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Experimental study of ionization-induced trapping in a laser wakefield accelerator

I. Gallardo González[1]*, M. Hansson[1], H. Ekerfelt[1], T. L. Audet[2], B. Aurand[1], F. G. Desforges[2], S. Dobosz Dufrénoy[3], A. Persson[1], C.-G. Wahlström[1], B. Cros[2], and O. Lundh[1]

[1]*Department of Physics, Lund University, P.O. Box 118, 22100 Lund, Sweden*
[2]*LPGP, CNRS-Université Paris-Sud 11, 91405 Orsay, France*
[3]*IRAMIS, LIDyL, CEA, Saclay, 91191 Gif-sur-Yvette, France*

Abstract

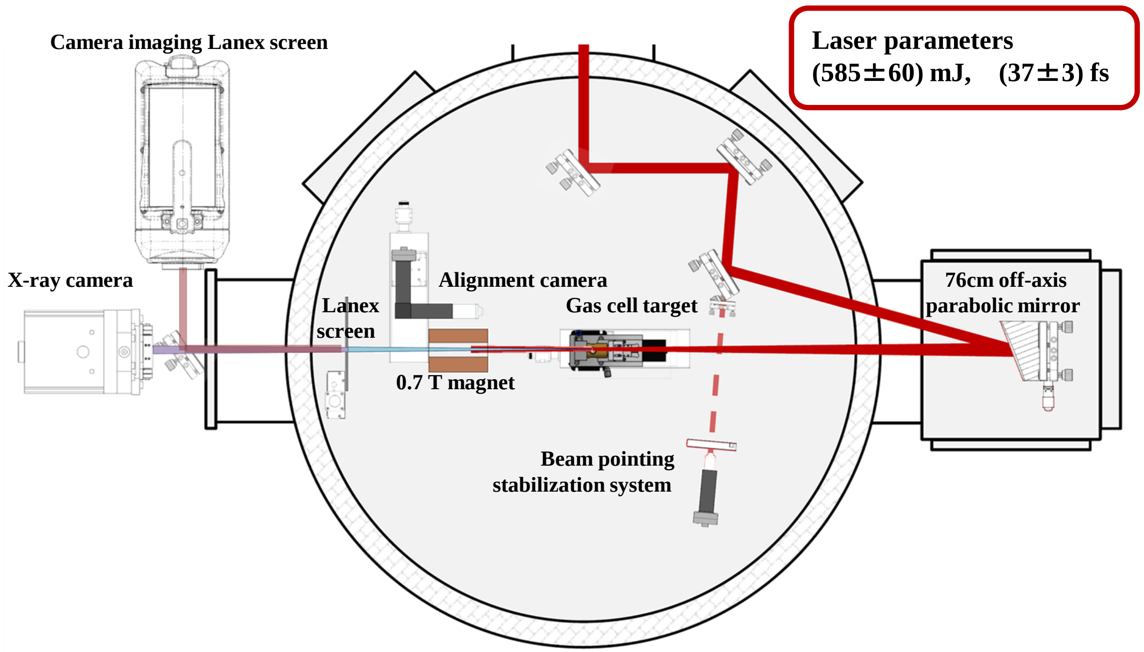
Since its first experimental manifestations, laser-wakefield acceleration has been considered a promising scheme for the generation of relativistic electrons. However, to be considered as an alternative to conventional electron beams sources, the electron beam must be stable, and its energy, charge and emittance must be controlled.

Ionization injection is able to increase the charge and decrease the divergence of the electron beams by adding a low percentage of a high atomic number gas, such as nitrogen, in a low atomic number gas, such as hydrogen. The inner shell electrons of the high atomic number gas are ionized only close to the maximum intensity of the laser pulse. This effect is used to control their injection in the plasma wave. The accelerated beams are also more stable and reproducible than the obtained with the pure low-Z gas.

In this work we study the influence of the N_2/H_2 gas mixture ratio on the generated electron beam parameters. The multi-terawatt laser beam at the Lund Laser Center (LLC) was focused to a peak intensity above 10^{18} W/cm^2 on a gas cell filled with the gas mixture. We analyse the electron beams charge, energy and divergence obtained when exploring different N_2 concentrations and electron densities.

Experimental set-up

Pulses from the multi-terawatt laser system at the Lund Laser Centre are focused at the entrance of a variable-length gas cell, filled with a mixture of hydrogen and a small concentration of nitrogen (up to 5.0%). The focal spot, optimized with a deformable mirror, has a size of 17 μm (FWHM), giving a peak intensity in vacuum estimated to $(3.0 \pm 0.5)\cdot 10^{18}$ W/cm^2.

