FACET-II: Status of the First Experiments and the Road Ahead

EAAC2023

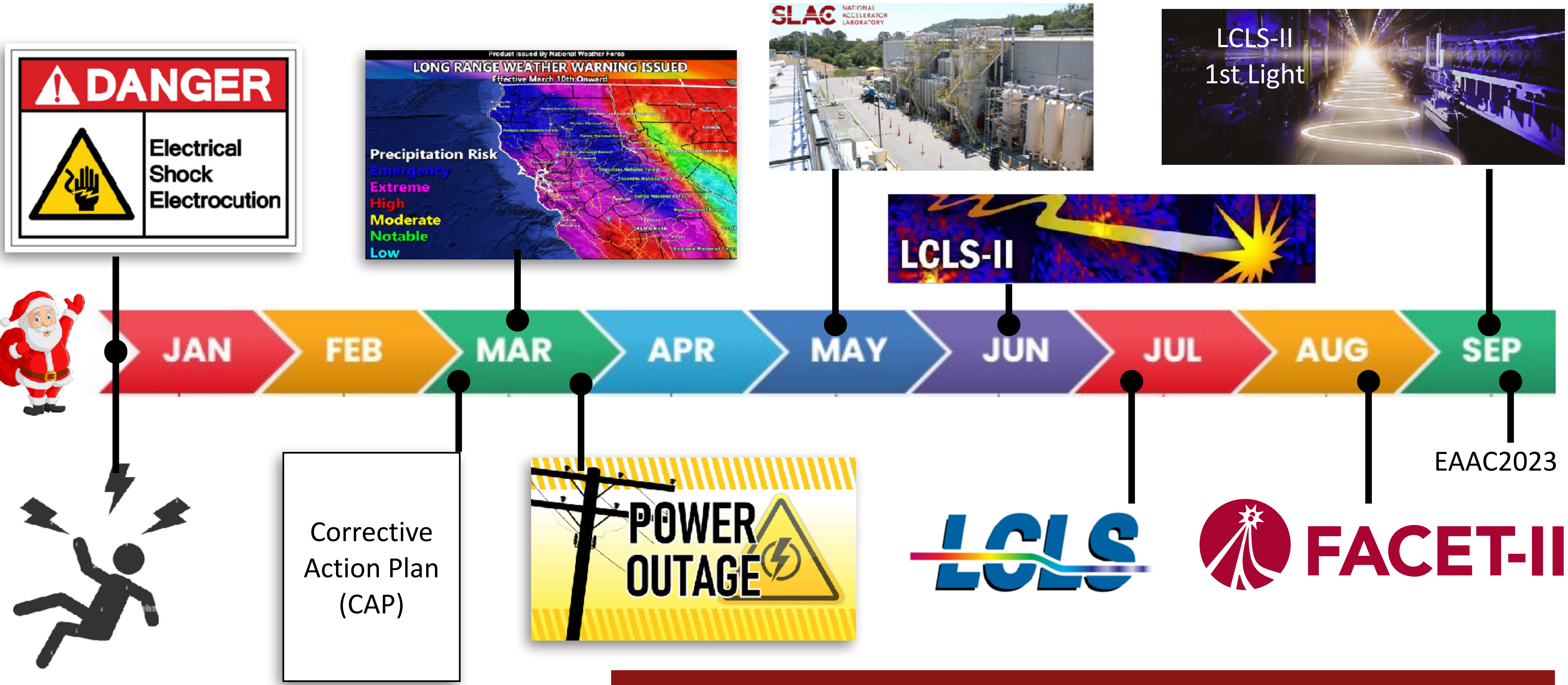
Mark J. Hogan / Senior Staff Scientist / FACET and Test Facilities Division Director

September 20, 2023

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

It Has Been an Eventful 2023 at SLAC



All SLAC Accelerators were off for 6-9 months

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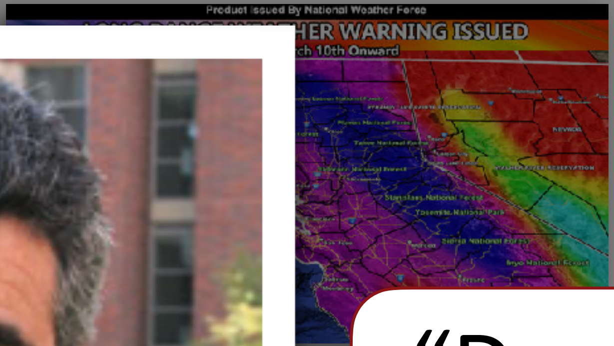
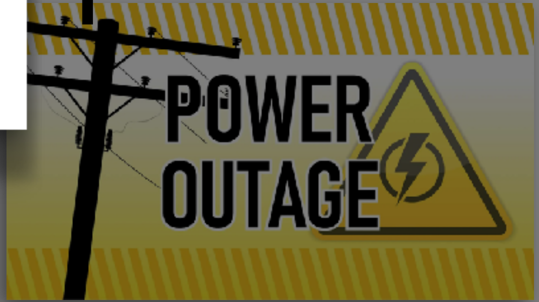


“Don’t complain and don’t explain”
– Tom Katsouleas

Action Plan (CAP)



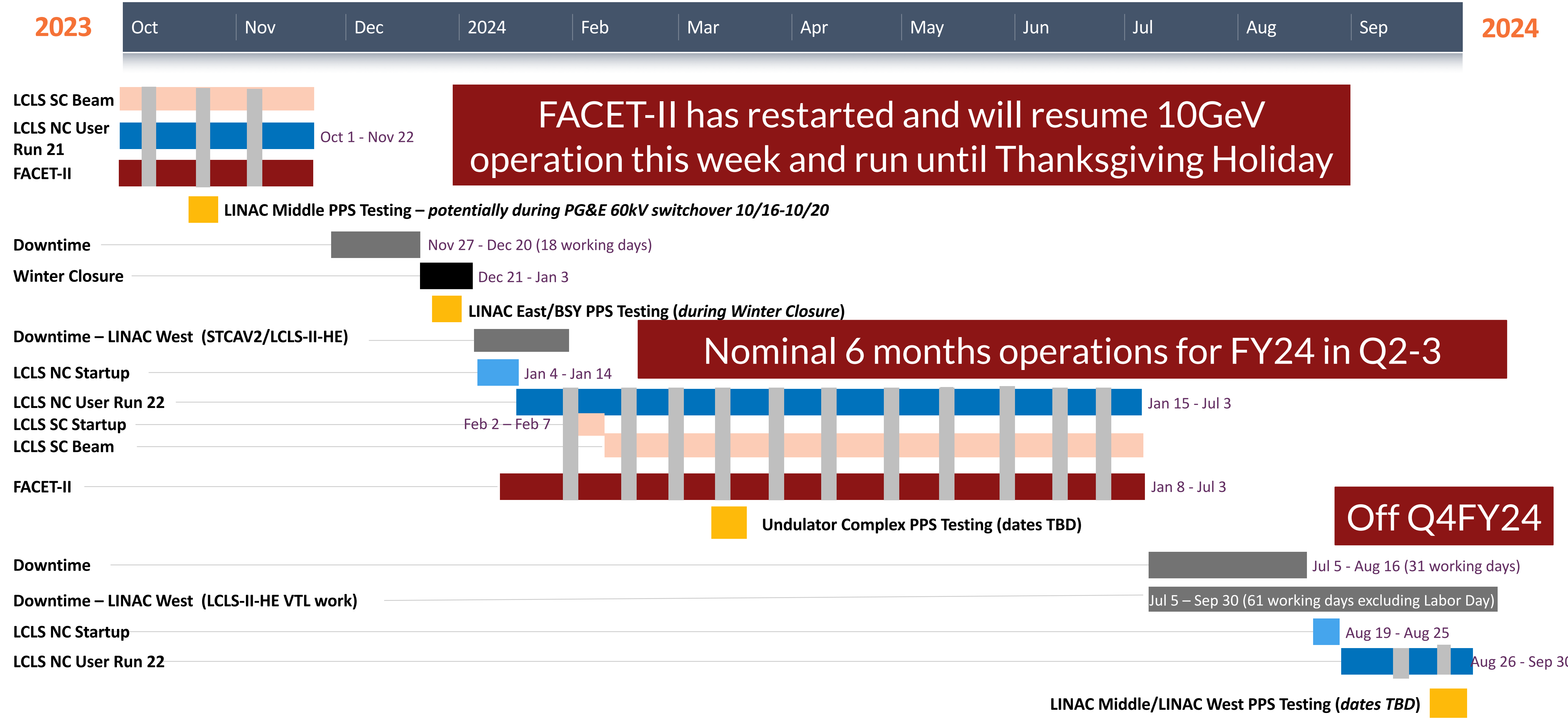
EAAC2023

LCLS

FACET-II

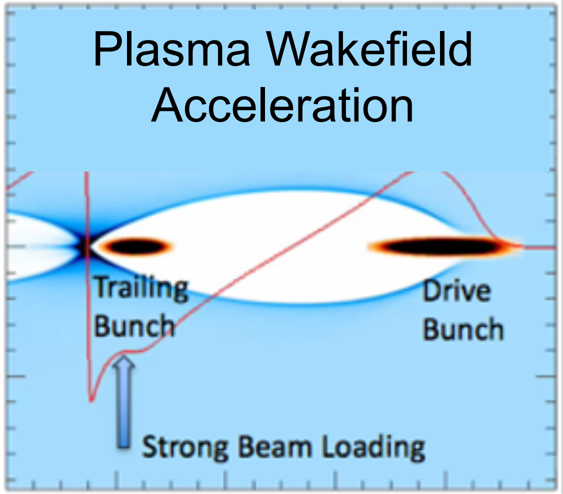
All SLAC Accelerators were off for 6-9 months

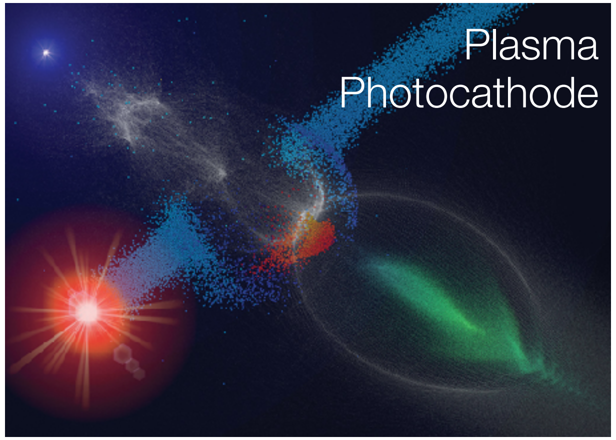
Oct 2023/Sept 2024 Accelerator Schedules & Downtimes

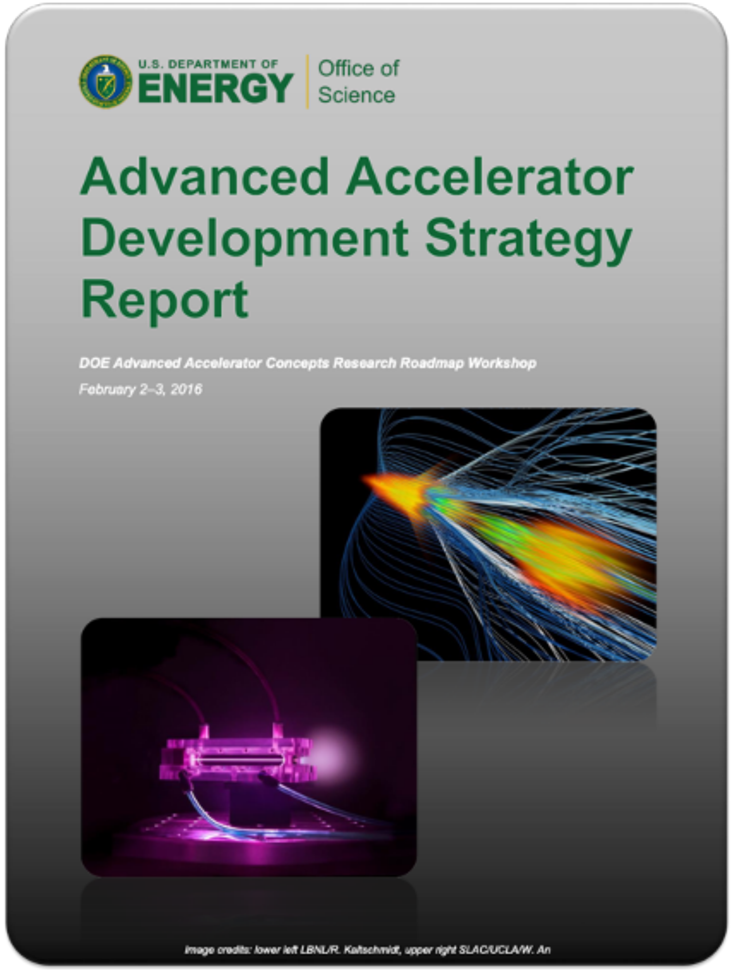


National User Facility with a Broad User Program Based on 10GeV Beams and Their Interaction with Lasers & Plasmas

- Initial focus on beam quality in **plasma wakefield accelerators** and generating beams with unprecedented brightness in **plasma based injectors**
- Additional programs will exploit unprecedented beam intensity to create bright **gamma-ray bursts** and study **SFQED** phenomena
- Creating **ML/AI** based virtual diagnostics to characterize extreme beams

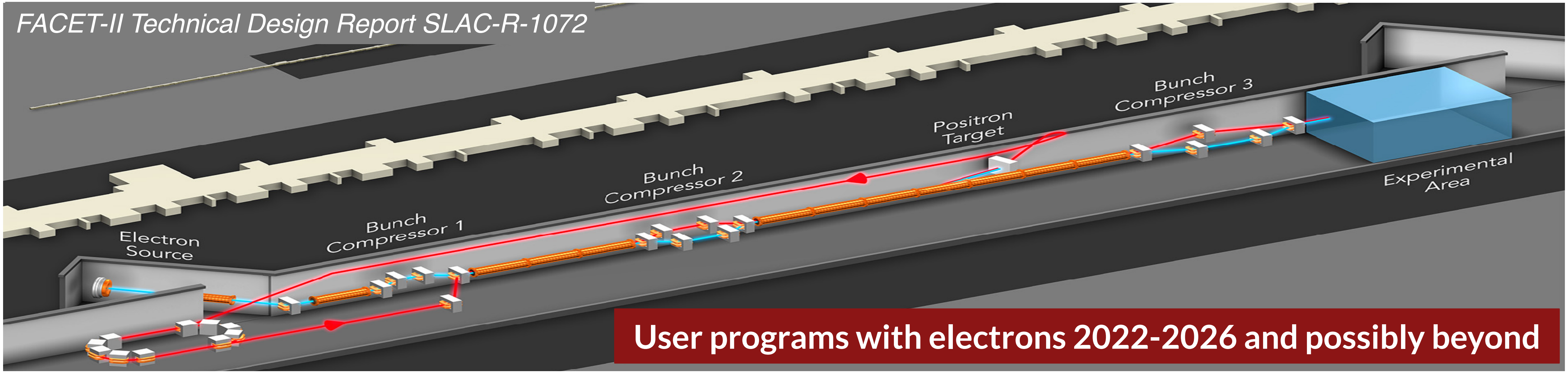






Developing plasma wakefield technology for energy frontier colliders and brighter X-ray beams aligned with HEP Roadmaps

