

REPORT DOCUMENTATION PAGE			1 Form Approved OMB NO. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE New Reprint		3. DATES COVERED (From - To) -
4. TITLE AND SUBTITLE A novel femtosecond-gated, high-resolution, frequency-shifted shearing interferometry technique for probing pre-plasma expansion in ultra-intense laser experimentsa)			5a. CONTRACT NUMBER W911NF-11-1-0116	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER 611102	
6. AUTHORS S. Feister, J. A. Nees, J. T. Morrison, K. D. Frische, C. Orban, E. A. Chowdhury, W. M. Roquemore			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Michigan - Ann Arbor 3003 S. State St Ann Arbor, MI 48109 -1274			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 57860-PH.3	
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.				
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.				
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15. SUBJECT TERMS Interferometry, Plasma Diagnostics, Relativistic, Extreme Light				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU		
			19a. NAME OF RESPONSIBLE PERSON John Nees	19b. TELEPHONE NUMBER 734-764-9271

Report Title

A novel femtosecond-gated, high-resolution, frequency-shifted shearing interferometry technique for probing pre-plasma expansion in ultra-intense laser experimentsa)

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Ultra-intense laser-matter interaction experiments ($>10^{18}$ W/cm²) with dense targets are highly sensitive to the effect of laser “noise” (in the form of pre-pulses) preceding the main ultra-intense pulse. These system-dependent pre-pulses in the nanosecond and/or picosecond regimes are often intense enough to modify the target significantly by ionizing and forming a plasma layer in front of the target before the arrival of the main pulse. Time resolved interferometry offers a robust way to characterize the expanding plasma during this period. We have developed a novel pump-probe interferometry system for an ultra-intense laser experiment that uses two short-pulse amplifiers synchronized by one ultra-fast seed oscillator to achieve 40-fs time resolution over hundreds of nanoseconds, using a variable delay line and other techniques. The first of these amplifiers acts as the pump and delivers maximal energy to the interaction region. The second amplifier is frequency shifted and then frequency doubled to generate the femtosecond probe pulse. After passing through the laser-target interaction region, the probe pulse is split and recombined in a laterally sheared Michelson interferometer. Importantly, the frequency shift in the probe allows strong plasma self-emission at the second harmonic of the pump to be filtered out, allowing plasma expansion near the critical surface and elsewhere to be clearly visible in the interferograms. To aid in the reconstruction of phase dependent imagery from fringe shifts, three separate 120° phase-shifted (temporally sheared) interferograms are acquired for each probe delay. Three-phase reconstructions of the electron densities are then inferred by Abel inversion. This interferometric system delivers precise measurements of pre-plasma expansion that can identify the condition of the target at the moment that the ultra-intense pulse arrives. Such measurements are indispensable for correlating laser pre-pulse measurements with instantaneous plasma profiles and for enabling realistic Particle-in-Cell simulations of the ultra-intense laser-matter interaction.

REPORT DOCUMENTATION PAGE (SF298) (Continuation Sheet)

Continuation for Block 13

ARO Report Number 57860.3-PH

A novel femtosecond-gated, high-resolution, fre...

Block 13: Supplementary Note

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A novel femtosecond-gated, high-resolution, frequency-shifted shearing interferometry technique for probing pre-plasma expansion in ultra-intense laser experiments^{a)}

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(Presented 2 June 2014; received 5 June 2014; accepted 18 June 2014; published online 17 July 2014)

Ultra-intense laser-matter interaction experiments ($>10^{18}$ W/cm²) with dense targets are highly sensitive to the effect of laser “noise” (in the form of pre-pulses) preceding the main ultra-intense pulse. These system-dependent pre-pulses in the nanosecond and/or picosecond regimes are often intense enough to modify the target significantly by ionizing and forming a plasma layer in front of the target before the arrival of the main pulse. Time resolved interferometry offers a robust way to characterize the expanding plasma during this period. We have developed a novel pump-probe interferometry system for an ultra-intense laser experiment that uses two short-pulse amplifiers synchronized by one ultra-fast seed oscillator to achieve 40-fs time resolution over hundreds of nanoseconds, using a variable delay line and other techniques. The first of these amplifiers acts as the pump and delivers maximal energy to the interaction region. The second amplifier is frequency shifted and then frequency doubled to generate the femtosecond probe pulse. After passing through the laser-target interaction region, the probe pulse is split and recombined in a laterally sheared Michelson interferometer. Importantly, the frequency shift in the probe allows strong plasma self-emission at the second harmonic of the pump to be filtered out, allowing plasma expansion near the critical surface and elsewhere to be clearly visible in the interferograms. To aid in the reconstruction of phase dependent imagery from fringe shifts, three separate 120° phase-shifted (temporally sheared) interferograms are acquired for each probe delay. Three-phase reconstructions of the electron densities are then inferred by Abel inversion. This interferometric system delivers precise measurements of pre-plasma expansion that can identify the condition of the target at the moment that the ultra-intense pulse arrives. Such measurements are indispensable for correlating laser pre-pulse measurements with instantaneous plasma profiles and for enabling realistic Particle-in-Cell simulations of the ultra-intense laser-matter interaction. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4886955>]

