Acceleration at the hundred GV/m scale using laser wakefields

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E. Michel, T. Cowan, UNR

S. M. Hooker, Oxford University, UK

D. Bruhwiler, Tech -X
J. Cary, Tech - X & U. Colorado
SLAC, 2007
Laser Plasma Interaction for Laser Acceleration

Pondermotive Force

Laser radiation pressure displaces electrons away from laser beam

Plasma Oscillation

Displacing plasma electrons induces an electric field

\[ E \propto n\delta \quad \rightarrow \quad F \propto n^2\delta \quad \rightarrow \quad \omega_p \propto \sqrt{n} \]

An oscillation of density (and field) results
Laser driven wakefield accelerators offer high gradients, short pulses.

Wakefield Acceleration

Laser • e-

Gas Jet

few mm

Breaking waves accelerate particles

Fields of 30 - 1000 GV/m
Bunches With % Spread at GeV Now Obtained: Scaling Towards Applications...

- LWFA basics
- Present experiments:
  - self modulation & trapping
  - guiding
  - 100 MeV and 1 GeV class experiments
- Physics of narrow energy spread beams
- Staging and scaling to higher energies and stability
- Radiation sources & beam diagnostics
- Future prospects
Limit on gradient for a cold plasma:

1D trapping in a wave with \( v \sim c \) approximately for:

\[
(E_{WB} e/m)(1/\omega_p) = c
\]

\( E_{WB} \sim 100 \text{ GV/m for } n \sim 10^{18} \), scaling up as \( \sqrt{n} \)

Intensity requirement: wake potential is order of ponderomotive potential:

\[
\Phi_p = mc^2a^2/4e \quad \text{with} \quad a = eE/\omega mc
\]

\[
E_{\text{wake}} \sim \Phi_p/(0.25\lambda_p) \sim mc^2a^2/e\lambda_p \sim 0.5 \ a^2 \ E_{WB}
\]

\[\text{---\rightarrow \ a of 1-2 to approach } E_{WB} \sim 40 \text{ TW for } a=2 \text{ in an } 16\mu\text{m spot}\]

Pulselength \( \sim (1/2)\lambda_p \rightarrow 50 \text{ fs for } n \sim 10^{18} \)

3d, nonlinear, & relativistic effects are important: numerics (fluid, PIC, etc.)
Wakefield Accelerator Physics:
Linear Model Pump, Wake, Particle Scalings

• Laser velocity

$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \quad v_p = \frac{\omega}{k} = \frac{c}{\eta} \quad v_g = \frac{d\omega}{dk} = c \eta$$

Acceleration limitations (1D linear):

Dephasing: \( L_d = \frac{\lambda_p^3}{\lambda_0^2} \)

Depletion: \( L_{\text{pump}} = 4 \frac{L_d}{a^2} \)

\( \Delta W = E_0 L_d \sim a^2 \frac{\lambda_p^2}{\lambda_0^2} \) MeV

Modeling required for detail, but scaling ~ correct.

Densities near \( 10^{18} \) and \( a=1-2 \) give GeV energies in few cm. \( W \sim 1/n, \ L_d \sim 1/n^{3/2} \)
Recent Experiments Extend Acceleration Region: $Z_R$ and Guiding

• High intensity required: $L_{acc} \sim Z_R$ without guiding

$$Z_R = \frac{\pi w_0^2}{\lambda}$$
$$a = 2 \rightarrow 200 \mu m \text{ @ } 10 \text{ TW}$$
$$2 \text{ cm @ 1 PW}$$

• Guiding from refractive index peak on axis.

for $n \ll n_c$:

$$\eta \approx 1 - \frac{\omega_p^2}{2\gamma_x \omega^2} = 1 - \frac{4\pi e^2 n_e(r)/m}{2(1 + a^2)^{1/2} \omega^2} \approx 1 - \frac{\omega_p^2}{2\omega^2} \left(1 - \frac{a^2}{2} + \frac{\delta n}{n} + \frac{\Delta n}{n}\right)$$

for small $a$ & $\omega_p$

• High density $\Rightarrow$ low $\eta = $ high $v_p$, low $v_g$

• Extend acceleration distance:
  1) extend $Z_R$ - expensive, PW for cm scale
  2) self guide: $a \sim 1$ - not effective for short pulses
      
      a $\gg 1$ bubble regime - seen in simulation
  4) Channel guide with density gradient - compensate self guide
Laser driven accelerator facility at LOASIS lab: development of GeV accelerators in centimeters

