Measurement of the decay rate of laser-driven linear wakefields

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Abstract

MP-LWFA is a scheme to reach high repetition rate laser wakefield acceleration by using a long pulse train to resonantly excite a wakefield, which requires knowledge of how long the wakefield survives. We have performed an experiment at Astra Gemini TA3 at the Central Laser Facility to measure the decay rates of laser-driven linear wakefields in 20 mbar Hydrogen and Deuterium, using parameters that are relevant for the MP-LWFA scheme.

1 Introduction

Laser wakefield acceleration (LWFA) is a method to use plasmas as an accelerating medium which could produce high energy particle beams in a much more compact way than conventional accelerators, which are based on RF technology. However, the repetition rate of LWFAs is limited to a rate on the order of a few Hz, due to the constraints of the laser technology used. High-repetition rates (∼kHz) is a requirement for the application of LWFAs in medicine and industrial research and development. Before the operation of a plasma based accelerator at a kHz repetition rate becomes feasible, a number of technical challenges need to be overcome. Perhaps most important, the drive laser itself need to be able to provide laser pulses at a kHz repetition rate. Multi-pulse laser wakefield acceleration (MP-LWFA) [1] represents a promising scheme to reach the kHz-range by exploiting high-repetition rate laser systems which could become available in the near future. Instead of using a single, high intensity laser pulse, the energy of N laser pulses in a pulse train is used each of which drives a low-amplitude linear wakefield. Resonant amplification of the plasma wakes is achieved when the inter-pulse distance equals an integer number of plasma wavelengths. This has been previously demonstrated in an Astra Gemini TA2 experimental campaign [2], where a pulse train of $N \approx 7$ pulses was used to excite a wakefield. The existence of a resonance condition was confirmed by tuning the plasma density and observing the wakefield amplitude.

Multi-pulse LWFA is similar to other schemes which relies on the resonant excitation of wakefields, such as self-modulated LWFA, beatwave acceleration [3], and plasma wakefield acceleration [4]. Indeed, MP-LWFA can be seen as a generalisation of the beatwave scheme. A common challenge for these schemes is that the temporal duration (τ) of the pulse or pulse train is longer than the plasma wavelength (λ_p): $\tau \geq \lambda_p/c$. In this case, the usual assumption that the plasma ions do not move may no longer hold, and the complex interaction between the ions and the plasma waves need to be taken into account. These interactions inevitably leads to a dissipation of energy as the wakefield decays into daughter waves [5, 6, 7]. The wakefield lifetime, τ_{wf}, limits the length of the pulse train that can be used to increase the wake amplitude, since the wake amplitude saturates for pulses longer than $\tau \geq \tau_{wf}$. The exact value of τ_{wf} depends on the plasma density, gas species, and the drive laser parameters, and so it is important to consider the parameters to be used [5]. In order to determine τ_{wf} with parameters relevant for MP-LWFA and to provide insight into the wakefield decay mechanism, we performed an experiment in Astra Gemini TA3. Using a single laser pulse as wakefield driver, we could measure the wake amplitude as a function of time after excitation by using the Temporally Encoded Spectral Shifting (TESS) technique [8, 9, 10].

2 Experiment

The experiment was set up according to Fig. 2 in the TA3 vacuum chamber. The South beam (centre wavelength 800 nm) was used as a drive beam with the energy of the beam limited to 1 J. The beam was focused down to a spot of radius $w \approx 40\,\mu\text{m}$ by using a combination of an $f/40$ gold-coated spherical mirror together with an adaptive optic and wavefront imaging sensor (HASO). The compressor gratings were set such that maximum pulse compression was achieved, approximately $\tau \approx 44$ fs. The plasma source was a gas cell with a length of 4 mm, with 200 µm diameter 3D-printer nozzles used as pinholes on either side to couple the laser into the cell. Fluid simulations in the computer software OpenFOAM [11] were performed to ensure that the gas density was homogeneous along the laser axis. The gas cell was backed with 20 mbar of either Hydrogen or Deuterium gas, in order to measure the impact of the ion mass on the wakefield lifetime. The North beam was used as a probe, and was frequency doubled to 400 nm using a 600 µm thick type I BBO crystal. A Michelson interferometer, with one arm offset to create an op-

