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Kilohertz Laser Wakefield Acceleration

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Outline

- Applications of particle accelerators
- Motivation for plasma-based particle accelerators
- The physics of laser wakefield and the bubble regime
- Achieving the bubble regime with a kHz, mJ laser system
- Future work at UCI

Glossary

- Peak amplitude of the normalized vector potential of the laser:

$$a_0 = 0.855\lambda[\mu m]\sqrt{I_0[10^{18}W/cm^2]}$$

- Plasma frequency:

$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{m_e}}$$

$$\lambda_p = \frac{2\pi c}{\omega_p}$$

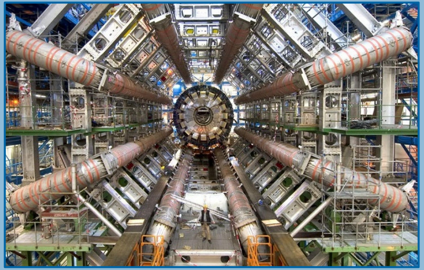
- Underdense plasmas have:

$$\omega_p < \omega_0$$

Applications of Particle Accelerators

High Energy Physics

The Large Hadron Collider at CERN

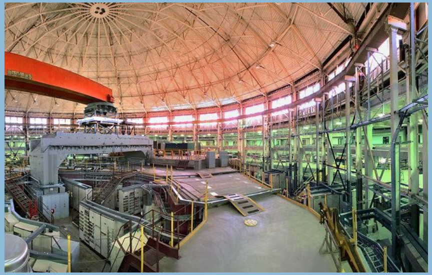


Medicine

Cancer Therapy

Light sources

X-Ray Imaging



Manufacturing

Electron Beam Lithography

Motivation for Plasma Acceleration

- Traditional linear particle accelerators use RF acceleration to accelerate particles to relativistic energies

- Acceleration gradients are limited by dielectric material breakdown to roughly 100 MV/m

Image by SLAC National Accelerator Laboratory

Motivation for Plasma Acceleration

- Laser wakefield accelerators present a compact method of obtaining high energy electrons and bright light sources

- The charge separation in the plasma can create acceleration gradients on the scale of 100 GV/m, compared to 100 MV/m for traditional accelerators

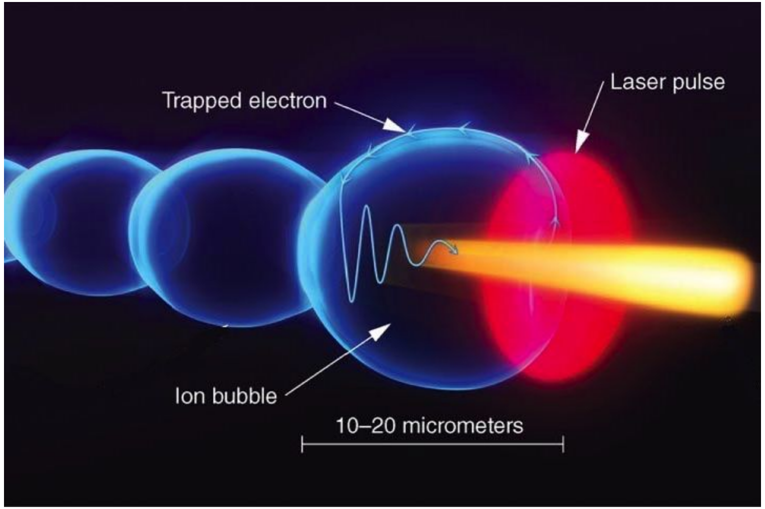


Image by Felicie Albert

Laser Wakefield Acceleration (LWFA)

- In laser wakefield acceleration, electrons can be accelerated to relativistic energies by surfing on a plasma wave driven by a laser pulse

- LWFA can also be used as a x-ray source due to the betatron radiation produced by electrons oscillating in the wake of the pulse

