Time-sequence imaging of relativistic laser–plasma interactions using a novel two-color probe pulse

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Abstract We describe and demonstrate a novel experimental technique to record two picosecond-separated images of the evolution of a single-shot laser-produced plasma using a two-color probe beam. In this technique, the probe beam was first partially frequency doubled. The 1ω and 2ω components were then temporally separated in a dispersive medium. The pulses remained intrinsically synchronized, both having a duration of ~ 150 fs, but they were separated by 4.1 ps. Using a Nomarskii-type interferometer, this novel technique was used to obtain two time-resolved snapshots of the evolution of the electron density at different time steps during the formation of a relativistic plasma channel.

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1 Introduction

Over the last two decades, the physics of relativistic laser–plasma interactions has attracted a great deal of attention due

to the rapid development of high-intensity laser systems using the technique of chirped pulse amplification (CPA) [1]. Both the tremendous increase in power and focused intensity of the laser pulses as well as the reduction in system size has opened a wide range of research areas such as acceleration of electrons [2–6], protons [7–9] and heavy ions [10], high-energy-density physics [11] and the concept of fast ignition in inertial confinement fusion [12]. However, to achieve a coherent picture of the underlying physics, the experimental conditions before and during the interaction have to be measured as accurately as possible. One important aspect to fully describe the interaction is the formation of a preplasma before the main-pulse arrival. Such a preplasma—generated by short prepulses or a quasi-cw pedestal due to amplified spontaneous emission—can significantly alter the interaction, e.g. by influencing the absorption of the laser pulse and the direction of the hot electron current [13]. It was also observed that the generation of electrons in underdense plasma is sensitive to the prepulse level [14, 15]. Furthermore, the acceleration of protons from thin foils is strongly affected by the prepulse-induced formation of a plasma on both target surfaces [16]. Shot to shot fluctuations of the prepulse level may have a non-negligible effect on the acceleration process and eventually on the energy spectra of the generated particle beams. Another example of the deleterious effect of the preplasma is the efficiency reduction in the high-harmonic generation from solid targets [17]. It is therefore apparent that in order to gain control over the interaction it is desirable to measure the dynamics of the preplasma formation and also the main-pulse interaction during a single laser shot.

A commonly used technique to detect the preplasma formation is the use of a synchronized probe pulse obtained by splitting off a part of the main pulse [18]. Such a probe

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pulse can be directed independently to the interaction region and serve as an ultra-short backlighter intrinsically synchronized to the main pulse. Imaging the interaction region onto a CCD camera then yields time-resolved images of the plasma; the time resolution is determined by the probe-pulse duration. In combination with different detection techniques such as interferometry, shadowgraphy, polarimetry or Schlieren imaging such images can provide different information about the plasma at the time of the probe-pulse arrival. To measure the time evolution of the plasma parameters, the straightforward solution is to take subsequent laser shots and change the delay between main and probe pulses from shot to shot. This heavily relies on the assumption that the interactions triggered by two subsequent laser shots are identical, which is not necessarily the case. For example, highly non-linear phenomena such as relativistic self-focussing, electron beam filamentation or the evolution of other plasma instabilities may sensitively depend on small variations of the initial laser or target conditions and thus vary significantly from shot to shot. As a consequence, a measurement of the temporal evolution of such phenomena becomes more and more complicated. Furthermore, laser systems of the 100-J class usually only deliver a few shots per hour, which further hampers the recording of the temporal evolution of the plasma. It would therefore be highly desirable to be able to measure the evolution of the plasma and possible instabilities during a single laser shot.