FACET-II National User Facility

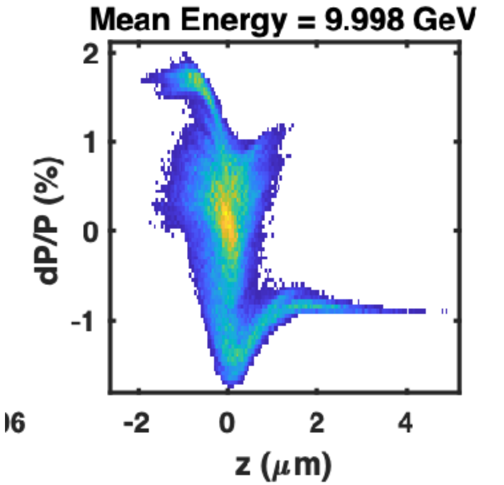


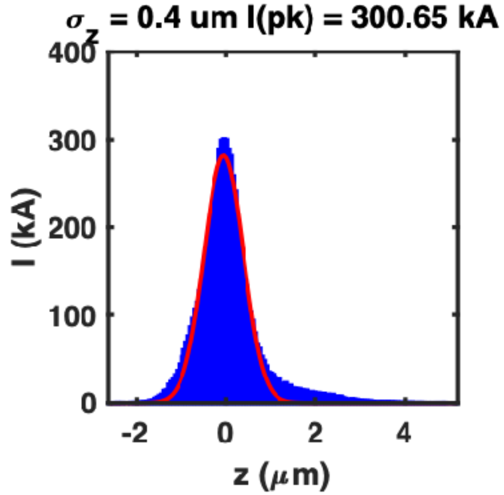
User programs with electrons 2022-2026 and possibly beyond

FACET-II will Access New Regimes

- ~10μm Emittance
- ~100kA Peak current (sub-μm bunch length)
- ~100nm focal size from plasma lens
- ~10^{12} V/cm radial electric field
- ~10^{24} e^-/cm^3 beam density

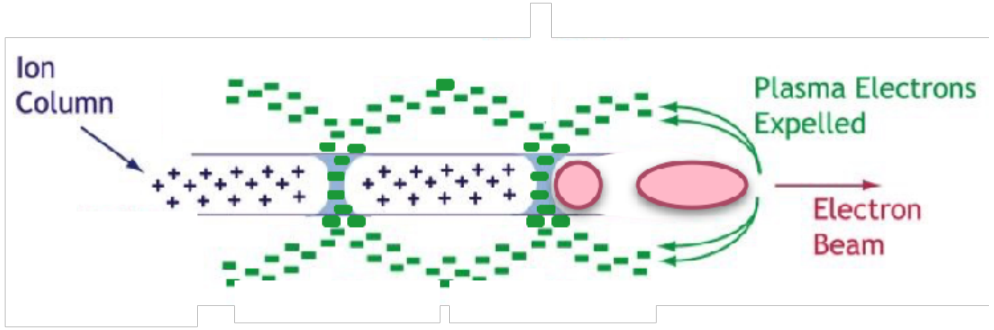
Electron Beam Parameter	Baseline Design	Operational Ranges
Final Energy [GeV]	10	4.0-13.5
Charge per pulse [nC]	2	0.7-5
Repetition Rate [Hz]	30	1-30
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19 [μm]	4.4, 3.2	3-6
Spot Size at IP $\sigma_{x,y}$ [μm]	18, 12	5-20
Min. Bunch Length σ_z (rms) [μm]	1.8	0.7-20
Max. Peak current I_{pk} [kA]	72	10-200

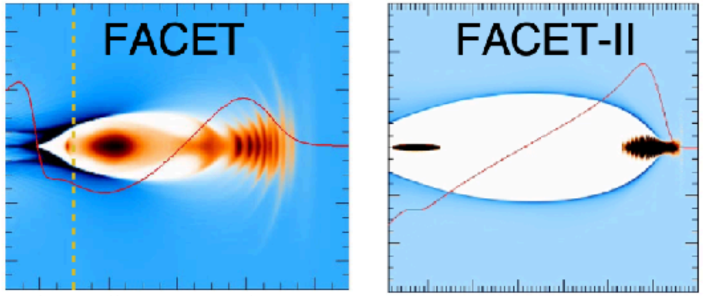


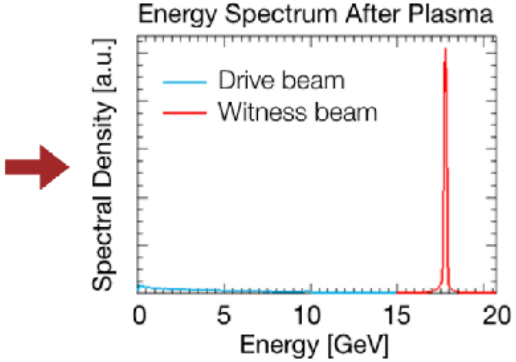


Improved longitudinal and transverse emittance from the photoinjector allows FACET-II to deliver beams with unprecedented intensities to address HEP roadmaps and open new science directions

Plasma Wakefield Acceleration at FACET-II (E-300)

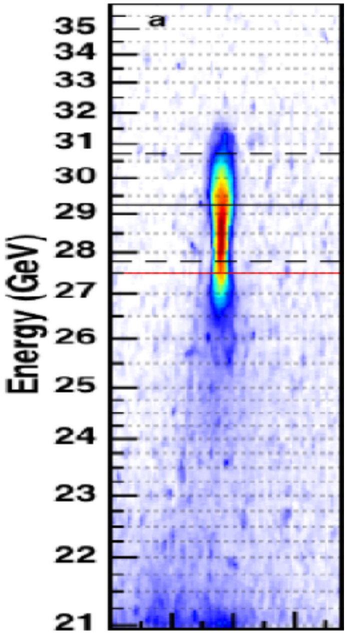






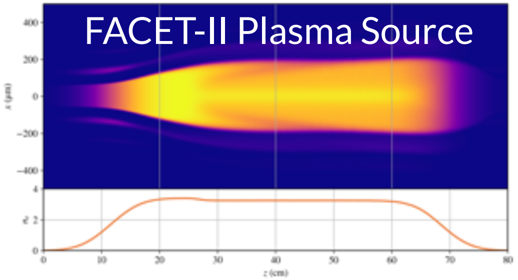
PWFA Experiments at FACET demonstrated:

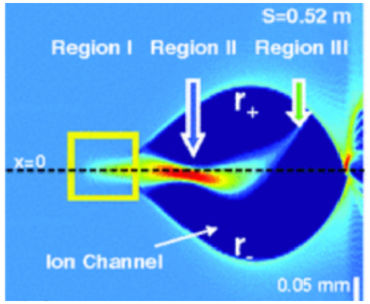
- High-gradients (>10GeV/m)
- Large energy gain (9GeV)
- High instantaneous efficiency (30%)

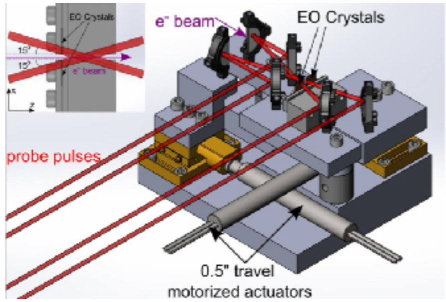


FACET-II experiments will focus on beam quality

- Facility upgrades: **photoinjector beam**, final focus, **differential pumping**
- Users developing upgraded plasma sources and specialized diagnostics
- Combines theory, advanced computation and experiments

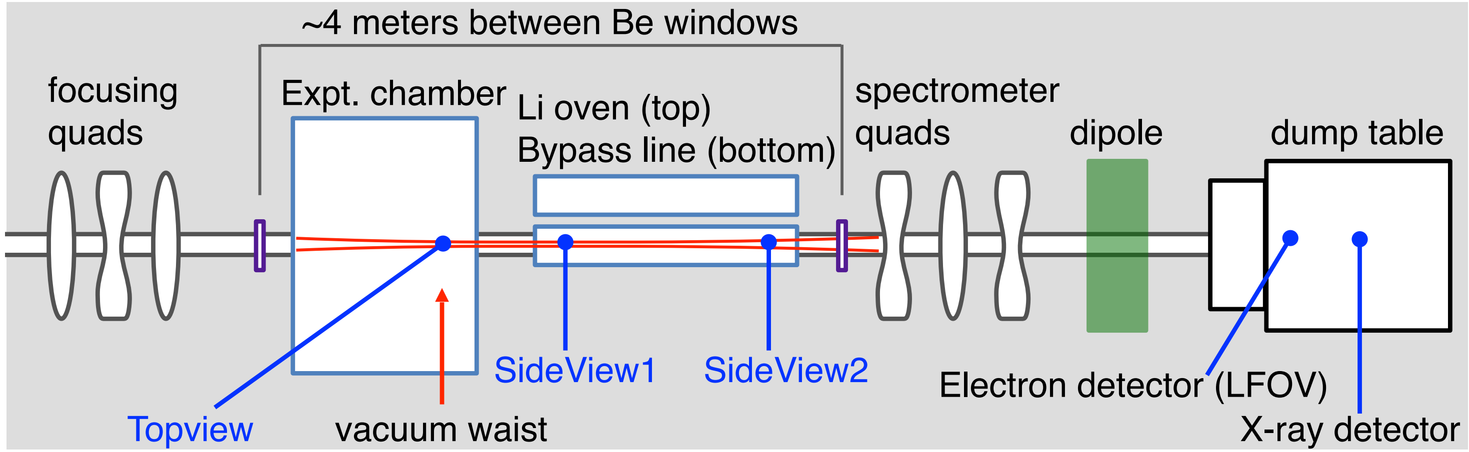


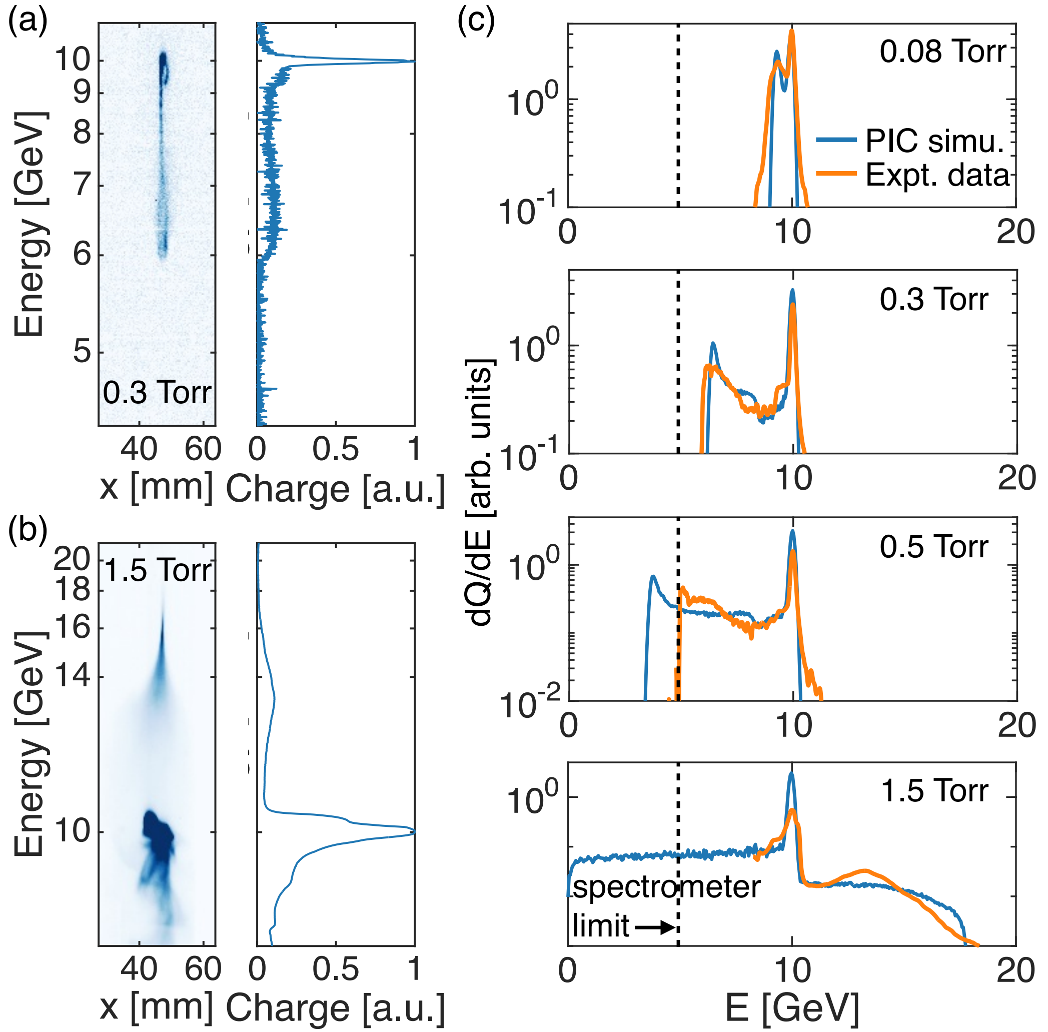




PWFA collaborations bring together state of the art SLAC accelerator facilities with the breadth of expertise in University communities to address research needs highlighted in HEP roadmaps

Started Experimental Programs Focussed on Single Bunch



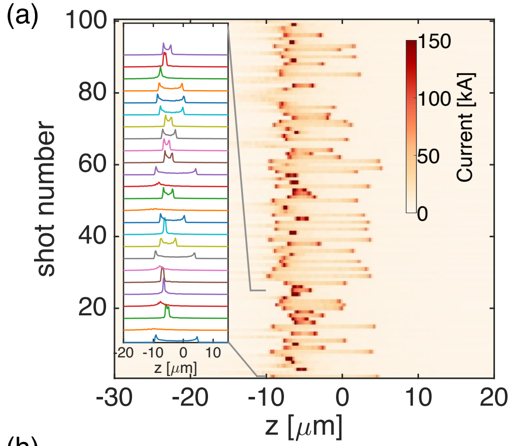


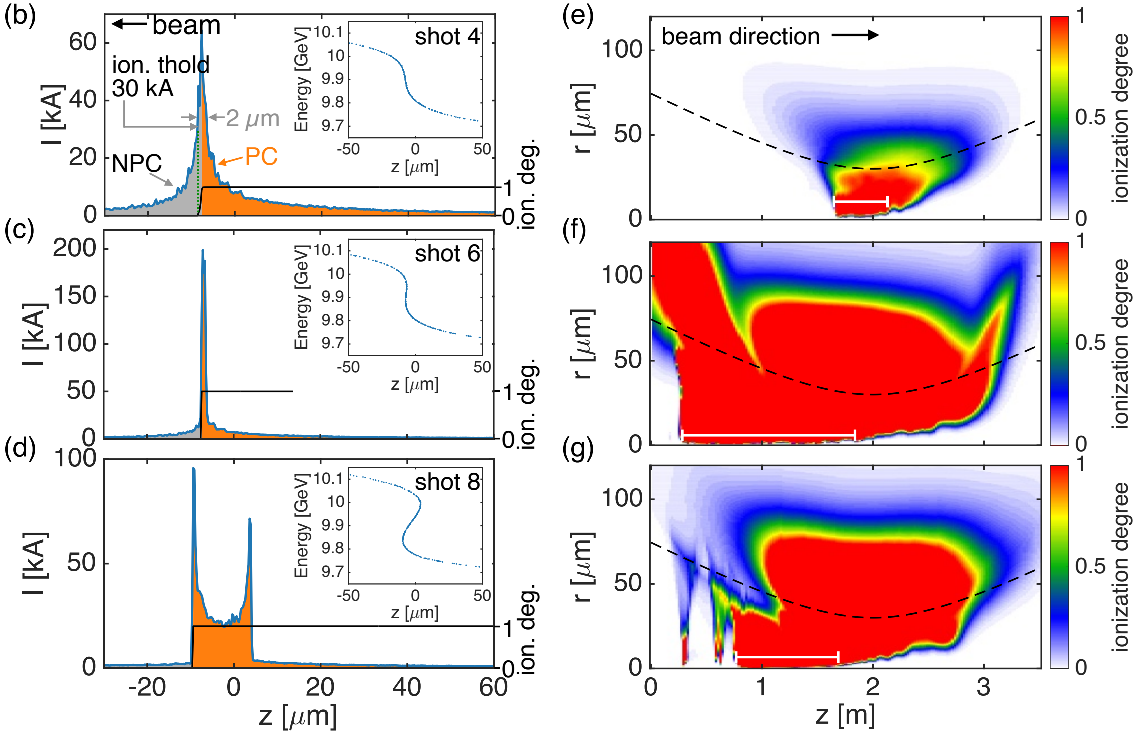
- Beam Ionized H_2 and He plasmas (and Be windows!)
- Data is qualitatively very similar to single bunch experiments at FFTB & FACET
- Deceleration of beam core down to < 1GeV with few GeV gain by tail particles
- Large energy fraction transferred to the wake
- No obvious reduction in performance due to CSR induced hosing

