# Recent results at FACET

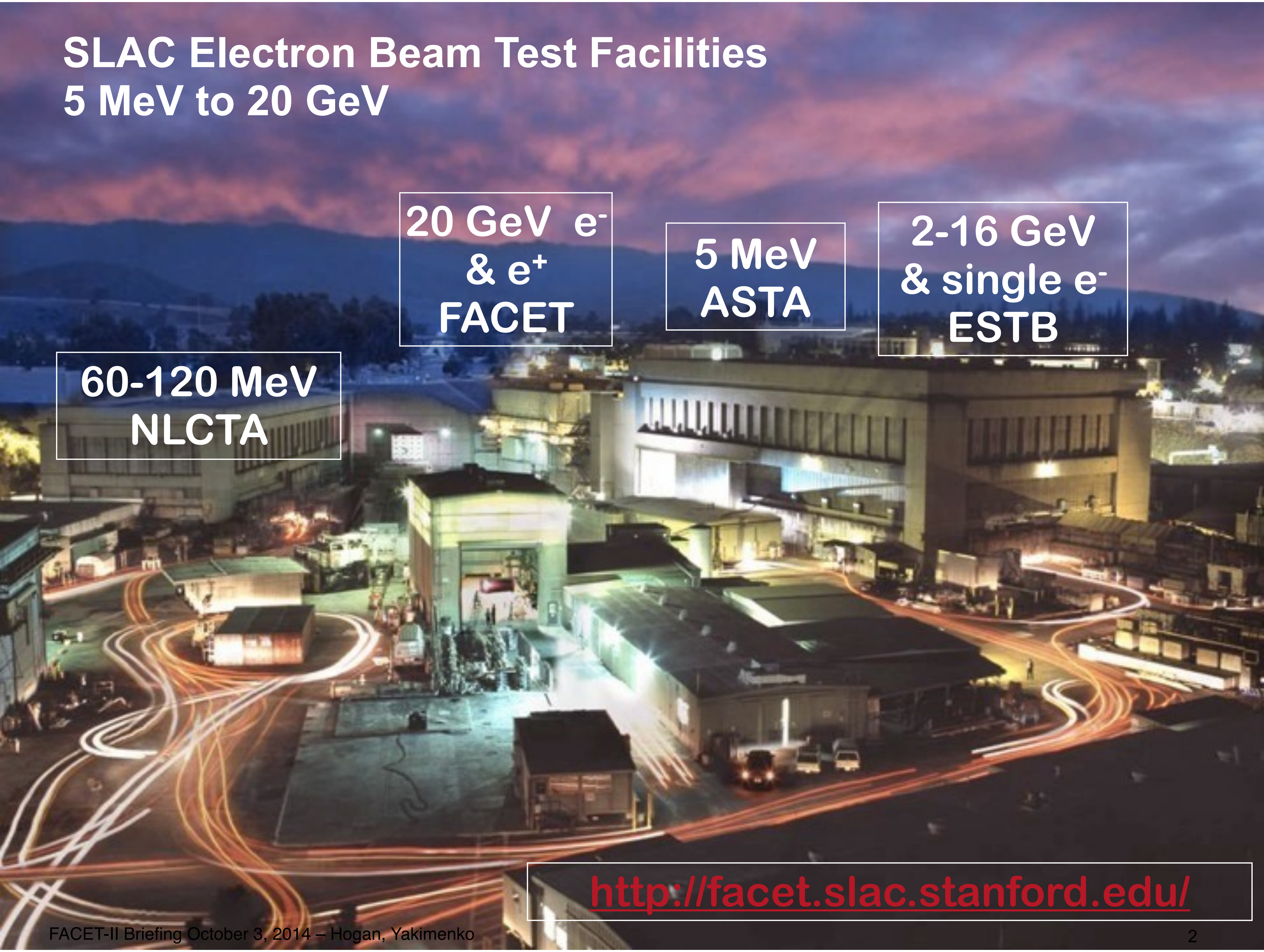
## CERN

Vitaly Yakimenko, November 27, 2014

U.S. DEPARTMENT OF ENERGY
Office of Science

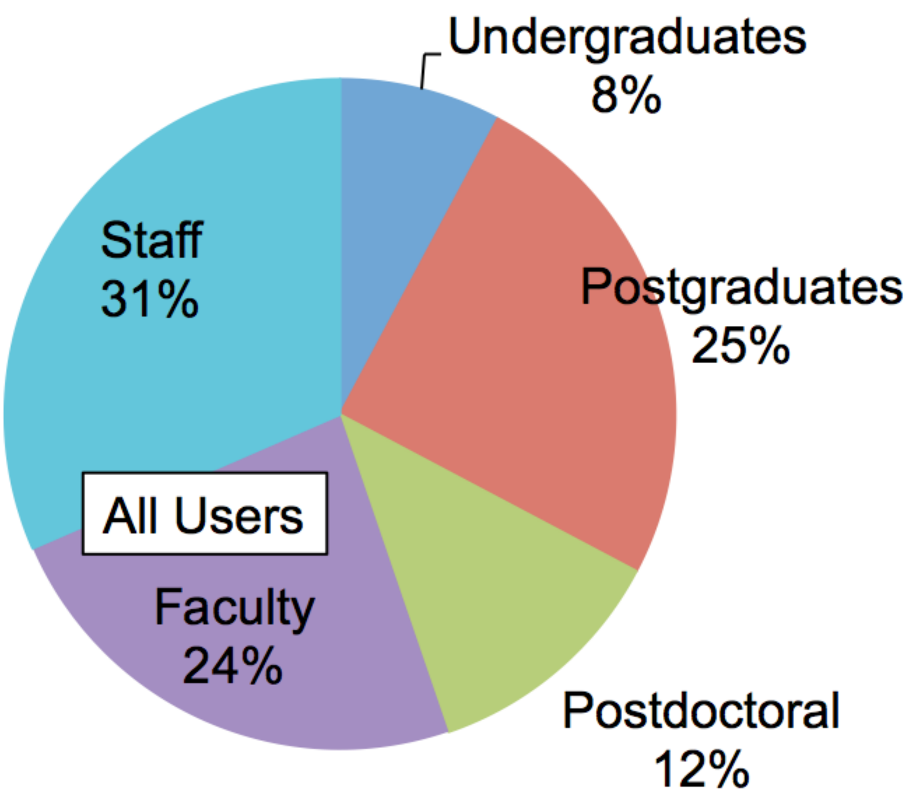
SLAC NATIONAL ACCELERATOR LABORATORY

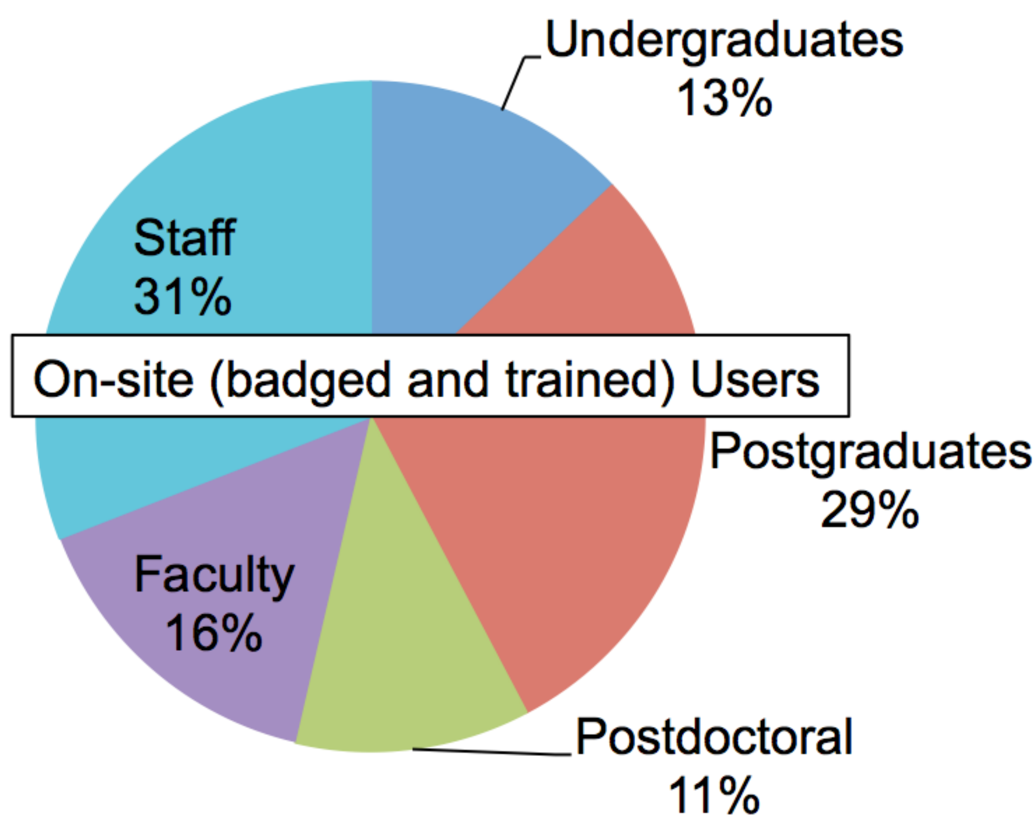
# SLAC Electron Beam Test Facilities
# 5 MeV to 20 GeV



# FY14 FACET and Test Beam Facilities Users

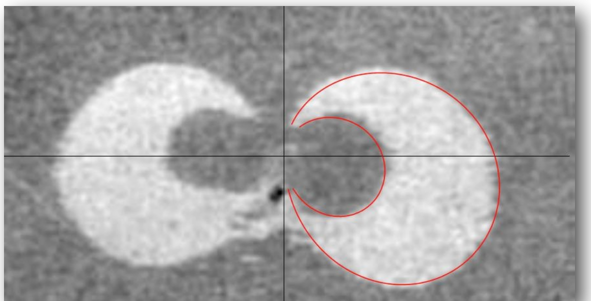
- 396 Scientists associated with 42 active (beam time in FY14) or planned experiments and beam tests at FACET, ESTB, NLCTA and ASTA
- ~60% (231) of these scientists working on the experiments are On-site Users (badged and trained for experimental work)



