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ABSTRACT

It is demonstrated the first time that plasma mirrors can be successfully applied for KrF laser systems. High reflectivity up to 70% is achieved by optimization of the beam quality on the plasma mirror. The modest spectral shift and the good reflected beam quality allow its applicability for high power laser systems for which a new arrangement is suggested.

Keywords: UV lasers, ultrashort pulses, laser-plasma interactions

I. INTRODCTION

Perhaps the ultimate method to remove prepulses or pedestals of ultrashort laser pulses is based on the self-induced plasma shuttering or plasma mirror technique. If the intensity of the laser pulse falling onto a transparent solid material is chosen so that only the leading edge of the main pulse is above the threshold for plasma production, prepulses or the pedestal of lower intensity will be suppressed. In case there is no preplasma or it is small, the created plasma does not have sufficient time to expand during the rise time of the main pulse, therefore only the main pulse will be reflected from the steep density gradient. A plasma mirror can improve the contrast with several orders of magnitude. Whereas plasma mirrors have been successfully applied to infrared lasers, they have not been used in visible and UV systems due to the larger penetration depth and the lower reflectivity. Herewith we demonstrate an efficiently reflecting plasma mirror arrangement reaching nearly 70% reflectivity for a KrF system on the 248 nm wavelength.

The idea of this technique goes back to 1991[1]. High reflectivity of 70% was demonstrated for 500fs and 80% for 90 fs infrared laser pulses[2]. In order to obtain larger contrast improvement double plasma mirrors were introduced[3] in 2006 reaching 4 orders of magnitude contrast improvement with higher than 50% efficiency[4,5]. The use of plasma mirrors enabled one to reach 10 orders of magnitude intensity contrast, and this led to the possibility of high harmonics generation up to several keV photon energies from laser-plasma interaction[6], thus opening the window for sub-attosecond pulse generation.

Different is the case for short pulse UV systems, in which case the application of plasma mirrors is not prevalent so far. One reason is that the application of short pulse KrF systems are not so spread due to the complicated discharge laser technology, although they can well be used for direct short pulse amplification[7]. The other reason is that UV laser pulses penetrate deeper into the plasma, therefore collisional absorption is stronger and consequently the reflectivity is lower. Recently however, plasma mirror effect was also demonstrated for KrF systems[8] and later reflectivity up to 50% was obtained[9]. Early investigations on the absorption of light in KrF laser produced plasmas[10] resulted in ~60% reflectivity for nearly perpendicular incidence. The simple estimations based on the Drude-model therein suggested that more than 70% reflectivity may be reached in case of an initially rather steep plasma gradient.

Short-pulse KrF laser systems are based on direct amplification, therefore the only source of pedestal is the amplified spontaneous emission (ASE) of the UV amplifiers. Up to 10 orders of magnitude contrast can be obtained in case of tight focusing[11]. Nevertheless in case of higher power and more amplifier stages the ASE background increases due to the characteristics of amplification in the presence of nonsaturable absorption[12] and gain dynamics of KrF amplifiers[13]. Additionally, the 5 eV energy of the KrF laser photons may generate ions due to photoablation and photoionization of the solid matter above 10^7 W/cm^2 prepulse intensity of nanosecond duration[14]. Therefore further tools for contrast improvement as plasma mirrors are needed. We optimized the reflectivity of a plasma mirror for the UV laser, thus the obtainable nearly 70% reflectivity allows its use in high intensity laser-plasma experiments.

II. EXPERIMENTAL

The twin-tube excimer laser was described in detail by S. Szatmári[7]. Using 3-times off-axis amplification arrangement 15 mJ energy was obtained with 500-600 fs duration. Recently two passes in a following power amplifier has been used, providing 60 mJ energy. In this case the first amplifier is also used with two passes which improves the energy stability for the ~15 ns discharge. To countervail the weight of ASE a spatial filter between the two amplifiers is introduced which improves the energy contrast. On the other hand – as mentioned earlier[8] – the intensity contrast on the target is not influenced by this filter, moreover the ASE becomes stronger due to the strongly saturated amplification of the main pulse. For the present plasma mirror experiments we used the twin-tube system, after two passes. This assured that the ASE pedestal after these two passes was low, i.e. the plasma gradient at the time of arrival of the main pulse was steep. The pulse duration was 500 fs in this case with maximum energy of 10 mJ. Experiments were carried out with pulses compressed to 220 fs, too.

