Results of the Energy Doubler Experiment at SLAC

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Why Plasma Accelerators?

- **Laser Wake Field Accelerator**
  A single short-pulse of photons
  
  \[ V_{gr} \]


- **Plasma Wake Field Accelerator**
  A high energy electron bunch


  - Wake: phase velocity = driver velocity

**Large wake for:**

- Laser amplitude \( a_0 = eE_0/m(\omega_0)c \sim 1 \) or
- Beam density \( n_b \sim n_o \)

**Accelerating Field:**

\[ 30\text{GeV}/m(10^{17}/n_o)^{1/2} \]
Laser Driven Plasma Accelerators:
• Accelerating Gradients > 100 GeV/m (measured)
• Narrow Energy Spread Bunches
• Interaction Length limited to cm’s

Beam Driven Plasma Accelerators:
Large Gradients:
• Accelerating Gradients > 50 GeV/m (measured!)
• Focusing Gradients > MT/m
• Interaction Length not limited

Unique SLAC Facilities:
• FFTB
• High Beam Energy
• Short Bunch Length
• High Peak Current
• Power Density
• e⁻ & e⁺

Scientific Question:
• Can one make & sustain high gradients in plasmas for lengths that give significant energy gain?
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  > 100 GeV/m (measured)
• Narrow Energy Spread Bunches
• Interaction Length limited to mm’s

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Scientific Question:
• Can one make & sustain high gradients in plasmas for lengths that give significant energy gain?
- Plasma wave/wake excited by a relativistic particle bunch
- Plasma $e^-$ expelled by space charge forces \(\Rightarrow\) energy loss
  (ion channel formation \(r_c \approx (n_b/n_e)^{1/2}\))
- Plasma $e^-$ rush back on axis \(\Rightarrow\) energy gain
  (>GeV/m)
- Linear scaling:
  \[ E_{\text{acc}} \approx 110 \left(\frac{MeV}{m}\right) \frac{N/2 \times 10^{10}}{\left(\sigma_z / 0.6\text{mm}\right)^2} \approx \frac{1}{\sigma_z^2} \]
  @ \(k_{pe}\sigma_z \approx \sqrt{2}\)
- Plasma Wakefield Accelerator (PWFA) = Transformer
  Booster for high energy accelerator
• Plasma wave/wake excited by a relativistic particle bunch

• Plasma e⁻ expelled by space charge forces  =>  energy loss

  (ion channel formation  \( r_c \approx (n_b/n_e)^{1/2} \sigma_r \) )

• Plasma e⁻ rush back on axis  =>  energy gain

  (\( > \text{GeV/m} \) )

• Linear scaling:  \( E_{\text{acc}} \approx 110(\text{MeV/m}) \frac{N/2 \times 10^{10}}{(\sigma_z / 0.6\text{mm})^2} \approx 1/\sigma_z^2 \)  (\( @ k_{pe} \sigma_z \approx \sqrt{2} \) )

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Beam Driven Plasma Wakefield Accelerator

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Experiments Located in the FFTB

Plasma Wakefield Acceleration at SLAC

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June 27, 2007
E-157/162 Beam-Plasma Experimental Results

**Focusing e⁻**

\[ \sigma_0 \text{ Plasma Entrance} = 50 \, \mu m \]

\[ \varepsilon_n = 12 \times 10^{-5} \, \text{m rad} \]

\[ \beta_0 = 1.16 \, \text{m} \]

\[ \Psi \propto n_e^{1/2} L \]


**X-ray Generation**

\[ \theta \propto 1/\sin \phi \]

\[ \theta \approx \phi \]


**Wakefield Acceleration e⁻**

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**Matching e⁻**

\[ L = 1.4 \, \text{m} \]

\[ \sigma_0 = 14 \, \mu m \]

\[ \varepsilon_n = 18 \times 10^{-5} \, \text{m rad} \]

\[ \beta_0 = 6.1 \, \text{cm} \]

\[ \alpha_0 = -0.6 \]

\[ \Psi \propto n_e^{1/2} L \]


**Electron Beam Refraction at the Gas–Plasma Boundary**

\[ \theta \propto 1/\sin \phi \]

\[ \theta \approx \phi \]


**Wakefield Acceleration e⁺**

Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)

Existing bends compress to <100 fsec

30 kAmps

28.5 GeV

80 fsec FWHM

1.5%
Short Bunch Generation in the SLAC Linac

Damping Ring

50 ps

RTL

1 GeV

9 ps

SLAC Linac

0.4 ps

20-50 GeV

FFTb

<100 fs

Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)

