

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

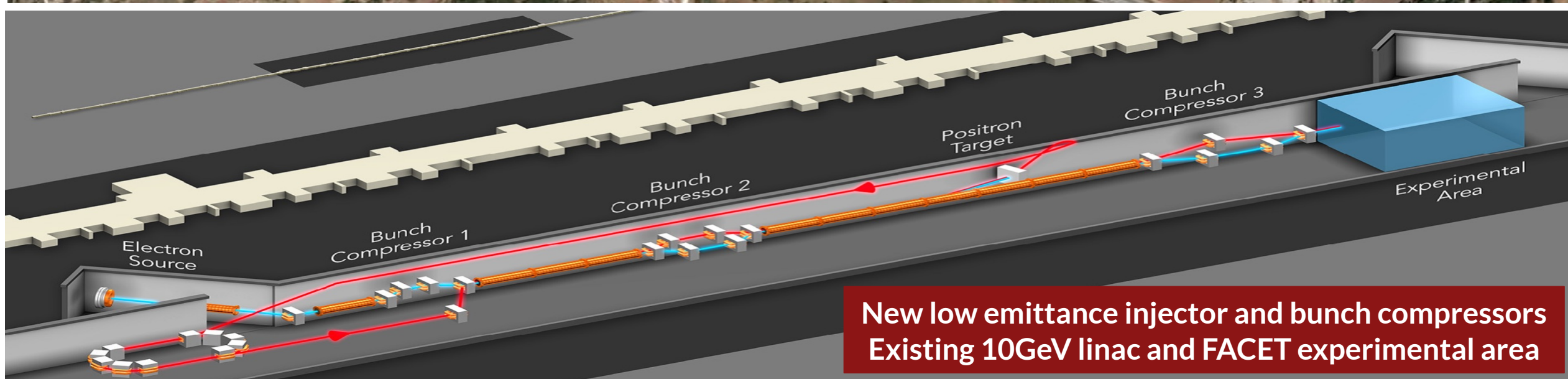


Facility for Advanced
Accelerator Experimental Tests

Mark J. Hogan / Senior Staff Scientist / FACET and Test Facilities Division Director
September 22, 2025

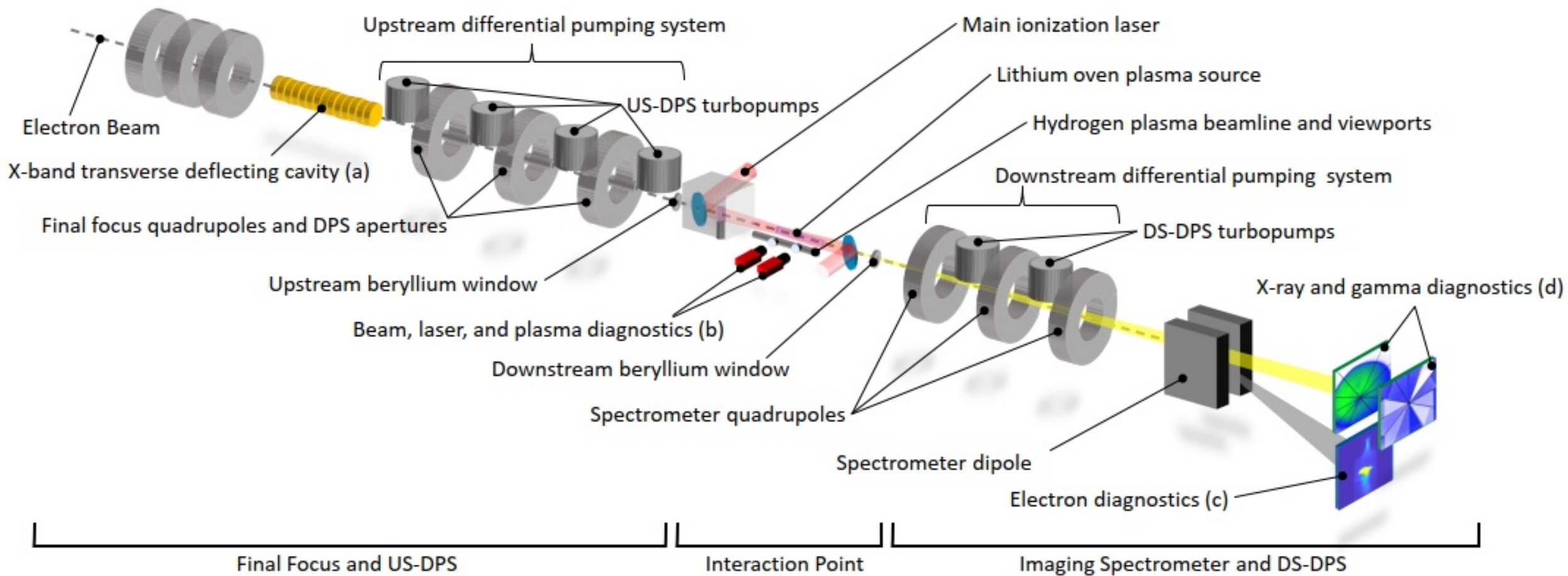
FACET-II @ SLAC: km-long electron linac delivering 10GeV beams

FACET-II Technical Design Report SLAC-R-1072
10 GeV, 2nC, single/double bunch, 10 μ m, 30fs



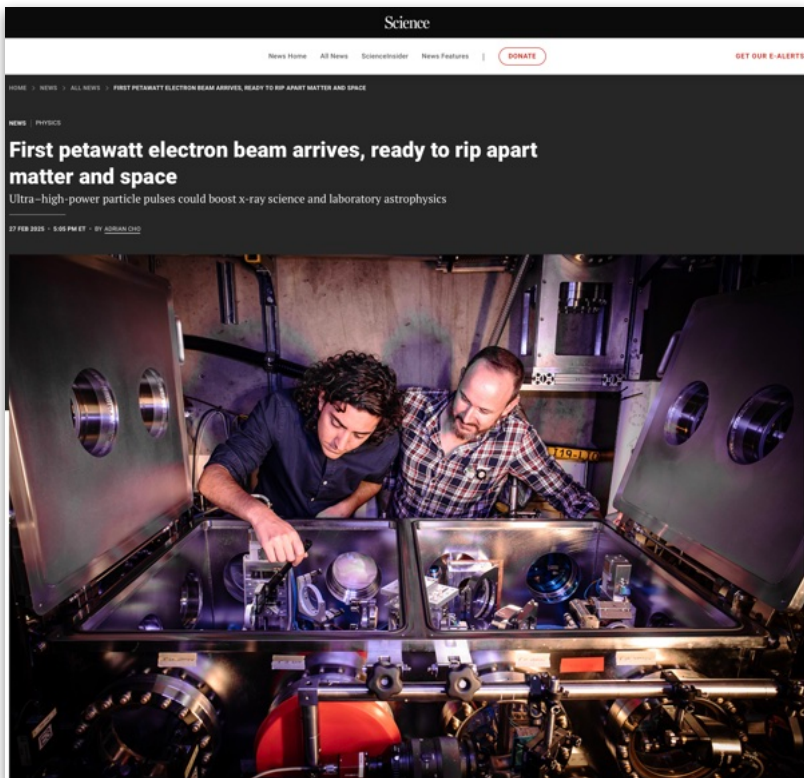
**New low emittance injector and bunch compressors
Existing 10GeV linac and FACET experimental area**

FACET-II Experimental Area Overview



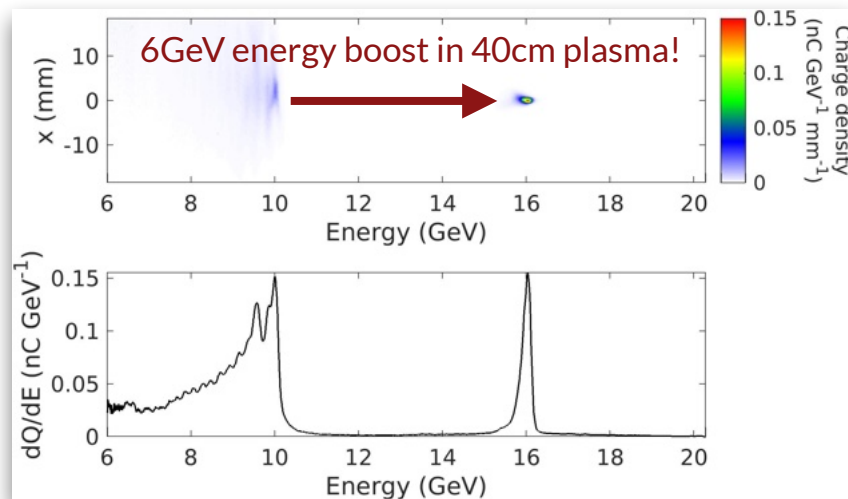
FACET-II: A National User Facility with a Broad User Program Based on 10GeV Beams and Their Interaction with Lasers, Materials and Plasma

Combining extreme beams ($>100\text{kA}$) and plasma to make high-gradient energy and brightness booster...



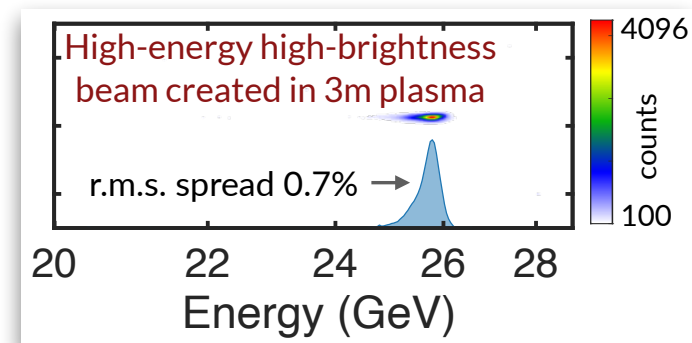
Plasma wakefield acceleration

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 $> 1\text{V}/\text{\AA}$ 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

