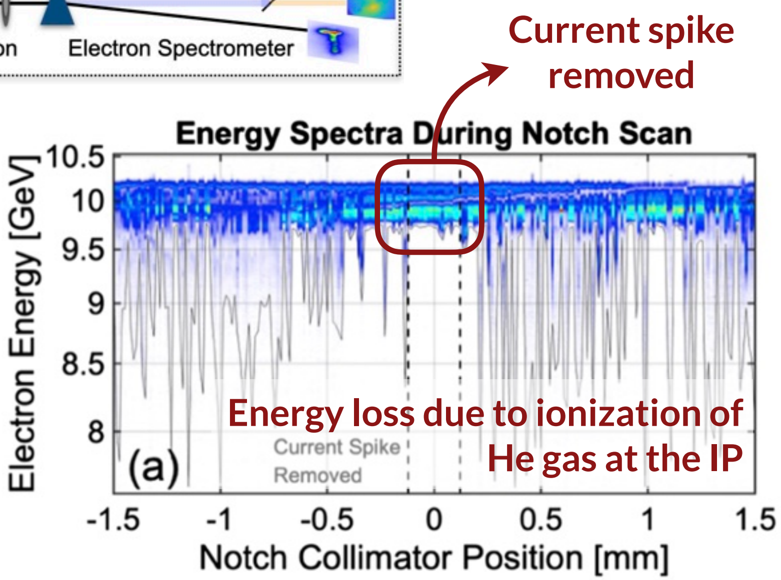
C. Emma, N. Majernik, K. K. Swanson, R. Ariniello, S. Gessner, R. Hessami, M. J. Hogan, A. Knetsch, K. A. Larsen, A. Marinelli, B. O'Shea, S. Perez, I. Rajkovic, R. Robles, D. Storey, and G. Yocky
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

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



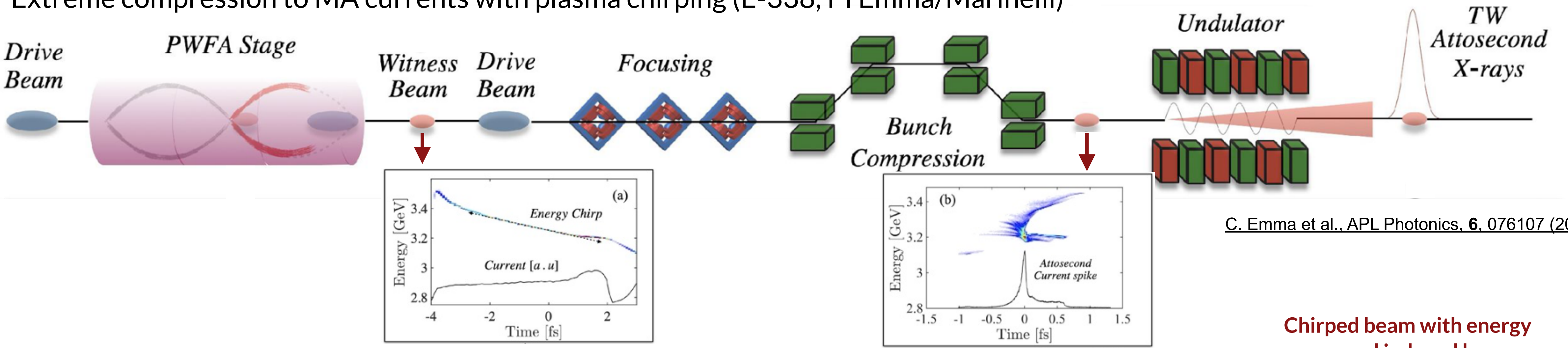






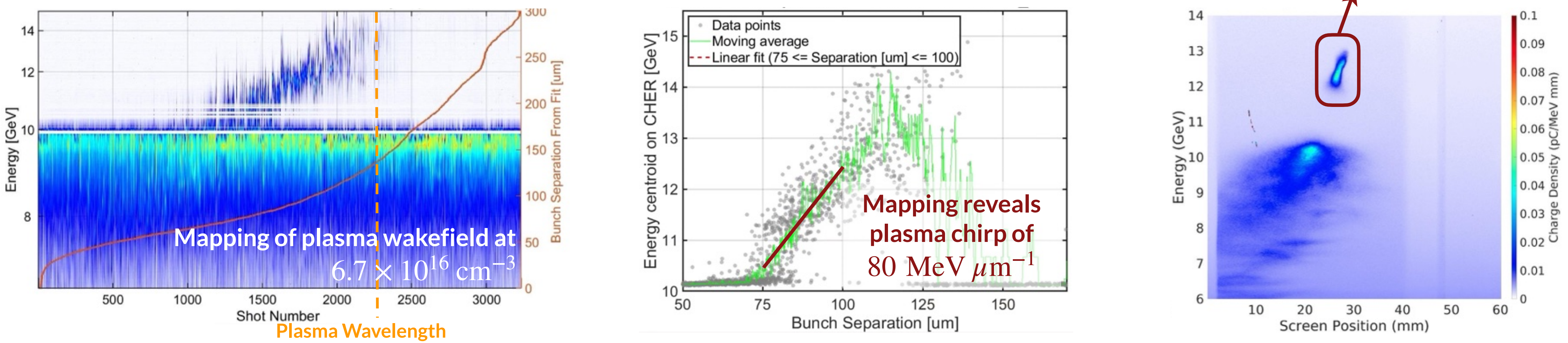
FACET-II highlight #1: extreme currents, compression and brightnesses

- Extreme compression to MA currents with plasma chirping (E-338, PI Emma/Marinelli)



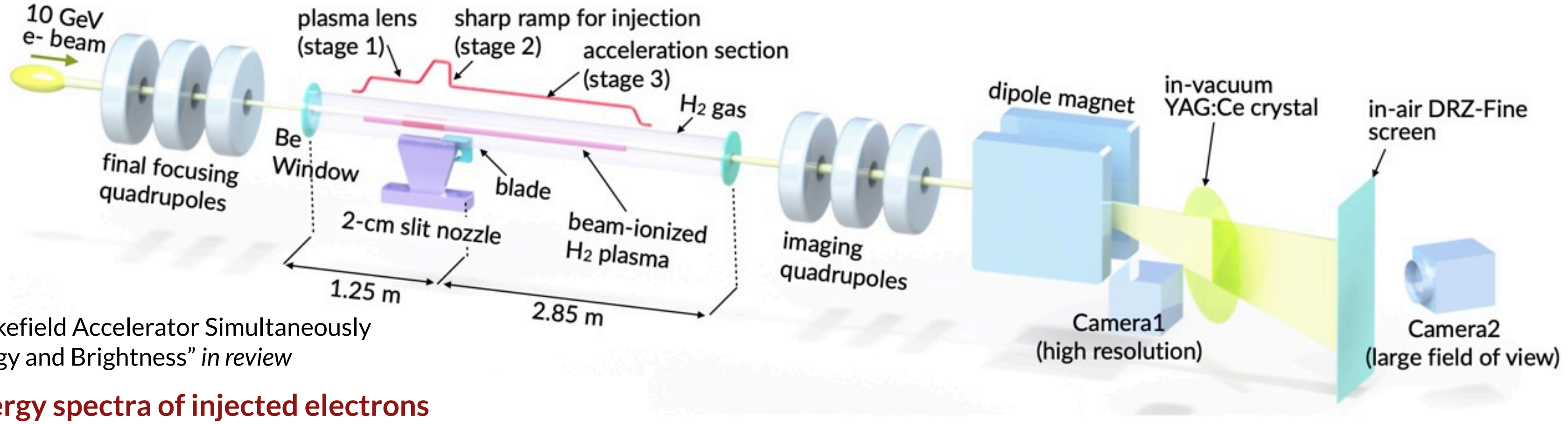
C. Emma et al., APL Photonics, **6**, 076107 (2021)

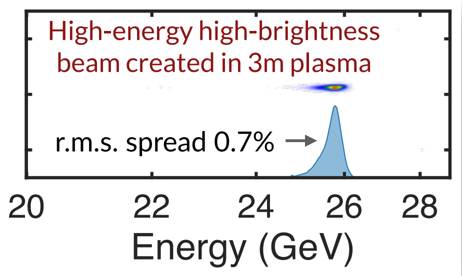
- Experimental demonstration of plasma chirping $\mathcal{O}(100\ \mathrm{MeV}\ \mu\mathrm{m}^{-1})$



FACET-II highlight #1: extreme currents, compression and brightnesses

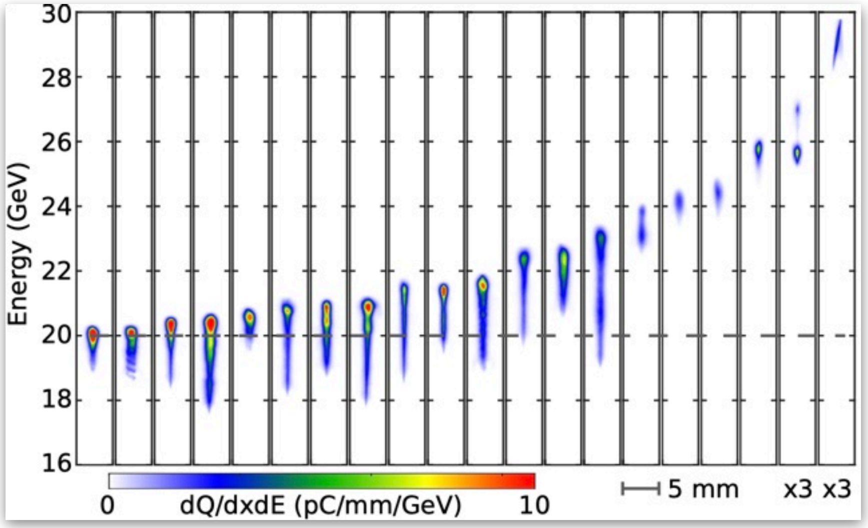
- Density downramp injection in a plasma wakefield accelerator (E-304, PI C. Zhang)

