Plasma Mirror Operation at High Intensity: Reflectivity and Beam Profile

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Abstract

Reflectivity and reflected beam profile from a plasma mirror at high incident intensities (on the order of 10^{19}-$10^{21}\,\mathrm{Wm^{-2}}$) was characterised for the Gemini North beam incident on $125\,\mu$m thick Kapton tape. Post-reflection pointing was characterised with an additional pointing variation of $\theta_{av} = 2.6\,$mrad generated by the formation of the plasma mirror. Adjusting focal spot area on the tape and pulse energy allowed for on-tape intensity variation. A maximum reflectivity above 70% was observed with a drop off for intensities nearing $3\times10^{21}\,\mathrm{Wm^{-2}}$. Focussing further from the tape resulted in a lower quality of reflected spot at comparable intensities, with less energy contained within the FWHM (20% compared to 10% at $10^{21}\,\mathrm{Wm^{-2}}$). The results presented below highlight important areas for development and optimal operation regimes of plasma mirrors for future staging applications.

1 Introduction

The implementation of plasma mirrors at high intensities, in lieu of curved accelerators [1], is vital for staging applications. Staging is an approach to overcoming the depletion and dephasing limits in laser-driven wakefield acceleration. It enables energy gain across separate acceleration stages driven by different laser pulses. Replenishing the driving laser whilst maintaining a high accelerating gradient requires an intense beam to be coupled into the next plasma stage over a short distance (L_c in figure 1).

Plasma mirrors offer a replenishable surface to couple in high intensity pulses close to focus. Staging with 3% charge capture and 100 MeV energy gain has previously been demonstrated at LBNL [2] using tape-based plasma mirrors [3], and an additional beam focussing optic between the stages. More traditionally plasma mirrors have been used for cleaning up the temporal profile of pulses. This is necessary for high intensity ion acceleration experiments [4–6]. For this application, plasma mirrors are utilised further from focus in a lower intensity regime.
Reflectivity is well characterised at relatively low intensities [7–13]. The quality of reflections degrades at higher intensities due to the preionisation of the plasma mirror before the arrival of the main pulse. During the time between ionisation and pulse reflection the mirror surface expands, resulting in the formation of underdense preplasma before the critical surface. This is problematic as it reduces reflectivity of the plasma mirror and, therefore, the en-

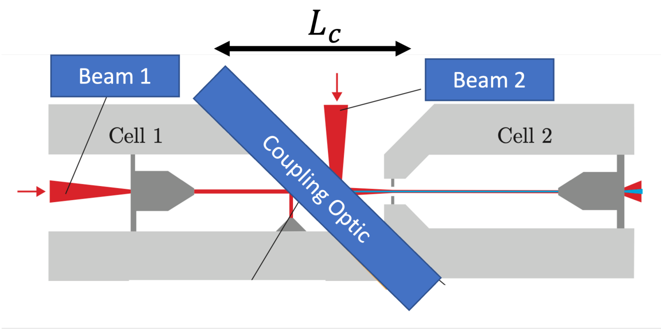

Figure 1: Diagram of staging set up, showing the injection (cell 1) and acceleration (cell 2) stages and the distance L_c required to couple in a secondary driving laser.

ergy contained in the reflected laser pulse. High intensity laser beams are vital for driving wakefield acceleration [14]. The laser strength can be characterised via the lasers normalised vector potential, a_0. a_0 determines the dynamics of the accelerating region, larger values can increase the size of the accelerating and focussing region. For $a_0 > 1$ the non-linear or blowout regime is entered. This regime enables self-guiding, maximises the charge that can be accelerated and generates linear focussing forces helping preserve beam quality [15]. A laser wakefield accelerator (LWFA) has yet to be driven in this non-linear regime by a laser pulse reflected off a plasma mirror.

In addition to reducing energy in the driving pulse, the use of a plasma mirror can contribute to transverse misalignments between the injected beam and the driving laser. These misalignments are a result of increased pointing variations. This can result in emittance growth and a reduction in charge capture. To study these effects an experiment was performed with the Gemini laser generating a plasma mirror at high intensities and exploring optimal operating regimes.

