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IMPLEMENTATION OF REFRACTION CORRECTION FOR BEAM ALIGNMENT AT CETAL PW LASER SYSTEM

Mihai-Gabriel BĂRBUȚĂ[1]

Complex high-power laser installations which require multiple mirrors in high vacuum conditions also require multiple diagnostics points to ensure that the laser beam is properly aligned before starting experiments. In some cases, the diagnostics beam is acquired using transmitted (leaked) beam from the rear of the alignment mirrors, but the refractive index of these mirrors will induce a deviation of the diagnostics beam position, which itself varies according to the mirror relative inclination. Correcting this deviation needs to be implemented in automated and manual beam alignment systems, to avoid clipping and internal reflections which can be detrimental to laser system infrastructure.

Keywords: PW lasers, refractive displacement, refractive correction, beam diagnostics, alignment algorithms.

1. Introduction

For radiation mitigation reasons [1][2], the ultra-short, ultra-high intensity pulses of petawatt (PW) class laser systems require a level of containment which can result in a complex beam transportation layout using high-quality mirrors [3]. The NILPRP CETAL 1PW laser system, which was completed in 2014 in Romania, is one such system, where the laser beam propagation between the laser system and the underground bunker at CETAL's 1 PW laser is accomplished by a complex configuration of motorized mirrors – as seen in Figure 1 [4] – and ~25m of vacuum tubes called the Beam Transportation Line system (BTL).

Fig. 1. BTL mirror in kinematic frame (dielectric reflective coating not visible)

[1] PhD student, Faculty of Applied Sciences, University POLITEHNICA of Bucharest, Romania, email: mihail.barbuta@protonmail.ch

This system requires multiple diagnostics points to ensure beam alignment, one of which use the transmitted beam through the mirror substrate to extract beam centering information. In this case, the mirror substrate acts as a refractive medium, deviating the resulting beam with a significant amount which needs to be corrected by the alignment software.

2. Calculation of refractive deviation

To achieve the high precision laser alignment required by experiments, multiple beam diagnostics points are installed at strategic points of BTL. The first such diagnostics point is used to align the M1 mirror using the leaked laser beam at the rear of the M2 mirror in a near-field configuration [5]. Approximately 1% of the incident laser radiation is transmitted through this mirror, allowing the capture of the laser beam shape and position on a diffusing screen installed after the vacuum viewport (see Figure 2).

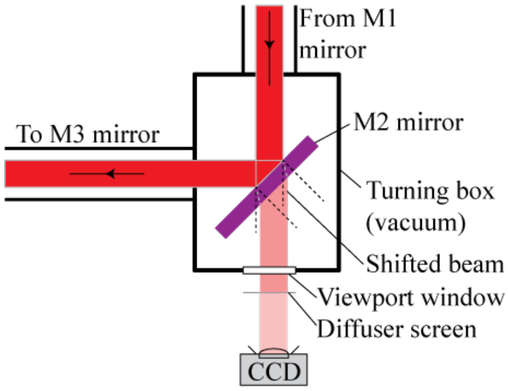

Fig. 2. Conceptual representation of laser diagnostics beam displacement

For calculating the refractive deviation, an optical study has been conducted at the CETAL petawatt laser system, taking several factors into consideration: laser parameters, beam transport system design, mirror constructive details and material parameters.

The front surface mirror substrate is manufactured using fused silica glass, having a refractive index of 1.4531 [5] at the central wavelength of 810 nm [6]. Since fused silica doesn't exhibit birefringence properties, the refractive index is independent of the laser beam polarization properties.

Figure 3 shows a schematic representation of the transmitted laser beam through a section of the mirror substrate, having a refractive index denoted by n_2 = 1.4531. The surrounding medium is high vacuum at a pressure of 10^{-6} mbar, so we can consider n_1 = 1. The laser beam wavefront reaches the substrate boundary at an angle θ_1 from the normal, changing the direction of wave propagation with an angle α within the mirror substrate. At the exit of the substrate, the wave propagation direction is again changed with the inverse of angle α, the resulting laser beam being parallel but displaced with distance t relative to the incident beam.

