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Abstract. Bunch driven plasma wakefield accelerators (PWFA), such as the "plasma afterburner," are a promising emerging method for significantly increasing the energy output of conventional particle accelerators [1]. The study and optimization of this method would benefit from an experimental correlation of the drive bunch parameters and the accelerated particle parameters with the corresponding plasma wave structure. However, the plasma wave structure has not been observed directly so far. We will report ongoing development of a noninvasive optical Frequency Domain Interferometric (FDI) [2] and Holographic (FDH) [3] diagnostics of bunch driven plasma wakes. Both FDI and FDH have been previously demonstrated in the case of laser driven wakes. These techniques employ two laser pulses co-propagating with the drive particle bunch and the trailing plasma wave. One pulse propagates ahead of the drive bunch and serves as a reference, while the second is overlapped with the plasma wave and probes its structure. The multi-shot FDI and single-shot FDH diagnostics permit direct noninvasive observation of longitudinal and transverse structure of the plasma wakes. The experiment is being developed at the 70MeV Linac in the Accelerator Test Facility at Brookhaven National Laboratory to visualize wakes generated by two [4] and multi-bunch [5] drive beams.

Keywords: Optical plasma diagnostics, Frequency domain holography, Plasma wakefield accelerator, Beam plasma interactions
PACS: 52.70.Kz, 52.40.Mj

INTRODUCTION

A series of collaborative experiments at SLAC have established the plasma wakefield accelerator (PWFA) as a very promising advanced acceleration method. The culminating experiment in this series produced one of the most striking recent results in this field, which demonstrated energy doubling of a part of 42GeV electron bunches [1] in just 85cm of lithium plasma. A new series of PWFA experiments at the FACET (Facilities for Accelerator Science and Experimental Test beams) user facility at SLAC aims to address a number of remaining issues (e.g. energy spread, emittance,..) before PWFA can become a practical tool [8]. The plasma wave itself, which is an inherent part of the acceleration process, has not been observed directly in the past PWFA experiments. The current method of studying the plasma wave, such as estimating the accelerating gradient, is indirect. It relies on analyzing the properties of the drive and witness bunches before and after the interaction with the plasma. A direct noninvasive diagnostic of the plasma wave structure would complement future PWFA experiments, providing a fuller picture of the beam plasma interaction.

Such diagnostics have already been demonstrated in the case of the laser wakefield accelerator (LWFA)[2,3,6]. The imaging of laser-driven wakes in plasmas of density 1.7 to 3×10^{17} cm^{-3} has been demonstrated using the multi-shot technique of Frequency Domain Interferometry (FDI) [3] and in plasmas of density 10^{18} cm^{-3} to 10^{19} cm^{-3} using the single shot technique of Frequency Domain Holography (FDH) [2]. Both techniques require two laser pulses: a reference preceding the plasma wave, and a probe co-propagating with the plasma wave and recording its refractive index. The refractive index variation is read out from the probe by observing its interference with the reference pulse in the frequency domain, i.e. in a spectrometer. The FDI technique uses two short pulses, probing the wake at a single location in one shot. Multiple shots, at various pump probe delays, are required to map out an extended section of the wake. Consequently the wake must be reproducible in structure from shot to shot, as is typical of a linear excitation regime, if the driver and plasma parameters are stable. This approach requires either very precise synchronization between the wake and probe (which is achieved automatically in laser-driven wakes) or a shot by shot measurement of their relative delay (which may be required for charged particle bunch-driven wakes). The method is however very amenable to averaging and low signal detection if the previous conditions are met. In FDH the probe and reference pulses are stretched in time by frequency chirping as in Ref. 2. In this case, the probe samples an extended section of the wake in a single shot. Probe and reference pulses, though temporally stretched, must contain frequency bandwidth exceeding a reciprocal plasma period to resolve sub-plasma-wavelength features. If the signal is sufficiently strong such that averaging is not required, FDH is the preferred method, giving a true snapshot of a single plasma wake. Both methods permit transverse spatial resolution.

