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Abstract. Electron density bubbles generated in plasma of density $n_e \sim 10^{19}/cm^3$ are shown to reshape copropagating probe pulses into optical "bullets." The bullets, reconstructed by frequency-domain interferometric techniques, are used to visualize bubble formation independently of relativistic electron generation.

Keywords: laser, plasma, electron accelerator, holography
PACS: 42.65.Ky, 32.80.Wr, 36.40.Gk

INTRODUCTION

Frequency Domain Holography (FDH), a technique for imaging objects moving at the speed of light, enables reconstruction of quasi-static structures in tenuous, non-refraction plasma from the phase modulation they imprint on a co-propagating probe pulse [1]. Here we present an entirely new set of experiments [2] that extends visualization of laser-plasma accelerator (LPA) structures to the most important regime in current LPA science: The “bubble” [3] or “blowout” regime. The bubble regime underlay an experimental breakthrough in 2004 in which LPAs for the first time produced high quality, monoenergetic, collimated beams of electrons just like conventional accelerators [4-6], with energy that had reached 1 GeV by 2006 [7]. The standard FDH techniques encountered new problems at high plasma density. Probe pulse phase often scrambled as it refracted and temporally compressed in the plasma bubble structure. Thus, probe pulse phase does not replicate the plasma structure. We developed the revised technique of Frequency Domain Shadowgraphy (FDS), which measures and analyzes the changes in amplitude, rather than phase, that the LPA structure imprints on a copropagating probe pulse. Because plasma bubbles focus, guide and compress the pulse that drives them [8], it is not surprising that they trap and compress probe light to form “optical bullets”.

The plasma bubble generation is represented by the formation of optical bullets, which is observed in the probe pulse amplitude. Plasma bubbles can reshape co-propagating probe pulses into optical bullets, which are a result of spatial focus and temporal compression. The plasma bubble has a transverse index of refraction that can guide and focus copropagating probe pulses like a lens or fiber moving at luminal velocity. The density gradient of the bubble sheath helps to modulate the probe pulse to the size of the bubble, thus compressing the probe pulse. The formation of these optical bullets resembles the controlled guiding of weak signals by optical solitons induced in Kerr media by intense light, a phenomenon that has been widely investigated as a potential basis of future all-optical processing networks [9].

EXPERIMENTAL RESULTS

With University of Michigan's Hercules system, we focused the 30 TW, 30 fs, 800 nm laser pulse to around 10 μm at the front edge of a ~ 2 mm gas jet with various plasma densities from ~ 8 $\times 10^{18}$/cm^3 to ~ 4 $\times 10^{19}$/cm^3. A Michelson interferometer measured the plasma density profiles. Electron spectra were acquired with a dipole magnet and a Lanex screen. FDS snapshots were measured with an imaging spectrometer. The formation of optical bullets was clearly observed. Figure 1 shows the temporal compression of the probe pulse by the plasma bubble. Spectral phase of the probe pulse at the position of the optical bullet is linear, representing a fully compressed pulse as short as ~ 30 fs. Spectral phase of the probe pulse away from the bullet is quadratic, which comes from the original chirping of the probe pulse (~ 1 ps). Figure 2 displays images of the probe pulses at the exit plane of the gas jet. Without plasma, the probe pulse had a long Rayleigh range and focused loosely on the gas jet. With plasma bubble, the probe pulse was guided and focused through the plasma, thus, ending up with a much smaller spot at the exit plane. Two typical FDS snapshots are shown in Figure 3. At low plasma density n_e = 1.2 $\times 10^{19}$/cm^3, we didn't detect electron beams generated. However, we saw a distinct optical bullet in the FDS snapshot. The formation of plasma bubbles below the electron trapping threshold, hinted by the formation of optical bullets, is observed experimentally for the first time. At higher plasma density n_e = 3.2 $\times 10^{19}$/cm^3, we observed that the laser shot that produced the brightest optical bullet also produced a monoenergetic electron beam (Figure 3 bottom). The detailed simulation of pump and probe propagation through the plasma using WAKE code and VLPL code [2] also revealed that the optical bullet resided at the front of the plasma bubble, thus was not affected by the electron trapping and acceleration process.

