Laser Wakefield Acceleration Beyond 1 GeV Using Ionization Induced Injection

Ken Marsh - University of California Los Angeles
Electrical Engineering

UCLA

UCSD

Collaboration

Kenneth Marsh, Chris Clayton, Chan Joshi, Wei Lu, Warren Mori, Art Pak
(UCLA, Los Angeles, California),

Bradley Pollock
(UCSD, La Jolla, California; LLNL, Livermore, California)

Felicie Albert, Tilo Doeppner, Catalin Filip, Dustin Froula
Siegfried Glenzer, Dwight Price, Joseph Ralph
(LLNL, Livermore, California)

Luis O. Silva (GoLP, Lisbon), Nuno Lemos
(GoLP, Lisbon; UCLA, Los Angeles, California)

Ricardo A. Fonseca, Samuel de Freitas Martins
(Instituto Superior Tecnico, Lisbon),

Overview

- Review of LWFA in the blow out regime

- Show blow out regime equations correctly predict experimental results. .
  Self guiding. An essential feature of blow out regime.
  Energy gain.

- Why ionization injection experiments?
  Self-injection experiments require a large wake potential and $a_0 > 3$
  Ionization injection can be done at lower laser power. $3 > a_0 > 1$

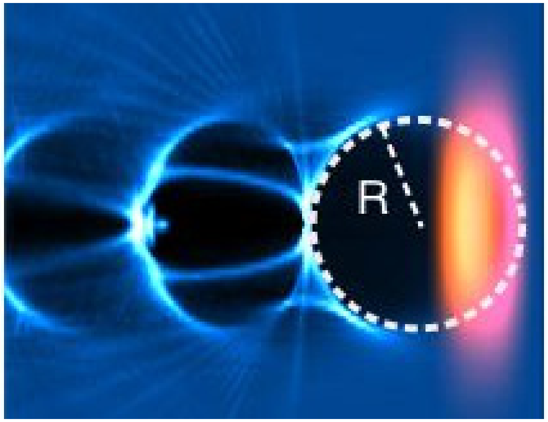
  For the same laser power;
  Self-injection experiments require higher density. $P/P_c > 4$
  Ionization injection can be done at lower density and achieve higher energy gain.

- Methods to reduce energy spread

- Staged injection experiment at LLNL

Description of the Blowout Regime

For $a_0 > 2$



- A short laser pulse traveling in an underdense plasma where the 3D radiation pressure causes complete electron cavitation.
- Creates a stable self-guided structure
- The wake retains a spherical shape with linear accelerating and focusing fields.
- High energy self-trapped electrons are a common feature when $a_0 > 3$

$a_0 \sim \sqrt{I}$ normalized vector potential

Electron Cavitation by Ponderomotive Force

The relativistic ponderomotive force equation

$$\frac{dn(r,z)}{n} = k_p^{-2}\nabla^2(1 + a_0^2\ /\ 2)^{1/2}$$

Results in 3D for $a_0 > 2$

$$dn\ /\ n\ ;\ -1$$

$$k_p R_b\ ;\ k_p w_0\ ;\ 2\sqrt{a_0}$$

Matching Condition

Equations for Self-Guiding and Pump Depletion

Self-guiding Matched Beam Equations

$$k_p^2 w_0^2 \; ; \; 4a_0$$

$$a_0 = 2(P / P_c)^{1/3}$$

The matched spot size w_0 has a weak dependence on laser power.

$$k_p w_0 = 2\sqrt{2}(P / P_c)^{1/6}$$

critical power for self-focusing

$$P_c(GW) = 17\omega_0^2 / \omega_p^2$$

Pump Depletion Equation

$$L_{pd} = \omega_0^2 / \omega_p^2 c\tau$$

Pump depletion length based on pulse etching due to localized pump depletion

W. Lu PRSTAB(2007)

Experimental Laser Parameters

What is the UCLA Terawatt Ti:Sapphire Laser?

Max power 10 TW

Pulse width FWHM 40-50 fs

Max Intensity 1.8×10^{19} Watts/cm^2

Useful normalized vector potential 1.5 to 2.8

What is the LLNL Callisto Ti:Sapphire Laser?

Max power 200 TW

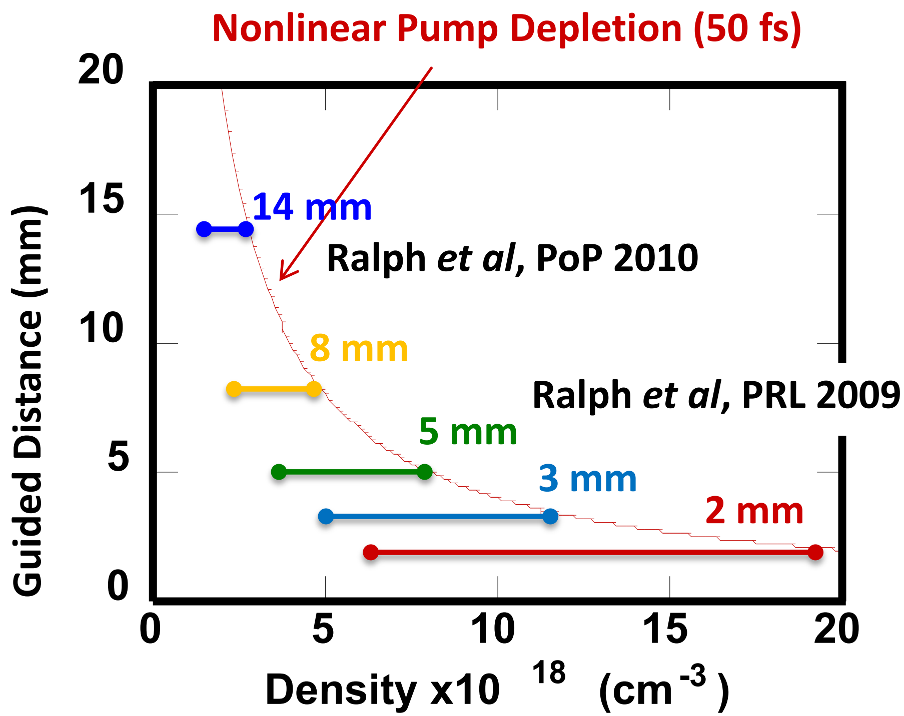
Pulse width FWHM 60 fs

Max Intensity 3×10^{19} Watts/cm^2

Useful normalized vector potential 2 to 3.5

The normalized vector potential $$a_0 = 8.6 \times 10^{-10} \sqrt{I(W/cm^2)}\lambda(\mu m)$$

