High contrast plasma mirror: spatial filtering and second harmonic generation at $10^{19}$ W cm$^{-2}$

R Hörlein$^{1,4}$, B Dromey$^{2,5}$, D Adams$^2$, Y Nomura$^1$, S Kar$^2$, K Markey$^2$, P Foster$^{2,3}$, D Neely$^3$, F Krausz$^{1,4}$, G D Tsakiris$^1$ and M Zepf$^2$

$^1$ Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany
$^2$ Department of Physics and Astronomy, Queen’s University, Belfast BT7 1NN, UK
$^3$ Central Laser Facility, CCLRC Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK
$^4$ Sektion Physik der Ludwig-Maximilians-Universität München, Am Coulombwall 1, D-85748 Garching, Germany

E-mail: b.dromey@qub.ac.uk

New Journal of Physics 10 (2008) 083002 (12pp)
Received 14 April 2008
Published 5 August 2008
Online at http://www.njp.org/
doi:10.1088/1367-2630/10/8/083002

Abstract. Recently, the use of plasma optics to improve temporal pulse contrast has had a remarkable impact on the field of high-power laser-solid density interaction physics. Opening an avenue to previously unachievable plasma density gradients in the high intensity focus, this advance has enabled researchers to investigate new regimes of harmonic generation and ion acceleration. Until now, however, plasma optics for fundamental laser reflection have been used in the sub-relativistic intensity regime ($10^{15}$–$10^{16}$ W cm$^{-2}$) showing high reflectivity ($\sim$70%) and good focusability. Therefore, the question remains as to whether plasma optics can be used for such applications in the relativistic intensity regime ($>10^{18}$ W cm$^{-2}$). Previous studies of plasma mirrors (PMs) indicate that, for 40 fs laser pulses, the reflectivity fluctuates by an order of magnitude and that focusability of the beam is lost as the intensity is increased above $5 \times 10^{16}$ W cm$^{-2}$. However, these experiments were performed using laser pulses with a contrast ratio of $\sim 10^{7}$ to generate the reflecting surface. Here, we present results for PM operation using high contrast laser pulses resulting

5 Author to whom any correspondence should be addressed.
in a new regime of operation—the high contrast plasma mirror (HCPM). In this regime, pulses with contrast ratio $>10^{10}$ are used to form the PM surface at $>10^{19}$ W cm$^{-2}$, displaying excellent spatial filtering, reflected near-field beam profile of the fundamental beam and reflectivities of $60 \pm 5\%$. Efficient second harmonic generation is also observed with exceptional beam quality suggesting that this may be a route to achieving the highest focusable harmonic intensities.

Plasma optics therefore offer the opportunity to manipulate ultra-intense laser beams both spatially and temporally. They also allow for ultrafast frequency up-shifting without detrimental effects due to group velocity dispersion (GVD) or reduced focusability which frequently occur when nonlinear crystals are used for frequency conversion.

Contents

1. Introduction 2
2. Experimental setup 3
3. Reflected beam quality and spatial filtering 4
   3.1. Focal scan 5
   3.2. Varying laser contrast 6
4. Second harmonic generation 8
5. Conclusions 10
Acknowledgments 11
References 11

1. Introduction

With the advent of increasingly intense ultra-short pulse laser systems\(^6\)–\(^9\) tailoring and modifying laser beams becomes increasingly difficult. At intensities approaching the breakdown threshold for the bulk materials/crystals, for example, spatial filtering and second harmonic generation become a problem. Consequently, for very high-intensity lasers a concept that can withstand arbitrarily high intensities is necessary.

The relatively new field of plasma optics [1] can achieve just that. Relying on the reflection of light off an overdense plasma layer, instead of an optical coating, such an optic can—in principle—withstanding arbitrarily high intensities.

