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Optical probing of preplasmas produced by the Vulcan-PW-solid interaction

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Abstract
We present results obtained in experiments in which the Vulcan Petawatt laser pulse was interacting with solid targets under different contrast conditions. The pre-plasma produced by the amplified spontaneous emission was characterized by imaging the interaction zone which was back-lighted by a short probe pulse. When no contrast improvement was employed, the scale length was as large as 5 µm which effectively increased the initial target thickness by a factor of two.

Introduction
The interaction of laser pulses delivered by the Vulcan Petawatt system with solid targets has been studied in a large number of experiments [1-4]. Delivering intensities of up to 10^{21} W/cm^2 with pulse durations of about 500 fs, it has proved to be a unique tool for laser-plasma interaction at extreme intensities. Laser pulses of such high powers are produced by chirped pulse amplification, a process which is usually accompanied by the production of spurious prepulse. Even with care to reduce its value, such as that due to amplified spontaneous emission (ASE) originating inside the amplifiers, this pedestal can reach intensities as high as 10^{-7} of the intensity of the main pulse. This ratio is usually referred to as the contrast ratio. For Vulcan, the ASE intensity can be as high as 10^{14} W/cm^2 and typically arrives at the target 1-2 ns prior to the main pulse. Therefore, in most scenarios the main laser pulse will interact with a preformed plasma, which is crucial for understanding and modelling of the physical processes involved.

In this report we present results on the characterisation of such ASE induced pre-expanded plasmas at the front of copper foils by means of a simple temporally gated optical probing techniques. The results indicate that with Vulcan operating under typical conditions the scale-length of the pre-plasma can be of the order of the initial target thickness itself. It was found that this early expansion could be suppressed when a plasma mirror was used to improve the contrast ratio by two orders of magnitude.

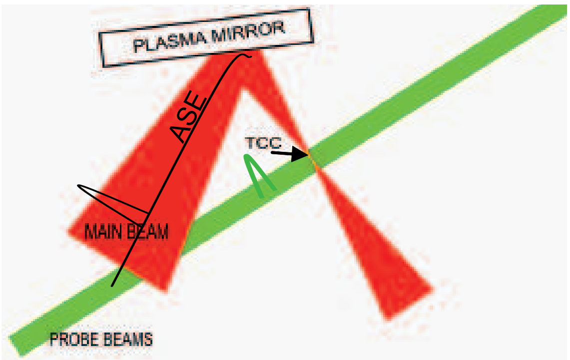

Figure 1. Experimental set-up.

Experimental setup
The experiment was performed on the Vulcan Petawatt facility [5]. P-polarized laser pulses of up to 400 J on target at wavelength λ_0=1054 nm (Nd:glass), were focused with an off-axis f/3 parabolic mirror onto 20 µm thick copper foils under normal incidence (Figure 1). The focal spot contained about 35% of the total energy within a diameter of around 7 µm (FWHM), giving an intensity in excess of 10^{20} W/cm^2. In order to improve the intrinsic contrast a single plasma mirror (PM) was employed. The anti-reflection (AR) coated substrate transmits the ASE pedestal and becomes reflective only when plasma is formed by the rising edge of the main pulse. One single PM [6] suppresses the ASE intensity by approximately two orders of magnitude. Alternatively, the AR coated substrate could be replaced by a high-reflective (HR) mirror which fully reflected the ASE enabling us to study ordinary contrast conditions. A small part of the laser was picked off the main path prior to focusing to produce a parallel frequency doubled probe pulse which was used to illuminate the target from the side. Its sub-ps pulse duration allowed snapshots of the target 10±3 ps before the arrival of the main laser pulse. The target was imaged on to a CCD camera with an f/6 lens (40 cm focal length) obtaining a resolution of approximately 6 µm.