In our first plasma mirror experiments 45° angle of incidence was used in which case the reflectivity did not exceed 33% [8]. In case of near perpendicular, 12.4° angle of incidence the reflectivity approached 50% [9]. In those experiments however the full beam (with the power amplifier) was used, moreover the beam profile was not optimized either, the optimum reflectivity was obtained by simple Z-scan. Now, after only two passes the contrast on the plasma mirror was high and the focal distribution was controlled. The distribution of the central spot of the focus was nearly Gaussian. It was shown earlier that an intensity dependent nonlinear effect introduced at the focal plane (or Fourier-plane) always leads to spatial modulation of the beam which includes the possibility of efficient spatial filtering[15]. Since the highest reflections were measured when the target was at the focal plane the amplitude modulation - introduced by the plasma mirror - can also be utilized for nonlinear Fourier-filtering. This makes possible to have temporal and spatial filtering at the same time[16].

In the present experiments the beam was focused by a 40 cm lens onto the surface of an antireflection coated quartz plate by 12° angle of incidence. Care was taken to avoid astigmatism. Both the incoming and the reflected energy was monitored by home-made fiber-coupled energy meters using peak hold detection[17] which were calibrated by a Gentec Joulemeter QE50LP. Although at near-perpendicular angle of incidence the reflectivity cannot depend strongly on the polarization of the laser beam, we carried out experiments both with p- and s-polarized radiation.

III. RESULTS AND DISCUSSION

Figure 1 shows the intensity dependence of the reflectivity both for s-and p-polarized 248 nm radiation. It demonstrates that the reflectivity is higher than 60% for intensities above 10^{15} W/cm^2 and it does not drop afterwards in case of s-polarization. This is possibly due to the good beam distribution on the target which prevents the development of instabilities on the initially steep plasma gradient. In some shots the reflectivity reaches as high as 70% efficiency. The measured intensity dependence of the reflectivity for p-polarized radiation is similar, however for p-polarized pulses the scatter of data is larger for high intensities, and the reflectivity starts to decline at the highest ones, which is probably due to the starting nonlinearities as resonance absorption and high-harmonic generation[18].

Similar results are obtained for shorter, 220 fs laser pulses as illustrated in Figure 2. It can be noted that in this case the maximum laser intensity and therefore the maximum reflectivity was slightly lower than for the 500 fs pulse duration. The reason is that during pulse compression we lost part of the energy that is why we could not get higher focused intensity and consequently the deeper saturation could not be reached. Even in this case the observed reflectivity is above 60%. Thus the efficient plasma mirror effect is herewith demonstrated even for short ultraviolet laser pulses.

One can compare these findings with the early results of Fedosejevs et al[10]. They carried out experiments either after two or after three pass amplification. In case of two passes the prepulse intensity (originating from the ASE of 15 ns duration) on target was less than 10^5 W/cm^2 well below the threshold for plasma generation, whereas for three passes the ASE intensity was estimated as ~10^8 W/cm^2 in which case a preplasma might have been present. The observed reflectivity from metallic target was always less than 60% after two passes and less than 50% in case of three passes. Thus our results of the nearly 70% reflectivity from the AR-coated quartz plates is significantly higher. In our preliminary experiments when we used the full (4-pass) laser beam[9] the maximum reflectivity was ~50% in agreement with the earlier results[10]. It is worth to mention that the highest reflection measured throughout our experiments could be obtained only for nearly Gaussian illumination of the plasma mirror target.

Fedosejevs et al[10] carried out detailed calculations based on the Drude model which can well be applied to our results. According to this model the less collisional is the plasma, the higher is the reflectivity. Their calculations suggested ~70% maximum reflectivity for exponential plasma profile in case of the optimal scale-length of $L/\lambda \approx 0.1$. In those calculations the electron-ion collisional frequency was assumed to be 1/10 of the laser frequency. Due to the sensitivity of the results on the collisional frequency it is very difficult to carry out accurate modelling. The temperature, density and consequently the collisionality can be different not only at the time of arrival of the short laser pulse but it may strongly vary during the interaction as well. Accurate modelling was given for shocked surfaces by Benuzzi et al[19] using the MULTI code which also applied the Drude-model. However the calculations therein were carried out for a hydrodynamically heated rear target surface, for which the time scales are significantly longer and thus the hydrocode could well estimate the temperature, density and the collisional frequency. Based on the simple estimations[10] we can only state that the estimated average scale-length during the laser-plasma interactions on the plasma mirror could be roughly $L/\lambda \approx 0.1$.

