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Final Technical Report on

DE-FG02-07ER54945:

"Holographic Imaging of Evolving Laser-Plasma Structures"

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(*Note:* Boldface literature citations (*e.g.* **[Li14]**) refer to our publications from the final 3-year funding period of DE-FG02-07ER54945. Other citations appear in italic type (*e.g. [Esa09]*).

INTRODUCTION. Interactions of intense ultrashort laser pulses with underdense plasmas underlie applications such as laser-plasma accelerators (LPAs) *[Esa09]*; fast ignition of laser fusion *[Moses09]*; generation of ultrashort, coherent x-ray pulses *[Corde13]*; remote sensing *[Luo06],* few-cycle optical pulse *[Hau04]* and THz *[D'Am07]* generation; and amplification *[Shvets98]* and compression *[Kalm05]* of intense optical pulses. These interactions create spatio-temporal electron density structures $n_e(r,\zeta,z)$ (*e.g.* Langmuir waves, "bubbles" *[Puk02],* plasma filaments, clustered nano-plasmas, ionization fronts) that vary rapidly on a micron-femtosecond scale as a function of radial distance r from the propagation axis and time ζ behind the driving pulse, and evolve as a function of drive pulse propagation distance z into the plasma medium. Prior to recent work by the PIs of this proposal, detailed knowledge of such elusive, micrometer-size, luminal-velocity structures came exclusively from intensive computer simulations based on estimated initial conditions. Now "snapshots" of quasi-static (*i.e.* z-independent), laser-driven Langmuir waves (see Fig. 2a) *[Matlis06]* can be acquired routinely in a single shot in the laboratory by Frequency-Domain Holography (FDH) [*LeB00*]. With the support of this grant for the last 4 years, we extended FDH to take snapshots of plasma "bubbles" (see Fig. 2b) [**Dong10**], and clustered nano-plasma ionization/expansion fronts (see Fig. 2c) [**Gao12,13**]. In addition, we produced single-shot frequency-domain tomographic (FDT) "movies" of an *evolving* (*i.e.* z-dependent) luminal-velocity object: the nonlinear refractive index envelope of a laser pulse as it self-focused, formed a filament and generated plasma while propagating through a Kerr medium (see Fig. 2d) [**Li12,13**]. These single-shot visualization capabilities are important for understanding, optimizing and scaling the above-mentioned applications of laser-plasma interactions.

SUMMARY OF MAJOR FINDINGS (2010-2014). One accomplishment of the last four years was our world-record-setting quasi-mono-energetic laser-plasma acceleration (LPA) of electrons to 2 GeV (see Fig. 1) using the Texas Petawatt Laser [*Gaul10*]. This result, published in *Nature Communications* [**Wang13**], and anticipated by computer simulations [**Kalm11**] also demonstrated a record low beam divergence of < 0.5 mrad, and a record low plasma density (n_e = 2 x 10^{17} cm^{-3}) for self-injected, quasi-monoenergetic LPA. Self-injected LPA was observed at densities as low as n_e = 1 x 10^{17} cm^{-3} [**Wang12**]. At such low densities (10x lower than previous self-injected, quasi-monoenergetic LPAs), acceleration to ~30 GeV is theoretically possible with the available pulse energy because of the large dephasing and pump depletion lengths *[Lu07,Esa09].* Pursuit of this theoretical possibility is a major component of continuing research in our group. Our paper **[Wang13]** has already been cited more than 100 times, according to Web of Science, and received wide publicity.

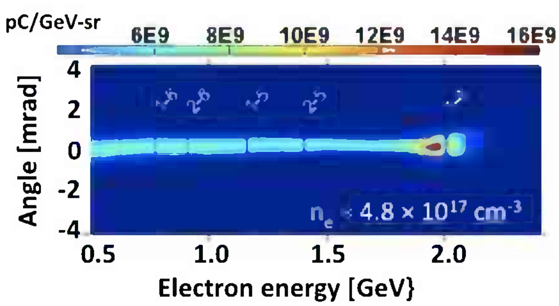

Fig. 1. *Magnetically-dispersed electron spectrum from a pure He LPA of density n_e = 4.8 x 10^{17} cm^{-3} driven by a 100 J, 150 fs, 1 μm laser pulse. The quasi-monoenergetic feature at 2.0 GeV has energy spread ΔE/E = 0.05, 60 pC charge, and 0.5 mrad angular divergence. Dark vertical lines are shadows of tungsten wire fiducials placed in dispersion region to calibrate the spectrometer* [**Wang13**].

