Laser-Driven Plasma Accelerators

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Acknowledgements

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Outline

• Laser-driven plasma accelerators
  – Overview of operation
  – Early experimental results
  – Scaling to higher energies

• Electron acceleration in a plasma waveguide
  – Generation of GeV beams

• Present status, future directions and potential applications
  – Controlled injection
  – Radiation generation
  – Increased beam energy
An intense electromagnetic pulse can create weak plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density $10^{18}$ W/cm$^2$ shine on plasmas of densities $10^{18}$ cm$^{-3}$ can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.
Introduction

Accelerators have many applications

- Synchrotrons (a few GeV)
- FELs (a few GeV to a few 10s of GeV)
- Particle physics (up to a few TeV)

Conventional radio-frequency accelerators are highly developed, so why bother with plasma accelerators?
Why might plasma accelerators be interesting?

- Big accelerators are:
  - big
  - expensive

Diamond
Length: 150 m
Beam energy (electrons): 3 GeV
Cost: £370M

CERN LHC
Circumference: 27 km
Beam energy (protons): 7 TeV
Cost: £2G
Why might plasma accelerators be interesting?

• The acceleration gradient in a plasma accelerator is much bigger:
  – In a conventional particle accelerator, acceleration gradient limited by electrical breakdown to:
    
    \[ E_z \approx 10 \text{–} 100 \text{ MV m}^{-1} \]

  – A plasma accelerator can reach acceleration gradients of order:
    
    \[ E_z \approx 100 \text{ GV m}^{-1} \]

  i.e. 3 to 4 orders of magnitude larger
Why might plasma accelerators be interesting?

• Plasma accelerators offer new possibilities:
  – Oscillation period of accelerating field is ~ 100 fs:
  – Allows generation and acceleration of femtosecond duration bunches
An ionized electron *quivers* in the E-field of the laser with a *ponderomotive energy*:

$$U_p = \frac{1}{2} m_e v^2 = 0.57 \ I_{18} \lambda_{\mu m}^2 \ m_e c^2$$

Spatial variation in the ponderomotive energy gives rise to a force, the *ponderomotive force*:

$$F_p = -\nabla U_p$$
Excitation of wakefield

The ponderomotive force in a laser pulses with intensity of order $10^{18}$ W cm$^{-2}$ expels electrons from the region of the pulse to form a trailing plasma wakefield.
The electric field within the plasma can reach the wave-breaking limit:

\[ E_{\text{wb}}^{\text{non rel.}} = \frac{m_e \omega_p c}{e} \]

\[ \omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}} \]

Example:

- \( n_e = 10^{18} \text{ cm}^{-3} \)
- \( \omega_p = 5.6 \times 10^{13} \text{ s}^{-1} \)
- \( T_p = 110 \text{ fs} \)
- \( E_{\text{wb}}^{\text{non rel.}} = 95 \text{ GV m}^{-1} \)
Several processes limit the length over which acceleration can occur:

- Defocusing of the pump beam
- Dephasing between electrons and plasma wave

In addition, we need some way of injecting electrons into the plasma wake…
Electron injection: External

- In a linear plasma wave, background electrons are not injected.
- Injection requires an initial positive velocity above a critical value.
- This initial energy can be provided by an external source such as:
  - Photoinjector
  - Another laser-driven accelerator
Electron injection: Internal

- Plasma waves of large amplitude become nonlinear and develop a “sawtooth” profile
- It is now possible for an initially stationary electron to reach $\nu > \nu_p$ and hence be trapped
- This is known as wavebreaking
Electron injection: Internal

- Nonlinear plasma waves develop curved phase fronts
- This allows electrons to be injected transversely
- This is known as **transverse wavebreaking**
At sufficiently high driving intensities the “bubble” or “blow-out” regime is reached. Most experiments to date operate in this regime.
Early results

- Early experiments on laser-driven plasma accelerators show continuous, quasi-thermal energy spectrum.
- Electrons injected from background plasma
- Maximum electron energy ~ 100 MeV


Laser parameters
- Energy 1 J
- Pulse duration 30 fs
Quasi-monoenergetic beams

Typical output parameters:

- Output energy: 100 - 170 MeV
- Energy spread: 2.5 - 8%
- Bunch charge: 20 - 500 pC