Self-Guiding and Pump Depletion Results



Limited by P/Pc > 1 and pump depletion $L_{pd} = \omega_0^2 / \omega_p^2 c\tau$

Energy gain equations

Dephasing length

$$L_d \;;\; \frac{2}{3}\frac{\omega_0^2}{\omega_p^2} R_b$$

Maximum useful electric field

$$\frac{eE_{\max}}{mc\omega_p} = \sqrt{a_0}$$

On axis electric field

$$E(z) \;;\; E_{\max}\frac{z}{R_b}$$

W. Lu PRSTAB(2007)

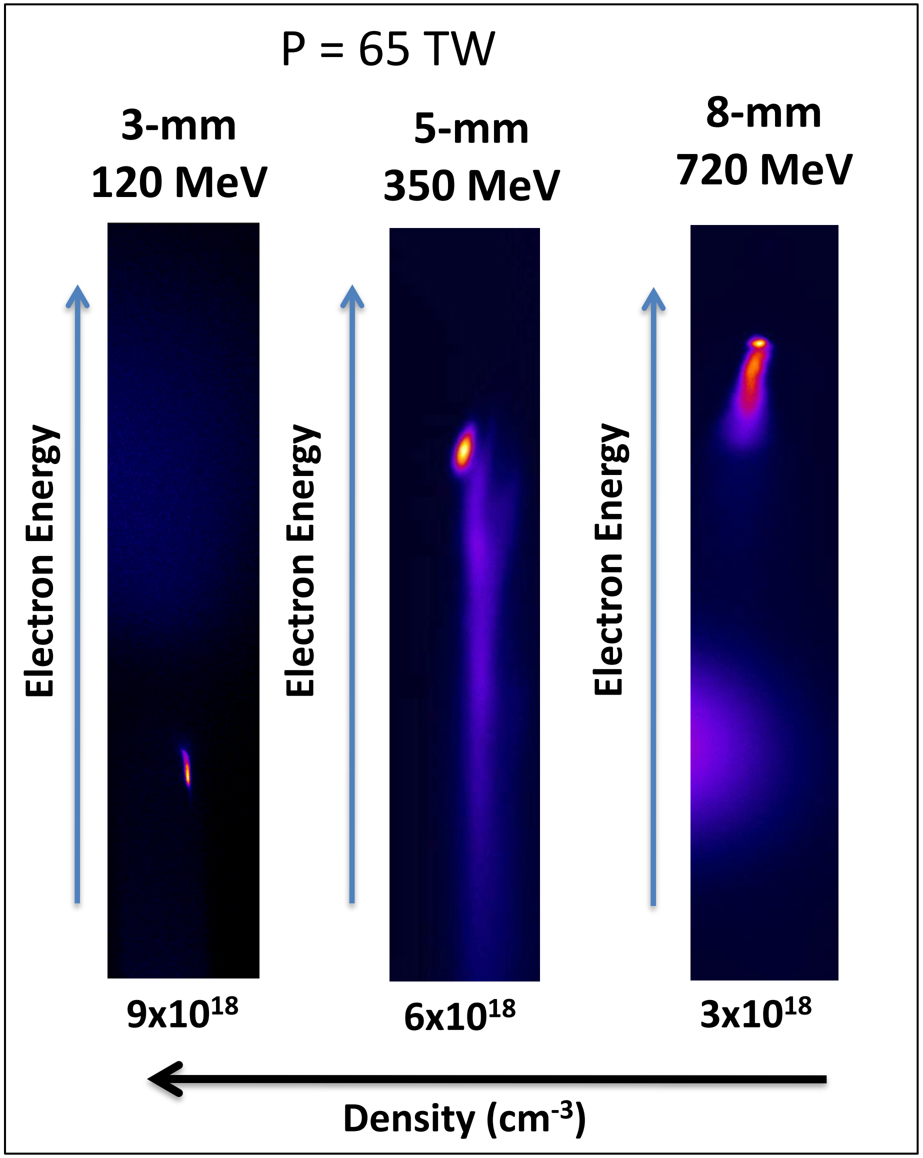
Maximum energy gain

$$\Delta W = \frac{2}{3}\frac{\omega_0^2}{\omega_p^2} a_0 mc^2$$

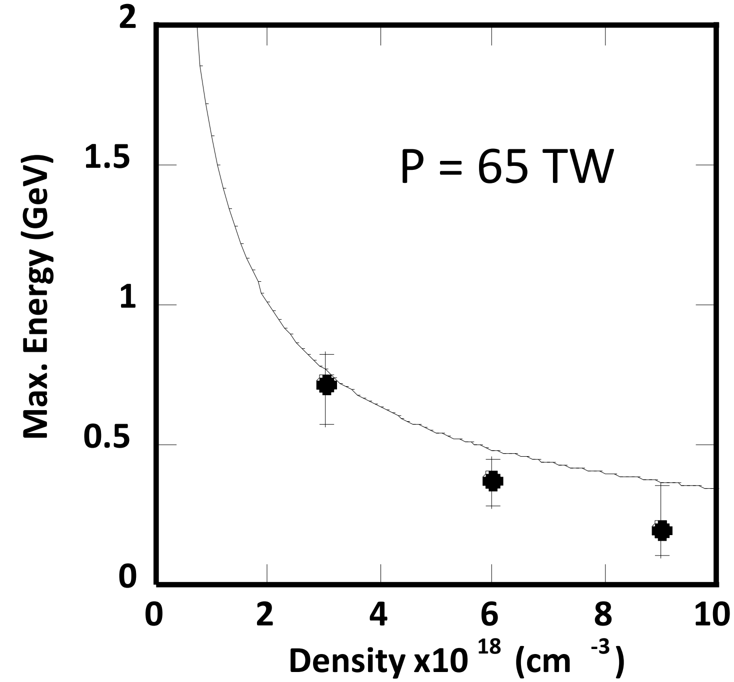
$$\Delta W = \frac{4}{3}\frac{\omega_0^2}{\omega_p^2}(P/P_c)^{1/3} mc^2$$

$$\Delta W \propto P^{1/3}(1/n)^{2/3}$$

Energy Gain Measurements at LLNL Callisto Laser



The measured energy increases with decreasing density and agrees well with analytical scaling



$$E_{\max} = 1.7\left(\frac{P}{100TW}\right)^{1/3}\left(\frac{10^{18}\,cm^{-3}}{n_e}\right)^{2/3}$$