We are currently working on adapting and demonstrating FDI and/or FDH techniques for the first time to imaging/measurement of wakes driven by charged particle bunches. Existing PWFA experiments at the BNL ATF (Accelerator Test Facility) developed with USC have shown controlled high gradient, low energy spread acceleration, using two sub-ps electron bunches to drive a plasma of electron density 10^{16} cm^{-3} to 10^{17} cm^{-3}[4]. In addition, the same collaboration developed a scheme for the generation of multiple sub-ps bunch trains, [5] permitting the study of resonant wakefield excitation. The FDI/FDH methods will complement these experiments by permitting a direct observation of the expected multi-bunch resonant wake enhancement as well as the correlation of the microbunch energy changes with the local wake amplitudes.

EXPERIMENTAL SETUP

The existing PWFA experiments use the ATF linac which produces electron macrobunches with ~70MeV energy. Subsequently, these macrobunches are modulated by masking the electron beam while it is dispersed in energy. Upon reversal of the dispersion, energy modulation is converted into temporal modulation, producing microbunches with adjustable sub-picosecond spacing. The trains of microbunches are then injected into a ~2cm long hydrogen plasma. The plasma is generated in a capillary (Length L ~ 2cm and diameter ~1mm) with pulsed hydrogen injection and ionization by a HV electrical discharge. Constraints on the current electron bunch duration and spacing set the plasma density in the range of 10^{16} to $10^{17}cm^{-3}$, corresponding to a plasma period in the range of 1 ps > T_p > 0.3ps. The beam transverse size is ~100microns and the charge per microbunch ~10's of pC. The plasma density perturbation is in the linear regime with $\delta n_e/n_e \sim 10^{-2}$. Existing diagnostics permit the characterization of the electron drive beam parameters including the energy as well the microbunch train profile (multi-shot measurement).

The FDH/FDI diagnostic is being adapted to these currently ongoing multi-bunch PWFA experiments. The schematic setup of the diagnostic being developed is shown in Figure 1. ATF is equipped with an existing Ytterbium fiber laser producing 150fs pulses synchronized to ~5ps with the electron bunches. The laser pulses are delivered to the experimental hall through an optical fiber. After exiting the fiber, depending on the chosen diagnostic method, these pulses can be either fully compressed, for FDI, or partially compressed, for FDH. The probe reference pair will be generated with a Michelson interferometer. These pulses will then co-propagate with the electron bunches through the plasma capillary. Natural points for laser beam injection and extraction already exist in the current PWFA experiment at a turning magnet and a spectrometer magnet. Little if any disturbance to the currently running PWFA experiment is expected. The probe and reference will be imaged from the capillary to a spectrometer after the interaction. The experimental setup is essentially the same for the FDI and the FDH experiments except for the necessity to scan the laser and electron bunch delay in the FDI case, and retaining some frequency chirping in the FDH case. Consequently, it should be possible ultimately to investigate both methods with little alteration to the setup.

EXPECTED ISSUES

At probe wavelength of λ_{pr} ~1 μm the expected refractive index variation is $\Delta n \sim 4.5 \times 10^{-8}$ to 4.5×10^{-7} and an observed probe phase shift of $\Delta\varphi = (2\pi/\lambda_{pr})\Delta nL \sim 5.6 \times 10^{-3}$ to 5.6×10^{-2} rad, for $n_e = 10^{16}$ cm^{-3} to 10^{17} cm^{-3}, and $\delta n_e/n_e \sim 10^{-2}$. These phase shifts are quite small, and in particular about one order of magnitude smaller than those ($\Delta f \sim 10^{-1}$ rad) measured by single-shot FDH in Ref. 2 for wakes in plasmas of density ~ 10^{18} cm^{-3}. On the other hand, they are of the same order as those ($\Delta f \sim 10^{-2}$ rad) measured by multi-shot FDI in Ref. 3 for wakes in plasmas of density ~ 10^{17} cm^{-3}, where signal averaging was used. However, an important advantage in probing electron-bunch- (compared to laser-) driven wakes is that the expected level of background noise is considerably smaller. The major problem in the case of laser-driven plasma wakes is the very intense background of white-light continuum and laser-generated harmonics from the pump pulses, which are not present here with electron-bunch drivers. It is expected, for this reason that both methods will be more sensitive in the case of PWFA.