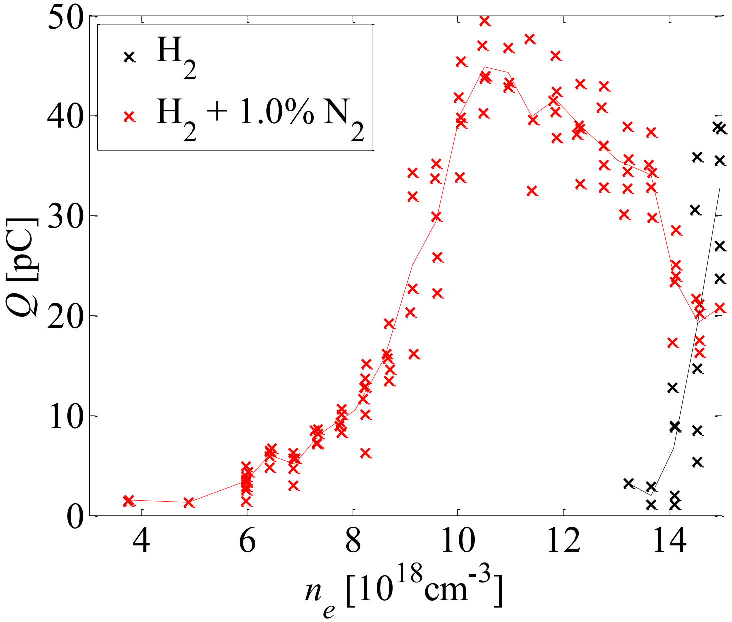


Influence of the N_2 concentration on the charge

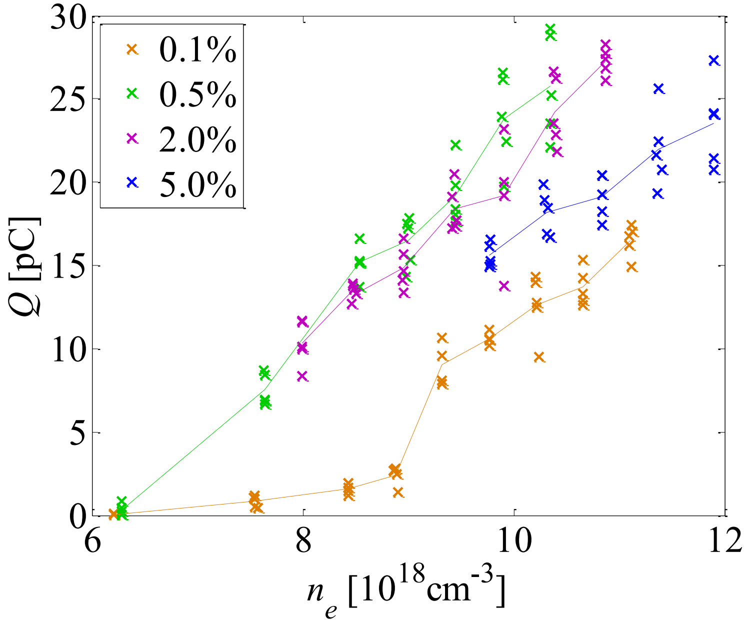
The presence of nitrogen molecules lowers the trapping electron threshold in comparison with pure hydrogen. Nevertheless, the total charge measured after the dipole magnet for electrons with energies above 45 MeV stops increasing when increasing the nitrogen concentration above 0.5%.

We compare the electron trapping threshold for two different gas cell configurations: on the left, with and without the presence of nitrogen molecules on the gas target [1]; and on the right, for different nitrogen concentrations filling the gas cell.

