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Citation: [AIP Conference Proceedings](#) **737**, 764 (2004); doi: 10.1063/1.1842620

View online: <http://dx.doi.org/10.1063/1.1842620>

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Towards Single-Shot Characterization of Near-Resonant LWFA in a Differentially-Pumped Gas Cell

Nicholas Matlis, Michael Downer

University of Texas at Austin, Austin TX 78712, USA

Abstract. We report on progress in the development of a single-shot diagnostic for measuring near-resonant laser-driven wakefields. The development entails the following critical steps: 1. Increase in laser pulse energy 2. development and characterization of a differentially pumped gas cell 3. development of a single-shot diagnostic with low phase noise 4. analysis of laser/plasma parameter space for maximizing the measured phase shift. As a result of this development we expect to be able to have detection sensitivity of $50 - 100$ mrad and we expect to be able to produce and measure wakefields with $dne/ne \sim 1$ and phase shifts of several hundred mrad.

INTRODUCTION

The development of a single-shot diagnostic for wakefield structure is of great importance to the further advancement of the wakefield acceleration scheme. As a greater number of researchers have demonstrated the capacity to accelerate electrons with laser wakefields, it becomes increasingly important to develop the technology to precisely control the properties of the wakefield structure in order to be able to produce electron beams with useful characteristics. Inherent in this goal is the need to be able to visualize the temporal and radial structure of these plasma waves, and to be able to do so in real time. The ability to compare actual measured structures with those of analytical and increasingly sophisticated numerical predictions should also yield a great deal of information.

Various methods such as Thomson side scattering [1] and Raman forward scattering [2] exist to indirectly diagnose the presence of a wakefield, but these methods do not give information about its structure. In previous work [3], we were among the first researchers to measure longitudinal structure of a resonantly driven wake using the method of Frequency Domain Interferometry (FDI). Unfortunately, these measurements did not resolve the transverse wake structure, and were done in multi-shot configuration, making them time consuming and prone to noise from shot-to-shot variations. In response to these issues, our group pioneered a technique called Frequency Domain Holography (FDH) [4] which has the capability to measure transverse as well as longitudinal density variations in a single-shot (real-time) configuration. In order to implement the FDH, we have analytically identified the range parameters to optimize recovery of the wakefield signal, and have developed a gas cell to optimize delivery of the pump intensity to the plasma interaction.

THEORETICAL ANALYSIS

The laser plasma interaction can be modeled with a perturbation treatment which yields analytic solutions for the longitudinal and transverse wakefield structure when a gaussian driving pulse is assumed. The solution is given in the literature [5].

$$\frac{\delta n_e}{n_e} = \frac{a_0^2}{2} e^{-(r/\sigma_r)^2} \left[1 + \frac{4}{(k_p \sigma_r)^2} \left(1 - \left(\frac{r}{\sigma_r} \right)^2 \right) \right] \sqrt{\pi} [k_p \sigma_z e^{-(k_p \sigma_z)^2 / 4}] \sin(k_p \zeta) \quad (1)$$

where a_0 is the normalized vector potential, σ_r is the 1/e radial spot size, σ_z is the 1/e longitudinal spot size and k_p is the plasma wave number. As in FDI, FDH relies on phase shifts imparted to a copropagating probe pulse by local variations in electron density. In general these phase shifts are small, so their detection requires that the measurement technique have a high degree of sensitivity, that the laser system be of sufficient power to produce large amplitude density oscillations over moderate interaction lengths, and that the laser and plasma parameters be correctly chosen to maximize the signal. Consequently, for this study we are interested in determining the parameters that will maximize the overall phase shift (and thus our signal) imparted by the wake onto the probe pulse. In general these need not be the same ones that maximize the wakefield amplitude (resonant excitation).