2 Experimental Methods

The Gemini laser produced s-polarised beams of 800 nm, containing up to 15 J within a

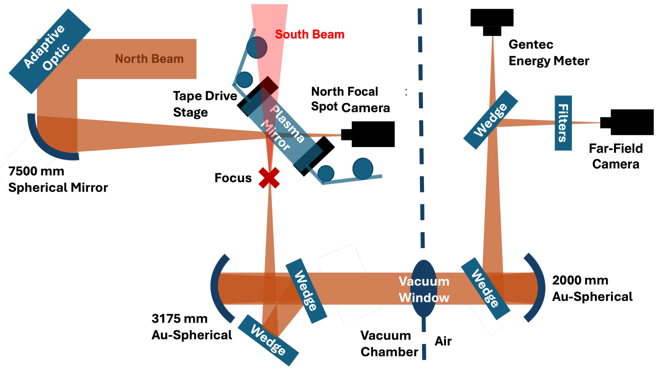

Figure 2: Experimental set up for reflectivity measurements in the Gemini TA3 vacuum chamber. Forward line diagnostics for post-reflection characterisation were included.

pulse duration of ∼50 fs. The North beam was focused by a 7500 mm dielectric spherical mirror from a diameter of 150 mm to a focal spot of ∼50 μm. A Shack-Hartmann wavefront sensor, the *Imagine Optics HASO*, and an adaptive optic (deformable mirror), were used to measure and optimise the wavefront. The North beam focal spot, shown in figure 3, was imaged by driving the tape/plasma mirror surface out, and driving in a focal spot camera with an attached microscope objective. This imaging system is referred to here as the North Focal Spot Camera, as labelled in figure 2. The input North beam had an average FWHM at focus of $57 \pm 13\,\mu$m. For the shots discussed here 24.7% of reflected energy was contained in the FWHM, with a major axis of 29.4 μm and a minor axis of 20.6 μm. The focus was driven to 9.0 ± 1.5 mm and 18 ± 3 mm after the tape, resulting in a waist of $110 \pm 20\,\mu$m and $190 \pm 40\,\mu$m on the plasma mirror.

The beam focus was re-imaged post-plasma mirror reflection using a dedicated transmitted beam imaging system, as shown in figure 2. The focus was adjusted relative to the plasma mirror, using the adaptive optic. This resulted in large uncertainties in focal spot location. The focal plane was located using the North Focal Spot Camera (as described above). The imaging system consisted of two Au-spherical

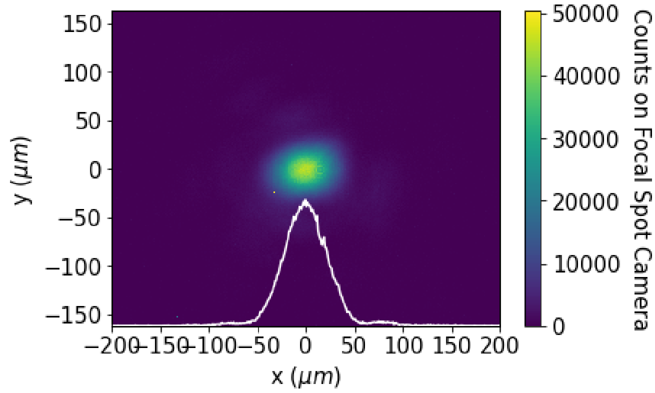

Figure 3: Example North focal spot before reflection from the plasma mirror, taken using North focal camera with a FWHM of 34 μm, and 41% of total energy contained within the FWHM.

mirrors, multiple wedges at 22° and a series of filters (see figure 2). At high intensities the focal spot location was found by scanning the plane imaged on a Andor Neo 2160 × 2560 sCMOS. A series of filters and wedges (see figure 2) were used to reduce the intensity of the transmitted pulse before imaging. The imaging plane of this imaging system was changed to compensate for shifts in the focal plane by moving the Au-coated spherical mirror and far-field camera on separate stages. The energy passing through a wedge was directed to a Gentec QE8SP-B-BL-D0 energy meter, which was used to measure the energy post-transmission through this optical system.

2.1 Calibrations

The laser energy at the target chamber centre (TCC) was significantly higher than that at the calorimeter. This is a result of the transmission through wedges and the reflections off unprotected Au-mirrors and protected Ag-mirrors. The reduction factor, calculated using the Fresnel equations, was 8.5×10^{-5} for an s-polarised pulse. This calculation assumes wedges are exactly angled at 22° and does not account for transmission through the vacuum window.

