High-Energy OPCPA at Lund Laser Centre and its Application to LWFA

Andrea Angella*, E. Löfquist , C. Gustafsson, C. Guo, V. Poulain, F. D'Souza, A. Persson, C.G. Wahlström and O. Lundh.

DEPARTMENT OF PHYSICS, LUND UNIVERSITY, SWEDEN. *andrea.angella@fysik.lth.se

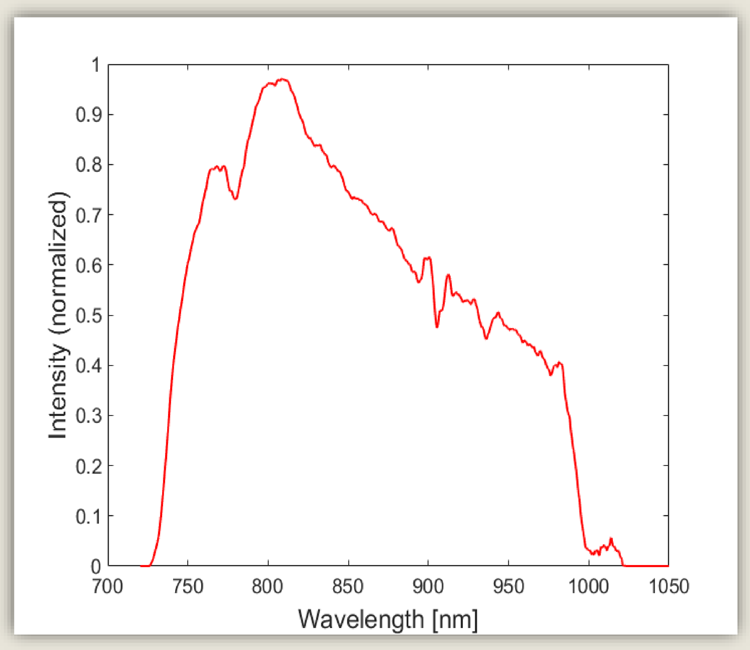
The high-energy OPCPA laser system

The new multi-terawatt laser at the **Lund High Power Laser Facility** was developed in collaboration with Light Conversion and is based on **O**ptical **P**arametric **C**hirped **P**ulse **A**mplification **(OPCPA)** technology. It is a modern, high-performance system featuring active pointing stabilization and multiple pulse characterization diagnostic stations.

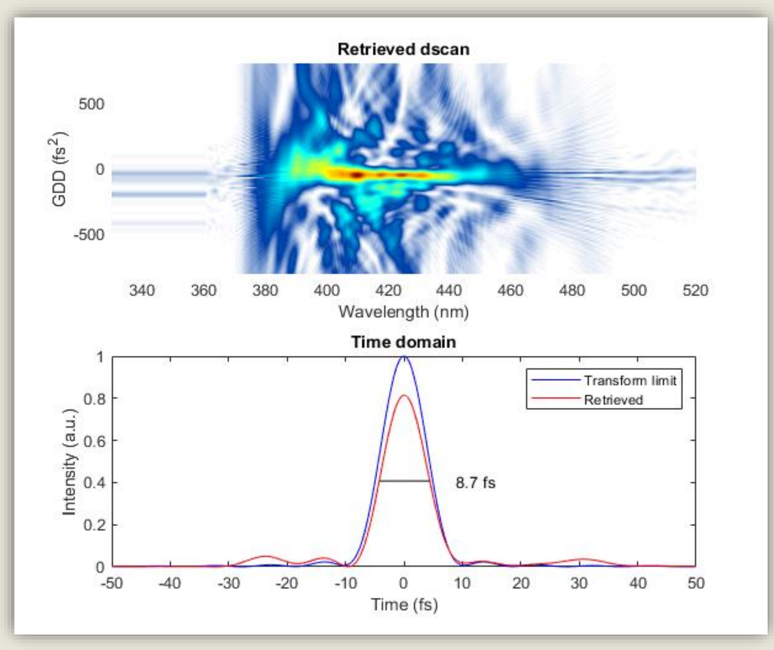
Pulse characteristics: 9 fs | 850 nm | CEP stable | 250 mJ (@ 10 Hz) | 50 mJ (@ 100 Hz)

Why OPCPA? It offers various advantages over traditional Ti:Sapphire-based systems:

- **Broad bandwidth:** Unlike Ti:Sapphire amplifiers, where the gain bandwidth limits pulse duration, OPCPA provides inherently broad amplification bandwidths. This allows for amplified pulses as short as a few fs.
- **High power:** In Ti:Sapphire systems, thermal effects limit the achievable energy and repetition rate. OPCPA is a non-thermal amplification process enabling high pulse energies without thermal distortion.
- **CEP control:** **C**arrier-**E**nvelope-**P**hase (**CEP**) stability is obtained thanks to non-linear amplification, which preserves the phase of the seed pulse. The CEP set point can also be controlled with glass wedges.
- **High temporal contrast:** Ti:Sapphire amplifiers suffer from **A**mplified **S**pontaneous **E**mission (**ASE**). OPCPA amplifies only the seed pulse without introducing ASE, resulting in superior temporal contrast.



Measured laser spectrum

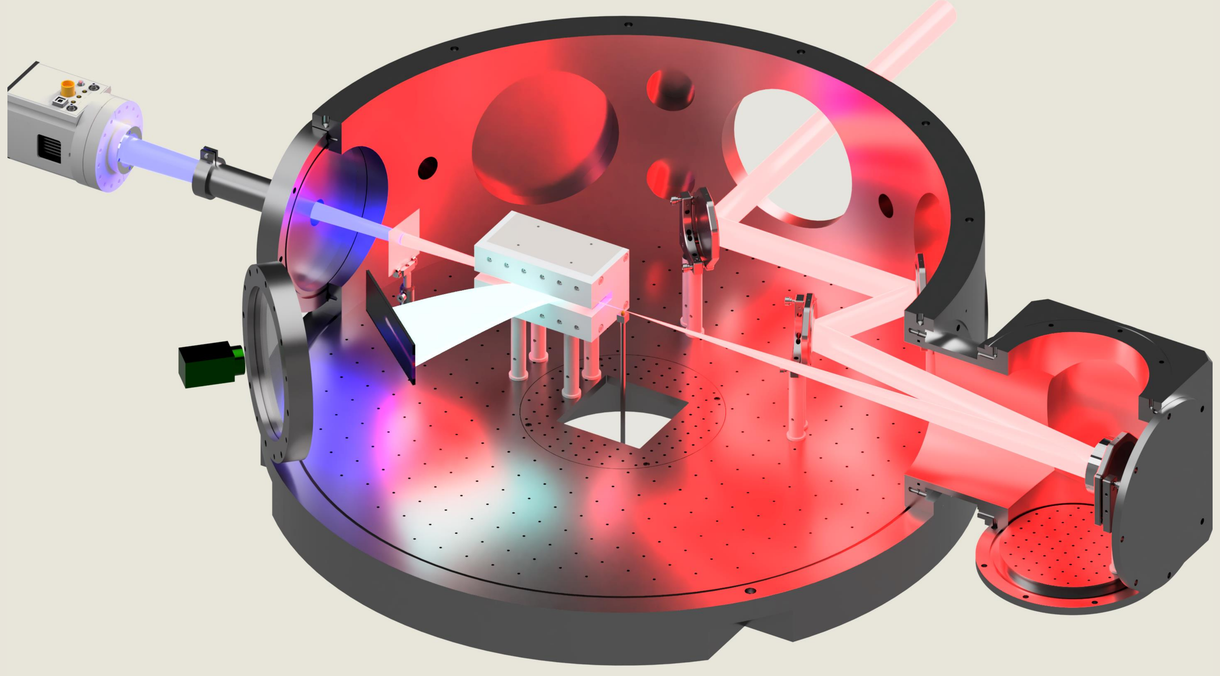


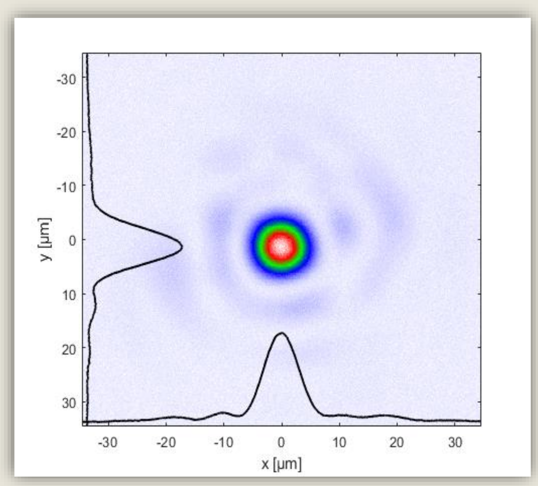
D-scan measurement and retrieval

Experimental setup

Parameters such as laser energy, gas jet backing pressure, CEP set point, **G**roup **D**elay **D**ispersion (**GDD**) and focus position can be tuned in the experiment. Adaptive optics is used to correct aberrations in the spatial profile of the laser, allowing a close to diffraction-limited focal spot.