The practical concern of the plasma mirror is however its possible applicability in high power systems. We could see that in order to obtain high efficiency the prepulse density must be low already on the surface of the plasma mirror. Since short-pulse KrF amplifiers have the capability for direct amplification of short pulses, temporal filtering can be easily applied before final amplification (between two amplifiers). The energy loss caused by the filter can be compensated by subsequent amplification. If the operational condition of the following amplifier is chosen properly, the gain for the main pulse and for the temporal background are the same, no or minor loss of the temporal contrast has to be considered.

The amplitude modulation of the plasma mirror in the Fourier-plane of the focusing lens results in the suppression of higher orders of the Airy-pattern, and consequently reduction of the beam inhomogeneities. Also, if not the full power is used for the plasma mirror - i.e. before the last amplifier – focusing with a relative short focal length (<1m) optics is sufficient, i.e. the several meter long vacuum tubes for long focal length lenses are not needed.

In order to be able to use plasma mirrors one must confirm that the pulse has similar beam quality after the plasma mirror as the incoming pulse, and that the Doppler-shifted spectrum is still within the gain bandwidth of the KrF amplifier. The latter is not a serious problem for the broad bandwidth Ti:sapphire systems, but it might be an issue for the KrF system of much narrower bandwidth.

Therefore in Figure 3 the spectrum of the incoming beam is shown together with the Doppler-shifted radiation reflected from the plasma mirror. The gain curve of the KrF amplifier is also indicated for comparison. It can be seen that although the Doppler shift is significant, the spectrum remains well within the gain curve, therefore it can be further amplified in a following amplifier stage.

The spatial quality of the reflected KrF laser pulse was controlled as well, and it was compared with that of the incoming pulse. Both were focused by a lens of 40 cm focal length and then imaged onto a Hamamatsu T7040 UV-sensitive CCD camera with a 12 times magnification.

The results - as seen in Figure 4 - show that the pulse could be well focused even after the plasma mirror. It must be also noted that if the following final amplifier sees a “near-field” distribution, the beam quality will be further improved, since the inhomogeneities will be smoothed out by the saturation of the amplifier.

III. CONCLUSION

The observed high reflectivity allows the use of the plasma mirror directly, in which case 2 orders of magnitude contrast may be reached as the AR coating of the plasma mirror target has a typical reflectivity less than 1% as compared with the 70% reflection from the plasma mirror. In the present system (60 mJ / 600 fs) it results in prepulse intensity less than the required[14] 10^7 W/cm^2 even in the case of tight laser focusing of the main pulse up to $>10^{17}$ W/cm^2. However in order to make it long focal length and corresponding meter lengths of vacuum tubes are needed to provide the high beam quality on the plasma mirror. This arrangement however is hard to use for more energetic, larger systems due to the required very loose focusing.

The result that despite the Doppler shift the spectrum remains within the gain bandwidth opens the possibility for its application in the short-pulse KrF laser system in front of the final amplifier. Figure 5 shows a suggested arrangement. It is a modified version of our present 60 mJ / 600 fs system[21]. The seed pulse is generated after frequency doubling of the 496 nm dye laser beam (an alternative is the third harmonic of a Ti:sapphire laser). The 20 μJ seed pulse is amplified in a pre-amplifier. After two passes of off-axis amplification the ~10 mJ pulse is focused onto the plasma mirror in a vacuum chamber. The reflected light is then collimated and amplified in the final amplifier. In the present system a simple pinhole is applied instead of the plasma mirror, and 60 mJ energy is obtained in 600 fs pulses after amplification. We expect that even when using the plasma mirror the output energy will not significantly decrease, i.e. we expect >50 mJ pulses. On the other hand the ASE prepulse will be attenuated by ~2 orders of magnitude, therefore the output prepulse energy will reduced in the 10 μJ range, thus the energy contrast will be nearly 4 orders of magnitude. In this case - even if we can reach 10^{18} W/cm^2 main pulse intensity - the focused prepulse intensity will be less than 10^7 W/cm^2 considering the 15 ns duration of the ASE. This prevents preplasma generation and corresponds to an 11 orders of magnitude intensity contrast.

