Laser Wakefield Experiments

Stuart P D Mangles
John Adams Institute for Accelerator Science
Imperial College London
Laser wakefield accelerators around the World

- There are many labs around the world doing laser driven wakefield experiments
- This lecture could never cover them all!
Laser Wakefield Accelerator Experiments can be split into a few broad categories:

- Electron beam energy frontier
- Stability frontier
- Characterising beam properties
- Diagnosing physics of wakefields
- Applications of wakefield accelerators
Laser Wakefield Accelerator Experiments can be split into a few broad categories:

- Electron beam energy frontier
- Stability frontier
- Characterising beam properties
- Diagnosing physics of wakefields
- Applications of wakefield accelerators
Fast progress in electron beam energy

Electron beam from laser wakefield accelerators has been going up steadily since 2004 results.

- How has this been achieved?
Experiments at the energy frontier: 2002

Electron Acceleration by a Wake Field Forced by an Intense Ultrashort Laser Pulse


- Extends to 200 MeV
- \( n_e = 2.5 \times 10^{19} \, \text{cm}^{-3} \), 3 mm gas jet
- \( P = 33 \, \text{TW} \), “Salle Jaune” laser at LOA
Experiments at the energy frontier: 2006

**GeV electron beams from a centimetre-scale accelerator**


- 1.0 GeV
- \( n_e = 4.3 \times 10^{18} \text{ cm}^{-3} \), 33 mm capillary discharge waveguide
- \( P = 40 \text{ TW}, \) TREX laser at LBNL
Experiments at the energy frontier: 2010

Self-Guided Laser Wakefield Acceleration beyond 1 GeV Using Ionization-Induced Injection

C. Clayton,1,8 J. E. Ralph,2 F. Albert,2 R. A. Fonseca,2 S. H. Glionner,2 C. Joshi,2 W. Lu,1 K. A. Marsh,1 S. F. Martins,3 W. B. Mori,1 A. Pak,1 F.-S. Tsung,1 B. B. Pollock,2,4 J. S. Ross,2,4 L. O. Silva,3 and D. H. Froula2

1Department of Electrical Engineering, University of California, Los Angeles, California 90095, USA
2LLNL, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, USA
3GodPOP/FA, Instituto Superior Técnico, Lisboa, Portugal
4MSE Department, University of California, San Diego, La Jolla, California 92093, USA

(Received 23 April 2010; published 1 September 2010)

The concepts of matched-beam, self-guided laser propagation and ionization-induced injection have been combined to accelerate electrons up to 1.45 GeV energy in a laser wakefield accelerator. From the spatial and spectral content of the laser light exciting the plasma, we infer that the 60 fs, 110 TW laser pulse is guided and excites a wake over the entire 1.3 cm length of the gas cell at densities below 1.5 x 10^{18} cm^{-3}. High-energy electrons are observed only when small (3%) amounts of CO₂ gas are added to the He gas. Computer simulations confirm that it is the K-shell electrons of oxygen that are ionized and injected into the wake and accelerated to beyond 1 GeV energy.


- Extends to 1.45 GeV
- nₑ = 4.3 x 10^{18} cm^{-3}, 1.3 cm gas cell
- P = 220 TW Callisto Laser at LLNL
Experiments at the energy frontier: 2013

Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV

Xiaoming Wang1, Refet Zgadzaj1, Neil Fazel1, Zhengyan Li1, S. A. Yi1, Xi Zhang1, Watson Henderson1, Y.-Y. Cheng1, R. Korzekwa1, H.-E. Isail1, C.-H. Pai1, H. Quevedo1, G. Dyer1, E. Gaul1, M. Martinez1, A. C. Bernstein1, T. Borger1, M. Spinks1, M. Donovan1, V. Khudik1, G. Shvets1, T. Ditmire1 & M. C. Downer1

2 GeV

\( n_e = 4.8 \times 10^{17} \text{ cm}^{-3} \), 7 cm gas cell

\( P = 1000 \text{ TW “Texas PetaWatt” at University of Texas} \)
Experiments at the energy frontier: 2013

Enhancement of Electron Energy to the Multi-GeV Regime by a Dual-Stage Laser-Wakefield Accelerator Pumped by Petawatt Laser Pulses

Hyung Taek Kim,1,2 Ki Hong Paik,1 Hyuk Jin Chun,1 Jong Kim,1,3 Taec Jun Yu,1,3 Jae Hee Sung,1,3 Seong Ku Lee,1,4 Taec Moon Jeong,1,4,5 and Jongmin Lee1,4

1Advanced Photonics Research Institute, DASTI, Daejeon 305-762, Korea
2Center for Relativistic Laser Science, Institute for Basic Science (IBS), Gwangju 500-712, Korea

(Received 17 July 2013, published 15 October 2013)

Laser-wakefield acceleration offers the promise of a compact electron accelerator for generating a multi-GeV electron beam using the huge field gradient induced by an intense laser pulse, compared to conventional rf accelerators. However, the energy and quality of the electron beam from the laser-wakefield accelerator have been limited by the power of the driving laser pulses and interaction properties in the target medium. Recent progress in laser technology has reached the realization of a petawatt (PW) femtosecond laser, which offers new capabilities for research on laser-wakefield acceleration. Here, we present a significant increase in laser-driven electron energy to the multi-GeV level by utilizing a 30-fs, 1-PW laser system. In particular, a dual-stage laser-wakefield acceleration scheme (driven and accelerator scheme) was applied to boost electron energies to over 3 GeV with a single PW laser pulse. Three-dimensional particle-in-cell simulations corroborate the multi-GeV electron generation from the dual-stage laser-wakefield accelerator driven by PW laser pulses.