I. INTRODUCTION

In ultra-intense laser systems, so-called “pre-pulses” are inexorably produced during the laser amplification process, and can pre-ablate the target, changing the condition of the target at the time of arrival of the main ultra-intense laser pulse. The outcome of this main pulse interaction sensitively depends on these pre-ablations.^{1,2} The pre-ablation of the target by the pre-pulse can be difficult to predict *ab initio* using hydrodynamic and particle-in-cell codes in large part due to the wide range of timescales involved in the laser-matter interaction. Relevant pre-pulses occur and their effects evolve on the nanosecond and/or picosecond scale, with consequences to the main laser-plasma interaction occurring on the femtosecond scale.³ Characterizing and controlling these

pre-plasma conditions is an integral part of ultra-short pulse experiments.^{4,5} Interferometry is a well-known technique that can reveal the plasma electron density profile.⁶ However, the temporal resolution of interferometric measurements, even with state-of-the-art streak camera technology, is typically limited to picosecond timescales and these devices are prohibitively expensive.

We present a pump-probe technique with precision timing features that allow interferometric phase reconstruction to occur on timescales of less than 100 fs, in a cost-effective manner, while retaining roughly nine orders of magnitude temporal dynamic range. Femtosecond timing stability between pump and probe beams is achieved through use of a common oscillator. The probe light is used in two ways: shadowgraphy reveals general features,⁷ while interferometry and an Abel inversion⁶ recover phase and reveal subtle features of plasma evolution.⁸

The contamination of shadowgraphs and interferograms by the plasma self-emission (e.g., Refs. 9 and 10) is avoided

^{a)}Contributed paper, published as part of the Proceedings of the 20th Topical Conference on High-Temperature Plasma Diagnostics, Atlanta, Georgia, USA, June 2014.

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by selective optical filtering and a frequency shift of the probe beam before amplification. These techniques create a unique platform for performing spatially and temporally resolved measurements of the target evolution. We show results from an experiment at the Air Force Research Lab (AFRL) in which a flowing water jet target^{11,12} is irradiated by nanosecond-scale and picosecond-scale pre-pulses that precede a 30-fs FWHM ultra-intense (10^{18} W/cm²) interaction. Section II describes the experimental setup, and Sec. III describes how the ultra-short timescale synchronization of the probe and pump pulse is achieved. Section IV describes the frequency shift of the probe pulse and selective filtering. Section V presents some preliminary data of the water jet expansion due to laser-target interactions, including Abel inversion of interferometric data. Section VI states our conclusions and describes how this instrument will be incorporated into future work.

II. EXPERIMENTAL OVERVIEW

Interferometry and shadowgraphy are used to characterize plasma expansion in experiments at the AFRL at Wright Patterson Air Force Base in Dayton, OH. An 800 nm, 30-fs FWHM pump beam produces high intensities (10^{18} W/cm², 2.6 μ m FWHM spot size) on flowing water jet column targets. To avoid disruption of the high intensity laser light as it propagates to focus and to prevent freezing of the water jet nozzle, the experiment is housed in a vacuum chamber that is held at 20 Torr partial vacuum using a thermocouple gauge solenoid valve feedback loop.

Known pre-pulse artifacts of the amplification process pre-ablate the target, creating conditions of interest picoseconds and nanoseconds before the main laser pulse interaction. To interrogate these conditions, a 420 nm, 80-fs FWHM probe beam is passed through the interaction region and subsequently split to image the target for shadowgraphy and interferometry. The pump-probe experimental layout is shown in Fig. 1. The probe beam is frequency-shifted, as discussed in Sec. IV.

Distortions to the probe pulse wavefront due to variations in the index of refraction along the line of sight are revealed by interfering the probe pulse with a reference pulse at the same frequency. In this laterally sheared Michelson interferometer setup,¹³ an image of the interaction region of the water jet is overlapped with a sheared image of the water jet downstream. Interference fringes shift in response to changes in line-of-sight index of refraction, allowing one to “see” ablated liquid and ionized plasma in a way complementary to shadowgraphy. With a high dynamic range timing setup (described next) and selective optical filtering, one can get a sense of the evolution of this ablated liquid and plasma.