The set-up described above was also used in

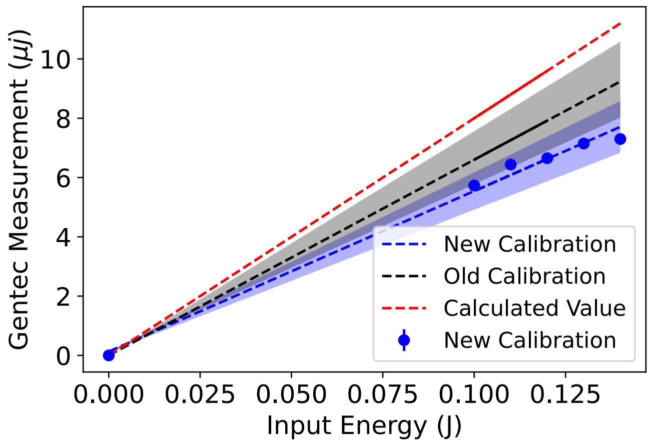

Figure 4: New calorimeter energies measured outside the vacuum chamber against the input compressor energies from the South beam, compared to the expected values and the old calibration values.

Gemini Target Area 3 during an earlier experiment [16]. During that experiment, the South beam was used for calibration as shown in figure 4. An additional calorimeter placed at TCC was used to find a transmission ratio of $6.6 \pm 0.6 \times 10^{-5}$. A different calibration was performed during this run. Instead of explicitly measuring energy at TCC, the energy at TCC was assumed to be the same as the input South compressor energy. The ratio between this compressor input energy and the energy measured at the Gentec outside the vacuum chamber was $5.4 \pm 0.6 \times 10^{-5}$. An average of the two experimental calibration values, with a transmission value of $6.0 \pm 0.7 \times 10^{-5}$, was used for the results. Uncertainties on this calibration originates from uncertainty on the compressor energy, the measured Gentec energy and the standard variation of their ratios.

3 Pointing Characterisation

Pointing variations were determined by spooling the tape and determining variations in the centre-of-mass (COM) of the imaged reflected spots. Variations resulting from the tape drive itself, without plasma mirror formation, were characterised using a HeNe reflected off the un-ionised tape. These variations were $\Delta\theta_x$= 0.9 mrad and $\Delta\theta_y$= 1 mrad, which over $\sim$ 1 cm would mean a variation in the focal plane below 10 μm.

Pointing variations of the Gemini laser before plasma mirror reflection were measured on the North focal spot camera, using Centre-of-Mass (COM) variations over 100 shots. The delivered Gemini North beam had average pointing variations on the order of $\Delta\theta$= 1.9 $\pm$ 0.2 μrad. This resulted in fluctuations of $\sim$20 μm at focus, which is 1 cm from the tape, and 750 cm from the focussing optic. Pointing variation after plasma mirror formation were measured by the far-field and averaged over 50 shots. Pointing variations with an average of 2.6 mrad were introduced by the plasma mirror, which over 1 cm from the tape corresponds to variations of $\sim$ 30 μm, similar to the on target pointing variations of Gemini itself.

4 Reflectivity Measurements

There was an overall trend of reflectivity falling with increasing incident intensity, as in figure 5. At focus close to the tape (9 mm), with

Focus	9 mm	18 mm
Input Energy(J)	7.3	8.4
Input FWHM(μm)	110 ± 20	190 ± 40
Energy Out(J)	3.73 ± 0.2	5.8 ± 0.2
FWHM Energy(J)	0.5 ± 0.2	0.5 ± 0.3
FWHM Out(μm)	49 ± 11	59 ± 9
a_0 **Value**	0.21	0.25

Table 1: Characterised input spots (incident on plasma mirror) and reflected spots focal spots, where focus is shifted from 9 mm to 18 mm.

on-tape intensities exceeding 2×10^{21} Wm^{-2}, a significant drop off in reflectivity was observed. Focusing further away from the tape (18 mm), resulted in a higher total reflected energy but with a lower fraction of the energy contained within the central spot (figure 6). Energy fraction within the FWHM fell for incident intensities of 1×10^{21} Wm^{-2} for a 18 mm focus and

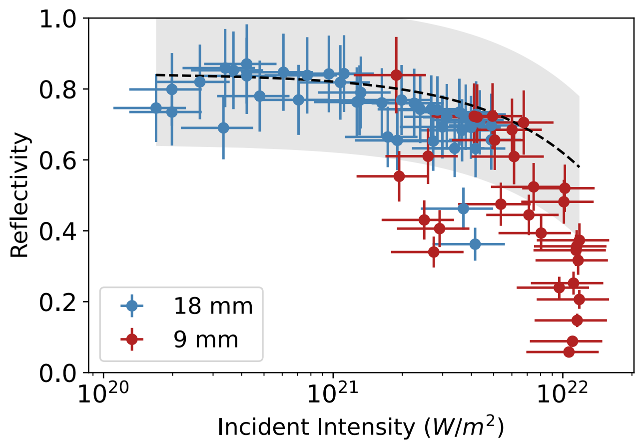

Figure 5: Decreasing reflectivity across incident intensities with a sharp reduction towards 1×10^{22} Wm^{-2})

2×10^{22} Wm^{-2} for 9 mm focus, as in figure 6. More of the pulse is contained outside the central spot for a larger focal area exposed to the tape, as is shown in the imaged focal spots in figure 7. The balance of focal spot quality and total reflectivity meant that both focal distances from the tape resulted in the same energy contained within the FWHM, with a maximum of 0.5 ± 0.2 J. However, the closer focus is contained within a smaller FWHM, and therefore higher intensity, as shown in table 1.