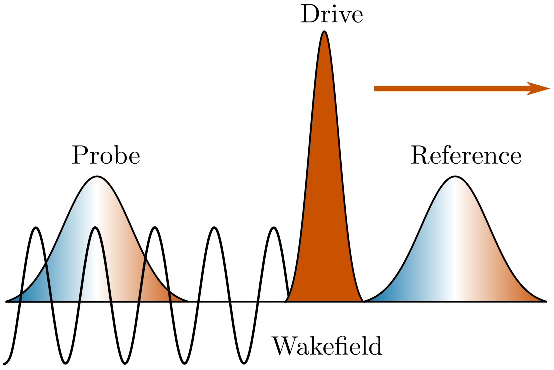

Figure 1: The TESS diagnostic pulses. The reference pulse, propagating ahead of the drive, is unperturbed by with wakefield, while the probe pulse co-propagates with it and suffers a phase shift [12].

tical path difference corresponding to 6 ps between the arms, was used to generate a probe-reference pulse pair. The pulses were then stretched to approximately 1.4 ps by propagating through a 160 mm long BK7 glass block, adding a group-delay dispersion of 20 000 fs^2. The pulses were co-axially injected onto the drive beam by propagating through a 25 mm hole cut in the center of a planar mirror. The reference pulse propagated ahead of the probe pulse and was not disturbed by the plasma, while the probe pulse co-propagated with the wakefield (see Fig. 1). The relative timing between the drive pulse and the probe pulse could be adjusted using a linear translation stage. After the gas cell, the 400 nm light was collected using a 10 inch, $f/10$ spherical mirror. However, since only 4 inch mirrors were used in the imaging system, the effective f-number of the imaging system was $f/25$, nevertheless an imaging resolution of 10 µm was achieved. The 800 nm light was dumped behind a dielectric mirror located after the spherical mirror. After this a set of lenses transported the probe beam and imaged the plasma region on the slit of an imaging spectrometer with spectral resolution better than 0.02 nm. The spectral interferogram, caused by the beating between the probe and reference pulses, was recorded on a CCD-camera and analysed by using the TESS method, shown in Fig. 3.

3 Conclusion

The MP-LWFA scheme offers a possible route to operating plasma wakefield accelerators at pulse repetition rates in the kHz range. The maximum length of the pulse train that can be used is limited by the wakefield lifetime: $\tau \leq \tau_{\mathrm{wf}}$. We have measured τ_{wf} using laser and plasma parameters that are relevant for the MP-LWFA scheme during an experiment at Astra Gemini TA3. Two different gases were used, Hydrogen and Deuterium, in order to measure the impact of ion mass on the decay

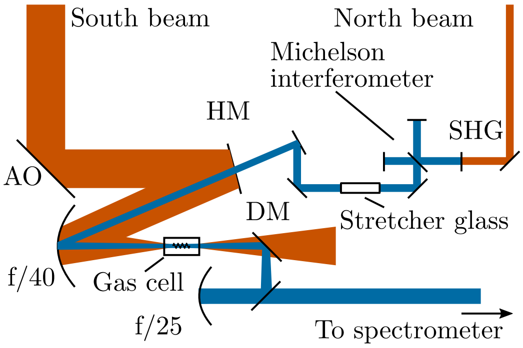

Figure 2: Experimental setup inside the Astra Gemini TA3 vacuum chamber. AO - adaptive optic, HM - holed mirror, DM - dichroic mirror, SHG - second harmonic generating crystal

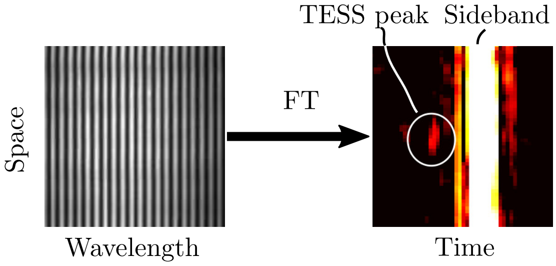

Figure 3: Principle of the TESS analysis technique. The probe-pulse interference is recorded on a CCD camera attached to a spectrometer. The interferogram (left) is analysed by calculating the magnitude of its Fourier transform along the temporal axis (right). The FT contains a zero-order peak (not shown above) and a sideband caused by the interference fringes. The phase modulation that the wakefield imprints on the probe beam is visible as a peak adjacent to the sideband. The ratio of the magnitudes of the peak and the sideband is used to extract the wakefield amplitude: $r = J_1(\phi_0)f(\omega_p)/J_0(\phi_0)$, where $\phi_0 = \omega_{p0}^2 L\delta n_e/2\omega c n_{e0}$, J_0 and J_1 are the Bessel functions of zeroth and first order, $f(\omega_p)$ a spectral overlap function, ω_p the plasma frequency, L the interaction length, δn_e the density modulation, ω the laser frequency, c the speed of light, and n_{e0} the unperturbed plasma density [12].

time. Our preliminary analysis shows that the measured ratio between these is consistent with that expected from theory.

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