SLAC AAC program and US roadmap

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Great Desire for Compact Access to High Energy Beams

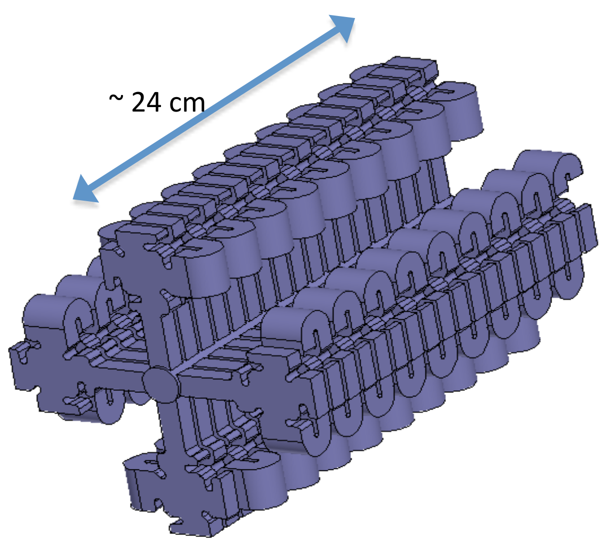
High energy particle accelerators are the ultimate microscopes

- Reveal fundamental particles and forces in the universe at the energy frontier
- Enable x-ray lasers to look at the smallest elements of life on the molecular level

Advanced concepts look to shrink the size and cost of these accelerators by factors of 10-1000

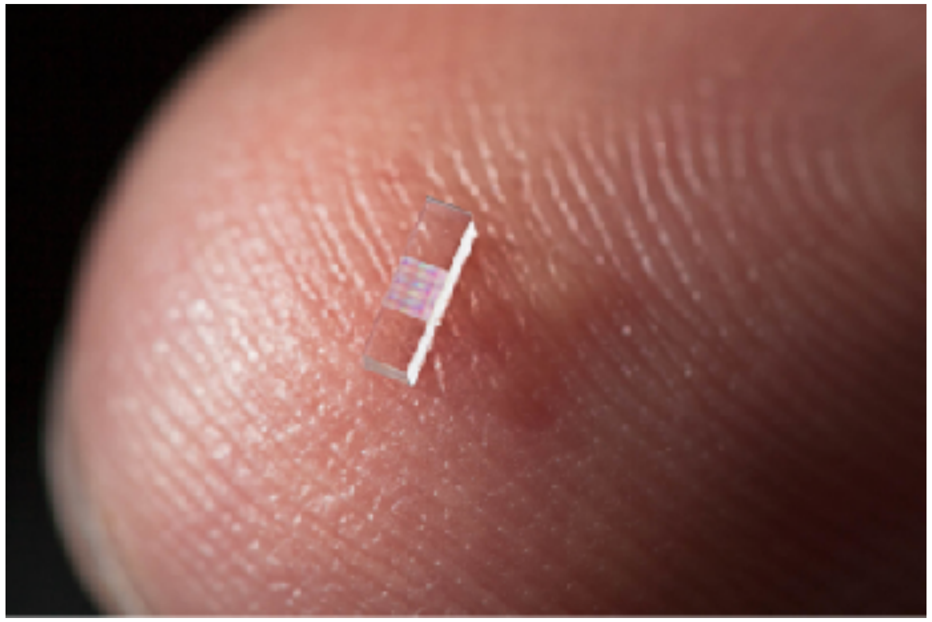
Combine efficient accelerator drivers with high-field dielectric and plasma structures to develop new generation of particle accelerators

~100MeV/m



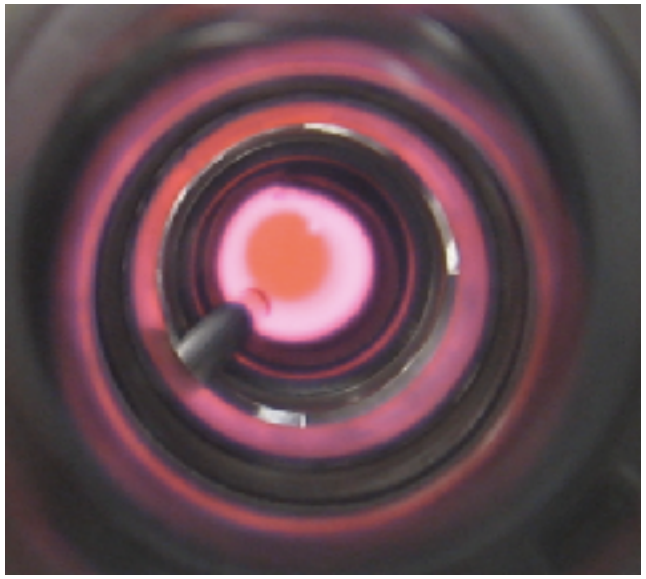
New designs and materials push metal structures to the limit

~1GeV/m



Telecom and Semiconductor tools used to make an 'accelerator on a chip'

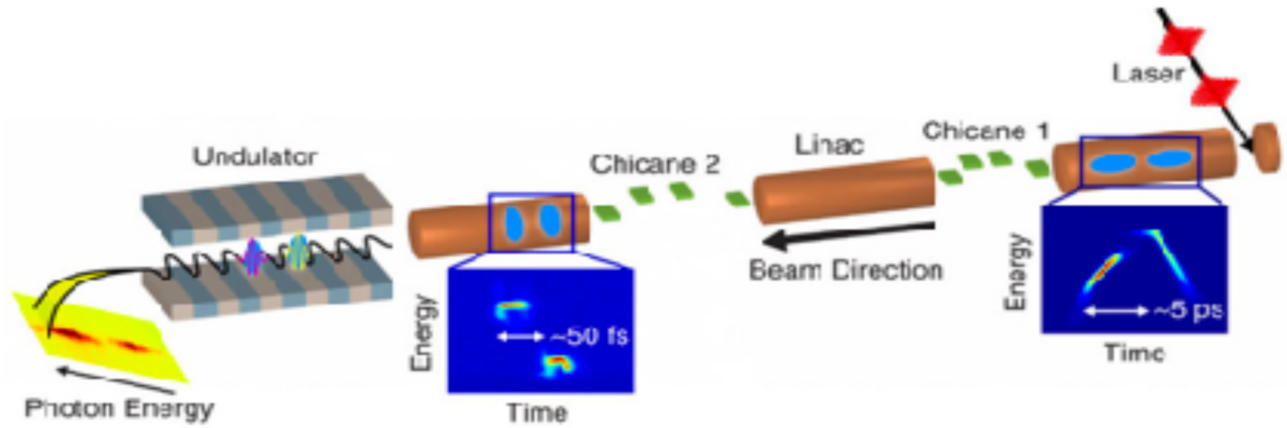
~10GeV/m

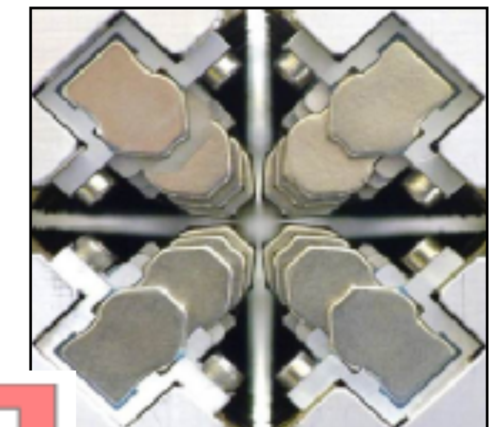


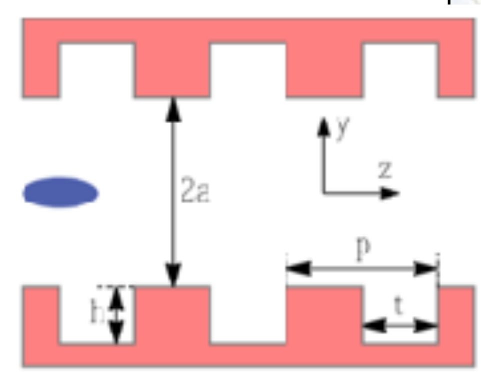
Extremely high fields in 1,000°C lithium plasmas have doubled the energy of the 3km SLAC linac in just 1 meter

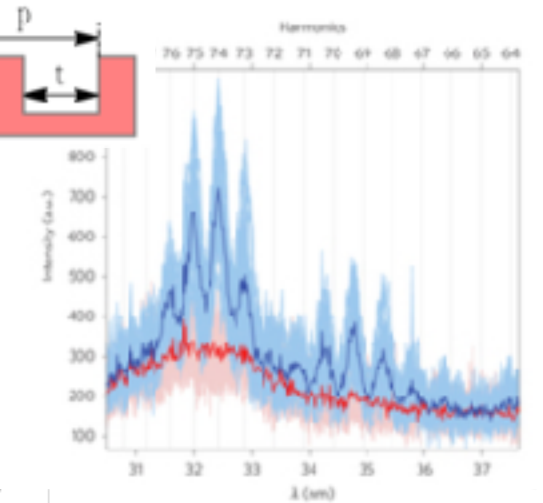

20 GeV
e- & e+
FACET
5 MeV
ASTA
2-15 GeV
& single e-
ESTB
60-120 MeV
NLCTA

FEL R&D Papers









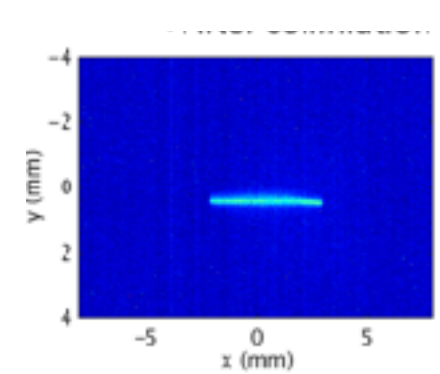
Twin/Double Bunch
Marinelli et al., Nature Communications, 6 6369 (2015)