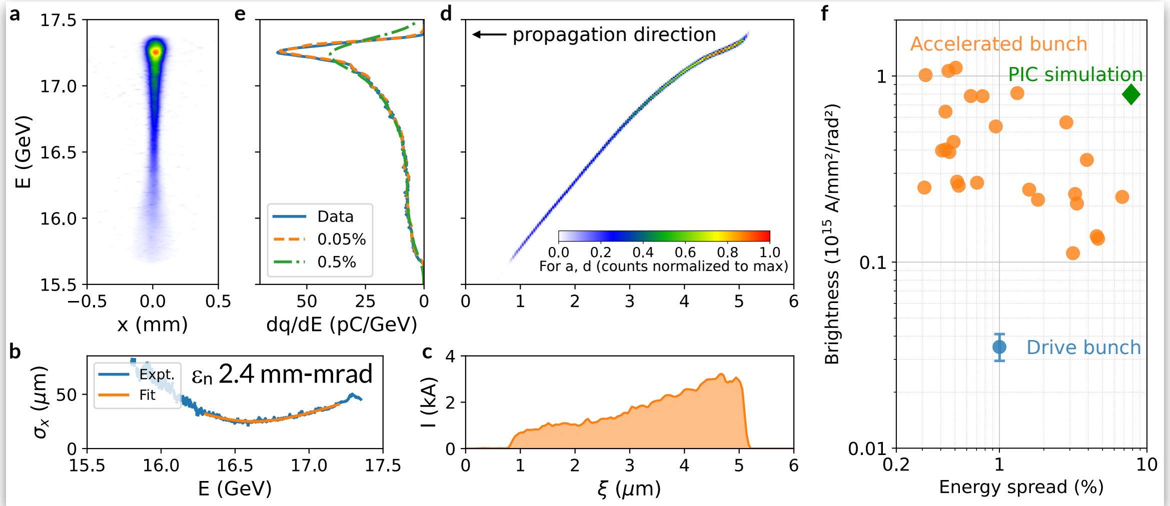




C. Zhang et al., "Plasma-Wakefield Accelerator Simultaneously Boosts Electron Beam Energy and Brightness" *in review*

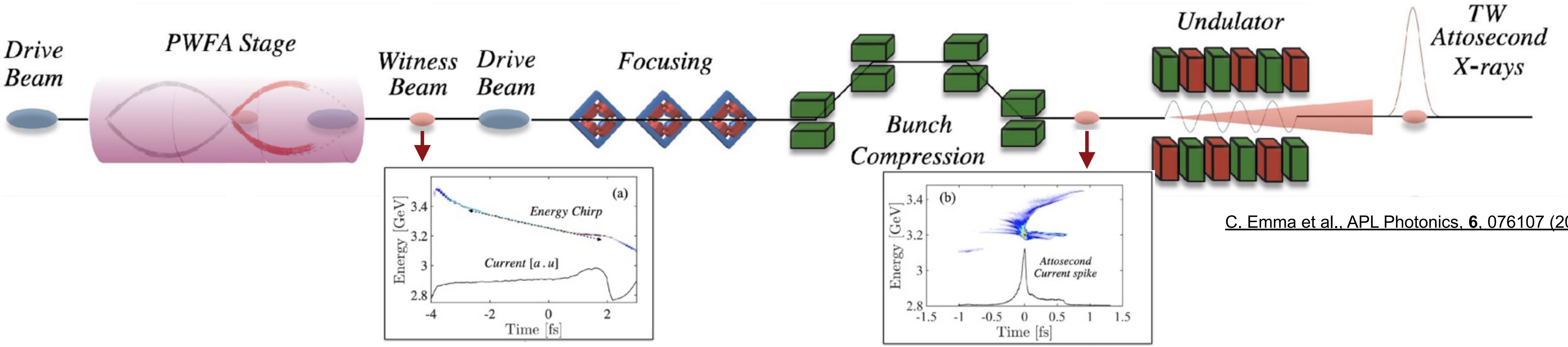
Energy spectra of injected electrons





Plasma acts as an energy and brightness transformer – creating new beams with higher energy and brightness

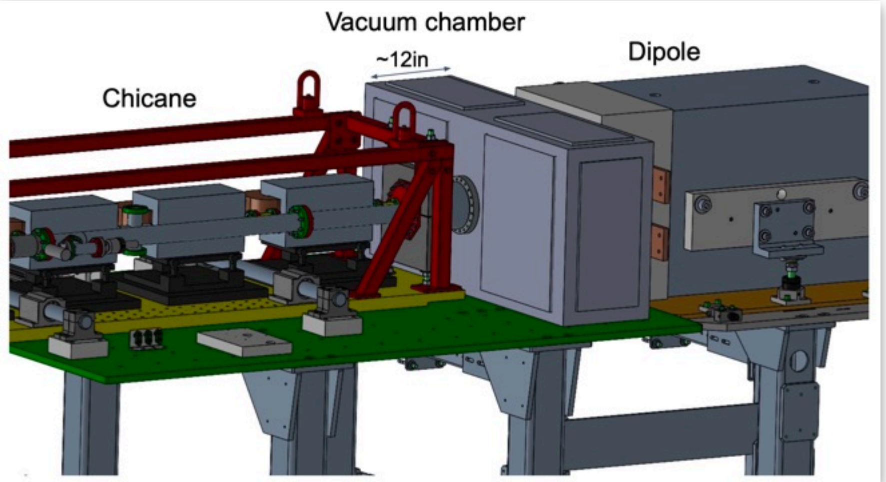
FACET-II highlight #1: extreme currents, compression and brightnesses



C. Emma et al., APL Photonics, **6**, 076107 (2021)

Looking ahead:

- Continued development of plasma injector concepts (DDR and Trojan Horse)
- Chicane installation end 2025
- Compression studies (kA to MA) in 2026
- Make X-rays in 2027



Outline for the remainder of the presentation

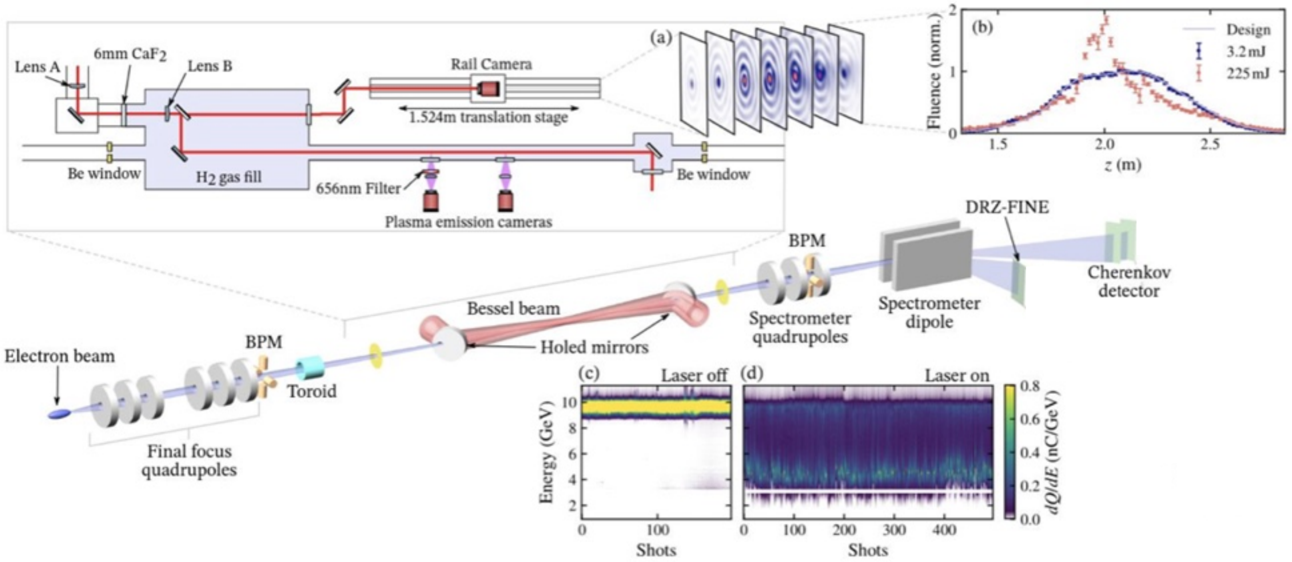
Recent progress at FACET-II

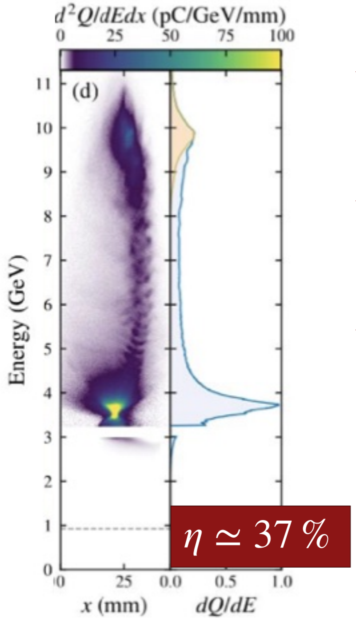
- Highlight #1: extreme currents, compression and brightnesses
- Highlight #2: high-field, efficient and uniform acceleration in plasma
- Highlight #3: extreme focusing of high-energy beams
- Highlight #4: strong field QED and quantum radiation reaction

See M. Litos Sep 24, 2025, 5:20 PM

FACET-II highlight #2: efficient transfer from drive to plasma

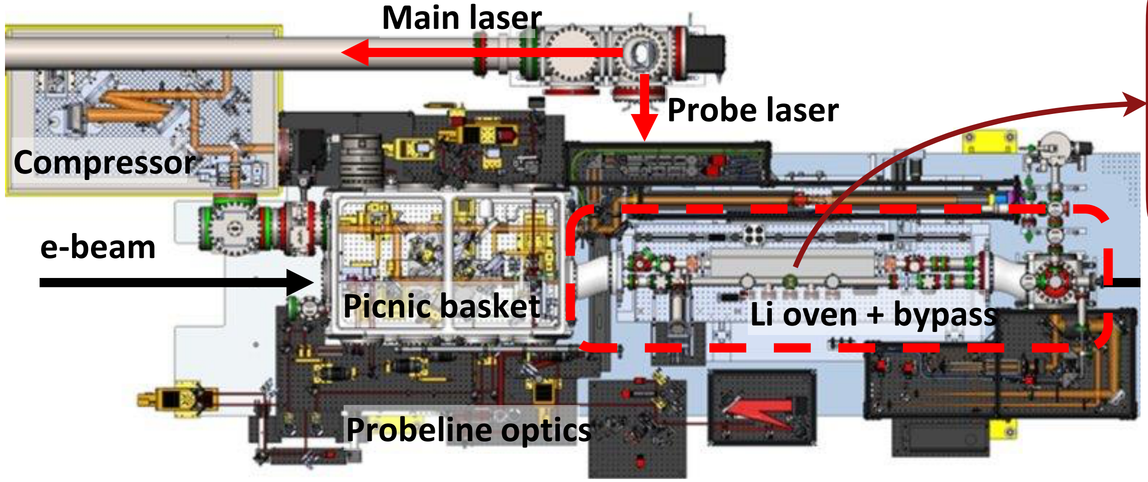
- PWFA in laser-ionized H2 static fill (E-301, PI M. Litos)