III. FEMTOSECOND RESOLUTION OVER MICROSECONDS

One commonly used approach to pump/probe experiment is to use two entirely separate femtosecond laser systems, synchronizing the laser oscillators via electronic signals. A typical setup gives picosecond stability between oscillators; achieving femtosecond stability requires advanced electron-

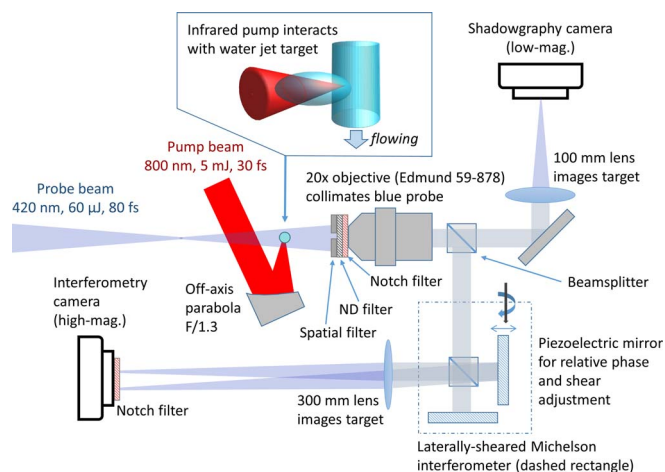


FIG. 1. The experiment employs a high-intensity pump and low-intensity probe, relatively timed with better than 40-fs precision. The pump beam (sketched in red) and its pre-pulses irradiate the water jet target, creating a dynamic laser-plasma interaction region. The probe beam (sketched in blue) envelops the interaction region and is then split for target-imaged interferometry and shadowgraphy. Within the laterally sheared Michelson interferometer, a piezoelectric mirror allows for controlled adjustment of phase (mirror translation) and shear (mirror tilt). The shear angle is out of the page, though sketched in the plane of the page for easy visualization. Optical notch filters and an iris (spatial filter) exclude unwanted light such as that from plasma self-emission (see Fig. 2).

ics and a reduction in the output repetition rate.¹⁴ Utilizing two pulses from a single oscillator is simpler and results in a more stable relative timing.

To achieve femtosecond relative precision in such a setup, the probe and pump beams must be seeded from a common oscillator. In a kHz system, a Pockels cell selects one oscillator pulse every millisecond to be further amplified as the pump pulse, rejecting all other pulses. The oscillator used in the experiment at AFRL produces pulses at 80 MHz, and the rejected pulses are routed into a second Pockels cell that selects a different pulse to be amplified as the probe pulse. By varying the pulse selected, coarse delays can be introduced between the pump and probe on the order of the oscillator rate, 80 MHz or 12.5 ns. After amplification, the probe pulse passes through a delay line. The double-passed delay line allows fine adjustments to the relative pump-probe delay, with < 40 fs resolution over 19 ns. Combining coarse and fine delay techniques results in 40 fs resolution over 10 μ s, and potentially even longer times (e.g., 900 μ s) if desired. The final resolution of the system is limited by the greater of the delay line resolution (< 40 fs in this setup) or probe pulse duration (80 fs in this setup).

The combination of pulse seed selection and delay line adjustment allows roughly nine orders of magnitude temporal dynamic range. Fig. 3 exhibits this dynamic range, showing the pre-plasma expansion before the arrival of the main ultra-intense pulse (upper sequence) and the hydrodynamic response of the water jet over 10 μ s of evolution (lower sequence).

IV. ELIMINATION OF PLASMA SELF-EMISSION NOISE

Irradiated by the pump beam at 800 nm, the target will naturally emit light at the second harmonic (400 nm),¹⁵ which

