# Plasma Wakefield Acceleration of Positron Beams

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Fermilab Seminar
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U.S. DEPARTMENT OF ENERGY
Office of Science
SLAC NATIONAL ACCELERATOR LABORATORY

# Motivation

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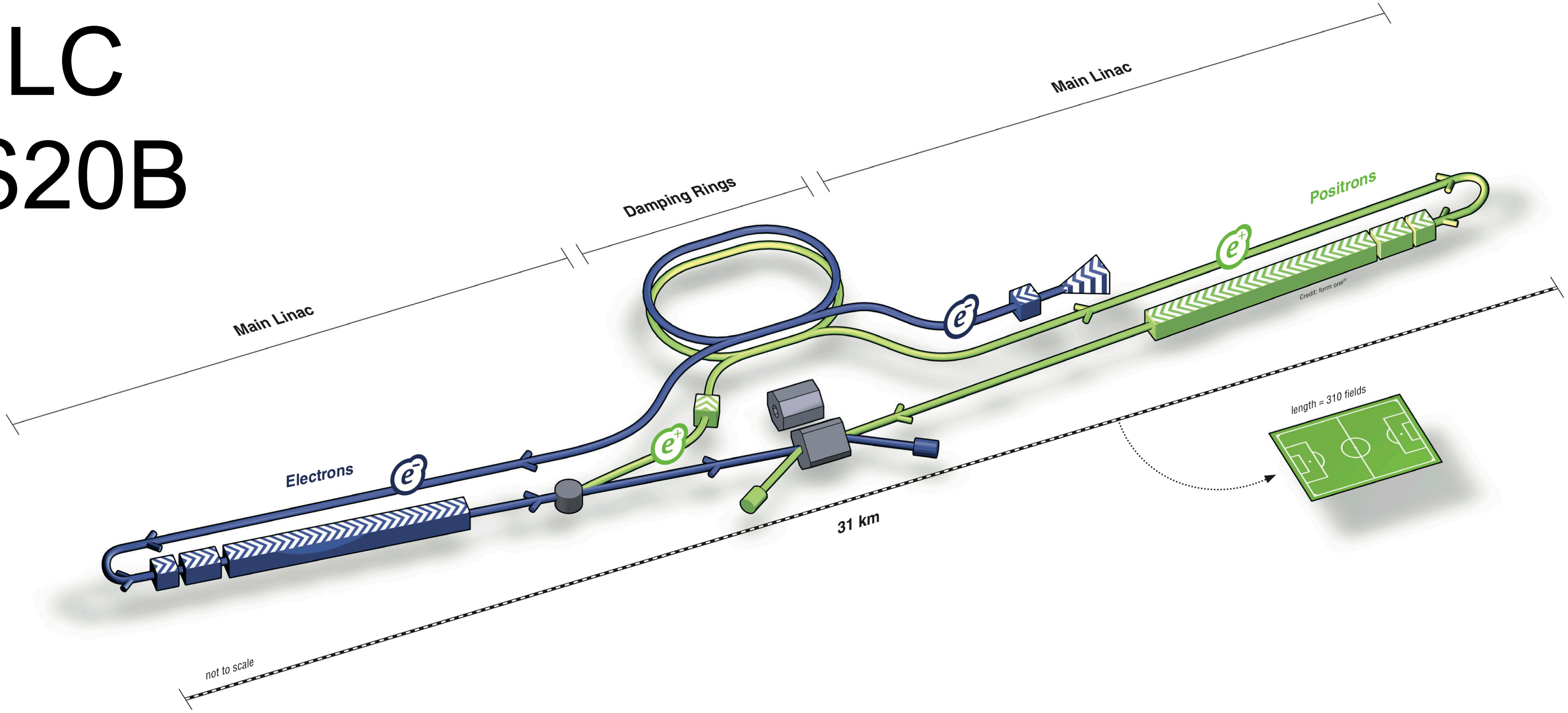
~$20B



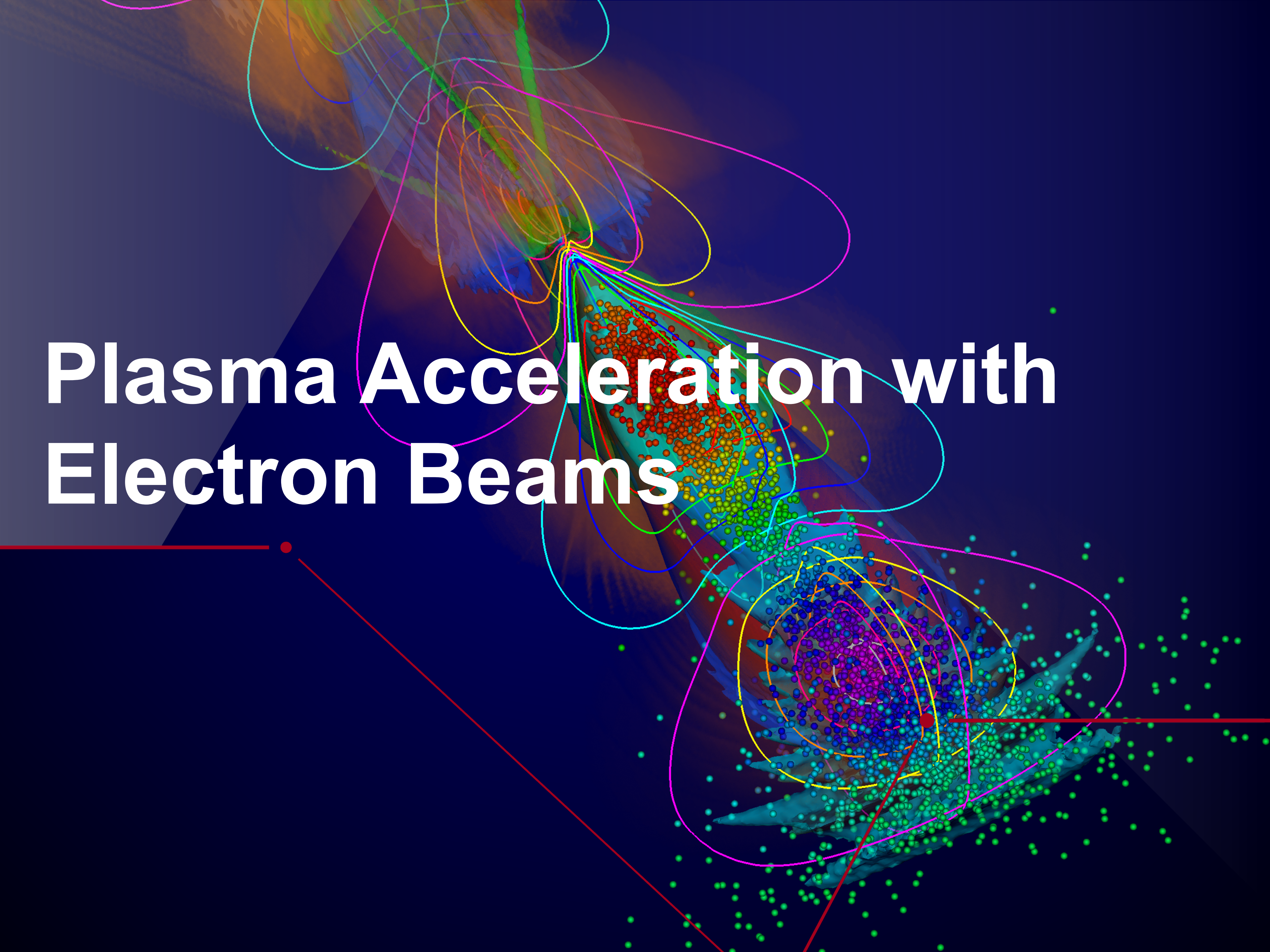

Can we use plasma to make the linear collider more affordable?

# This Talk

1. Describe recent progress in the study of positron plasma wakefield acceleration (PWFA) at FACET.

2. Identify the major opportunities and challenges on the path toward a plasma-based linear collider.

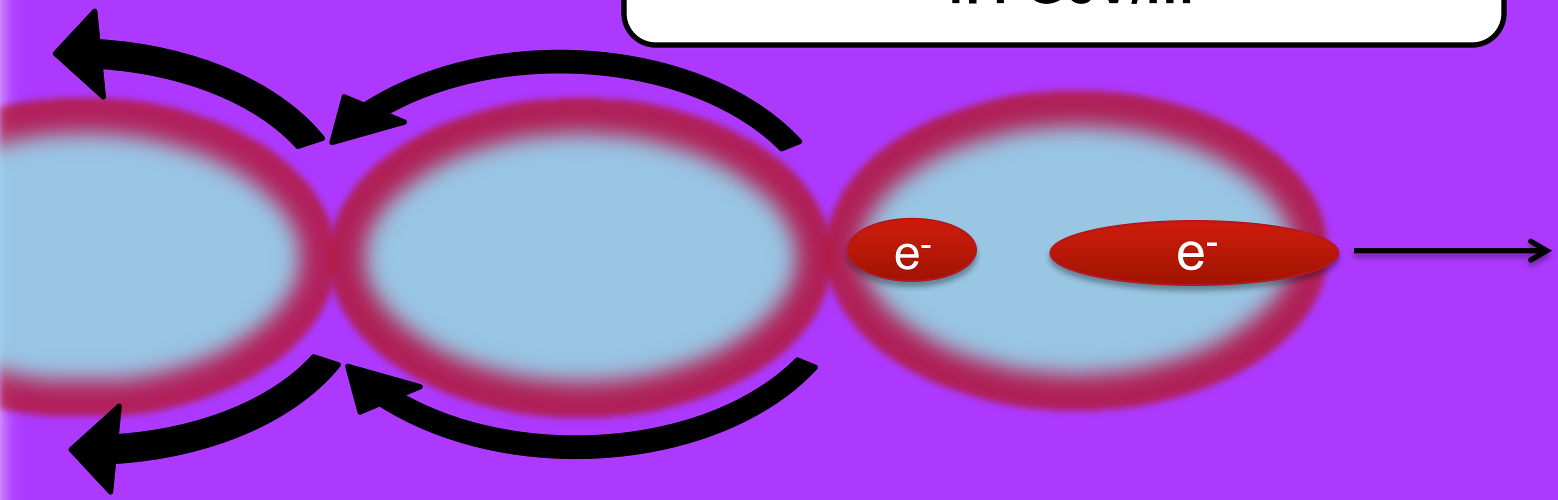
# Plasma Acceleration with Electron Beams



# How does Plasma Wakefield Acceleration Work?

Plasma

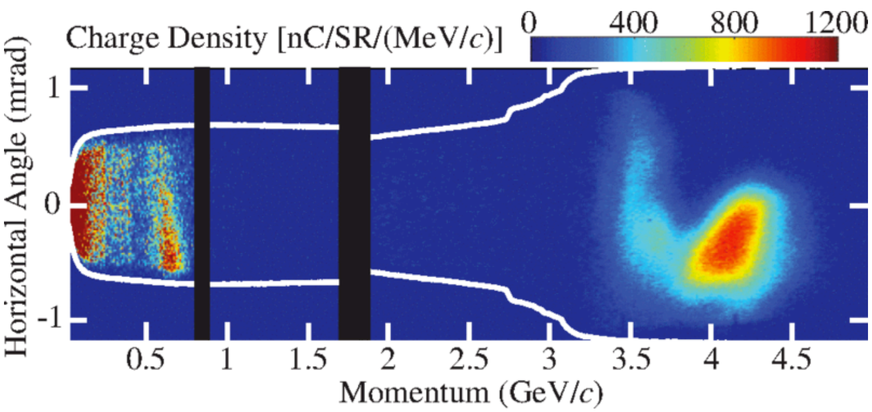
**Demonstrated at FACET in 2014**
**4.4 GeV/m**

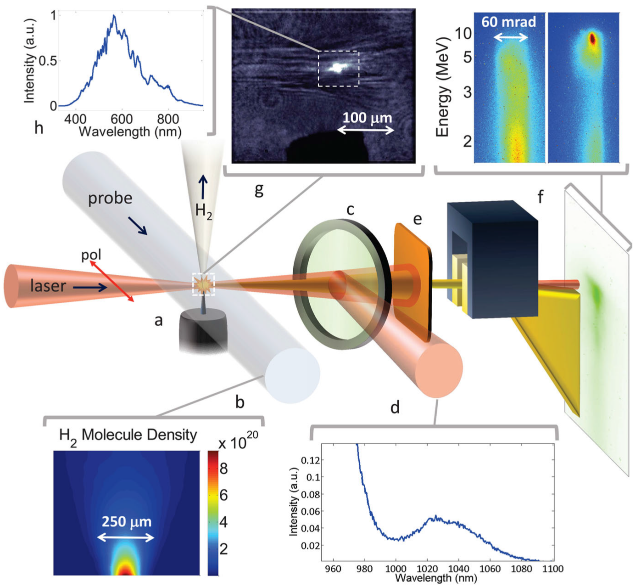




**To extract energy from the wakefield, we place a “witness” bunch in the back of the bubble, where it can ride the wake and gain energy.**

# Rapid Progress in Laser Wakefield Acceleration




**BELLA, LBNL (2014):**

- 100 TW laser
- 4.2 GeV Energy Gain in 9 cm
- Operating at < 1 Hz

**University of Maryland (2015):**

- ~1 TW laser
- 10 MeV Energy Gain in 250 μm
- Operating at 1 kHz!