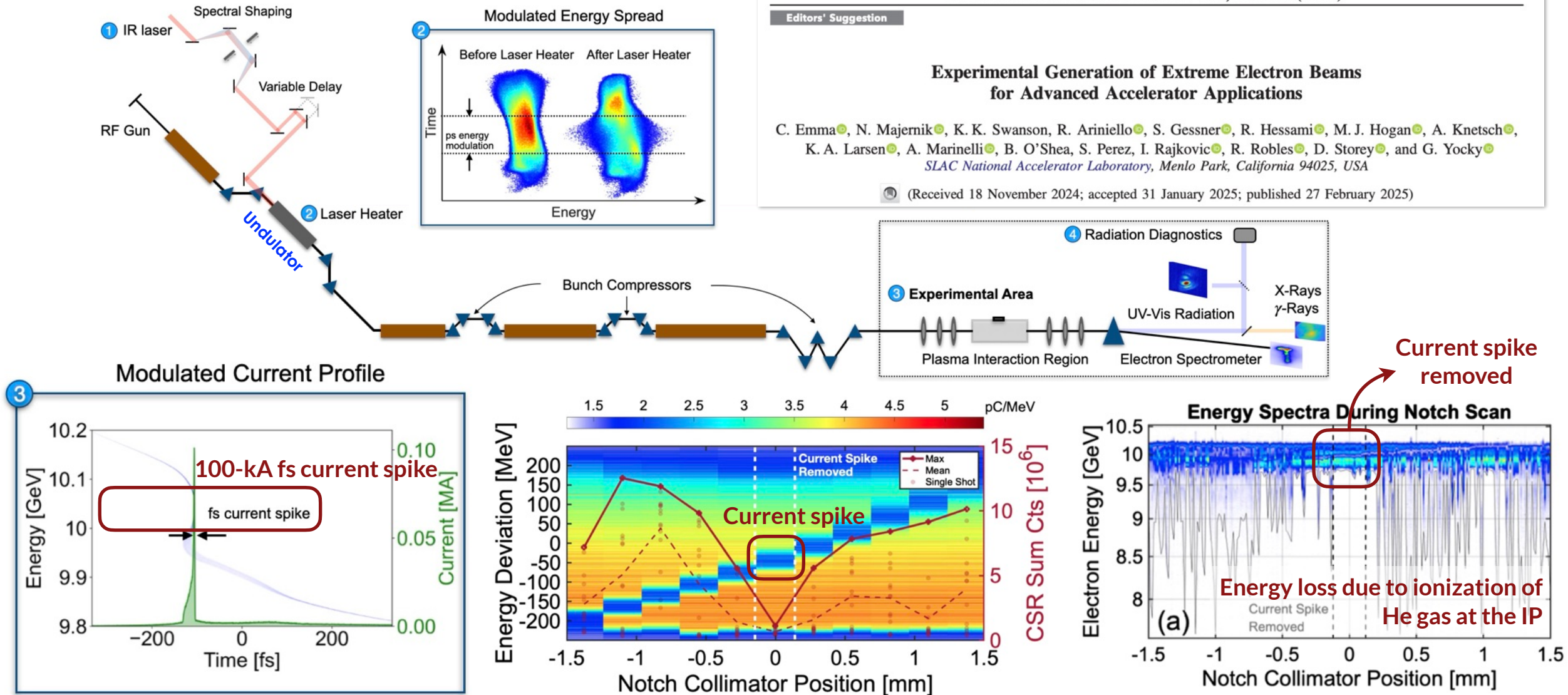
Outline for the remainder of the presentation

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

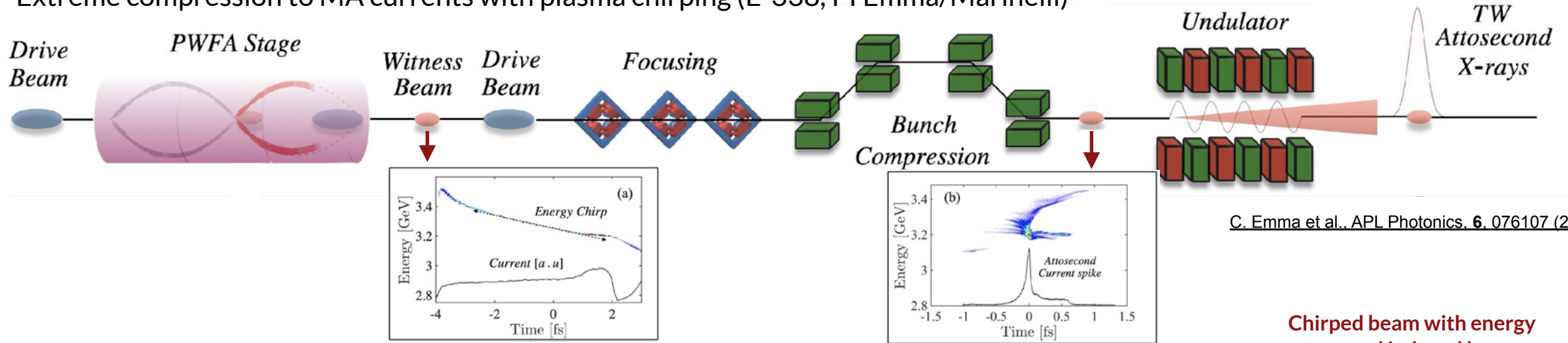
FACET-II highlight #1: extreme currents, compression and brightnesses

- Generate 100-kA-scale currents with laser heater

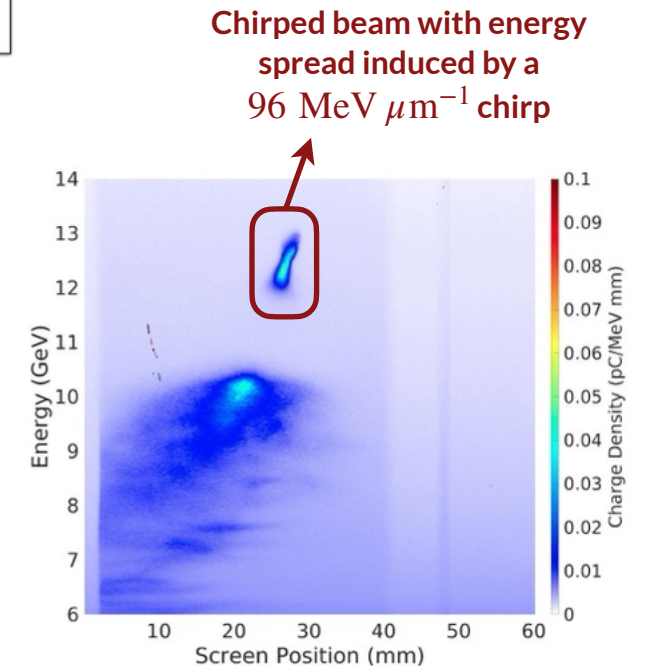
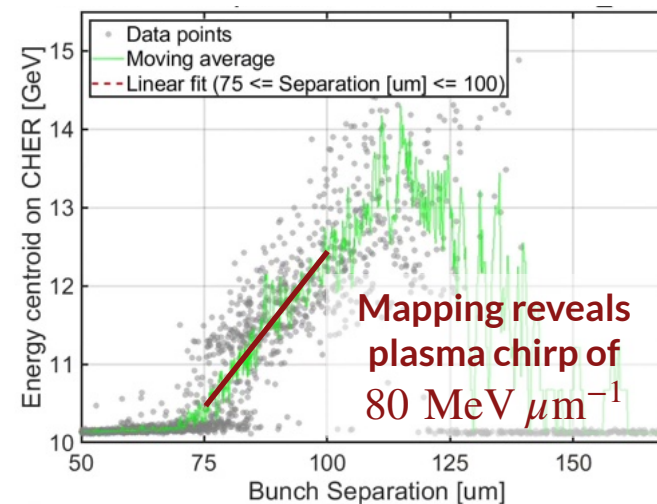
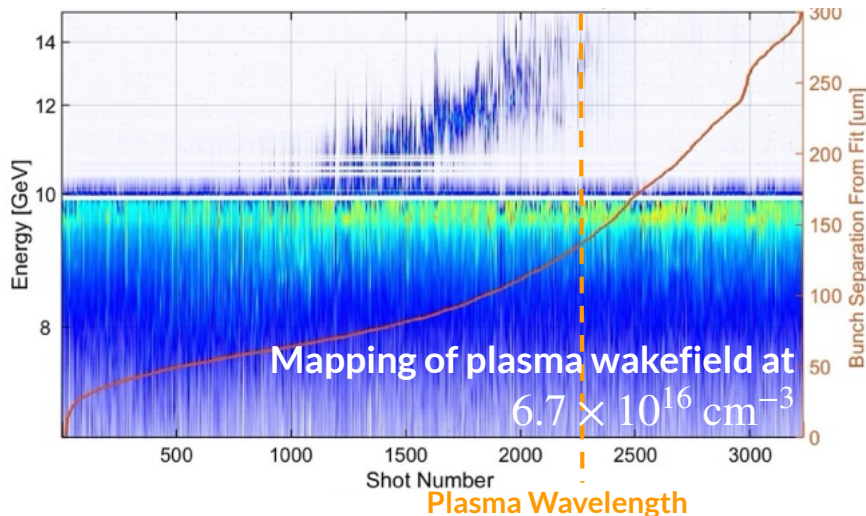


FACET-II highlight #1: extreme currents, compression and brightnesses

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

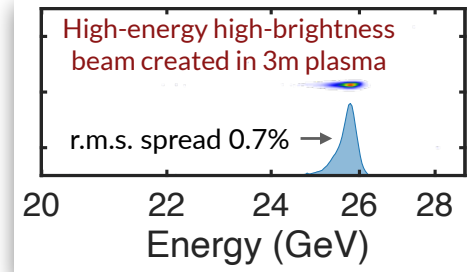
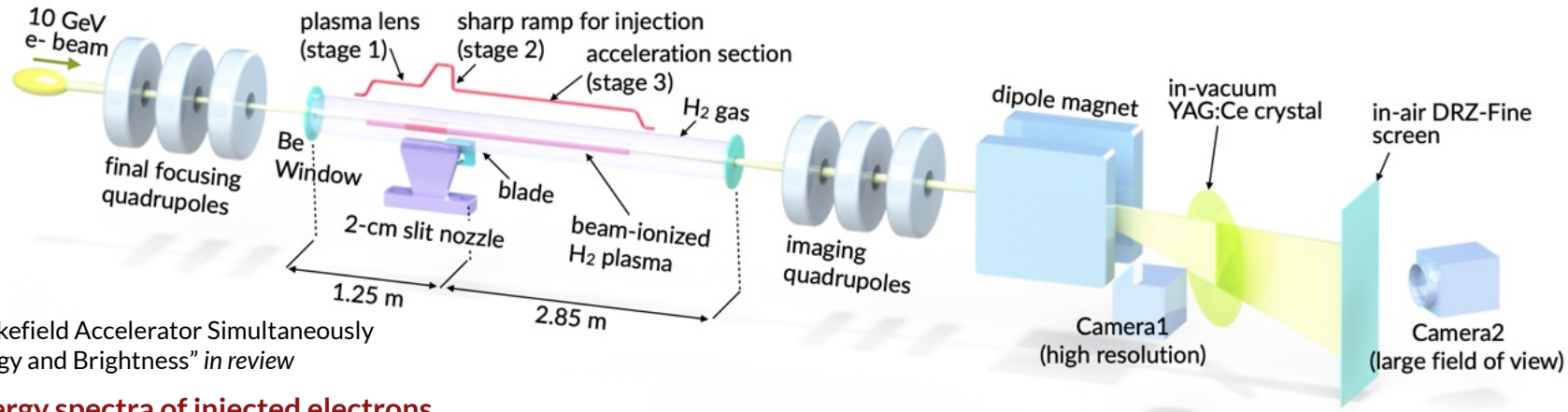