- 3 GeV
- \(n_e = 8 \times 10^{17} \text{ cm}^{-3}, 4 + 10 \text{ mm dual gas jet}
- P = 1 \text{ PW laser at APRI}
Experiments at the energy frontier: 2014

Multi-GeV electron beams from capillary-discharge-guided subpetawatt laser pulses in the self-trapping regime
Accepted 21 October 2014

ABSTRACT
Multi-GeV electron beams with energy up to 4.2 GeV, 6-10% rms energy spread, 8.1\text{pc}oln\text{cm}^2\text{pico\text{coulumb}} charge, and 0.3\text{mrad} rms divergence have been produced from a 9 cm laser/meter-long capillary discharge waveguide with a plasma density of 7 \times 10^{17}\text{cm}^{-3}, powered by laser pulses with peak power up to 0.3 PW. Preformed plasma waveguides allow the use of lower laser power compared to unguided plasma structures to achieve the same electron beam energy. Detailed comparison between experiment and simulation indicates the sensitivity in this regime of the guiding and acceleration in the plasma structure to input intensity, density, and near-field laser mode profile.

- 4 GeV
- \( n_e = 7 \times 10^{17} \text{ cm}^{-3} \), 9 cm capillary discharge waveguide
- \( P = 300 \text{ TW “Bella” at LBNL} \)
Experiments at the energy frontier: 2019

- 7.8 GeV
- \( n_e = 7 \times 10^{17} \text{ cm}^{-3} \), 9 cm capillary discharge waveguide
- \( P = 850 \text{ TW} \) “Bella” at LBNL
But science isn’t about collecting World Records…. Can we extract some physics from the data trends?

• Collection of data from a variety of experiments
  – (not just the record breakers, but probably the highest beam each experiment was capable of producing)
  • Trend is: higher laser power = higher electron energy
  • What is physics behind this?
Electron energy is limited by dephasing – move to lower densities

- Beam energy, $W_{\text{max}}$, is inversely proportional to plasma density as expected for dephasing
Electron energy is limited by dephasing – move to lower densities

Beam energy, $W_{\text{max}}$, is inversely proportional to plasma density as expected for dephasing.

$$W_{\text{max}} = \frac{n_c}{n_e} m_e c^2$$
Electron energy is limited by dephasing – move to lower densities

\[ W_{\text{max}} = \frac{2}{3} a_0 \frac{n_e}{n_e} m_e c^2 \]

• In 3D non-linear wakes expect \( W_{\text{max}} \propto a_0 \) [Wei Lu, PRSTAB 2007]

• But these experiments were not at fixed value for vacuum \( a_0 \)
  
  – Implies that plasma “prefers” (pulse evolution) \( a_0 \approx 3 \)
Electron energy is limited by dephasing
– move to lower densities and longer accelerators

- Accelerator length increases for lower density experiments
  – consistent with dephasing limit
Electron energy is limited by dephasing
– move to lower densities and longer accelerators

- Accelerator length increases for lower density experiments
  – data lies close to dephasing length (even for simplest linear regime expression)
Electron energy is limited by dephasing
– lower densities need more laser power

\[
\text{Power} = \text{intensity} \times \text{area} \propto a_0^2 w_0^2
\]

- Driving large amplitude plasma waves at lower density needs more laser power
  - So we expect an inverse relationship between the laser power used to drive the experiment and the density where highest energy beams are reported
Electron energy is limited by dephasing – lower densities need more laser power

- We do indeed see this inverse scaling – can this data tell us anything else?
Electron energy is limited by dephasing – lower densities need more laser power

- We do indeed see this inverse scaling
  - can this data tell us anything else?
To guide or not to guide?

• Data shows that experiments in pre-formed plasma structures are “best” performers
  - i.e. for a given laser power the highest energy beams produced come from guided experiments
  - one (common) explanation is that guiding structure is less lossy
Is injection mechanism the same?

But is that the final answer?

- In 2008 an Oxford-led experiment at Astra in UK showed that ionisation injection can play a role inside capillary discharge waveguides

- Could injection mechanism be the reason behind better performance?
To inject or not to inject?