W. Leemans *et al. PRL* **113**, 245002 (2014)
A.J. Goers *et al. PRL* **115**, 194802 (2015)

# Towards a Plasma-Driven FEL

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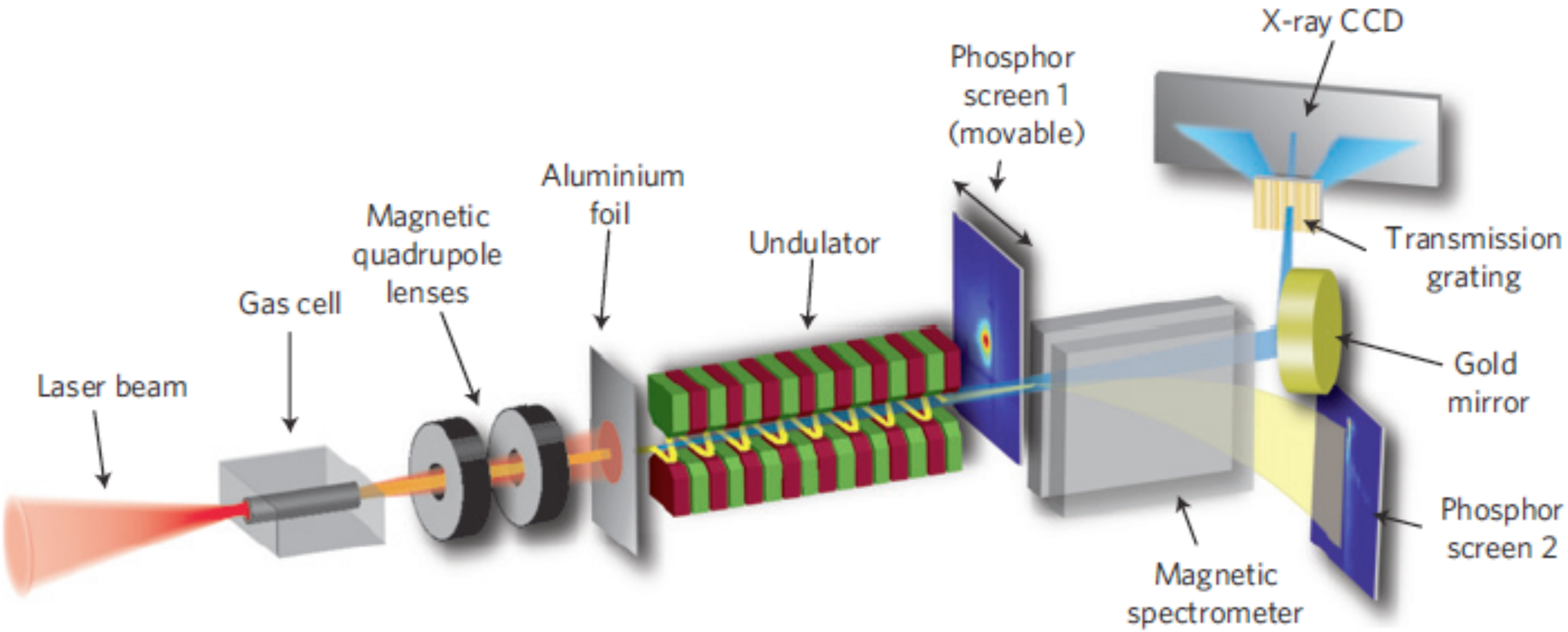



**EuPRAXIA** at **DESY** and **kBella** at **LBNL** seek to demonstrate the first plasma-driven FELs.

M. Fuchs et al., Nature Physics (2009)

# Plasma Acceleration with Positron Beams

# The Challenge with Positrons


$$m_i >> m_e$$

The plasma electrons are mobile but the ions are not.

The symmetry of the accelerating mechanism is broken.

# Positron PWFA Before FACET

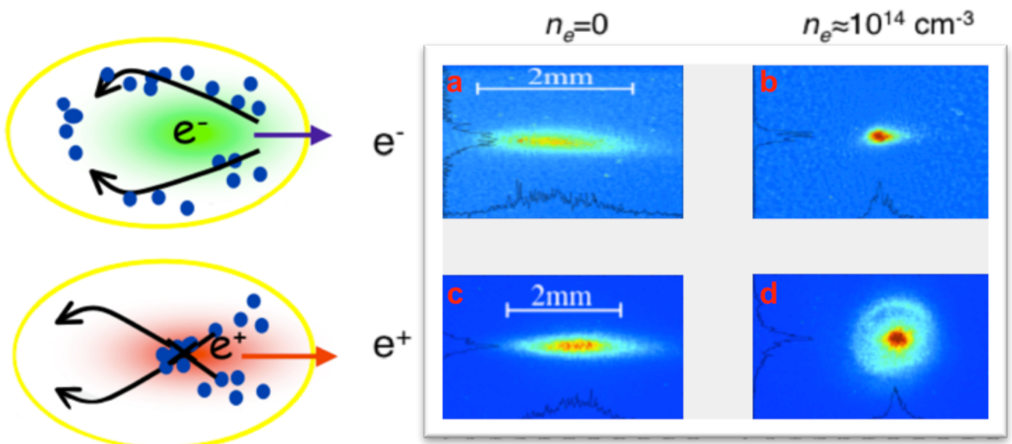
## SLAC FFTB, 2003:

First acceleration of positrons in plasma:

- B. Blue et. al. *PRL* 2003

Two studies on positron beam transport and beam quality:

- M.J. Hogan et. al. *PRL* 2003
- P. Muggli et. al. *PRL* 2008




**No new research on positron PWFA from 2003 to 2014!**

# Positrons at FACET

FACET was the only facility in the world producing positron beams for PWFA research.

FACET delivered positron beams with up to 1.5 nC charge, 20.35 GeV energy, with bunch lengths and spot sizes below 20 microns.

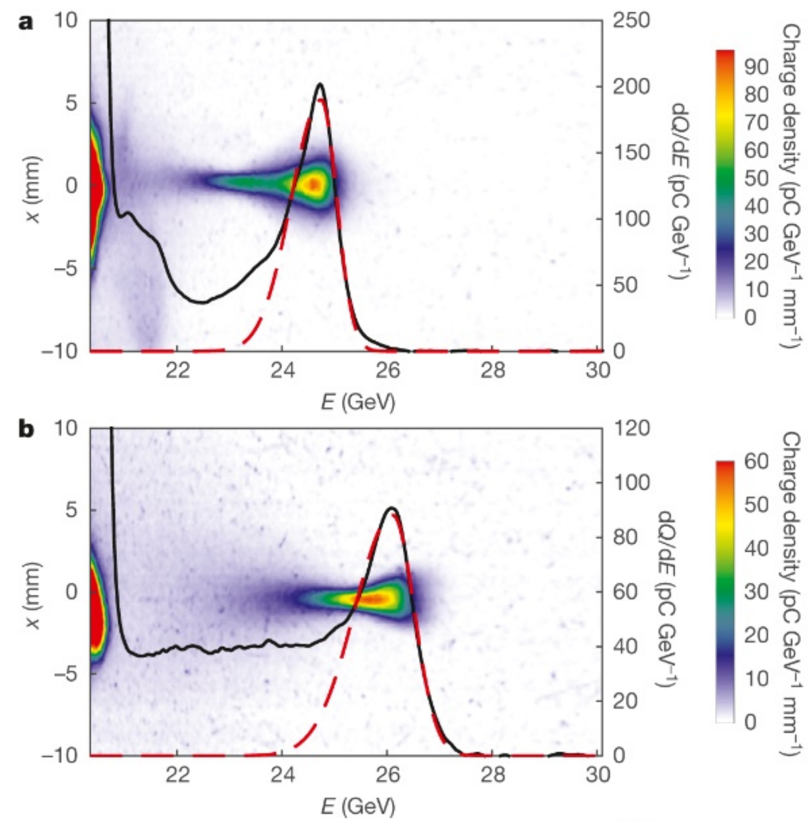
FACET provided a TW-class laser and plasma source, which are critical for PWFA research.

# High Gradient Positron PWFA

**FACET 2014**: Breakthrough! First high gradient acceleration of positrons in plasmas.

Accelerated beamlet **gains 6 GeV energy** in 1.3 m-long plasma.

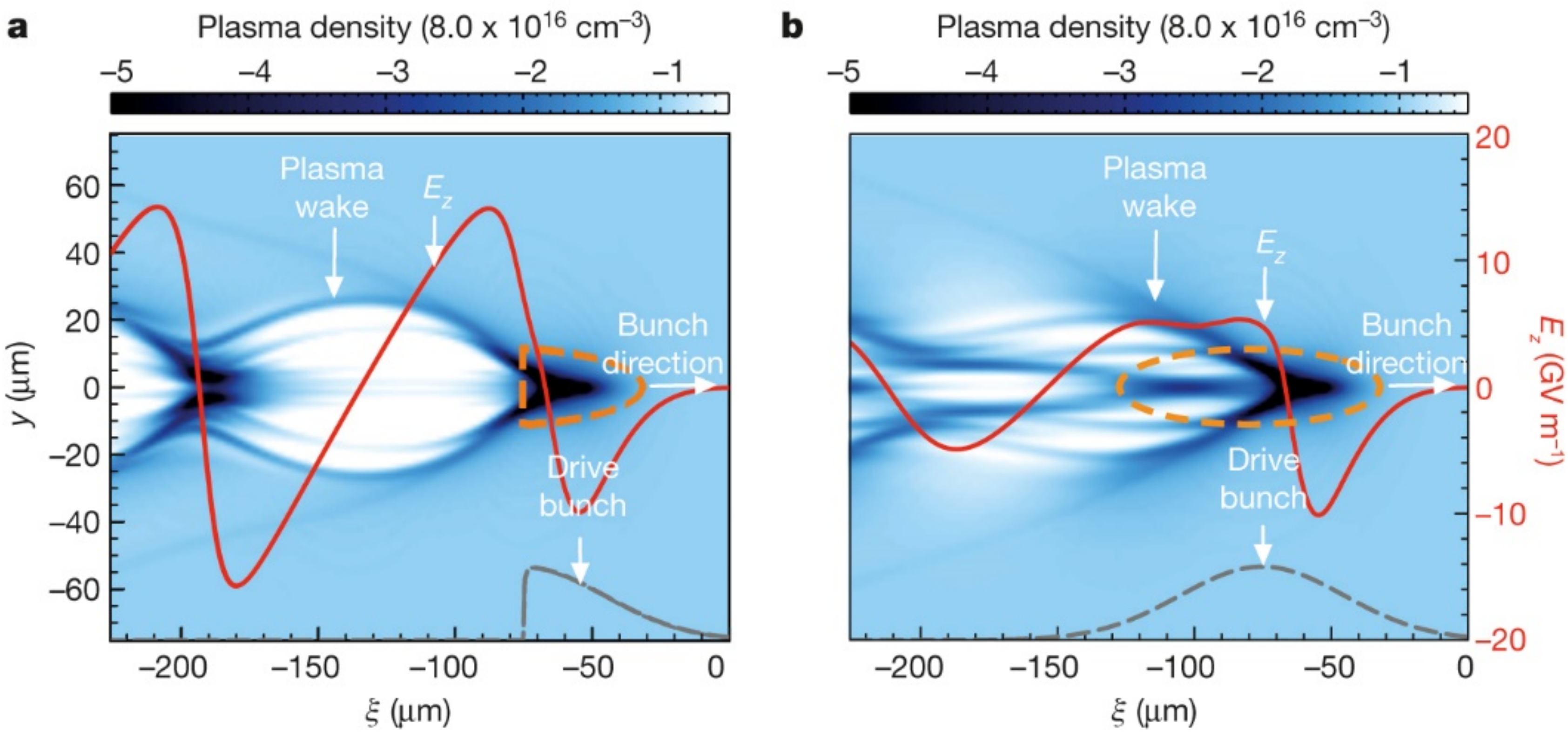
**Low energy spread** and **high-efficiency!**




**Results were neither predicted nor well-understood at time of experiment.**

S Corde *et al. Nature* **524**, 442-445 (2015)

# What's Going On?




The long positron bunch draws plasma electrons through the beam volume, which modifies the transverse shape of the beam and wake.