An off-axis parabolic mirror (f = 775 mm) focuses the 50 mm laser beam to a 15 µm spot (FWHM), above a 1.5 mm wide supersonic gas jet (99:1 helium + nitrogen mixture) reaching optical intensities on the order of 10^{19} W/cm². The accelerated electrons are dispersed to a phosphor screen (Lanex) with a 20 cm long 0.8 T permanent dipole magnet.

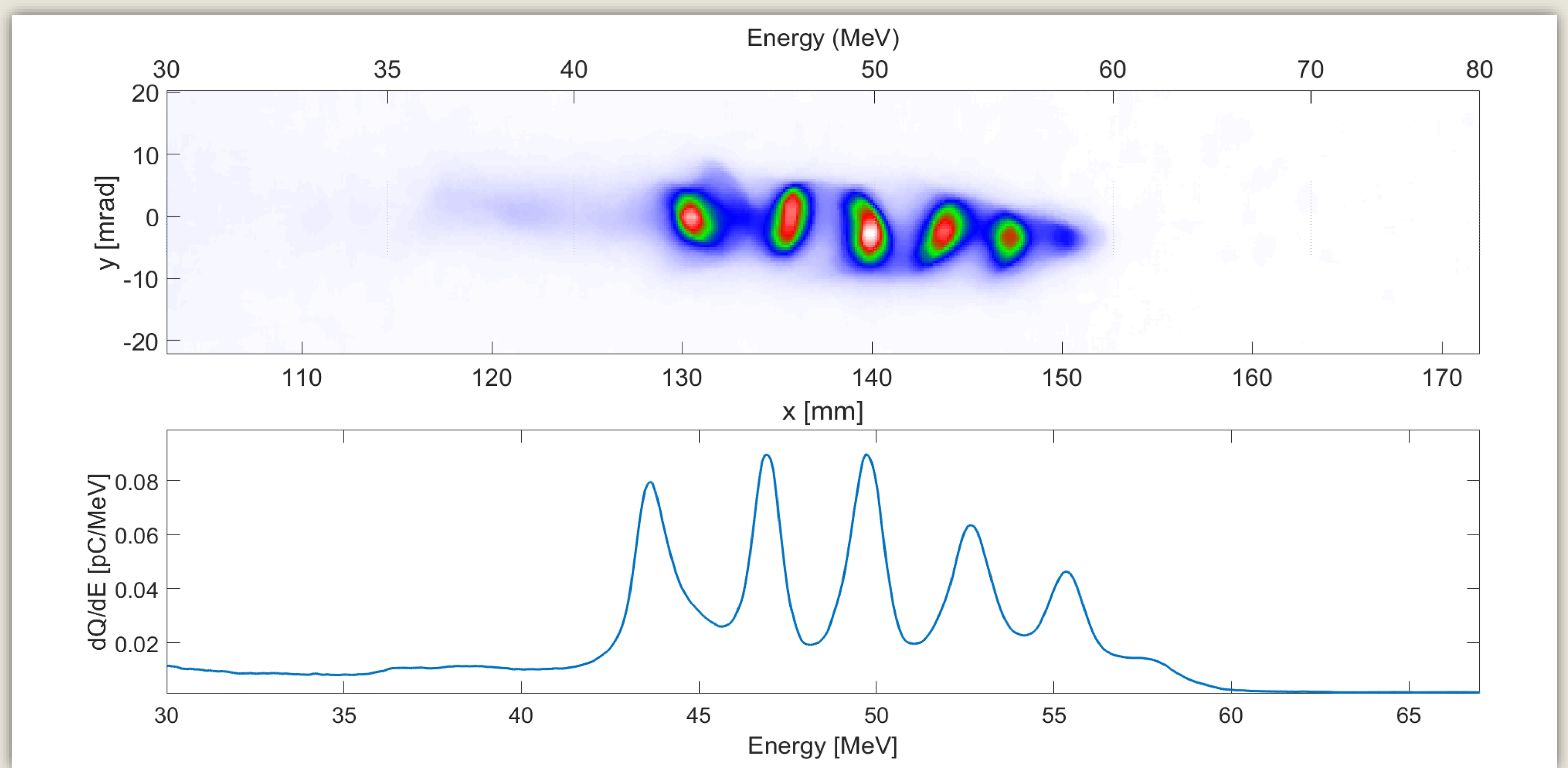




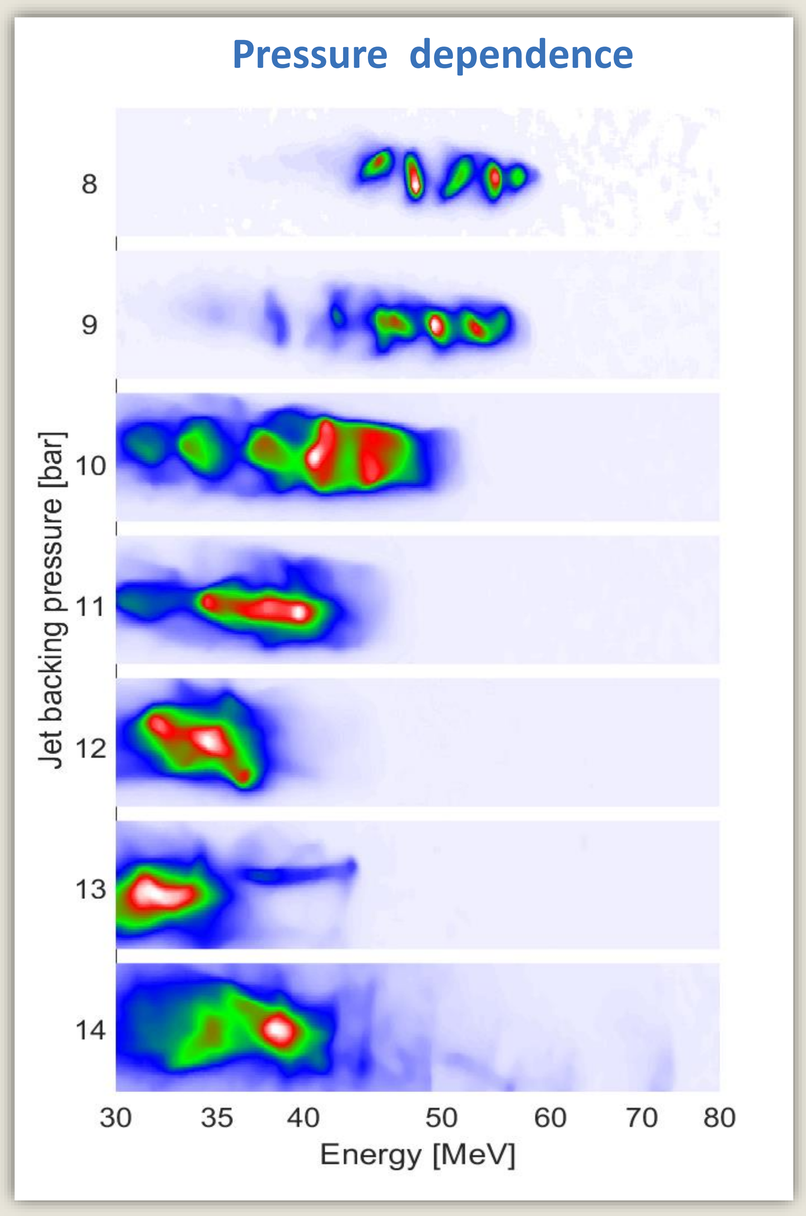
Laser focal spot

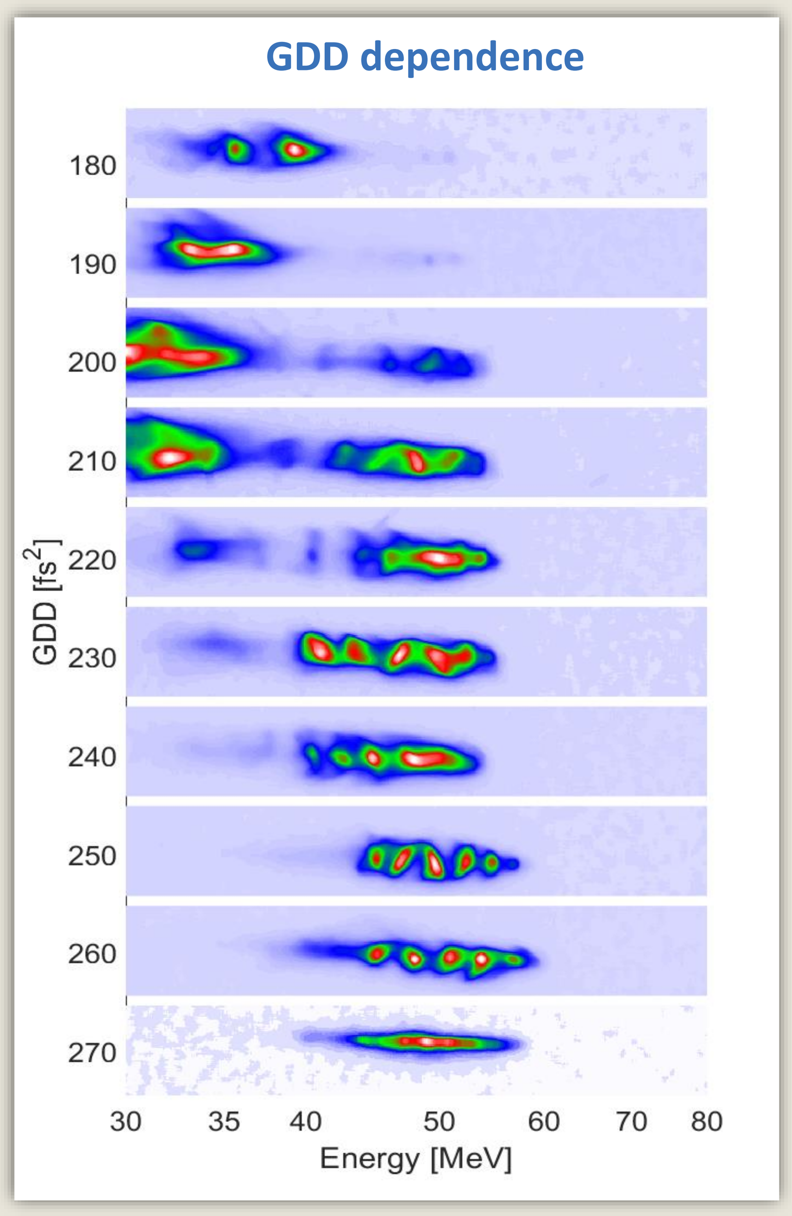
Energy modulations in the few-cycle regime

The figures below show a typical electron spectrum in the few-cycle regime, when working with a gas mixture for ionization injection. The uppermost figure is the raw spectrum as imaged on the Lanex screen. The lowermost picture shows the spectrum in a linear energy scale. The laser energy for this particular shot was 220 mJ, and the backing pressure of the jet was 9 bars. The modulations are not present when using pure helium, indicating that this is an effect of ionization.