Summarizing the results it was demonstrated that plasma mirrors can be efficient tools for contrast improvement even for the UV laser pulses. The demonstrated ~70% efficiency and the good beam quality after the plasma mirrors allowed us to suggest a practical scheme for a high contrast short-pulse KrF laser system of either 600 fs or 200fs pulse duration.

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FIGURES

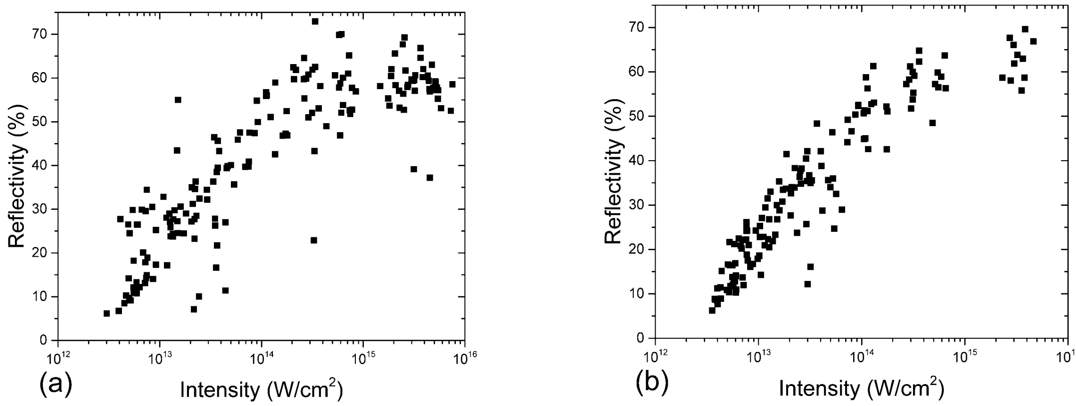

FIG. 1. Intensity dependence of the reflectivity for p- (a) and s-polarized (b) beam. Pulse duration: 500 fs.

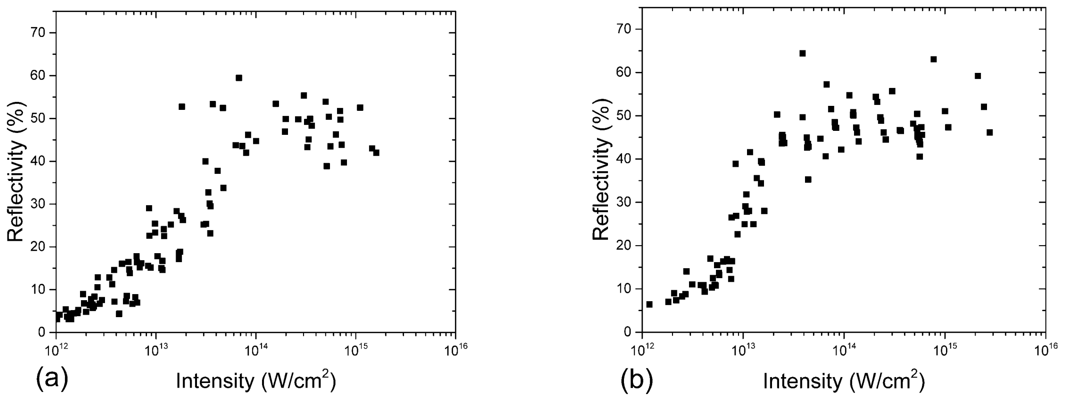

FIG. 2. Intensity dependence of the reflectivity for p- (a) and s-polarized (b) beam. Pulse duration: 220 fs.