As our main thrust under this grant, we also made new advances in laboratory visualization of laser-plasma structures beyond our widely cited "snapshots of laser wakefields" *[Matlis06]* (see Fig. 2a). Laboratory visualization of LPA structures is important for understanding, optimizing and scaling LPAs. Computer simulations visualize LPA structures under idealized conditions, but must be supplemented by *laboratory* visualization when initial conditions are imprecisely known. *Single-shot* visualization is essential for non-repetitive or stochastic events typical of highly nonlinear interactions, or for interactions driven by sources with low repetition rate, unstable pointing, or other shot-to-shot fluctuations. FDH recovers an image in a single shot from phase modulations that the object imprints on a co-propagating temporally-stretched probe pulse *[LeB00,Kim02]*. In a collaboration with U. Michigan [**Dong10**], we visualized plasma bubbles, a critical element in quasi-monoenergetic LPA *[Puk02,Lu07, Esa09]*, via their ability to capture co-propagating probe light into optical "bullets" (see Fig. 2b). Beyond accelerator science, we used FDH to measure cluster mass fraction f_c in supersonic cluster jets by measuring the *two-step fs evolution* of the jet's refractive index [**Gao12**] -- (*i*) instantaneous monomer ionization followed by (*ii*) delayed cluster expansion (see Fig. 2c) -- enabling straightforward recovery of f_c. The high speed of single-shot measurement enabled *multi-shot* scans of the dependence of f_c on position within the jet, time after valve opening, temperature and backing pressure [**Gao13**].

An important limitation of FDH is that it averages over *evolution* of the light-speed structure – *i.e.* changes in structure translate into "blur" in the images. To overcome this limitation, we recently produced single-shot "movies" of *evolving* light-velocity objects -- the nonlinear refractive index of a laser pulse as it self-focused, filamented and generated plasma while propagating through a Kerr medium (see Fig. 2d) [**Li14**] -- by Frequency-Domain Tomography (FDT), a generalization of FDH in which the object imprints phase "streaks" *[Li10]* on multiple probes crossing its path at different angles. This work, published in Nature Communications [**Li14**], was highlighted in a recent *News & Views* article in *Nature Photonics* [**NatPhotN&V14**]. FDT movies visualize evolving light-speed plasma structures with fidelity comparable to a computer simulation, except that they are *actual* structures and there is no guesswork about initial conditions. In our continuing research we plan to visualize evolving LPA structures directly with FDT. We envision that FDT can become a standard in-line metrology at many plasma-based accelerator facilities around the world.

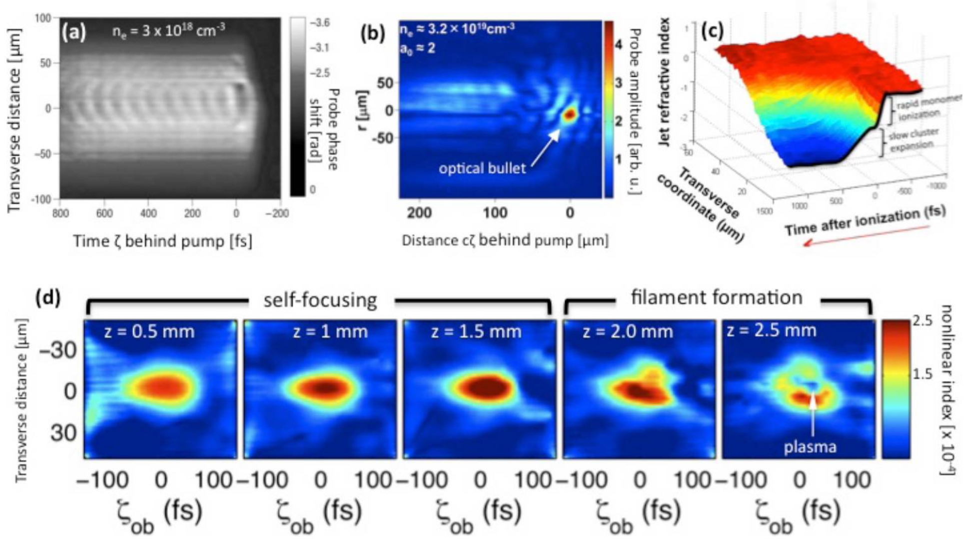

Fig. 2. ***Examples of single-shot visualization of laser-plasma structures by the PI.*** ***(a)*** *Laser wake in plasma of density $n_e = 3 \cdot 10^{18}$ cm^{-3}, showing relativistically curved wave fronts [Matlis06];* ***(b)*** *"optical bullet" of probe light trapped inside a co-propagating plasma bubble* [**Dong10**]; ***(c)*** *"Texas two-step": fs evolution of the refractive index of a clustered plasma behind a fs ionization/heating pulse, consisting of instantaneous monomer ionization (step 1) followed by delayed cluster expansion (step 2), used to measure cluster mass fraction in-situ* [**Gao 12,13**]; ***(d)*** *5 frames of a single-shot tomographic movie of self-focusing and filament formation by a 100 fs laser pulse in a fused silica Kerr medium* [**Li13**].