One prominent and well-studied example of plasma optics is the plasma mirror (PM) used at laser intensities of roughly $5 \times 10^{15}$ W cm$^{-2}$ to significantly increase the contrast between the peak and the picosecond pedestal of high-intensity laser pulses [2]–[6]. In this scheme, the rapid transition from low reflectivity (e.g. an anti-reflection (AR)-coated surface) to a highly reflective plasma surface results in an optical switch with a rise time of several hundred femtoseconds [2]. For high-power laser systems laser prepulse and amplified spontaneous emission are set to be below threshold intensity and are therefore transmitted through the PM, while the peak of the

\(^{6}\) www.extreme-light-infrastructure.eu
\(^{7}\) www.hyper-laser.org
\(^{8}\) www.attoworld.de/research/PFS.html
\(^{9}\) www.clf.rl.ac.uk/Facilities/AstraWeb/AstraGeminiHome.htm
pulse is reflected. The contrast enhancement (CE\textsubscript{PM}) is defined as the ratio of plasma reflectivity (R\textsubscript{PM}) to that of the AR coated optic (R\textsubscript{AR}), i.e. as:

\[
\text{CE}_{\text{PM}} = \frac{R_{\text{PM}}}{R_{\text{AR}}}.
\]  

(1)

The key constraint on the quality of the reflected radiation is the quality of the reflective plasma surface generated. Therefore, the intensity of the pulse on target must stay below a certain value to avoid significant distortion of the smooth plasma surface. Previous experiments have shown that pulses obeying the constraint \(c_s\Delta t < \lambda_{\text{Laser}}\), where \(c_s\) is the expansion velocity of the plasma, \(\Delta t\) is the time between plasma formation and the peak of the laser pulse and \(\lambda_{\text{Laser}}\) is the laser wavelength, permit efficient specular reflection of the incident light.

Another example for an effect specific to plasma optics is the efficient generation of high-order harmonics of the fundamental laser frequency from the plasma generated at the surface of a solid density target [1], [7]–[12]. Harmonic generation is due to two distinct processes: i) coherent wake emission (CWE) as described by Quéré et al [8] and ii) relativistically oscillating plasma surface (ROS), described in detail by the theory of relativistic spikes of Baeva et al [9]. Recent experiments studying relativistic oscillating plasma harmonics have demonstrated diffraction-limited XUV beams at a wavelength of 40 nm [10] and shown the generation of harmonics extending as high as the 3000th order of the fundamental laser frequency corresponding to photon energies of up to 3 keV [12].

In this paper, we quantify for the first time, the beam quality for the reflection of the fundamental (800 nm) and the second harmonic (400 nm) of a 50 fs laser pulse interacting with a fused silica target at intensities of up to \(2 \times 10^{19} \text{ W cm}^{-2}\) with a contrast ratio > 10\(^{10}\)—constituting a high-contrast plasma mirror (HCPM). Clear evidence of significant spatial filtering of the incident laser beam, dispersion-free generation of high-quality second harmonic of the laser radiation with an efficiency of the order of > 5% and a near-Gaussian beam profile are observed. Thus plasma optics constitute a promising route to overcome the limitations of conventional optics for spatial filtering, frequency doubling and contrast enhancement for the new ultra-high-intensity laser systems and also gives important insights into the process of high-order harmonic generation.

2. Experimental setup

The experiments described in this paper were performed using the ASTRA laser at the Central Laser Facility (CLF) of the Rutherford Appleton Laboratory [13]. It delivers pulses of 800 mJ in 50 fs with a contrast of 1 : 10\(^{7}\) at 500 fs before the main pulse. The contrast of the beam was further improved using a PM in the near-field of the laser before the beam is focused onto the target. A sketch of the experimental setup is shown in figure 1. Typical images taken with cameras N and F are shown in figures 1(b) and (c), respectively, indicating that the beam from the PM is still focusable and that the flat-top beam profile is preserved. The hole in the beam (labeled y) originates from a hole in a mirror of the ASTRA compressor used to split-off a small part of the beam for diagnostic purposes and is also well reproduced after the reflection of the PM.

