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Holographic visualization of laser wakefields

Focus on Laser- and Beam-Driven Plasma Accelerators

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Abstract

Part of Focus on Laser- and Beam-Driven Plasma Accelerators

We report 'snapshots' of laser-generated plasma accelerator structures acquired by frequency domain holography (FDH) and frequency domain shadowgraphy (FDS), techniques for visualizing quasi-static objects propagating near the speed of light. FDH captures images of sinusoidal wakes in mm-length plasmas of density $1 < n_e < 5\times10^{18}$ cm^{-3} from phase modulations they imprint on co-propagating probe pulses. Changes in the wake structure (such as the curvature of the wavefront), caused by the laser and plasma parameter variations from shot to shot, were observed. FDS visualizes laser-generated electron density bubbles in mm-length plasmas of density $n_e \geq 10^{19}$ cm^{-3} using amplitude modulations they imprint on co-propagating probe pulses. Variations in the spatio-temporal structure of bubbles are inferred from corresponding variations in the shape of 'bullets' of probe light trapped inside them and correlated with mono-energetic electron generation. Both FDH and FDS average over structural variations that occur during propagation through the plasma medium. We explore via simulations a generalization of FDH/FDS (termed frequency domain tomography (FDT)) that can potentially record a time sequence of quasi-static snapshots, like the frames of a movie, of the wake structure as it propagates through the plasma. FDT utilizes several probe–reference pulse pairs that propagate obliquely to the wake, along with tomographic reconstruction algorithms similar to those used in medical CAT scans.

GENERAL SCIENTIFIC SUMMARY

Introduction and background. Within the last six years, centimeter-long, laser-driven plasma accelerators, an idea first proposed thirty years ago, have been shown to be capable of producing mono-energetic, collimated GeV-range electron beams of a quality comparable to those from conventional accelerators. The quality and energy of the beam depend critically on sub-micrometer details of the laser-driven electron density structure on which the accelerating electrons surf. However, these details are usually known only from intensive computer simulations.

Main results. We demonstrate techniques for single-shot imaging of laser-plasma accelerator structures in the laboratory over a range of laser-plasma conditions. Frequency domain holography captures 'snapshot' images of sinusoidal wake oscillations in mm-length plasmas less than 10 per cent as dense as the atmosphere from the phase modulations they imprint on co-propagating probe pulses. We observe shot-to-shot variations in the period, curvature and amplitude of plasma waves, confirming simulation results. Frequency domain shadowgraphy visualizes laser-generated electron density bubbles, a key structure for mono-energetic electron production, in mm-length plasmas of nearly atmospheric density. When bubbles appear, they re-shape co-propagating probe pulses into optical 'bullets', which are correlated with monoenergetic electron spectra. Finally, we propose a generalized frequency domain tomography technique for capturing multiframe 'movies' of temporally evolving laser-plasma structures in a single shot by probing them at multiple oblique angles.

Wider implications. The ability to capture detailed shapshots and movies of elusive luminal-velocity plasma accelerator structures will help to understand the acceleration mechanism and to optimize and scale compact accelerators for future applications in high-energy physics, radiotherapy and molecular biology.

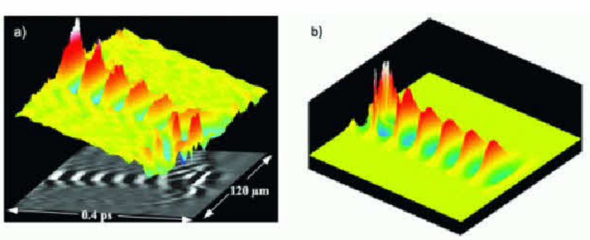

Figure. (a) Single-shot image of sinusoidal electron density oscillation propagating left to right behind drive laser pulse (not shown), captured by frequency-domain holography. Vertical scale of color plot shows phase change of probe pulse, which is proportional to local electron density; grey-scale image is a projection onto a plane. (b) Computer simulation of the plasma wave, showing agreement on main structural features: oscillation period, wavefront curvature, growth of wave amplitude behind drive laser pulse.

PACS

52.38.Kd Laser-plasma acceleration of electrons and ions

29.20.-c Accelerators

41.75.Jv Laser-driven acceleration

42.40.-i Holography

52.65.-y Plasma simulation

Subjects

Accelerators, beams and electromagnetism

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