Electron and Positron Plasma Wakefield Acceleration at FACET

Spencer Gessner

IPAC 2015

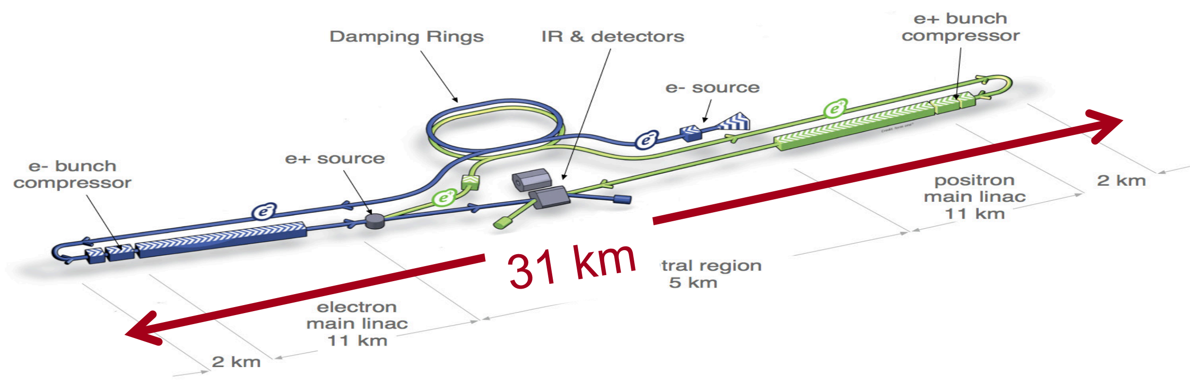
May 5th, 2015

U.S. DEPARTMENT OF ENERGY
Office of Science

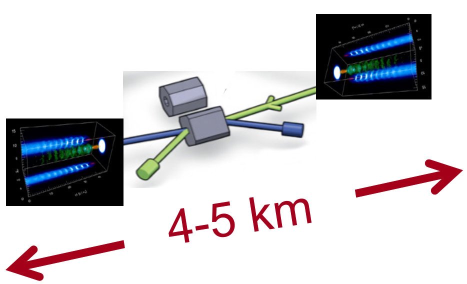
UCLA SLAC NATIONAL ACCELERATOR LABORATORY

Motivation

ILC Technology



Can we use plasma wakefield technology to create high-gradient, highly-efficient accelerators?



$$\mathcal{L} = \frac{\boxed{P_b}}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

From Conception to Experiment

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VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JU

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen[(a)]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024
(Received 20 December 1984)

A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma_0 mc^2$ to $3\gamma_0 mc^2$ before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to $4\gamma\delta mc^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.

PACS numbers: 52.75.Di, 29.15.−n

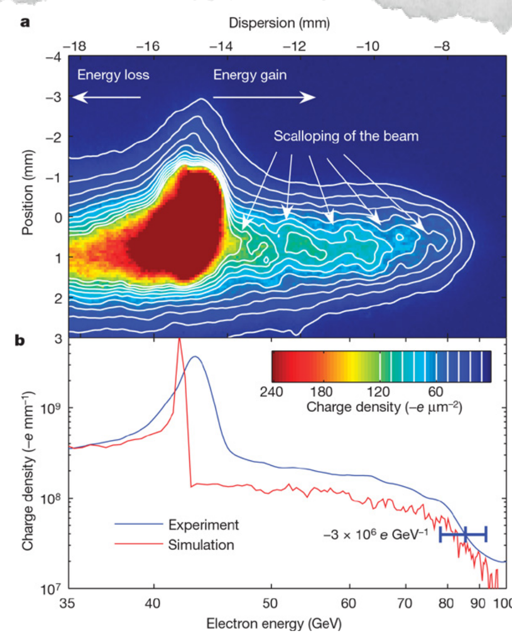
Vol 445|15 February 2007|doi:10.1038/nature05538 nature

LETTERS

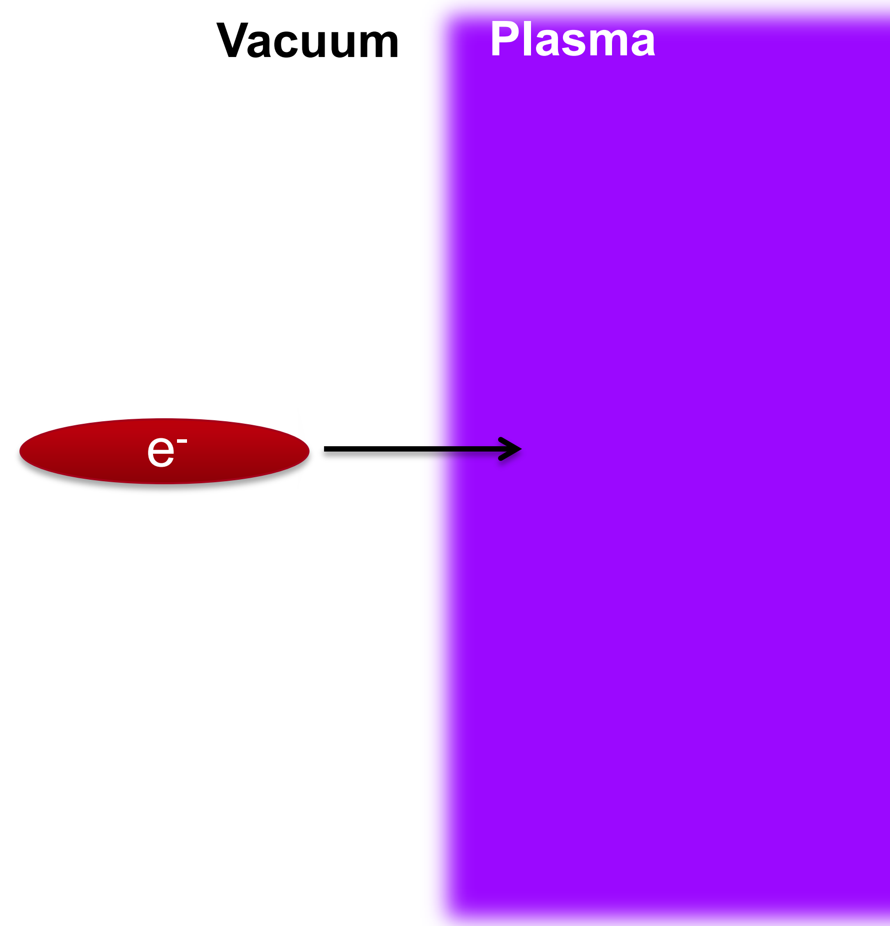
Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

Ian Blumenfeld[1], Christopher E. Clayton[2], Franz-Josef Decker[1], Mark J. Hogan[1], Chengkun Huang[2], Rasmus Ischebeck[1], Richard Iverson[1], Chandrashekhar Joshi[2], Thomas Katsouleas[3], Neil Kirby[1], Wei Lu[2], Kenneth A. Marsh[2], Warren B. Mori[2], Patric Muggli[3], Erdem Oz[3], Robert H. Siemann[1], Dieter Walz[1] & Miaomiao Zhou[2]

$eE_z > 50$ GeV/m

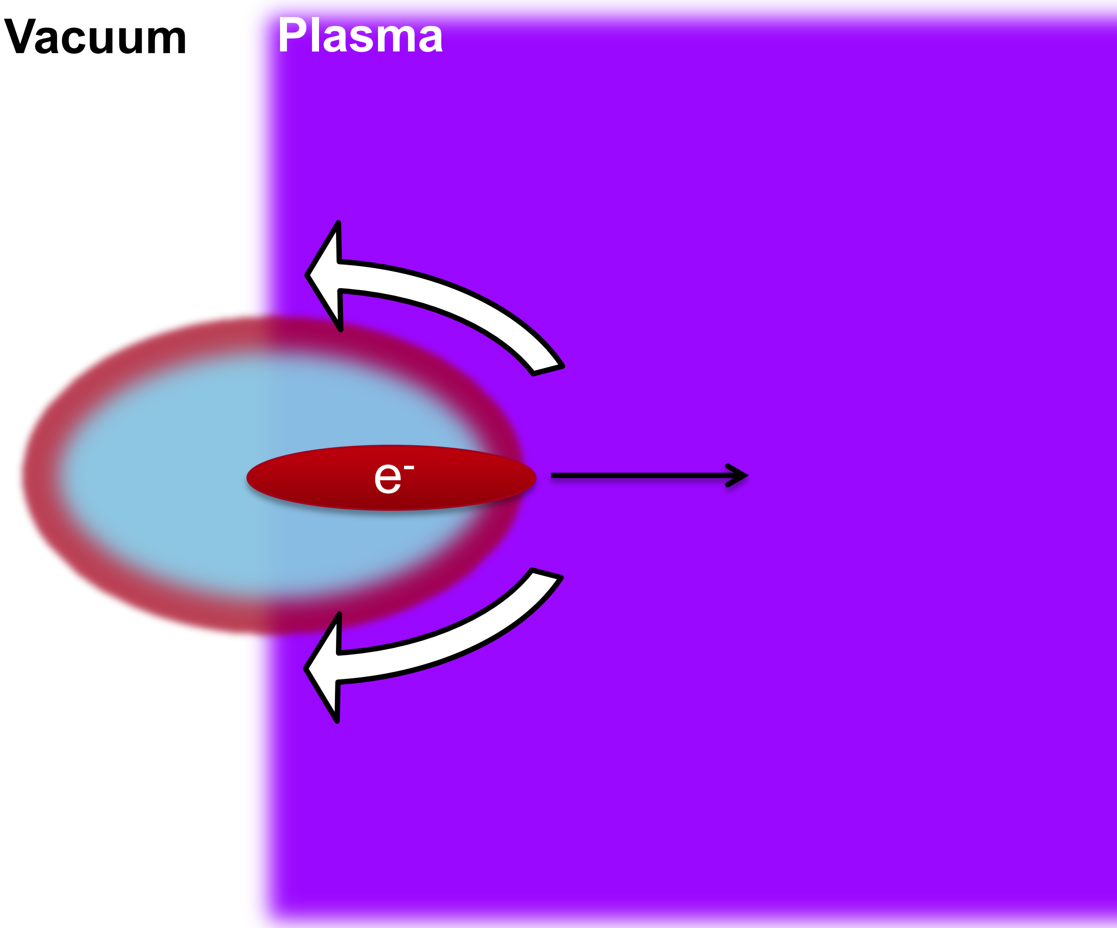


What is a Plasma Wakefield Accelerator?



An electron beam propagates to the right into a neutral plasma.

What is a Plasma Wakefield Accelerator?



As the beam enters the plasma, plasma electrons are expelled, leaving behind plasma ions.

What is a Plasma Wakefield Accelerator?

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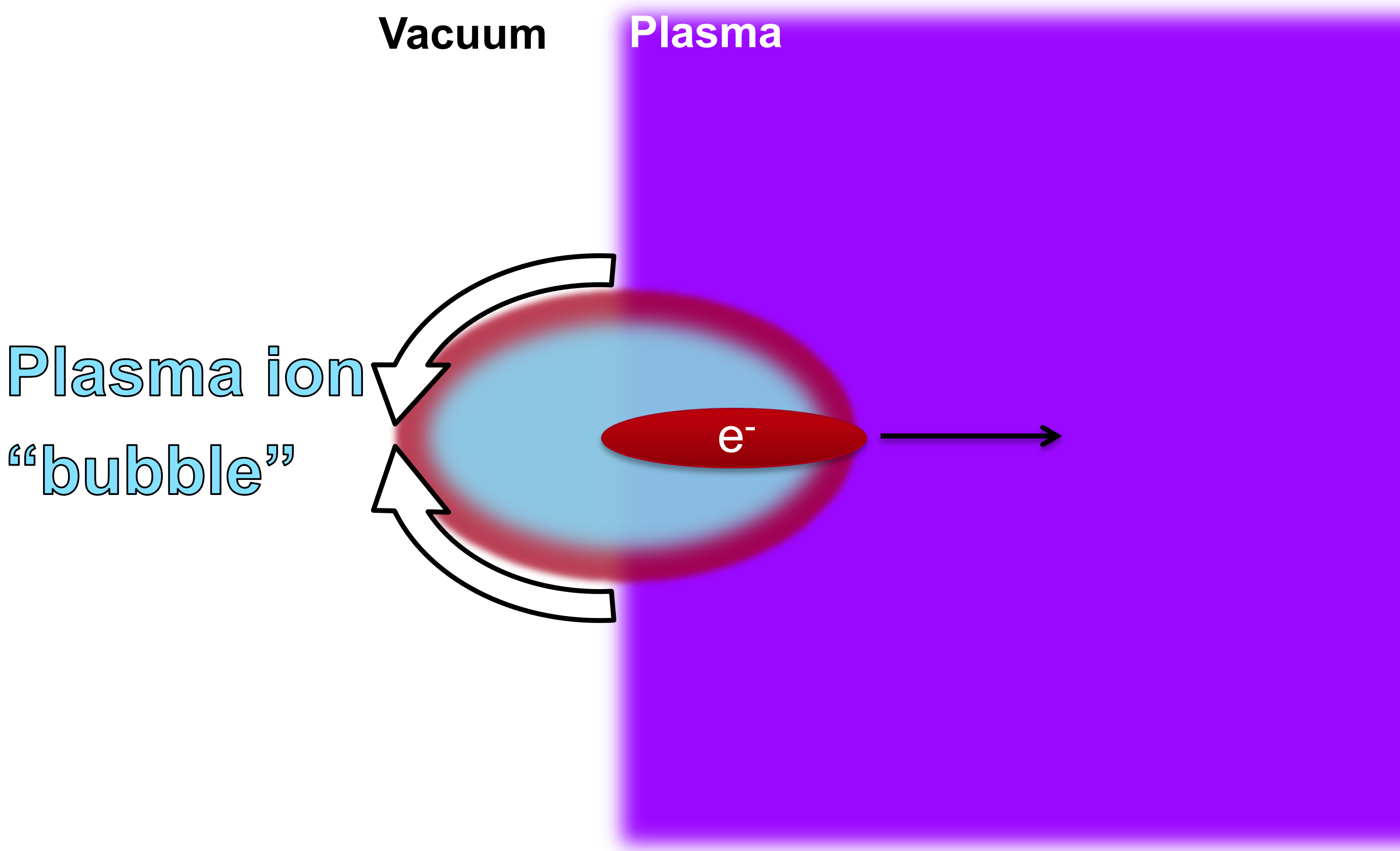
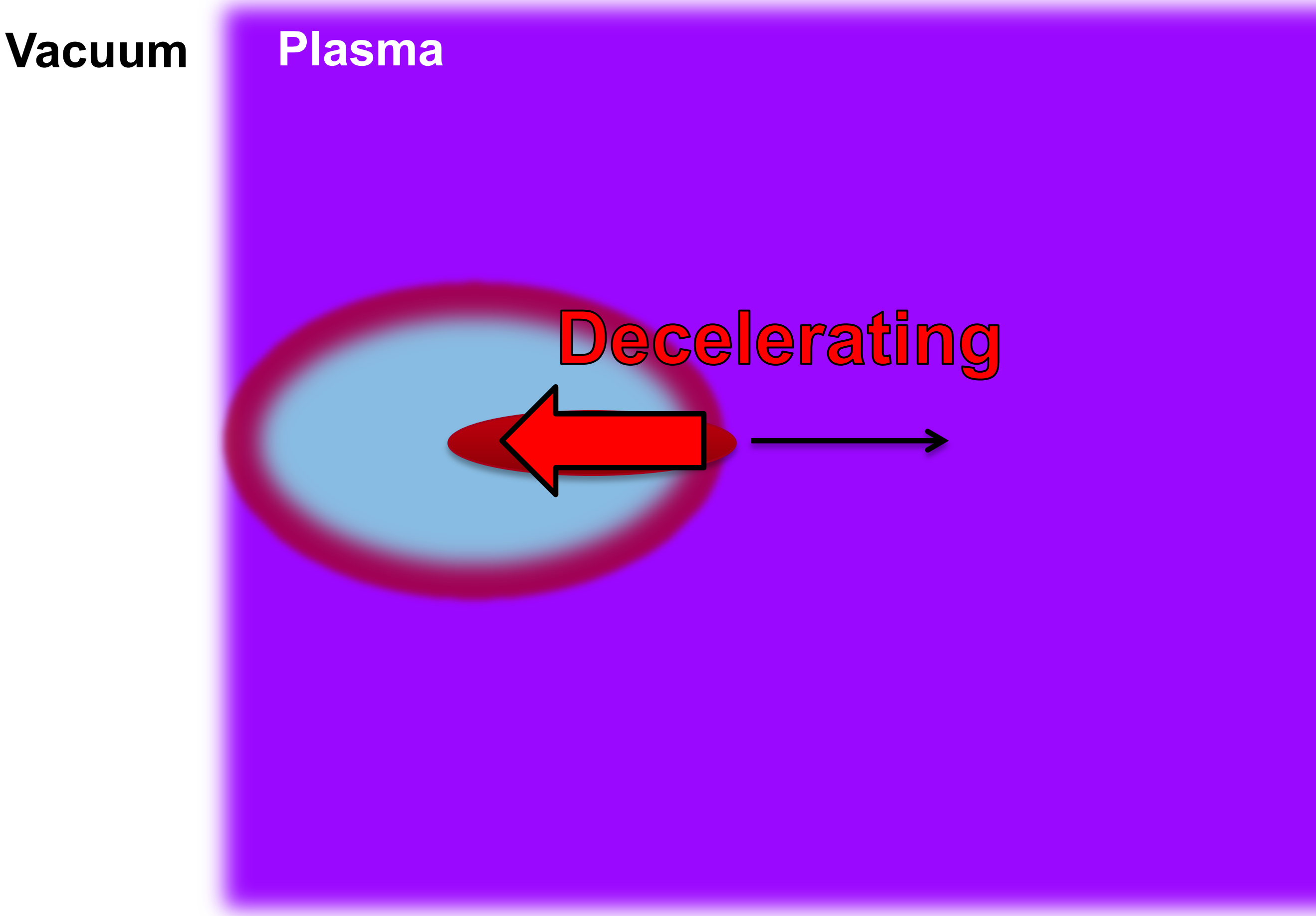


