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Diamond machining of a single shot ellipsoidal focusing plasma mirror

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ABSTRACT

Plasma mirrors have become an important tool in high power laser physics due to their ability to suppress laser pre-pulses and amplified spontaneous emission allowing a cleaner and sharper rising edge pulse to be focused onto a target. A PMMA ellipsoidal plasma mirror used to increase the peak intensity of a high power laser pulses before it reaches the target is presented. The ellipse has been designed to increase by a factor 3, between input and output, the F-number of the beam, inducing in theory a factor 9 gain in peak intensity. Diamond machining, which is a technique capable of producing sub-micron accuracy on steep, freeform surfaces, is an ideal process for manufacturing these types of mirrors. In this paper, we discuss the diamond machining requirements to manufacture such near diffraction limited high numerical aperture mirrors.

Keywords: Diamond turning, tool servo, freeform optics, precision machining, Plasma mirror

1. INTRODUCTION

Plasma mirrors are transparent optical components on which a thin plasma is created at the surface by an intense laser beam, and this plasma acts as a temporal reflective coating, enabling the incident light to be reflected.[1] As the plasma occurs above a specific intensity threshold level, when the density at which the plasma frequency matches the frequency of an electromagnetic electron wave in the plasma, plasma mirrors are mainly used as low intensity filters.[2] They allow the removal of the pre-pulses and amplified spontaneous emission which intrinsically occur when generating an intense laser pulse, subsequently improving the quality of the pulse before it hits the target. The addition of an anti-reflective coating on the mirror increases the threshold intensity required to ionise the surface, enabling the shaping of an even more intense laser pulse. The description of the design and test of a single use elliptical plasma mirror has been reported in.[3] We refer to this paper for details about the experiment. In this paper, the discussion will be mainly focused on the manufacturing of the plasma mirror by diamond machining, with an emphasis on how machining errors, such as tool offset or tool radius, can affect the mirror shape of fast optics and subsequently how these surface errors alter the Point Spread Function (PSF) created at the focus of the plasma mirror when in its operational configuration.

2. SURFACE DEFINITION

The ellipsoid surface specification is given in Tab. 1 and an optical layout is given in Fig. 1.

The mirror works in a 1/3 magnification configuration to decrease the F-number and consequently the size of the spot at the target plane. The mirror mechanical aperture has been oversized to increase the surface acceptance angle and therefore allow the system to work with a different magnification.

Single point diamond turning is a widely used machining technique which consists of cutting material with a diamond tool using a purpose built ultra-high precision turning machine. While the part is rotating, the tool moves axially (Z-axis) and transversally (X-axis) relative to the axis of rotation, cutting the desired shape. By synchronizing the angular position of the part (C-xis) with both X and Z axes, the machine can cut non-rotationally symmetrical parts, with large sag and steep slope. This method is commonly referred to as slow slide servo (SSS) machining. The quality of the spot at the target plane is determined by the alignment of the

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Specification
Base radius : 6.915mm
Conic constant : -0.5310798
Off axis : 19.7°
Input F-number : 3
Output F-number : 1
Useful aperture :7.2 x 5.1mm
Mechanical aperture : 18.5 x 14.5mm

Table 1: Ellipsoid specifications

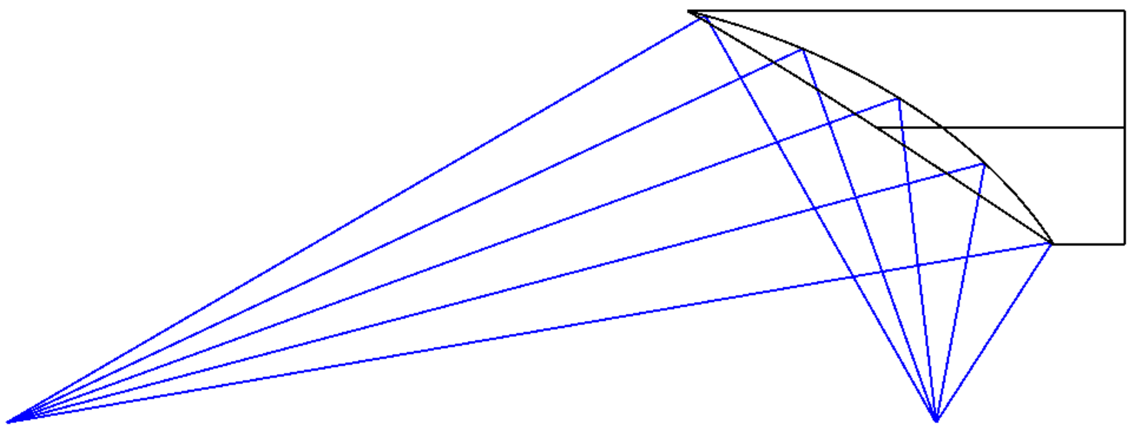


Figure 1: Optical layout. The input beam enters the system at the left focus, and the target is placed at the right focus.

