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BY LONGITUDINAL INTERFEROMETRY

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First Measurement of Laser Wakefield Oscillations by Longitudinal Interferometry

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Because the electrostatic fields present in plasma waves can exceed those achievable in conventional accelerators and approach atomic scale values ($E_a \sim 500$ GV/m), plasma based accelerators have received considerable attention as compact sources of high-energy electron pulses [1]. Although stimulated Raman scattering [2] or terahertz radiation at ω_p [3] provided spatially averaged optical signatures of the plasma wave's existence, new diagnostic techniques are required to map the temporal and spatial structure of the plasma wave directly since such information is vital for addressing fundamental issues of wakefield generation and propagation. In this paper, we report femtosecond time resolved measurements of the longitudinal and radial structure of laser wakefield oscillations using an all optical technique known as interferometric "photon acceleration" [4], or Longitudinal Interferometry [5].

In a simple version of the experiment, a probe pulse co-propagates behind an intense pump pulse ($I = 3 \times 10^{17} \text{ W/cm}^2$, $\lambda = 0.8 \mu\text{m}$, $\tau = 100 \text{ fs}$) tightly focused ($f^\# = 4.2$) in helium gas. As the pump pulse ionizes the gas and exerts ponderomotive pressure on the resulting plasma, the probe pulses experiences electron density gradients behind the pump pulse which cause both DC phase shifts as well as blue/red shifting of the probe pulse frequency spectrum. In order to detect the small changes in frequency ($\Delta\omega/\omega \sim 10^{-4} - 10^{-5}$) and phase with femtosecond resolution, our photon accelerator diagnostic uses multiple, temporally separated probe pulses which produce frequency domain interferograms [5].

Figure 1: Measured wakefield oscillations in helium. For the 4.8 Torr data, the two probe pulses are separated by 2.2 ps about the pump, while in the 2.7 Torr data (offset from zero and shifted by -400 fs) the probes trail the pump with 415 fs separation. For the 4.8 (2.7) Torr data, 10 (9) mJ of energy was focused with an e^{-1} radius of 3.6 (5.0) μm . The solid lines show the calculated phase shift due to the wakefield oscillations, while the top line of data shows the noise level for a scan in an evacuated chamber

Two types of experiments were conducted to temporally resolve the wakefield oscillations. In the first, probe pulses propagated in front of and behind the pump pulse and the delay of the pump pulse was varied relative to the two probe pulses. Fig. 1 shows measured phase shifts in 4.8 (2.7) Torr helium oscillating with a period of 220 ± 25 fs (270 ± 10 fs) and an amplitude of 0.007 rad (0.005 rad). Under these conditions, we detect wakefield oscillations 3-5 (4-5) cycles behind the pump pulse. From the amplitude of the phase modulation in Fig. 1, we estimate that the amplitude of the wakefield oscillation is at least $\delta n_e/n_e = 0.8$. This amplitude is much larger than a simple one dimensional estimation of the laser plasma interaction due to the fact that the radial component of the ponderomotive force is order ten times larger than the axial component. The peak longitudinal electric field is estimated as ~ 10 GV/m.

Figure 2: Phase shift as a function of the He gas pressure. (a) For two pulse energies: 10 mJ (filled square) and 2.5 mJ (circle). The solid line indicates a theoretical calculation of the phase shift for the higher energy. Representative error bars shown. (b) Pressure scan (10 mJ) with narrow slit. Curves are theoretical calculations of the phase shift without (dotted line) and with (solid line) radial averaging.

on the time scale of the data collection (~ 40 sec for each data point) have been found to contribute significantly to such noise in the data. Even so, nonlinear effects such as radial density peaking, radial dephasing and wave breaking [6] may also contribute to the data in ways which are not well understood at present.