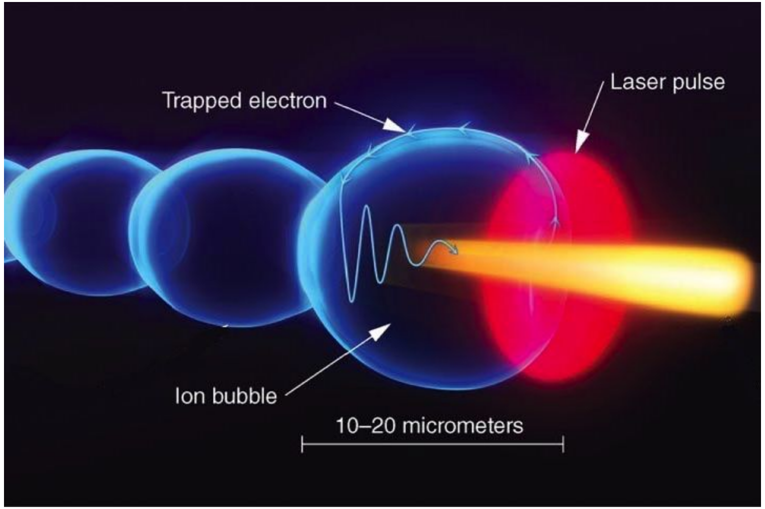


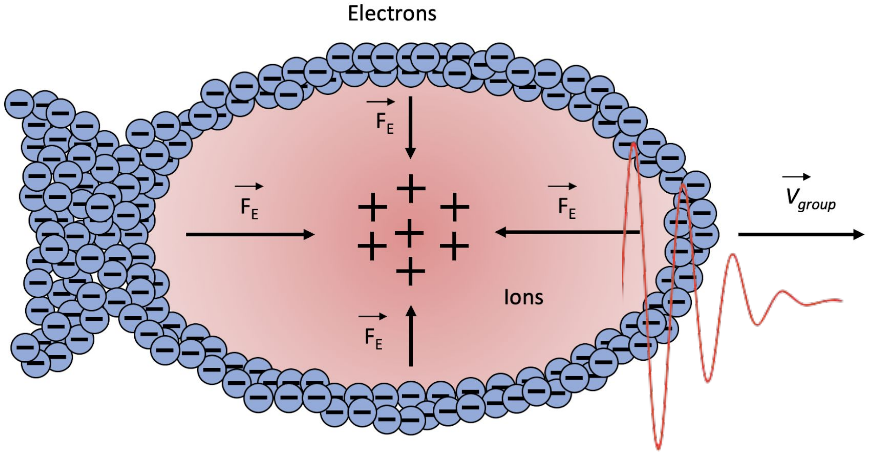
Image by Felicie Albert

The Physics of the Bubble Regime

- In the bubble regime, the laser pulse expels nearly all the electrons to form a bubble around a fixed ion core

- The charge separation creates a strong electric field inside the bubble

- Important parameters include plasma electron density, laser spot size, pulse duration, and a_0 .