Plasma parameters:

- Plasma density of ~ $10^{19}$ cm$^{-3}$
- Length of gas jet ~ 1 - 2 mm

Quasi-monoenergetic beams

Quasi-monoenergetic bunch production relies on 4-step process:

- Self-focusing and self-modulation of laser pulse to excite non-linear wakefield
- Self-injection of background electrons (transverse wave breaking)
- Termination of self-injection (beam loading)
- Acceleration of electrons over distance approx. equal to dephasing length.
Plasma accelerators: Scaling to higher energies

Accelerating field: \( E_z \propto \omega_p \propto \sqrt{n_e} \)

Dephasing length: \( L_{\text{deph}} \approx \frac{\lambda^3}{\lambda^2} \propto \frac{1}{n_e^{3/2}} \)

Energy gain: \( \Delta W = E_z L_{\text{deph}} \propto \frac{1}{n_e} \)

Factor 10 increase in energy requires:
- Factor 10 decrease in electron density \( \rightarrow \sim 10^{18} \text{ cm}^{-3} \)
- Factor 30 increase in length \( \rightarrow \sim 30 - 60 \text{ mm} \)

Diffraction limits the interaction length to the order of the Rayleigh range:

\[ Z_R = \frac{\pi W_0^2}{\lambda} \]

Eg. \( W_0 = 10 \text{ µm}; \lambda = 1 \text{ µm} \)

\( \Rightarrow Z_R = 0.3 \text{ mm} \)
Gradient refractive index guiding

A propagating beam will be focused if the refractive index \textit{decreases} with distance from the axis.

\textbf{Relativistic self-focusing:} transverse variation of intensity yields refractive index profile:

\[
\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2} \frac{n_e e^2}{\gamma(r) m_e \varepsilon_0 \omega^2}
\]

This leads to self-focusing for beams above a critical power:

\[
P_c = 17.4 \left(\frac{\omega}{\omega_p}\right)^2 \text{ GW}
\]

\textbf{Example}

\[n_e = 10^{18} \text{ cm}^{-3}, \lambda = 800 \text{ nm}: P_c = 8 \text{ TW}\]
Gradient refractive index guiding

A propagating beam will be focused if the refractive index decreases with distance from axis.

**Plasma channel:** transverse variation of electron density yields refractive index profile:

\[
\eta = \sqrt{1 - \left( \frac{\omega_p}{\omega} \right)^2} \approx 1 - \frac{1}{2} \frac{n_e(r)e^2}{\gamma m_e \varepsilon_0 \omega^2}
\]

A parabolic electron density profile supports matched guiding of Gaussian beams with a constant spot size:

\[
N_e(r) = N_e(0) + \Delta N_e \left( \frac{r}{r_{ch}} \right)^2
\]

\[
W_M = \left( \frac{r_{ch}^2}{\pi r_e \Delta n_e} \right)^{1/4}
\]
Gas-filled capillary discharge waveguide

Gas-filled capillary discharge waveguide

Mechanisms responsible for channel formation described in detail in:


Plasma channel formed by heat conduction to capillary wall.

Channel is fully ionized and stable.
Capillary discharge waveguide: Interferometry


Phase shift of probe beam:

\[ \Phi_p(y, z) = -r_e \lambda \int_{-X/2}^{X/2} n_e(x, y, z) dx \]
Oxford/LBNL experiments: Set-up

Oxford/LBNL experiments
Guided beam (low power)


capillary exit plane

~ 100 mJ/pulse

no capillary with capillary
Guiding achieved over 33 mm:

- Capillary 190 μm
- Input laser power 40 TW
- Peak input intensity > $10^{18}$ W cm$^{-2}$
- Plasma: $3 \times 10^{18}$ cm$^{-3}$
- Spot size at entrance 26 μm
- Spot size at exit 33 μm

Oxford/LBNL experiments
1 GeV beams


Experiment conditions:

- Capillary: 33 mm, 312 μm diam.
- Density $4.3 \times 10^{18}$ cm$^{-3}$
- Laser: 40 TW: 1.5 J, 37 fs

In recent experiments with the Astra-Gemini laser by the Imperial College et al, 0.8 GeV beams were generated by relativistically-guided (200 TW) laser pulses [Kneip et al. *Phys. Rev. Lett.* **103**, 035002 (2009)]
• Laser-driven plasma accelerators have made very significant advances in the last few years.