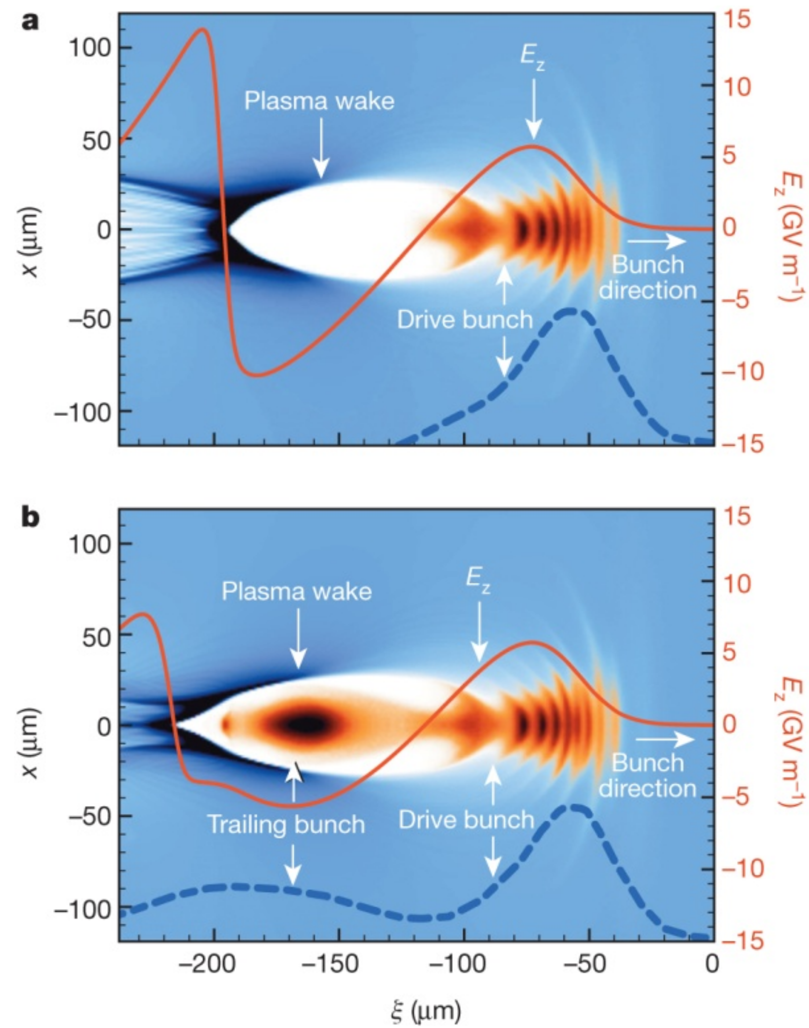
S Corde *et al. Nature* **524**, 442-445 (2015)

# Beam Loading in Electron Driven Wakes

The electron witness bunch changes the shape (flattens) the longitudinal wakefield.

But the transverse force inside the blow-out is not affected by the presence or absence of beam electrons.

There is no transverse beam loading effect in electron beam PWFA.





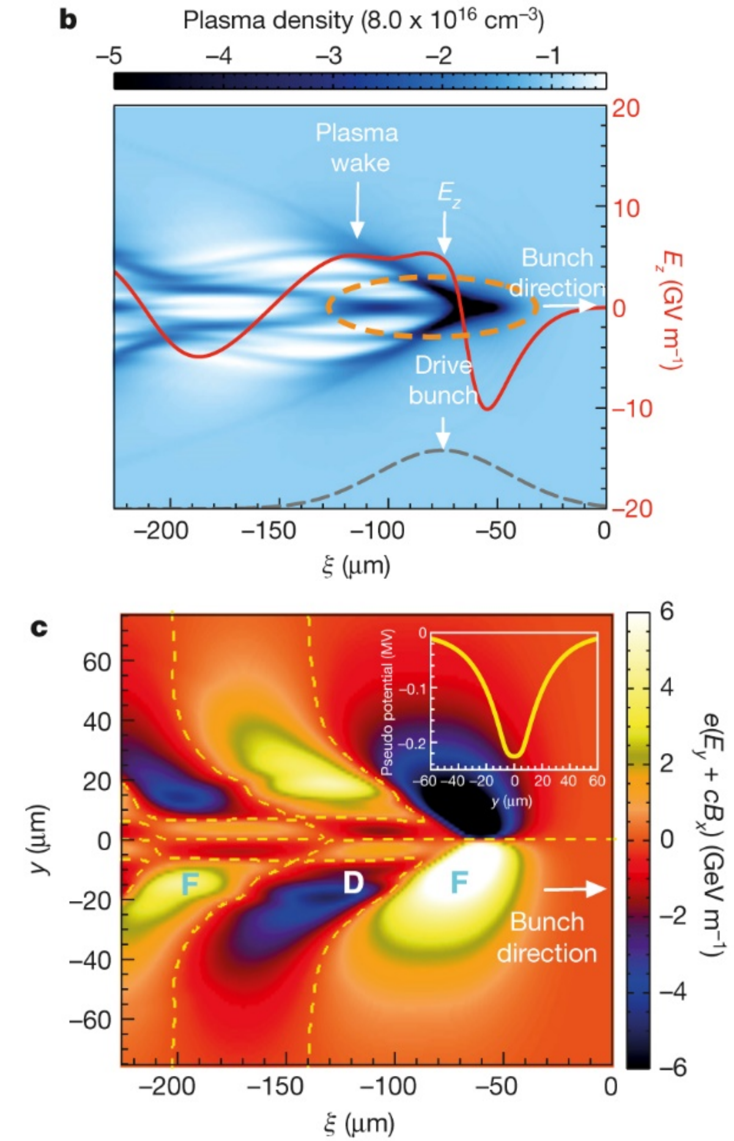

M. Litos *et al. Nature* **515**, 92-95 (2014)

# Transverse Beam Loading with Positrons

**Positrons pull plasma electrons into the beam.**

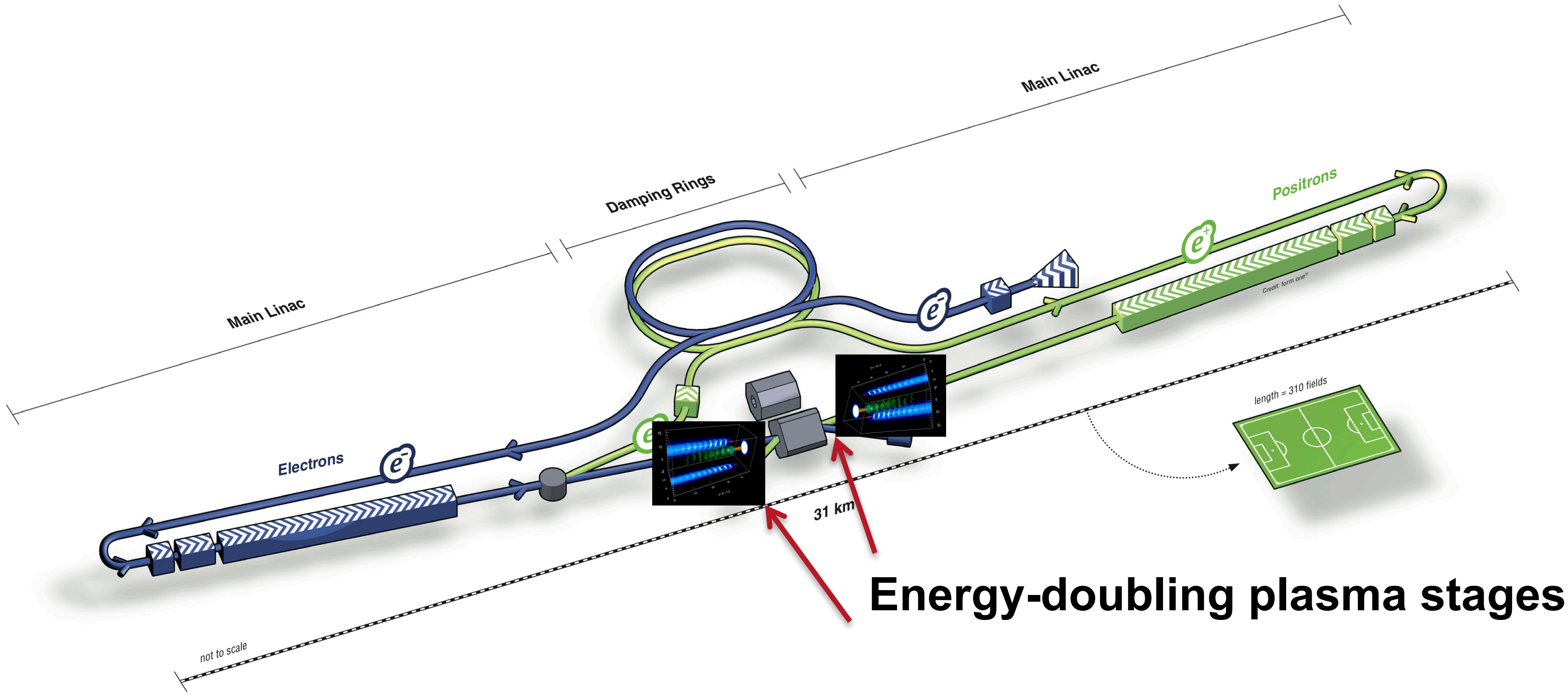
**The focusing force due to the plasma electrons increases.**

**Positron beam profile pinches and becomes more dense.**




S Corde *et al.* *Nature* **524**, 442-445 (2015)

# A Plasma Afterburner




Simulation studies are underway at UCLA to search for useful steady-state solutions for a positron afterburner.

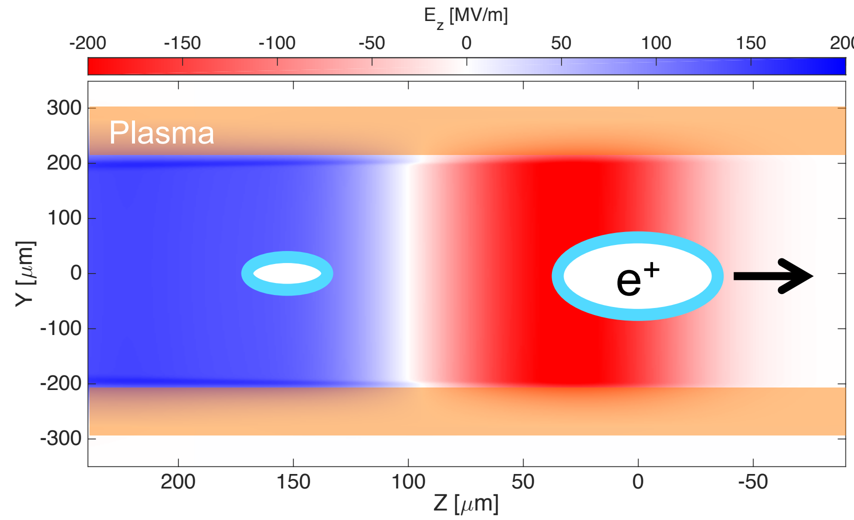
# Positron Acceleration in Hollow Channel Plasmas

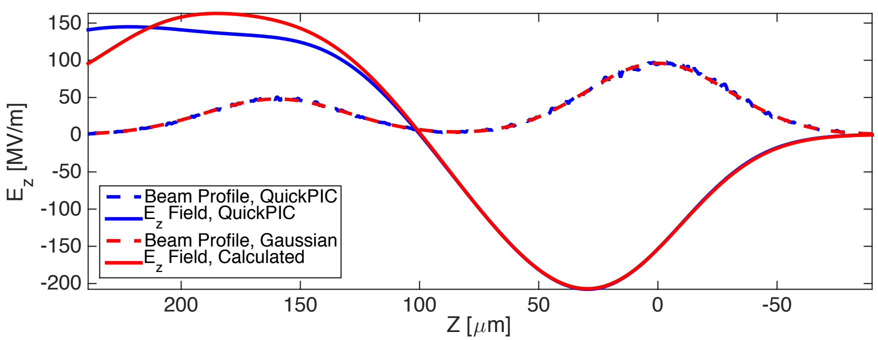
# Hollow Channel Plasmas

First proposed in 1995, hollow channel plasmas are an attempt to *engineer* the plasma to produce the desired fields.

Wakefield is radially uniform within channel. No transverse wake if beams are on axis.

This experiment was my graduate thesis project.