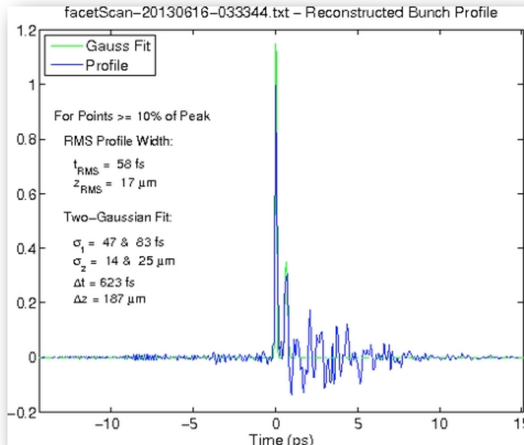



# FY13 FACET Run – Six Experiments

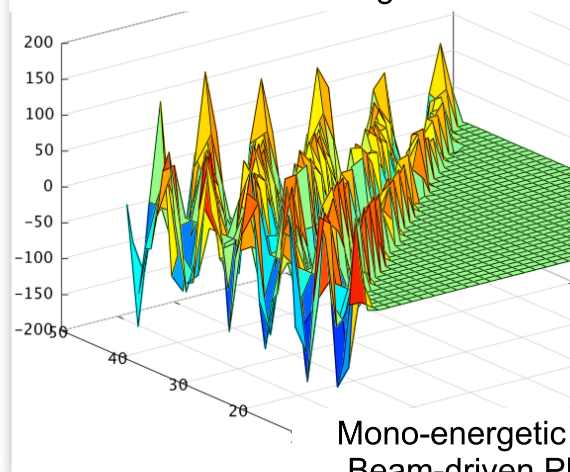
Switching Mechanisms in Ultrafast Electromagnetic Pulses



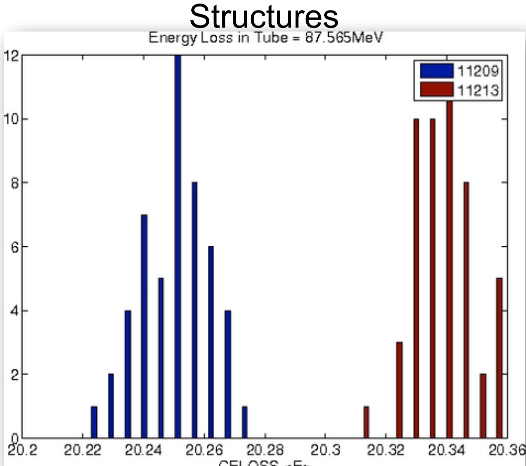
THz Reconstruction of Two-Bunch Profile

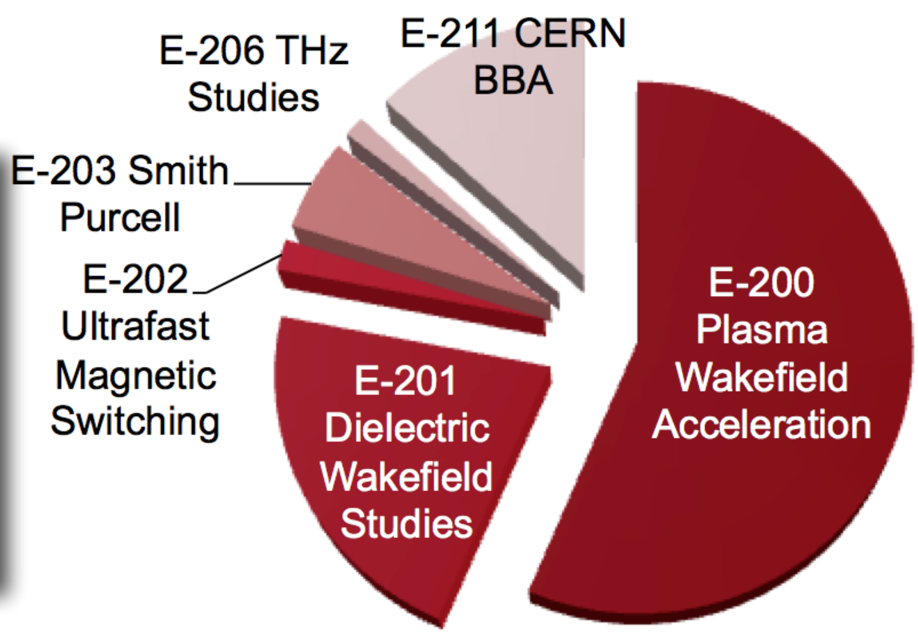



An Automated Method for Dispersion Free Steering

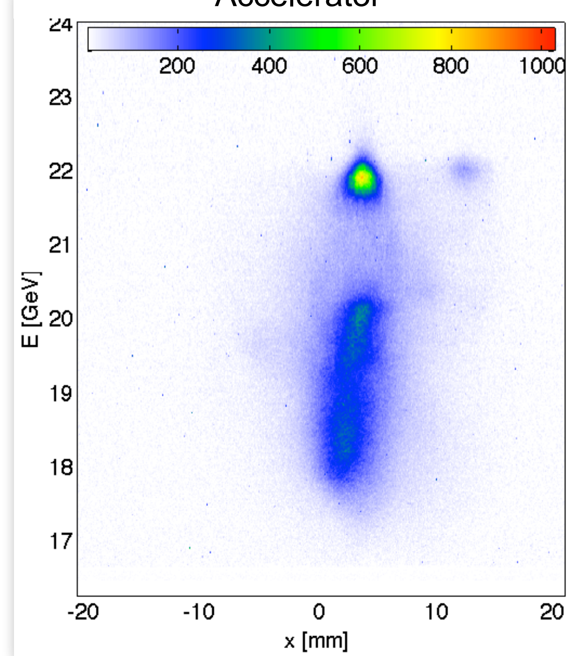


Demonstration of Gigavolt- per-meter Accelerating Gradients in Dielectric Wakefield Accelerating Structures




Mono-energetic Acceleration in a Beam-driven Plasma Wakefield Accelerator



# FY14 FACET Run – Fifteen Experiments

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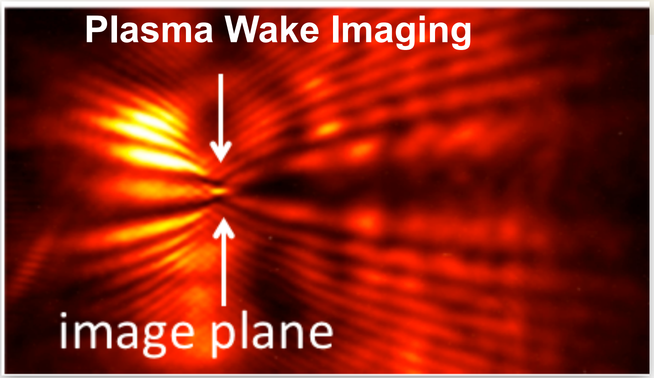
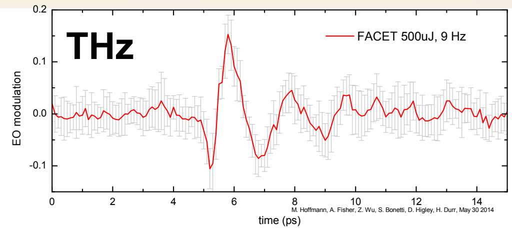
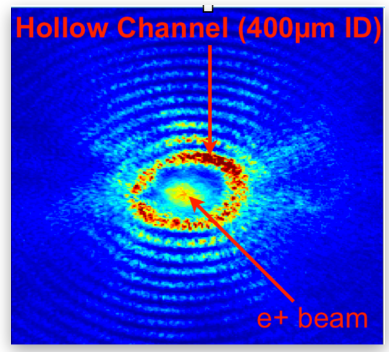
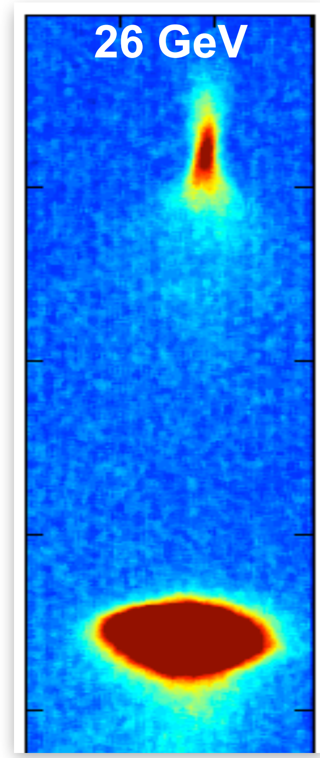
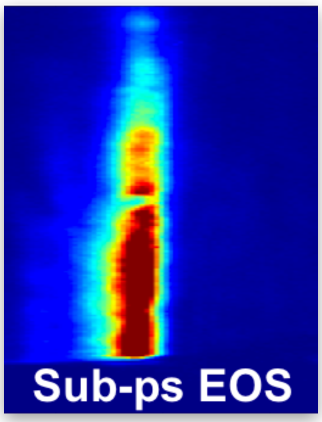
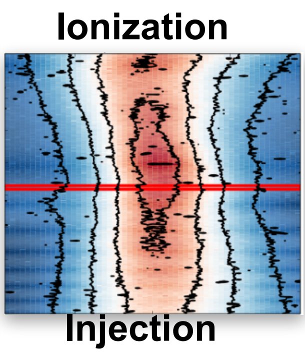


