Demonstration of the Hollow Channel Plasma Wakefield Accelerator

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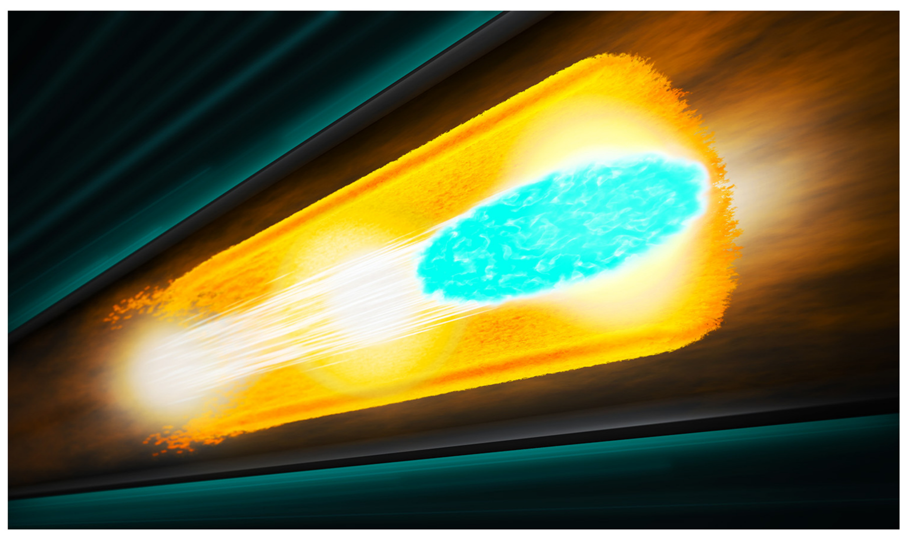
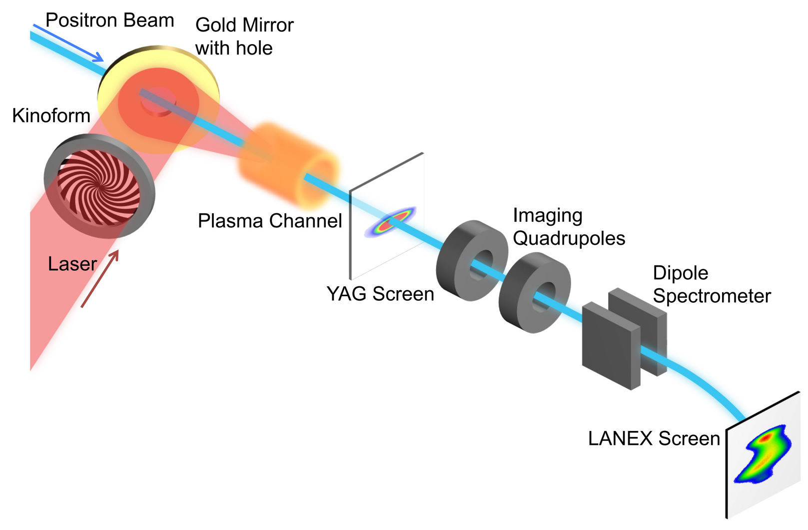
Introduction

Over the past decade, there has been enormous progress in the field of beam and laser-driven plasma acceleration of electron beams. However, both electron beams and positrons beams are needed for a high-energy linear collider. Accelerating positron beams in a plasma is particularly challenging, because the plasma response to positrons is different from that of electrons, with plasma electrons being pulled through the positron beam and creating a non-linear focusing force.

Here, we demonstrate a technique called hollow channel plasma acceleration that symmetrizes the wakefield response to beams of either charge. Using a transversely shaped laser pulse, we create an annular plasma of fixed radius measuring 25 cm long. We observe the acceleration of a positron bunch with energies up to 33.4 MeV in a 25 cm long channel, with effective accelerating gradients greater than 100 MeV/m.





Left: A cut-away of the hollow channel plasma, showing the plasma channel (orange), positron beam (blue), and trailing wakefield (white). There are neutral vapor particles within the channel. The beam creates a longitudinal field in the channel that can be used to accelerate a trailing bunch. Right: A schematic of our experiment, showing all of the critical elements needed to create a hollow channel plasma and measure its effect on the beam.

