Fruit of our labor:
Observations of accelerated particles from laser-driven plasmas

Mike Downer
University of Texas-Austin
Conventional RF acceleration is limited by material breakdown

\[ E_{\text{breakdown}} \approx 10^7 \text{ to } 10^8 \text{ V/m} \]

1 GeV \Rightarrow 0.1 \text{ km}

30 GeV \Rightarrow 3 \text{ km (SLAC)}

1 \text{ TeV} \Rightarrow 100 \text{ km}

Stanford Linear Accelerator Center
LASER-PLASMA ACCELERATORS: overcome 3 problems simultaneously


1. $E_\perp \rightarrow E_z$

2. fully damaged

3. supports large internal electrostatic fields

\[ E_0 [V/cm] = \frac{mc \omega_p}{e} = 0.96(n_e [cm^{-3}])^{1/2} \]

\[ 10^{11} \text{ V/m} \quad 10^{18} \text{ cm}^{-3} \]
I) Proton, ion, positron acceleration in laser-driven **overdense** plasmas

initial accelerating field: \[ E_z \sim \frac{kT_{\text{hot}}}{\lambda_{\text{Debye}}} \sim 10^{12} \text{ V/m} \]
Early experiments yielded proton energies $<<$ 200 MeV & broad energy distributions


Angular divergence: 30° - 60°

Scaling TNSA to 200 MeV protons requires $\sim 4 \times 10^{21}$ W/cm²

$\Rightarrow$ PW pulse focused to $w_0 < 10$ μm
Acceleration of quasi-mono-energetic protons from microstructured targets


Conclusion: Much of the energy spread of the proton beam originates from non-uniformity of the virtual cathode field.
3D computer simulations suggest a modified approach to laser-proton acceleration will scale more favorably:


**Experimental parameters**
- Ultrahigh contrast (~10^{11})
- Circularly polarized

**Dominant acceleration mechanisms**
- Radiation Pressure Acceleration (RPA)
- Coulomb explosion

**Circ-polarized RPA**
- 2 \times 10^{21} \text{ W/cm}^2
  - Monoenergetic
  - > 200 \text{ MeV}
  - Achievable intensity

**Conventional TNSA**
- 2 \times 10^{21} \text{ W/cm}^2

QuickTime™ and a decompressor are needed to see this picture.
Positron Creation & Acceleration in Overdense Plasmas


**LLNL 2-pulse TITAN laser**

- Short pulse: 1 µm, ~150 J, ~1 ps, \( w_0 \sim 10 \) µm
- Long pulse: 0.5 µm, ~150 J, ~1 ns, \( w_0 \sim 600 \) µm

**TNSA creates a directed positron beam with:**

\[ 10^{10} \text{ e}^+ / \text{shot} \]

**Pair production creates positrons inside Au target:**

- Relativistic e-
- Photon (γ)
- Positron (e+)  

**β-decay sources:** \( 10^6-12 \) e+/s, \( E < 1 \) MeV

**Accelerator-based sources:** \( 10^9 \) e+/bunch, \( E > 100 \) MeV

*courtesy Scott Wilks*
II. Electron & Positron Acceleration by Underdense Plasma Waves

• Resonantly-driven plasma waves
  (linear regime)

• Far-off-resonantly-driven plasma waves
  (nonlinear regime)

• Resonantly-driven plasma waves
  (nonlinear “bubble” or “blowout” regime)

  --- self-injected vs externally injected
  --- self-guided vs externally guided
Resonant Excitation of a Water Waves creates High Tides

Bay of Fundy, Newfoundland
Laser-acceleration experiments have resonantly driven plasma waves in three ways

1) Single Laser Pulse Driver (LWFA)
\[
\vec{F}_{\text{ponderomotive}} = -\frac{e^2}{4m\omega^2}\nabla(E^2)
\]
\[\tau_{\text{pulse}} \approx \omega_p^{-1}\]

