# Ultrafast Laboratory Snapshots and Movies of Intense Laser-Plasma Interactions

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**Abstract:** I will describe ultrafast holographic and tomographic methods for single-shot visualization of refractive index structures created by intense laser or charged particle pulses, including plasma wakefields, plasma bubbles, ionization fronts, and self-focusing filaments.

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## 1. Introduction

Our ability to see small, inaccessible or distant objects accurately is fundamental to scientific advance. Indeed throughout the history of science, new visualization tools (*e.g.* telescope, CT scan, scanning probe microscope) have revolutionized fields of study (*e.g.* astronomy, medicine, solid state physics, respectively). Here I will describe recently developed methods for visualizing objects that move at the speed of light in the wake of ultra-intense laser pulses or particle bunches. Details of such micrometer-scale, luminal-velocity plasma structures are traditionally known only through intensive computer simulations based on estimated initial conditions. Laboratory visualization opens them to direct, immediate view, and promotes the understanding, optimization and scaling of plasma-based particle and x-ray sources. Since intense pulses are usually available only at low repetition rate with significant shot-to-shot fluctuations, single-shot imaging is essential. I will first review single-shot holographic methods for obtaining “snapshots” of quasi-static light-velocity objects --- *i.e.* those that retain approximately the same shape as the drive pulse propagates through a medium. I will then describe emerging single-shot tomographic methods for producing multi-frame “movies” of objects that evolve significantly during the drive pulse propagation.

## 2. Visualization of quasi-static light-velocity objects

Frequency-domain holography (FDH) [1] yields detailed snapshots of quasi-static light-velocity objects. In FDH, a wide-bandwidth, temporally extended, loosely focused probe pulse co-propagates through the medium with the drive pulse, illuminating the entire refractive index object $\Delta n(\zeta_{ob}, r_{ob})$ at once. Here $\zeta_{ob}$ denotes distance behind the drive pulse, $r_{ob}$ distance from the propagation axis. Interference of this probe with a temporally advanced “reference” pulse at the detection plane of an imaging spectrometer encodes the object’s phase and amplitude structure, which is subsequently “read” by Fourier transform methods to reconstruct the object in a single shot.

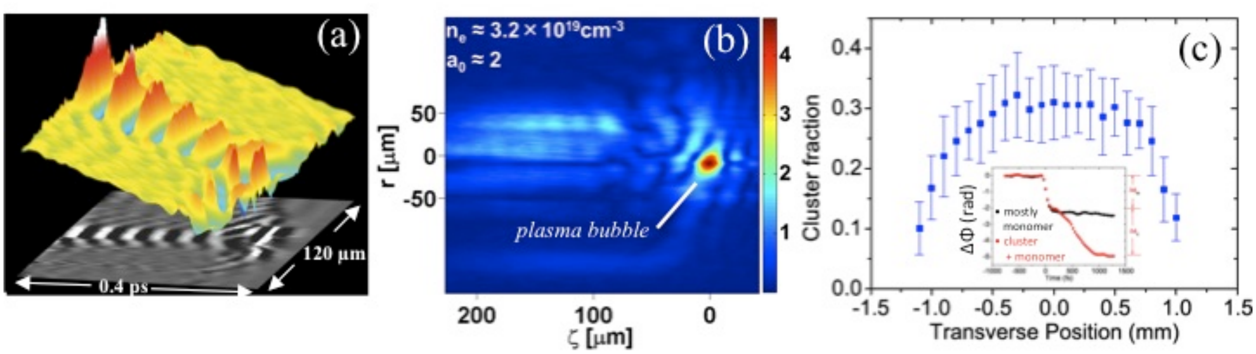


**Fig.1:** Examples of single-shot images obtained via frequency-domain holography. **(a)** Weakly nonlinear plasma wake behind intense laser pulse (not shown) propagating left to right. Vertical axis is probe phase shift, proportional to local plasma density; grey-scale is a 2D projection of the 3D false-color plot. Curved wave fronts, and peaks that grow, spike and eventually break behind the drive pulse reveal relativistic plasma dynamics. **(b)** Bright “optical bullet” from probe light trapped inside a plasma bubble created by intense laser pulse propagating from left to right. Such images reveal bubble formation and shape independently of electron acceleration. **(c)** Inset: single-shot measurement of 2-step refractive index dynamics (red curve) in a clustered gas jet, showing rapid monomer ionization and delayed cluster expansion, contrasted with 1-step dynamics (black curve) due to monomer ionization alone. Main panel: cross sectional profile of cluster fraction in a supersonic gas jet, obtained from single-shot measurements like those shown in inset.