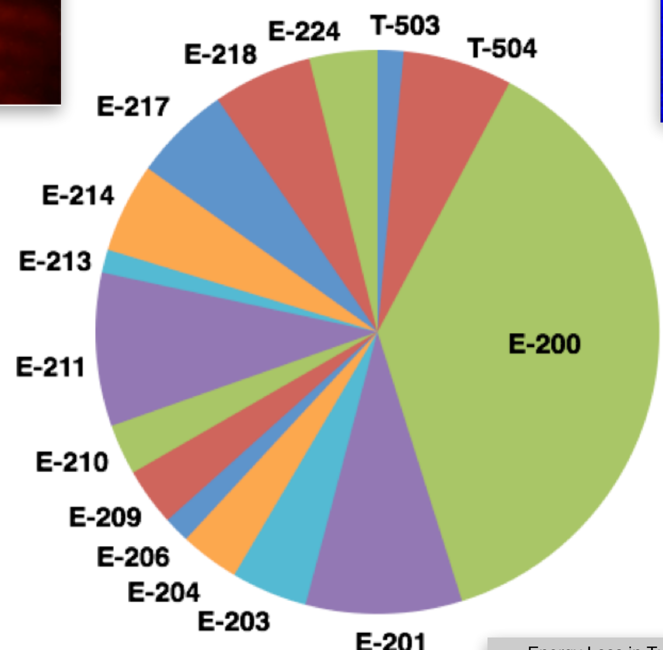



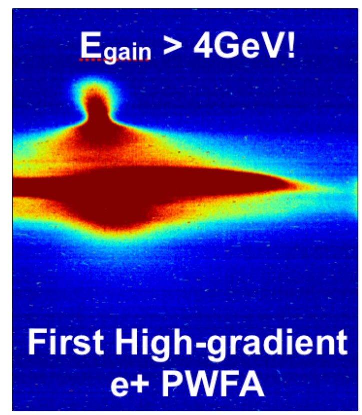



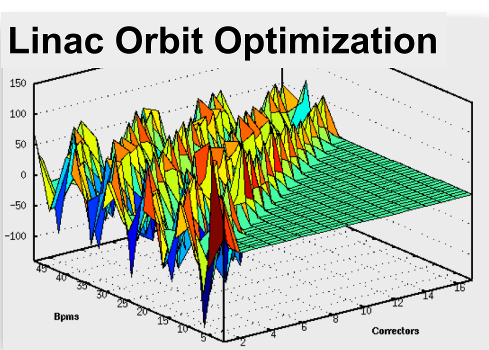



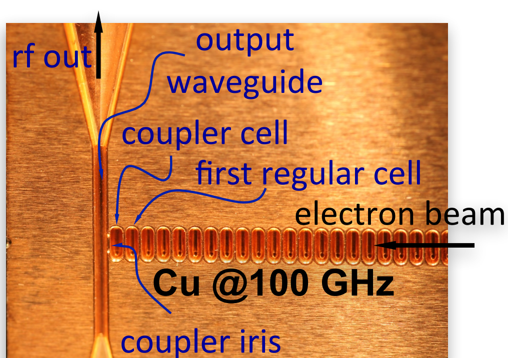



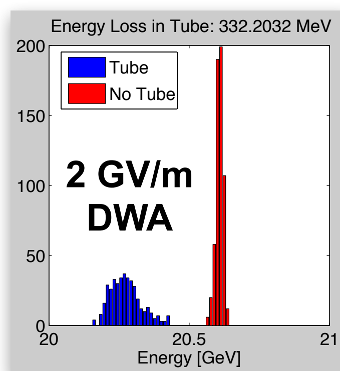



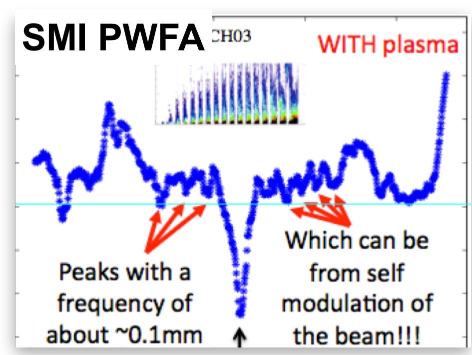



# FACET is a National User Facility


**Primary Goal**: Demonstrate a single-stage high-energy plasma accelerator for electrons.

- Meter scale ✓
- High gradient ✓
- Preserved emittance
- Low energy spread ✓
- High efficiency ✓

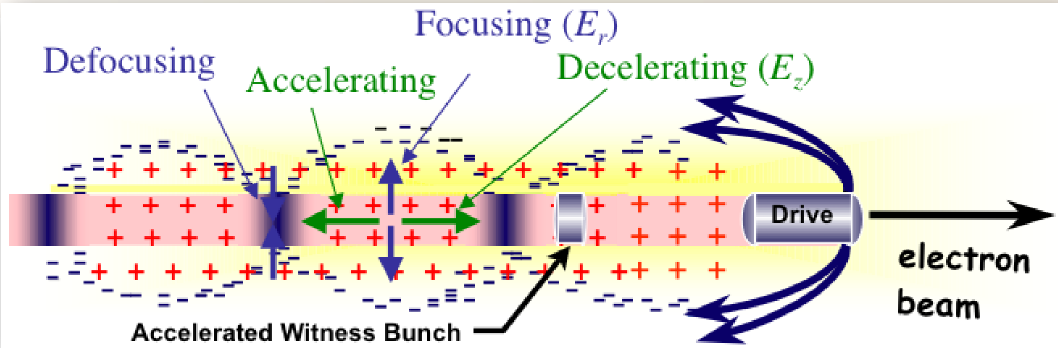
**Timeline:**

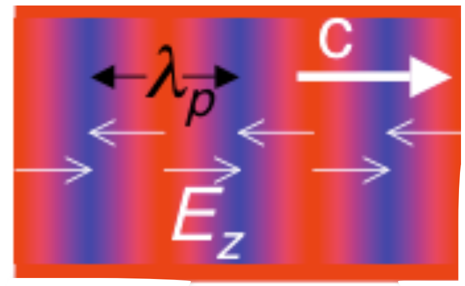
- Commissioning (2012) ✓
- Drive & witness $e^-$ bunch (2012-2013) ✓
- Optimization of $e^-$ acceleration (2013-2015)
- First high-gradient $e^+$ PWFA (2014-2016)

FACET user program is based on high-energy high-brightness beams and their interaction with plasmas and lasers

# Why Plasmas?





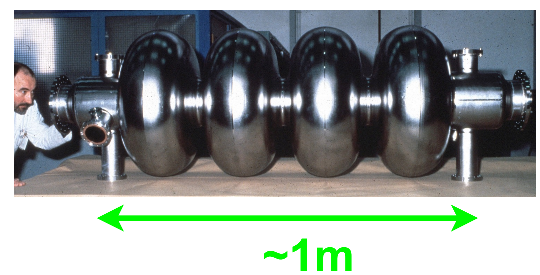

Large
Collective Response!

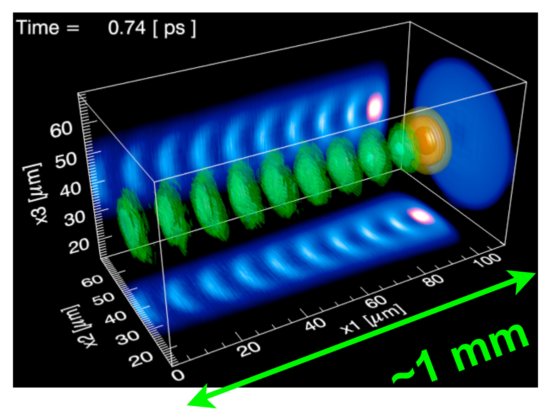
Relativistic plasma wave (electrostatic):

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \qquad k_p E_z = \frac{\omega_{pe}}{c} E_z = \frac{n_e e}{\varepsilon_0}$$

$$E_z = \left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2} \cong 100\sqrt{n_e(cm^{-3})} = \underline{1GV/m}$$

$n_e=10^{14}$ $cm^{-3}$




- Plasmas are already ionized, no break down
- Plasma wave can be driven by:
  - Intense laser pulse (LWFA)
  - Short particle bunch (PWFA)

# E200: Plasma Wakefield Acceleration

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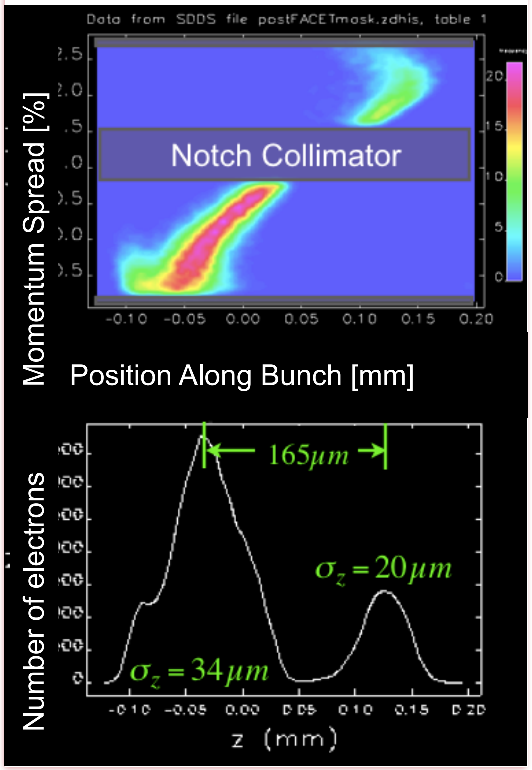
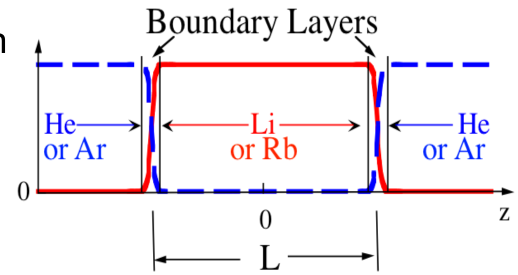
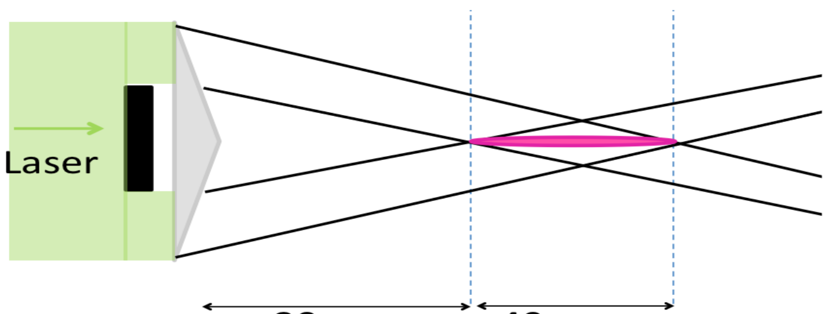
Simulation of Collimated Longitudinal Phase Space



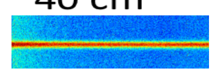

Heat Pipe Oven for uniform column of low ionization potential vapor




Line focus defines plasma channel aligned onto e⁻ beam orbit

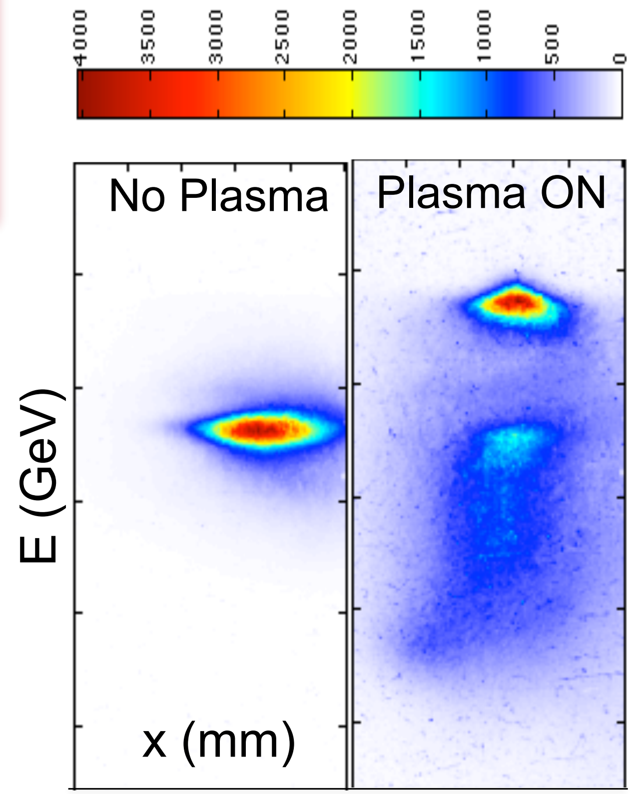



Side View of Plasma Column:



**2013**

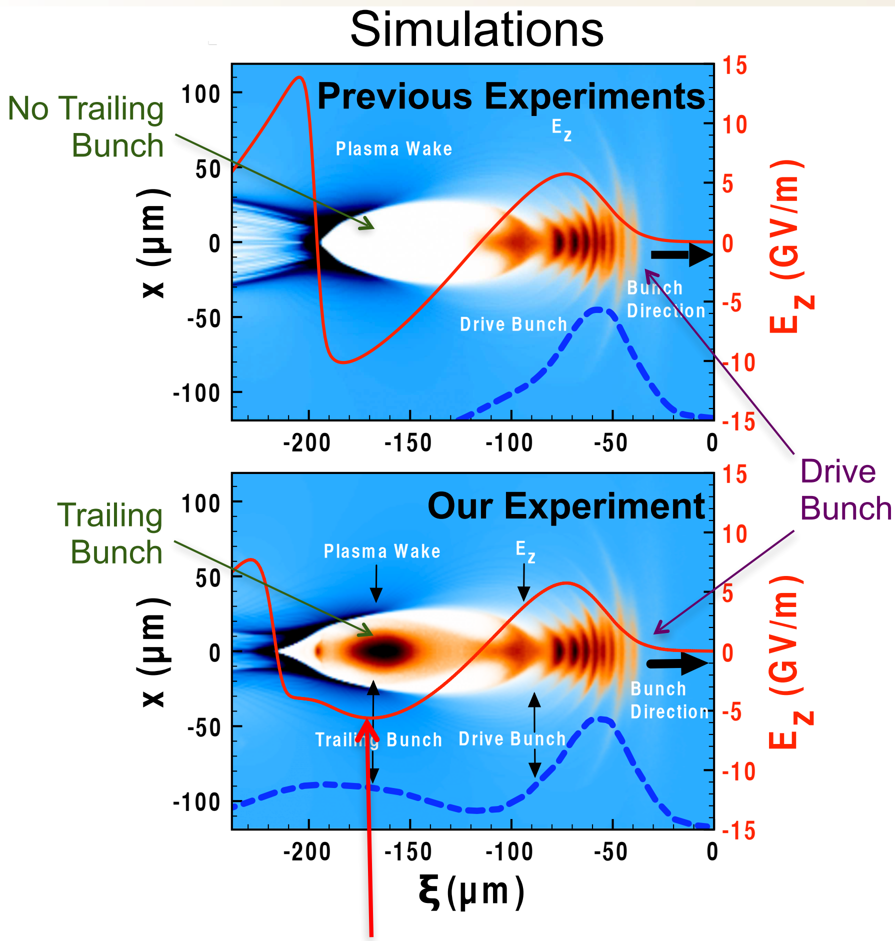
electron density ($e^- mm^{-2}$)



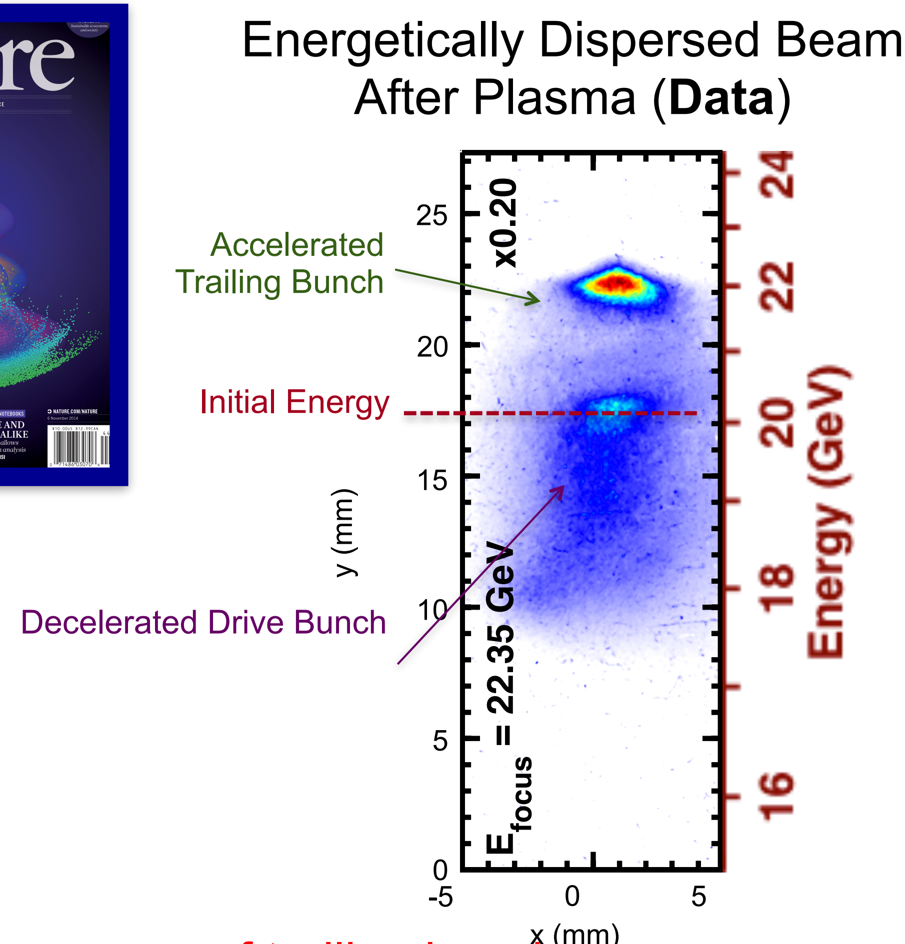

**2 GeV Energy Gain**
**~2% dE/E**

Up to 50% energy transfer from drive to witness was measured

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







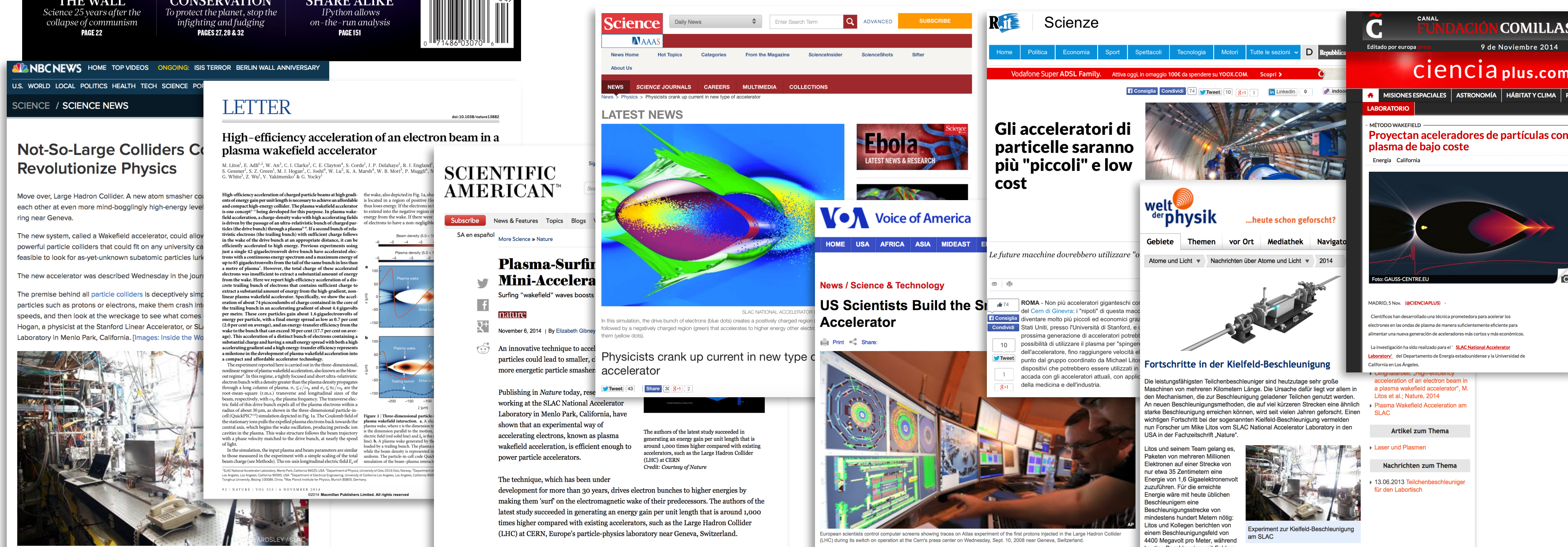

- Electric field in plasma wake is loaded by presence of trailing bunch
- Allows efficient energy extraction from the plasma wake

This result is important for High Energy Physics applications that require very efficient high-gradient acceleration

# Great result: 5 years in making

UCLA SLAC

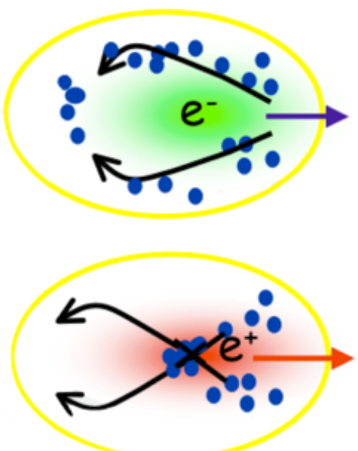

- One high profile result a year
- Priorities balanced between focused plasma wakefield acceleration research and diverse user programs with ultra-high fields

