Independent Control of Electron Injection and Acceleration in a Laser Plasma Accelerator

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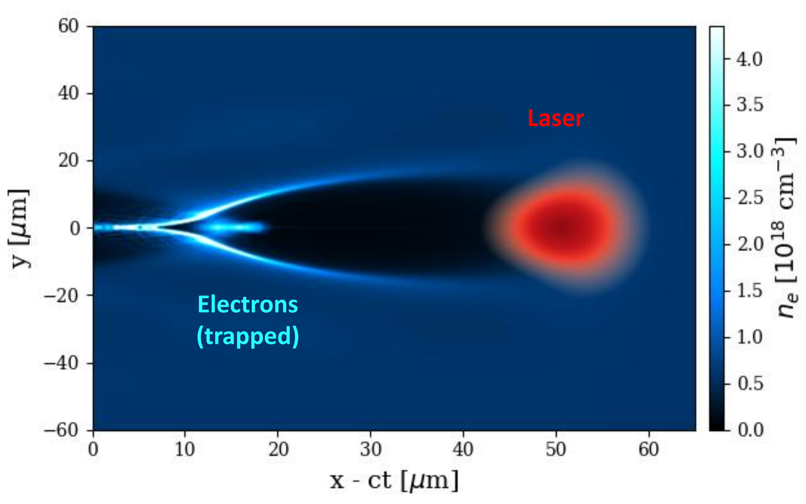
Introduction

Laser Wakefield Acceleration

Focusing ultra-intense laser pulses into a gas target to create plasma waves that trap and accelerate electrons to relativistic energies in a few millimeters.



Plasma wakefield formation by intense laser[1]

Challenges for producing high quality electrons

- Charge conservation at higher energies
- Achieving low emittance/divergence
- Minimizing energy spread

Electron bunch properties depend mainly on the laser intensity (a_0) and plasma density profile ($n_e(x)$). Beam quality can be improved using techniques such as :

- Ionization injection → adding high-Z impurity (e.g., N_2) → higher charge[2]
- Downramp injection → controlled trapping → lower energy spread[3]
- Plasma lensing → reduced divergence[4]

Although several techniques exist to address one or more of these challenges, integrating them without introducing trade-offs in stability, diagnostic accessibility, or experimental complexity remains difficult.

Compact laser-plasma accelerators have diverse applications, each with its own definition of a high-quality electron beam:

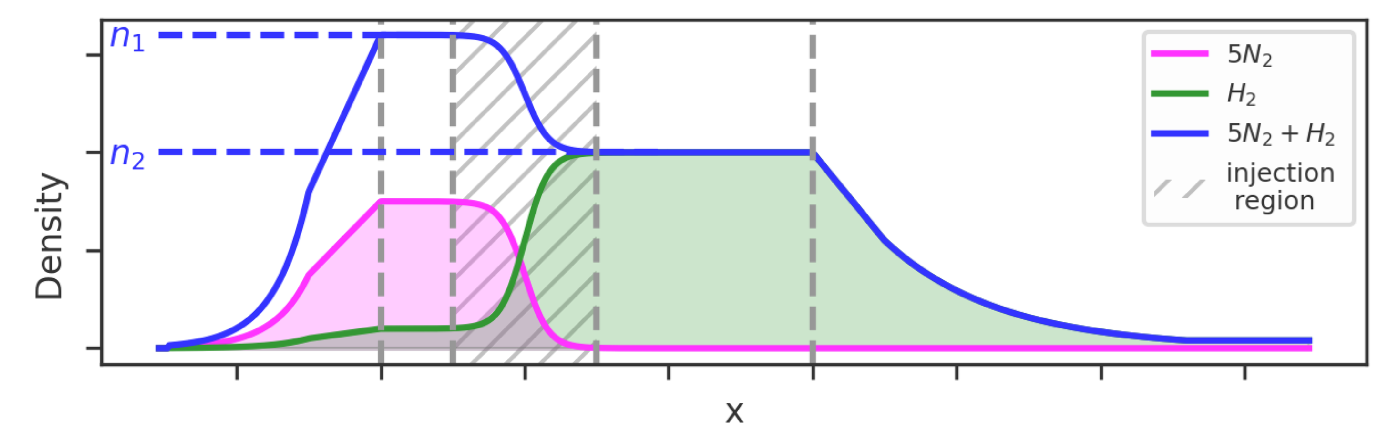
- Medical - *high charge and high stability*
- X-ray production / FELs - *low emittance and energy spread*
- High energy Physics / linear colliders - *high energy, high charge and low emittance*

Thus, the characterization of beam quality depends on the intended application.