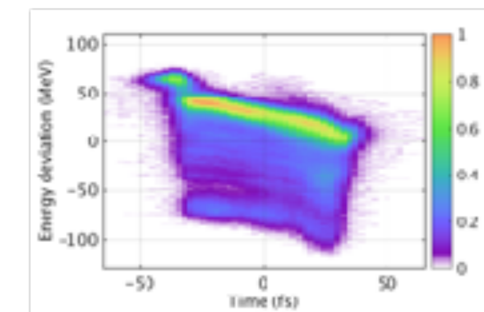
DELTA (Polarization control)
A. Lutman et al., Nature Photonics 10, 468-472 (2016)

Fresh slice (Dechirper)
A. Lutman et al., Nature Photonics 10, 745-750 (2016)

Seeding
D. Ratner et al. Phys. Rev. Lett. 114 054801 (2015).
E. Hemsing et al., Nature Photonics 10 512 (2016)

Horn Cutting
Y. Ding et al., Phys. Rev. AB, 19, 100703 (2016)





FACET Project History

Primary Goal:

- Demonstrate a single-stage high-energy plasma accelerator for electrons

Timeline:

- CD-0 2008
- CD-4 2012, Commissioning (2011)
- Experimental program (2012-2016)

A National User Facility:

- Externally reviewed experimental program
- >200 Users, 25 experiments, 8 months/year operation

Key PWFA Milestones:

√ Mono-energetic e- acceleration

√ High efficiency e^- acceleration (*Nature* **515**, Nov. 2014)

√ First high-gradient e^+ PWFA (*Nature* **524**, Aug. 2015)

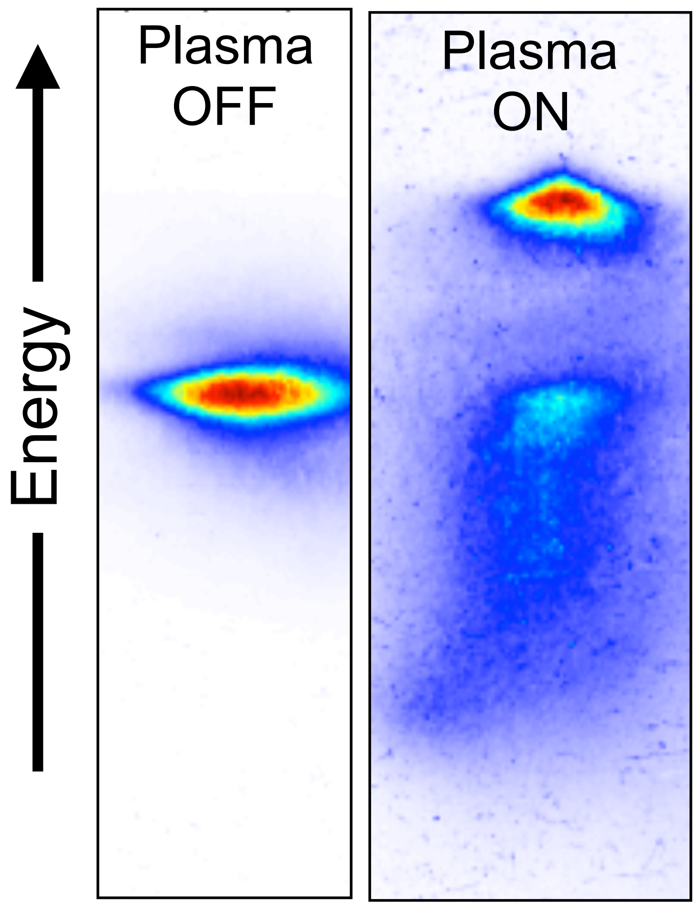
- Demonstrate required emittance, energy spread (FY16 in preparation for *Nature*)

Premier R&D facility for PWFA: Only facility capable of e+ acceleration
Highest energy beams uniquely enable gradient > 1 GV/m

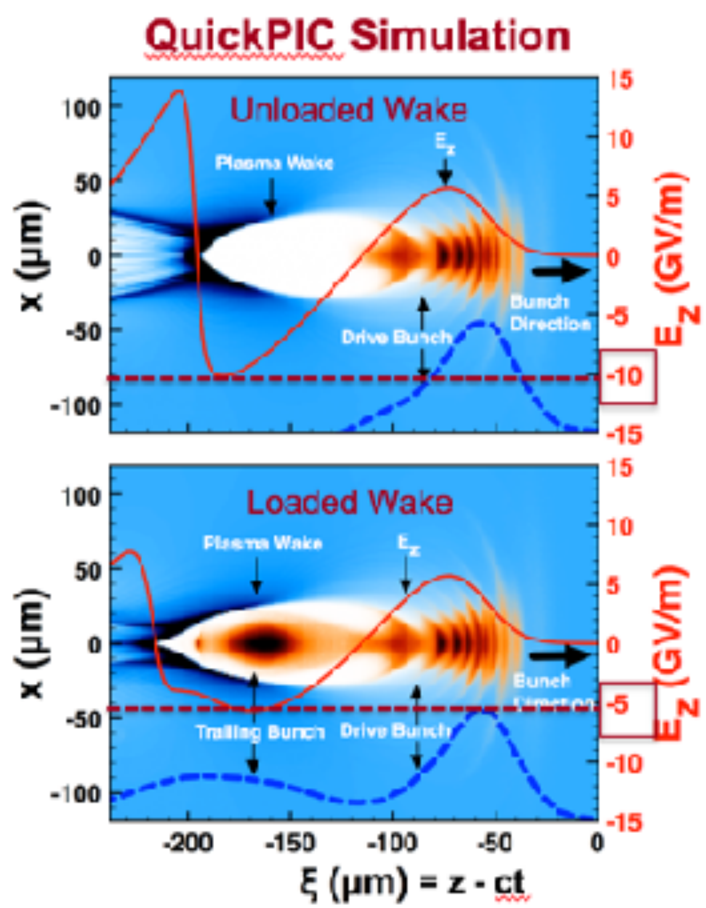
Litos et al., *Nature* November 2014

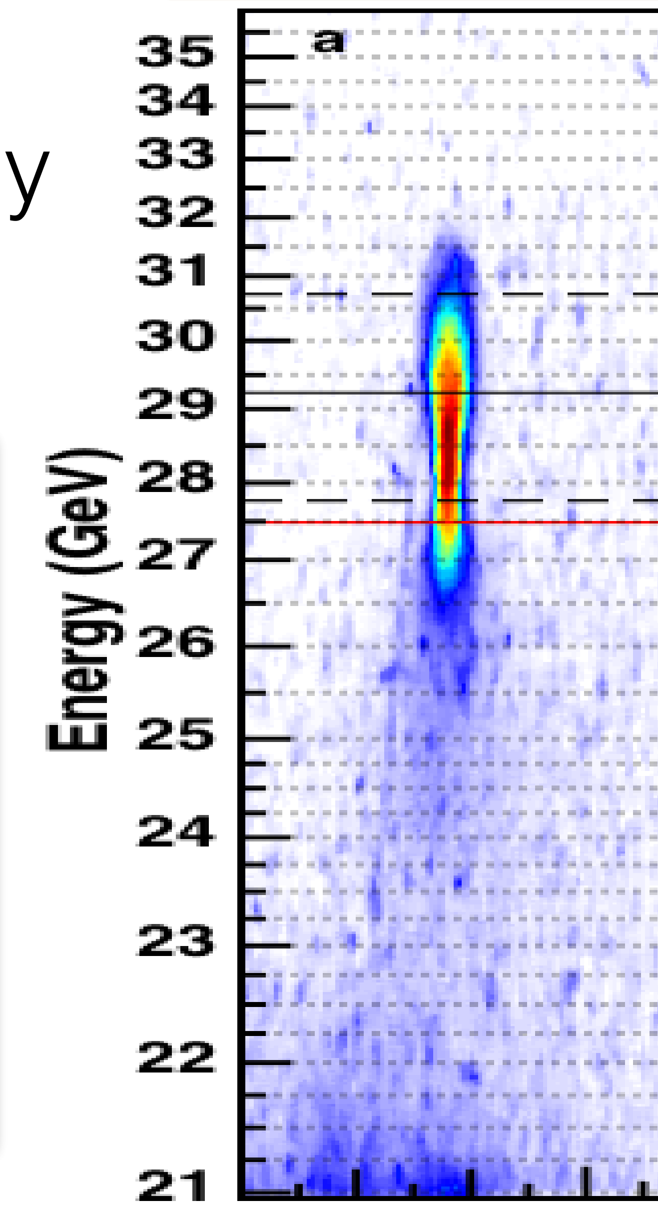
High-Efficiency Acceleration of an Electron Bunch in a Plasma Wakefield Accelerator