Energy gain experiments with self trapped electrons

Experimental challenges and Limitations

- imperfect beam spot size and aberrations reduce coupling
- simulations show laser evolves for some distance before trapping occurs
- for maximum energy gain you need the lowest possible density
- self-trapping energy gain limited by $P/P_c > 4$

Why How Ionization Injection

Why

- Self injection requires $a_0 > 3$ or $P/P_c > 4$
- Ionization injection can be done at lower density. $P/P_c > 1$
- For the same laser power, electrons can reach higher energy by using ionization injection .

How

- Electrons from the K shell of Nitrogen can be tunnel ionized near the peak of the laser pulse and trapped by the wake.

Physical Picture of Electron Trapping

Electron's Change in Potential

$$\Delta\Psi = -\int_{z_i}^{z_f} E_{\max} \frac{z}{R_b} dz$$

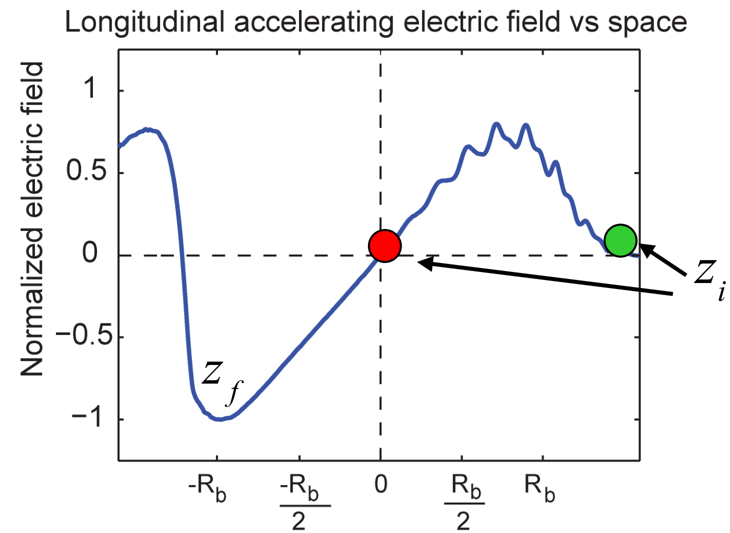
Electrons are trapped when $v_e = v_\varphi$

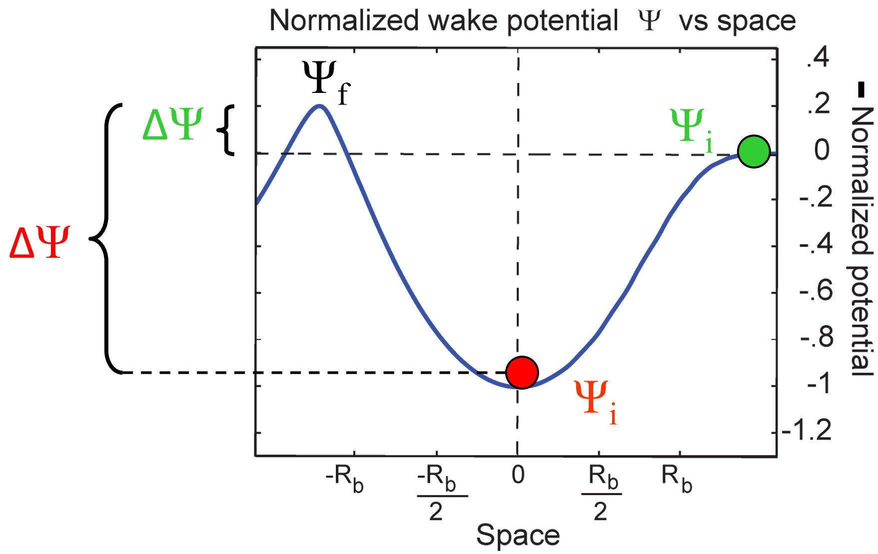
- 🟢 Background electron
- 🔴 Injected electron