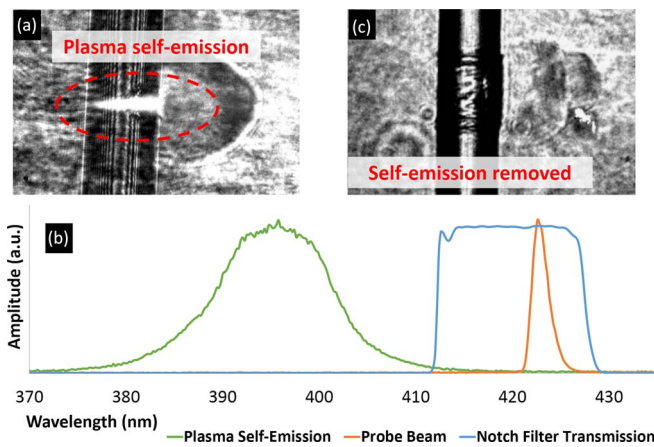


FIG. 2. The deleterious effect of plasma self-emission on the diagnostics is avoided by a frequency shift in the probe beam and aggressive optical filtering. (a) Near the critical surface of laser-plasma interaction, plasma self-emission at 400 nm saturates imagery. (b) To avoid this effect, the probe beam is frequency shifted to 840 nm, amplified, then frequency doubled to 420 nm. At the imaging cameras, notch filters are used to remove plasma self-emission at the pump's second harmonic, 400 nm. The notch filter transmission band includes the entire probe beam spectrum and only the tail of the plasma self-emission spectrum. (c) The effect of the frequency shift and optical notch filters is to reveal previously obscured interaction areas.

is the source of the plasma self-emission that is the subject of this subsection. Plasma self-emission complicates and frustrates probe-beam interferometry and shadowgraphy because it obscures areas of interest near the critical surface (see Fig. 2(a)).

The solution to this obfuscation problem, which we have implemented in this setup, is to apply optical filtering that excludes plasma self-emission while passing the probe beam. Even with specially selected optical notch filters, this is only possible if the probe spectrum sits outside of the plasma self-emission spectrum. However, because the pump and probe share a common oscillator, the probe pulse naturally shares the frequency of the pump harmonic. To circumvent this issue, the frequency of the probe pulse is shifted in two steps.

Prior to amplification, the broadband 800 nm seed pulse of the probe beam is optically filtered using Schott RG850 glass, moving the central wavelength to 840 nm by preferentially attenuating lower wavelengths. Next, a hard spectral cutoff is applied in the pulse stretcher, by physically clipping lower wavelength regions of the beam during grating dispersion. This frequency-shifted (and much attenuated) pulse is next passed through a regenerative amplifier, which smooths the spectral profile, and after re-compression the pulse remains centered at 840 nm. Finally, the probe beam is frequency doubled to 420 nm via a β -barium borate crystal (AR/AR coated, 300 μm thick, Type I). During imaging, two optical notch filters (Semrock FF01-420/10-25; 10 nm bandwidth, and nominally 15 nm FWHM) select for the 420 nm probe and reject the plasma self-emission at 400 nm (Figs. 2(b) and 2(c)).

V. ACQUISITIONS AND ANALYSIS

By varying probe beam delay time, an image sequence can be created that shows the development of pre-plasma, the main ultra-intense pulse interaction, and the hydrodynamic recovery of the target (see Fig. 3). The image acquisitions are performed in the following way. A sequence of delay times is chosen so as to acquire many frames shortly before the main pulse interaction while keeping a wide temporal view of the interaction. Once programmed, the sequence is serially executed. To create a given delay, Pockels cell seed selection and delay line position are adjusted automatically. For each delay, one shadowgraphic frame and three interferometric frames are acquired (corresponding to three positions of the piezoelectric mirror which varies Michelson interferometer phase difference). Because stochastic events can cause occasional extreme outliers shot-to-shot, 10 images are acquired for each frame, corresponding to ten independent laser shots. The image most similar to the average is incorporated as the frame.

Interferograms must be analyzed to recover phase data. Phase shifts are reconstructed from fringe shifts using the