Beam loading is key for:
Narrow energy spread & high efficiency



2 GeV Energy Gain
~2% dE/E
~30% efficiency





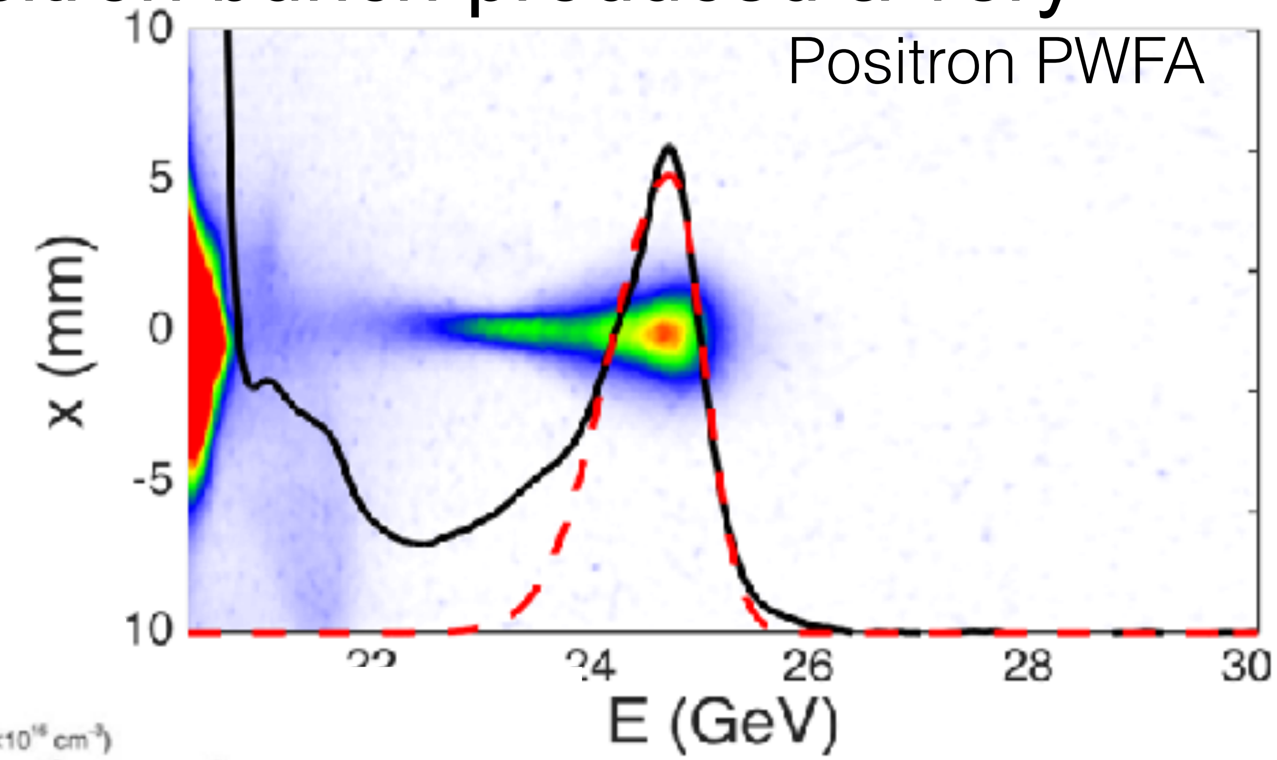
9 GeV
Energy Gain

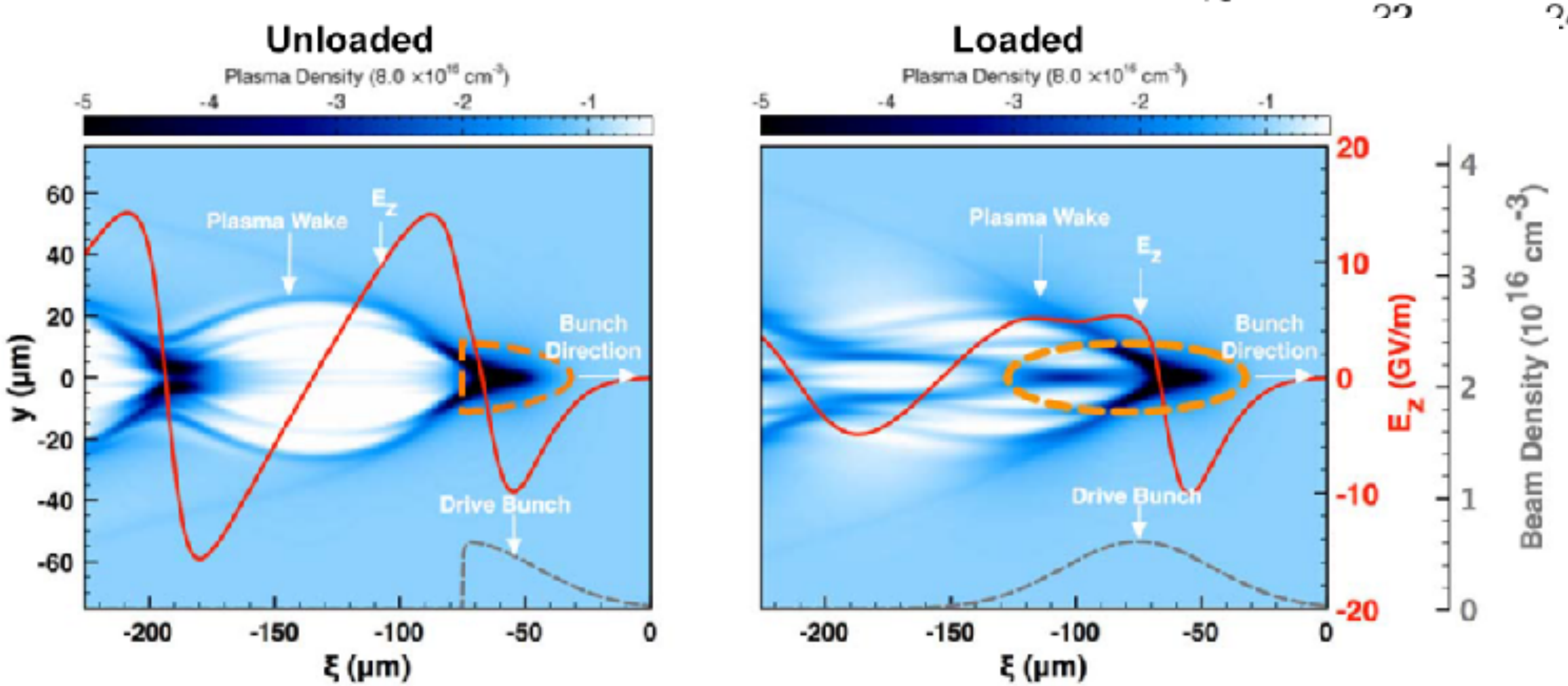
Narrow energy spread acceleration with high-efficiency has been demonstrated
Next decade will focus on simultaneously preserving beam emittance

Multi-GeV Acceleration of Positrons

Injecting a single high-intensity positron bunch produced a very surprising result!

- Energy gain 4 GeV in 1.3 meters
- 1.8% energy spread
- Low beam divergence
- No halo