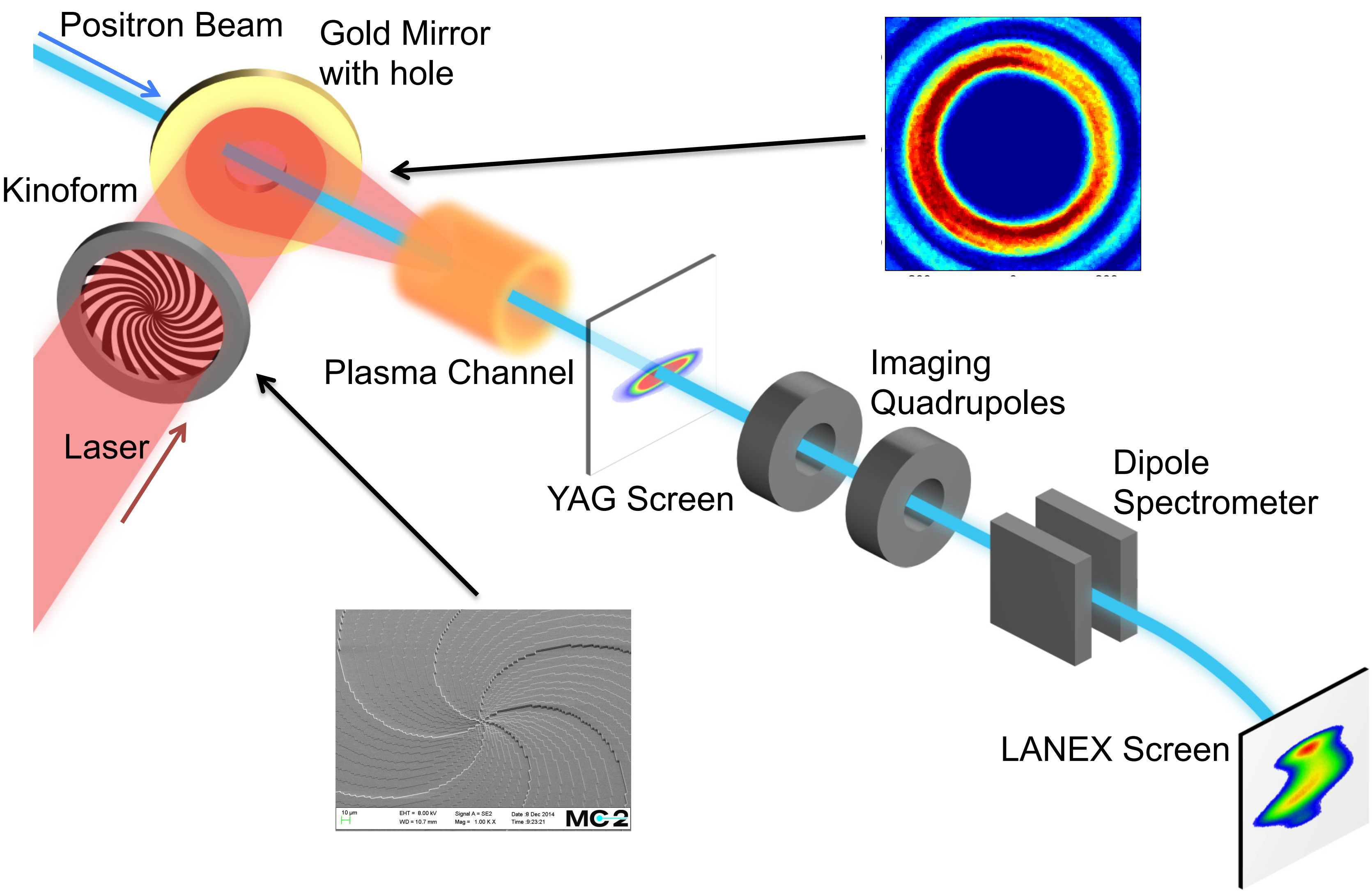




T.C. Chiou et al., *Physics of Plasmas* (1995).
T.C. Chiou and T. Katsouleas, *PRL* (1998).
C.B. Schroeder et al., *PRL* (1999).

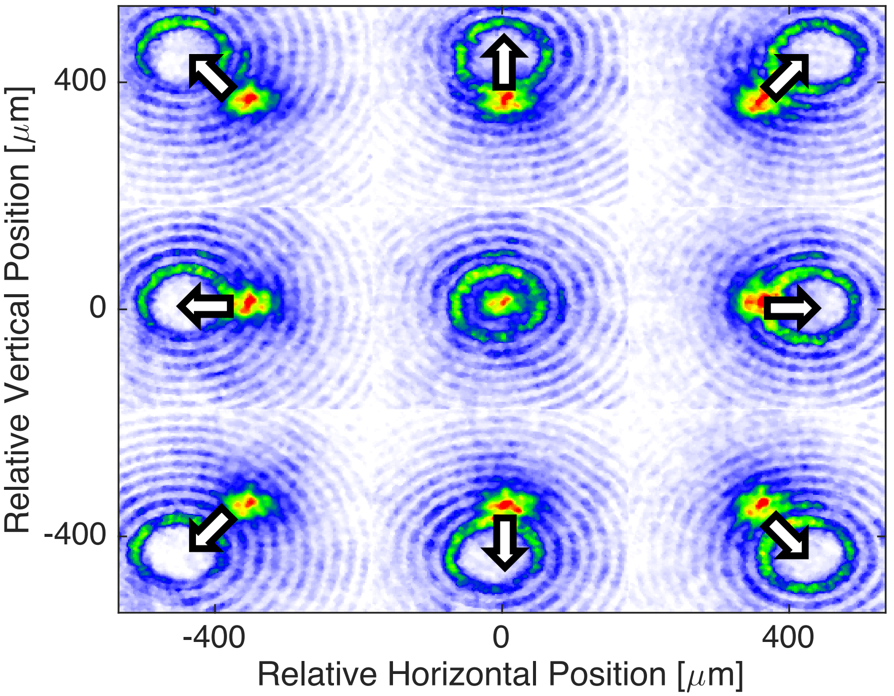
# Experimental Setup



# How do we measure the shape of the channel?

The positron beam (bright spot) feels an attraction to the nearest ionized region (ring).

We shift the laser in parallel to the beam trajectory, and measure it's affect on the beam.



# How do we measure the shape of the channel?

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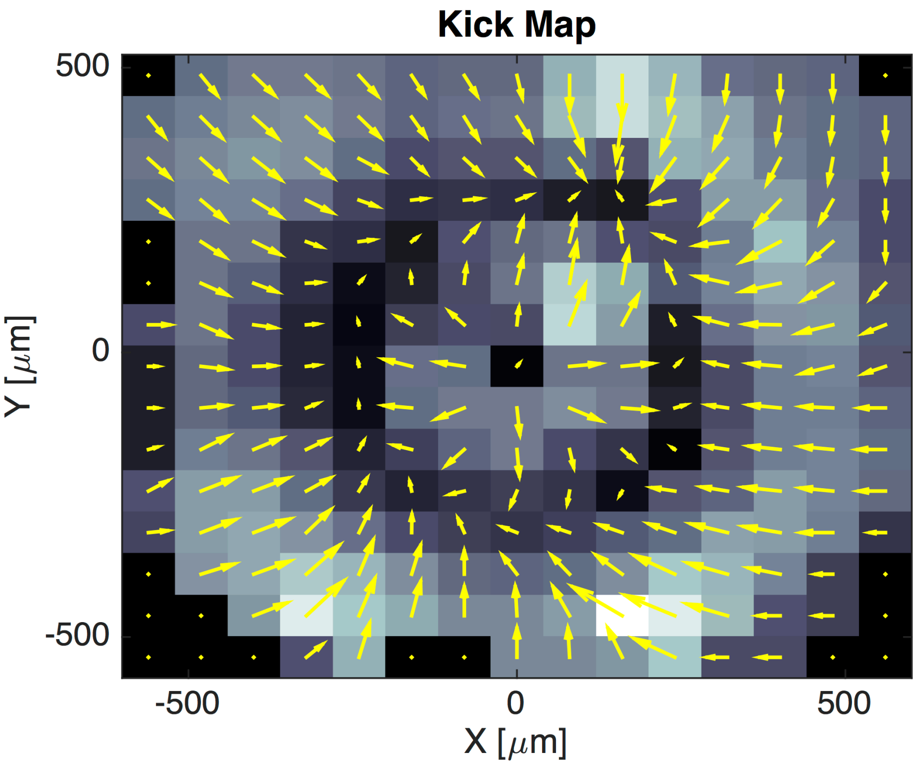
We use a beam profile monitor downstream of the plasma to measure changes, or “kicks”, to the beam trajectory.

The Kick Map shows that the beam is attracted to an annular region with the expected radius, and there is a point in the middle of the channel where the beam is not deflected at all.

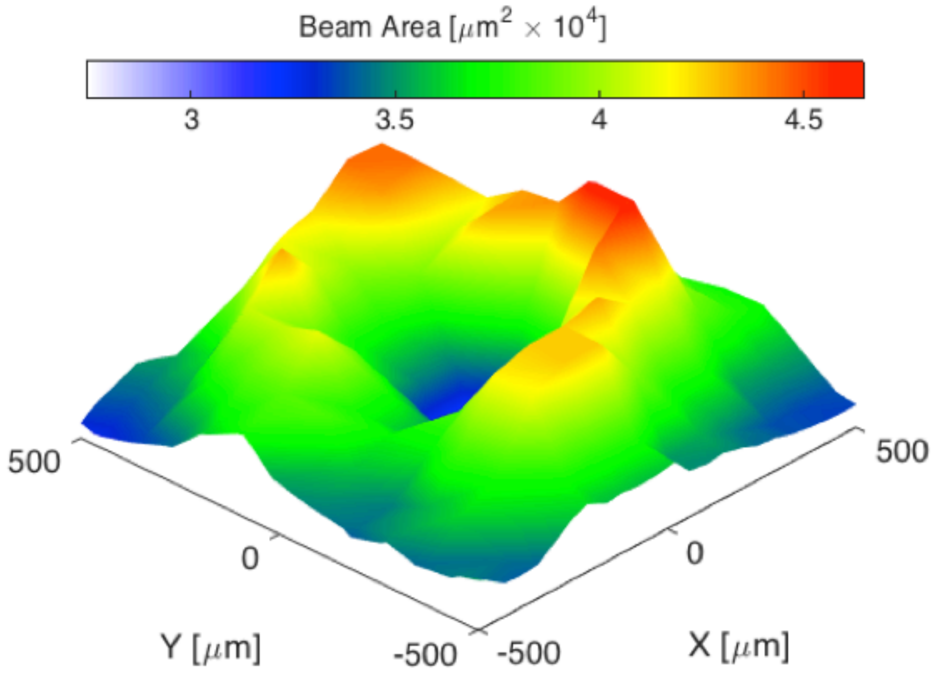


# How do we measure the shape of the channel?

SLAC

We also use the beam profile monitor to measure changes, to the transverse beam size. The beam size increases when the beam interacts with the plasma channel.

Both the Kick Map and Beam Area Measurement (Volcano Plot) are consistent with an annular plasma channel.



# Demonstration of the Hollow Channel Plasma

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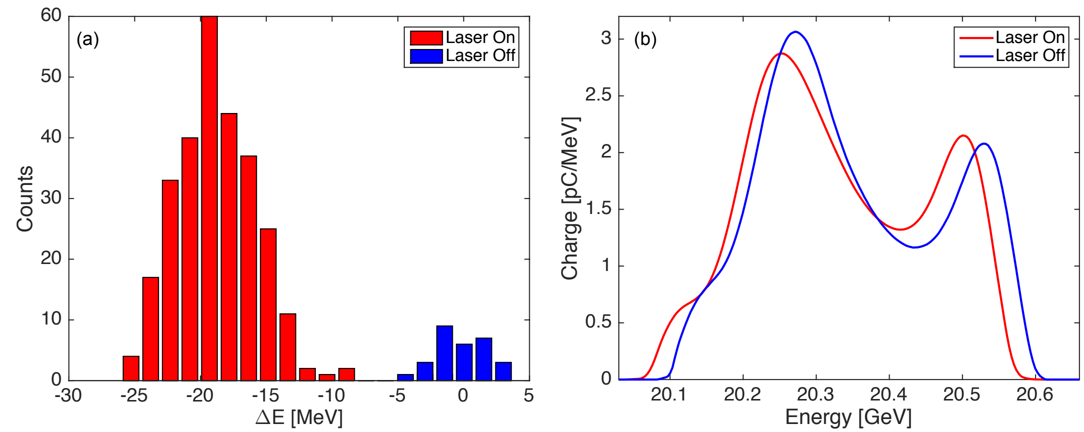
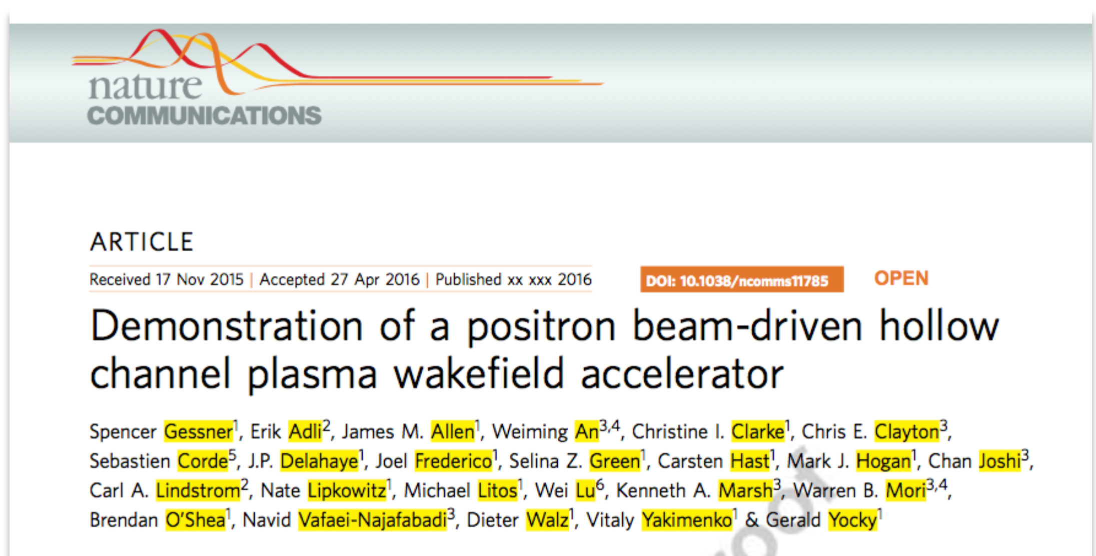
We also measure a decelerating wakefield of 230 MeV/m, which is consistent with theory and PIC simulations.




