Multi-GeV electron acceleration with self-guided laser wakefield accelerators


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25 September 2017
Plasma accelerators

100s GV/m accelerating fields in bubble moving with $\gamma_p^2 \simeq n_c/n_e$

Femtosecond bunch duration yielding kA current\(^1\)

Bright, coherent betatron x-rays suitable for imaging\(^2\)
(Also see J. Wood talk Fri 12:00 and J. Cole talk, Tue WG4 16:30)

\[^1\text{Lundh et al., Nat Phys 7, 2011}\]
\[^2\text{Cole et al., Sci Rep 5, 2015}\]

$$E_0 = 96 \sqrt{\frac{n_e}{10^{18}\text{cm}^{-3}}} \text{ GV/m}$$
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How do laser wakefield accelerators work?

\[ \vec{F}_p \propto -\nabla a_0^2 \]

\[ \vec{a}_0 = \frac{q_e \vec{E}}{m_e c \omega_L} \]

\[ \vec{F}_p \propto -\frac{q_{e,i}^2}{m_{e,i}} \nabla (1/\lambda^2) \]

\[ \nabla^2 \phi = -\frac{q_e (n_i - n_e)}{\epsilon_0} \]

\[ \vec{E}_z \propto \frac{\delta n}{n_e} \]
Energy scaling in laser wakefield accelerators

Linear theory\(^3\) gives

$$\Delta W \propto n_e^{-1}$$

But dephasing length

$$L_{dph} \propto n_e^{-3/2}$$

With lowering plasma density

$$L_{dph} \gg z_R$$

Need guiding!

\(^3\)Tajima, Dawson, PRL 43, 1979
Self-guiding

Can derive an envelope equation\(^4\) for the laser spot size \(R\):

\[
\frac{d^2 R}{dz^2} + \frac{\langle K^2 r^2 \rangle}{R} - \frac{\epsilon^2}{R^3} = 0
\]

**Self focussing**

Increasing \(R\) reduces diffraction, allowing self-guiding at lower \(n_e \rightarrow\) increasing \(\Delta W\)

\(^4\)Sprange et al., IEEE T Plasma Sci, 15 1987
The Gemini laser

- 15 J at 800 nm in 2 independently compressed and timed beams
- Pulsed length < 40 fs
- 20 s repetition rate
- $f/20$ for LWFA setups ($a_0 \sim 4$)
- $f/2$ for ion acceleration setups ($a_0 \sim 20$)
- $f/2 - f/20$ combination for pump-probe experiments

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$^5$Sarri et al, PRL 113, 2014
Experimental setup for F/40

- Deformable mirror
- Spherical mirror
- High DT mirror
- 13 J, 40 fs
- X-ray CCD
- 42 cm, 0.95 T magnet
- Ronchi gratings
- CCD
- Exit mode spectrum & imaging

\[ a_0 = 1.7 \sqrt{\frac{E_L}{10}} \]
Electron acceleration with F/20

Kneip et al., PRL 103, 035002 (2009)

M. Bloom, PhD thesis, in preparation


Multi-GeV electron acceleration in Gemini

Krisjan Poder et al., JAI
Energy on target
5.0 ± 0.7 J
Plasma density
2.3 \cdot 10^{18} \text{ cm}^{-3}
Length scans probe injection and acceleration

Energy on target

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Length scans probe injection and acceleration

Nearly 2 GeV electron energies with $P_L = 125$ TW!

Linear increase with charge up to 10 mm with $\nu_i = (13.5 \pm 0.5) \text{ pC mm}^{-1}$

Secondary injection at 10 mm leads to reduced maximum energy and reduced charge at highest energies
Measuring acceleration gradient from length scan

In a nonlinear bubble\(^6\),

\[
E_a(x) = E_p - \frac{E_p}{L_d}x; \ 0 \leq x \leq 2L_d
\]

Thus electron energy is

\[
E(x) = \int_0^{x_c} E_a(x) \, dx + E_0
\]

And at length \(x_c\)

\[
E_{x_c} = -x_c^2 \frac{E_p}{2L_d} + x_c E_p + E_0
\]

\(^6\text{Cardenas et al, ArXiv:1505.05732v2}\)
Experimental scan of peak E-field

In 3D nonlinear theory\(^7\)

\[ E_{\text{peak}} = \sqrt{a_0} E_0 \]

and

\[ L_{\text{dph}} = \frac{4}{3} \frac{c}{\omega_p} \frac{\omega_0^2}{\omega_p^2} \sqrt{a_0} \]

Matched spot size

\[ k_p w_m = 2 \sqrt{a_0} \text{ yields} \]

\[ a_m = \left( \frac{a_0 w_0 \omega_p}{2c} \right)^{2/3} \]

Data suggests \( \sqrt{a_0} \simeq 3 \)

\(^7\)Lu et al., PRL 96, 2006
Multi-GeV electron energies from 250TW laser

![Graph showing electron energy distribution]

<table>
<thead>
<tr>
<th>Shot</th>
<th>( \xi_L ) [J]</th>
<th>Beam charge [pC]</th>
<th>Beam energy [mJ]</th>
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<tr>
<td></td>
<td>&gt; 2 GeV</td>
<td>&gt; 1 GeV</td>
<td>&gt; 0.25 GeV</td>
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<tr>
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<tr>
<td>5</td>
<td>11.31</td>
<td>15.2</td>
<td>127.8</td>
</tr>
</tbody>
</table>
3D PIC Simulations examine physics of increased energy gain

- Using EPOCH 3D PIC code\(^8\)
- Exact phase front of laser unknown $\implies$ simulations to study underlying physics and not to reproduce exact results
- \(n_e = 3 \times 10^{18} \text{ cm}^{-3}\) plasma, \(\tau_{\text{laser}} = 45\text{ fs}\)
- Gaussian laser with \(w_y = 37\mu\text{m}\) and \(w_z = 48\mu\text{m}\) and \(a_0 = 2\) to mimic the \(f/40\) results
- Gaussian laser with \(w_y = 18.5\mu\text{m}\) and \(w_z = 24\mu\text{m}\) and \(a_0 = 4\) to compare to \(f/20\) focusing

\(^8\)Arber \textit{et al.}, PPCF 57, 2015
3D PIC Simulations: enhanced energy gain

Longer focal length leads to higher energy gain for the the same laser power!
3D PIC Simulations: origins of enhanced energy gain

Large variations in laser intensity after injection lead to rapid dephasing from high field. Higher energy gain seen due to more stable bubble structure.
Enhanced energies and empirical scalings

Compilation of data\textsuperscript{9} from \textasciitilde 70 results published between 2004-2015

\textsuperscript{9}S. Mangles, CERN Yellow Reports, 1, 289.
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\textsuperscript{9}S. Mangles, CERN Yellow Reports, 1, 289.
Conclusions

▶ Experimentally measured peak accelerating fields of 100s GV/m
▶ Extended electron energy beyond 2 GeV with 250 TW laser in self-guided, self-injected regime by employing f/40 focussing
▶ Simulations imply optimised bubble dynamics avoiding dephasing during bubble evolution