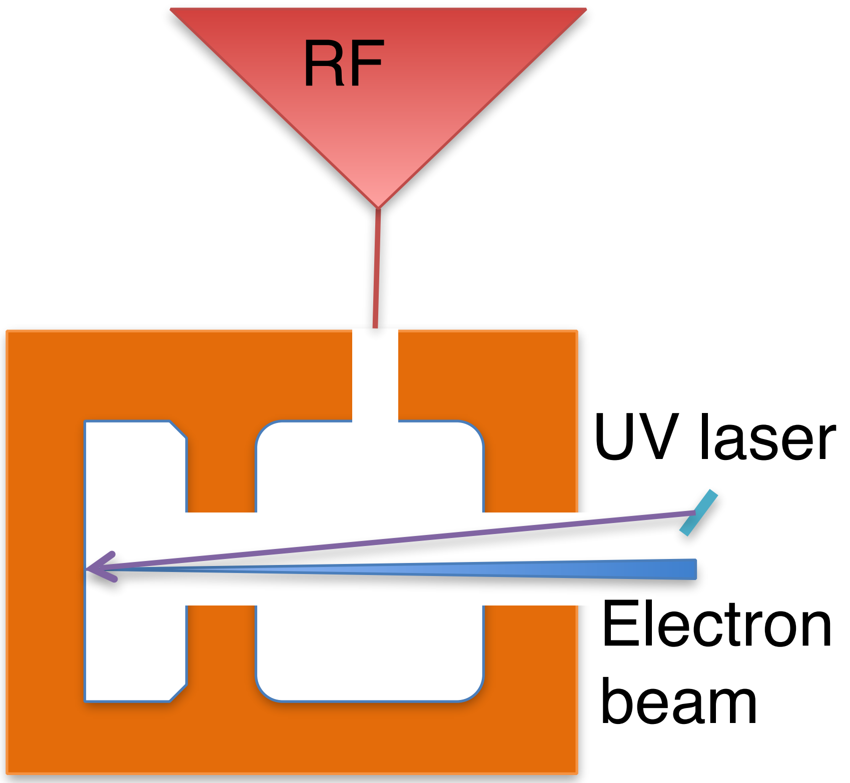


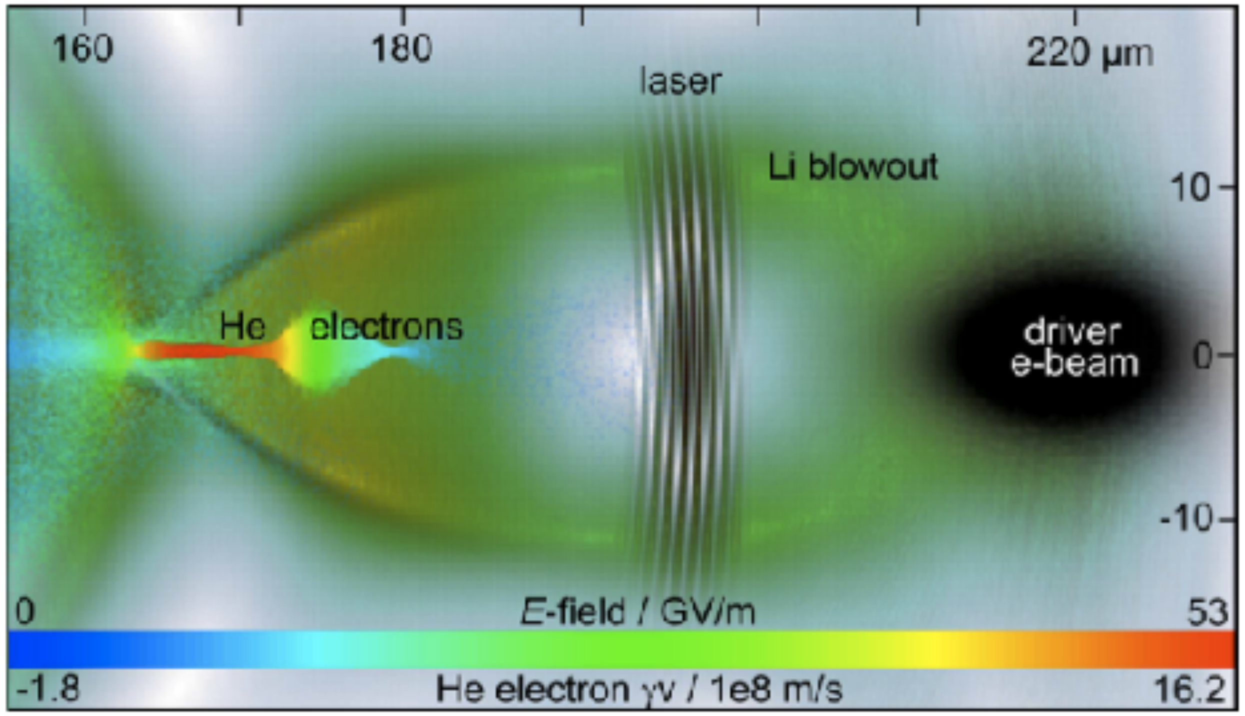
New PWFA regime warrants further exploration and development towards PWFA-LC application

Development of High-Brightness Electron Sources

LCLS Style Photoinjector

- 100MeV/m field on cathode
- Laser triggered release
- ps beams - multi-stage compressions & acceleration
  - Tricky to maintain beam quality (CSR, microbunching…)

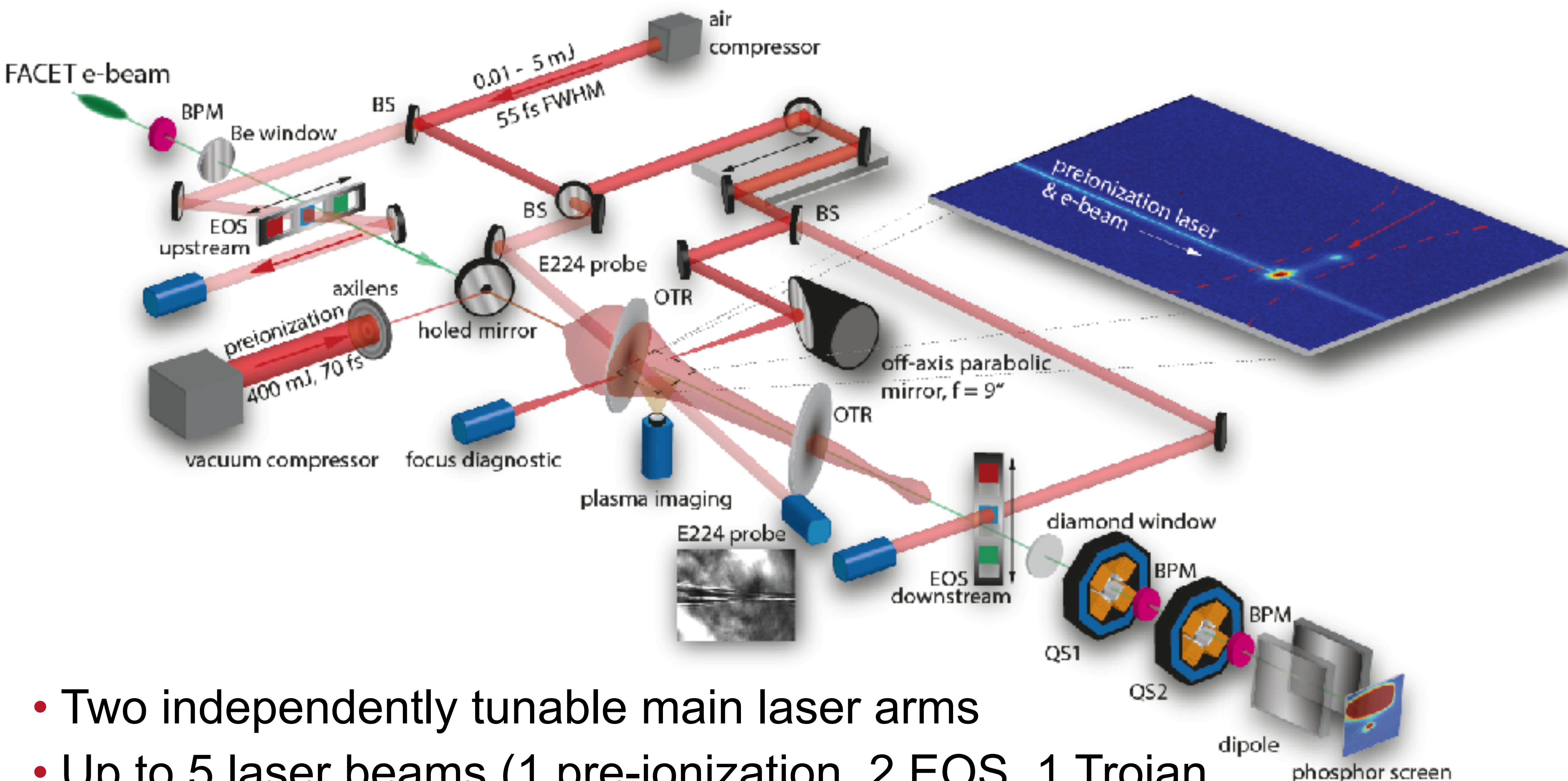




Plasma Photoinjectors

- 100 GeV/m
- fs beams, μm size
- Promise orders of magnitude improvement in emittance
- Injection from: TH, Ionization, DDR, CP…

