

Alignment of solid targets under extreme tight focus conditions generated by an ellipsoidal plasma mirror

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Abstract

The design of ellipsoidal plasma mirrors (EPM) for the PEARL laser facility is presented. The EPM achieved a magnification of 0.32 in the focal spot size and the corresponding increase in focused intensity is expected to be ~ 8 . Designing and implementing such focusing optics for short pulse (< 100 fs) systems paves the way for their use in future high power facilities where they can be used to achieve intensities beyond 10^{23} W/cm². A retro-imaging based target alignment system is also described, which is used to align solid targets at the output of the ellipsoidal mirrors (numerical aperture of 0.75 in this case).

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1. Introduction

The consistent technological development of high intensity short pulse lasers and the corresponding improvement in focused intensity over the last few decades have led to the exploration of new frontiers of basic science and applications[1].

5 Current generation of petawatt (PW) class lasers provide focused intensities around $\sim 10^{21-22}$ W/cm² with traditional focusing optics of about f/3. In upcoming facilities like Apollon[2], ELI pillars[3, 4, 5], etc. the corresponding focused intensities will increase to about $\sim 10^{22-23}$ W/cm². **However, the ability to achieve higher intensities of the order of 10^{23-24} W/cm²**

10 **will enable the possibility of exploring novel phenomena like radiation reaction[6] and ion acceleration to relativistic energies[7]. Laser plasma interaction in the radiation reaction dominated regime is qualitatively different from the currently achievable regimes of focused intensities $\lesssim 10^{22}$ W/cm² because the energy radiated by the oscillating**

15 **electrons at the focus is comparable to the energy the electrons gain from the laser field. Consequently, a significant fraction of the laser energy is expected to be emitted in multi-MeV X-rays[8, 9].** Thus it will be highly beneficial to increase the achievable intensities, for e.g., by tightly focusing the laser beam to a spot size of the order of the laser wavelength. To

20 achieve this, scientists have either used a small f-number parabola[10] or an ellipsoidal plasma mirror (EPM)[11, 12, 13, 14]. Because of debris damage to the parabola and the associated financial implications, using a small f-number parabola is not a viable option for upcoming facilities like ELI Beamlines[3]. Thus the performance of the EPMs on currently available PW class short pulse

25 lasers is being studied to gain valuable experience in pursuing this technology on future high intensity laser facilities.

An EPM is a small mirror designed to be placed after the focus of the main focusing element. It images the first focus into the second one with a significantly smaller f-number in order to **reduce** the focal spot. The EPM acts
30 in the plasma mirror regime with very high irradiance on the surface and so is a single-use optic. Since 2010, when the first use of the EPM on short pulse lasers was demonstrated[11], there has been steady experience gained on the use of such optics on glass laser systems with pulse lengths of the order of a ps[12, 13]. The optimal geometrical parameters like eccentricity and angle of incidence of
35 the EPM to achieve the desired **magnification** under paraxial approximation have been described earlier[15]. The only remaining parameter for designing the EPM is its scale size, which is set to optimize the reflectivity of the main laser pulse on the EPM[13]. **This paper describes the design of an EPM for the PEARL laser facility[16, 17] at Nizhny Novgorod, Russia. The laser**
40 **uses large-aperture nonlinear DKDP crystal for optical parametric amplification of the main pulse at a central wavelength of 910 nm and provides a maximum energy of $\lesssim 20$ J. A four grating compressor with a total efficiency of about 77% compresses the beam to a pulse duration of ~ 60 fs. The main beam, which has a diameter of about**
45 **18 cm, is then focused using an f/2 parabola.** The EPM was coupled to the focus of **the off-axis parabola (OAP)** to tightly focus the beam with a numerical aperture of 0.75 at the output. To the best of our knowledge, this is the first instance of using the EPM on a short pulse (< 100 fs) laser system.

For such a tightly focused spot, the front surface of the solid target needs
50 to be positioned within the Rayleigh length of about $2 \mu\text{m}$ (for a diffraction limited spot). This is a challenging requirement because many precision measurement devices are not suitable for the harsh laser-plasma environment. For e.g., several encoders like the resistive or magnetic encoders are susceptible to electro-magnetic pulse (EMP). Thus optical methods for aligning the target are
55 often used. In many such cases the rear surface of the target is aligned with respect to a reference (for e.g., a microscope objective or a chromatic confocal sensor). Then the target is translated by a distance equal to its thickness in