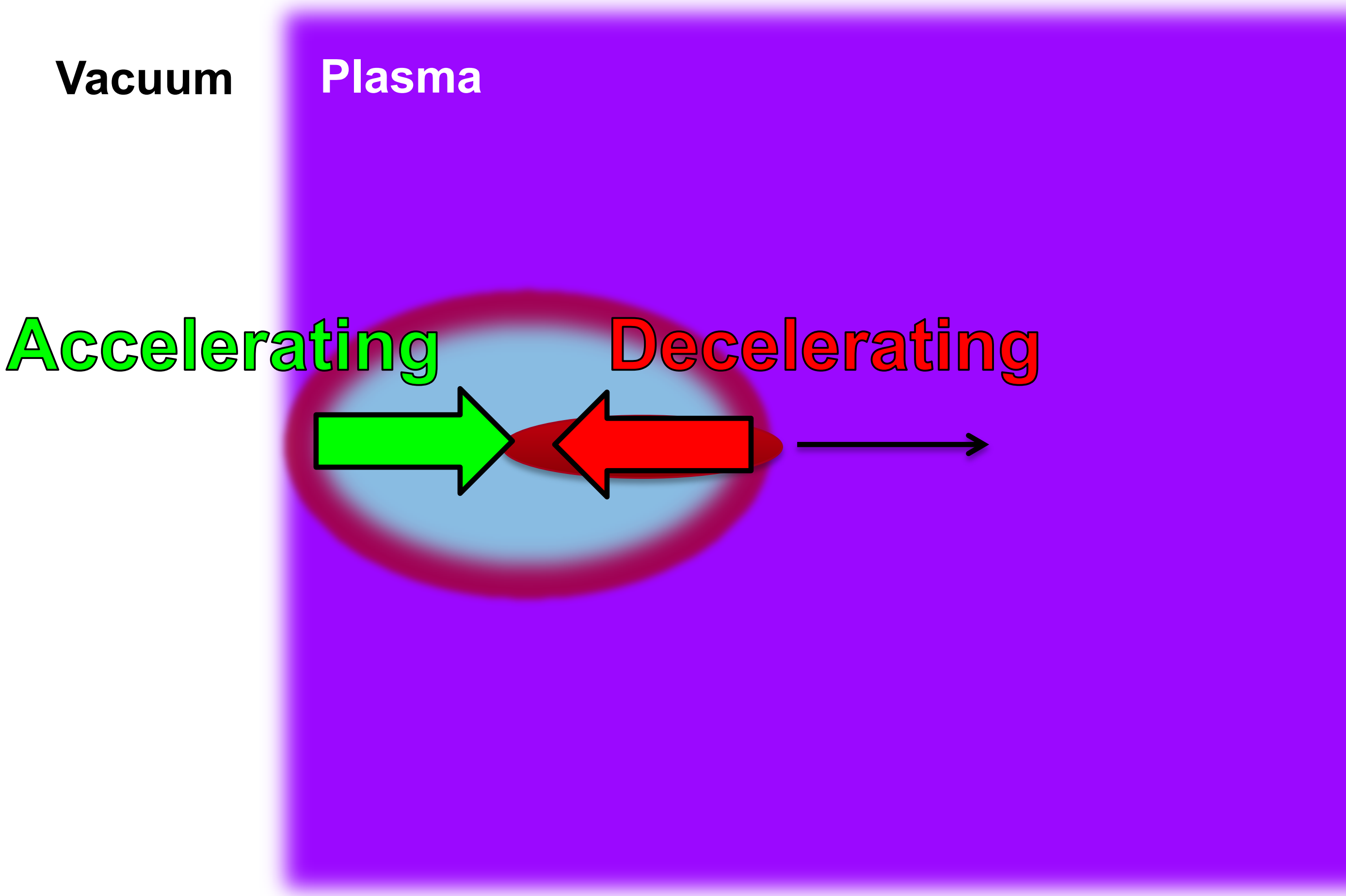
The plasma ions are heavy and stationary. They exert a restoring force on the plasma electrons pulling them back to the axis.

What is a Plasma Wakefield Accelerator?



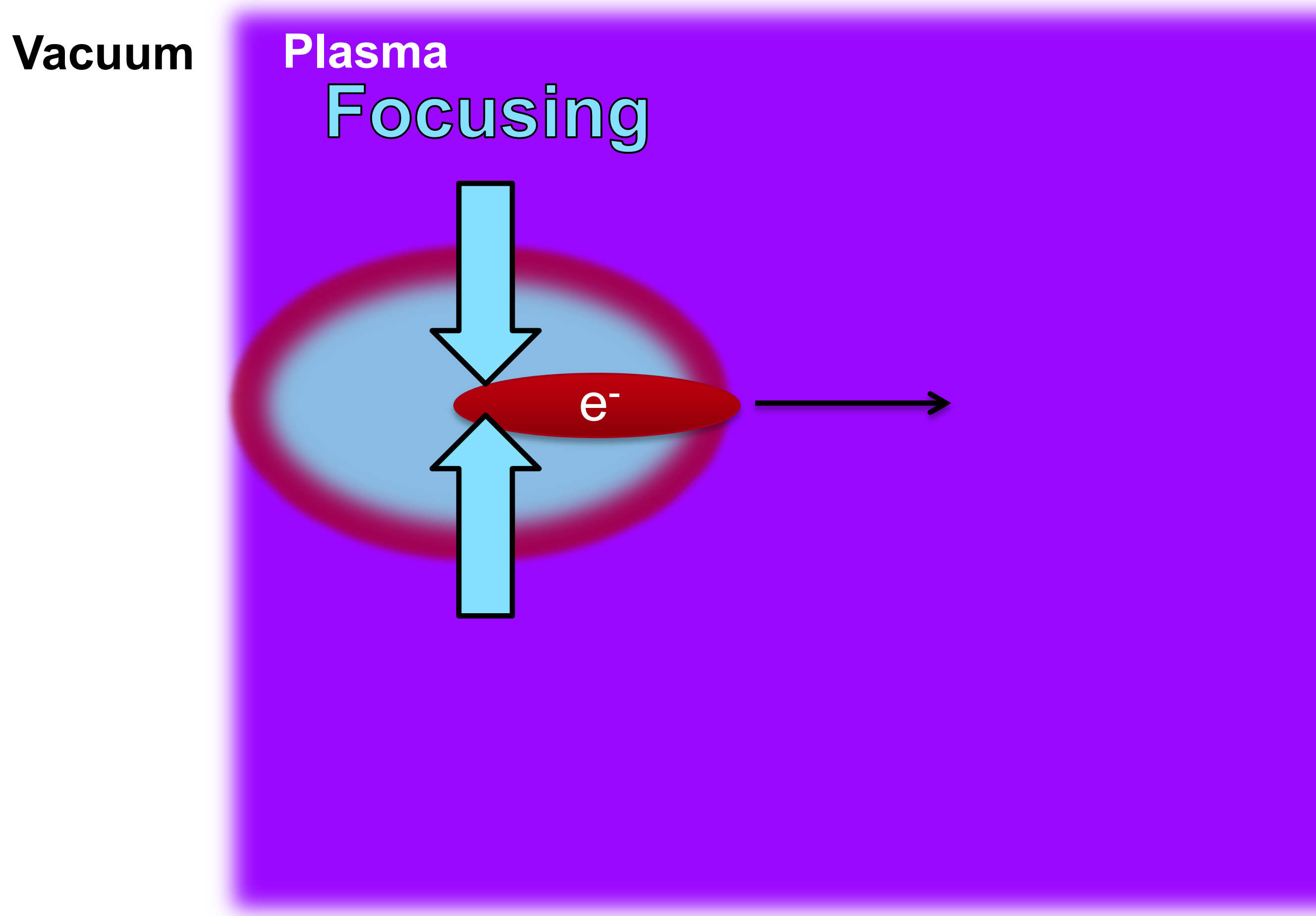
The field is decelerating in the front half of the bubble. The plasma extracts energy from the electron beam.

What is a Plasma Wakefield Accelerator?



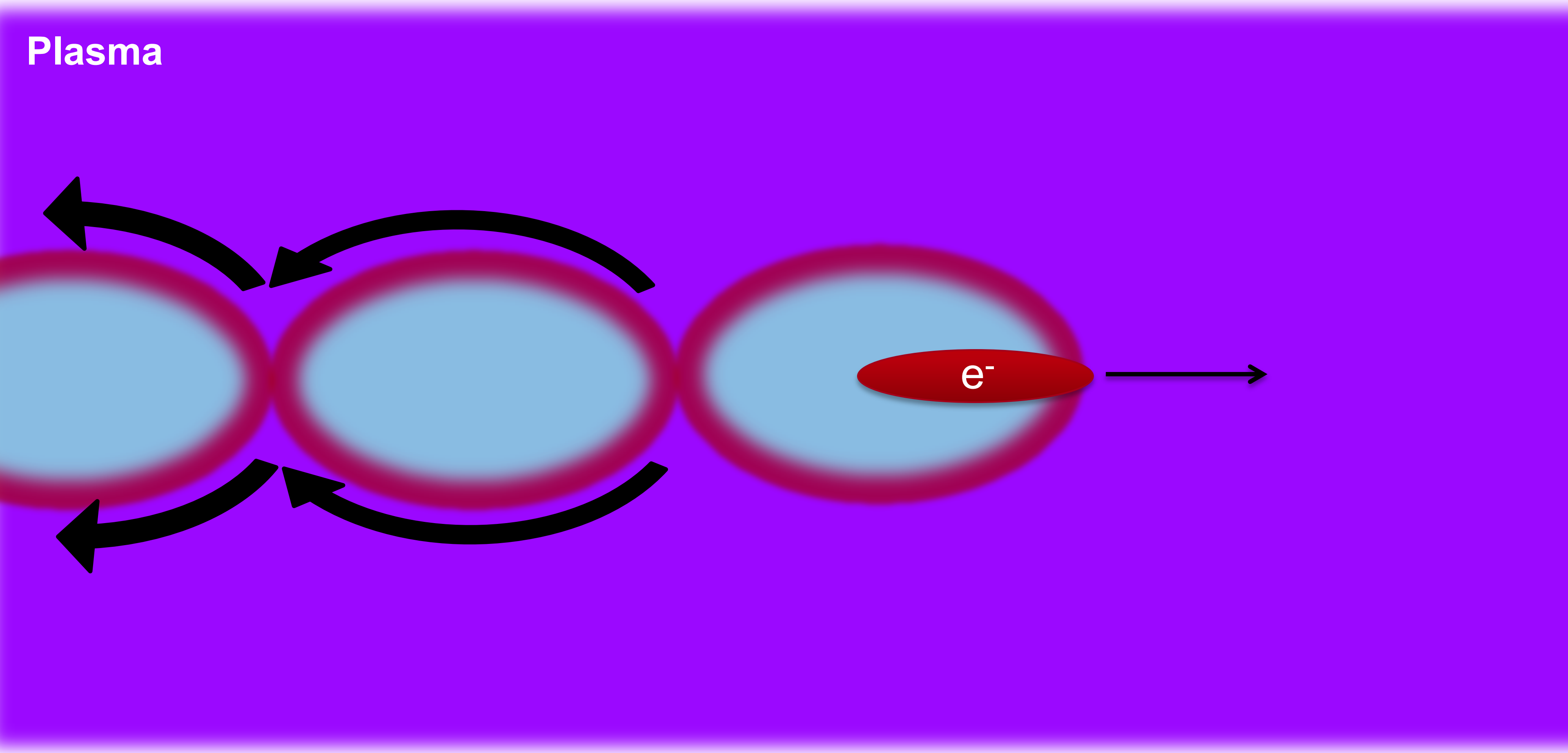
The field is accelerating in the back half of the bubble. Beam electrons can extract energy from the plasma wake in this region.

What is a Plasma Wakefield Accelerator?



The field is focusing *everywhere* in the bubble.

What is a Plasma Wakefield Accelerator?



The plasma electrons keep oscillating after the beam has passed by.

