

EuCARD-2

Enhanced European Coordination for Accelerator Research & Development

Presentation

Recent results at FACET

Yakimenko, Vitaly (SLAC)

27 November 2014



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The electronic version of this EuCARD-2 Publication is available via the EuCARD-2 web site <http://eucard2.web.cern.ch/> or on the CERN Document Server at the following URL:
<<http://cds.cern.ch/search?p=CERN-ACC-SLIDES-2016-0006>>

Recent results at FACET

CERN

Vitaly Yakimenko, November 27, 2014

SLAC Electron Beam Test Facilities

5 MeV to 20 GeV

20 GeV e^-
& e^+
FACET

5 MeV
ASTA

2-16 GeV
& single e^-
ESTB

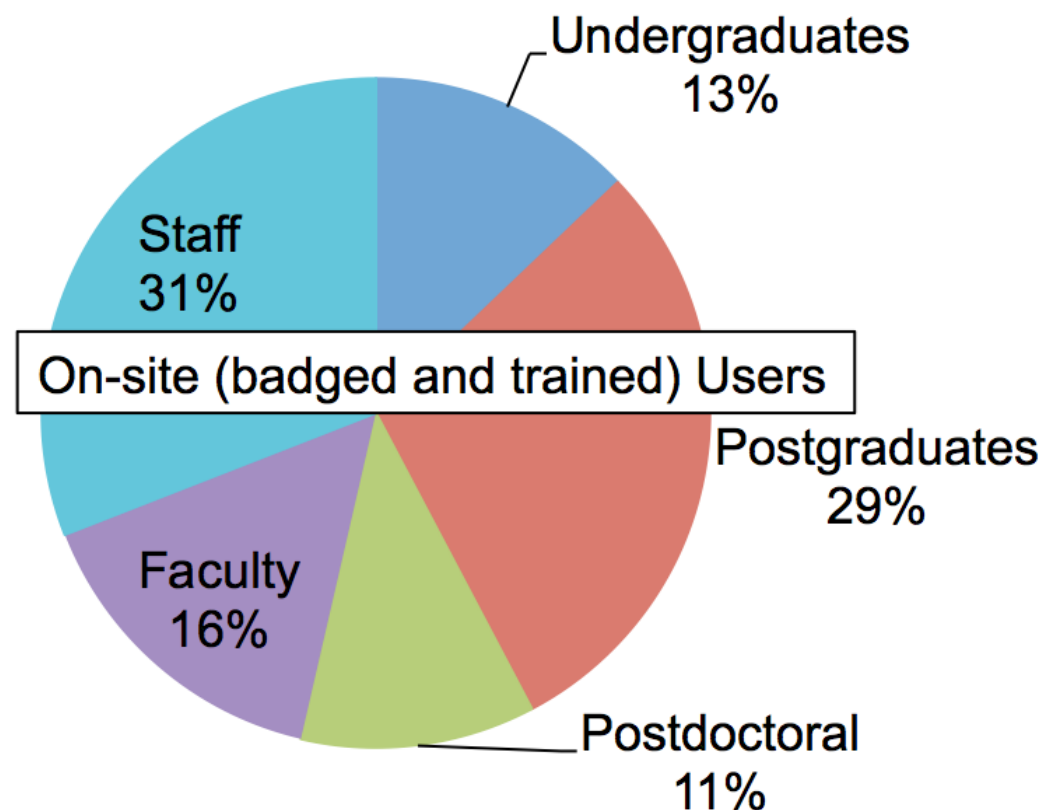
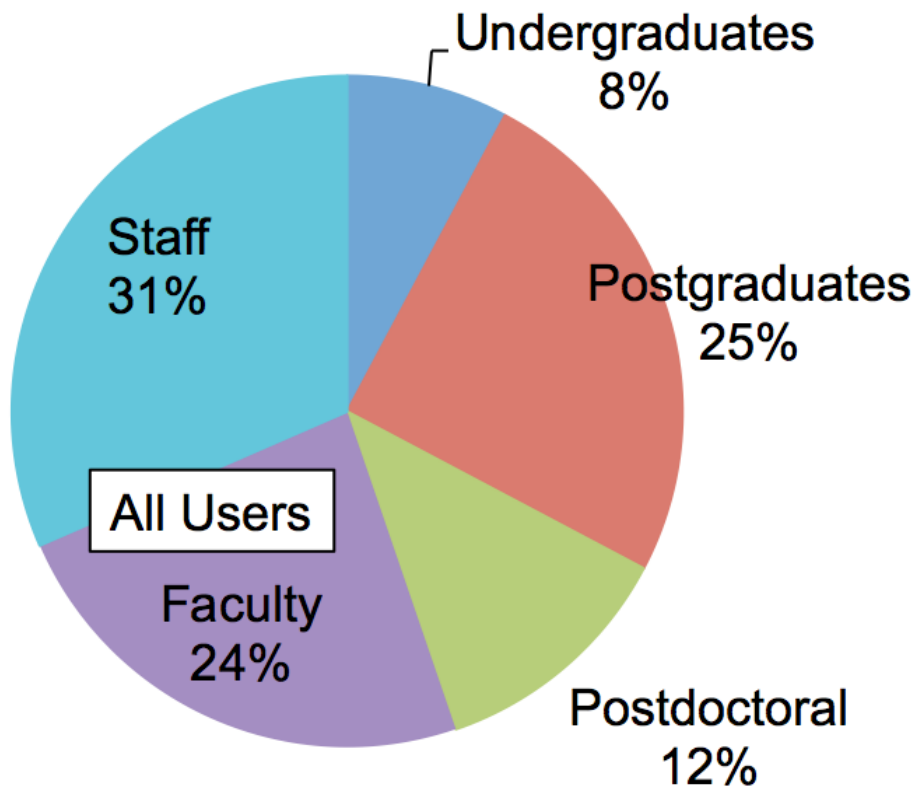
60-120 MeV
NLCTA

<http://facet.slac.stanford.edu/>

FY14 FACET and Test Beam Facilities Users

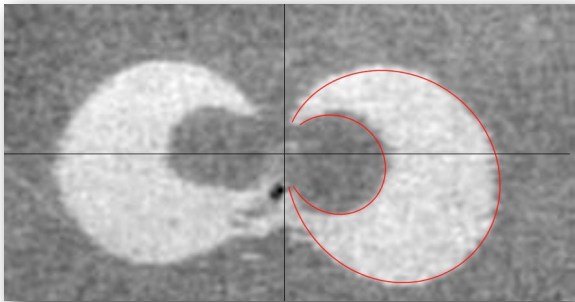


- 396 Scientists associated with 42 active (beam time in FY14) or planned experiments and beam tests at FACET, ESTB, NLCTA and ASTA
- ~60% (231) of these scientists working on the experiments are On-site Users (badged and trained for experimental work)

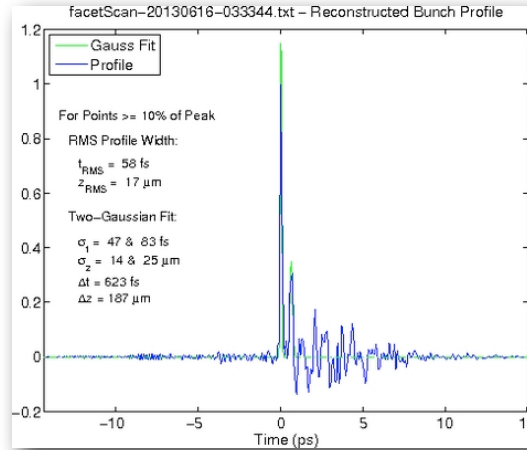


FY13 FACET Run – Six Experiments

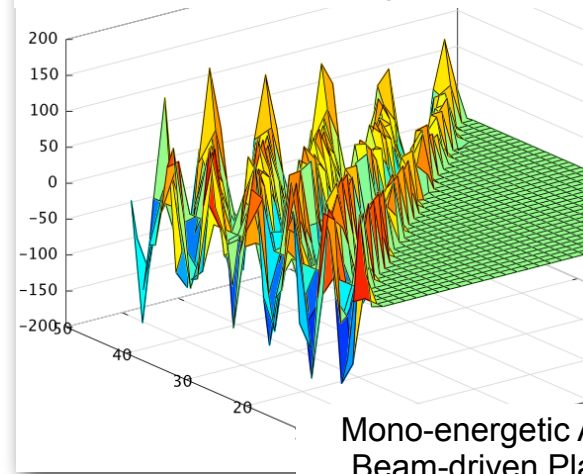
Switching Mechanisms in Ultrafast Electromagnetic Pulses