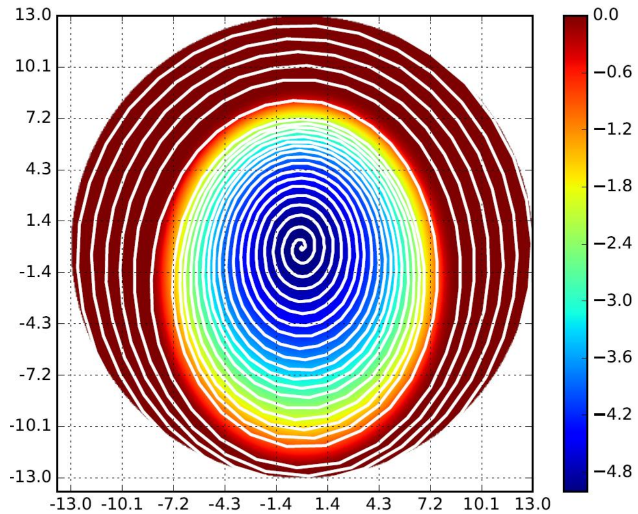
input spot at the focus of the ellipse as it has been shown here,[3] but it is also related to the accuracy with which the surface has been machined. In SSS, there are a number of reasons which can limit the machining accuracy such as:

- The positional error (also called following error). This error corresponds to the difference between the commanded position and actual position effectively reached by the machine axis. This error is influenced by the dynamic performance of the machine, in particular the effect of acceleration and deceleration of each axis.
- The tool setup error. This introduces a number of positional or dimensional errors such as the tool radius uncertainty, tool waviness, tool offset and tool height.[4]
- Orthogonality or more generally the residual misalignment of each axis with respect to the other.
- Thermal variations.

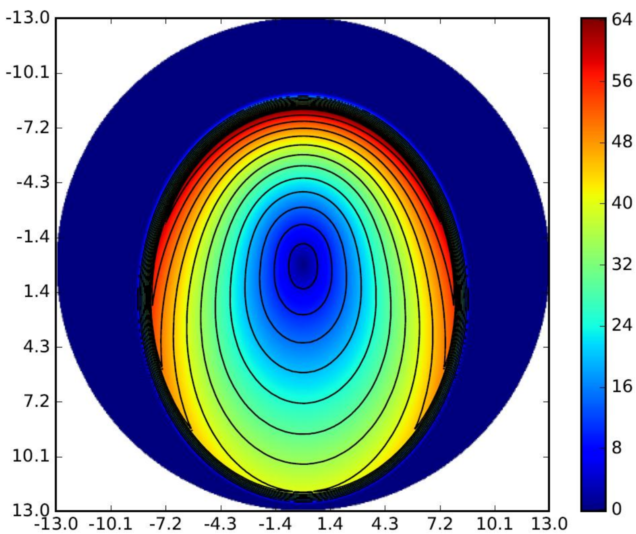
Although all these causes need to be considered and minimised or corrected for, each one contributes in its own way depending on the surface geometry, machining time, and environmental conditions. As the ellipsoid described here is a relatively small aperture surface, we would expect (3) and (4) to have less impact particularly in a thermally controlled environment. (1) and (2) can however have a measurable effect and therefore need to be addressed.

An image of the ellipsoid is shown in Fig. 2a. The mirror comprises a reference flat with a concave ellipsoid at the centre. Because of the high incidence of the beam (38°) on the mirror surface, the beam footprint is elliptical and the ellipsoid aperture has therefore been made elliptical. The flat surface is used to register the mirror position in the experiment, to facilitate its accurate positioning relative to the target when the plasma mirror, damaged by the plasma creation, is replaced by a new one. Both plane and ellipsoid are machined in a single pass with a single hybrid tool path program.