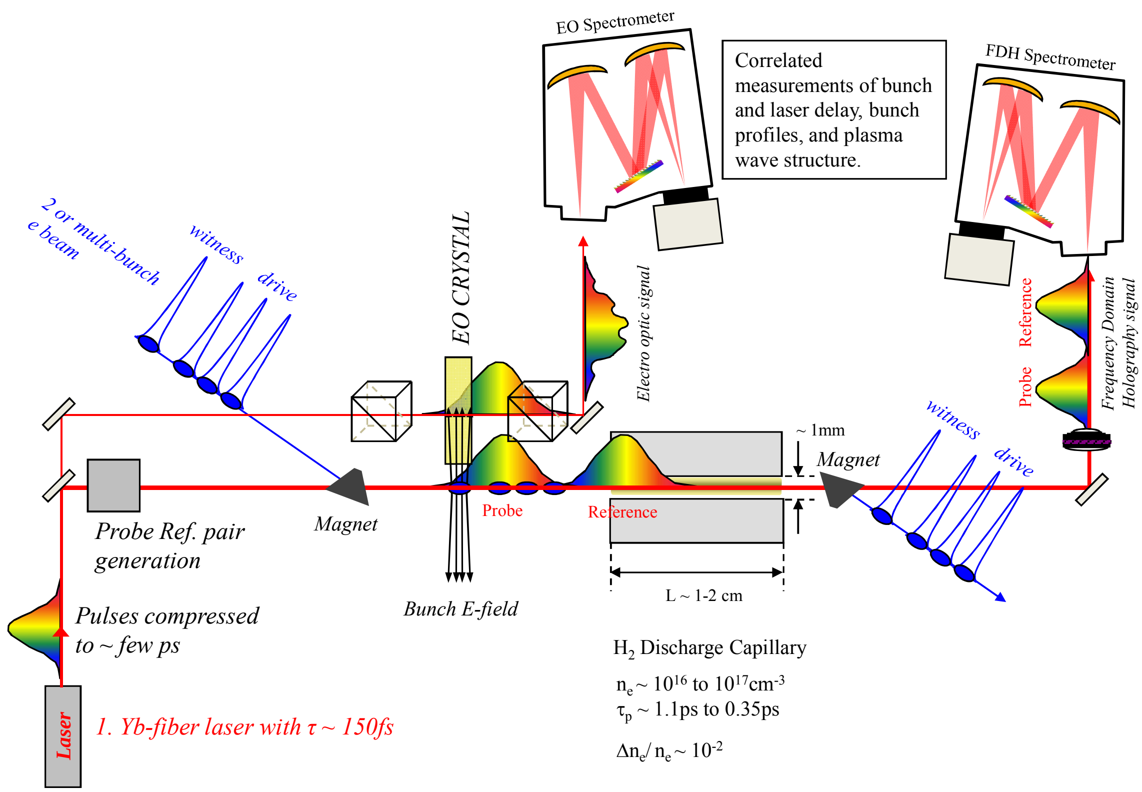

FIGURE 1. Schematic of the proposed FDI/FDH experimental setup. The FDH variant is shown along with the electro-optic diagnostic of the electron bunch profile.