In an effort to evaluate nonlinear contributions quantitatively, numerical simulations were performed with a 2D, multi-grid, fully relativistic, cold fluid model in which a Gaussian laser pulse propagates through a preformed plasma. The $\mathbf{v} \times \mathbf{B}$ term of the Lorentz force was not included; thus only relativistic and electrostatic influences on ω_p were modeled. Figure 3 shows the calculated wakefield structures for near-resonant excitation for the same focal geometry and pulse energies (2.5 and 10 mJ) as used in the experiment. The higher energy simulation (Fig. 3a) clearly shows the excitation of nonlinear plasma waves with significant density peaking and a maximum $\delta n/n \sim 5$. Even in the intense focus, these plasma waves oscillate for at least five cycles after the pump pulse. The lower energy simulation (Fig. 3b) shows significantly reduced peaking with $\delta n/n \sim 1$, as expected from an analytic solution. Careful examination showed that the higher energy simulation

A second set of experiments was conducted by fixing the pump and probe pulse delays while varying the helium gas pressure. Such a pressure scan allows the wakefield to be scanned across the second probe pulse. Fig. 2a shows the measured phase shift between probe pulse 1 and 2 for two different pump pulse intensities as the helium pressure varied from 2-12 Torr He. Resonant excitation of the wakefield is obtained when the plasma wave period ($2\pi/\omega_p$) is approximately twice the pump pulse duration. Longitudinal and radial averaging cause the measured phase shifts to be similar for the two different pump pulse intensities. To help reduce the effect of radial averaging, a second pressure scan (Fig. 2b) was performed with a smaller spectrometer entrance slit.

Though our use of dual-beam spectroscopy eliminates most systematic contribution to our data on a 2000:1 (long term) level, approximately 10% of the data points fall significantly away from the calculated pressure scan curves in Fig. 1 and 2. Uncorrected drifts in beam pointing, center wavelength, and spectral shape

has a period longer than either the lower energy simulation or the linear result in the focus, thus suggesting that relativistic period lengthening dominates over electrostatic period shortening. Thus for our parameters only a slight ($\sim$ few percent) period lengthening is expected and then only in the most intense portion of the focus, consistent with the observed wakefield periods.

Numerical integration of the data in Fig. 3 confirms that $\Delta\phi \sim 10$ mrad is expected for our focal geometry and probe pulse widths for both 2.5 mJ and 10 mJ pump energy, consistent with the data in Fig. 2a and with predictions ($\delta n/n \sim 1, \Delta\phi \sim 10$ mrad) for the 2.5 mJ pump. The sharply peaked density perturbation in Fig. 3a does not result in a larger measured $\Delta\phi$ than the broader, lower peak in Fig. 3b because the high electron density is concentrated in a volume smaller than the probe pulse, and thus is not spatially resolved in our experiment.

In summary, we have used longitudinal pump-probe interferometry to excite and measure laser wakefield oscillations with femtosecond resolution in both time-delay and pressure scan configurations. From the data, we estimate density perturbations of order unity and longitudinal fields of order 10 GV/m, consistent with the predictions of both an analytic 2D linear non-relativistic fluid analysis and a fully relativistic nonlinear 2D self-consistent numerical model. By using tightly focused laser pulses, nonlinear wakefield oscillations were driven with subrelativistic laser intensity ($I < 10^{18}$ W/cm²). As this technique utilizes a necessary component of any laser-based plasma accelerator, i.e. the intense driving pulse, it promises to be a powerful tool for on-line monitoring and control of future plasma based particle accelerators.

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Figure 3: Two dimensional (r, z) numerical simulation of wakefield oscillations $\delta n_e/n_e$ corresponding to $E = 10(2.5)$ mJ, $3.6\mu\text{m}$ spot radius, $\tau = 100$ fs, $n_e = 3 \times 10^{17}\text{cm}^{-3}$. The figure shows the electron density oscillations within the confocal parameter of the tightly focused beam and in the moving frame of the pump pulse (centered at $z = 111\mu\text{m}$ and moving in the positive z direction, but not shown). The heavy line represents the e^{-1} contour of the laser focus.

By using tightly focused laser pulses, nonlinear wakefield oscillations were driven with subrelativistic laser intensity ($I < 10^{18}$ W/cm²). As this technique utilizes a necessary component of any laser-based plasma accelerator, i.e. the intense driving pulse, it promises to be a powerful tool for on-line monitoring and control of future plasma based particle accelerators.

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