Optical diagnostics of plasma waves

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Abstract

Although it has been studied theoretically and numerically, the excitation of a plasma wave created in a wave guide over several centimetres has never been measured experimentally. As this achievement is crucial for standard Laser Wakefield Accelerator (LWFA), we plan to carry out optical probing diagnostics to determine experimentally the amplitude and the duration of the plasma wave.

We summarize here the modelling of diagnostics planned to measure the amplitude of the plasma wave excited by LWFA inside capillary tubes.

Introduction

The interaction of intense laser pulses with plasmas produces large amplitude wakes. The high field strength associated with these waves can be used to accelerate particles to high energies over very short lengths. In linear or moderately non linear regimes, these fields are of the order of 1 to 10 GV per meter, and relativistic electrons injected into the wave can acquire an energy of the order of one GeV over a length of the order of a few centimetres. The control of the characteristics of the accelerated electron beam as it is accelerated is crucial for achieving a usable laser-plasma accelerator unit. The experimental demonstration of an accelerating electric field over several centimetres in a plasma is a key issue for the development of a controlled laser-plasma accelerator. The control of the electrostatic fields implies detailed knowledge of its structure and time evolution.

The diagnostics of plasma waves produced by laser wakefield is a difficult task. At relativistic intensities, nonlinear processes lead to the production of relativistic electrons and their observation has been used to infer the value of the accelerating field and acceleration length with the help of PIC simulations. Recently, frequency-domain holography has been employed by Matlis[1] and co-workers to visualise laser wakefield accelerator structures. In the linear regime considered here, the envisaged technique relies on the measurement of the frequency shifts of the laser pulse spectrum induced by the time dependent refractive index of the plasma.

Simulation results

The envisaged diagnostics will permit the measurement of the amplitude of the plasma wave at different instants after it has been created by the laser beam. The general picture of the temporal evolution of the excited plasma wave and the induced modulation on a chirped probe beam are shown in figure 1 after 5 cm of propagation inside a capillary tube filled with hydrogen gas at resonant pressure.

These simulations[2] have been performed with realistic parameters: main pump laser wavelength λ_0 =0.82 µm, pulse duration (full width at half maximum duration of intensity) τ_{FWHM}= 75 fs), pulse energy 275 mJ, power 3.5 TW, spot size of the Gaussian radial distribution of the laser field at the capillary entrance r_0 = 33 µm, I_L= 2.2×10^{17} W/cm^2, chirp of the pulse produces the FWHM spectral width $\Delta\lambda$ = 20 nm. The study carried out using cylindrical geometry, takes into account gas ionisation by the pump beam; transverse boundary conditions include reflections of the fields at the wall of the capillary tube.

The pump beam (red curve in figure1), creates the wakefield in the plasma which causes density variations during the laser pulse. These density variations reach a minimum at the rear part of the laser pulse, and cause a red spectral shift of the pump spectrum, which becomes significant after a few centimetres of propagation (left part of figure 2). This red-shift is proportional to the distance over which the plasma wave is created, and to the amplitude of the first minimum of the density perturbation[3].

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[1] Matlis et al., *Snapshots of laser wakefields*, Nature Physics, Nov. 2006

[2] N. E Andreev et al., *Spectral diagnostics of laser wakefield in capillary tubes*, Physics of Plasmas, **13**, 053109 (2006)

[3] N.E. Andreev et al. , *Wakefield generation as the mechanism behind spectral shift of a short laser pulse*, JETP **101**, 56 (2005).

