Enhancing Electron Beam Quality Through Customized Density Gradients in Laser Wakefield Acceleration

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Abstract

The quality of electron beams produced by Laser Wakefield Acceleration (LWFA), is controlled through laser parameters and plasma density distribution. Gas cells are particularly suitable to manipulate the density profile through the definition of the geometry. Before conducting experiments, we design the plasma density distribution for ionisation injection. This poster presents our numerical study using Computational Fluid Dynamics (CFD) and Particle-In-Cell (PIC) simulations.

Objectives for electron beam quality

- Low energy Spread $< 10\%$
- High Charge $> 50\ pc$
- Low divergence $< 1\ mrad$

Control of injection and acceleration

- Injected electrons are from the ionization of Nitrogen
- Controlling the location of Nitrogen injection
- The beam is accelerated in a pure hydrogen plasma without further injection
- The outlet ramp at the exit of the plasma, controls divergence through plasma lens/ Adiabatic matching.

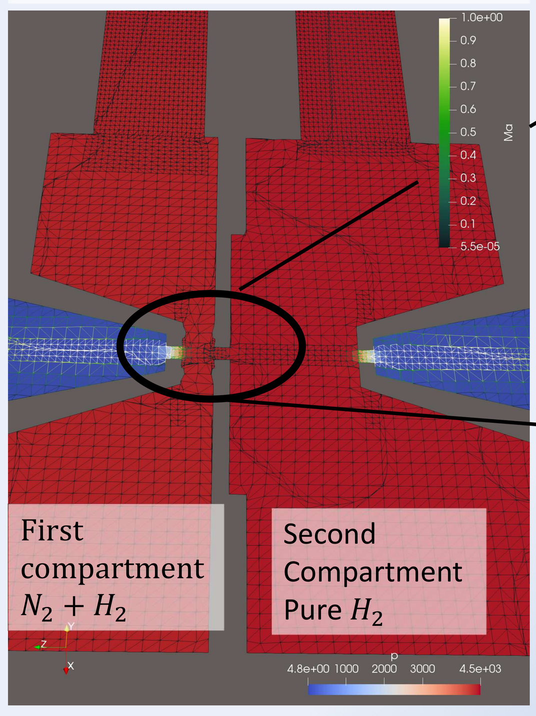
Workflow

1. CFD description of density profile
2. Parameterize density profile
3. PIC simulation of injection, acceleration
4. Parametric study using Gaussian Processes
5. Comparison with experiment

1. CFD Simulation with OPENFOAM

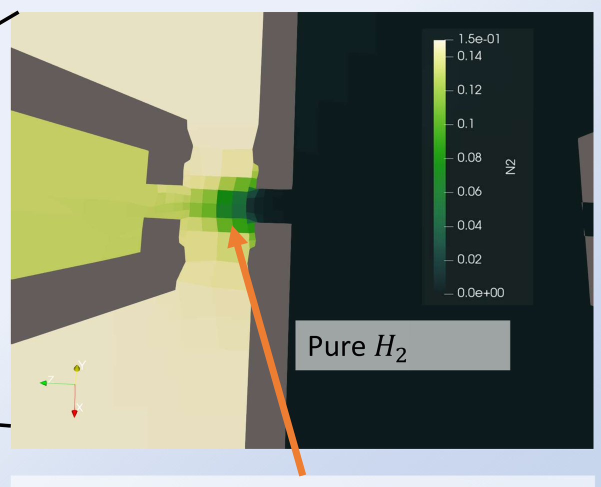
Pressure and Velocity

- Black and white lines: simulation grid indicating flow velocity as Mach Number
- Blue and red shows pressure



Nitrogen fraction

- 1 mbar pressure Imbalance
- Leak between compartments
- Changes transition location and gradient of electron density

