Investigation on material and timing influences on high-reflective double-pulsed plasma mirrors with emphasis on scale length and absorption control

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Introduction

With the rising demand of contrast enhanced intense laser pulses and more plasma mirror systems being installed all over the globe, further investigations on the topic are required in order to unfold the entire potential of plasma mirrors. In particular, as plasma mirror system operation always represents a trade-off between contrast and remaining energy in the laser pulse, a general understanding of the reflectivity performance dependency on all relevant parameters of both the laser and plasma, is needed.

Here, we present our results from our access period in target area 2 of Gemini in late 2017/ early 2018. The driving laser was the Astra frontend, delivering up to 500 mJ in a 53 fs pulse with a laser wavelength of 800 nm. We examined material and double-pulse plasma mirror performance. This includes testing different target materials as potential plasma mirrors for single- and double-pulse operation such as glass, parylene, sapphire, aluminium and gold as well as the influence of the pulse length on single-pulsed plasma mirrors. For double-pulse mirrors, we characterised the reflectivity behaviour as a function of polarisation, angle and most importantly plasma scale length as a consequence of the inter-pulse delay. Concluding the study, we investigated the damage from laser shots with a white-light interferometer, comparing ablated mass for single- and double-pulse operation.

Experimental setup

We set up a prepulse generator as introduced by *I Musgrave* [1] with an energy ratio between main and prepulse of 10:1 before the vacuum compressor. Focusing was achieved by using a protected gold off-axis parabolic mirror with a focal length of 50.8 mm with an incoming aperture of ~ 55 mm.

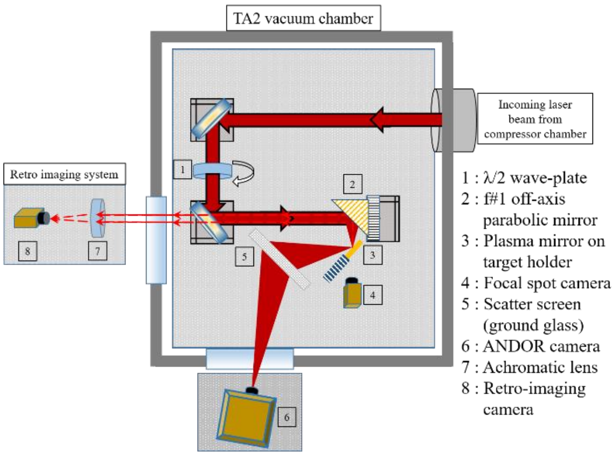

Figure 1: Double-pulse plasma mirror setup in the TA2 vacuum chamber.

For the initial target positioning we matched the focal spot camera with a retro imaging system which has a slightly lower resolution in comparison to the focal spot camera as presented by *Carroll et al* [2] but can easily operate at extreme target angles. The central angle of incidence was 48 degree with an angular range of 36 degrees on the scatter screen. As the beam rapidly expands post-interaction, the maximal theoretical angular range of 56 degrees could not be reached. The scatter screen which imaged the near field of the reflected signal was captured by a high-dynamic range ANDOR camera. Control over the polarisation was obtained by installing a motorised half wave-plate in the chamber. Figure 1 illustrates the setup as realized in the target area 2 vacuum chamber.

Material influences on single-pulse plasma mirror

Initially we measured the reflectivity as a function of intensity to confirm performance. A first data set was recorded using glass as the target material. The intensity was varied by defocusing the target while keeping the laser energy constant.

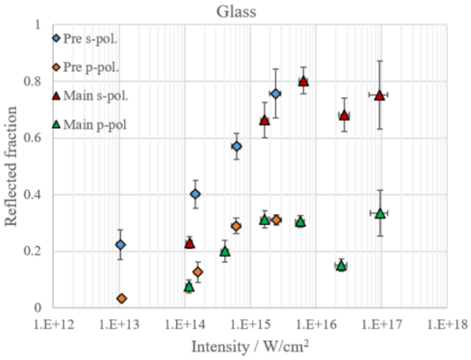

Figure 2: Single-pulse reflectivity as a function of intensity for s- & p-polarisation on glass.