- some ionisation injection experiments also lie at upper edge of distribution
  - data too noisy for a definitive answer, but an interesting research question
Self-injection threshold model

$$\frac{\alpha P}{P_c} > \frac{1}{16} \left[ \ln \left( \frac{2n_c}{3n_e} \right) - 1 \right]^3$$

- Simple model for self-injection threshold [Mangles PRSTAB 2012]
  - takes into account pulse evolution (self-focusing and compression)
  - looks to see if bubble will reach size (amplitude) needed for SI
    - Experimental data where threshold is specifically reported agrees
    - what about this larger data set?
Self-injection threshold model

- many self-injection experiments (mostly) lie above this threshold
- other injection method experiments often lie below this threshold
Electron beam charge

- Electron beam charge very variable between experiments
  - different measurement techniques?
  - different focal spot qualities?
But only energy within the focal spot is captured and drives the wakefield.

Most (not all) groups only quote the total power for their laser system (i.e. total energy / pulse duration).

But some of this is wasted and not coupled into the wake – e.g. Mangles PRSTAB 2012, Genoud POP 2013 – this is possibly why there is so much noise in the scaling plots.

- Same pulse energy, different quality focal spots:
What are the next big directions going to be?
What are the next big directions going to be?
– more power, more energy

Turn up the power, turn up the energy!
What are the next big directions going to be?
– more power, more energy

– **BUT** remember it’s not really the power that is important… pump depletion in blow-out regime is \( L_{pd} \sim \frac{n_e}{n_c} c \tau_L \)
– compare this with simple expression for dephasing length \( L_{dp} \sim \frac{n_e}{n_c} \lambda_p \)
– so, to get to dephasing energy we need pulse lengths \( c \tau \sim \lambda_p \)

» to reach higher energy we need high energy laser pulses
What are the next big directions going to be?
– more power, more energy

• Apollon laser in France
  – 150 J; 15 fs (10 PW)
  – 1 shot per minute
  – multiple beams
  – OPCPA front end with TiSapph amplifiers
What are the next big directions going to be?
– more power, more energy

- CALA laser facility at MPQ in Germany
  - ATLAS 3000
    - 50 - 75 J, 25 fs (2 - 3 PW)
    - 1 Hz
  - PFS & PFS Pro
  - 100 mJ, 5 fs (20 TW) or 1 J, 5 fs (200 TW)
What are the next big directions going to be?
– more power, more energy

- ELI Nuclear Physics (Romania)
  - 2 x 10 PW
  - 1.3 PW demonstrated
What are the next big directions going to be?
– more power, more energy

- ELI Beamlines (Czech Rep.)
  – 10 PW, 1.5 kJ in 150 fs
What are the next big directions going to be?
– more power, more energy

• OPAL, Rochester USA
  – 75 PW (1.5 kJ, 20 fs)
What are the next big directions going to be?
– more power, more energy

• CoReIs Korea
  – 30 fs, 1.5 PW dual laser system
What are the next big directions going to be?
– more power, more energy

- SULF, Shanghai China
  – 5.3 PW, 120 fs

- Station of Extreme Light, 100 PW expected online 2023
What are the next big directions going to be?
– applications, applications, applications

See talk by Zulfikar Najmudin!
What are the next big directions going to be?
– increasing the repetition rate

- very high repetition rates needed for many applications
  - (parameter scans, statistics, accumulation of low signals)
- e.g. lights sources, colliders
  - can we every get to > 10 kHz needed at the very high laser powers needed?
    - Ti:Sapph and OPCPA lasers are < 0.1% efficient, at > 10 kHz that is an expensive electricity bill
- is it time for a new approach?
What are the next big directions going to be?
– increasing the repetition rate

• High rep rates are easier for lower pulse energies
  – can we combine many lower energy pulses to get make a high rep rate LWFA?
  – highly efficient diode pumping can be used, e.g. fibre lasers can have > 20%

• Three approaches (that I know of)
  – Coherent combination (N lasers coherently combine to make one big pulse) [ICAN project]
  – Incoherent combination ( N lasers incoherently combine to make one big pulse) [LBNL, Schroeder et al Phys Plasma 2014]
  – Resonant excitation (separate pulses buy plasma period) [JAI + Jena, Hooker et al J Phys B 2014]
What are the next big directions going to be? – staging to beat depletion: a TeV collider?

Leemans & Esarey, Physics Today 2009

Length of a 1 TeV (CoM) laser plasma collider

Schroeder et al PRSTAB 2010
What are the next big directions going to be? – staging to beat depletion: a TeV collider?

- "low" energy staging demonstrated in 2016
  
  » 120 MeV beam from gas jet accelerated to 200 MeV in second stage

Steinke et al Nature 2016
Summary

- LWFA are a rapidly growing area
  - I gave you an overview of the high energy frontier
    - there’s much more to LWFA than that though
      (see other talks on diagnostics, applications etc)
  - I showed you some of the trends in the experimental data
    - higher energy beams needs lower density plasma, longer accelerator & higher power laser
  - Future directions:
    - energy
    - repetition rate
    - applications
    - staging -> colliders