- Experimental demonstration of plasma chirping $\mathcal{O}(100 \text{ MeV } \mu\text{m}^{-1})$



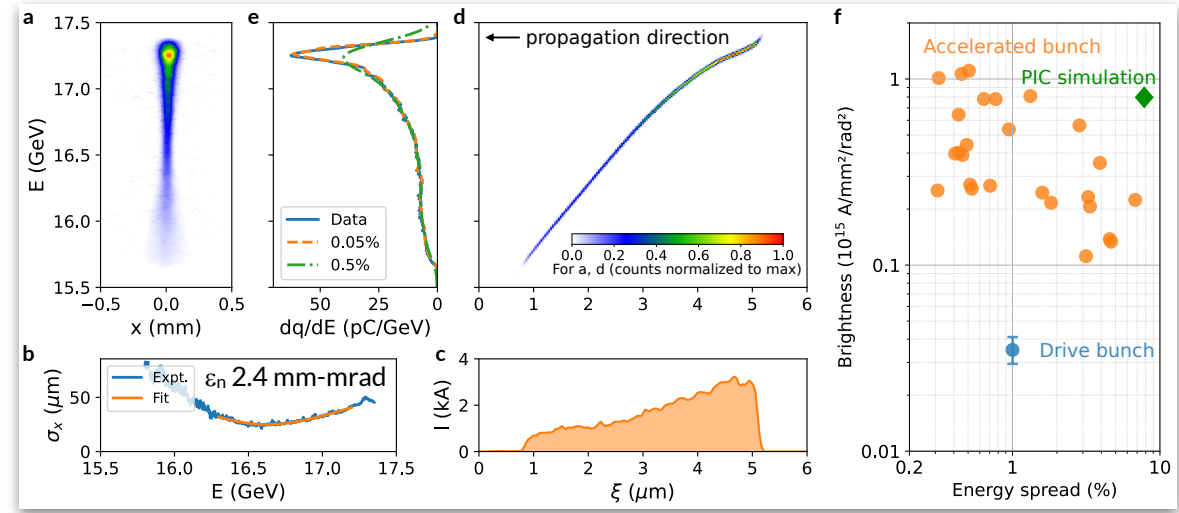
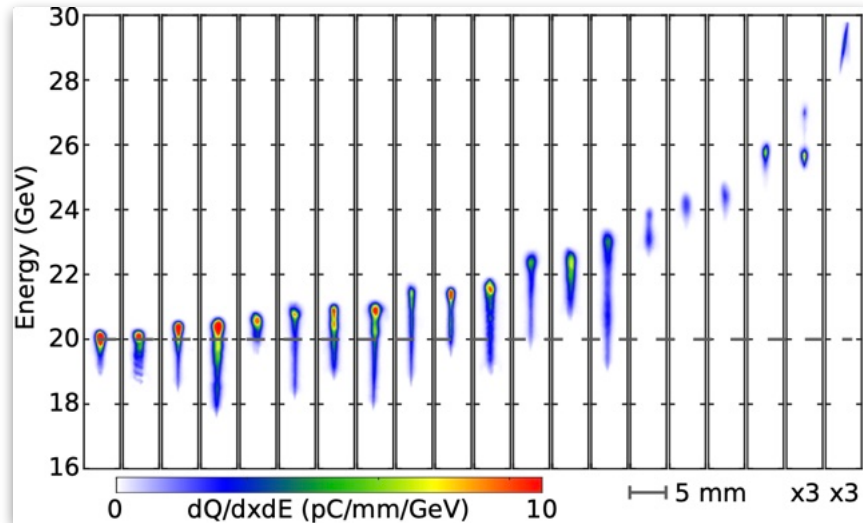
FACET-II highlight #1: extreme currents, compression and brightnesses

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



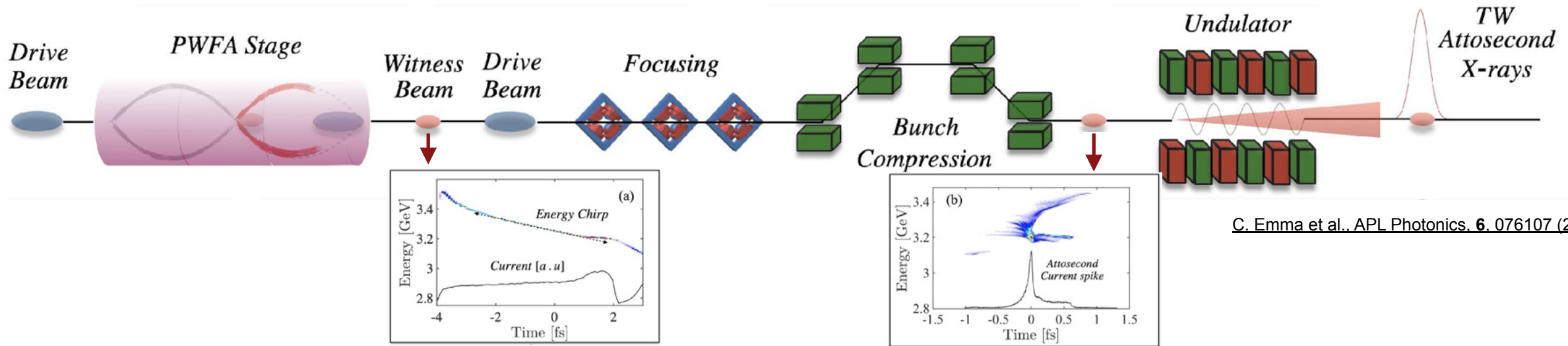
C. Zhang et al., "Plasma-Wakefield Accelerator Simultaneously Boosts Electron Beam Energy and Brightness" in review

Energy spectra of injected electrons



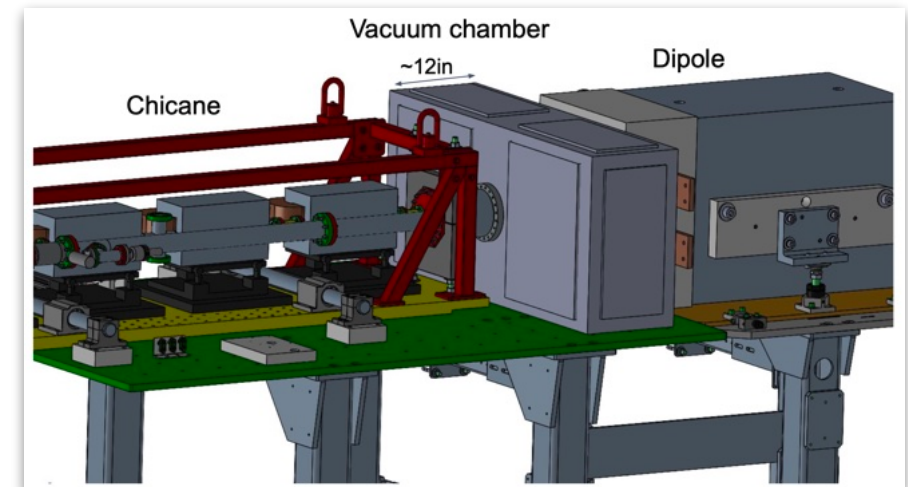
Plasma acts as an energy and brightness transformer – creating new beams with higher energy and brightness

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



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



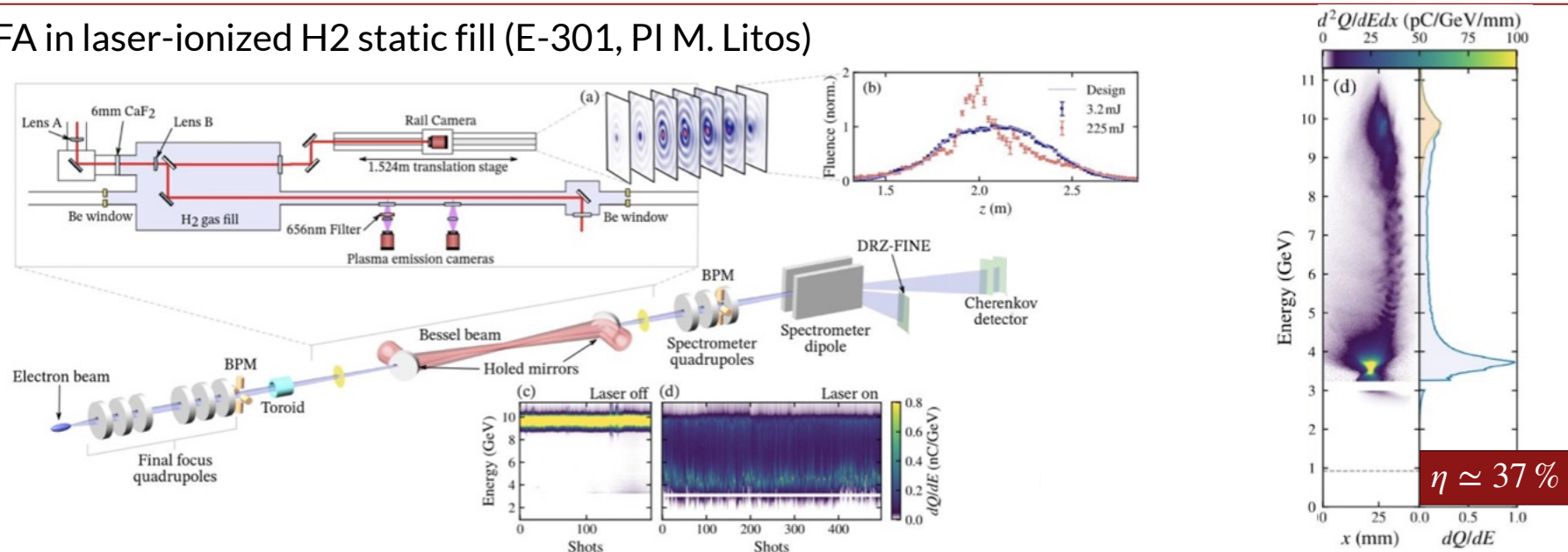
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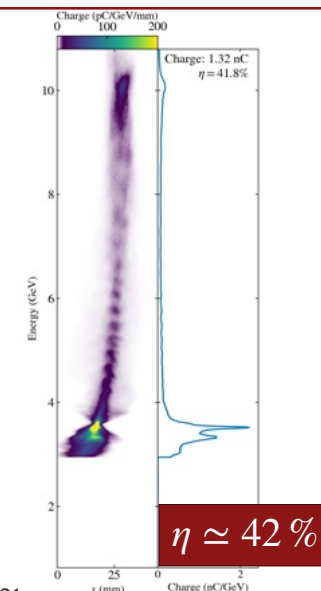
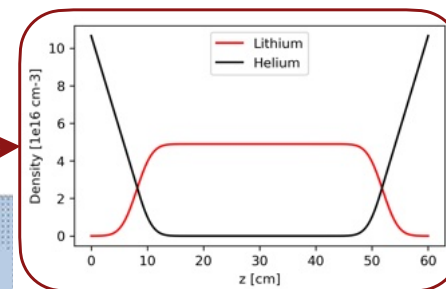
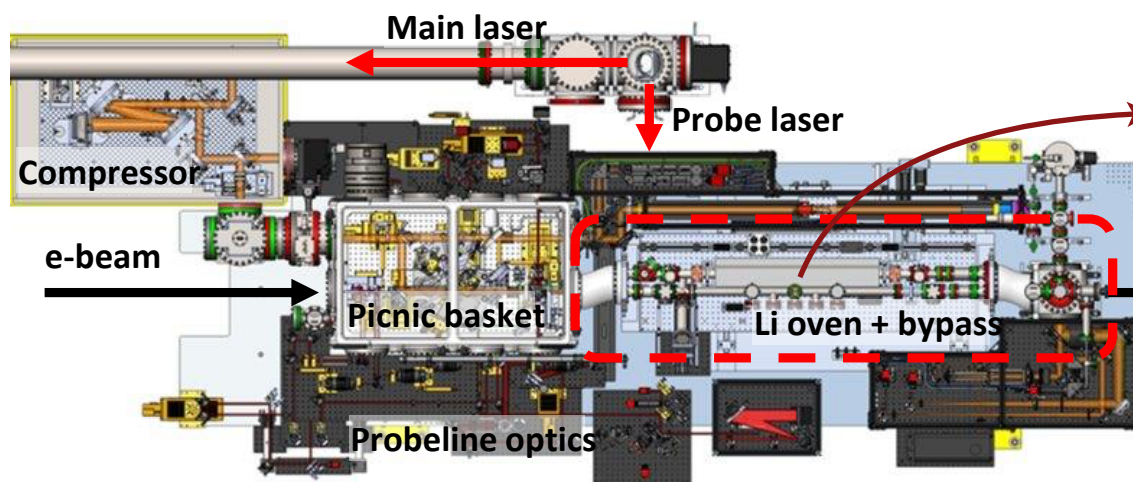
FACET-II highlight #2: efficient transfer from drive to plasma