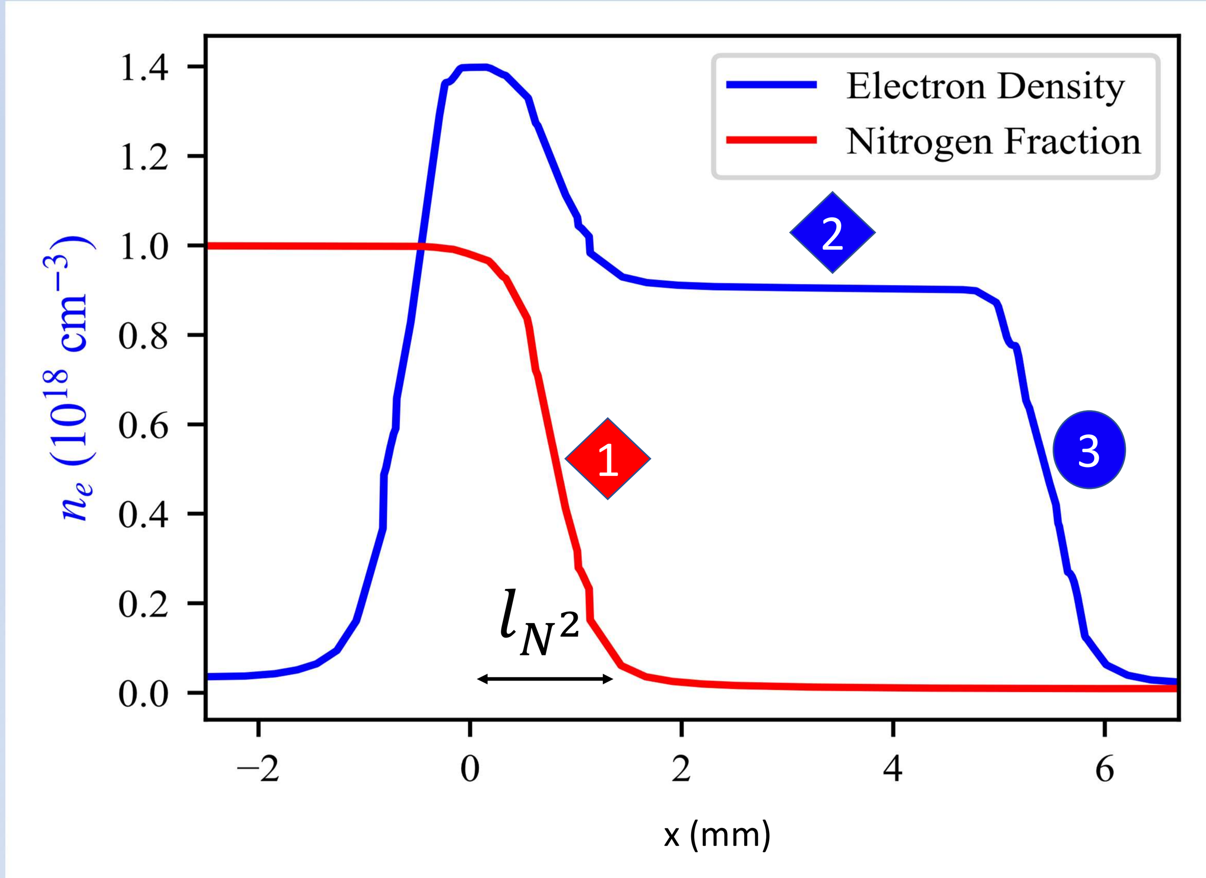


- Hydrogen displaces nitrogen, caused by pressure imbalance
- This displacement changes the density profile leading to failed injection
- For proper injection, pressure balance is required, with $\Delta P < 1$ mbar

2. Parameterized density profile

Nitrogen fraction leads to electron density ramp

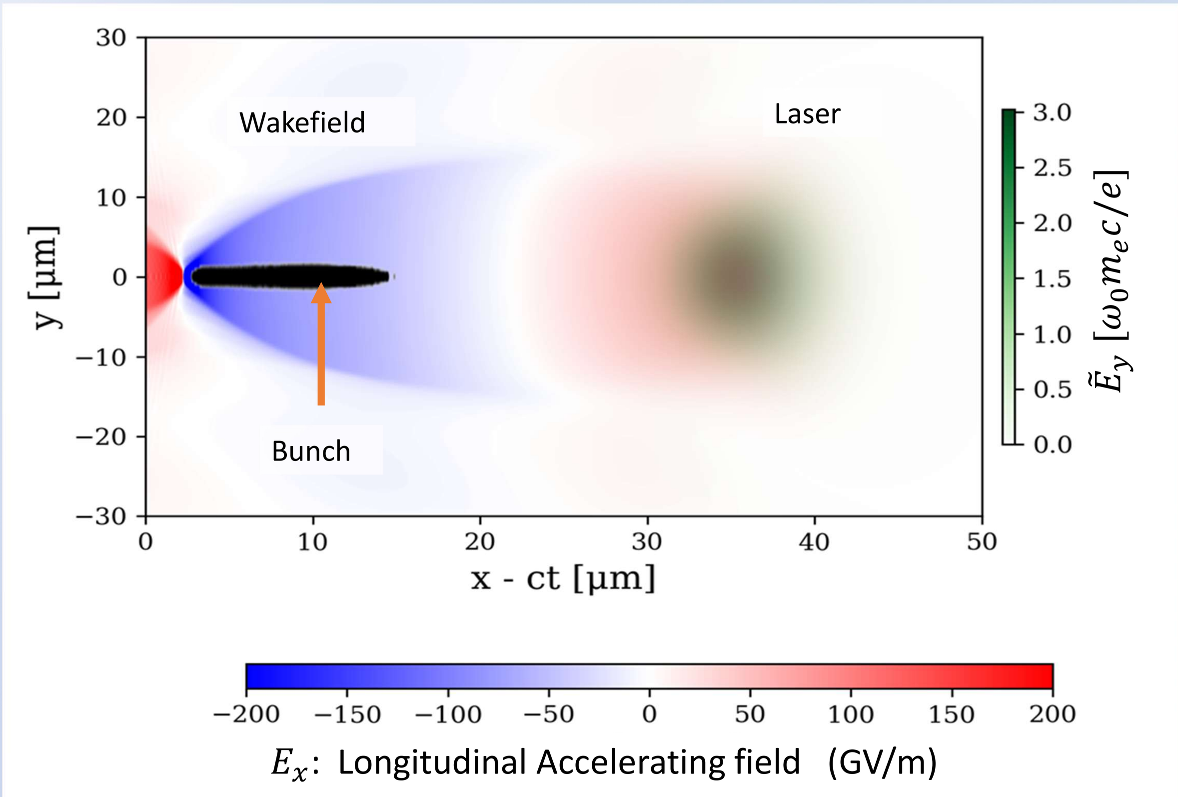
1. Nitrogen ramp
   Injection occurs inside the ramp.
   The length of the ramp is a key parameter
2. Acceleration over length of plateau
3. Divergence control with outlet ramp
   - Adiabatic matching
   - Plasma lens