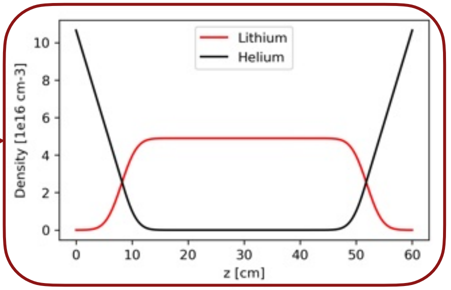


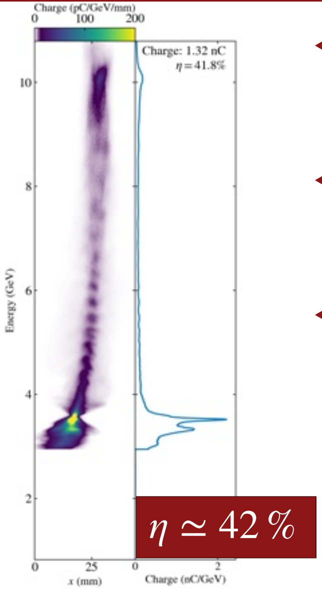


- Single drive bunch started at 10 GeV
- Decelerated down to ~3 GeV
- 37% of beam energy transferred to the H_2 plasma at $4.5 \times 10^{16}\ \mathrm{cm}^{-3}$

- PWFA with Li oven plasma source (E-300, PI Joshi/Hogan)





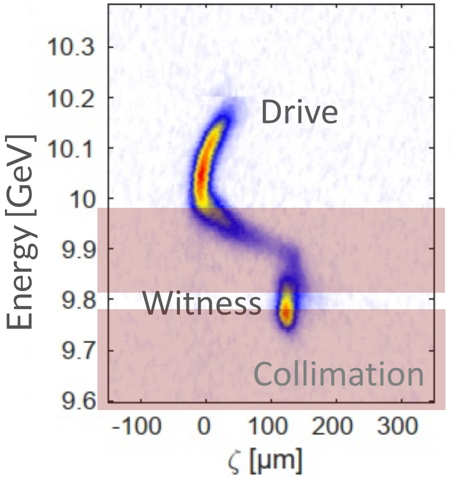


- Single drive bunch started at 10 GeV
- Decelerated down to ~3 GeV
- 42% of beam energy transferred to the Li plasma at $4.3 \times 10^{16}\ \mathrm{cm}^{-3}$

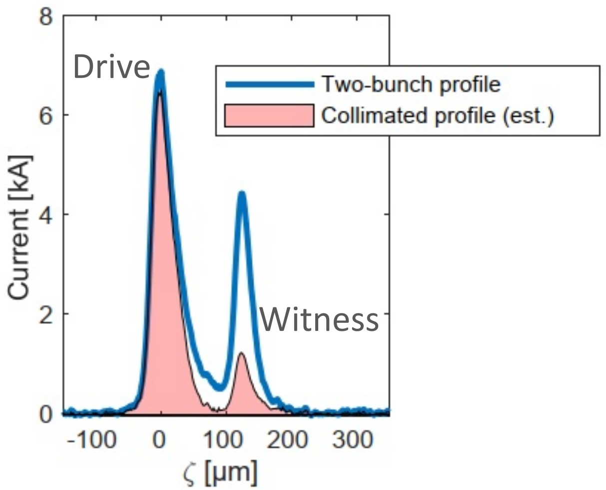
Developed a range of two-bunch (drive and witness) configurations with typically ~1nC drive, 200-400pC witness

EOS BPM See C. Hansel Sep 22, 2025, 5:20 PM

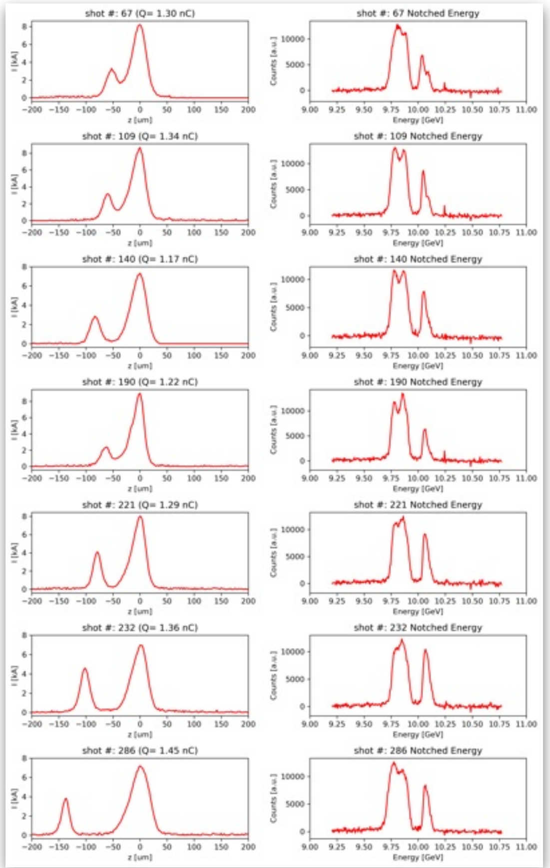
- Create two-bunches at the photocathode
- Accelerate and compress from 10ps to 100fs
- Use RF phasing and collimation to tailor profiles at IP



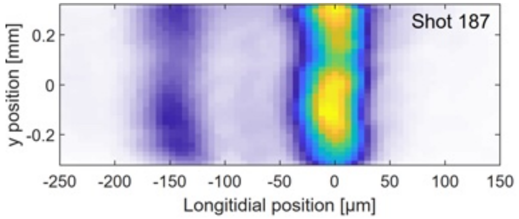
Longitudinal Phase Space Profiles from TCAV + Spectrometer

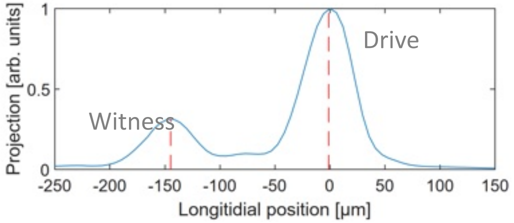


Time Energy

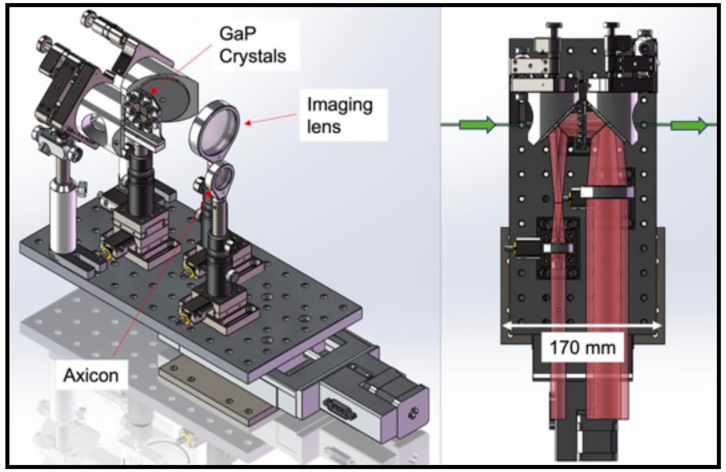


EOS Temporal Profile





EOS BPM v2 Coming Soon!
CU Boulder – RadiaBeam collaboration

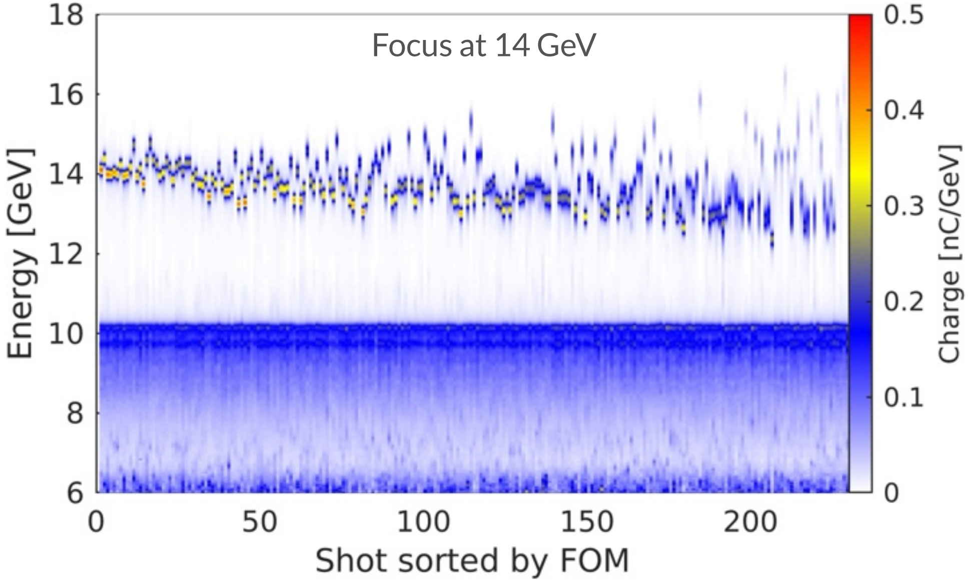


FACET-II highlight #2: uniform acceleration in plasma

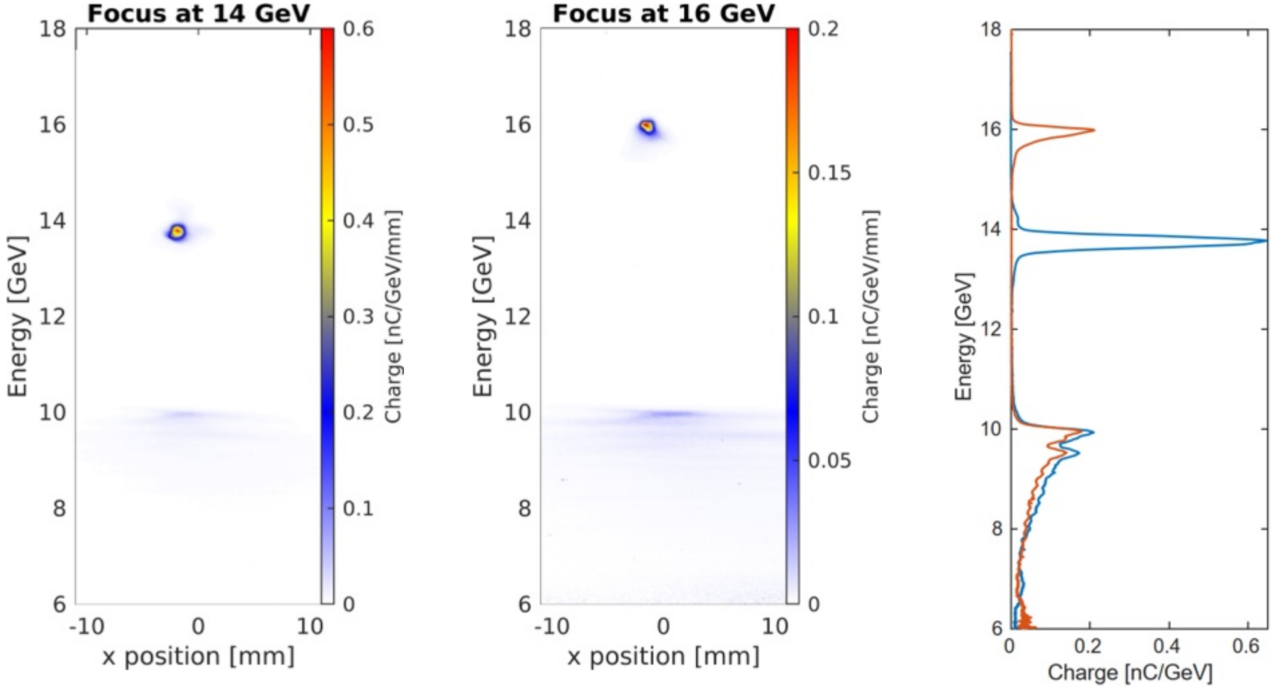
Two-bunch configuration

- Driver: ~1.2 nC, 6-8 kA
- Witness: 150-250 pC incoming charge
- Plasma: 40cm long lithium plasma, 4e16 cm^{-3}

