Visualising the Dynamics of a Plasma-Based Electron Accelerator

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Thanks to All Collaborators!

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Motivation and Outline

• Compact **laser-driven** plasma-electron accelerators:
  o plasma formed and modulated by high-intensity laser pulse
  o electrons accelerated by fields of laser-generated plasma wave („wakefield“)
  o electron pulse parameters determined by details of interaction
  o generation and evolution of this wakefield?
  o acceleration dynamics?

• High relevance for future **beam-driven** plasma-electron accelerators:
  o research programs started or planned e.g. at SLAC and DESY
  o first experimental results

• **Pump-probe geometry** well suited for investigation:
  o accelerator driven by main pulse (“pump pulse”),
  o can be characterized (“probed“) using synchronized probe pulse

• **Generate synchronized electro-magnetic probe pulses:**
  o investigate details of interaction with high temporal and spatial resolution
High-energy particle accelerators
- for protons,
- heavy ions,
- electrons – linacs,
- electrons – synchrotrons
are well established.

However, they are large because of limited acceleration field strength to avoid break-through or ionization.
Conventional Particle Accelerators

High-energy particle accelerators

• for protons,
• heavy ions,
• electrons – linacs,
• electrons – synchrotrons

are well established. However, they are large because of limited acceleration field strength to avoid break-through or ionization.

Use plasma as the medium, high-intensity laser or electron pulse as the driver!
What are „High Intensities“?

Laser intensity $I_L \geq 10^{19} \text{ W/cm}^2$

Intensity of sun @ earth $\approx 10^3 \text{ W/m}^2$

Earth’s cross section $\approx 10^{14} \text{ m}^2$

Total power of the sun reaching the earth $\approx 10^{17} \text{ W}$
What are „High Intensities“?

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Focussing this power

to (1 cm)$^2$: $I_L = 10^{17}$ W/cm$^2$

to (1 mm)$^2$: $I_L = 10^{19}$ W/cm$^2$

to (0.1 mm)$^2$: $I_L = 10^{21}$ W/cm$^2$
What are "High Intensities"?

JETI @ FSU Jena and LWS 20 @ MPQ Garching

10...30-TW Ti:Sapphire Laser

- pulse duration: 85 ... 35 fs
- pulse energy: 750 mJ
- focus diameter: <3 µm
- max. intensity: >1×10²⁰ W/cm²

Multi-TW OPCPA Laser

- pulse duration: 8.5 fs
- pulse energy: 65 mJ
- focus diameter: <3 µm
- max. intensity: >1×10²⁰ W/cm²

Visualising Plasma-Based Acceleration
Plasma Wakefield Acceleration

Principle of the acceleration process

- Plasma wave excited by $F_{\text{pond}}$ of high-intensity laser pulse
  \[ \equiv \text{modulation of } n_e \text{ against ion background} \ (v_{\text{ph,plasma}} = v_{\text{gr,laser}}) \]

\[ \Rightarrow \text{longitudinal E-fields (~0.1...1 TV/m)} \]

- injection of electrons into the wave (e.g. by wave breaking or externally)

\[ \Rightarrow \text{quasi-monoenergetic, ultra-short electron pulse} \]
Plasma Wakefield Acceleration

Principle of the acceleration process

- Plasma wave excited by $F_{\text{pond}}$ of high-intensity laser pulse
  $\equiv$ modulation of $n_e$ against ion background ($v_{\text{ph,plasma}} = v_{\text{gr,laser}}$)

$\Rightarrow$ longitudinal E-fields ($\sim 0.1...1$ TV/m)

- injection of electrons into the wave (e.g. by wave breaking or externally)

$\Rightarrow$ quasi-monoenergetic, ultra-short electron pulse

$\Rightarrow$ relativistic electron current

$\Leftrightarrow$ azimuthal B-fields

Image courtesy of A.G.R. Thomas

Electromagnetic Probe Pulses
Probe-pulse generation

- Generation of synchronized optical probe pulses:
  - split off part of the main pulse
  - guide it towards interaction along different path
  - adjust temporal delay

⇒ perfect synchronization
⇒ probe pulse duration similar to main pulse
⇒ record movie from subsequent shots at different delays (requires good shot-to-shot stability!)
Electromagnetic Probe Pulses
Measuring B-fields: the Faraday effect

• Transverse probing of B-fields in underdense plasma with linearly-polarized probe pulse:
  if $\vec{k}_{\text{probe}} \parallel \vec{B}$ ⇒ B-field induced difference of $\eta$ for circularly-polarized probe components

⇒ rotation of probe polarization:

$$\phi_{\text{rot}} = \frac{e}{2m_e c} \int \frac{n_e(\vec{r})}{n_{cr}} \vec{B}(\vec{r}) \cdot \frac{\vec{k}_{\text{probe}}}{k_{\text{probe}}} d\vec{s}$$

⇒ measure $\phi_{\text{rot}}$ to get signature of B-fields, measure $n_e$ to get amplitude!

