Recent Progress in Laser Wakefield Acceleration Experiments at APRI

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• Introduction

• Recent Results in the Field by other groups

• Recent Results at APRI

• Summary
Laser interaction with an electron in vacuum

C. A. Brau “Classical Electrodynamics”

Plane wave

$10^{18} \, W / cm^2$

& above

$I \ll 10^{18} \, W / cm^2$

\[
\vec{F} = e\vec{E}
\]

\[
\vec{F} = e\vec{E} + e\vec{V} \times \vec{B}
\]

Electron motion

\[
a_0 = 8.6 \times 10^{-10} \lambda[\mu m] \sqrt{I} \, [W / cm^2]
\]

\[
u_\perp (\phi) = eA_\perp (\phi) / m_0 c = a_0
\]

Transverse Motion

\[
u_z (\tau) = \gamma_0 \left\{ \beta_0 + \left[ eA_\perp (\phi) / m_0 c \right] \right\} \left\{ \left[ 1 + \beta_0 / 2 \right] \right\}
\]

Longitudinal Motion

\[
\gamma (\tau) = \gamma_0 \left\{ 1 + \left[ eA_\perp (\phi) / m_0 c \right]^2 \right( 1 + \beta_0 \right) / 2 \right\}
\]

Quiver Energy

Electron motion
Excitation of Plasma Wakefield by Lasers

T. Tajima and J. Dawson-PRL 1979

Ponderomotive force

\[ f_p = -\frac{\omega_p^2}{8\pi\omega_0^2} \nabla \langle E^2 \rangle \]

\[ \tau_L \leq 100 \, \text{fs} < \omega_p^{-1} \]

Ions are immobile, plasma in stable
Electron acceleration in the Wakefield Bubble

Femtosecond Electron bunches

\[ n = 3.4 \times 10^{18} \text{cm}^{-3} \] (3D)

Wakefield Bubble

Plasma

Laser pulse

\[ E_x \text{ at 5.95mm} \]
1. **Master Oscillator:** 20 fs, 6 nJ
2. **Stretcher:** 500 ps
3. **Regen. Amp.:** 1 mJ with 10-mJ pump at 1 kHz
   (10 Hz after pulse picker)

**Diagram:**
- Master Oscillator
- Stretcher
- Pre-Amp.
- Regen. Amp.
- 1st Main Amp.
- 2nd Main Amp.
- Pump Lasers 1-14
- Vacuum Compressor

**Key Points:**
4. **Pre-Amp.:** 4 pass, 50 mJ, 130-mJ pump at 10 Hz
5. **1st Amp.:** 4 pass, 1.8 J with 4.4-J pump at 10 Hz
   (35 TW with direct pulse compression)
6. **2nd Amp:** 2 pass, 5.0 J with 12-J pump at 10 Hz
7. **Compressor:** 3.5 J, 32 fs, >100 TW at 10 Hz

**Green pump lasers**
- **Pump Laser 1:** Nd:YLF (SHG), 527 nm, 10 mJ at 1 kHz (*JADE* series)
- **Pump Laser 2:** Nd:YAG (SHG), 532 nm, 200 mJ at 10 Hz (*COMP* series)
- **Pump Laser 3-14:** Nd:YAG (SHG), 532 nm, 1.2 J at 10 Hz (*SAGA* series)

**Final Parameter:**
3.5 J, 32 fs, >100 TW at 10 Hz
Pump power supplies
Pulse compressor
Target Chamber
Pump power supplies
Master Clock
Pump laser
Oscillator
Stretcher
Regenerative
http://apri.gist.ac.kr/
Laser-Driven Electron Beams Before 2004 (Example: LOA Results)

(V. Malka, Science 2002)

1 GeV in Plasma capillary 33 mm

50 TW, 40 fs

200 MeV in Gas jets Few mm

30 TW, 30 fs

Our Recent Results
Self-modulated LWFA at KERI in 2003-2005


\[ F_{\text{Lorenz}} = -e(\vec{E} + \vec{V} \times \vec{B}) \]

Laser: 2TW ~ 1ps
ND: Glass
Gas jet: 0.8 mm He and N
ICT: 1pC resolution
Magnet: up to 10 MeV
Al-foil: 16 μm
Self-modulated LWFA at KERI in 2003-2005