10-100 TW Ti:sapphire
Shileded target room

5+ Beams on Target

Chirped Pulse System
oscillator
compress
stretch
amplyfy

Control Room

Typical:
10 Hz Ti:S lasers
few J energies
50 fs pulses match $\omega_p$

Unique:
Multiple beams, shielded
State of the Art 2003- Early 2004: High Gradients, but Low E and large $\Delta E/E$

Tightly focused laser ionized gas jet & drove wake

Laser self modulation to plasma period drives wake to trapping

Acceleration to 50 MeV in ~1 mm

Drive beam
10 TW, 500mJ 50fs, $10^{19}$W/cm$^2$

Hydrogen gas jet

Enlarged wake

1.4mm propagation

0.5mm propagation

nC charge few % > 10 MeV

$\frac{dN}{dE}$ [a. u.] vs. $E$ [MeV]

Detection Threshold
Hydrodynamic Channels Guided Unaberrated Modes at Relativistic Intensity

Main beam <500mJ >50fs
Ignitor Beam 20mJ
Heater beam 150mJ 250ps

2ω probe
H, He gas jet
Side Interferometer
CCD & Spectrometer

Plasma ionized by ignitor heated by heater
Expansion shock yields guiding profile

Channel profile
Channel only
Channel density
No channel leakage
Guided drive beam
Unchanneled drive beam
Guiding over > 10 ZR ~ 2mm relativistic intensity

High quality guiding up to 4TW
C.G.R. Geddes et al, PRL, 2005
Intense Beams with Low Energy Spread and High Energy from Channeled Accelerator

Laser = 9TW, 50 fs, $Z_R=200\mu$m

Plasma = $1.8e19\text{cm}^{-3}$, 1.7mm

**Magnetic Spectrometer**

High quality beams: 300pC @ 86 MeV

Peak energies 150-170 MeV

High quality, intense beams*

- 2e9 electrons
- Energy Spread < 4MeV
- Divergence 3mrad
- Normalized Geometric Emittance $2\pi \text{mm-mrad}$

Energy enhancement is due to channeling not pre ionization

Pre ionized plasma: ignitor @t₀-80ps

Magnetic Spectrum:
Single Beam same as Pre Ionized

Well Guided Optical Beams Correlated to Highest Energy Electrons

Electrons > 100MeV

Guided Optical Beam Intensity
I/Imax

0419&0571 output

0.1 0.2 0.3 0.4 0.5 0.6 0.7 1.0

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Guided Optical Beam Intensity
I/Imax

0419&0571 output
Several groups observed
Mononoenergetic beams from unchanneled accelerators

RAL:
12 TW, 40fs, Z_R~ 1mm
Plasma n ~ 2e19, 2mm
(Mangles, Nature 2004)

LOA:
30 TW, 33fs, Z_R~ 1mm
Plasma n ~ 3.5e18, 3mm
(Faure et al, Nature 2004)

Michigan:
40 TW, 30fs, Z_R~ 1mm
Plasma n ~ 2.5e19, 2mm
(Maksimchuk et al, submitted)
Simulations show laser evolution and electron acceleration: VORPAL particle in cell code

Start: Laser un-modulated and ~ 1.5 times $\lambda_p$, small wake

900\(\mu\)m: Laser modulated, large wake excited

Simulations grid space, deposit current from particles, finite difference Maxwell
Wake Evolution and Dephasing Yield Low Energy Spread Beams

1150µm: particles trapped, wake damped preventing further trapping

1750µm: particles dephase, minimizing energy spread

Matching Plasma Length to Dephasing & Depletion Optimizes Performance

Simulation: optimal acceleration at length = dephasing length

Experiment: plasma length variation confirms optimal performance at dephasing

Multi Shot Experimental Energy Spectra

- 600µm Plasma Slit Jet
- 2000µm Plasma Cylindrical Jet

\[ n_e = 4 \times 10^{19}/cm^3 \]

GeV laser accelerator: channeling over cm-scale

- Increasing beam energy requires increased dephasing length and power:
  \[ \Delta W_d [\text{GeV}] \sim a^2 \lambda_p^2 \sim I [\text{W/cm}^2] / n [\text{cm}^{-3}] \]

- Scalings indicate cm-scale guide at \( \sim 10^{18} \text{ cm}^{-3} \) and 40-100 TW laser for GeV

- Laser heated channel formation inefficient at low density

- Use capillary channels for cm-scale guides driven by upgraded laser

**TREX Laser**

- 1-2 GeV
- 40-100 TW
- 40 fs
- 3-5 cm
3 cm capillary channels at reduced density: increased laser $v_{\text{group}}$ produces GeV ebeams