How do we make a hollow channel?

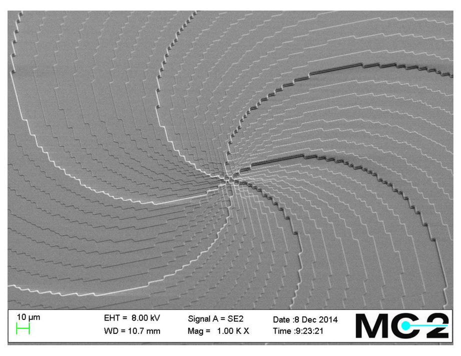
We developed a special optic, called a kinoform, which we use to create hollow laser beams. The optic is a thin piece of fused silica that is etched with a spiral phase pattern given by

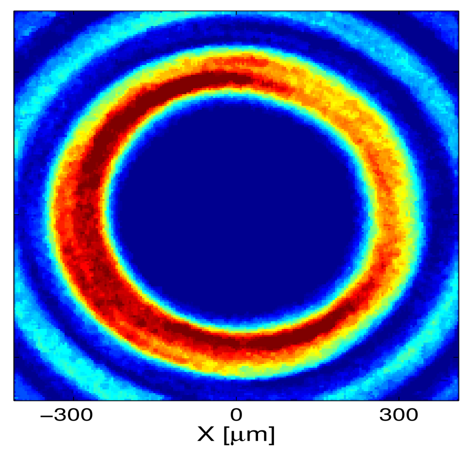
$$\Psi_0 = k_\perp r + m\phi$$

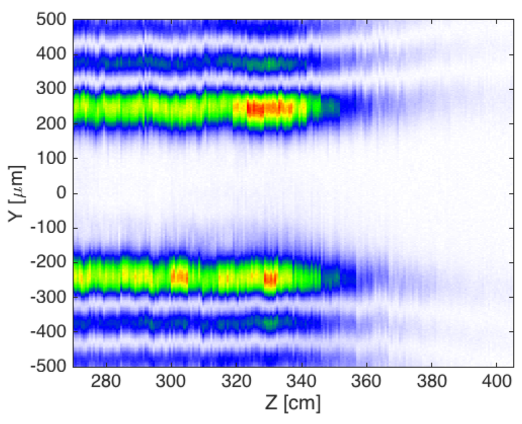
This phase pattern produces a focus downstream of the plasma with a high-order Bessel intensity profile

$$I(r,z) = \eta I_0 2\pi\gamma^2 kz J_m^2(k_\perp r)$$

The transverse intensity profile does not depend on the longitudinal position of the focus, which allows us to create long channel with constant radius.