Normalized Trapping Condition

$$\Delta\Psi = \frac{\sqrt{1 - p_{\perp f}^2}}{\gamma_\phi} - 1$$

$$\approx -1$$





PAC 2011

Experimental Setup UCLA Ti:Sapphire Laser

Ti:sapphire laser

λ_o = 815 nm

Pulse width = 40-50 fs

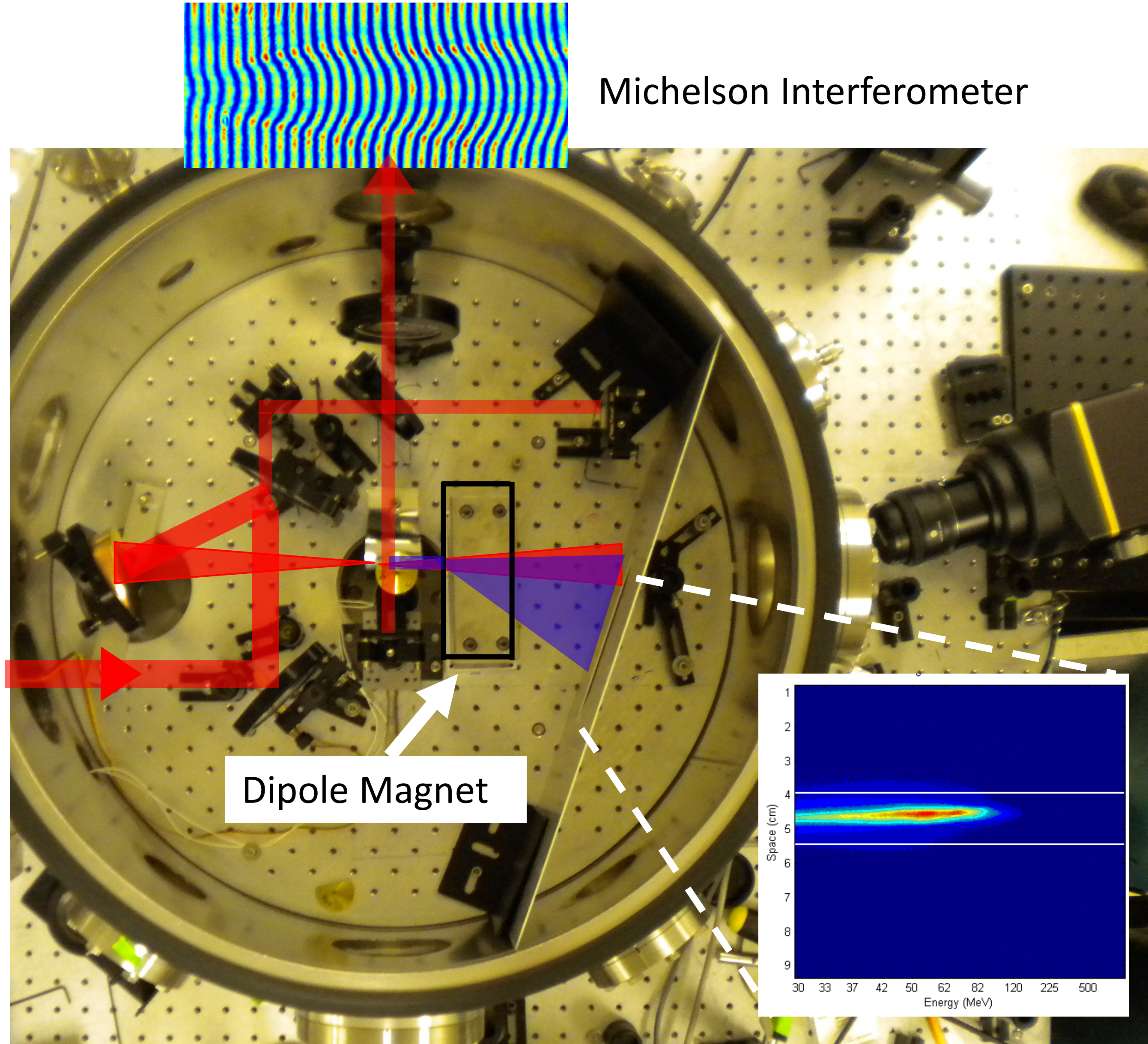
Power ≤ 10 TW

Spot size w_o = 6 μm

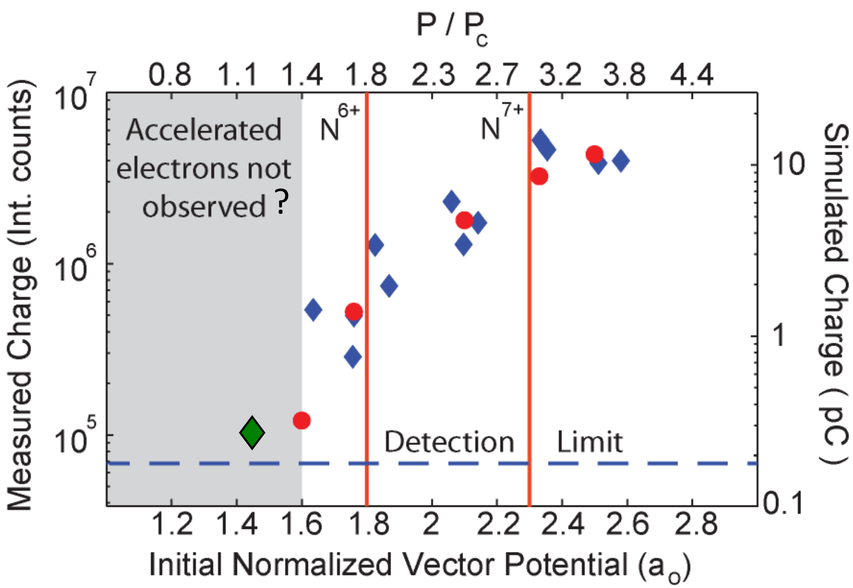
$a_o \leq 2.6$

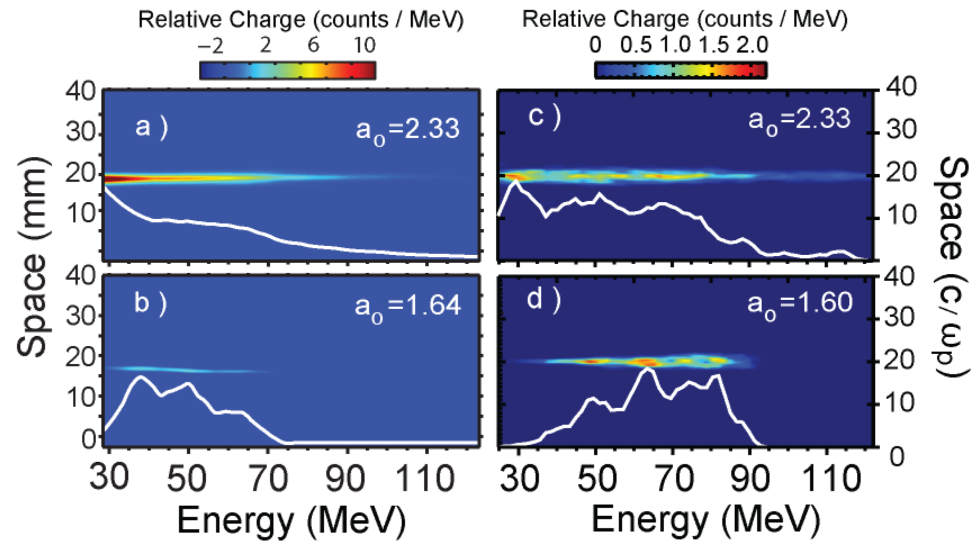
Gas jet target 1-2 mm

Gas used: 90:10 and 95:05 $He:N_2$ gas mix.



