Plasma Scale Length Effects on an Imaging Geometry

Contact: myron.huzan@stfc.ac.uk

M. S. Huzan
Department of Physics,
Nottingham Trent University,
NG11 8NS, United Kingdom

C. D. Armstrong
Department of Plasma Physics,
University of Strathclyde,
Glasgow, G4 0NG, United Kingdom

D. Neely
Central Laser Facility,
STFC Rutherford Appleton Laboratory,
OX11 0QX, United Kingdom

Abstract

Plasma mirrors are optical elements that are capable of achieving high reflectivities with contrast enhancements of up to 10^4. This investigation of plasma mirrors focused on optimising the geometrical parameters to minimise optical aberrations. Ray trace simulations characterised the severity of induced aberrations with the significance to plasma scale lengths. An optimised elliptical geometry of $b/a = 0.654$ was deduced, complementing previously explored experimental investigations.

1 Introduction

Plasma mirrors have been established as a crucial tool for enhancing temporal and spatial contrast being used extensively as an ultra-fast optical switch [1]. The application extends through to a multitude of scientific disciplines and is used in the majority of modern high powered laser facilities around the world [2–4].

An inherent damage threshold of $\sim 10^{13}$ Wcm^{-2} exists for conventional optics, commonly alleviated through reduction of the fluence by increasing beam diameter. Consequently, this requires larger and more expensive optics when operating at higher intensities. Plasma mirrors mitigate this restriction and enable the possibility of significantly greater fluences due to the reflection medium being a plasma. Plasma mirrors operate as a single use optic, therefore disregarding any proximity restriction imposed from target debris enabling the construction of compact, closer proximity optics.

The current generation of planar plasma mirrors are capable of achieving contrast enhancements of up to three orders of magnitude with an associated 80% reflectivity [5, 6]. Enhancements of the contrast can be achieved of up to four orders of magnitude through the use of a dual plasma mirror configuration but restricted to only 50% reflectivity [7]. Recent investigations have established the significance of plasma scale length to the reflectivity having achieved a peak reflectance of 96% through manipulation of a collinear laser pulse. An intensity ratio of 1:8 of pre-pulse to the main pulse established a hydrodynamic expansion of the plasma medium achieved a plasma scale length of $0.3\mu m$ with an optimum inter-pulse delay observed to be 3ps [8].

Focusing plasma mirrors were recently developed to combine the contrast enhancements inherent in plasma mirrors with the feasibility of achieving higher intensity beams. This method of increasing intensity is an alternative to altering the input energy or pulse duration and would enable simple implementation into target areas without effecting the main laser system.

Simulations provide the freedom to explore a broader range of plasma scale lengths while characterising the severity of aberrations for an expansive set of plasma mirror geometries. This article covers numerical models used to investigate the optical aberrations due to plasma scale lengths within planar and focusing plasma mirror geometries.

2 Simulation

The propagation of light within the plasma medium was achieved through tray trace simulations within MATLAB. This treatment of geometric optics describes light as a propagation of rays through a medium while an iterative solution of Snell's law deduces the appropriate refraction. While ray tracing neglects the wave nature of light it provides a powerful technique of investigating the severity of optical aberrations and the implication of each plasma parameter.

Expansion of the plasma medium is neglected and assumed stationary throughout the simulation interaction. This is assumed appropriate due to the small time scales of interaction in which light-plasma interactions arise with no significant time for hydrodynamic expansion of the plasma to occur.

To compare the relative aberrations of the geometries the wavelength of light was defined as 800nm and the surface of each plasma mirror was set to the critical surface density, expressed as:

$$N_c = \frac{4\pi^2 \epsilon_0 m_e c^2}{e^2 \lambda^2} \tag{1}$$

where ϵ_0 is the permittivity of free space, m_e and e are the mass and charge of an electron, and λ and c the wavelength and speed of light.

Through previous investigations, it has been established that a single radially exponentially decaying profile of the plasma medium is sufficient to model the appropriate electron density [9].

$$N(r) = N_s e^{-r/L_s} \tag{2}$$

where N_s is the surface density and L_s is the scale length of the plasma.

3 Planar Plasma Mirrors

A planar coordinate system was selected that imposed translational invariance parallel to the y-axes and an exponentially decaying profile in x, Figure 1.

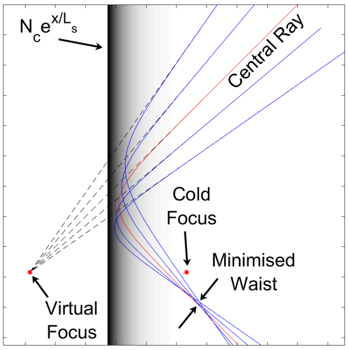


Figure 1: Schematic of a focusing beam incident into an exponentially decaying plasma profile from a planar plasma mirror.

