PHOTON ACCELERATION AS THE LASER WAKEFIELD DIAGNOSTIC FOR FUTURE PLASMA ACCELERATORS

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Abstract

In the near future, laser-plasma particle accelerators will be able to sustain electric fields in excess of 100 GeV/m, along plasma channels several Rayleigh lengths long. For these extreme conditions, present day laser wakefield diagnostics such as Frequency Domain Interferometry will not be able to resolve the wake field structure and determine the magnitude of the electric field. In this paper, we present a detailed comparison between frequency-domain interferometry and a photon acceleration based wake field diagnostic. We determine the experimental parameters for which photon acceleration becomes the only viable diagnostic technique. Dispersion effects on the probe beam and the implications of an arbitrary phase velocity of the plasma wave are discussed for both diagnostic techniques. We also propose an experimental set-up for a photon acceleration diagnostic allowing for the simultaneous measurement of the electric field structure and the laser wake field phase velocity. Comparison with results from photon acceleration experiments by ionization fronts will also be presented.

1 INTRODUCTION

One of the most important goals in the plasma particle accelerators research field of is the development of experimental techniques to characterize the electron plasma wave (EPW) generated by intense laser pulses [1, 2].

The first measurements of the temporal and spatial characteristics of the plasma waves generated by an ultrashort laser pulse (laser wakefield) were recently reported [3, 4], using the frequency-domain interferometric technique (FDI) [5]. The purpose of FDI is the measurement of the phase shift experienced by a probe laser pulse travelling through an electron density plasma perturbation. The experimental principle is the following: a double pulse beam (probe and reference pulses) is co-propagating with the EPW (described by the electron density $n_e(z,t)$). The probe pulse will experience an optical phase shift $\Delta\phi$ proportional to $n_e(z,t)$, while the reference pulse, which precedes the laser wakefield, propagates through the interaction region unperturbed. The relative phase shift between these two probing pulses is then measured by the FDI technique. Finally, by sweeping the probe pulse along one or more periods of the plasma wave with a temporal delay line, it is possible to reconstruct the wakefield oscillation. It is important to notice that in experiments [3, 4], the frequency shift and the dependence of the group velocity of the probe pulse on the local plasma density $v_{g_{probe}}(\delta n_e)$ were not taken into account.

Other experiments were performed with the purpose of studying the frequency up-shift resulting from the interaction of short laser pulses with relativistic ionization fronts [6, 7]. An estimate for the velocity of the ionization front and its maximum electron density was obtained, clearly pointing to the feasibility of a new diagnostic tool, the photon acceleration diagnostic (PAD). The frequency shift experienced by a probe laser pulse co-propagating with a relativistic EPW is proportional to the density gradient of the plasma perturbation. Like in the FDI diagnostic technique we can easily map the plasma wave by injecting the probe laser pulse at different positions of the plasma oscillation.

In this work, a detailed comparison of these two diagnostic techniques is carried out. A numerical simulation based on the ray tracing equations for the probe laser pulse is employed to calculate the frequency shift due to photon acceleration and also allows us to determine the phase shift of the laser pulse propagating in the laser wakefield.

2 RAY-TRACING SIMULATIONS

In this ray-tracing simulations the probe pulse length is not considered and the wave packet is only characterized by its central frequency and central wavenumber. When probing is performed by a low-intensity, ultra-short pulse, with a central frequency much higher than the electron plasma frequency we can use the linear dispersion relation in a plasma to describe the probe pulse propagation in the presence of an electron density perturbation. Assuming 1D propagation along the z direction we can then obtain the ray-tracing equations:

$$\frac{dz}{dt} = \frac{\partial \omega}{\partial k} = c\sqrt{1 - \frac{\omega_p^2(z,t)}{\omega^2}} \tag{1}$$

$$\frac{dk}{dt} = -\frac{\partial \omega}{\partial z} = -\frac{1}{2\omega}\frac{\partial \omega_p^2(z,t)}{\partial z} \tag{2}$$

These equations allow us to calculate the frequency shift of the probe laser pulse at any point of its trajectory.

$$\Delta\omega(z,t) = \sqrt{k^2(z,t)c^2 + \omega_p^2(z,t)} - \omega_0 \tag{3}$$

where $k(z,t)$ is the pulse wavenumber and $\omega_p(z,t)$ is the plasma frequency of the wakefield at a point (z,t) along the laser pulse trajectory. ω_0 is the pulse frequency before interacting with the plasma wave. The phase shift ϕ experienced by the laser pulse in the wakefield is determined by

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using the same ray-tracing trajectories and writing:

$$\phi_{probe}(z,t) = \int_0^z k(z,t)dz - \int_0^t \omega(z,t)dt \qquad (4)$$

where $k(z,t)$ and $\omega(z,t)$ are the wavenumber and frequency along the ray-tracing trajectory. We can then determine the total phase shift relative to a pulse propagating in an unmodulated plasma

$$\Delta\phi(z,t) = \phi_{probe}(z,t) - \phi_{ref}(z,t) \qquad (5)$$

For the laser wakefield scaling, we used the expressions for the laser wakefield excitation in the linear nonrelativistic two-dimensional (2D) limit resonant regime [8, 9, 10]. For simplicity, we have decided to analyze, in all the simulations, only the trajectories along the laser wakefield axis (1D simulations).

