Plasma wakefield diagnostics with oblique crossing angle probe

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Introduction

Plasma accelerators are promising future generation of particle accelerators. A plasma accelerator can generate electric fields up to 10-100 GV/m, three orders of magnitude larger than conventional accelerators [1]. Applications of plasma accelerators include table-top bright x-ray sources [2] and shorter particle accelerators [3]. In plasma accelerator, a driver, e.g. an electron beam, proton beam, or laser pulse, is fired into plasma and induces a modulation in the electron density of the plasma. This modulation is called a wakefield and the electric field in the wakefield can be employed to accelerate particles.

Diagnosing the wakefield itself is a challenging task because the wakefield propagates with speed near the speed of light and has small structures (~μm). To achieve this task, one usually uses optical probe diagnostics, which involves sending another laser pulse copropagating with [5] or perpendicular to [6] the plasma wakefield driver, and using frequency interferometry to retrieve the plasma wakefield structures. There is also another method that sends the probe laser pulse at an oblique angle to the driver to obtain the evolution of the wakefield in a single shot without obtaining a clear structure of the wakefield [7]. The method presented in this report is complementary to the latter method, i.e. using a probe laser pulse sent in an oblique angle to diagnose the structures of the wakefield at a certain point in the plasma. This configuration makes it possible to diagnose the plasma wakefield at the different positions in the plasma.

Theory

As the electron density of the plasma wakefield is modulated in space and time, its refractive index also varies. The equation relating the refractive index of the plasma, η, and the modulated electron density, n, is

$$\eta(\mathbf{r},t) = \left(1 - \frac{n(\mathbf{r},t)}{n_0}\frac{\omega_p^2}{\omega_0^2}\right)^{1/2},$$

where ω_p is the plasma frequency with no modulation, ω_0 is the probe's frequency, and n_0 is the unmodulated plasma density. If a laser pulse propagates through a non-uniform medium with refractive index $\eta(\mathbf{r},t)$ as above, then the phase of the laser pulse is modulated. As the refractive index is related to the electron density, one can obtain the electron density by measuring the phase modulation of the laser pulse. This can be done using spectral interferometry as described in [8].

The case considered in this report is illustrated in Figure 1. If $v_g \cos\theta \approx u_p$, it can be assumed that the probe pulse is crossing the wakefield perpendicularly in a frame co-moving with the wakefield. Therefore, a part of the pulse always interacts with the same longitudinal position of the wakefield. If the wakefield is assumed to have a cylindrical symmetry, then one can use Abel inversion [9] to retrieve the radial profile of the electron density modulation. Thus, the phase modulation of the probe and the electron density modulation in this case can be related by the equation below,

$$\phi(\zeta,y) = -\frac{\omega_p^2}{\omega_0 c}\int_0^\infty \frac{\Delta n(\zeta,r)}{n_0}\frac{2r}{\sqrt{r^2-y^2}}\,dr,$$

where $\zeta = z - u_p t$ is the longitudinal position in the moving frame, Δn is the density modulation, and the integral represents the Abel transformation.

Experimental setup

An experiment to test this diagnostic method was performed with the Astra laser in Target Area 2 for 12 weeks from June – November 2016. The main laser pulse had wavelength 800 nm, pulse duration 45 fs, energy 480 mJ, and focused using an *f*/17 parabolic mirror to produce a 29 μm focused beam diameter (FWHM). The parameters yield the normalised intensity, $a_0 = 0.72$. A gas jet with a 3 mm nozzle diameter was used, with methane gas as the target.

The probe pulses for diagnosing wakefield consist of two chirped pulse with a chirp coefficient of 0.021 nm/fs separated by 1.5 ps, split using a Michelson interferometer. The probe pulses were frequency doubled to 400 nm with a longer pulse duration of 570 fs, energy 500 μJ, and were focused to 120 μm diameter focal spot. The timing between the probe and the main laser pulses was tuned so that one of the probe pulses did not interact with the plasma wakefield. The angle between the main laser pulse and the probe pulses was 8°. Both of the pulses were sent to a spectrometer for the spectral interferometry.

For the plasma density profile diagnostic, a Mach-Zehnder interferometer was employed using a single short probe with a wavelength of 800 nm. This probe crossed the wakefield in the perpendicular direction.

During the experiment, shots without gas were taken occasionally as reference shots, to be compared with the shots

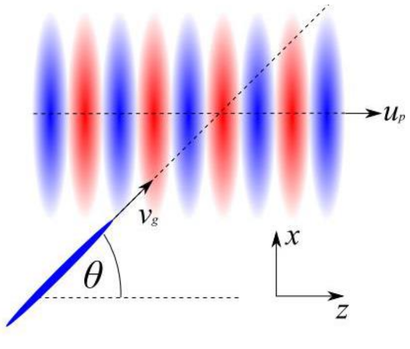

Figure 1. Illustration of the case. The y-axis (not shown) is coming out of the plane.

