Perspectives on Beam Driven Plasma Acceleration:

How We Got Here and Where Might We Be Going?

IEEE PAST Prize Award Session
NA-PAC'13

Mark Hogan October 3rd, 2013

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Great Desire for Compact Access to High Energy Beams

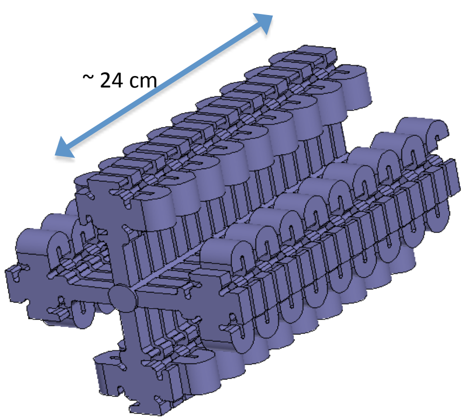
High energy particle accelerators are the ultimate microscopes

- 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

Looking to advanced concepts to shrink the size and cost of these accelerators by factors of 10-1000

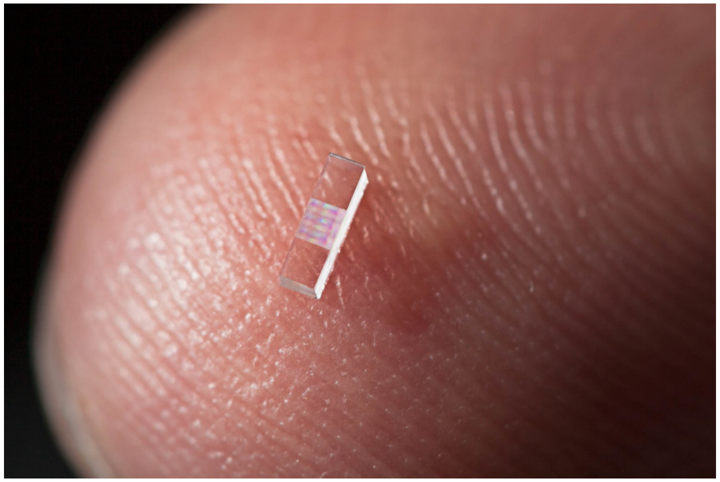
Combine efficient accelerator drivers with high-field dielectric and plasma structures to develop new generation of particle accelerators

~100MeV/m



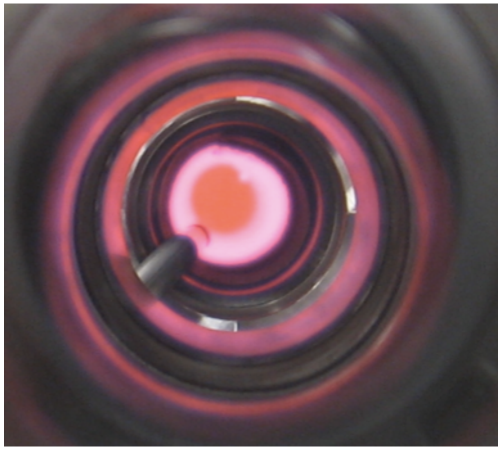
New designs and materials push metal structures to the limit

~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

Why Plasmas?

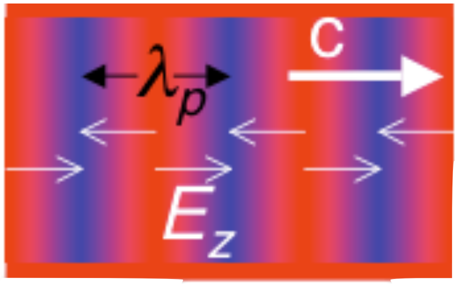
SLAC

Relativistic plasma wave (electrostatic):

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

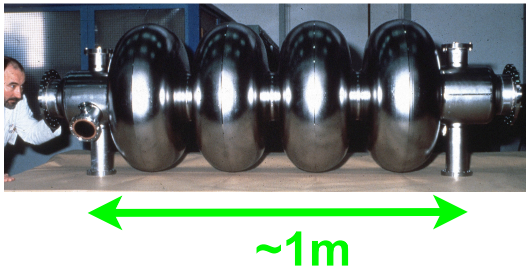
$$E_z = \left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2} \cong 100\sqrt{n_e(cm^{-3})} = \underline{1GV/m}$$

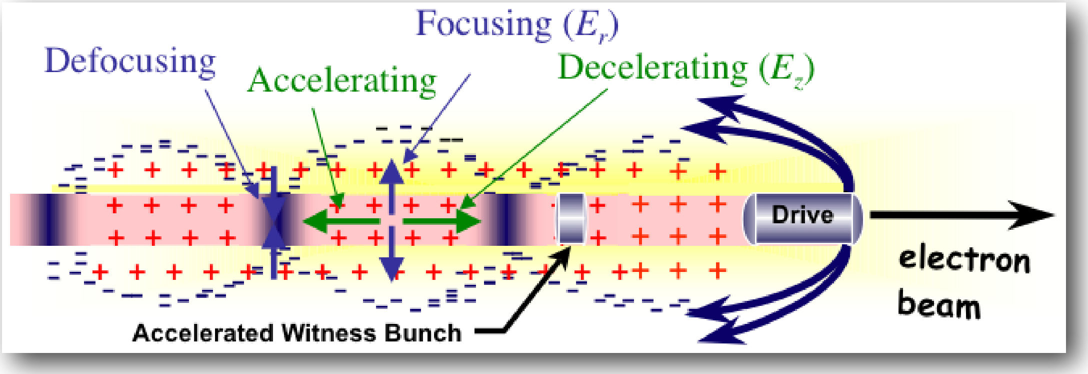
$n_e = 10^{14}$ cm^{-3}

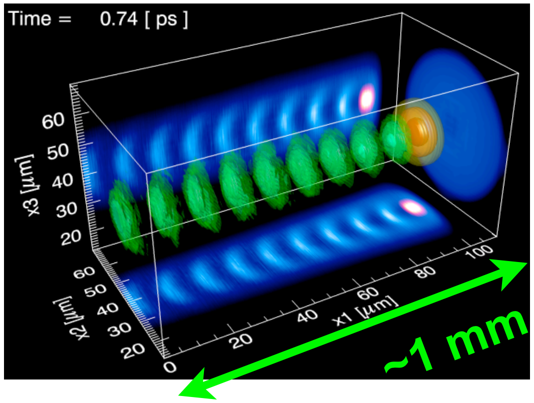


Large
Collective Response!

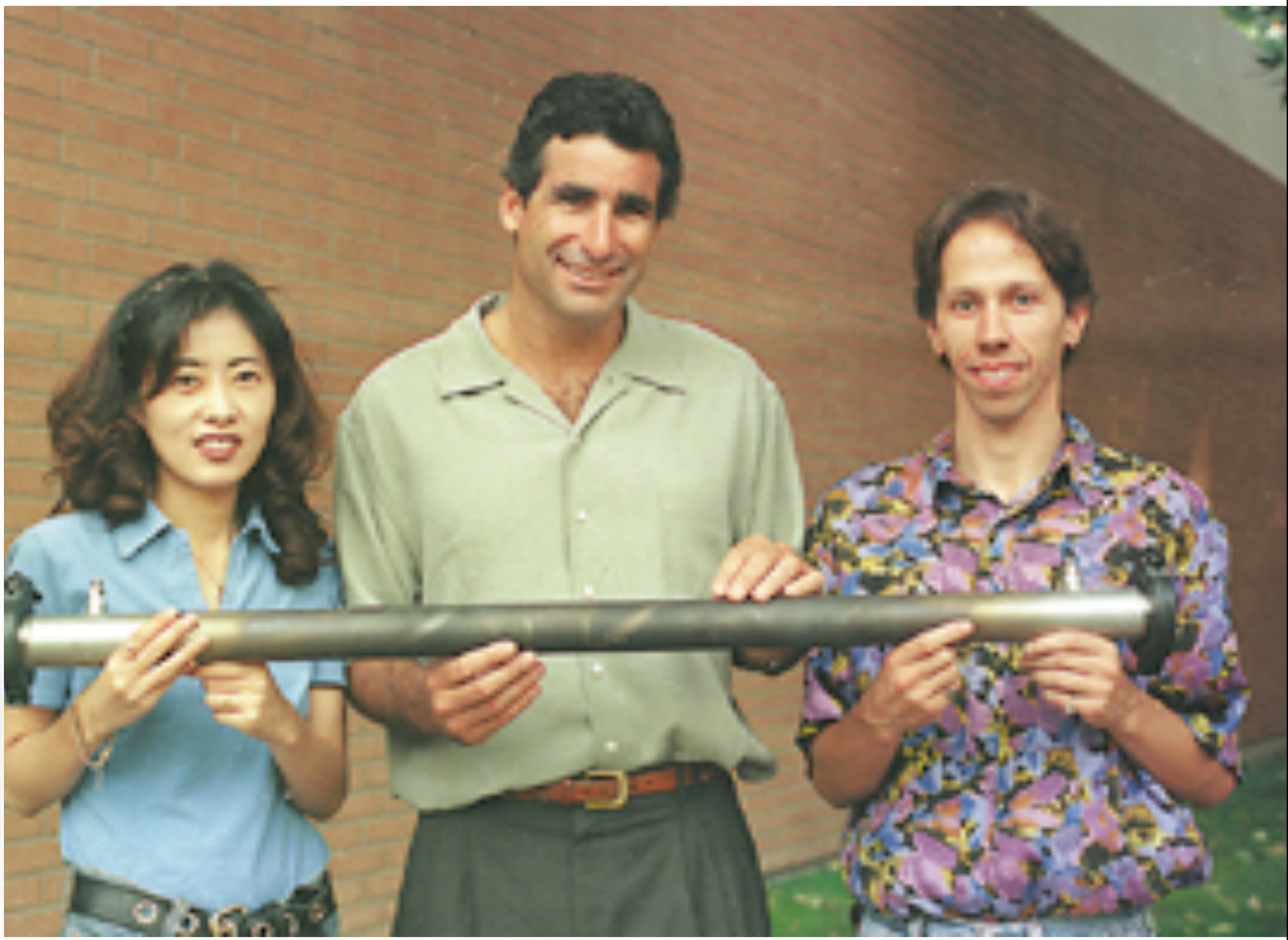
- Plasmas are already ionized, no break down
- Plasma wave can be driven by:
  - Intense laser pulse (LWFA)
  - Short particle bunch (PWFA)







Like Prof. Hansen on Stanford Campus Many Decades Before



"We have accelerated electrons."