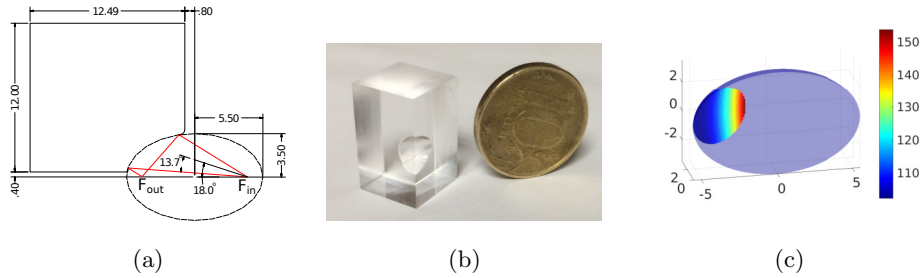


Figure 1: (a) Sectional view of the EPM depicting the geometry. The boundary of the laser beam path is shown in red. F_{in} (F_{out}) is the input (output) focus of the EPM. (b) Image of a machined EPM placed next to a 10 € coin of diameter 17.5 mm. (c) Expected fluence in J/cm^2 on the surface of the EPM when used with the PEARL laser delivering 20 J on target. All dimensions are in mm.

order to align the front surface. An alternative method is to align the front surface of the target with using a retro imaging system which has been demonstrated to work well with precision comparable to the Rayleigh length of the focusing optic[18]. Alignment based on retro reflection has the advantage of being immune to surface irregularities on the target introduced while mounting the target. This paper describes a retro imaging system for aligning a solid target to the tightly focused output from an EPM. The performance of the retro alignment system is bench-marked against an alternative alignment technique based on monitoring the near field of the beam being obstructed by the target.

This paper is structured as follows. Section 2 describes the geometry of the EPMs and characterizes their performance. Section 3 describes two different procedures for aligning the target at the output focus of the EPM. Finally, the paper concludes with section 4.

2. EPM geometry and performance characterization

Geometry of the EPM. The EPMs designed for the PEARL campaign had a major axis of 5.5 mm and a minor axis of 3.5 mm as shown in figure 1a. The axis of the EPM was oriented at an incident angle of 18° with respect to the axis of the incoming beam focused by an $f/2$ parabola. Such a geometry transforms

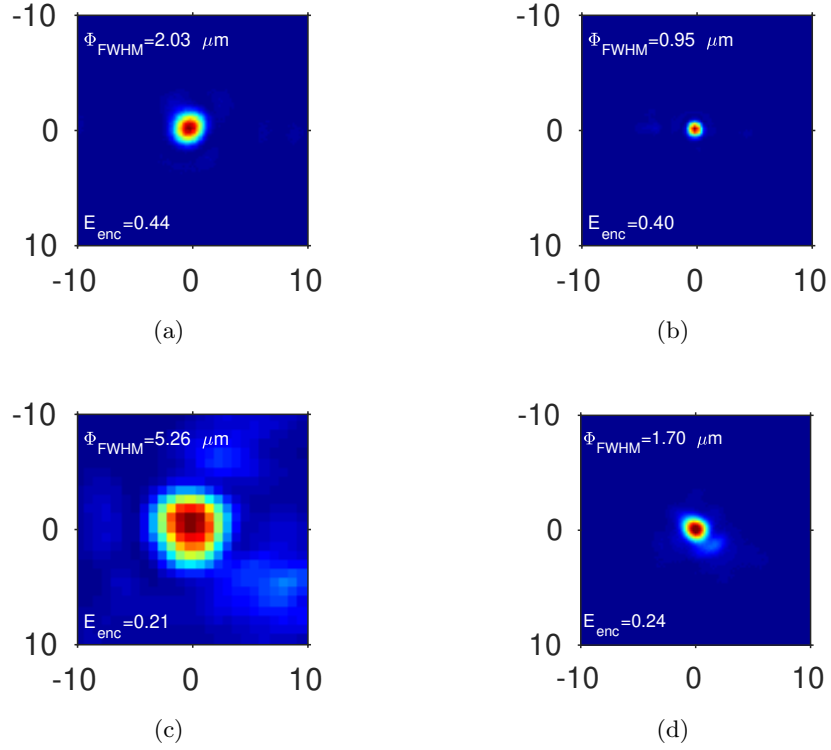


Figure 2: Focal spot images characterizing the performance of the EPMS. Focal spot at the input (a) and at the output (b) of the EPM at the test bench. Focal spot at the input (c) and at the output (d) of the EPM at the PEARL laser facility as measured with low power alignment beam. Field of view in all the images is $20\ \mu\text{m}\times 20\ \mu\text{m}$. The diameter of the full width at half maximum (FWHM) of the focal spot (Φ_{FWHM}) and the fraction of energy enclosed within the FWHM (E_{enc}) is mentioned in each image.

the input beam numerical aperture of 0.24 to an output numerical aperture of 0.75, i.e., an expected magnification of approximately 0.3[15]. The EPM was machined by single point diamond turning from a polymethyl methacrylate (PMMA) substrate. An example of a machined EPM is shown in figure 1b. For
80 the geometry of the EPM described above, the expected fluence on the surface of the EPM was calculated when used with the PEARL laser (20 J, 60 fs) and is shown in figure 1c. For an average fluence of about $110\ \text{J}/\text{cm}^2$, we expect a reflectivity of about 60 – 70%[19].