The main beam is focused under an angle of 30° onto a fused silica target, T, using a 15 cm f/3 off-axis parabola P3 resulting in < 3 \(\mu\)m near-diffraction limited spot with a spot-averaged intensity \(2 \times 10^{19} \text{ W cm}^{-2}\). The profiles of the reflected fundamental and second harmonic are
Figure 1. (a) Schematic drawing of the experimental setup. The laser beam incident from the left side of the plot is first focused and then recollimated using two identical off-axis parabolas P1 and P2. The PM is placed in the near-field of the focusing beam to enhance the laser contrast. Near- and far-fields of the beam reflected off the PM are routinely monitored with cameras N and F. The beam is then focused onto a fused silica target using a third off-axis parabola P3. The near-field of the fundamental and the second harmonic reflected off the target are observed on a polytetrafluoroethylene (PTFE) screen using a charge coupled device (CCD) camera C. (b) Typical image of the laser near-field after reflection and recollimation off the PM. The hole in the beam, y, marked with the dashed circle, originates from a pick-off mirror after the laser compressor used for temporal characterization and is well reproduced in the reflection off the PM. The hole on the left side of the beam (x) is due to clipping in the diagnostic system and can be disregarded. (c) Typical image of the laser far-field after the reflection from the PM. In (d), we show a lineout along the dashed line in (b). The hole in the beam is clearly visible. The large intensity modulations in the center of the beam are due to interference fringes caused by contaminations on the optics in the imaging system.

observed with a third camera C on a PTFE screen placed roughly 20 cm behind the target in the direction of the specular reflection. Suitable color filters CF (i.e. 800 and 400 nm interference) were used in front of camera C to distinguish the signal generated by the fundamental and second harmonic, respectively. The possibility of x-ray fluorescence was eliminated by the use of a glass pellicle placed in the reflected beam in front of the PTFE screen.

3. Reflected beam quality and spatial filtering

In this section, we show experimental evidence of high-quality reflection and significant spatial filtering of the fundamental laser beam at intensities up to $2.0 \pm 0.5 \times 10^{19}$ W cm$^{-2}$. This high-quality reflection, returning a highly focusable beam, is the key in determining whether a plasma optic is a useful tool for applications. In fact, it is the necessary prerequisite to make these methods applicable in ultra-high-power laser systems.
3.1. Focal scan

To study the reflection of the fundamental laser beam off the target under different conditions, we conducted a series of measurements with different positions of the laser focus relative to the target surface, thus probing both the reflection in the near- and far-fields of the laser.

When the front surface of the target is placed 200 µm in front of, or behind the best focus, the reflecting overdense plasma is formed in the near-field of the incident focusing laser beam at an intensity of $\sim 10^{17}$ W cm$^{-2}$ that is roughly constant over the whole extension of the flat-top laser beam. Under these conditions all features of the incident flat-top beam are reproduced well in the reflected beam, as can be seen in figures 2(a) and (c) and the red lineout in figure 2(e). The edges of the beam profile remain steep and the hole in the beam originating from the laser compressor (see figure 1) is well reproduced suggesting that the reflectivity of our HCPM is constant over the whole near-field beam diameter. Note that the lineouts shown in figures 1(d) and (e) were acquired using different methods. While figure 1(b) is a direct image of the beam, figure 2(a) is an image of the diffuse reflection off the PTFE screen. This in itself will contribute strongly to the blurring of the hole in the beam visible when comparing figures 1(d) and figure 2(e). However, the hole in the beam is still clearly visible in 2(e) for near-field reflection, whereas it is completely gone when the target is positioned in the far-field.

This is the first observation of PM operation at relativistic intensities $> 10^{18}$ W cm$^{-2}$ and suggests that extremely high pulse contrast can indeed be achieved by a simple cascade of multiple PMs between the focusing optic and the final target as suggested by Dromey et al [2]. This implies that extremely high-contrast interactions will be possible for the next generation laser systems using cascaded PMs to maintain an acceptable contrast for mirror formation far beyond the regimes currently exploited using double PMs.

In contrast, when the front surface of the target is positioned in the tight focus, i.e. the far-field of the laser beam, significant spatial filtering of the reflected light is observed. In figure 2(b) and the blue lineout in figure 2(e) the hole in the beam has completely disappeared and the edges of the pulse profile are less steep. This suggests that higher spatial frequencies of the beam, that are located further out in the wings of the focal region, are reflected less efficiently than those spatial frequencies focused in the center of the beam.

The effect of spatial filtering using a PM can be understood when compared to previous experiments performed at lower contrast and intensities [2]–[6], [14]. Typical high-power laser systems have a flat-top near-field laser beam profile for maximum energy extraction from the amplifier chain. In the far-field (focal plane) this flat-top profile corresponds to an Airy profile. For conditions of high intensity the central focal region is strongly reflective while the intensity in the wings is not sufficient to generate such a high-quality reflective surface. As a result the higher frequency contributions to the beam profile are suppressed and the resulting reflected beam is significantly smoothed.