FACET Milestones

FACET is executing a five year program that will help answer whether or not PWFA can be used as a technology in future accelerators:

- Meter scale plasmas
- High gradients
- Low energy spread
- High efficiency
- Multi GeV e^+ PWFA
- Emittance preservation

FACET Milestones

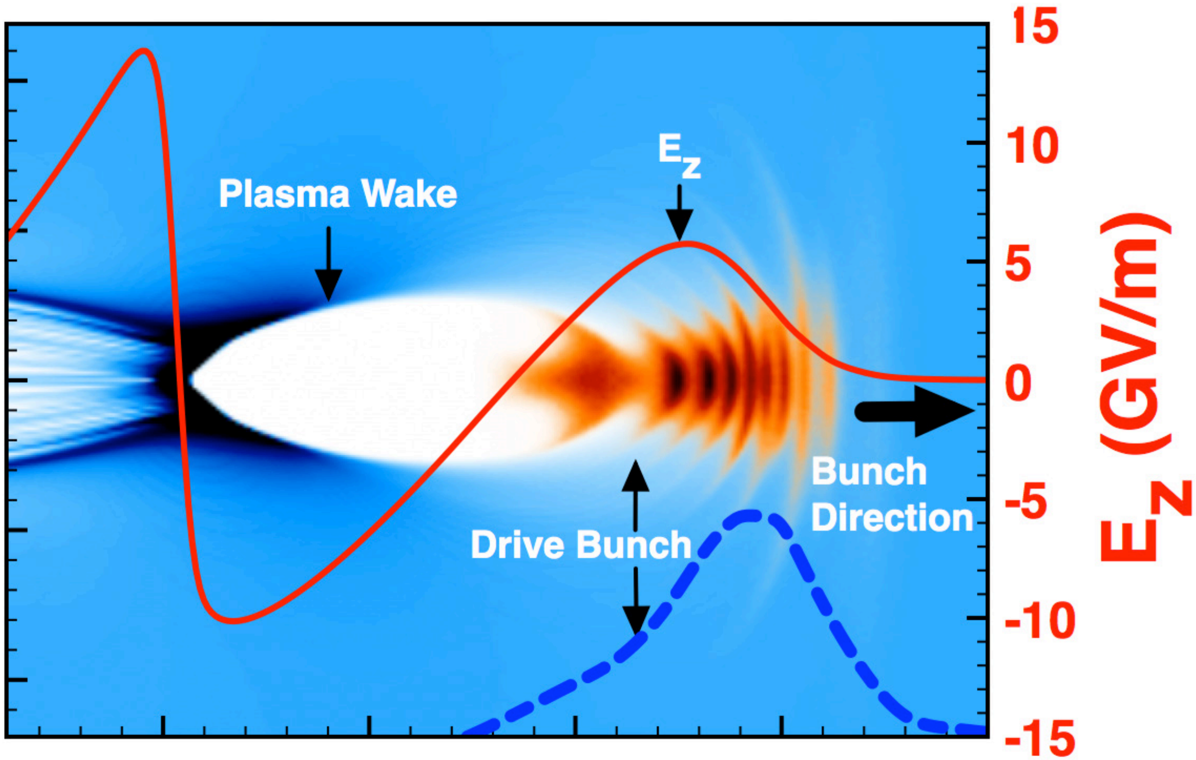
FACET is executing a five year program that will help answer whether or not PWFA can be used as a technology in future accelerators:

- Meter scale plasmas ✓
- High gradients ✓
- Low energy spread ✓
- High efficiency ✓
- Multi GeV e^+ PWFA ✓
- Emittance preservation

Plasma Wakefield Acceleration: High Gradients

QuickPIC (UCLA) simulation for FACET beam and plasma parameters:

$$n_0 = 5 \times 10^{16} \text{cm}^{-3}$$
$$N_b = 1.0\text{nC}$$
$$\sigma_z = 25\mu\text{m}$$



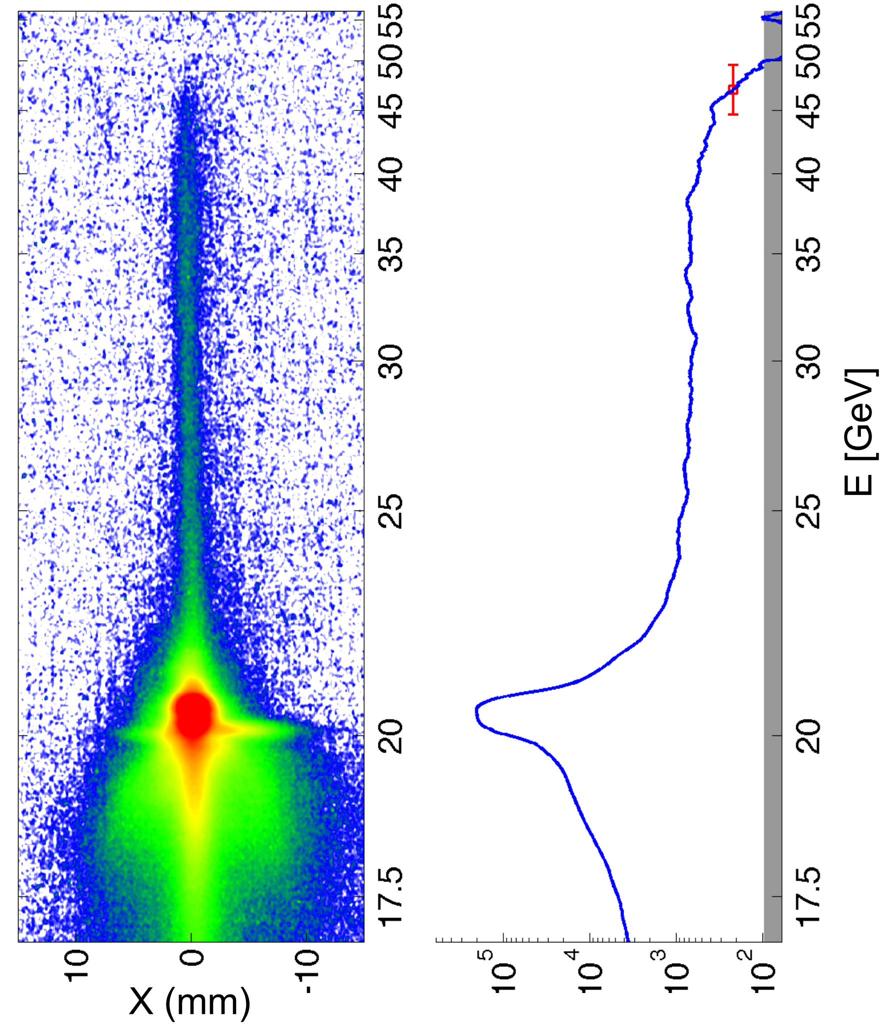
GeV/m: The unit of measure for PWFA

Results: Extremely High Gradients in Ar

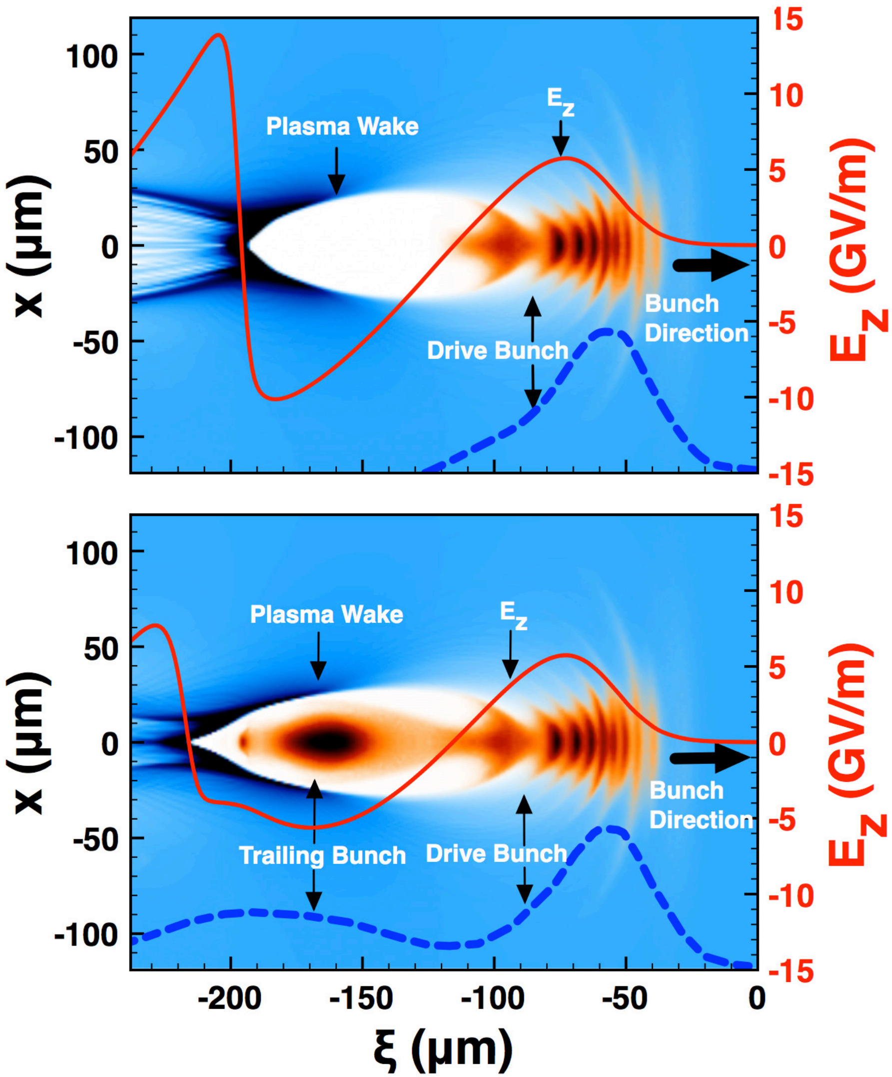
27 GeV energy gain in just 25 cm of plasma!

The accelerating gradients are larger than 100 GeV/m!

Energy Spectrum in Argon (2013)



Plasma Wakefield Acceleration: High Efficiency



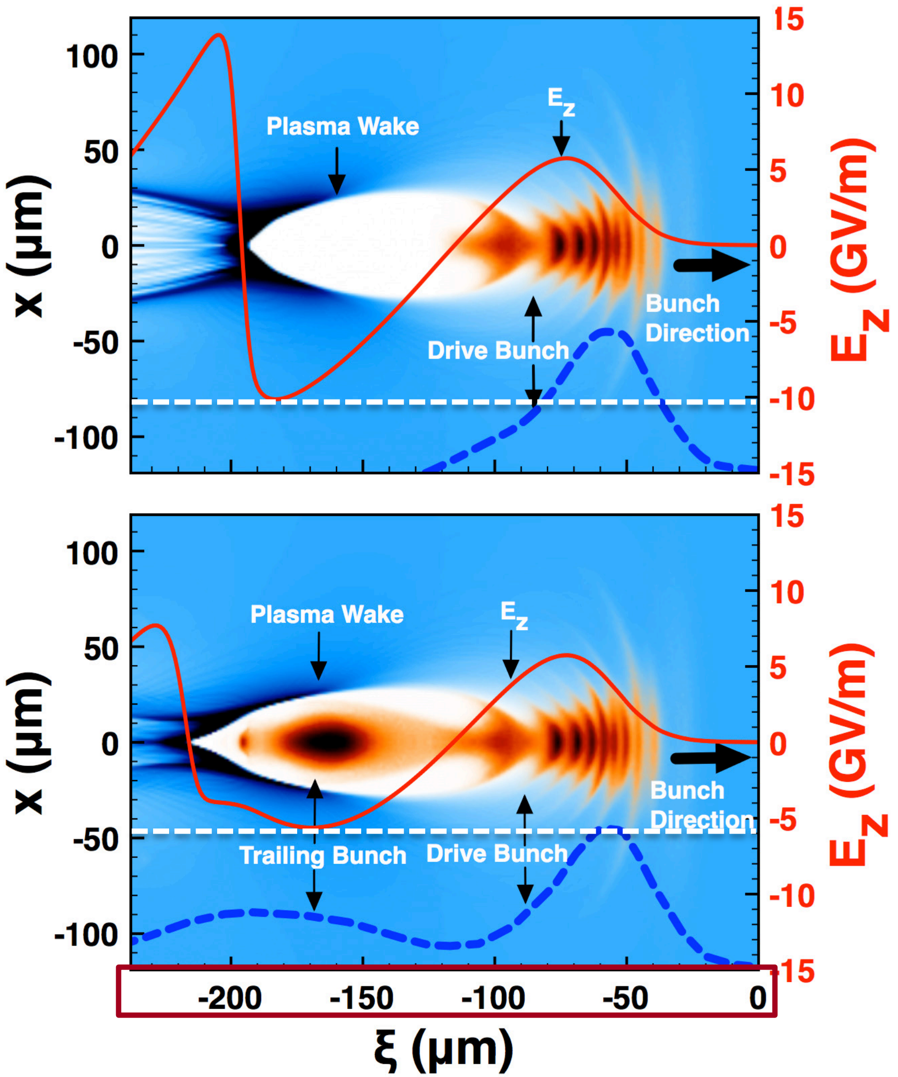
Electron and Positron Plasma Wakefield Acceleration at FACET

Beam loading: The process we use to extract energy from the wake.

The presence of witness electrons "flattens" the E_z field.

NEW

Plasma Wakefield Acceleration: High Efficiency

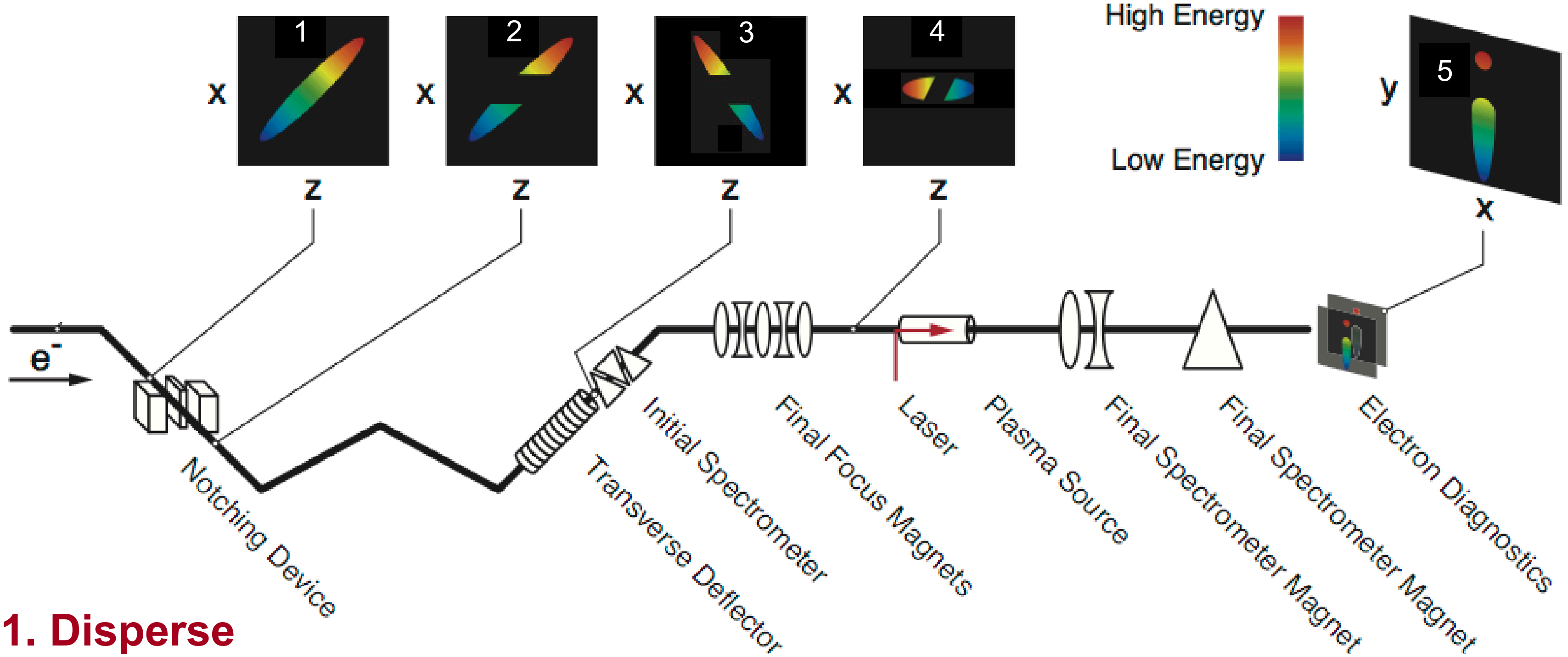


Beam loading: The process we use to extract energy from the wake.

