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ABSTRACT

We show experimentally and theoretically that plasmas created by a sufficiently short (<500 fs) intense \(10^{14}-10^{15}\) W/cm\(^2\) laser pulse on the surface of dielectric material act as nearly perfect mirrors: reflecting up to 90% of the incident radiation with a wavefront quality equal to that of the initial solid surface.

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The increasing peak power available from solid-state, short-pulse lasers, made possible by new laser materials, the chirped-pulse amplification technique and Kerr-lens mode-locking, has produced new opportunities and challenges in the design and use of high power lasers. New components and concepts are required to manipulate the extremely high power density pulses present in systems currently under consideration. The recently demonstrated Petawatt laser at Lawrence Livermore National Laboratory operates at peak power density of 700 GW/cm² and will produce a focused irradiance over 10²¹ W/cm². Operation at this power density precludes the use of transmissive optics due to the accumulated nonlinear phase given by the "B-integral". When "B-integral" exceeds a value of ~\( \pi/2 \), small-scale self-focusing of the pulse severely distorts the wavefront of the pulse which limits pulse focussability and results in damage to the optics. At 700 GW/cm², the nonlinear phase associated with the transmission through 1 cm of fused silica is over 4\( \pi \), while transmission through 1 m of air would yield a B=1.4. As a result, beam transport and focusing must be done in vacuum with reflective optics.

This presents a significant problem in practical use of such lasers. While focusing the beam can be accomplished by a parabolic mirror, protection of the mirror from target debris (which is necessary because of high cost of the mirror) by the use of a transparent debris shield is not possible. To be of optical quality for a 60 cm diameter of the Petawatt beam, such a shield would have a thickness of several centimeters causing beam breakup and associated with unacceptable level of nonlinear phase.

Another significant issue in using of petawatt power pulses is the pulse contrast. The pulses produced by ultra-high power lasers usually contain a long duration pedestal resulting from imperfect recompression and/or spectral modification in the amplification process. With great care and attention to details, contrast ratio of 10⁷ can be achieved. In this case, the plasma creation threshold in dielectric of ~10¹³ W/cm² can be reached many picoseconds before the main pulse of the peak irradiance 10²¹ W/cm². As a result, the high intensity part of the pulse interacts with a performed plasma in front of the target instead of a solid target.

Both of these problems can be overcome by the use of a plasma as the secondary mirror. Instead of focusing petawatt pulses directly with a parabolic mirror, we add a small fused silica substrate in between the parabolic mirror and the target (Fig. 1). This eliminates the need for a debris shield since there is no line of sight from the target to the paraboloid. A low intensity pedestal is transmitted through the substrate. A high intensity pulse creates plasma on the substrate surface and is reflected toward the target. Additional advantage of a plasma mirror approach is a possibility of changing the f-number of a focusing system by simply changing the curvature of low cost substrate (~$100) and leaving the high cost ($150,000) parabolic mirror unchanged. The concept relies on the ability to form a highly reflecting plasma with a nearly perfect phase front.

Conventional laser-produced plasmas are far from being ideal plasma mirrors. They are highly absorbing and have a very nonuniform critical surface as a result of nonuniform hydrodynamic expansion. Plasmas produced by ultrashort (<1ps) pulses can, in principle, be quite different as there is not sufficient time for such plasmas to acquire long scalelength which would result in high absorption. Similarly, plasma instabilities have not sufficient time to develop and cause deviation of critical surface from a substrate-like shape it initially had.

The short pulse experiments performed earlier (Milchberg, et al `88, Fedoseev et al'90, Teubner et al'93) on metal targets showed absorption around 50% at intensities 10¹⁴-10¹⁵ W/cm². We believe that the results on metal targets are significantly affected by a preplasma formation as it was discussed above. The reason for that is that the plasma
creation threshold for metals is only ~ $10^9$ W/cm$^2$. For dielectrics the contrast issue is of less concern as the threshold of plasma formation is 3-4 orders of magnitude higher comparing to metals.

Experiment performed by Price, et al (Phys.Rev'95)\textsuperscript{7} mostly on metals but also on fused silica did show drop in absorption for higher intensities however absorption measured in that work for our region of interest (1PW/cm$^2$) was still significant (~30%).

We demonstrate here that plasma mirror made by irradiating a dielectric could have reflectivity as high as 90% and preserve the diffraction limited quality of the reflected beam.

The experiments were performed with a front end of the Petawatt laser. The front end is a hybrid system(Ti:sapphire/Nd:glass) which produces 10 J energy in a half picosecond pulse. We limited output energy to 1J in order to use an air compressor for this experiment. The target was a superpolished fused silica flat with an rms. surface flatness of $\lambda/20$. It was placed in near field of a focused beam where the intensity profile is still flat-topped. The energy reflected and transmitted through the substrate along with transverse beam profile in near and far field were measured. In addition we measured the energy of plasma emitted X-rays by using a CCD covered with 9 $\mu$m thick Al filter.

Plasma mirror reflectivity grows from 10\% value corresponding to Fresnel reflection from a glass substrate in the absence of plasma production to 90\% at intensities exceeding several hundred terawatt per square centimeter (Fig.2). Comparison of near and far fields corresponding to a beam reflected from plasma mirror and from the substrate at low intensity in absence of plasma shows that plasma mirror preserves the diffraction limited beam quality (Fig.3). There are some deviation from diffraction limited beam profile in the wings of the far field intensity distribution reflected from the plasma mirror, but the main part of the beam is the same as in the case where the beam undergoes Fresnel reflection from the glass substrate.

Two sets of calculations were carried out to explain the observed experimentally raise in mirror reflectivity at higher intensities. The first uses our short pulse laser damage theory to calculate the initial generation of conduction electrons and compute the resultant reflectivity assuming a Drude dielectric. Hydrodynamics is ignored during the time of the pulse. The second set of calculations employs the radiation-hydrodynamics HYADES code to estimate the influence of hydrodynamics and radiation transport.

The result of creating a high density hot plasma early in the pulse is the complete reflection of most of the pulse. Since the high reflectivity turns on very abruptly as the electron density becomes large, the reflected pulse is free from the low level prepulse. Because of the limitations of the model it overestimates reflectivity at lower intensities (e.g.80\% reflectivity is calculated at 50 TW/cm$^2$, while experimental results show this level of reflectivity only at several hundreds TW/cm$^2$).

In conclusion we demonstrated:
1. Mirror for handling high power short pulse laser beam with 90\% reflectivity and diffraction limited quality of the reflected beam. It can improve the pulse contrast by 3 orders of magnitude.
2. Owing to prepulse absence experiments with transparent target are well suited for creating high density nonideal plasmas.
3. Because of rapid cooling these plasmas potentially could be short pulse X-ray sources.

References:

Fig. 1 Petawatt focusing system using a plasma mirror

Fig. 2 Dependence of plasma mirror reflectivity on incident intensity (circles-experiment, solid line- hydrodynamic simulation).

Fig. 3 Far field intensity distribution: solid line- reflection from substrate, circles- reflection from plasma mirror. Inserts: near field intensity distribution reflected from: plasma mirror (left), from substrate (right)