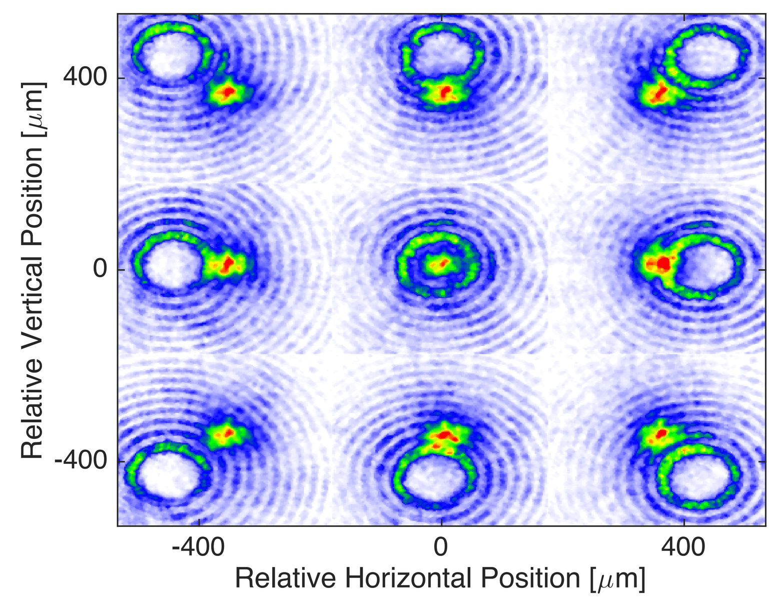


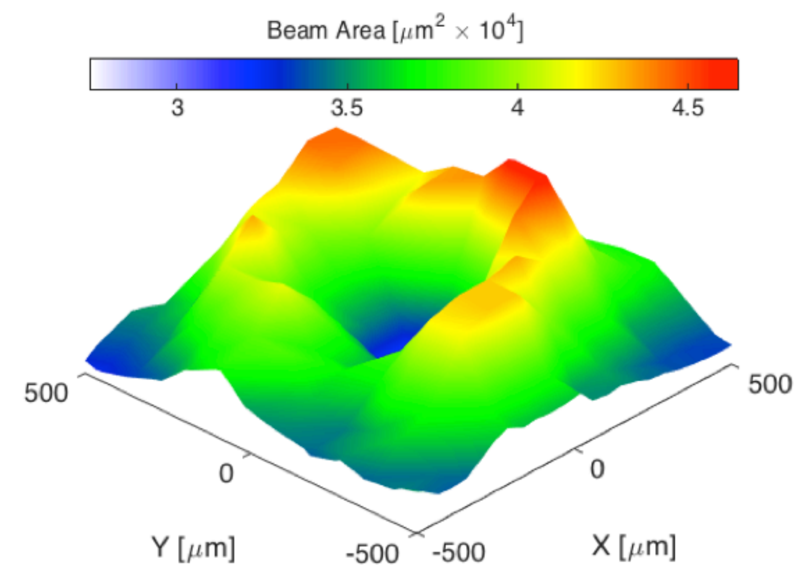


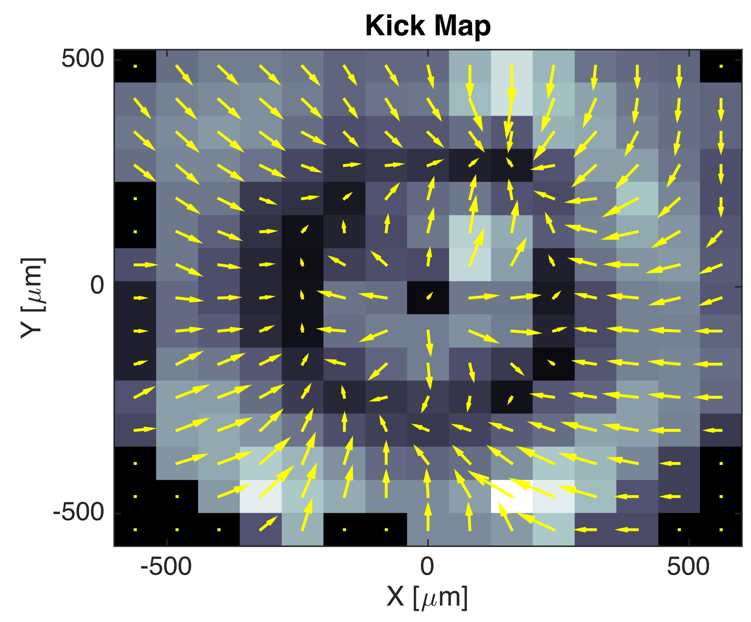


How do we measure the channel shape?

We use the dipole deflecting mode induced by an offset beam to infer the shape of the channel. Our "raster scan" shifts the laser in parallel with the beam, and we measure the resulting deflections downstream. Both the kick map and beam area map show an annular ionized region.