The presence of witness electrons "flattens" the E_z field.

Electron and Positron Plasma Wakefield Acceleration at FACET

Two-Bunch Beam Generation



1. Disperse

2. Chop

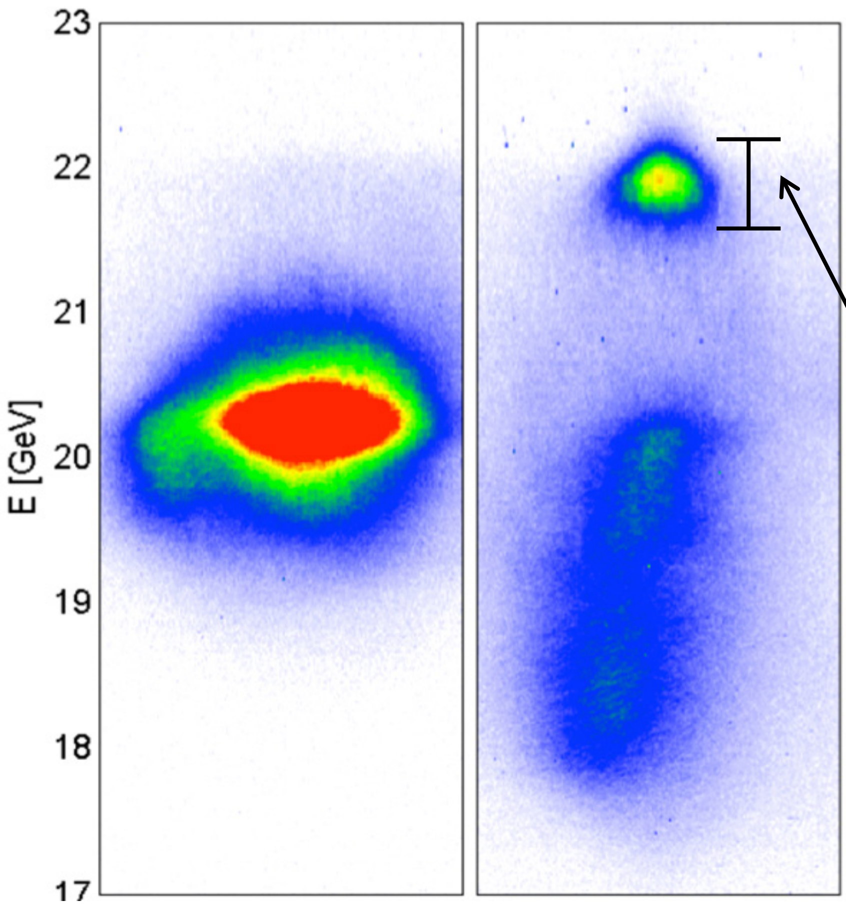
3. Compress

4. Accelerate

5. Diagnose

Results: High-efficiency PWFA

No Plasma 0.3 m Plasma



2013

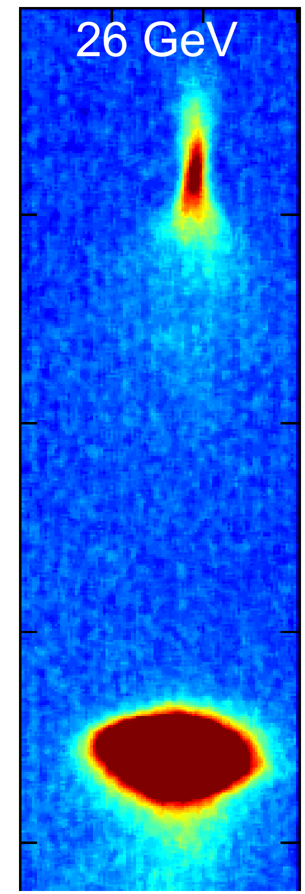
2 GeV Energy gain in less than 30 cm of plasma.

2% dE/E

30% Drive-to-Witness efficiency.

6 GeV Energy gain in 1.3 m of plasma!

1.3 m Plasma



2014

Results: Hi

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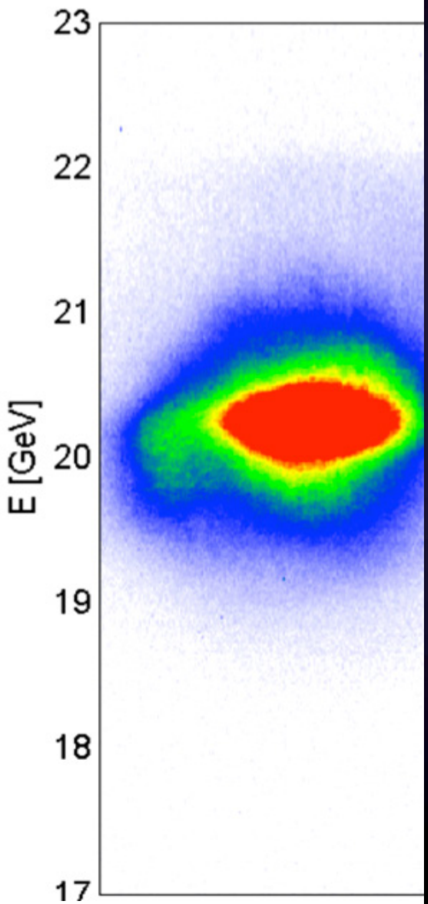
No Plasma

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THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

FULL SPEED AHEAD

Plasma wakefield machines — the particle accelerators of the future? PAGES 40 & 92

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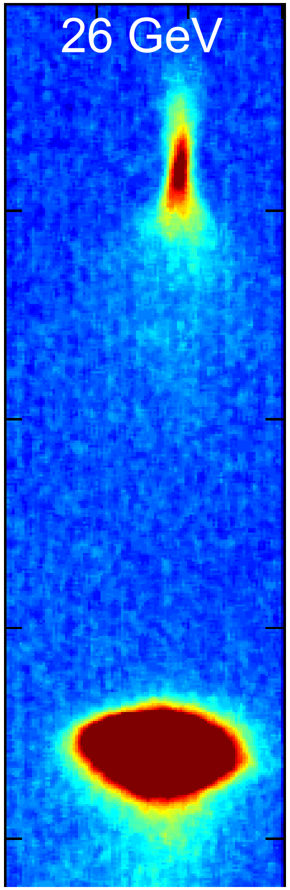
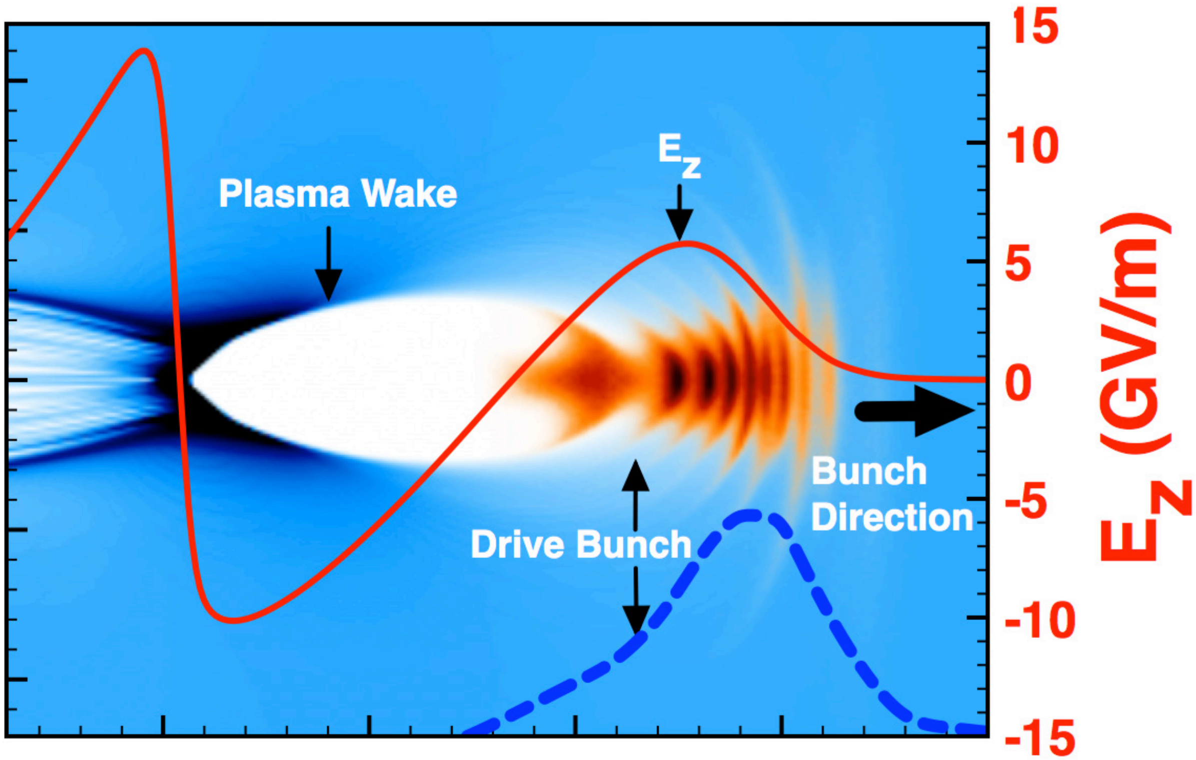
1.3 m Plasma



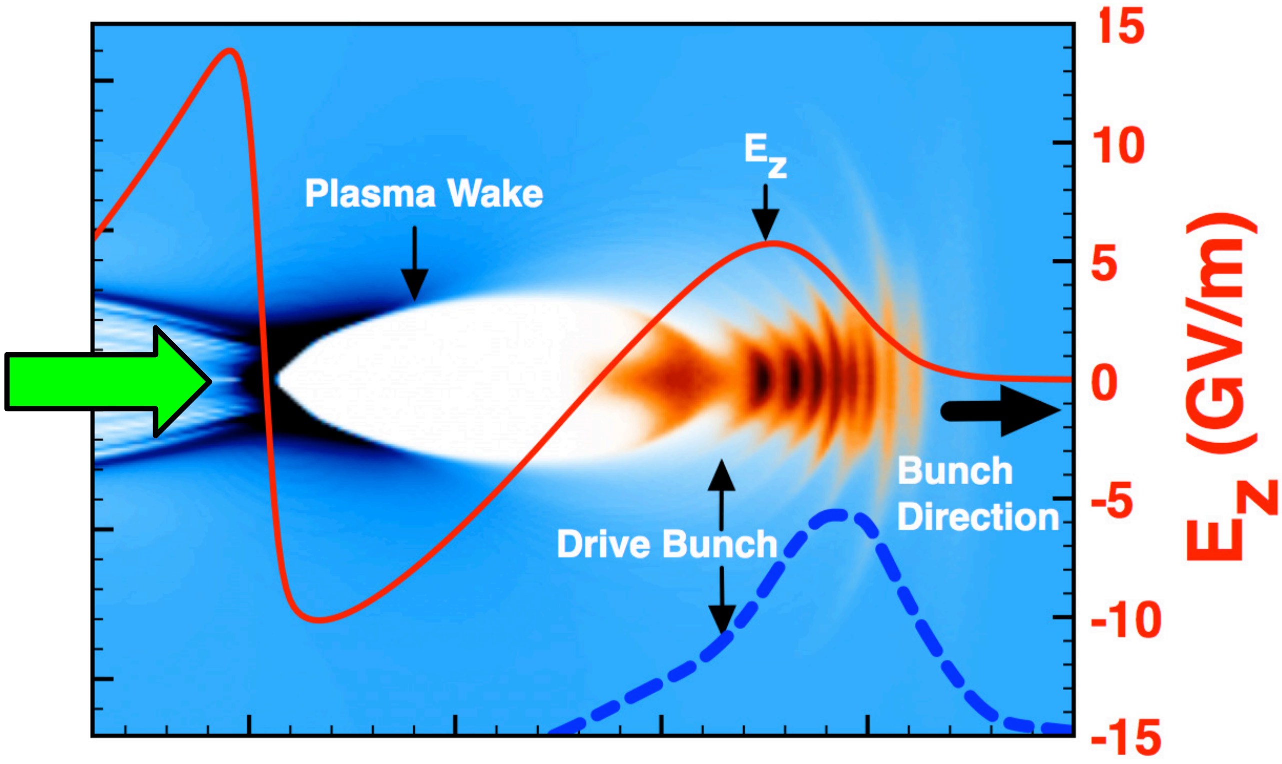
2014

Plasma Wakefield Acceleration: Positrons



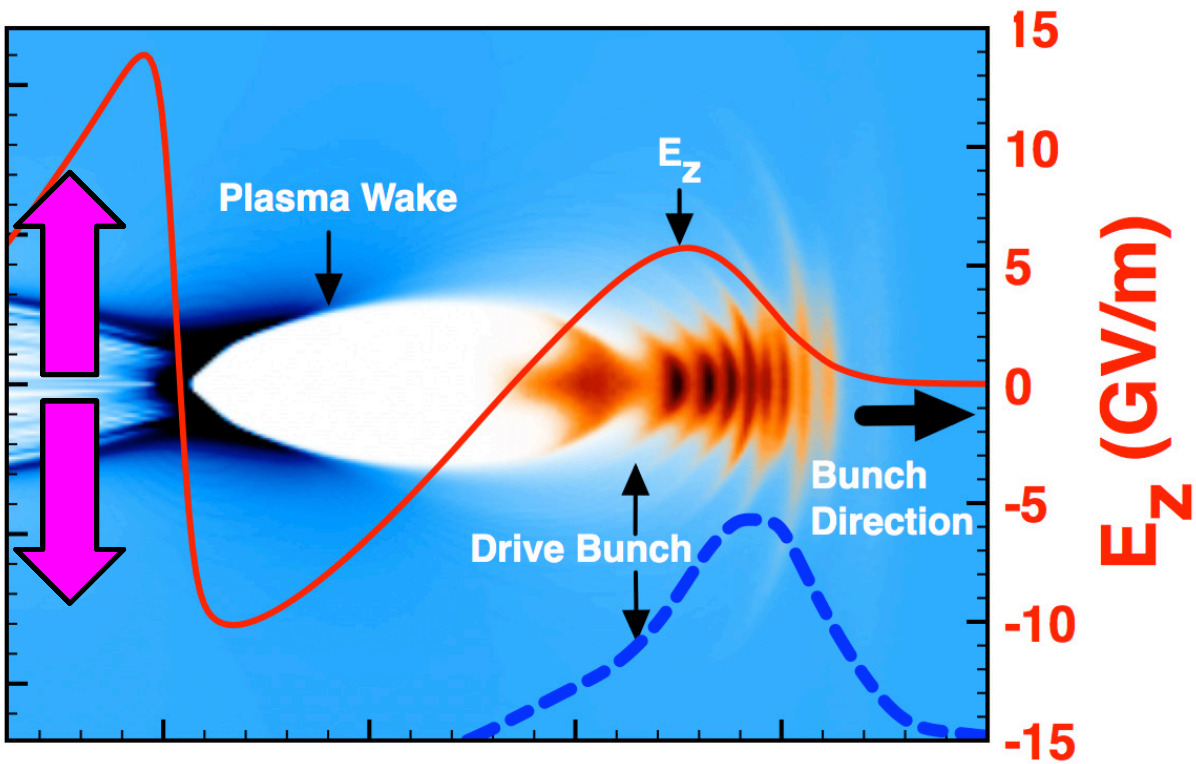
Where can positrons be accelerated and focused in a non-linear plasma wakefield?