700 μm long gas cell



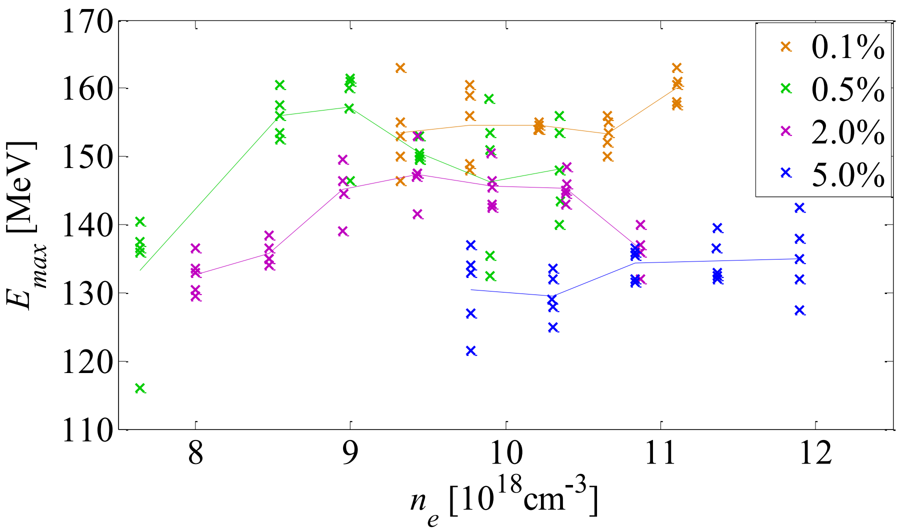
800 μm long gas cell

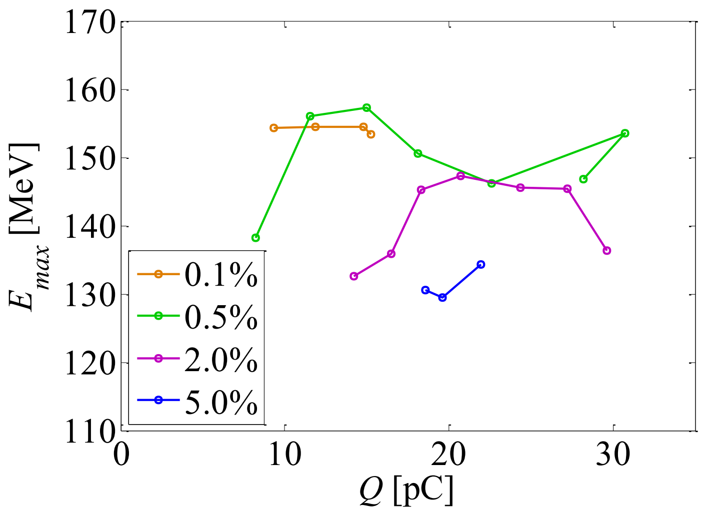


[1] Hansson M. *et al*, "*Localization of ionization-induced trapping in a laser wakefield accelerator using a density down-ramp*", submitted to New J. Phys.

Influence of the N_2 concentration on the maximum energy

The accelerated electrons can reach higher energies at low concentration of nitrogen on the gas target.