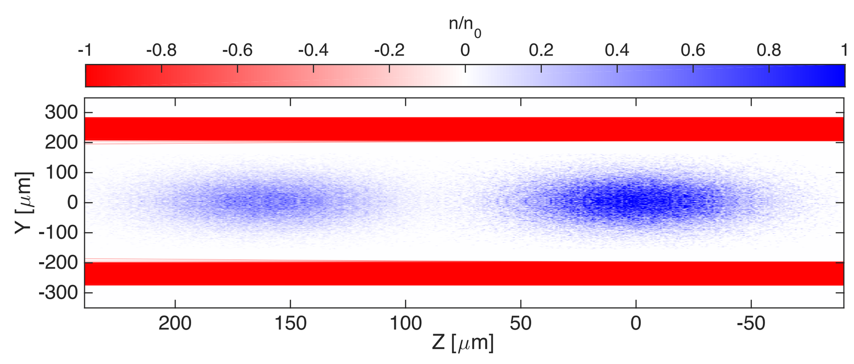


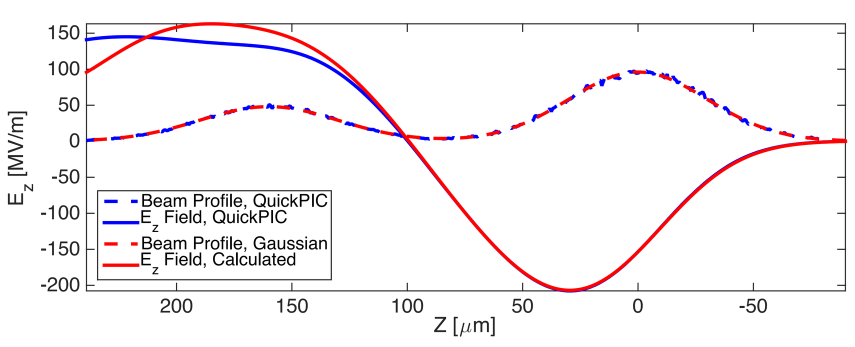




How do we use HC-PWFA to accelerate e⁺?

We use a high-charge positron beam to create the wake in the plasma and low-charge witness beam trails the drive beam and is accelerated. Using the particle-in-cell code QuickPIC, we can estimate both the field strength and its wavelength for our experiment. The expected accelerating gradient is about 140 MeV/m.





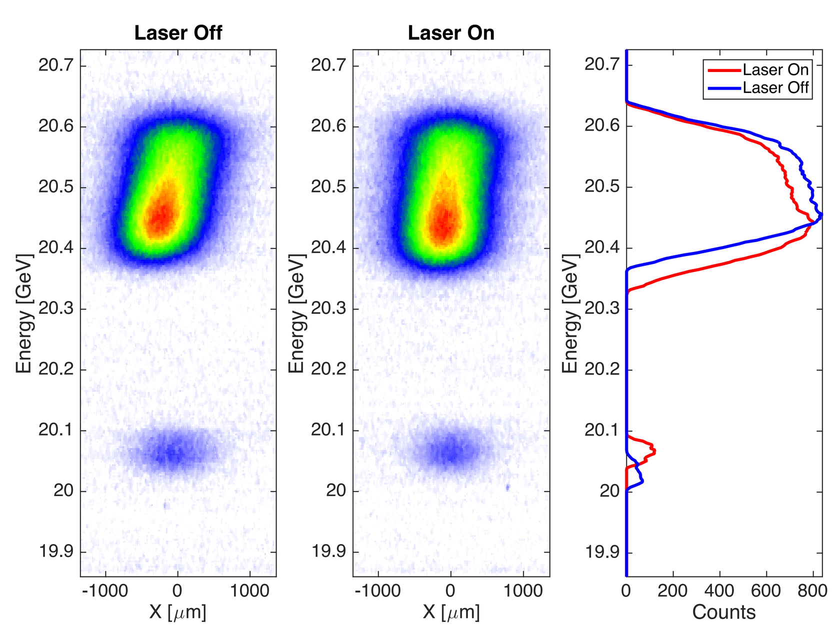
We also developed an analytical theory for determining the amplitude and wavelength of the field. We treat the plasma as a dielectric and solve the wave equation