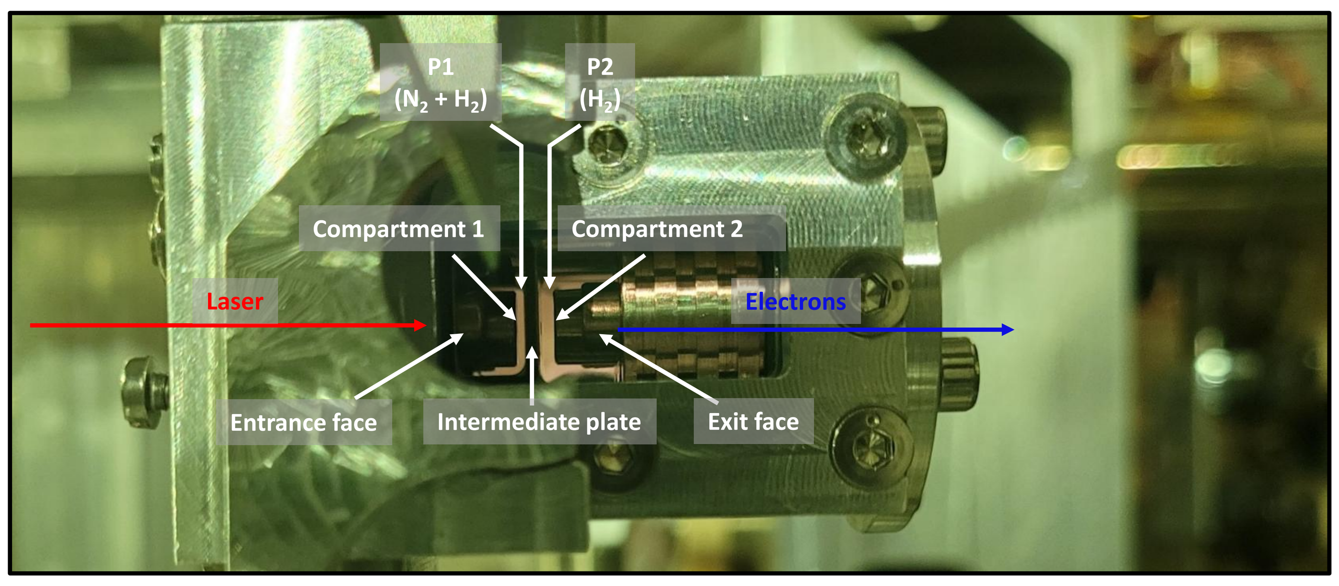
Double Compartment Gas Cell

Improved beam quality can be achieved by decoupling the injection and the acceleration mechanism.

A 2-compartment gas cell with modular design and individual gas injection system allows us to tailor the density profile.