• It is now possible to generate monoenergetic electron beams with energies comparable to those used in synchrotrons.

• In the near-term we can expect controlled and stable laser-accelerated beams with parameters suitable for applications.

Likely near-term parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>few GeV</td>
</tr>
<tr>
<td>ΔE</td>
<td>~1%</td>
</tr>
<tr>
<td>σ_x</td>
<td>~ 5 µm</td>
</tr>
<tr>
<td>σ'_x</td>
<td>~ 1 mrad</td>
</tr>
<tr>
<td>Bunch duration</td>
<td>~ 10 fs</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>10-100 pC</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
</tr>
</tbody>
</table>
Current research on laser-driven plasma accelerators may be divided into several themes:

• Improved shot-to-shot stability
  – Imperative for applications
• Increased beam energy
• Better (single-shot) diagnostics
  – emittance
  – bunch duration (~ 10 fs?)
• Development of applications

• In current experiments the generated beams have relatively poor shot-to-shot stability
  – jitter in E ~ 5%
  – jitter in Q ~ 50%
  – beam pointing ~ 5 mrad
• Some of these are caused by fluctuations in the laser and plasma conditions
  – Require engineering solutions

• Controlling the injection offers potential for significant improvements
Improved stability: controlled injection

Colliding pulse (LOA)

- Plasma electrons heated stochastically at collision, allowing some to be injected
- Energy tuned from 50 – 300 MeV by changing collision point

Density down-ramp (LBNL)

- Velocity of wake slowed, trapping easier
- Low absolute energy spread of ~ 0.2 MeV/c at a momentum of 0.76 MeV/c


Near-term applications: Radiation generation

Laser-driven accelerators could be used to drive very compact, tunable sources of:

- Femtosecond electron bunches: 0.1 - 1 GeV
- Femtosecond x-rays:
  - Bending magnet: 5 keV (0.2 nm)
  - 10 mm period undulator: 1 keV (1 nm)

_all intrinsically synchronized to a femtosecond visible laser system_
Undulator equation:

\[ \lambda = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right) \]

where,

\[ K = \frac{eB_0\lambda_u}{2\pi m_e c} \]
Near-term applications: Radiation generation


Generation of undulator radiation demonstrated for first time by Jena-Strathclyde collaboration

- Electron beam: 55 – 75 MeV
- Undulator: $\lambda_p = 20$ mm, $N = 50$, $K = 0.6$
- Peak brilliance est. to be $6 \times 10^{16}$ ph/s/mrad$^2$/mm$^2$/0.1%
Near-term applications: Radiation generation

Recently extended to soft x-ray wavelengths by MPQ-Oxford collaboration

- Electron beam: 210 MeV
- Undulator: $\lambda_p = 5$ mm
- Radiation at 18 nm & 9 nm (2\textsuperscript{nd} harmonic)
- Peak brilliance est. to be $2 \times 10^{17}$ ph/s/mrad\(^2\)/mm\(^2\)/0.1%
- Preliminary tuning demonstrated

Free-electron lasers

- Spontaneous radiation causes electron **microbunching** on scale of radiation wavelength
- Leads to coherent emission of radiation; **self-amplification**
- Exponential gain in power output:

\[ P \propto \exp \left( \frac{Z}{L_G} \right) \]

where,

\[ L_G = \frac{\lambda_u}{4\sqrt{3}\pi\rho} \]
Free-electron lasers

- The LCLS FEL uses the last one-third of the two-mile SLAC accelerator
- Recently demonstrated lasing at 0.15 nm
- Project cost ~$350M ($300M saved by using SLAC)
## FELs: Key electron bunch parameters

