Modeling of a Plasma Mirror for a Laser Plasma Wakefield Staging Experiment

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Abstract

The particle-in-cell EPOCH code was used to simulate the reflection of a high intensity laser pulse ($\approx 2 \cdot 10^{18}$ W/cm^2) with a pre-plasma formed by its pedestal incident on a 25 μm thick Kapton ®tape. The reflectivity was investigated as a function of the distance between focal plane and tape. The pedestal pre-ionises the tape with the resulting pre-plasma scale-length depending on the distance between the tape and the focus plane. The different scale-lengths of the density gradients influence the reflectivity significantly. The polarisation of the incoming laser pulse was found to be important: an increasing fraction p-polarisation results in harmonic generation and absorption of laser pulse energy in the pre-plasma.

1 Introduction

Laser plasma wakefield acceleration has the advantage of generating ultra-relativistic electron bunches in distances on the centimeter scale. It has been shown that electron bunches to > 2 GeV can be reproducibly generated at the Gemini laser system at CLF, Rutherford Appleton Laboratory [1]. The energies obtained are limited by dephasing and the depletion length of the laser pulse. A two-stage scheme, using two gas cells and two laser pulses, is a promising techniques to overcome these limitations as shown schematically in Fig. 1. The second laser pulse has to be overlapped with a prior generated electron pulse and both be injected into a second gas cell for further acceleration of the electron beam. This requires highly reflective and thin optics in order to minimise laser pulse energy loss and reduce the disturbance of the electron bunch. Plasma mirrors (PM) seem to fulfil these requirements as these can be thin foils down to e. g. 25 μm thickness and prove to have high reflectivities at ultra-high intensities [2]. Of importance are the reflection coefficient at high intensities, the reflected wavefront and the proportion of higher order harmonics generated on the plasma surface [3]. This was investigated using 2D particles-in-cell EPOCH simulations for the parameters of the aforementioned Gemini laser system [4].

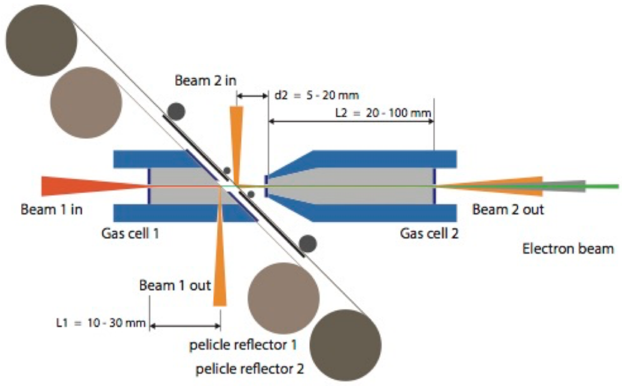

Figure 1: Possible set-up of a Laser Plasma-Wakefield staging experiment. A first laser beam is injected into a gas cell creating an accelerated electron bunch. A plasma mirror on a tape drive extracts the beam and a second tape drive injects a second laser pulse into a second gas cell to accelerate the electron beam even further.

2 Simulations

The experimental set-up allows the tape, which is mounted on a tape drive, to be positioned at different distances from the second gas cell, whos entrance is set at the focal plane as seen in Fig. 1. This results in different intensities impacting the tape. The $\approx$ 45 fs long Gemini laser pulse was focused with a $f/40$ parabolic mirror resulting in an intensity of $\approx 8 \cdot 10^{18}$ W/cm^2 and a laser spot size of ≈ 55 μm at focus. The pedestal, which is 15 ps long and rises exponentially from $\approx 10^{-9} - 10^{-4}$ relative to the main pulse energy [5], interacts with the Kapton tape ($C_{22}H_{14}N_2O_7$). The pedestal ionises the tape before the main pulse arrives and the plasma expands. This plasma expansion was simulated using the hydrodynamics code FLASH for the varying pre-pulse intensities. For the plasma mirror being 10 mm in front of the focal plane, the intensity yields $\approx 3.1 \cdot 10^{18}$ W/cm^2, for 15 mm $\approx 1.8 \cdot 10^{18}$ W/cm^2 and for 20 mm $\approx 1.2 \cdot 10^{18}$ W/cm^2. The resulting plasma electron density distributions for each distance can be seen in Fig. 2. Each density distribution was modelled with a partitioned exponential function in the form of:

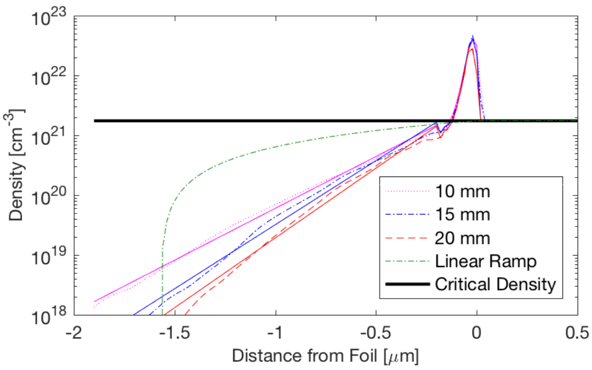

Figure 2: Electron density distribution resulting from the interaction between the pedestal of the laser pulse and the Kapton tape from the FLASH simulations and their exponential fits. The critical density is marked in black.

$$n_e = \exp \sum_{n=0}^{4} p_n x^n \; . \tag{1}$$

To investigate the significance of a steep increase of the electron density, an additional distribution with a linear ramp was also simulated. The electron density resulting for the 15 mm case was taken and a first order polynomial was fitted onto the data, instead of an exponential function. This is displayed as a green line in Fig. 2.
The data from the simulation revealed that that only the outer-shell electrons of the elements were ionised. Thus the EPOCH simulations were set-up to include ionisation for carbon, oxygen and nitrogen from their inner 1s electrons, thus including the option of further ionisation [6]. The tape was set up 45° degree to the laser pulse, as can be seen in Fig. 3.
More efficient reflection is achieved using s-polarised as this accelerates the electrons in plane, whereas p-polarised light accelerates the electrons into vacuum and reaccelerate them back into the plasma causing energy loss due to Brunel absorption [7].

