ABSTRACT We developed for the first time, very compact (<1 cm^3) extremely low f-number (f/# = 0.4) confocal ellipsoid focusing systems. Direct measurement of the laser focal spot using a low-energy laser beam indicates 1/5 reduction of the spot size compared to standard focusing (using a f/2.7 optics). Such mirror is thus able to achieve significant enhancement of the focused laser intensity without modifying the laser system itself. The mirror is then used under plasma mirror regime which enables us to compactify the size, to liberate us from the anxiety of protecting the optics from target debris after shots, and to enhance the temporal contrast. In this paper, we focus our attention to designing and optimizing the geometry of such innovative plasma optics.

1. Introduction and motivation
With the rapid advances in laser technology, laser beams are now available that can be routinely focused to intensities approaching >10^{21} W/cm^2. There are already ongoing projects worldwide aiming to reach and even exceed the PetaWatt power level. A host of potential applications are proposed ranging from fast ignition of compressed inertial fusion targets, ion and electron acceleration, and diagnostics for high energy density plasma science. At very high intensity levels, such as \( I_{\text{Laser}} > 10^{22} \) W/cm^2, physical processes are presently poorly understood but a wide area of potential applications is proposed. There are several methods to bring the intensity of light to such levels, for example, by increasing the input energy or shortening the pulse duration. An alternative method is to obtain a tight focus which is more effective because the intensity is proportional to the square of the inverse of the focal spot size. Recently, 0.8 \( \mu m \) focal spot size was achieved using small f-number off axis parabola focusing optic (f/0.6) [1]. However, the distance between the target and the focusing optics decreases with decreasing the f/#, so care must be taken to protect the mirror surface from debris induced by the exploded target flow after laser irradiation. One way to alternate the concern of damage only the optics...
is to use plasma-based optics, there so called “plasma mirror (PM)” [2] were proposed and investigated in detail [3]. Such plasma-based mirror is single-use, thus concerns about debris will naturally eliminated. In addition, as plasmas are already ionized, the PM can be used under much higher laser energy fluence than solid optics where fluence is restricted by their damage threshold (~10^{11} \text{W/cm}^2), i.e. under at least 100-times higher fluence compare to the damage threshold of solid optics (typically 0.1-1 J/cm^2 for ~1ps laser pulse [4]). Thus, the optics size can be reduced by at least a factor of 10. Thus, the PM is more like laser experiment targets, rather than permanent mirrors. This change in thinking frees us from the anxiety of protecting the focusing optics from solid target debris after shots, thus enabling us to shorten dramatically the distance between the mirror surface and the target. In addition, a plasma mirror can enhance the temporal and spatial contrast ratio of the laser [5] [6] which improve the light pulse quality for many applications, such as the generation of high-order harmonics, directed electron beams, relativistic ions. Here, we developed for the first time, a plasma-based extremely small f-number focusing mirror to enhance the laser intensity through reduction of the spot size. In previous study, plasma mirrors are applied to only enhancement of temporal contrast of the laser (i.e., an improvement of the light pulse quality that is absolutely crucial for solid-interaction applications, such as the generation of high-order harmonics [6], ion acceleration [7], etc.). In this paper, we concentrate on the design of such extremely low f/# plasma-focusing mirror and demonstration of focal spot reduction by using low energy laser. Around 10-fold enhancement of the laser intensity was obtained under plasma-mirror condition in high-energy laser experiment.

2. Design of the mirror, experiment and discussion

2.1. Design of the ellipsoid focusing mirror

Our aim was to design a plasma-based extremely small low-f/# focusing mirror. We chose an ellipsoid (ellipsoid of revolution) for our focusing mirror, rather than parabolic or hyperboloid, because the ellipsoid was point-to-point imaging optics, and strict alignment accuracy was not required to create the image free from astigmatism. In addition, as there are two foci, the ellipsoid mirror can be simply placed after the focal point of the OAP, with one of the foci of the ellipsoid coinciding with the OAP focus. We optimized its shape for the purpose of enhancing the laser intensity through reduction of the focal spot size. The ellipsoid can be expressed as \( \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{b^2} = 1 \) (a>b). Here a and b represent the major- and minor-axis, respectively. As expressed in Fig.1(a), \( \rho \) represents the distance between the first focus of the ellipsoid (here, the focal point of the OAP) and the cross point between the chief ray and the ellipse, and \( r' \) is the distance between the cross point and the secondary focus (the other focus).

