Electron rephasing in laser-wakefield accelerators

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Talk outline

• Laser wakefield acceleration
• Electron dephasing
• Adapting the wake velocity
• Experimental results & discussion
Laser wakefield acceleration in the blowout regime

\[ R_{\text{bubble}} \propto \sqrt{\frac{a_0}{n_0}} \]
Laser wakefield acceleration
in the blowout regime

$R_{\text{bubble}} \propto \sqrt{\frac{a_0}{n_0}}$

Up to TV/m accelerating fields!
Limits on energy gain in a resonance accelerator

Sustaining the accelerating structure:
- Plasma length
- Defocusing
- Depletion

Keeping resonance:
- Match phase velocity with particle velocity
Limits on energy gain

Electron dephasing

\[ L_d \simeq \frac{c_0}{c_0 - v_\phi} r_B \]
Limits on energy gain
Electron dephasing

- Dephasing reduces efficiency of LWFA
- Dephasing is the final limit on energy gain
- But: Dephasing reduces energy spread

Can we increase the gain of a dephasing limited accelerator?
Limits on energy gain
Electron dephasing

\[ L_d \sim \frac{c_0}{c_0 - v\phi} r_B \]

What is the phase velocity of the wake?

Non evolving bubble:
- Group velocity \( 1 - \frac{n_e}{2n_c} \)
- Etching \(-\frac{n_e}{n_c}\)

\[ E_z \sim -\frac{m_e \omega_p^2}{2e} (1 - \phi) r_B \]

\[ \phi = \frac{\text{Distance to back}}{\text{Cavity size}} \]
Limits on energy gain
Electron dephasing

\[ L_d \approx \frac{c_0}{c_0 - v_\phi} r_B \]

What is the phase velocity of the wake?

Non evolving bubble:
- Group velocity \( 1 - \frac{n_e}{2n_c} \)
- Etching \(-\frac{n_e}{n_c}\)

Evolving bubble:
- Additional contraction / expansion term

\[ E_z \approx -\frac{m_e \omega_p^2}{2e} (1 - \phi) r_B \]

\[ \phi = \frac{\text{Distance to back}}{\text{Cavity size}} \]
Adjusting the wake velocity
Density downramp injection

- Locally slow down plasma wake
- Injection threshold lowered

wake velocity = driver velocity – expansion rate

wake slowed down by cavity expansion!

- plasma density decreases
- bubble expands

Adjusting the wake velocity
Injection in sharp density gradients

- Pump Laser: 1.2 J, 30 fs
- Dipole Magnet
- f/10 off-axis parabola
- Laser
- Shock front
- 500 μm Silicon wafer
- Supersonic gas flow

Adjusting the wake velocity
PIC simulation of shock injection

Shock injection
Dephasing

* $1500 \times 250$ cells, $\Delta x = 0.3 \, k_0^{-1}$, $\Delta r = 1.5 k_0^{-1}$. $\lambda_0 = 0.8 \mu m$. 
Adjusting the wake velocity

Electron rephasing

- Invert principle of downramp injection: an increase of plasma density can lead to bubble contraction
- Electron is rephased

wake speeds up by cavity contraction!
Adjusting the wake velocity
Electron rephasing

- Invert principle of downramp injection: an increase of plasma density can lead to bubble contraction
- Electron is rephased

**wake speeds up by cavity contraction!**

- Theoretical framework only developed for phase locking in linear regime
- Non-linear regime is more complex due to self-focusing

* e.g. Sprangle et al., PRE 2001, Pukhov et al., PRE 2008, Rittershofer et al. PoP 2010
Adjusting the wake velocity

Electron rephasing

Propose phase reset instead of phase locking!*

Gain estimation* for complete instantaneous phase reset at different position $x$:

$$\Delta \gamma_{\text{max}}(x_{\text{boost}}) = \left(1 + \frac{x}{L_d} - \frac{3}{4} \frac{x^2}{L_d^2}\right) \times \Delta \gamma_{\text{max}}(n_0)$$

maximum gain of $\sim 30$ percent close to dephasing length

* Ta Phuoc et al., PoP (2008)
Adjusting the wake velocity
PIC simulations of acceleration with density step

Shock injection
Dephasing

* 1500 x 250 cells, $\Delta x = 0.3 \text{k}_0^{-1}$, $\Delta r=1.5\text{k}_0^{-1}$. $\lambda_0=0.8$\text{\mu m}.
Adjusting the wake velocity

PIC simulations of acceleration with density step

* 1500 x 250 cells, Δx = 0.3 k_0^{-1}, Δr=1.5k_0^{-1}. λ_0=0.8μm.
Adjusting the wake velocity
PIC simulations of acceleration with density step

... so shocks might work better!

* 1500 x 250 cells, Δx = 0.3 k₀⁻¹, Δr=1.5k₀⁻¹. λ₀=0.8μm.
Experimental setup
Experimental setup

Turn around shock front injector setup

- f/10 off-axis parabola
- 500 μm Silicon wafer
- gas jet

Graph showing plasma density ($n_e$) versus position ($z$):

- Out
- 1.8 mm
- 2.0 mm
- 2.3 mm
Experimental results

Raw data

raw LANEX data of 5 consecutive shots without density transition
raw LANEX data of the next 5 shots with density transition
Electrical results
Deconvolved data

- Electrons accelerated beyond cut-off
- Rear part of the bunch is decelerated and defocussed

* Submitted
Experimental results
Comparison to PIC for experimental parameters

- Observe non-linear field increase at the rear of the bubble
- Rotation in $z/p_z$ space reduces energy spread: (leads to quasi-monoenergetic beam)

* 3672 x 400 cells, $\Delta x = 0.3 \text{k}_0^{-1}$, $\Delta r=1.5\text{k}_0^{-1}$. $\lambda_0=1\text{\mu m}$. 

\[ \Delta x = 0.3 \text{k}_0^{-1}, \quad \Delta r=1.5\text{k}_0^{-1}. \quad \lambda_0=1\text{\mu m}. \]
Experimental results
Energy gain of monoenergetic beams

- Electrons injected via shock front injection
Electrical results

Energy gain of monoenergetic beams

- Electrons injected via shock front injection
- Energy increases with backing pressure of second jet
Experimental results
Energy gain of monoenergetic beams

- Electrons injected via shock front injection
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Experimental results
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Experimental results
Energy gain of monoenergetic beams

- Electrons injected via shock front injection
- Energy increases with backing pressure of second jet
- At high pressure electrons are entirely defocused
Conclusions

• Dephasing effects can be mitigated by density tailoring

• Simple experimental setup (shock front)

• Observed gain of ~50 %, exceeding linear E-field model (~30%)

• Best suited for monoenergetic beams

By the way: electrons never leave the bubble, same laser, same jet – in contrast to staging …
Thank you for your attention!
Setup for rephasing of shock injected beams

(b) f/10 off-axis parabola

Pump Laser
1.2 J, 30 fs

Dipole Magnet

Probe beam

Scintillator

Interferometer

Divergence [mrad]

Energy [MeV]

(i) $n_e = 3.1 \times 10^{19}$ cm$^{-3}$

(ii) $n_e = 2.6 \times 10^{19}$ cm$^{-3}$

(iii) $n_e = 2.1 \times 10^{19}$ cm$^{-3}$

(iv) $n_e = 1.8 \times 10^{19}$ cm$^{-3}$

Blade, jet and needle jet

Blade, jet and needle jet

btw.