Characterization of the EPM. The EPMs were characterized in a non-plasma
85 regime on a test bench where a collimated 5 cm diameter HeNe laser beam was
focused by an $f/2$ OAP. The setup was similar to that described by Wilson et
al[13] and the f-number of the parabola matched that of the PEARL facility.
The **focal spots produced** by the EPM on the test bench and also on the
PEARL laser facility are shown in figure 2. On the test bench the measured
90 **magnification** was about 0.48, significantly weaker than the predicted **mag-**
nification of 0.3. **In order to explain this discrepancy, we are currently**
developing optical models which calculate exact solution of focused
intensity in the non-paraxial regime and also incorporate wavefront
errors[20]. On the PEARL facility the observed **magnification** was 0.32.
95 The corresponding increase in focused intensity that can be expected **at the**
PEARL laser facility is about 8 when compared to operation of the laser with
normal $f/2$ OAP[13, 11]. When compared to a setup including a planar plasma
mirror operating at similar fluence, the expected enhancement of intensity is
even higher ≈ 11 .

100 **3. Target alignment: setup and results**

Setup for alignment. The EPM and the target at the second focus were mounted
on 3-axis motorized linear stages with picomotor actuators (Model number 8302
from Newport Corporation). The picomotors had a minimum step size of < 30
nm and thus were very useful in precisely aligning the EPM and the target. The
105 setup of the EPM and targetry stages is shown in figure 3. In order to align
the front surface of the target, a retro imaging system was assembled as shown
in the figure. The laser light reflected from the front surface of the target is
collected by the EPM. The pellicle beam splitter of thickness $5 \mu\text{m}$ then reflects
the light which is then focused by a retro imaging lens on to a camera. The retro
110 imaging lens used in the setup had a focal length of 10 cm and an aperture of
 7.5 cm. Such high f-number lens enabled collecting all the light reflected from
the pellicle and also ensured a desired magnification of about 10 by the lens

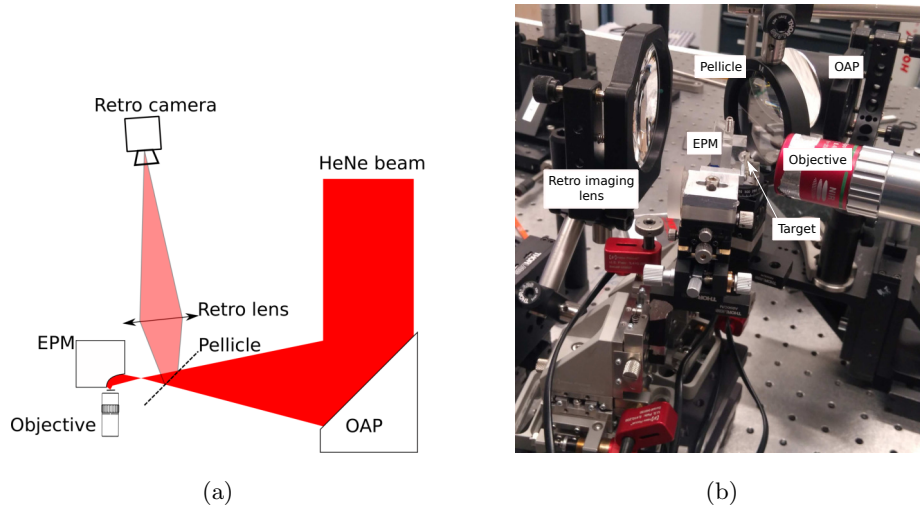
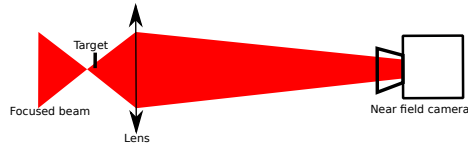


Figure 3: (a) Schematic of the setup used on the test bench to characterize the EPMS and bench mark the retro alignment system. (b) Image of the setup showing the physical layout of the components.

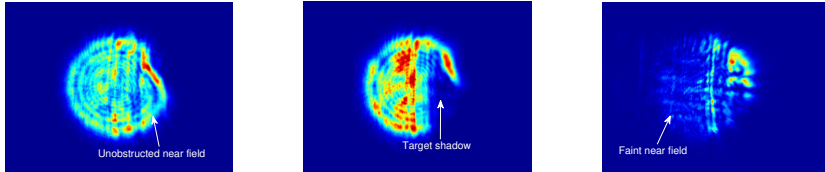
within a reasonable space.