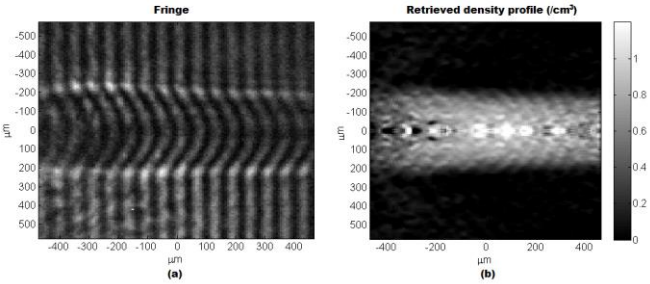

Figure 2. Mach-Zehnder interferometer result on the plasma density profile diagnostic. The modulation at the axis position in Figure (b) is due to the singularity near the axis in Abel inversion.

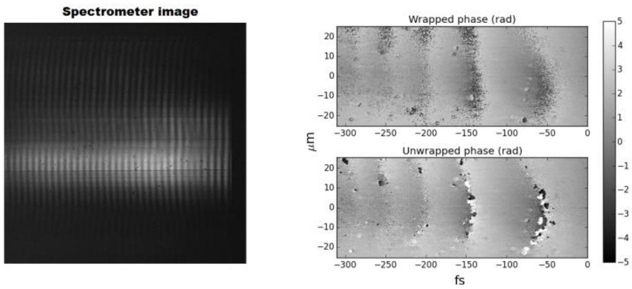

Figure 3. (Left) The spectrometer image of the spectral interferometry by the oblique angle probe pulses. (Right) The retrieved wrapped and unwrapped phase modulation when the plasma was present.

with gas. The backing pressure of the gas was also varied to give different plasma densities.

Results

The plasma density was varied from 5×10^{18} to 1.1×10^{19} cm^{-3} during the experiment. This is calculated from the results of Mach-Zehnder interferometry of a single pulse probe. The interferometry picture is inverted using Abel inversion to obtain the radial profile of the plasma. Figure 2 shows the interferometry picture and the extracted plasma density profile as a function of the longitudinal position and radial distance from the axis. The radial axis was chosen by maximizing the convolution of the profile along the transversal direction.

Some modulations were captured during the experiment. Figure 3 shows the spectrometer results on a shot with gas and phase modulation of the probe pulse. Unwrapping the phase was done by the method from [10].

In the figure, the modulation's wavelength is large at the front and decreases at the back, as well as the amplitude. This indicates the wakefield non-linearity, where the wakefield's wavelength increases as the modulation increases [11].

As a confirmation method to make sure that the modulation is a wakefield, the wavelength of the wakefield is measured and compared to the theoretical estimate of the wavelength. The wakefield's wavelengths from the experimental results were obtained by measuring the wavelength for the third modulation, so that the non-linear effect of the lengthening wavelength is reduced. Figure 4 shows the plot of measured wavelengths against the plasma densities which agrees quite well with the theoretical estimate. A slight overestimate on the experimental results is probably due to the non-linear effect of the wakefield.

Conclusions

A method to diagnose plasma wakefield in a spatially-resolved manner is presented in this report. Frequency-doubled probe pulses were sent crossing the wakefield in an oblique angle. When the probe pulse interacts with the plasma wakefield, the pulse's phase is modulated because of the variation in the refractive index in the plasma wakefield. This phase modulation can be captured in a spectrometer using spectral interferometry.

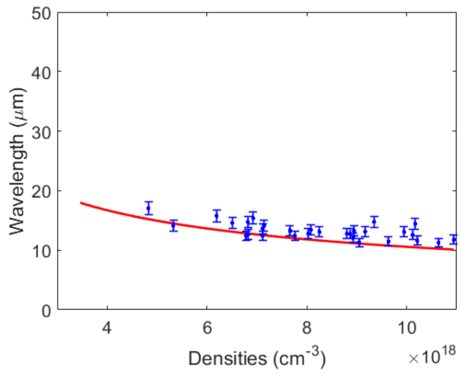

Figure 4. Plot of wakefield wavelengths against the plasma densities. The red line shows the theoretical wavelength.

In this report, the experimental results of this diagnostic technique from the Target Area 2 (TA2) are presented. In the experiment, periodic modulation in the probe pulse's phase was found. The modulation indicates that the wakefield is in the non-linear regime as the wavelength of the modulation is slightly larger than the linear plasma wakefield wavelength. This is confirmed by comparing the observed modulation wavelength and the theoretical estimate of the wavelength.

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