The drive beam is meeting the requirements for two-bunch PWFA to come

Plasma Accelerated Spectra Reveal Details of Incoming Beam

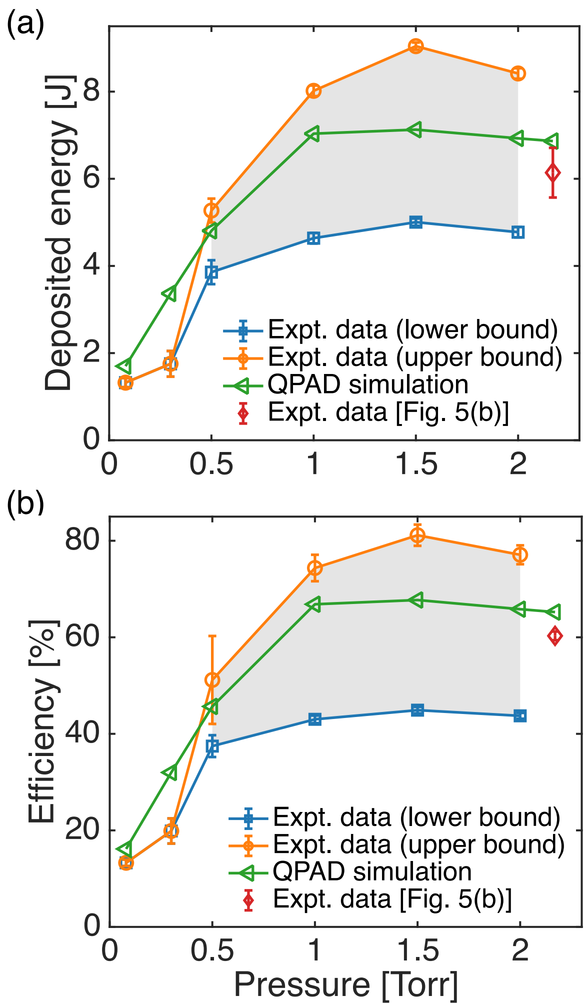
- Small changes to compression can lead to large change in peak current and field-ionized plasma distribution
- Participating charge and energy are loss sensitive current profile





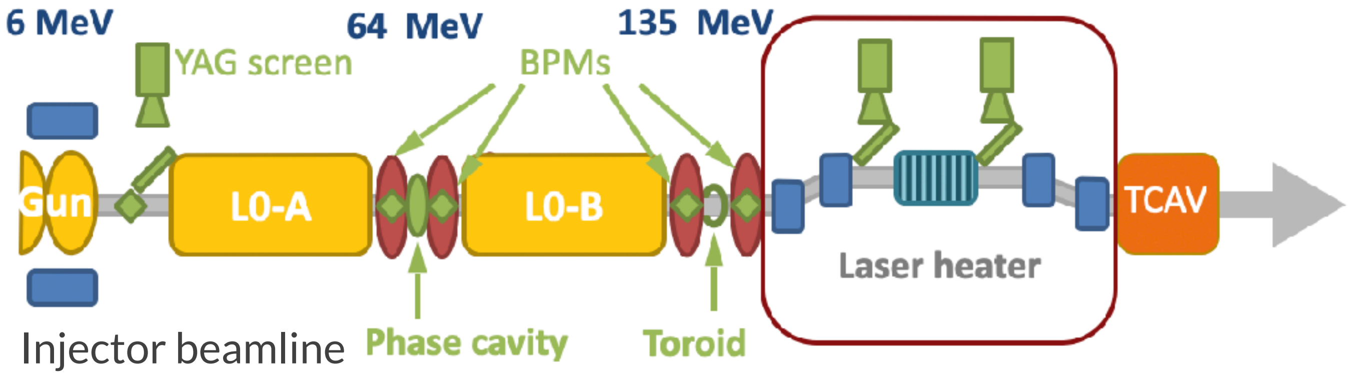
(h)

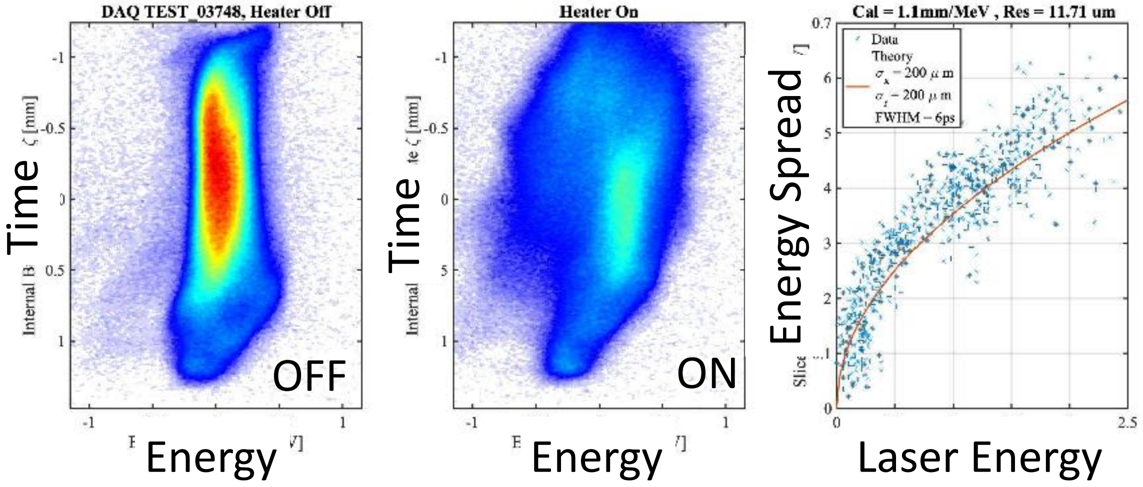
Shot num.	Q_{NPC} fraction	Peak den. [10^{16} cm^{-3}]	Plasma length [m]	Max E_{DEC} [GV/m]
4	30%	6.48	0.50	14.0
6	21%	6.48	1.57	16.4
8	9%	6.48	0.93	28.1



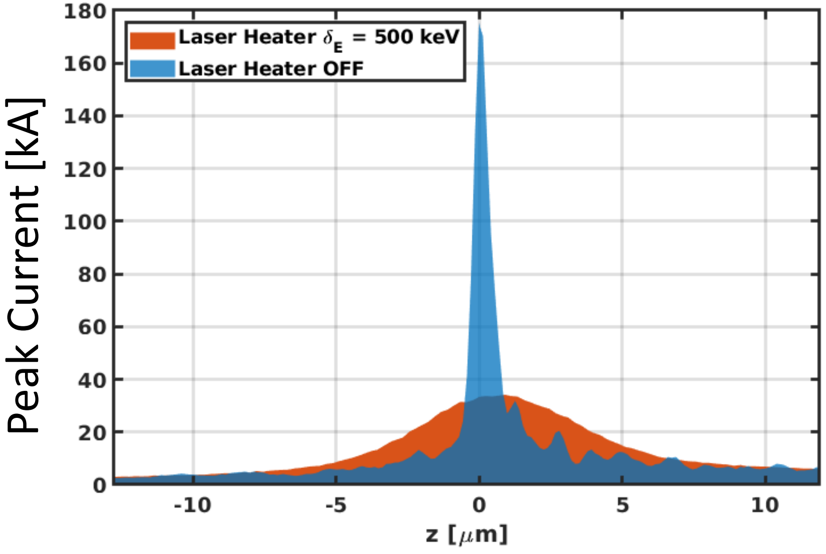
Next steps: Fall 2023 use laser heater for additional stability, pre-ionized plasma (Li and H_2) for improved efficiency, and two-bunch setup to add witness bunch to study energy gain 2024

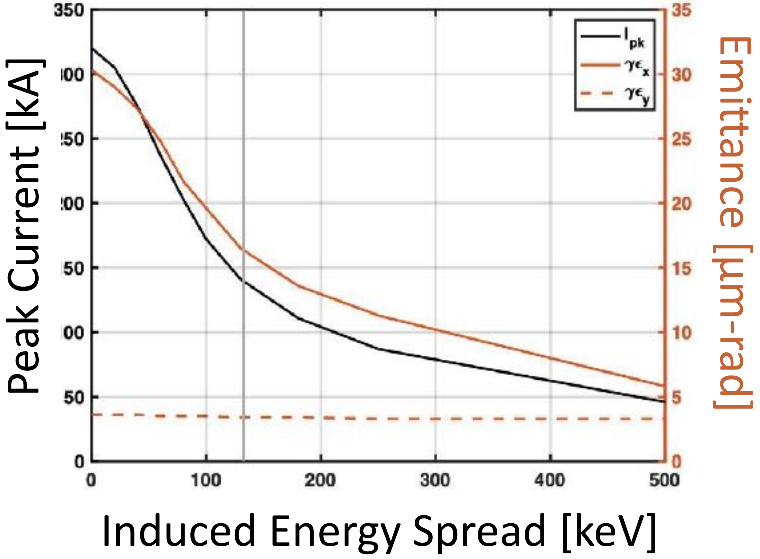
FACET-II Injector Laser Heater





- Laser heater increases uncorrelated energy spread using inverse FEL process
  - Effective tool for limiting microbunching & CSR
  - Tunable peak current
- Similar to LCLS laser heater, but more laser power

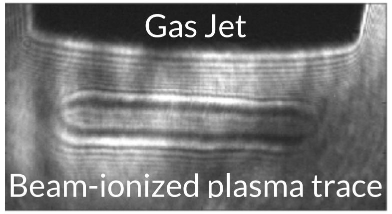


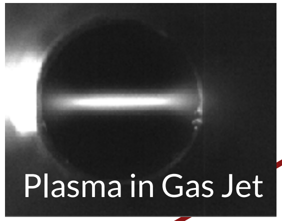


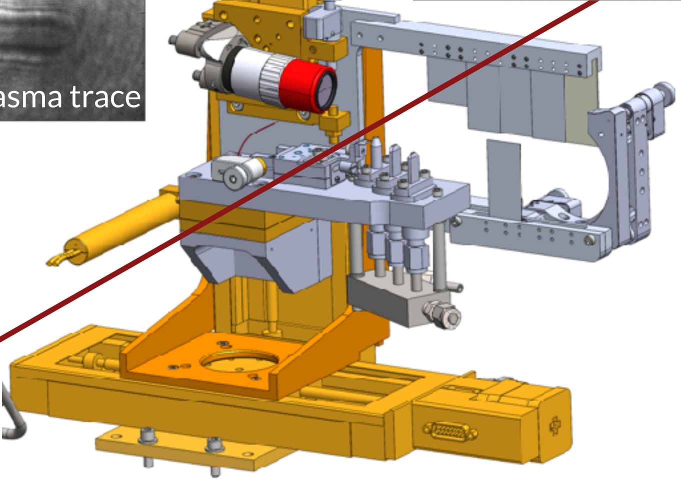
Injector laser heater suppresses COTR and provides tunable peak current

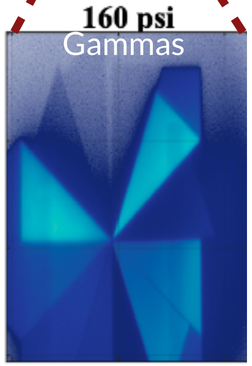
E-305: Beam Filamentation and Bright Gamma-ray Bursts

- Relativistic streaming plasma instabilities are pervasive in astrophysics
- CFI and oblique instabilities are believed to:
  - Mediate slow down of energetic flows (e.g. in GRBs and blazars), shock formation and cosmic-ray acceleration
  - Determine radiation signatures of energetic environments

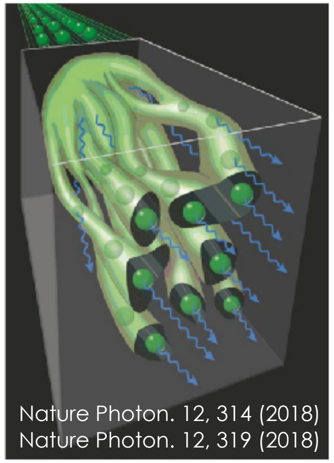




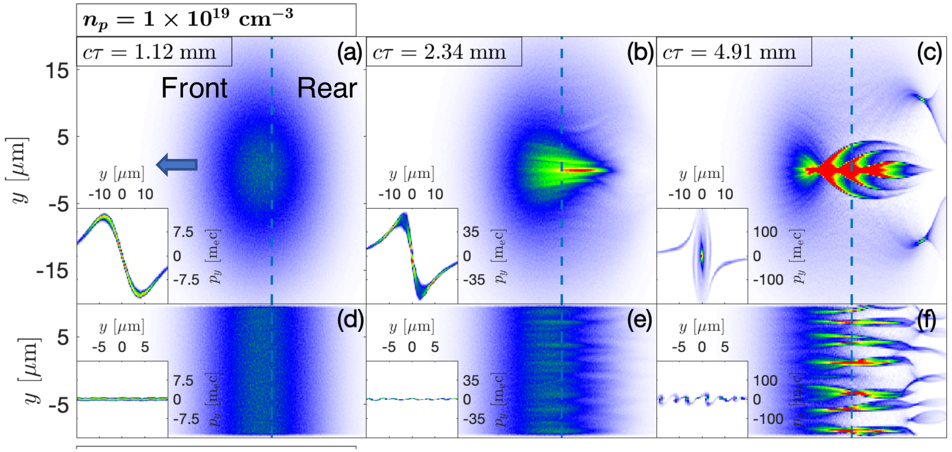




Beam size much larger than bubble size → Beam modulation & filamentation → Large fields → Bent trajectories for filaments → Gamma-ray emission



Nature Photon. 12, 314 (2018)
Nature Photon. 12, 319 (2018)