- 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 H₂ plasma at $4.5 \times 10^{16} \text{ cm}^{-3}$

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

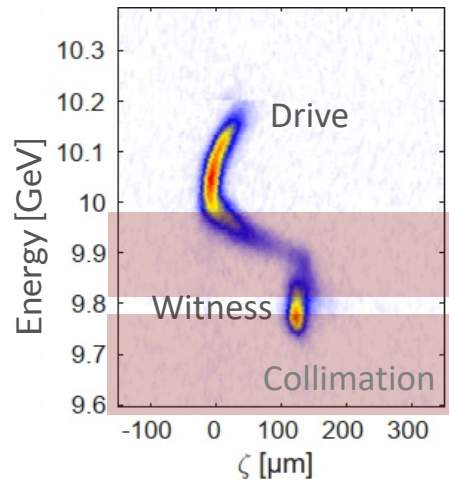


- Single drive bunch started at 10 GeV
- Decelerated down to ~3 GeV
- 42% of beam energy transferred to the Li plasma at $4.3 \times 10^{16} \text{ cm}^{-3}$

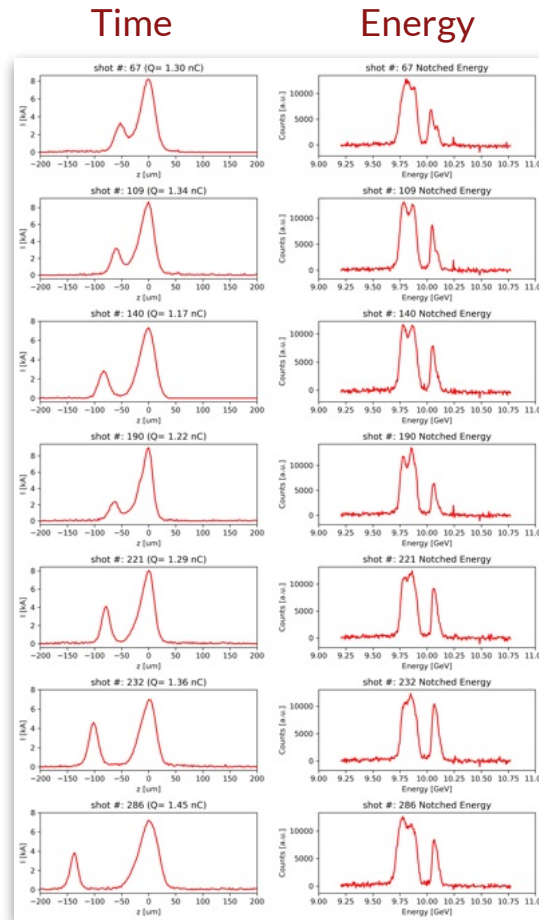
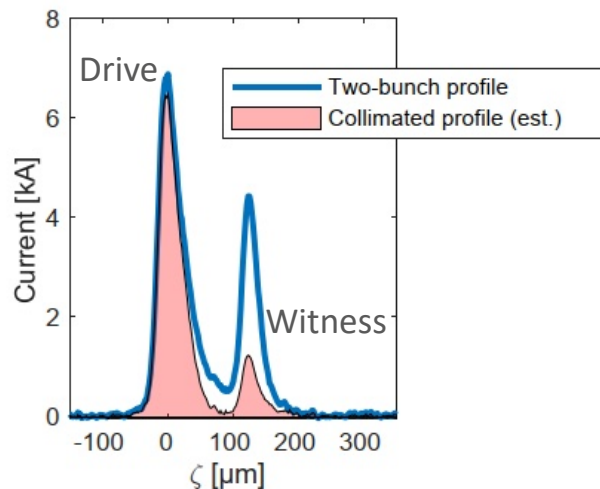
Developed a range of two-bunch (drive and witness) configurations with typically $\sim 1\text{nC}$ drive, 200-400pC witness

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

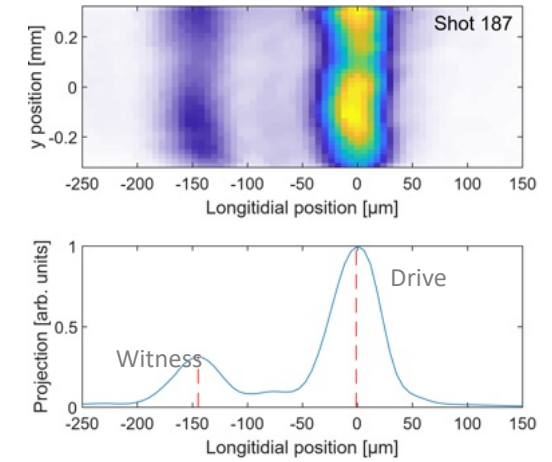
- Create two-bunches at the photocathode
- Accelerate and compress from 10ps to 100fs
- Use RF phasing and collimation to tailor profiles at IP



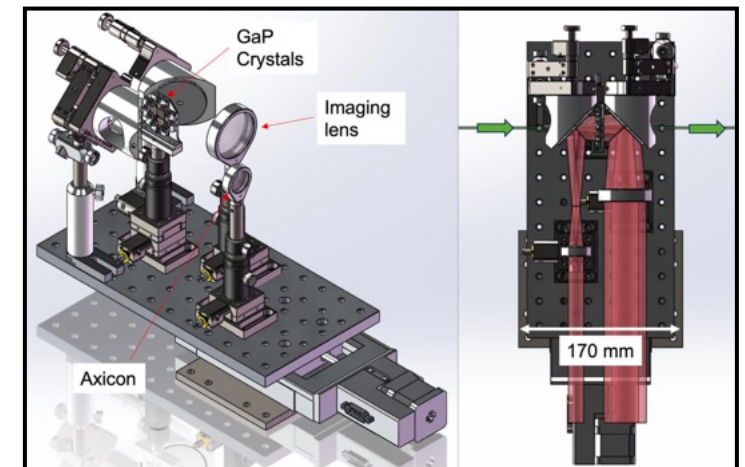
Longitudinal Phase
Space Profiles from
TCAV +
Spectrometer