Almost the Beginning

ONE GeV BEAM ACCELERATION
IN A ONE METER LONG
PLASMA CELL

A Proposal to the
Stanford Linear Accelerator Center

Primary Investigators:

R. Assmann, C. Joshi, T. Katsouleas, W. Leemans, R. Siemann

Collaboration:

S. Chattopadhay, W. Leemans, LBNL

R. Assmann, P. Chen, F.J. Decker, R. Iverson, P. Raimondi, T. Raubenheimer, S. Rokni, R.H. Siemann, D. Walz, D. Whittum, SLAC

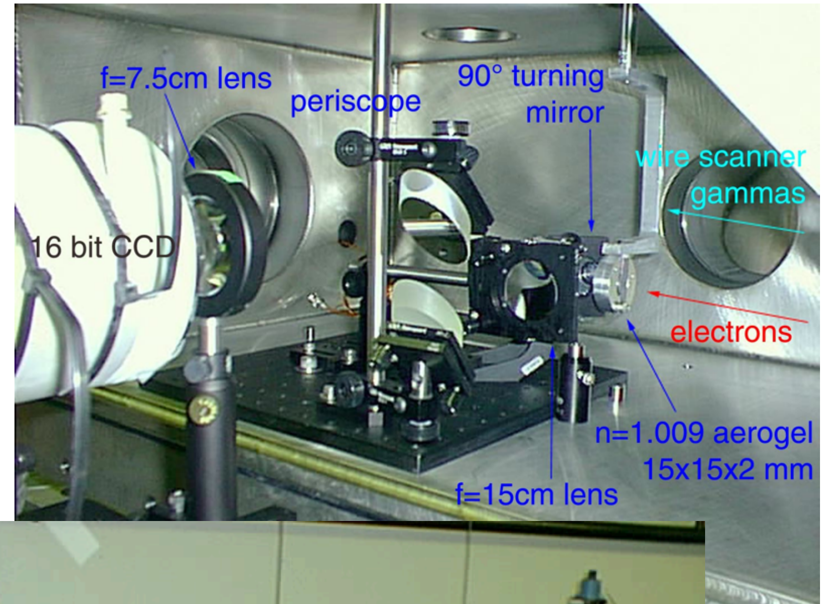
C. Clayton, C. Joshi, K. Marsh, W. Mori, G. Wang UCLA

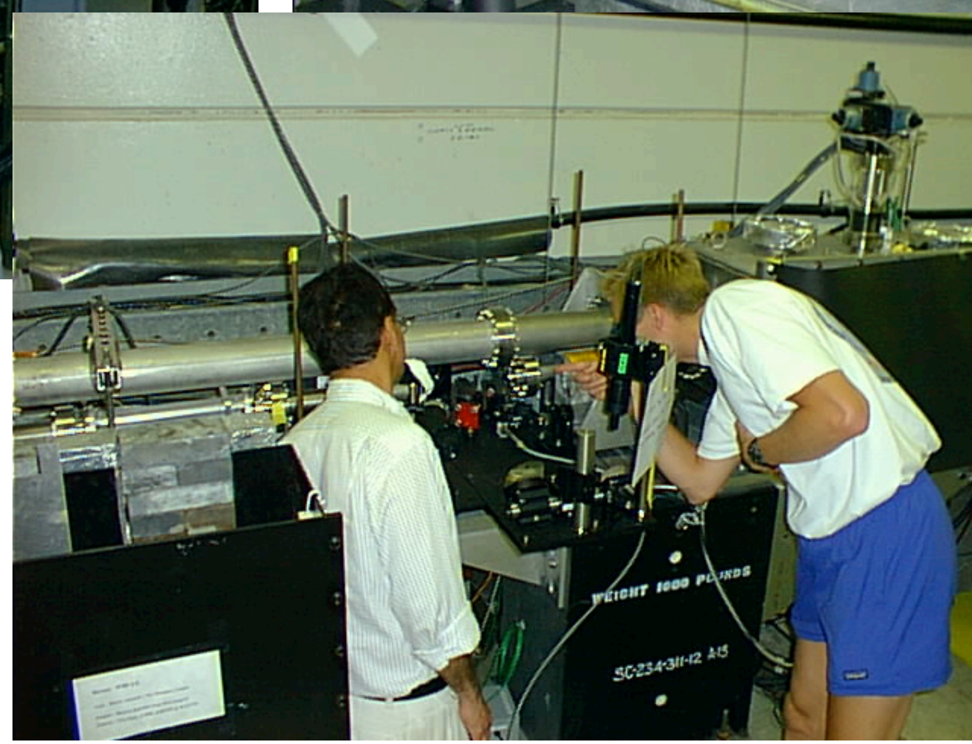
T. Katsouleas, S. Lee, USC

April 1997

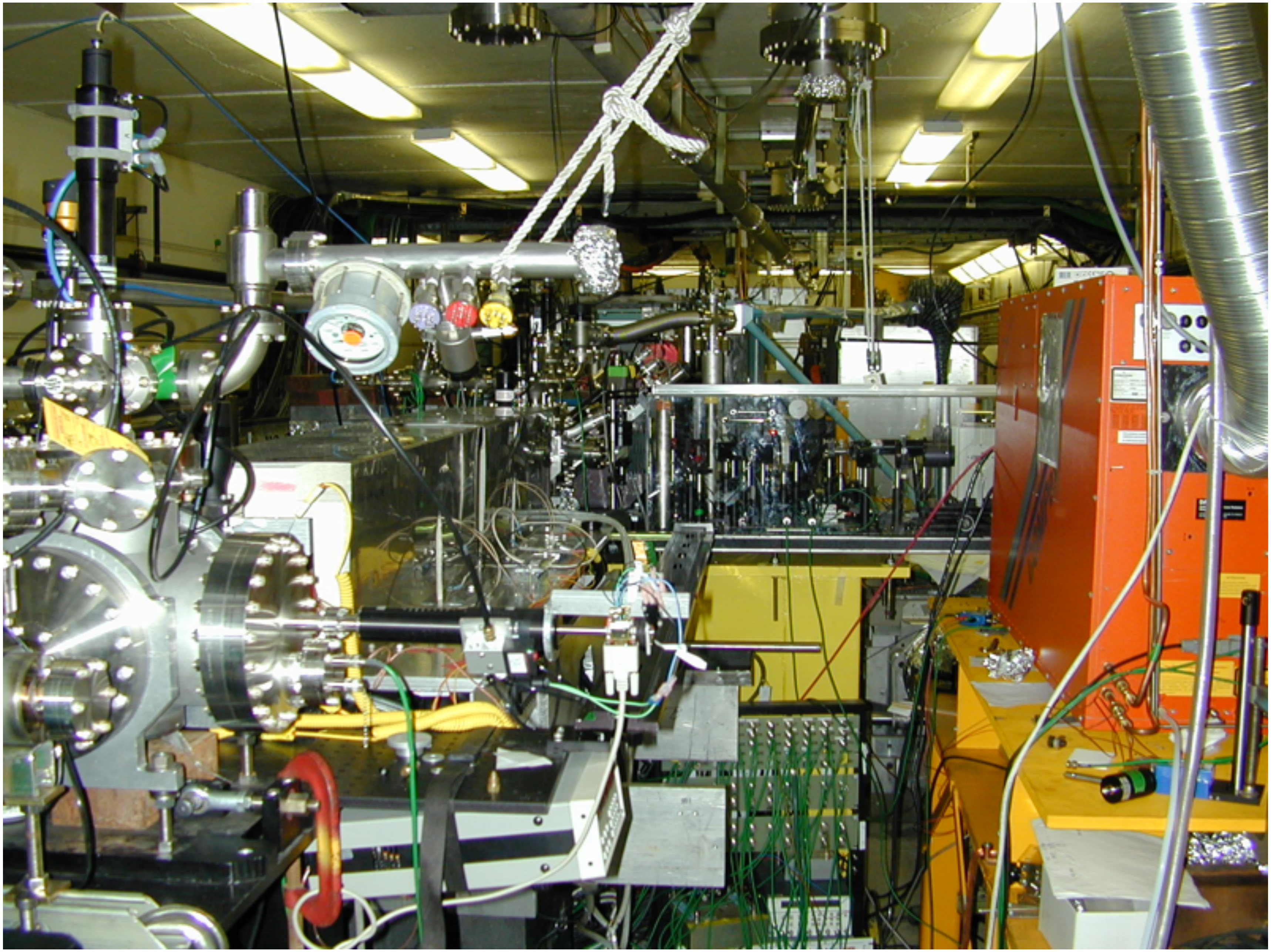
We Made a Home for Ourselves at SLAC

We Started to Develop the Needed Diagnostics



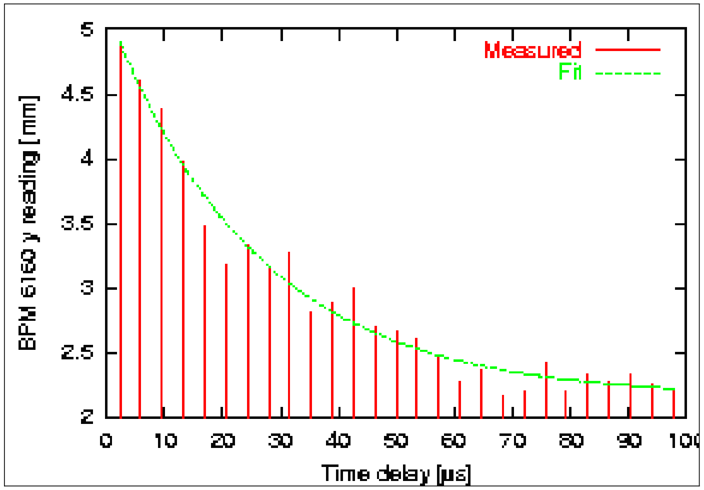


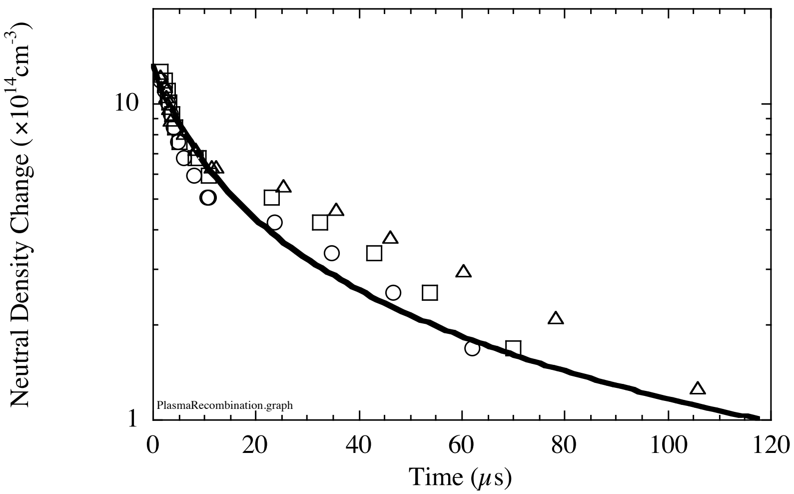
Soon We Had Built Our Own Laboratory



First Experimental Result: Plasma Induced Beam Motion

N=2×10^{10} e$^-$, ΔE≈0.3%





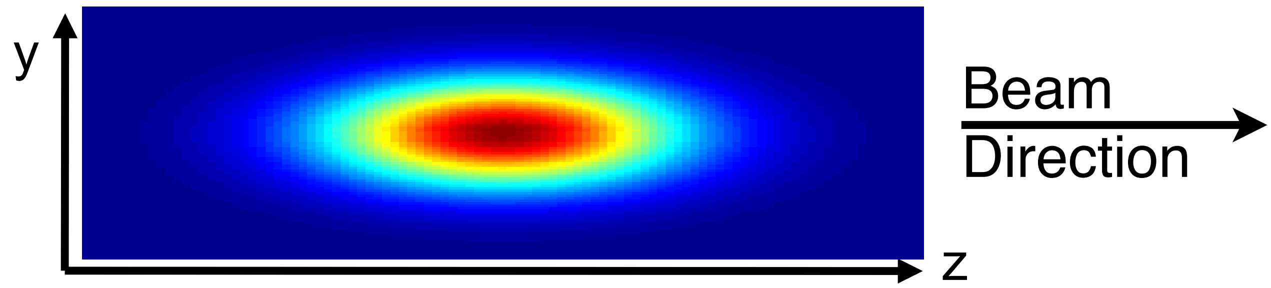
n_e≈e$^-$ pulse-laser pulse delay

- Vertical motion of the beam centroid as a function of ionizing laser-e$^-$ beam delay i.e., plasma density
- $n_e \approx n_{e,max} e^{-t/\sigma}$, $\sigma \approx 27\ \mu s$
- Time evolution of the plasma density as measured by laser visible interferometry
- n_e decreases by a factor of 2 in ≈12 μs