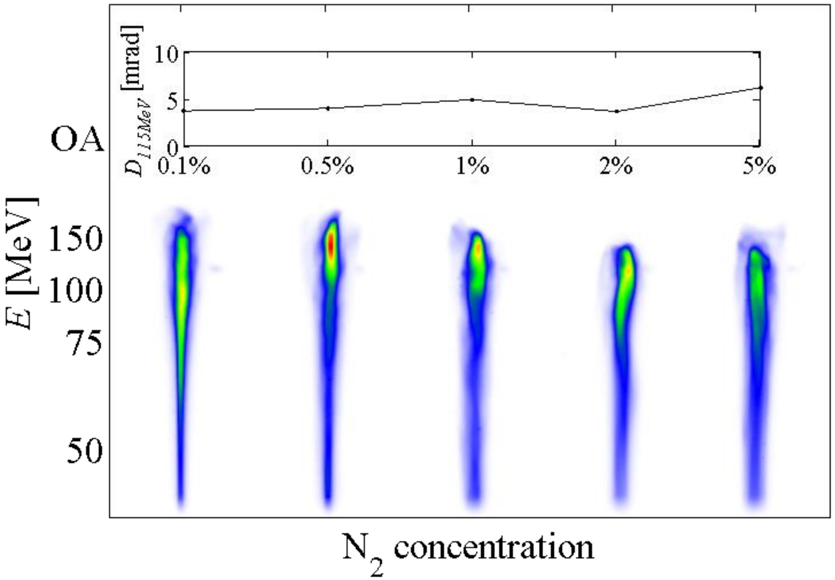


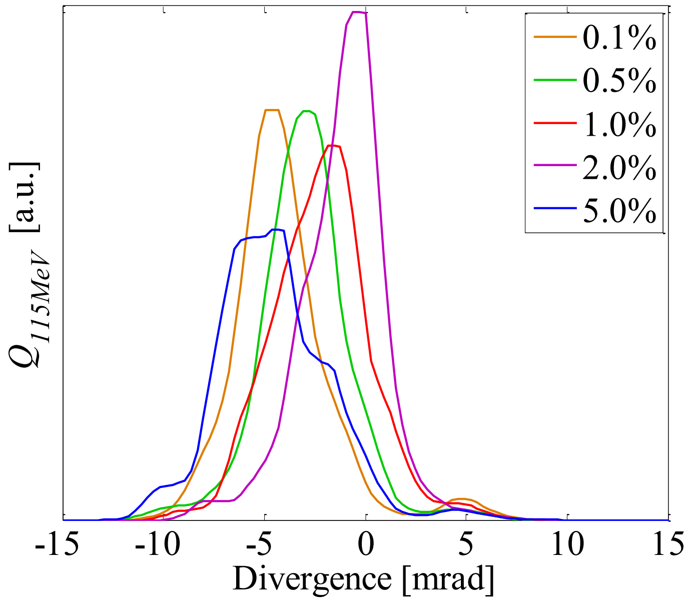


There is a tendency to get a lower maximum electron energy when measuring more charge after the magnet dipole on the lanex screen for all the concentrations.

Influence of the N_2 concentration on the beam divergence

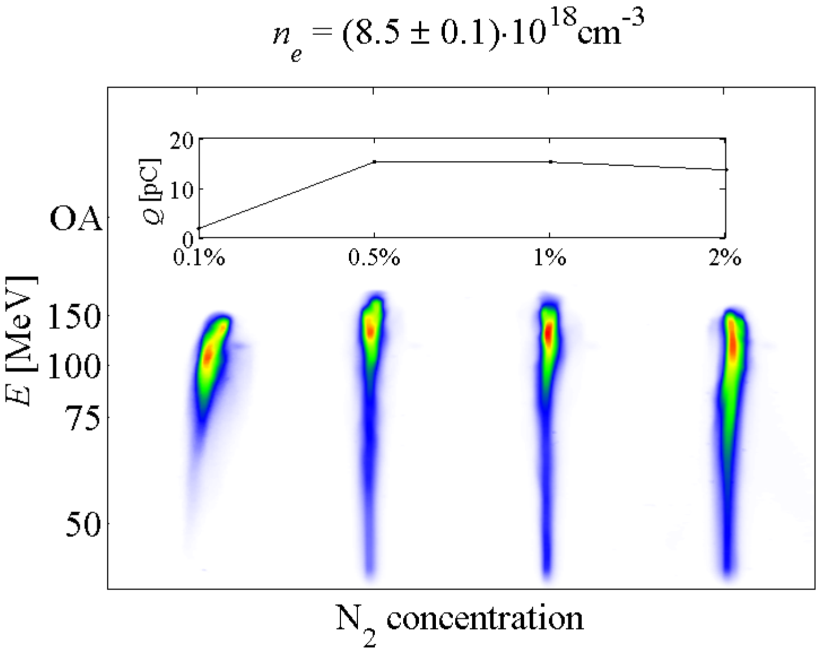
The divergence of the dispersed electron beam is compared for the same measured charge (15.3 ± 0.6) pC generated using different nitrogen concentrations, and it is measured as the FWHM of the transversal electron beam trace at a level equivalent to 115 MeV. The divergence increases (from 3.7 to 6.2 mrad) when the nitrogen concentration is increased.

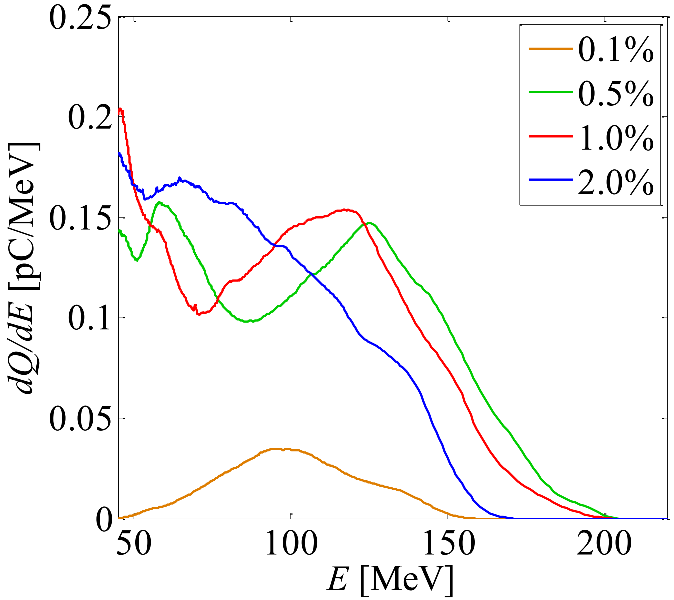




Influence of the N_2 concentration on the spectrum

At low electron densities, the electrons accelerated in 0.1% of nitrogen gas mixture have a peaked electron spectrum around 100 MeV. The extracted spectra show that the peak around 100 MeV vanishes as the N_2 concentration increases.