EOS Temporal Profile



EOS BPM v2 Coming Soon!
CU Boulder – RadiaBeam collaboration

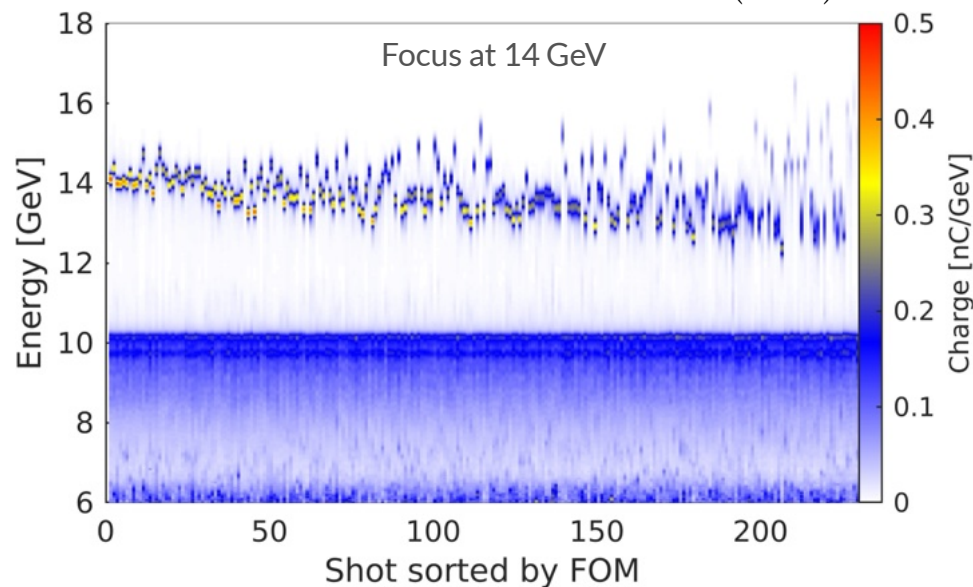


FACET-II highlight #2: uniform acceleration in plasma

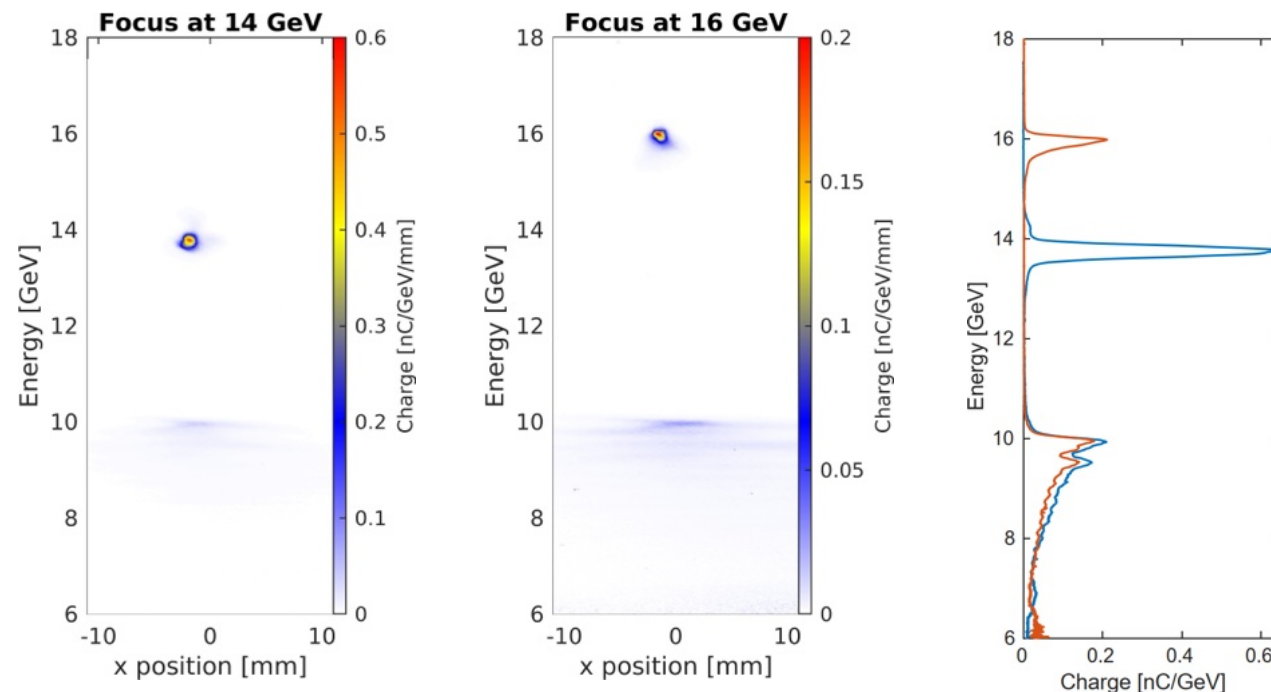
Two-bunch configuration

- Driver: ~1.2 nC, 6-8 kA
- Witness: 150-250 pC incoming charge
- Plasma: 40cm long lithium plasma, $4 \times 10^{16} \text{ cm}^{-3}$

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



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



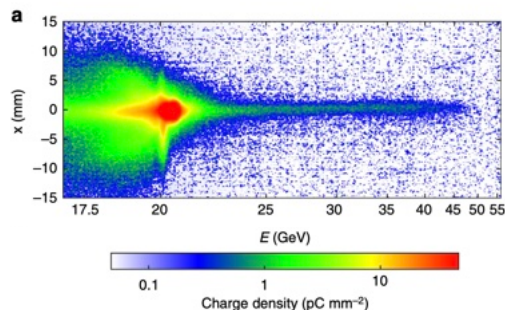
$\Delta E = 3.8 \text{ GeV}$
 $\sigma_E = 0.76 \%$
 $\eta_{tot} = 6 \%$
 $Q_w = 180 \text{ pC}$

$\Delta E = 6 \text{ GeV}$
 $\sigma_E = 0.69 \%$
 $\eta_{tot} = 3 \%$
 $Q_w = 60 \text{ pC}$

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

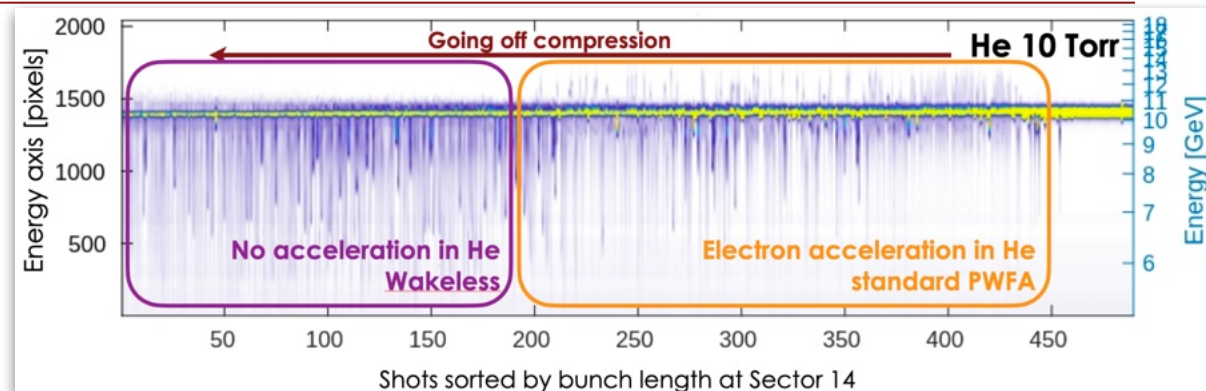
Transition to wakeless regime first observed in FACET



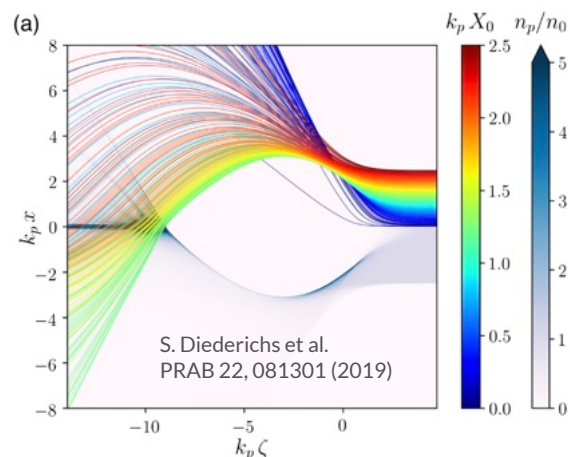
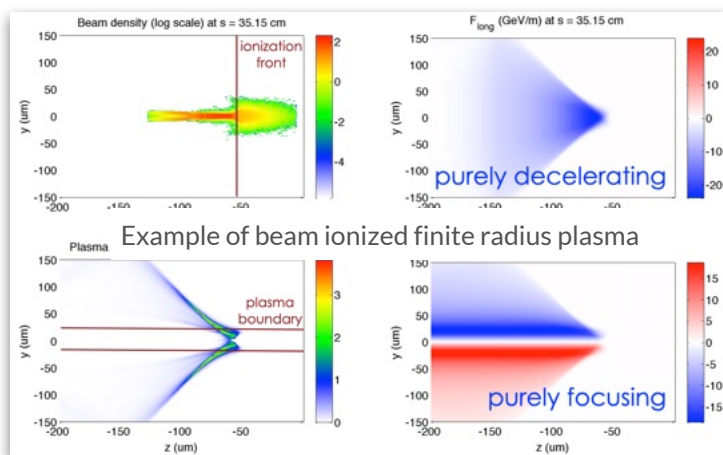
Nature Commun. 7, 11898 (2016)

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



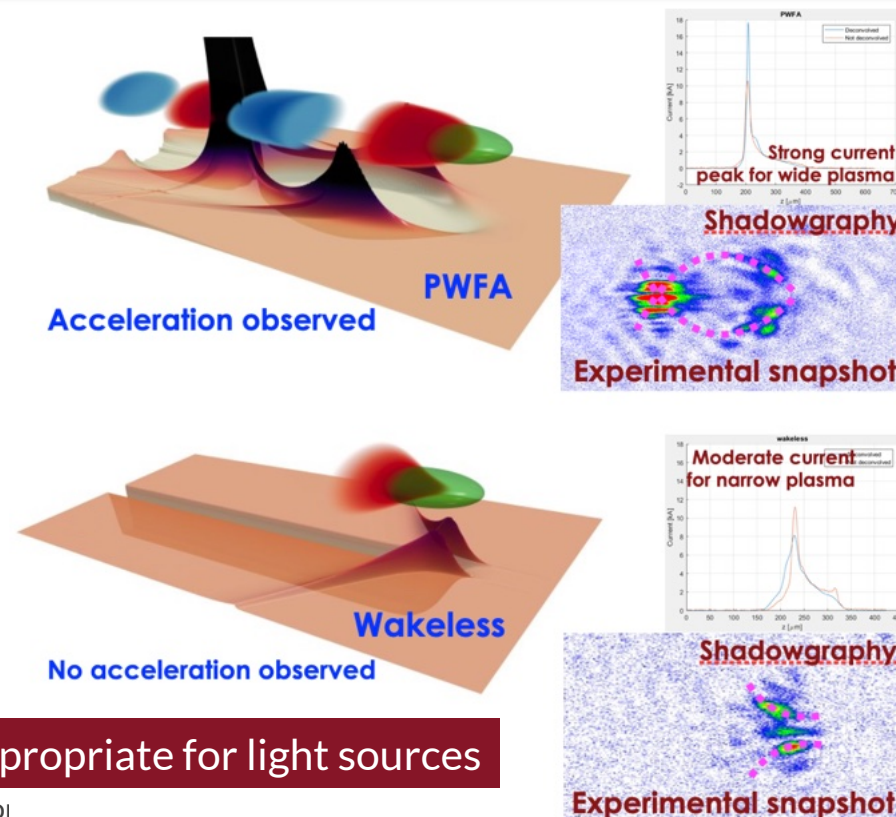
Finite radius plasmas proposed for applications to ion channel laser and positron acceleration



- New regimes in narrow beam-ionized He plasma (E-340, PI Corde/Litos/Emma)

- Narrow laser-ionized H₂ plasma for positron PWFA (E-333, PI Gessner/Litos)