One possible candidate for such a probing technique is proton radiography [19], which provides a set of images of the plasma taken at different times due to the combination of the velocity dispersion of a proton pulse with a broad energy spectrum in combination with an energy-sensitive detector stack. However, this technique requires two synchronized high-intensity CPA pulses. Furthermore, the temporal resolution of this technique is determined by the width of the energy window to which each detector is sensitive and the initial duration of the proton pulse. In practice, the temporal resolution is of the order of several ps, which may be too long for phenomena evolving on a time scale of the pump-pulse duration that can be shorter than 100 fs. Another optical multi-frame technique [20] generates up to six replicas from a single probe pulse using beam splitters. Although this technique offers six snapshots of a single interaction it requires a careful alignment of the paths of the different pulses, which also cross the target under different angles, which might be prohibitive for experiments using thin foils where the probe beam has to propagate parallel to the target surface to avoid obscuration.

In this paper, we report the development of a novel two-color probe pulse that is well suited to characterize the evolution of preplasmas and rapidly evolving features therein such as the formation of relativistic plasma channels. Such a double-pulse system can easily be implemented into already existing probe-pulse set-ups. In combination with

Fig. 1 Temporal intensity profile of the two probe pulses after their passage through the 2-mm-thick KDP crystal. While the duration of the two pulses changes by a few percent only, they are separated by approximately $\Delta t_{\text{KDP}} = 130$ fs due to group velocity dispersion in the crystal

other probing techniques such as polarimetry, Raman back- or forward scattering or frequency-domain interferometry, a large variety of plasma parameters can be investigated at different times during a laser–plasma interaction triggered by a single laser shot only.

2 Experimental set-up

The measurements were carried out with the ATLAS laser system at MPQ in Garching, Germany. To generate the two synchronized probe pulses, a fraction of the stretched pulse was split off before the final amplifier and compressed to 130 fs in a separate grating compressor, while the main part of the pulse was further amplified and compressed to the 8-TW main pulse. The small fraction of the pulse contained a few mJ at a wavelength of 790 nm and a diameter of 55 mm. On its way to the interaction chamber it passed an adjustable delay line. Before entering the chamber the diameter was reduced by a factor of five using a lens telescope. Its plane of polarization could be changed arbitrarily using a $\lambda/2$ plate. After that it was sent into a 2-mm-thick type-1 KDP crystal where the second harmonic was generated. The plane of polarization of the 2ω pulse was rotated by 90° with respect to the fundamental.

During its passage through the 2-mm-thick KDP crystal about 30% of the pulse energy was converted to 2ω . A simulation of the process of frequency conversion assuming optimal phase matching shows that due to the group velocity dispersion (GVD) in KDP the blue pulse exits the crystal about $\Delta t_{\text{KDP}} = 130$ fs after the red one. The duration of both

Table 1 Sellmeier coefficients for BK 7 glass

$A_1 = 1.0396100$	$\omega_1^2 = 5.912883 \times 10^{32} \text{ s}^{-2}$
$A_2 = 0.2317923$	$\omega_2^2 = 1.772484 \times 10^{32} \text{ s}^{-2}$
$A_3 = 1.0104694$	$\omega_3^2 = 3.426150 \times 10^{28} \text{ s}^{-2}$

pulses is maintained within a few percent; the red pulse is slightly shortened to 127 fs while the blue one is stretched to 134 fs. The temporal profile of the two pulses after the crystal is shown in Fig. 1.

After frequency doubling, the two pulses were guided into the evacuated target chamber through a $x_{\text{BK7}} = 20\text{-mm}$ -thick window of BK 7. To estimate the temporal broadening and the delay due to GVD, we use a Sellmeier equation to calculate the refractive index:

$$\eta(\omega) = \sqrt{1 + \sum_{i=1}^3 A_i \cdot \frac{\omega_i^2}{\omega_i^2 - \omega^2}}, \quad (1)$$

using values from Schott [21], which are given in Table 1. With this expression for $\eta(\omega)$, the temporal broadening of the two pulses can be calculated as a function of the propagation length in the glass using

$$\tau(x) = \tau_L(0) \cdot \sqrt{1 + \left[\frac{4 \ln 2}{\tau_L^2(0)} \cdot x \frac{\partial^2}{\partial \omega^2} \frac{\omega \cdot \eta(\omega)}{c} \right]^2}, \quad (2)$$