Sorted by figure of merit: $$\Omega = \frac{\left(\frac{\sigma_{E_W}}{\Delta E_W}\right)}{\eta_{tot}\left(\frac{\Delta E_W}{10\ \mathrm{GeV}}\right)}$$



- PWFA with Li oven plasma source (E-300, PI Joshi/Hogan)

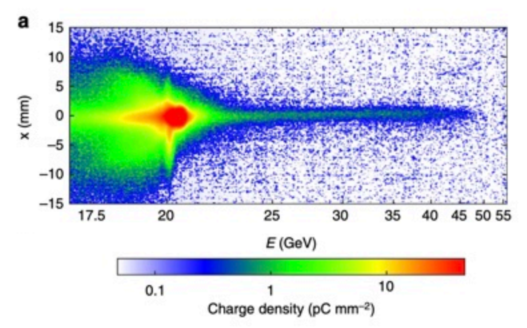


Focus at 14 GeV	Focus at 16 GeV
$\Delta E = 3.8$ GeV	$\Delta E = 6$ GeV
$\sigma_E = 0.76\ \%$	$\sigma_E = 0.69\ \%$
$\eta_{tot} = 6\ \%$	$\eta_{tot} = 3\ \%$
$Q_w = 180$ pC	$Q_w = 60$ pC

Uniform acceleration with field uniformity ~2%, up to 6 GeV energy gain in 40-cm-long Li plasma, and up to 5% total efficiency from initial drive energy to trailing bunch

FACET-II highlight #2: advanced regimes and probing

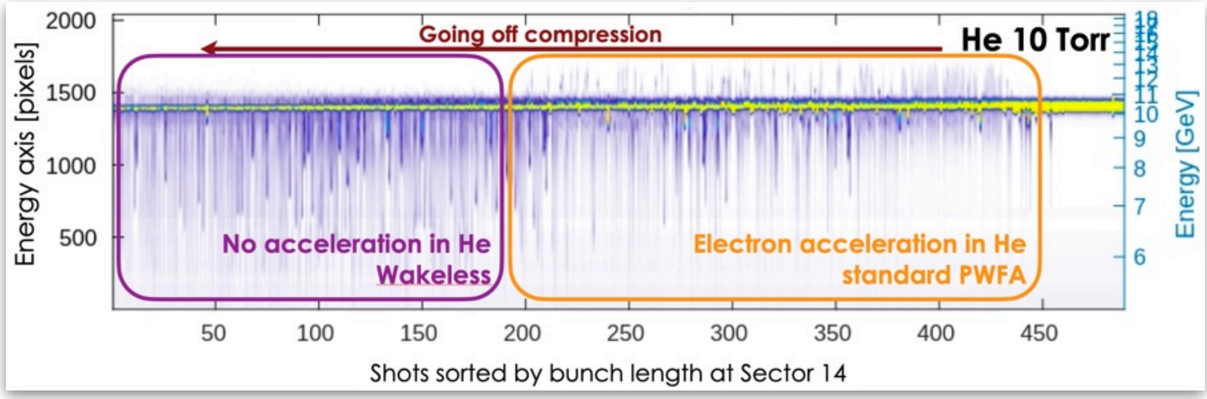
Transition to wakeless regime first observed in FACET



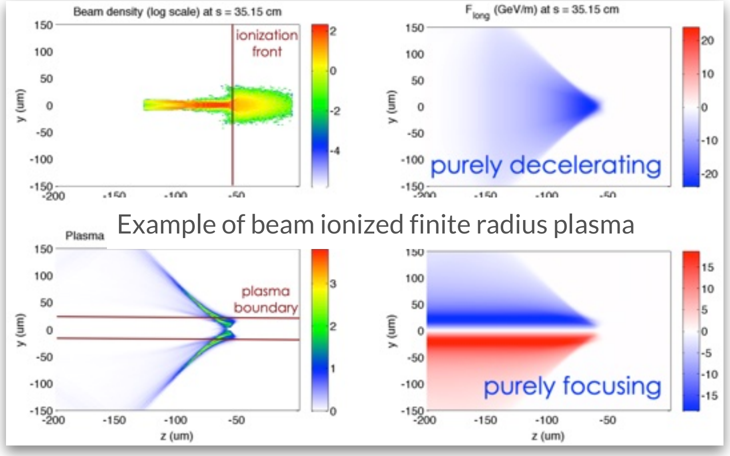
Nature Commun. 7, 11898 (2016)

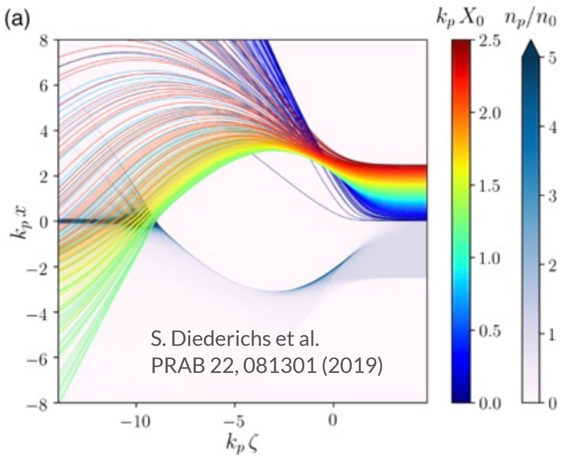
E-200 observations:

- Pure Ar: energy-doubling acceleration observed from 16 Torr
- He-Ar: mixture at 32 Torr: acceleration observed above 40% Ar
- Pure He: never observed any acceleration despite full energy loss, tested up to 64 Torr

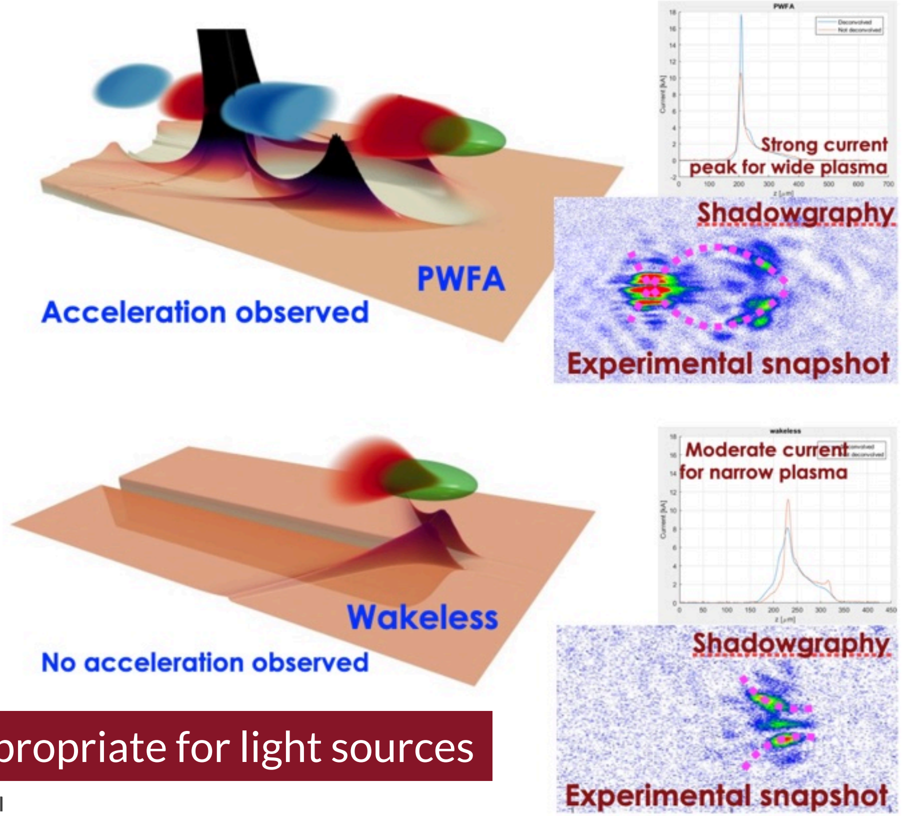


Finite radius plasmas proposed for applications to ion channel laser and positron acceleration





S. Diederichs et al.
PRAB 22, 081301 (2019)



- New regimes in narrow beam-ionized He plasma (E-340, PI Corde/Litos/Emma)
- Narrow laser-ionized H_2 plasma for positron PWFA (E-333, PI Gessner/Litos)