- The plasma kicks around the beam tail ⇔ observe centroid motion
- Beam tail due to wake fields in the accelerator

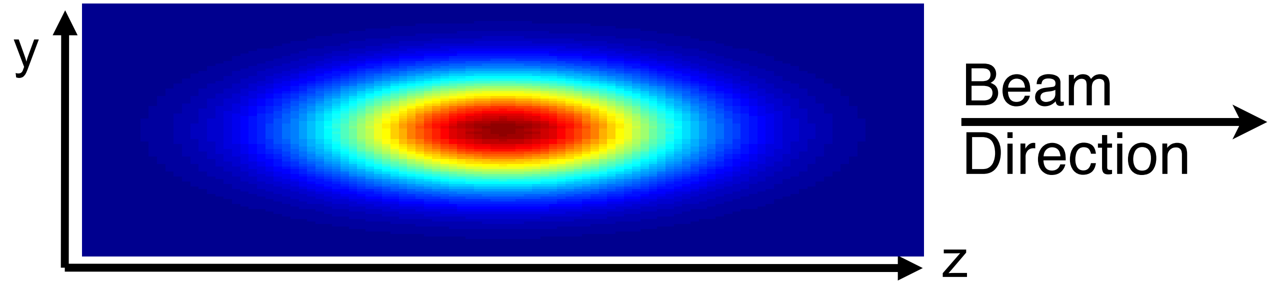
Need Everyone to Speak the Same 'Language'

This is how the scientists at the Universities assumed the beam would be...

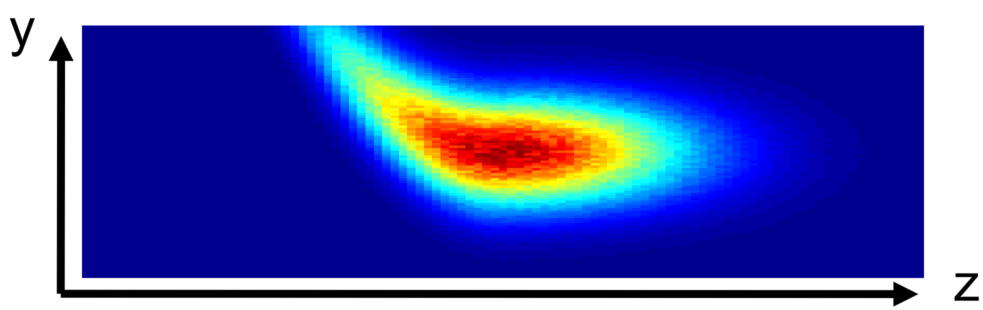


Need Everyone to Speak the Same 'Language'

This is how the scientists at the Universities assumed the beam would be...



The Accelerator Physicists at SLAC assumed everyone knew the beam can easily be this...

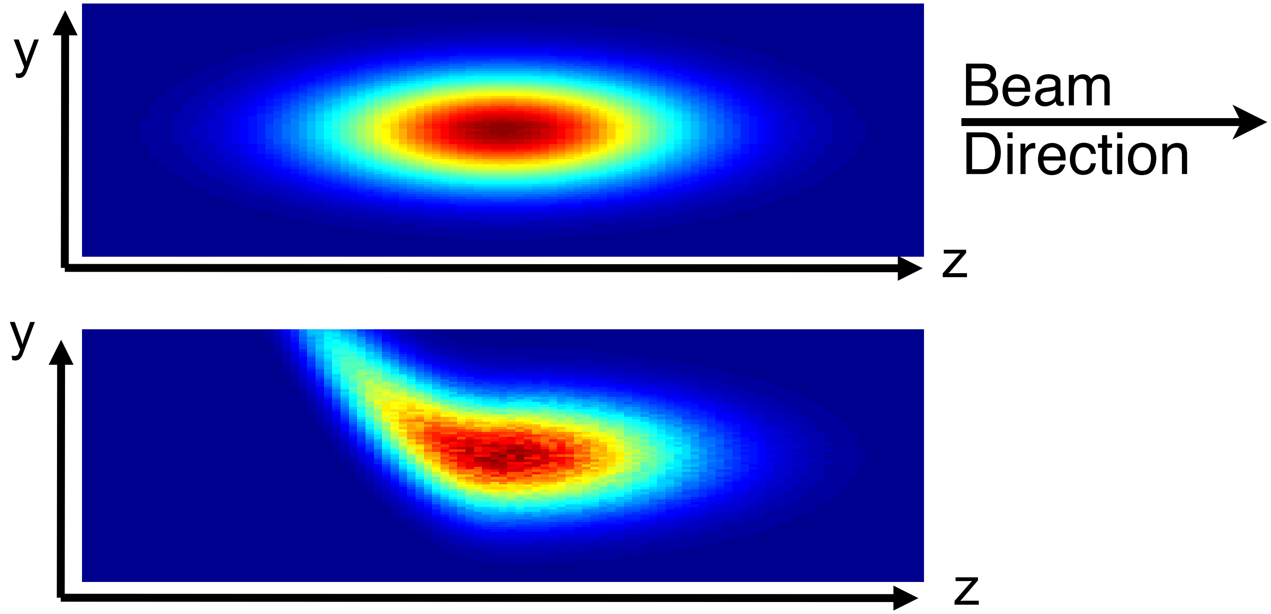


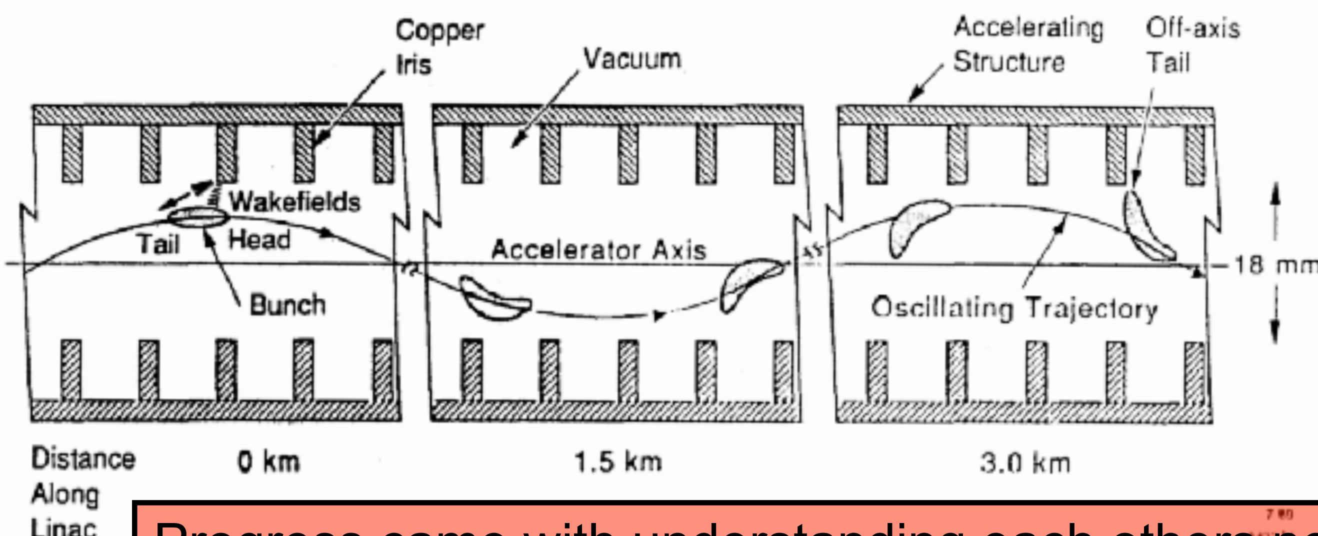
Need Everyone to Speak the Same ‘Language’

SLAC

This is how the scientists at the Universities assumed the beam would be...

The Accelerator Physicists at SLAC assumed everyone knew the beam can easily be this...





LINEAR COLLIDER ACCELERATOR PHYSICS ISSUES REGARDING ALIGNMENT, JOHN T. SEEMAN SLAC (1989)

Progress came with understanding each others needs, concerns and limitations

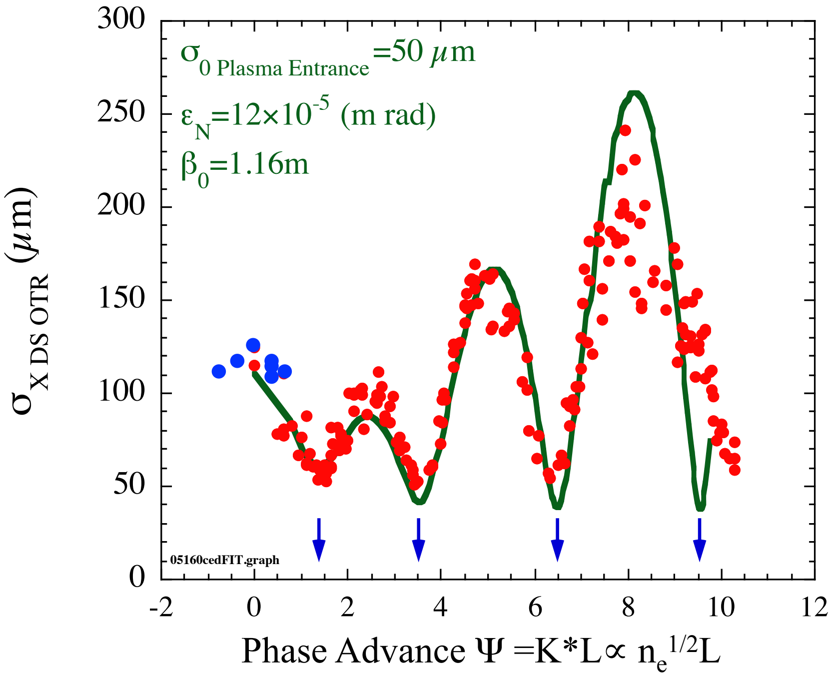
Plasma Focusing of Electrons

USC UCLA SLAC

Transverse Envelope Dynamics Of A 28.5 Gev Electron Beam In A Long Plasma

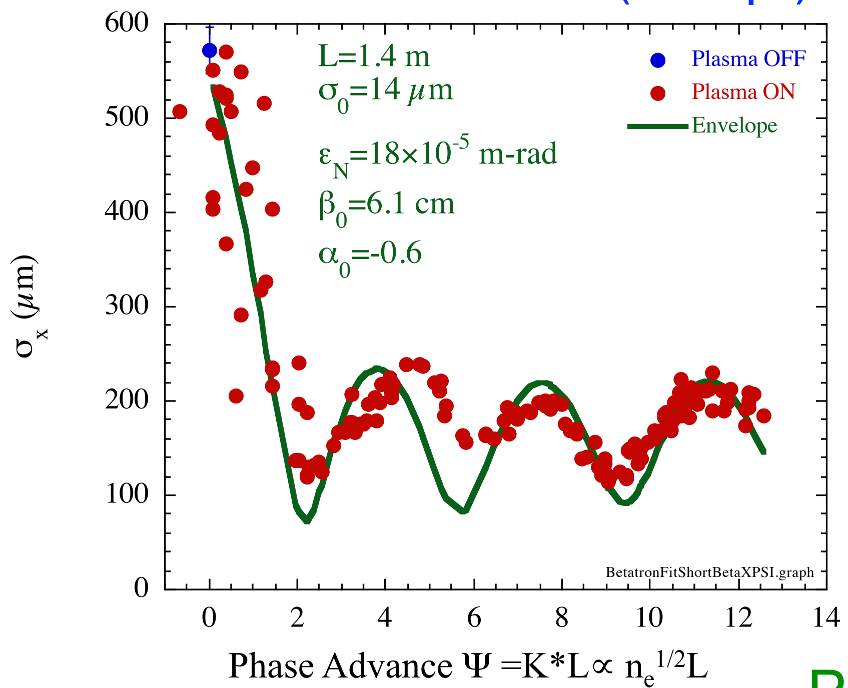
Meter-Scale Plasma-Wakefield Accelerator Driven By A Matched Electron Beam