**Out this Thursday!**



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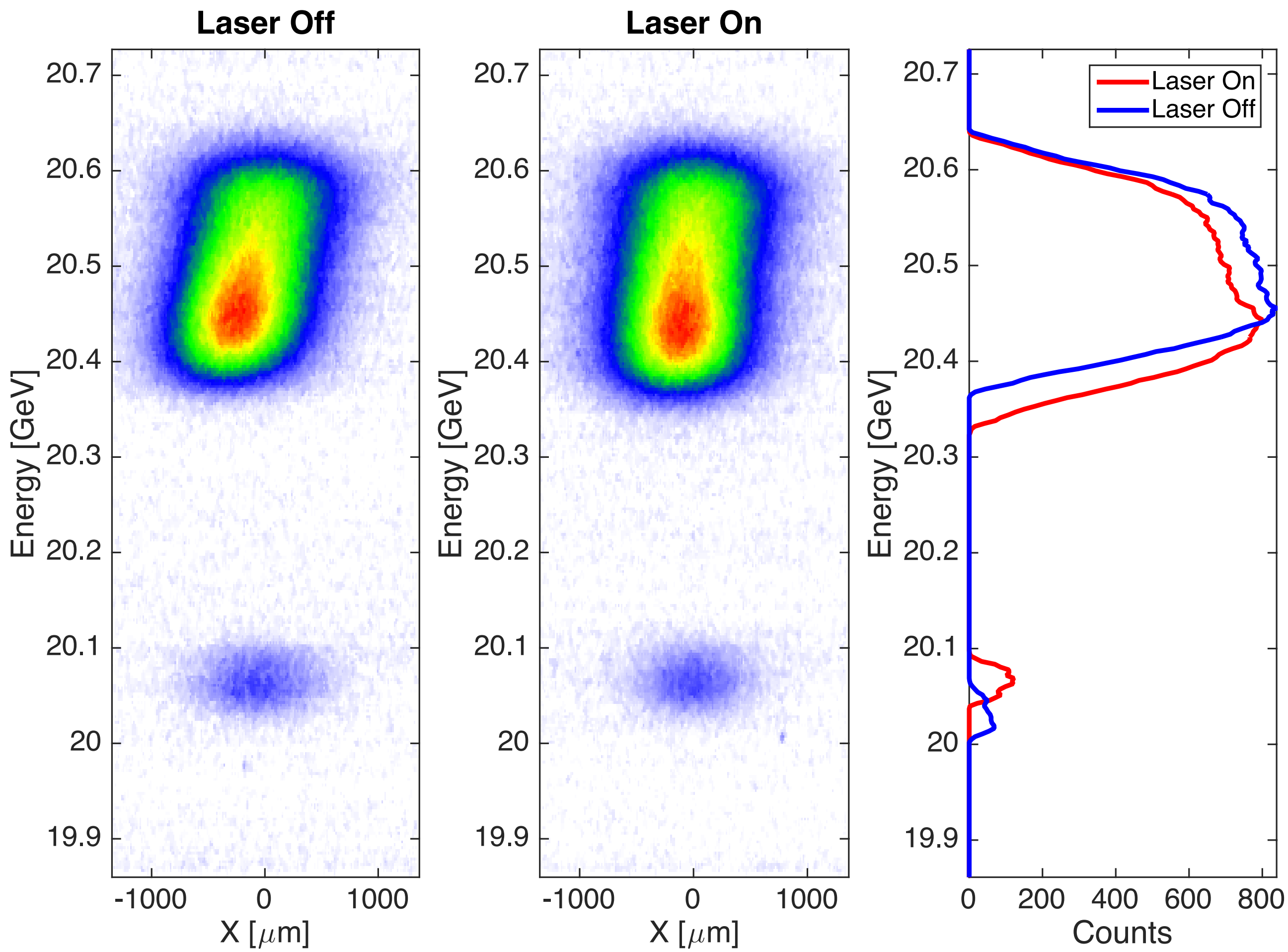
OPEN


Demonstration of a positron beam-driven hollow channel plasma wakefield accelerator


Spencer Gessner[1], Erik Adli[2], James M. Allen[1], Weiming An[3,4], Christine I. Clarke[1], Chris E. Clayton[3], Sebastien Corde[5], J.P. Delahaye[1], Joel Frederico[1], Selina Z. Green[1], Carsten Hast[1], Mark J. Hogan[1], Chan Joshi[3], Carl A. Lindstrom[2], Nate Lipkowitz[1], Michael Litos[1], Wei Lu[6], Kenneth A. Marsh[3], Warren B. Mori[3,4], Brendan O'Shea[1], Navid Vafaei-Najafabadi[3], Dieter Walz[1], Vitaly Yakimenko[1] & Gerald Yocky[1]

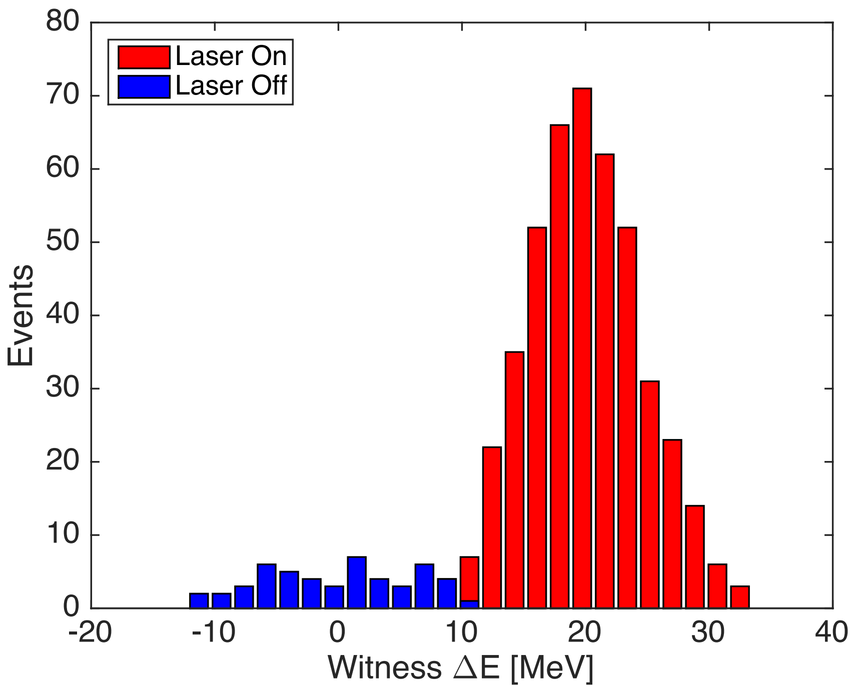
# Acceleration of a Positron Witness Beam

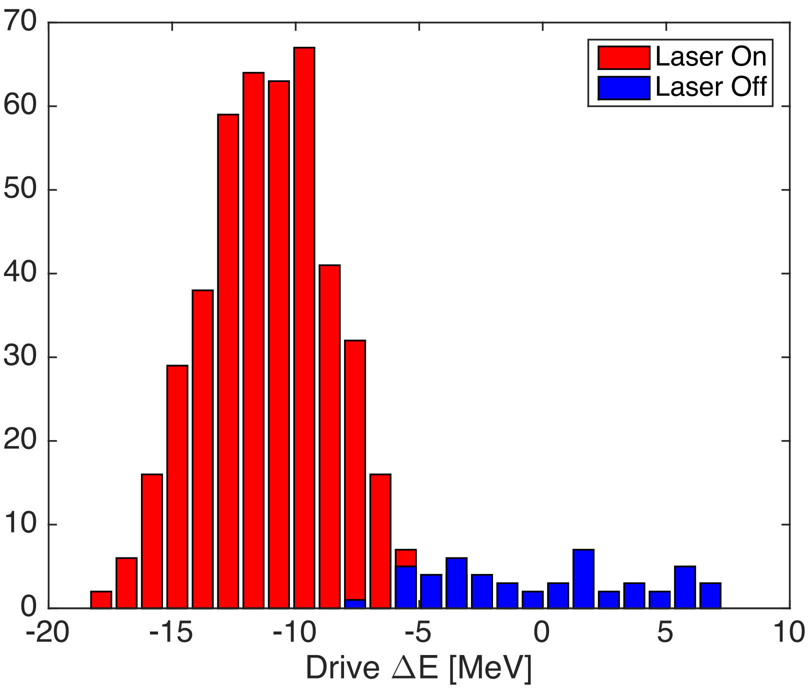





We have since demonstrated acceleration of a positron witness beam in the hollow channel plasma.