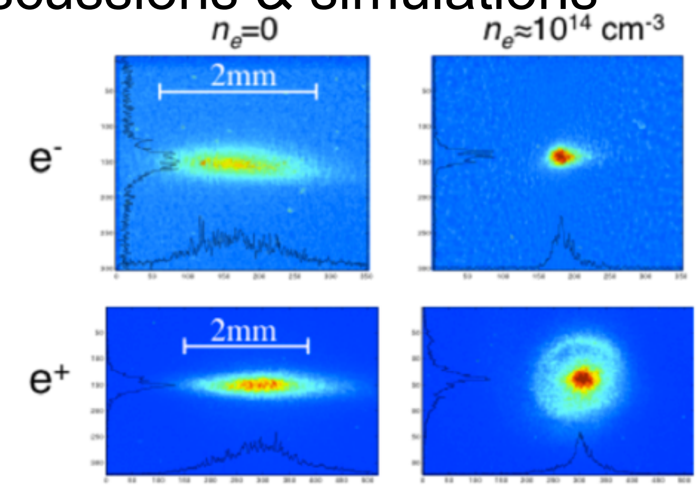


# First Experiments with GeV/m Positron PWFA

UCLA SLAC

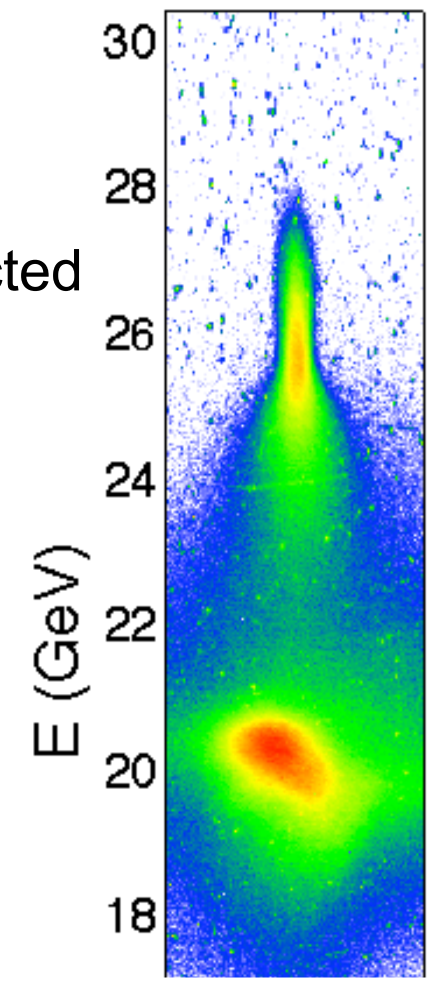
- Early experiments followed rapid commissioning of positrons
- Unanticipated features in the data
  - Beam Quality: Divergence of accelerated positrons similar to electrons, emittance growth less than expected
- Source of active discussions & simulations




*Phys. Rev. Lett.* **90**, 205002 (2003)    *Phys. Rev. Lett.* **101**, 055001 (2008)

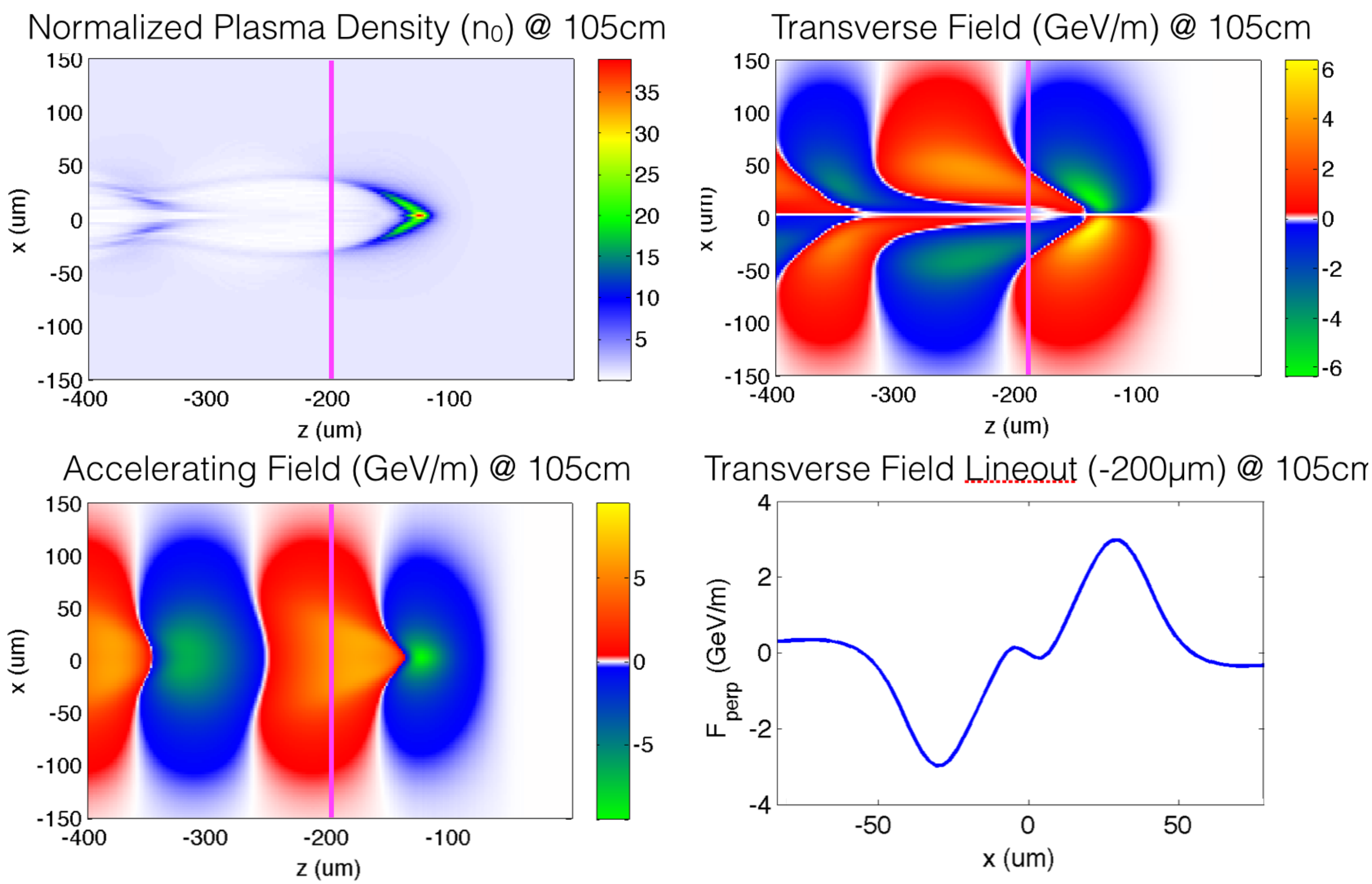
*Log Color Scale*




**FACET has the only program in the world studying plasma acceleration of positrons**

# Simulations Providing Insight into Positron Driven Wakes

New regime: focusing and accelerating region for positrons in the wake of a positron beam

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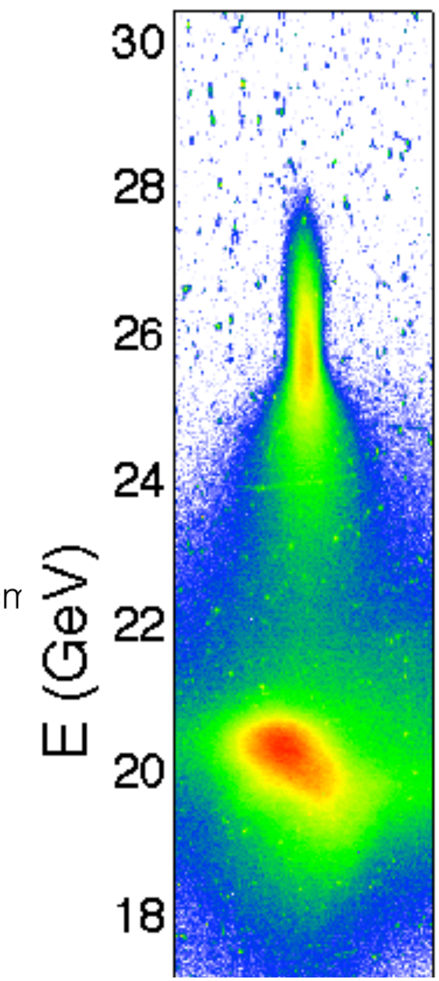


**This study is important for plasma afterburner as an energy doubler**

# Plasma Wake Driven by a Short and Intense Positron Bunch

UCLA SLAC

Science AAAS

Submitted Manuscript: Confidential

**Title: High-field positron acceleration in a plasma wake driven by a charged-particle bunch**

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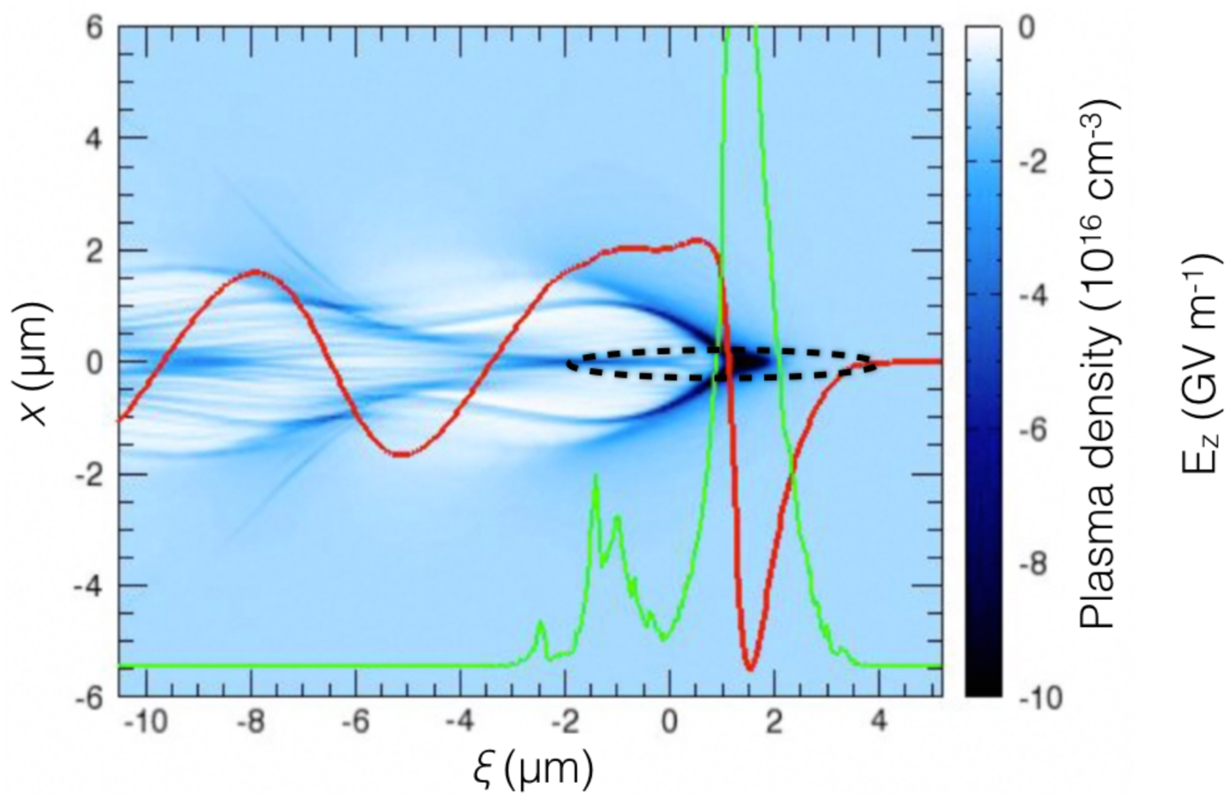
**Abstract:** New accelerator concepts must be developed to make future particle colliders more compact and affordable. The Plasma Wakefield Accelerator is one such concept, where the electric field of a plasma wake excited by a charged-particle bunch is used to accelerate particles. To apply plasma acceleration to particle colliders, it is imperative that both the electron and its antimatter counterpart, the positron, can be accelerated at high field in the plasma. Here we show that, as positrons in the front of a bunch transfer their energy to those in the rear of the same bunch by exciting a wake in the plasma, about a billion positrons gain four gigaelectronvolts of energy in a 1.2-meter distance. They extract 30% of the wake's energy and form a spectrally distinct bunch with a 3.8% r.m.s. energy spread.