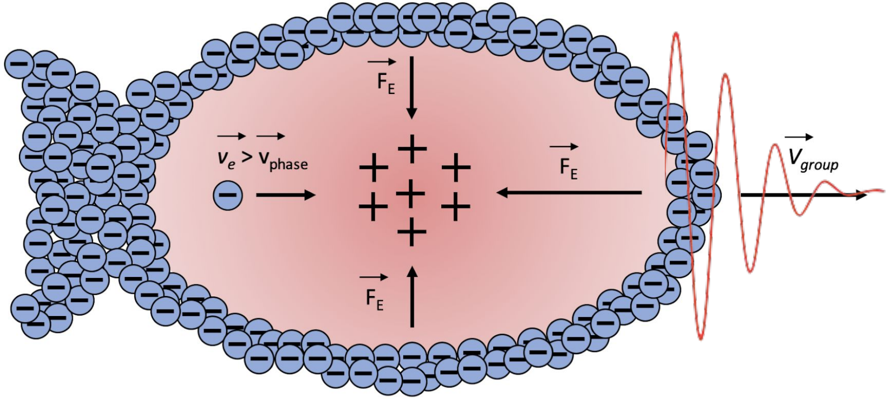


Bubble regime

$$\tau_L < \frac{\lambda_p}{2}$$

The Physics of the Bubble Regime

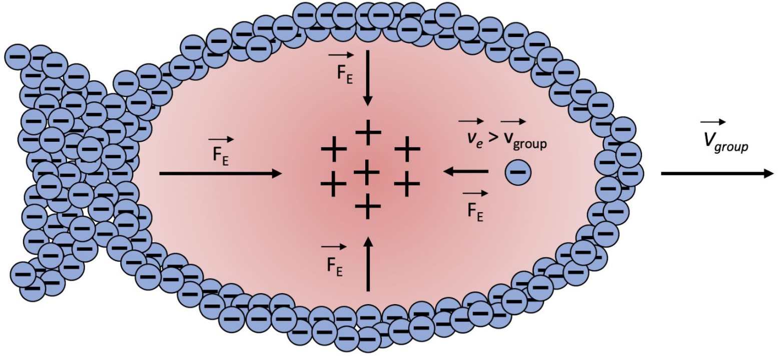
- Electrons are accelerated in the bubble directly behind the laser pulse
- Electrons at the back with v_e > v_{phase} can undergo self-injection into the bubble

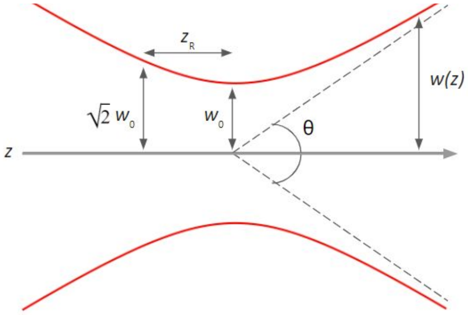


Electron Self-Injection

Limiting Factors for LWFA

- Dephasing[1] $$L_d = \frac{4\sqrt{a_0}}{3c}\left(\frac{\omega_0^2}{\omega_p^3}\right)$$
- Depletion[1] $$L_{dp} = \tau_0 c\left(\frac{\omega_0}{\omega_p}\right)^2$$
- Diffraction $$z_r = \frac{\pi w_0^2}{\lambda}$$



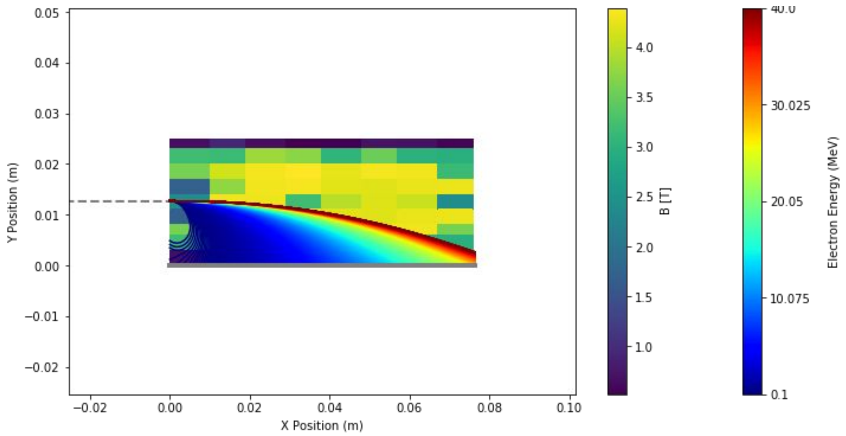


[1] A. Debus, et. al. Circumventing the Dephasing and Depletion Limits of Laser-Wakefield Acceleration. Physical Review X (2019)

Achieving LWFA with a kHz laser system

- kHz Ti:Saph laser system at UCI
  - λ = 800 nm, τ = 35 fs
  - 0.2 TW, a_0 = 2.16
- High repetition rate: better statistics, changing the wavelength
- Currently working on improving our electron diagnostic capabilities