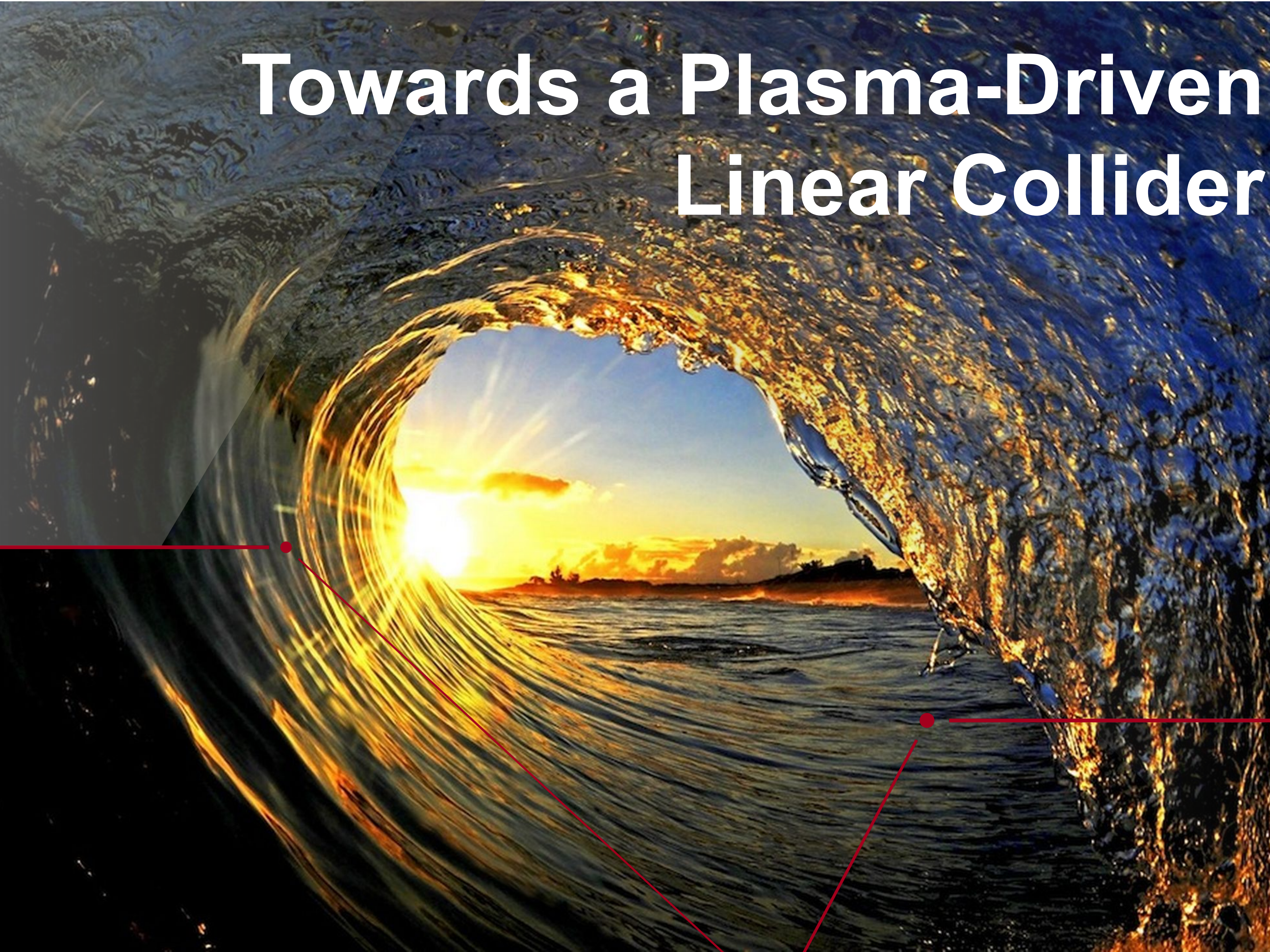
# High Transformer Ratio



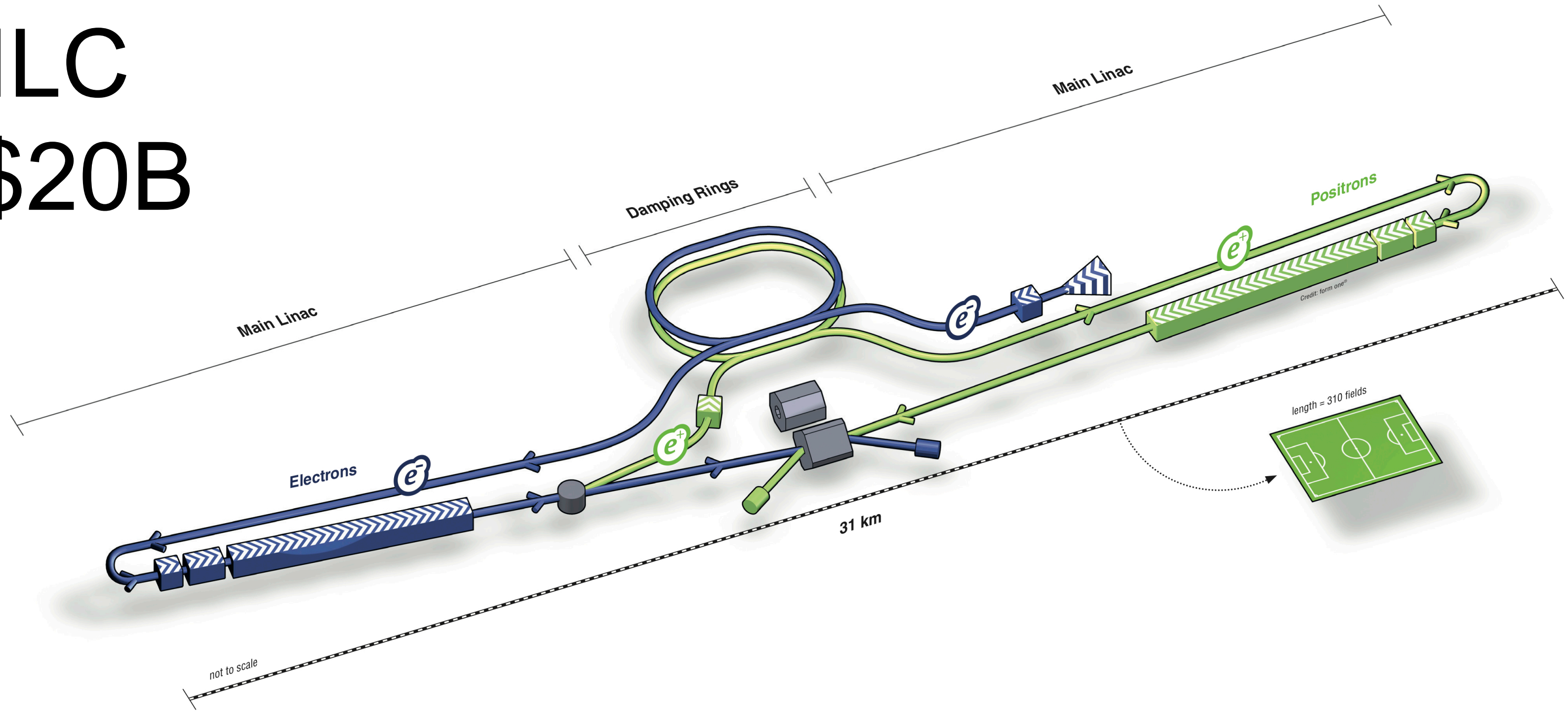

The witness beam gains about 20 MeV on average, while the drive beam loses about 11 MeV, giving a transformer ratio of 1.8.

# Towards a Plasma-Driven Linear Collider



# Can plasma make the linear collider more affordable?

ILC
~$20B



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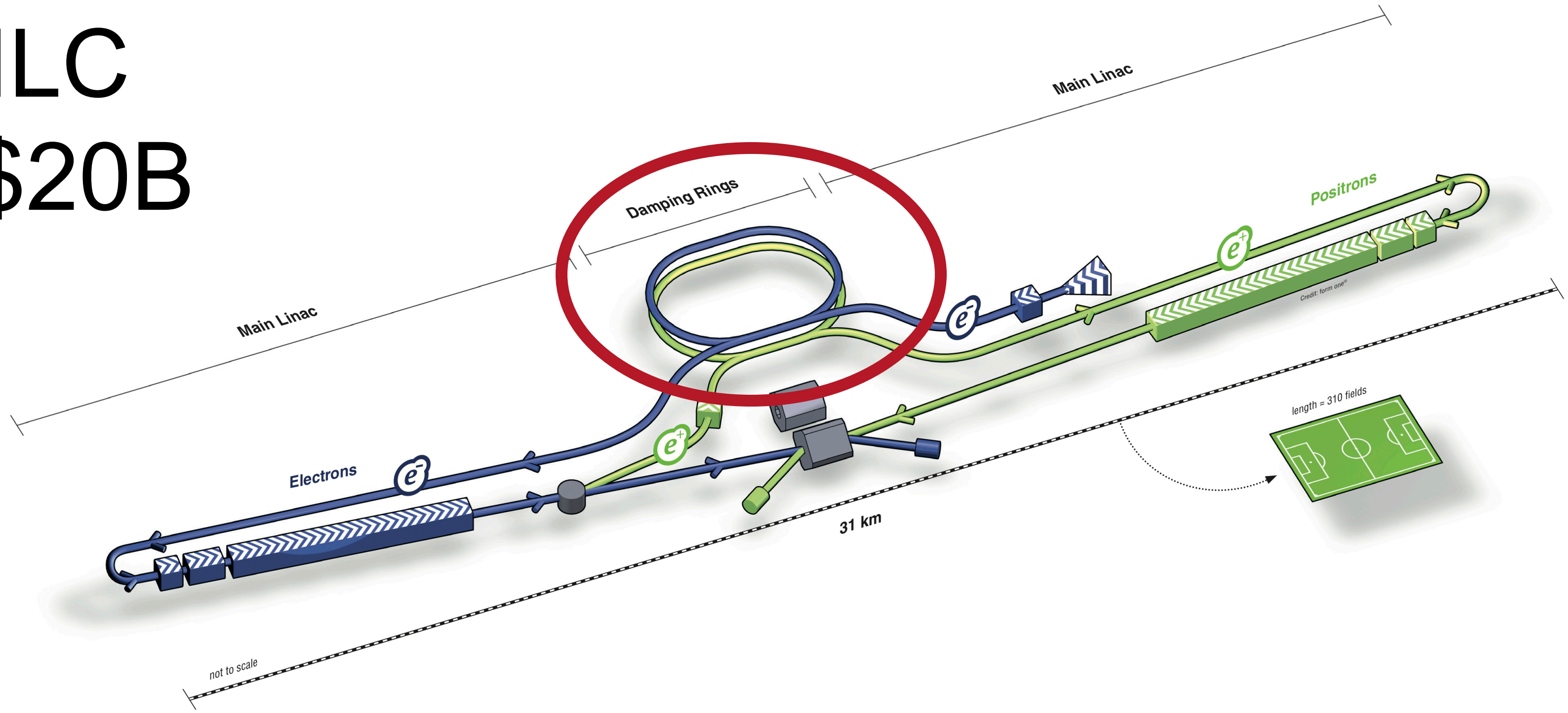



**Beam Source (~$1B)**

Plasma Solution: Replace damping rings with plasma source (e.g. downramp, ionization, colliding pulse, or Trojan Horse injection)

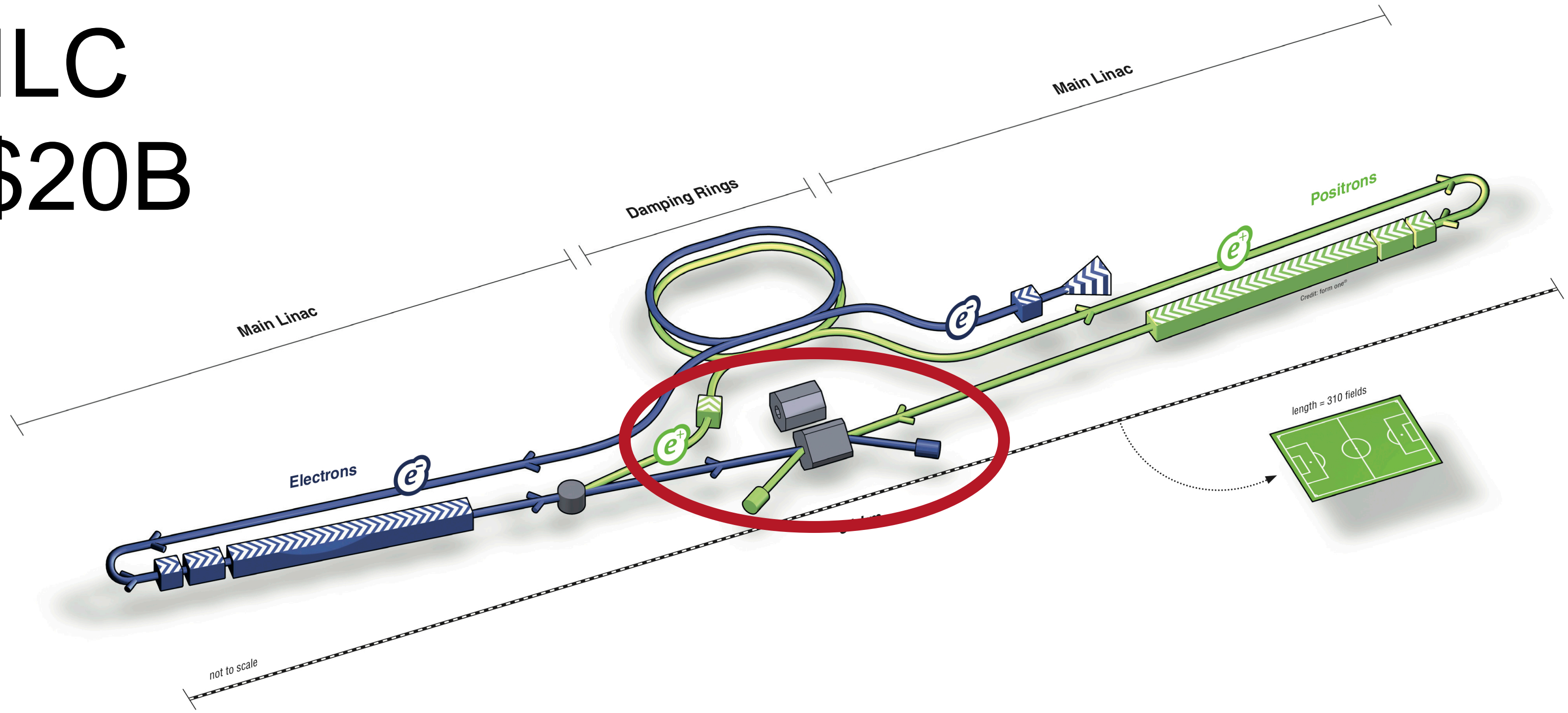
Demonstrated 20 μm emittance at FACET. (N. Vafaei-Najafabadi et al, PPCF 2016)

Challenge: No equivalent method for positrons?