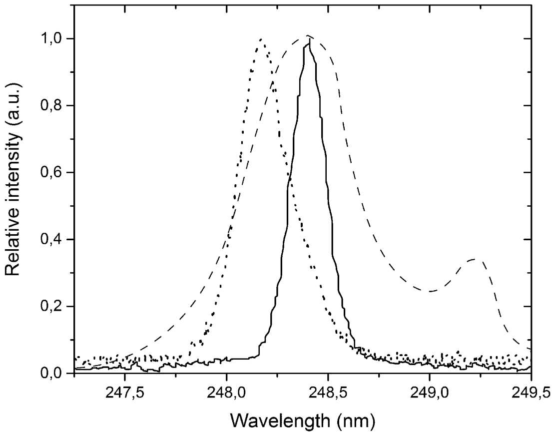

FIG. 3 The laser spectrum before the plasma mirror (solid line) as compared with the reflected pulse (dotted line) as compared with the gain spectrum (dashed line)[20].

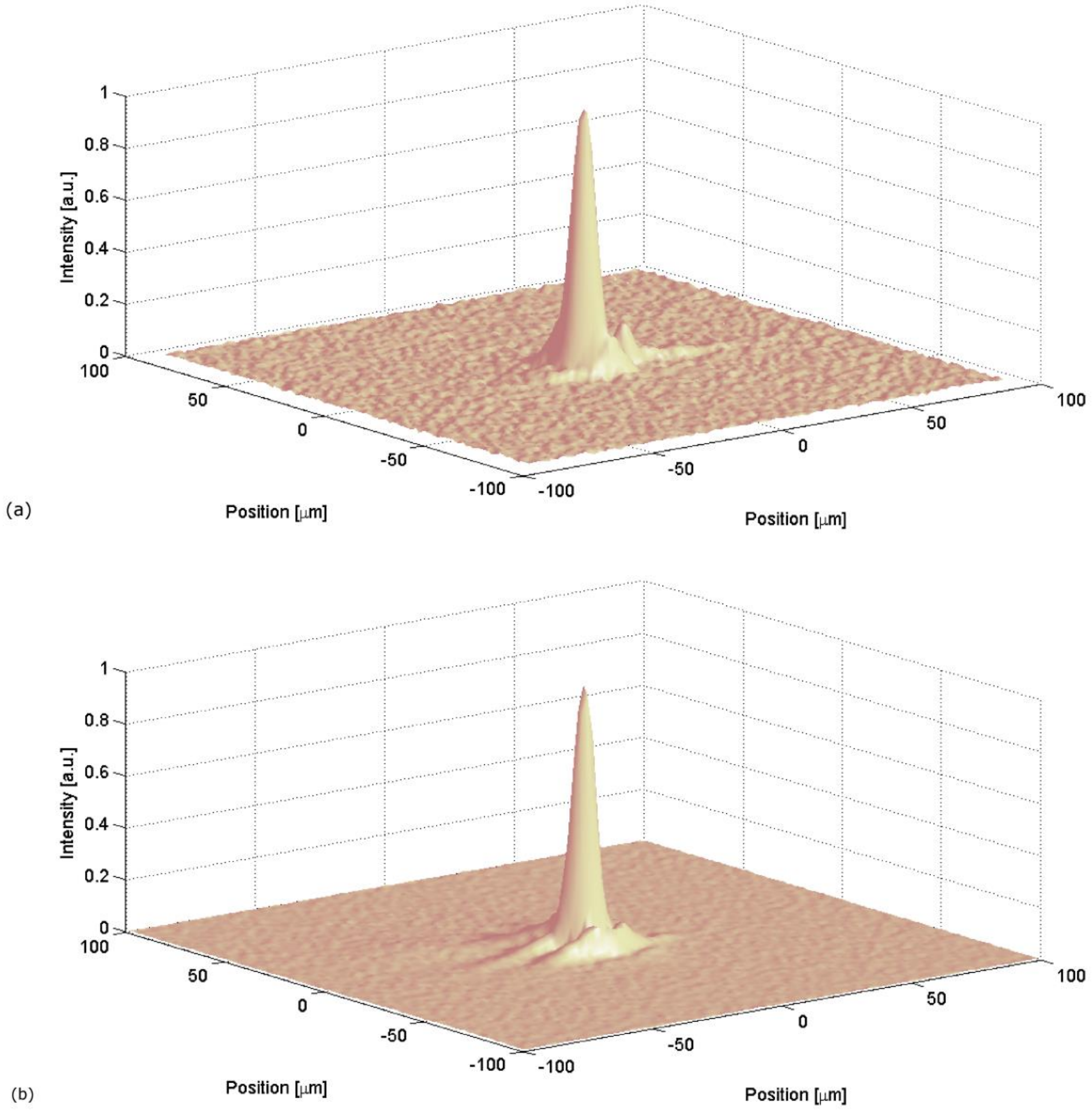

FIG. 4. Focal distribution of the laser pulse before (a) and after (b) the plasma mirror.

