Hollow Channel Plasma Wakefield Acceleration

CLIC Working Group, October 13, 2017

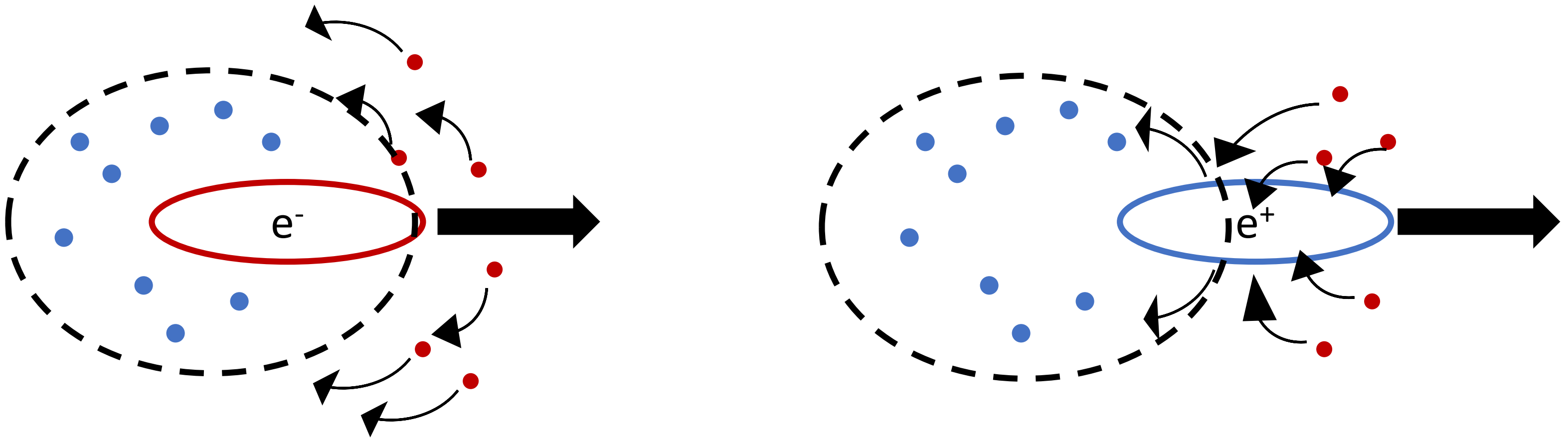
Spencer Gessner
CERN


I'd kill for a working Plasma Wakefield Accelerator!

Outline

- Motivation and History
- Theory
- Creating a Hollow Channel Plasma
- Experimental Results
- Future Directions

Plasmas are Asymmetric Accelerators



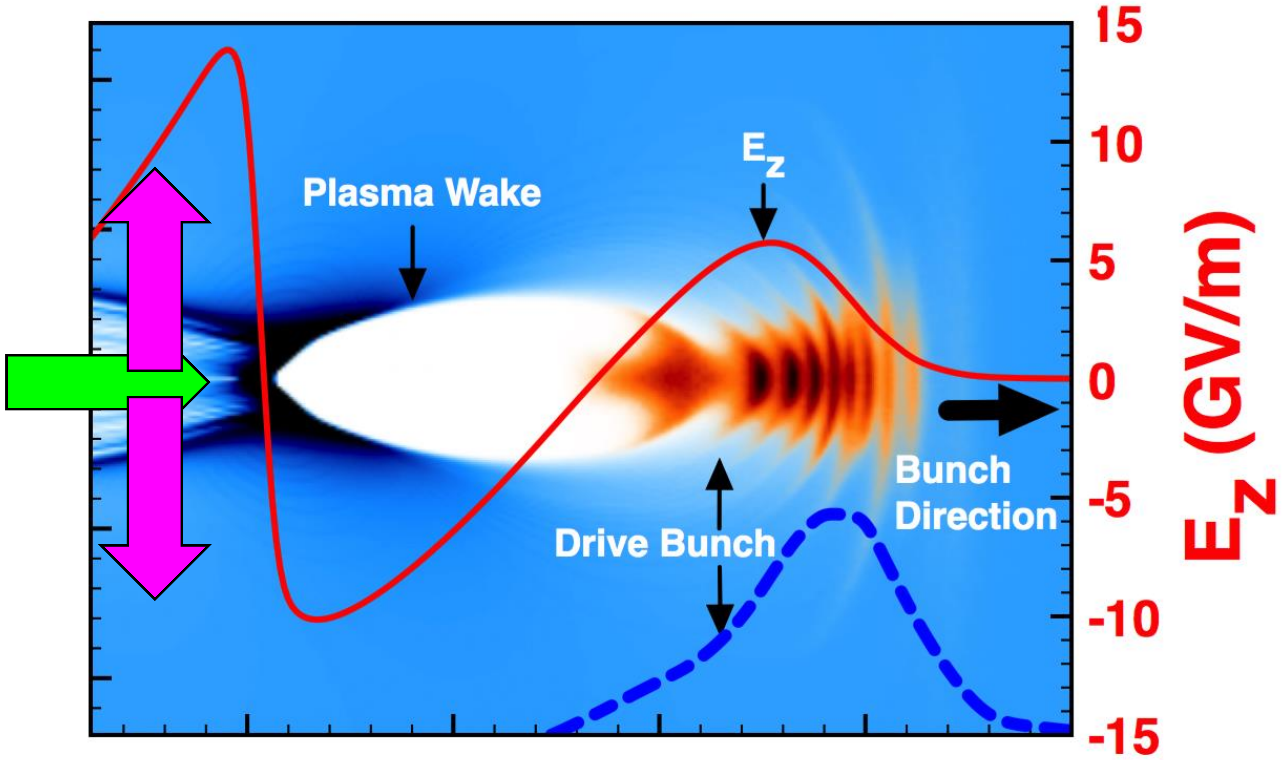
$m_i >> m_e$

The plasma electrons are mobile but the ions are not.

The symmetry of the accelerating mechanism is broken.