There are too many variables to do a brute force parameter search for a global maximum, so we must choose an intelligent strategy for optimizing the signal: we search for the largest combination of δn_e and interaction path length. As an additional constraint, we require that the wakefield oscillations remain linear; first, because we want the wakefield to remain well-behaved; second, because we expect diminishing returns on our energy investment in the nonlinear regime; and third, because our analytic treatment is only technically valid for “small” wakefield amplitudes of $\delta n_e/n_e \leq 1$, so we have no easy method for exploring the nonlinear parameter regime. We therefore search for solutions that satisfy $\delta n_e/n_e = 1$ as a way of maximizing the amplitude of the electron density variations while remaining in the linear regime. This yields an expression for the spot size as a function of electron density for a given pulse energy and pulse duration:

$$\sigma_{r0}^2 = \frac{\kappa E_p}{2} \left[1 + \sqrt{1 + \frac{16}{\kappa E_p k_p^2}} \right] \quad \text{where} \quad \kappa \equiv \left[\frac{\lambda^2 (r_e/c) v_g}{\pi^2 m_e c^2 \sigma_z} \right] k_p \sigma_z e^{-(k_p \sigma_z)^2 / 4},$$

where E_p is the pulse energy, and v_g is the group velocity. The phase shift is calculated by integrating the change in the index of refraction through the interaction region:

$\phi(z, r) = \int_{-\infty}^{\infty} [\eta(n_e + \delta n_e) - \eta(n_e)] dz$ where $\eta(n_e) \equiv \sqrt{1 - (n_e/n_c)}$ is the refractive index of the plasma and n_c is the critical density. We can then vary the electron density and search for a maximum in the phase shift. Interestingly, we find that the maximum phase shift does not occur at the resonant density for the specified pulse duration. We find that by increasing the electron density and shifting slightly away from resonance, we can decrease the focal spot size and increase the accrued phase while maintaining a linear wake (see fig.1).

FIGURE 1. Amplitude of the phase shift (100 mJ, 100 fs pump pulse) vs. electron density.

Figure 1. shows a comparison of the phase shift calculated by fixing the spot size at the value required to achieve unity wake at the resonant density (red-dashed line) to the maximum phase shift calculated by requiring that the spot size satisfy the above condition for unity wake for all densities (black line). It is relevant that the black curve intersects the red one at its peak.

For a given pulse duration, we can now calculate the maximum expected phase shift as a function of the driving pulse energy, and the spot size required to achieve that phase shift. The results are shown in fig. 2. We can see that for 100fs pulses with energies in the range of 100 mJ – 200 mJ we should be able to expect phase shifts of on the order of 350 mrad – 525 mrad.

FIGURE 2. a) Max phase shift vs. pulse energy b) required spot size vs. pulse energy

OPTIMIZING FREQUENCY DOMAIN HOLOGRAPHY

In this method, a short (~ 70 fs) reference pulse and a long (~ 1 ps) probe pulse, both at 400 nm, propagate colinearly with an intense ($\sim 1 \times 10^{18}$ W/cm²), short (~ 100 fs) driving pulse at 800 nm. The long probe pulse experiences the medium perturbed by the driving pulse and has its phase modulated by the resultant variations in the index of refraction of the medium. The probe pulse then interferes with the unaffected reference pulse in the spectrometer, producing fringes which are sensitive to the phase

variations accrued in the interaction. The interferogram is then analyzed by taking the Fourier Transform and extracting phase information from either of the side peaks.

The sensitivity of the FDH diagnostic is ultimately limited by noise, however, for phase shifts with a periodic nature the method can be tailored to optimize the signal-to-noise for signals with that periodicity. To understand this, assume a sinusoidal wake:

$$\phi_{wake}(t) = A_{wake} \sin(\omega_p t) \quad (2)$$

The sinusoidal phase will amplitude-modulate the narrow spectrum of the probe pulse according to the Bessel identity:

$$e^{iA_{wake} \sin(\omega_p t)} = \sum_{n=-\infty}^{\infty} J_n(A_{wake}) e^{in\omega_p t} \quad (3)$$

and will produce spectral sidebands that are identical to the central peak:

$$E_{probe}^{out}(\omega) = \sum_{n=-\infty}^{\infty} [J_n(A_{wake}) E_{probe}^{in}(\omega + n\omega_p)] \quad (4)$$

In practice, the wakefield is not a perfect sinusoid, but rather has an envelope, so the sidebands will be somewhat broadened and smoothed out (fig. 3).

FIGURE 3. a) Narrow spectrum of long probe pulse b) simulated wakefield density modulation c) spectrum of probe pulse modulated by wakefield (effects exaggerated for clarity).

Since most of the information about the wakefield is contained within the 1st Bessel side-band, the signal-to-noise of the recovered phase can be enhanced by optimizing the fringe contrast of the interferogram at the side-band location. This can be done by adjusting the relative intensity of the probe and reference pulses and spectrally filtering the interferogram so that the fringe amplitude at the side-band location spans the entire dynamic range of the detector. We verified the effectiveness of this concept by simulating the phase recovery process with and without filtering the central peak in the presence of a fixed level of random background noise. The results show that the recovered phase more closely resembles the original when the optimization algorithm is applied (see fig.4).