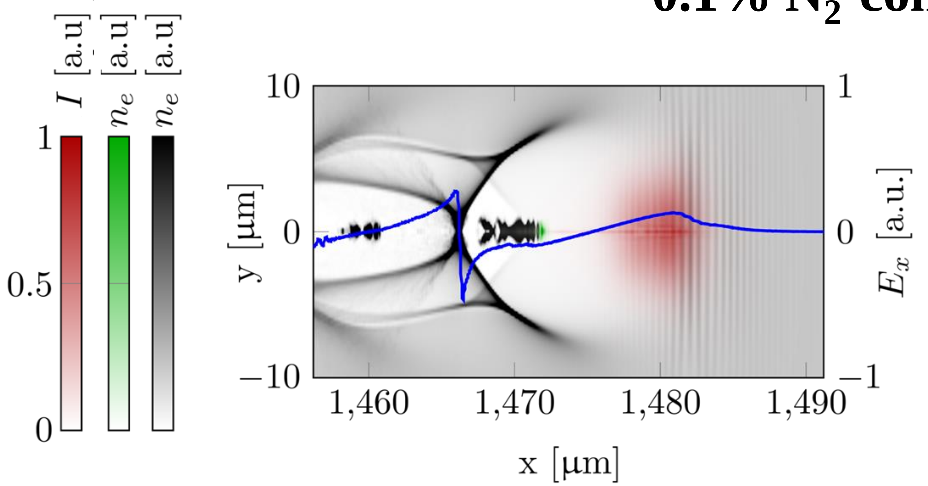


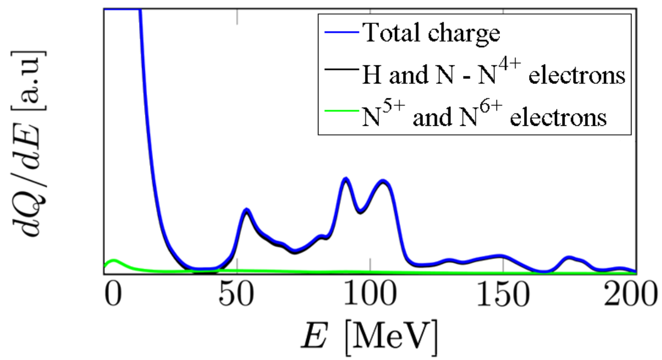
3D PIC simulations

A gas cell with a 800 μm inner length and filled to an electron density of $9.9 \cdot 10^{18}$ cm^{-3} is simulated with the relativistic 3D particle-in-cell code CALDER-Circ [2]. The simulations are performed for the same concentrations of nitrogen on the hydrogen gas as in the experiment. The laser pulse is defined by the experimental parameters.

The density down-ramp at the exit of the gas cell is able to trap the background electrons and accelerate them to high energies. Nevertheless, the density down-ramp trapping mechanism is suppressed by the presence of ionization injected charge, larger for higher nitrogen concentrations.

0.1% N_2 concentration





[2] Lifschitz A. *et al*, "*Particle-in-Cell modelling of laser-plasma interaction using Fourier decomposition*", J. Comput. Phys **228**, 1803-1814 (2009).