Electron Spectrometer Simulation



Future Work at UCI

- Self-injection of electrons is extremely sensitive to laser parameters when the pulse power is low
- Shock-front injection: sharp change in density profile can slow down the back of the bubble and can prompt electron self-injection
- Reliable and controllable method of injecting electrons

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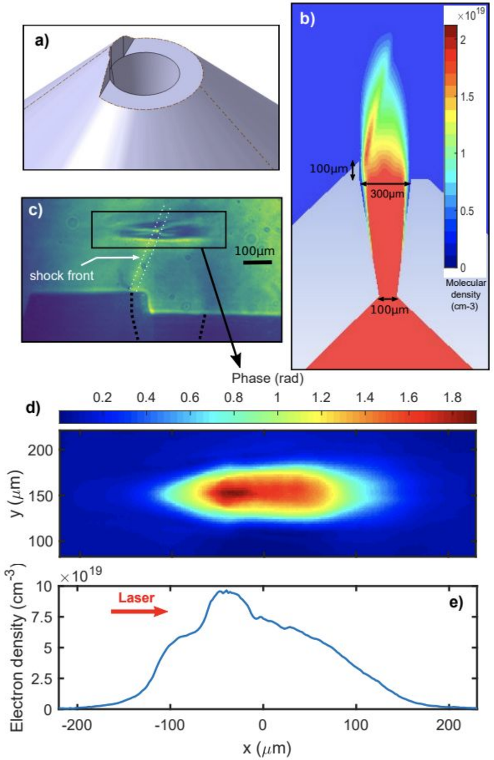

[3] L. Rovige, et. al. Demonstration of stable long-term operation of a kilohertz laser-plasma accelerator. Submitted (2020)

Future Work at UCI

- By using pulse compression to compress our 35 fs pulse to 7 fs, we can increase our intensity
- Next steps: Replicate previous experiment at UCI with more sensitive electron diagnostics
- Implement shock-front injection and/or few cycle LWFA

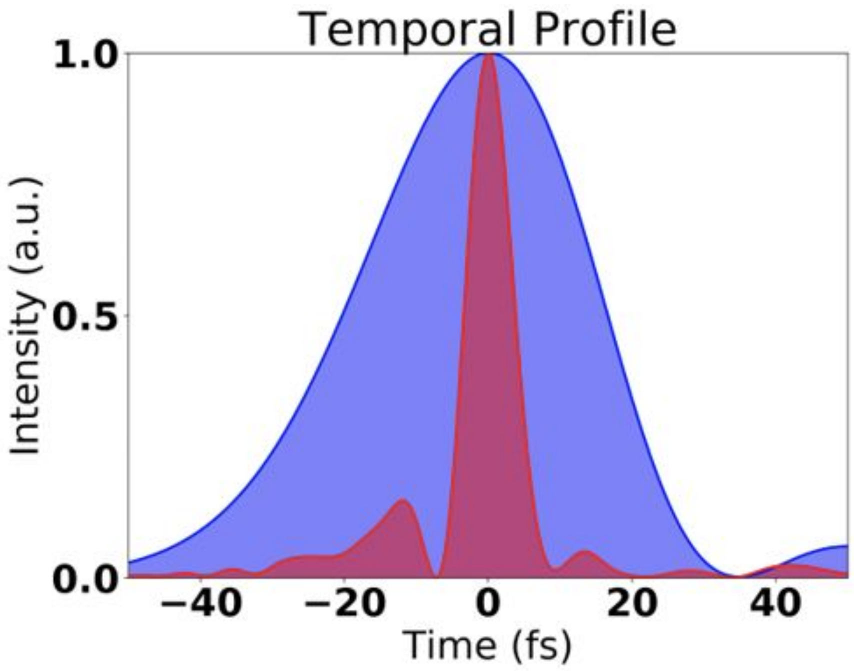

Image by Matthew Stanfield

Questions?