Plasma Wakefield Acceleration: Positrons



The field is accelerating behind the pinch in the first bubble.

Plasma Wakefield Acceleration: Positrons

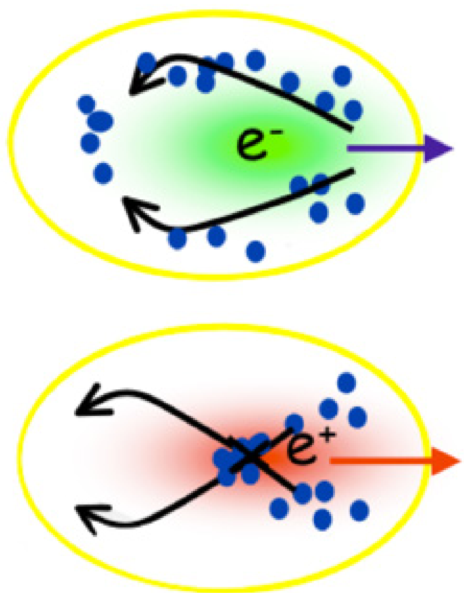


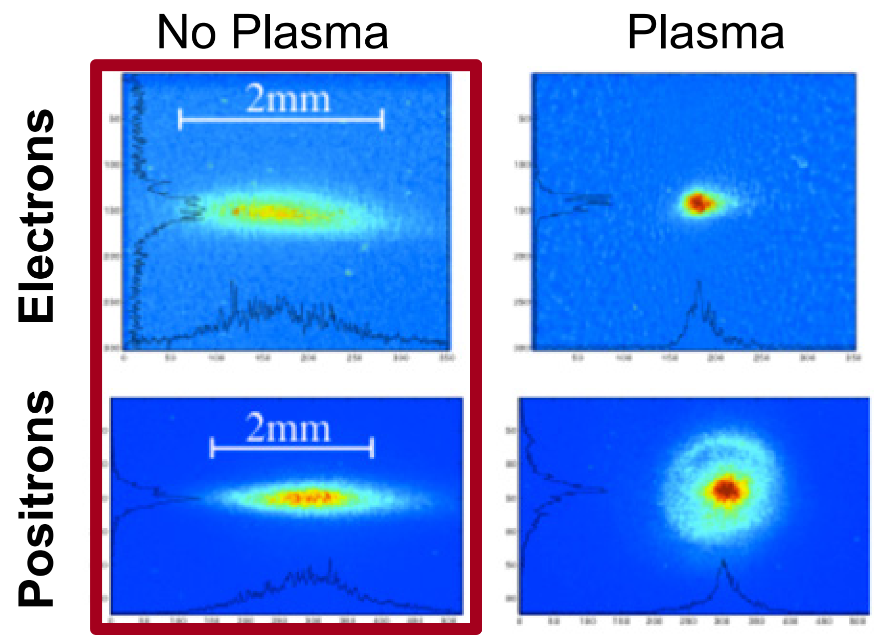
But the field is defocusing in this region.

Previous results with positrons

“Blow-out”

“Suck-in”





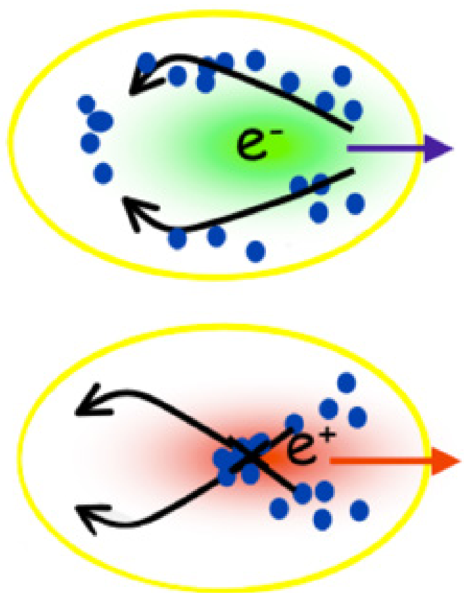
Phys. Rev. Lett. **90**, 205002 (2003)   *Phys. Rev. Lett.* **101**, 055001 (2008)

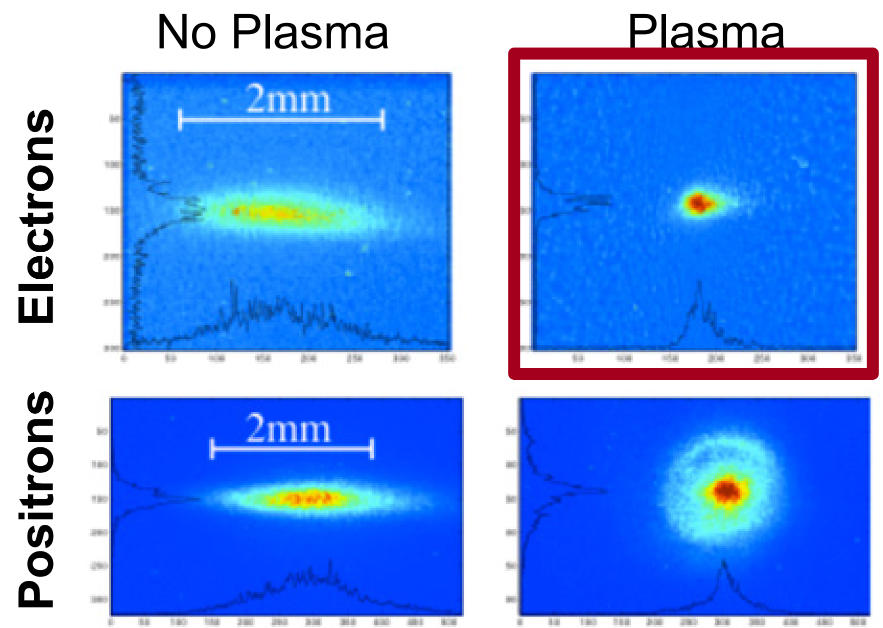
Experiments at SLAC FFTB in 2003 showed that the positron beam was distorted after passing through a low density plasma.

Previous results with positrons

"Blow-out"

"Suck-in"



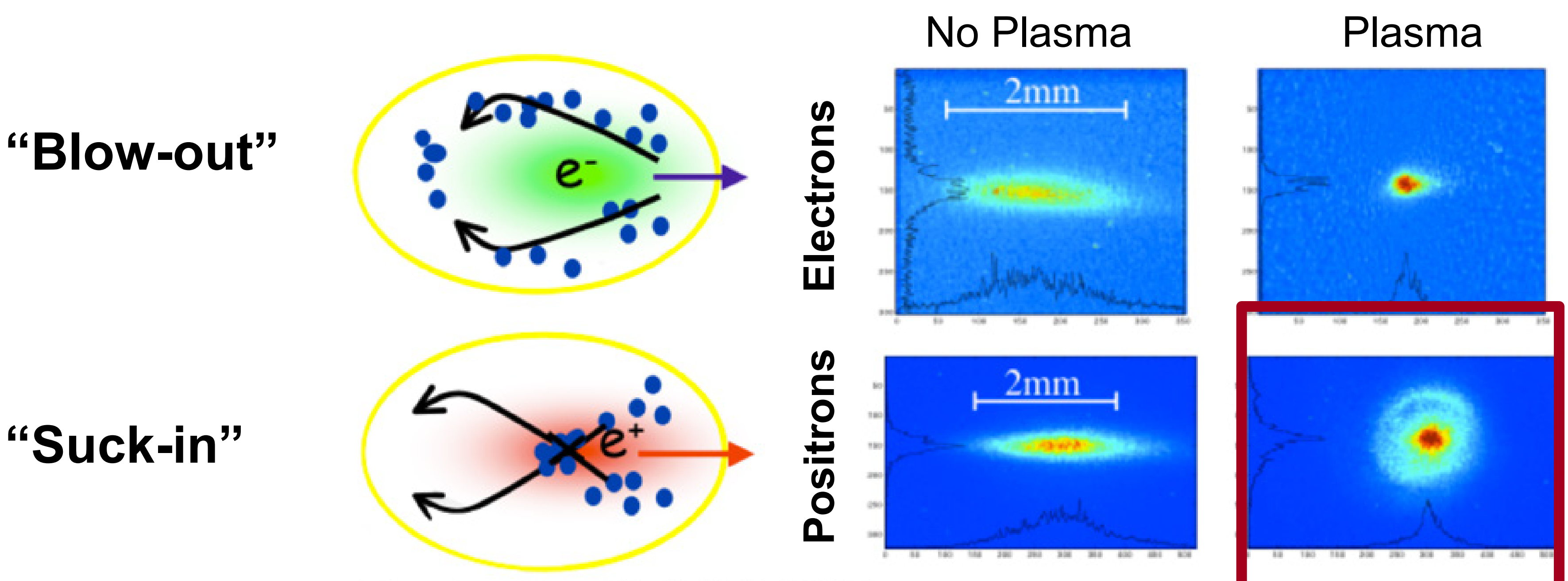


Phys. Rev. Lett. **90**, 205002 (2003)

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

The plasma confines and channels the electron beam as it passes through the plasma.

Previous results with positrons



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

For similar beam and plasma parameters, the plasma distorts the positron beam and a halo forms.

Results: Multi-GeV Acceleration of Positrons

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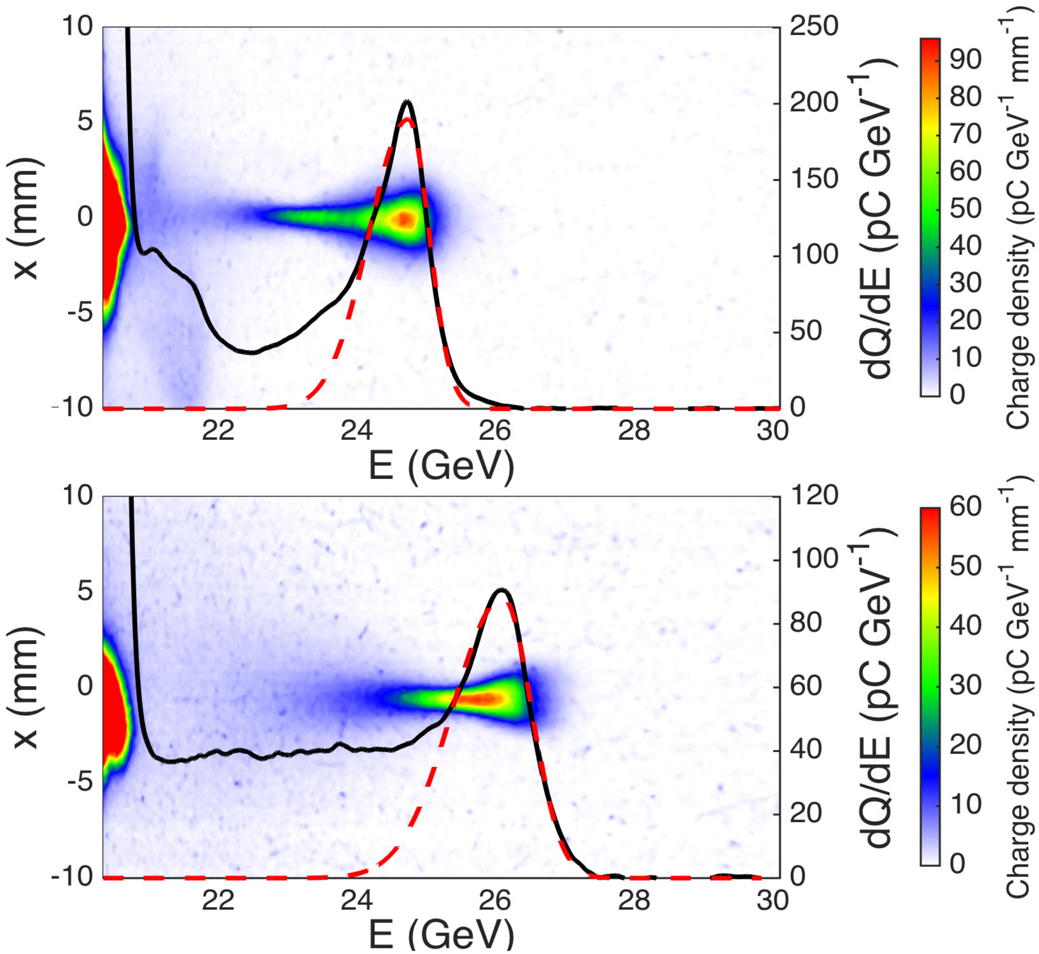
SLAC

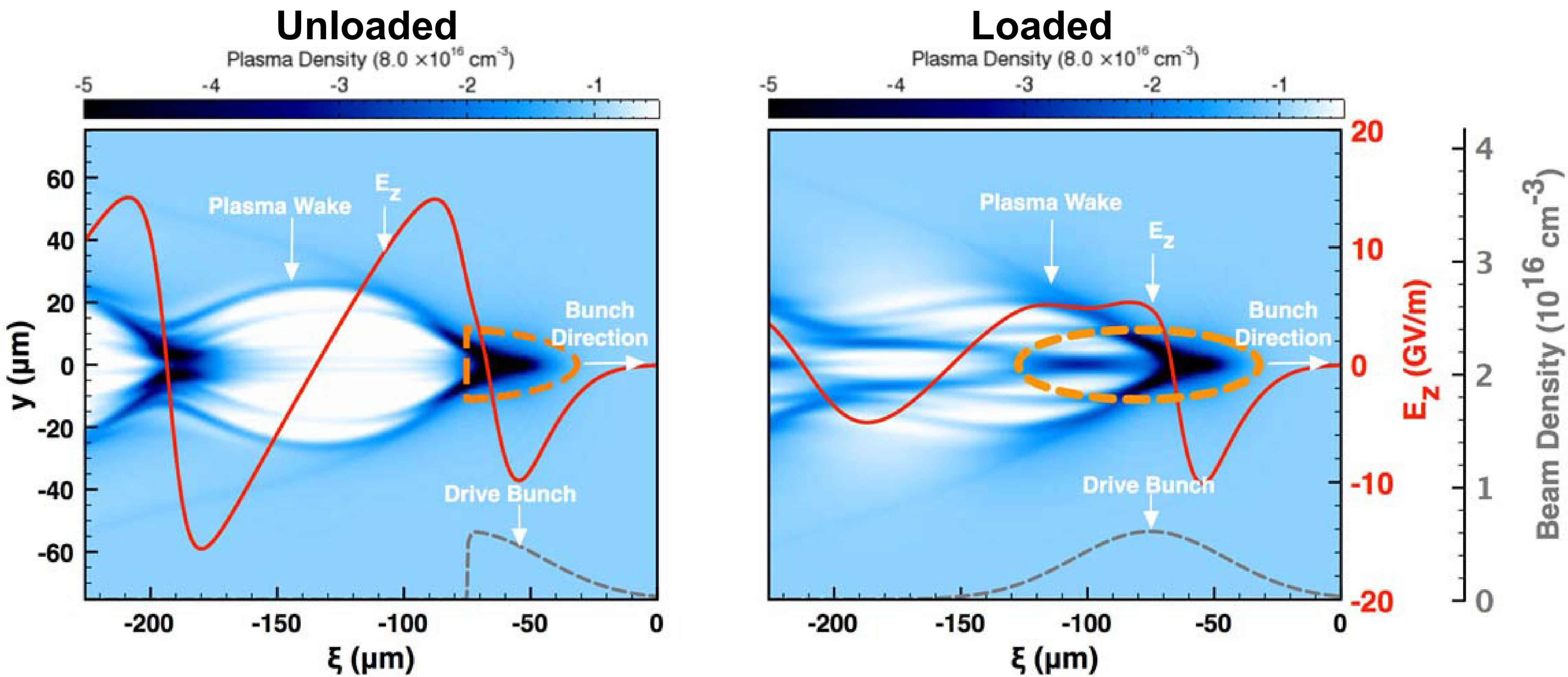
An unexpected result!