Demonstration of a pure ion channel appropriate for light sources

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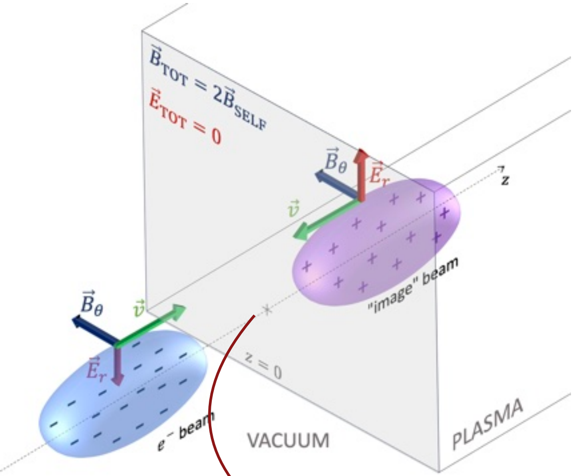
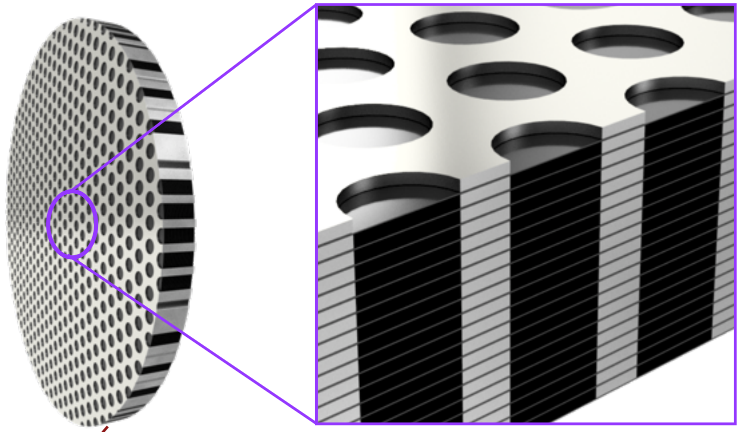
FACET-II highlight #3: extreme focusing of high-energy beams

- Principle of extreme focusing

E-332 multifoil (PI Corde/Tamburini)

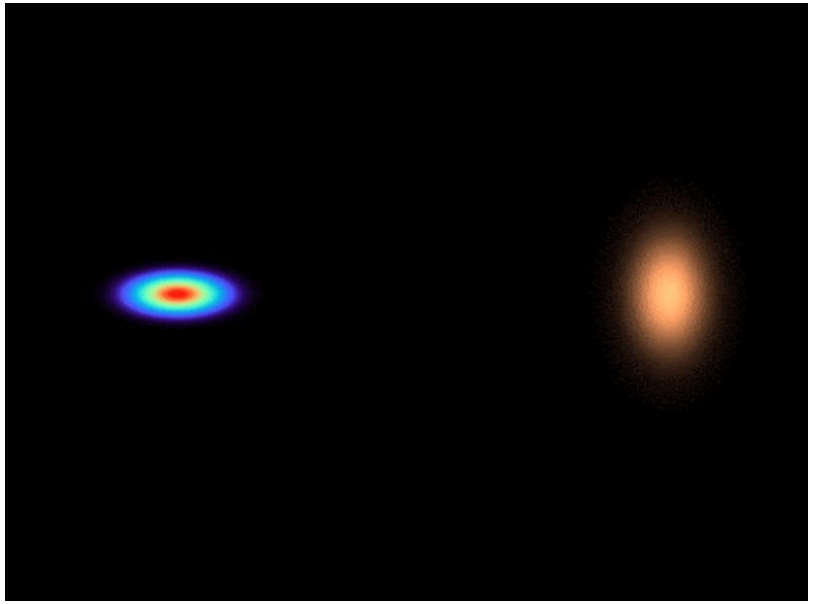


Focusing effect!

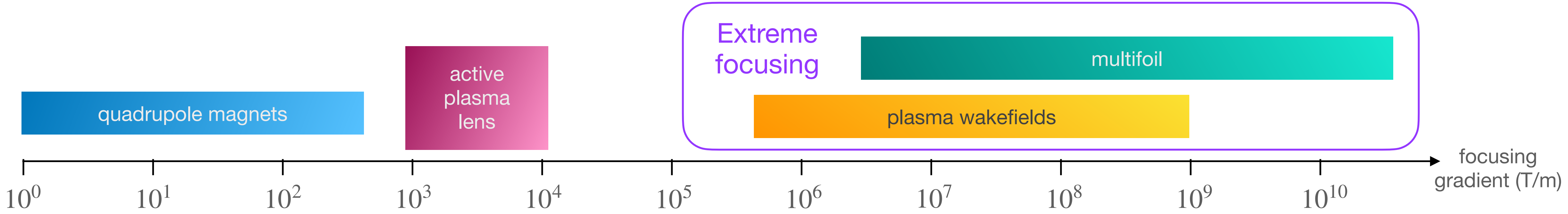


Strongly-enhanced focusing

E-308 thin plasma lens (PI M. Litos)

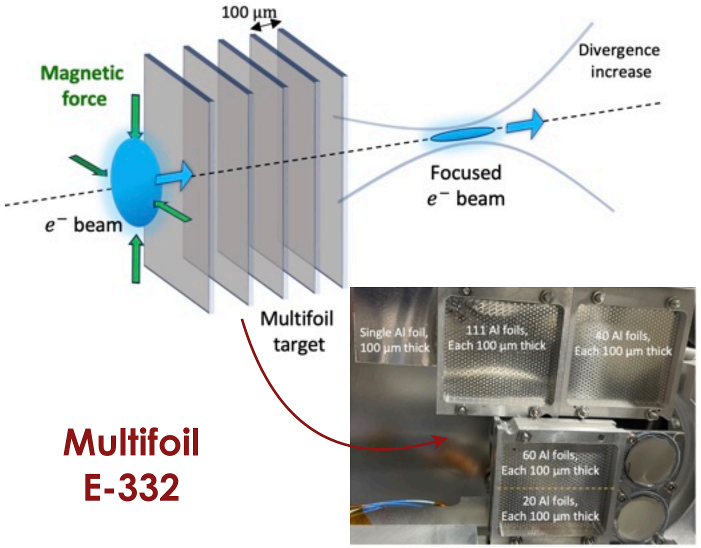


- Focusing gradient for extreme focusing

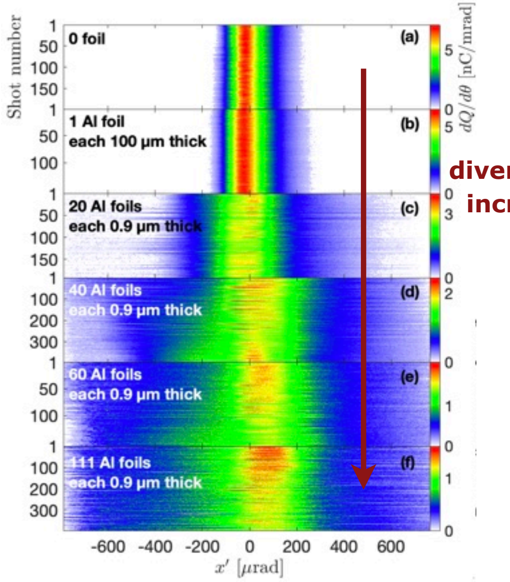


FACET-II highlight #3: extreme focusing of high-energy beams

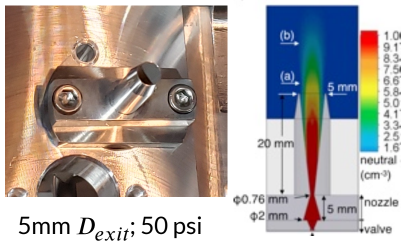
- Experimental evidence of extreme focusing with divergence increase