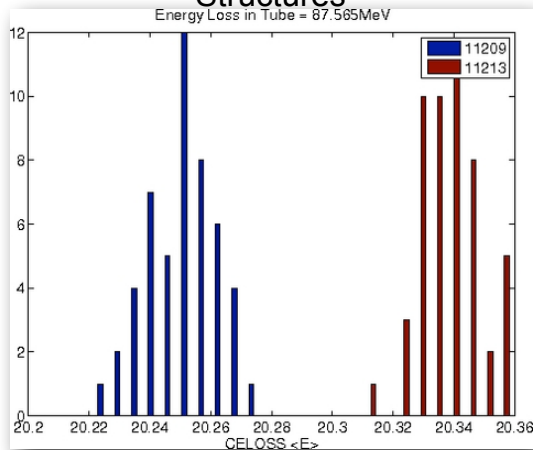
THz Reconstruction of Two-Bunch Profile



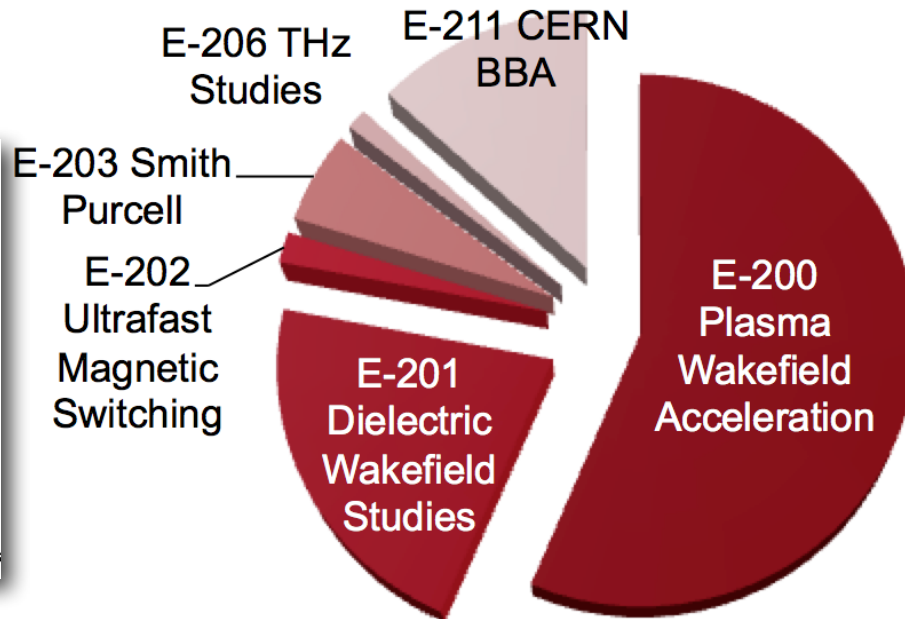
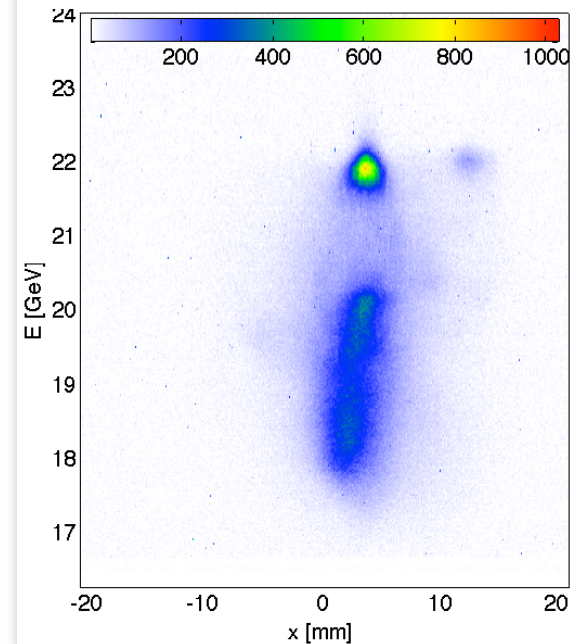
An Automated Method for Dispersion Free Steering



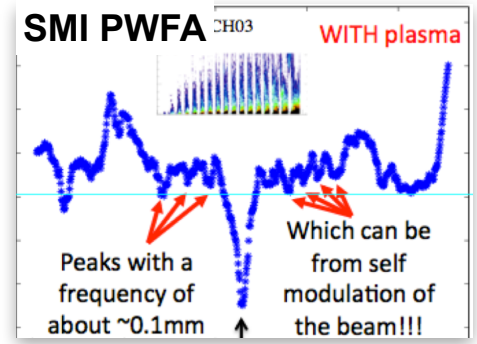
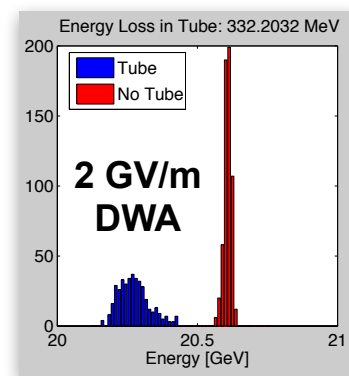
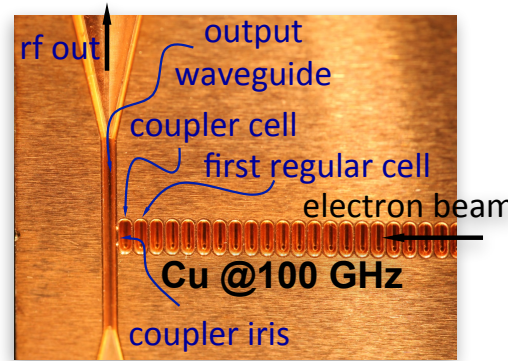
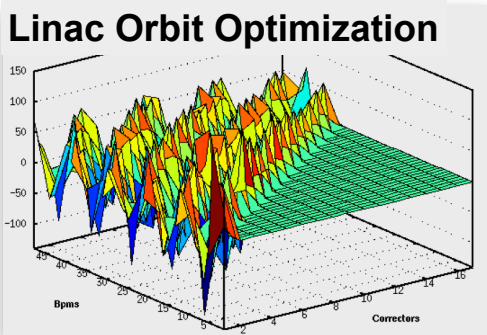
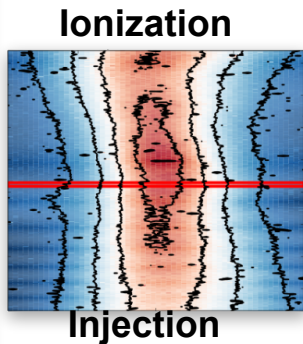
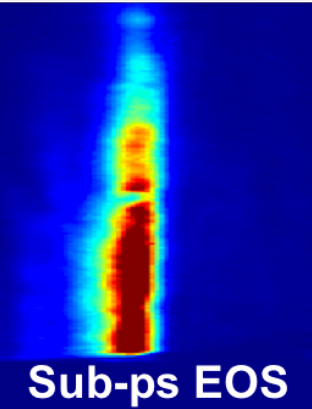
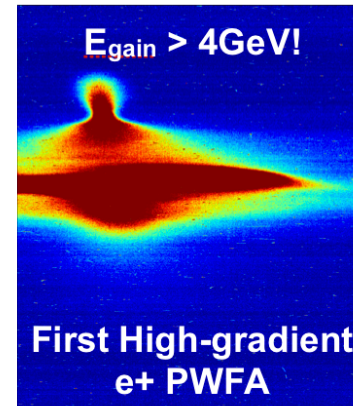
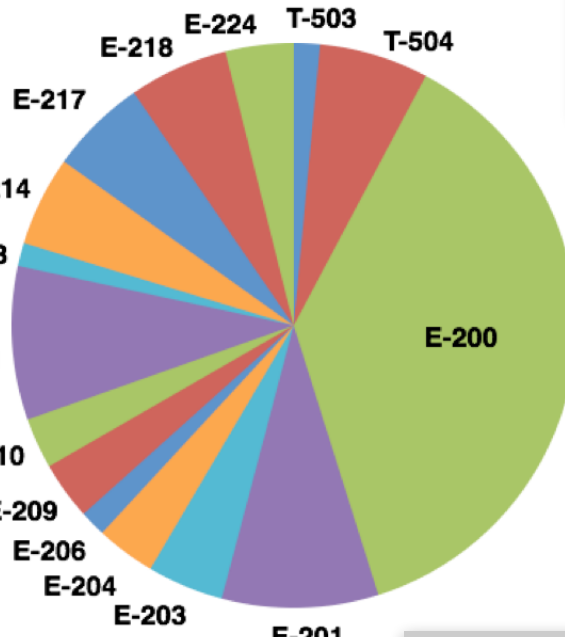
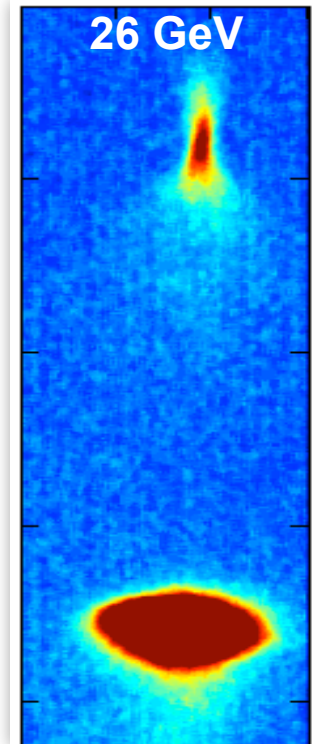
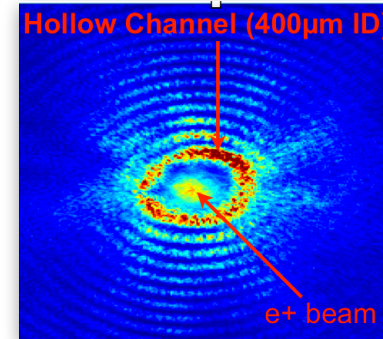
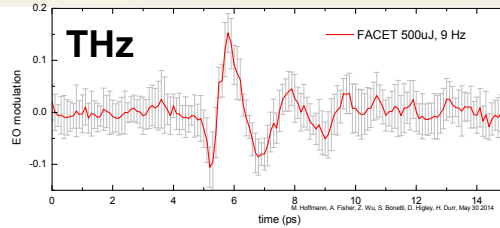
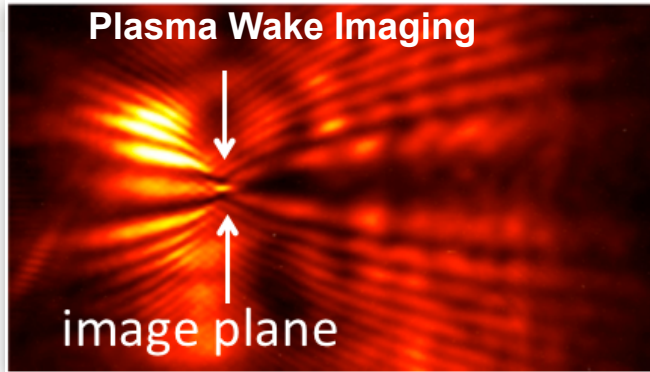
Demonstration of Gigavolt-per-meter Accelerating Gradients in Dielectric Wakefield Accelerating Structures