Generally, the solution of the ray-tracing equations can only be obtained numerically; however, fully analytical results can be achieved for some electron density perturbation. For instance, we can easily calculate the frequency shift which occurs when a wave packet (classical analog of a photon) crosses over an ionization front without reflection [11]

$$\Delta\omega = \frac{\omega_{p0}^2}{2\omega_0}\frac{\beta}{1\pm\beta} \qquad (6)$$

where the initial frequency of the photon is much higher than the maximum frequency of the plasma behind the ionization front, i.e., $\omega_0 \gg \omega_{p0}$. The sign $+$ $(-)$ refers to counter-propagation (co-propagation) where $v_p = \beta c$ is the velocity of the ionization front. It is very important to mention that in this new description of the frequency-shift diagnostic technique, the assumption $v_{g_{probe}} = v_p$ is no longer necessary and the limitation to small frequency shifts does not exist.

2.1 Propagation velocity effects

It is currently assumed in the FDI diagnostic [3, 4] that the probe laser pulse always stays in phase with the plasma wave, i.e. $v_{g_{probe}} = v_p$. This is not valid for two reasons: i) the probe group velocity depends on the local electron plasma density $v_{g_{probe}}(z,t) = c\sqrt{1-\omega_p^2(z,t)/\omega}$ at each point of the pulse trajectory (see eqs.(1) and (2)); ii) the phase velocity of the wakefield v_p, which is nearly equal to the group velocity of the pump laser pulse, can be considerably different from the velocity given by the linear dispersion relation in a plasma ($v_{g_{pump}} \neq c\sqrt{1-\omega_p^2/\omega}$), due to nonlinear [12] and 3D effects[13].

In our simulations these two aspects of the velocity effects were analyzed for both FDI and PAD diagnostic techniques[10]. For FDI the wakefield oscillation reconstructed from the measured phase shifts is significantly modified in amplitude, if the dispersion effects in the probe beam are included. On the contrary, for the PAD technique, the results are not affected by these dispersion effects, which in fact are fundamental processes in the PAD. When we assume that the phase velocity v_p of the wakefield is no longer equal to the group velocity of the pump, given by the linear dispersion relation in a plasma, both amplitude and wavelength of the phase shift oscillation, as well as the frequency shift oscilation, were modified [10]. To overcome this problem we need an independent measure of the phase velocity of the plasma wakefield, which can be obtained by comparing the frequency shift in co- and counter-propagation, as demonstrated in recent photon acceleration experiments [7].

In these simulations we have considered typical parameters for the pump laser pulse used in recent laser wakefield experiments [3, 4].

2.2 Large frequency shifts effects

In the near future it will be possible to excite larger EPW with the help of more powerful lasers, and extend the focal region to longer distances [14]. This will lead to much larger frequency shifts of the probe laser pulse. In order to examine the importance of a large frequency shift in FDI we have changed the pump laser pulse parameters: we have increased the pulse energy to $E_0 = 100mJ$ and decreased the pulse duration to $\tau_{pump} = 30fs$. The new plasma wakefield perturbation obtained from the scaling laws in the 2D resonant regime is $\delta n_e \approx 1.93 \times 10^{18} cm^{-3}$ in the laser focus.

From Fig.1(b) we can see that the frequency shift experienced by the probe pulse is $\Delta\lambda = |\lambda_0 - \lambda| \approx 200nm$ which is of the same order of its initial frequency, $\lambda_0 = 800nm$. But in the present situation the maximum frequency up-shift ($\Delta\lambda_+ \simeq 113nm$) is much smaller than the maximum frequency downshift ($\Delta\lambda_- \simeq 196nm$). This nonlinear effect arises from the fact that the frequency shift at each point of the ray-tracing trajectory of the probe pulse is inversely proportional to its frequency (see eq.(2)).

In Fig.1(a) we can notice that not only the phase shift oscillations become several times larger than π, but a similar nonlinear behavior is also present. This is due to the fact that the final frequency of the probe pulse is very different from the reference pulse frequency (which is constant). Thus the phase difference will depend not only on the plasma length but also on the dispersive optics installed in their optical path before reaching the detector device. This fact, added to the complexity of measuring phase shifts much larger than π and the difficulty of using the FDI of two laser beams with very different frequencies, will be the major drawback of this laser wakefield diagnostic technique. On the other hand, the large frequency shifts play in favor of the PAD technique due to the fact that the extraneous data contributions, such as stray light, pump leakage and detector defects are no longer a technical problem.