Large Beam Size ($K>1/\beta_0$)



Phys. Rev. Lett. **88**, 154801 (2002)

Small Beam Size ($K\leq1/\beta_0$)



Phys. Rev. Lett. **93**, 014802 (2004)

- No emittance growth observed as n_e is increased
- Stable propagation over 1.4m at up to $n_e = 1.8\times10^{14}$ e^-/cm^3
- Channeling of the beam over 1.4m or > 12 β_0

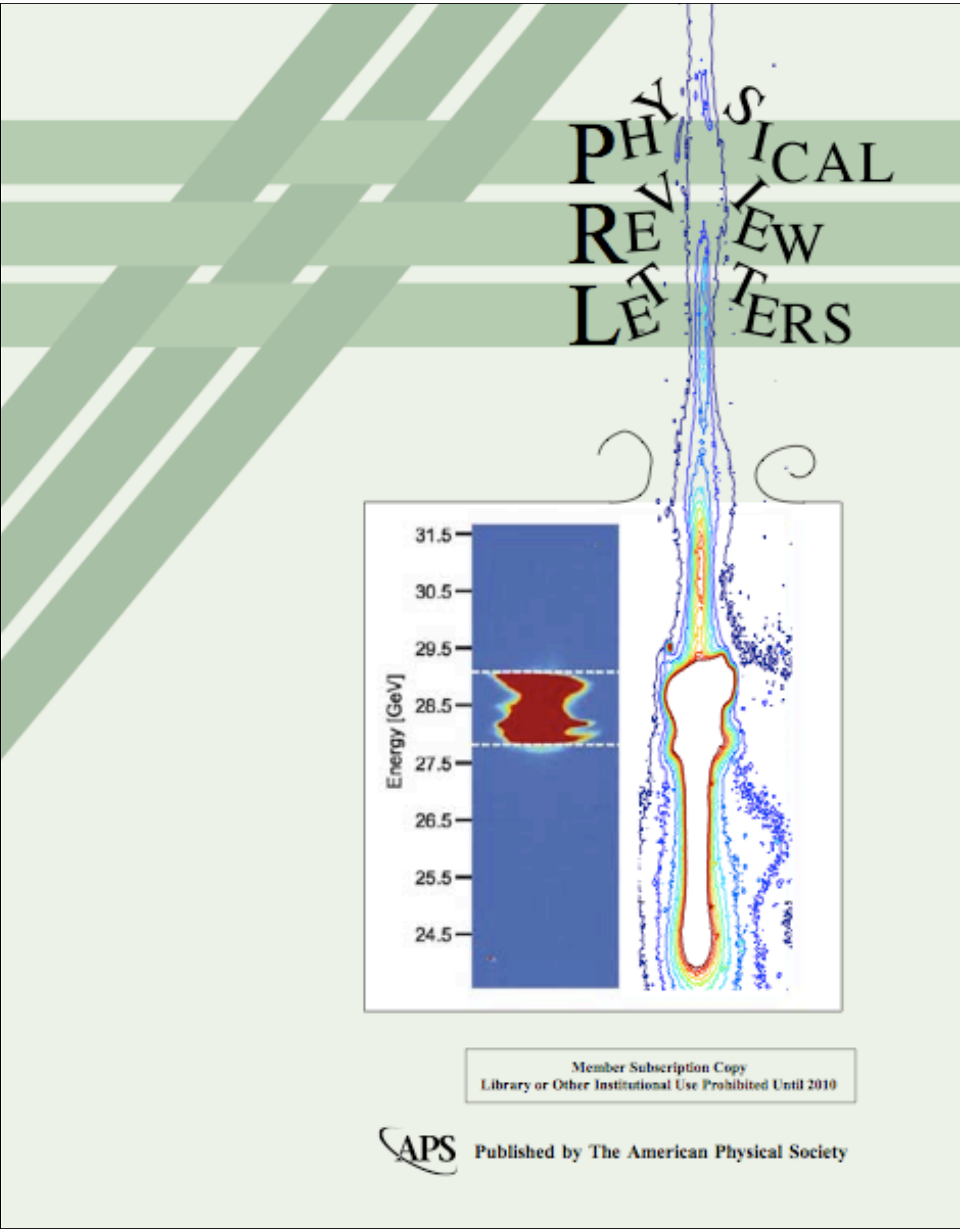
Plasma = Ideal Thick Lens

<u>Summer 2004:</u>

- **Results Recently Published**
- **Outdated within two weeks!**

<u>Summer 2005:</u>

- **Increased beamline apertures**
- **Plasma Length increased from 10 to 30 cm**



Summer 2004:

- **Results Recently Published**
- **Outdated within two weeks!**

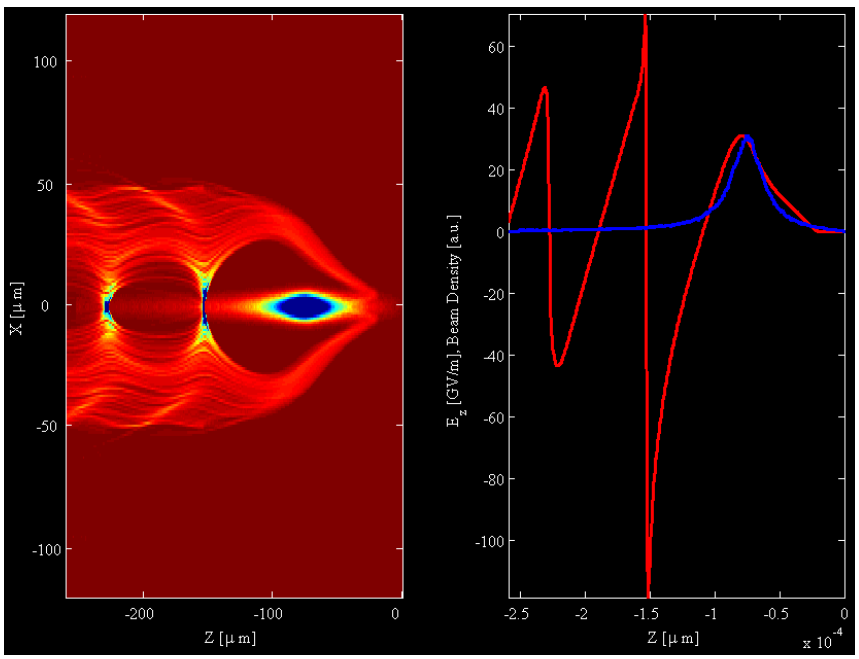
Summer 2005:

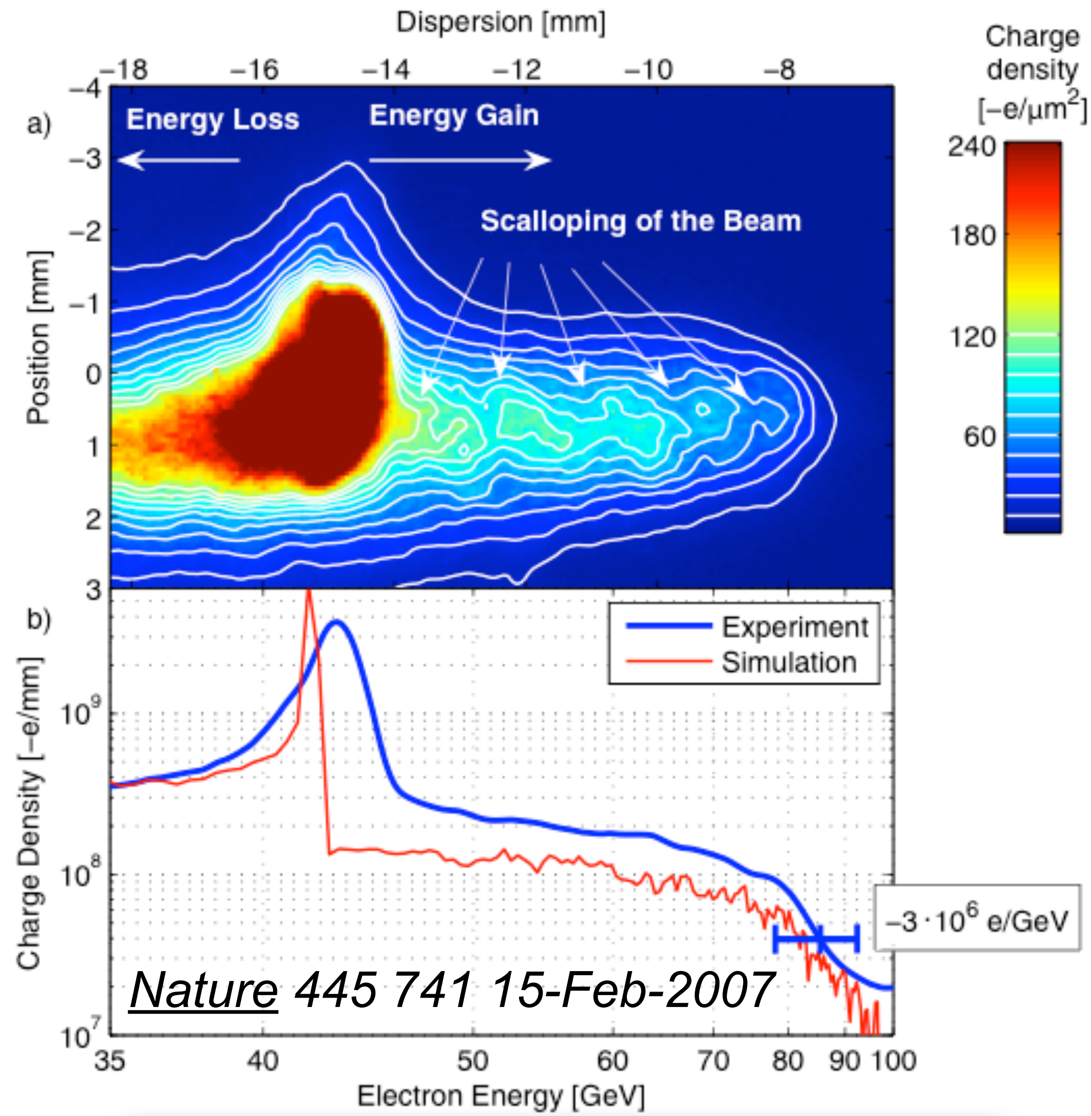
- **Increased beamline apertures**
- **Plasma Length increased from 10 to 30 cm**
- **Energy Gain > 10GeV!**