- Pierce parameter, $\rho$, characterizes strength of coupling between electrons and radiation field

\[
\frac{\sigma_{\gamma}}{\gamma} < \rho = \frac{1}{2\gamma} \left[ \frac{I_p}{I_A} \left( \frac{\lambda_u K f_K}{2\sqrt{2\pi} \sigma_b} \right)^2 \right]^{1/3}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Plasma accelerator</th>
<th>TESLA XFEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>0.5 – 1</td>
<td>10 - 20</td>
</tr>
<tr>
<td>Energy spread $\sigma_{\gamma}/\gamma$ (%)</td>
<td>1 – 5</td>
<td>0.02</td>
</tr>
<tr>
<td>Bunch charge (pC)</td>
<td>100 – 250</td>
<td>1000</td>
</tr>
<tr>
<td>Bunch duration (fs)</td>
<td>10</td>
<td>80</td>
</tr>
<tr>
<td>Peak Current $I_p$ (kA)</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Norm. emittance (mm mrad)</td>
<td>1 – 10</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Generation of 50nm radiation

**Electron parameters:**
- $E = 400$ MeV
- $\Delta E = 1\%$
- $Q = 250$ pC
- $\tau = 10$ fs rms
- $\epsilon = 1$ mm mrad normalized

**Undulator:**
- 2 cm period
- $K = 2$
FELs: GENESIS Simulations

- Variation of saturation length and power at 50 nm (Xie scaling):

- Further simulations ($Q = 250$ pC, $\varepsilon_n = 1$ mm mrad):

<table>
<thead>
<tr>
<th>Rad. ($\lambda$ (nm))</th>
<th>Undulator ($\lambda_u$ (mm), $K$)</th>
<th>Electrons ($E$ (MeV), $\sigma_E/E$ (%), $\tau_e$ (fs))</th>
<th>Output characteristics ($L_{sat}$ (m), $P_{sat}$ (GW), $N \gamma$/pulse, $\tau_r$ (fs), B.W. (%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>20, 2.0</td>
<td>400, 1, 10</td>
<td>5.1, 4.2, 7.8 $10^{12}$, 4.3, 2.7</td>
</tr>
<tr>
<td>10</td>
<td>15, 1.9</td>
<td>750, 1, 10</td>
<td>18.3, 1.6, 1.1 $10^{12}$, 7.8, 12.6</td>
</tr>
<tr>
<td>10</td>
<td>15, 1.9</td>
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<tr>
<td>5</td>
<td>10, 2.2</td>
<td>950, 0.5, 5</td>
<td>5.1, 283.0, 7.6 $10^{12}$, 1.7, 0.7</td>
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</table>
FELs: Comparison to conventional sources

Ackermann et al., Nat. Photon. 1, 336 (2007)
The challenges for a laser-driven plasma accelerator operating at TeV energies are daunting…

<table>
<thead>
<tr>
<th></th>
<th>1 GeV</th>
<th>1 TeV (ILC class)</th>
</tr>
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<tbody>
<tr>
<td>No. electrons</td>
<td>$2 \times 10^8$</td>
<td>$2 \times 10^{10}$</td>
</tr>
<tr>
<td>Energy in e⁻</td>
<td>0.03 J</td>
<td>3.2 kJ</td>
</tr>
<tr>
<td>Laser energy</td>
<td>1.5 J</td>
<td>160 kJ</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>10 Hz</td>
<td>14 kHz</td>
</tr>
<tr>
<td>Mean laser power</td>
<td>15 W</td>
<td>2.2 GW</td>
</tr>
<tr>
<td>Electrical energy</td>
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<td>2.2 TW</td>
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The challenges for a laser-driven plasma accelerator operating at TeV energies are daunting...

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<td>14 kHz</td>
</tr>
<tr>
<td>Mean laser power</td>
<td>15 W</td>
<td>2.2 GW</td>
<td>220 MW</td>
</tr>
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<td>2.2 TW</td>
<td>2.2 GW</td>
</tr>
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Indeed, in USA the BELLA (laser-driven) and FACET (beam-driven) projects have been funded (~$50M) to investigate potential for scaling to collider-type energies.
Laser-driven plasma accelerators have made significant advances in the last 5 years.

Now possible to generate monoenergetic electron beams with energies comparable to those used in synchrotrons.

It is likely that in the next few years these will be used to drive incoherent sources of tunable, femtosecond x-rays.

It remains to be seen if the brightness of the electron beam is sufficient to drive very compact FELs.

Extending to TeV (esp. high pulse rep. rate) level is challenging and will require significant advances in both plasma accelerators and laser technology.