A laser-to-beam-driven plasma wakefield accelerator

Towards Laser-driven PWFAs: *Hybrid plasma accelerators*

**Theory: Energy booster**

![Diagram showing the process of energy booster in LWFA and PWFA stages.](image)

B. Hidding et al. PRL 104, 195002 (2010)

**Theory: Energy and quality boosters**

![Diagram showing the process of energy and quality boosters.](image)


**Experimental wakefields demonstration**

![Diagram showing the experimental setup for wakefields demonstration.](image)

S. Chou et al., PRL 117, 144801 (2016)

A. M. de la Ossa et al., PRL 111, 245003 (2013)
Why adding PWFA stage?

➤ **Energy boost**: High transformer ratio in blowout regime.

➤ **Quality boost**: Novel injection techniques* in PWFA for the generation of low emittance beams.

➤ **Low energy spread**: Energy chirp balance by means of beam-loading requires high-current witness.

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A. M. de la Ossa et al., PRL 111, 245003 (2013).

A. M. de la Ossa et al., PRAB 20, 091301 (2017).

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* High-brightness GeV class electron beams for applications demanding high-quality (e.g. FELs).
A laser-to-beam-driven plasma wakefield accelerator: EuPRAXIA example

**Laser beam**
- $P_0 = 500$ TW
- $\lambda_0 = 800$ nm
- $w_0 = 41$ $\mu$m
- $a_0 = 3$
- $\tau = 100$ fs
- Energy = 53 J

**Electron beam**
- $I_0 = 15$ kA
- $\varepsilon_n = 130$ nm
- $\tau = 700$ as
- $Y_{mc^2} = 10$ GeV
- $\Delta Y/Y = 0.1 \%$
- Charge = 10 pC

**Energy doubling**
- $\Delta \gamma_w = R \gamma_d$

**Brightness booster**
- $B \propto \frac{I_0}{\varepsilon_n^2} \times 10000$
PWFA stage with WII injection (OSIRIS 3D)

Wakefield cathode
Helium ionization

plasma blowout

drive-beam
(10 kA)

A. M. de la Ossa et al., PRL 111, 245003 (2013)
PWFA stage with WII injection (OSIRIS 3D)

Witness beam

A. M. de la Ossa et al., PRL 111, 245003 (2013)
**PWFA with WII injection**

**Requirements:**

- **High-current drivers (GeV class):**
  Needs a strong blowout regime for trapping.
- **Appropriate dopant species:**
  Ionisation is triggered by the wakefields only.

**Features:**

- **Short and high-quality witness:**
  Low-emittance witness $\varepsilon_n \approx 0.1 / k_p$
- **High-energy witness:**
  Energy-per-electron can double/triple the driver
  High transformer ratio: $\Delta E_{\text{wit}} = R E_{\text{dri}}$
- **High-current and low energy spread witness:**
  High-current witness is needed for beam-loading at high transformer ratio.

**Self-Similar Staging**

Witness beams from WII injection can drive WII injection in a higher density plasma

Energy doubling and order of magnitude reduction of length and emittance in each stage.

**Can LWFA beams drive PWFA with WII injection?**

Towards Laser-driven PWFA: *Proof-of-concept* experiment at HZDR

**Demonstration of a beam loaded nanocoulomb-class laser wakefield accelerator**

J. Couperus et al., Nature Communications 8, 487 (2017)

"Ionization injection enables loading of ~0.5 nC within a mono-energetic peak"

> 30 kA peak current electron beams with low energy spread
Towards Laser-driven PWFA: *Proof-of-concept* experiment at HZDR

**LWFA with ionization injection**

- **Proof of concept experiment at Dresden**
  - Demonstration of injection and acceleration in a PWFA stage driven by a LWFA beam.

- **Laser parameters**:
  - Laser: 2.8 J, 28 fs, 20 μm (on target)
  - Peak energy: ~ 283 MeV
  - Energy spread: ~ 40 MeV (14%)
  - More stable: charge, pointing, energy
  - Estimated peak current: ~ 30 kA

- **Radiation parameters**:
  - Energy: [MeV]
  - Divergence
  - Helium+1% Nitrogen

- **Results**:
  - Charge: ~ 400 pC

- **Reference**:
  - J. Couperus et al., Nature Communications 8, 487 (2017)
Towards Laser-driven PWFA: *Proof-of-concept* experiment at HZDR
LWFA beams from ionization injection: A 3D simulation for HZDR

**DRACO laser**

\[ \begin{align*}
    P_0 &= 98 \text{ TW} \\
    \lambda_0 &= 800 \text{ nm} \\
    w_0 &= 17 \mu\text{m} \\
    a_0 &= 3.18 \\
    \mathcal{E} &= 2.8 \text{ J} \\
    \tau &= 27 \text{ fs}
\end{align*} \]

**Jet 1:**

He + N\(_2\) (dopant)

\[ n_0 \approx 10^{18} \text{ cm}^{-3} \]

**LWFA stage**

**ionisation injection**

![Diagram of DRACO laser and LWFA beams from ionization injection](image)

**3D PIC simulation (OSIRIS)**

\[ E_z = 2.00 \times 10^{18} \text{ cm}^{-3} \]

\[ n_p / n_0 \]

\[ E_z [\text{GV/m}] \]

\[ x [\mu\text{m}] \]

\[ z = 1.03 \text{ mm} \]
First jet: LWFA with Ionisation injection OSIRIS 3D with DRACO-laser
LWFA beams from ionization injection: OSIRIS 3D with HZDR parameters

Witness bunch LWFA (after 1.8 mm)
- Energy: 340 MeV
- Energy spread: 10%
- Charge: 162 pC
- Current: 35 kA
- Length (rms): 0.5 μm (~4 fs fwhm)
- Norm. emittance: 6 μm
Laser-to-beam-driven WFA: **PWFA with HZDR-type drive-beam**

Second jet: PWFA with Ionisation injection
Second jet: PWFA with Ionisation injection (HZDR-type driver)
Laser-to-beam-driven WFA: PWFA simulation with HZDR beam
LWFA beams from ionization injection: PIConGPU simulation (HZDR)

Witness bunch LWFA (after 1st jet)
- Energy: 450 MeV
- Energy spread: 12%
- Charge: 220 pC
- Current: 22 kA
- Length (rms): 1.70 μm (~13 fs fwhm)
- Norm. emittance: 3.6 μm
Laser-to-beam-driven WFA: **Start-to-end simulation (PiConGPU input)**

Second jet: PWFA with Ionisation injection
Second jet: PWFA with Ionisation injection (start-to-end)
Second jet: PWFA with Ionisation injection (start-to-end)
Laser-to-beam-driven WFA: PWFA simulation with PIConGPU beam
Conceptual design for a laser-to-beam driven plasma accelerator:
For the production of multi-GeV, high-brightness, FEL capable beams.

Preliminary working point achieved by means of PIC simulations:
Energy and brightness booster: 2 x energy, 10000 x brightness.

Proof-of-concept experiment at HZDR (LPWFA experiment):
Injection of electron beams in a PWFA driven by electron beams from LWFA.

Preliminary start-to-end simulations for the LPWFA experiment:
Energy doubling of low-emittance beams in the PWFA stage.

Thank you