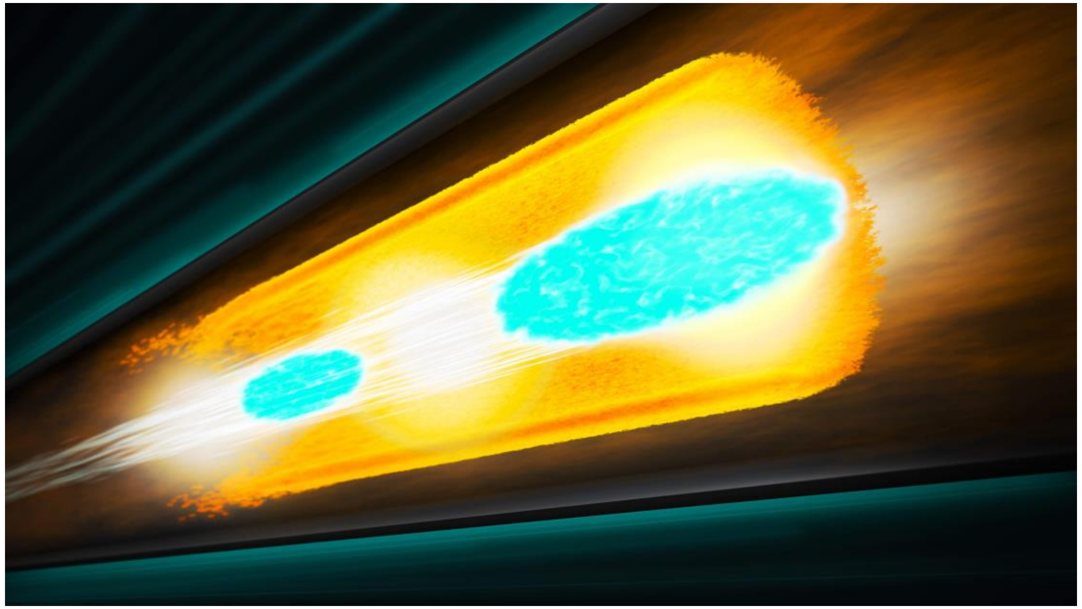
Positron PWFA is a Challenge

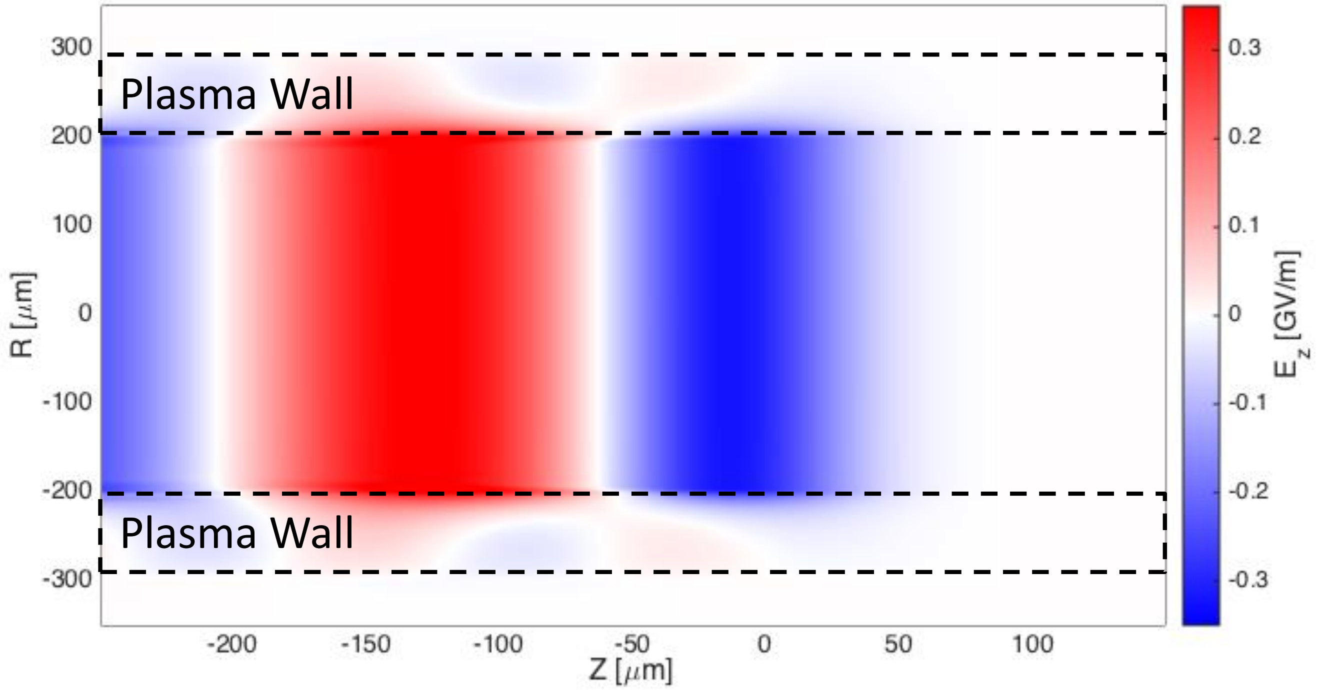
Electron-driven blowout wakes:



But the field is defocusing in this region.

The Hollow Channel Plasma Accelerator





The Hollow Channel Plasma is a *structure* that symmetrizes the response of the plasma to electron and positron beams.

There is no plasma on-axis, and therefore no focusing/defocusing force from plasma ions.

History

1992

Laser wakefield acceleration & optical guiding in a hollow plasma channel

T. Katsouleas, T. C. Chiou, C. Decker, W. B. Mori, J. S. Wurtele, G. Shvets, and J. J. Su

Citation: AIP Conference Proceedings **279**, 480 (1992); doi: 10.1063/1.44067
View online: http://dx.doi.org/10.1063/1.44067
View Table of Contents: http://aip.scitation.org/toc/apc/279/1
Published by the American Institute of Physics

1995

Laser wake-field acceleration and optical guiding in a hollow plasma channel

T. C. Chiou and T. Katsouleas
Department of Electrical Engineering–Electrophysics, University of Southern California, Los Angeles, California 90089-0484
C. Decker and W. B. Mori
University of California, Los Angeles, California 90024
J. S. Wurtele and G. Shvets
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
J. J. Su
National Central University, Taiwan, Republic of China

1996

IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 24, NO. 2, APRIL 1996 351

Excitation of Accelerating Wakefields in Inhomogeneous Plasmas

G. Shvets, J. S. Wurtele, T. C. Chiou, and Thomas C. Katsouleas, *Fellow, IEEE*

1998

VOLUME 81, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1998

High Beam Quality and Efficiency in Plasma-Based Accelerators

T. C. Chiou and T. Katsouleas
Department of Electrical Engineering-Electrophysics, University of Southern California, Los Angeles, California 90089-0484
(Received 3 April 1998)

The question of what beam quality and efficiency are ultimately achievable in plasma-based accelerators is addressed analytically and through self-consistent particle-in-cell simulations. A strategy for phasing and beam loading to minimize energy spread while at the same time achieving high energy extraction efficiency is proposed. Preservation of beam emittance is facilitated by the use of a hollow channel. [S0031-9007(98)07381-5]

Originally conceived as a solution for the laser guiding and dephasing problem.

Not a new idea!

Reminder: Characteristic Plasma Scales

The characteristic plasma length, time, and field scales with the plasma density.

$$\omega_p = \sqrt{\frac{4\pi e^2 n_0}{m_e}} \qquad E_0 = \frac{m_e c \omega_p}{e}$$

The characteristic field strength of the plasma is typically measured in GV/m.

$$E_0 \approx 33\sqrt{n_0 \ \left(10^{17}\mathrm{cm}^{-3}\right)} \ [\mathrm{GV/m}]$$

The characteristic frequency is measured in THz, with the plasma wavelength around 100 microns.

$$\omega_p \approx 20\sqrt{n_0 \ \left(10^{17}\mathrm{cm}^{-3}\right)} \ [\mathrm{THz}]$$

Dielectric Description

We treat the plasma as a dielectric with constant:

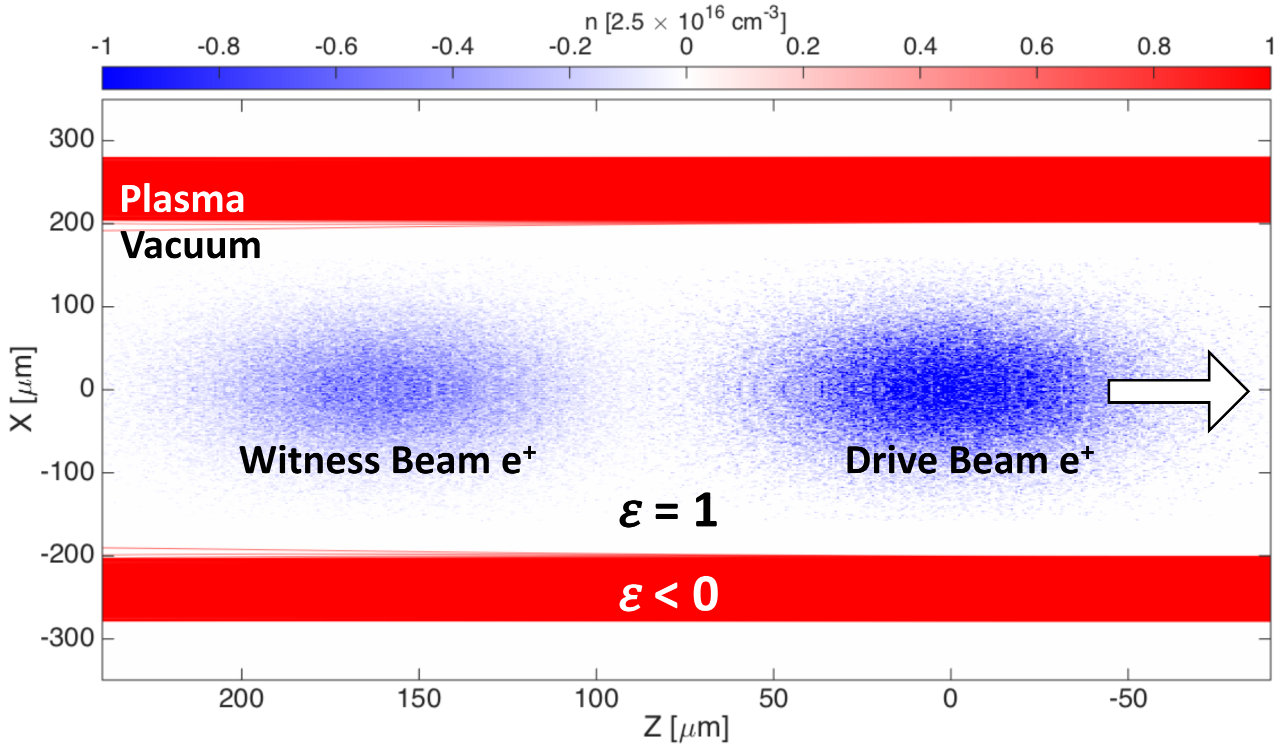
$$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2}$$

In the channel, $\varepsilon = 1$. The frequency of the hollow channel mode ω is less than the plasma frequency ω_p. Therefore, $\varepsilon < 0$ in the plasma.

We seek the mode structure of the hollow channel for waves which propagate at the speed of the drive beam. We work in the co-moving frame:

$$\xi = z - v_b t$$

We make the ultra-relativistic assumption $v_b = c$. The remainder of the problem is to solve for the fields using the dielectric boundary condition.



Channel Modes: m = 0

We decompose the fields into their azimuthal modes:

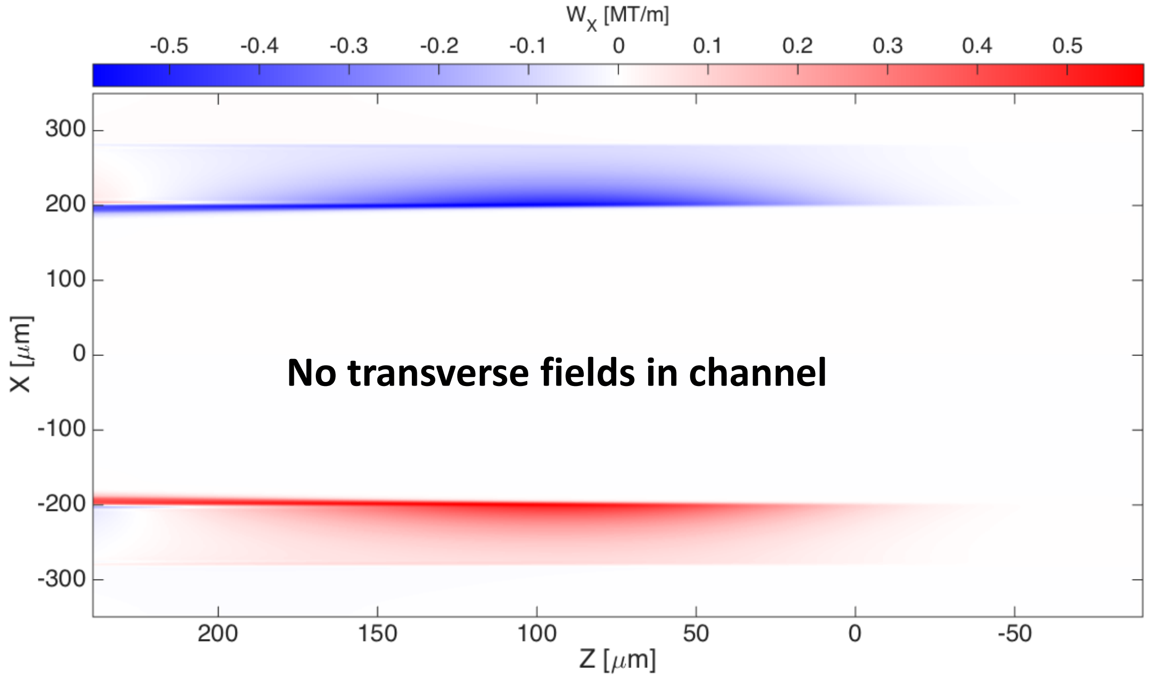
$$\vec{E}(r,\phi,z,t) = \sum_m \vec{E}_m(r,z,t)e^{im\phi},$$
$$\vec{B}(r,\phi,z,t) = \sum_m \vec{B}_m(r,z,t)e^{im\phi}.$$

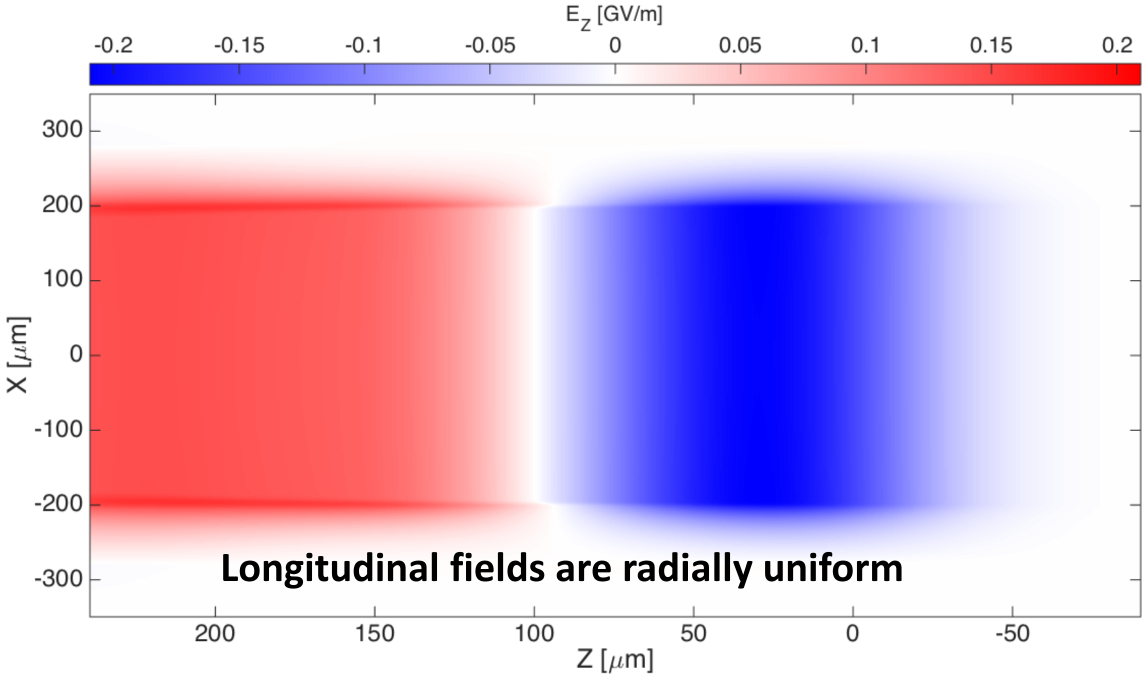
For the m = 0 mode, we find that E_z is constant in radius across the aperture of the plasma channel, and that $E_r - B_\phi = 0$. (Carl will discuss $m > 0$ modes).