Figure 1 shows several examples of FDH images that I will discuss in detail: (a) a plasma wake behind a multi-terawatt 30 fs drive laser pulse [1]; (b) a plasma "bubble" that, because it has higher refractive index than the surrounding plasma, traps co-propagating probe light within its profile, thereby illuminating its structure [2]; (c) a 2-step ionization front (inset, red curve) in a clustered, supersonic gas jet due to immediate monomer ionization followed by delayed cluster expansion, that enables rapid profiling of cluster fraction within the jet (main panel) [3].

## 3. Visualization of evolving light-velocity objects

When the object $\Delta n(\zeta_{ob},r_{ob},z_{ob})$ evolves as a function of drive pulse distance $z_{ob}$ into the medium, FDH snapshots become blurred. It then becomes necessary to introduce several Frequency-Domain Streak Cameras (FDSCs) [4] --- *i.e.* probe-reference pulse pairs that cross the object's path simultaneously at different angles. The evolving object imprints a phase "streak" --- a temporal sequence of its projections --- onto each probe, from which a single-shot multi-frame movie is produced using tomographic reconstruction algorithms resembling those used in medical CT scans. I will describe compact methods we have developed to generate the multi-probe array in a single-step by standard nonlinear optical methods, and to collect and process streaks from all probes in a single spectrometer. As a result, the entire Frequency-Domain Tomography (FDT) system is only slightly more expensive and complex than a FDH experiment. Fig. 2 shows several FDT movies depicting the evolution of the nonlinear refractive index envelope of a laser pulse propagating through glass, as it evolves under the competing influences of diffraction, self-focusing and plasma generation at different power levels.

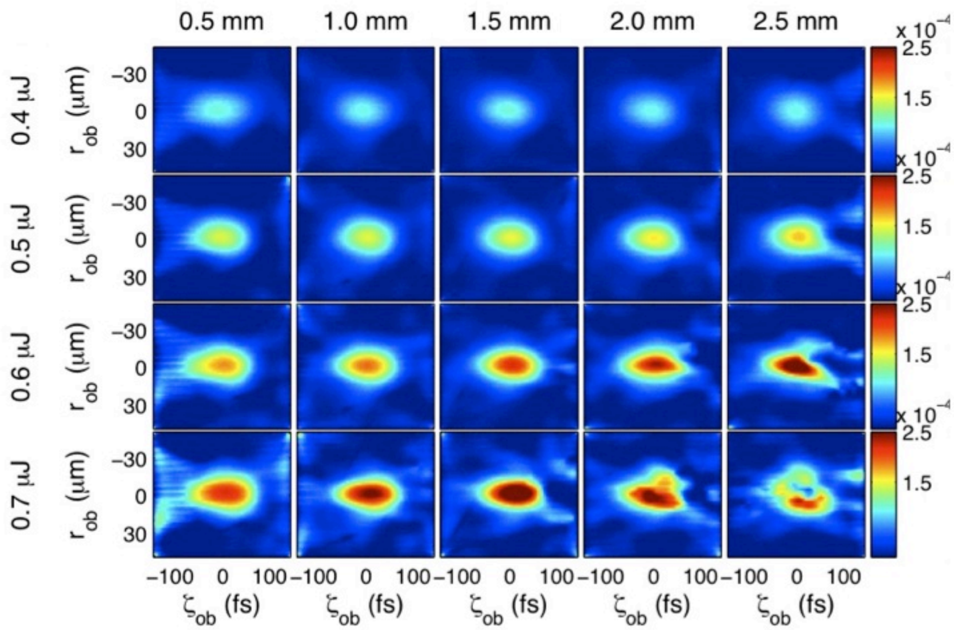


**Fig.2:** Examples of sequential movie frames (left to right) of the evolving nonlinear refractive index profile $\Delta n(\zeta_{ob},r_{ob})$ created by a pump laser pulse of energy 0.4 (top row), 0.5 (2nd row), 0.6 (3rd row) or 0.7 (bottom row) μJ energy propagating through a 3 mm thick glass plate. The selected frames show the profile at positions $z_{ob}$ = 0.5, 1.0, 1.5, 2.0 and 2.5 mm into the plate. The top row depicts nearly linear, Gaussian propagation. Subsequent rows display increasingly strong self-focusing, filamentation and plasma generation. Each movie was produced in a single shot using Frequency-Domain Tomography.

I will describe straightforward modifications to the FDT system that will be required to produce single-shot movies of evolving plasma wakes, plasma bubbles, etc. in tenuous plasma.

## 4. References

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