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



FY14 FACET Run – Fifteen Experiments



FACET is a National User Facility



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

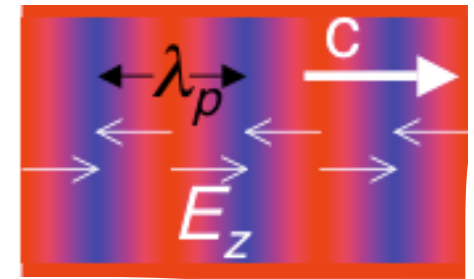
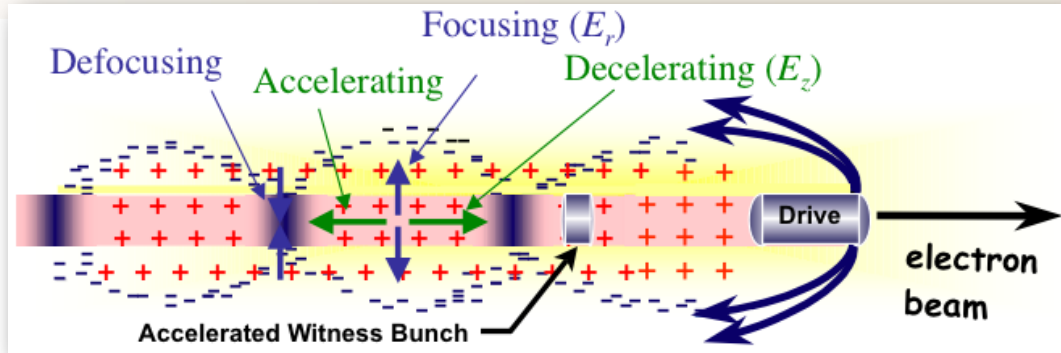
- Meter scale ✓
- High gradient ✓
- Preserved emittance
- Low energy spread ✓
- High efficiency ✓

Timeline:

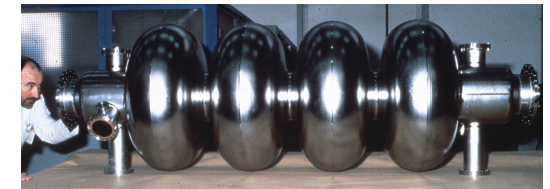
- Commissioning (2012) ✓
- Drive & witness e⁻ bunch (2012-2013) ✓
- Optimization of e⁻ acceleration (2013-2015)
- First high-gradient e⁺ PWFA (2014-2016)

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

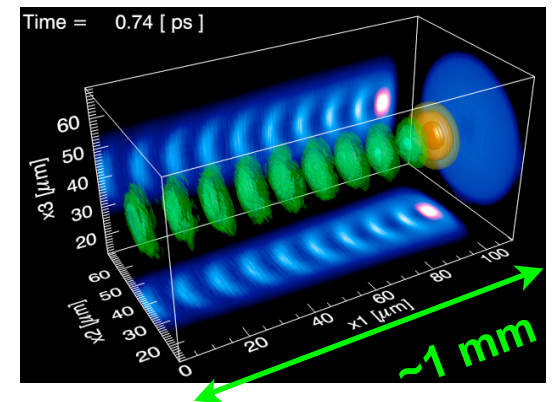
Why Plasmas?



Large
Collective Response!



~1m



Relativistic plasma wave (electrostatic):

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0} \quad k_p E_z = \frac{\omega_{pe}}{c} E_z = \frac{n_e e}{\epsilon_0}$$

$$E_z = \left(\frac{m_e c^2}{\epsilon_0} \right)^{1/2} n_e^{1/2} \cong 100 \sqrt{n_e (\text{cm}^{-3})} = \underline{1 \text{GV} / \text{m}}$$

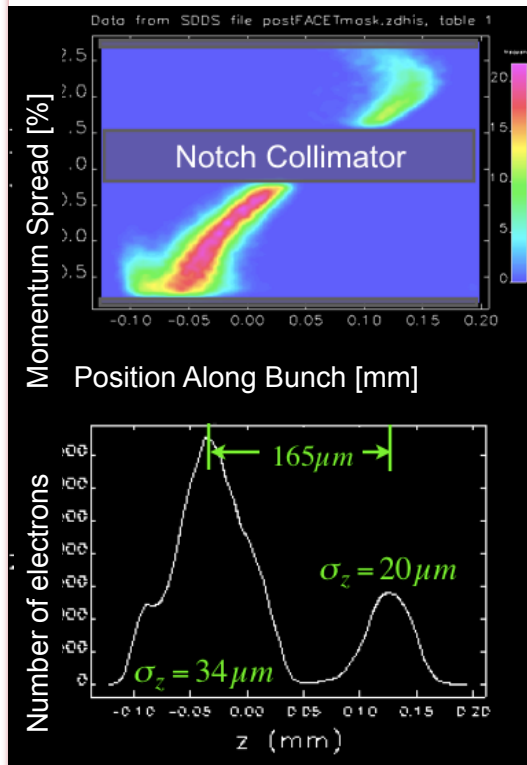
$$n_e = 10^{14} \text{ cm}^{-3}$$

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

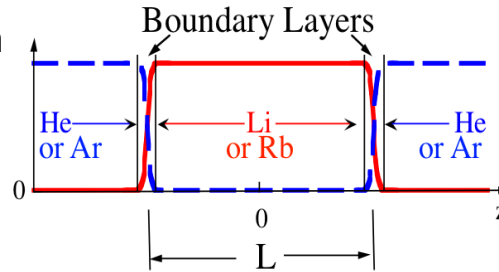
E200: Plasma Wakefield Acceleration

2013

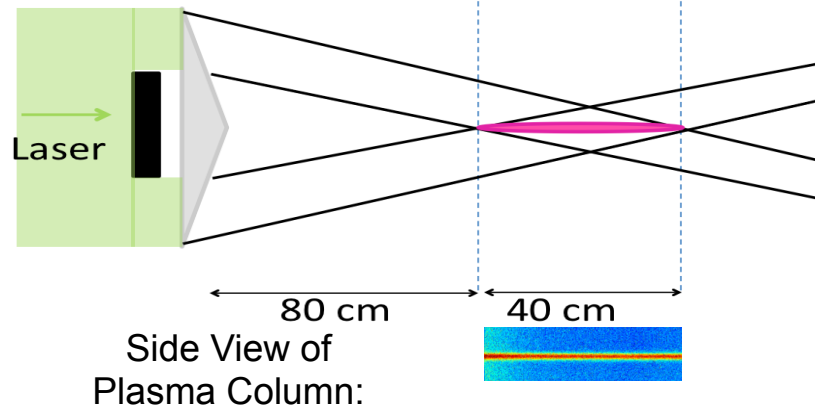
Simulation of Collimated Longitudinal Phase Space



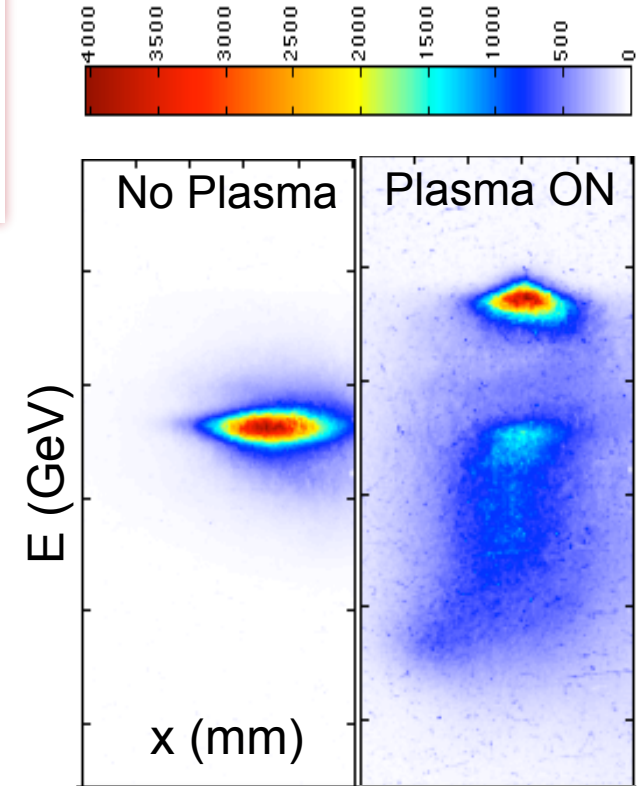
Heat Pipe Oven for uniform column of low ionization potential vapor



Line focus defines plasma channel aligned onto e⁻ beam orbit



electron density (e⁻ mm⁻²)