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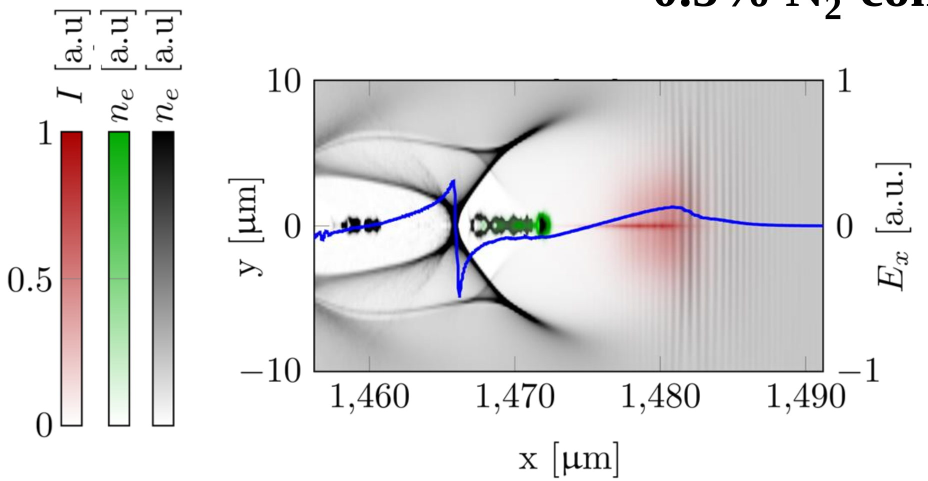
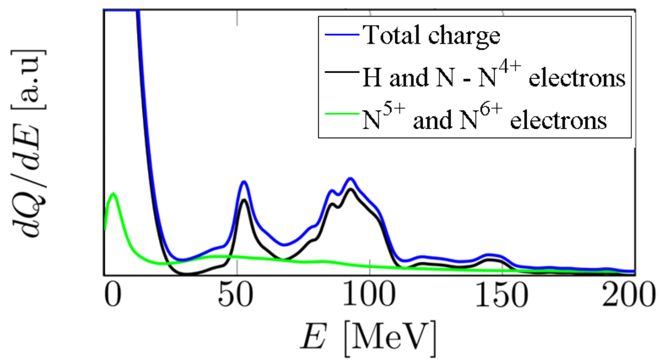
0.5% N_2 concentration





[2] Lifschitz A. *et al*, "*Particle-in-Cell modelling of laser-plasma interaction using Fourier decomposition*", J. Comput. Phys **228**, 1803-1814 (2009).

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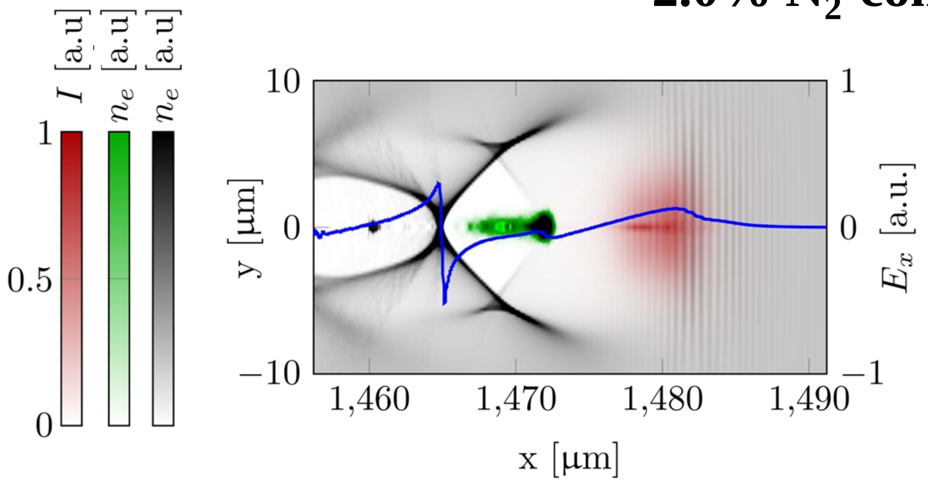
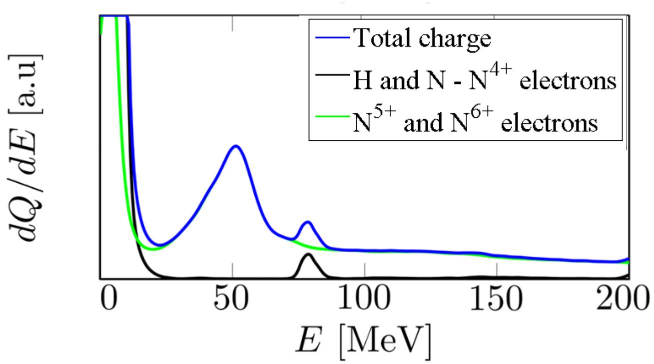
2.0% N_2 concentration





[2] Lifschitz A. *et al*, "*Particle-in-Cell modelling of laser-plasma interaction using Fourier decomposition*", J. Comput. Phys **228**, 1803-1814 (2009).

Conclusion

The effect of the nitrogen concentration on the gas mixture in the electron trapping process affects the electron charge, maximum energy, divergence and spectrum. The comparison with CALDER-Circ Particle-In-Cell simulations suggests a suppression of the density down-ramp injection due to ionization injection in the plasma wave.