We observed a spectrally-distinct positron beamlet gain 6 GeV of energy.

The beamlet has low energy spread.



Understanding the Result: Longitudinal and Transverse Beam Loading



Transverse beam loading is an important effect for positron driven wakes!

Plasma Wakefield Acceleration: Hollow Channels

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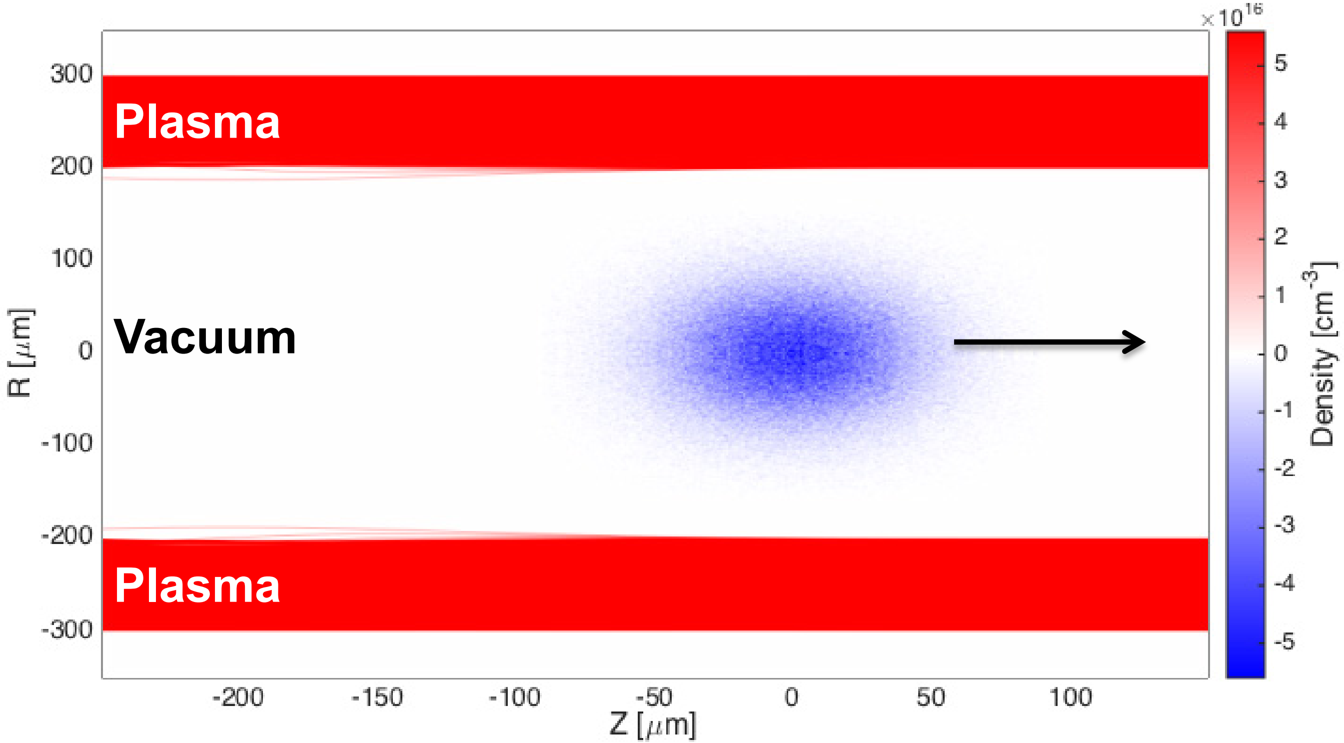
Charge Density



Can we harness the accelerating power of plasmas without the transverse forces?

Plasma Wakefield Acceleration: Hollow Channels

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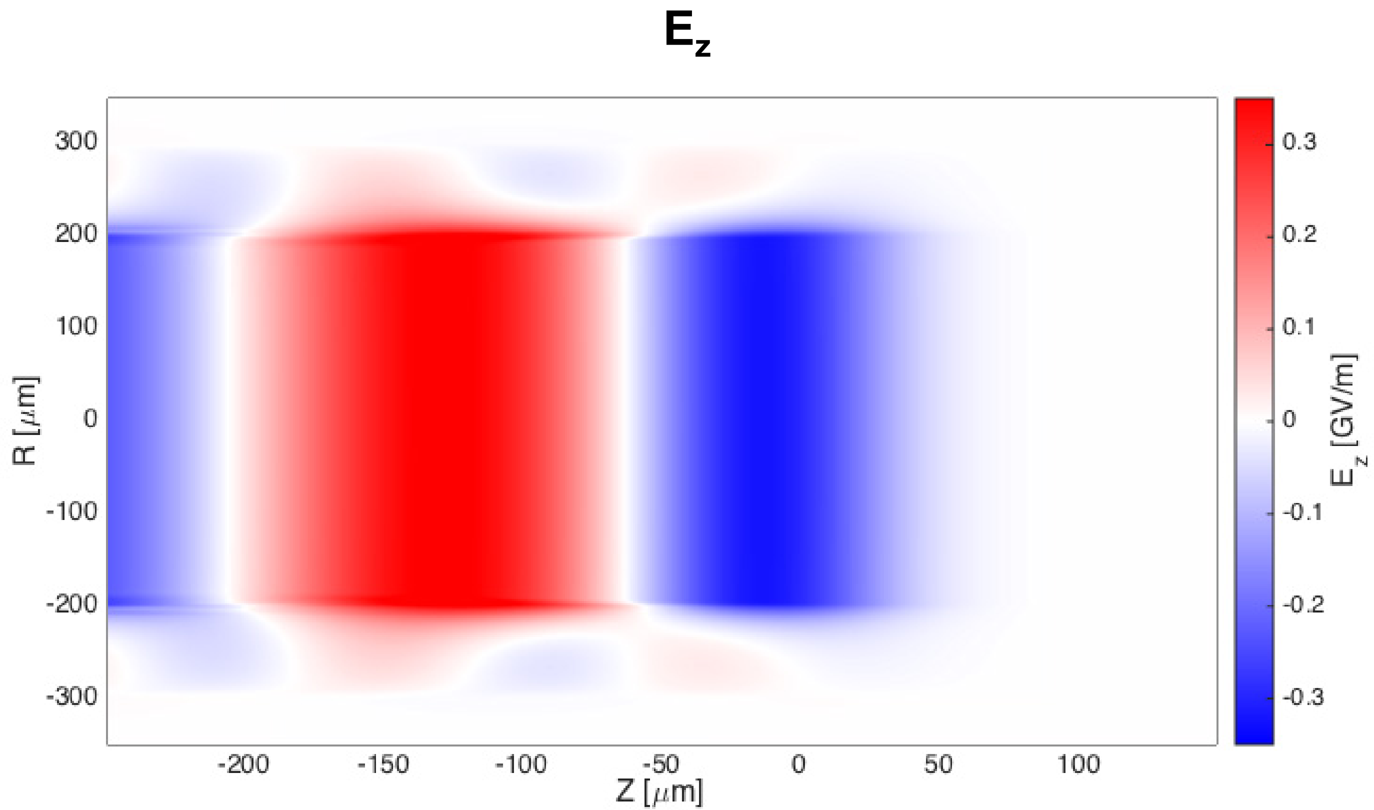
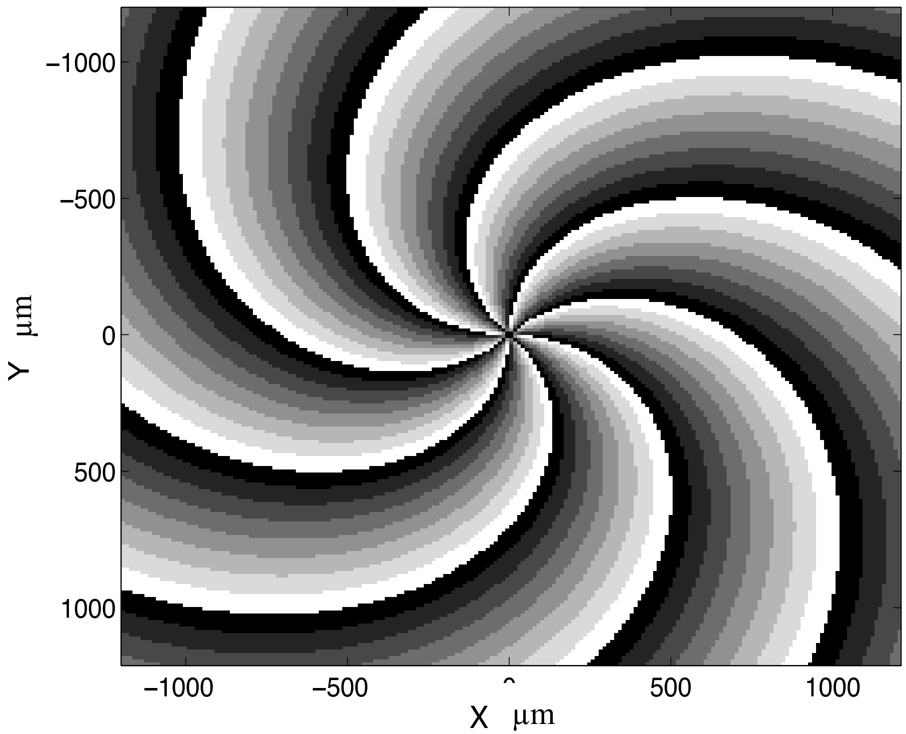
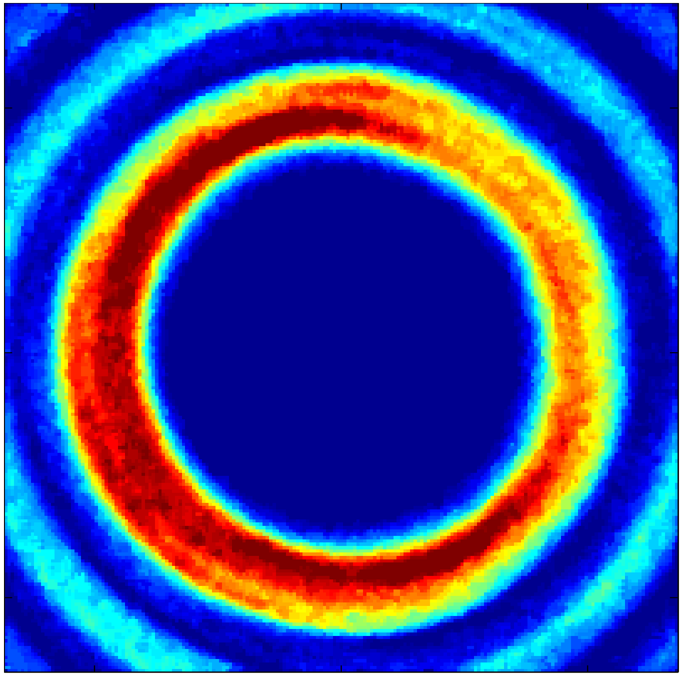


Hollow channels provide large accelerating fields *without* focusing fields.

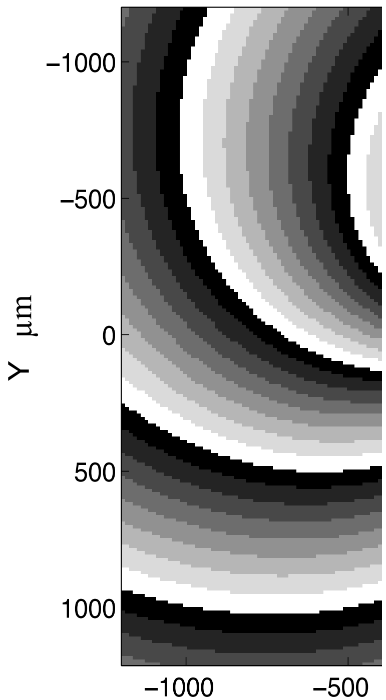
Creation of a Hollow Channel Plasma

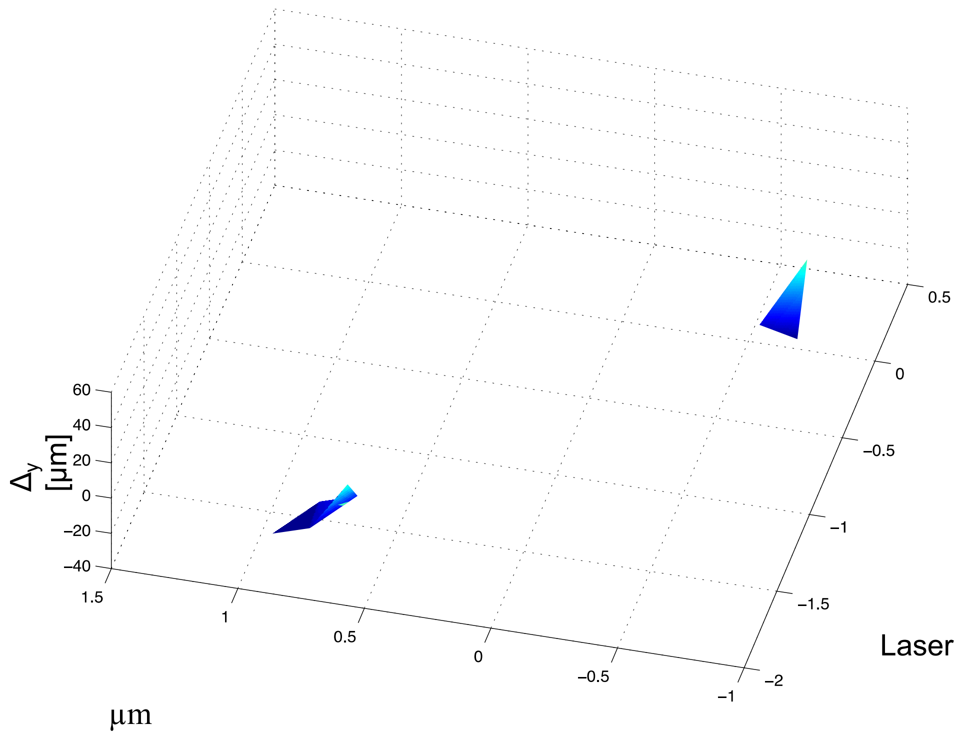


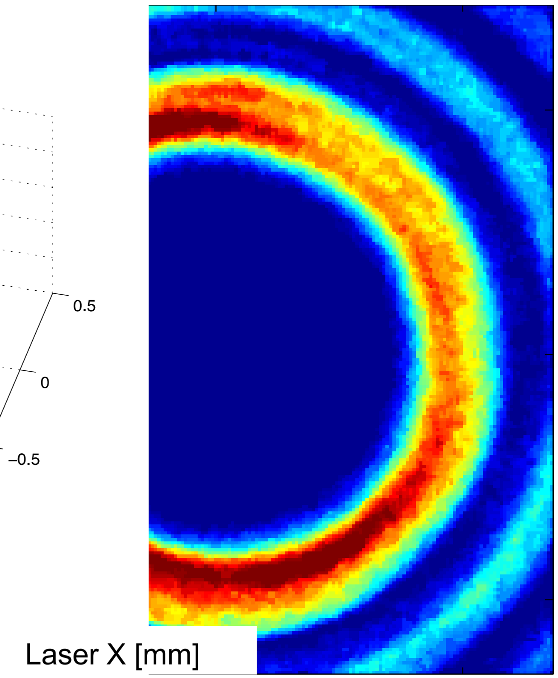


We use a spiral phase grating to create hollow laser beams.