Demonstration of a pure ion channel appropriate for light sources



Outline for the remainder of the presentation

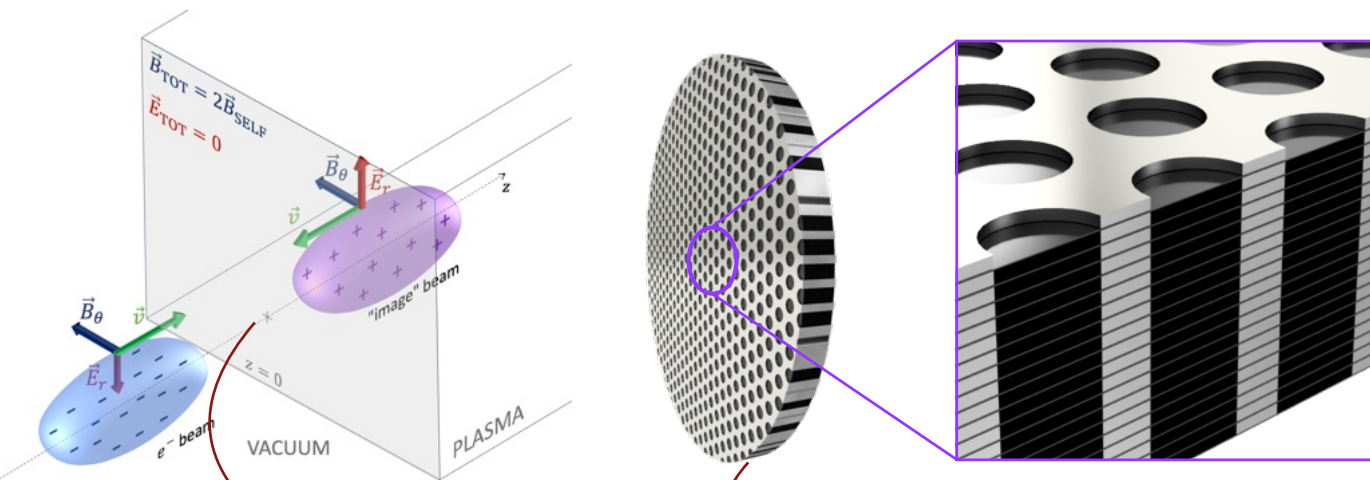
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FACET-II highlight #3: extreme focusing of high-energy beams

▸ Principle of extreme focusing

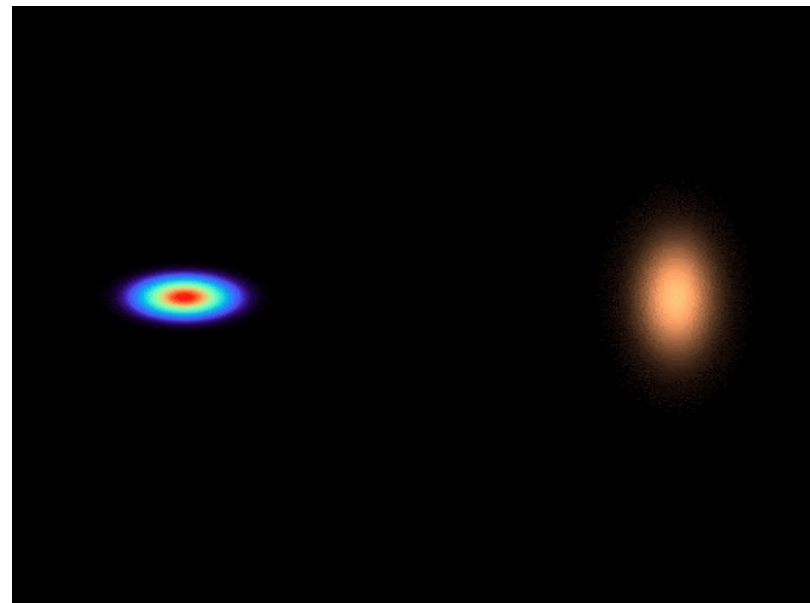
E-332 multifoil (PI Corde/Tamburini)



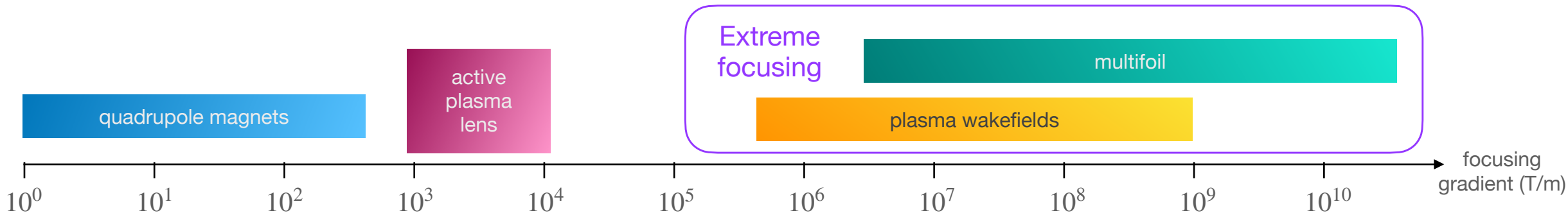
Focusing effect!