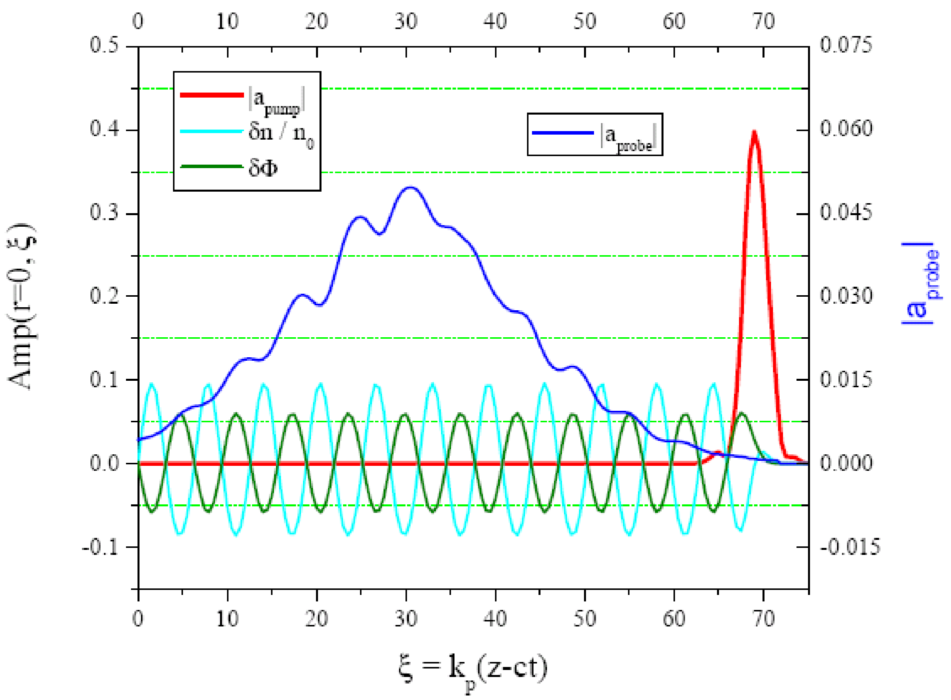

Figure 1 : Amplitude at the centre of the capillary tube of i) the pump laser beam (red curve), ii) the density perturbation (light blue curve), and iii) the probe beam (dark blue curve), as a function of time after 5 cm of propagation.

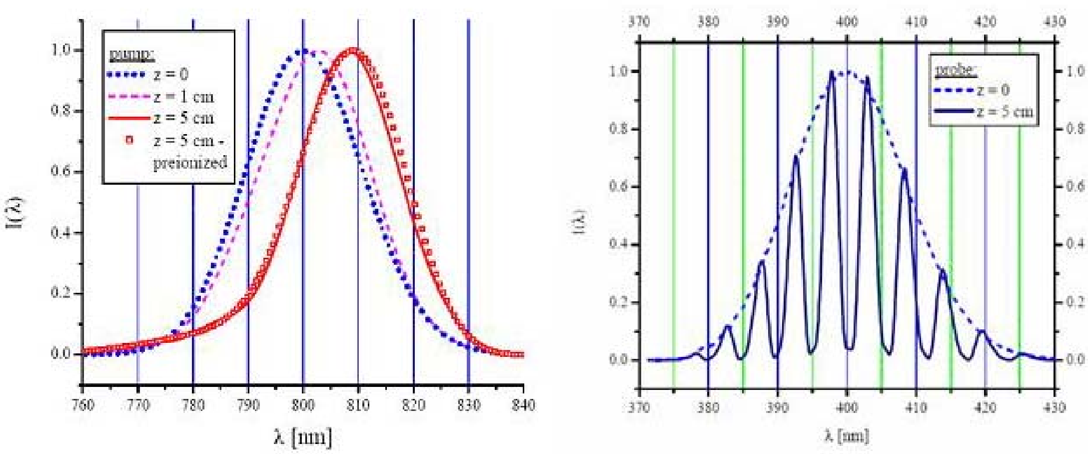

Figure 2 : Spectra of the pump (left-side) and probe (right-side) beams after a propagation length of 5 cm.

A chirped probe beam, travelling behind the pump beam, propagates in a medium of varying permitivity which modulates the spectrum. This modulation can reach a 100% after a few centimetres of propagation as shown in the right side of figure 2. Analytical calculations show that the amplitude of the intensity modulation of the probe beam is proportional to the density perturbation, the propagation distance and a sine function with an argument which depends on the duration of the probe beam.

Conclusion

The modification of the spectrum of a probe pulse travelling behind a short pump pulse exciting a plasma wave in a capillary tube has been modelled. The analysis performed with realistic parameters (a few percent wake-field amplitude and a few centimeters-long capillary tube) shows that the measurement of the probe pulse spectrum will allow to determine experimentally the amplitude of the plasma wave in a capillary.

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