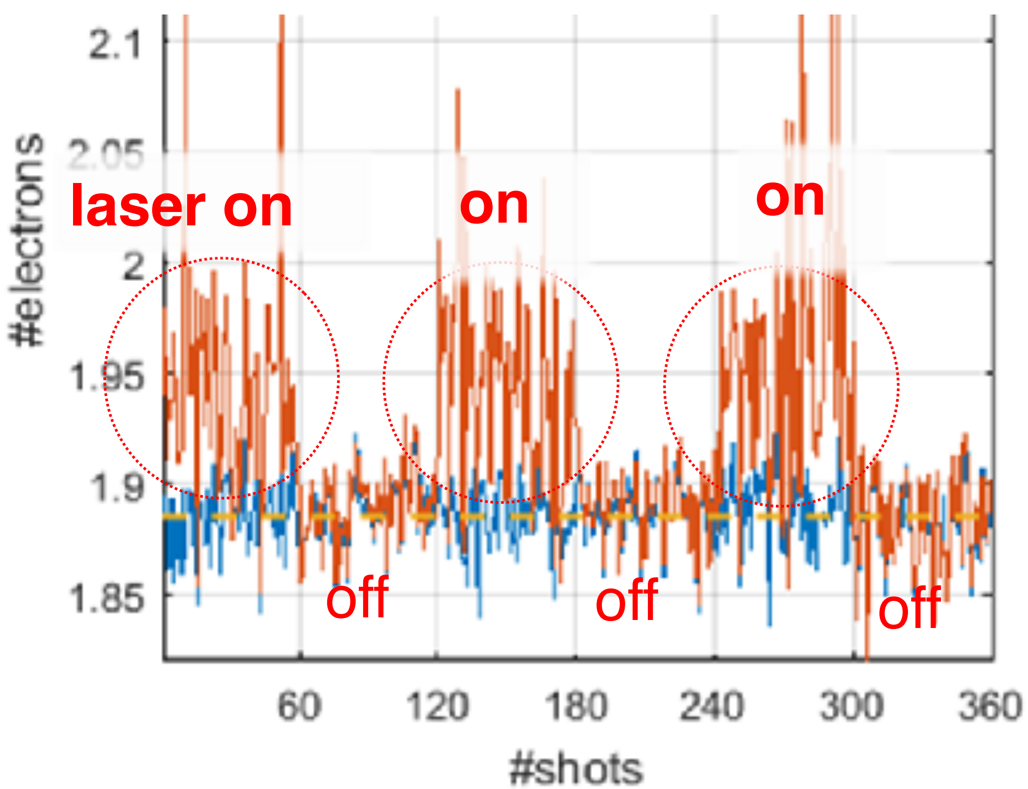
2015/2016: Full Trojan Horse setup

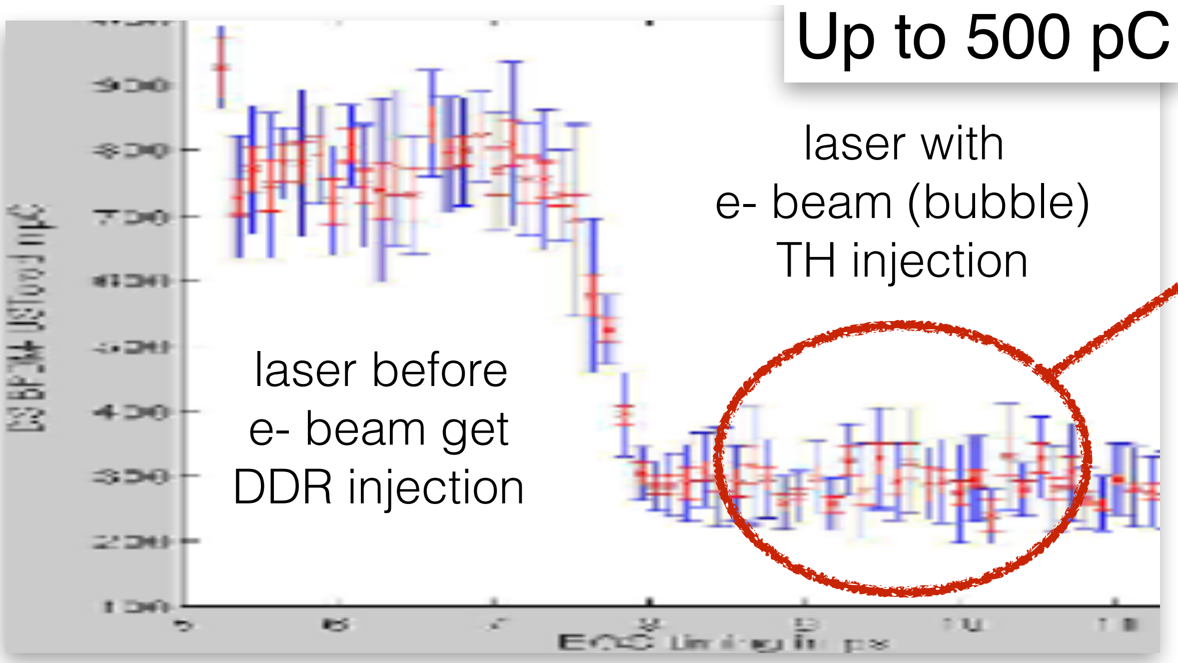


- Two independently tunable main laser arms
- Up to 5 laser beams (1 pre-ionization, 2 EOS, 1 Trojan photocathode, 1 probing) synchronized with the electron beam driver

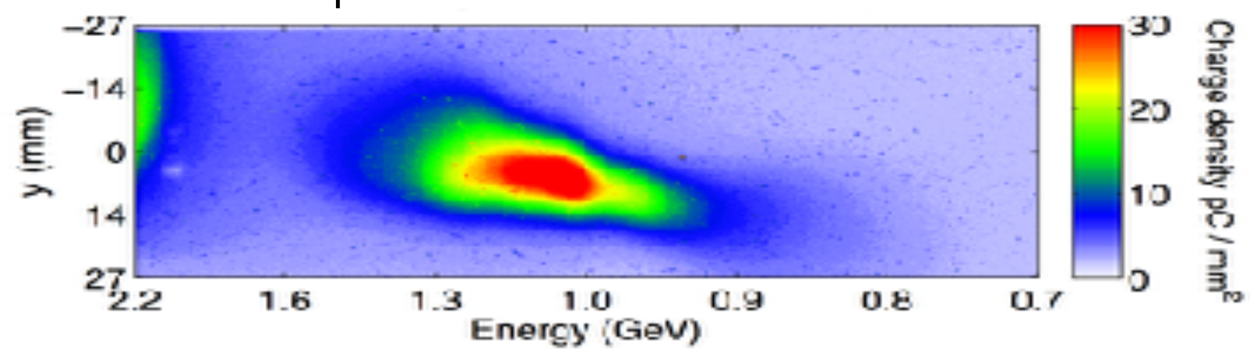
Experimental Data from Trojan Horse Injection Experiment