30 kAmps

28.5 GeV

Existing bends compress to <100 fsec

1.5%

<100 fsec FWHM

3.2

2.0

1.4

80 fsec FWHM

FRPMS063 Ian Blumenfeld

M. J. Hogan PAC2007
Plasma Source Starts with Metal Vapor in a Heat-Pipe Oven

Peak Field For A Gaussian Bunch:

\[ E = 6GV/m \frac{N}{2 \times 10^{10}} \frac{20\mu}{\sigma_r} \frac{100\mu}{\sigma_z} \]

Ionization Rate for Li:

\[ W_{Li} [s^{-1}] \approx \frac{3.60 \times 10^{21}}{E^{2.18} [GV/m]} \exp\left(\frac{-85.5}{E [GV/m]}\right) \]

See D. Bruhwiler et al, Physics of Plasmas 2003

Space charge fields are high enough to field (tunnel) ionize - no laser!
- No timing or alignment issues
- Plasma recombination not an issue

- However, can’t just turn it off!
- Ablation of the head
E-167: Energy Doubling with a Plasma Wakefield Accelerator in the FFTB

- Linac running all out to deliver compressed 42GeV Electron Bunches to the plasma
- Record Energy Gain
- Highest Energy Electrons Ever Produced @ SLAC
- Significant Advance in Demonstrating Potential of Plasma Accelerators

Some electrons double their energy in 84cm!

Can you just make the plasma longer?

Plasma Length = 84cm

Plasma Length = 113cm
Energy Gain Limited by Head Erosion

Near term solution will likely involve either a low density pre-ionization or integrated permanent magnet focusing. Longer term – get a better emittance.
New Phenomena: Trapped Particles

Electrons Are Trapped at He Boundaries and Accelerated Out of the Plasma

Two Main Features
• 4 times more charge
• \(>10^4\) more light!

Two energy populations (MeV & GeV)

Note: Primary beam is also radiating!
Visible Light Spectrum Indicates Time Structure of Trapped Electrons

\[ \tau \Delta \omega = 2\pi \]

Bunch Spacing \( c\tau \approx 70 \mu \), plasma wavelength, \( \lambda_p = 64 \mu \).

Trapped Particles Have Short Time Structure

OSIRIS Simulations:
- He electrons in several buckets
- Spaced at plasma wavelength
- Bunch length \( \sim \text{fs} \)
High Brightness Electron Source?
- Multi-GeV Energy
- fs pulse length
- Normalized Emittance 10 smaller than the drive beam

Designing next generation experiments to better understand and produce more of them!
Can Be Optimized by Varying Beam and Plasma Parameters

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**Study Trapped Particles with OSIRIS Simulations**

- **Helium**
- **Lithium**

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### Ionization level

<table>
<thead>
<tr>
<th>Ionization Energy (eV)</th>
<th>He</th>
<th>Li</th>
<th>Ar</th>
</tr>
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<tbody>
<tr>
<td>1st</td>
<td>24.587</td>
<td>5.392</td>
<td>15.759</td>
</tr>
<tr>
<td>2nd</td>
<td>54.416</td>
<td>75.638</td>
<td>27.629</td>
</tr>
<tr>
<td>3rd</td>
<td>122.451</td>
<td>40.74</td>
<td></td>
</tr>
</tbody>
</table>

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**Graphs:**

- **2μm FWHM!**
- **Peak at 11 GeV**
- **FWHM ~4%**
Next generation experiments will focus on two major themes:

- **Two Bunch Experiments**
  - Accelerate an electron bunch with narrow energy spread and preserved emittance – not just particles

- **High Gradient Positron Acceleration**
  - Need both for a collider
  - Two bunch positron experiments will follow
- Plasma Wakefield Accelerator (PWFA) = Transformer
  Booster for high energy accelerator
Recall Why We Want Drive + Witness Bunch

Simulations by C. Huang, UCLA

\[ N_D = 3 \times 10^{10}, \quad N_w = 10^{10}, \]

\[ \varepsilon_{nx} = \varepsilon_{ny} = 2230 \times 10^{-6} \text{ m-rad}, \quad \sigma_x = \sigma_y = 15 \mu m, \quad (\text{beam matched to the plasma}) \]

\[ \sigma_{zD} = 145 \mu m, \quad \sigma_{zW} = 10 \mu m, \quad \Delta z = 100 \mu m \]

\[ N_e = 5.66 \times 10^{16} \text{ cm}^{-3}, \quad L_p = 30 \text{ m} \]