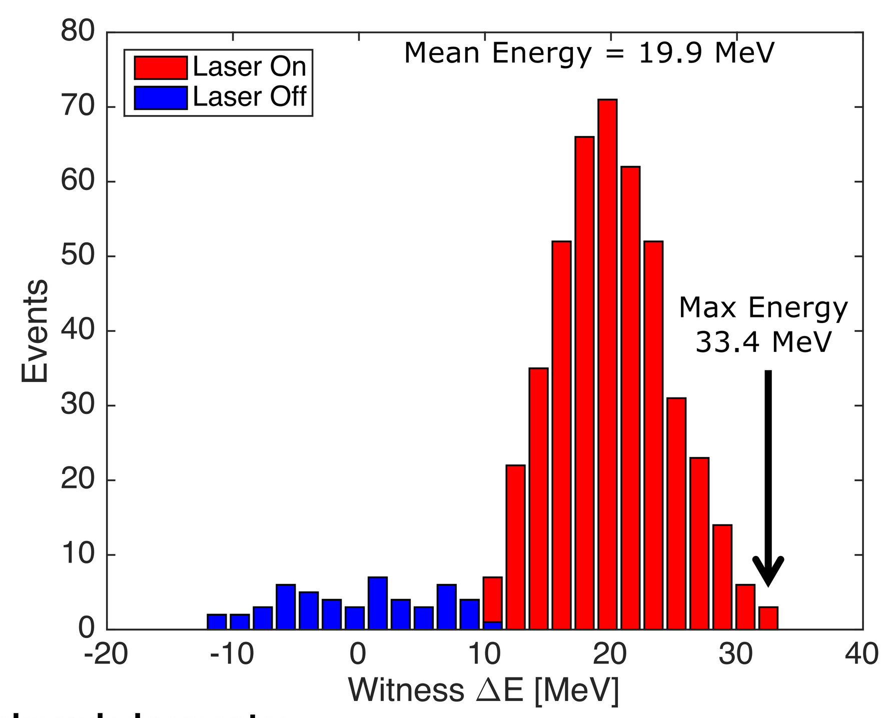
$$\nabla^2 E_z - \frac{\varepsilon}{c^2}\partial_t^2 E_z = 0$$

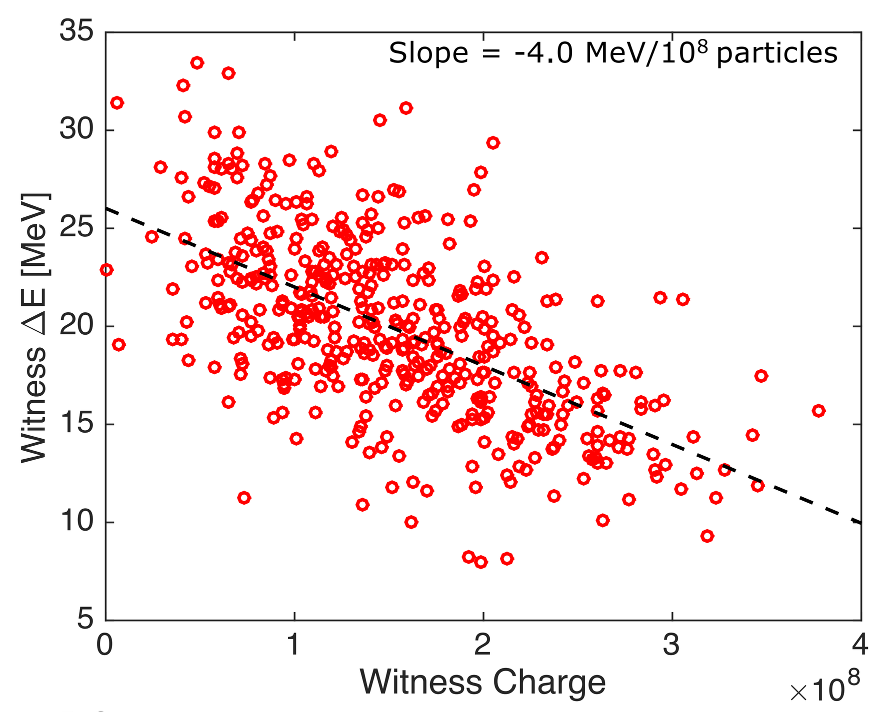
with the dielectric boundary conditions. We overlay our analytical model with the results from simulation above. There is good agreement between theory and simulation up until the back of wake, where plasma electrons leave the wall and the dielectric boundary condition is violated.

Observation of Acceleration

We compare the spectra with plasma (laser on) to without plasma (laser off) to measure the energy gain. The average witness energy gain is 19.9 MeV, and the average drive beam energy loss is 11 MeV, indicating a transformer ratio of 1.8.







Acknowledgements:
Thanks to the E200/E225 collaboration and FACET OPs for making the experiment happen. Thank you to J. Goodman, W. Kimura, and NIL Technologies for help with the kinoform design and to my advisor Tor Raubenheimer for support. This work is supported by DOE contract DE-AC02-76SF00515.

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