We find the following Green's function for the longitudinal field:

$$E_{z0} = \frac{4qk_p^2 B_{00}(a,b)}{k_p a\left[2B_{10}(a,b) - k_p a B_{00}(a,b)\right]} = \frac{4qk_z^2 \varepsilon}{(k_p a)^2}$$

Here, a is the radius of the channel, and k_p is the inverse of the plasma skin depth.





Experimental Approach

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

Hollow plasma channel for positron plasma wakefield acceleration

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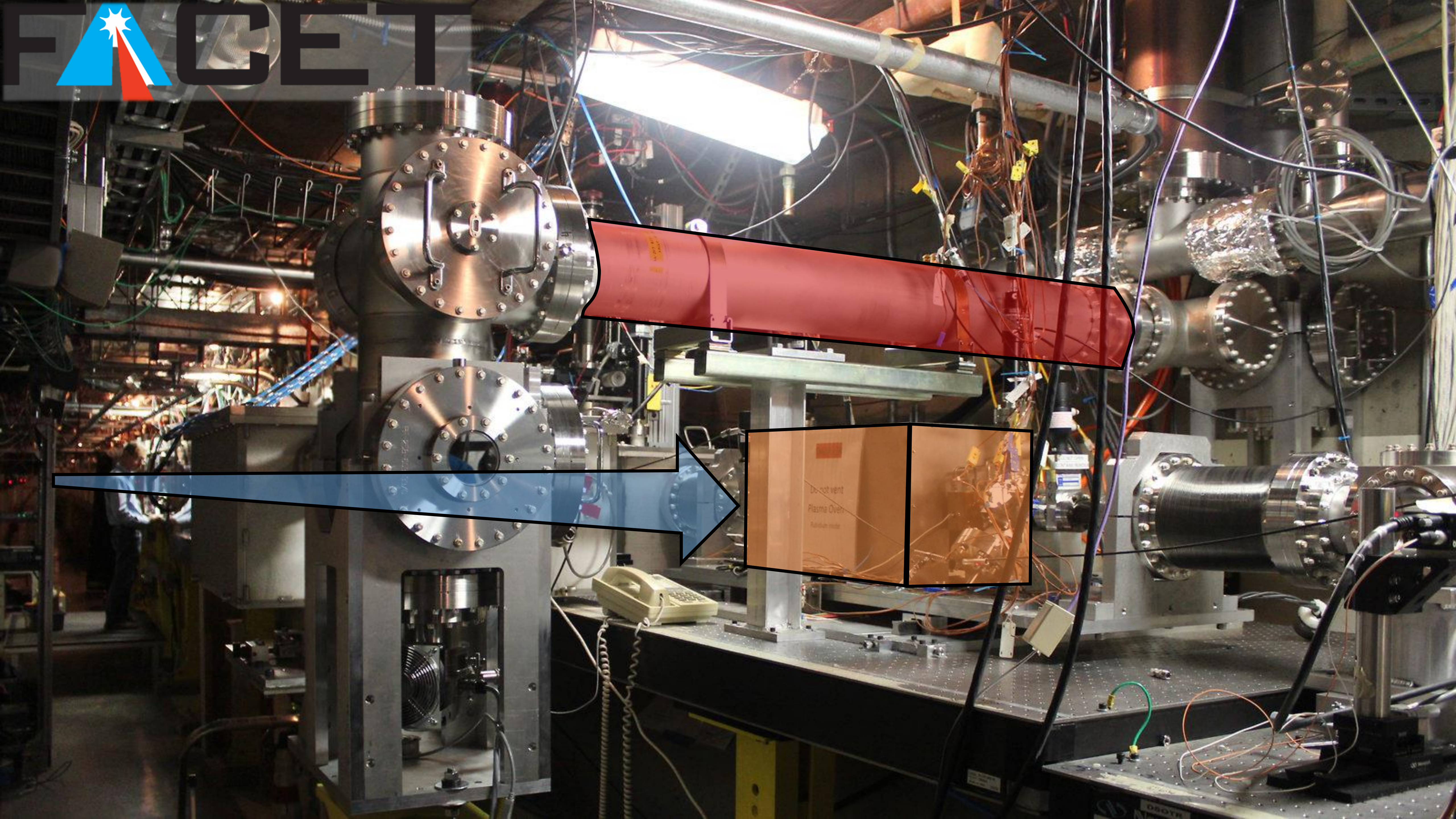
(Received 9 September 2010; published 18 April 2011)

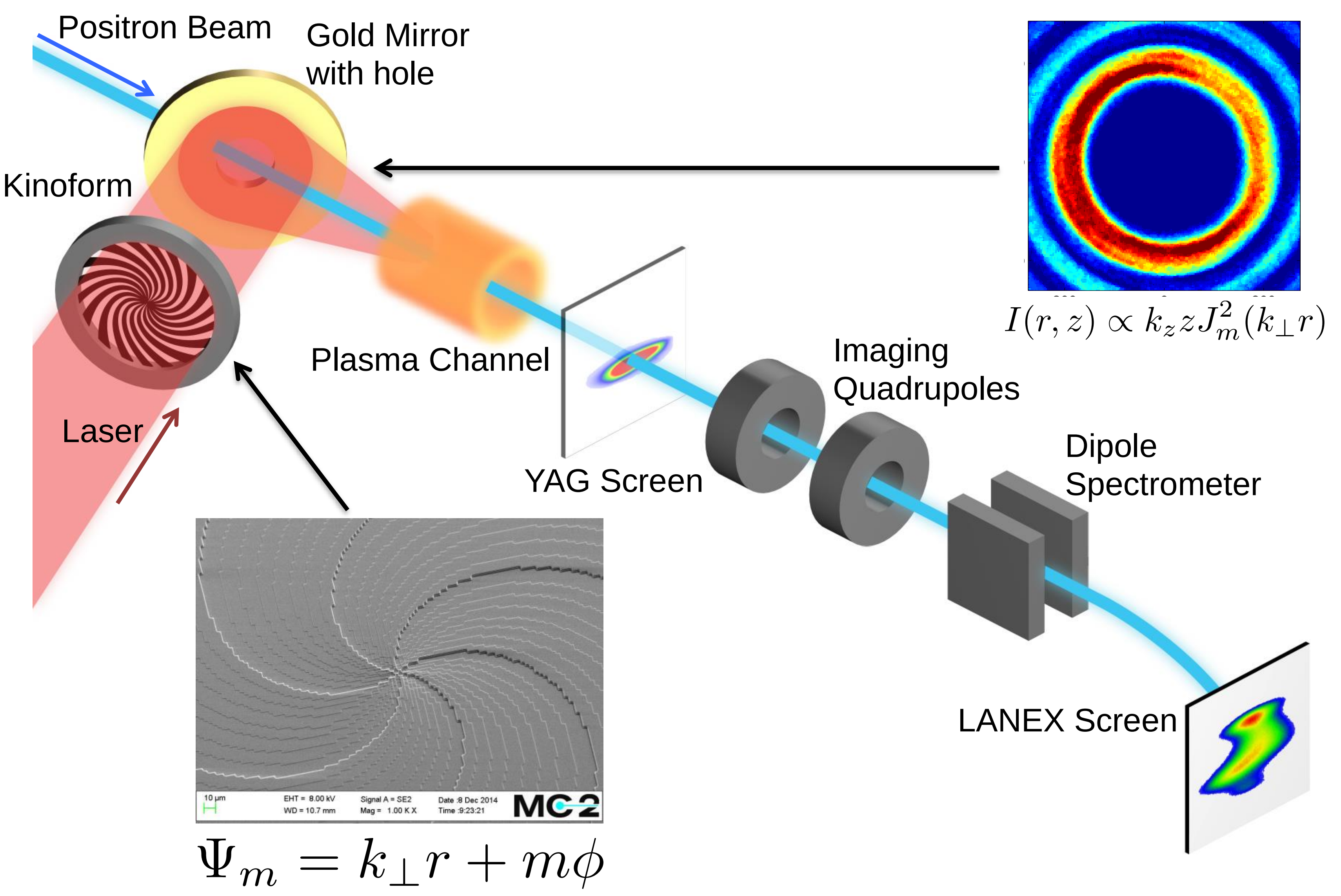
Proposal by Kimura: Use a hollow laser beam to create a hollow channel plasma. For this approach we need:

- TW-class laser
- Plasma source
- Positron beam

FACET @ SLAC is the only facility in the world which provides all of the above.

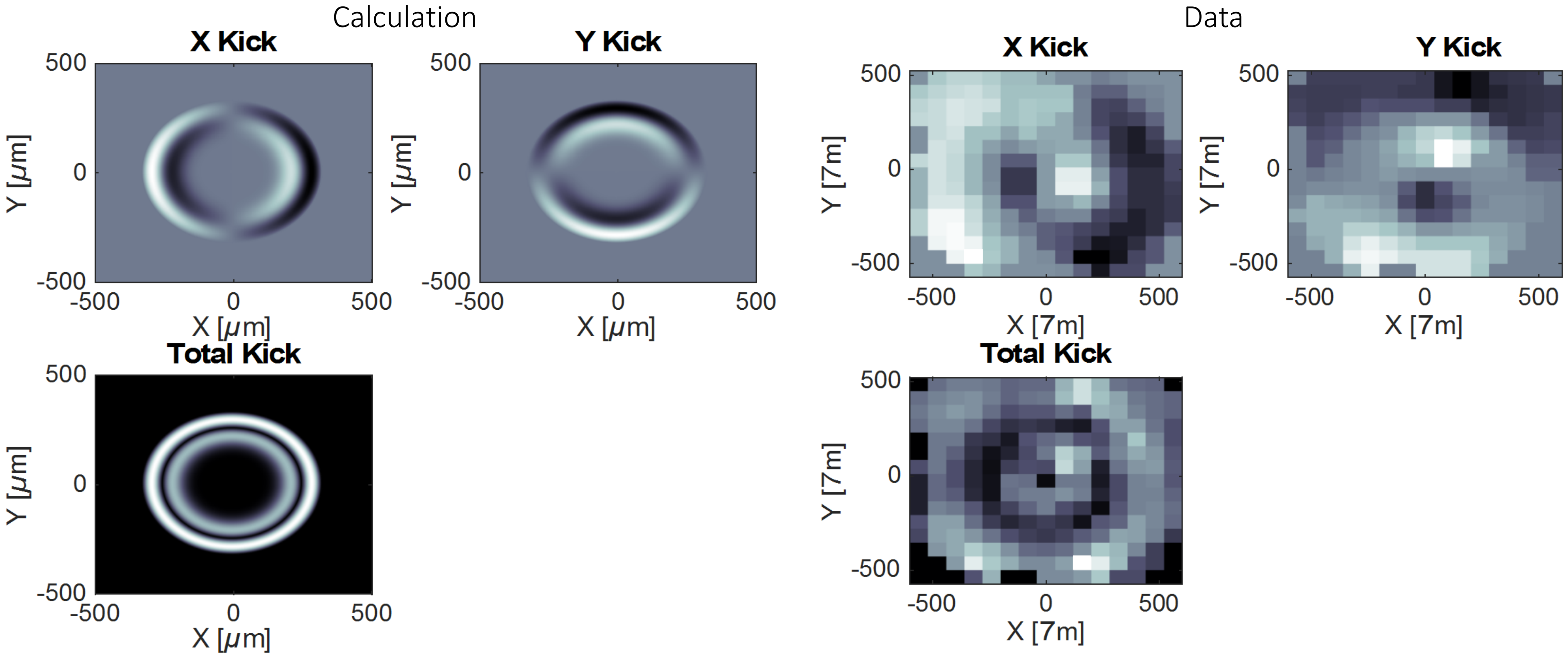

Do not vent
Plasma Oven

Creating a Hollow Channel Plasma



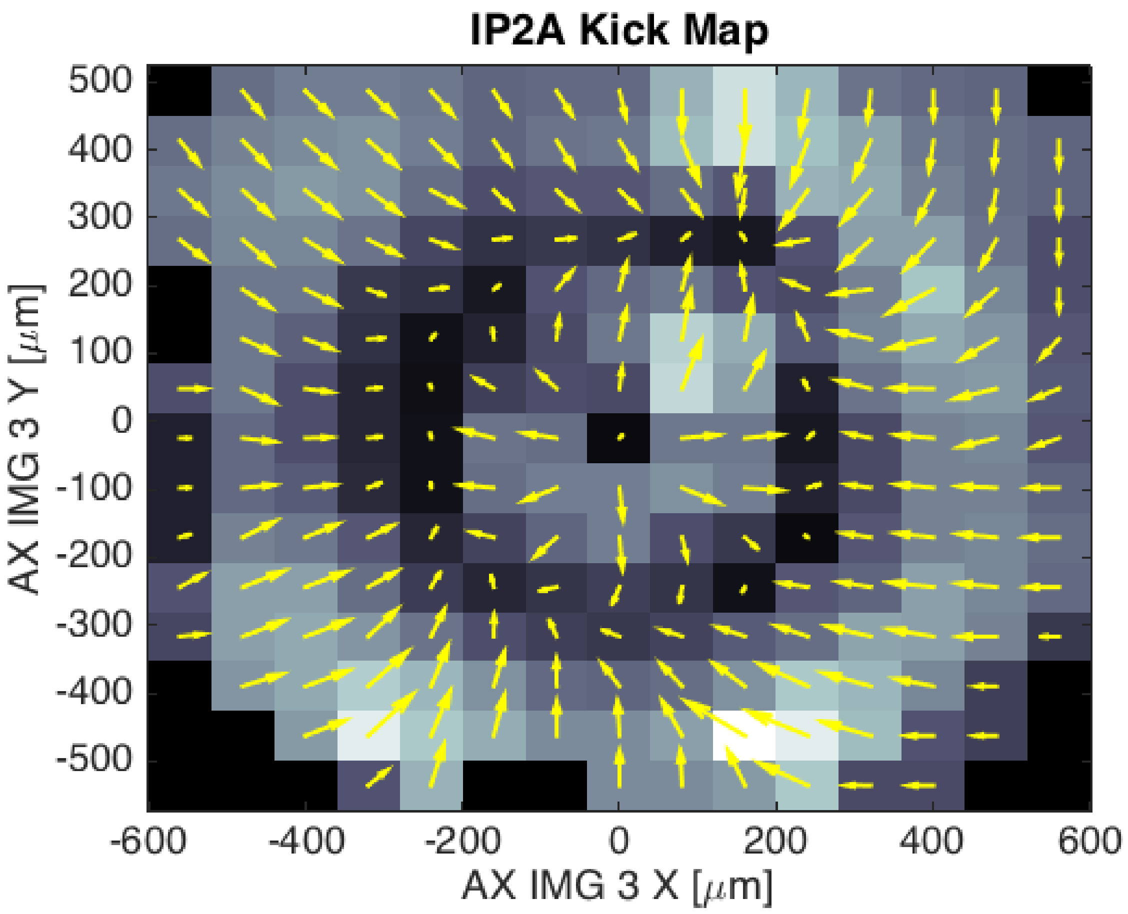
S. Gessner et. al. *Nat. Comm.* 7, 11785

