A HIGH REPETITION PLASMA MIRROR FOR STAGED ELECTRON ACCELERATION*

T. Sokollik[†,#], S. Shiraishi, J. Osterhoff, E. Evans, A.J. Gonsalves, K. Nakamura, J. van Tilborg, C. Lin, C. Toth and W.P. Leemans[†]
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Abstract

In order to build a compact, staged laser plasma accelerator [1] the in-coupling of the laser beam to the different stages represents one of the key issues. To limit the spatial foot print and thus to realize a high overall acceleration gradient, a concept has to be found which realizes this in-coupling within a few centimeters. We present experiments on a tape-drive based plasma mirror which could be used to reflect the focused laser beam into the acceleration stage.

INTRODUCTION

Staged laser driven electron acceleration is one of the milestones towards building a laser plasma accelerator (LPA) scalable and thus, suitable to provide beams with high energies. The main idea is a sequence of accelerator modules each driven by a separate laser beam (c.f. Fig. 1). The overall length of the accelerator is then determined by the length of each module but also by the distance between the modules. By using conventional mirrors for

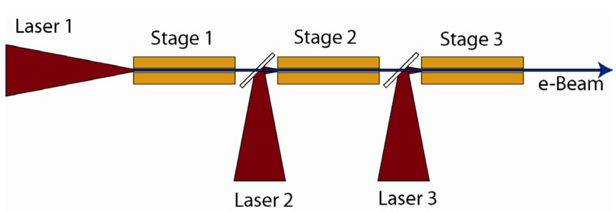

Figure 1: Principle of a staged laser driven electron accelerator. Each acceleration stage is driven by a separate laser beam. In order to couple the laser pulses into the stages thin plasma mirrors could be used reducing the distance between the stages.

the in-coupling of the laser beam, this distance is defined by the damage threshold of the mirror. The fluence of the laser pulse close to the acceleration stage (focus) exceeds the damage threshold of any currently available mirror coatings. The plasma mirror technology provides a way to overcome this limitation. A substrate is placed in a loosely focused laser beam (around intensities of 10^{16} W/cm^2). The rising edge of the laser pulse ionizes the surface layers creating an overdense plasma. The main part of the laser pulse is reflected at the critical surface where the plasma frequency equals the laser frequency. Plasma mirrors composed of antireflection coated glass substrates are usually used to improve the temporal contrast of laser pulses by several orders of magnitudes [2-6]. Several publications [2,3] demonstrate a conservation of the spatial beam quality and a reflectivity about 70 %. The drawback of this technique is the limited repetition rate. In the past years several novel approaches for high repetition rate plasma mirrors have been developed [7,8]. Nevertheless, for the staged accelerator scheme a second important requirement has to be considered. Since the electron beam has to propagate through the mirror, the thickness of the substrate has to be as thin as possible to reduce the distortion of the electron beam. In this paper we will present experiments where we used a tape based plasma mirror. The tape of only several micrometer thicknesses will allow us to overcome this disadvantage. It can be used with a sufficient repetition rate (e.g. the repetition rate of the laser – 10 Hz) while it allows the electron beam to propagate though without significant disruption.

EXPERIMENT

A schematic picture of the tape drive is shown in Fig. 2 (a). Two motors are used to spool the tape of a width of 0.5 inch and a thickness of 25.4 µm over several rollers [9]. One of the motors is pulling the tape while the other is used as a tension brake. The surface of the Mylar tape was characterized using an interferometric microscope from the Optical Metrology Laboratory at LBNL. The surface roughness was measured to be about 64.36 nm (RMS) with a peak to valley value of about 651.6 nm [see Fig. 2 (c)]. Additionally, the surface roughness of a Kapton tape and a commercial video tape (VHS) was measured [Fig. 2 (d)]. The flattest surface was found for the VHS tape with 14.3 nm (RMS) and 168.2 nm peak to valley roughness. Although a higher surface quality would improve the performance of the plasma mirror a Mylar tape was used for the experiments.

In the experiments a short focal length lens (15 cm) focused the laser beam with a wavelength of λ=800 nm to a focal spot of about 6.6 microns (FWHM) on a Mylar tape. Intensities between 10^{12} and 10^{17} W/cm^2 were achieved by varying the laser energy of the short pulses (42 fs) between 0.1 µJ and 5 mJ. To increase the reflectivity of the plasma mirror, s-polarized laser pulses were used. Since the temporal contrast of the laser influences the performance of the plasma mirror, the

*Work supported by the DOE grant DE-AC02-05CH11231 and the National Science Foundation
[†]Also at University of California, Berkeley, CA 94720
[#]TSokollik@lbl.gov