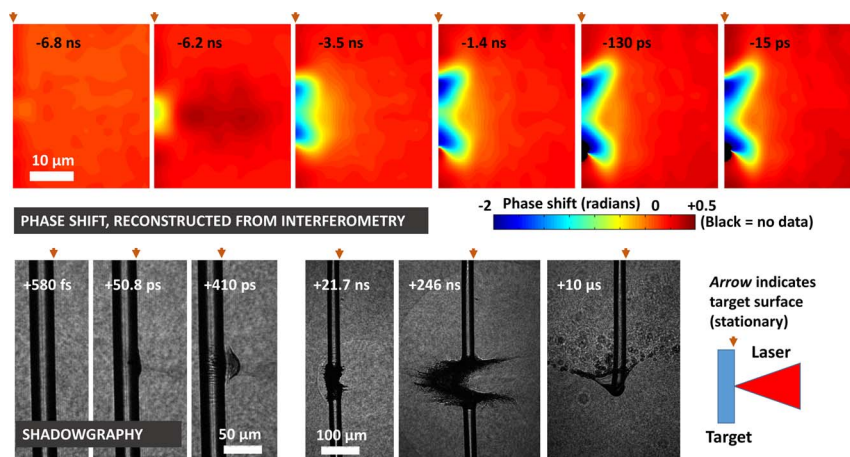


FIG. 3. Precise probe pulse timing (< 40 fs resolution) over a wide dynamic range (> 10 μs) gives a detailed view of pre-plasma evolution, intense laser-plasma interaction, and target recovery. Upper sequence: Recovered phase shifts from interferometry show the in-vacuum development of pre-plasma nanoseconds before the main interaction, consistent with known pre-pulse on this timescale. Delay times relative to the main ultra-intense laser pulse are marked. Interferometric reconstruction after the main pulse arrives (≥ 0 fs, not shown) fails due to steep phase gradients. Lower sequence: Shadowgraphy shows timescales of in-air target evolution: hydrodynamic reaction in picoseconds, expansion in nanoseconds, and recovery in microseconds.

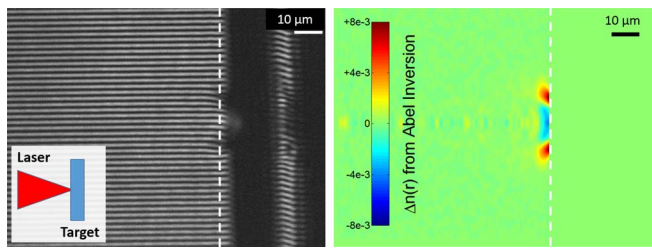


FIG. 4. To aid in the reconstruction of phase dependent imagery from fringe shifts, three separate 120° phase-shifted (temporally sheared) interferograms are acquired for each probe delay. Left: an interferogram is shown for -15 ps delay for an in-vacuum target. Its corresponding phase image is reconstructed using the Speckle Phase of Difference algorithm in IDEA software – the vertical dashed line represents the rightmost boundary of reliable phase reconstruction. Abel inversion allows recovery of index of refraction and potentially electron density. Right: recovered index of refraction shifts for the interferogram at left are shown. The radial index change from negative to positive suggests pre-plasma on-axis and ablated neutral material off-axis.

IDEA software¹⁶ Speckle Phase of Difference algorithm (three-frame technique, 120° phase shift). Abel inversion can be performed to recover the changes in index of refraction (see Fig. 4 for an experimental example). Abel inversion analysis requires an added assumption of the experiment's radial symmetry, about the laser axis. From the Abel inversion, electron densities can potentially be inferred.

VI. SUMMARY AND CONCLUSIONS

We have described a frequency-shifted, femtosecond-gated interferometric setup and demonstrated its capability for a flowing water jet experiment in which this target is irradiated by nanosecond-scale and picosecond-scale pre-pulses in advance of the arrival of an ultra-intense (10^{18} W/cm²) pulse. The combination of a timing system for observing evolution from femtoseconds to microseconds and elimination of plasma self-emission noise light delivers improved shadowgraphy and interferometry. Phase shift reconstruction from interferometry reveals changes in the index of refraction near the target. This information can be used to infer electron densities through Abel inversion. With precise optical filtering and by frequency shifting the probe pulse away from the self-emission frequencies, the problem of plasma self-emission is avoided.

The diagnostic has been demonstrated to produce interferometric and shadowgraphic image sequences of laser-matter interactions which show nanosecond formation of pre-plasma, femtosecond interaction of the ultra-intense main pulse, picosecond hydrodynamic expansion, and microsecond recovery of the target. Fielding the diagnostic has already contributed in two ways to our experimental understanding. First, tens-of-microseconds target recovery time indicates that the experiment could be performed at significantly higher than

kHz repetition rates. Second, expectations prior to the arrival of the main pulse of pre-plasma formation along the laser axis with neutral material off-axis are confirmed. By providing on-demand femtosecond resolution at arbitrary delay times, this diagnostic will soon be used to track the effects of known femtosecond-duration pre-pulses as they arrive on target picoseconds to nanoseconds prior to the main pulse, and to improve laser-driven electron acceleration and X-ray production techniques.¹⁷ Future improvements to the diagnostic may include additional views of the interaction region or on-the-fly interferogram analysis for fast feedback to the experimenter.

ACKNOWLEDGMENTS

This research was sponsored by the Quantum and Non-Equilibrium Processes Department of the (U.S.) Air Force Office of Scientific Research (USAFOSR), under the management of Dr. Enrique Parra, Program Manager. S.F. was supported in part by the DOD HPCMP high performance computing internship program. The authors thank Mario Manuel, University of Michigan, for insightful discussions.

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