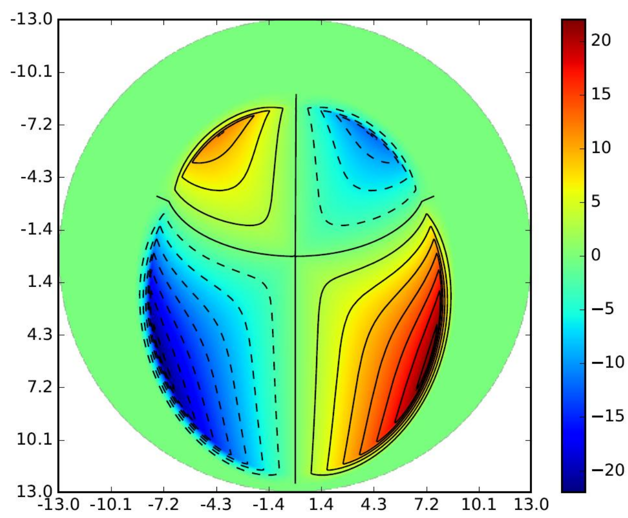
(a) Photo of the plasma mirror. The surface is registered from the front plane, the flat at the edge, and the outer diameter.



(b) Surface sag in mm, overlayed with the adaptive toolpath in white.



(c) Radial slope in degrees.



(d) Concentric slope in degrees.

Figure 2: Ellipsoidal surface prescription

3. SLOW SLIDE SERVO WITH AN ADAPTIVE TOOL PATH

The tool path definition is of great importance to minimise the positional error. In particular, the use of a circular tool path when machining an elliptical aperture is not optimal because the cut becomes interrupted, leading to larger axial amplitude in the tool displacement as the surface is virtually extended. This leads to more inertia and the potential for increased positional error.

Durham University and Eyejusters have developed a software tool to generate an adaptive tool path with a view to minimising the movement amplitude of the axes, and consequently the positional error. The surface sag is shown in Fig. 2b as a colormap, with the tool path overlaid in white. The infeed spacing has been increased for clarity. The tool path starts with a circular spiral trajectory while cutting the flat and changes to an elliptical spiral path when entering the elliptical aperture. As a result, the tool never leaves the surface, thus minimising the cutting time. The tool path follows the contour line of the radial gradient map shown in Fig. 2c. Fig. 2d shows the contour line and colormap of the concentric slope. The ellipsoid has been designed to have a zero gradient at the centre to avoid possible cutting artefacts induced by residual tool offset and tool height as discussed in.[4]

4. EFFECT OF TOOL OFFSET AND TOOL RADIUS ERROR ON THE PSF

The tool offset is, in essence, the discrepancy between the required tool position as considered in the tool path program and its actual position in the machine reference frame. A difference in these creates a surface error which is a function of the tool offset and the local radial gradient in the first approximation. As for the tool radius error, it is induced by the difference between the tool actual radius and its measured value as used in the machine program to calculate the tool path. The amplitude of the surface distortion depends on the tool radius error as well as the cosine of the local radial gradient. Both errors are usually minimised by the operator prior to cutting the part, but the residual uncertainty in their measurement inevitably induces an error in the surface form. These effects usually translate onto the surface as defocus plus a high order term. In the case of the ellipsoid, which produces in optimal conditions an aberration free spherical wave, the difference between machining and operational orientation can contribute to produce a specific surface distortion. The ellipsoid machining orientation, which considers the surface as viewed from a direction normal to the centre (such as in Fig. 2b), is different from the functional 38° tilt mirror orientation (as shown in Fig. 1). As a result, a surface form error, which is created during the machining process will affect the optical path in a different way.

The software package Zemax was used to evaluate the effect on the PSF of an altered surface, cut in the presence of either tool offset or tool radius error. The simulation was carried out in two steps. First, an 801 x 801 pixel grid surface representing the ellipsoid surface machined with tool error was generated using Python. A tool radius of 1mm was used with an in-feed of 2 μm. The altered surface was then imported in Zemax using a Grid Sag surface, and was placed in its functional orientation. The source and image position, as well as mirror tilt were optimised using the built-in optimisation module to minimise the RMS wavefront. This alignment procedure is in fact the one followed in,[3] when a newly installed plasma mirror needs to be positioned and aligned with respect to the input laser beam. Both tool offset and radius errors generate primarily defocus aberration, and this defocus was minimised during the optimisation, leaving only the higher order surface form error.