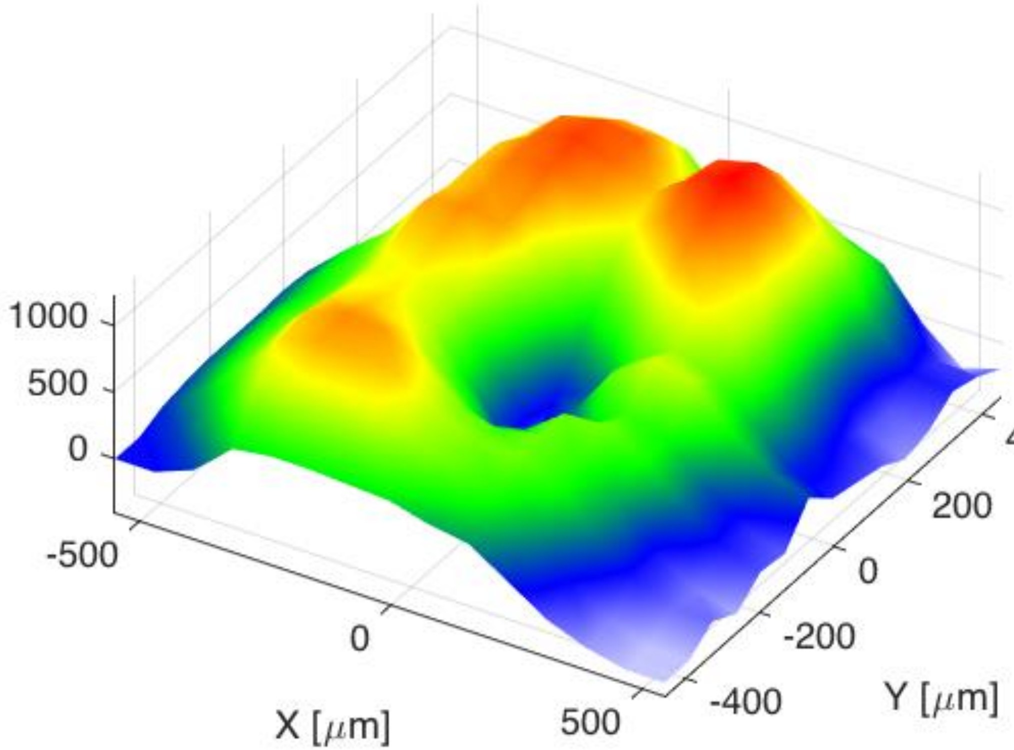
Beam-Based Investigation of Hollow Channel Structure



We use a single beam to probe the structure of the channel. The beam receives a kick if it is offset from the channel center, and we measure the kicks to recreate the channel shape.

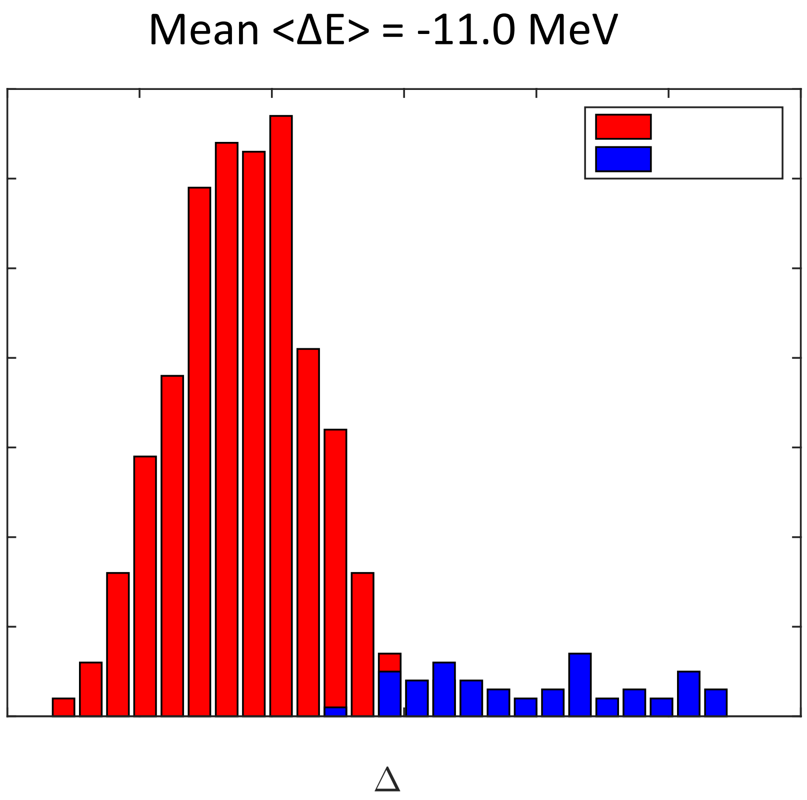
Reconstruction of the Hollow Channel

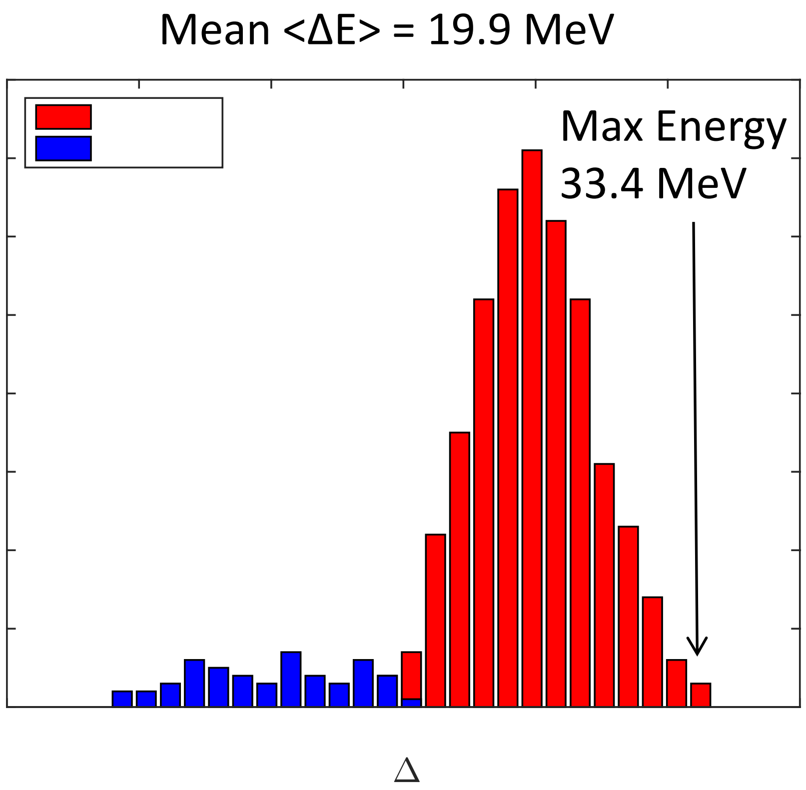




Using the kick data, we can “reconstruct” the shape of the channel.