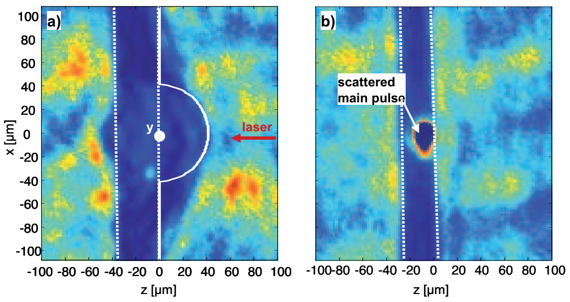

Figure 2. Typical image obtained for low (a) and high (b) contrast. The two regimes were realised by HR- and AR-coated substrates in the plasma mirror setup, respectively. The white line (a) indicates a shadow which resulting from a spherically symmetric electron density distribution (eq.(2)) with l_s = 4.2 µm. The pre-plasma in (b) is barely visible and corresponds to l_s < 0.5µm.

Results and method

A typical image obtained from the interaction with low contrast 10 ps prior to the arrival of the main pulse is shown in figure 2a. The front surface of the target, which is irradiated by the laser (right in the image) shows a large, bell-shaped shadow border. To investigate the image we follow the procedure described by Sweeney *et al.* [7] and consider an electron density distribution $n_e(r)$ centred at the focus and thus the origin of the plasma expansion positioned at r=0. The plasma is reimaged with a lens which has an angle of acceptance Θ_A. The probe pulse illuminates the plasma transversely and will be represented by parallel rays which initially propagate along the y-axis. According to the generalized Snell's law

$$\frac{d}{ds}\left[\eta(\mathbf{r})\frac{d\mathbf{r}}{ds}\right] = \nabla\eta(\mathbf{r}) \tag{1}$$

light rays are deflected along their path is due to the spatially varying refractive index, which for a plasma is given by $\eta(\mathbf{r}) = (1-n_e(\mathbf{r})/n_c)^{1/2}$. The critical density $n_c = m_e\varepsilon_0\omega_L{}^2/e^2$ defines the maximum electron density in which light waves with angular frequency ω_L can propagate. It may be tempting to interpret the line which separates dark and bright regions in figure 2a as the transition where the electron density becomes larger than n_c. This is not true which we demonstrate by solving equation (1) numerically for a spherical electron density distribution of the form

$$n_e(\mathbf{r}) = n_0 \cdot \exp\{-(x^2 + y^2 + z^2)^{1/2}/l_s\},$$

where n_0 and l_s are the maximum density and scale length of the plasma, x is the transverse dimension of the image and the z-axis points opposite to the direction of laser propagation. The y-axis points out of the paper plane in fig 2 and is the initial direction of the rays before they are deflected by the plasma. Rays are started at different initial positions $\mathbf{r}_0 = (x_0, -y_{max}, z_0)$, where y_{max} is sufficiently large to ensure the rays are not initialized inside the plasma, x_0 and z_0 are varied across the vertical and horizontal dimension of the image in figure 2a. This models the parallel probe beam and the shadow border is obtained by the following two constraints; i) only light rays collected by the imaging lens can contribute to the image, and ii) amongst those, the rays are projected back onto the imaging plane (y = 0) in order to define the shadow border. The result of this calculation for a spherical electron density distribution with $n_0 = 1.6 \times 10^{24}$ e^-/cc according to 19 times ionised copper and l_s = 4.2 µm is represented by the white line in figure 2a. In contrast to this extended preplasma for low contrast ratio, there is almost no preplasma formation observed when the plasma mirror was in operation (Fig. 2b). In this case, the main laser pulse could produce a much larger 2ω emission (at the wavelength of the probe pulse) which disturbs the image. Close to this interaction there is a sign of only a small plasma disturbance indicating a short preplasma with a scale length smaller than 0.5 µm.

Summary

We have presented results on the optical characterisation of the preplasma caused by the amplified spontaneous emission pedestal of the Vulcan-PW laser pulse when interacting with solid foils. It could be shown, that the comparably simple method of imaging the interaction zone with a short, well-timed probe pulse illumination gives information of the scale-length of the pre-plasma. This information is essential for the modelling and understanding of physical processes of high-intensity laser-solid interaction. In particular, when no enhancement of the contrast was implemented, the initially 20 µm thick copper foil exhibited a largely extended pre-plasma with a scale length of around 5 µm by the time when the main laser pulse arrived. Thus, the critical surface where the main interaction occurs, is located around 25 µm in front of the original target surface which effectively increases the target thickness by a factor of two. Our technique also confirms the correct functionality of the plasma mirror setup in order to improve the contrast and reduce the generation of pre-plasma.

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