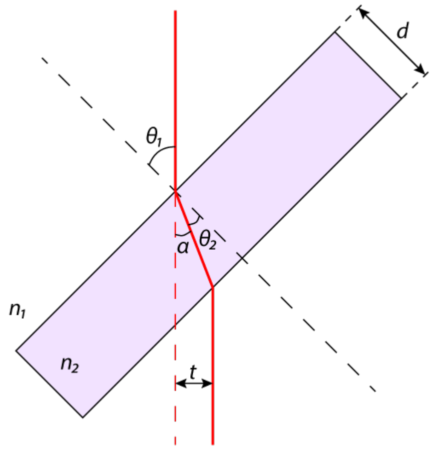

Fig. 3. Beam transmission deviation through mirror substrate

Calculating the beam deviation angle is done using Snell's law [7]:

$$\frac{n_1}{n_2} = \frac{sin\theta_2}{sin\theta_1} \Rightarrow sin\theta_2 = \frac{n_1 \cdot sin\theta_1}{n_2} = \frac{sin\theta_1}{1.4531} \quad (1)$$

The range of incident beam angle is determined by BTL's constructive details [4]:

- beam diameter at FWHM: 160 mm
- vacuum tube internal diameter: 250 mm
- mirror width on relevant axis: 310 mm
- mirror substrate thickness: 65 mm
- distance between M1 and M2 mirror centres: 3650 mm
- distance between M1 mirror and end of vacuum tube: 3270 mm
- nominal M2 mirror inclination relative to vertical: 45°

After simple trigonometric calculations, we deduce that the maximum laser beam deviation from mirror M1 (without clipping) is arctan[(250mm-160mm)/3270mm] = 1.58°. Additionally, the M2 mirror inclination range (without reflection clipping) – is between 0° and arccos(160mm/310mm) = 58.93°. The resulting full range at maximum beam tilt would be between 0 to 60.51°, which will be used to define the θ_1 variable in Formula (1).

The final beam deviation can be calculated using Formula (1) and applying trigonometric rules:

$$t = a \cdot sin\alpha = sin(\theta_1 - \theta_2) \cdot d \cdot tan\theta_2 = = d \cdot \left[\theta_1 - arcsin\left(\frac{sin\theta_1}{n_2}\right)\right] \cdot tan\left[arcsin\left(\frac{sin\theta_1}{n_2}\right)\right], \quad (2)$$

where a is the propagation length inside the mirror substrate medium.

Having an equation with a single variable, it is possible to plot the resulting beam deviation function of angle of incidence, which can be observed in Figure 4.

3. Experimental setup

Validating the results required a simple experimental setup of CETAL's Beam Transport Line: keeping M1 aligned and using the M2 motor encoders outputs, 5 near-field diagnostics captures were taken on November 2015, at 30°, 35°, 40°, 45° and 50° (higher angles were not advised by the operators).

For each inclination data point, the projected image of the transmitted laser beam through the M2 mirror substrate was recorded and the beam center coordinates were calculated. Using predefined markers, the deviation was then calculated and correlated with the mirror inclination values.

4. Results

The experimental results are shown in Figure 4 as well, to facilitate comparison with calculated deviation curve.

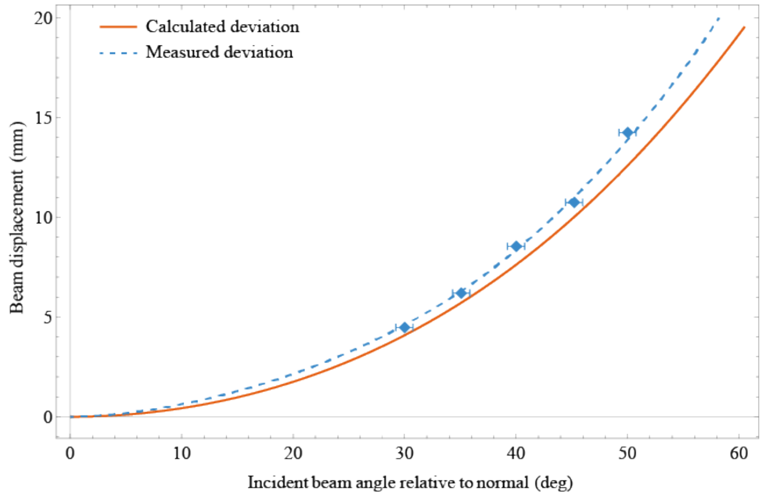

Fig. 4. Calculated and measured beam displacement variation function of mirror inclination

Angular error bars are due to cumulative backlash of Stögra SM 56.1.18 stepper motors [8]. The difference between calculated and experimental results can be attributed to material properties and wavelength shift. The experimental curve corresponds to a refractive index n_2 closer to 1.51, which would suggest that the mirror substrate could also contain borosilicate glass or a similar material [9].