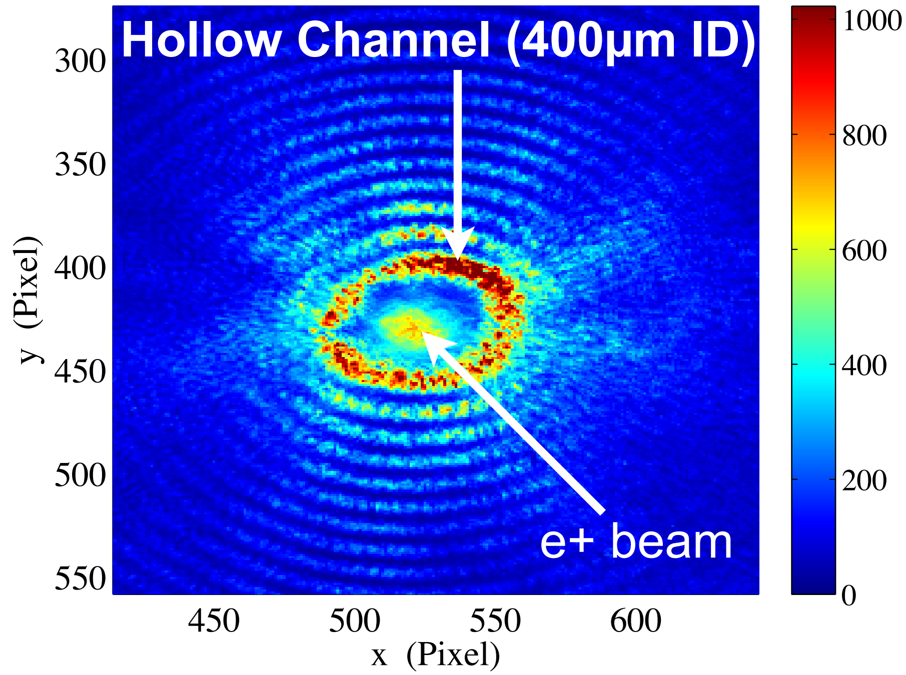
**Main Text:** Future high-energy particle colliders operating at the energy frontier of particle physics will be in the range of several trillion electronvolts (*1*). The currently proposed machines based on the existing radio-frequency technology, such as the International Linear Collider (ILC) and the Compact Linear Collider (CLIC) (*2, 3*), are very expensive and tens of kilometers long. Looking beyond these machines, novel methods for building compact and efficient particle colliders, such as the muon collider (*4*), the laser-plasma accelerator (*5*) and the plasma wakefield accelerator (PWFA) (*6*), are under development. Of these, the PWFA has recently demonstrated high-efficiency acceleration of a bunch of electrons at a high gradient of energy gain per unit length (*7*). In this experiment, a high-current and ultra-relativistic bunch of electrons was used to drive a space-charge disturbance—or wake—in a column of ionized gas



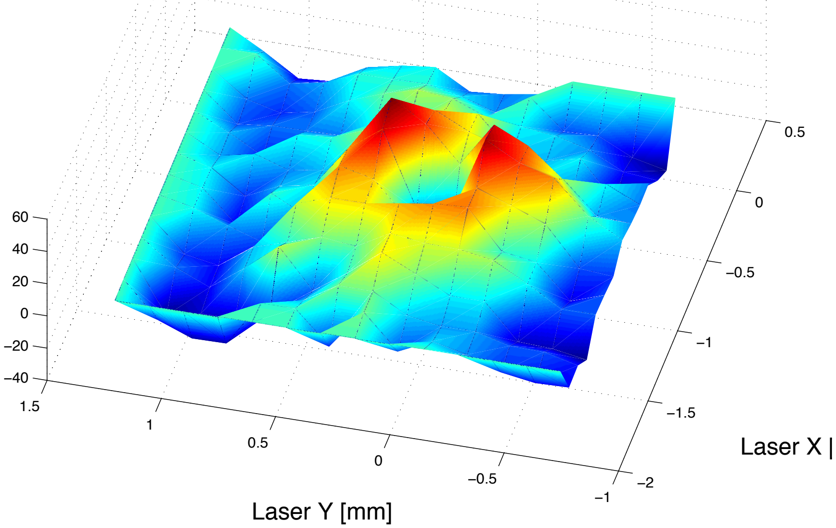

Manuscript is in an advanced state – expect to confirm results this FACET run

# Positrons and Hollow Channel Plasmas

Hollow channel plasmas are considered a viable method for accelerating positrons in electron driven wake




## e+ Beam Displacement vs. Laser Alignment




- Several orders of magnitude difference between BBU theory and preliminary experimental data
- Need to improve theory, compare with simulations and experiments

**This study is important for e- driven collider stage**

# PWFA Program Plan as Shown December 2012

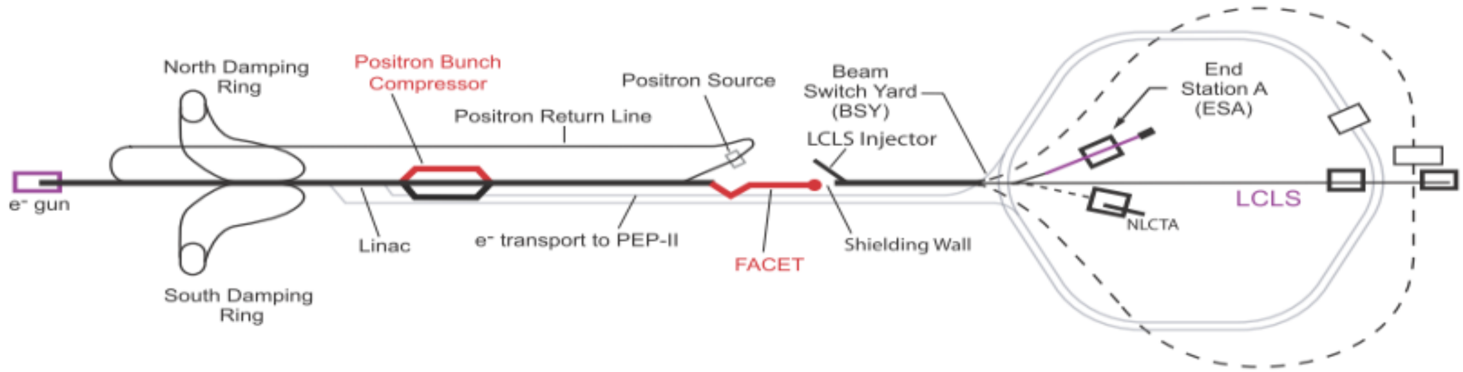
SLAC

| FY | Facet Run | LCLS off | PWFA goal |
|---|---|---|---|
| 2013 | 2/1 - 6/30 | 8/6 - 9/30 | 2 beam generation, laser commissioning, **2 beams with laser**-> mono energetic acceleration **(all successful and more…)** |
| 2014 | 10/15-12/20<br>2/1 - 6/30 | 8/1 - 9/30 | 2 beams with laser-> **mono energetic acceleration**, positron commissioning, positron PWFA, high brightness PWFA injector **(all successful & positrons!)** |
| 2015 | 10/15-12/20<br>2/1 - 6/30 | 8/1 - 9/30 | **positron PWFA**, one stage, efficiency, high brightness PWFA injector |
| 2016 | 10/1-5/31 | 6/1<br>S0-10<br>D&D | Finalizing the program, **single stage demonstration** (energy spread, emittance, efficiency) |

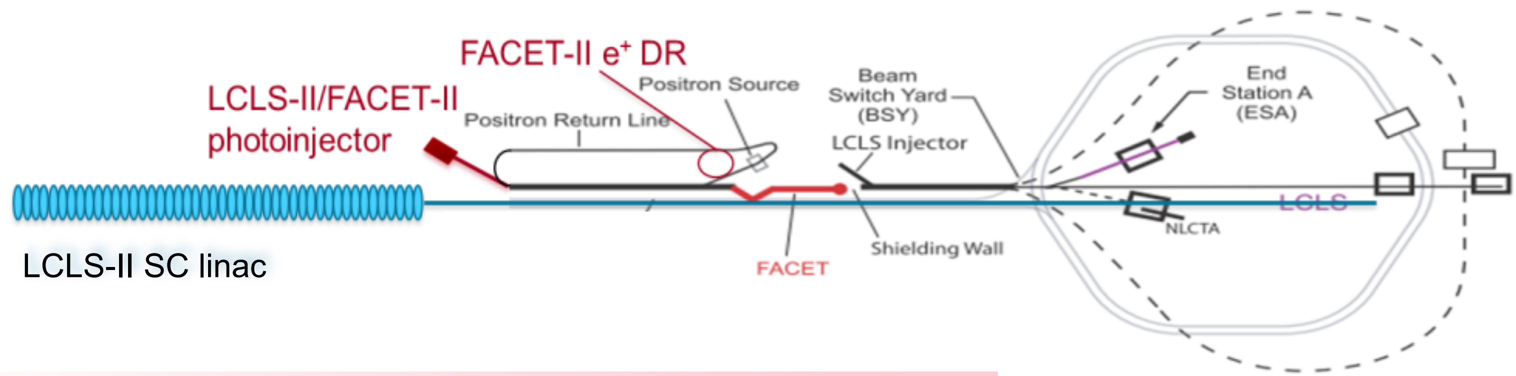
**Steady, methodical progress according to our plan**