The considerable temporal jitter of~5ps, between the Yb-fiber laser and the electron bunches, may be an obstacle to implementing FDI, since this jitter is considerably larger than the plasma period. FDH is obviously preferable in this case since it captures the plasma wave structure on one shot. For FDH the jitter will simply cause the wakefield to be randomly shifted within the probe observation window. Although, it may, on some shots, jump entirely outside of this window. FDI can still be possible in the presence of temporal jitter if the delay between the electron bunch and the laser pulses is known on every shot. In fact if, as expected, shot-to-shot jitter ranges over a 5 ps interval, then it may not be necessary to build an adjustable delay line for the probe pulse in the case of FDI.

Instead, we could let the built-in jitter explore the necessary range of time delays, and simply record the bunch-probe time delay on each shot.

In order to record the bunch-probe delay during the experiment, however, the delay measurement must be non-destructive to the electron bunch. To accomplish this we have been designing an electro-optic measurement scheme of bunch delay relative to the laser pulse, as shown in Figure 1. (Alternatively, a sensitive streak camera could be used to capture diffraction radiation as well as the laser pulses.) This scheme has the added advantage of providing a simultaneous microbunch train profile on every shot. This capability will permit a direct correlation between the plasma wave structure and the microbunch train profile, which would be a very useful tool in the study of the resonant wake excitation process.

Large plasma density variations can be a detrimental issue for FDI, since plasma wavelength variations may then preclude the reconstruction of the entire wave from multiple shots. We have made interferometric measurements of the plasma density to gauge this stability. An example of these measurements is shown in Figure 2. The variations are not very large, with an RMS spread of about 20%. A more serious problem would be caused by significant plasma density gradients. The same interferometric results show large transverse gradients for large densities, well above 10^{17} cm^{-3}, however they show very good uniformity for densities of interest, i.e. < 10^{17} cm^{-3}. Longitudinal variations cannot be ruled out with this measurement but are not expected to be significant. The observed, longitudinally averaged, variations are due mostly to shot to shot variations in the pressure of the injected hydrogen. The geometry of gas injection into the capillary is designed to ensure constant longitudinal gas density.

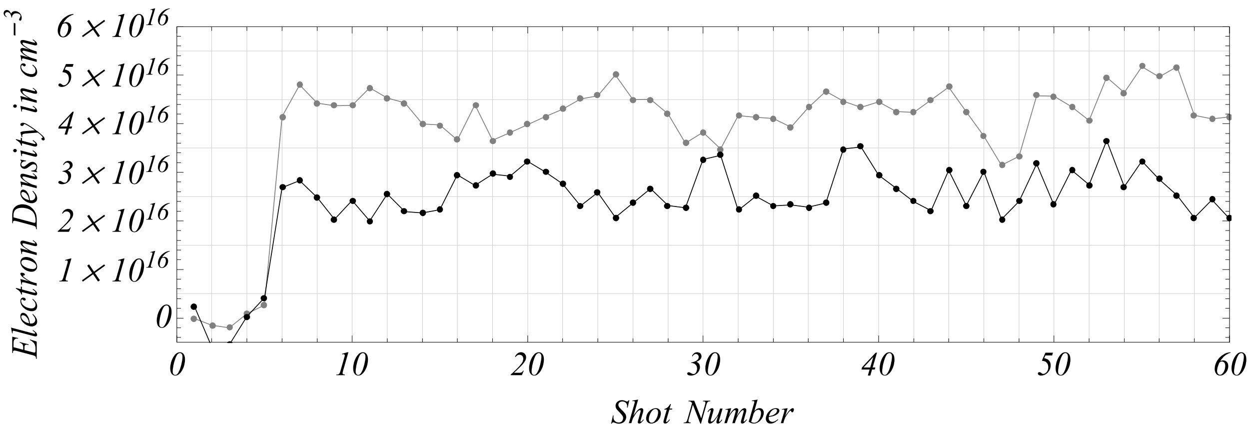

FIGURE 2. Examples of interferometric measurements of capillary plasma density at two different HV settings. First few shots at ~0 correspond to no HV discharge. The density is longitudinally averaged along the 2cm plasma column. The magnitude of the variations agrees with shot to shot changes in neutral gas density, which were also measured interferometrically.

