Optical transverse injection in laser-wakefield acceleration

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Outline of the presentation

• Principles and applications of laser-wakefield accelerators

• Existing methods of injection

• Optical transverse injection: a new mechanism of injection

• Conclusion: properties of the beam
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Principles of laser-wakefield acceleration

• Occurs when a **short and intense** laser pulse is focused into a gas jet. (~30 fs, ~100 TW)

• The laser **ionizes the gas** and drives a **wakefield**.
Principles of laser-wakefield acceleration
Principles of laser-wakefield acceleration

- **Accelerating and focusing** fields (for the electrons) inside the cavity

- Yet for electrons to be accelerated, one needs **injection**.
Applications

• Produces electron beams at \(~100 \text{ MeV} - 1\text{GeV}\) over an accelerating distance of \(\sim 1 \text{ mm} - 1 \text{ cm}\)

• Conventional accelerators require a \(~1000 \text{ times}\) longer distance

• Prospective applications:
  - Radiotherapy
    (Glinec et al., Medical Physics, 2006)
  - Non-destructive testing
Applications: Free electron laser

• Several **simultaneous** requirements on the quality of the electron bunch
  
  - low energy dispersion \( \Delta E \)
  - low emittance \( \epsilon_{\perp} \)
  - high charge/current \( Q \)

• These quantities are in principle **conserved** during the acceleration, and are thus **determined by injection**.

(Z. Huang, K. Kim, PRSTAB, 2007)
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Existing methods of injection: self-injection

**Spontaneous** injection due to the nonlinear propagation of the laser

- **Transverse self-injection**
  - High charge (100-200 pC)
  - Large energy spread
  - Strong shot-to-shot fluctuation
  - Not tunable

- **Longitudinal self-injection**
  - Low shot-to-shot fluctuation
  - Low charge (~5 pC)
  - Not tunable

(S. Corde et al., Nat. Com., 2013)
Existing method of injection: optical injection

- Injection is **triggered** by a less-intense counter-propagating pulse.

- The mechanism is essentially **longitudinal**.

- Beam properties:
  - Tunable and stable electron beams
  - Low energy spread (~1 MeV)
  - Intermediate charge (~20 pC)
  - Relatively high emittance (~0.5-2 mm.mrad)
A new regime of injection: optical transverse injection

• New mechanism observed in numerical simulations, in the regime:

\[ k_p w_0 \approx 2 \quad a_0 \approx 4 \]
\[ w_1 \geq w_0 \]

• The mechanism is mainly **transverse**.

• Produces high-quality beams:
  - High charge (~50-100 pC)
  - Low energy spread (~0.6 MeV)
  - **Low emittance (0.15 mm.mrad)**
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Methods : Particle-in-cell (PIC) simulations

- PIC code : integrates
  - the **Maxwell equations** on a discrete grid
  - the **equations of motion** for (macro)particles of the plasma

- **Calder-Circ** : quasi-cylindrical code
  (Lifschitz et al., JCP, 2009)
  - captures all the relevant 3D effects
  - runs much faster than a fully-3D PIC code

- Results were confirmed by (time-intensive) fully-3D simulations.
Why some electrons are injected

- The laser collision causes the bubble to transiently expand.

- The bubble expansion triggers the injection of off-axis electrons.

- Explained (in the context of an expansion caused by a density gradient) by simplified-bubble models.
Why the bubble transiently deforms

- Explained by the ponderomotive force \( \vec{F}_{pond} \propto -\nabla I_{laser} \)

- The electrons spend more time inside the pulse, when there is no collision.
Why the obtained emittance is low

- Selection of the electrons with low radius and low transverse momentum

- This phenomenon does not occur for optical longitudinal injection.
Numerical growth of emittance

- Low emittance at the moment of injection (0.15 mm.mrad)

- Emittance grows throughout the acceleration (but should in theory remain constant)

- The growth of emittance is a **numerical artifact** (due to numerical Cherenkov effect in PIC codes)
  
  (Lehe et al., PRSTAB, 2013)

\[
\epsilon_x = \frac{1}{mc} \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle xp_x \rangle^2}
\]
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Resulting beam

- Peak: transverse injection (50 pC)
  Tail: longitudinal injection (13 pC)

- In the peak, simultaneously:
  - short duration (3 fs)
  - high current (7 kA)
  - low energy spread (0.6 MeV)
  - low emittance (0.15 mm.mrad)

- Can be obtained with current laser facilities
  (needed laser energy: 1.6 J, with tighter focusing and lower plasma density compared to previous experiments)

- Stable and robust scheme: does not rely on self-focusing, or external guiding, or density gradient
Conclusion

• A laser collision can produce a transient expansion of the accelerating bubble.

• This expansion leads to transverse injection.

• In this process, high-quality electron bunches are produced, having simultaneously high charge, low energy spread, low emittance.
Thank you for your attention

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