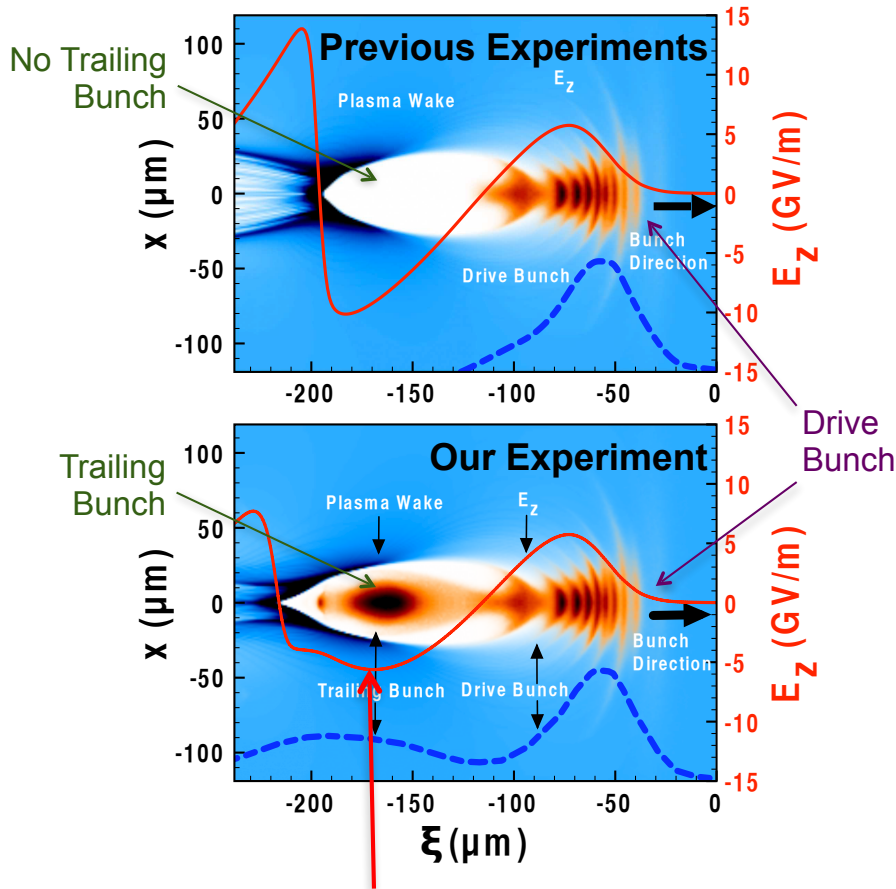


2 GeV Energy Gain
~2% dE/E

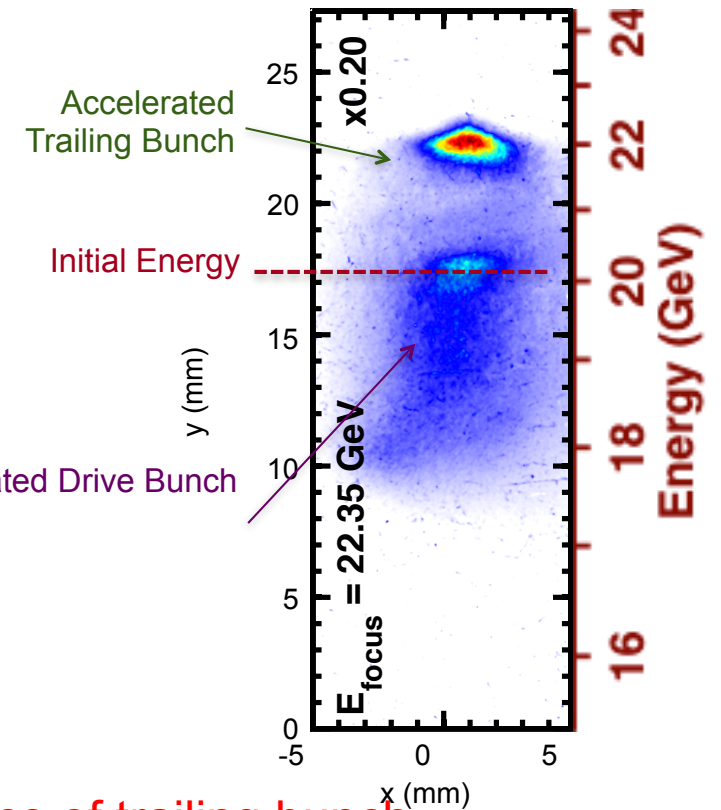
Up to 50% energy transfer from drive to witness was measured

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

Simulations



Energetically Dispersed Beam After Plasma (Data)



- 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

Not-So-Large Colliders Could Revolutionize Physics

Move over, Large Hadron Collider. A new atom smasher could smash each other at even more mind-bogglingly high-energy levels near Geneva.

The new system, called a Wakefield accelerator, could allow powerful particle colliders that could fit on any university campus to look for as-yet-unknown subatomic particles lurking near Geneva.

The new accelerator was described Wednesday in the journal *Nature*.

The premise behind all particle colliders is deceptively simple: particles such as protons or electrons, make them crash into each other, and then look at the wreckage to see what comes out. Hogan, a physicist at the Stanford Linear Accelerator, or SLAC, Laboratory in Menlo Park, California. [Images: inside the Wakefield Accelerator]

LETTER

High-efficiency acceleration of an electron beam in a plasma wakefield accelerator

M. Jovan, S. Abit, T. W. Lee, C. C. Chang, C. G. Charney, S. Ghelard, J. P. Dittmar, R. J. England, S. Green, S. Z. Green, M. J. Hogan, C. Joshi, W. Li, K. A. Marsh, W. B. Mori, P. Muggli, S. G. White, E. Wu, Y. Yamamoto & K. Yokoyama

The wake, also depicted in Fig. 1a, is located in a region of positive electric field in a region of positive magnetic field. However, the total charge of the wakefield is zero. The electric field is directed along the direction of the drive beam, and the magnetic field is directed perpendicular to the drive beam. The electric field is directed along the direction of the drive beam, and the magnetic field is directed perpendicular to the drive beam. The electric field is directed along the direction of the drive beam, and the magnetic field is directed perpendicular to the drive beam.

SCIENTIFIC AMERICAN

Plasma-Surfing Mini-Accelerator

Surfing 'wakefield' waves boosts energy

November 6, 2014 | By Elizabeth Gibney

An innovative technique to accelerate particles could lead to smaller, more energetic particle smashers.

Publishing in *Nature* today, researchers working at the SLAC National Accelerator Laboratory in Menlo Park, California, have shown that an experimental way of accelerating electrons, known as plasma wakefield acceleration, is efficient enough to power particle accelerators.

The technique, which has been under development for more than 30 years, drives electron bunches to higher energies by making them 'surf' on the electromagnetic wake of their predecessors. The authors of the latest study succeeded in generating an energy gain per unit length that is around 1,000 times higher compared with existing accelerators, such as the Large Hadron Collider (LHC) at CERN, Europe's particle-physics laboratory near Geneva, Switzerland.

Science

Physicists crank up current in new type of accelerator

LATEST NEWS

US Scientists Build the Smallest Accelerator

Physicists crank up current in new type of accelerator

The authors of the latest study succeeded in generating an energy gain per unit length that is around 1,000 times higher compared with existing accelerators, such as the Large Hadron Collider (LHC) at CERN.

VOA Voice of America

News / Science & Technology

US Scientists Build the Smallest Accelerator

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Scienze

Gli acceleratori di particelle saranno più "piccoli" e low cost

welt der physik

...heute schon geforscht?

Fortschritte in der Kiefeld-Beschleunigung

Die leistungsfähigsten Teilchenbeschleuniger sind heutzutage sehr große Maschinen von mehreren Kilometern Länge. Die Ursache dafür liegt vor allem in den Mechanismen, die zur Beschleunigung geladener Teilchen genutzt werden. An neuen Beschleunigungsmethoden, die auf viel kürzeren Strecken eine ähnlich starke Beschleunigung erreichen können, wird seit vielen Jahren geforscht. Einen wichtigen Fortschritt bei der sogenannten Kiefeld-Beschleunigung vermelden nun Forscher um Mike Liton vom SLAC National Accelerator Laboratory in den USA in der Fachzeitschrift 'Nature'.

Liton und seinem Team gelang es, Paketen von mehreren Millionen Elektronen auf einer Strecke von nur etwa 35 Zentimetern eine Energie von 1,8 Gigaelektronenvolt zuzuführen. Für die enorme Energie wird mit heute üblichen Beschleunigern eine Beschleunigungstrecke von mindestens hundert Metern nötig. Liton und Kollegen berichten von einem Beschleunigungsfeld von 4400 Megavolt pro Meter, während heutige Beschleuniger mit Feldern

ciencia plus.com

Proyectan aceleradores de partículas con plasma de bajo coste

LABORATORIO

Proyectan aceleradores de partículas con plasma de bajo coste

El Laboratorio de Energía está ubicado en la Universidad de California en Los Angeles.

El grupo de investigación de plasma de partículas de la Universidad de California en Los Angeles, liderado por el profesor Michael Liton, ha desarrollado una técnica prometedora para acelerar los electrones en un plasma de manera más eficiente y económica que en un acelerador convencional. Este nuevo método de aceleración de partículas podría permitir la construcción de aceleradores más compactos y económicos.

La investigación ha sido realizada para el SLAC National Accelerator Laboratory, un Departamento de Energía establecido en la Universidad de California en Los Angeles.