3. PIC Simulation with Smilei)

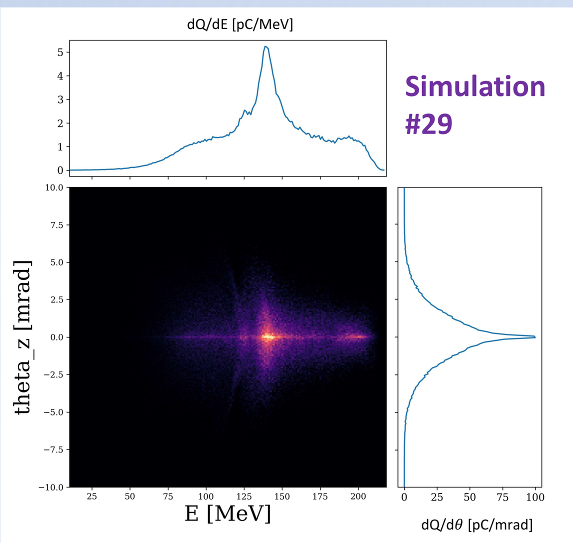
Electron beam dynamics in plasma

Snapshot at x = 3 mm

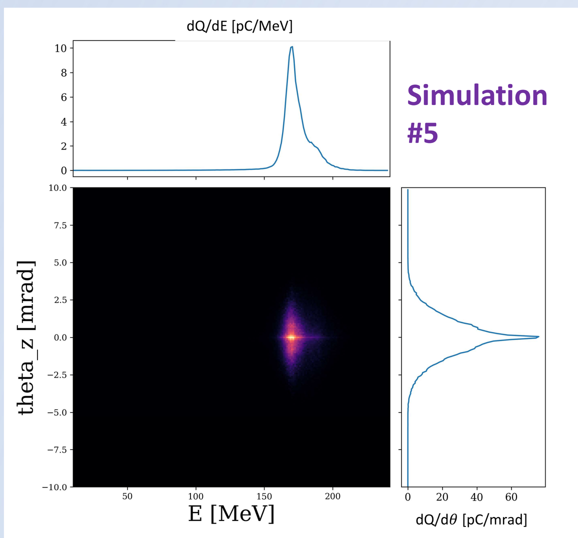


Spectra at x = 6 mm and $l_{N^2} = 1.8\ mm$

Simulation #29 focus x= 2.1 mm
Large charge and large energy spread



Simulation #5 focus x = 2.7 mm
Optimal energy spread



Simulation information

Smilei

- Laser envelope model
- Flattened Gaussian Beam order 8, $w_0 = 14\ \mu m$
- 2 particles per cell
- $dx = 0.15\ \mu m$, $dr = 0.35\ \mu m$