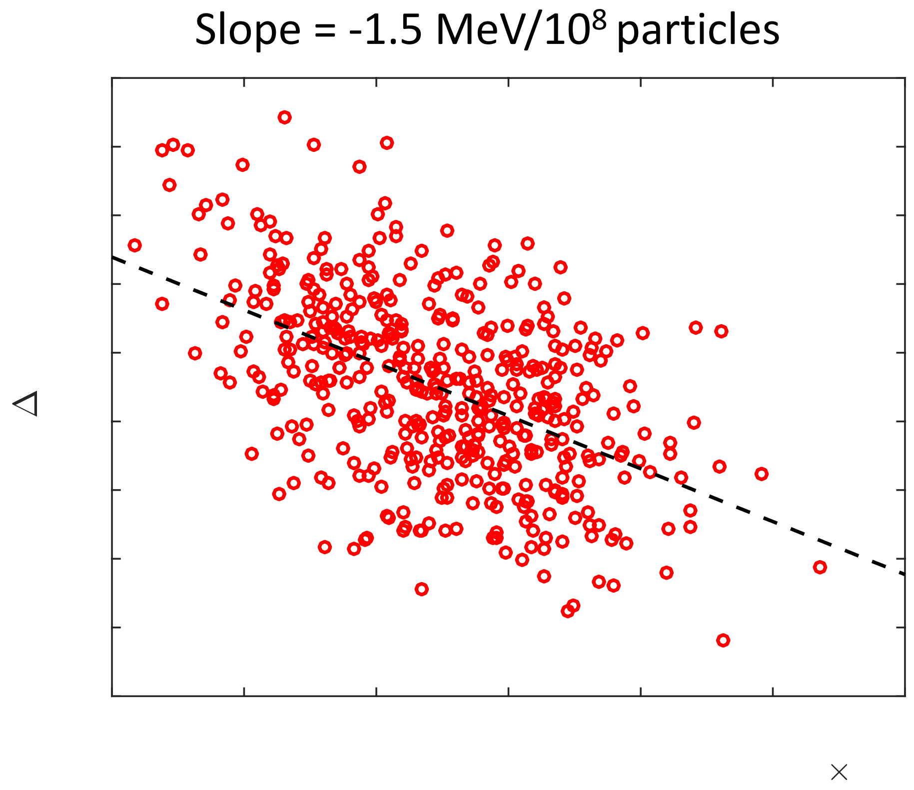
Positron Acceleration

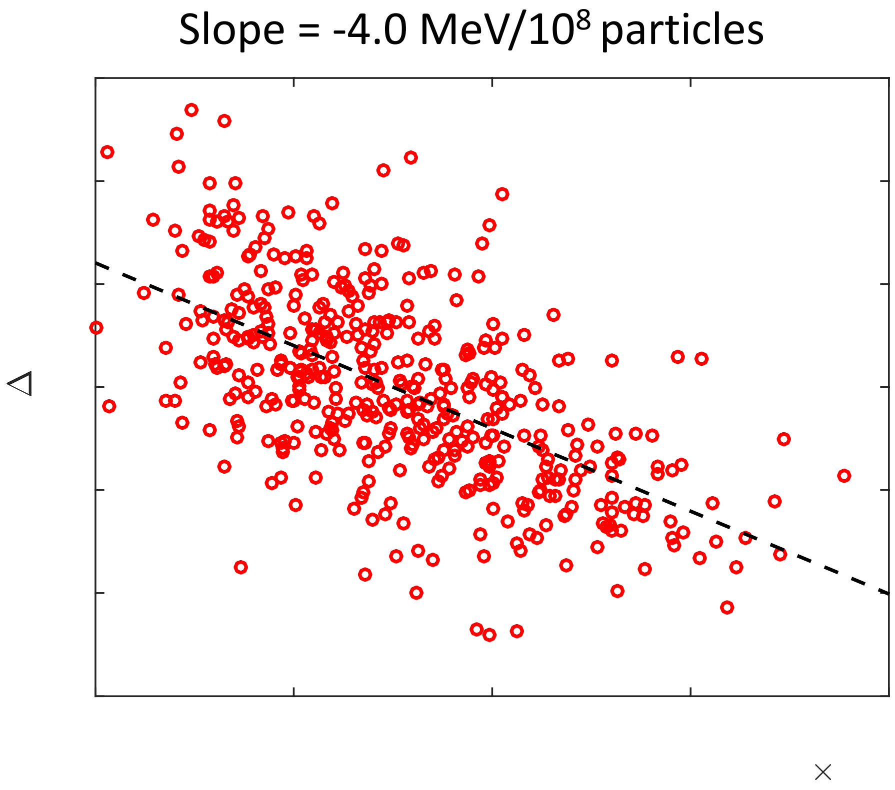




Using a drive beam, we create a wake in the channel. A witness beam follows and it accelerated in the wake.