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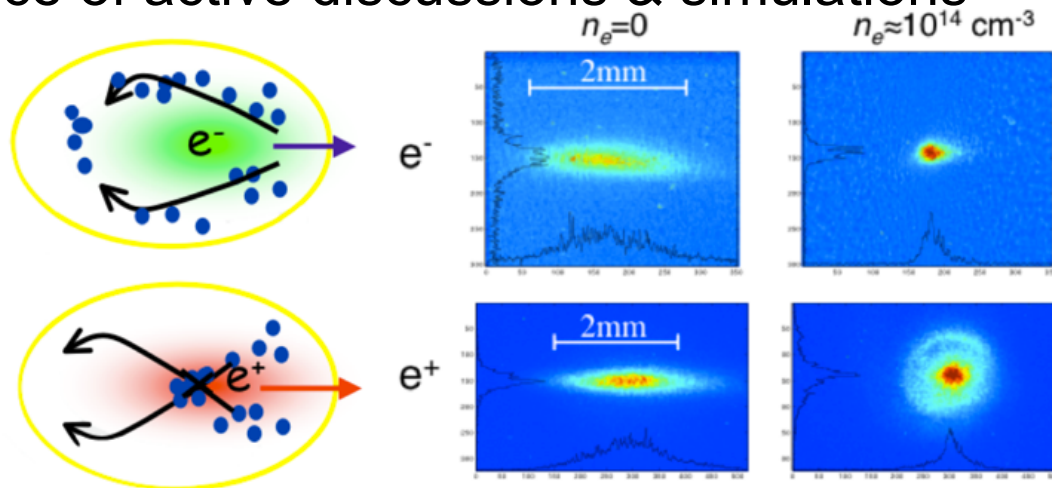
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First Experiments with GeV/m Positron PWFA

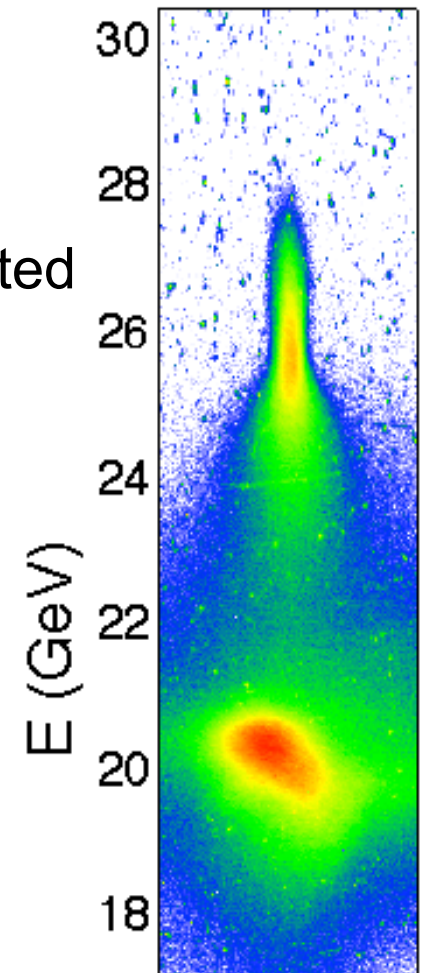
- Early experiments followed rapid commissioning of positrons
- Unanticipated features in the data
 - Beam Quality: Divergence of accelerated positrons similar to electrons, emittance growth less than expected
- Source of active discussions & simulations



Phys. Rev. Lett. **90**, 205002 (2003)

Phys. Rev. Lett. **101**, 055001 (2008)

Log Color Scale



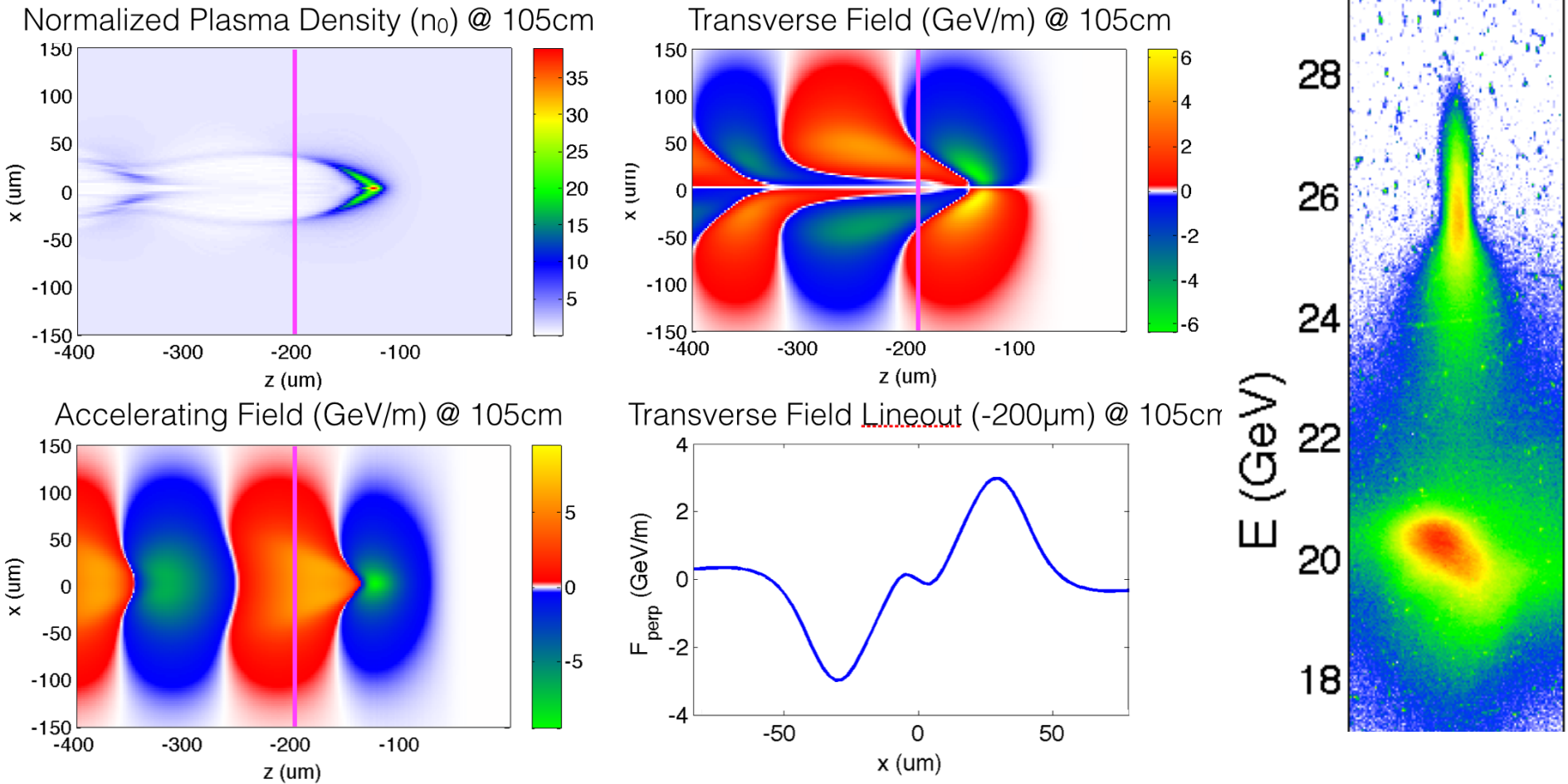
FACET has the only program in the world studying plasma acceleration of positrons

Simulations Providing Insight into Positron Driven Wakes

UCLA SLAC

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

Log Color Scale



This study is important for plasma afterburner as an energy doubler

Plasma Wake Driven by a Short and Intense Positron Bunch

UCLA SLAC



Submitted Manuscript: Confidential

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

Authors: S. Corde^{1*}, E. Adli^{1,2}, J. M. Allen¹, W. An³, C. I. Clarke¹, C. E. Clayton⁴, J. P. Delahaye¹, J. Frederico¹, S. Gessner¹, S. Z. Green¹, M. J. Hogan¹, C. Joshi⁴, M. Litos¹, W. Lu⁵, K. A. Marsh⁴, W. B. Mori³, P. Muggli⁶, M. Schmeltz¹, N. Vafaei-Najafabadi⁴, D. Walz¹, and V. Yakimenko¹

Affiliations:

¹SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA.

²Department of Physics, University of Oslo, 0316 Oslo, Norway.

³Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, CA 90095, USA.

⁴Department of Electrical Engineering, University of California Los Angeles, Los Angeles, CA 90095, USA.