# Can plasma make the linear collider more affordable?

SLAC

ILC
~$20B




**Beam Delivery (~$1B)**

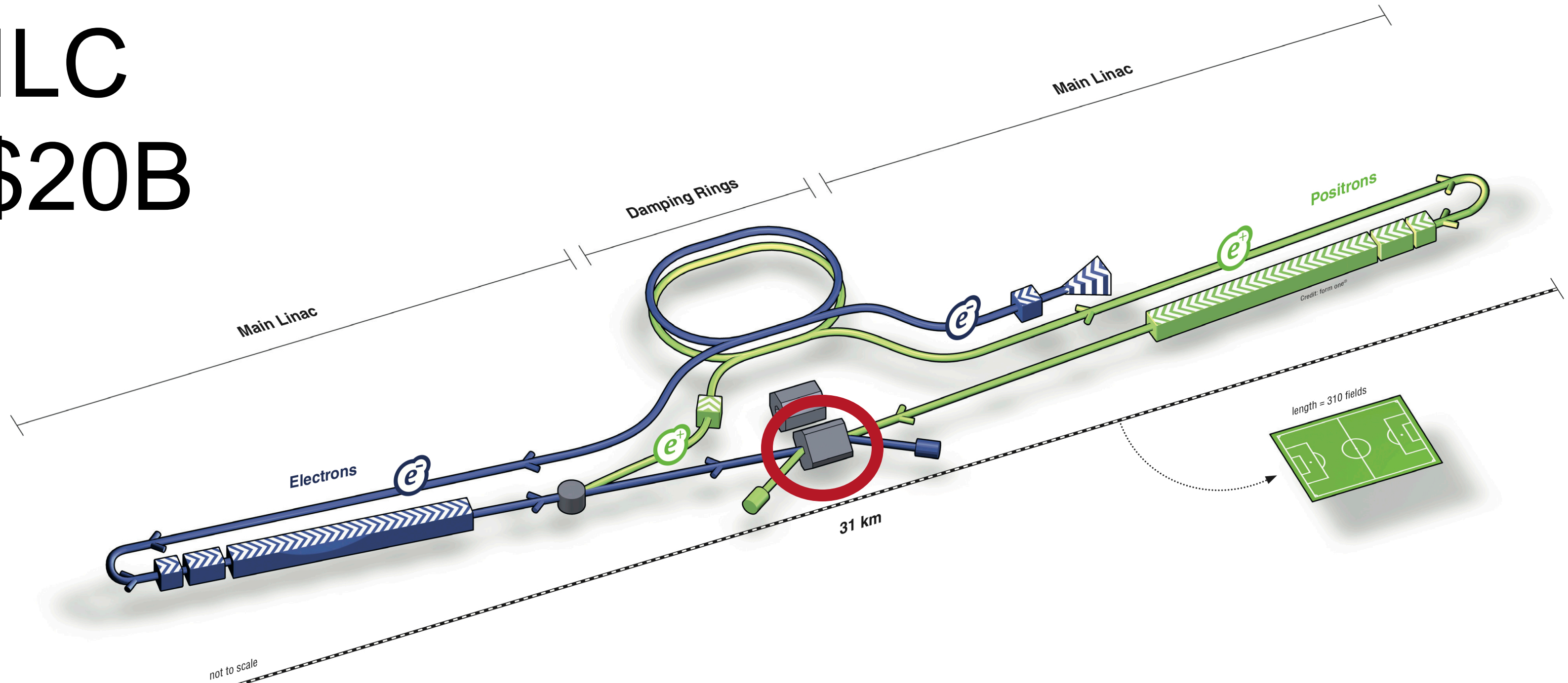
Plasma Solution: Replace final focusing quadrupoles with plasma.

Demonstrated at FFTB (J.S.T. Ng et al, PRL 2001)

Challenge: Plasma should be overdense. Abberative focusing may be z-dependent.
Scattering and energy spread compete with plasma focusing.

# Can plasma make the linear collider more affordable?

ILC
~$20B




## Beamstrahlung Mitigation (Reduces Operating Cost)

Plasma Solution: Use plasma at IP to reduce beamstrahlung (increase luminosity) by neutralizing beam fields.

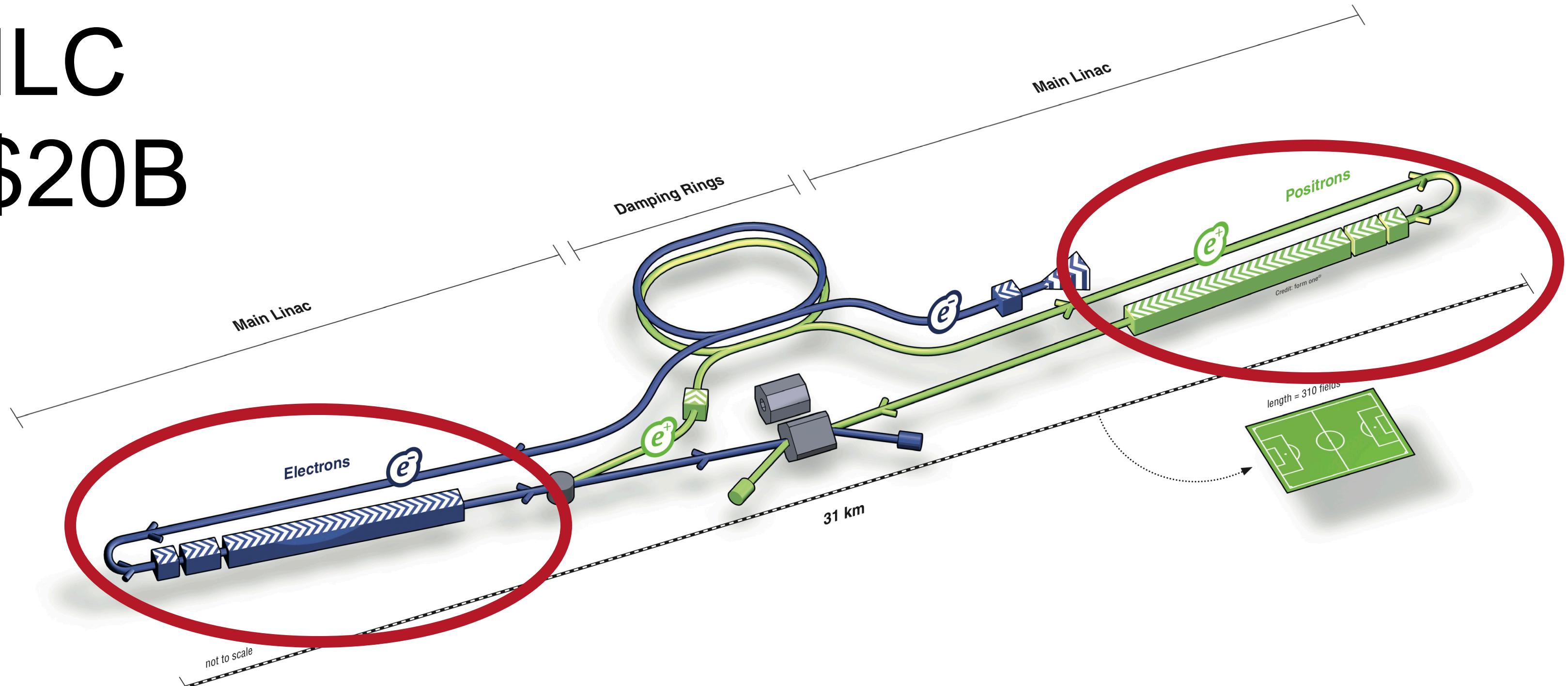
See for example D Whittum et al, LBL-25759 1988

Challenge: Plasma at IP will affect detector performance. May require positronium plasma. Not demonstrated experimentally.

# Can plasma make the linear collider more affordable?

SLAC

ILC
~$20B




**Linac (~$10B)**

Plasma Solution: Use plasma to accelerate main beams.

Challenge(s): Emittance preservation. Staging. Positrons!

See critiques: V Lebedev and S. Nagaitsev PRSTAB 2013 and Burov et al arXiv: 1602.05260 2016

# Positron PWFA for a Linear Collider

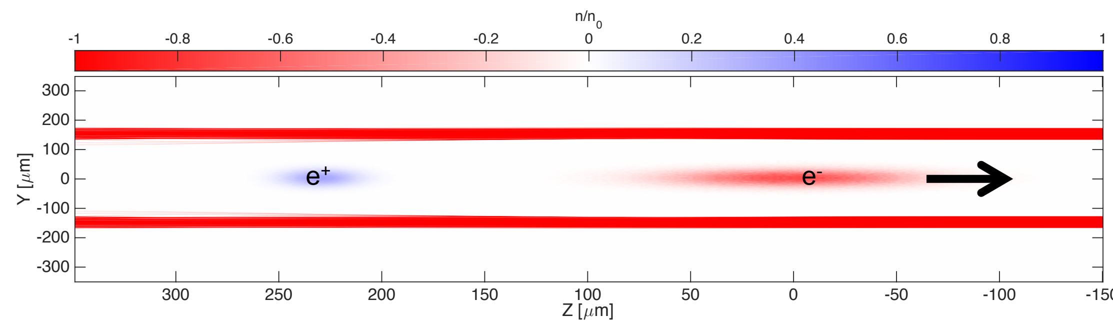
| | Advantages | Drawbacks | Open Questions |
|---|---|---|---|
| **Non-Linear Acceleration** | Extremely large gradients.<br><br>Simple experimental setup. | No known solution using an electron drive beam. | What are the optimal beam and plasma parameters for an afterburner application? |
| **Quasi-Linear Acceleration** | Very large gradients.<br><br>Works with a driving electron beam. | Scaling the plasma and drive beam parameters for an LC-quality witness bunch looks challenging. | Can the emittance of the witness beam preserved? |
| **Hollow Channel Acceleration** | Emittance preservation by precise alignment.<br><br>Works with a driving electron beam. | Modest accelerating gradients. | Can we increase the wake amplitude without a strong transverse instability? |

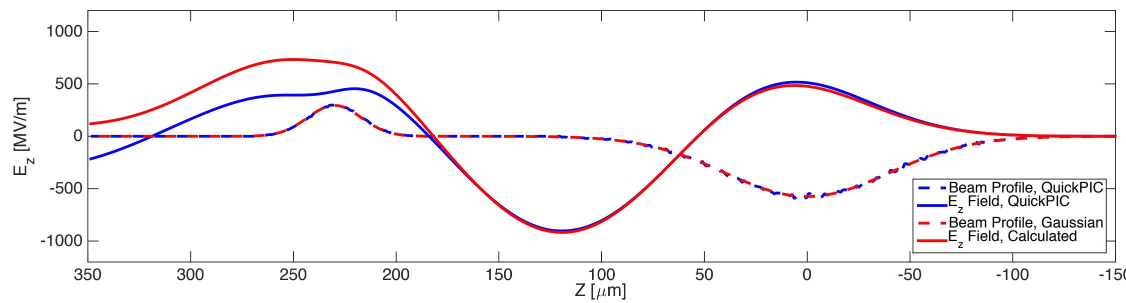
# FACET-II

FACET-II is the successor facility to FACET.

Need to address the questions asked on the previous slide.

Demonstrate positron acceleration in the wake of an electron drive bunch.




**Need to engage all physicists interested in a positron PWFA.**

# Conclusions

FACET demonstrated positron plasma wakefield acceleration in highly-nonlinear, quasi-linear, and hollow channel plasmas in just two years!

The possibility of positron PWFA is the most important open question remaining on the path to a plasma-based linear collider.

FACET-II will be the only research facility worldwide where experiments on positron PWFA can be carried out.

Any researchers who are interested in this topic should join the work at FACET-II!

# Thank You!

# Collaboration

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

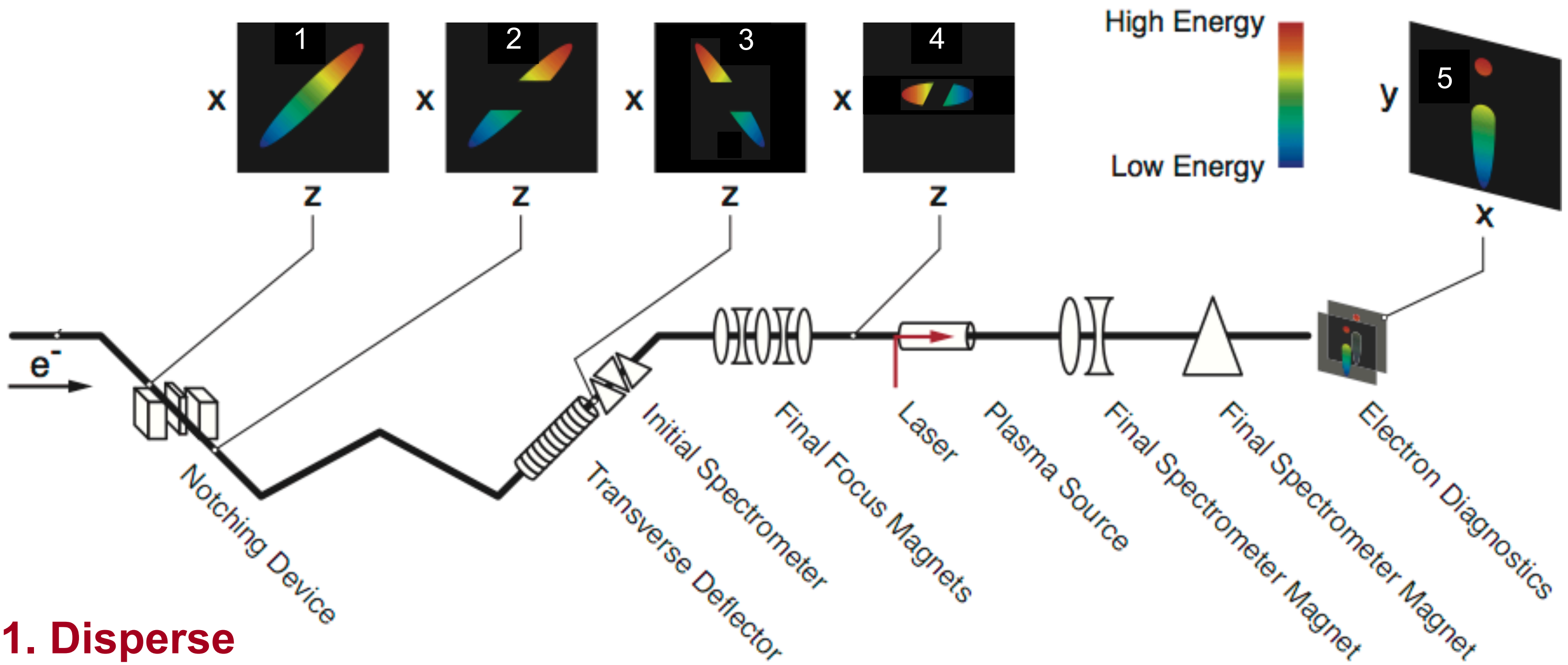
W. An, C. Clayton, C. Joshi, K. Marsh, W. Mori, N. Vafaei, W. Lu