where $\tau_L(0)$ is the initial duration of each pulse before entering the glass. This leads to an increase in duration of 1.2% to 128.6 fs for the 790-nm pulse and of 7.1% to 143.6 fs for 395 nm, reducing the temporal resolution only slightly. However, the delay between the pulses is not negligible and it can also be described by GVD, $v_{\text{gr}}(\lambda) = c/(\eta(\lambda) - \lambda \partial \eta(\lambda)/\partial \lambda)$, leading to a delay Δt_{BK7} between the pulses after passing through the glass given by $\Delta t_{\text{BK7}} = x_{\text{BK7}}(1/v_{\text{gr}}(395 \text{ nm}) - 1/v_{\text{gr}}(790 \text{ nm})) = 3.95 \text{ ps}$. Together with the temporal delay between the two pulses generated in the doubling crystal, the total delay between the two pulses when they pass the target is $\Delta t_{\text{tot}} = \Delta t_{\text{KDP}} + \Delta t_{\text{BK7}} = 4.1 \text{ ps}$, while the duration of both pulses is still below 150 fs as shown above.

Using these two probe pulses, temporally resolved images of a relativistic laser–plasma interaction were taken. Using the set-up shown in Fig. 2, a preplasma was generated by a synchronized frequency-doubled Nd:glass laser pulse on a $40 \mu\text{m}$ polypropylene foil. These laser pulses of 3-ns duration contained up to 12-J energy at 527 nm. The pulses were focused to a $200 \mu\text{m}$ spot using an aspheric lens. This resulted in an averaged intensity of 10^{13} W/cm^2 generating a preplasma with a scale length of $110 \mu\text{m}$ extending several hundreds of microns in front of the target foil. The 8-TW ATLAS laser pulse was focused into this preplasma using an $f/2.5$ -off-axis parabolic mirror to intensities in excess of

Fig. 2 Experimental set-up to measure the plasma evolution using two synchronized probe pulses of different wavelengths. BS: beam splitter, $\lambda/2$: half-wave plate, KDP: type-1 KDP crystal, OAP: off-axis parabola, DM: dichroic mirror, IF: interference filter. The two pulses pass the interaction region where a preplasma was formed by a ns pulse from a synchronized Nd:glass laser. The main pulse is then focused into this preplasma forming a relativistic plasma channel

10^{19} W/cm^2 . The distance of the vacuum focus to the initial target surface was about $150 \mu\text{m}$. The interaction region was imaged onto a pair of CCD cameras with a magnification of ~ 10 using an $f/4$ lens. Each camera was equipped with a narrow-bandwidth interference filter, one for $\lambda_1 = 790 \text{ nm}$ and the other for $\lambda_2 = 395 \text{ nm}$. A dichroic mirror transmitting the fundamental and reflecting the second harmonic was used in addition to ensure that both cameras were sensitive to one of the two pulses only. Furthermore, a Wollaston prism and a polarizer were placed between lens and dichroic mirror to generate interferograms of the interaction region. Each camera could be aligned individually to compensate for chromatic aberrations of the imaging lens, providing two well-focused images of the interaction taken at the two different wavelengths.

3 Experimental results

Due to the high power of the main pulse, relativistic self-focussing of the laser pulse occurred in the preplasma forming a plasma channel extending for several hundreds of microns along the laser axis [22]. The ponderomotive potential of the laser pushed plasma electrons out of the channel, forming a shock front propagating outwards perpendicular to the laser axis and reducing the electron density inside the channel. Due to this variation of the electron density in the channel, the refractive index of the plasma, $\eta = (1 - (\omega_{\text{pl}}/\omega_L)^2)^{1/2} = (1 - n_e/n_{\text{cr}})^{1/2}$, varied accordingly. Here, $\omega_{\text{pl}} = (n_e e^2 / \epsilon_0 m_e)^{1/2}$ is the plasma frequency depending on the electron density n_e , charge e , mass m_e and the dielectric constant ϵ_0 . $n_{\text{cr}} = \epsilon_0 m_e \omega_L^2 / e^2$ is the critical density up to which laser light with the frequency ω_L