Figure 2(f) shows the result of a calculation illustrating this. The initial model beam profile (red) is Fourier transformed to determine the intensity distribution in the focus of the incident beam. We assume that only those frequency components focused within the second minimum of the focal pattern are reflected efficiently on the PM. The inverse Fourier transform of these components yields a beam profile corresponding to the blue curve in figure 2(f). Qualitatively the blue curve from this simple model calculation shows the same features as the experimentally measured reflected beam profile shown in the blue curve of figure 2(e), the slopes of the profile became shallower and the hole in the beam has disappeared.

New Journal of Physics 10 (2008) 083002 (http://www.njp.org/)
Figure 2. Spatial filtering of the fundamental can be observed when scanning the focal spot position with respect to the surface of the target. Figures (a)–(c) show near field images of the reflected infrared beam at focus positions of (a) 200 $\mu$m in front of the target, (b) best focus on the target and (c) 200 $\mu$m behind the target. Clear spatial filtering (i.e. disappearance of the hole in the incident beam (see also figure 1) can be observed. In (d), we show the radius of the focusing laser beam on the target as a function of target position. The red-dashed lines indicate the positions of the laser focus with respect to the target surface corresponding to the reflection conditions under which images (a)–(c) were taken. Graph (e) shows lineouts through figures (a) (red) and (b) (blue), respectively. (e) Shows the results of a calculation comparing a near-flat-top incident beam with a hole (red) to the reflected beam (blue) assuming the target is positioned in best focus and only the energy within the second Airy minimum of the focus is reflected.

3.2. Varying laser contrast

The key to the operation of the plasma optics in the HCPM regime is that the intensity on target is sufficiently low prior to switch-on intensity for reflection, such that the plasma surface is not
deformed due to preplasma expansion, resulting in specular reflection. This implies that, for high intensity ($>10^{18}$ W cm$^{-2}$), the pulse must already have a significant contrast ($>10^{10}$) so that by the time of arrival of the main pulse the target surface is essentially still at solid density, and not a tenuous plasma with a long density scale length, $L > \lambda_{\text{Laser}}$, compared to the laser wavelength.

Figure 3 shows the reflected near-field profile for reflection of our fundamental 800 nm laser beam at an intensity of $10^{19}$ W cm$^{-2}$ from the fused silica target under HCPM and low contrast PM conditions, respectively. The nanosecond pulse contrast at the target position was changed from high contrast ($\sim 10^{10}$) to low ($\sim 10^{8}$) contrast by shifting the rising edge of the gate of the fast rise time ($\sim 200$ ps) Pockels cell in the laser chain. In the high-contrast case, it was positioned at the foot of the main pulse while it was shifted to a position several nanoseconds before that in the low contrast case.

Note that in both, the low- and the high-contrast case, the laser beam was cleaned using the PM and the near- and far-fields of the cleaned beam look identical. This proves that in both cases the PM was switched on only a few picosecond before the arrival of the main pulse and not by the nanosecond pedestal [2]. The consequence of this is that the shape of the prepulse determined by the timing of the fast Pockels cell is preserved but the intensity of it is reduced by a factor given by the ratio of the reflectivity of the plasma divided by the reflectivity of the unionized PM-substrate (see equation (1)). This has been shown in detail using a third-order autocorrelation in previous experiments [2, 5].

In contrast to that a striking difference can be observed in the reflected beam profile from the relativistic interaction on the main target for the low- and the high-contrast case. For low contrast the reflected beam profile breaks up completely and no beaming is observed in the direction of the specular reflection (the dashed circle in figure 3 marks the area where the specular reflection would be expected). In the high-contrast case, the behavior of the high-intensity PM is very different. Figure 3 shows a high-quality beam reflected from the target surface. This is a clear indication that the beam was reflected off a well-defined surface with a very short scale-length preplasma and that despite the high-focused intensity of the laser beam the contrast was high enough to prevent an early ionization of the target.
The different behavior for high and low nanosecond-contrast can be attributed to different plasma switch-on times. In the low contrast case the nanosecond pedestal ionizes the target leading to a reflection of the beam off a long scale-length preplasma. As has been pointed out earlier [2] this leads to a break-up of the reflected beam and a loss of specular reflection. In the high-contrast case, the plasma is switched on by the foot of the main pulse not giving the target enough time to significantly expand resulting in specular reflection. The reason why the interaction on the target is more sensitive to the intensity of the prepulse than that on the conventional PM can be readily understood when considering that the interaction intensity at the target is three to four orders of magnitude higher than at the PM while the contrast is only two orders better. Thus, while the prepulse level is low enough to prevent early ionization on the PM even in the low contrast case, this is not the case at the main target leading to the destruction of the reflected beam under these conditions.

