Plasma mirror effect with a short-pulse KrF laser

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Abstract. Plasma mirror effect is demonstrated for short-pulse KrF lasers. It is shown that the reflectivity of the plasma starts to increase at the plasma threshold of $10^{12}$W/cm² and it saturates at $10^{14}$W/cm². The maximum reflectivity was ~33% for 45° angle of incidence, and ~50% was reached for 12.4°. This strong reflection allows even its direct application for short-pulse 248 nm systems whereas using it before the last amplifier may even clean the pulse from spatial inhomogeneities.

1. Introduction

Plasma mirrors or self-induced plasma shuttering[1] are at present the final tools to clean laser pulses from prepulses. Ultrashort laser pulses are generally preceded by prepulses originating either from the incomplete compression of the chirped pulses or from the long ASE of the amplifier as in our case which will be called pedestal throughout this paper. Pedestals can be detrimental for the investigations of high intensity laser-matter interactions, because they may generate preplasmas even if the intensity of the pedestal is several orders of magnitude less than that of the main pulse. In this case the main laser pulse interacts not with the solid target but with the preformed plasma. The principle of plasma mirror is that in case the intensity of the laser pulse which falling onto a transparent solid material is chosen so that only the leading edge of the main ultrashort pulse is above the threshold for plasma production, the pedestal of lower intensity will be transmitted. Thus the part of the pulse reflected from the plasma (which does not have time to expand during the short pulse duration) can be separated resulting in a contrast improvement up to several orders of magnitude. Several successful experiments were carried out, cleaning the pulses of titanium-sapphire and OPA laser systems by plasma mirrors [2,3]. Such a scheme was applied to the Vulcan facility allowing high-harmonics generation from solid surfaces to the multi keV level[4].

The short pulse KrF laser in our laboratory is based on direct amplification of 500-600fs pulses without using the chirped pulse amplification (CPA) scheme. Therefore the pedestal originates only from the ASE of the KrF amplifiers allowing a contrast as high as $10^{10}$. However, in the case of KrF laser pulses of ~5eV photon energy free ions are generated by photoablation and photoionization below $10^{7}$W/cm² intensity as reported earlier [5]. It means...
that for intensities above $10^{17}$W/cm$^2$ free ions will be in the focal volume by the time the main pulse arrives. According to the results of mass spectroscopy [5] it is desirable to keep the prepulse level below $2 \times 10^6$W/cm$^2$.

Herewith we report about experiments in which we investigate the possibilities for applications of plasma mirrors for short–pulse KrF systems. It is shown that the plasma mirror effect can be observed at this wavelength with a similar behavior than in the infrared. Although the shorter wavelength of the KrF laser results in a lower reflectivity than for Nd or Ti-sapphire systems, it is shown that plasma mirrors may be applied for short-pulse KrF systems, too. The optimum intensity range with the corresponding plasma temperature is estimated below, and possible schemes for plasma mirrors in KrF systems are given.

2. Experimental arrangement

Our short-pulse KrF laser system is based on a double discharge EMG150 Lambda-Physik excimer laser [6]. The XeCl laser pumps a dye-laser chain which – after frequency conversion – provides the seed-pulse for the KrF amplifier. A half-wave plate was inserted after the frequency conversion in order to change the polarization of the beam. In order to reach the highest reflectivity, s-polarized beam was used for the reflection experiments. The beam has two off-axis passes in the preamplifier, then - after a vacuum pinhole spatial filter – two additional off-axis passes through the main amplifier. This system gives 70mJ pulses of 620±10fs duration in a nearly diffraction-limited beam. The beam can be focused with an off-axis parabola mirror to a spot of 2µm diameter[7] reaching $\sim 10^{18}$W/cm$^2$ intensity.

In the present investigations the laser beam was focused by an F/10 lens onto an antireflexion-coated glass-plate. Reflection experiments were carried out both using 45° and 12.4° angle of incidence. The target was moved by stepping motors shot-by-shot. The laser energy was kept constant, the intensity was varied by shifting the lens relative to the target, which offered more than 4 orders of magnitude intensity range, from less than $10^{12}$W/cm$^2$ up to above $10^{16}$W/cm$^2$. The energy was monitored for each shot and the reflected radiation was measured by calibrated photodiodes. The diode signal was integrated by a peak-hold detector and digitized, controlled by a microprocessor. Fiber-based communication provided the isolation from electronic noises.

In addition, VUV spectroscopy was carried out using a Jobin-Yvon toroidal grating. The toroidal grating of 550 lines/mm imaged the target onto an MCP detector equipped with a phosphor screen. The visible light of the screen was imaged to a CCD camera. For the spectral investigations the glass target plates were coated by a low-Z material, (i.e. by LiF), spectra were obtained in the 10-20nm spectral range with~0.1nm resolution.

3. Results and discussion

Figure 1. illustrates the intensity dependence of the reflectivity for 45° angle of incidence. The reflectivity is less than 1% from the AR-coated target below the plasma threshold of $\sim 10^{12}$W/cm$^2$. Above the plasma threshold the increase is nearly logarithmic up to 30-35% at $\sim 10^{14}$W/cm$^2$ while the scatter of the data increases significantly with increasing intensity. For higher intensities (above $10^{15}$W/cm$^2$) the reflectivity even decreases with strong shot-to-shot variations. The saturation behavior is similar to the observations of Zienert et al.[2] for the infrared radiation but the maximum observed reflection is significantly lower. Thus, the experiment clearly demonstrates that the plasma mirror effect is present for the KrF radiation as well.