Ionization Injection Results From UCLA





- Measured charge above 25 MeV
- Simulated charge above 25 MeV
- Required a_o for ionizing $N^{6+,7+}$
- Threshold for Argon trapping

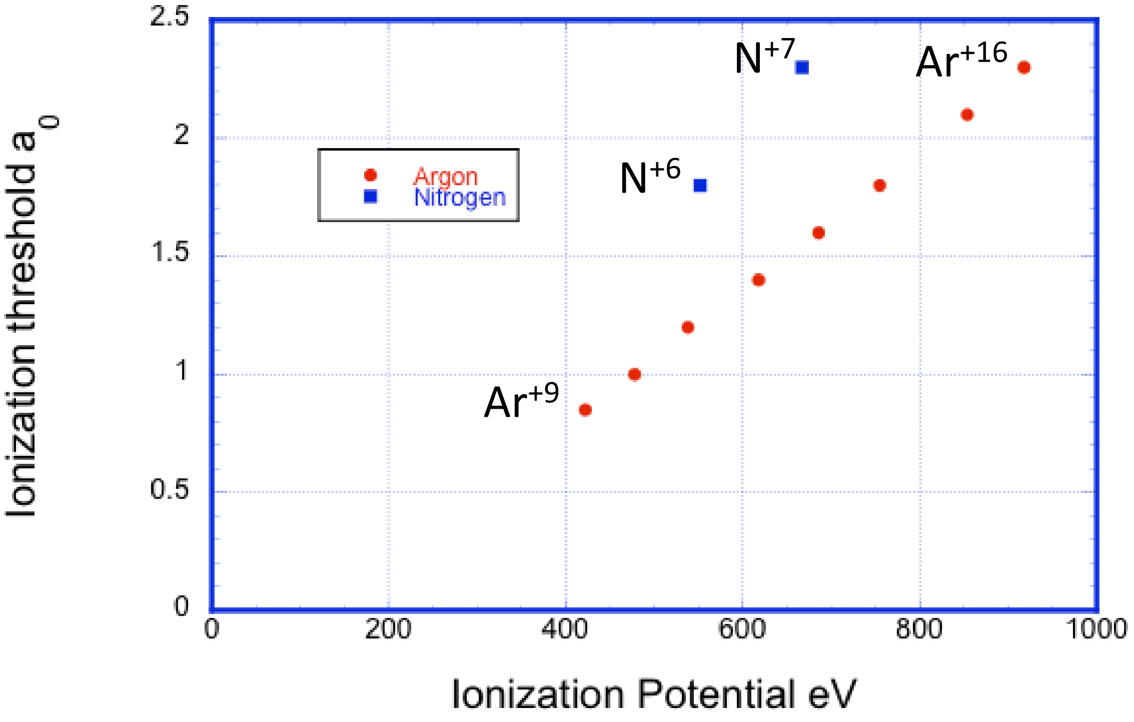
•Agreement with 3-D OSIRIS simulations

•Continuous electron energy spectrum

PAC 2011

Test Lower Bound for Ionization Injection

Want to see if ionization injection works for $a_0 < 1$



Ionization Threshold of Argon and Nitrogen

*Scaling of Ionization Trapping with a_0

Change in potential as a function of a_0

$$\Delta\Psi = -a_0(1 - z_i^2 / R_b^2)$$

For trapping

$$\Delta\Psi \approx -1$$

In practice $R_b / 2 < z_i < 3R_b / 4$

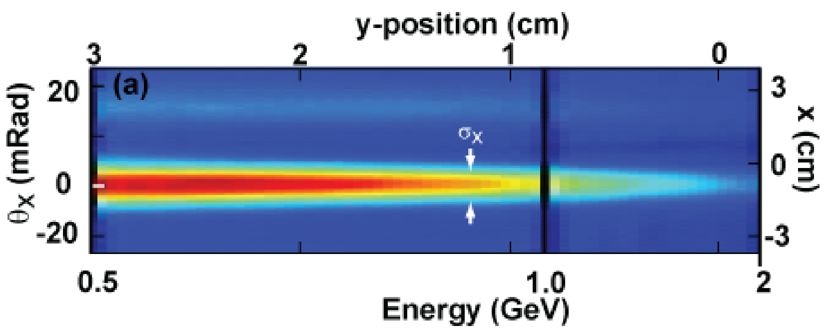
Therefore trapping threshold for a_0 is between 1.3 and 2.3 regardless of the impurity ionization threshold?

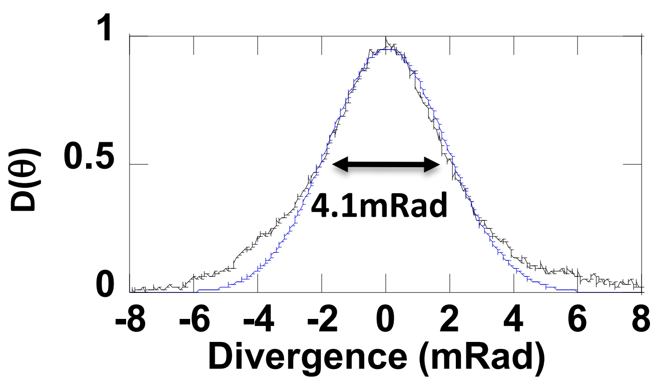
*(A. Pak dissertation)

Ionization Injection Experiment with the Callisto Laser

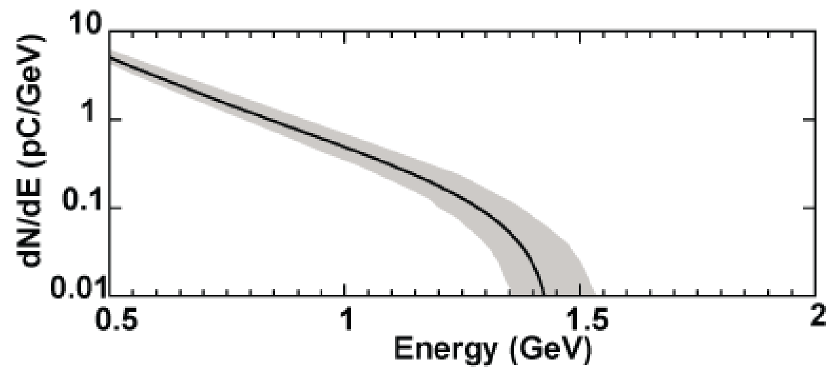
110 TW 1.3×10^{18} cm^{-3} 1.3 cm gas cell 3% O_2 impurity

