Laser wakefield acceleration of ions with a transverse flying focus

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Generating GeV-class ion beams using compact, high-repetition-rate laser-plasma interactions remains a grand challenge due to the low charge-to-mass ratio of ions. Traditional laser-ion acceleration methods, such as TNSA and shock acceleration, suffer from limited energy gains, poor beam quality, and low repetition rates. In this work, we present a novel ion acceleration scheme that leverages a transverse flying focus (TFF) laser configuration to realize laser wakefield acceleration (LWFA) of ions in underdense plasma [1]—a mechanism previously thought to be infeasible for heavy particles.

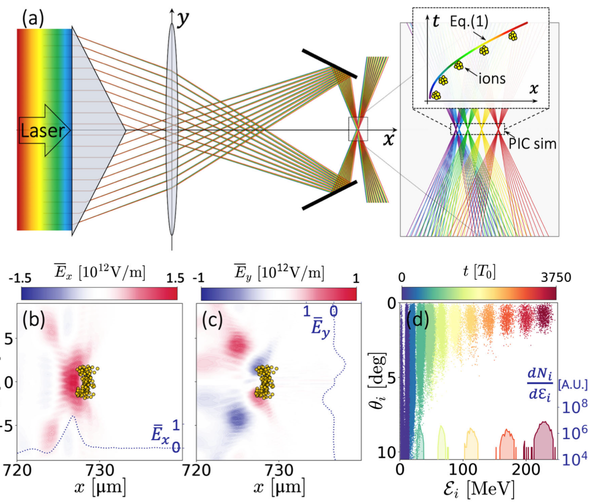

Figure 1, (a) Schematic of an axisymmetric transverse flying focus, where solid lines represent light ray propagation and colors denote frequency components. The panel at right shows details near focus. PIC simulations are conducted within the dashed black box, where the inset shows flying-focus position as given by Eq. (1). (b)–(d) 3D PIC simulations. Distribution of (b) Ex and (c) Ey at t=3150T0. In (b) and (c), yellow dots show trapped protons with electric fields shown by blue dotted lines. (d) The proton distribution in energy-angle space for different times.

By engineering a laser pulse whose focal spot moves transversely to the propagation direction, we sustain a co-moving electrostatic potential that traps and synchronously accelerates ions from rest. Three-dimensional particle-in-cell (PIC) simulations demonstrate that this relativistic-intensity TFF configuration produces monoenergetic, collimated proton beams with peak energy 1.64 GeV, 3.7% energy spread, and 23.1 pC charge, over an acceleration distance of just 4.4 mm, using a 0.8 kJ, 21 ps laser pulse [1].

We develop an analytic trapping criterion based on a conserved Hamiltonian in the co-moving frame [1-3], which predicts ion trapping and acceleration efficiency across a wide range of parameters. The resulting energy gain agrees with theory, reaching acceleration gradients of ~ GeV/cm. Unlike conventional schemes, our approach avoids high-Z targets, prepulse-induced damage, and severe instabilities, making it scalable and compatible with existing high-power laser systems [1].

This demonstration of ion LWFA using TFF opens a pathway to high-flux, high-energy ion sources suitable for applications in hadron therapy, nuclear physics, and laboratory astrophysics. The optical flexibility of the TFF platform further suggests its applicability to other advanced plasma photonics applications, including electron acceleration, photon acceleration, and ultrafast x-ray or XUV generation.

References

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