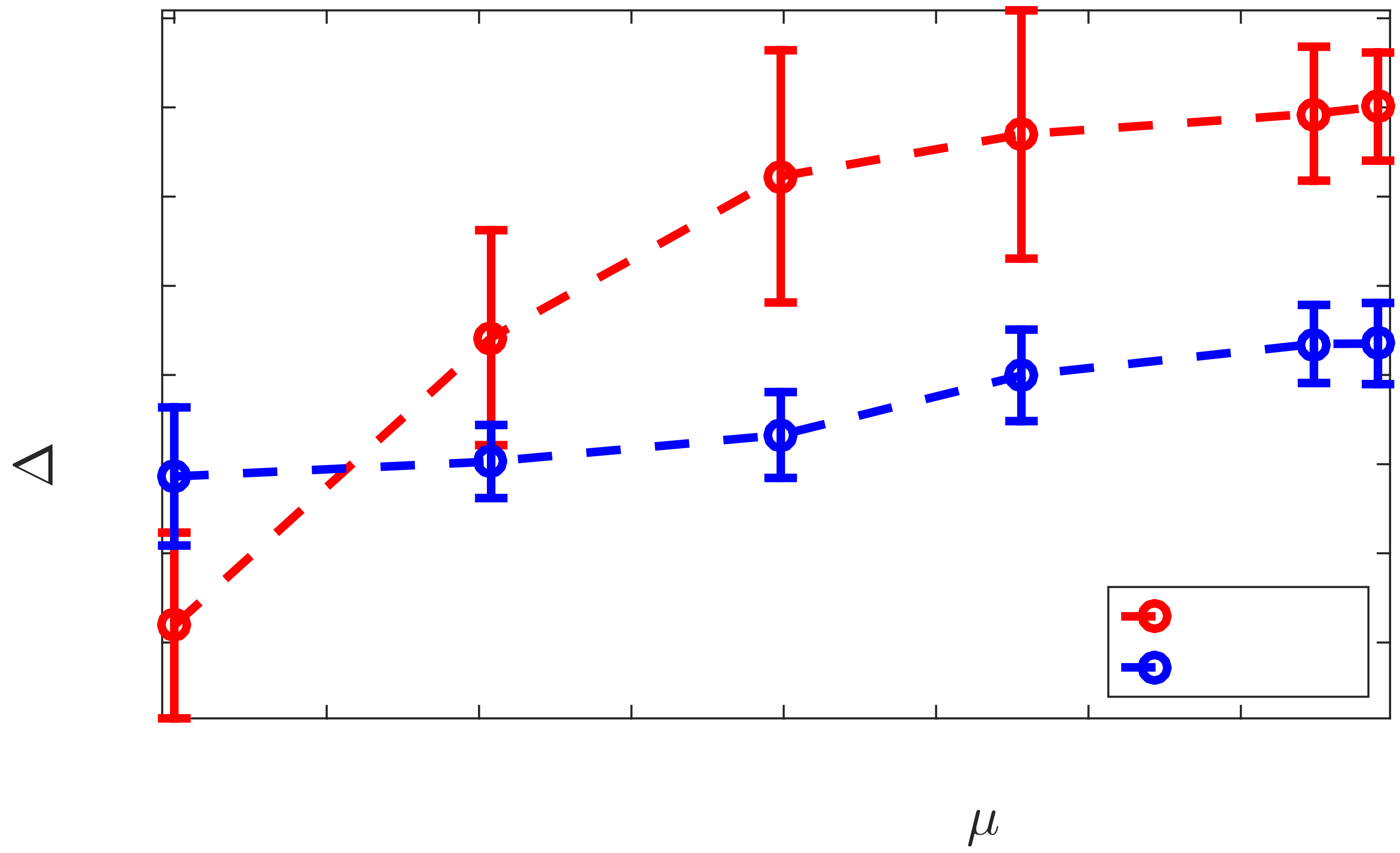
Beam Loading





We see that increasing the charge in the witness beam leads to a decrease in energy gain of the witness beam. However, the drive and witness charge are coupled.

Longitudinal Field Map



In the two-bunch experiment, we scan the distance between the drive beam and the witness in order to map the longitudinal structure of the wake. For the first time, we observe acceleration of positrons in the hollow channel plasma wakefield.

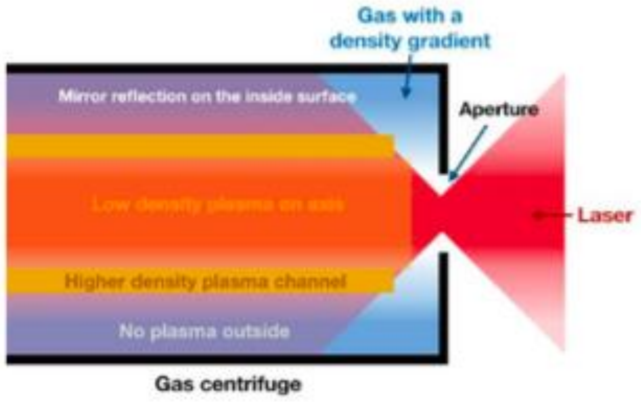
Future Directions: Experiment

The main limitation of the experiments at FACET was the remaining neutral vapor on axis:

- Limits the usable bunch charge
- Limits the accelerating gradient

Can we produce hollow channel plasmas with no plasma on axis?

- Centrifuge technique (idea from C. Lindstrøm)
- Cryo-cooled gas techniques (used for corregated plasma channels by H. Milchberg)



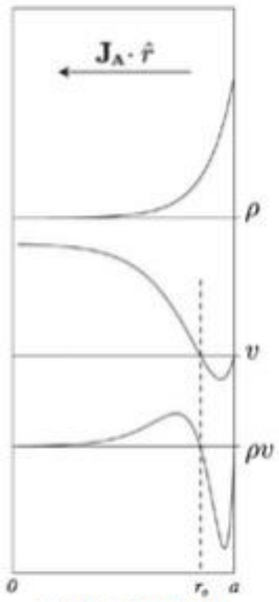


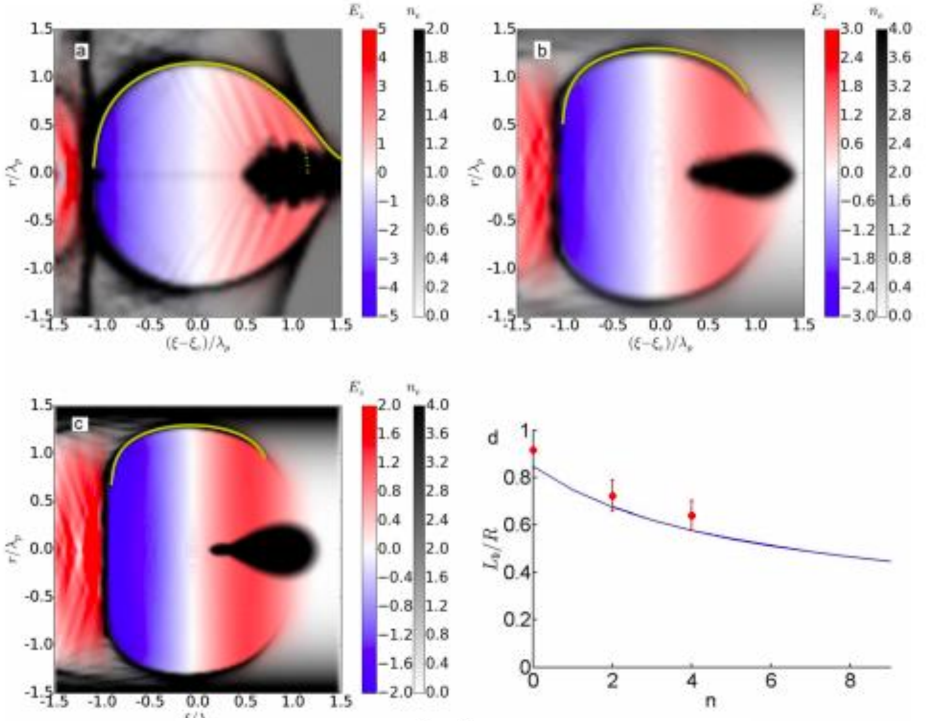
Image source:
Gas Centrifuge Theory and Development: A Review of U Programs by R. Scott Kemp

Image source:
H. Milchberg (Uni Maryland), EAAC2017 talk

Future Directions: Theory

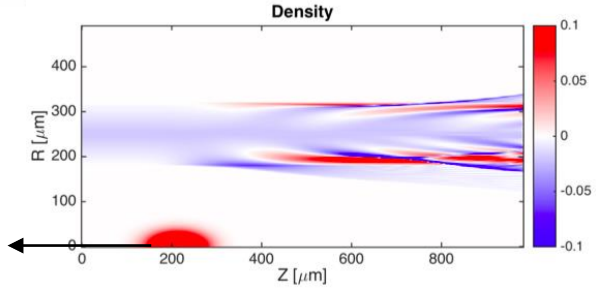
Non-linear hollow channel (J. Thomas et. al. PoP. 23 053108 (2016).

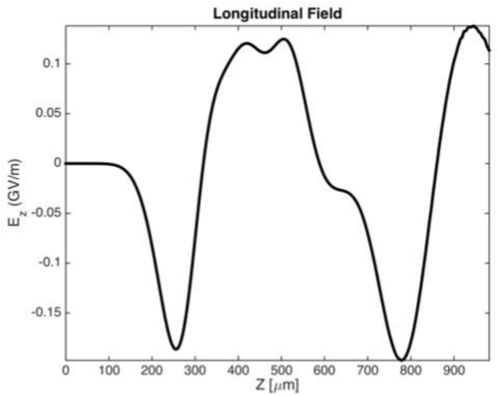
- Some nice properties relative to normal bubble structure.
- Not suitable for positrons!



Soft-walls in the linear regime:

- First investigated by G. Shvets (IEEE 1996)
- Energy from electromagnetic channel modes transferred to electrostatic plasma motion.
- Implies a “low-Q” cavity but also can be used to remove energy from transverse modes.





Takeaways

- Hollow channel PWFA is a promising approach for accelerating positrons in plasma.
- However, transverse wakefields are a fundamental challenge (see Carl's talk).
- We have created a plasma *structure* and we are now engineering the fields to produce the desired results.

Thank You!

FACET End-of-Run Party 2016

E200/E225 Collaboration

SLAC

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