Run time: 256 cpu x 6 hrs

Openfoam

multicomponentFluid package combined with PIMPLE

- Run time: 20 cpu x 72 hours

4. Parametric Study with Gaussian Process

Effect of laser focus position and l_{N^2} on charge and energy spread

$$E_{MAD} = Median(E - Median(E))$$

$\Delta E_{FWHM} \approx 3.2\ E_{MAD}$ for Gaussian Distributions

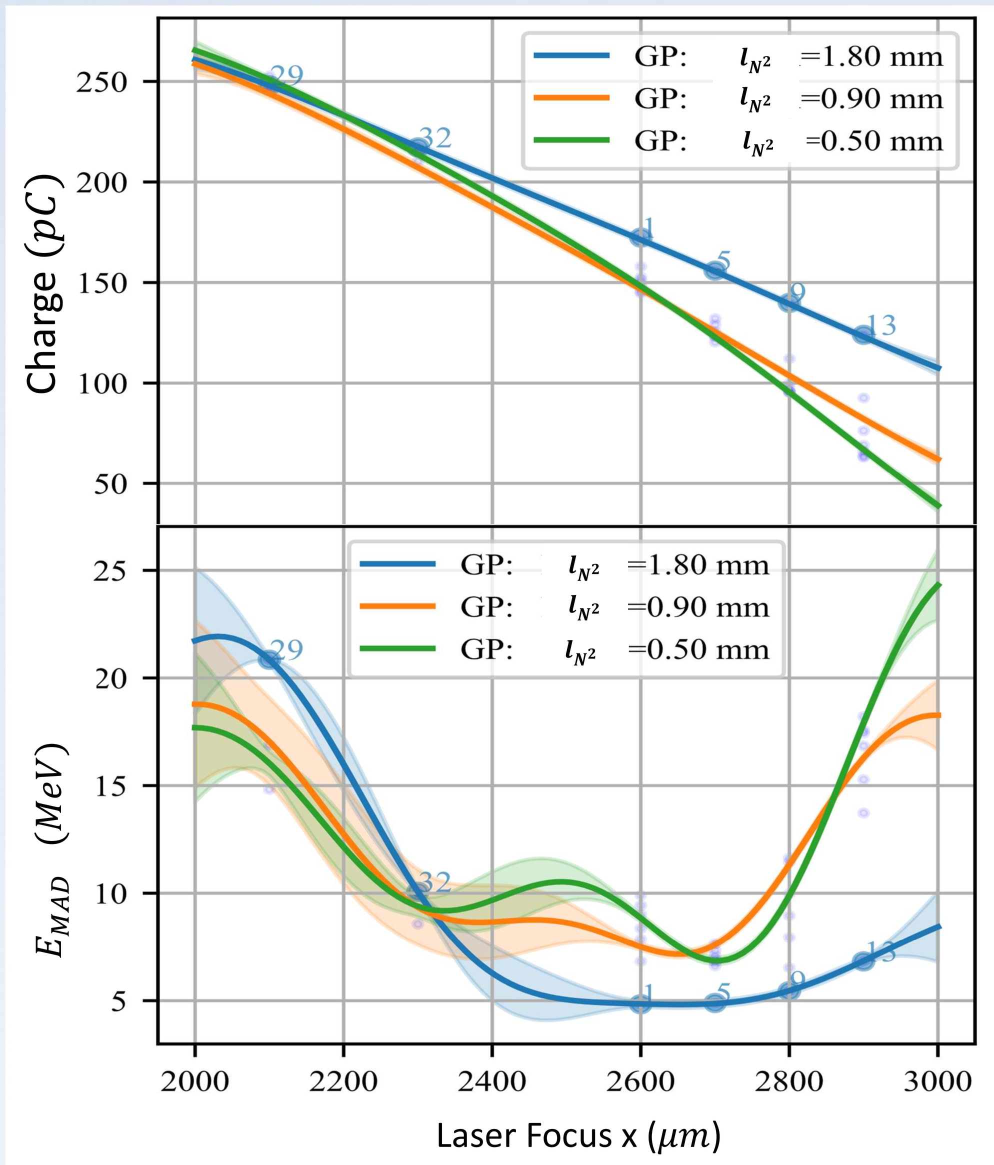
Parametric study:

- Here 36 Simulations
- Parameter 1: Nitrogen ramp length l_{N^2}
- Parameter 2: Laser focus position
- A Gaussian process is used to interpolate in unknown regions.

- The charge depends highly on the focus position.
- The nitrogen ramp length primarily modifies the shape of the spectrum (E_{MAD})
- $l_{N^2} < 1$mm is geometrically achievable

Laser fluctuations lead to fluctuations in spectra shape

Laser focus position fluctuates $> 100\ \mu m$ in experiments



Summary

- CFD simulations give the ability to predict and design density profiles
- CFD predicts the necessity of good pressure control $\Delta P < 1\ mbar$
- PIC simulations give the electron beams produced by laser Wakefield acceleration from the density profile.
- The length of the Nitrogen ramp and laser focus is key to producing good quality electron beams
- Optimal Nitrogen ramp predicted by PIC simulation is geometrically difficult in CFD/Experiment.

References

All references found here

- https://doi.org/10.48550/arXiv.2506.18047

Related Poster
Independent Control of Electron Injection and Acceleration in a Laser Plasma Accelerator - A. Panchal
Related Talk
Observation of improved electron beam quality from a LPA by post acceleration beam shaping.

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