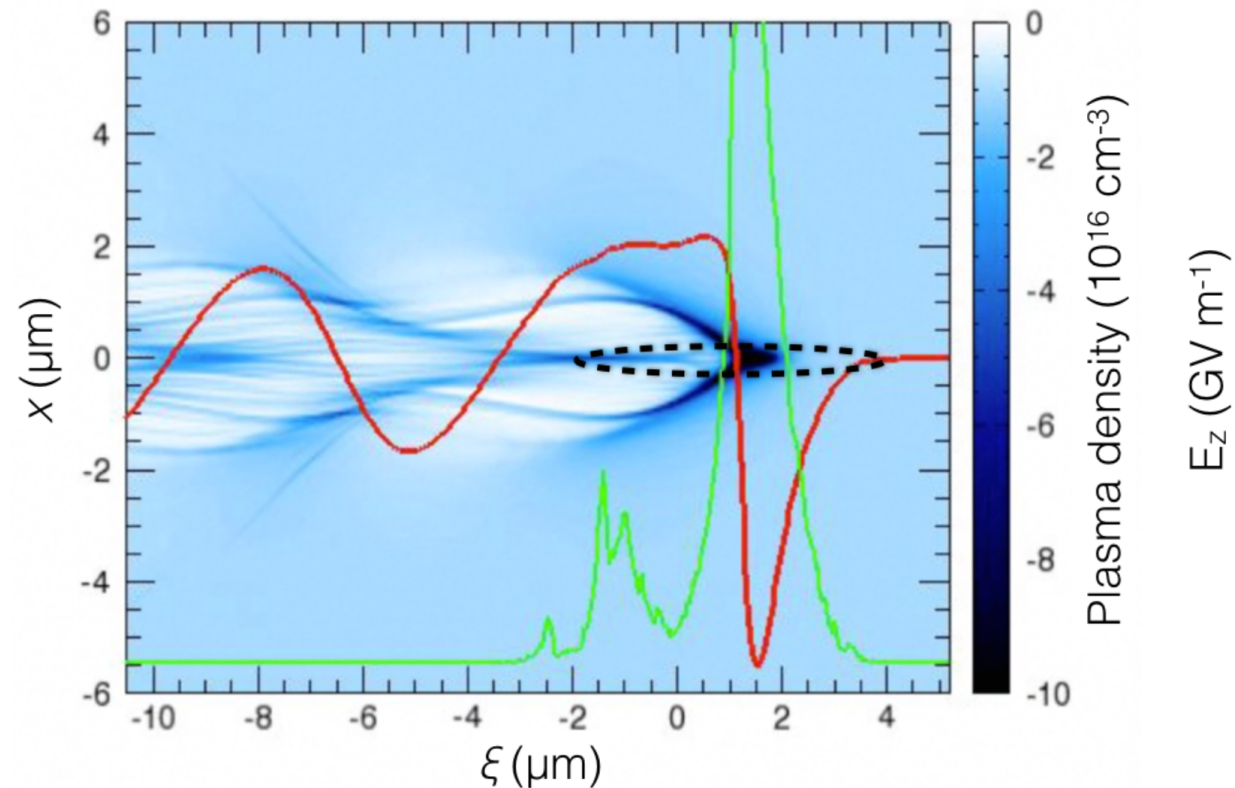
⁵Department of Engineering Physics, Tsinghua University, Beijing 100084, China.

⁶Max Planck Institute for Physics, Munich, Germany.

*Correspondence to: Sébastien Corde (email: corde@slac.stanford.edu)

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.

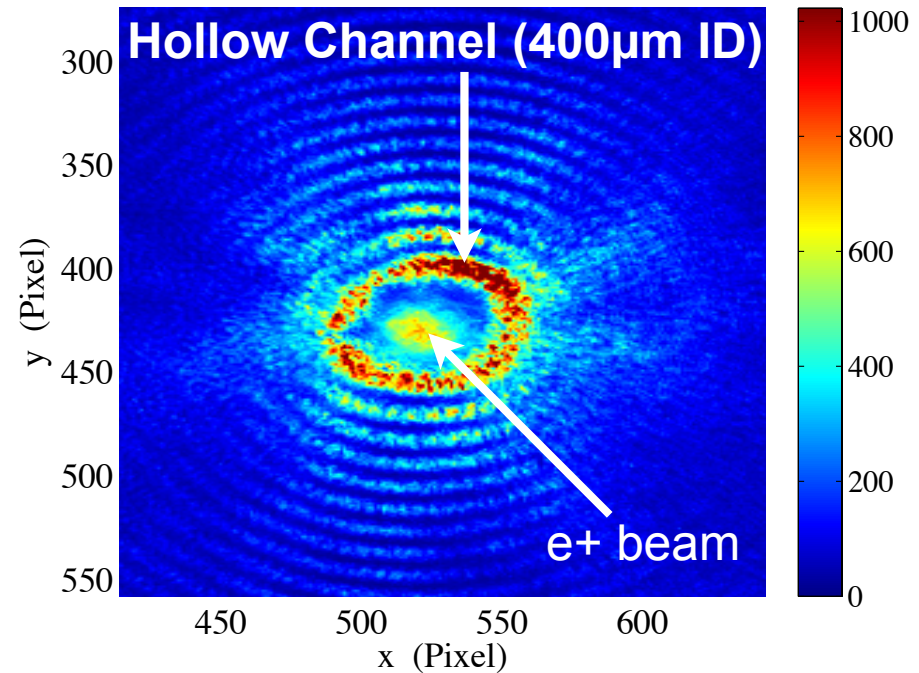
Main Text: Future high-energy particle colliders operating at the energy frontier of particle physics will be in the range of several trillion electronvolts (1). The currently proposed machines based on the existing radio-frequency technology, such as the International Linear Collider (ILC) and the Compact 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



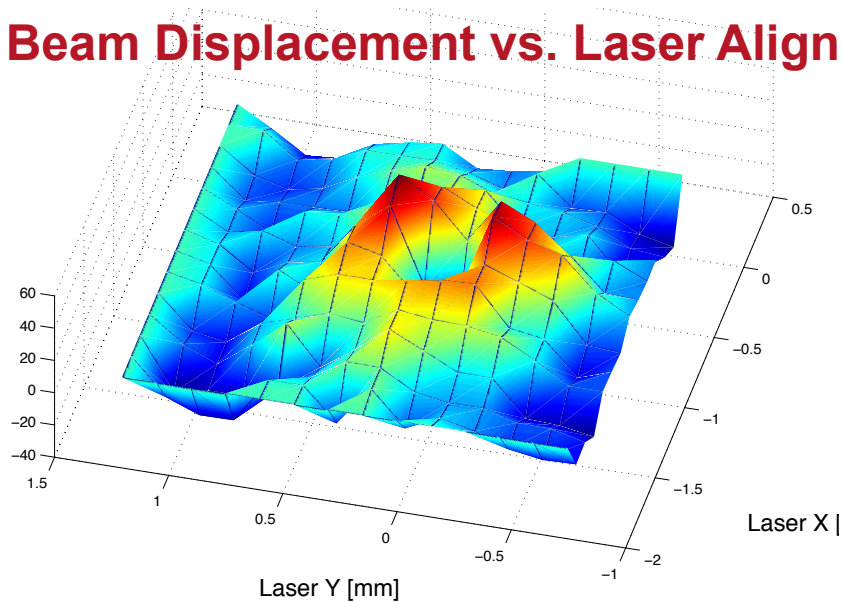
Manuscript is in an advanced state – expect to confirm results this FACET run

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

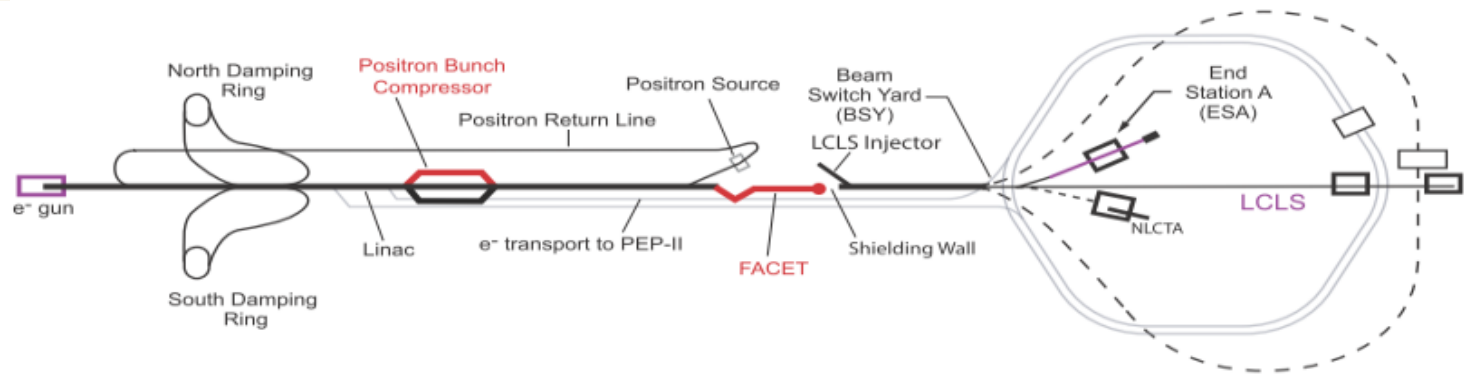
PWFA Program Plan as Shown December 2012

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 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 2/1 - 6/30	8/1 - 9/30	positron PWFA , one stage, efficiency, high brightness PWFA injector
2016	10/1-5/31	6/1 S0-10 D&D	Finalizing the program, single stage demonstration (energy spread, emittance, efficiency)

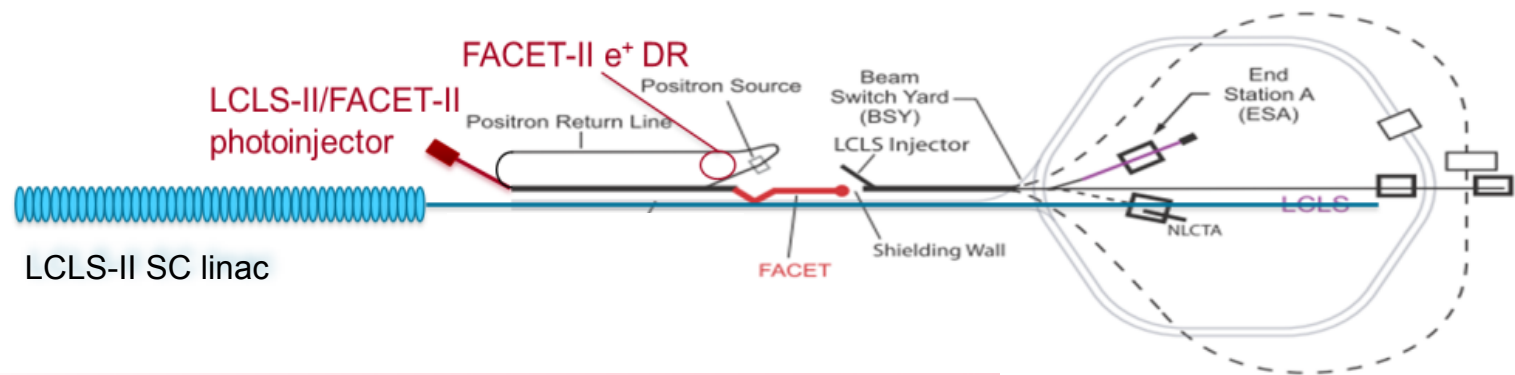
Steady, methodical progress according to our plan