Fig. 3 Two interferograms taken with the two temporally separated probe pulses during the same laser shot. In the *left-hand image* taken with the red (790 nm) pulse only the (time-integrated) self emission from the plasma channel can be seen. No disturbance of the preplasma density distribution is detectable. In the *right-hand image* taken with the blue (395 nm) pulse, the self emission and the formation of the plasma channel can be seen by the diffraction of the probe pulse at the walls of the plasma channel forming characteristic horizontal diffraction lines around the channel

can propagate. Due to the spatial variation of the refractive index, the plasma channel can be seen in an interferogram. As the plasma channel expands laterally with high speed, a probe pulse with a duration well below 1 ps is needed to freeze the motion of the channel in a single image. On the other hand, as the expansion of the plasma channel itself takes place on a ps time scale the two probe pulses being separated by 4.1 ps offer an appropriate tool to take two snapshots of the formation of the channel with a suitable temporal separation. Figure 3 shows two interferograms taken during the same laser shot with the two probe pulses. The left-hand image was taken with the CCD camera equipped with the 790-nm interference filter, the right-hand one with the CCD camera with the 395-nm filter. The ns-long laser pulse forming the preplasma and the 8-TW main interaction beam forming the relativistic plasma channel were incident from the left. The bright emission in both images is due to laser light scattered off plasma electrons in the direction of the imaging lens. The two images taken during the same laser shot are separated by 4.1 ps. The timing of the two pulses with respect to the main interaction pulse was adjusted such that the earlier (red) pulse passed the target *before* and the later (blue) pulse *after* the arrival of the main pulse. It is obvious that in the right-hand image the channel formation had started already, visible from the characteristic horizontal diffraction lines caused by the deflection of the probe at the channel walls. However, in the left-hand image no clear evidence of the channel formation can be seen.

By changing the delay between the main interaction and the probe pulses it was possible to estimate the delay between the two individual probe pulses. The delay between the case that no channel was visible in both images (both pulses too early) and the case that the channel could be seen in both images (both pulses after the main pulse) was found

to be 3 ps at least and 6 ps at most. The theoretically estimated value for the delay of 4.1 ps lies well within this range.

4 Conclusions and outlook

In conclusion, we demonstrated for the first time the realization of a synchronized two-color probe pulse suitable to take two subsequent snapshots of the formation of a relativistic, laser-generated plasma channel with a well-defined delay between the two pulses. The recording of the two time-separated images was possible by using two different CCD cameras equipped with different interference filters which were then sensitive to only one of the two probe colors. In this paper we have described experiments which used interferometric methods to measure the electron density distribution in the plasma. This could also be used to observe rapidly changing target parameters such as the orientation of the rear surface, influencing the direction of a proton pulse accelerated during the interaction [23]. It is also imaginable to use the two optical probe pulses in combination with other diagnostic techniques. Employing the Faraday effect in underdense plasma, polarograms can be taken giving spatially resolved information about the generation and evolution of magnetic fields at two different time steps. In combination with Thomson scattering techniques, it also seems possible to measure the plasma temperature at two different time steps during a single interaction, yielding information about the temperature evolution on a ps time scale. While during the experiments described in this paper the delay between the two pulses remained fixed, different delays between the two pulses could be obtained by changing the thickness of the glass through which the two pulses propagate before passing the interaction region. For pulses longer than 100 fs the temporal broadening plays a minor role only, while the temporal separation between the two pulses can easily be adjusted from a few 100 fs to more than 10 ps. Finally, as large-bandwidth laser pulses have become available over the last few years, it seems possible to use such a laser pulse having a broad wavelength range in combination with a number of CCD cameras, each of them being equipped with a narrow-band interference filter. Imprinting a temporal chirp on the probe pulse in combination with the different CCD cameras will again give a sequence of time-resolved images of rapidly changing processes in the plasma.

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