Ion acceleration from high-density transparent gas jets: towards high-repetition rate sources for fundamental science and applications

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This work investigates ion acceleration driven by the interaction of an ultra-intense ($> 10^{21}$ W/cm^2), ultra-short (<100 fs) laser pulse with a gaseous plasma target at near-critical electron density ($\sim 10^{21}$ cm^{-3}). In contrast to solid targets, where Target Normal Sheath Acceleration (TNSA) dominates, laser–gas interactions rely on alternative acceleration mechanisms that typically generate ions with broad angular distributions. Since many applications require forward-directed ion beams, achieving efficient direct acceleration demands precise control of the interaction parameters.

Particle-in-cell (PIC) simulations were performed to study ion acceleration under conditions compatible with multi-petawatt laser facilities. A parametric study was conducted by varying the laser intensity and pulse duration, and ion momentum distributions were analyzed to extract forward-directed energy spectra. The results reveal the existence of optimal laser parameters that maximize the on-axis ion cut-off energy, reaching values of several tens of MeV. This study identifies a well-defined and experimentally accessible parameter window, which will be directly tested at the ELI-NP (Romania) and Apollon (France) multi-petawatt laser facilities.

In parallel, the optimization of gas-jet density profile in order to enhance efficient ion acceleration was investigated. Conventional nozzles produce extended low- to moderate-density wings ($10^{18} - 10^{20}$ cm^{-3}) over several hundred microns, which can significantly degrade the laser pulse before it reaches the peak density region. To address this issue, a complementary study focuses on the optical shaping of gas jets using a nanosecond laser pre-pulse. Hydro-radiative simulations performed with the FLASH code model target shaping using a Nd:YAG laser pulse ($\sim$ 8 ns, 1 J) with either Gaussian or Laguerre–Gauss intensity profiles. First results indicate that a Laguerre–Gauss profile enables the formation of an overcritical-density plasma ($> 10^{21}$ cm^{-3}) from an initially sub-critical gas target ($< 10^{20}$ cm^{-3}), thereby improving target conditions for efficient ion acceleration.