…but spectrometer redesign necessary to transport more of the low energy electrons

E-167: Energy Doubling with a Plasma Wakefield Accelerator in the FFTB

- Acceleration Gradients of ~50GeV/m (3,000 x SLAC)
  - Doubled energy of 45 GeV electrons in 1 meter plasma
- Single Bunch





Next Step: Particle acceleration to beam acceleration @ FACET

FACET Has a Multi-year Program to Study PWFA

Primary Goal:

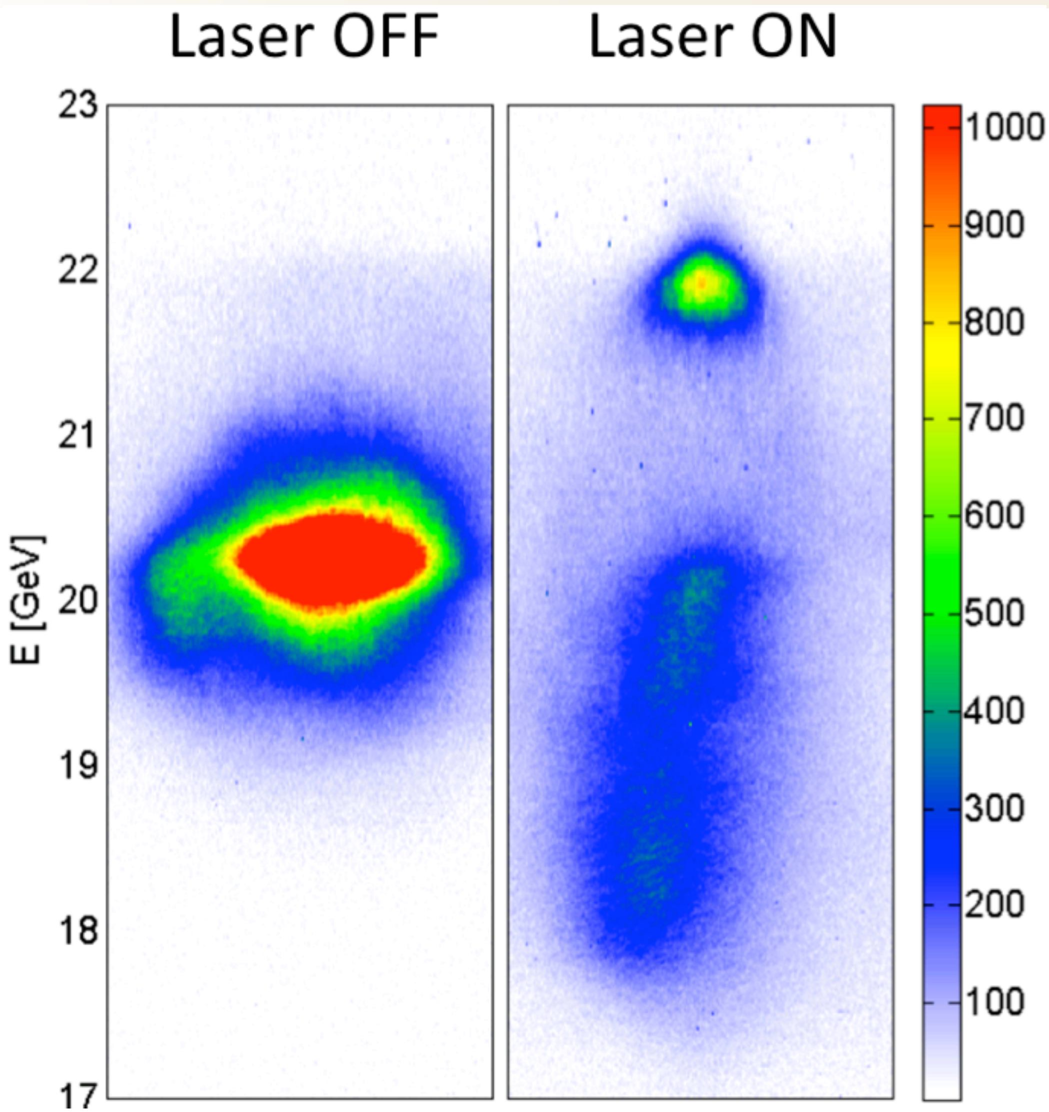
Demonstrate a single-stage high-energy plasma accelerator for electrons.

- 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)

Multi-GeV Energy Gain in <30cm plasma!

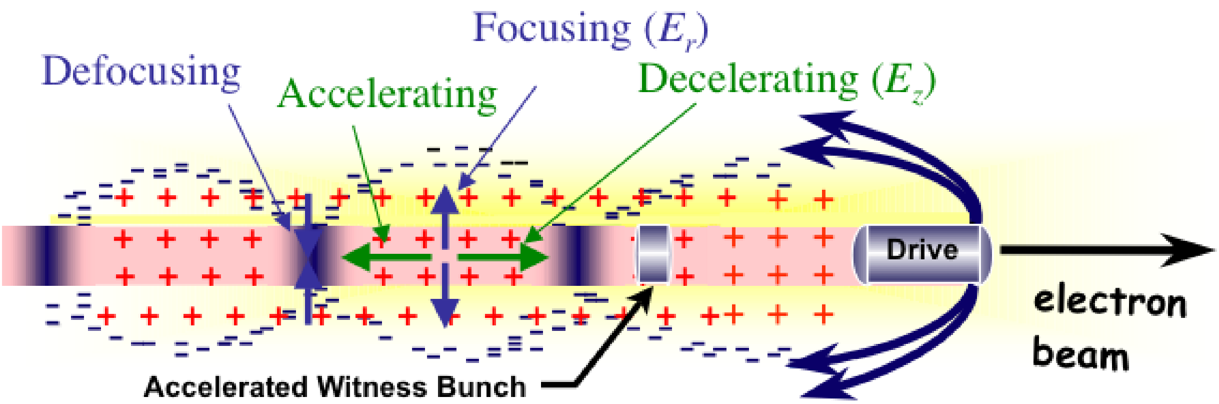


- Negligible wakefield without pre-formed plasma
- Drive bunch looses energy
- Witness gains nearly 2GeV
- Accelerating wakefield ~ 6GeV/m

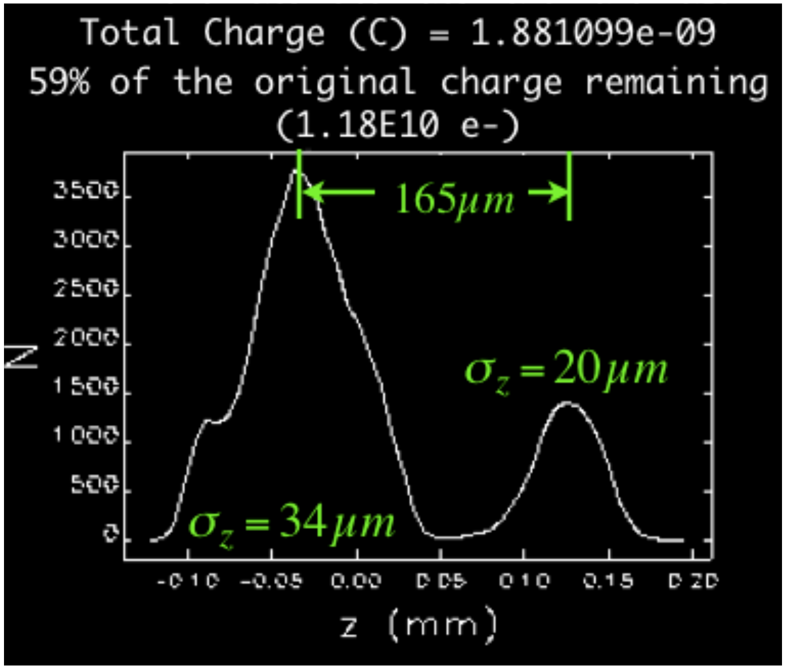
FY13 FACET Run put all the tools in place: pre-ionized plasma and tailored two-bunch structure for first beam driven mono-energetic acceleration

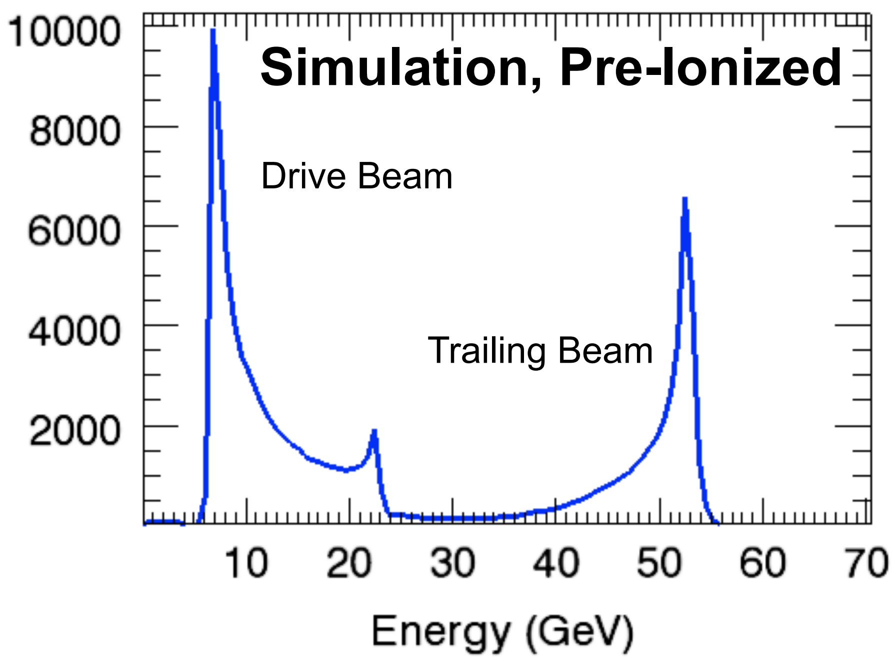
Primary Scientific Goal of FACET:
Demonstrate a Single Stage Plasma Accelerator for Electrons