Raw Electron Data on Image Plate





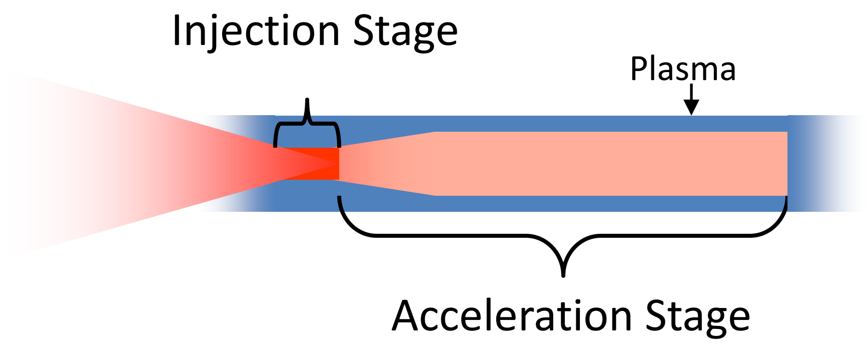
The de-convolved energy spectrum



$$\frac{dN}{dE} = \frac{dN}{dy}\sum_{\theta} D_y(\theta)\frac{dy(\theta)}{dE}$$

Clayton et al. PRL 2010

Methods to Reduce the Energy Spread



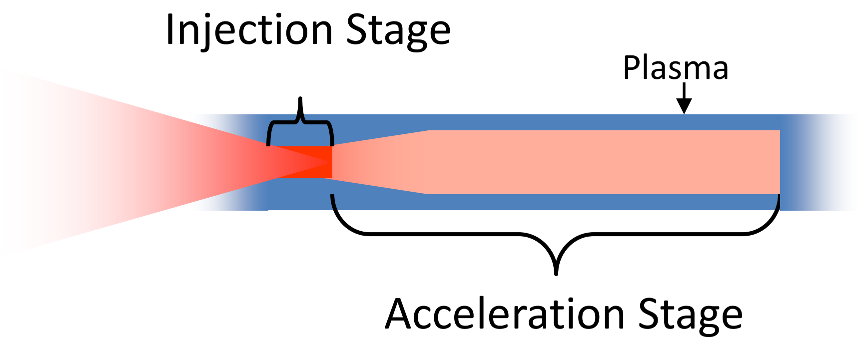
- Turn off injection after a short propagation distance

In a LWFA where weak self guiding occurs, the electric field will quickly fall below the ionization threshold for K shell electrons.

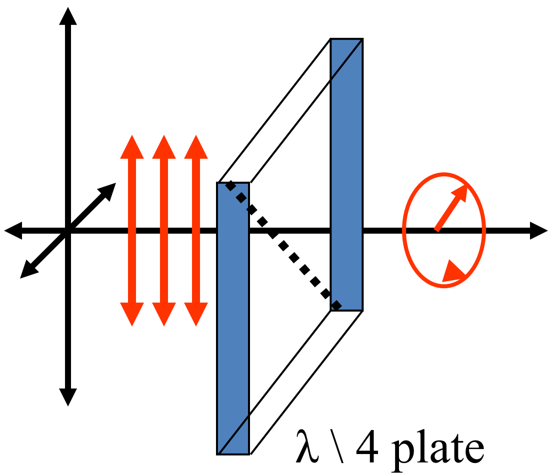
Using a circular polarized laser can reduce the ionizing electric field by $\sqrt{2}$ without changing laser intensity.

Staged injection + accelerator

Want to avoid Continuous Ionization.



Circular Polarization Reduces Field Amplitude While Maintaining Intensity.



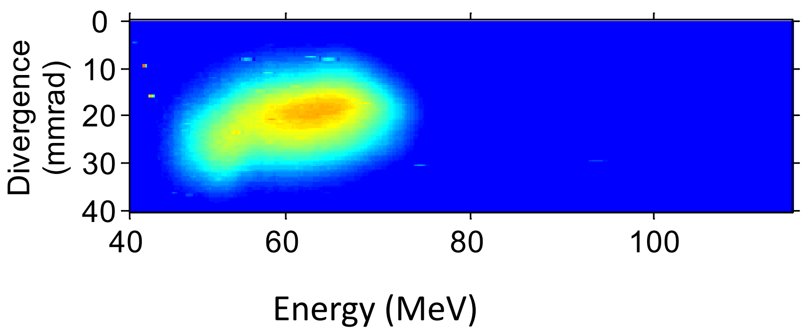
- Need a relatively high intensity for self-guiding.
    - Want to lower the field amplitude to limit ionization distance.

- Field amplitude drops by $\sqrt{2}$
- Intensity is unchanged.

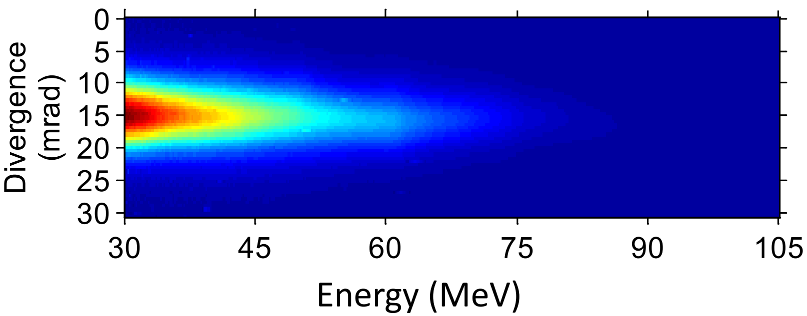
Comparison of Linear vs Circular Polarized Laser