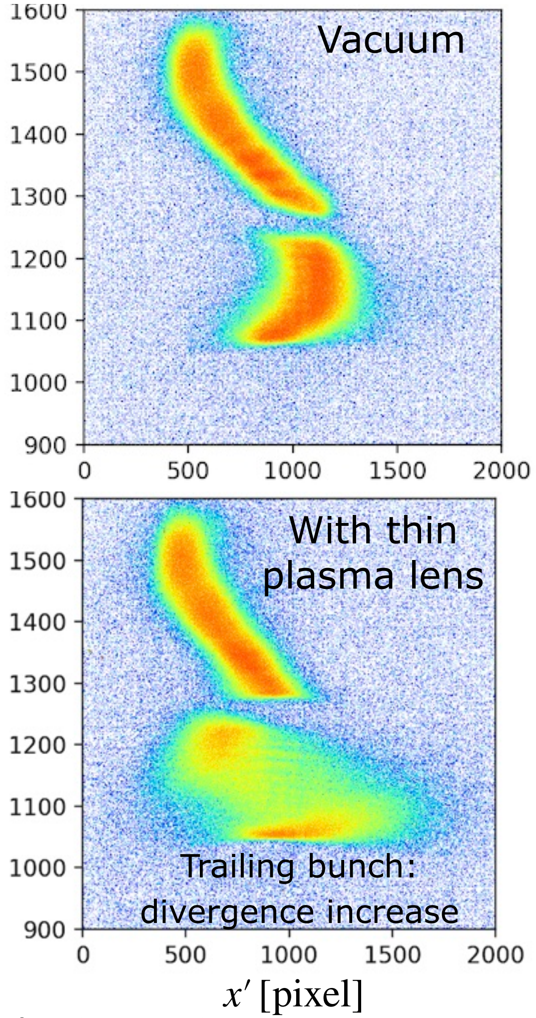


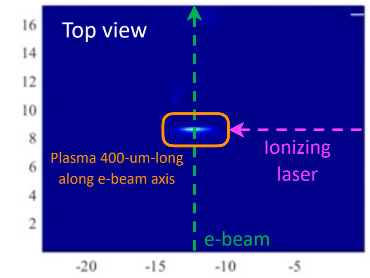
Multifoil E-332



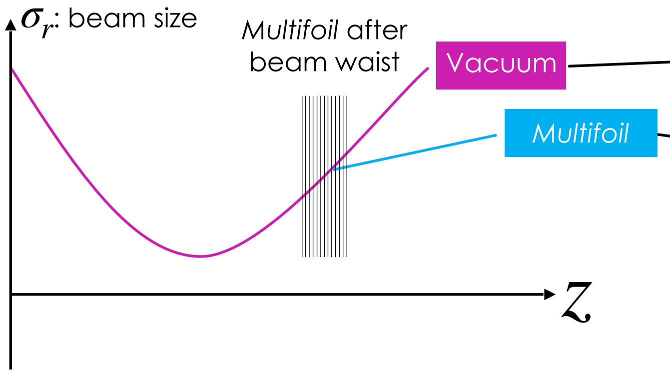
Laser-ionized plasma lens E-308

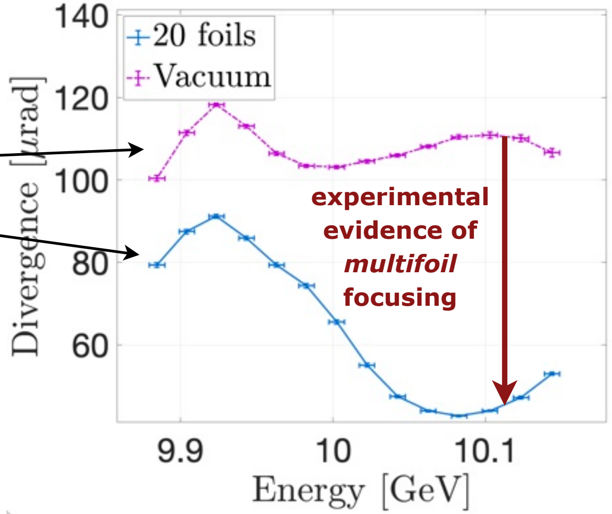


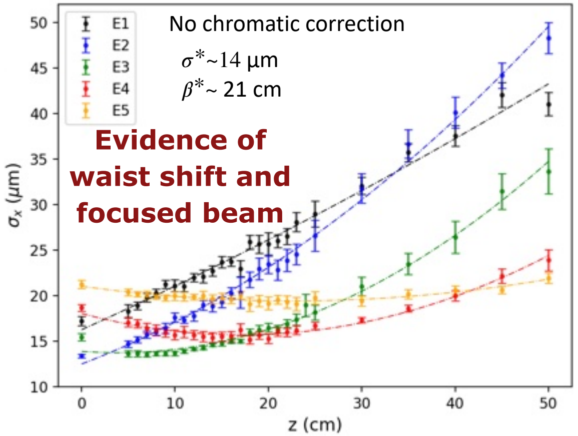




- Direct focusing observation







Demonstration of a thin plasma lens with f = 19 cm

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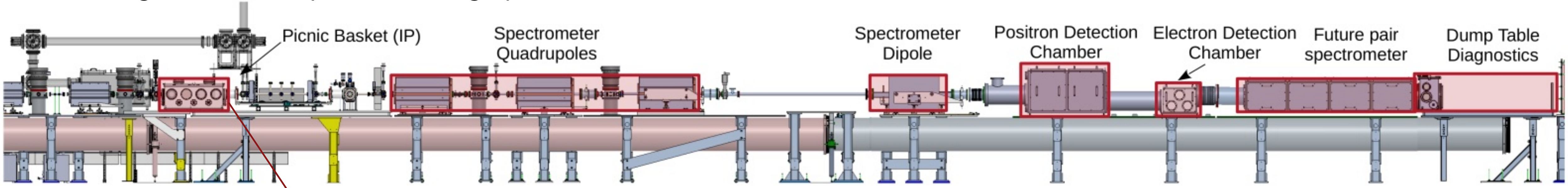
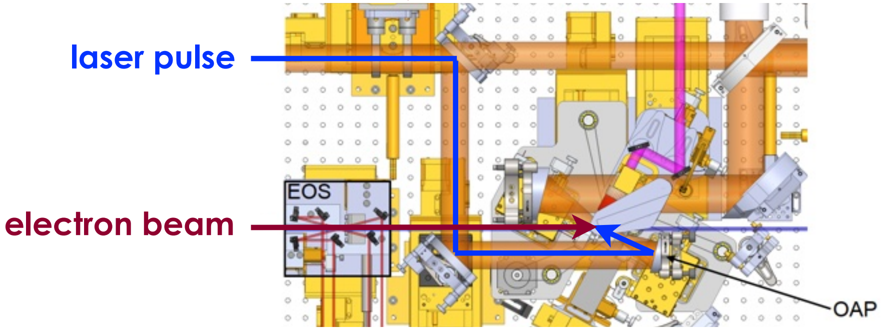
FACET-II highlight #4: strong field QED and quantum radiation reaction

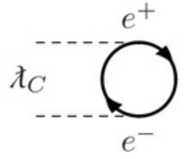
- Colliding intense laser pulses with highly relativistic electron beam (E-320, PI S. Meuren)





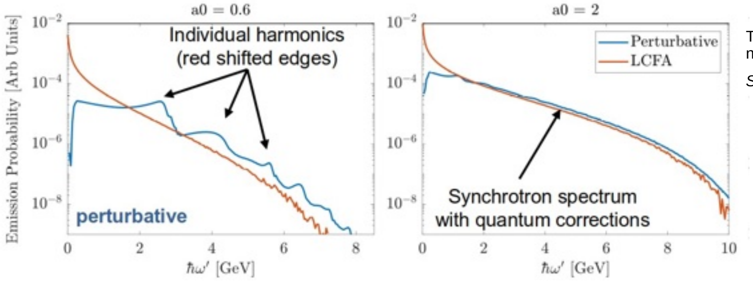
- **Electron beam parameters**
  - 10 GeV electrons
    $\rightarrow\ \gamma \sim 20000$
  - Bunch length: ~10 μm

- **10 TW Laser parameters**
  - Wavelength: 0.8 μm
  - Spot size: ~2 μm (FWHM)
  - Pulse duration: ~50 fs (FWHM)
  - Energy on target: < 0.4 J
  - a_0: 0.4 – 4



Length: $\lambda_C = \hbar/(mc)$
Energy: $\mathscr{E} = mc^2$
Critical field: $eE_{cr} = mc^2/\lambda_C$

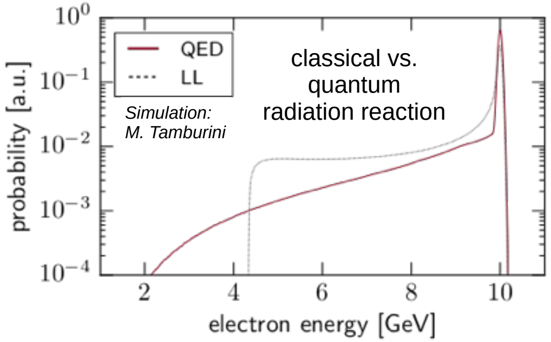
- Fundamental QED at electric fields approaching the **Schwinger critical field** in the electron beam rest frame



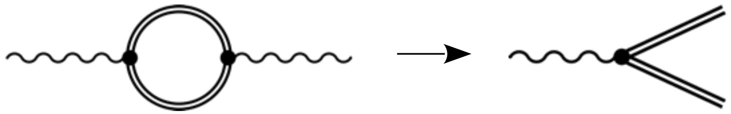
Transition from perturbative to nonperturbative interaction

Simulations: C. Nielsen (Aarhus)

Compton edges red shift in laser field, and smear out when fully nonperturbative in a_0



Most precise tests of quantum radiation reaction



Vacuum polarization
photon transforms temporarily into an electron-positron pair

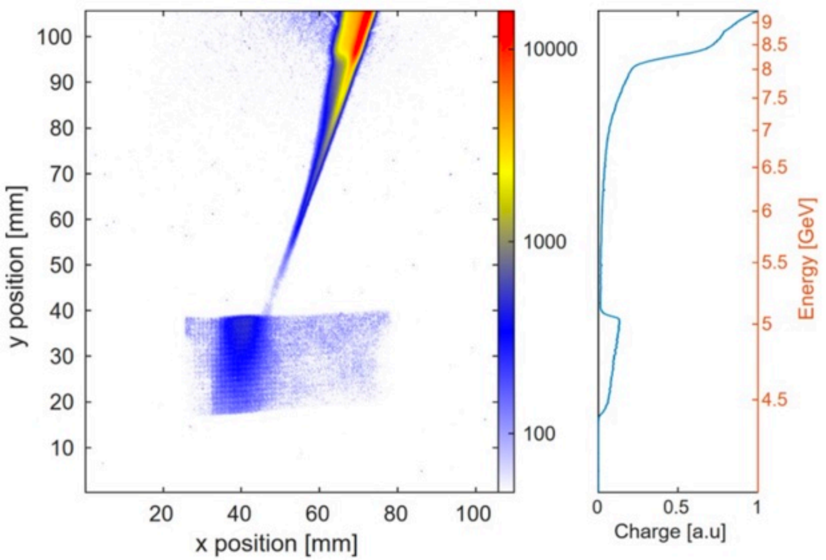
Pair production
virtual pair is "ionized" by laser at QED critical field

From multi-photon (E-144) to nonlinear/tunneling (E-320) Breit-Wheeler pair production

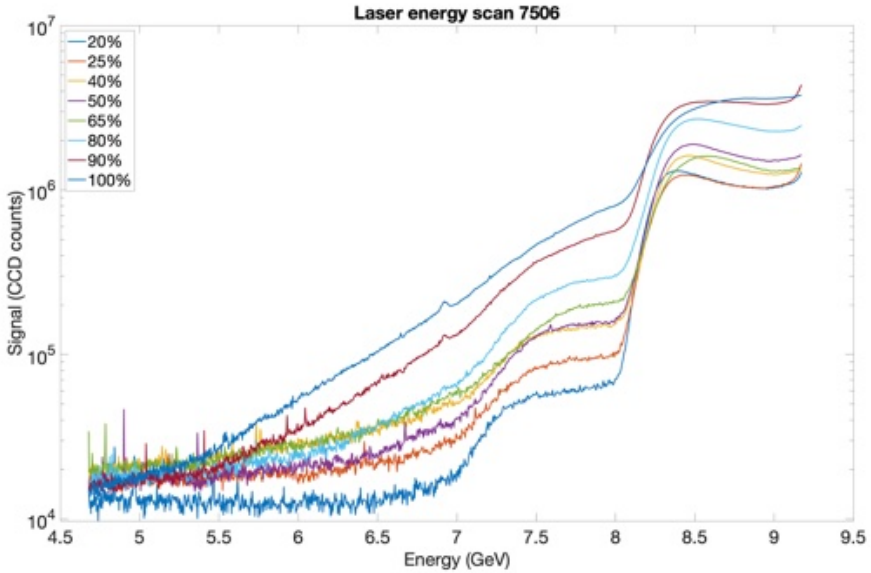
FACET-II highlight #4: strong field QED and quantum radiation reaction