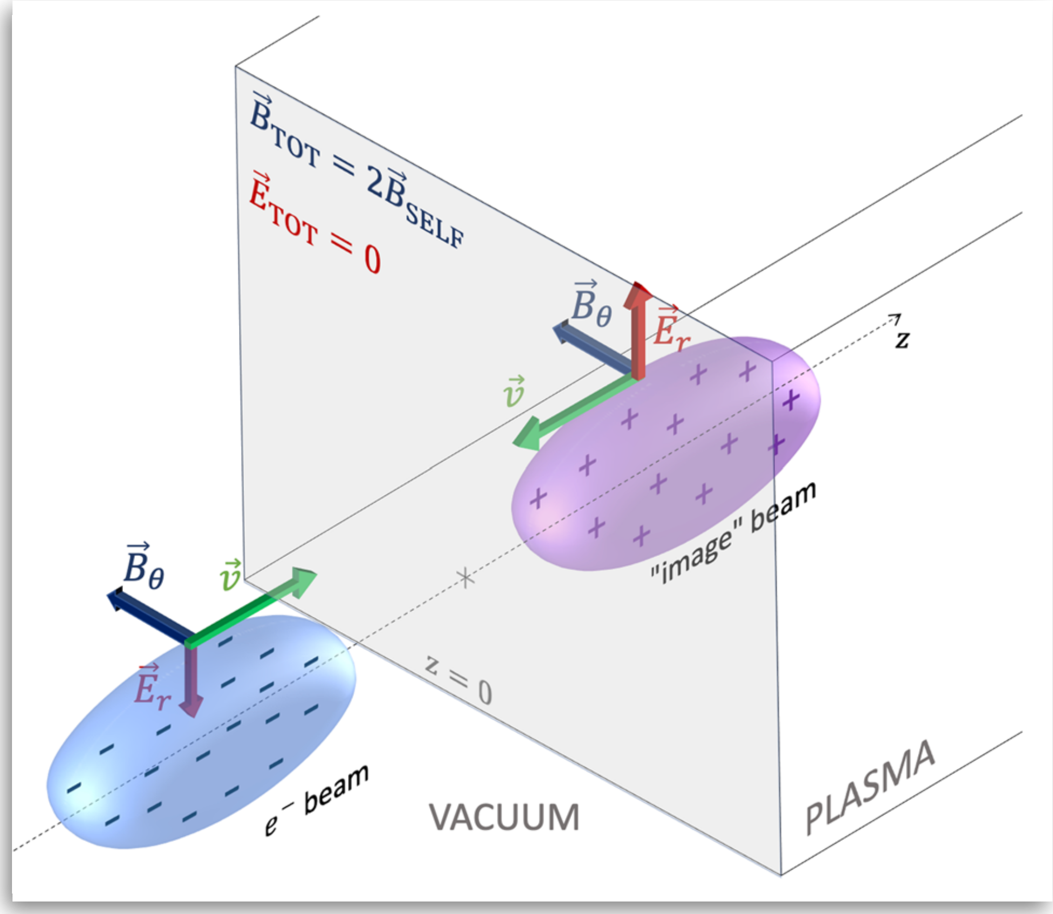


Phys. Rev. Research 4, 023085 (2022)

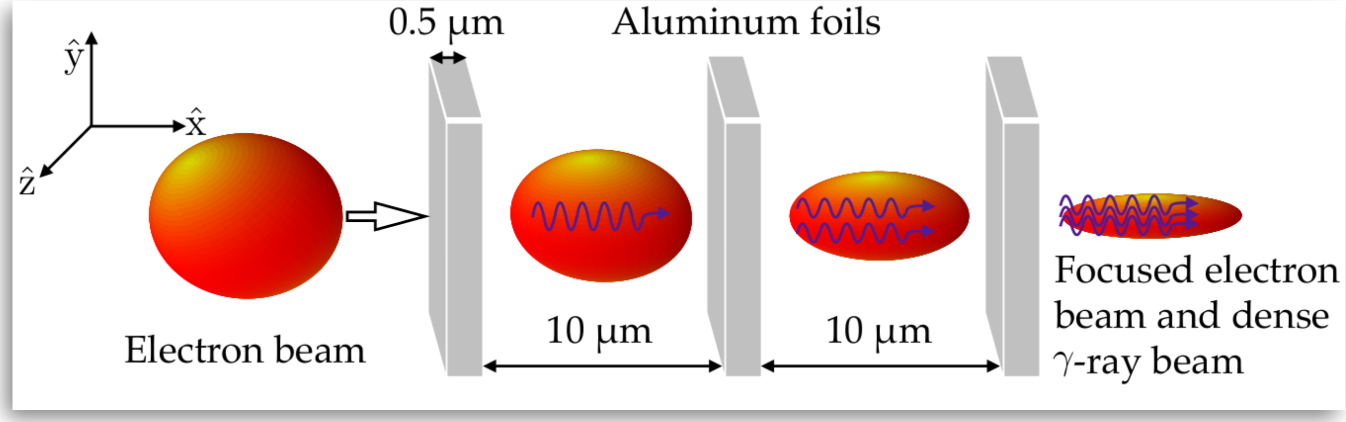
Commissioned many parts of the experiment

- Targets (gas jet and solids)
- Electron and gamma diagnostics
- Laser ionization of gas jet with E305 focusing optics
- Low-resolution shadowgraphy, tests for high-resolution
- Beam-laser overlap methods
- Beam-based characterization of laser-generated plasma

E-332: Near-field CTR Focusing and Gammas in Beam-multifoil Collisions



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



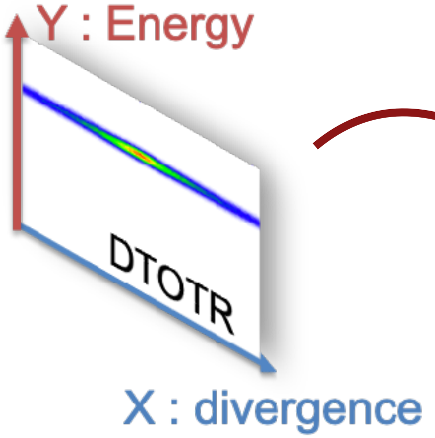
Sampath et al., Phys. Rev. Lett. 126, 064801 (2021)

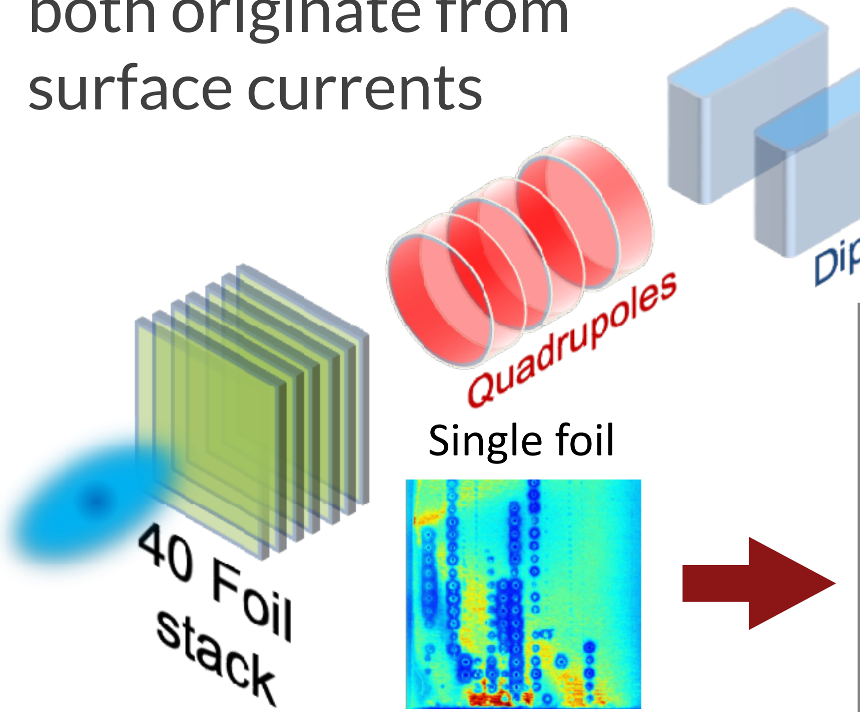
- An ultrarelativistic, high-density electron beam entering a solid experiences the intense self fields of its image charge
- At the surface the electric field vanishes while the magnetic field doubles
- Repeating for many surfaces focuses the beam similar to lens with very short focal length ~ cm

See Aimé Matheron plenary R 09:00 'Probing strong-field QED in beam-plasma collisions'

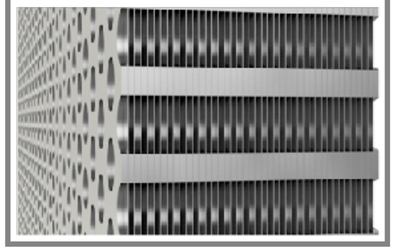
E-332: Near-field CTR Focusing and Gammas in Beam-multifoil Collisions

Foil damage studied in detail as a proxy for strong near-field CTR as they both originate from surface currents

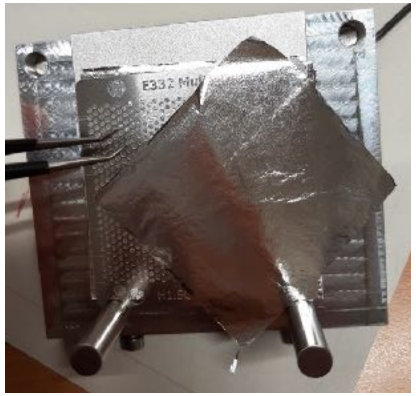


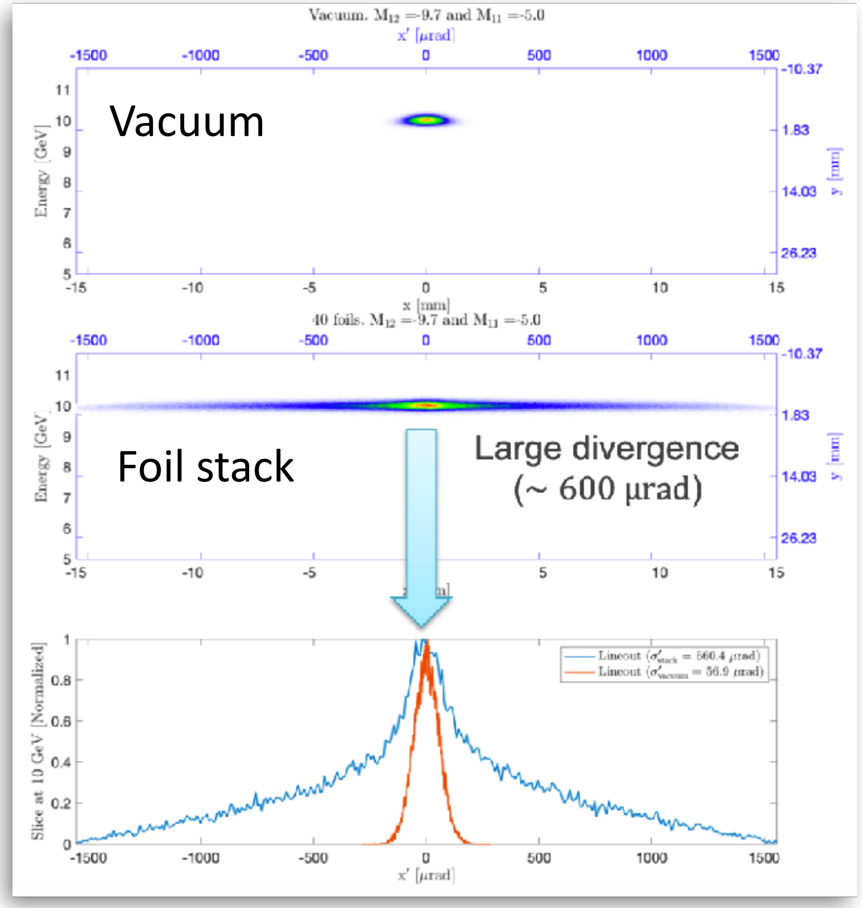


1µm thick Al foils
100µm foil seperation
40 foils in the stack
1mm apertures



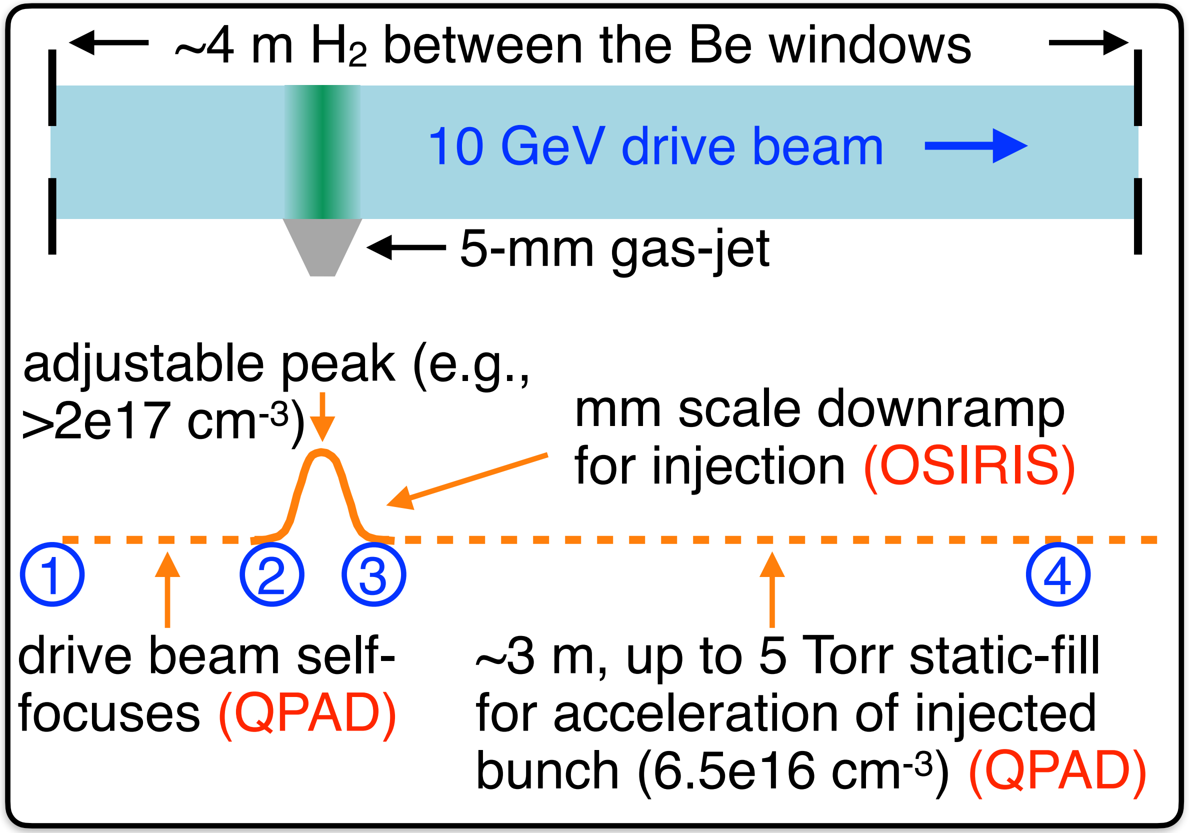
En route to 'As Built'