Plasma density profile



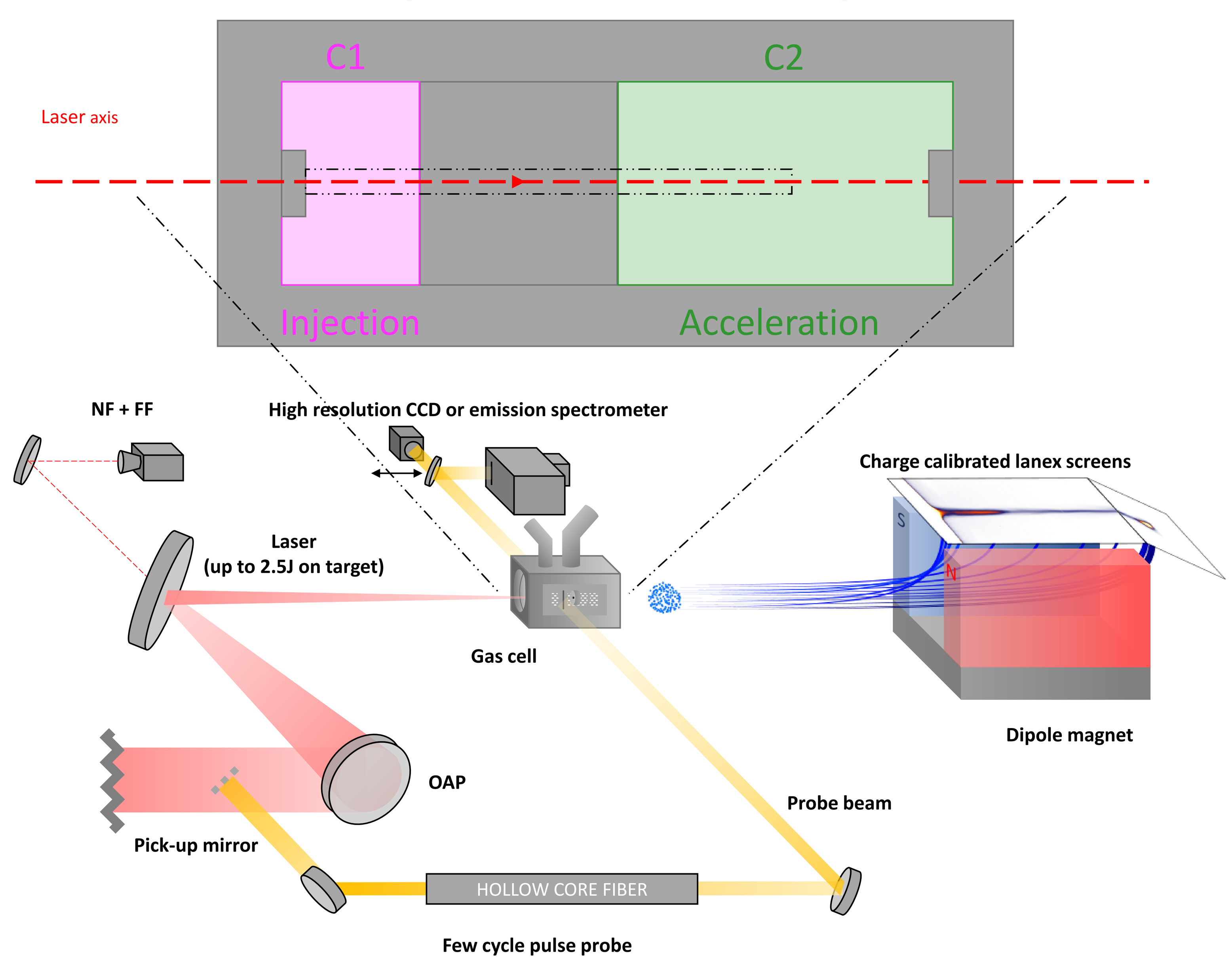
Gas cell picture

Tunable parameters: compartment lengths, intermediate plate thickness, entry/exit diameters, nitrogen impurity level, pressure, trigger delay & window.

Tailored density profiles: enables controlled shaping of the plasma environment.

Combined techniques: ionization injection, downramp, and plasma focusing → localised injection and acceleration to optimize beam shape while preserving charge.