Fig.1 (a) Schematic drawing of an ellipsoid mirror to focus a laser to a tight spot. The incoming laser is focused by conventional parabola mirror on the focus point \( \alpha \). (b) Magnification from the first focus (\( \alpha \)) to the second focus point (\( \beta \)) as a function of the ratio b/a (minor-/major- axis). The right vertical axis indicates an estimated enhancement factor of the focused laser intensity through reduction of the focal spot. The calculation was done for various incident angle of the laser respect to the major axis of the ellipsoid.
The magnification from the first focus to the second one can be simply estimated as \( m' = \frac{1 + \varepsilon^2 - 2\varepsilon \cos \theta}{1 - \varepsilon^2} \) [8]. Here, \( \varepsilon \) is its eccentricity and \( \varepsilon = \sqrt{1 - \frac{b^2}{a^2}} \). The magnification is calculated based on this expression for various incident angle of the laser respect to the major axis of the ellipsoid (\( \theta \)) and is summarized in Fig. 1(b). The horizontal axis indicates the ratio between the minor- and the major-axis (b/a). The equivalent intensity enhancement factor is simply estimated as \( (\rho' / \rho)^{-2} \). We found that optimized geometry (thus, smaller magnification) varies with \( \theta \), and smaller magnification is expected for smaller incident angles. However, if the incident angle is too small, the incoming laser will hit the target (which is placed at the focus point after the ellipsoid) before reflecting from the ellipsoid surface. Finally, the incident angle is decided by taken into account the f-number of incoming beam (determined by the OAP). In our experiment, such f-number was 2.7 (10.5\(^o\) in collecting half angle), thus we chose 13 \(^o\) as the incident angle. Figure 1(b) suggests that the optimum ratio of the minor-axis to the major-axis at this angle is 0.6. The size of the mirror is determined by taking with account the laser energy fluence on the ellipsoid surface, as this ellipsoid mirror will be used under the PM condition. The working fluence for the PM is between 10 and 1000 J/cm\(^2\) [3] [9]. Finally, we decided our ellipsoid mirror geometry to be a=3.5 mm, b=2.0 mm. In this case, the estimated average fluence on the surface of the EPM is 100-300 J/cm\(^2\) (3-8\( \times \)10\(^{14}\) W/cm\(^2\)) for 3-11 J laser energy. The Resulting f-number after the EPM becomes 0.4. To our knowledge, such f/# is the smallest value even achieved for a high intensity laser system. Note that the ratio of the f/# (0.4/2.7~0.13) is not same as the magnification because the paraxial approximation is not valid for such low f/#. The expected magnification of spot size and corresponding intensity enhancement are 0.24 and 19, respectively. The material of the mirror was chosen to glass (K-PBK40).

2.2. Spot size measurement after reflecting from the ellipsoid mirror

To confirm our design and set-up, we directly measured the focal spot of the laser after reflecting from the ellipsoid mirror. This measurement was performed at the LULI 100TW laser facility. As shown in Fig. 2, to cover the large aperture after the ellipsoid mirror, we placed a infinity-corrected large aperture microscope objective (Edmond optics, \( \times 20, \) N.A.0.6) at around 1.3 cm after the focal spot of the ellipsoid mirror. The laser beam was then collimated and was re-focused on an ANDOR 16 bits CCD.
camera by an achromatic lens (400 mm focal length). The total magnification of the system was 40. To avoid a damage of the objective, the laser energy was reduced at the µJ level (10 Hz operation). In this case, the ellipsoid mirror was not turned into plasmas but act as conventional solid-mirror. After doing rough positioning using a mock-up alignment system outside the chamber, we did put the ellipsoid mirror in its position determined by to the focal spot position of the OAP. Final alignment was done using the 10 Hz laser (i.e. it in the same laser as the one used for high power shots, but without amplification), by monitoring the laser spot at the focal point after the ellipsoid mirror. The laser was frequency doubled (528 nm). After doing precise positioning of the elliptical mirror, we finally obtained a 0.9 µm full width at half maximum (FWHM) spot after the ellipsoid mirror. This is around 5-times smaller spot size compare to the one obtained at the focal point of the f/2.7 OAP (4.4 µm, Fig. 2 (a)). The obtained magnification of 0.2 shows that good agreement with the geometrically expected value, as indicated in Fig. 1(b). Analysis of the focal spot image (shown in Fig. 3) shows the encircled energy for the two configurations is very similar, i.e. 27 % at FWHM and 55 % at 1/e2. Then the reflectivity of the PM (30±10%) is measured by using a calibrated calorimeter. So we indeed expect the magnification is 5-10 [10].

3. Conclusion
We proposed an ellipsoidal focusing mirror which is able to focus ultra-intense laser pulses into much reduced size compare to conventional focusing. The geometry was optimised by taking into account the magnification as well as laser energy fluence on the ellipsoid mirror surface. We demonstrated 5-fold reduction of the focal spot size (down to 0.9 µm FWHM) by using this ellipsoid mirror compared to standard focusing (f/2.7 OAP). The measured magnification (~ 0.2) matches the geometrically expected value. This mirror has then been used under plasma-mirror condition (>50 J.cm⁻², 2-10 J). We clearly obtained a significant enhancement of laser intensity (by a factor of ~10) by using the ellipsoid plasma-mirror. As a result, the proton maximum energy produced by irradiating a thin (few µm) metal foil with laser pulses was remarkably enhanced by a factor of 3-9 with the ellipsoid plasma-mirror as well as laser intensity. The detailed of this experimental result is described in Ref [10]. We believe such compact, extremely low f/# plasma-optics can contribute to the offspring of the next-generation of high power lasers, opening the door to access high-energy density science and applications.

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