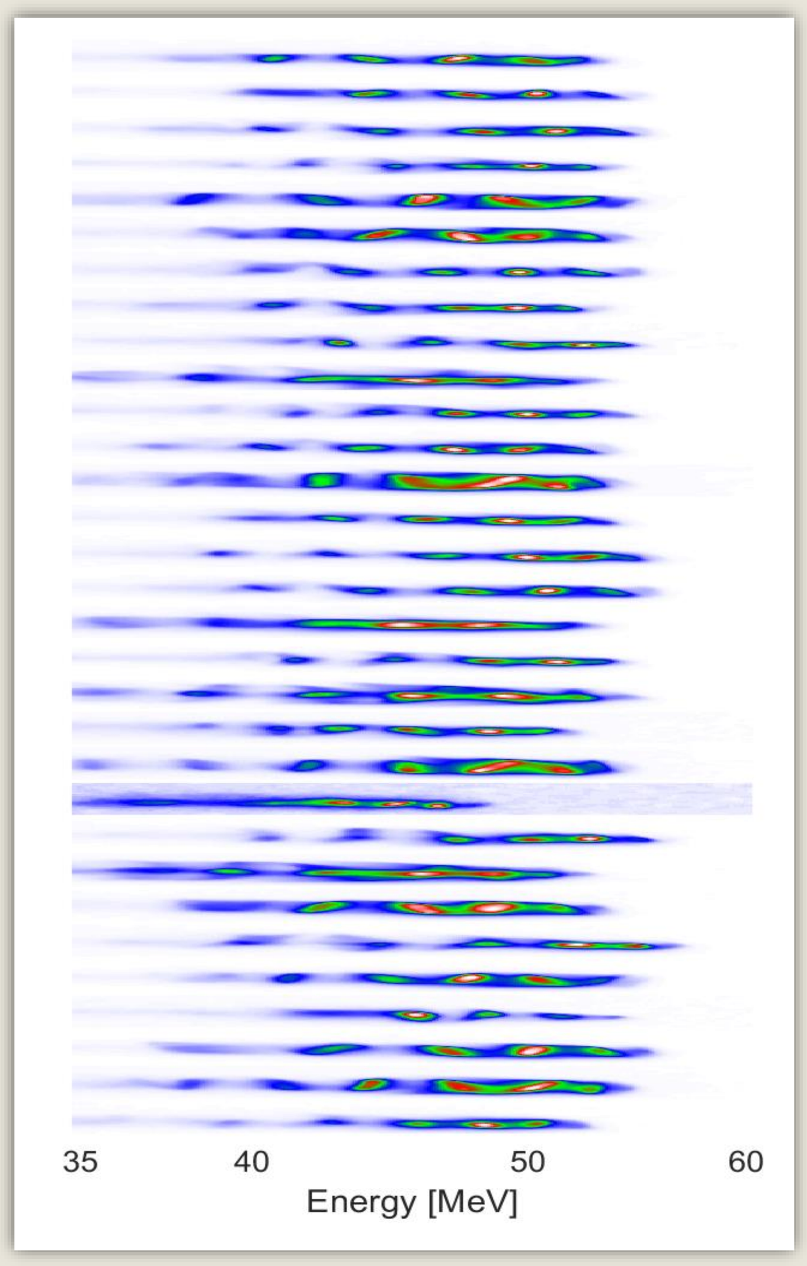
Pressure and energy dependence

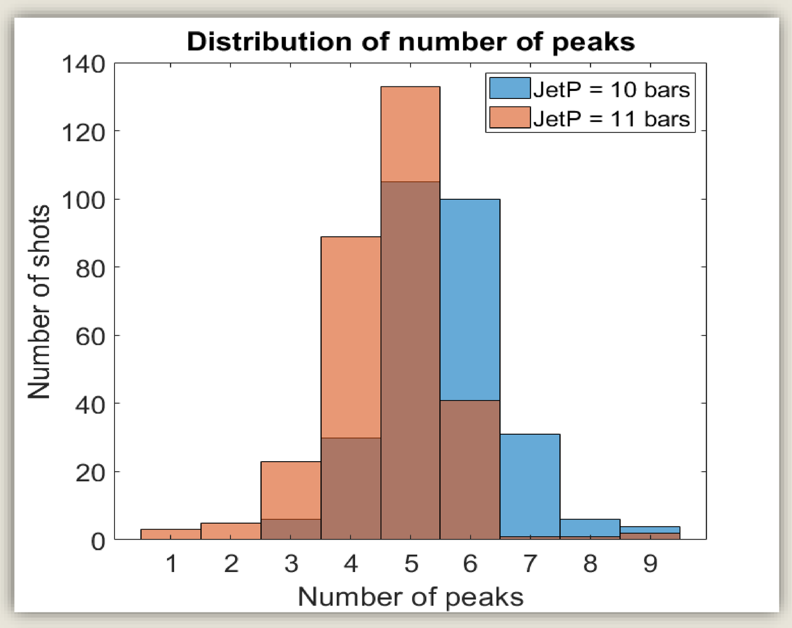


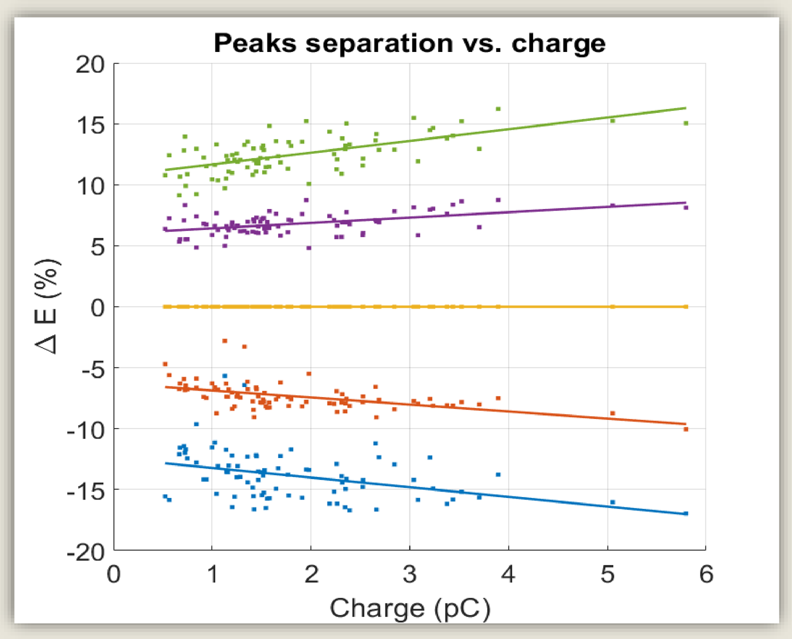


Selected shots from two distinct scans of 10 shots per setting. The counts have been normalized for each shot to better display the behavior of the modulations and their energies. While changing the pressure, the GDD was kept at 250 fs². Below 8 bars, no electrons were detected. For the GDD scan, the pressure was 9 bars.

Repeatability and statistics

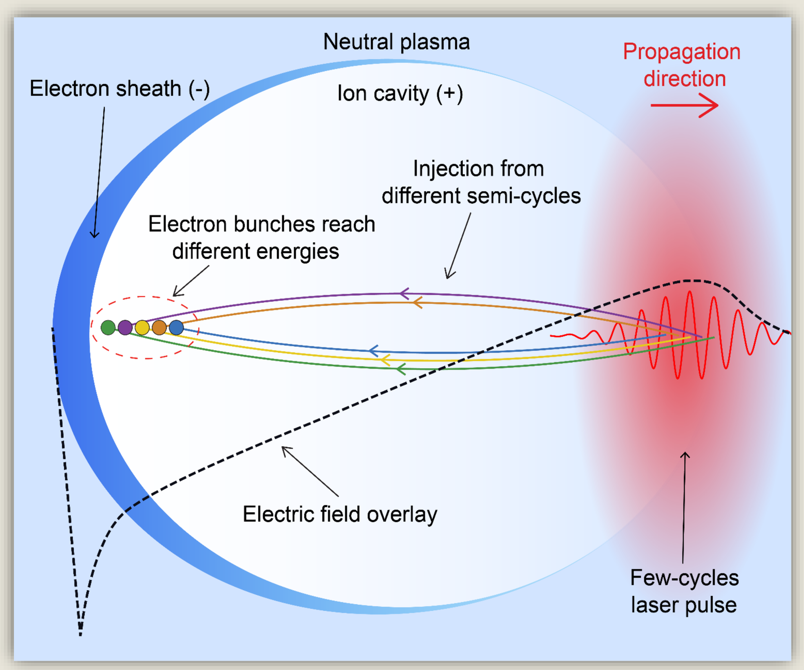






Left: 30 consecutive Lanex measurements from a total of 300 shots, obtained with a jet backing pressure of 10 bars, consistently showing modulations from shot to shot.
Top right: Distribution of the number of peaks over two different data sets of 300 shots per pressure.
Bottom right: Relative energy displacement of the spectral peaks vs. total bunch charge. Each point is a different peak of the 105 measurements at 10 bar with 5 peaks. Colors indicate peak index. The displacements are expressed in percentage from the middle peak (3rd peak).

Ionization mechanism



As the laser propagates through the plasma, different semi-cycles of the laser can locally ionize the nitrogen atoms in time, leading to intermittent trapping of electrons. This occurs also due to CEP slippage within the plasma, as the phase velocity is higher than the group velocity of the laser. Due to this, the bunches see different accelerating fields, thereby obtaining different final energies. This interpretation is based on a simulation study of few-cycle ionization injection by Lifschitz and Malka [New J. Phys. **14**, 053045 (2012)].