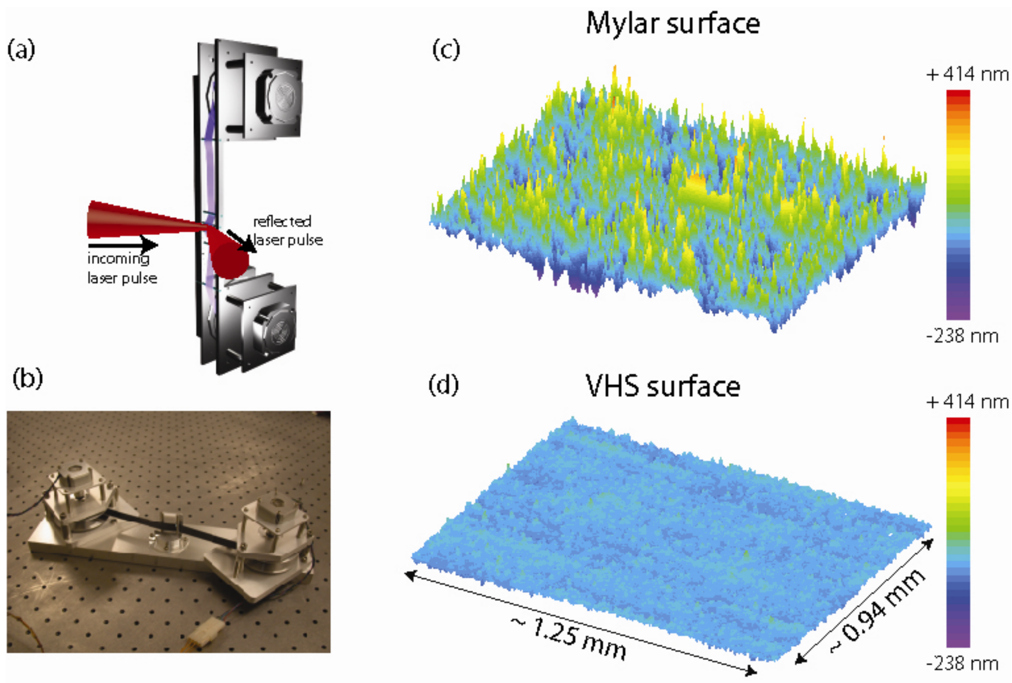

Figure 2: (a) Schematic picture of the tape drive. (b) Improved version of the tape drive. (c) Surface roughness measurement of a Mylar tape. (d) Surface roughness measurement of a VHS tape.

contrast before the main peak was measured to be about 10^{-8} up to 5 ps using a third order autocorrelator (Sequoia, Amplitude Technologies). To measure the reflectivity an energy meter and photo diodes were used. The focal distribution of the reflected beam was simultaneously measured by a 12 bit CCD camera. In Fig. 4 the energy reflectivity (ratio of the reflected energy and the input energy) is plotted versus the intensity at the target. At low intensities the reflectivity is about 10 %, which is consistent for reflection of s-polarized light on a Mylar surface.

At higher intensities, at about 10^{13} W/cm^2 the reflectivity starts to increase up to a maximal value of about 78 % at 10^{17} W/cm^2. At these intensities the laser pulse creates a plasma and is reflected at the critical surface. Since the area where a sufficient high intensity is reached to generate an overdense plasma increases for increasing peak intensities, the overall reflectivity increases. Similar reflectivity curves were observed in former experiments [3,4]. Also the beam quality in terms of the Strehl ratio, defined as the ratio of the energy inside the FWHM focus of the measured focal distribution to an ideal Gaussian distribution, is shown in Fig. 3. The Strehl ratio of the incoming beam is about 0.75. The value of the reflected beam is constant up to an intensity of about 5×10^{15} W/cm^2 and decreases for higher intensities. This can be explained by the expansion of the plasma which can be estimated by the speed of sound ($c_s \approx 7.5\times10^7$ cm/s [4]). If the time between the creation of the plasma and the reflection of the main pulse (Δt) is short enough so that no significant expansion of the plasma can occurs ($c_s\Delta t<\lambda$) the critical surface will be flat and the wave front of the reflected beam will be undistorted. At higher intensities the plasma mirror is triggered earlier in time. If there is enough time for the plasma to expand before the main pulse arrives the reflected wave front will be distorted [4]. Using $\Delta t \approx 2.5$ ps for our contrast parameter and at an intensity of 10^{17} W/cm^2 the plasma expansion can be roughly estimated by $c_s\Delta t \approx 1.9$ µm.