Strongly-enhanced focusing

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

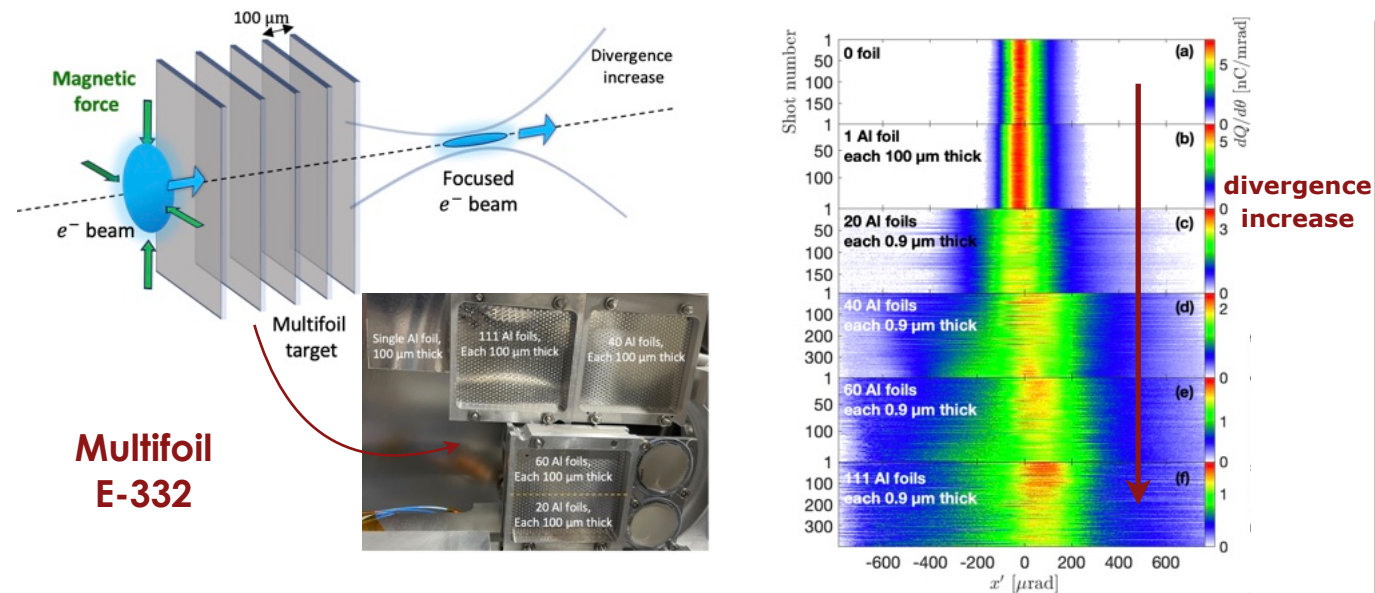


▸ Focusing gradient for extreme focusing

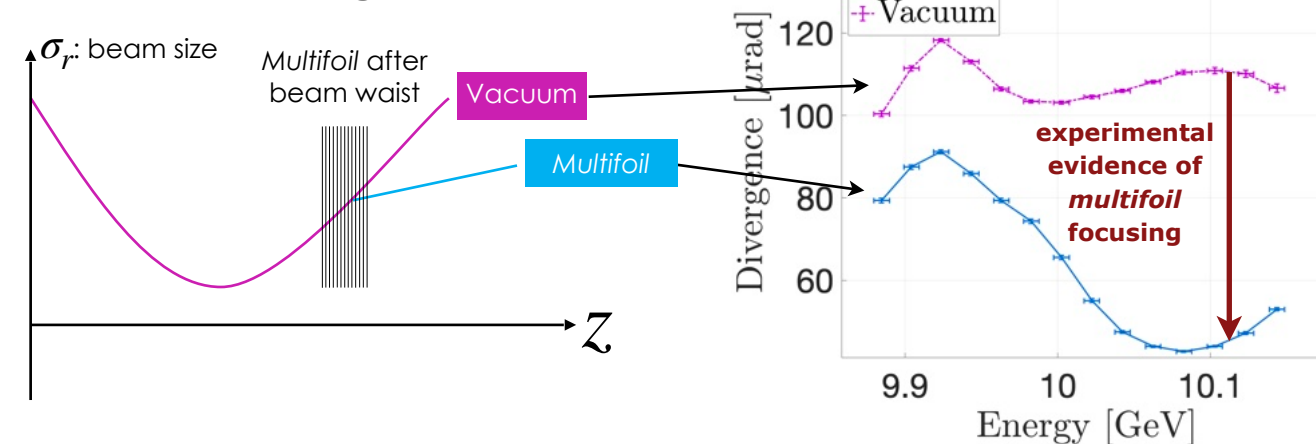


FACET-II highlight #3: extreme focusing of high-energy beams

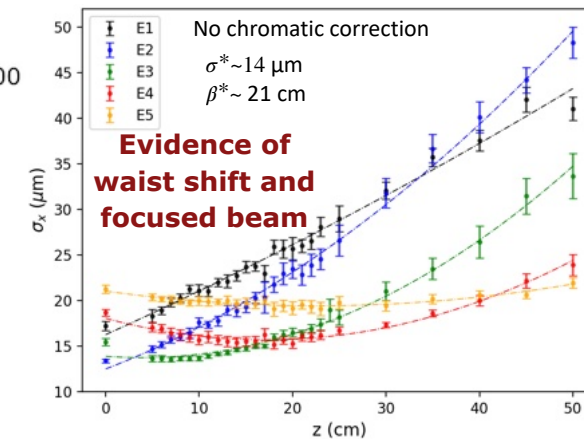
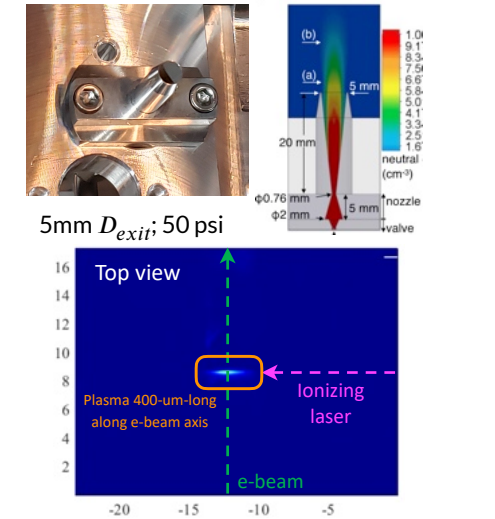
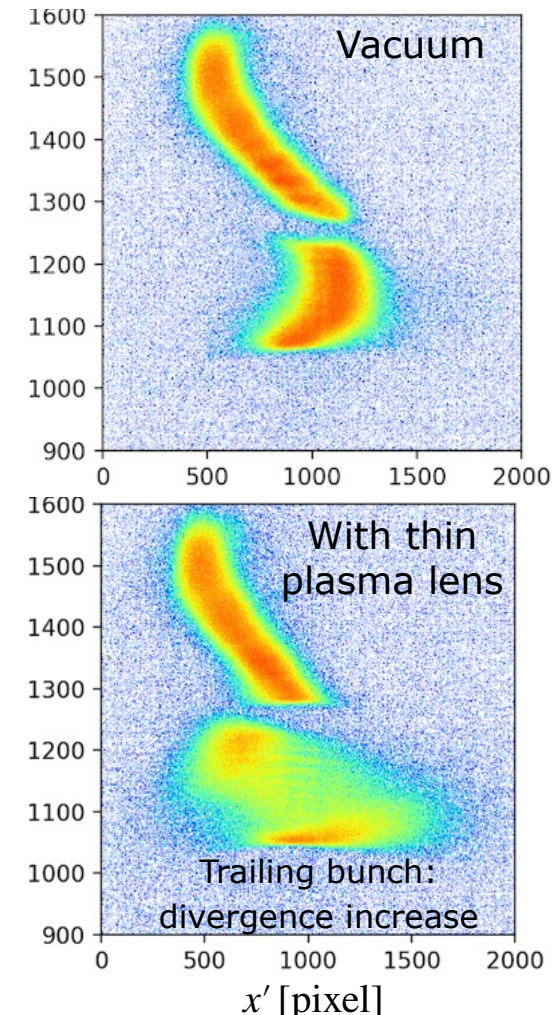
- Experimental evidence of extreme focusing with divergence increase



- Direct focusing observation



Laser-ionized plasma lens E-308



Demonstration of a thin plasma lens with $f = 19 \text{ cm}$

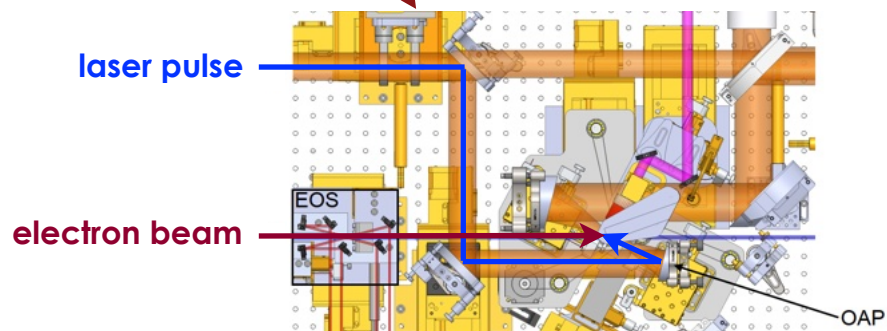
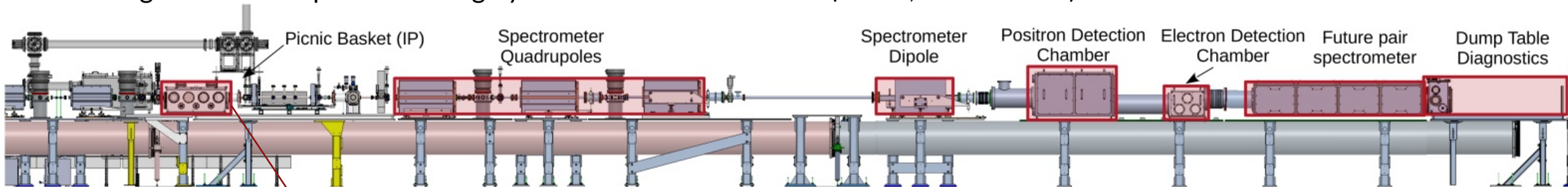
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Recent progress at FACET-II

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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)

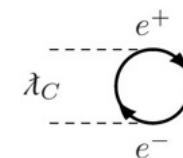


Electron beam parameters

- 10 GeV electrons
 $\rightarrow \gamma \sim 20000$
- Bunch length: $\sim 10 \mu\text{m}$

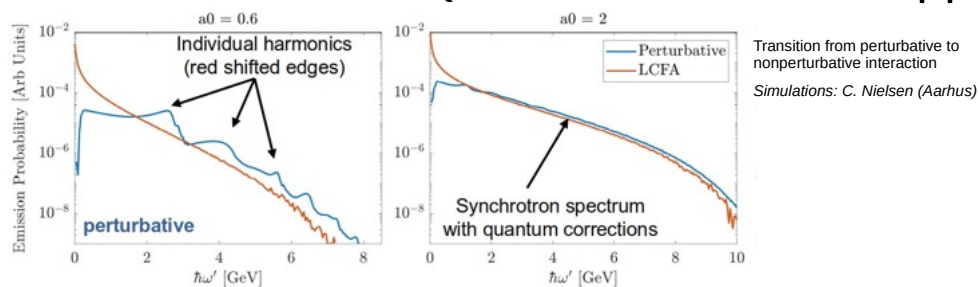
10 TW Laser parameters

- Wavelength: $0.8 \mu\text{m}$
- Spot size: $\sim 2 \mu\text{m}$ (FWHM)
- Pulse duration: $\sim 50 \text{ fs}$ (FWHM)
- Energy on target: $< 0.4 \text{ J}$
- a_0 : $0.4 - 4$

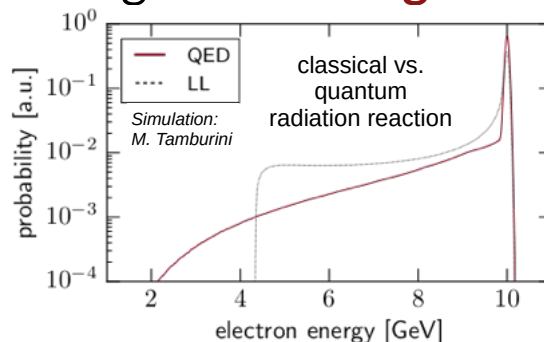


Length: $\lambda_C = \hbar/(mc)$
 Energy: $\mathcal{E} = mc^2$
 Critical field: $eE_{cr} = mc^2/\lambda_C$

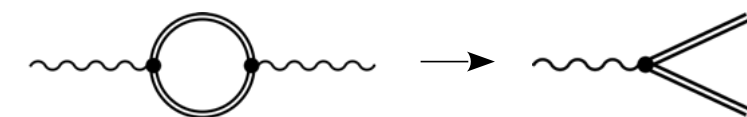
- Fundamental QED at electric fields approaching the **Schwinger critical field** in the electron beam rest frame



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

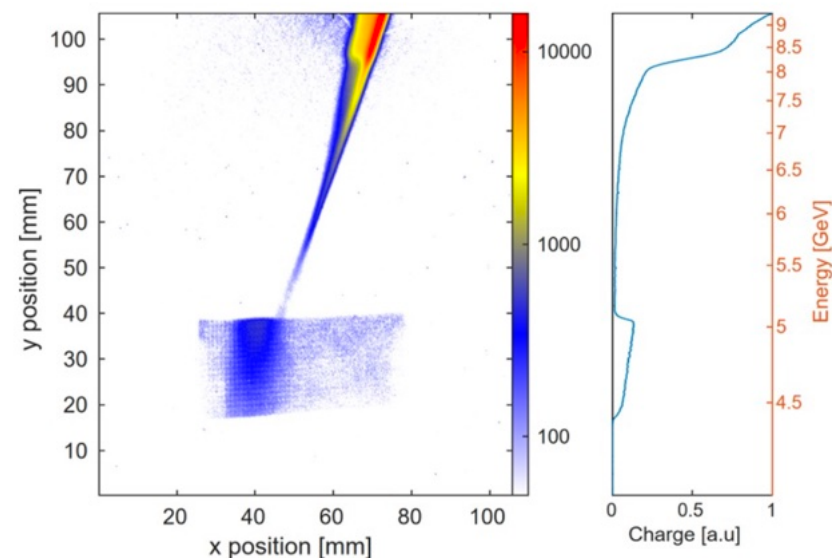
Pair production
 virtual pair is "ionized" by laser at QED critical field

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

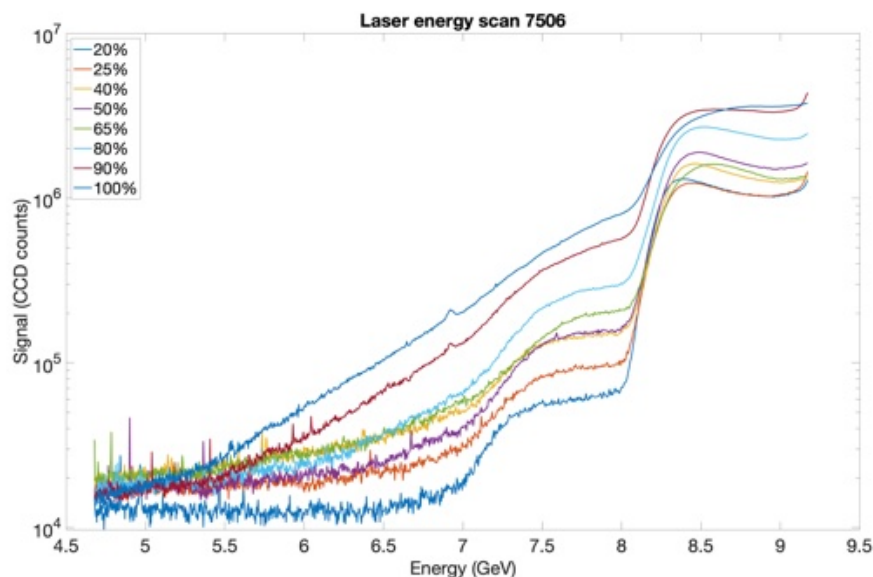
FACET-II highlight #4: strong field QED and quantum radiation reaction

