PROSPECTS OF LASER-PLASMA ACCELERATION

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Modern accelerators are large-scale machines

European XFEL at DESY, Hamburg
Electron energy: 17.5 GeV, acceleration gradient: 23 MV/m,
length of beam line: ~3 km, length of accelerator: ~1 km
Plasma accelerators allow for extreme electric fields

LOASIS TREX at LBNL, Berkeley
Laser-driven plasma accelerator for electrons with 1.0 GeV
Length: 3.3 cm, average acceleration gradient: 30 GV/m
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$10^3$ times larger than in conventional accelerators
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Laser Electron Accelerator

T. Tajima and J. M. Dawson

Department of Physics, University of California, Los Angeles, California 90024

(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density $10^{18}$ W/cm$^2$ shine on plasmas of densities $10^{14}$ cm$^{-3}$ can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.
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40 TW laser pulse ($3\times10^{18}$ W/cm$^2$) inside plasma with $n_e = 4.3\times10^{18}$ cm$^{-3}$

→ 30 pC of electrons at 1 GeV

accelerated over a distance < 3 cm
(with > 33 GV/m fields)

Lasers provide sub-femtosecond synchronization

Potentially useful in various scientific fields:
- 4D imaging of electronic motion in atoms, molecules, solids, and plasmas
- Nonlinear QED
Laser-plasma accelerator basics

Wake excitation

Electron injection
High-intensity lasers can drive large plasma wakes

Laser pulse properties

- $a = 2$
- $\lambda_c = 800 \text{ nm}$
- $\Delta \tau = 25 \text{ fs FWHM}$
- $w_0 = 23 \mu\text{m FWHM}$

Plasma background density

- $n_p \leq 5 \times 10^{18} \text{ cm}^{-3}$

Laser pulse propagates into a plasma-density ramp, electrons get trapped
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Controlled injection: control over accelerated charge, bunch energy spread, and emittance, less fluctuations
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- control over accelerated charge,
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**Methods for controlled injection:**
- **Density down-ramp injection**

- **Laser-triggered injection**

- **Ionization injection**

- **External beam injection**

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Generation of soft-X-rays from an LPA driven undulator

Fuchs et al., Nature Physics 5, 826 (2009)

Laser pulse parameters
- 850 mJ, 37 fs FWHM
- 23 µm focus FWHM

Undulator parameters
- 1.2 mm gap, K = 0.55
- $\lambda_u = 5$ mm, 60 periods

Undulator
Gas cell
Magnetic quadrupole lenses
Aluminium foil
Phosphor screen 1 (movable)
Phosphor screen 2
Magnetic spectrometer
X-ray CCD
Transmission grating
Gold mirror

Undulator parameters
Generation of soft-X-rays from an LPA driven undulator

- 1 pC of charge in effective electron spectrum
- \(~10^5\) photons per shot
- Estimated peak brilliance \(1.3\times10^{17}\) (s mrad\(^2\) mm\(^2\) 0.1% BW\(^{-1}\)

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Resonance condition:

\[
\lambda = \frac{\lambda_u}{2n\gamma^2} \left( 1 + \frac{K^2}{2} + \gamma^2\Theta^2 \right)
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Phase-space characterization of LPA beams needed

Many properties of electrons beams from laser-wakefield accelerators have only been insufficiently characterized:

- **Pulse duration**
  upper limit ~50 fs RMS with electrooptic sampling [van Tilborg, Leemans et al., Phys. Rev. Lett. 96, 014801 (2006)]

- **Slice energy spread**
  inferred from PIC simulations

- **Longitudinal and transverse beam density modulations** (e.g. at $\lambda / 2$)
  inferred from PIC simulations

- **Transverse beam emittance and source size**
  inferred from PIC simulations, old pepper pot measurements [Fritzler et al., Phys. Rev. Lett. 92, 165006 (2004)]
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Know how at established accelerator facilities would help to analyze LPA beams more thoroughly:

(C)OTR, IR/THz spectrometry, transverse deflection cavities, characterization of XUV/x-ray emission from undulators, characterization of betatron emission

Also important: beam position measurements (BPMs), transport and imaging (magnetic beam transport systems)
Energy gain scalings and single-stage limitations