3 Results and Discussion

The reflectivity of the laser pulses before and after the tape was compared using the ratio between input and output energy of the laser beam. The result for the different distances between tape and focal plane, p-polarisation and artificial linear ramp can be seen in table 1. As expected the p-polarised pulse generated higher harmonics, which can be seen in Fig. 4. This feature was not significantly observed in any of the other simulations. The change in reflection of the simulations can be explained by the gradient of the electron density. If the gradient of the plasma density is steep, the pulse travels through less plasma and loses less energy compared to a slowly rising electron density as shown in the case of the linear ramp. The wavefront in all the s-polarised simulations not altered strongly as can be seen in the exemplary case of 15 mm in s-polarisation in Fig. 5. Since the pulse is focussing towards the gas cell the beam size decreases.

Sim.	10 mm	15 mm	20 mm	lin.	p-pol.
Refl.	91.1%	93.9%	96.3%	79%	31.7%

Table 1: Reflection in percent for the different distances between PM and focal plane and for the artificial linear ramp and p-polarised light both 15 mm from the focal plane.

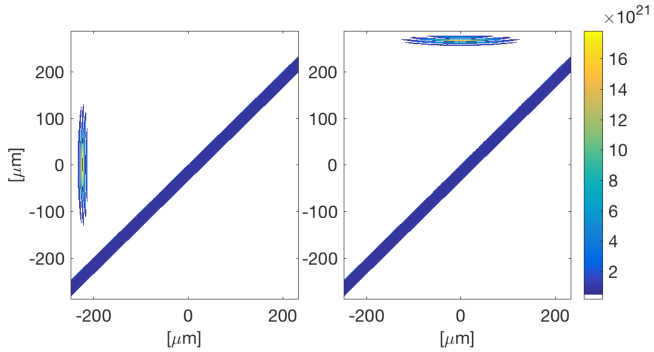

Figure 3: Left: Start of the simulation, the laser pulse coming from the left side of the window in 45° degrees towards the tape. Right: End of the simulation at which the laser pulse was reflected on the foil (in blue here).

For further comparison, a last simulation was performed assuming no pedestal thus elementary Kapton tape. This results in a lower reflection coefficient down to 77.24 %, as at the begging of the interaction between the foil and the pulse no free electrons are available for reflection.

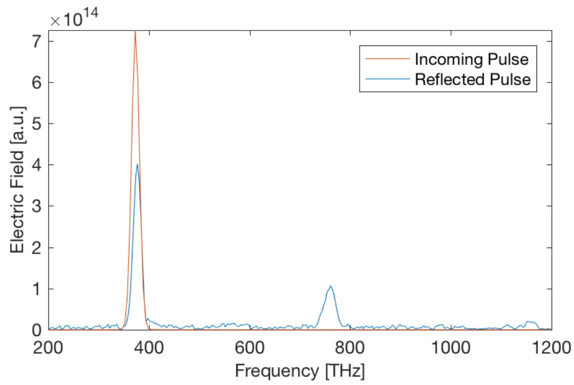

Figure 4: Spectrum of the incoming and reflected pulse of the p-polarised laser pulse.

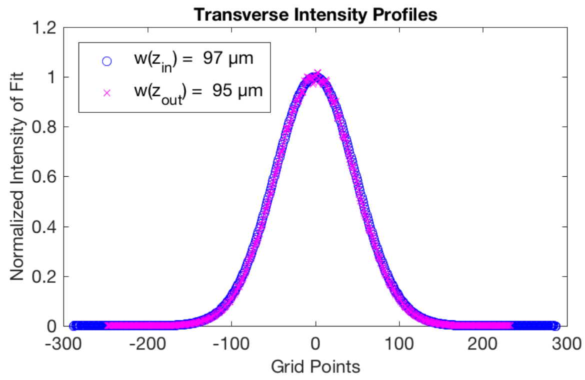

Figure 5: Transverse profile of the incoming and reflected s-polarised pulse for the plasma mirror being 15 mm in front of the focal plane.

4 Conclusion and Outlook

The simulations show the importance of the state of polarisation of the laser pulse as well as the density gradient of the plasma originating from the pedestal of the pulse. The ideal case is a steep electron density up to the critical density so that little absorption occured. If the energy of the pedestal is too high, equivalent to a low contrast-ratio, the tape ionises early and the plasma expansion causes higher energy loss. The pulse suffers too, if no pre-ionisation occurs as the energy is absorbed. A possible optimum could be found, if all pedestal is removed entirely, but a controlled pre-pulse is introduced with just enough intensity to pre-ionises the foil just before the main pulse arrives [8].

5 Acknowledgement

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