E200: Collaboration between SLAC/UCLA



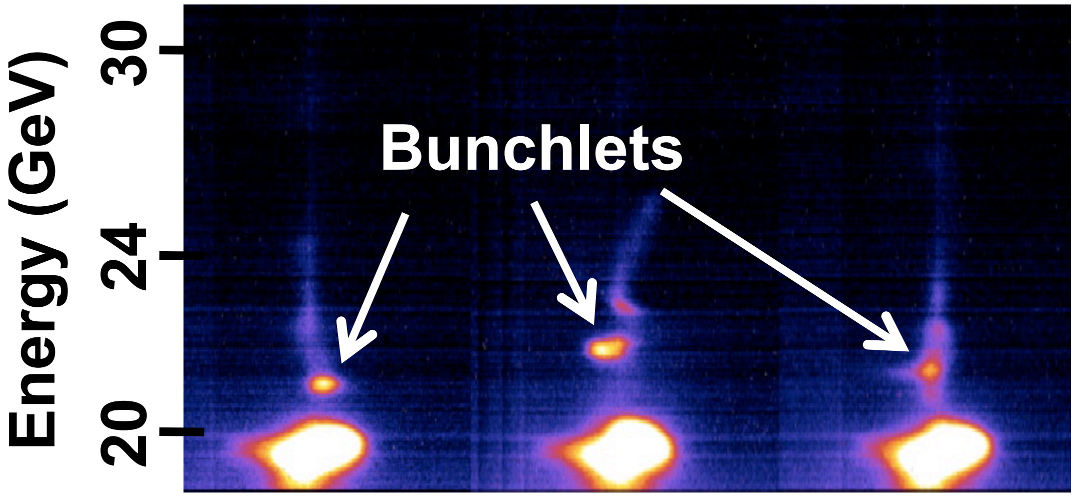
After 143 cm of 5 x 10^{16} plasma
- Energy Gain 30 GeV
- Energy Spread ~ 5%
- Energy Loss 17 GeV, Beam loading efficiency 64%



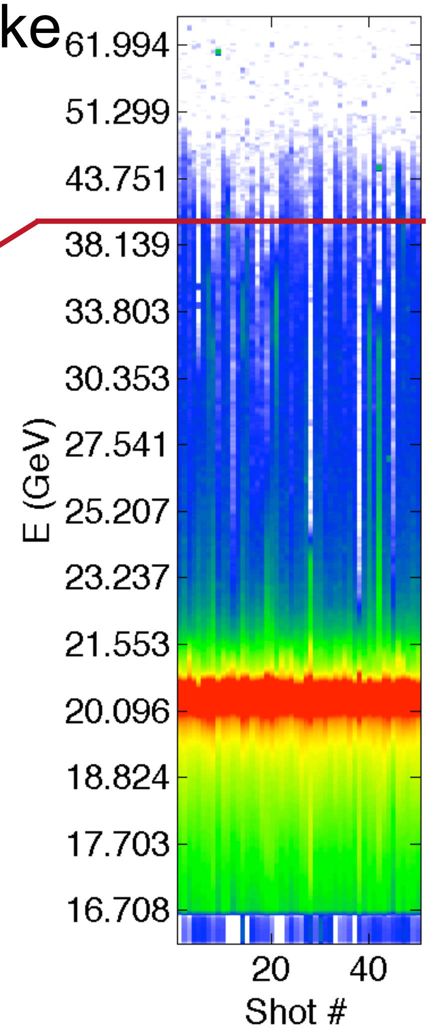


High Brightness Beam Development

- Quest for better beam quality in LWFA has led to investigation of many ways to control injection into the plasma bubble/wake
- Large fields generated by focused FACET beam have given rise to additional methods of injection
  - Beam fields large enough to melt Be, Ti
  - Ionization of Li, Rb, Rb++, Ar, He...



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

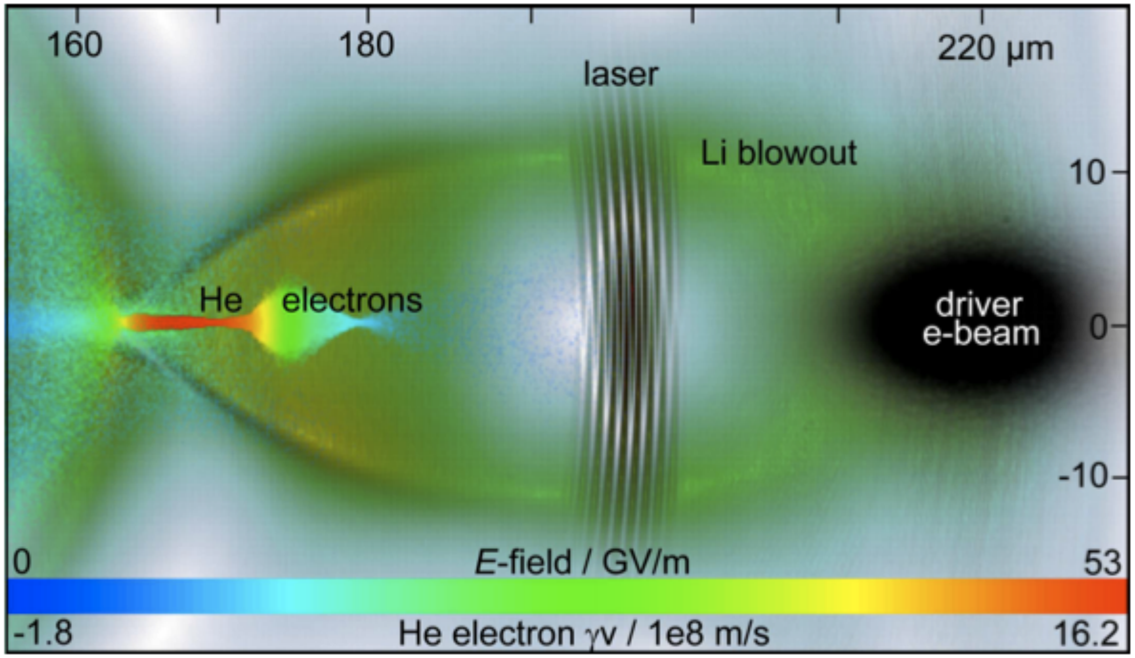


Tailored plasma can act as high-brightness injector AND high-gradient accelerator

Creating Ultra High-Brightness Beams with PWFA

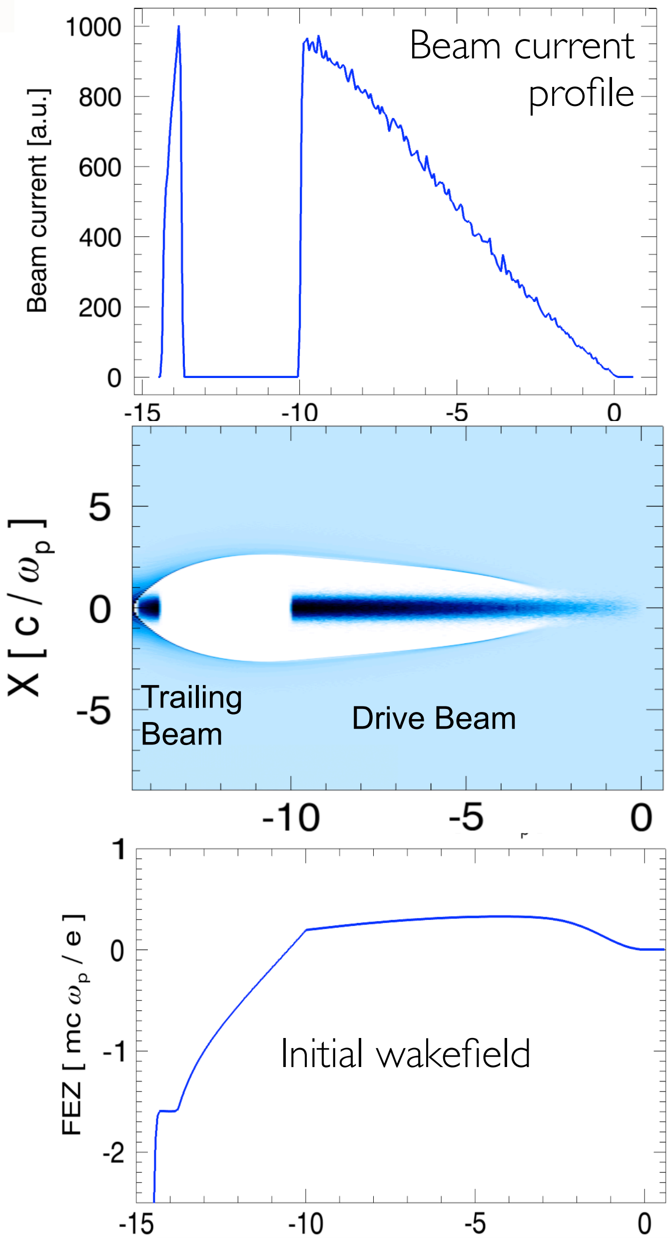
- Plasma bubble (wake) can act as a high-frequency, high-field, high-brightness electron source
- Photoinjector + 100GeV/m fields in the plasma =
  - Unprecedented emittance (down to 10^{-8} m rad)
  - Sub-μm spot size
  - fs pulses

'Trojan Horse Technique'

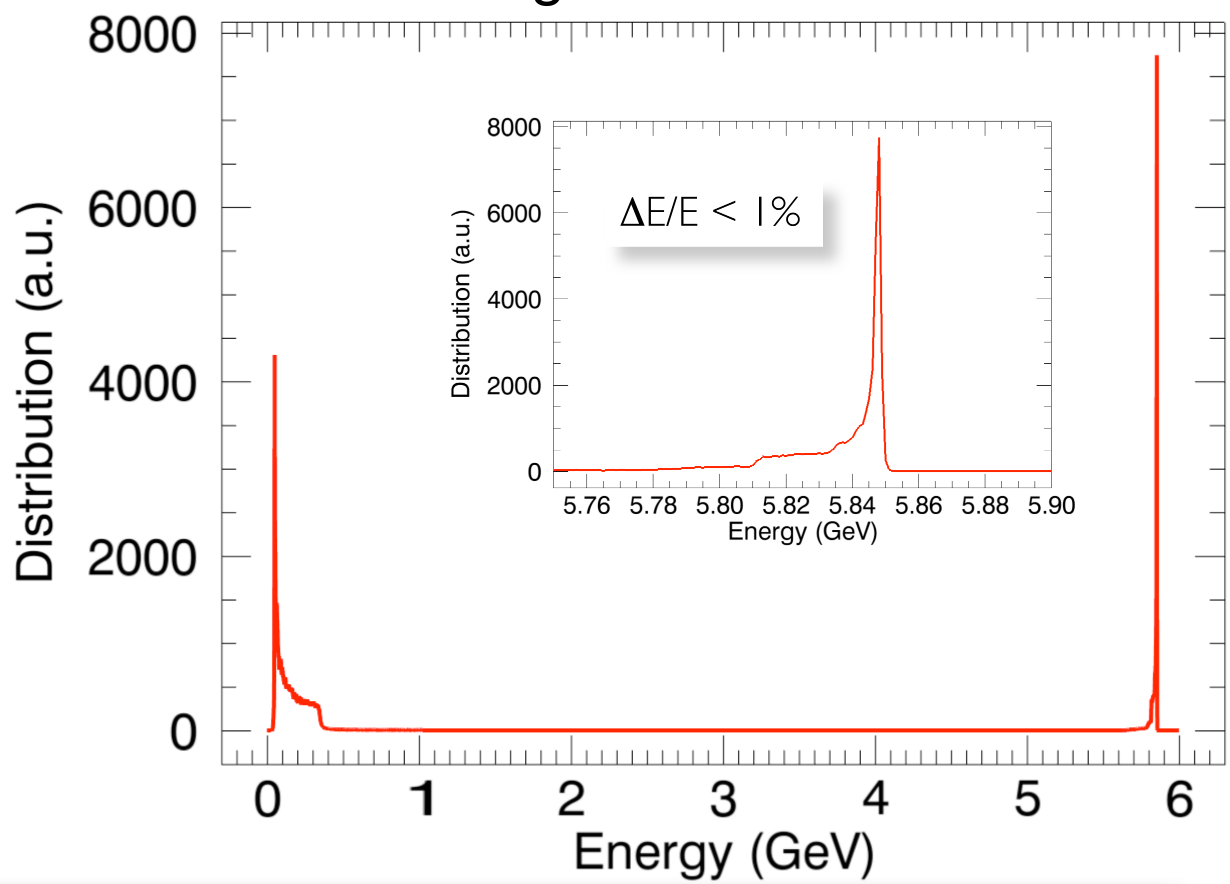


Leverages efficiency and rep rate of conventional accelerators to produce beams with unprecedented brightness for collider & XFEL applications