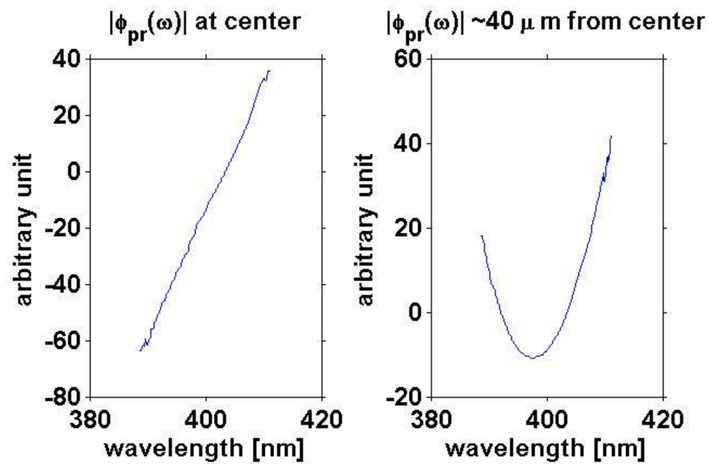

FIGURE 1. Probe pulse spectral phase ϕ(r, ω) at at r=0 μm (left) and ϕ(r, ω) at at r=40 μm (right).

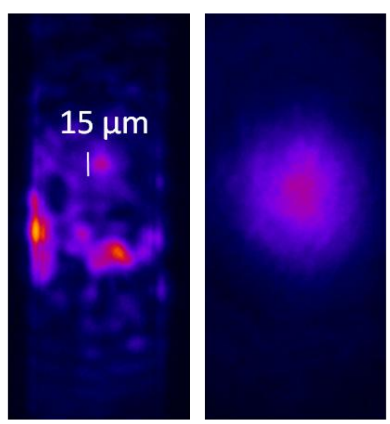

FIGURE 2. Probe pulse image at the exit plane of the gas jet. Left: in the plasma (pump pulse unblocked). Right: in vacuum.

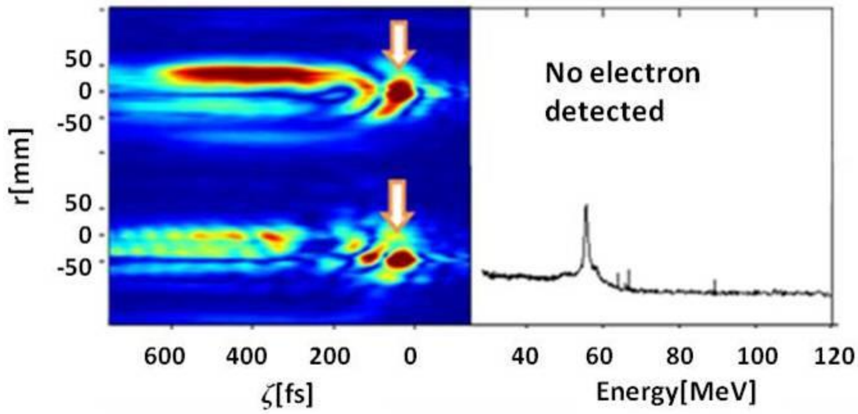

FIGURE 3. FDS-reconstructed probe amplitude profiles $|E_{pr}(r, \zeta)|$ at plasma electron density $n_e = 1.2 \times 10^{19}/cm^3$ (top), where optical bullet appears (below the arrow) without electrons detected. Bottom: $n_e = 3.2 \times 10^{19}/cm^3$, single bright optical bullet with monoenergetic electron beams generated.

APPLICATION

Researchers have been trying to utilize nonlinearity of the gas [10] or plasma [11] media to increase laser pulse bandwidth and subsequently compress the pulse to short duration in another gas or plasma media with high group velocity dispersion (GVD). The results of this experiment suggest that plasma bubble is a promising and unique pulse compressor for ultra-intense laser pulses. It can increase the pulse bandwidth and compress the pulse in one step. It's simple to align, just requiring the overlap of the pump pulse and probe pulse. It's cost effective, only needing a gas jet to work as dispersive media. The measured bullet duration (~ 30 fs), however, is limited by our experimental resolution. Simulations suggest that the plasma bubble can compress the co-propagating probe pulse to as short as ~ 10 fs [2]. A next- step experiment will be performed to confirm this result.

ACKNOWLEDGMENTS

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