1. Laser diffraction: mitigated by transverse plasma density tailoring (plasma channel)

Plasma waveguide

Laser

Capillary discharge plasma waveguides

- Plasma fully ionized for $t > 50$ ns
- After $t \sim 80$ ns plasma is in quasi-equilibrium: Ohmic heating is balanced by conduction of heat to wall
- Ablation rate small: cap. lasts for $>10^6$ shots
- $n_p \approx 10^{17} - 10^{19}$ cm$^{-3}$
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In this example:
- \( Z_R = 2 \text{ mm}, \) guiding over 16 mm, guiding efficiency > 90%

Energy gain scalings and single-stage limitations

2. Electron-laser dephasing: mitigated by longitudinal plasma density tailoring (plasma taper)

Constant density plasma

Laser pulse, plasma wave travel with $v_{\text{wave}} = v_g < c$

Electrons travel with $v_e \approx c > v_{\text{wave}}$

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- **Rising density plasma**
  - Plasma wave phase velocity $v_{\text{wave}}$ may be set to $v_e$
  - $\Rightarrow$ electrons can be phase locked
  - [Rittershofer et al., Phys. Plasmas 17, 063104 (2010)]
Energy gain scalings and single-stage limitations

3. Laser depletion: energy loss into plasma wave excitation

$$U_L \propto n_p^{-\frac{3}{2}}$$

Coefficients determined from PIC simulations in the quasi-linear regime ($a_0 = 1.5$) by courtesy of C. B. Schroeder et al., Proceedings of Advanced Accelerator Concepts Workshop (2010)
Energy gain scalings and single-stage limitations

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Single-stage laser energy

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Accelerating gradient

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Single-stage length

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Single-stage energy gain

\[ W \propto n_p^{-1} \]

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Staging necessary for higher electron energies

Constructing a TeV-class LPA-based linear collider

Design based on
- 10 GeV LPA modules at $n_e \approx 10^{17} \text{ cm}^{-3}$
  BEnkeley Lab Laser Accelerator (BELLA)
- quasi-linear wake: e- and e+, wake control
- staging and coupling modules

W. P. Leemans and E. Esarey, Physics Today (March 2009)
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Laser technology requirements?
Size of accelerator?

W. P. Leemans and E. Esarey, Physics Today (March 2009)
Future user facilities require beam parameter stability

Laser-plasma accelerators have suffered from low shot-to-shot reproducibility

Ways to improve electron beam stability

• Minimizing variations in laser and plasma parameters

• Improved control over crucial laser parameters
  e.g., pulse-front tilt (Popp, Osterhoff et al., Phys. Rev. Lett. 105, 215001 (2010)),
  laser pointing (Gonsalves, Osterhoff et al., Phys. Plasmas 17, 056706 (2010))

• Employing laser pulses matched to plasma conditions $\tau_L \approx \frac{\lambda_p}{2c}$

• Driving acceleration process in the quasi-linear regime, no dark currents $a \approx 1$

• Separating injection & acceleration stages, controlling injection, no wavebreaking
A steady-state-flow gas cell stabilizes plasma conditions

Steady-state-flow gas cell advantages over gas jets

- Allows for high repetition rates (10's of kHz)
- Lasts > $10^5$ shots
- Virtually no gas flow in the interaction region
- No turbulence or shocks (compared to jets)

A steady-state-flow gas cell stabilizes plasma conditions

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<thead>
<tr>
<th>Acceleration results</th>
<th>Gas cell</th>
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<tbody>
<tr>
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Beam divergence
0.9 mrad RMS

 Counts (arb. units)

Counts (arb. units)

Spectral reproducibility

Tuesday, February 22, 2011
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…in 2008!

LWFA record

Intensity or pulse-front tilt usually originates from laser angular chirp (AC) caused by an imperfect stretcher/compressor alignment:
- hard to diagnose
- small amounts of AC have large effect on the stability of LPAs

Eliminating laser intensity-front tilt increases stability

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Eliminating laser intensity-front tilt increases stability
Collective beam oscillations
→ way to tailor betatron radiation?
→ useful for beam cooling?
Laser-plasma accelerator technology has advanced quickly in recent years

**Milestone experiments:** quasi-monoenergetic beams, plasma guiding and GeV electron energies, controlled injection, stability enhancements, soft-X-ray undulator radiation

Lots of research still to be done for compact photon source or collider applications

**Milestone experiments needed:** emittance measurements, slice energy spread characterization, FEL, 10 GeV accelerator module, staging, positron capturing, advancements in laser technology (luminosity requirements)

Plasma accelerators may have the potential to revolutionize accelerator technology and could make them much more **compact, affordable, and therefore accessible**
Thanks for your attention!