J. A. Stamper et al., PRL (1975)
Probing Laser-Driven Wakefields

Experimental setup I

JETI parameters:
\[ E_{\text{laser}} = 800 \text{ mJ}, \ \tau_{\text{laser}} = 85 \text{ fs}, \]
\[ f/6 \text{ OAP}, \ I_{\text{laser}} \approx 3 \times 10^{18} \text{ W/cm}^2 \]

probe pulse:
\[ \tau_{\text{probe}} \approx 100 \text{ fs @} \ 1\omega \]
Probing Laser-Driven Wakefields

Polarimetry results

Two polarograms from two (almost) crossed polarizers:

\[
Polarogram 1: \quad I_{pol1}(x, y) = I_0 \left[ 1 - \beta_1 \sin^2(90^\circ - \theta_{pol1} - \phi_{rot}) \right]
\]

\[
Polarogram 2: \quad I_{pol2}(x, y) = I_0 \left[ 1 - \beta_2 \sin^2(90^\circ + \theta_{pol2} - \phi_{rot}) \right]
\]

Deduce rotation angle \( \phi_{rot} \) from pixel-by-pixel division of polarogram intensities:

\[
\frac{I_{pol1}(x, y)}{I_{pol2}(x, y)}
\]
Probing Laser-Driven Wakefields
Polarimetry results

Experimental evidence for B-fields from MeV electrons and bubble!
MCK et al., PRL 105, 115002 (2010)
Probing Laser-Driven Wakefields
Experimental setup II

JETI parameters:
- $E_{\text{laser}} = 800 \text{ mJ}$, $\tau_{\text{laser}} = 85 \text{ fs}$,
- $f/6$ OAP, $I_{\text{laser}} \approx 3 \times 10^{18} \text{ W/cm}^2$
- probe pulse: $\tau_{\text{probe}} \approx 100 \text{ fs @ } 1\omega$

LWS-20 parameters:
- $E_{\text{laser}} = 80 \text{ mJ}$, $\tau_{\text{laser}} = 8.5 \text{ fs}$,
- $f/6$ OAP, $I_{\text{laser}} \approx 6 \times 10^{18} \text{ W/cm}^2$
- probe pulse: $\tau_{\text{probe}} = 8.5 \text{ fs @ } 1\omega$
Probing Laser-Driven Wakefields

Polarimetry results

Electron bunch length: \( \Delta z = 4 \, \mu m \)

\( \tau_{\text{FWHM}} = (6 \pm 2) \, \text{fs}, \tau_{\text{RMS}} = (2.5 \pm 0.9) \, \text{fs} \)

A. Buck et al., Nature Physics 7, 543 (2011)
• Polarimetry: visualize e-bunch via associated B-fields
• change delay between pump and probe ⇒ movie of e-bunch formation
• observe e-bunch formation on-line!

A. Buck et al., Nature Physics 7, 543 (2011)
Probing Laser-Driven Wakefields

Shadowgraphy results

- Shadowgraphy: visualize plasma wave
- change electron density $\Rightarrow$ change plasma wavelength

$$\lambda_p = v_{ph} T_p \approx \frac{2\pi c}{\omega_p} = 2\pi c \sqrt{\frac{\varepsilon_0 m_e}{n_e e^2}}$$

A. Buck et al., Nature Physics 7, 543 (2011)
Probing Laser-Driven Wakefields
Experimental setup III

- Experiments with 30-TW JETI-laser system
- Similar resolution, but with 35-fs driver laser:
  - frequency-broadening of probe pulse
    (in gas-filled hollow fiber)

⇒ shorter $\tau_{\text{probe}}$

$\tau_{\text{probe}} = (5.9 \pm 0.4)$ fs

⇒ sub-main pulse temporal resolution,
1.1 µm spatial resolution with optimized imaging system

Probing Laser-Driven Wakefields

Few-Cycle Microscopy

- Few-cycle probe pulses

Probing Laser-Driven Wakefields

Probing of plasma wakefield acceleration process

Measuring the length of the 2\textsuperscript{nd} plasma wave period (at fixed position in the plasma) and the electron charge:

\[ \lambda_p = 2\pi c \sqrt{\frac{m_e e_0}{n_e e^2}} \]


Critical power for self injection:

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

for our parameters: \( n_e > 1.5 \times 10^{19} \text{cm}^{-3} \)

S.P.D. Mangles \textit{et al.}, PRSTAB \textbf{15}, 011302 (2012)
Probing Laser-Driven Wakefields
Results from Few-Cycle Microscopy