2) Electron Bunch Driver (PWFA)
\[
\vec{F}_{\text{Coulomb}} = -mc^2\nabla\phi
\]
\[\tau_{\text{bunch}} \approx \omega_p^{-1}\]

3) Two-pulse Beat-wave Driver (PBWA)
\[\omega_1 - \omega_2 = \omega_p\]
PBWA requires very UNIFORM plasma
Resonant Plasma Wakefield Acceleration


Linear regime: \( n_{\text{bunch}} < n_e \)

Wakefield drive electron bunches:
21 MeV, ~ 8 ps, ~ 2 nC, \( n_{\text{bunch}} \approx 10^{12} \text{ cm}^{-3} \)

Witness bunches:
15 MeV, variable delay

Plasma:
\( n_e \approx 10^{13} \text{ cm}^{-3} \), \( L \approx 30 \text{ cm} \)

Plasma density perturbation:
\( \delta n_e/n_e \approx 0.1 \)

Longitudinal accelerating field:
\( E_z \approx 1 \text{ MeV/m} \) (less than SLAC)
Resonant Plasma Beat-Wave Acceleration
Everett et al., Nature 368, 527 (1994)

**CO$_2$ laser:**
- $\lambda = 10.6 \, \mu$m, 10.3 $\mu$m
- $n_{res} = 8.6 \times 10^{15} \, \text{cm}^{-3}$

**Other resonant PBWA results:**

**Injected e- from rf linac:**
- 2 MeV
- $L = 6000 \, \mu$m micropulses
- $6 \, \mu$m-$\text{mm}$-mrad

**Resonance**

- $\lambda_p = 360 \, \mu$m
- $\delta n/n_e \sim 0.3$
- $E_z \sim 2.8 \, \text{GV/m}$
- $L_{\text{plasma}} \sim 1 \, \text{cm}$

- $L_{\text{depk}} \sim 50 \, \text{cm}$
Resonant Laser Wakefield Acceleration


laser: 400 fs, 1 µm, 4 to 9 J, 20 < \( w_0 < 30 \) µm

externally injected e\(^-\): 3 MeV, 300 µA cw, \( \sigma_r \sim 30 \) µm

target: gas-filled chamber

maximum energy gain observed: \( \Delta E_{\text{max}} \sim 1.6 \) MeV

acceleration gradient: \( E_z \sim 1.5 \) GV/m

Fs-time-resolved frequency-domain interferometry yielded sub-\( \lambda_p \) characterization of resonant LWF structures


resonant: \( \omega_p \tau_p \sim 1 \)

\( n_e \sim 10^{17} \) cm\(^{-3}\), \( \delta n_e / n_e \sim 1 \), \( E_z \sim 10 \) GV/m, \( E_r \sim 5 E_z \)
Electron Acceleration by Plasma Waves Driven Resonantly & Linearly: Summary

- externally injected electrons needed
  -- separate linac (PBWA, LWFA)
  -- witness pulse split-off from drive pulse (PWFA)

- wide energy spread
  -- reflects stringent requirements on injection

- low energy gains
  -- $\Delta E \sim .05$ MeV: PWFA
  -- $\Delta E \sim 3$-15 MeV: LWFA, PBWA

- high accelerating gradients demonstrated
  -- $E_z \approx 10^6$ V/m (PWFA)
  -- $E_z \approx 3 \times 10^9$ V/m (PBWA)
  -- $E_z \approx 10^{10}$ V/m (LWFA)
  -- $10^7$ V/m (SLAC)
1995ff.: The “jet-age”* of laser-plasma accelerators

Characteristics of the jet-age:
- Driven by wide availability of TW-scale laser systems
- Simply focus TW laser pulse into a gas jet
- Self-injection of electrons
- Copious yield: up to $10^{10}$ e-/shot, up to 100 MeV
- Highly collimated e- beams
- Suddenly, laser-plasma acceleration had become easy!