Figure 2 shows the experimental results on glass for the intensity ranges of the main and prepulse in s- and p-polarisation. The data has been averaged over the whole range of angles and agrees well with the literature references for s-polarisation as given by *Scott* [3]. As the component of the electric-field for p-polarisation is in the direction of the target normal which couples more energy into the plasma due to collisional and collisionless absorption, it was anticipated that the signal for p-polarisation would be significantly lower than in s-polarisation. It has to be stated that the data points in the higher intensities have significant uncertainties due to major wave-front distortion in the reflected beam which limits the analysing method. After the data set on glass, parylene (C_8H_8) and sapphire were examined. The following figures 3 & 4 show the corresponding results.

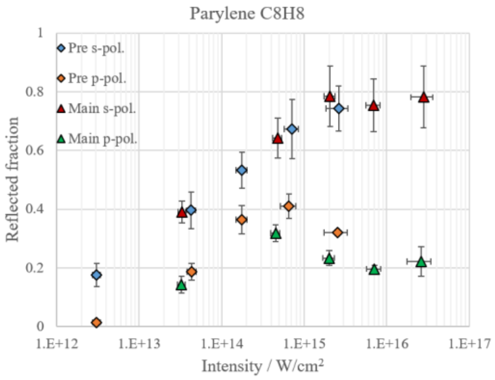

Figure 3: Single-pulse reflectivity as a function of intensity for s- & p-polarisation on parylene.

As for glass, the plastic and sapphire targets show a similar reflectivity behaviour, activating the plasma mirror in the mediate 10^{12} to low 10^{13} W/cm² regime and peaking at 10^{15} W/cm² with about 80 % reflectivity. Extrapolating the s-polarisation curve of sapphire gives an indication that the switch-on intensity is considerably higher than for glass and parylene which is due to the higher damage threshold of the corundum. The results show that plastic and sapphire are contemplable alternatives to glass.

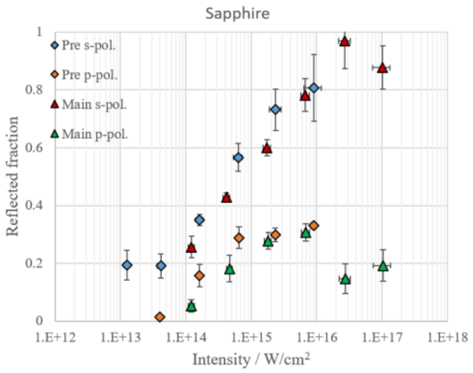

Figure 4: Single-pulse reflectivity as a function of intensity for s- & p-polarisation on sapphire.

For parylene, aluminium and gold, coated substrates from the Target Fabrication were provided. Each material consists of a 300 nm thick layer on a microscope slide. Figure 5 & 6 show the results on aluminium and gold. In comparison to the dielectrics, the metals already has a high cold reflectivity of about 86 % for aluminium and 96 % for gold for the centre laser wavelength. With increasing intensity and the activation of the plasma mirror, the reflectivity for s-polarised light reduces at first for both materials but increases again after a local minimum of approximately 78 – 80 % in the low 10^{14} W/cm² regime.

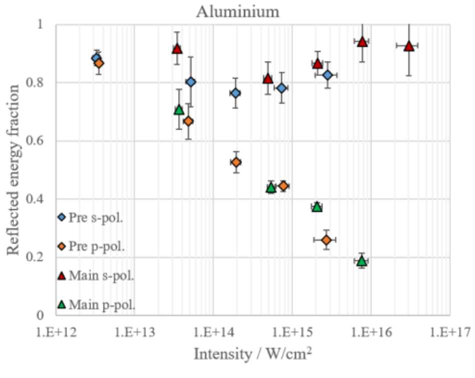

Figure 5: Single-pulse reflectivity as a function of intensity for s- & p-polarisation on aluminium.