Helium Plasma

Laser beam position

200pC

< 100 % dE/E (Energy Spread)

Energy Spectrum from Nitrogen Plasma

Hafz, G. Kim, C. Kim, H. Suk, Int. J. Mod. Phys. B. 2007
Laser Wakefield Acceleration at APRI in 2006

Experimental Parameters

Plasma (He) density = \(1 \times 10^{19} \text{ cm}^{-3}\)
Laser pulse duration = 30 fs
Plasma length = 4 mm
Laser power ~ 20 & 40 TW
Spot size: 10, 25, 30 \(\mu\text{m}\)

LWFA in the f/2.5 focusing geometry: 10 μm spot size

The f/2.5 focusing is very tight and it results in deflection and break up of the laser and electron beams.

LWFA in the f/10 focusing geometry: 25 µm spot size

Soft focusing
$I \sim 5.6 \times 10^{18} \text{ W/cm}^2$
$n_e \sim 1 \times 10^{19} \text{ cm}^{-3}$
Rayleigh Length $\sim 1.7 \text{ mm}$
Gas jet length $\sim 4 \text{ mm}$

Well collimated beam
LWFA in the f/10 focusing geometry

N. Hafz et al., APL, 90, 151501 (2007)

The f/10 focusing is relatively stable and it results in quasi-monoenergetic electron beam generation.
LWFA in the f/14 focusing geometry: 30 μm spot size

Plasma channel

1.5 mm long channel = dephasing length
25 μm diameter

Energy Spectrum

Small mono-peaks

1.99 mm shift

Intensity (arb.u)
Energy (MeV)

N. Hafz et al., APL, 90, 151501 (2007)
Effect of Laser Spot Size on LWFA

Experiments in the bubble regime 2007

\[ a_0 = 8.6 \times 10^{-10} \lambda [\text{\mu m}] I^{1/2} [\text{W/cm}^2] \]

Long Rayleigh Range, several mm's.

High laser power that leads to relativistic self-focusing

Long Dephasing Length, 1 cm, so higher electron energy

\[ P_c (GW) = 17 (\omega / \omega_p)^2 \]

\[ L_d = 2a_0^2 (\omega^2 / \omega_p^2) \lambda_p \]
Experimental Scheme for Generation of Stable Electron Beams

- Up to 50 TW, 35 fs Laser Pulses
- Nozzle
- Gas jet
- 8-bit CCD
- 12-bit CCD
- Filter
- Spherical Mirror $f = 1.5$ m
- Mirror with Hole
- Wave-front corrected
- Electron Beam Energy Monitoring
- Band-pass filter
- Gated ICCD
- ICT
- 12-bit CCD
- Filter
- Side View Monitor
- Top View Monitor
- 5 mm channel
- 3.7 mm channel
225 MeV Electron Beam Generation: 4 mm nozzle, 27 TW laser

**Input Parameters**

Laser: 27 TW, 35 fs, 24 μm (FWHM)
Plasma: 4 mm gas jet, Density: $7 \times 10^{18}$ cm$^{-3}$
Dephasing length= 3.1 mm

**Electron Beam**

Energy: 225 MeV, Charge: 100 pC
Divergence: 5.8 mrad (FWHM)
Energy Spread: 7 %

Reproducing LOA 2004-Nature

170-200 MeV Beams by 27 TW Laser Pulses

27 TW, 35 fs, 24 μm spot size
4 mm nozzle, $n_o \sim 7 \times 10^{18} \text{cm}^{-3}$,
$L_d \sim 3.16 \text{ mm}$

\[ E_{\text{peak}} = 174 \text{ MeV} \]
\[ E_{\text{spread}} = 32 \% \]

\[ E_{\text{peak}} = 192 \text{ MeV} \]
\[ E_{\text{spread}} = 41 \% \]

\[ E_{\text{peak}} = 190 \text{ MeV} \]
\[ E_{\text{spread}} = 49 \% \]

Charge: 100 pC
Reproducible Quasi-monoenergetic Beams: 4 mm Gas Jet

**Mean Energy = 236.9 MeV**
SD/Mean E = 5 %

**Mean Laser (J) = 36.8 TW**
SD/Mean E = 4.6 %

Charge: 200 pC

Generation of $330 \pm 17\text{MeV}$ Electron Beams and 4 mm Gas Jet

Laser: 50TW, 35 fs, 24 $\mu$m (FWHM)
Plasma: 4 mm gas jet
Density: $6.6 \times 10^{18}$ cm$^{-3}$
Dephasing length= 3.3 mm