Improvements to laser, e-beam, diagnostics, real-time analysis…

Typical single shot spectrum

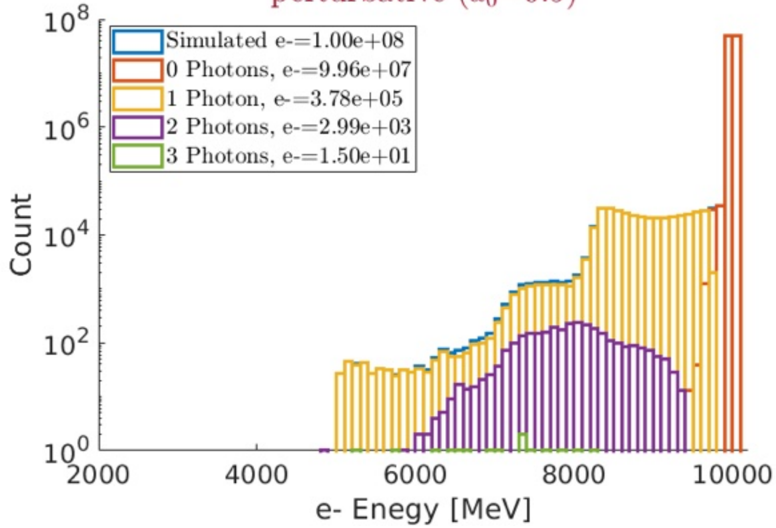


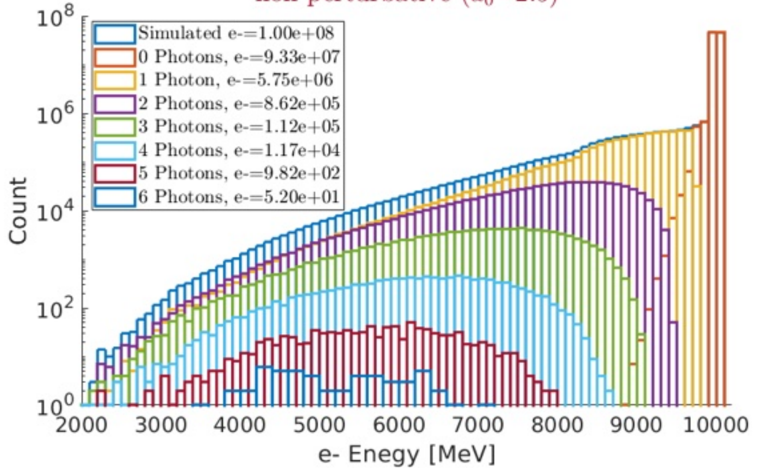
Intensity dependent spectra



Preliminary

Simulations





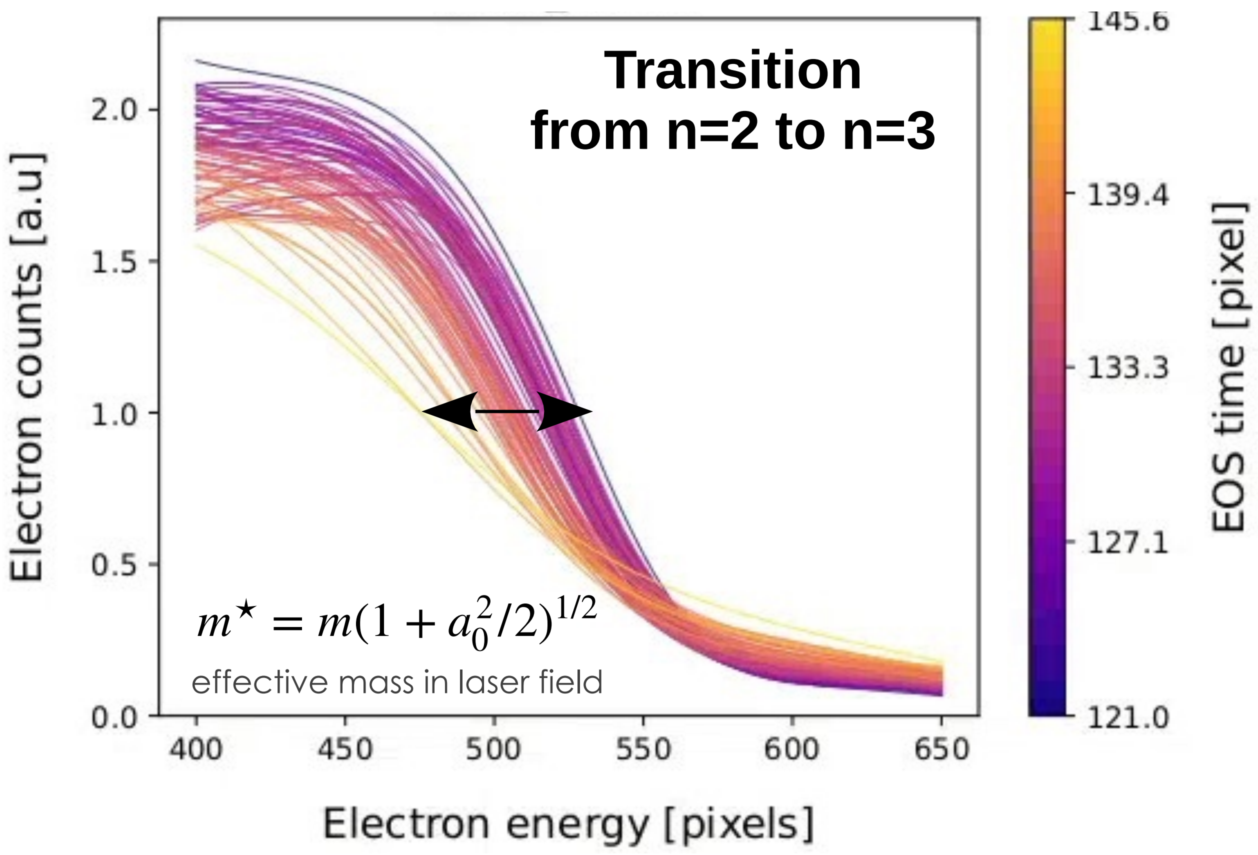
- High energy electrons in n=1 region dominated by tails of laser
- Low energy exponential spectrum consistent with QRR

Simulation plots by R. Holtzapple, analysis plots by T. Smorodnikova, S. Rego, R. Hessami and J. Wang

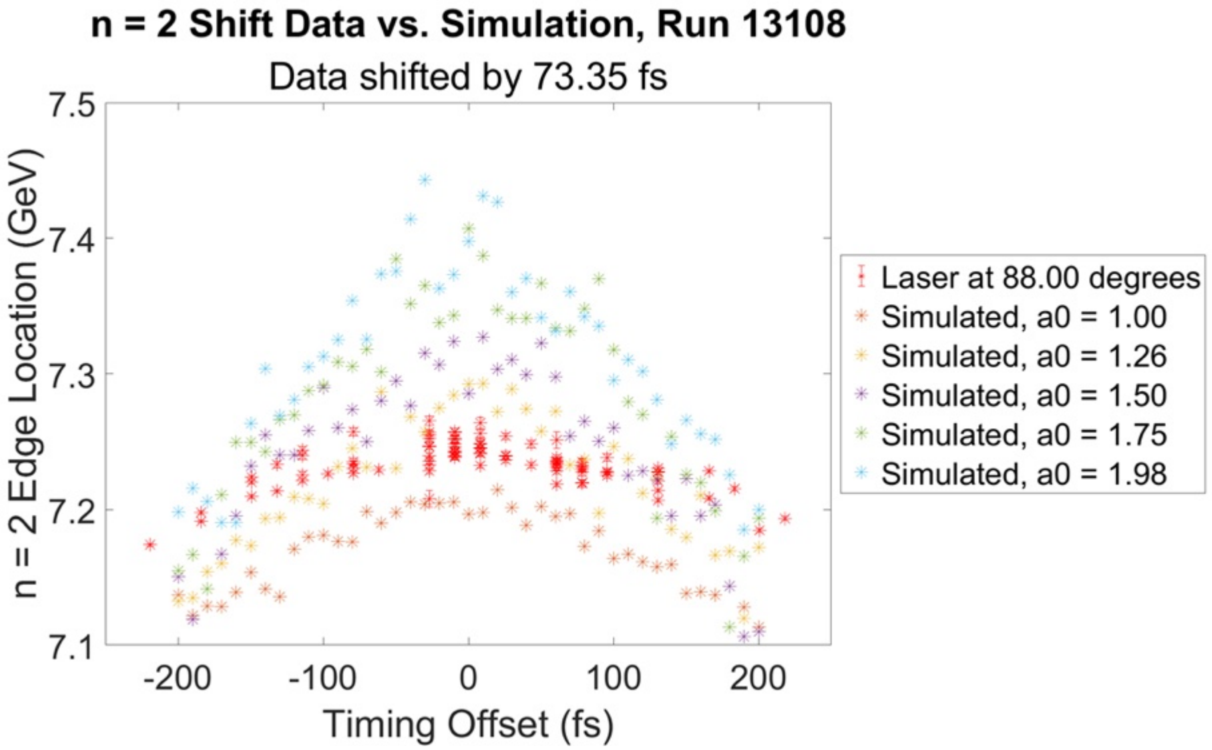
Hints of transition to non-perturbative regime (Spring 2025)

FACET-II highlight #4: strong field QED and quantum radiation reaction

- Experimental data with first observation of Compton edge shift with ponderomotive mass dressing



Inside a laser field the electron mass increases, which shifts the positions of the Compton edge



Laser field is varied with laser-ebeam timing, showing a clear edge shift when on time.

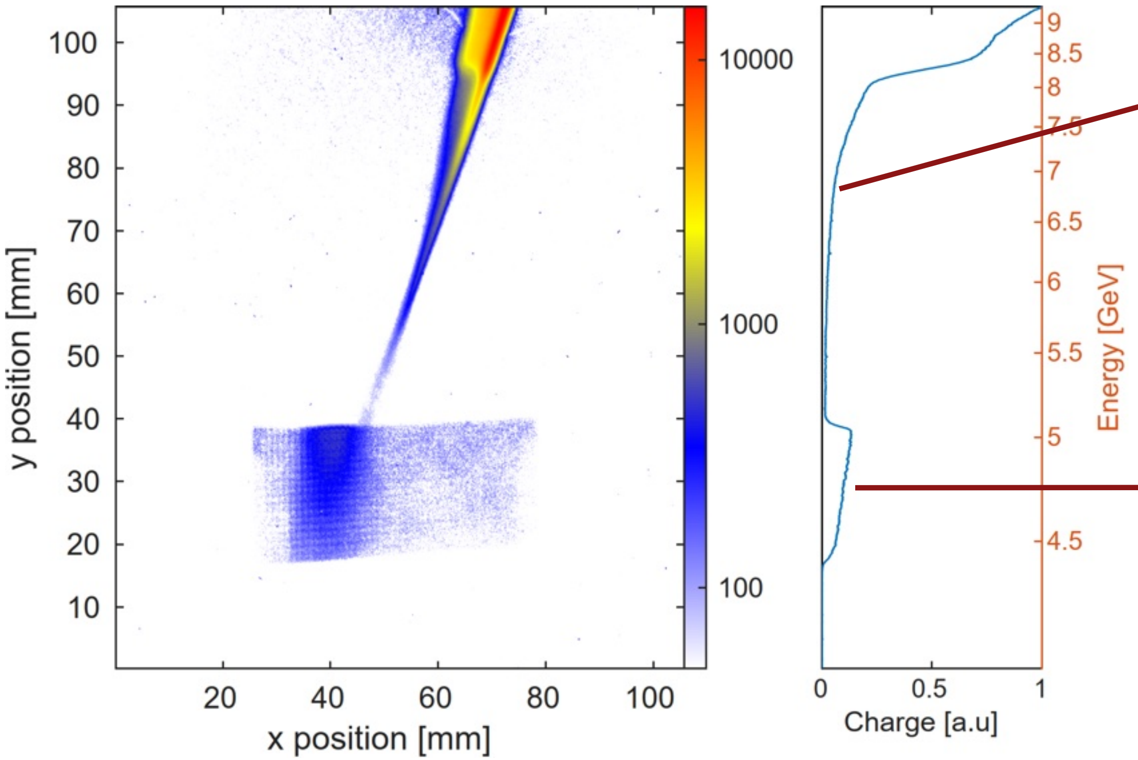
FACET-II highlight #4: strong field QED and quantum radiation reaction