A similar setup for mounting the EPM and the target was also used for
 115 real laser-plasma experiments at the PEARL laser facility. The retro imaging
 system was not installed at the PEARL facility as only thin targets were shot
 as discussed in the next paragraph.

Target alignment by monitoring the near field. At the PEARL laser facility,
 3 μm thick Al foils were aligned to the output focus of the EPM. The target
 120 thickness was comparable to the Rayleigh length and so, the target was aligned
 by monitoring the near field after the EPM focus as shown in figure 4a. The
 microscope objective used for aligning the EPM was defocused and used as a
 lens for monitoring the near field. The near field images obtained during the
 alignment procedure are shown in figure 4b. As the target moves to intercept
 125 the incoming alignment beam, the shadow of the target is clearly visible in the
 near field. The direction from where the shadow enters the near field image
 depends on whether the target is in front or behind the focus. When a thin



(a)



(b)

Figure 4: Target alignment by monitoring the near field. (a) Schematic of the alignment method. (b) Near field images during target alignment at PEARL facility showing unobstructed near field, shadow of target moving from the right and shadow of the near field when target is at focus.

target is at the focus, the entire near field profile diminishes simultaneously as seen in the figure (4b, right). If the target thickness ($3 \mu\text{m}$ in our case) is comparable to the Rayleigh length (expected to be around $3 \mu\text{m}$ for the output of EPM at the PEARL facility) then two shadows approaching from either side on the near field can also be observed and the shadow from the front side of the target (figure 4b center) can be distinguished from the shadow from the rear side of the target. On the PEARL facility, front side of the targets were aligned by monitoring the shadow from the front surface and placing the front surface at the focus. When shot with the full energy beam, a significant increase in the X-rays and the maximum ion energy were measured as compared to normal OAP shots. These results will be described in subsequent publications.

Target alignment by retro imaging. The retro imaging system, which is useful for aligning thicker targets was assembled only on the test bench in order to bench-mark its performance. A $0.8 \mu\text{m}$ thick Al target was chosen to compare

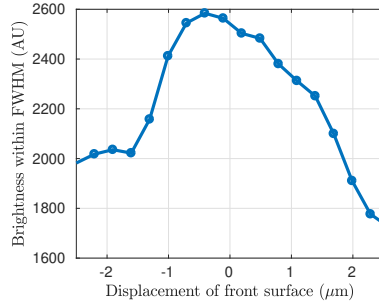


Figure 5: Average brightness of the spot measured on the retro imaging camera as a function of the target displacement. A displacement of 0 corresponds to the reference location of the target where it was aligned by monitoring the near field.

the two alignment procedures, as the target thickness was comparable to the Rayleigh length on the test bench (see figure 2b). Initially the target was aligned at the focus by monitoring the near field as described in the previous paragraph.

145 Subsequently, the axial location of the target was varied around this reference location. The location of the target was absolutely measured using a Fabry-Pérot interferometer based displacement sensor. Figure 5 shows the average brightness of the measured spot on the retro imaging camera as a function of target displacement. The result shows that optimizing the target location for

150 maximizing the average intensity measured in the retro imaging camera can be used for aligning the target at the focus of the EPM within the Rayleigh length (approximately $\pm 1 \mu\text{m}$ on the test bench). Such a retro imaging system is planned to be implemented on future campaigns involving thicker targets with EPMs. **It should be noted that on high power facilities, the pellicle**

155 **will have to be removed from the beam path before the full power shot in order to avoid the beam wavefront distortion due to nonlinear interaction of high intensity laser beam with the pellicle.**

Retro imaging setups on existing facilities[18] utilize the focusing OAP to collect light reflected from the target front surface. However, the retro imaging

160 setup described in this paper uses the EPM to collect the reflected light. The EPM in this configuration for collecting the reflected light acts like a high mag-

nification objective to create an image at the front focus which is then imaged on the retro imaging camera with a lens. The pellicle beamsplitter used in the alignment process introduces significant wavefront errors in the reflected light, but as is evident from figure 5 the alignment procedure is still robust.

4. Conclusion

This paper presents the design of EPM for PEARL laser facility and the retro-focus alignment procedure for aligning solid targets to the focus of the EPM. Measurement of the focal spots before and after the EPM on the PEARL facility yield an expected enhancement in intensity of ~ 8 during its operation. For a tightly focused beam at the output of the EPM, the Rayleigh length is extremely small ($\approx 2 \mu\text{m}$) and front surface of solid targets have to be aligned within this precision. Two different methods for aligning the target at the focus of the EPM were described. The retro imaging system which aligns the target by collecting the reflected light was shown to have a precision of alignment within the Rayleigh length.

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