This has two important implications. One is that a PM can be operated properly at intensities much higher than those quoted in [2]–[6] provided the contrast of the laser beam incident on the PM is sufficient. The other is that the reflected fundamental of the driving laser from a solid target can be used to monitor the quality of the surface at the time when the main laser pulse is incident on it. Good reproduction of the near-field indicates an interaction with a well defined, steep density gradient, while beam breakup implies that a long scale length preplasma was formed.

As a result monitoring the reflected fundamental light in, for example an ion acceleration experiment from very thin foils could give important insight into the state of the target at the instance of the interaction with the main laser beam. It is also of interest in high harmonic generation experiments from solid targets since a surface that is ‘clean’ enough to reflect the fundamental laser beam is the absolute prerequisite for the observation of near diffraction limited harmonic beams as have been demonstrated [10].

4. Second harmonic generation

Another interesting aspect of high-intensity laser-solid interactions is the efficient generation of the second harmonic and its high beam quality. In general, second harmonic generation with nonlinear crystals (e.g. potassium dihydrogen phosphate (KDP) and beta barium borate (BBO)) works very well. However, for the shortest pulses frequency doubling crystals are not ideal. Firstly, they lengthen the pulse of the frequency doubled beam. This occurs because they do not have sufficient bandwidth and due to GVD walk-off between the fundamental and the harmonic [15]. For high power femosecond laser beams (such as the PFS (see footnote 8) or ASTRA Gemini (see footnote 9)) which have intensities of 2–4 TW cm$^{-2}$ in the expanded beam, nonlinear effects both in time and space become intolerable even for ultra-thin crystals (B-integral >5 in a few 100 µm of crystal).

Harmonics from solid targets may provide an attractive alternative because the second harmonic is predicted to reach reflectivities $R_{2\omega} > 0.5R_{\omega}$ [16] for $\alpha_0 > 3$—provided high efficiency can be demonstrated without degradation of the beam quality. Since the harmonic generation is a surface effect, there should also be no pulse stretching due to dispersive effects or bandwidth limitations.

To investigate the properties of the second-harmonic emission as an alternative means of achieving $2\omega$ operation, we have studied the near-field beam profile of, and the conversion efficiency using our HCPM. Figure 4(a) shows a comparison of the reflected beam profile of the
Figure 4. Comparison of fundamental and second-harmonic emission from the target. (a) shows a comparison between the beam profiles of the fundamental (red) and the second harmonic (blue) measured on the PTFE screen (see figure 1(a)). In (b), we plot the profile of the source on the target for the fundamental (red) and second harmonic (blue) calculated via Fourier transform from the beam profiles shown in (a). The dashed black line corresponds to a Gaussian fit to the central part of the $2\omega$ focal distribution.

fundamental and the generated second harmonic when the target is positioned in the focus of the incident laser beam. A lower bound for the conversion efficiency is estimated by comparing the signals measured for the fundamental and the second harmonic and the filters used in the measurements. This comparison shows that $>5\%$ of the incident laser light is converted into the second harmonic. This value approaches $\approx 0.2$, the value achievable with nonlinear crystals at femosecond pulse durations. Note that the conversion efficiency may in fact be substantially higher because the reflected second harmonic is expected to have a bandwidth $>2\times$ that of the interference filter and the redshift due to holeboring [17] will result in the second harmonic being shifted with regards to the maximum transmission of the $2\omega$ filter.