FAR-OFF-RESONANT LWFA in dense plasma yielded copious MeV electrons


Dewa, NIMPRA 410, 357 (1998)

>10^{10} electrons per shot


10^{11} V/m

Energy Gain (MeV)

2-3 TW laser pulse

400 fs

plasma wave

4 fs

He gas nozzle

n_e \sim 10^{19} \text{ cm}^{-3}

“accelerator-quality” beams in all respects except energy spread
Theory: “Self-modulated” LWFA (SM-LWFA) grows by Forward Raman Scattering (FRS) instability

Experiment 1:

- ne ~ 10^{19} cm^{-3}
- incident pump modulates plasma noise
- pump
- time-resolved forward probe scatter

Theory: "Self-modulated" LWFA (SM-LWFA) grows by Forward Raman Scattering (FRS) instability


Experiment 2: SM-LWFA produces red/blue sidebands on a probe pulse*

Plasma Wave Decays in < 2 ps because of Beam Loading


Ionization front triggers growth of Plasma Wave

* a.k.a. “collective Thomson scatter”

data from LeBlanc (1996)
RELATIVISTIC SELF-FOCUSBING guides laser pulse, collimates e- beam during self-modulated LWFA

\[ P_{\text{crit}} = 17\left(\frac{\omega_0}{\omega_p}\right)^2 \text{ GW} \]


Side scatter from jet
Wagner et al., PRL 78,3125 (1997)

Density depression on axis
Chen et al., PRL 80, 2615 (1998)

Electron beam profile:

- 0.6 TW
- 1.1 TW
- 2.0 TW
- 2.9 TW

\[ \Delta \Theta = 1^\circ \]
\[ \varepsilon_t = 0.06 \pi \text{ mm mrad} \]
In SM-LWFA, plasma waves are driven to wave-breaking limit, causing (uncontrolled) self-injection & self-trapping of background plasma electrons

TW laser pulses get shorter: $\tau_p \rightarrow \omega_p^{-1}$ and “Self-modulated” $\rightarrow$ “Forced” LWFA

Laser pulse can evolve in ways that enhance LWFA
Self-modulated & Forced Laser Wakefield Acceleration: the early “jet-age”

• Electrons self-inject uncontrollably as high-amplitude \((\delta n_e/n_e \sim 1)\) plasma wave breaks

• Laser pulse self-guides by relativistic self-focusing, extending acceleration length & collimating beam

• Laser pulse can self-compress prior to generating wake

• high energy gains \((\Delta E \text{ up to } 200 \text{ MeV})\)

• ultrahigh accelerating gradients \((E_z \sim 10^{11} \text{ V/m})\)

• wide energy spread \((\sim 100\%)\)

*Items in red are the important legacy of the early jet age for the modern jet age*
2004: “Bubble” regime bursts on the scene


- $n_e = 2 \times 10^{19} \text{ cm}^{-3}$
- $I = 2.5 \times 10^{18} \text{ W/cm}^2$
- $\tau_p = 40 \text{ fs}$
- $E = 500 \text{ mJ}$
- $3\%$ spread

Data from Mangles (2004)

Data from Faure (2004)
Since 2004, quasi-monoenergetic electrons have been observed in laboratories around the world.

**Stable quasi-mono-energetic beams demonstrated**


... and many more.....

Unpublished data from Umstadter (U. Nebraska-Lincoln):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Angular position (mrad)</th>
<th>Divergence (mrad)</th>
<th>Energy (MeV)</th>
<th>Energy spread (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0</td>
<td>5.3</td>
<td>344</td>
<td>38.4</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.1</td>
<td>1.7</td>
<td>35</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Laser: 37 TW, 35 fs, 24 µm spot

Jet: \( n_0 \sim 7 \times 10^{18} \text{cm}^{-3}, L \sim 3 \text{mm} \)

**Electron energy:** 237 MeV ± 5%
Production of quasi-monoenergetic electrons is a highly nonlinear process that includes formation of plasma “bubble”

When $n_e$ at the walls reaches a threshold value self-injection occurs at the back of the bubble, then stops abruptly when the trapped $e^-$ density approaches the wall density

Short, localized injection leads to formation of a quasi-monoenergetic electron bunch.