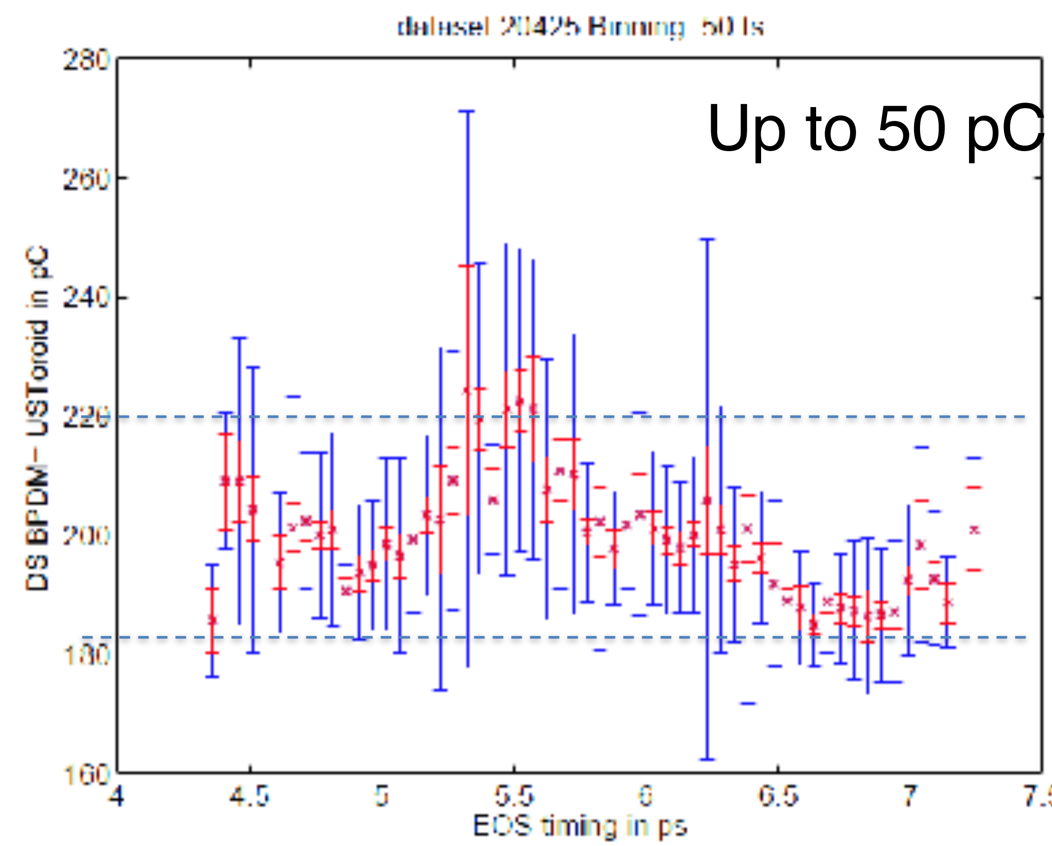
Laser Triggered Charge

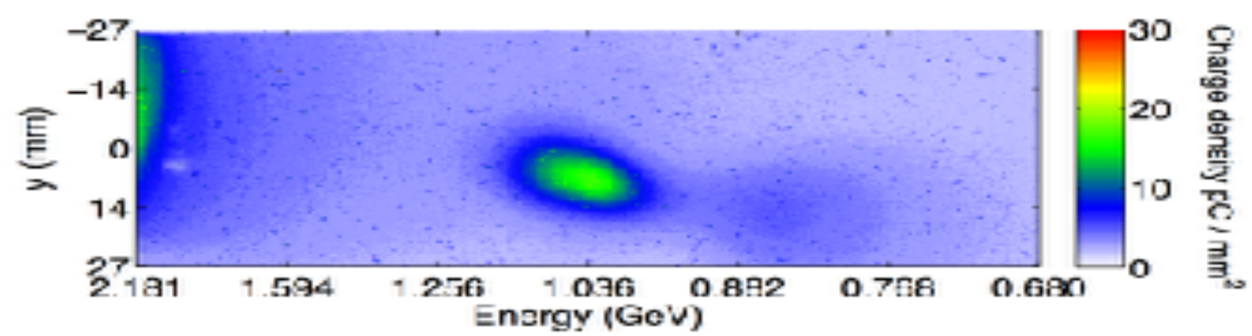




Up to 4 GeV measured



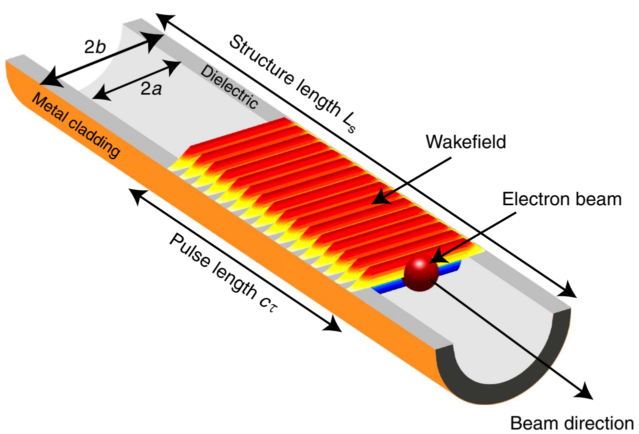


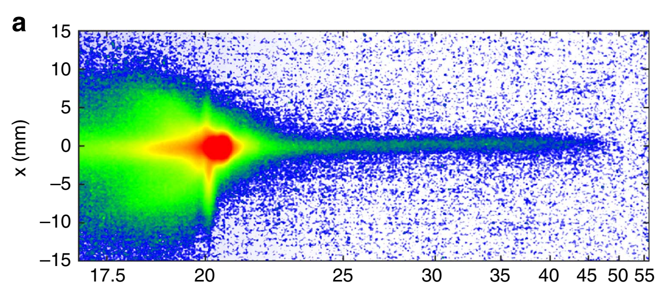


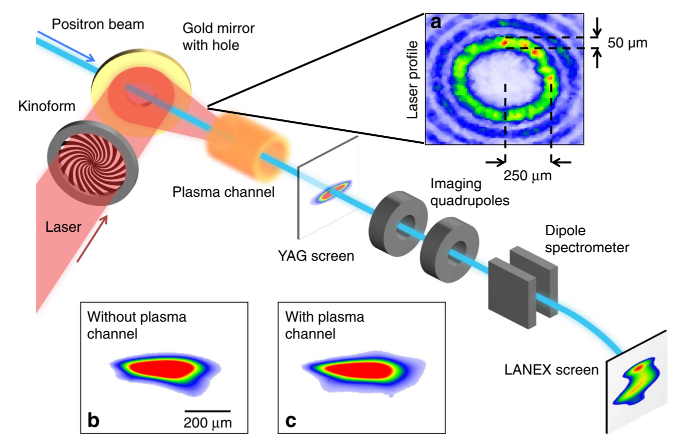
Latest High Impact Results from FACET

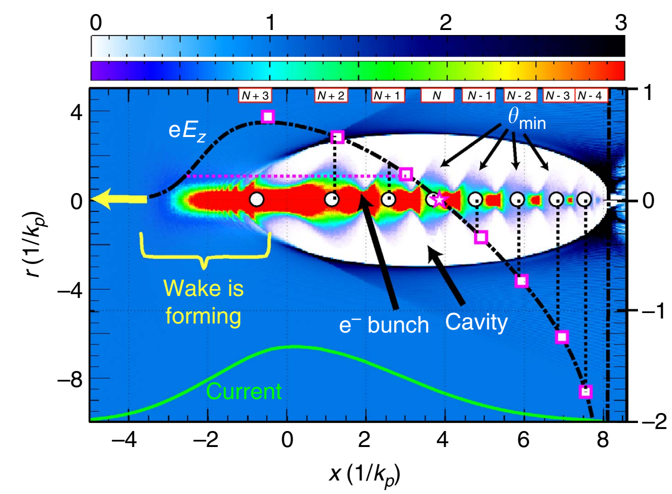
Four papers published in Nature Communications in 2016:

- S. Gessner et al. “Demonstration of a Positron Beam-Driven Hollow Channel PWFA” **7**, 11785 (2016)
- S. Corde et al. “27 GeV plasma acceleration in a high-ionization-potential gas” **7**, 11898 (2016)
- C.E. Clayton et al. “Self-Mapping the longitudinal field structure of a nonlinear PWFA cavity” **7**, 12483 (2016)
- B. O’Shea et al. “Observation of acceleration and deceleration in frontier gradient DWFA” **7**, 12763 (2016)









In process of submitting:

- A. Doche et al. “Acceleration of a trailing positron bunch in a PWFA” submitted to ***Nature Communications***
- B. O’Shea et al. “High-Field Induced Damping in DWFA” submitted to ***Nature Materials***
- A. Deng et al. “Laser-triggered injection in electron-beam driven PWFA” in preparation for ***Nature***

FACET-II is an Exciting Place for Young Researchers

High-impact science in a fast paced environment:

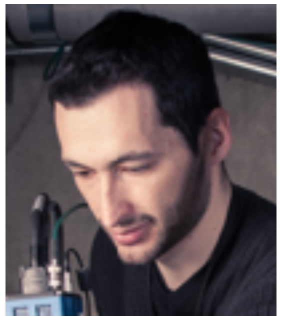
- National User Facility environment working closely with multiple collaborations of Faculty, Staff, Postdocs and PhD students from Universities, National Labs and different countries
- Typical PhD research includes theory, simulations and experimental effort

Track record with students & postdocs over the last two years:

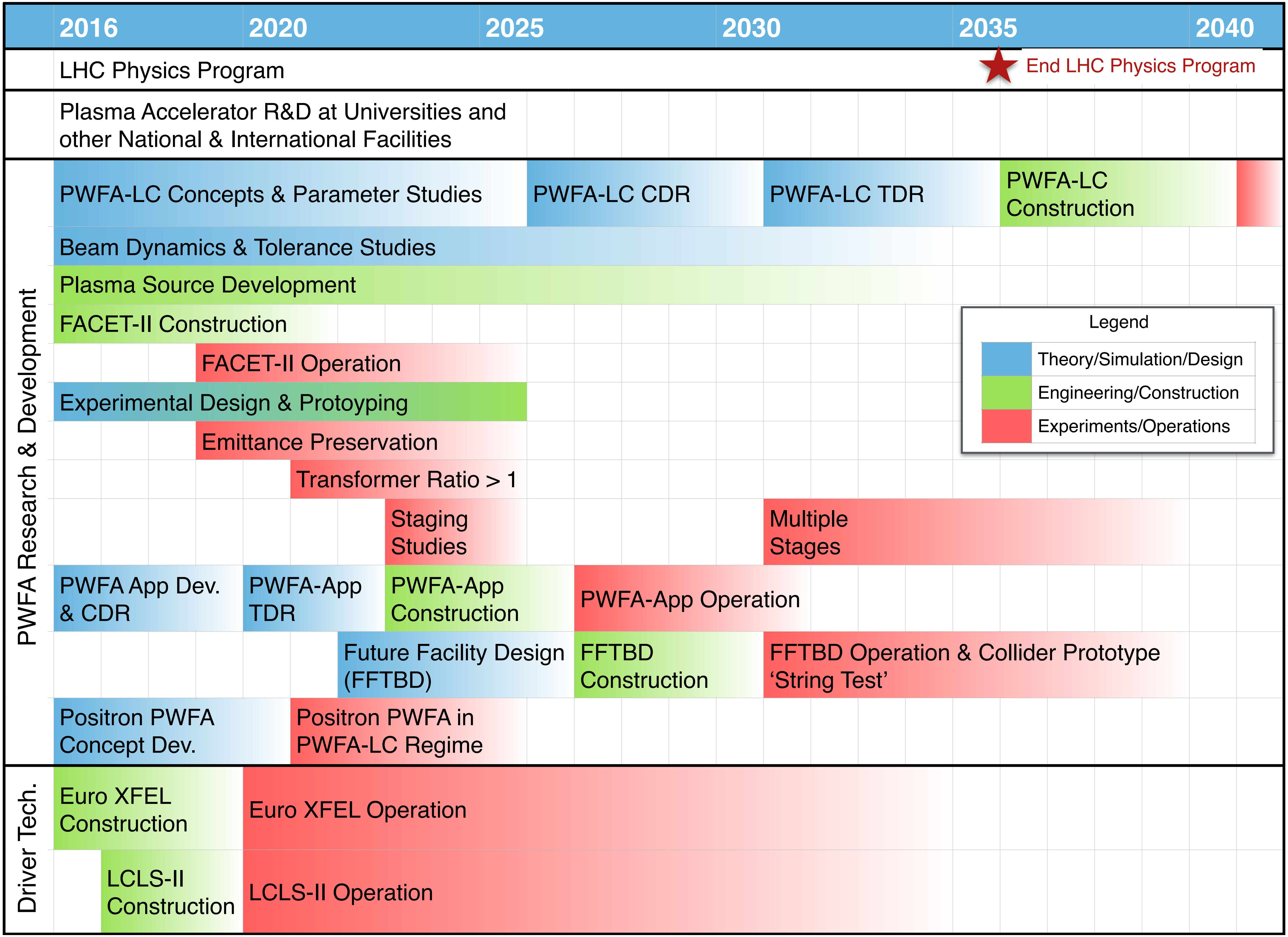
- Spencer Gessner (Stanford PhD 2016) → CERN Fellow with offers from DESY, U. Chicago, UCLA. **APS-DPB PhD Thesis Award**
- Joel Frederico (Stanford PhD 2016) → Hughes Research Laboratory
- Navid Vafaei-Najafabadi (UCLA PhD 2016) → **Professor** Stony Brook University
- Michael Litos (SLAC Postdoc 2016) → **Professor** University of Colorado Boulder
- Sebastien Corde (SLAC Postdoc 2015) → **Professor** Ecole Polytechnique
- Erik Adli (SLAC Postdoc 2015) → **Professor** University of Oslo
- Brendan O'Shea (UCLA PhD 2015) → SLAC Research Associate







Beam Driven Plasma Accelerator Roadmap for HEP



FACET-II Project Plan

Timeline:

- ✓ **Nov. 2013, FACET-II proposal, Comparative review**
- ✓ **CD-0 Sep. 2015**
- ✓ **CD-1 Oct. 2015 *(ESAAB, Dec.2015)***
- ✓ CD-2/3A Sep. 2016
- CD-3B Sep. 2017
- CD-4 2022

Experimental program (2019-2026)

Key R&D Goals:

- Beam quality preservation, high brightness beam generation, characterization
- e^+ acceleration in e^- driven wakes
- Staging challenges with witness injector
- Generation of high flux gamma radiation

Three stages:

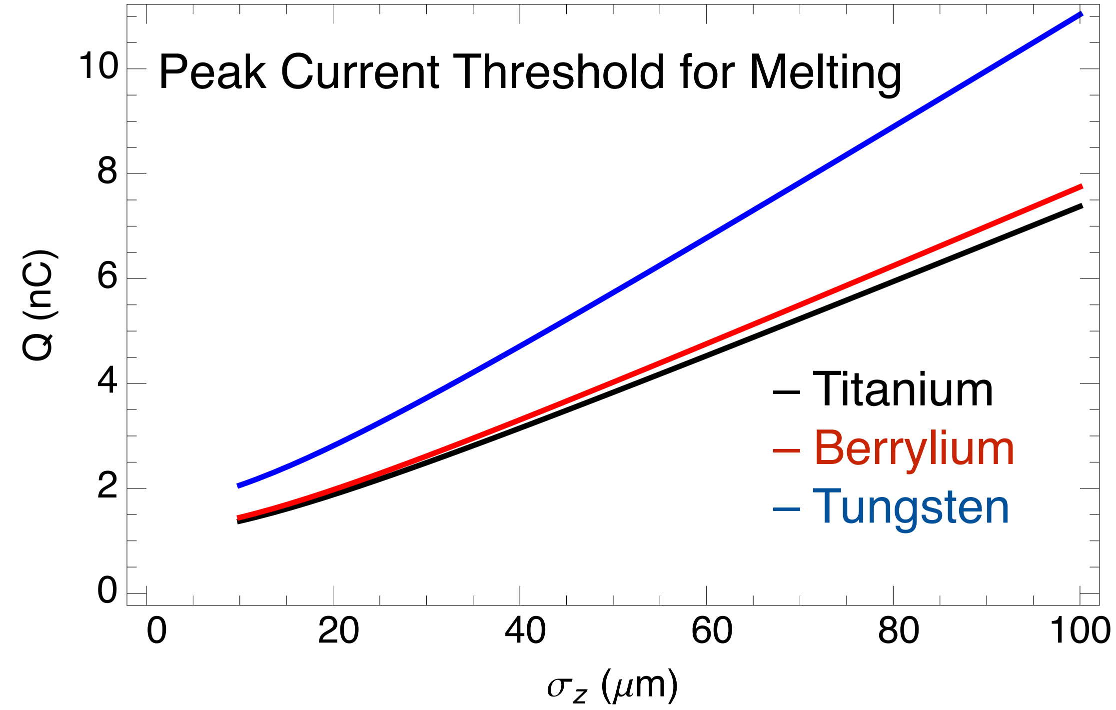
• Photoinjector	(e- beam only)	FY17-19
• e+ damping ring	(e+ or e- beams)	FY18-20
• "sailboat" chicane	(e+ and e- beams)	

FACET-II will operate as a National User Facility with an external program advisory committee reviewing proposals and recommending priorities for the experimental program

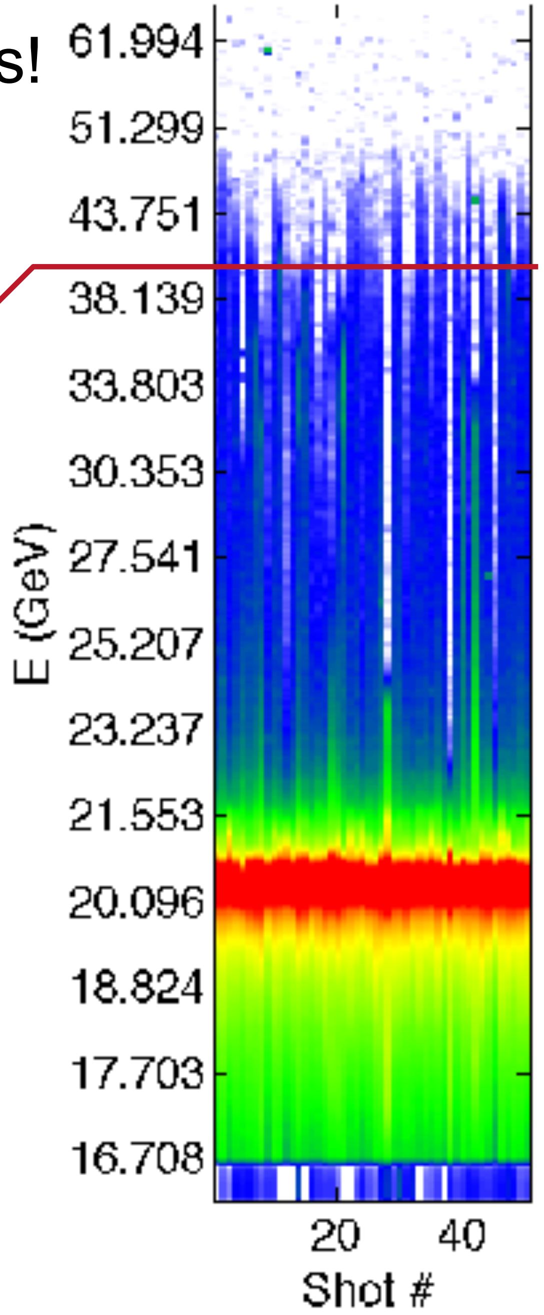
Extreme Beams: A Challenge *and* Opportunity!

- We know from experience – extreme beam densities developed at FACET and FACET-II turn materials into plasma physics experiments!
- Allows experiments to access new regimes

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



Energy doubling
>100GeV/m
in 10^{18} Ar gas

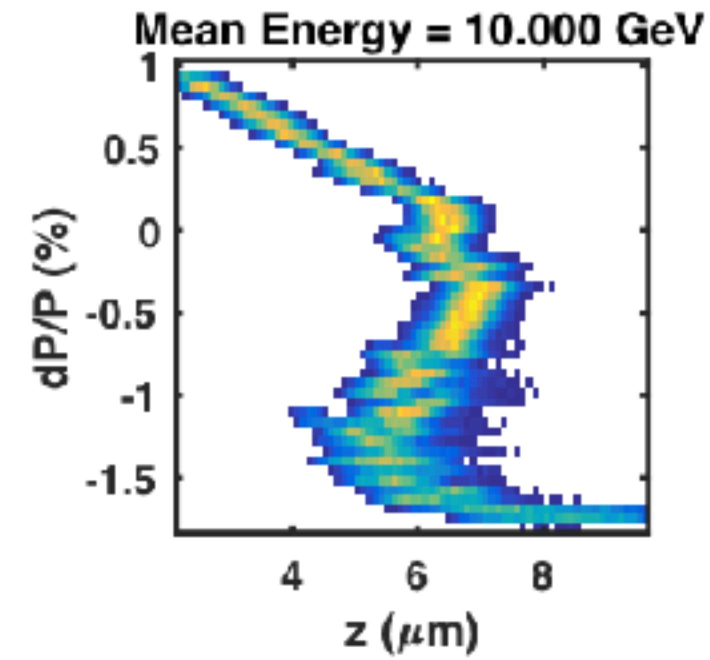


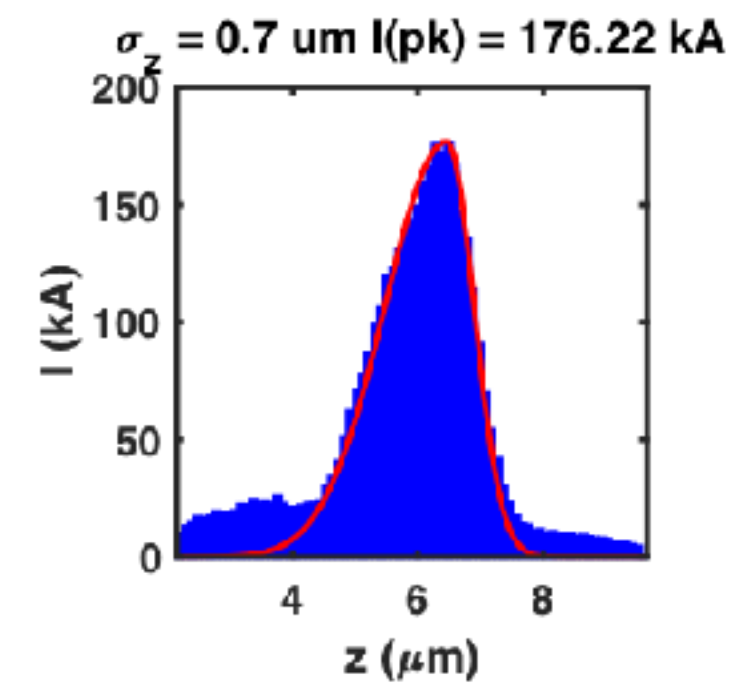
FACET-II will transition from 100 GeV/m to 1-100 TeV/m