# From FACET to FACET-II

FACET today




FACET-II




Three main stages:

- electron beam photoinjector (e⁻ beam only)
- positron damping ring (e⁺ or e⁻ beams)
- “sailboat” chicane (e⁺ and e⁻ beams)

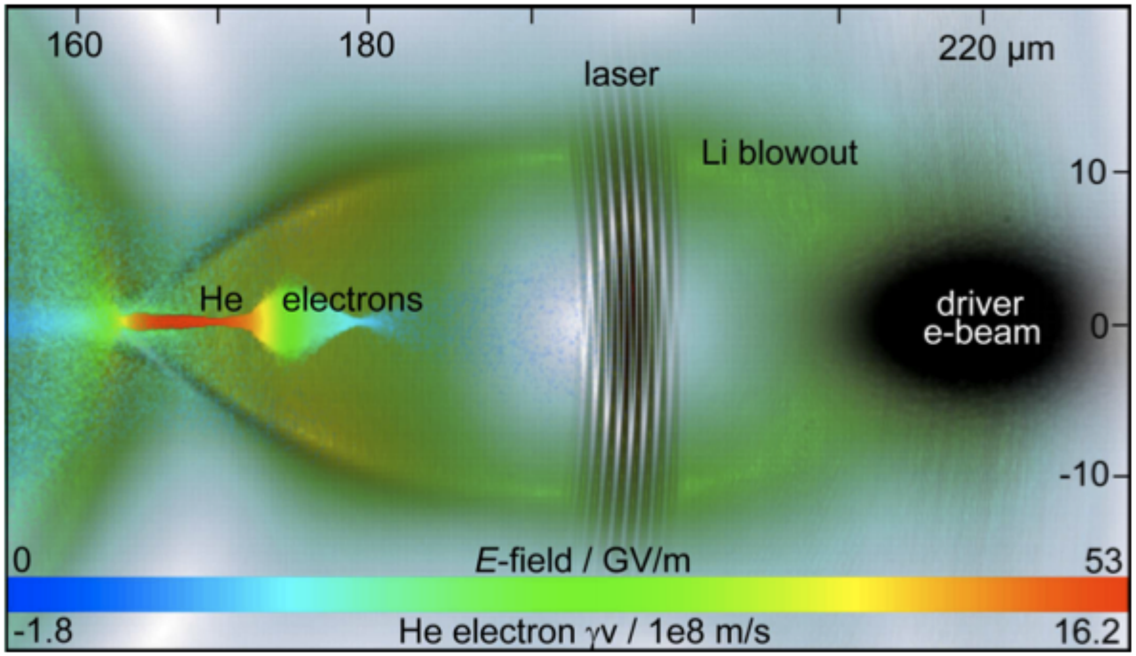
# PWFA Goals for FACET-II

| FY | FACET-II | PWFA Goals |
|---|---|---|
| 2017 | Construction (Phase 1) | Finalize FACET data analysis, prepare FACET-II experiments |
| 2018-19 | Phase 1 ($e^-$ only) | **Staging studies** with witness injector (synchronization, alignment), high transformer ratio (with shaped bunches) |
| 2020-21 | Phase 2 ($e^-$ or $e^+$) | $e^-$ or $e^+$ acceleration in $e^+$ wakes (physics of p driven PWFA), **high-brightness beam** generation, preservation, characterization |
| 2022-23 | Phase 3 ($e^-$ and $e^+$) | **$e^+$ acceleration** in $e^-$ driven wakes, demonstration of $e^+$ acceleration stage |
| 2024-25 | | Witness bunch acceleration in **two PWFA stages** (independently driven) |

# Creating Ultra High-Brightness Beams with PWFA

- Plasma bubble (wake) can act as a high-frequency, high-field, high-brightness electron source
- Photoinjector + 100GeV/m fields in the plasma =
  - Unprecedented emittance (down to $10^{-8}$ m rad)
  - Sub-µm spot size
  - fs pulses

'Trojan Horse Technique'

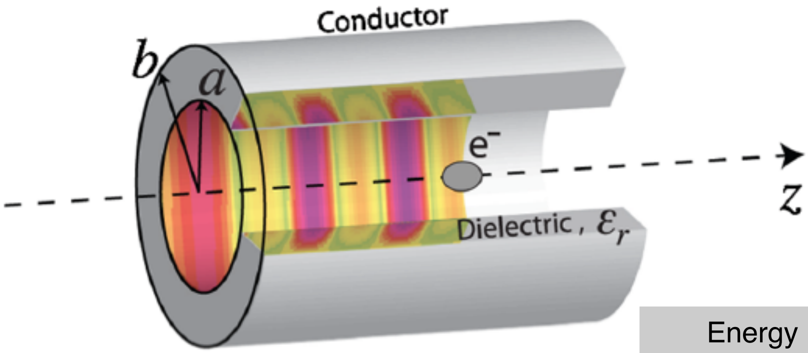



Leverages efficiency and rep rate of conventional accelerators to produce beams with unprecedented brightness for collider & XFEL applications

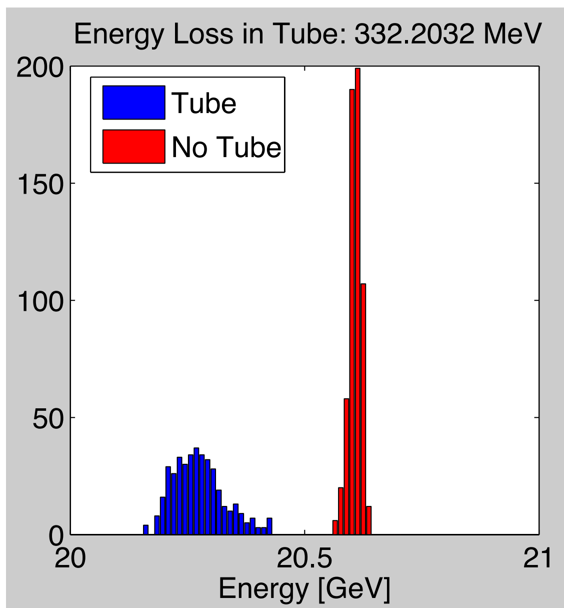
# Testing Dielectric Structures at and Above Breakdown Voltage

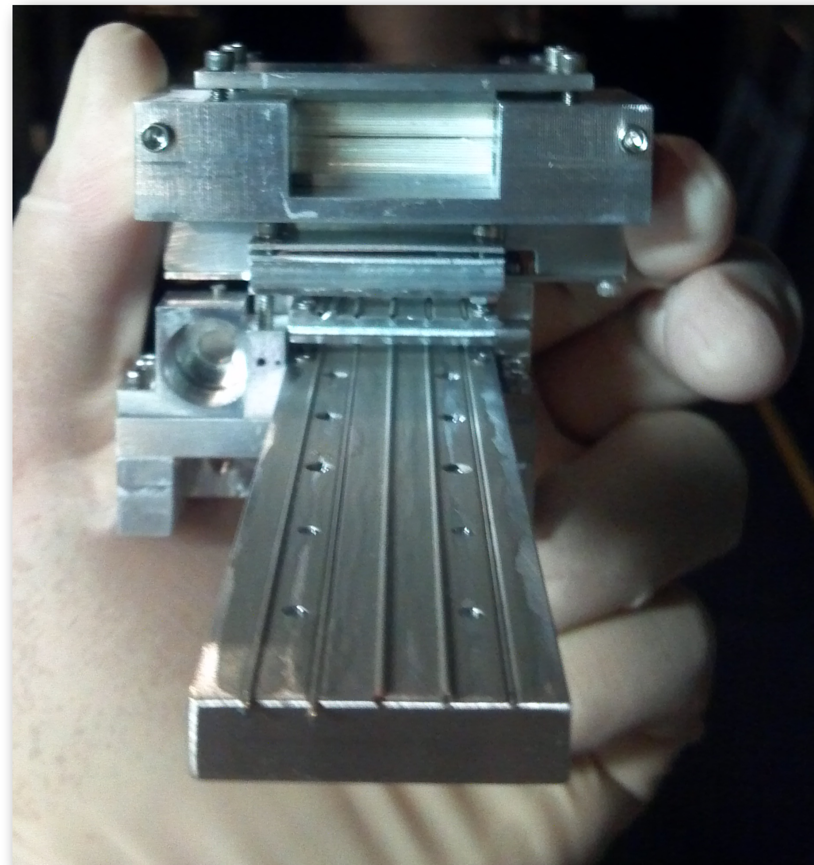
UCLA, Euclid Techlabs, Tech-X, Radiabeam Technologies, NRL, SLAC, MPI, Argonne

- High-energy beam allows access to narrow structures and high gradients




- 15cm quartz tube
- 300μm diameter
- 2 GV/m fields from Energy loss
- Next step - two bunch acceleration!



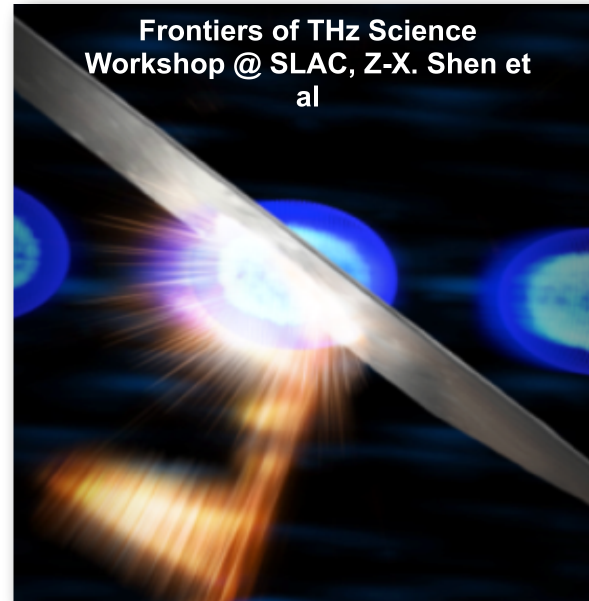



Demonstration of Gigavolt- per-meter Accelerating Gradients in Dielectric Wakefield Accelerating Structures