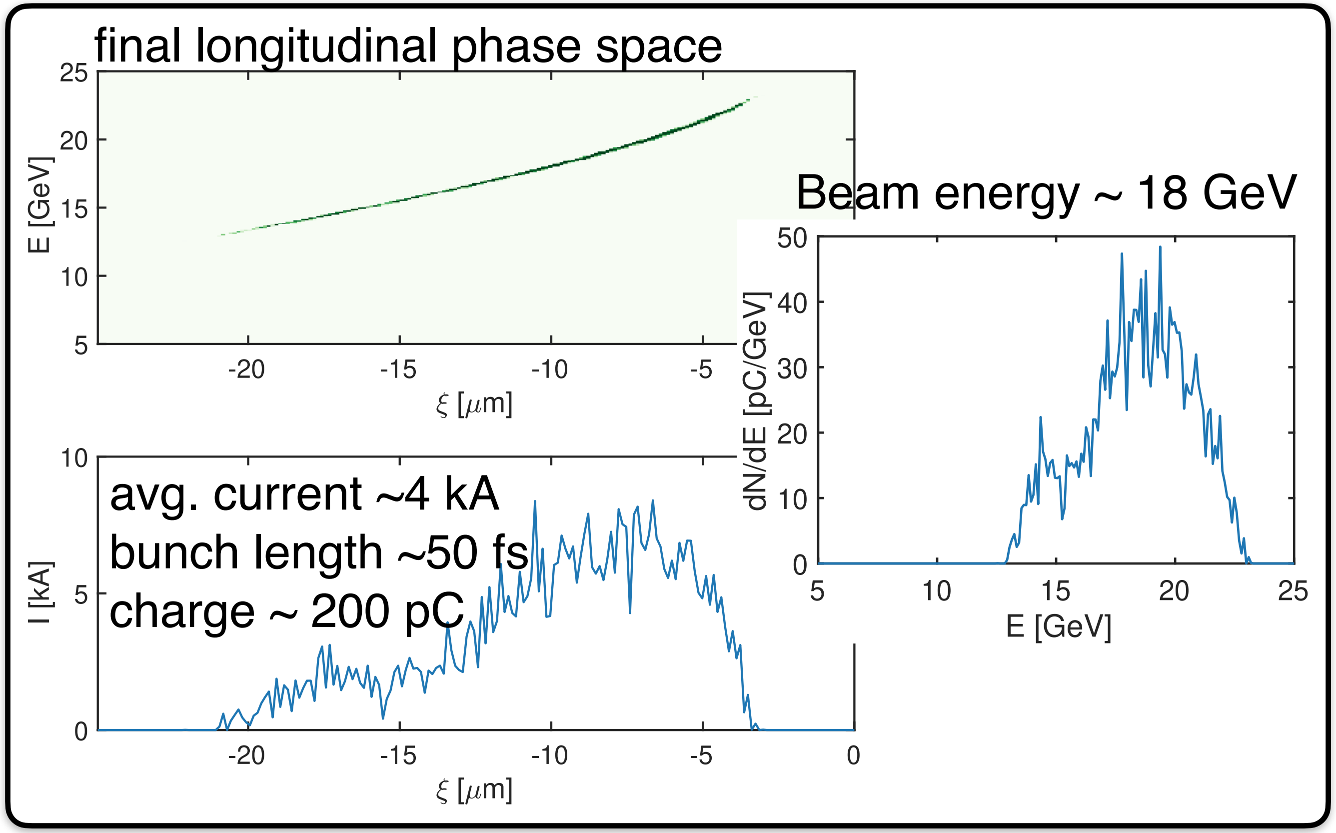


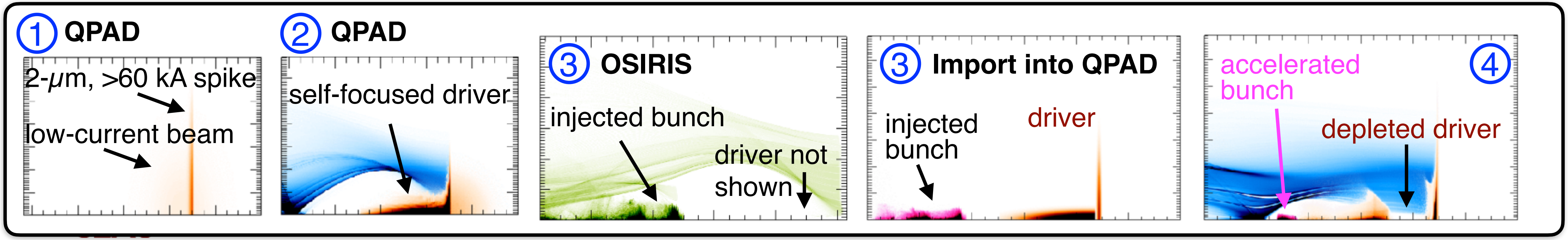


10-fold increase in divergence will be clear signature and first experimental demonstration of near-field CTR focusing expected in near future

E-304: Density Downramp with Gas-jet in Static-fill (GIS) Configuration

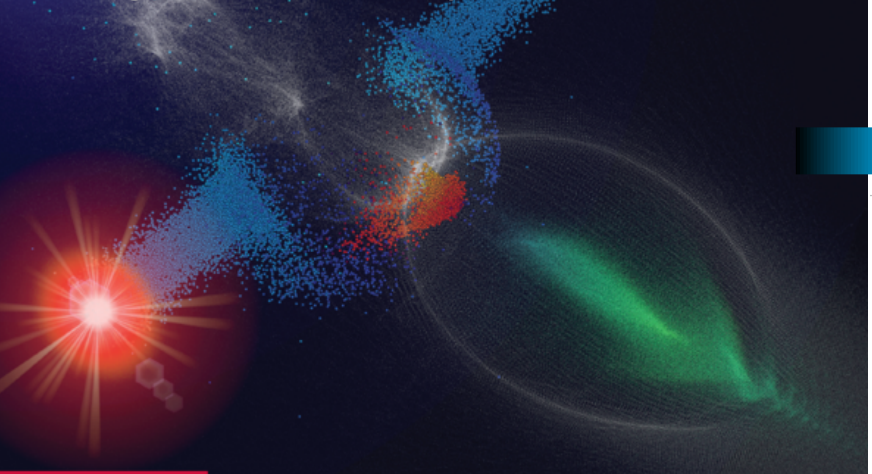






E-310 Trojan Horse-II

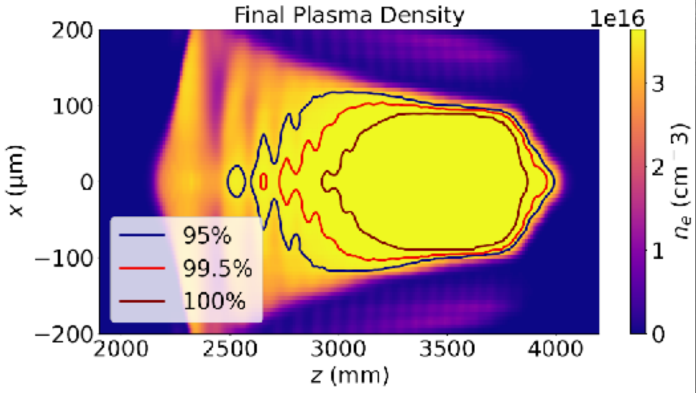
Deng *et al.*, Nature Physics 15, 1156, (2019)



FACET E-210 Trojan Horse: Perpendicular geometry, thin channel bottleneck: $\varepsilon_n \sim \mu$m-rad ~1 GeV, poor charge capture

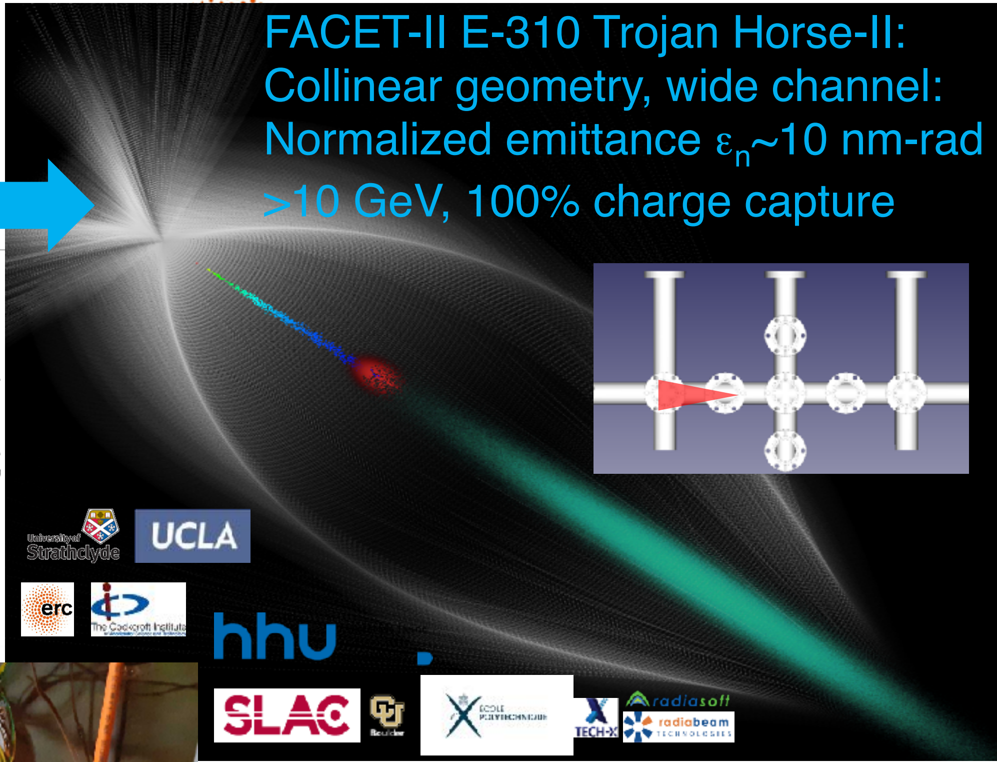
THE ROYAL SOCIETY PUBLISHING

1. Bespoke crossed pipe system to host tailored, wide plasma channel...

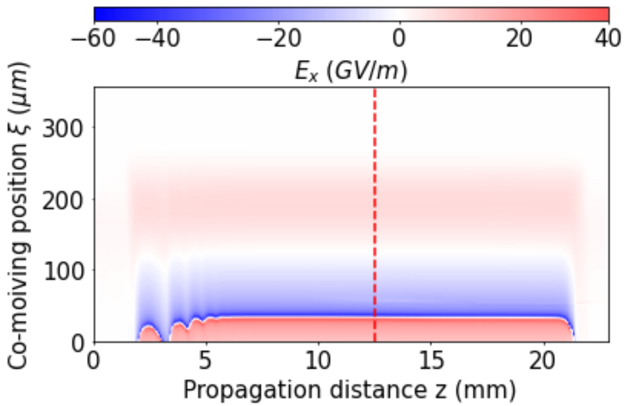


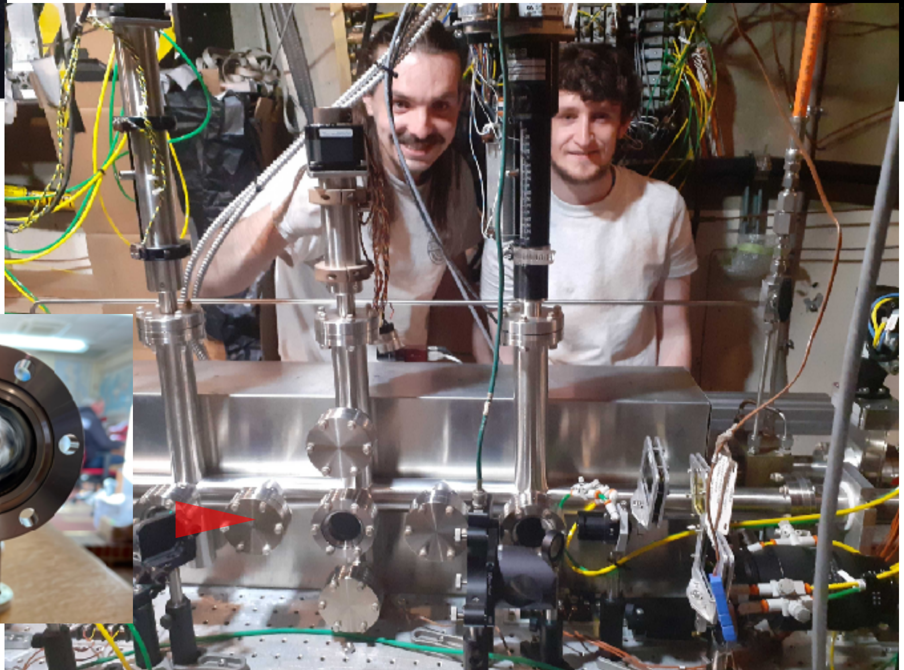
erc NeXource (Hidding)

FACET-II E-310 Trojan Horse-II: Collinear geometry, wide channel: Normalized emittance $\varepsilon_n \sim 10$ nm-rad >10 GeV, 100% charge capture

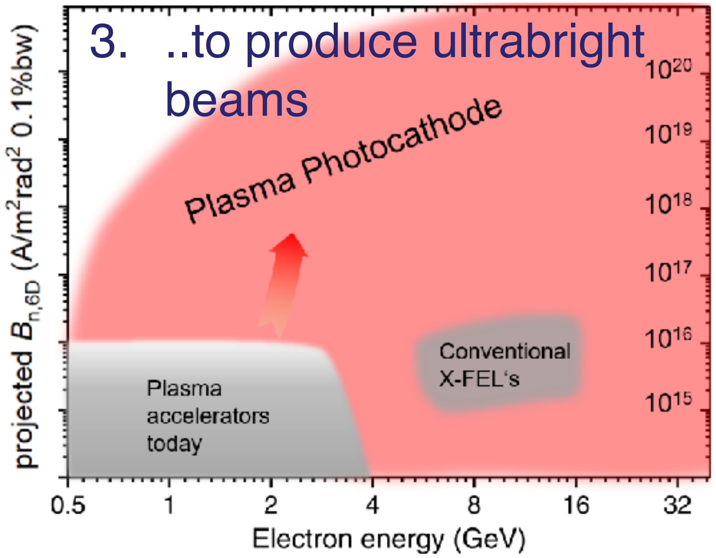


2. ...to allow stable collinear injection and acceleration...





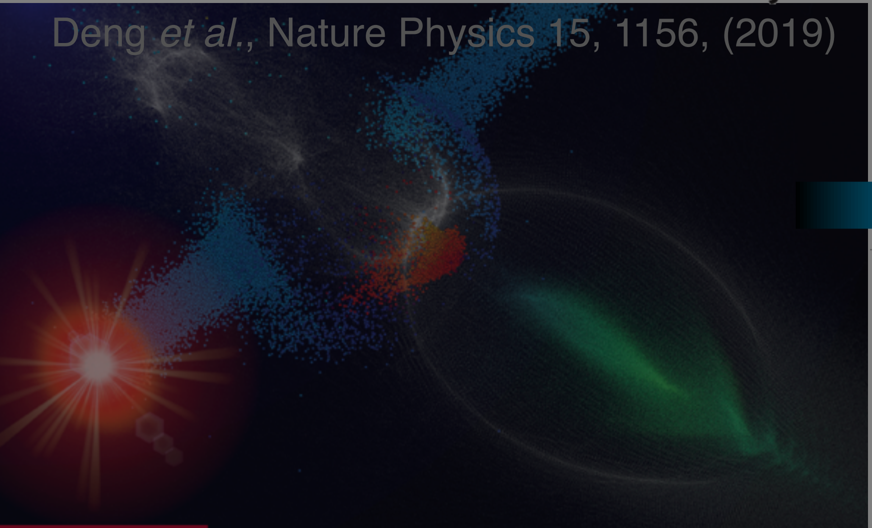
3. ..to produce ultrabright beams



E-310 Trojan Horse-II

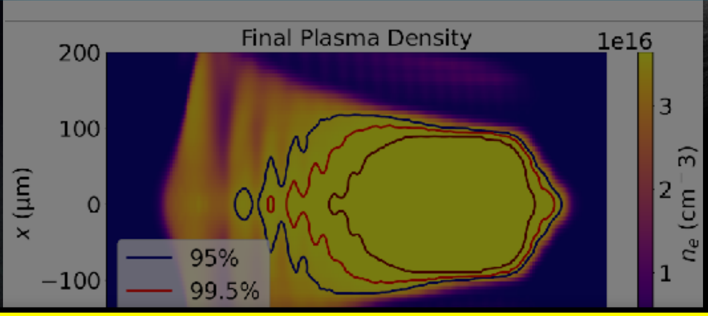
University of Strathclyde | UCLA

erc NeXource (Hidding)