Figs. 3 and 4 show the PSF and wavefront at the image plane respectively with a tool offset and a tool radius error for a wavelength of 633nm (the wavelength used for metrology not the operational wavelength). In Fig. 3, the PSF tends to become elliptical with increasing tool offset. The system is not limited by diffraction for a tool offset larger than 2 μm at the alignment wavelength of 633nm. At an operational wavelength of 1.053um, a tool offset larger than 5 μm prevents the system from working at the diffraction limit as some of the energy is transferred into the first diffraction ring. As the tool offset is usually minimised to be better than 1 μm, it should not be a limiting factor in surface form accuracy. As for tool radius error in Fig. 4, an error of 5 to 10 μm has a negligible effect on the PSF and it remains diffraction limited even at 633nm. As a result, we show that tool related errors do not have a significant impact on the PSF in the case of this ellipsoidal surface, working at F-number 1. It is believed that residual misalignment between mirror and input spot, as well as between the spot image and the target will have significantly more influence in the loss of peak intensity.

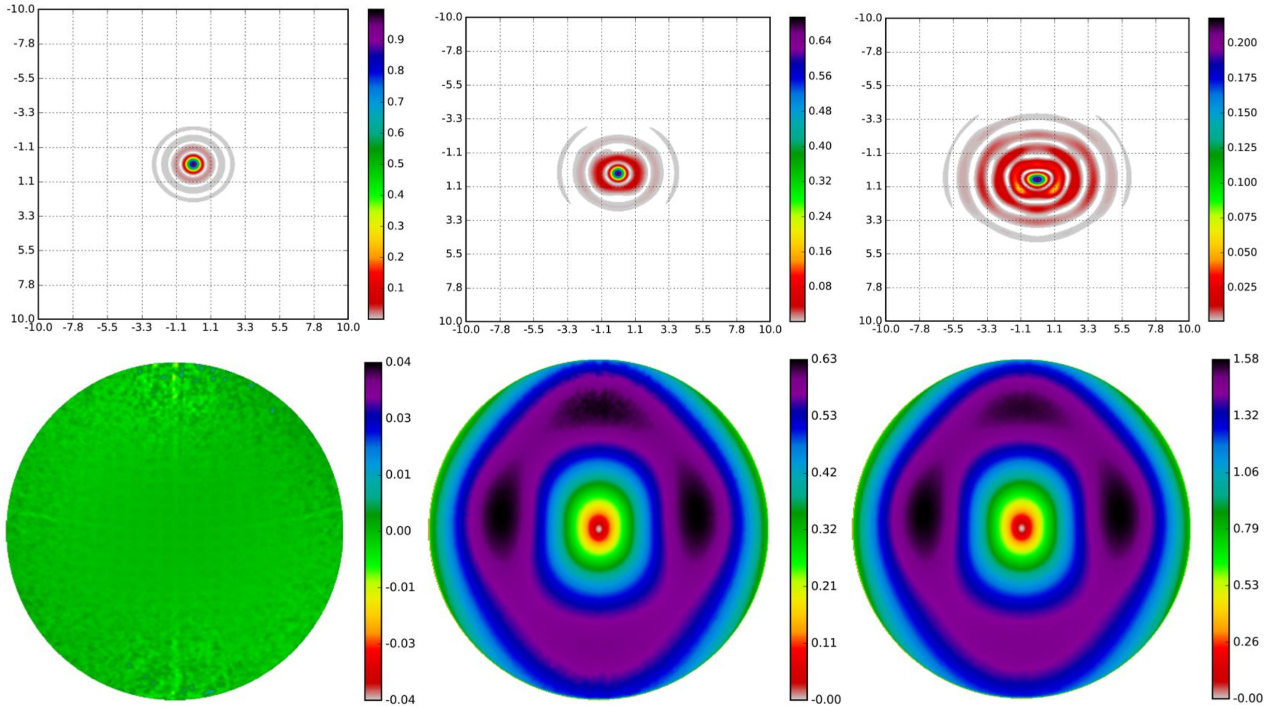


Figure 3: PSF (top) and Wavefront (bottom) in presence of a tool offset. Left is with no tool offset. Strehl Ratio (SR) is 1 and the wavefront is about 0 wave RMS (at 633nm). The visible noise is from the interpolation from polar to Cartesian coordinates and remapping. Middle is with 2 μm tool offset: SR is 0.72 and the wavefront is 0.1 wave RMS. Right is with 5 μm tool offset: SR is 0.24 and the wavefront is 0.25 wave RMS.