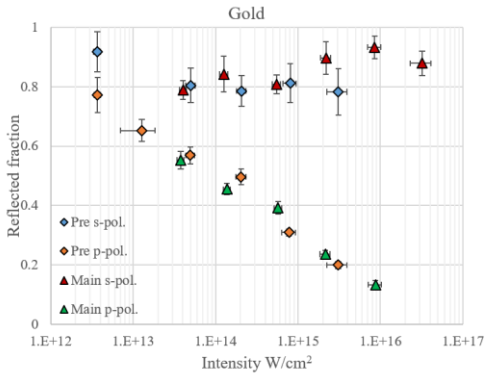

Figure 6: Single-pulse reflectivity as a function of intensity for s- & p-polarisation on gold.

On the contrary, the absorption for p-polarisation increases as a function of intensity, constantly reducing the reflected signal. Comparing the polarisation trends for both materials, it becomes obvious that in s-polarisation the behaviour is fairly similar while for p-polarised light, the reflectivity curve of gold seems to fall much earlier than for aluminium.

Pulse length insignificance on plasma mirror reflectivity

Following the single-pulse reflectivity measurements for various target materials, we looked into the pulse length dependent behaviour of the reflectivity. In order to do so, we detuned the target area 2 pulse compressor from its original 53 fs to approximately 40 ps in multiple steps. In doing so, we repeated the intensity dependent reflectivity measurements which can be seen for four exemplary pulse lengths in figure 7.

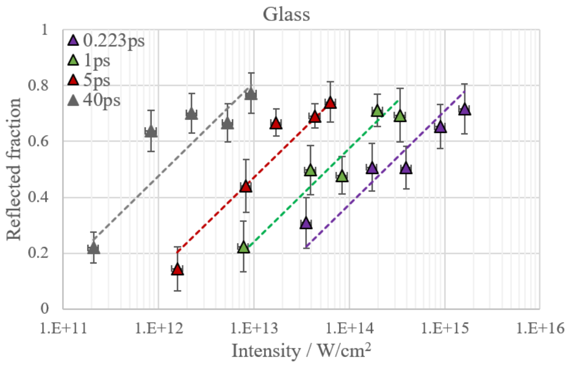

Figure 7: Plasma mirror reflectivity as a function of intensity for 4 example pulse lengths (45 degree) in s-pol.

As the curves of different pulse lengths follow the same trend, the results give rise to the assumption that the reflectivity is in fact time independent and therefore not a function of the logarithmic intensity but of fluence. The following figure 8 shows the data bunches within a certain reflectivity range.

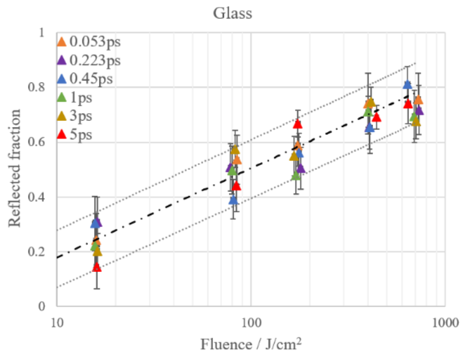

Figure 8: Plasma mirror reflectivity as a function of fluence.

High-reflective double-pulsed plasma mirror with emphasis on scale length control

We investigated the scale length dependent reflectivity and therefore absorption behaviour with the help of an artificially created prepulse. Within the prepulse generator we installed a variable motorised stage which granted full control over the inter-pulse delay between the two pulses. This gave us the possibility to let the plasma expand for a certain amount of time before the second pulse was reflected. Defining the on target intensity and estimating a realistic electron density, gives rise to a certain electron temperature which has been calculated by the model given by *Rozmus* and *Tikhonchuk* [4]. From the electron temperature, a plasma expansion velocity can be determined and in combination with the inter-pulse delay a scale length can be estimated. The following figure 9 shows the recorded reflectivity as a function of the scale length at ~45 degrees.