Experimental Setup

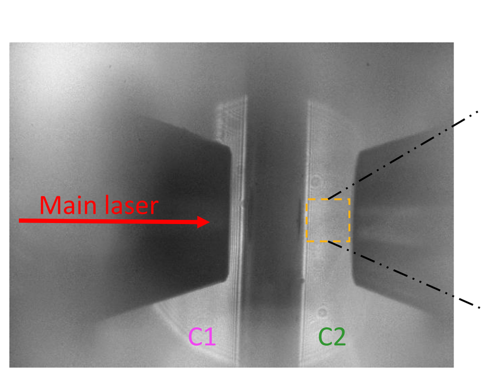


Experimental setup at the 300TW DRACO laser facility in HZDR, Germany

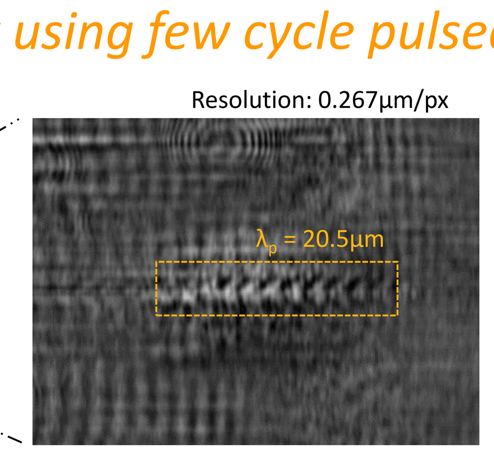
Laser and Plasma Diagnostics

Laser NF & FF (on-shot)	Tracks beam quality and pointing
Emission spectrometer	Monitors presence of N_2 leaking into C2
High-res probe CCD	Measures plasma density using few cycle pulse probe shadowgraphy
Charge calibrated lanex screens and dipole magnet	Beam characterization with charge and energy distribution

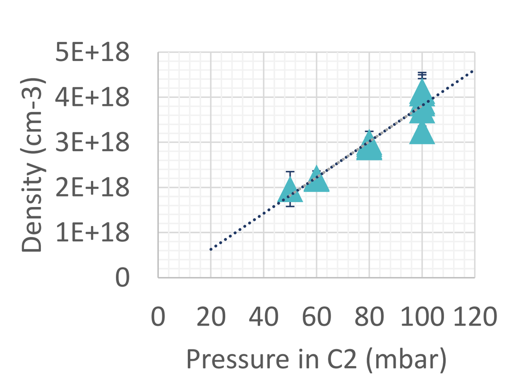
Estimation of plasma density using few cycle pulsed probe shadowgraphy[5]



Plasma wave only visible in the longer compartment

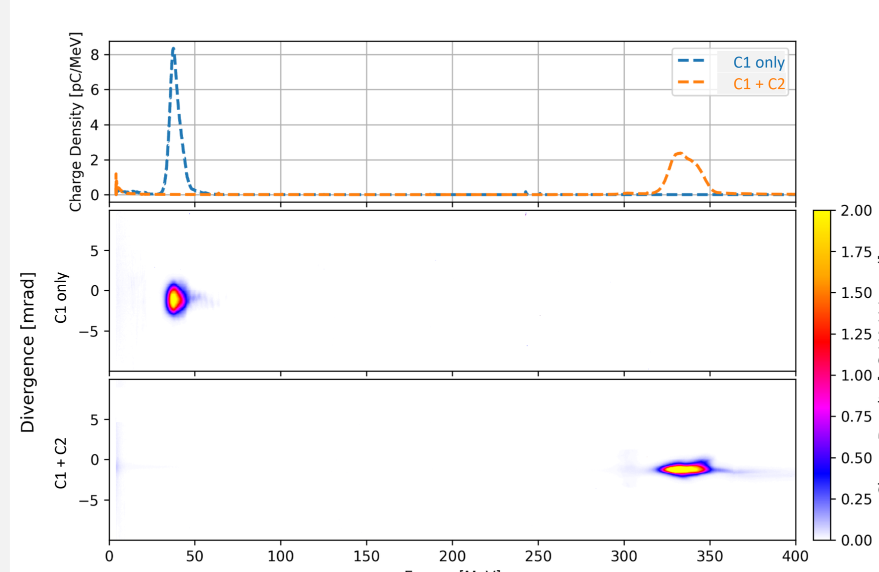


Shadowgram with 5 plasma cavities (for high pressure cases)