Electron Beam:
Peak at 330 MeV, Max. at sub GeV,
Charge: $\sim$500 pC
Divergence: few mrad (FWHM)
Energy Spread: $\sim$ 30 %

Beam Energy Doubling by doubling the Laser power

$320 \pm 25 \text{ MeV}$ Beams by 50 TW Laser Pulses and 4 mm Gas Jet

50 TW, 35 fs, 24 μm spot size, 4 mm nozzle, $n_0 \sim \mathcal{N}(6.5 - 6.8 \times 10^{18} \text{cm}^{-3})$, $L_d \sim 3.16 \text{ mm}$

- **# 582**
  - Peak = 300 ± 30 MeV
  - $E_{\text{spread}} = 50\%$
  - Relative Intensity (arb.u.)
  - Divergence (mrad)

- **# 583**
  - Peak = 320 ± 25 MeV
  - $E_{\text{spread}} = 31\%$
  - Relative Intensity (arb.u.)
  - Divergence (mrad)

- **# 584**
  - Peak = 303 ± 9 MeV
  - $E_{\text{spread}} = 30\%$
  - Relative Intensity (arb.u.)
  - Divergence (mrad)

- **# 586**
  - Peak = 285 ± 12 MeV
  - $E_{\text{spread}} = 42\%$
  - Relative Intensity (arb.u.)
  - Divergence (mrad)

Four successive shots with small change in density

3.7 mm channel
1 Centimeter Gas Jet Results

Laser: 50TW, 35 fs, 24 μm (FWHM)
Plasma: 1 cm gas jet
Density: $3.4 \times 10^{18}$ cm$^{-3}$
Dephasing length $\approx 1$ cm

$E_{\text{peak}1} = 540$ MeV, $E_{\text{max}1} > 1$ GeV,
$E_{\text{peak}2} = 320$ MeV,
$E_{\text{spread}2} = 11\%$, $E_{\text{spread}1} = 30\%$,
$Q_{\text{peak}1} = 200$ pC & $Q_{\text{peak}2} = 20$ pC

$E_{\text{peak}} = 480 \pm 60 \text{ MeV}$

$E_{\text{peak}} = 320 \pm 10 \text{ MeV}$

$E_{\text{peak}} = 330 \text{ MeV}$

$E_{\text{peak}} = 500 \pm 20 \text{ MeV}$

$E_{\text{spread}} = 23 \%$

$E_{\text{peak}} = 480 \pm 60 \text{ MeV}$

$E_{\text{peak}} = 500 \pm 20 \text{ MeV}$

50 TW, 35 fs, 24 $\mu$m spot size, 10 mm nozzle, $n_0 \sim 3.4 \times 10^{18} \text{ cm}^{-3}$, $L_d \sim 10 \text{ mm}$
Asymmetric laser pulse with fast rising time generates larger wakefield intensity
Electron-Yield Enhancement in a Laser-Wakefield Accelerator Driven by Asymmetric Laser Pulses


Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720
(Received 1 February 2002; published 8 October 2002)

Case 1: Low density $2 \times 10^{18}$ cm$^{-3}$
Case 2: High density $3 \times 10^{19}$ cm$^{-3}$
2009 Experiment at APRI

Initial Laser-Plasma Parameters Experimental Scheme

- Laser pulse energy 0.8 – 0.9 J (\(\lambda = 800\) nm, \(\Delta \lambda \approx 50\) nm FWHM)
- Laser Spot size (FWHM) 25 \(\mu\)m.
- Pulse duration 37 fs (symmetric pulses)…
  (Intensity \(\rightarrow 1.46 \times 10^{18}\) W/cm\(^2\), \(a_0 = 0.83\)).
- Pulse duration 74 fs (asymmetric at the grating detuning of -200 \(\mu\)m)
  (Intensity \(\rightarrow 7.5 \times 10^{17}\) W/cm\(^2\) (Nonrelativistic) \(a_0 = 0.59\)).
- Target: Gas Jet of Helium: 4 mm long
  Density (very low): \(10^{17} - 10^{18}\) cm\(^{-3}\).
- Interaction length \(\approx 3 \sim 4\) mm.