FIGURE 4. a) No noise, perfect phase recovery b) 1% noise, but no optimization, fringes maximized at peak, poor phase recovery c) 1% noise, optimization by maximizing side-band fringes improves signal recovery

Proof of Principle Experiment: Cross Phase Modulation

Ultimately, the feasibility of the experiment is determined by the actual noise levels measured in the recovered signal. To determine these levels we performed a test experiment by focusing a weak driving pulse in a thin slab of glass and measuring the phase shift of the probe pulse due to the pump-induced nonlinear index of refraction in the glass. The results show a ~ 200 mrad peak in the phase (corresponding to the pump pulse), which can easily be distinguished above the noise. By varying the delay of the pump and probe, we verified that we have excellent temporal resolution (fig. 5). These results indicate that the FDH diagnostic should easily be able to resolve the 350+ mrad wakefield shifts we expect to be able to achieve with our laser system.

FIGURE 5. a) 3D phase image of cross-phase modulation in glass b) relative temporal delay of pump and probe is easily resolvable over ~ 1 ps.

GAS CELL

We have employed a differentially-pumped gas cell to implement precise control over the experimental conditions at the interaction region. The gas density in the cell is easily and precisely adjustable, the density profile is very uniform and the length of the interaction region is essentially infinitely scalable and has well defined, sharp boundaries. The ability to precisely adjust the gas density and interaction length are critical for enabling us to investigate the dependence of the wakefield signal on these parameters. The need to confine the gas arises as a result of the deleterious effects of ionization-induced defocusing that would prevent the pump pulse from reaching the peak vacuum intensities necessary to excite wakefields. To address this latter point, we have performed a series of experiments to determine the range of parameters in which we can expect the pump pulse to traverse the cell with minimal loss of energy or distortions to its mode or spectrum. Figure 6 shows the main results: the transmission characteristics depend strongly on the gas species, the gas pressure and the interaction length. In particular for Hydrogen and Helium, relativistic pulses ($I \sim 10^{18} \text{ W/cm}^2$) can traverse the gas cell with nearly no distortion to the mode shape or spectrum, and negligible drop in transmitted energy over the entire range of tested parameters. For higher-Z gases, the energy, mode and spectrum start to noticeably worsen above $\sim 100 \text{ Torr}$ for a 1 mm interaction length, and above $\sim 50 \text{ Torr}$ for a 2 mm interaction length. Thus we find that the transmission characteristics of the cell are excellent for the parameters of interest to our experiments.

FIGURE 6. a) transmitted mode profiles at 300 Torr for a 1 mm interaction length b) Transmitted spectra for the same c) Energy Transmission for same d) Energy Transmission for a 2 mm interaction length.

CONCLUSIONS

We have made significant progress in developing our capability to measure wakefields. This progress includes upgrading our laser system from the 10 mJ – 20 mJ level to the 100 mJ – 200mJ level, developing and characterizing a gas cell to confine the plasma to the interaction region and provide the necessary control over the critical parameters of gas species, density and interaction length, developing our

analysis to identify the parameter space that will optimize the wakefield phase shift, and most importantly we have developed our technique of Frequency Domain Holography and proven that it has the sensitivity to measure the wakefields that we expect to produce. Implementation of the technique is now ready to commence, and we expect to have actual measurements to compare to our simulated wakefield density and recovered phase profiles shortly. Below are calculated profiles of the wakefield density $\delta n_e/n_e(z, r)$, and phase profile $\delta\phi(z, r)$ for a $\lambda = 800$ nm $E_p \sim 100$ mJ, $t_p \sim 100$ fs driving pulse focused down to $\sigma_{r1/e} \sim 6.4$ μm in a plasma of $n_e \sim 5.35 \times 10^{17} \text{cm}^{-3}$ measured by a 1 ps, 400 nm probe pulse.

FIGURE 7. a) $\delta n_e/n_e$ of wakefield b) recovered phase

ACKNOWLEDGMENTS

This work is supported by Department of Energy Grant No. DEFG03-96-ER-40954 and NSF Physics Frontier Center Grant No. PHY-0114336

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