The penetrative depth of oblique light through a plasma medium is dependent on the angle of incidence, θ_i. The severity of iterative refraction is measured through Snell's law, however the depth at which the turning moment exists is characterised as:

$$N_e = N_c \, cos^2 \theta_i \tag{3}$$

where N_e is the reduced critical surface and maximum electron density an oblique light ray is subjected to.

The angle of incidence was varied to replicate a large numerical aperture to explore and characterise a broad range of incident angles penetrating into the plasma medium. Radial displacement of the loci of neighbouring rays was measured relative to the cold reflection focus. This investigation was repeated for a range of plasma scale length values, Figure 2.

The optimum imaging regime is indicative of the greatest angular range that results in the smallest optical aberration. From this investigation, it would seem apparent that operating at angles nearer normal incidence would be the most beneficial for imaging from planar plasma mirrors due to the increased line density of neighbouring angular loci measurements.

Radial displacement was observed to increase as the plasma scale length is increased. However, normalisation of the radial displacement to the plasma scale length yields a single angular aberration profile. Consequently, this can enable the evaluation of optical aberrations as a function of plasma scale length, as appropriate to the experimental environment.

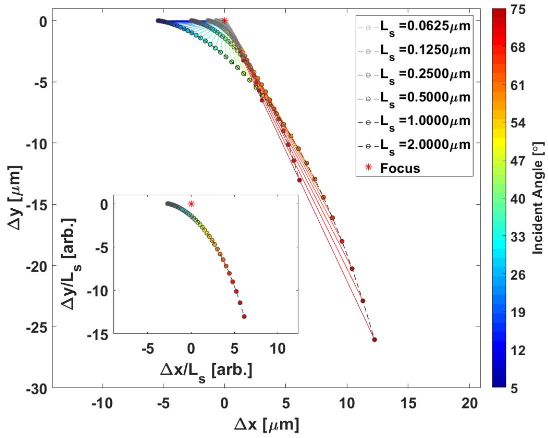
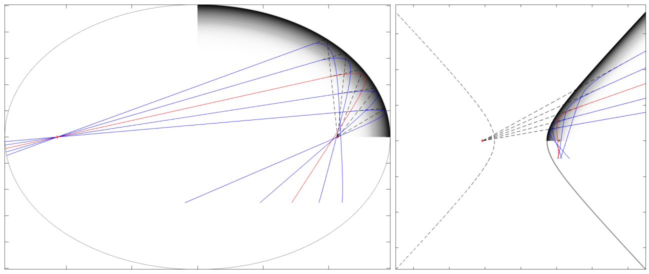


Figure 2: Angular investigation of the intersection between neighbouring equidistant rays from reflection off of a planar plasma mirror. Inlay graph represents the normalisation of the relative focal shift to the plasma scale length.

4 Focusing Plasma Mirrors



(a) Ellipse (b) Hyperbolic

Figure 3: Schematics of elliptical and hyperbolic plasma mirrors with an associated radially exponentially decaying plasma scale length.

Optical equipment within the experimental area dictates the incident F/# beam which is directed to the plasma mirror, typically an F/3.1 off-axis parabolic mirror. Previous elliptical plasma mirror studies established a geometric arrangement capable of 3× demagnification off the parabolic mirror [10].

While there exists a multitude of geometric and optical parameters capable of being explored within the simulation, this article focuses on characterising the significance of geometric eccentricity. The optical arrangement was replicated to that of the previous study; a 3 times demagnification of an F/3 incidence beam for a broad range of geometries. The resulting F/1 reflected beam would establish a smaller diffraction limited spot and a greater target intensity. Through geometric optimisation this could be applied to a multitude of laser-matter investigations.

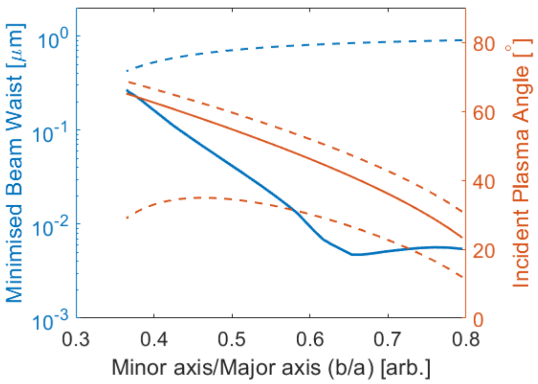
Focusing is achieved through magnification of the beam due to a reduction in the optical path length upon reflection. The severity of this is dictated by the geometry and the angle of incidence, θ_{in} and is defined as:

$$m = \frac{(1 + e^2) - e\,2\,cos(\theta_{in})}{(1 - e^2)} \quad (4)$$

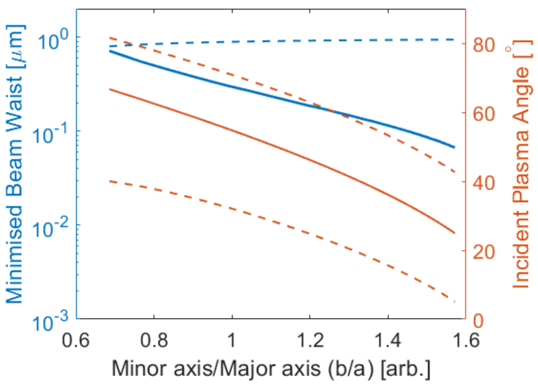
where $e = \sqrt{1 \pm b^2/a^2}$ is the eccentricity for an ellipse (-) and hyperbolic (+) with the associated semi-major, a and semi-minor, b axis lengths respectively [11].