Creation of a Hollow Channel Plasma







We've observed the effect of the hollow channel on a positron beam!

Take-Aways

- Progress at FACET has been rapid:
  - Meter-long plasma source (2012)
  - Ultra-high gradient accelerator (2013)
  - High-efficiency, two-bunch acceleration (2013)
  - Multi-GeV positron acceleration (2014)
- Unexpected positron results means that there is a lot more to study! There is more positron beam time planned for FACET.
- Lot’s of momentum. We want to keep it going at FACET-II !

Thanks!

J. Allen, C. Clarke, J.P. Delahaye, A. Fisher, J. Frederico, M. Hogan, S. Green, M. Litos, N. Lipkowitz, B. O'Shea, D. Walz, V. Yakimenko, G. Yocky

W. An, C. Clayton, C. Joshi, K. Marsh, W. Mori, N. Vafaei

E. Adli, C. A. Lindstrom

S. Corde, M. Schmeltz

P. Muggli

R. Zgadaj, Z. Li, M.C. Downer

Work supported by DOE contracts DE-AC02-76SF00515, DE-AC02-7600515, DE-FG02-92-ER40727 and NSF contract PHY-0936266

Thanks!

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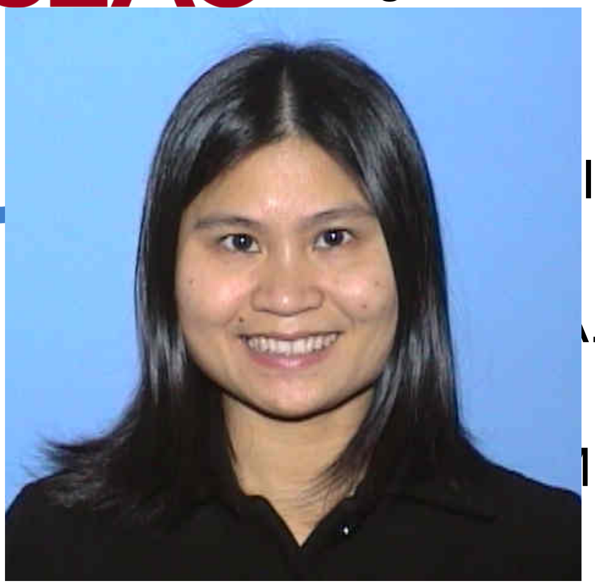
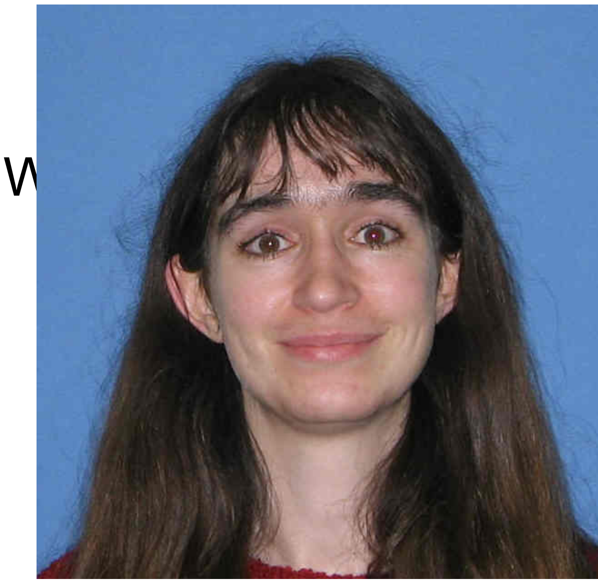


Selina Green

Mike Litos



Christine Clarke

R. Zgadaj, Z. Li, M.C. Downer

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References

First Concepts:

- T. Tajima, J. Dawson, Phys. Rev. Lett. 43, 4 (1979)
- P. Chen, J. Dawson, R. Huff, T. Katsouleas, Phys. Rev. Lett. 54, 7 (1985)
- R. Ruth, A. Chao, P. Morton, P. Wilson, SLAC-PUB-3374 (1984)

PWFA Experiments with electrons:

- J. Rosenzweig, Phys. Rev. Lett. 61, 98 (1988)
- M. Hogan, et. al. Phys. Rev. Lett. 95, 054802 (2005)
- I. Blumenfeld et. al. Nature 445, (2007)
- M. Litos et al. Nature 515 (2014)

PWFA Experiments with positrons:

- B. Blue et. al. Phys. Rev. Lett. 90, 214801 (2003)
- M. Hogan et. al. Phys. Rev. Lett. 90, 20 (2003)
- P. Muggli et. al. Phys. Rev. Lett. 101, 055001 (2008)
- S. Corde et. al. *To Be Published*

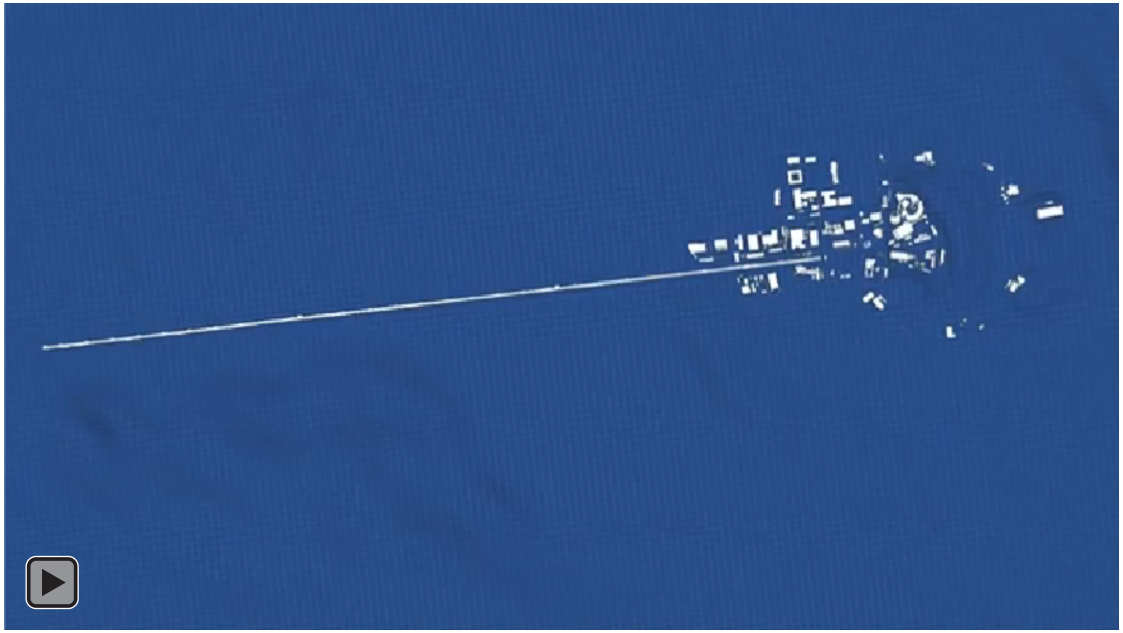
Hollow Channel concept

- T. C. Chiou, T. Katsouleas, Phys. Plasmas 2, 310 (1995)
- C. Schroeder, D. Whittum et. al. Phys. Rev. Lett. 82, 1177 (1999)

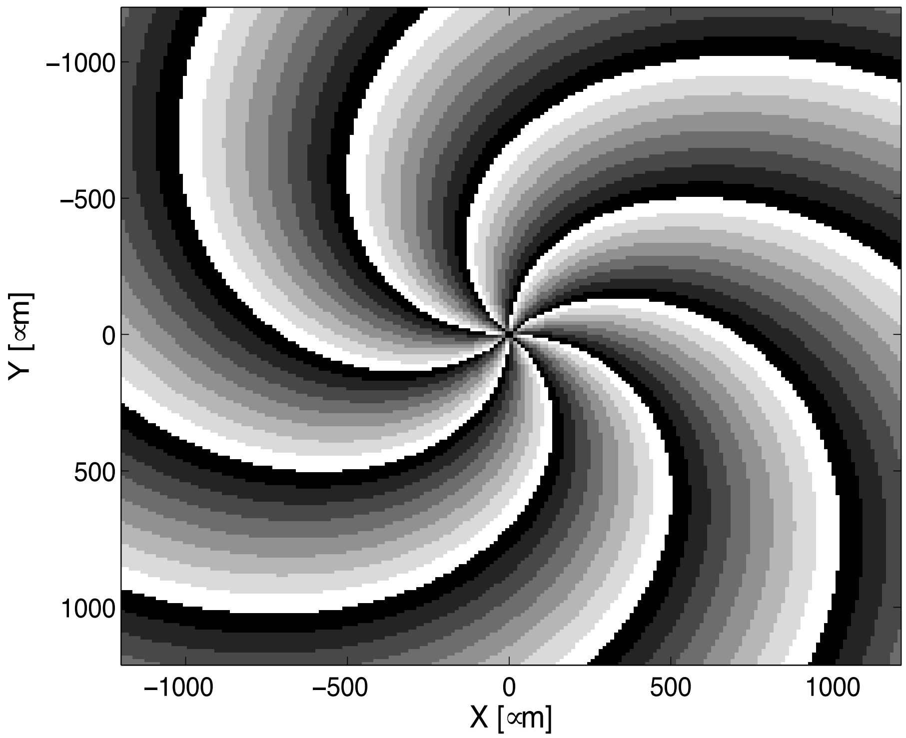
Hollow channel creation:

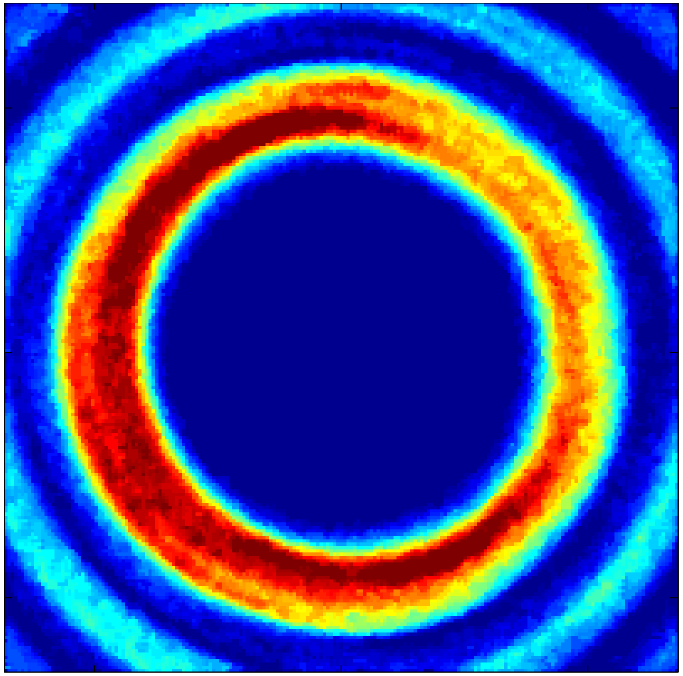
- J. Fan, H. Milchburg et. al. Phys. Rev. E. 62, 7603 (2000)
- W. Kimura et. al. Phys. Rev. STAB 14, 041301 (2011)