Laser pulse self-focuses & self-compresses, then blows out an electron-evacuated cavity (bubble) filled with ions and surrounded by dense wall of electrons (like a moon crater).

but, self-injection is nonlinear & uncontrolled.

Injection from conventional linacs is not an option -- the bunches are too short ...

simulations below courtesy S. Kalmykov
Researchers are working on several approaches to CONTROL localized injection into a highly nonlinear plasma wave. This requires some pre-acceleration.
Injection controlled using a second “colliding” laser pulse


Short scale length $\lambda_0/2$

$\Rightarrow$ strong, highly localized ponderomotive injection force $F \propto 2a_0a_1/\lambda_0$

- colliding pulses create STANDING plasma beat wave $v_\phi = 0$
to capture SLOW plasma electrons.

Injection location & electron energy
are easily tuned by adjusting
pump-injection pulse time delay
Gas-filled capillary discharge waveguides extend acceleration length to several cm ...


$n_\text{e}$ is minimum, and refractive index maximum, on the waveguide axis.
... yielding quasi-monoenergetic beams up to 1 GeV, the current world record for laser-plasma acceleration


BEYOND GeV:
- PW laser pulses
- staging

beam divergence: 1.6 mrad
energy spread: 5%
charge per bunch: ~0.1 nC
accelerator length: 3 cm

The achievement of quasi-monoenergetic laser-plasma accelerated e\(^-\) up to 1 GeV opens a multitude of applications

• **Table-top, fs X-ray FELs**
  

• **\(\gamma\)-ray radiography for materials science**
  

• **Compact injectors for HEP accelerators**

• **Efficient on-site production of radioisotopes**
  

• **Radiotherapy with tunable, high-energy electrons**
  
On-site production of short-lived isotopes for medical imaging

Limitations to the widespread use of PET arise from the high costs of cyclotrons needed to produce the short-lived radionucleotides for PET scanning. Few hospitals and universities are capable of maintaining such systems.

Positron Emission Tomography

<table>
<thead>
<tr>
<th>Radiotracer</th>
<th>Activation Reaction</th>
<th>Half-Life</th>
<th>Medical Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{15}$O</td>
<td>$^{16}$O (γ,n)$^{15}$O</td>
<td>2 minutes</td>
<td>Neuro-imaging</td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>$^{12}$C(γ,n)$^{11}$C</td>
<td>20 minutes</td>
<td>Neuro-receptor-specific brain imaging</td>
</tr>
<tr>
<td>$^{18}$F</td>
<td>$^{19}$F(γ,n)$^{18}$F</td>
<td>110 minutes</td>
<td>Clinical oncology</td>
</tr>
</tbody>
</table>

Laser-generated quasi-mono-energetic electrons efficiently photo-activate materials of interest.

- High Rep rate
- Low cost
- Compact

The “blowout” regime was first explored in connection with PWFA, and is a close analog of the LWFA “bubble” regime


Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

Plasma Afterburner:  


courtesy Frank Tsung (UCLA)  

Plasma energy doublers can potentially impact high-energy colliders at the energy frontier.

e\text{-} and e\text{+} driven wakes differ greatly in structure

Blue et al., PRL (2006)
How far can laser-plasma acceleration go?