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

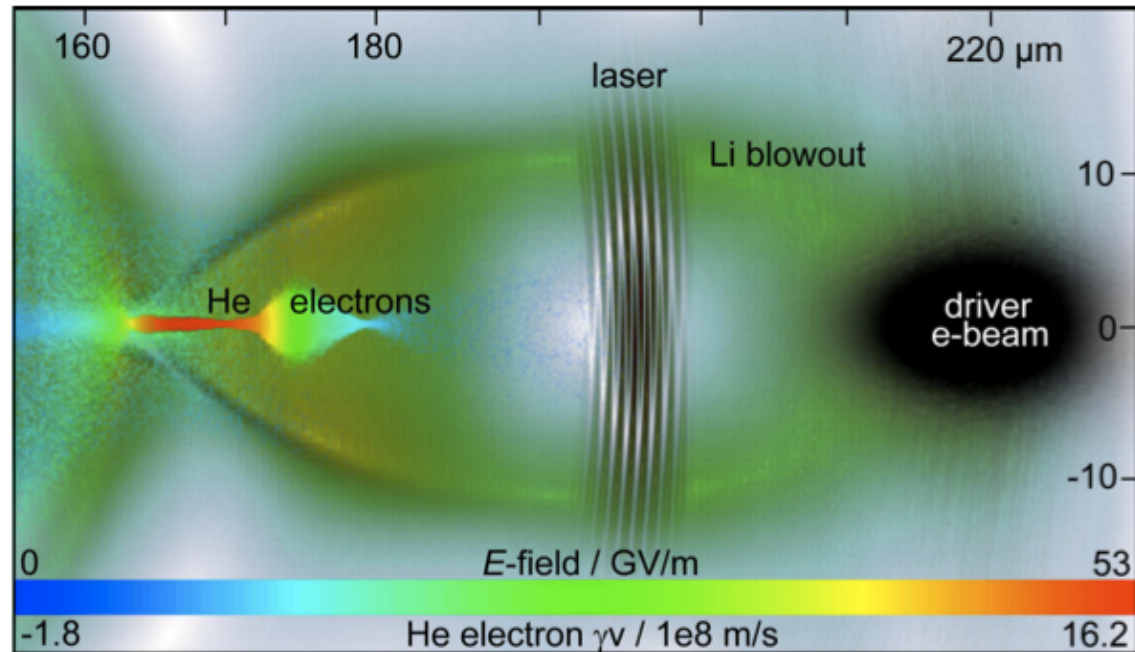
FY	FACET-II	PWFA Goals
2017	Construction (Phase 1)	Finalize FACET data analysis, prepare FACET-II experiments
2018-19	Phase 1 (e ⁻ only)	Staging studies with witness injector (synchronization, alignment), high transformer ratio (with shaped bunches)
2020-21	Phase 2 (e ⁻ or e ⁺)	e ⁻ or e ⁺ acceleration 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'



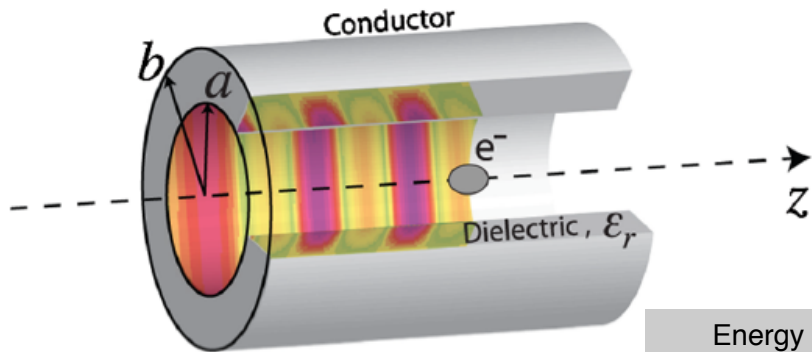
Leverages efficiency and rep rate of conventional accelerators to produce beams with unprecedented brightness for collider & XFEL applications

Testing Dielectric Structures at and Above Breakdown Voltage

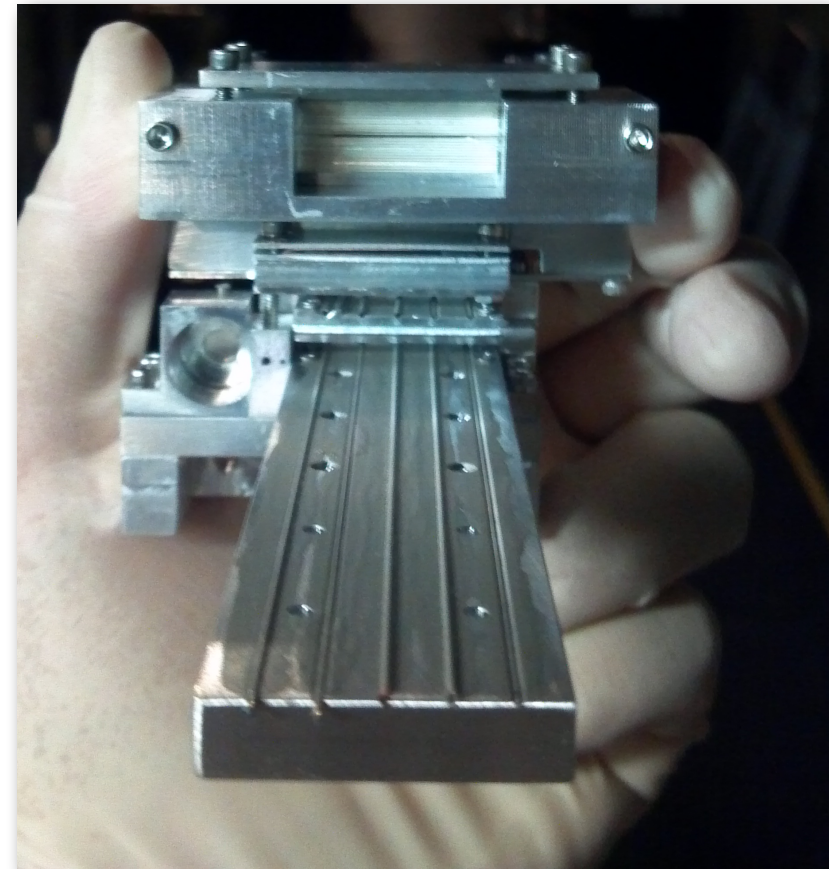
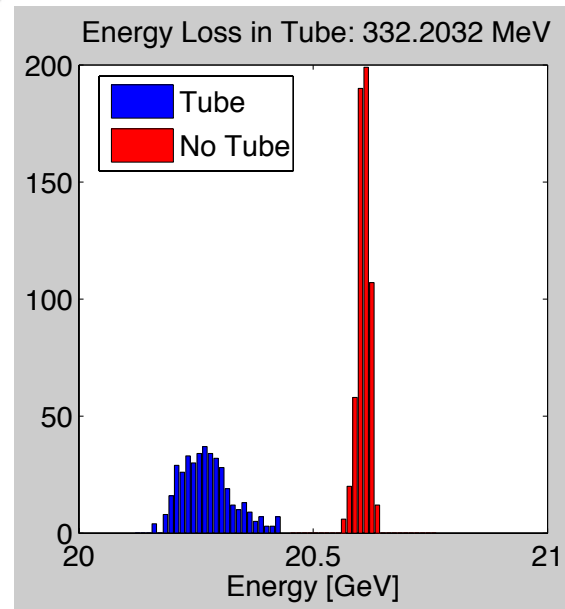
UCLA, Euclid Techlabs, Tech-X, Radiabeam Technologies, NRL, SLAC, MPI, Argonne



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



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



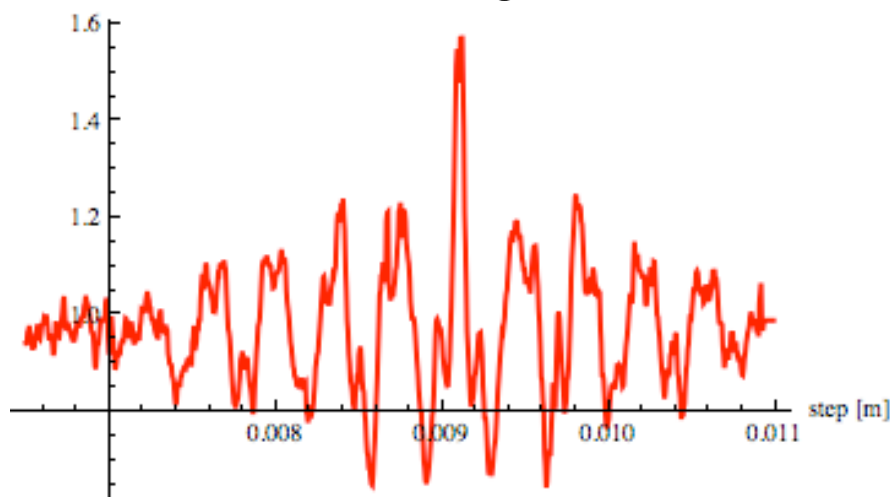
Demonstration of Gigavolt- per-meter Accelerating Gradients in Dielectric Wakefield Accelerating Structures