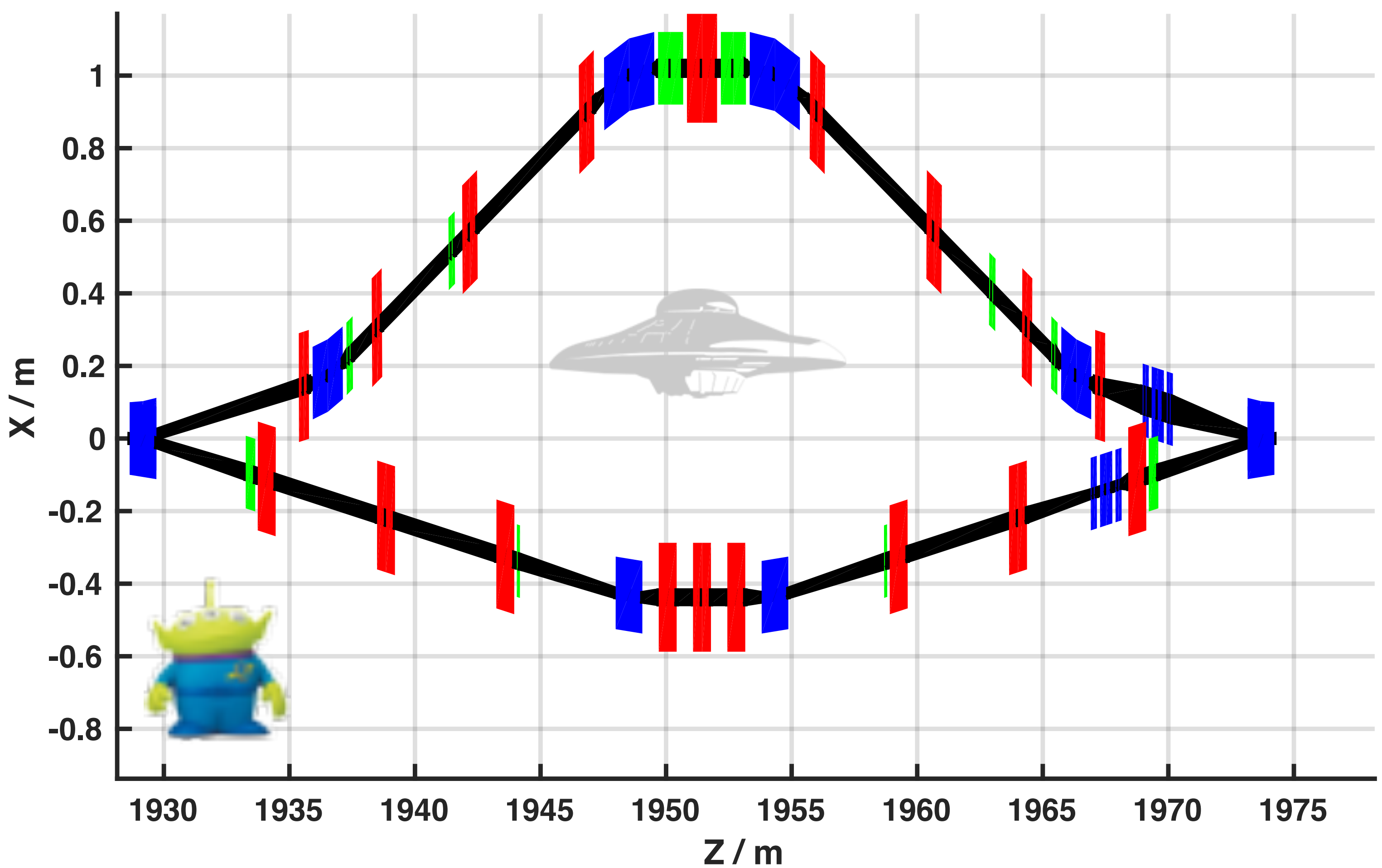
FACET-II Beam will Access New Regimes

Low-emittance (state of the art photoinjector) and ultra-short (improved compression) beam will generate:

- >175 kA peak current (~1 μm long)
- ~100 nm focus by plasma ion column
- **~10^{12} V/cm** radial electric field (Es=1.3x10^{16} V/cm)
- **~10^{23} cm^{-3}** beam density







Next Generation High Field Facilities

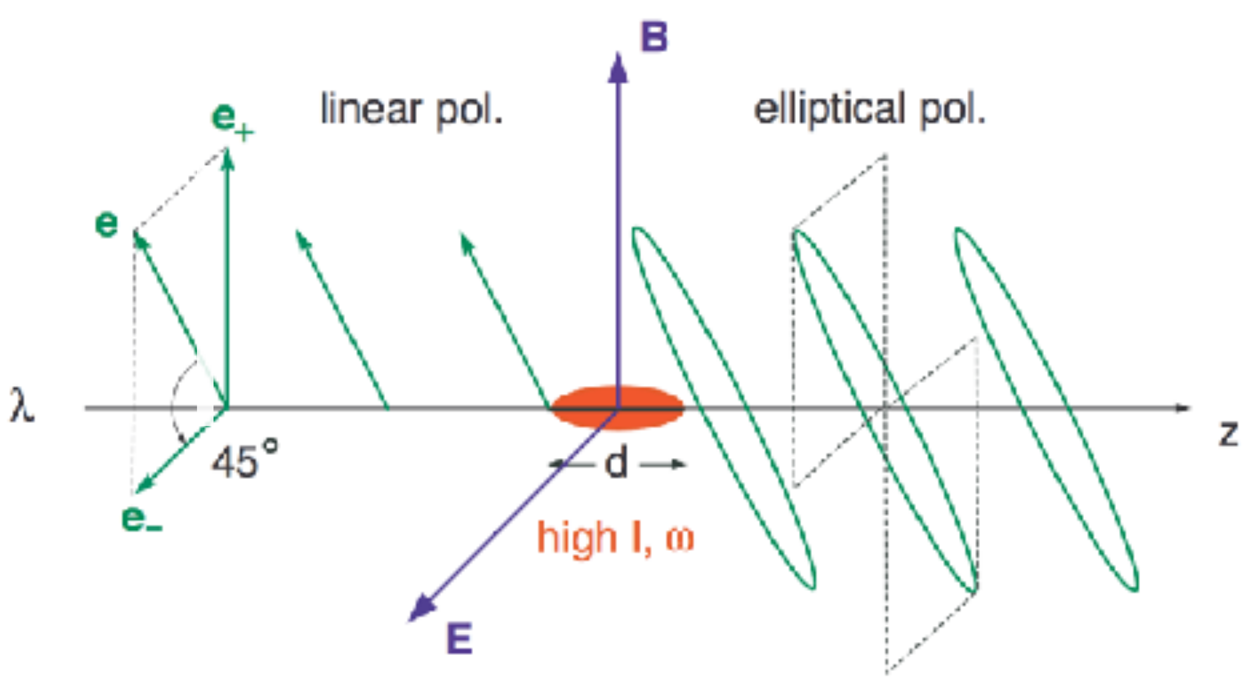
Some of the particular QED phenomena that will be studied at ELI are :

- Electron - positron plasmas
- Vacuum birefringence
- Vacuum four - wave mixing
- Vacuum polarisation
- Unruh radiation
- QED cascades : Inverse Compton Scattering
- Quark - gluon plasmas

$$I = 10^{22}\text{-}10^{23}\ W/cm^2 \rightarrow 10^{25}\ W/cm^2$$

$$E \gtrsim 3\cdot 10^{12}\text{-}10^{13} V/cm \rightarrow 10^{14} V/cm$$

Schematic experimental setup to measure vacuum birefringence via an ellipticity signal



Four Options to Study High Field QED at SLAC

SLAC

Option 1: ***LCLS X rays and 1GeV LWFA beam*** ⇨ χ ***~0.1*** ($\chi = E_p/E_s$)

Experiments at MEC; Can start now - all hardware ~ exist

Option 2: ***Laser field and 10GeV beam*** ⇨ χ ***~1-3***

~300TW laser focussed to $I \sim 10^{21}$ *W/cm*^{2} ($E \sim 3 \cdot 10^{12}$*V/cm*) and

Experiments at FACET-II or LCLS; can start in ~1-2 years

Option 3: ***10GeV FACET-II beam and 300MeV "witness injector"***

175kA FACET-II beam focused to 100nm ($E \sim 1.5 \cdot 10^{12}$*V/m*) ⇨ χ ***~0.1 in e-beam field***

Experiments at FACET-II; can start in ~3-5 years

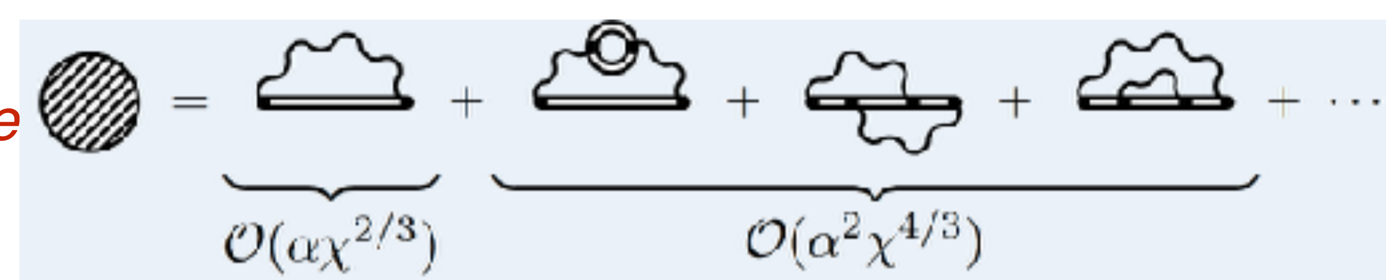
FACET·II
Facility for Advanced Accelerator Experimental Tests

Option 4: **100GeV collider e^-e^+** with $E_p \approx 10^{14}$ ***V/cm***, $\chi \approx 10^3$ **!**

Future facility ~20 year

N.B. Narozhny, Phys. Rev. D 21, 1176 (1980)

Full breakdown of perturbation theory
So far theoretical calculations are impossible



Option 4:

100GeV collider e⁻e⁺ (Future facility ~10-20 years)

SLAC

Beam field:

$\gamma \simeq 2\ 10^5$, $I_b = 10^6 A$, $\sigma_r = 10nm$, $\sigma_z = 0.3\mu m$

$$E_r = \frac{I_b/c}{2\pi\varepsilon_0\sigma_r} \simeq 10^{14}\, V/cm$$

$$\chi = \gamma\, E_r/E_s \simeq 1800$$

Field expansion parameter: N.B. Narozhny, *Phys. Rev. D 21, 1176 (1980)*

$$g = \alpha\,\chi^{2/3} \simeq 1$$

⇨ ***Perturbation theory does not work***
HEP in the presence of extreme field is unexplored

Beam disruption parameter

$$D = \frac{2r_e N_e \sigma_z}{\gamma\,\sigma_r^{\ 2}} \simeq 15$$

Beamstrahlung parameter R.J. Noble, Nucl. Instrum. *Methods Phys. Res. A 256 (1987) 427*

$$\Upsilon = \frac{5}{12}\frac{r_e^{\ 2} N_e \gamma}{\alpha\,\sigma_r\,\sigma_z} \simeq 10^3$$

Average energy loss in quantum regime $(\Upsilon > 100)$
P. Chen and V. Telnov, *Phys. Rev. Lett. 63, 1796 (1989)*

$$\delta = \frac{6}{5\sqrt{\pi}}\frac{\alpha\,\sigma_z}{\gamma\,\lambda\!\!\!^{-}_c} \simeq 3$$

Observables: beam energy spectrum, radiation spectrum, pair creation, ???