E. Adli, C. A. Lindstrom

S. Corde, A. Doche, C. Beekman

# Backup Slides

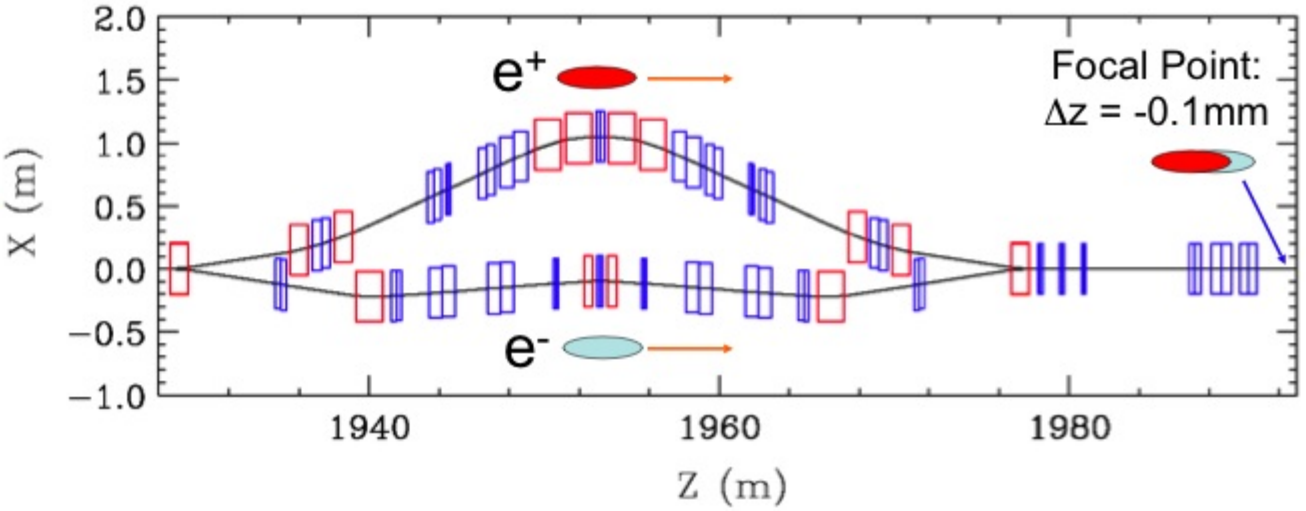
# Two-Bunch Beam Generation




1. Disperse
2. Chop
3. Compress
4. Accelerate
5. Diagnose

# Concept: Accelerate $e^+$ with an $e^-$ driver

FACET Sailboat Chicane




**Positrons are expensive! Electrons are cheap.**

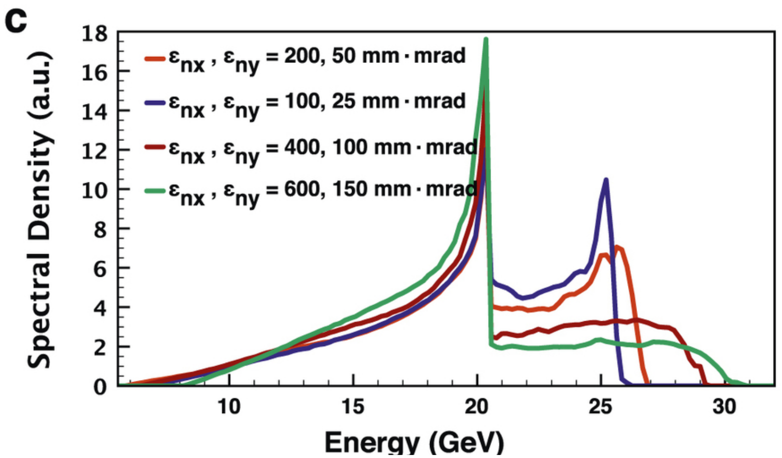
**Use electrons to drive the wake and accelerate positrons.**

# Loading is sensitive to beam parameters

The transverse and longitudinal beam loading depend on how many positrons are near the beam axis.

In simulation, we observe that low emittance beams load and flatten the wake. The outgoing energy spectra are peaked.

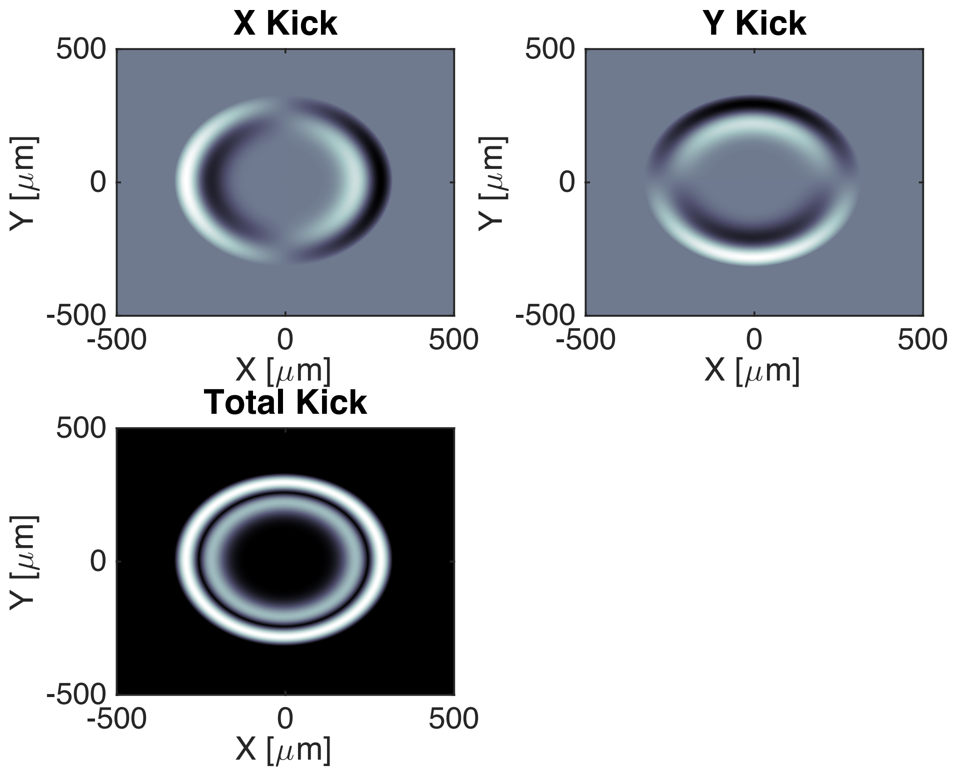
High emittance beams do not load the wake and produce spectra with long tails.

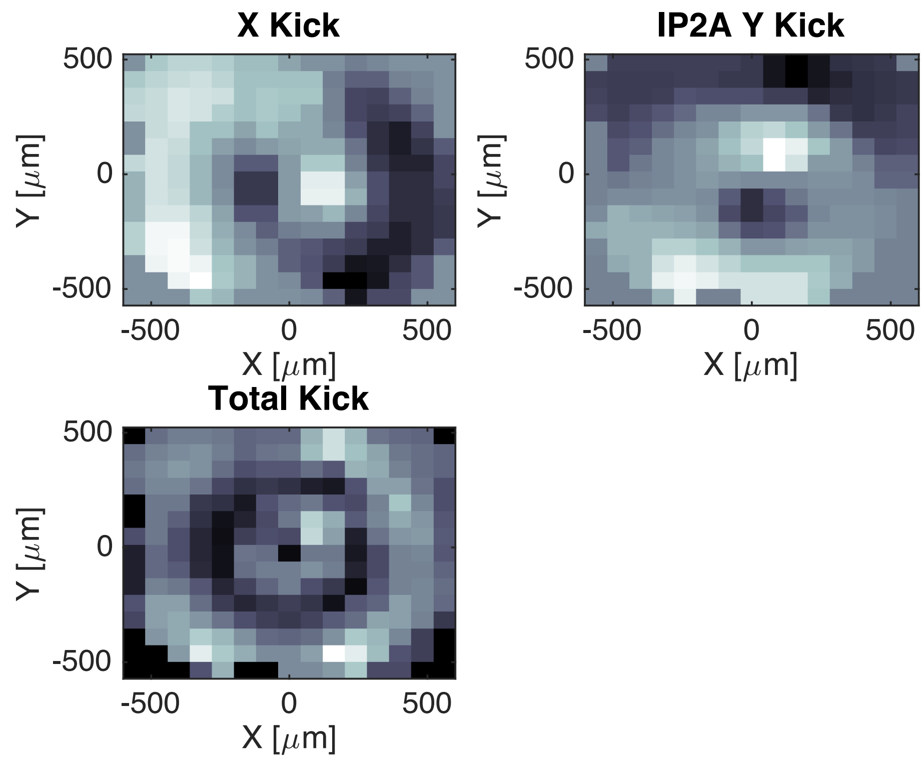



Energy spectra for different incoming positron beam emittances. Lower emittances produce spectral peaks after acceleration. Simulations from QuickPIC.

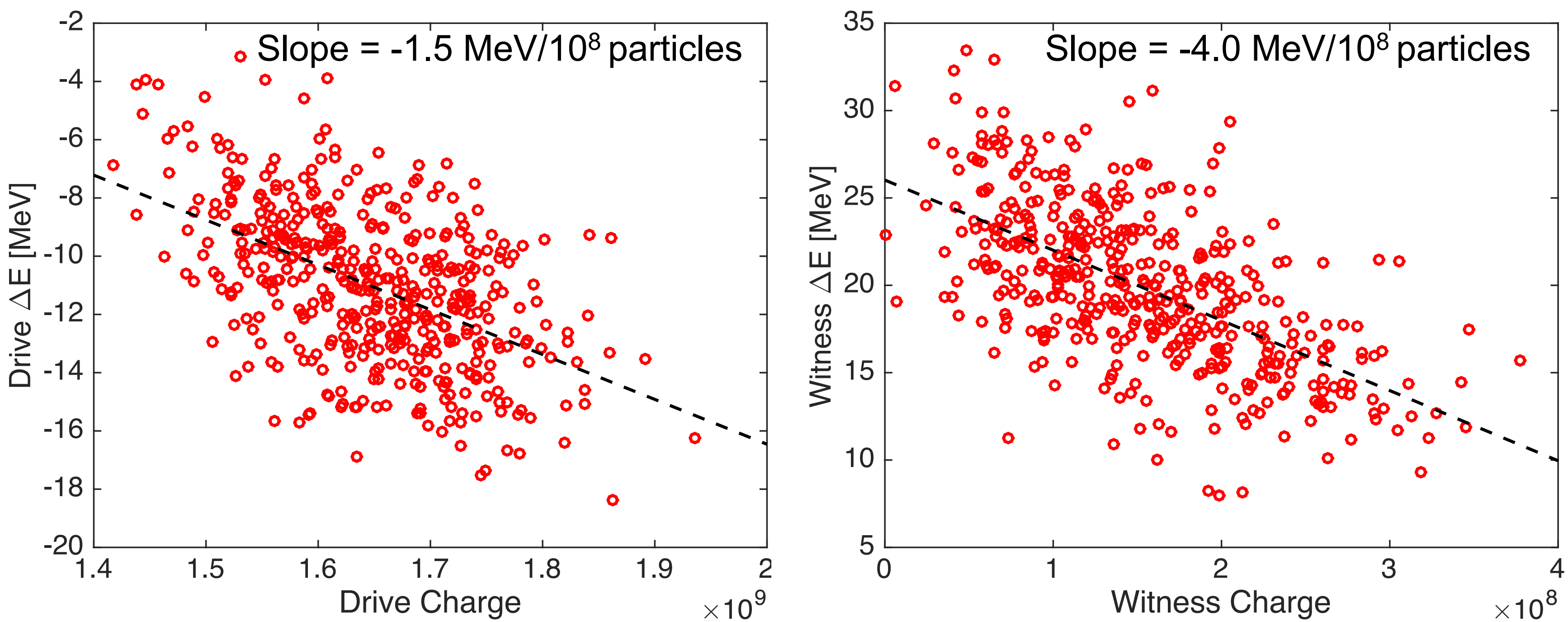
S Corde *et al.* *Nature* **524**, 442-445 (2015) doi:10.1038/nature14890

# Understanding the Raster Scan



# Beam Loading




Beam loading is an important consideration when trying to optimize the gradient and efficiency. The average drive-to-witness efficiency in this experiment was 18%.

# Acceleration of Positrons in Quasi-Linear Regime

SLAC

High-gradient result, may be useful for afterburner. What about main linac?

**FACET 2016**: Acceleration of a trailing positron bunch in a new regime.

Greater than **1 GeV energy gain** of witness beam in 1.3 m-long plasma.

Of interest to both the PWFA and LWFA communities for linear collider applications.