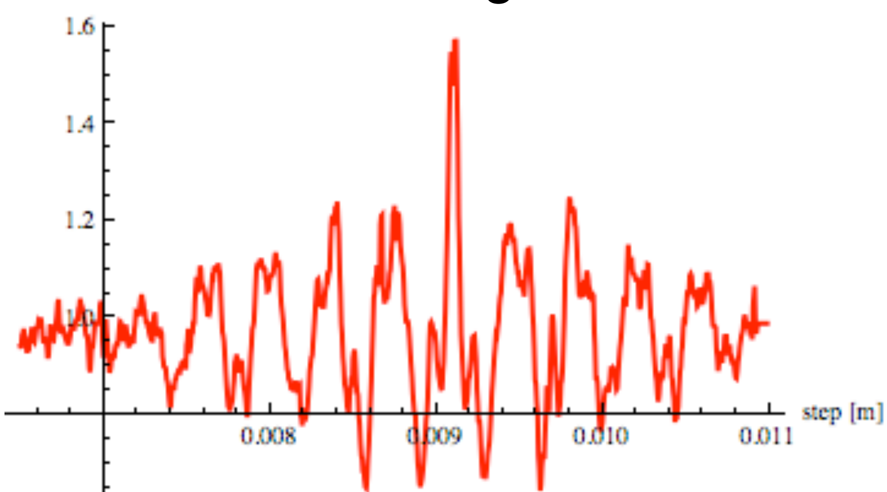
# Strong Wakefields in Dielectric Tubes Have Applications Beyond Acceleration

SLAC

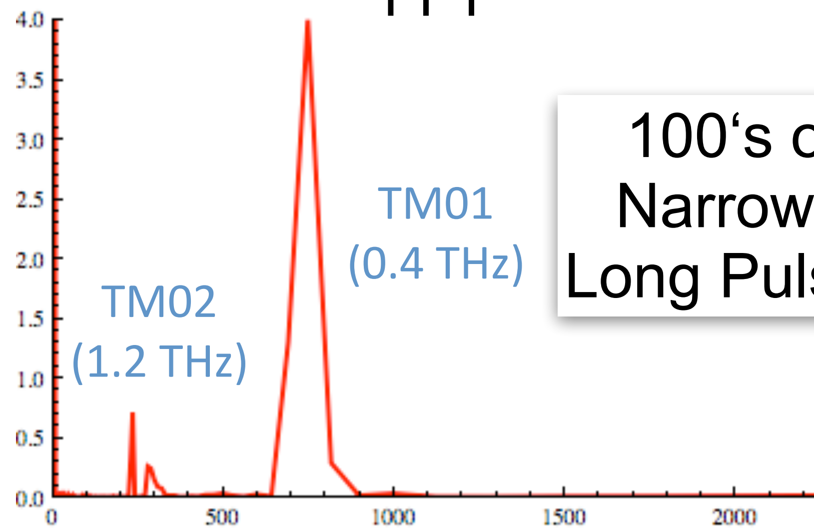
- De-chirper: remove correlated energy spread for narrow bandwidth FEL
- Electron beams can make unrivaled THz source
  - CTR gives mJ, broadband, short pulse
  - Dielectric structures can extract 100's of mJ, narrowband, long pulse
- FACET developing techniques for THz transport




Interferogram

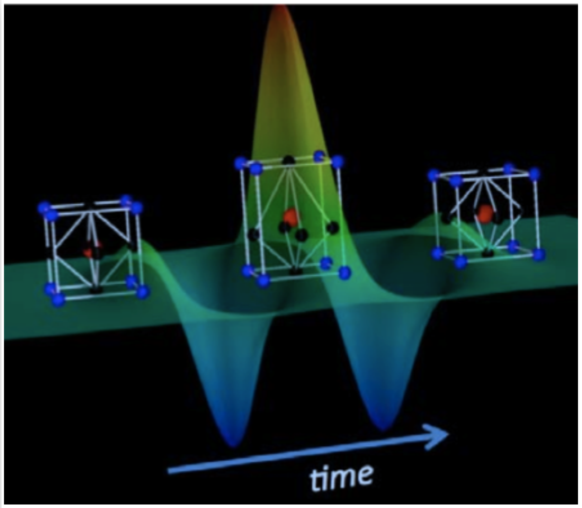



FFT




100's of mJ
Narrowband
Long Pulse THz

# Science Opportunities at FACET




Record THz energies (narrow band *and* broad band) for pump-probe experiments

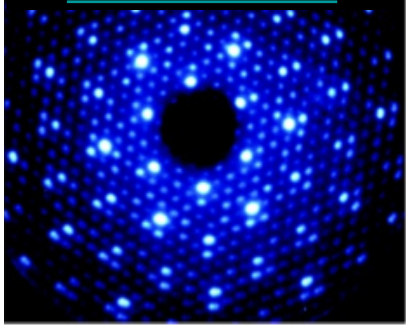
- Focused THz creates fields approaching V/Å

Ultrafast Electron Diffraction

*(recent hire: X.J. Wang to develop program)*

- PWFA witness bunch can offer real-time fs imaging using UED

P. Zhu et al
arXiv:1304.5176



Record intensity of monochromatic gamma-ray beams

- Noteworthy opportunities for materials research with gammas from Compton backscattering

FACET-II unique capabilities may open up many new opportunities for ultrafast sciences

# Gamma Gamma collider

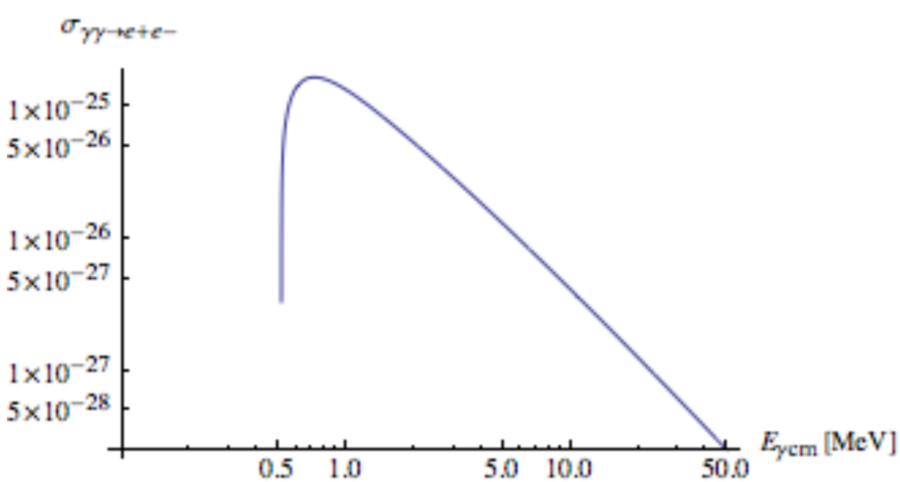
$E_e = 4GeV$

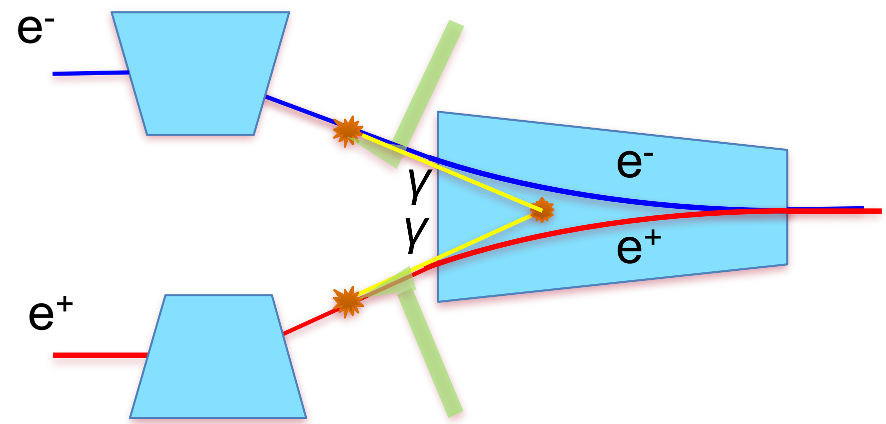
$E_\gamma \sim 30$ MeV, $\alpha \sim 0.05$

$E_{\gamma cm} \sim 1.5$ MeV

$L \sim 5x10^{24}$ $cm^{-2}$ $sec^{-1}$

$\sigma_{\gamma\gamma\text{->}e+e-} \sim 10^{-25} cm^2$ @ 1.5MeV




Will focus on technology research for gamma gamma collider.

Will test for the first time ability to generate $e^+e^-$ pairs with real (not virtual) photons

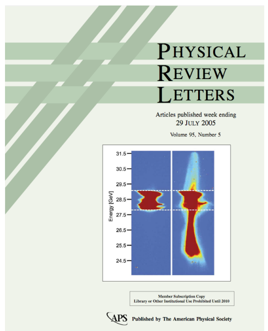
This would be the first pair creation test using two real photons

# Summary

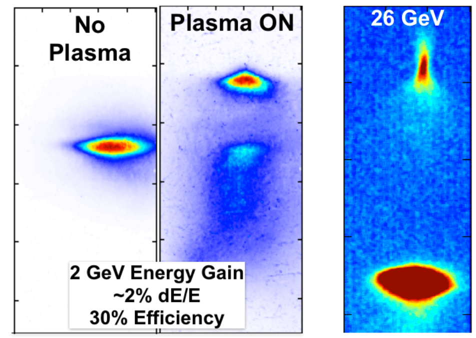
Plasma wakefield acceleration presents an enormous opportunity!

- Success follows naturally from mixture of compelling scientific questions, strong collaborations and powerful test facilities

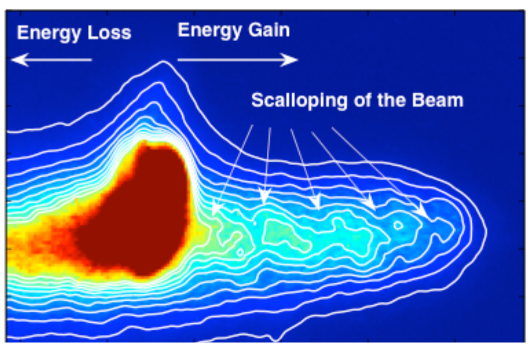
**Accelerating Gradient**



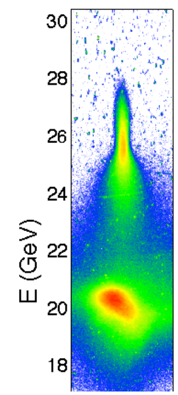

**Beams, Efficiency**

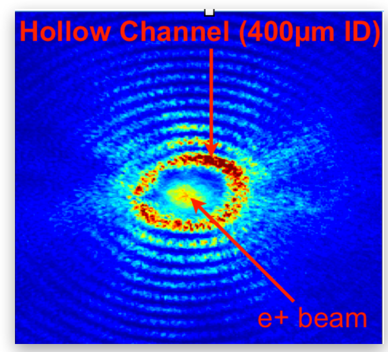



**High Energy**




**Positrons**




SLAC linac continues to play an invaluable role advancing understanding of plasma acceleration: FFTB, FACET, FACET-II