Shaped Current Profile Maximizes Efficiency, Energy Gain



- Application to colliders & X-FELs
- Reduced energy spread
- Higher efficiency (beam power)
- Fewer stages



see W. Lu et al "High Transformer Ratio PWFA for Application on XFELs", PAC2009 Proceedings

Applications Go Beyond HEP

Plasma Based FEL Concept

Resonant Wavelength ~ 5Å
Saturation Length ~ 6m

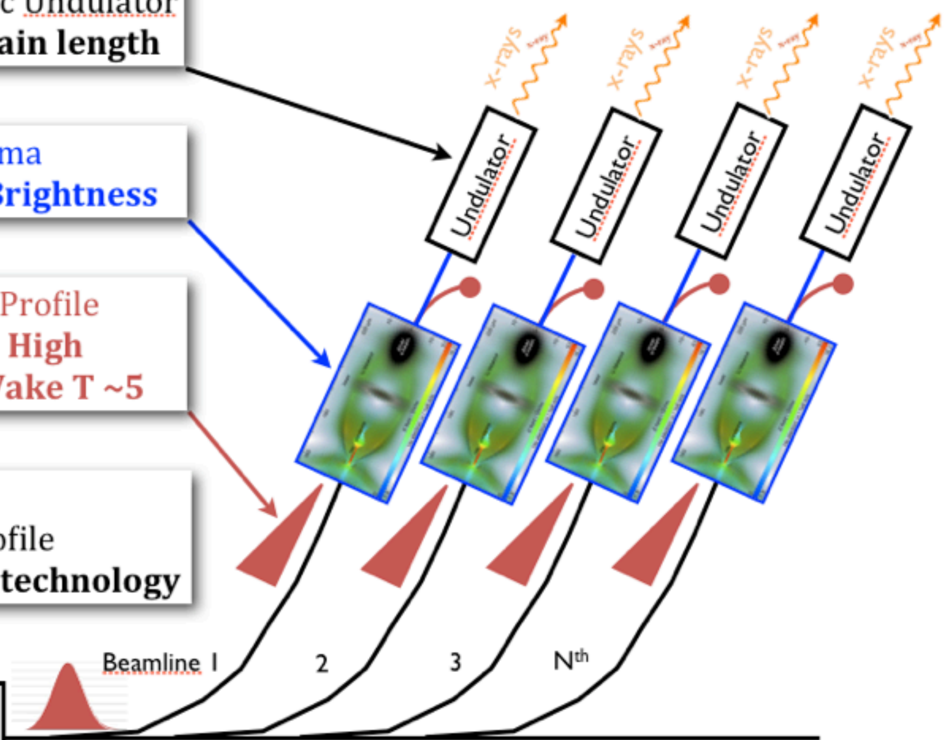
Cryogenic Undulator
Short gain length

Trojan Horse Plasma
High Energy AND High Brightness

Triangular Current Profile
Large Amplitude, High Transformer Ratio Wake T ~5

Drive Beam
Gaussian current profile
Compact, efficient, mature technology

NC or SC Linac
$E_0 \sim 500$ MeV

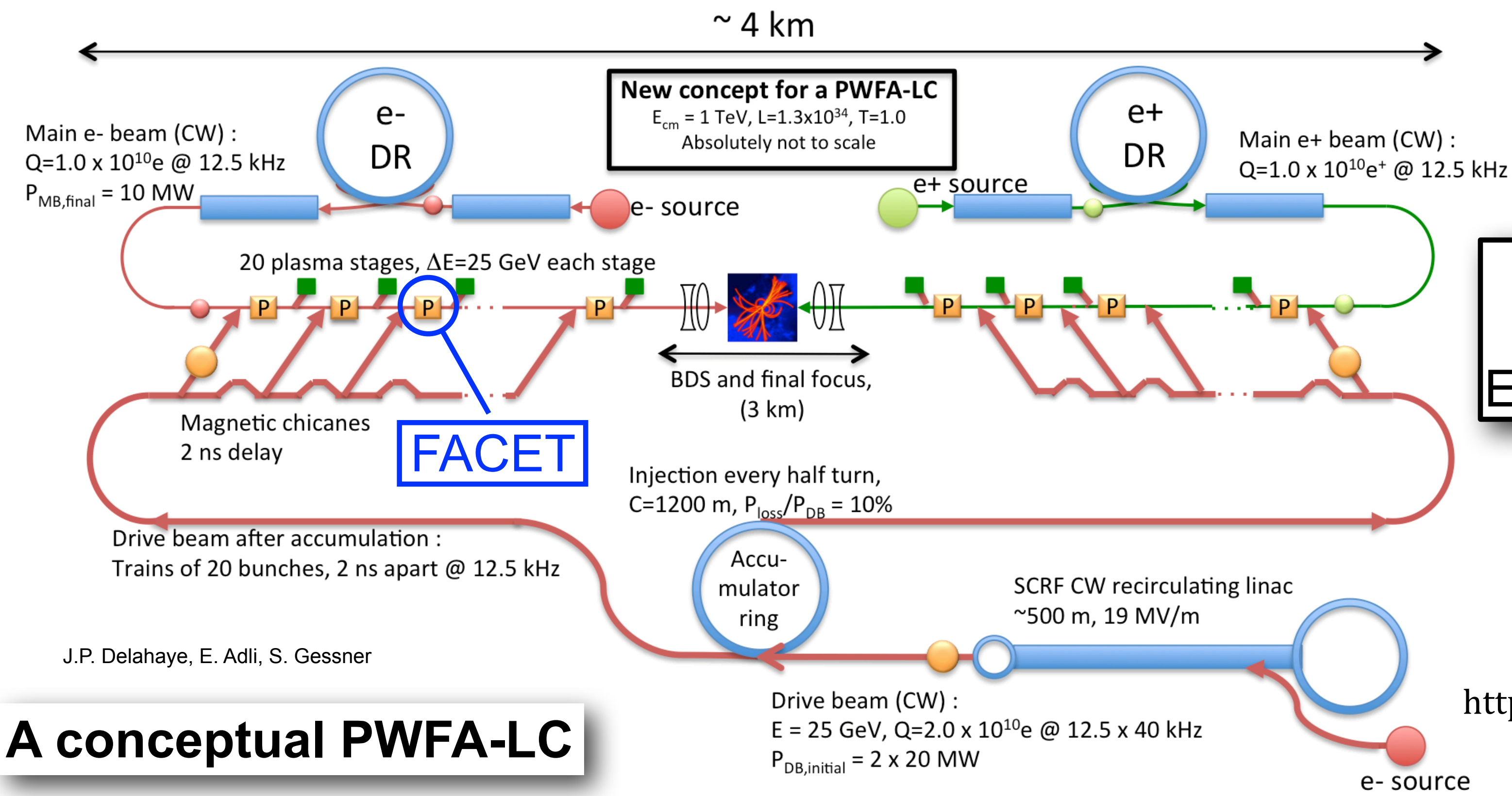


Drive Beam	
Charge	3nC
Energy	500 MeV
Rep Rate	1MHz
Bunch length	210µm, ramped
Peak Current	8.5kA
Normalized Emittance	2.25 mm-mrad
Trojan Horse (plasma)	
Plasma Density	10^{17} e^-/cc
Plasma Length	20 cm
Transformer Ratio	5
Trojan Horse (beam)	
Charge	3 pC
Energy	2.5 GeV
Energy Spread	2×10^{-4}
Normalized Emittance	3×10^{-8} m-rad
Peak Current	300A
Bunch length	12 fs
Brightness	7×10^{17} A/m^{2}rad
Undulator Parameters	
Period	9 mm
K	2
Number of periods (N)	660
Radiation Parameters	
Wavelength	5.4 Å
Single pulse energy	50 µJ
Number of Photons	$>10^{11}$
Peak Power	1.6 GW

FACET-II has the opportunity to develop next-generation light sources using plasma accelerators as drivers, and to test novel concepts.

FACET Begins 2nd Phase of PWFA

- SLAC FFTB demonstrated electron acceleration with 50GeV/m for 85cm
- FACET issues single stage
- FACET-II staging, high-brightness beams



E_{cm} = 1 TeV
L = 10^{34} cm^{2}s^{-1}
Efficiency$_{\text{wall plug}}$ ~ 11%

SLAC-PUB-15426
http://arxiv.org/abs/1308.1145

A conceptual PWFA-LC

FACET program is a transition from particle acceleration to beam acceleration to demonstrate a single PWFA stage with a high-quality beam

Summary

This work is a lot of fun because it combines three important things:

1. Compelling scientific questions
2. University – National Lab Collaborations (Thank you to my colleagues!)
3. State of the art facilities

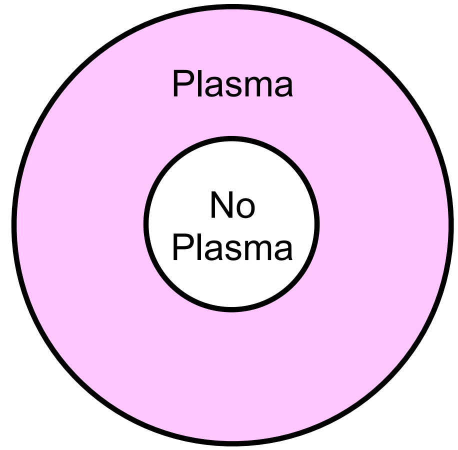
... and rapid scientific progress has followed