**Doubling 500GeV in 30m!** (simulation)
Creating Two Bunches: Use a Notch Collimator

Magnetic Bunch Compression (conceptual, $\gamma >> 1$)

$\delta \equiv \Delta E/E$

$\sigma_{\delta_i}$

$\sigma_{\delta_i}$

$V = V_0 \sin(kz)$

$\Delta z = R_{56} \delta + T_{566} \delta^2$

RF Accelerating Voltage

Path-Length Energy-Dependent Beamline

Courtesy P. Emma
Exploit Position-Time Correlation on e⁻ bunch to create separate drive and witness bunch

Access to *time* coordinate along bunch
Exploit Position-Time Correlation on e⁻ bunch to create separate drive and witness bunch

$x \propto \frac{\Delta E}{E} \propto t$

1. Insert tantalum blade as notch collimator

Access to time coordinate along bunch
Exploit Position-Time Correlation on $e^-$ bunch to create separate drive and witness bunch

$x \propto \Delta E/E \propto t$

1. Insert tantalum blade as notch collimator
2. Do not compress fully to preserve two bunches separated in time
Change Incoming Chirp to Change Bunches

Bunch Separation = 146 µm; Nwitness/Ndrive = 0.12

Profile
Drive: 6.8 kA, 30 µm
Witness: 1.8 kA, 15 µm

Bunch Separation = 125 µm; Nwitness/Ndrive = 0.12

Profile
Drive: 9.5 kA, 21 µm
Witness: 1.9 kA, 14 µm

Bunch Separation = 109 µm; Nwitness/Ndrive = 0.11

Profile
Drive: 14 kA, 14 µm
Witness: 2.2 kA, 13 µm

Bunch Separation = 89 µm; Nwitness/Ndrive = 0.12

Profile
Drive: 20 kA, 9.4 µm
Witness: 2.3 kA, 12 µm
Test of Notch Collimator - December 2005

Ta Blade
100-300µm Wide
1.6cm Long (4 X₀)

Energy Spectrum Before Plasma:
- High Energy
- Low Energy

Energy Spectrum After Plasma:
- Energy Gain
- Energy Loss

Shot # (Time)

- Acceleration correlates with collimator location (Energy)
- No signature of temporally narrow witness bunch - yet!
- Collimated spectra more complicated than anticipated
- Will be a major component of long term program @ SABER
- The only technique that will work for positrons too!

June 27, 2007
• FFTB provided better access for test than the linac chicane (LBCC)
• 1D simulations not adequate
• 3D models using ELEGANT & SHOWER (EGS4) reproduce measured spectra from tests in 2005
• Simulations show can create two bunches in the chicane!
• Only technique that will work for both e- & e+
• Collimator optimization in progress
PWFA Mechanism Different For A Positron Beam

Blow-out electron Flow-in positron
Positron Focusing varies with radius

\[ n_e = 0 \quad n_e \approx 10^{14} \text{ cm}^{-3} \]

- Ideal Plasma Lens in Blow-Out Regime
- Plasma Lens with Aberrations

E-162 Data
PWFA Mechanism Different For A Positron Beam

Positron Focusing varies with radius and position along the bunch

- Ideal Plasma Lens in Blow-Out Regime
- Plasma Lens with Aberrations

E-162 Data

(M.J. Hogan et al., PRL 2003)
Although the wakes are more complicated, have demonstrated positron acceleration with long bunches and low density (E-162).
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A Compelling Question: 
*Can the large amplitude wakes measured for electrons be created and sustained for a positron drive beam?*

Evolution of a positron beam/wakefield and final energy gain in a **self-ionized** plasma

Will require iteration with plasma source development to minimize emittance growth (hollow channel plasma?)

\[ N_b = 8.79 \times 10^9, \sigma_r = 11\mu m, \sigma_z = 19.55\mu m, n_p = 1.8 \times 10^{17} \text{ cm}^{-3} \]
Future Experiments Require a New Facility: SABER

Beam Transport Hall (previously FFTB*)

Linac

* Final Focus Test Beam

Facing West

B. Hall
Conclusions:

- **Exciting Time for Plasma Wakefield Experiments**
- **Plasma Wakefield Accelerators** have demonstrated gradients >50 GeV/m and energy gain >40 GeV
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- Much more work to be done:
  - Instabilities, Ion motion etc under extreme beams
  - Accelerate a second bunch (not just particles) with narrow energy spread and good emittance
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- Continued progress requires an accelerator research facility to replace the FFTB while providing additional capabilities → SABER