Laser Wakefield Acceleration

D. H. Froula

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Laser Power (TW)

Electron Energy (GeV)

Linear Regime: $a_0 < 2$

Injection Regime

UCB Nature 2006

GIST, Korea Nat. Phot. 2008

LLNL/UCLA/UCSD PRL 2009, PRL2010

UCLA

C. Clayton
K. Marsh
A. Pak
S. Martins
W. Lu
F. Tsung
C. Joshi
W. Mori

UCSD

B. Pollock
J. S. Ross
G. Tynan

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Part I: Introduction to Laser Wakefield Acceleration

• Physical picture for LWFA
• Review basic scalings

Part II: Summary of LWFA Experiments

• Diagnostics are helping understand the wake dynamics (Holography, 2ω radiation, 2-screen spectrometer)
• Length scaling experiments support current theory on acceleration
• Self-injection threshold is measured (P/P<sub>cr</sub> ~ 3)
• Ionization induced injection is demonstrated
• Injection is used to extend the maximum energy electron beams to 1.5 GeV

Part III: Future LWFA at LLNL/UCLA

• Two stage accelerator is expected to produce narrow energy spread (<1%) >1 GeV beams
Many groups around the world have performed experiments in the non-linear ($a_0 > 2$) LWFA regime using a similar setup.

Our experiments at LLNL use the 250 TW, 60 fs Callisto Laser at the Jupiter Laser Facility.

We estimate that there is 30% to 50% of the total laser energy in the central f/8 laser spot; all peak powers have been reduced accordingly.
In the nonlinear regime ($a_0 > 2$), the laser produces an ion bubble with a GeV/cm accelerating gradient.

The system evolves to where the ion attraction balances the ponderomotive force: $R_b k_p \approx 2 \sqrt{a_0}$

Typically, LWFA produce a GeV/cm electric field.

Lu et al., PRSTAB 2007
Electrons that cross the sheath can be trapped in the accelerating field “self-injection.”

Electrons that are not fully expelled by the laser field can cross into the bubble

Injection occurs when electrons are moving at the phase velocity ($v_\phi$) of the wake: ($v_e > v_\phi$)

Phenomenologically, sheath crossing occurs for $k_p R_b > 3$ which corresponds to $a_0 \sim 2$ or $P/P_{cr} \sim 1$

Increasing the power or the density increases the wake potential and the ability to self-inject

Lu et al., PRSTAB (2007)
Electrons injected at the rear of the bubble will be accelerated to the center of the bubble over a dephasing length.

The laser propagates slower than the accelerating electrons.

Lowering the density increases the speed of the laser.

As electrons accelerate beyond the center of the bubble, they begin to lose energy (“dephase”).

A dephasing length of 1.5 cm requires a density of \( \sim 1.3 \times 10^{18} \text{ cm}^{-3} \). The relationship is given by:

\[
L_d \propto \frac{P^{1/6}}{n_e^{4/3}}
\]
Reducing the density reduces the longitudinal field but the dephasing length increases faster.

The maximum energy gain for electrons injected in the rear of the bubble

\[ \Delta E = qE_L L_{acc} \]

\[ \Delta E = 1.7 \left( \frac{P[\text{TW}]}{100} \right)^{1/3} \left( \frac{10^{18}}{n_e[\text{cm}^{-3}]} \right)^{2/3} \]

Maximum Energy Gain (dephasing limited)

\[ \Delta E_{\text{max}} \approx 38 \frac{P}{[\text{TW}]} \text{[MeV]} \]

For 40 TW of coupled laser power, a maximum energy gain of 1.5 GeV is estimated

(L~1.5 cm, n_e~1.3x10^{18} cm^{-3})

An \( a_0=2 \) is required for an optimal accelerator in the nonlinear regime

When \( a_0>2 \), the laser spot is too small, the density is too high, and the dephasing length too short for maximum energy gain.

Lu et al., PRSTAB 2007
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Lu et al., PRSTAB 2007
For an optimized accelerator, the pulse width of the laser is set by the non-linear pump depletion length.

Energy from the front of the laser beam is transferred to the wake (“pump depletion”)

- **Dephasing Length**
  \[ L_{dp} \approx \frac{2}{3} \frac{\omega_0^2}{\omega_p^2} R \]

- **Pump Depletion Length**
  \[ L_{pd} = \frac{n_{cr}}{n_e} c \tau \]
  \[ \tau = \frac{4}{3} \frac{1}{\omega_p} \sqrt{a_0} \]

Increasing the pulse length of the laser increases the pump depletion length (“etching length”)

For a given laser energy, there is an optimum pulse length

1.5 J, 40 fs, (~40 TW) \rightarrow 1.5 GeV

but the laser intensity must be maintained over ~1.5 cm

Lu et al., PRSTAB 2007
UCLA experiments demonstrated that a 50 fs laser pulse can be self-guided over the nonlinear pump depletion length


The laser beam can be self-guided when the laser produces the “sheath” before it can diffract

Self-guiding over the nonlinear pump depletion length for a range of densities

Self-guiding was demonstrated over 1.5 cm at densities required to produce 2 GeV energy electrons
Experiments at MPQ have used these LWFA concepts to demonstrate a “table-top” light source

Laser-driven soft-X-ray undulator source
Fuchs et al, Nature Physics (2009)

Although the electron beams in these experiments were not ideal, many groups are working to optimize LWFA with a near term goal of producing a “table top” electron beam suitable for light sources

See F. Grüner WG1 Wednesday 4:00 pm
Frequency Domain Holography (FDH) results visualize formation of plasma bubbles

**Reconstructed probe PHASE** $\phi_{pr}(r,\zeta)$

**Reconstructed probe AMPLITUDE** $|E_{pr}(r,\zeta)|$

**Past work:** sinusoidal wakes  

**New work:** bubbles  

See Thursday WG1 presentation by P. Dong for more details.