UCLA Proof of Principle Experiment

Circularly Polarized

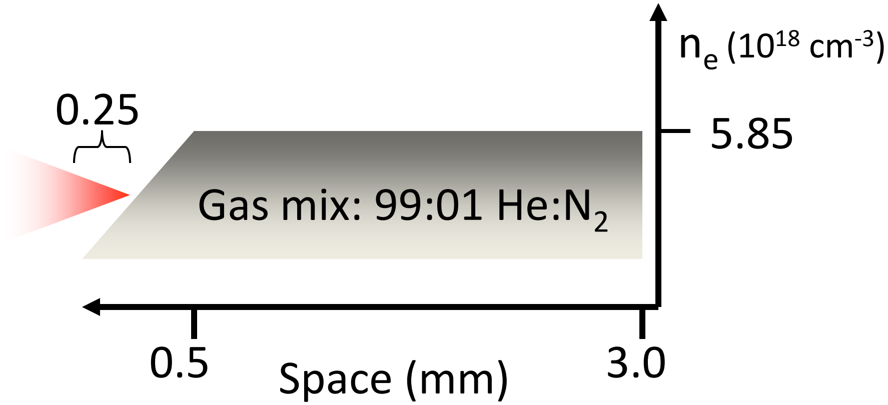


Linearly Polarized



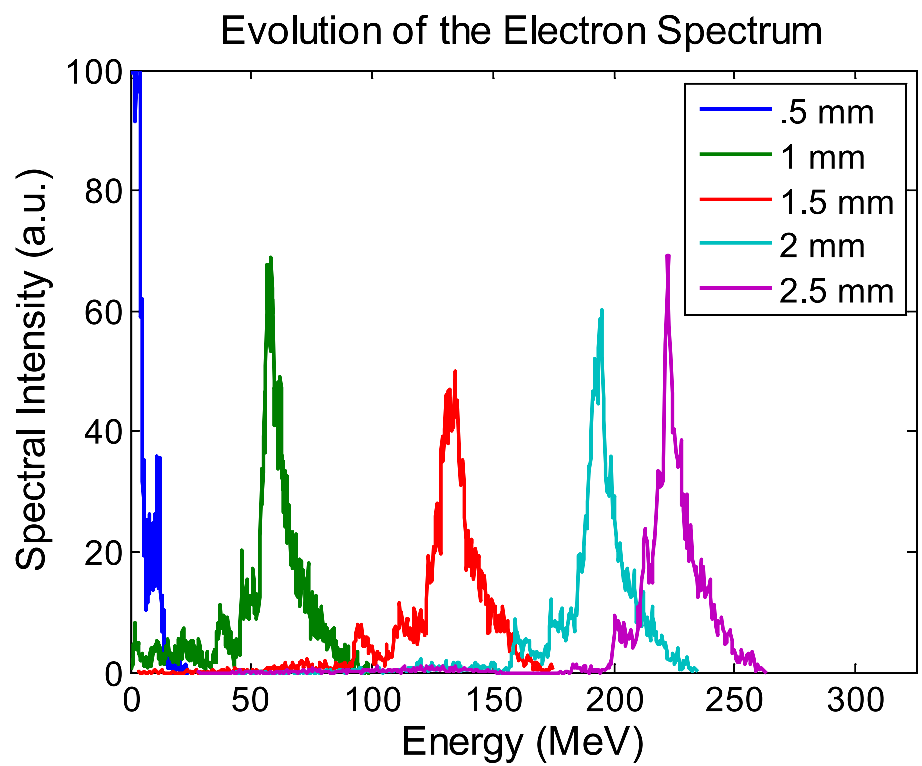
- peak a_o = 1.8 circular, 2.5 linear
- 1 mm gas jet
- $n_e \sim 2 \times 10^{19}$ cm^{-3}
- Gas mixture 95:05 He:N_2
- $P/P_c < 4$

Simulations to Optimize the Energy Spread of Electron Beam



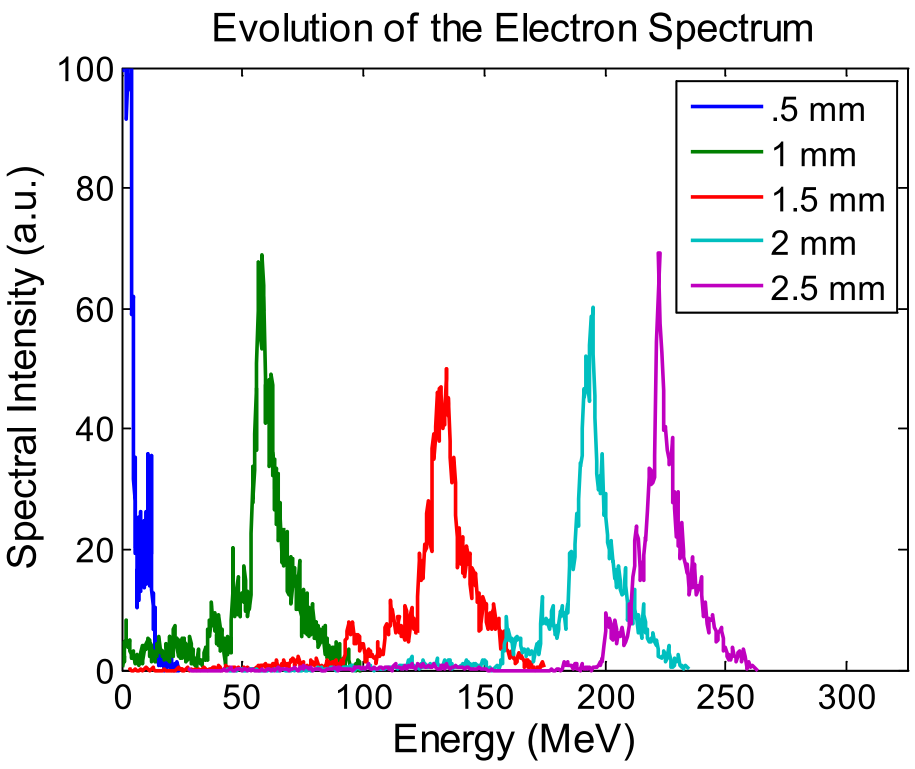
- 2-D OSIRIS
- Circular polarization vs Linear polarization
- $P / P_c \sim 1.5$
- **peak a_o = 1.6 circular, 2.25 linear**
- $n_e = 5.85 \times 10^{18}\ cm^{-3}$
- $I_o \sim 1 \times 10^{19}\ W/cm^2$
- $P \approx 7.5$ TW
- $w_o = 6.65\ \mu m$ ($k_p w_o \approx 3$)
- $\tau_{(fwhm\ Int.)} = 35$ fs ($c\tau \approx \lambda_p / 2$)