3D computer simulations increasingly guide development of future experiments

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0.04</strong></td>
<td>30</td>
<td>1.5x10¹⁸</td>
<td>14</td>
<td>0.011</td>
<td>0.25</td>
<td><strong>0.95</strong></td>
<td>channel-guided, self-injected</td>
</tr>
<tr>
<td><strong>1.0</strong></td>
<td>80</td>
<td>5x10¹⁷</td>
<td>34</td>
<td>0.08</td>
<td>1.3</td>
<td><strong>5.7</strong></td>
<td>self-guided, self-injected</td>
</tr>
<tr>
<td>2.0</td>
<td>100</td>
<td>3x10¹⁷</td>
<td>47</td>
<td>0.18</td>
<td>1.8</td>
<td>10.2</td>
<td>self-guided, self-injected</td>
</tr>
<tr>
<td><strong>2.0</strong></td>
<td>310</td>
<td>10¹⁶</td>
<td>140</td>
<td>16.3</td>
<td>1.8</td>
<td><strong>99</strong></td>
<td>channel-guided, externally injected</td>
</tr>
<tr>
<td>40</td>
<td>330</td>
<td>4x10¹⁶</td>
<td>146</td>
<td>4.2</td>
<td>8</td>
<td>106</td>
<td>self-guided, self-injected</td>
</tr>
<tr>
<td>20</td>
<td>1000</td>
<td>10¹⁵</td>
<td>450</td>
<td>500</td>
<td>5.7</td>
<td>999</td>
<td>channel-guided, externally-injected</td>
</tr>
</tbody>
</table>

Table entries feature:
1. stable plasma structure
2. \( L_{\text{dephasing}} = L_{\text{pump depletion}} \)
3. balance between energy extraction & beam quality

One school of thought maintains that the “bubble” regime is scalable all the way to the energy frontier
SUMMARY: Plasma acceleration experiments

I. OVERDENSE PLASMAS:

• TNSA (2000-present)
  - low MeV protons, mostly wide energy spread

• RPA regime (simulations, experiments at early stage)
  - promise of >200 MeV quasi-monoenergetic protons at feasible intensity if stringent technological requirements (ultrahigh contrast laser pulses, ultrathin targets) can be met

II. UNDERDENSE PLASMAS:

• Early experiments (1988-94): resonant, linear PWFA, PBWA, LWFA
  - difficult, equipment-intensive experiments (injection accelerators, gas cells)
  - low MeV electron energy gain, wide energy spread, proof-of-principle only

• “Jet-age” of laser-plasma accelerators (1995-present):
    - accelerator-quality electron beams in most respects except energy spread
    - relatively easy experiments yielding > 100 MeV, collimated electron beams
  -- near-resonant, nonlinear “bubble” accelerators (2004-present)
    - quasi-monoenergetic e- bunches up to GeV, controlled injection, stable & tunable energy
    - multiple applications, appears scalable to multi-GeV (maybe further)
    - most experiments now operate in this regime

• Bunch-driven plasma-afterburner doubles energy of conventional accelerator (2007): Potential to impact high-energy colliders at the energy frontier

Some review articles focusing on experiments:
Joshi, Phys. Plasmas 14, 055501 (2007)
____ , Scientific American (Feb. 2006), pp. 41-47
Potential to impact high-energy colliders at the energy frontier
END
Proton Therapy enables precise exposure of small tumors with minimal damage to surrounding healthy tissue ... ... but requires large, expensive facilities

“There are too few physicists in the world, and they are an incredibly important part of doing this... We have one of the largest physics departments in the world, with more than 50 medical physicists.”

--- Dr. James D. Cox, head of Radiation Oncology at MD Anderson Cancer Center, Houston, Texas

Laser proton therapy could be much smaller & cheaper:

V. MeV Protons & Ion Beams

courtesy Prof. Dr. Oswald Willi, U. Düsseldorf

V. MeV Protons & Ion Beams

Target Normal Sheath Acceleration: hot electrons traversing target electrostatically accelerate impurity hydrogen ions on the rear surface

courtesy Prof. Don Umstadter, U. Nebraska-Lincoln
Radiation losses are negligible for linear accelerators

\[
\frac{P_{\text{loss}}}{P_{IN}} = \frac{2}{3} \frac{(e^2 / mc^2)}{mc^2} \frac{dE}{dx}
\]