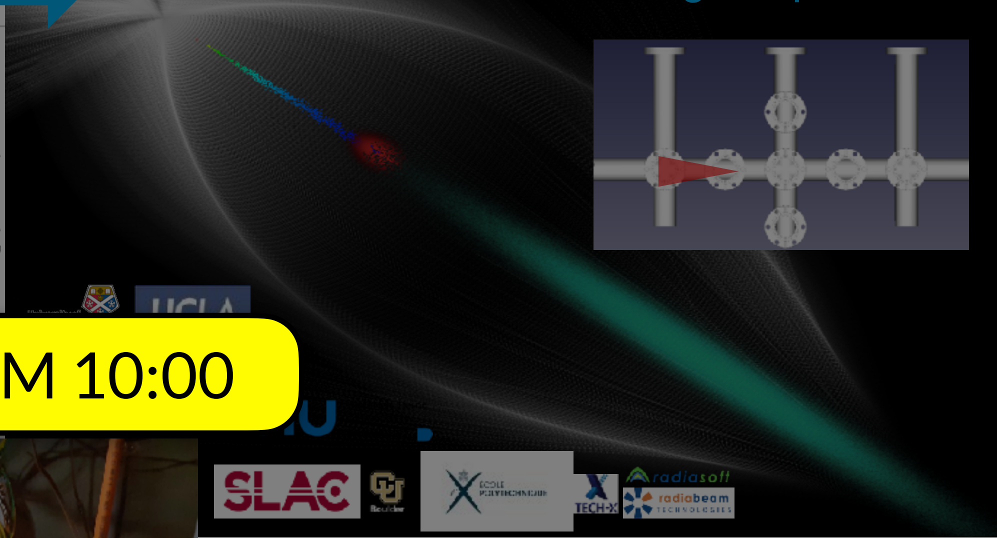


Deng *et al.*, Nature Physics 15, 1156, (2019)

1. Bespoke crossed pipe system to host tailored, wide plasma channel...



FACET-II E-310 Trojan Horse-II:
Collinear geometry, wide channel:
Normalized emittance ε_n~10 nm-rad
>10 GeV, 100% charge capture



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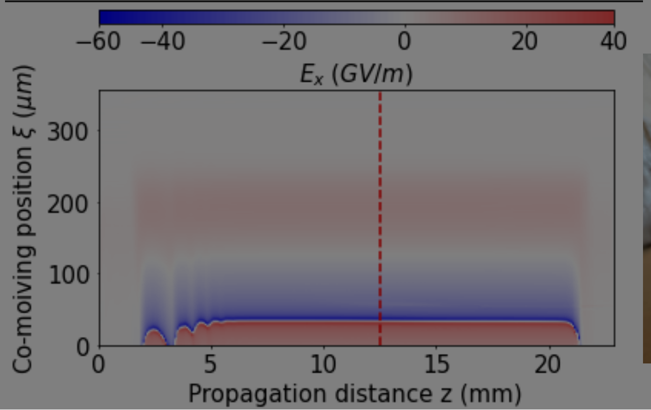
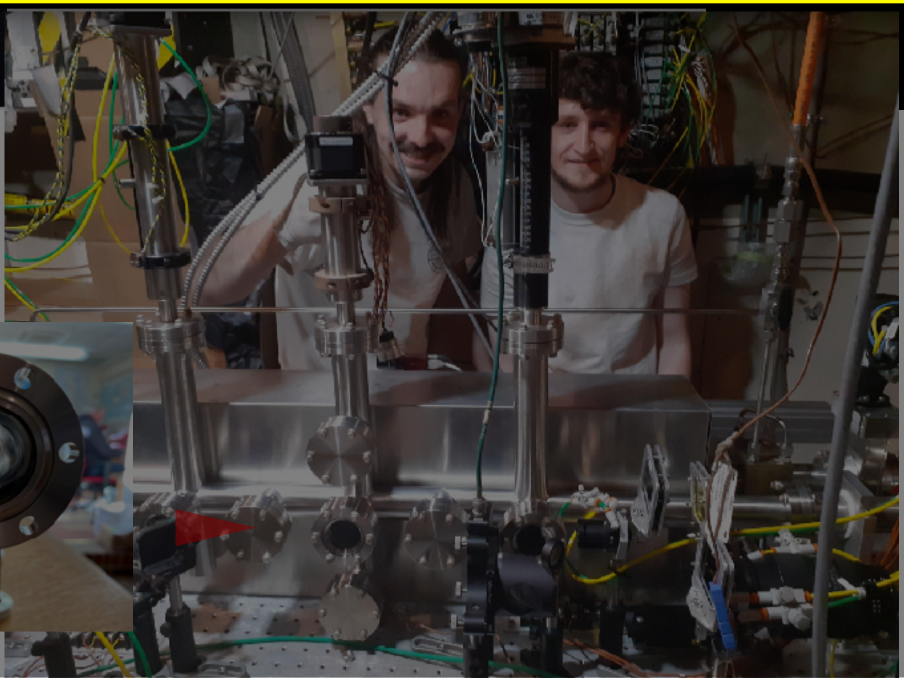
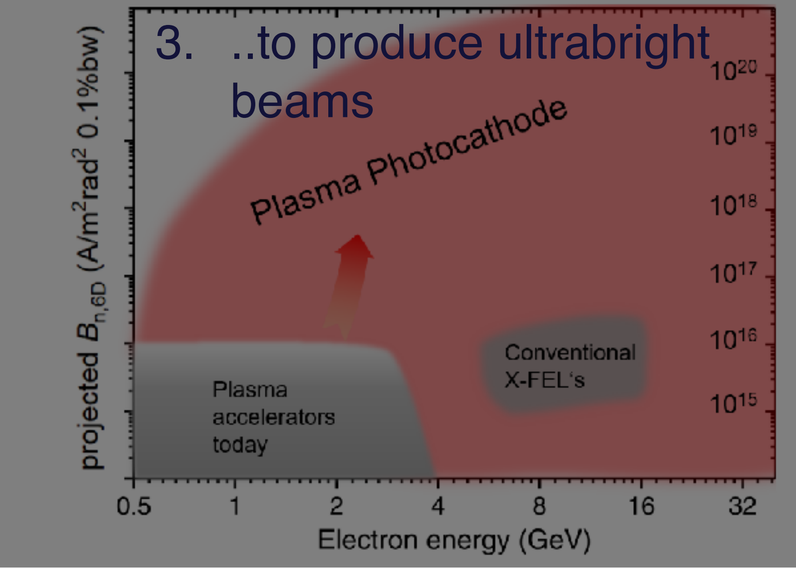
FACET E-210 Trojan Hors[e]
Perpendicular geometry, t[...]
channel bottleneck: ε_n~μm-rad
~1 GeV, poor charge capture

Bernhard Hidding plenary M 10:00

2. ...to allow stable collinear injection and acceleration...







E-338 PAX: Plasma-driven Attosecond X-ray Source

Science Goals

Demonstrate post-plasma sub-fs compression of e- beams

Measure + characterize XUV CSR for compressed e- beam down to 50-100 nm

Using beams from plasma injector (density down ramp, Trojan Horse…), compress + measure coherent XUV at 50 nm or below

Phased Approach

First stage will chirp + compress beams from FACET-II photoinjector

Second stage will compress ultra-high brightness beams generated from plasma injector

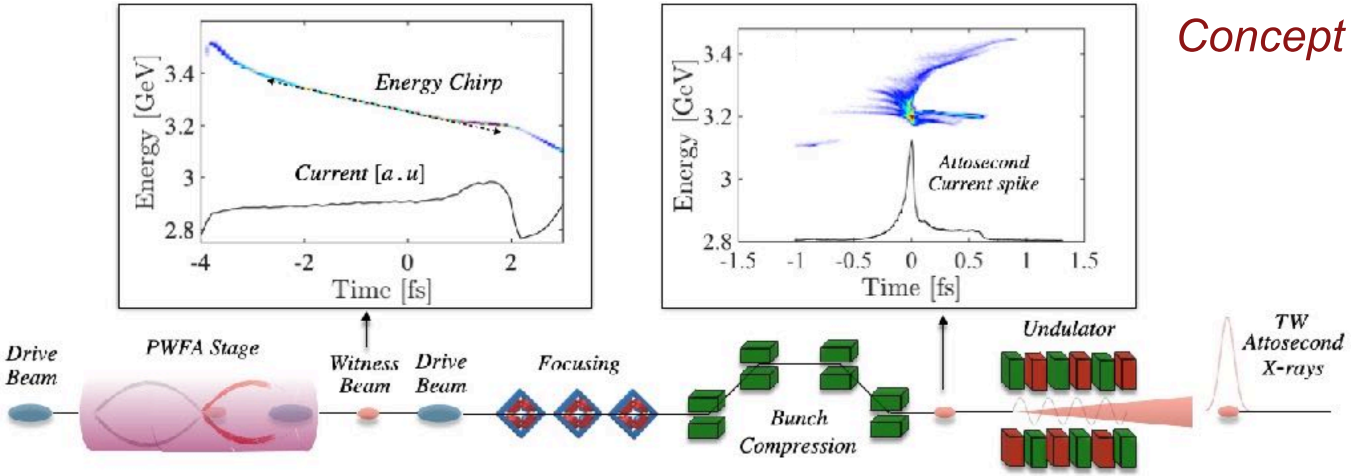
Current progress

UV-vis and XUV spectrometers commissioned/installed

Compressor chicane design review completed. Installation targeting summer 2024 downtime

See plenary talk by Michael Litos M 09:00

Concept



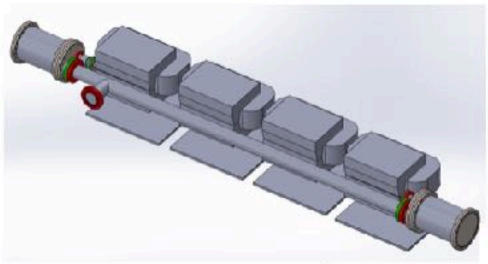
C. Emma et al., APL Photonics, **6**, 076107 (2021)

FACET-II Experiment Schematic

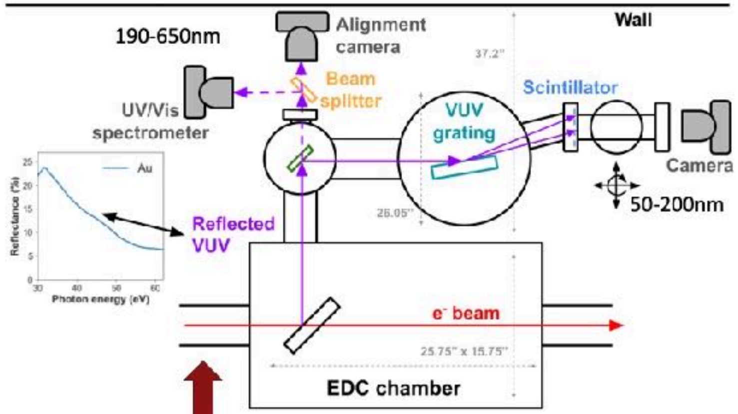
Plasma Sources

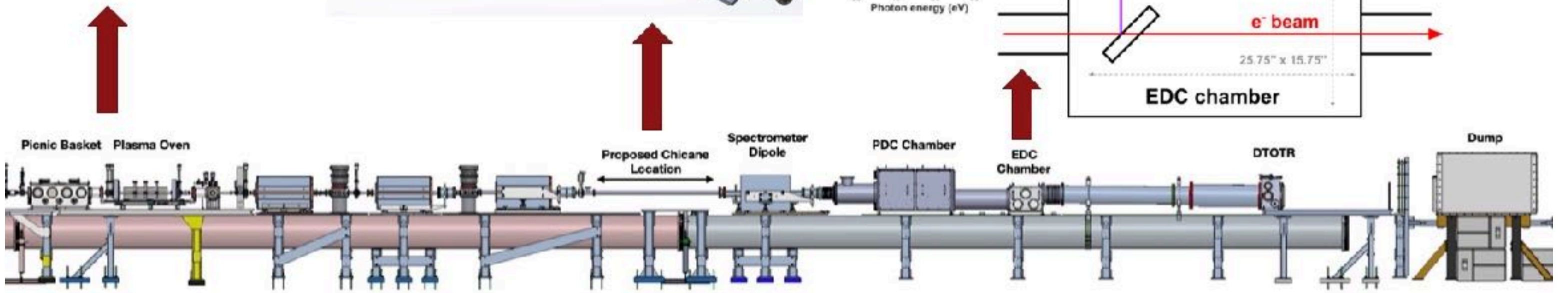
- Gas Jet ne = 1e18 – 1e20 cm^-3
- Li Oven ne = 1e16 cm^-3