Strong Wakefields in Dielectric Tubes Have Applications Beyond Acceleration

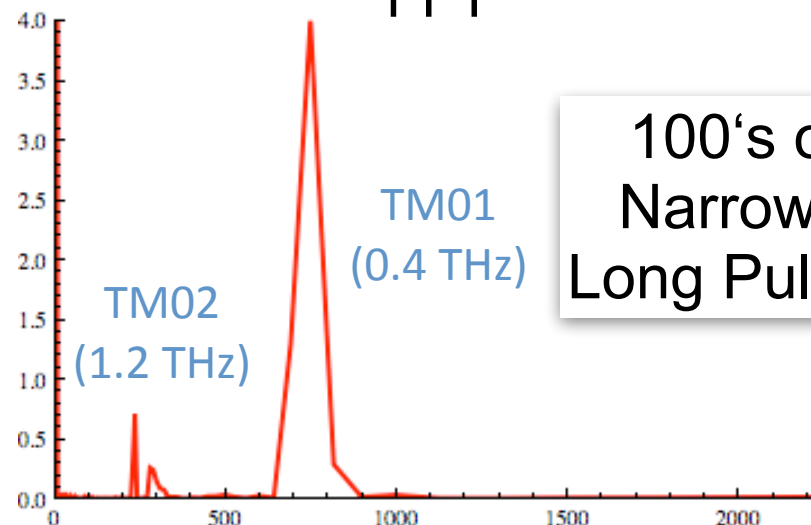
- De-chirper: remove correlated energy spread for narrow bandwidth FEL
- Electron beams can make unrivaled THz source
 - CTR gives mJ, broadband, short pulse
 - Dielectric structures can extract 100's of mJ, narrowband, long pulse
- FACET developing techniques for THz transport



Interferogram

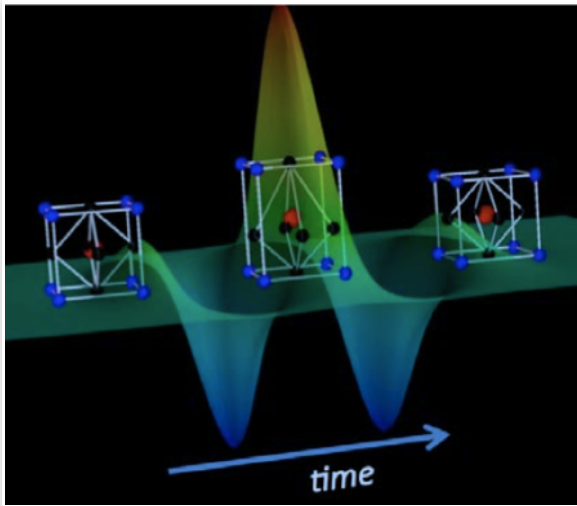


FFT



100's of mJ
Narrowband
Long Pulse THz

Science Opportunities at FACET



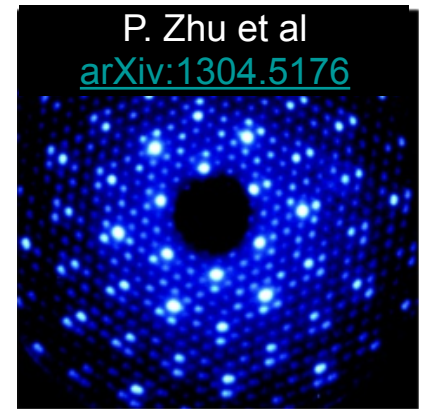
Record THz energies (narrow band *and* broad band) for pump-probe experiments

- Focused THz creates fields approaching $V/\text{\AA}$

Ultrafast Electron Diffraction

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

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



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

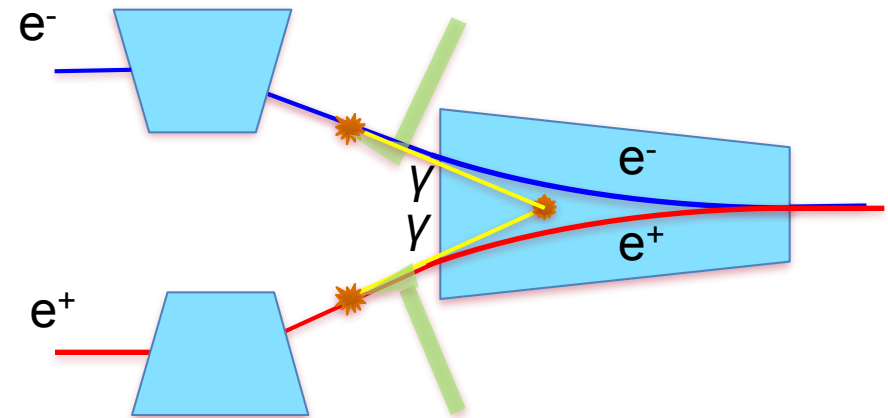
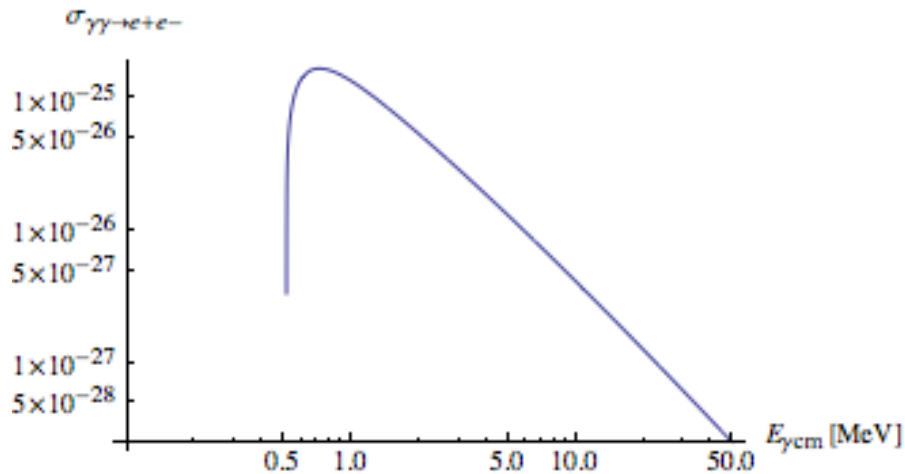
$$E_e = 4\text{GeV}$$

$$E_\gamma \sim 30\text{ MeV}, \alpha \sim 0.05$$

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

$$L \sim 5 \times 10^{24}\text{ cm}^{-2}\text{ sec}^{-1}$$

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



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

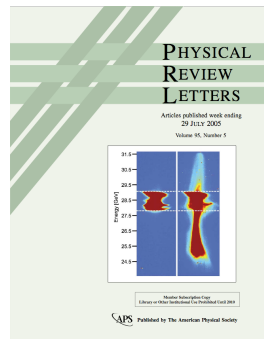
This would be the first pair creation test using two real photons

Summary

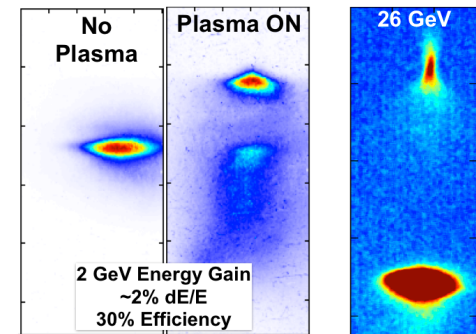
Plasma wakefield acceleration presents an enormous opportunity!

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

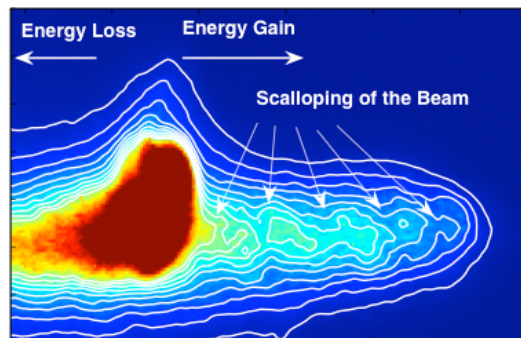
Accelerating Gradient



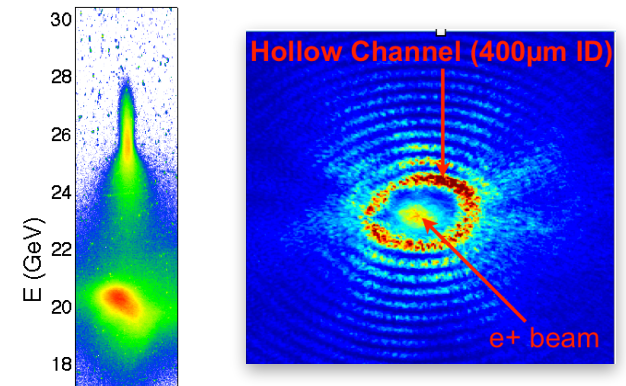
Beams, Efficiency



High Energy



Positrons



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