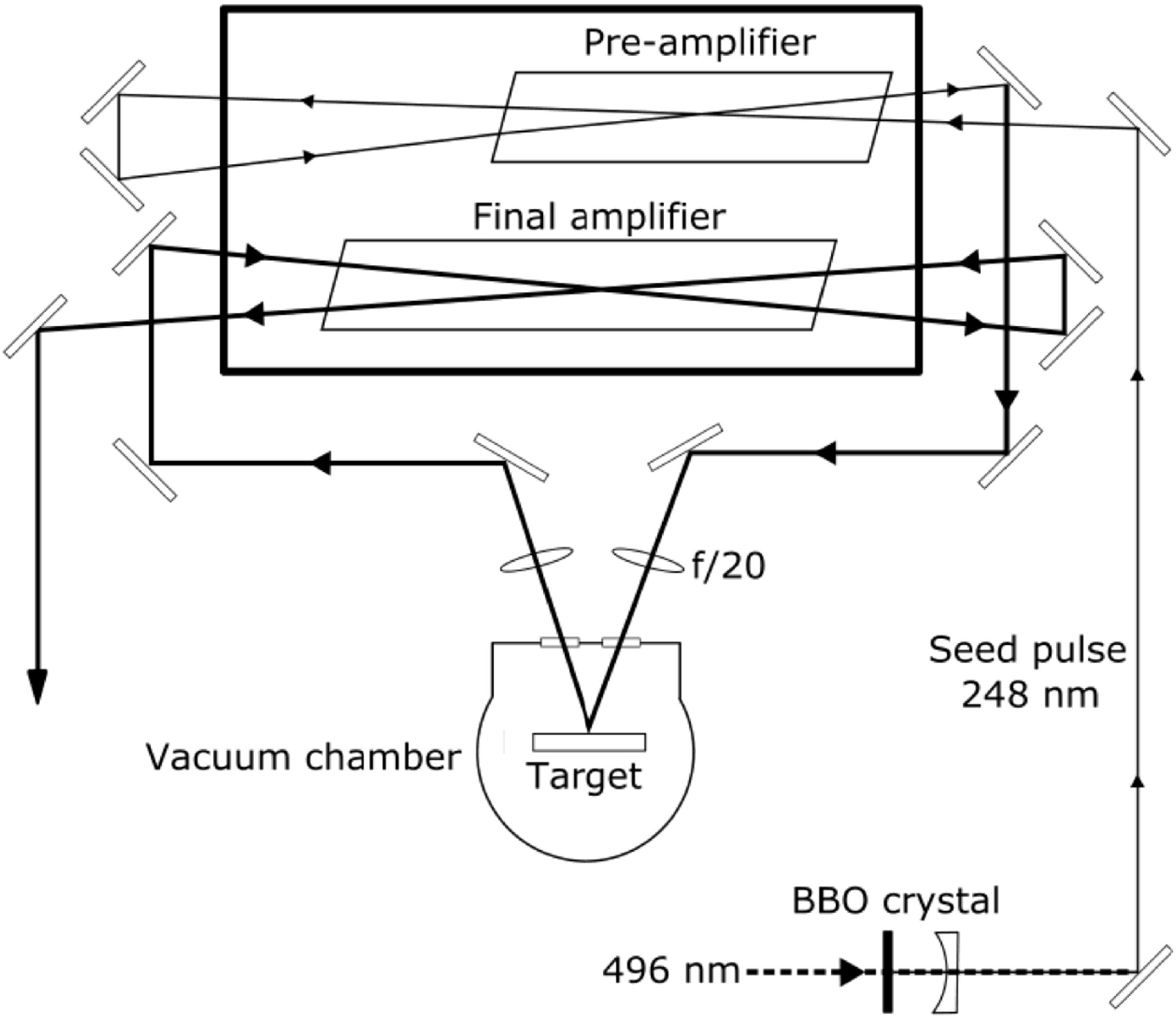

FIG. 5. Arrangement for the 100 GW KrF laser system using a plasma mirror.