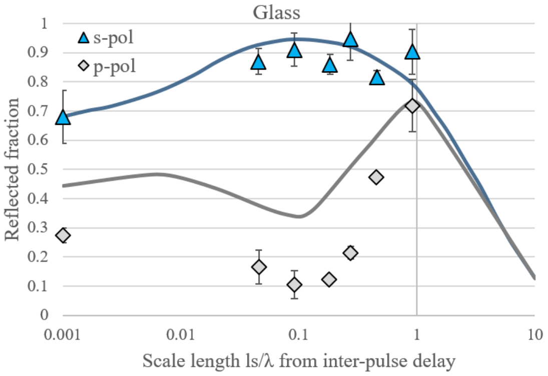

Figure 9: Double-pulse reflectivity as a function of the plasma scale length, calculated from the inter-pulse delay for a 54 fs pulse.

The continuous curves correspond to the simulated reference data from *Kieffer et al*, converted from absorbed to reflected signal. The offset in p-polarisation between theoretical and experimental trends can be explained by the difference in estimated electron temperature. Whilst *Kieffer* used a value of 200 eV, we estimated a prominent electron temperature of about 70 eV for the experimental conditions, corresponding to an energy regime which is more affected by collisional absorption. This results in a higher absorption and therefore lower signal in comparison to the reference data.

As the absorption behaviour is distinct for certain scale length and is reproducible for all previously presented materials and prominent for intensities from the middle 10^{13} to the low 10^{15} W/cm^2, this method can be used to define the scale length as a function of absorption. For instance, a local maximum absorption in p-polarisation is always present at a scale length of approximately $l_s/\lambda = 0.1$ for 45 degrees. From this and with a linear relation between scale length and inter-pulse delay, shorter or longer scale lengths can be extrapolated or the trend reproduced with only a few laser shots.

Ablated mass comparison of single- and double-pulsed operation

Additionally, we investigated the ablated mass for single-pulsed and double-pulsed plasma mirror operation with a white-light interferometer from Target Fabrication. We present data on sapphire as target material. The following figure 10 shows the ablated mass in grams as a function of inter-pulse delay.

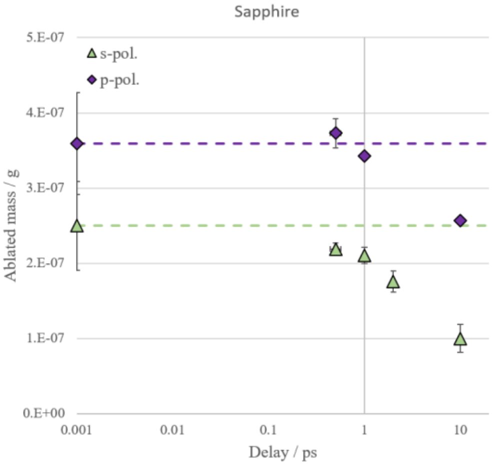

**Figure 10: Ablated mass in grams of sapphire for s- & p-polarisation as a function of inter-pulse delay.
The first data points at 0.001 represent the single-pulse plasma mirror ablation.**

The results show an expected higher ablation for p-polarisation and a continuous trend to a reduction of ablated material towards higher delays. The first data point in each curve and the dashed lines correspond to the single-pulse operation of a plasma mirror for the main pulse only. In comparison to the single-pulsed plasma mirror, the ablated mass for a delay of 10 ps which matches a plasma scale length of approximately 1, the amount of ablation can be reduced by a factor of 1.4 in p-polarisation and 2.5 for s-polarised light.

Conclusions

The characteristic single-pulse reflective behaviour for glass, parylene, sapphire, aluminium and gold as a function of intensity and their suitability for plasma mirror operation has been investigated. In addition we looked into the pulse length influence on single-pulse reflectivity for durations from 53 femtoseconds up to several picoseconds.

We successfully operated a high-reflective double-pulsed plasma mirror system (>90 %) with a prepulse which only held a tenth of the main pulse energy. Investigating the polarisation dependent absorption behaviour as a function of inter-pulse delay and therefore scale length, developing a multi-shot method for estimating the prominent plasma scale length.

References

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