\(a_0 < 1, c\tau \leq w_0 < \lambda_p\)
Asymmetric Laser Pulses

-250 μm
75 fs FWHM

-200 μm
50 fs FWHM

0 μm
37 fs FWHM
Pointing Angle Optimization

Hafz et al., Applied Physics Express 3(2010) 076401

Laser Height = 3.25

Density: $10^{17} - 10^{18}$ cm$^{-3}$
Electron Beam from 20 Successive Shots

Hafz et al., Applied Physics Express 3(2010) 076401
Unambiguous Electron Beam Energy Measurement

- Laser pulse length 74 fs (asymmetric)
  (Intensity $\rightarrow$ $7.5 \times 10^{17}$ W/cm$^2$
  (Non-relativistic) $a_0 = 0.59$).
- Target: Gas Jet of Helium: 4 mm long
  Density (very low): $10^{17}$–$10^{18}$ cm$^{-3}$.
- Interaction length $\approx 3 \sim 4$ mm.
Electron Beam Energy at Optimum Detuning & Height

Electron Energy (MeV)

Grating Detuning (µm)

> 100 fs

75 fs Range

37-40 fs Range

Original position for shooting

Hafz et al., in preparation
For 20 Shots At -200 µm detuning

Hafz et al., in preparation

Mononenergetic Peaks at 380 MeV, Mononenergetic Peaks at 210 MeV
SD in Energy is ± 40 MeV
Mean Energy is 255 MeV
Most frequent Energy is 240 MeV
This is a Stable “Electron Beam Accelerator”

An initially non-relativistic interaction producing highly relativistic electron beams

Laser pulse length 74 fs (asymmetric) (Intensity $\rightarrow$ $7.5 \times 10^{17}$ W/cm$^2$ (Non-relativistic) $\alpha_0 = 0.59$).

Target: Gas Jet of Helium: 4 mm long Density (very low): $10^{17} - 10^{18}$ cm$^{-3}$.

Interaction length $\approx 3 \sim 4$ mm.

300 MeV per 3 mm $\rightarrow$ 1 GeV per cm

Hafz et al., in preparation
COMPACT X-RAY SOURCES

Towards a table-top free-electron laser

Synchrotron radiation generated using an electron beam from a laser-driven accelerator opens the possibility of building an X-ray free-electron laser hundreds of times smaller than conventional facilities currently under construction.

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Synchrotron radiation sources have become an indispensable tool in a wide range of disciplines, including physics, biology, materials science, chemistry and medicine. The reason they are so useful is the high intensity of X-rays they produce — generated when the path of a beam of electrons moving at relativistic speeds is bent by a periodic magnetic field — in comparison with other X-ray sources. Such utility is expected to grow still further with the
### Undulator Parameters

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<table>
<thead>
<tr>
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<tr>
<td><strong>Type</strong></td>
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<tr>
<td><strong>Field Strength</strong></td>
<td>0.5 Tesla</td>
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<tr>
<td><strong>Length</strong></td>
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<tr>
<td><strong>Period</strong></td>
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</tbody>
</table>

Undulator was designed through collaboration with KAERI, Quantum Optics Division

\[
\lambda = \frac{\lambda_u}{2n\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2\right)
\]
Gas Density = 1 atm
Laser Height = 3.25 mm
Laser ~ 12 TW, 74 fs
Grating Detuning = −200 μm

Preliminary Undulator Experiment September 2009
**Preliminary Undulator Experiment September 2009**

- **# 2382**
  - 170 MeV
- **# 2395**
  - ~180 MeV
- **# 2356**
  - ~170 MeV
- **# 2365**
  - ~170 MeV
Summary and Conclusion

- Using 2 TW class laser and 800 um gas jet we generated 5 MeV quasimonoenergetic electron beam.

- Using 1 cm gas jet and < 50 TW, we have produced GeV-class electron beams.

- By sing asymmetric laser pulses and low plasma density, we could stabilize the electron beam pointing angle and produce highly relativistic electron beam despite the fact that initial interaction conditions were not relativistic.

- We have performed preliminary undulator radiation experiment using 1 m helical undulator.
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