Chicane + bypass line design

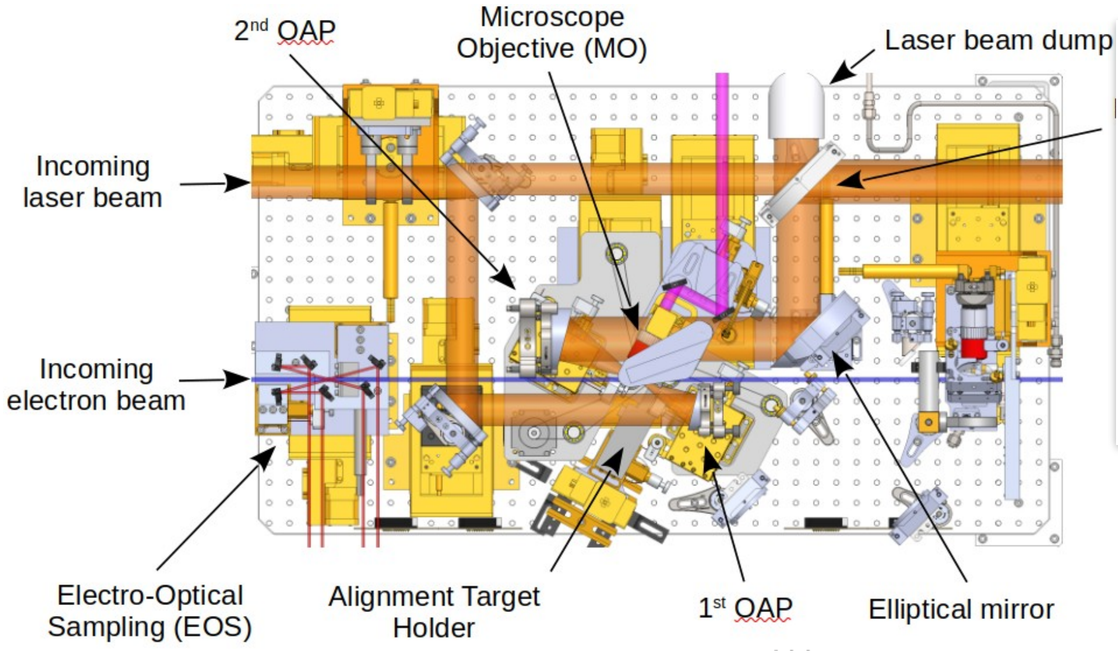


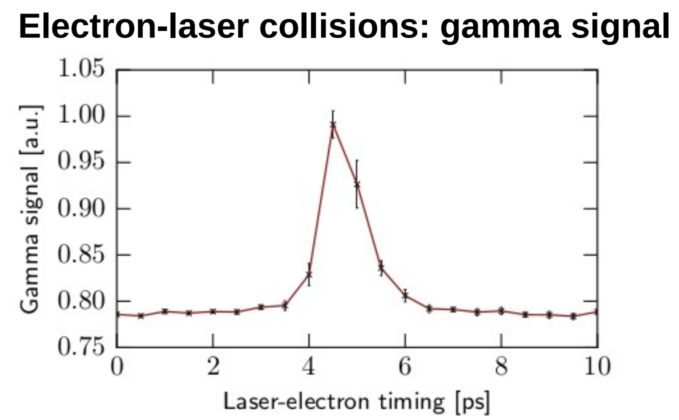
Spectral Measurement Setup

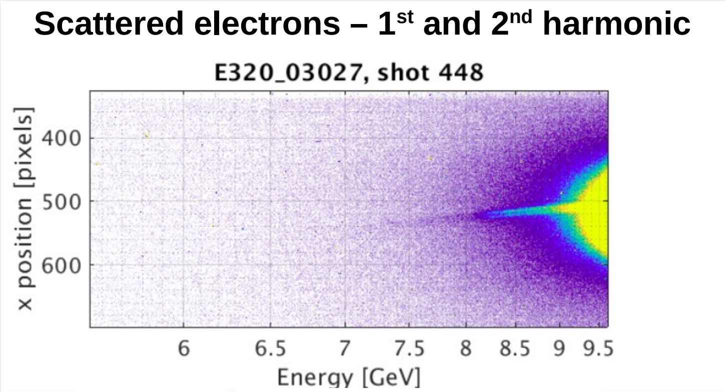


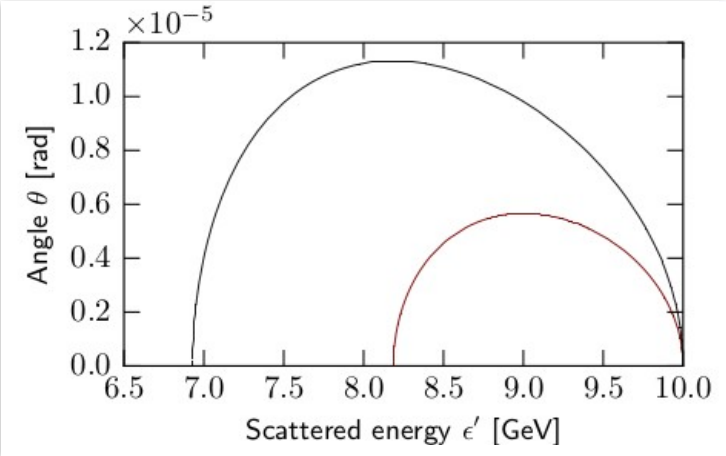


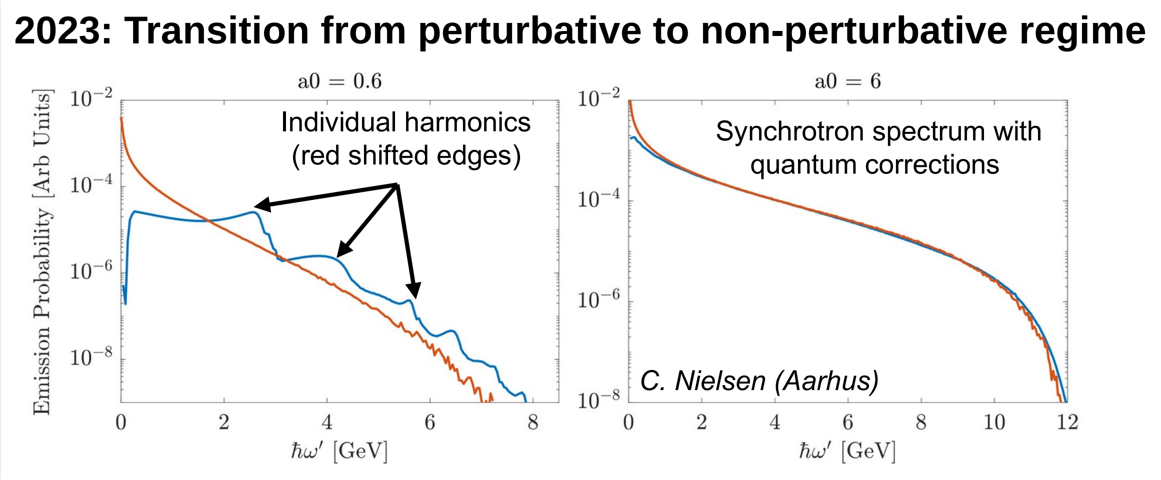
E-320: Probing Strong-field QED on FACET-II











- Observe the transition from multi-photon Compton scattering (a_0~0.4, χ~0.04) to quantum synchrotron radiation (a_0~4, χ~0.4)
- Witness QED-vacuum breakdown via tunneling electron-positron pair production

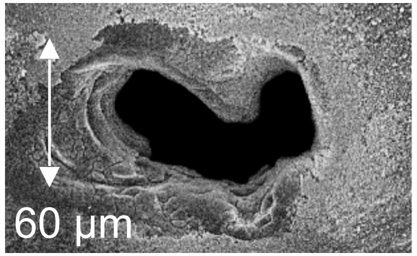
Nest steps: push the laser intensity up (energy, duration, OAPs) and push the backgrounds down

Extreme Beams Can Be Challenging

Be vacuum window damage at FACET expected for 2nC with

$$\sigma_x = \sigma_x = \sigma_x = 20\mu m$$

$$P \propto \frac{Q^2}{\sigma_r^2 \sigma_z^2} F\left({}^{\sigma_r}/_{\sigma_z}\right)$$



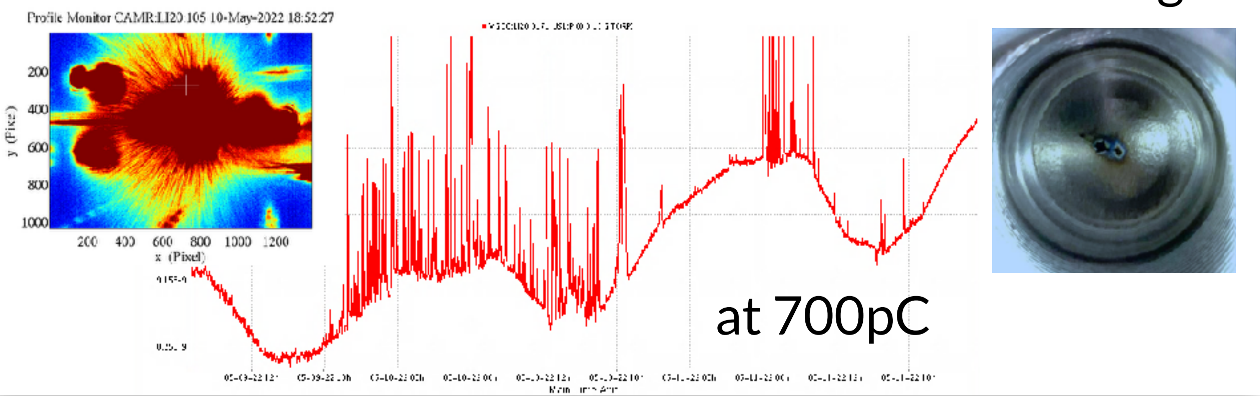
[SLAC-PUB-15729]

New threshold for micro bunched beams at FACET-II

COTR

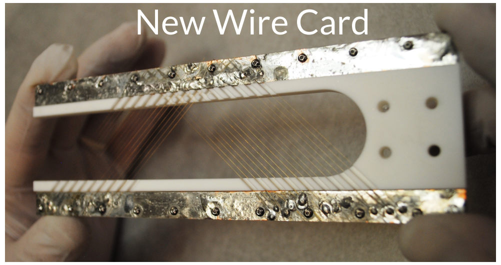
Vacuum activity

Be window damage



at 700pC

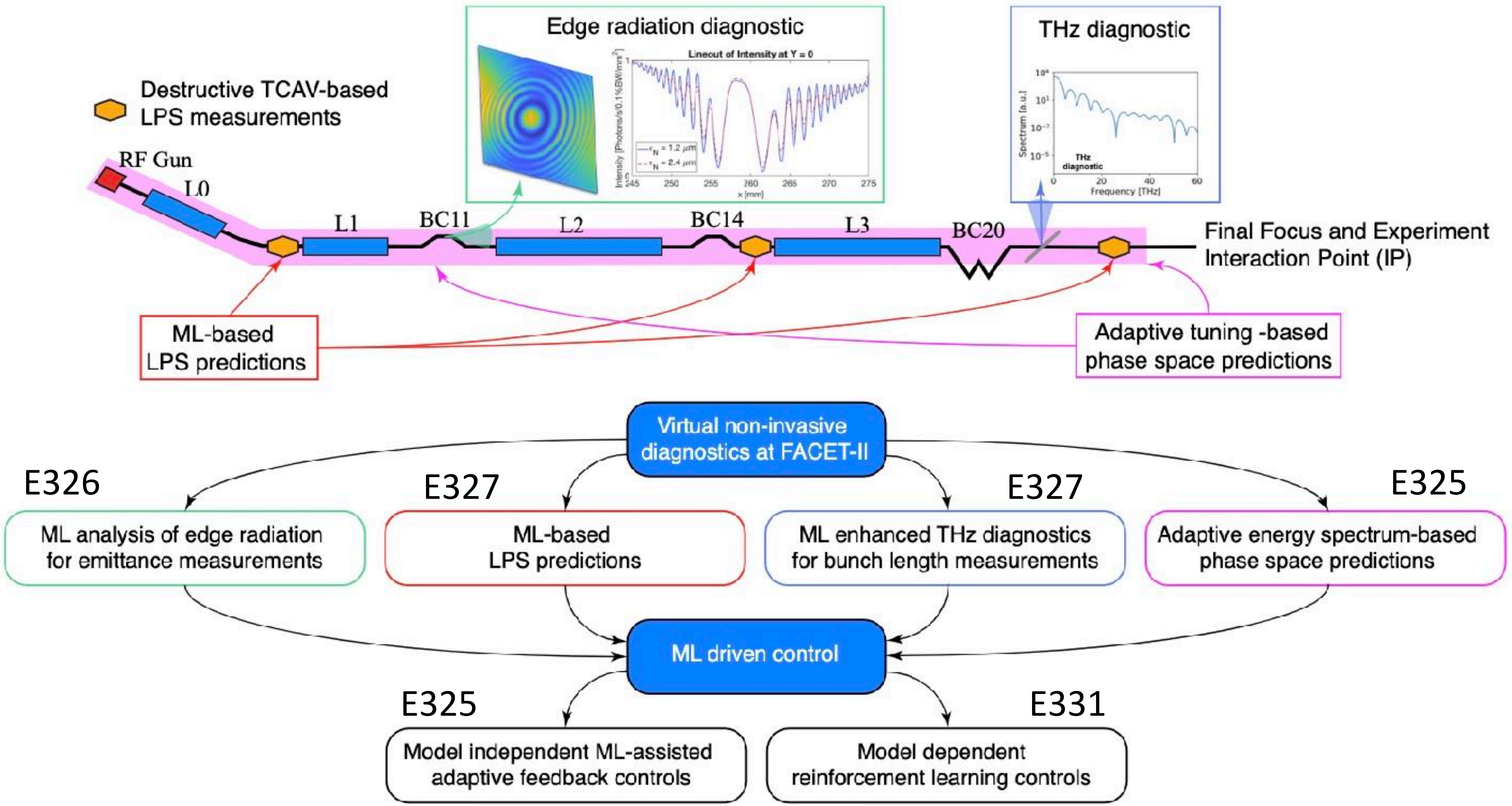
Traditional diagnostics become consumables



- Laser heater installation will mitigate microbunching and control peak current
- Differential pumping system removed vacuum windows from experimental area

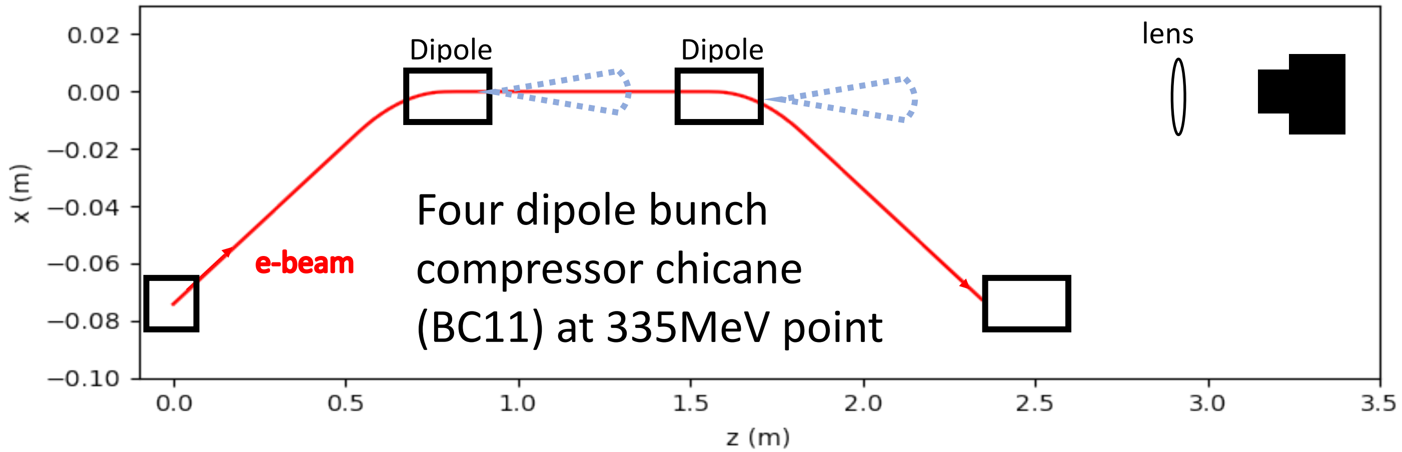
FACET-II has unique challenges related to high intensity beams that require new approaches to diagnostics that benefit from advances in ML/AI

Landscape of AI/ML Activities at FACET-II



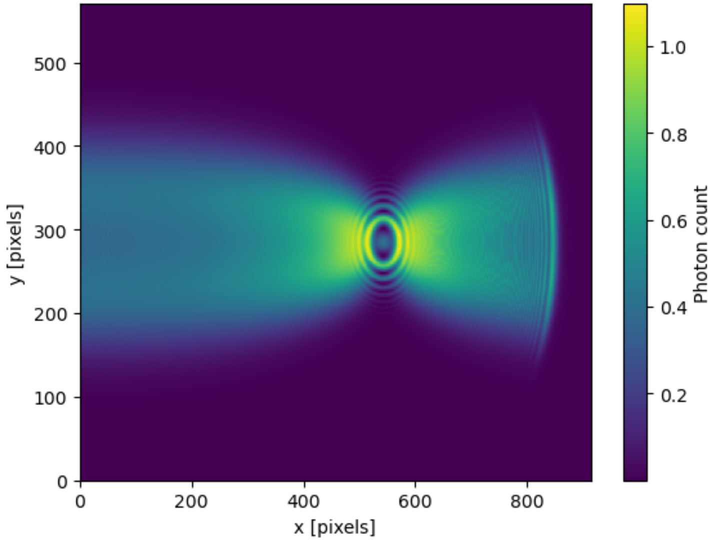
Synergistic experiments, individual success enhances all research + facility operation by providing new methods to characterize, model and control extreme beams

E-326: Emittance Diagnostics Optimized for Artificial Intelligence

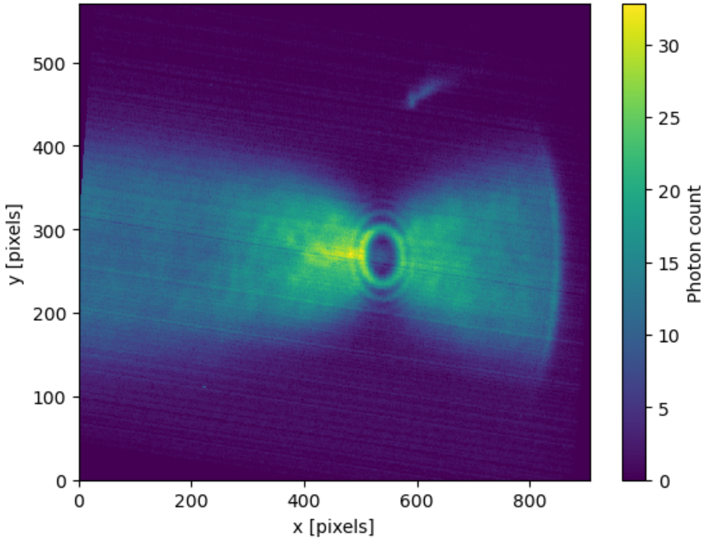


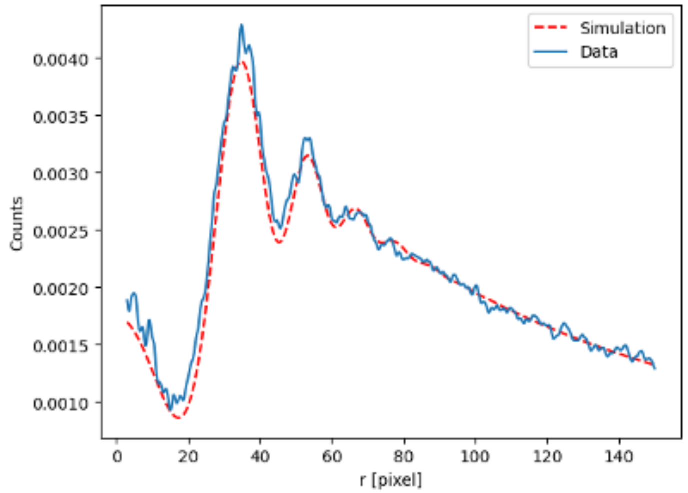
- Fringe pattern from interference of dipole edge radiation strongly correlated with beam emittance and energy spread
- Measured changes to fringe pattern for increased emittance and energy spread qualitatively agree with simulations
- Comparing approaches to minimize time required to match data to simulations