Since the tape is moving the stability in terms of beam pointing and reflectivity is important for any application. Therefore, we measured the reflectivity of about 100 shots in two different modes – a single shot mode (moving the tape, tensioning the tape and firing the laser) and a continuous movement of the tape (repetition rate 0.8 Hz). The measured reflectively was (73.5 ± 6.4) % in case of the single shot mode and (74.8 ± 6.6) % for the

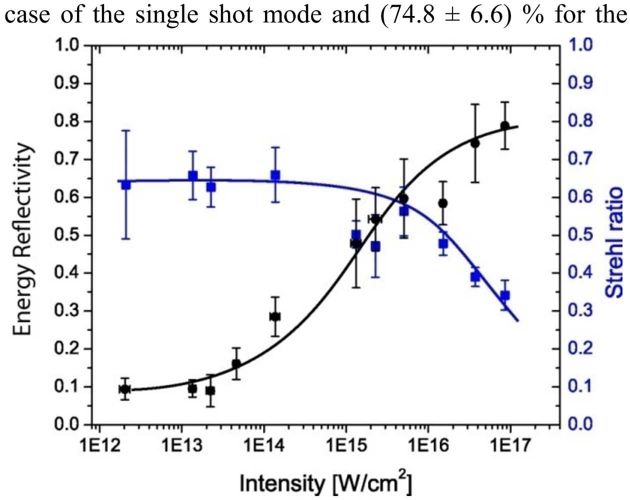

Figure 3: Energy reflectivity (black circles) and Strehl ration (blue squares) as a function of the laser intensity. The solid lines are used to guide the eyes.

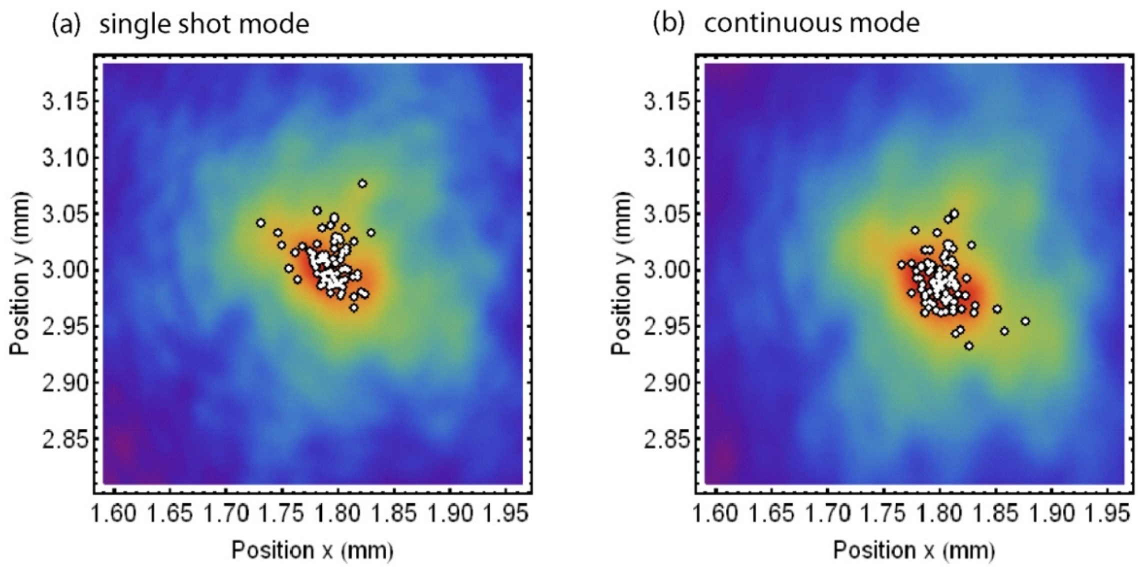

Figure 4: Beam pointing measurement for (a) single shot mode and (b) continuous mode. The white dots represent the centroid of the beam for each individual measurement. The background is the sum of all measurements.

continuous mode. Simultaneously, the beam pointing was measured with a CCD camera. The laser beam pointing stability before the plasma mirror is about 9.3 µrad (RMS). The measured pointing fluctuation after reflection off the plasma mirror is 2.24 mrad and 2.35 mrad, respectively (cf. Fig. 4). The fluctuations in reflectivity and beam pointing could be caused by the surface movement, by fluctuations of the laser contrast or by different surface conditions. Since the laser spot size is on the same order of the surface modulations [cf. Fig. 2 (d)], the latter one is most likely the dominant effect. Using a tape with a better surface quality should reduce the fluctuations in reflectivity as well as in beam pointing. Experiments with an improved design of the tape drive (c.f. Fig 2 (b)) have been done and show a reduction of the laser pointing fluctuation (<1 mrad).

CONCLUSION

In summary, we presented preliminary experimental results using a tape-based plasma mirror. We measured a maximum reflectivity of (78 ± 6.2) %. Taking the reflected beam quality into account, the optimal intensity range is around 10^{16} W/cm^2 with a reflectivity of about (60-70) % for the presented experimental conditions. We observed an increased beam pointing variation introduced by the plasma mirror of about 2.3 mrad. This value has to be reduced for future applications. This can be achieved by using tapes with a higher surface quality, e.g. VHS tapes.

The tape could also be used to improve the temporal contrast of the laser pulse. For that purpose p-polarized light would be required to decrease the reflectivity from the tape surface. Additionally, in reference [7] it was proposed to irradiate the mirror at the Brewster angle to improve the contrast enhancement. With these techniques a contrast improvement of roughly 2 orders of magnitude would be feasible. The drawback would be the reduced reflectivity of the main pulse around (50 - 60) % [7].

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