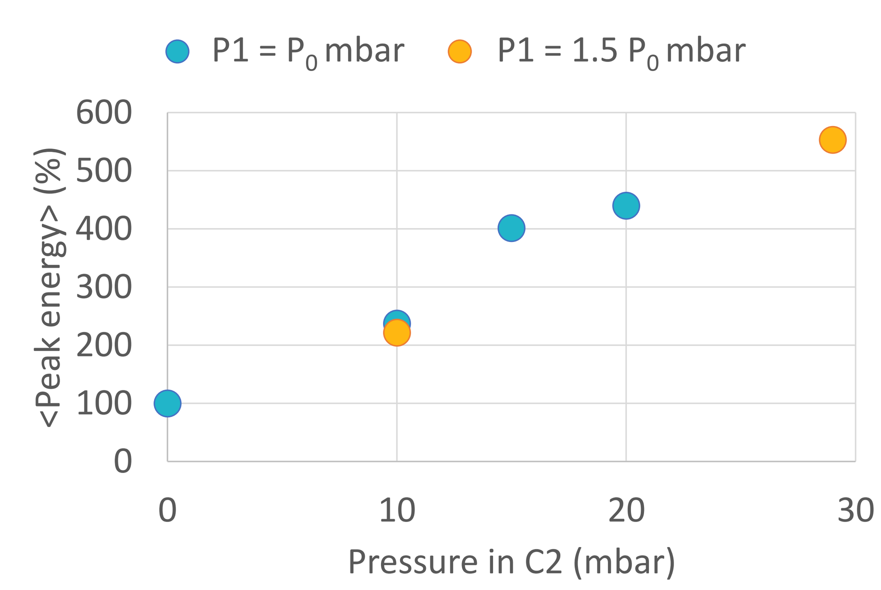


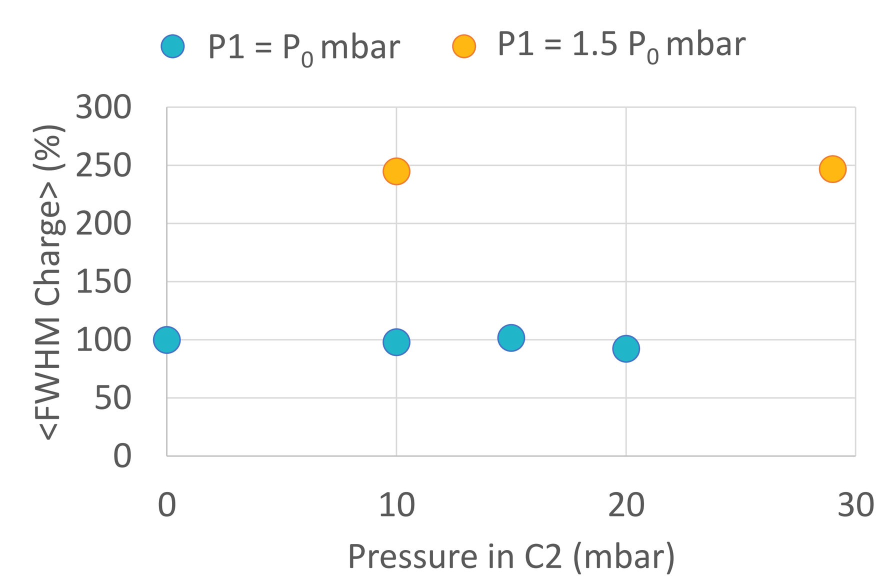
Plasma density extrapolated for low pressure cases

Results



2D energy spectrum and lineout





Q_{FWHM} is conserved at higher energies, evidencing the role of C1 for injection and C2 for acceleration.

1. Peak energy increases linearly with C2 pressure (for both C1 settings) → tunable energy
2. FWHM charge remains constant with C2 pressure → stable charge output

Together, these results demonstrate a high quality electron source with tunable energy and charge using one single laser beam[6].

A tunable and compact high quality e^- source

For external beam radiotherapy

- High charge, variable-energy beams → VHEE source (50–250 MeV)

For studying Ultra High Dose Rate Effects or FLASH effect

- LPAs naturally produce ultrashort electron bunches (≈ps - fs)
- Extremely high peak dose-rate

References & Acknowledgements

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[5] Susanne Schöbel et al, New J. Phys. (2022)
[6] The study of minimizing the divergence can be found in this paper: https://arxiv.org/abs/2506.18047 and at the poster of L. Steyn titled: "Enhancing electron beam quality through customized density gradients in Laser Plasma accelerators"

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