Simulations



Experimental Data





Pushing to online non-invasive single shot beam characterization

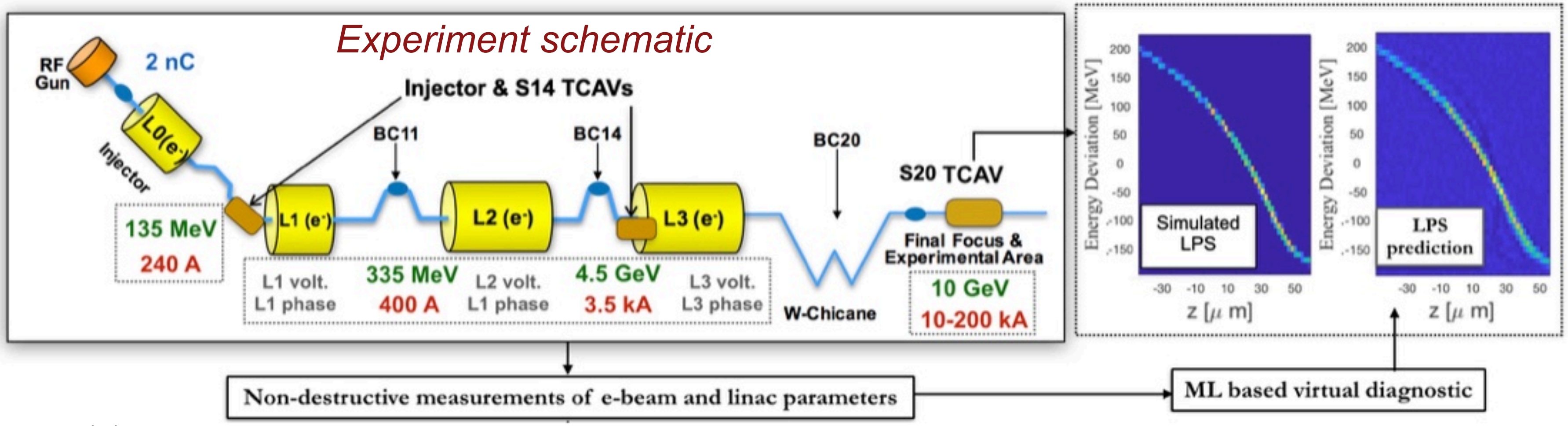
E-327: Virtual Diagnostic for Longitudinal Phase Space Prediction and Optimization

Science Goals

Implement a single-shot non-destructive ML diagnostic to predict the e-beam LPS along the linac.

Use the ML-diagnostic to customize/ control the LPS for different experiments.

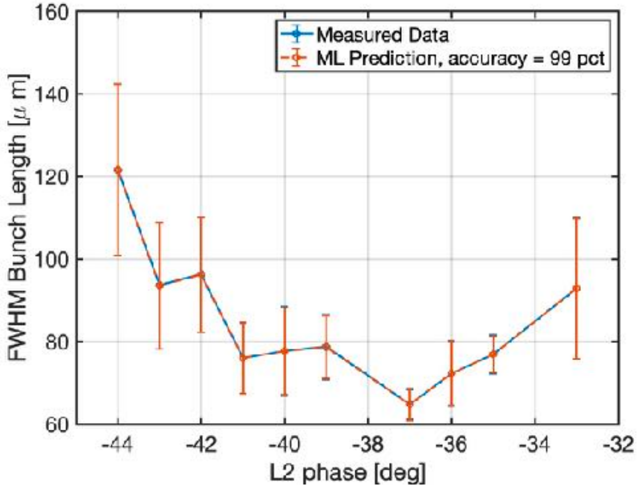
C. Emma and A. Edelen et al.,PRAB 21 112802 (2018)

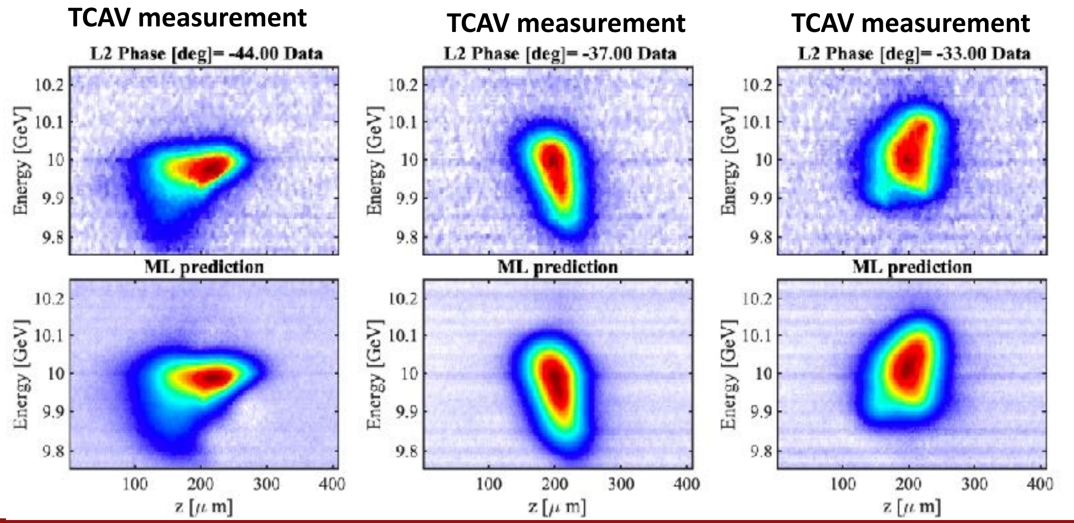


First results

Neural network prediction of bunch length and LPS in FACET-II experimental area

Data from 7/8/22





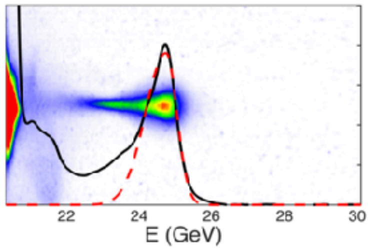
ML based LPS diagnostic feasibility demonstrated at FACET-II.
Upcoming work focused on shorter bunches, robustness + multiple locations/beam configurations

FACET-II Positron Upgrade

Positrons represent a unique scientific opportunity with global enthusiasm reflected in European Strategy updates, Snowmass preparations and recent workshops

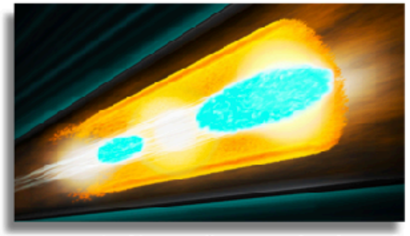
Demonstrated @ FACET

Non-linear wakes in self-loaded regime of PWFA



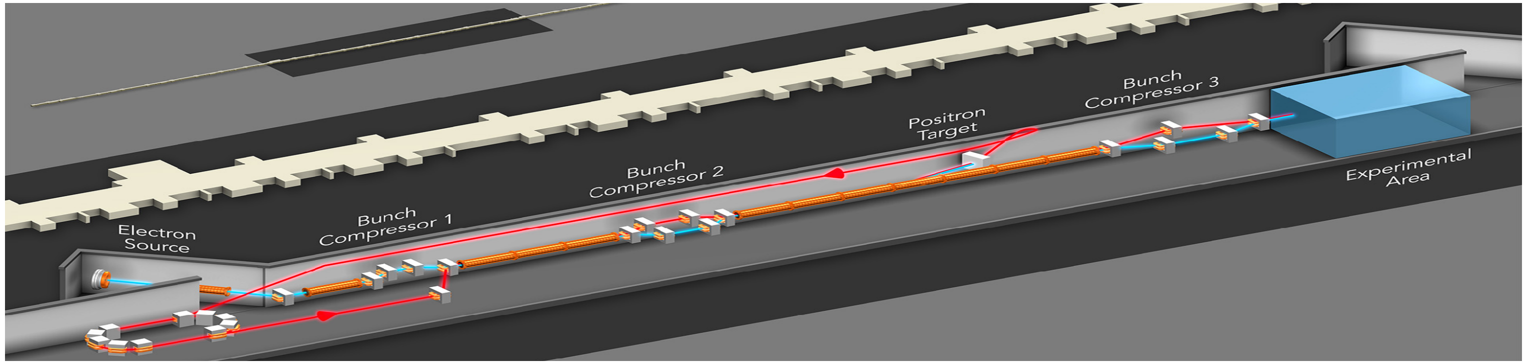
Corde et al., ***Nature*** August 2015

Hollow Channel Plasma Wakefield Acceleration



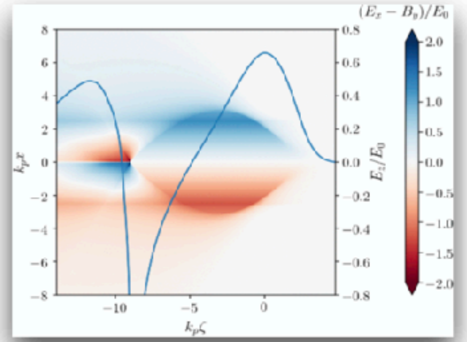
Gessner et al., ***Nature* Communications** 2016
Lindstrom et al., ***Phys. Rev. Lett.*** 2018

- Base infrastructure exists



Proposed @ FACET-II

- Finite-channel plasmas are predicted to preserve emittance
- LBNL, DESY, CU Boulder and SLAC collaboration



S. Diederichs et al., Phys. Rev. Accel. Beams 22, 081301 (2019)

Potential for experiments on positron PWFA has stimulated creative new ideas

Will re-examine options with DEO HEP once P5 report is available. With a commitment and strong support from SLAC the plan could be executed on 5 year time scale without interruption of existing user program.

Presenting on Behalf of Many Collaborations and Colleagues

E300 Collaboration

- Presenting on behalf of the E300 collaboration:
  - PIs: C. Joshi (UCLA) and M. Hogan
- SLAC team: J. Allen, R. Ariniello, C. Clarke, C. Emma, E. Gerstmayr, S. Gessner, B. O'Shea, D. Storey, G White, M. Hogan

SLAC NATIONAL ACCELERATOR LABORATORY · FACET-II Facility for Advanced Accelerator Experimental Tests · U.S. DEPARTMENT OF ENERGY Office of Science · UCLA · loa · Stony Brook University

AAC 22, Nov 6-11, 2022 D. Storey E300 Progress towards Energy Doubling & Emittance Preservation through PWFA at FACET-II 2

E-304 Collaborations

UCLA

UCLA	C. Joshi, K. Marsh, W. B. Mori, Y. Wu, Z. Nie, H. Fujii
SLAC	X. Xu, M. Hogan, V. Yakimenko, FACET-II staff
loa	Sebastien Corde's group
CU	Mike Litos' group

31

E-305/E-332 collaboration and institutions

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

H. Ekerfelt, C. Emma, F. Fiuza, E. Gerstmayr, S. Gessner, M. Hogan, A. Marinelli, J. Peterson, B. O'Shea, D. Storey, X. Xu, V. Yakimenko

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

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

E. Adli

J. Yan, N. Vafaei-Najafabadi

SLAC AAC 22, Nov 6-11, 2022 30

E-31x Collaboration

University of Strathclyde · TECH-X · radiasoft · radiabeam TECHNOLOGIES · hhu Heinrich Heine Universität Düsseldorf · UCLA · The Cockcroft Institute of Accelerator Science and Technology · ÉCOLE POLYTECHNIQUE · SLAC · CU Boulder · erc · NeXource

32

The E-320 collaboration

Additional support: Juan Cruz, Joe Frisch, Shembhu Ghimire, Carl Hudspeth, Cindy Patty, Nadya Smith, Takahiro Sato, the PULSE Team (in particular Ritu Khurana and Sheetal Singhal), and many more

Carleton University, Ottawa, Ontario, Canada	Thomas Koffas
Aarhus University, Aarhus, Denmark	**Christian Nielsen**, Allan Sørensen, Ulrik Uggerhøj
École Polytechnique, Paris, France	Sébastien Corde, Pablo San Miguel Clave, Aimé Matheron
Technical University (TU) of Darmstadt	Christian Rödel
University of Hamburg	Tais Gorkhover, Stephan Kuschel
MPI für Kernphysik, Heidelberg, Germany	Antonino Di Piazza, Christoph H. Keitel, Matteo Tamburini
HI Jena and University of Jena, Germany	**Harsh, Felipe Salgado**, Jannes Wulff, **Matt Zepf**
Universidade de Lisboa, Portugal	Thomas Grismayer, Luis Silva, Marija Vranic
Imperial College London, UK	Stuart Mangles
Queen's University Belfast, UK	Niall Cavanagh, **Elias Gerstmayr,** Gianluca Sarri, **Matthew Streeter**
California Polytechnic State University, CA USA	**Robert Holtzapple,** Maison Singleton, Liam Frank, Jack Kloeckl, Adam Callman, Ben Knudson, Max Varerakis, and Sebastian Turkewitz
Lawrence Livermore National Laboratory, CA USA	Félicie Albert
SLAC National Accelerator Laboratory and Stanford PULSE Institute, Menlo Park, CA USA	Robert Ariniello, **Phil Bucksbaum**, Christine Clarke, Angelo Dragone, Alan Fisher, Frederico Fiuza, Alan Fry, Spencer Gessner, Siegfried Glenzer, Carsten Hast, Mark Hogan, Chris Kenney, Doug McCormick, **Sebastian Meuren (PI), Rafi Mir-Ali Hessami**, Brendan O'Shea, **David Reis, Tania Smorodnikova, Douglas Storey**, Glen White, **Vitaly Yakimenko**
University of California Los Angeles, CA USA	Chan Joshi, Warren Mori, **Brian Naranjo, James Rosenzweig**, Oliver Williams, Monika Yadav
University of Colorado Boulder, CO USA	Chris Doss, Michael Litos
University of Nebraska - Lincoln, NE USA	Matthias Fuchs, **Junzhi Wang**
Former members	**Zhijiang Chen, Henrik Ekerfelt**, Erik Isele

FACET-II empowers broad user community and user community enables FACET-II

Summary and Outlook

- There has been a lot of progress since the last EAAC – we finished the project, commissioned the accelerator and recently began the experimental programs
- 2023 presented some challenges but our collaborations have made steady progress and are ready for more beam
- FACET-II is delivering high-intensity beams that open new scientific directions strongly aligned with HEP roadmaps for plasma acceleration
- FACET-II is leveraging SLAC ML/AI initiatives to develop new methods to diagnose and control extreme beams
- We are installing and commissioning important hardware & capabilities to benefit the experimental programs: laser heater, LLRF for more stable delivery, and two-bunches from the FACET-II injector

Our Users are engaged, we are excited to be beginning the science programs and we look forward to many face to face discussions at EAAC2023