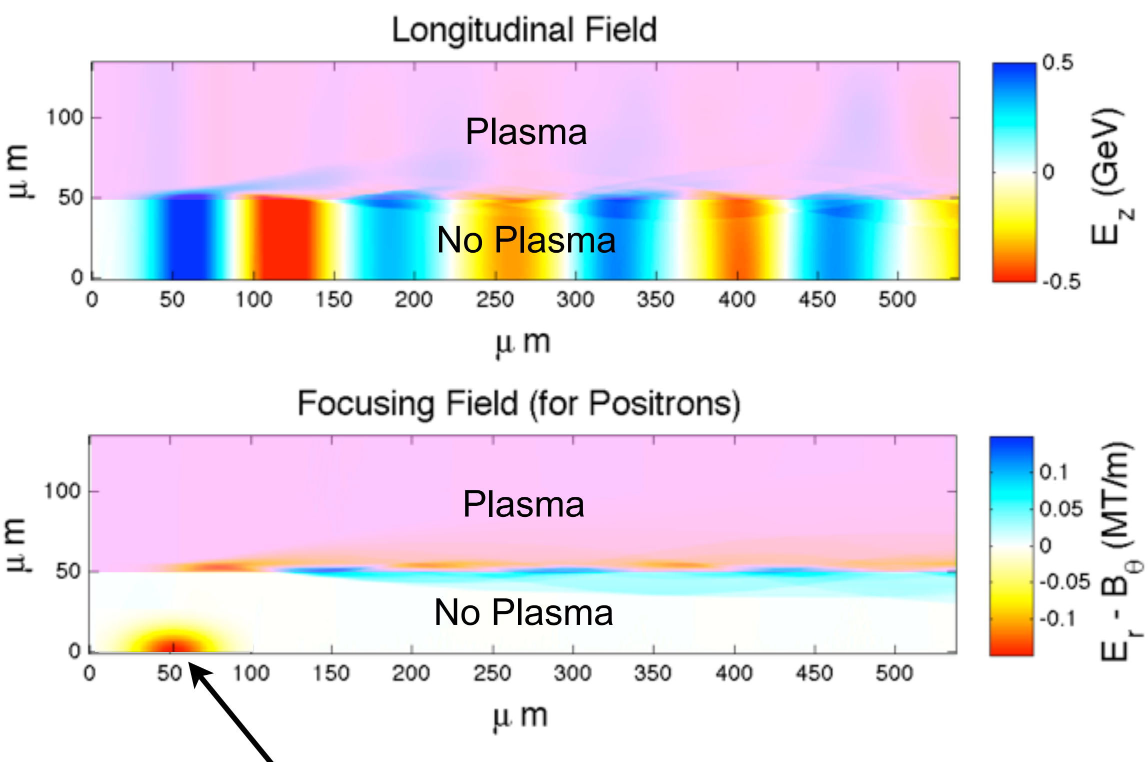
My outlook for the years ahead:

- It is a very exciting time for our beam driven plasma accelerators!
- Optimistic we will see demonstration of high-gradient meter scale plasma stage within the next year with good beam quality and efficiency
- Coming years will build on this with injection and higher brightness beams paving the way for the first applications

Hollow Channel Plasmas

- Beam propagates down the axis in no plasma
- Plasma wake from inner sheath of channel
  - Acceleration
  - No focusing (no emittance growth)





Uniform longitudinal fields

No focusing fields on axis

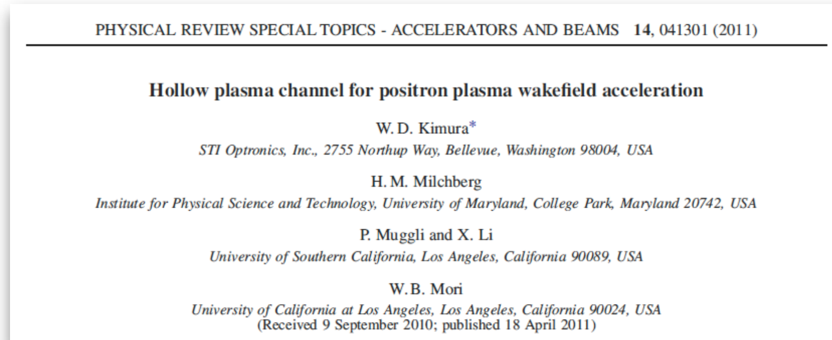
Electron beam driver

2D Osiris Simulations
Run on Hoffman2 Cluster at UCLA

Hollow Channel Plasma Experiments at FACET

Kimura et. al. propose using a high-order bessel beam to create an annular ionization region in the gas. See also:

- J. Fan et. al. J. Fan, E. Parra, I. Alexeev, K.Y. Kim, H. M. Milchberg,L.Ya. Margolin, and L. N. Pyatnitskii, Phys. Rev. E 62, R7603 (2000).
- N. E. Andreev, S. S. Bychkov, V.V. Kotlyar, L.Ya. Margolin, L. N. Pyatnitskii, and P. G. Serafimovich, Quantum Electron. 26, 126 (1996).



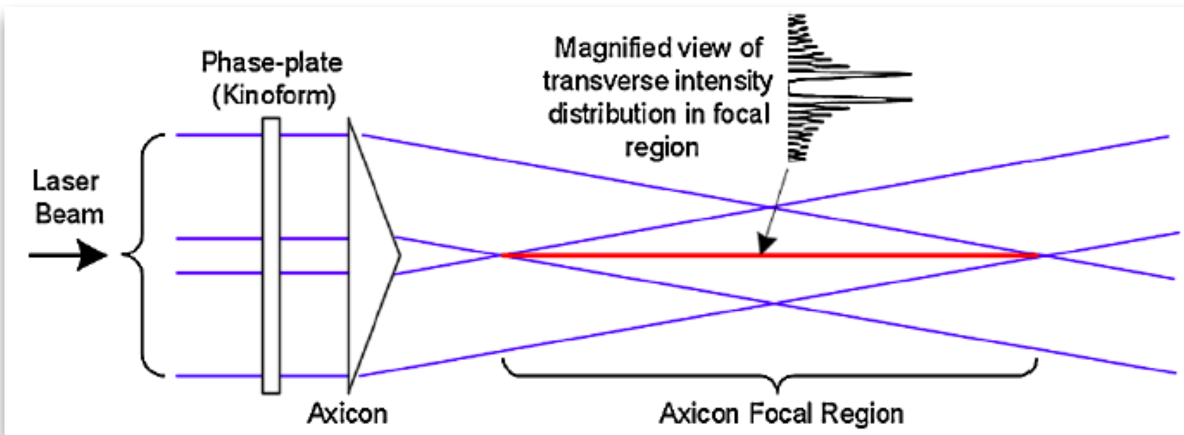
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 041301 (2011)

Hollow plasma channel for positron plasma wakefield acceleration

W. D. Kimura*
STI Optronics, Inc., 2755 Northup Way, Bellevue, Washington 98004, USA
H. M. Milchberg
Institute for Physical Science and Technology, University of Maryland, College Park, Maryland 20742, USA
P. Muggli and X. Li
University of Southern California, Los Angeles, California 90089, USA
W. B. Mori
University of California at Los Angeles, Los Angeles, California 90024, USA
(Received 9 September 2010; published 18 April 2011)

Laser/Kinoform Parameters

Power	1 TW (300 mJ/ 300 fs)
$r_{kinoform}$	1.6 cm
Bessel Mode	5
“Axicon Angle”	1°



Plasma Parameters

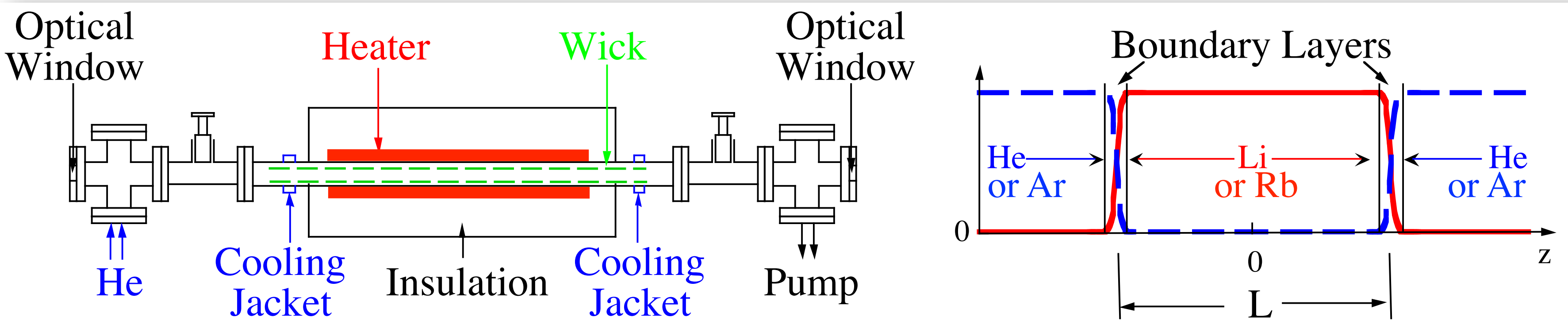
Density	1×10^{17}
J_5 Peak	46 μm
Plasma Start	40 cm
Plasma End	91 cm

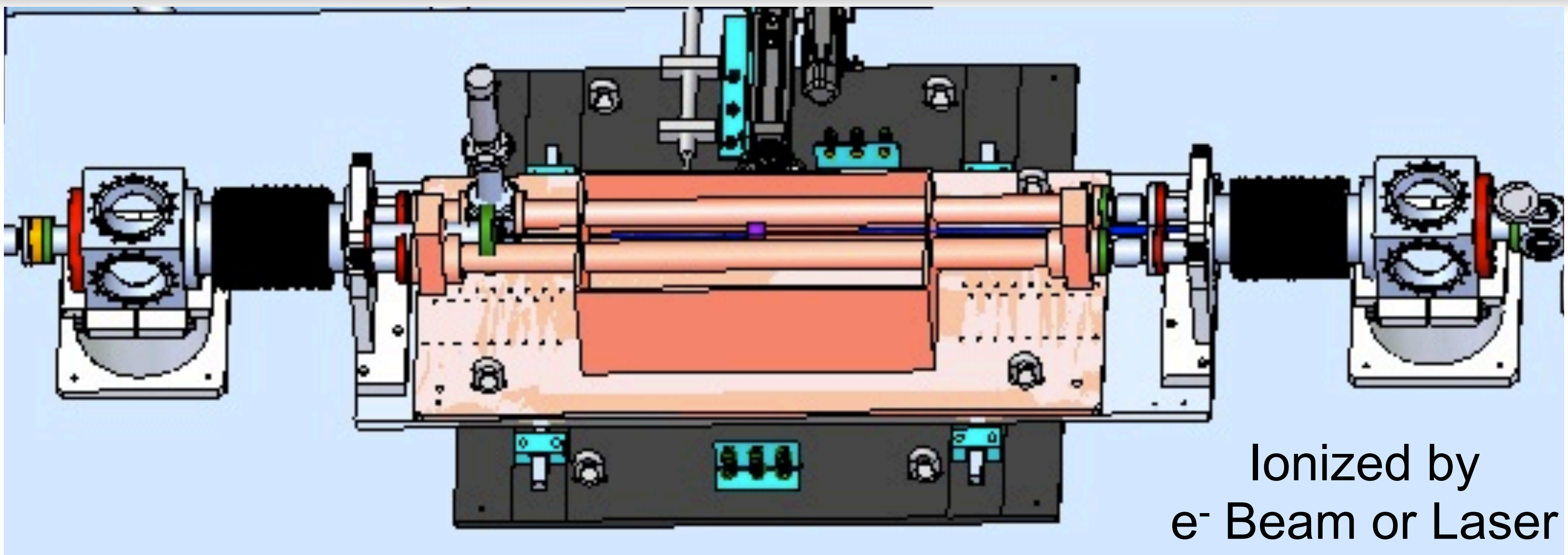
Positron Systems will re-commission this Fall with first experiments in 2014

Heat Pipe Oven Has Been Heart of Plasma Source Since 1998

UCLA SLAC

Plasma source starts with a heat pipe oven: Scalable, $n_0 = 10^{14}$-10^{17} e^-/cm^3, L = 20-200 cm





High-energy accelerator requires meter scale uniform high-density plasma