Besides looking at the conversion efficiency, comparing the beam profiles of fundamental and second harmonic (figure 4) yields interesting insight into the interaction of the laser with the HCPM. Firstly, the divergence of the fundamental and the $2\omega$ beams are very different and secondly, the beam profile of the second harmonic is much smoother and more Gaussian-like than that of the fundamental. The divergence of the $2\omega$ beam corresponds to a diffraction limited second harmonic beam being emitted from a source the same size as the laser focal spot. Consequently the $2\omega$ beam must be focusable to near-diffraction limit for its wavelength. This implies that even at the lower bound of the conversion efficiency the peak intensity that can be achieved at $2\omega$ is likely to exceed that of a beam frequency doubled in a crystal, where the divergence of the frequency doubled beam is typically similar to that of the fundamental and consequently non-diffraction limited. Once the shorter pulse duration that is achievable for femtosecond-pulses is taken into account using HCPM appears to be favorable in terms of the peak intensity that is achievable.

To understand the difference between the beam profiles it is important to consider that the fundamental and the second harmonic have a very different origin. While the fundamental is the reflection of the incident laser beam off the over-critical plasma density surface formed on the target the second harmonic is generated during the relativistic interaction of the driving laser with the target. This difference becomes obvious when considering what kind of intensity distribution in the focus results in the experimentally measured beam profiles after the beam has expanded from the target. Figure 4(b) illustrates this by comparing the normalized intensity...
distributions of the fundamental and the second harmonic in the focus of the incident beam, i.e. in the source of the expanding beam. The focal distributions were calculated from the measured beam profiles via Fourier transform taking into account the different wavelengths of fundamental and second harmonic.

For the fundamental, we still expect substantial reflectivity of the mirror at intensities of $10^{17} \text{ W cm}^{-2}$ and thus it is reasonable that the side maxima of our focal distribution at least partially reflect the incident light as can be seen in the red plot in figure 4(b). In contrast to this the second harmonic shows no emission originating from the side maxima of the focal distribution (blue curve in figure 4(b)). Instead the source distribution is nearly Gaussian with some extra energy in the wings smearing out across the first minimum in the fundamental distribution. This distribution suggests that the second harmonic is generated via the relativistic oscillating surface mechanism. The intensity in the central part of the focus is sufficiently high to generate harmonics, whereas the side lobes with intensities below the relativistic limit show negligible conversion efficiency [7]. Note that the central peak in the source is not narrowed despite the nonlinearity of the generation process. The transverse motion of the electrons in the oscillating surface [10] results in an oscillating mirror of about the same width as the focal spot.

While the source distribution can be nicely explained in this way the lack of emission from the side lobes with focal intensities of a few times $10^{17} \text{ W cm}^{-2}$ seems surprising at first glance. CWE harmonics can be generated at intensities as low as $10^{16} \text{ W cm}^{-2}$, more than one order of magnitude lower than the intensity in the side lobes, and the conversion into CWE harmonics is found in [8] to depend only weakly on intensity. To understand why we still do not observe any emission in the wings of the focus it is important to consider that the CWE mechanism requires a density gradient in order to generate harmonics [8, 18]. A step-like density ramp does not create any CWE [19]. If we now take into account that the second harmonic is generated at a density of $n = 4n_c$, simulations show that the relativistic laser pulse steepens the density profile in this density range so strongly that the scale length becomes practically zero [20]. In this case the main source for harmonic emission is the ROS [9] which is only efficient for intensities higher than the relativistic limit of $I \lambda^2 = 1.38 \times 10^{18} \text{ W cm}^{-2} \mu \text{m}^2$ leading to practically no emission from the side maxima of the focus.

Especially interesting is that this approach is obviously not limited to generating the second harmonic. It can also be used to generate, for example, third or fourth harmonic efficiently for application in an experiment. It is important to note though that the beam profile for these harmonics would have to be investigated in detail since the CWE contribution to these harmonics is generated at higher densities in the preplasma gradient where the effect of steepening from the laser may be less pronounced.

5. Conclusions

In conclusion, we have demonstrated stable operation of plasma optics under high contrast conditions at intensities of $2 \times 10^{19} \text{ W cm}^{-2}$—three orders of magnitude more intense than in previous PM experiments [1]–[6]. We have shown that in this new regime of operation, the HCPM is capable of reproducing the beam profile of the incident laser beam very well when operated in the near-field, and functions like an efficient spatial filter in the far-field. This demonstrates that ultra-high contrast operation is scalable to lasers with highest peak intensities by cascading multiple PMs and provides a means of spatial filtering that in contrast to the conventional method with pinholes, is scalable to arbitrarily high intensities.
The observation of near diffraction limited and efficient reflection of the fundamental laser light off a target at intensities above $10^{19}$ W cm$^{-2}$ also provides a precise diagnostic for truly high contrast interactions, e.g. for thin-foil ion acceleration experiments.