CONCLUSION

The fortuitous existence of ports permitting co-axial optical probe and electron bunch propagation in this experiment may not be always possible. Extensions of the FDH technique to non-collinear geometries, Frequency Domain Streak Camera (FDSC), as well as to multi-probe geometries, Frequency Domain Tomography (FDT), are being currently developed [9]. Both of these techniques provide additional information about temporal evolution of the plasma wave, information which is averaged out in the conventional collinear FDH.

Other parameters of PWFA can also significantly affect FDH and its derivative diagnostics. In the current experiments we must contend with very small signals. In experiments on the scale of the SLAC/FACET experiments, where the wake may be very large and the interaction length on the order of a meter or more, the signal may become too large for conventional FDH. It may then be necessary to implement FDSC or FDT. In these cases the design of the plasma source will have an impact on the choice of the technique. The heat pipe oven used in the SLAC experiments can accommodate longitudinal as well as slightly oblique probes, for example. However, it is not designed to allow transverse probing.

Multi-shot FDI and single-shot FDH diagnostics of bunch-driven wakes, developed and refined through this research, might ultimately be used to characterize such effects as the fundamental structural differences between electron-driven [10] and positron-driven [11] plasma wakes. Electron bunches “blow out” plasma electrons, whereas positron bunches “suck in” plasma electrons, resulting in very different wake structures and acceleration properties. Currently computer simulations are the only source of detailed knowledge of the relationship between these plasma structures and the accelerated particles.

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REFERENCES

1. Ian Blumenfeld, Christopher E. Clayton, Franz-Josef Decker, Mark J. Hogan, Chengkun Huang, Rasmus Ischebeck, Richard Iverson, Chandrashekhar Joshi, Thomas Katsouleas, Neil Kirby, Wei Lu, Kenneth A. Marsh, Warren B. Mori, Patric Muggli, Erdem Oz, Robert H. Siemann, Dieter Walz & Miaomiao Zhou, *Nature* **445**, 741-744 (2007).
2. N. Matlis, S. Reed, S. S. Bulanov, V. Chvykov, G. Kalintchenko, T. Matsuoka, P. Rousseau, V. Yanovsky, A. Maksimchuk, S. Kalmykov, G. Shvets and M. C. Downer, *Nature Physics.* **2**, 749-753 (2006).
3. C. W. Siders, S. P. Le Blanc, D. Fisher, T. Tajima, and M. C. Downer, *Physical Review Letters* **76**, 3570 (1996).
4. Efthymios Kallos, Tom Katsouleas, Wayne D. Kimura, Karl Kusche, Patric Muggli, Igor Pavlishin, Igor Pogorelsky, Daniil Stolyarov, and Vitaly Yakimenko, *Physical Review Letters* **100**, 074802 (2008).
5. P. Muggli, V. Yakimenko, M. Babzien, E. Kallos, and K. P. Kusche, *Physical Review Letters* **101**, 054801 (2008).
6. Peng Dong, S. A. Reed, S. A. Yi, S. Kalmykov, G. Shvets, and M. C. Downer, *Physical Review Letters* **104**, 134801 (2010).
7. S. P. Le Blanc, E. W. Gaul, N. H. Matlis, A. Rundquist, and M. C. Downer, *Optics Letters* **25**, 764-766 (2000).
8. M J Hogan, T O Raubenheimer, A Seryi, P Muggli, T Katsouleas, C Huang, W Lu, W An, K A Marsh, W B Mori, C E Clayton and C Joshi, *New Journal of Physics* **12**, 055030 (2010)
9 Zhengyan Li, “Frequency domain streak camera for ultrafast imaging of evolving wakefields”, paper in this Proceedings.
10 M. Hogan *et al*., *Physical Review Letters* **95,** 054802 (2005).
11 B. E. Blue *et al*., *Physical Review Letters* **90**, 214801 (2003).