Laser-Plasma Acceleration WG

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### AAC 2004 Experimental Results Laser-Plasma Accelerator WG

<table>
<thead>
<tr>
<th>Scheme</th>
<th>LOA</th>
<th>LBNL</th>
<th>RAL-alphaX</th>
<th>AIST</th>
<th>University of Tokio</th>
<th>Neptune, UCLA</th>
<th>NRL</th>
<th>JAERI</th>
<th>Osaka University</th>
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<tbody>
<tr>
<td>Laser params</td>
<td>SM(LWFA)</td>
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<td>SM(LWFA)</td>
<td>PBWA</td>
<td>SM(LWFA)</td>
<td>SM(LWFA)</td>
<td>LWFA</td>
<td>SM-LWFA</td>
</tr>
<tr>
<td></td>
<td>30TW 0.8 mkm, 3x10^18 W/cm^2, W0=18 mkm, 30fs</td>
<td>8TW 0.8 mkm,1x10^19 W/cm2W0=7 mkm, 55fs</td>
<td>16TW 0.8 mkm,1x10^18 W/cm2W0=25 mkm,40fs</td>
<td>2TW 0.8 mkm,5x10^18 W/cm2W0=5 mkm,50fs</td>
<td>6TW 0.8 mkm,1x10^19 W/cm2W0=6 mkm,50fs</td>
<td>1TW 10.3+10.6 mkm</td>
<td>10TW 1.06 mkm,3x10^18 W/cm2W0=12 mkm,500s</td>
<td>20TW 0.8 mkm,2x10^19 W/cm2W0=5 mkm,23fs</td>
<td>30TW 1.06 mkm</td>
<td>2TW 0.8 mkm</td>
</tr>
<tr>
<td>Plasm. Density</td>
<td>6x10^18 cm^{-3}</td>
<td>2x10^19 cm^{-3}</td>
<td>2x10^19 cm^{-3}</td>
<td>.5x10^20 cm^{-3}</td>
<td>1.8x10^19 cm^{-3}</td>
<td>1x10^16 cm^{-3}</td>
<td>1x10^19 cm^{-3}</td>
<td>1.4x10^20 cm^{-3}</td>
<td>6x10^16 cm^{-3}</td>
<td>1x10^18 cm^{-3}</td>
</tr>
<tr>
<td>Energy Gain</td>
<td>&gt;170±15 MeV, 500 pC,</td>
<td>86 ±2 -150 MeV, 300 pC</td>
<td>78 ±2 MeV 20 pC</td>
<td>7 ±1 MeV 2 pC</td>
<td>40 MeV</td>
<td>38 MeV</td>
<td>20 MeV</td>
<td>40 MeV</td>
<td>100 MeV</td>
<td>2 MeV</td>
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<tr>
<td></td>
<td>Channel</td>
<td>Integrated over 90 shots spectrum</td>
<td>Ponderomotive channel</td>
<td>2 TW beam for LIPA injector</td>
<td>Glass capillary</td>
<td></td>
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</table>
Experimental Set-Up

Energy: 360 - 540mJ
(50% in focal spot)

Pulse Duration: 40fs (FWHM)

Focal Spot Diameter: 25 µm

Vacuum Intensity: $9 \times 10^{17} - 2 \times 10^{18} \text{ Wcm}^{-2}$

$a_0: 0.7 - 1.0$
Breakthrough: 85 MeV e-beam with %-level energy spread from laser accelerator (LBNL)

Beam profile

Unguided

Guided

2-5 mrad divergence

Spectrum

Charge>100 pC

Charge Density (pC/MeV)

Energy (MeV)

Electron Energy (MeV)

Detection Thresh.
Recent results on e-beam:
Energy distribution improvements
V. Malka (LOA)
Recent results on e-beam:
Energy distribution improvements

N.B. : color tables are different
Results (C.Murphy, IC/RAL)

• Electron Spectrum:
  – A single mono-energetic feature over the top of an exponential observed at energies in excess of 50MeV
  – Underestimate of energy due to neglect of fringe fields
Electron Energy Spectrum including quasi-monoenergetic beam

K. Koyama (AIST, Japan)

Monoenergetic beam was emitted in an narrow divergence angle.
Production of a Monoenergetic Beam

1. Excitation of wake (e.g., self-modulation of laser)
2. Onset of self-trapping (e.g., wavebreaking)
3. Terminatinon of trapping (e.g., beam loading)
4. Acceleration

If > dephasing length: large energy spread
If < dephasing length: monoenergetic

Optimal choice of the plasma density: the smallest possible density
For conditions 1 -4 to be fulfilled.
2D PIC Code (W. Mori, UCLA)
Beam loading of first bunch contributes to the generation of a second bunch

(b) y

-28μm

(ε) z

x (k)
Electron Energy of ~1GeV range observed in our 3D channel simulation

- (3D) Maximum Energy = 840 MeV (over a distance .84 cm)
- 2 acceleration stages, the first bunch reaches ~500MeV then dephases. The second bunch achieves much higher energies (~840MeV)
- 2D Simulations only has 1 group of fast electrons
- 2D simulations underestimate maximum energy gain
- 2D simulations overestimate accelerated charge
Ultra-Intense Laser is illuminated into a glass capillary, which accelerates plasma electrons to 100 MeV