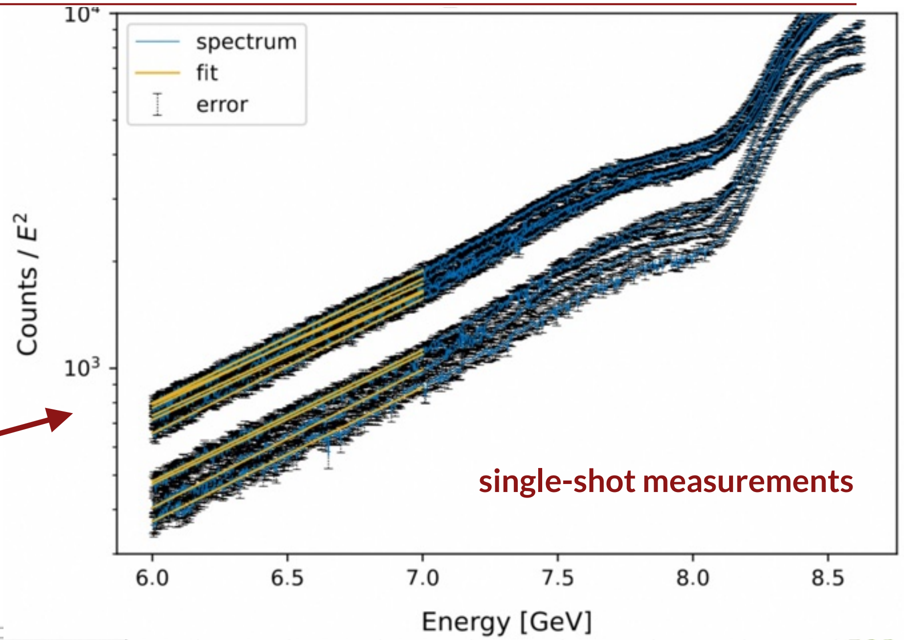
- **Most precise measurements of quantum radiation reaction to date**

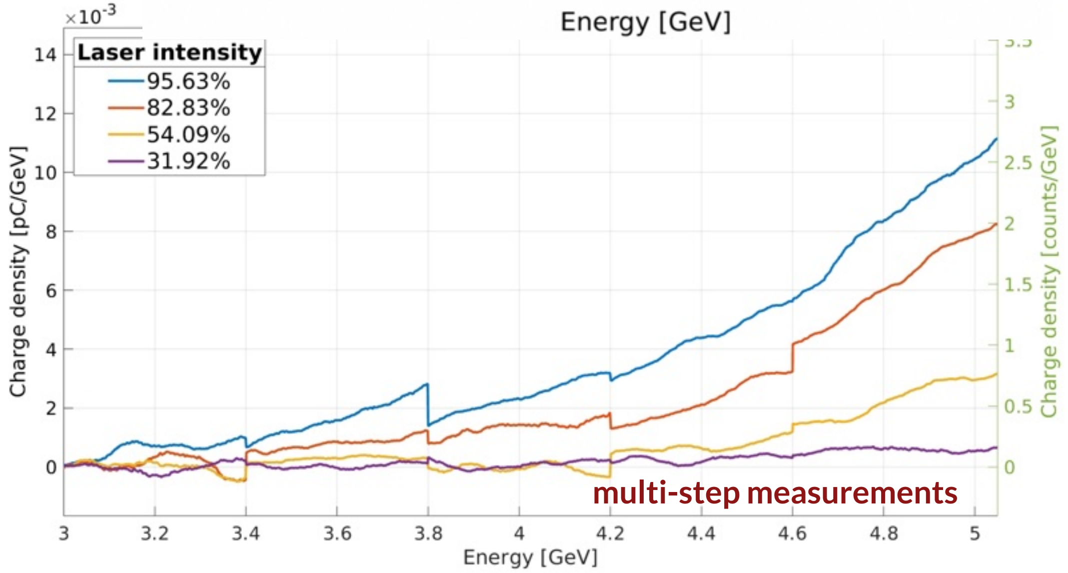
Low background electron spectrometer

- Top: GOS (DRZ fine) scintillator, limited sensitivity, appropriate above 5 GeV
- Bottom: GAGG crystal array, near single electron detection, well suited below 5 GeV

- **Quasi-continuous, exponential scattered electron spectrum consistent with quantum radiation reaction with $a_0 \gtrsim 4$**

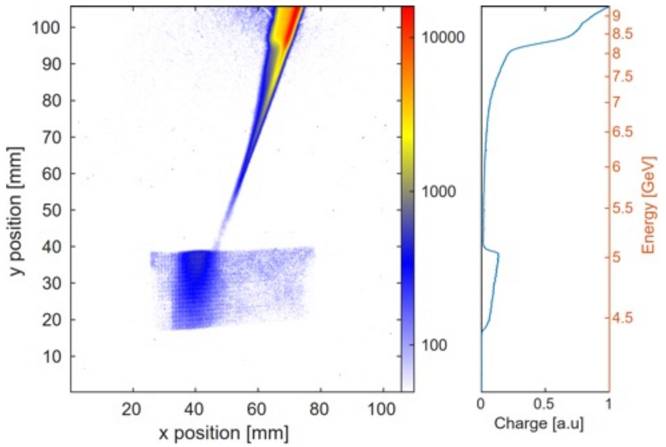


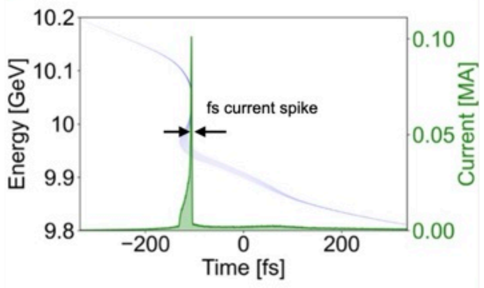




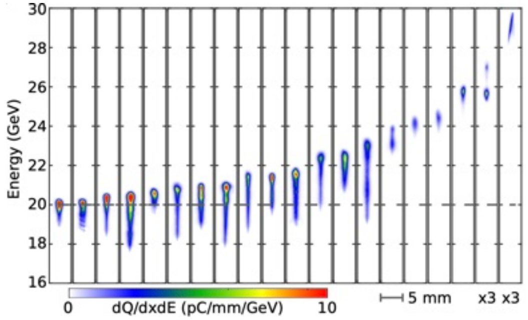
Conclusion: many exciting recent results at FACET-II

- Most precise measurements of quantum radiation reaction to date, evidence of ponderomotive mass dressing in laser field

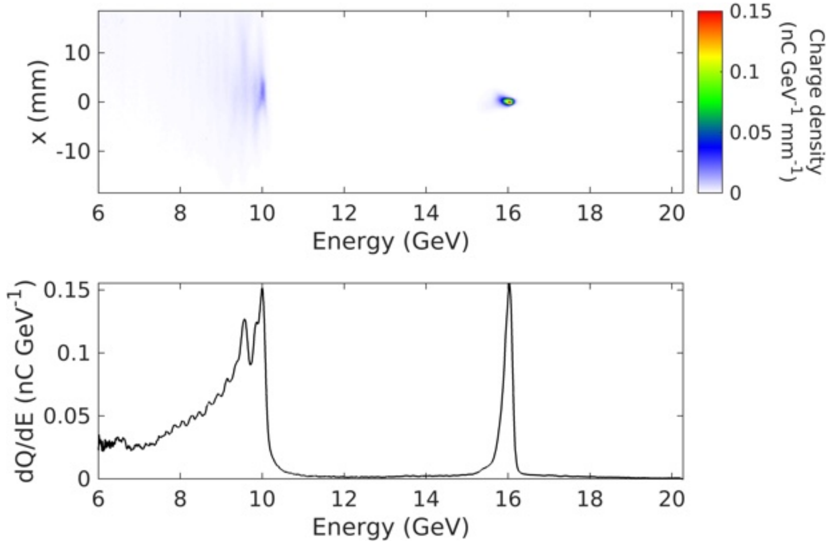




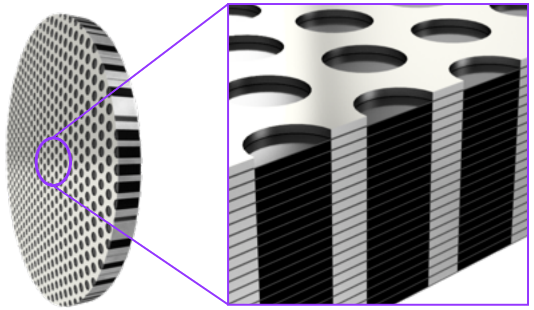
- 100-kA spikes

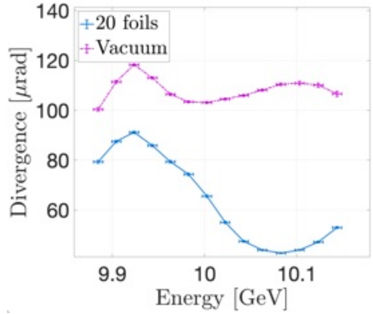


- Energy and brightness transformer

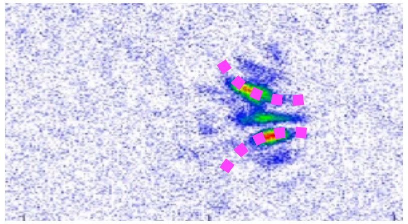


- GeV-scale plasma acceleration with high field uniformity





- Extreme focusing



- Probing, wakeless and e+ regimes

Many thanks

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  - Z. Buschmann, S. Kalsi, R. Loney, M. Parker, G. Yocky
- Joined for on-site efforts:
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Editors' Suggestion

Experimental Generation of Extreme Electron Beams for Advanced Accelerator Applications

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Questions?