The observation of dispersion free, diffraction limited second harmonic generation offers an advantageous method for frequency doubling ultra-short or ultra-high power laser pulses (see footnotes 6–9). Also, owing to the harmonic nature of the generation process, this method is obviously not limited to the generation of the second harmonic, even though the beam profile of higher harmonics would need to be investigated in detail.

Acknowledgments

We thank S Rykovanov and M Geissler for helpful discussions. This work was supported in part by DFG-Project Transregio 18 and by the association EURATOM—Max-Planck-Institut für Plasmaphysik.

References

[1] Thaury C et al 2007 Plasma mirrors for ultrahigh-intensity optics Nat. Phys. 3 424–9
[2] Dromey B, Kar S, Zepf M and Foster P 2004 The plasma mirror—A subpicosecond optical switch for ultrahigh power lasers Rev. Sci. Instrum. 75 645
[3] Kapteyn H, Murnane M, Szoke A and Falcone R 1991 Prepulse energy suppression for high-energy ultrashort pulses using self-induced plasma shuttering Opt. Lett. 16 490
[4] Gold D M 1994 Direct measurement of prepulse suppression by use of a plasma shutter Opt. Lett. 19 2006
[5] Nomura Y, Veisz L, Schmid K, Wittmann T, Wild J and Krausz F 2007 Time-resolved reflectivity measurements on a plasma mirror with few-cycle laser pulses New J. Phys. 9 9
[6] Doumy G, Quéré F, Gobert O, Perdrix M, Martin Ph, Audebert P, Gauthier J C, Geindre J-P and Wittmann T 2004 Complete characterization of a plasma mirror for the production of high-contrast ultraintense laser pulses Phys. Rev. E 69 026402
[7] Tsakiris G D, Eidmann K, Meyer ter Vehn J and Krausz F 2006 Route to intense single attosecond pulses New J. Phys. 8 19
[8] Quéré F, Thaury C, Monot P, Dobosz S, Martin P, Geindre J-P and Audebert P 2005 Coherent wake emission of high-order harmonics from overdense plasmas Phys. Rev. Lett. 96 125004
[9] Baeva T, Gordienko S and Pukhov A 2006 Theory of high-order harmonic generation in relativistic laser interaction with overdense plasma Phys. Rev. E 74 046404
[10] Dromey B et al Diffraction limited performance and focusing of high harmonics from relativistic plasmas submitted
[11] Dromey B et al 2006 High harmonic generation in the relativistic limit Nat. Phys. 2 456–9
[12] Dromey B et al 2007 Bright multi-keV harmonic generation from relativistically oscillating plasma surfaces Phys. Rev. Lett. 99 085001
[13] Langleby A J, Divall E J, Hooker C H, Hutchinson M H R, Lecot A J-M P, Marshall D, Payne M E and Taday P F 2000 Central laser facility annual report 2000 (ral-tr-2000-036 p 196) Technical Report Rutherford Appleton Laboratory
[14] Moncur K 1977 Plasma spatial filter Appl. Opt. 16 1449
[15] Marcinkevicius A, Tommasini R, Tsakiris G D, Witte K-J, Gaizauskas E and Teubner U 2004 Frequency doubling of multi-terawatt femtosecond pulses Appl. Phys. B 79 547–54
[16] Gibbon P 1996 Harmonic generation by femtosecond laser-solid interaction: a coherent water-window light source? Phys. Rev. Lett. 76 50–3
[17] Zepf M et al 1996 Measurements of the hole boring velocity from doppler shifted harmonic emission from solid targets Phys. Plasmas 3 3242–4
[18] Brunel F 1987 Not-so-resonant, resonant absorption Phys. Rev. Lett. 59 52
[19] Quéré F, Thaury C, Geindre J-P, Bonnaud G, Monot P and Martin Ph 2008 Phase properties of laser high-order harmonics generated on plasma mirrors Phys. Rev. Lett. 100 095004
[20] Geissler M, Rykovanov S, Schreiber J, Meyer-ter-Vehn J and Tsakiris G D 2007 3D simulations of surface harmonic generation with few-cycle laser pulses New J. Phys. 9 218