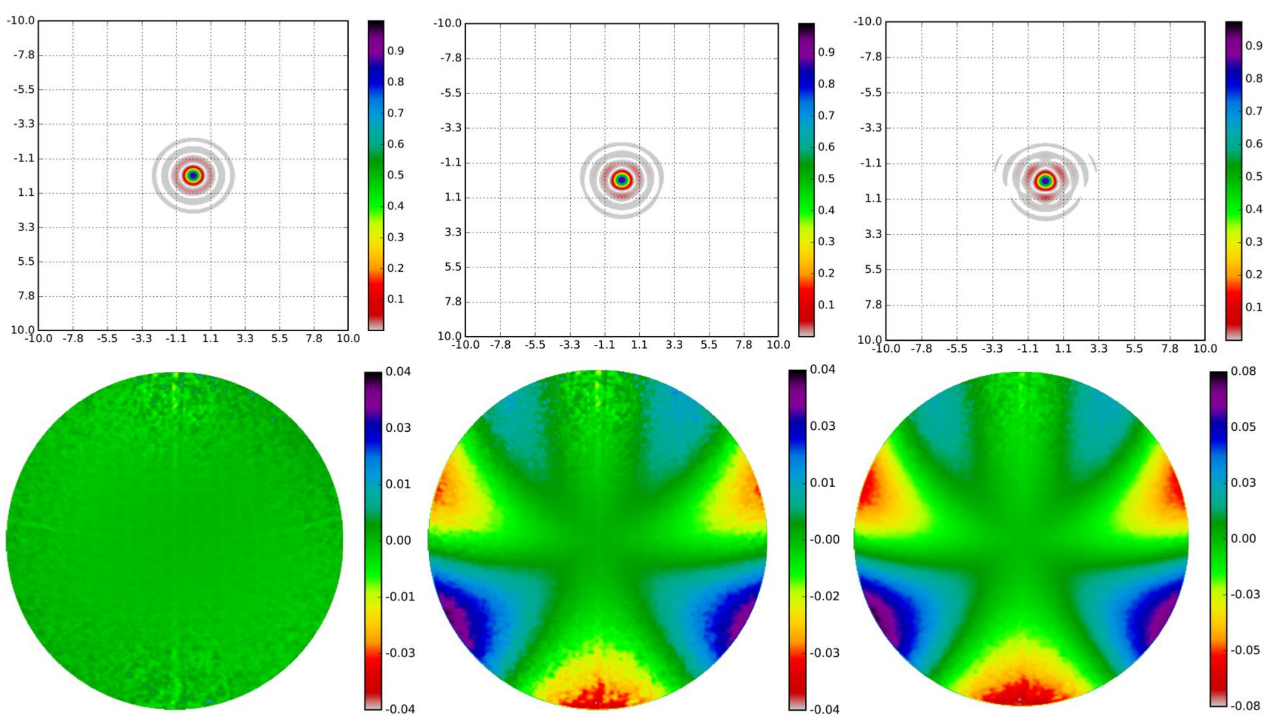


Figure 4: PSF (top) and Wavefront (bottom) in presence of a radius error. Left is with no error. SR is 1 and the wavefront is about 0 wave RMS (at 633nm). Middle is with 5 μm radius error: SR is 0.99 and the wavefront is 0.009 wave RMS. Right is with 10 μm radius error: SR is 0.97 and the wavefront is 0.16 wave RMS.

5. CONCLUSION

High aperture single shot PMMA concave plasma mirrors can offer an attractive alternative to expensive glass optics with longer working distance and larger aperture. Diamond machining is an ideal production technique for these types of mirror, providing a high surface accuracy to maximise the peak intensity at the target plane. Durham University and Eyejusters have developed an adaptive tool path machining process that follows the contour path of the radial gradient, reducing machining time, and which prevents the tool leaving the surface at any point during the tool path cycle. One of the objectives was to limit the axes inertia, hence reducing the tool following error. This paper has also investigated the effect of tool offset and tool radius error on the surface accuracy, and also on the PSF when the mirror is in its operational configuration. Both errors create mainly defocus which is subsequently compensated during the alignment procedure, but also a higher order distortion. At 633nm, a tool offset larger than 2 μm (which is more than the typical accuracy achievable in tool offset alignment) starts to impact the quality of the PSF. At operational wavelength (1.053 μm), tool offset become a critical parameter beyond 5 μm. Finally, tool radius error of the order of 5 to 10 μm (which is larger than the typical error for tool radius measurement), has a negligible impact on the PSF.

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