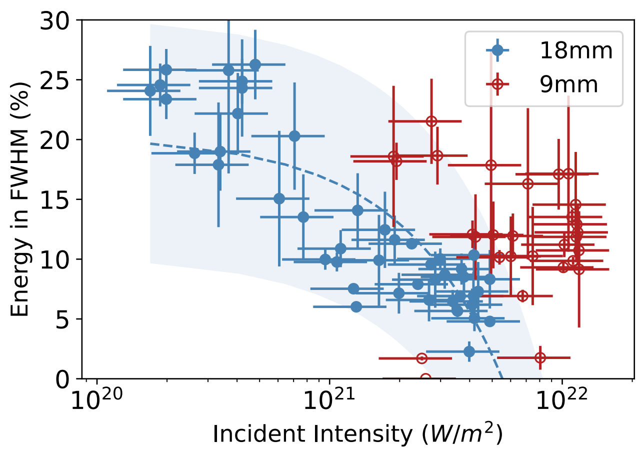

Figure 6: Ratio of energy in the FWHM of a reflected spot for different focal distances and input intensities.

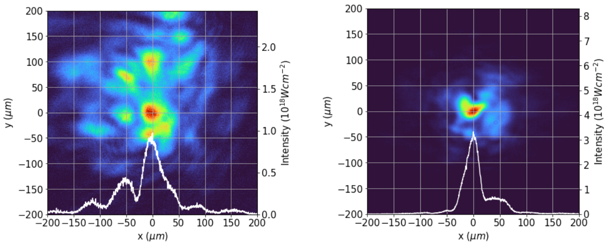

Figure 7: Focal Spot image on far-field camera for focus at (a) 9 mm and (b) 18 mm after tape, with an intensity line out on the x-axis.

5 Discussion

Large pointing variations would make aligning the injected beam from the first cell with the laser reflected into the second cell challenging. This may result in lower charge capture and increased emittance growth. Both the laser itself and the active plasma mirror discussed here result in pointing variations near the scale of the wavelength of the relativistic plasma wave. The added pointing from the active plasma mirror exceeds the pointing variations inherent to the laser. This means that the distance we choose to operate from the plasma mirror needs to be minimised. Day-to-day changes in pointing variations, insensitive to incident intensity, were also observed. Finding the source of these will be necessary for future staging runs and may require investigations into tape drive performance.

The drop in reflectivity at intensities exceeding $10^{22}\,\mathrm{Wm}^{-2}$ is indicative of the formation of a longer underdense ramp before the critical surface [17]. This would result in increased energy absorption and, if the intrinsic prepulse of the laser cannot be improved, a reduction in reflectivity. Operating at a lower intensity may be a necessity to couple in more energy to the second cell. To do this focus must be pushed further from the tape. It was shown that pushing focus further from the tape produced worse quality spots, increasing energy contained outside the FWHM. The reduced quality of the spot is likely to be due to exposure to tape surface variations or the non-uniform expansion of the plasma mirror. The maximum a_0 value fell significantly below 1, and was limited by this poor reflectivity and reflected spot quality. Ideal operation would maximise reflected encircled energy in the FWHM, requiring high total reflectivity and spot quality.

If the sources of focal spot quality degradation cannot be isolated and mitigated, operating the plasma mirror at high intensities may still be possible. Operation at high intensities makes improving the temporal profile of the input pulse a priority, as this would prevent early pre-ionisation and surface expansion. An additional plasma mirror system, like one previously implemented at Gemini TA3 [6], would allow for the impact of pre-pulses and the ASE pedestal to be mitigated and therefore to push the limit at which reflectivity drops further away. This requires a high reflectivity double plasma mirror system, which has been previously demonstrated [18], to maintain energy efficiency. Operating at lower intensities may be an option if the causes of focal spot deterioration and pointing variations can be identified, however, shifting focus further from the tape would increase L_c and complicate beam transport for staging applications. Increasing ramp lengths at the end of the first cell and the entrance of the second cell may help minimise emittance growth in vacuum and increase charge capture in the second cell [19].

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