Y. Kitagawa-Osaka
Enhanced acceleration of externally injected electrons in a PBWA

Injection of an electron beam into a 3-cm long ponderomotively formed plasma channel

$\omega_1 - \omega_2 = \omega_{\text{plasma}}$

$10.3 \mu m - 10.6 \mu m = 340 \mu m$ or $\approx 1 \text{ THz}$

10-psy e-bunch

10^6

10^4

100

1

Electrons/MeV

Energy (MeV)

1.3 GeV/m x 0.03 m

Noise Level

F/18 1 TW CO$_2$ Laser Beam

$I \approx 5 \times 10^{14} \text{ W/cm}^2$

F/75 12 MeV e-beam

PBWA Phase II

$\Delta E/E \approx 10\%$

S. Tochitsky et al, PRL, March, 2004
Staged Optical Injection and Laser Wakefield Acceleration

- Synchronized, collinear, two jet, two-beam (2TW/10TW) laser configuration
First demonstration of staged optical injection/acceleration LWFA experiment

- Injection electrons <0.5 MeV (high-density LIPA)
- Accelerated electrons >10 MeV
- Injection/Acceleration occurs only for time delays of <4 psec
- Delay of electrons from peak forward Raman signal shows:
  - Injection electrons not from background plasma
  - Slippage of injection electrons from laser pulse
Scaling Laws for LWFA

Depletion vs. Dephasing

- **Dephasing length**
  \[ L_{dph} = \frac{1}{2}(\lambda_p^3/\lambda^2) \times \begin{cases} 1, & a_0^2 \ll 1 \\ (2/\pi) a_0 / N, & a_0^2 \gg 1 \end{cases} \]

- **Pump depletion length**
  \[ L_{pdl} = \frac{1}{2}(\lambda_p^3/\lambda^2) \times \begin{cases} 2/a_0^2, & a_0^2 \ll 1 \\ (2/\pi) a_0, & a_0^2 \gg 1 \end{cases} \]

- **Summary**
  \[ a_0^2 \ll 1 \Rightarrow L_{dph} \ll L_{pdl} \]
  \[ a_0^2 \gg 1 \Rightarrow L_{dph} \sim L_{pdl} \]

Energy Gain:

\[ \Delta W = e F_s L_{acc} \]

- **Diffraction**
  \[ L_{acc} \approx \pi Z_{le} = \pi^2 \ell_0^2 / \lambda \]
  \[ \Delta W[MeV] \sim 740(\lambda / \lambda_p)(1 + \ell_0^2 / 2)^{-1/2} P[TW] \]

- **Dephasing**
  \[ L_{acc} \approx L_{dph} \]
  \[ \Delta W \approx (\pi/2) me^2(\lambda_p^3/\lambda^2) a_0^2 \times \begin{cases} 1, & a_0^2 \ll 1 \\ (2/\pi) / N, & a_0^2 \gg 1 \end{cases} \]

\[ \Delta W[MeV] \approx 630 \frac{I[W/cm^2]}{n[cm^{-3}]} \times \begin{cases} 1, & a_0^2 \ll 1 \\ (2/\pi) / N, & a_0^2 \gg 1 \end{cases} \]

- **Depletion**
  \[ L_{acc} \approx L_{pdl} \]
  \[ \Delta W \approx \pi mc^2(\lambda_p^3/\lambda^2) \times \begin{cases} 1, & a_0^2 \ll 1 \\ (1/\pi) a_0^2, & a_0^2 \gg 1 \end{cases} \]

\[ \Delta W[MeV] \approx \begin{cases} 3.4 \times 10^{21} / (\lambda^2 [\mu m] n[cm^{-3}]), & a_0^2 \ll 1 \\ 400 I[W/cm^2] / (n[cm^{-3}]), & a_0^2 \gg 1 \end{cases} \]
One of many 1 GeV scenarios

**Energy Gain: Example**

- **Optimal Regime:** Nonlinear $a_0^2 \gg 1$
  
  Larger energy gain, larger fields, shorter distance
  Dephasing $\sim$ depletion, more energy efficient

- **Laser:**
  
  $P = 100 \text{ TW}$, $a_0 = 3$, $\lambda = 0.8 \mu\text{m}$, $r_0 = 18 \mu\text{m}$
  
  $I = 1.9 \times 10^{19} \text{ W/cm}^2$, 55 fs, 5.5 J

- **Plasma:** $L_L = \lambda_p/2$
  
  $\lambda_p = 33 \mu\text{m}$ ($n_0 = 10^{18} \text{ cm}^{-3}$)

- **Wakefield**
  
  $F_z = 190 \text{ GeV/m}$

- **Diffraction:** Unchanneled
  
  $L_{\text{acc}} = 0.1 \text{ cm}$
  
  $\Delta W = 750 \text{ MeV}$

- **Depletion/ Dephasing:** Channeled
  
  $L_{\text{acc}} = 3.8 \text{ cm}$
  
  $\Delta W = 7.2 \text{ GeV}$
Next step: 1 GeV compact module
100 TW laser + plasma channel

L'OASIS Laser technology

Plasma channel technology

Laser

Electron injector

Plasma channel

$10^{16}-10^{18} \text{ cm}^{-3}$

100 TW, 40 fs
10 Hz

< 3 mm

< 10 cm

1-3 GeV e-beam

High energy e-beams

Femtosecond x-rays

THz radiation

Radio-isotopes