Even higher reflectivity was reached when the angle of incidence was nearly perpendicular, i.e. 12.4° as shown in Fig. 2. Here again we can observe the logarithmic increase of reflectivity at low intensities, and a saturation near $10^{14}$W/cm$^2$ laser intensity. The saturation behavior is similar to the observations with infrared radiation [2] but the maximum reflectivity is below the one observed therein. It was found to be a little above 30% for 45° angle of incidence whereas it exceeds 40% (in
some shots even 50%) for 12.4°. Thus it is still well below the 70-80% obtainable reflectivity for the infrared radiation and it is also less than that obtained with KrF laser pulses of shorter duration [8].

**Figure 1.** Intensity dependence of the reflectivity for 45° angle of incidence.  

**Figure 2.** Intensity dependence of the reflectivity for 12.4° angle of incidence.

In order to estimate the optimum plasma parameters spectroscopic investigations were carried out in the VUV. The spectra at 10¹⁴W/cm² intensity show strong H-like and He-like radiation from Li, whereas the B- and Be-like F-lines appear between 14 and 18 nm. Even Li-like F-lines can be observed at wavelengths shorter than that of the Lyman-α radiation of the Li ions, referring to temperatures of 20-25eV [9].

The observation that the reflectivity was lower in our case with 620fs laser pulses than with the earlier ones using 250fs duration is not surprising. The larger plasma in the present case simply leads to the enhancement of absorption. The decrease of reflectivity above the optimum conditions is a probable consequence of the initiation of nonlinear phenomena as high harmonics generation [10]. These effects reduce the absorption and they also contribute to the larger shot-to-shot variation of the measured reflectivity, which deteriorate the quality of the reflected beam, too.

4. Conclusions

Plasma mirror effect was demonstrated for ultrashort KrF laser pulses. The reflectivity is shown to increase above the plasma threshold logarithmically and it saturates below 10¹⁴W/cm² when the plasma temperature is ~25eV. The measured maximum reflectivity was found to be ~33% for 45° angle of incidence, and it was nearly 50% for 12.4°. Although this reflectivity is lower than that for 800 nm radiation, these results show that plasma mirrors can be applied even directly for increasing the contrast of short-pulse high-power KrF systems. For a pulse of ~100fs [6] higher reflectivity is expected.

There is however another possibility for its application using the properties of short pulse amplification of KrF systems. We can use the fact that KrF amplifiers work in saturation regime. Consequently, if one applies the plasma mirror before the final amplifier the output energy will not be significantly reduced, whereas only the pedestal of the ASE from the final amplifier will remain. This ASE does not give a significant contribution in the focus because - due to its larger divergence - it will remain practically unfocused in the focal plane.
A further advantage of this setup can be utilized if the plasma mirror is positioned in the focal plane. This not only relaxes the energy requirements but due to the diffraction limited property of the KrF laser beam - the plasma mirror will not deteriorate the beam quality. There is no structure within the diffraction limited focal spot, and thus the plasma mirror acts as a secondary source of radiation operating as a spatial filter [11]. Such a scheme is capable for cleaning the laser beam from the Fourier-components with higher spatial frequency, thus from the spatial inhomogeneities of the main pulse.

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References
[1] Kapteyn H, Murnane M, Szoke A and Falcone R 1991. Opt. Lett. 16 490-492
[2] Ziener Ch, Foster P S, Divall E J, Hooker C J, Hutchinson M H R, Langley A J and Neely D 2003 J. Appl. Phys. 93 768
[3] Doumy G, Quéré F, Gobert O, Pendrix M, Martin P, Audebert P, Gauthier J C, Geindre J P and Wittmann T 2004 Phys. Rev. E 69 026402
[4] Dromey B, Kar S, Bellei C, Carroll D C, Carroll R J, Green J S, Kneip S, Markey K, Nagel S R, Simpson P T, Willingale L, McKenna P, Neely D, Najmudin Z, Krushelnick K, Norreys P and Zepf M 2006 Phys. Rev. Lett. 99 085001
[5] Földes I.B, Bakos J S, Gál K, Juhász Z, Kedves M Á, Kocsis G, Szatmári S and Veres G 2000 Laser Physics 10 264-269
[6] Szatmári S 1994 Appl. Phys. B 58 211-223
[7] Rácz E, Földes I B, Kocsis G, Veres G, Eidmann K, Szatmári S 2006 Appl. Phys. B 82 13-18
[8] Fedosejevs R, Ottmann R, Sigel R, Kühnle G, Szatmári S and Schäfer F P 1990 Appl. Phys B 50 79-99
[9] Salzmann D 1998 Atomic Physics in Hot Plasma Oxford University Press Oxford UK ISBN 0-19-510930-9
[10] Földes I B, Bakos J S, Veres G, Bakonyi Z, Nagy T, Szatmári S 1996 IEEE J.Selected Topics in Quantum Electronics 2 776-781
[11] Szatmári S, Bakonyi Z, Simon P 1997 Opt. Commun. 134 199-204