CAUTION: The $\phi_{pr}(r,\zeta)$ and $|E_{pr}(r,\zeta)|$ reconstructions shown are from different shots under different conditions.
Second Harmonic Rings Correlate with Wake Formation

$2\omega$ emission indicates the formation of a sheath

Interference indicates multiple bubbles ("Self-Modulated LWFA Regime")

Images filtered for $2\omega$

For low density conditions, large angle electrons are observed (Kaganovich et al., PRL 2008)

For high density conditions, electrons are observed in the forward direction

Gordon et al, NJP (2010)
Max-Planck-Institut für Quantenoptik

show the effect of the laser beam “angular chirp” on the electron beam pointing

3D simulations: adding a pulse front tilt to the laser beam, “drives” the bubble off-axis

Experiments: pointing stability can be enhance by tuning out the pulse front tilt

Optical steering of a laser-wakefield accelerated electron beam
Popp et al., In Review PRL (2010)

See S. Karsch WG1 Thursday 3:30 pm
A two-screen spectrometer simultaneously measures the deflection angle and electron energy beam.

Clayton et. al., To be submitted J. Instrum. (2010)
A two-screen spectrometer simultaneously measures the deflection angle and electron energy beam.

Clayton et. al., To be submitted J. Instrum. (2010)
Electron Acceleration with 180 TW Astra Gemini


The plasma length was scaled from 2 mm to 8 mm

The electron beam energy was shown to scale with the plasma length consistent with 3D theory but were limited to densities above $\sim 4 \times 10^{18} \text{ cm}^{-3}$

See Kneip WG1 Thursday 3:30pm
A self-injection threshold \( \left( \frac{P}{P_{cr}} \approx 3 \right) \) was measured and agrees well with 3D OSIRIS simulations.

The Callisto Laser (200 TW, 60 fs) was used to measure the self-injection threshold \( \left( \frac{P}{P_{cr}} \approx 3 \right) \). This threshold limits the maximum energy for self-injection experiments to <1 GeV for laser powers <50 TW.

These experiments produced 720 MeV narrow energy spread beams.

UCLA has shown that adding trace amounts of an impurity gas can reduce this injection threshold

(Adapted from: Oz et al., Phys Rev Lett 98 084801 (2007))

REMINDER: Self-Injection is limited at low densities and powers \( (P/P_{cr} \sim 3) \)

These experiments show that the injection threshold is consistent with the appearance intensity for k-shell electrons

See A. Pak’s Tuesday 2pm for new details on the injection physics

Self-Injection \( (P/P_{cr} < 3) \): The wakefield is not strong enough to accelerate the electrons to \( v_\phi \)

This technique provides injection below the self-injection threshold

UCLA has shown that adding trace amounts of an impurity gas can reduce this injection threshold.

See A. Pak’s Tuesday 2pm for new details on the injection physics.

These experiments show that the injection threshold is consistent with the appearance intensity for $k$-shell electrons.

This technique provides injection below the self-injection threshold.

Varying the dopant gas changes the region of the bubble where the electrons are injected which can lead to improved beam quality, higher energy gain, enhanced charge.


See McGuffy WG1 Tuesday 1:30pm
University of Michigan demonstrated that ionization induced trapping can enhance the injected charge for a variety of dopant gases.

Varying the dopant gas changes the region of the bubble where the electrons are injected which can lead to improved beam quality, higher energy gain, enhanced charge.
Experiments at LLNL added 3% CO\(_2\) to the 1.4-cm long He gas filled cell producing a continuous electron spectrum.

The maximum energy increases with decreasing density.

Continuous spectrum are expected: injection is maintained until laser is sufficiently pump depleted.
Increasing the laser power by 25%, increased the electron energy well-beyond 1 GeV.

The maximum energy increases with increasing power.

Results suggest increased power increases pump depletion length.
The divergence of the electron beam must be deconvolved to determine a maximum energy.

The divergence at 1 GeV is measured to be ~4.1 mRad.

The divergence can be deconvolved to produce a spectrum.

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

Clayton et al., In Review PRL 2010
To produce a beam with a narrow energy spread, a two stage accelerator has been designed.

The two stages have adjustable lengths:
- Adjustable Lengths:
  - 0.5 – 2 mm
  - 1.0 – 1.5 cm
- He/O₂ Gas Mix
  - Gas Fill (<15 psi)
- Pure He Gas
  - Fill (<15 psi)

OSIRIS Simulations show a <1% energy spread:
- (100 TW, 60 fs, 1.5x10¹⁸ cm⁻³)

See B. Pollock (Friday 10:30 am) for initial results.

No electrons are trapped with pure He gas is used in both cells.
Summary

- Discussed the physical picture in the nonlinear regime where an optimal LWFA design occurs for $a_0 \sim 2$
- Experiments show that self-guiding can effectively propagate short pulse over 1.5 cm at $n_e$ to produce 2 GeV electrons
- Experiments show an self-injection threshold which limits energy to less than $\sim 1$ GeV ($P < 50$ TW)
- Experiments demonstrate ionization induced injection to extend energy gains to 1.5 GeV
- Experiments demonstrate the first “table-top” light source
- Many groups are working on diagnostics to improve the electron beams which will lead to the realization of “table-top” light sources