Circularly polarized case

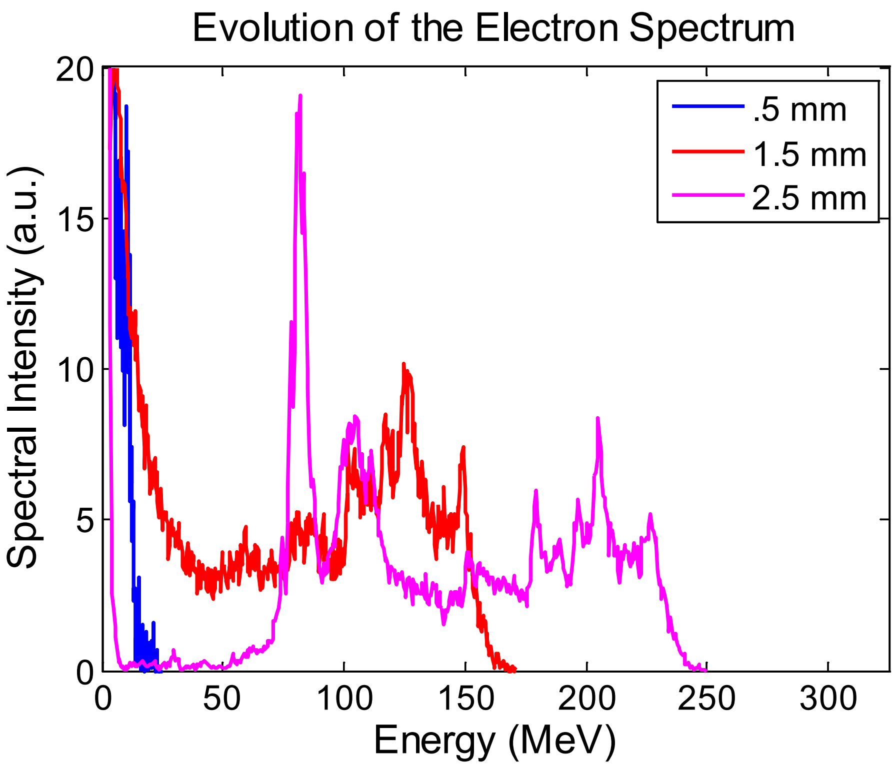


Comparison of Ionization Injection for Circular and Linear Polarization

Circularly polarized case



Linearly polarized case

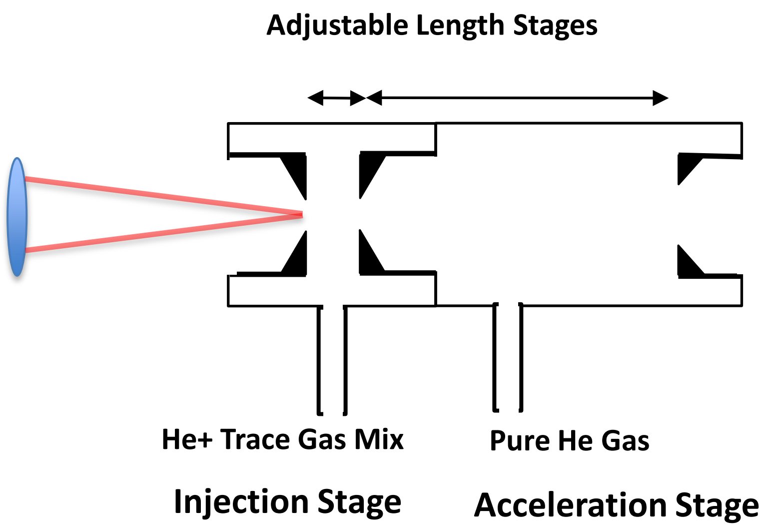


Staged Injection LWFA

- The idea is to have a short first stage which contains a trace impurity gas for ionization injection.
- The second stage is pure helium where a_0 is below the threshold for self injection.
- A 2D OSIRIS simulation demonstrates the concept

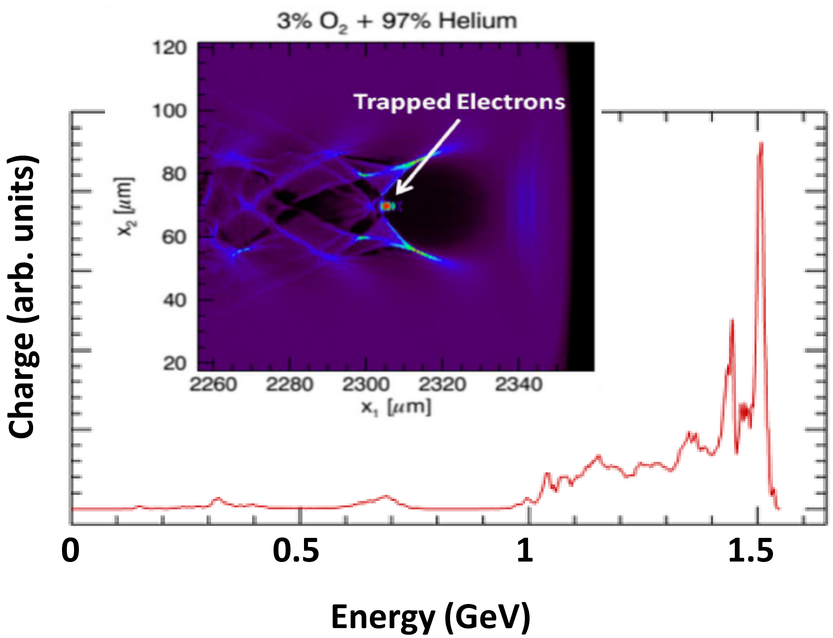
Staged Injection LWFA

Illustration of staged injection concept



The two stages have adjustable lengths

OSIRIS Simulations shows 1.5 GeV energy spread <1%



100 TW, 60 fs, 1.5x10^{18} cm^{-3}
500 um injector 1.4 cm accelerator

Summary of Results

- Experimentally and in simulations we have verified many the physical effects and equations for LWFA in the blow out regime.

- Matched beam condition and self guiding
- Pump depletion
- Max energy gain with self injection
- Minimum a_0 for ionization injection
- Continuous energy gain up to 1.5 GeV with ionization injection
- Circular polarized ionization injection with narrow energy spread
- Staged ionization injection with narrow energy spread

UCLA

UCSD

And More

- Brad Pollocks talk, Wednesday 9:30 and Warren Mori, LWFA tutorial Thursday 8:30

UCLA

UCSD