Guiding over $> 10 \ ZR \sim 3 \ cm$ relativistic intensity


Leemans et al, Nature physics, 2006
LOASIS GeV Spectrometer

- Maximum resolving energy: \(~1.1\) GeV
- Large momentum acceptance (>factor 35)
- High resolution (bottom: <1\%, forward: 2\~4\%

Chamber

Capillary

Interaction point

Beamline

Yoke

Pole

Chamber

Phosphor

Bottom view: 40-160 MeV high resolution

Forward view: 0.16 - 1GeV moderate resolution

Mirror and cameras

Shielded mirror and cameras
1 GeV bunches with narrow energy spread achieved with 40 TW laser pulses

Leemans et al, Nature Physics 2006
Staging and controlled injection for next generation accelerators

- GeV experiments close to predicted energy

\[ \Delta W_d[GeV] \sim a^2 \lambda_p^2 \sim I[W/cm^2]/n[cm^{-3}] \]

- Energy spread limited measurement

- Bunches may be percent energy spread

- Staging \( \sim \) preserves \( \Delta E \)
  - stage a low energy injector, injector and 1-10 GV accelerator modules
  - 10 GeV using \( \sim \) PW of laser energy and m-scale plasma

![Diagram showing stage 1: optical injector and stage 2: channel with energy output.]

Laser \( \rightarrow \) stage 1: optical injector \\
\( \sim 1\text{mm} \)

\( \rightarrow \) stage 2: channel \\
\( \sim 1-10 \text{GeV} \)
\( \approx 100\text{pc, 8fs} \)

\( \Delta W_d[GeV] \sim a^2 \lambda_p^2 \sim I[W/cm^2]/n[cm^{-3}] \)

Experiments close to predicted energy

Energy spread limited measurement

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Staging \( \sim \) preserves \( \Delta E \)

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Staging and controlled injection for next generation accelerators

- Couple downramp to capillary channel

- Staging
  - GeV experiments close to expected energy
  - stage low energy injector and 1-10 GV accelerator modules
  - 10 GeV using ~ PW of laser energy and meter-scale plasma
  - Gain in emittance, stability, efficiency by separating injection, acceleration

Laser → stage 1: optical injector → stage 2: channel → 1-10 GeV e-beam

- SMLWFA, Downramp Colliding pulse
- Plasma channel
- ~100pc, 8fs
- few cm, n~few $10^{17}$ cm$^{-3}$
THz radiation from the Laser-Wakefield Accelerator:
Intense THz source, and ultra-fast bunch diagnostic

Electro-optic sampling for THz detection

![Electro-optic setup diagram]

THz profile

Dashed fit: Single 50 fs Gaussian e-beam
Solid fit: double pulse - possibly due to geometry

Scanning and single shot measurements done - stable source
Sample using downstream foils -> understand beam expansion

J. van Tilborg et al., PRL 2006
Single-Shot THz technique
Information on every bunch

- < 50 fs bunches
- peak E-field of $E_{CTR} \approx 400$ kV/cm

J. van Tilborg et al., OL 2007
Betatron X-rays
Diagnostic of Electron Motion, Broadband source

• Betatron (synchrotron) emission:

• Transverse dynamics diagnostic

Material courtesy of Pierre Michel and collaboration with UNR and LLNL, see also: E. Esarey et al., PRE 2002, A. Rousse et al., PRL 2004
Channeled Laser Accelerators Produce Intense High Quality Electron Beams

- Demonstrated high quality beams from compact accelerators
  - Channel guided relativistic intensities
  - Low energy spread low divergence electron beams
  - Tuning by dephasing

- Physics is self trapping limited by beam loading, then dephasing concentration of particles in energy space (simulations)

- GeV energies demonstrated, consistent with predictions

- Simulations indicate stable sources possible at higher densities/powers but with tradeoff in energy spread

- Low energy low absolute energy spread beams demonstrated
  - Staged experiments for improved stability, quality

- Radiation sources used as diagnostics
Scaling to Future Laser Driven Accelerators

Understanding of:
- Laser evolution, shaping, depletion, spectral shifting
- Bubble guiding experiments
- Beam dynamics, applications, optimization (THZ, X-rays, FEL’s)

Lasers at > 300 TW, > 300 W

Staging of modules: ΔE, phase
Stable injection

10 GeV, low energy spread & emittance
Guiding over meter scale

One-to-one, 3-D modeling
Improved algorithms

Challenges