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

Typical single shot spectrum



Intensity dependent spectra

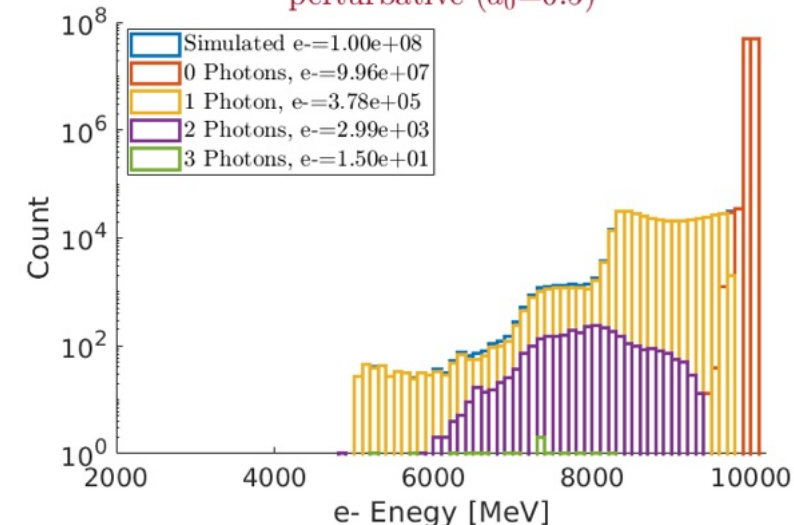


Preliminary

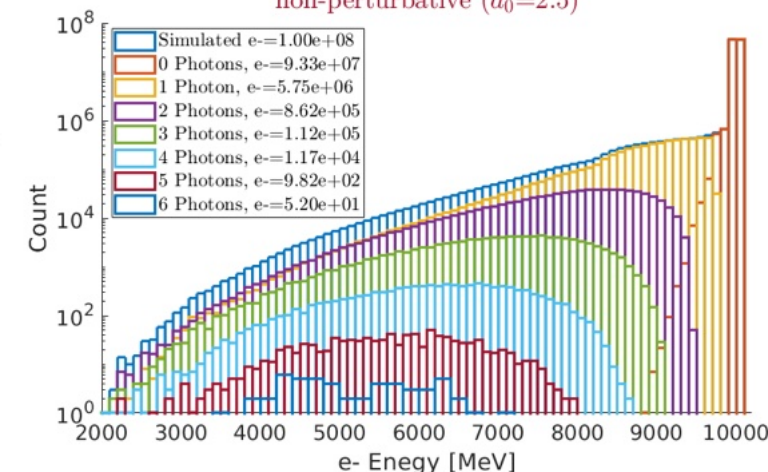
- High energy electrons in $n=1$ region dominated by tails of laser
- Low energy exponential spectrum consistent with QRR

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

Simulations
perturbative ($a_0=0.5$)



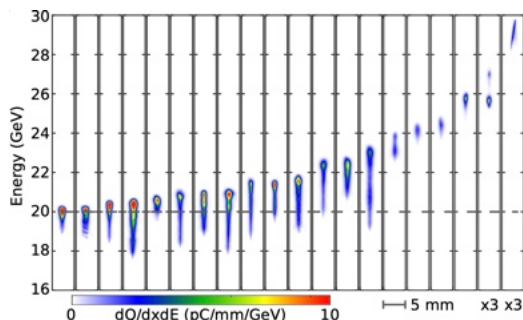
non-perturbative ($a_0=2.5$)



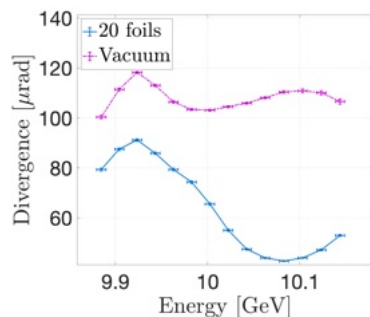
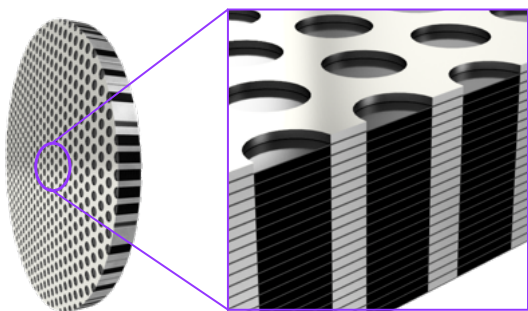
Hints of transition to non-perturbative regime (Spring 2025)

Conclusion: many exciting recent results at FACET-II

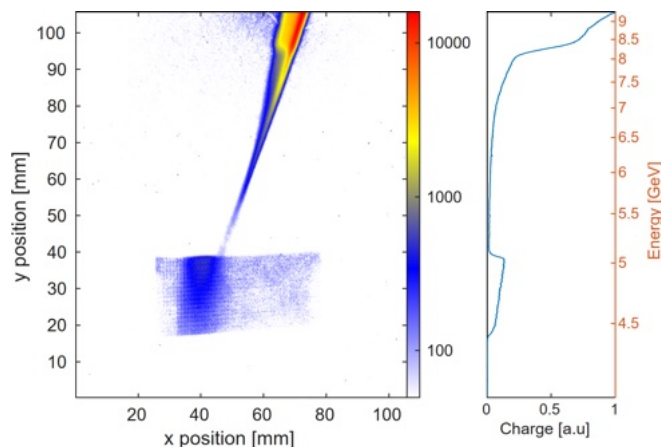
- ▶ Most precise measurements of quantum radiation reaction to date, evidence of ponderomotive mass dressing in laser field



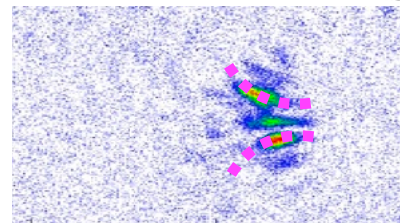
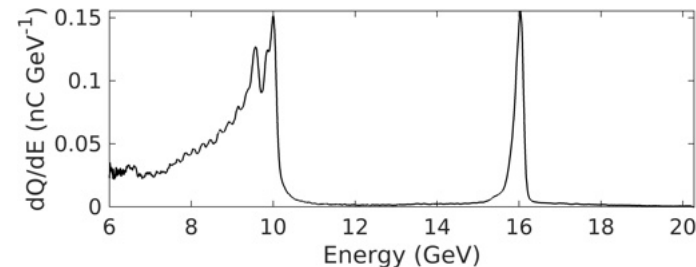
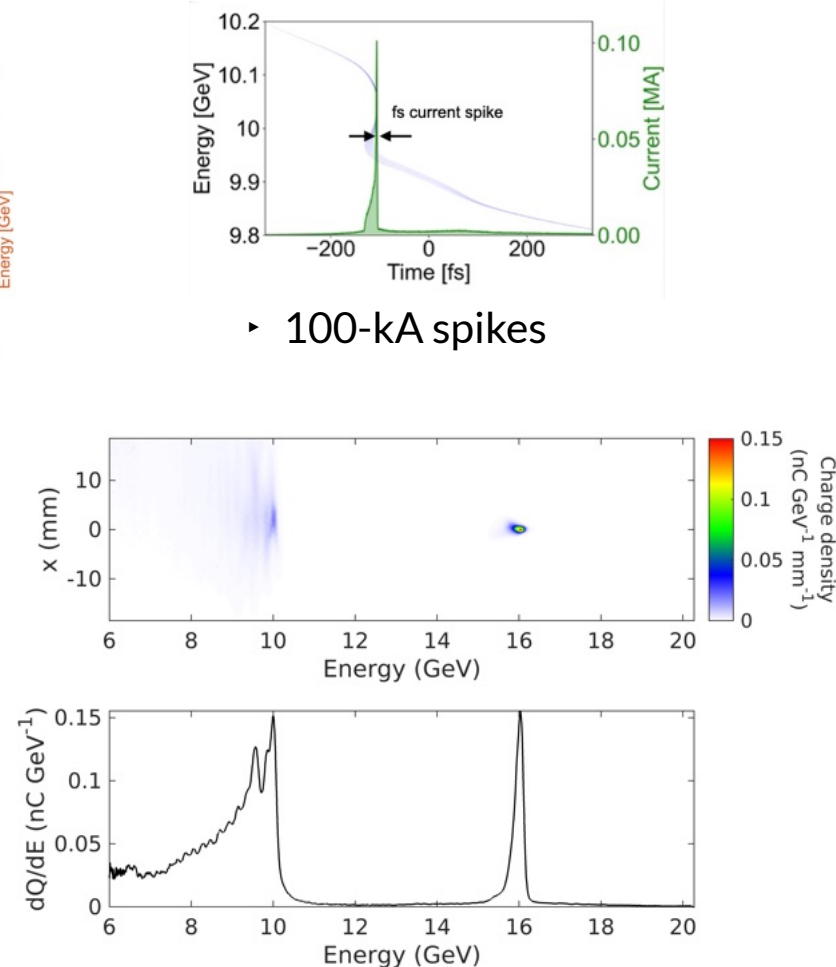
- ▶ Energy and brightness transformer



- ▶ Extreme focusing



- ▶ GeV-scale plasma acceleration with high field uniformity



- ▶ Probing, wakeless and e^+ regimes

Many thanks

E300 collaboration – PI's C. Joshi (UCLA) and M. Hogan (SLAC)

- SLAC Advanced Acceleration Research Department team:
 - R. Ariniello, S. Corde (Ecole Polytechnique), T. Dalichaouch (UCLA), A. Edelen, C. Emma, S. Gessner, A. Knetsch, N. Majernik, B. O'Shea, S. Perez, I. Rajkovic, D. Storey, K. Swanson, Y. Ye, M. Hogan
 - Z. Buschmann, S. Kalsi, R. Loney, M. Parker, G. Yocky
- Joined for on-site efforts:
 - S. Rego, V. Zakharova (Ecole Polytechnique), O. Finnerud, D. Kavli, E. Adli (University of Oslo), C. Hansel, V. Lee, M. Litos (CU Boulder)



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E332 collaboration



I. Andriyash, S. Corde, M. Gilljohann, A. Knetsch, O. Kononenko, Y. Mankovska, A. Matheron, P. San Miguel Claveria, V. Zakharova

C. Keitel, S. Montefiori, A. Sampath, M. Tamburini

X. Davoine, J. Faure, L. Gremillet, S. Passalidis

R. Ariniello, H. Ekerfelt, C. Emma, F. Fiuza, S. Gessner, M. Hogan, N. Majernik, A. Marinelli, J. Peterson, B. O'Shea, I. Rajkovic, D. Storey, V. Yakimenko

C. Joshi, K. Marsh, W. Mori, N. Nambu, Z. Nie, Y. Wu, C. Zhang

J. Cary, C. Doss, C. Hansel, K. Hunt-Stone, V. Lee, M. Litos

G. Cao, E. Adli

J. Yan, N. Vafaei-Najafabadi

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Editors' Suggestion

Experimental Generation of Extreme Electron Beams for Advanced Accelerator Applications

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Questions?