(Jackson 14.29)

\[r_e = 2.82 \times 10^{-13} \text{ cm}\]

\[0.5 \text{ MeV}\]

\[\rightarrow 1 \text{ only for } dE/dx \sim 10^{20} \text{ V/m} \]
Relativistic electrons propagate collisionlessly through plasmas

mean free path:

\[ \lambda = (n \sigma)^{-1} \approx 10^{-7} \frac{E^2 [eV]}{n [10^{19} \text{ cm}^{-3}]} \text{ cm} = \begin{cases} 
10^{-3} \text{ cm} & 1 \text{ keV} \\
1 \text{ km} & 1 \text{ MeV} \\
10^6 \text{ km} & 1 \text{ GeV} 
\end{cases} \]
Limits to Single-Stage Plasma Acceleration Length

**Diffraction**

\[ z_R = \frac{\hat{U} w_0^2}{\lambda} \]

10^{-2} < z_R < 10^{-1} cm

[1 TW] [10 TW]

**Dephasing**

\[ L_{\text{deph}} = \frac{\lambda_p^3}{\lambda^2} \]

10^{-1} cm < L_{\text{deph}} < 10^3 cm

[10^{19} cm^{-3}] [3 \cdot 10^{16} cm^{-3}]

**Depletion**

\[ L_{\text{depletion}} \]
Efficient initiation of photonuclear reactions using quasimonoenergetic electron beams from laser wakefield acceleration.

1 J laser pulse $\rightarrow$ 10% efficiency $\rightarrow$ $\sim$150 MeV mono-energy electrons $\rightarrow$ Ta converter $\rightarrow$ bremsstrahlung $\gamma$-rays $\rightarrow$ activated tracer, e.g. $^{12}$C($\gamma$,n)$^{11}$C

$10^5$ reactions

$\gamma$-ray spectrum

activation window

1 nC

Energy (MeV)

Intensity (a.u.)

Phots/Mev/electron

Photon energy (MeV)
QuickTime™ and a decompressor are needed to see this picture.

~10 μm
### Petawatt laser wakefield accelerators

**1st generation**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>30</td>
<td>10¹⁸</td>
<td>14</td>
<td>0.016</td>
<td>0.18</td>
<td><strong>0.99</strong></td>
<td>Leemans (2006)</td>
</tr>
<tr>
<td>1.0</td>
<td>80</td>
<td>5x10¹⁷</td>
<td>34</td>
<td>0.08</td>
<td>1.3</td>
<td><strong>5.7</strong></td>
<td>self-guided</td>
</tr>
<tr>
<td>2.0</td>
<td>310</td>
<td>10¹⁶</td>
<td>140</td>
<td>16.3</td>
<td>1.8</td>
<td><strong>99</strong></td>
<td>channel-guided</td>
</tr>
<tr>
<td>20</td>
<td>1000</td>
<td>10¹⁵</td>
<td>450</td>
<td>500</td>
<td>5.7</td>
<td>999</td>
<td>channel-guided</td>
</tr>
</tbody>
</table>

* from 3D PIC simulations by W. Lu, F. Tsung, M. Tsourfraz & W. B. Mori (UCLA)

**2nd generation**

- Relativistic electrons generated by wave-breaking or injection pulse
- a₀ ~ 1

**Wakefield**

- \( \lambda_p \approx 65 \mu m \)
- \( 2w_0 \approx 68 \mu m \)

**Table entries feature:**

1. stable plasma structure; 2. \( L_{dephasing} = L_{pump \ depletion} \) 3. balance between energy extraction & beam quality
Texas Petawatt Laser

first light in 2007

Todd Ditmire, director

Pulse Energy: >100 J  Pulse Duration: 100 fs
Nonlinear "Blowout" or "Bubble" regime summary

-- 42 GeV: recent PWFA experiments at SLAC, potential to impact high-energy colliders at energy frontier

Most laser- and particle-beam driven plasma accelerators now operate in the "blowout" or "bubble" regime