5 Results

An investigation of the optical aberrations was performed for a range of elliptical and hyperbolic geometries. Characterisation was achieved through measurement of the reflected beams minimised waist. The angle of incidence was chosen to establish a central magnification of 1/3 for a F/3 beam for all of the explored geometries with a plasma scale length of $L_s = 0.25\mu m$.



(a) Ellipse



(b) Hyperbolic

Figure 4: Minimised waist measurements for a geometric investigation of an F/3 incident beam with 1/3 magnification. Diffraction limit is illustrated by the dashed blue line for the reflected beam. Orange line indicates the central ray plasma angle while the dashed orange lines signify the upper and lower extremes.

For both geometries there exists a common trend; as the ratio of minor and major (b/a) increases the minimised beam waist decreases. This would imply a more spherical ellipse and a flatter hyperbolic. The consequence of this is inferred due to the reduced angular incidence of the rays initially penetrating through the plasma, collectively resulting in a reduced aberration.

As characterised through the planar investigation a smaller aberration was observed for angles that approached closer to the normal of the surface. Figure 4 illustrates the angular range of the F/3 beam penetrating the plasma. Intuitively, the geometry which provides a smaller angular range and angular incidence would be most beneficial. This is verified with the elliptical plasma mirror consistently achieving a smaller beam waist over the full range of geometry eccentricities.

For all of the explored geometries the minimised waist was consistently below the diffraction limit and frequently negligible in comparison. While the diffraction limit imposes a fundamental experimental limit, simulation results signify a theoretical minimum. Therefore, these results provide the foundation of optimising the geometry, from which the minimised waist will broaden once realistic experimental values are incorporated.

The geometric reflection the elliptical surface imposes generates a cusp within the beam profile. The formation of a cusp folds the envelope of the reflected beam over forming further reduction in the waist of the beam. The technique of harnessing cusps is used extensively in beam optics and is directly observed within this simulation. An optimised geometric ratio of, $b/a = 0.654$ harnesses the caustic most effectively producing the smallest beam waist and as a consequence is the most optimum elliptical geometry.

5.1 Demagnification

Solution of equation 4 provides the available geometric ranges for which demagnification is achievable for an elliptical plasma mirror with an incident F/3 beam. Larger demagnifications achieve a subsequently reduced F/# beam. While this reduces the diffraction limited spot there is an increase to the minimised waist and experimentally provides more susceptibility to misalignments, Figure 5.

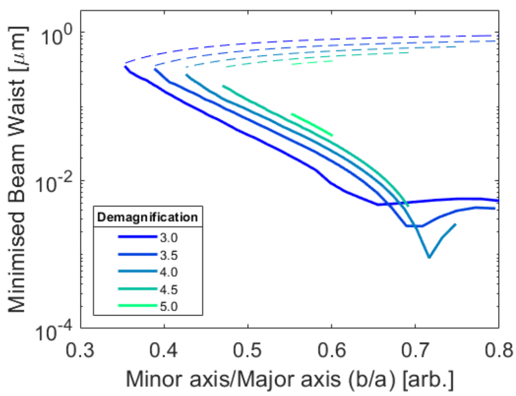


Figure 5: Minimised waist measurements for a geometric investigation of an F/3 incident beam with a range of demagnifications. Diffraction limit illustrated by dashed lines.

6 Summary and Outlook

Through these simulations it has become apparent that an elliptical geometry exceeds the capabilities of a hyperbolic and is recommended to be the geometry of choice for future simulation and experimental investigations. Moreover, an optimised elliptical geometry has been deduced for a focusing plasma mirror achieving a magnification of an F/3 beam to F/1, $b/a = 0.654$.

While these simulations provide a preliminary investigation into the severity of optical aberrations, future work should investigate the significance of adapting the parameters to exhibit a more realistic experimental environment.

Previous experimental investigations of elliptical plasma mirrors used PMMA as the material and to replicate a realistic surface density this should be increased to approximately, $N_s = N_c \cdot 10$. Furthermore, the integration of a Gaussian broadband beam representative of Gemini (800±20nm) and Vulcan (1053±2nm) at CLF would enable the characterisation of wavelength dispersion within the medium.

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