Plasma wave evolution above injection threshold:
\( n_e = 1.6 \times 10^{19} \text{ cm}^{-3} \)

Probing Laser-Driven Wakefields  
Results from Few-Cycle Microscopy

Measuring length of 1\textsuperscript{st} plasma wave period (at \(n_e=1.6\times10^{19} \text{ cm}^{-3}\)) at different positions:

- Wavebreaking radiation

\[ \lambda_p \text{ for } n_e=1.6\times10^{19} \text{ cm}^{-3} \]

- Bubble expansion starts before injection.
- No beam-loading but amplification of pump pulse: \( \lambda_p^* \approx \lambda_p (1 + a_0^2/2)^{1/4} \)

After injection: strongly non-linear evolution

“well behaved”

- Beam-loading dominated
- Single-bubble regime
- Multiple-bubble regime

Probing Laser-Driven Wakefields
Comparison with numerical simulations

3D PIC simulation (EPOCH), 150x70x70 µm³ sliding box, 2700x525x525 cells

E. Siminos et al., submitted (2015)
Bubble expansion starts before injection. No beam-loading but amplification of pump pulse.

Probing Beam-Driven Wakefields

Probing of plasma waves at lower background densities

- Energy gain: \( \Delta E [\text{GeV}] \approx 1.7 \left( \frac{P_L}{100 \, \text{TW}} \right)^{1/3} \left( \frac{10^{18} \, \text{cm}^{-3}}{n_e} \right)^{2/3} \left( \frac{0.8 \, \mu\text{m}}{\lambda_L} \right)^{4/3} \)
- when reducing \( n_e \)

- plasma wave length \( \lambda_{pl} \) increases
- consequences for probing?

W. Lu et al., PRSTAB 10, 061301 (2007)
Probing Beam-Driven Wakefields
Probing of plasma waves at lower background densities

\[ n_e = 1.7 \times 10^{19} \text{ cm}^{-3}, \lambda_{\text{plasma}} = 9 \, \mu\text{m} \]

\[ n_e = 4.8 \times 10^{18} \text{ cm}^{-3}, \lambda_{\text{plasma}} = 17 \, \mu\text{m} \]

- Sensitivity/contrast depends on \( \lambda_{\text{probe}}/\lambda_{\text{plasma}} \) (~1/12 optimal)
  \( \Rightarrow \) increase \( \lambda_{\text{probe}} \) to mid-IR (8...10 \, \mu\text{m} for \( n_e \leq 10^{17}/\text{cm}^3 \))
- Space and time scales of plasma wave increase similarly
  \( \Rightarrow \) few-cycle probe pulse in mid-IR gives similar relative resolution!

E. Siminos et al., submitted (2016)
Probing Beam-Driven Wakefields
Probing of plasma waves at lower background densities

**near-IR:** $\lambda_{pr} @ 800 \text{ nm}$
spectral broadening
+ compression

**mid-IR:** $2 \mu\text{m} \leq \lambda_{pr} \leq 10 \mu\text{m}$
shift $\lambda_{pr}$
(+ amplification in an OPA)
+ spectral broadening
+ compression

synchr. few-cycle, **near-IR probe**
works @ $n_e = 0.5...1 \times 10^{19}\text{cm}^{-3}$

synchr. few-cycle, **mid-IR probe**
works @ $n_e = 3 \times 10^{16}...1 \times 10^{18}\text{cm}^{-3}$

M. Schwab *et al.*, APL 103, 191118 (2013)
Probing Beam-Driven Wakefields

Probing of plasma waves at lower background densities

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- when reducing \( n_e \)

- plasma wave length \( \lambda_{pl} \) increases
- consequences for probing?

\( \Rightarrow \) use synchronized few-cycle mid-IR pulses,
adapt diagnostic components (lenses, cameras, polarizers,...)

\( \Rightarrow \) probe electrons’ B-fields in plasma using Faraday-effect:

\( \Rightarrow \) High-resolution diagnostic for visualization of wake field and for synchronization of e-bunch and driver for external injection

A. Buck et al., Nature Phys. 7, 543 (2011)
Conclusions

• Probing diagnostics reveal detailed insight into plasma-based electron accelerators
• Few-cycle optical pulses can be used to deduce density and accelerating field distributions in the plasma
• Study non-linear evolution of plasma wave ⇒ quantitative information about acceleration details
• Use of these diagnostics might help to overcome current issues of plasma accelerators (stability/reproducibility) in the future ⇒ Further improve plasma diagnostics, their sensitivity and their resolution in the future!
⇒ Adapt probing wavelength to match requirements for high-energy plasma electron accelerators!

Thank you for your attention!