The existing alignment algorithms for CETAL's beam transport system were updated to include mirror-angle-driven refraction correction based on the experimental data curve obtained above. The integration of the new correction component in the automated alignment software architecture is illustrated in Fig. 5.

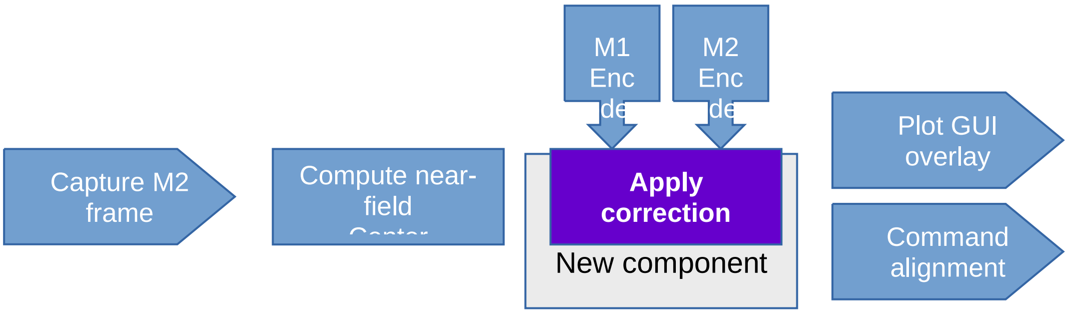

Fig. 5. Integration of beam deviation correction in the automated alignment software architecture

Encoded mirror inclination values are captured, and corresponding refractive deviation is automatically calculated by an additional algorithm written in Python programming language. The substrate refractive index is configurable, in the eventuality that a different type of mirror is installed in the BTL system.

The alignment software then calculates the correct beam center coordinates, which are plotted to the Graphical User Interface, as shown in Fig. 6. The same beam center coordinates will be used to command the M1 motor to properly align the beam.

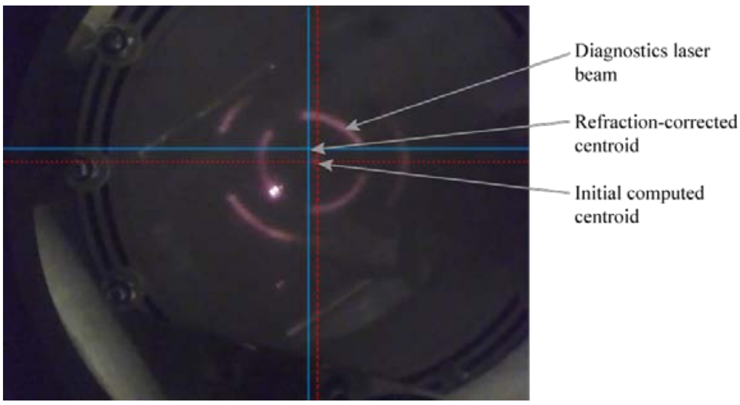

Fig. 6. Laser beam centering diagnostics with initial and corrected beam center representation

5. Conclusions

Implementing refraction correction for CETAL's Beam Transport Line system resulted in significant improvement in alignment and beam centering accuracy, correcting diagnostics beam shifts 12 mm at nominal mirror inclination of 45 degrees and up to 18 mm in extreme mirror tilt situations.

Scientific literature search has revealed no previous studies of refraction correction for laser beam diagnostics and alignment. This solution can be implemented in existing and future high-power laser systems to aid in achieving higher alignment precision and efficiency, and can be easily adapted to various material and laser parameters.

R E F E R E N C E S

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