A limitation of both FDH and FDT is that they have only ~ 1 cm depth of field. Thus they are not suitable for single-shot imaging of multi-GeV LPAs or particle-beam-driven PWFAs, in which plasma structures propagate over distances of 10 cm to several meters. To overcome this limitation, we developed and tested a Multi-Object-Plane Imaging (MOPI) technique [**Li13**]. In MOPI, as in FDT, one or more probe pulses cross the path of the light-speed object at a small angle. The illuminated object sweeps transversely across the probe profile(s), mapping its evolving index profile onto transverse position on the probe profile. However, instead of imaging the phase-modulated probe(s) to a detector from a *single* plane at the *end* of the interaction region, as in FDH and FDT, copies of the phase-modulated probe(s) created by beam splitters are imaged from multiple object planes (MOPs) *within* the interaction region to detectors located at the corresponding image planes. Details are presented in **[Li13]**, along with test data in which refractive index changes induced in air by a laser pulse filament were successfully imaged over a 12 cm path length with high fidelity. Spurred by this successful demonstration, the PI's group has fielded a MOPI visualization system at the Texas Petawatt Laser and at the Facility for Accelerator Science and Experimental Tests (FACET) at SLAC National Accelerator Laboratory, where it will visualize laser- and electron-beam-driven plasma accelerator structures as they evolve over path lengths from 0.1 to 1 meter.

PUBLIC SERVICE: The PI served as Chair of the 15th Advanced Accelerator Concepts (AAC) workshop held June 2012 in Austin, Texas. R. Zgadzaj, a postdoc supported partially by this grant, served as editor of the AAC 2012 Proceedings, which was published on-line by The American Institute of Physics (AIP) **[Zga12].**

PhD DEGREES AWARDED under this project (2010-2014):

Peng Dong, PhD (2010): *"Laboratory visualization of laser-driven plasma accelerators in the bubble regime."*
Xiaohui Gao, PhD (2012): *"Single-shot characterization of cluster mass fraction in supersonic gas jets"*
Zhengyan Li, PhD (April 2014): *"Laboratory visualization of evolving light-velocity objects"*
James Sanders, PhD (June 2014): *"Terawatt Raman laser system for 2-color laser-plasma interactions"*

2010-2014 PUBLICATIONS (all acknowledge support of this grant, and others as indicated)

[Dong10a] P. Dong, S. A. Reed, S. A. Yi, S. Y. Kalmykov, G. Shvets, M. C. DOWNER, N. H. Matlis, W. P. Leemans, C. McGuffey, S. S. Bulanov, V. Chvykov, G. Kalintchenko, K. Krushelnick, A. Maksimchuk, T. Matsuoka, A. G. R. Thomas, V. Yanovsky, "Formation of optical bullets in laser-driven plasma bubble accelerators," *Physical Review Letters* **104**, 134801 (2010).

This grant was the primary support. It supported Dong, Reed and Downer, plus supplies. DOE supported Yi, Kalmykov, Shvets through grants to the Institute for Fusion Studies, U.-Texas-Austin. The NSF Physics Frontier Center FOCUS (Grant PHY-011436) supported the co-authors from U. Michigan.

[Dong10b] P. Dong, S. A. Reed, S. A. Yi, S. Y. Kalmykov, G. Shvets, M. C. DOWNER, and 10 others, "Holographic Visualization of Laser Wakefields," *New Journal of Physics* **12**, 045016 (2010).

Remarks under [**Dong10a**] *apply here, too.*

[Dong10c] P. Dong, S. A. Reed, S. A. Yi, S. Y. Kalmykov, G. Shvets, M. C. DOWNER and 10 others, "Visualization of plasma bubble accelerators using Frequency-Domain Shadowgraphy," *High Energy Density Physics* **6**, 153-156 (2010).

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[Gao12] X. Gao. X. Wang, B. Shim, A. Arefiev and M. C. DOWNER, "Characterization of cluster/monomer ratio in pulsed supersonic gas jets," *Applied Physics Letters* **100**, 064101 (2012).

This grant is the primary support. It supported Gao, Wang, Shim and Downer, plus supplies. DOE supported Arefiev through a grant to the Institute for Fusion Studies, U. Texas-Austin. NSF PHY-0936283 provided supplementary support for an undergraduate assistant not listed among the co-authors.

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This grant and NSF-PHY0936283 provided primary support for Li and Zgadzaj. DOE-HEP supported Wang and Downer. Li and Chang were also supported by internal U. Texas fellowships.

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DOE-HEP is the primary support for the LPA experiment. It supported Wang, Zgadzaj, Henderson, Fazel, Chang, Korzekwa, Tsai, Pai, Li, Downer, plus equipment and supplies directly related to the experiment. This grant and NSF-PHY0936283 provided supplementary support for Zgadzaj and Li. DoE NNSA supports the TPW facility and its overall scientific mission under Cooperative agreement DE-FC52-03NA00156, including support for Gaul, Martinez, Dyer, Quevedo, Bernstein, Donovan and Ditmire. DOE supported the simulation team of Yi, Khudik, Shvets under DE-FG02-04ER41321.

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Research Highlight Articles about work under DE-FG02-07ER54945:

[NatPhotHighlight11] Research Highlight, "Streak Cameras: In the Frequency Domain", *Nature Photonics* **5**, 68 (February 2011).

[NatPhotN&V14] Simon Pleasants, "Movies of evolving objects from a single laser shot," *Nature Photonics* **8**, 271 (2014). **News & Views** article in featuring work in **[Li13a].**

Invited Conference Presentations about work under this project (2010-2014): 16

Contributed Conference Presentations about work under this project (2010-2014): 22

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