3 DISCUSSION

We will now discuss the limits of application for each of the two diagnostic techniques. In order to illustrate these limits

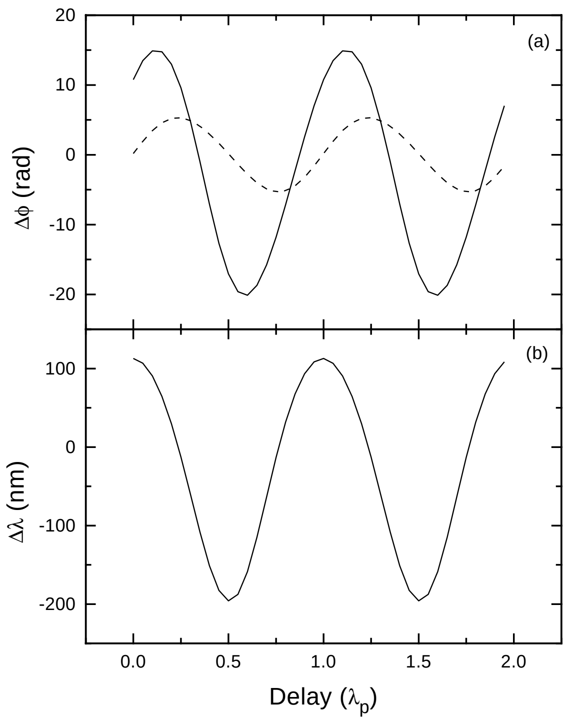

Figure 1: Wakefield oscillation map giving (a) the phase shift and (b) the frequency shift for the laser pulse parameters: $E_0 = 100mJ$, $\tau_{pump} = 30fs$. The calculated phase shifts in (a) are obtained by neglecting the frequency shift of the probe pulse (dashed curve) or by retaining it (solid curve).

we have built up a map representing the pump laser parameters, energy E_p versus pulse length τ_p (see Fig.2). For each set of parameters, the corresponding laser wakefield scaling is obtained for the optimized situation $\delta n_e/n_{e_0} \approx 1$ for the resonant density in the 2D limit. The criteria used to define the limiting curves are as follows. The solid curve is given by the condition of frequency shift $\Delta\omega_{shift}$ measured by the PAD technique equal to the spectral width of the probe pulse $\Delta\omega_{p_{FWHM}}$ The FDI technique is limited by the measured phase shift $\Delta\phi$, which must be lower than 2π. The dotted curve considers the phase shift as given by the refraction index $\Delta\phi_k$, and the dashed curve retains the contribution of the frequency variation $\Delta\phi_{k,\omega}$, eqns. (4)-(5). In this map, we also represent two lines defining the $100GeV/m$ goal for accelerating gradients, already measured by indirect techniques in recent experiments [15]. The lines correspond to the 2D and 1D limits of the resonant density. A close analysis of this map clearly shows that photon acceleration is the most appropriate diagnostic technique for the future laser wakefield accelerators.

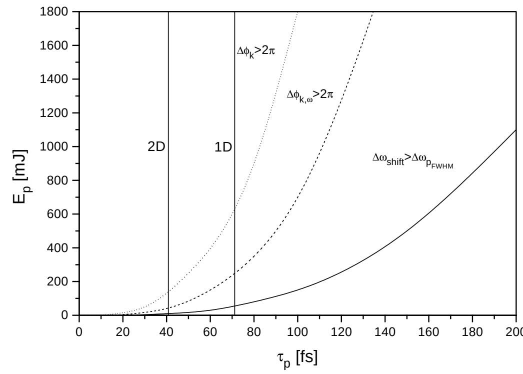

Figure 2: Map of the pump laser pulse parameters. Solid curve defines the limit of applicability of the PAD ($\Delta\omega_{shift} = \Delta\omega_{p_{FWHM}}$). Dashed and dotted curves define the limits of applicability of the FDI. The vertical lines indicate the $100GeV/m$ goal for the 2D and 1D scaling laws.

Recent experimental results [7] have shown a very good agreement with this ray-tracing formalism. The results of the frequency up-shift in the co- and counter-propagation setups of this experiment allow us to determine the electron plasma density and the ionization front velocity, by using the 2D version of eq.(6) [7]. This clearly points to the feasibility of PAD for relativistic coherent structures in laser produced plasmas like that presented in [7]. For all the reasons discussed above PAD is the most promising diagnostic for large amplitude plasma waves in future laser wakefield accelerator experiments.

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