The Plasma Source



More Results: Hollow Channel Acceleration





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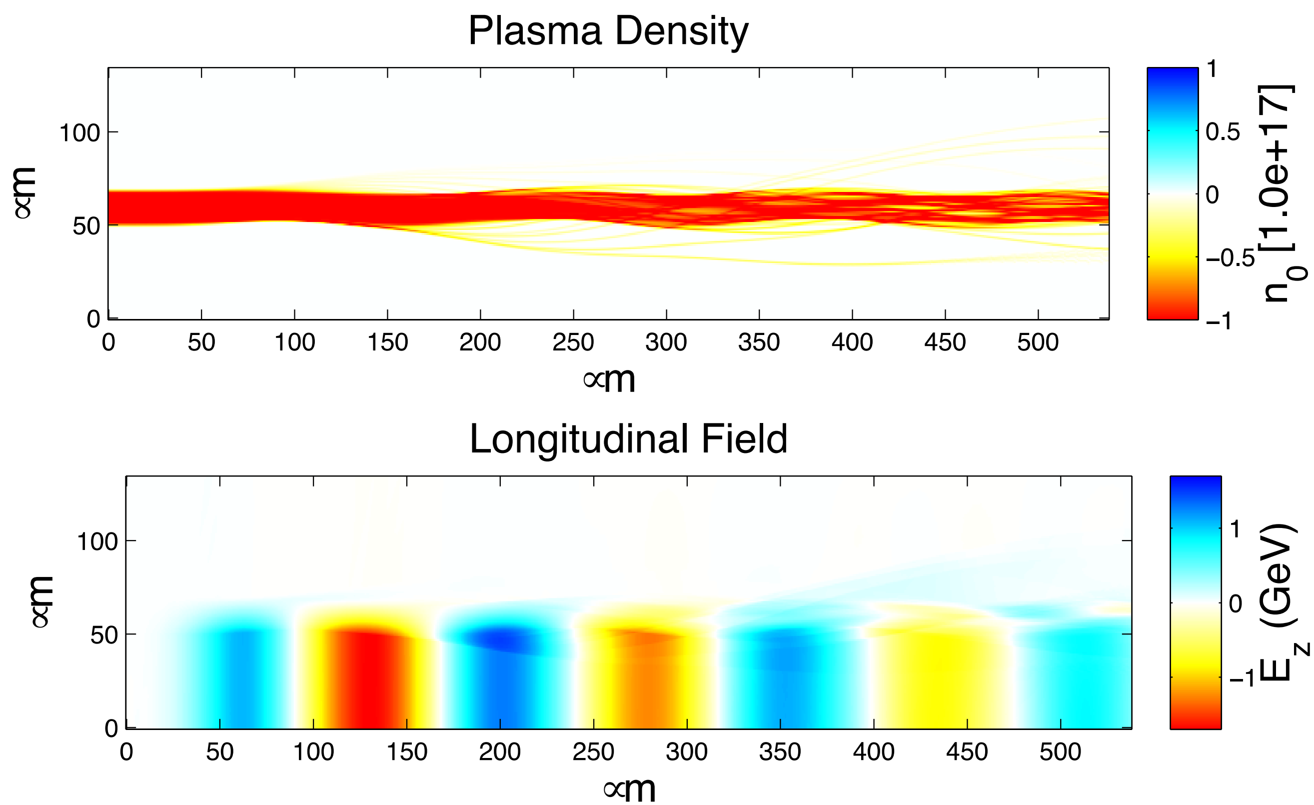
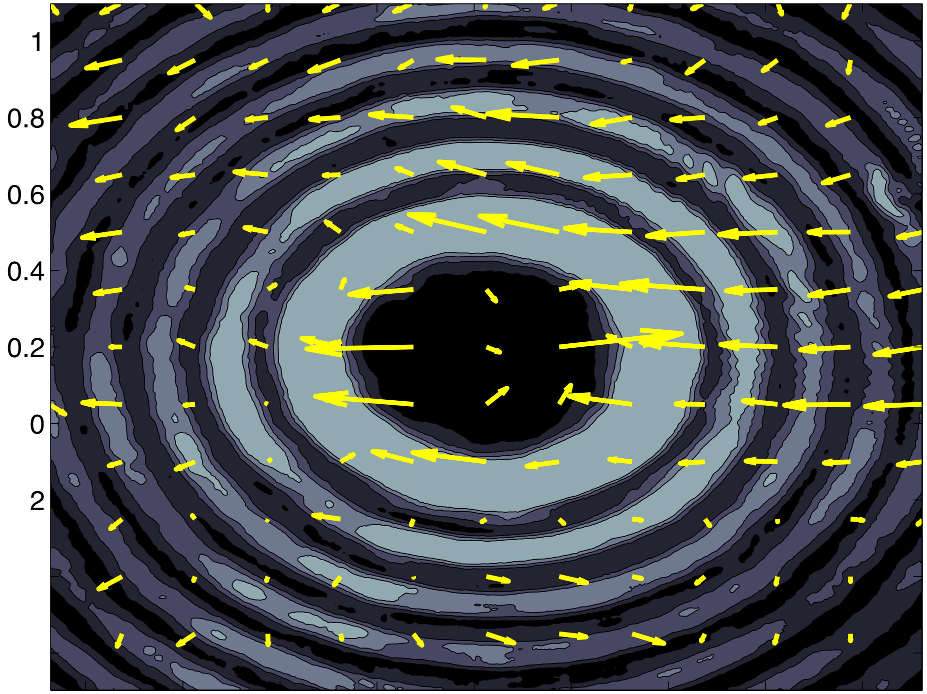


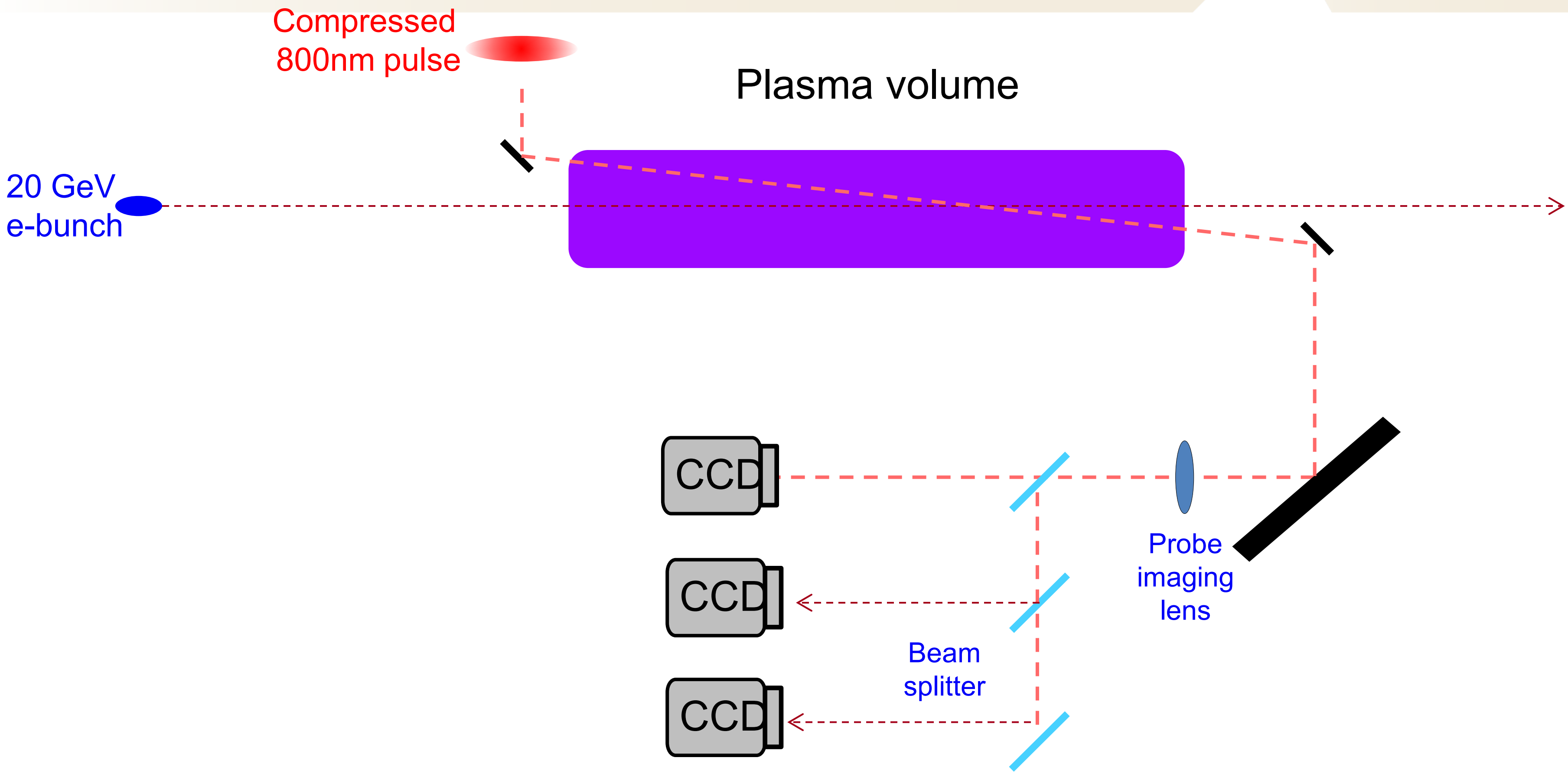
The laser ionizes an annulus of plasma.

More Results: Hollow Channel Acceleration



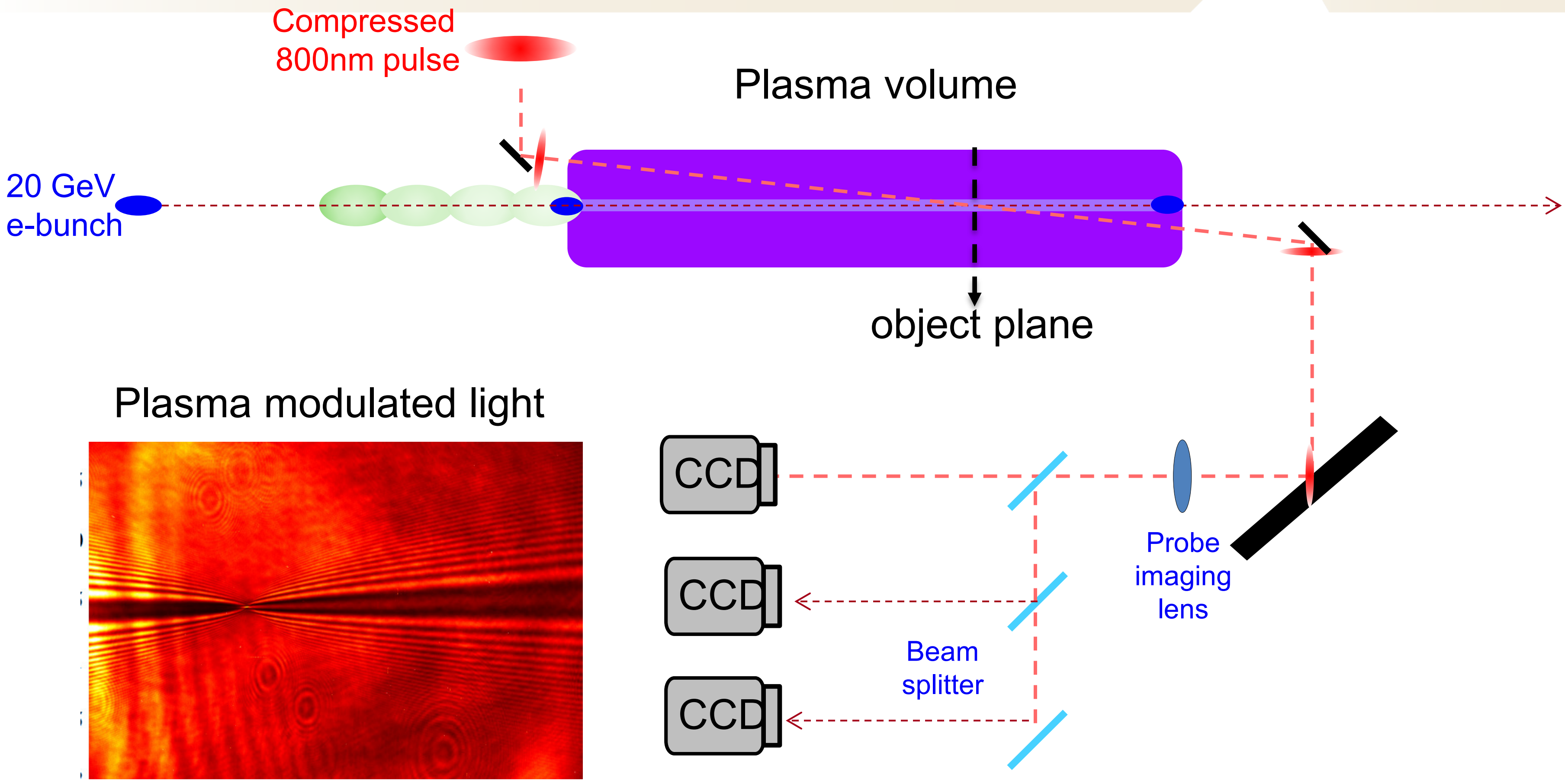
We've observed the effect of the hollow channel on a positron beam!

More Results: Plasma Imaging



Slide courtesy of Rafal Zgadaj

More Results: Plasma Imaging



Slide courtesy of Rafal Zgadaj

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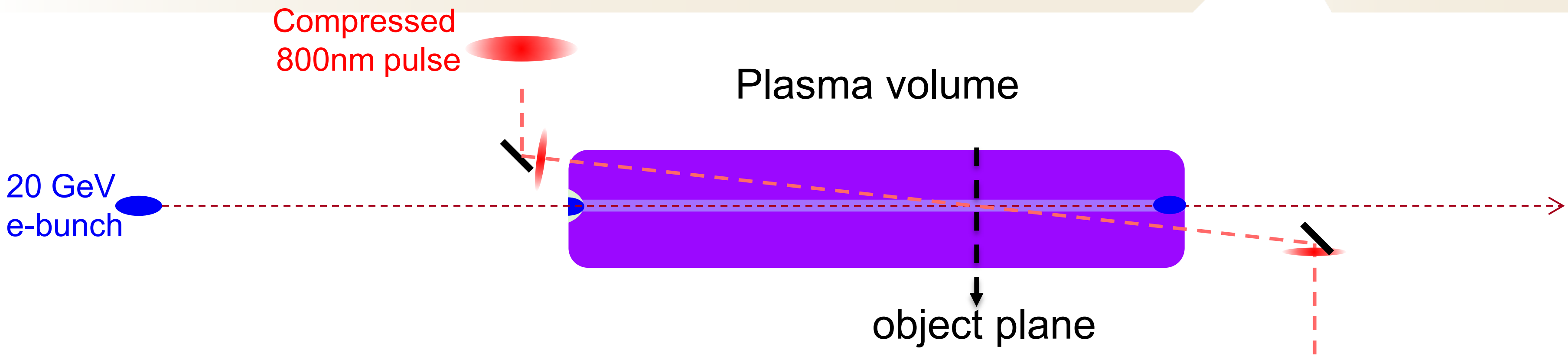
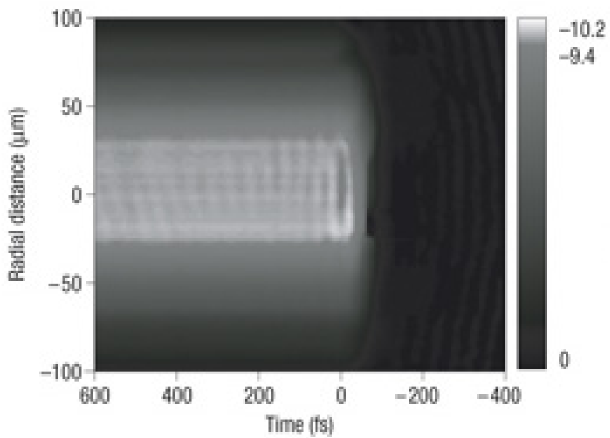
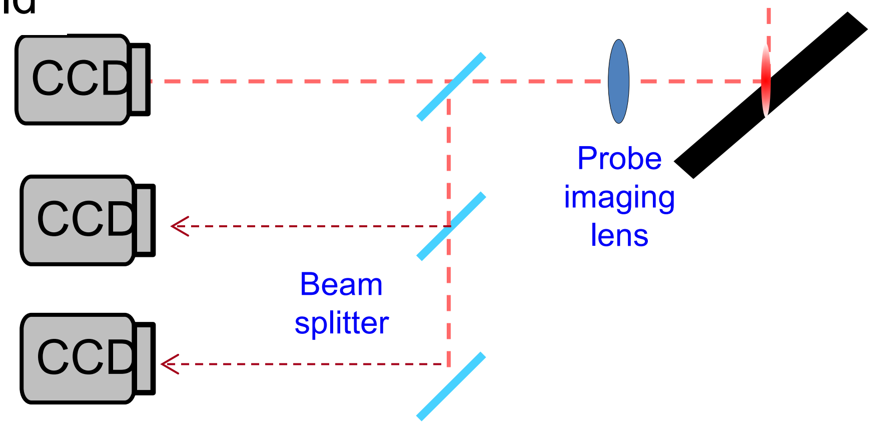


Goal: Reconstruct plasma wakefield





Slide courtesy of Rafal Zgadaj