Optimising and Improving the Flux Intensity in a Reflective type Laser Focusing system

Rufus Nathanael Patrick[1], Ashok Sharma[2]
1. PTDC, Larsen & Toubro, Powai, India
2. PTDC, Larsen & Toubro, Powai, India

Abstract

A Laser Focusing system (LFS) focuses a single laser beam (single Channel) or multiple laser beams (multi - channel) of continuous or pulsed beam of light onto a surface of a Specimen. This Beam of light is absorbed by the specimen and heats up its surface. In a Reflective type LFS, there is a small focal shift from the geometric focus point when the Laser Source feed is placed at an offset from the Optical Axis of the Mirrors[1]. Aim of this paper is to optimise and improve the Directivity of the Reflective based LFS by shifting the high - tapered feed axially away from the Reflector, so that the Specimen can be heated up expeditiously. This focal shift phenomenon was also verified with some theoretical calculations and the same was observed in a ray tracing simulation. A 3D model of the LFS was modelled, meshed and analysed using COMSOL. The Simulation yields a reduction in the size of the heat spot on the Specimen after implementing the algorithm. This Algorithm is yet to be implemented and validated in Realtime.

Introduction

A Reflective type LFS generally consists of a Laser source, folding Mirrors to bend the beam (Beam-Steering) and a pair of Primary and Secondary Parabolic Mirrors that aids in focusing the laser beam depending on the center distance between them[2]. Since the Secondary Mirror is in the path of the focusing beam, the laser source is placed with an offset from the optical axis of the Primary and Secondary mirrors such that the focusing beam crosses the secondary mirror. The Secondary mirror (Convex mirror) is mounted onto the linear stage which changes the center distance between the mirrors based on the theoretical formula given in the next section. The size of the hot spot and the energy density (Intensity Flux) deposited on the surface determines how quickly the Specimen will heat up. The Specimen starts heating up when a part of the Intensity flux is absorbed on its surface [3]. There are many external parameters that affect the size of the hot spot and the Laser Power received on the Surface. Some external parameters like accuracy of the linear stage that varies the center distance between the Primary and Secondary mirrors, Optical Alignment errors, wind velocity, particles present in the atmosphere (aerosols, molecules, moisture and dust) greatly affects both the hot spot size and the intensity of laser light reaching the Specimen[4]. Hence, a good focusing Algorithm helps in further reducing the spot size and thereby aids in heating a surface immediately.

Finite element method (FEM) can be used to compute the path length and direction of rays by ray tracing simulation in COMSOL. Further, the size and Intensity of the hot spot can be derived using the Poincaire Plot. The aim of this simulation is to verify that the Algorithm can indeed reduce the size of the hot spot by varying the center distance between the mirrors. The size reduction of the hotspot inturn increases the Intensity flux of the laser beam. The simulation was verified in Comsol for a wide range of Target distances and only one data set (distance to Specimen – 3000m) is published in this paper. Ray Tracing Simulation results was also validated mathematically in the 3rd section. A Thermal Analysis was conducted to compare the rise in Temperature of the Specimen when the laser beam was shot with and without the Algorithm for 10 Seconds.

FE Modelling

The Complete laser Focusing system was modelled and meshed in COMSOL MultiPhysics. The Rear surfaces of the mirrors were meshed with a very fine free quad mesh of size 0.2 mm and this Surface boundary mesh was swept over their respective mirror domains. If the size of the mesh element are too large, it would induce a lot of ray deviations as they act as reflecting surfaces for the incoming ray[5].

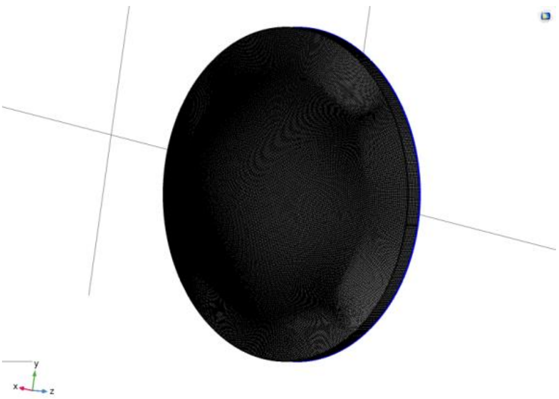

Figure 1. Mesh on the Secondary Mirror

Following assumptions and parameters were considered for the FE Simulation.

a) The substrate material of the mirror and their respective coatings are considered to be completely homogeneous, isotropic and defect free.

b) Effect of External parameters like Atmospheric Attenuation, Wind velocity is neglible.

c) Effect of moisture present in the focusing system's enclosure is neglible.

d) System is Damped so that there in no vibration that causes Jittering effect of the laser beam.

e) Laser Offset from the Optical Axis is about 16mm.

f) A Single Laser source with a Beam Diameter 10mm with a Power of 100W.

g) Curvature of the Primary and Secondary Mirrors are 220mm and 60mm respectively.

h) Distance to the Specimen from the Focusing setup is 3 kms.

i) Number of Radial and Angular rays are 70 and 180 respectively.

The Material and Coating properties used in this simulation is given in 'Table1'.

Table 1. Material Properties used in Modelling of the Laser Focusing System.

Components	Material	Properties	Value
Mirror Substrate	Aluminium T6061	Thermal Conductivity	180 W/mK
		Specific Heat Capacity	897 J/KgK
		Density	2710 kg/m^3
HR Coating on Mirror	Protected Gold	Reflectivity	> 99.8% @ 1064nm
		LIDT	1 MW/cm^2
Optical Window	UVFS	Thermal Conductivity	1.38 W/mK
		Specific Heat Capacity	770 J/KgK
		Density	2201 kg/m^3
AR Coating on Window	YAG_BBAR	Reflectivity	< 0.25% @ 1064nm
		LIDT	15 J/cm^2,20ns,20Hz
Laser Source	Nd:YAG	Wavelength	1064 nm
		Power	100 W
Specimen	HS Steel Alloy	Thermal Conductivity	44.5 W/mK
		Specific Heat Capacity	475 J/KgK
		Density	7850 kg/m^3

Ray Tracing Analysis

In this Analysis, we will numerically calculate the center distance between the mirrors so as to achieve the desired geometrical focal point of the Laser Focusing system and the same was verified in Comsol. The Ray Tracing is done by using only the Paraxial Ray Tracing [6] as shown in 'Figure 2'.

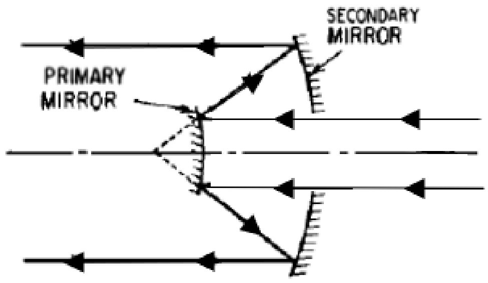

Figure 2. Ray Tracing of Paraxial rays

The Center distance between the Primary and Secondary Mirror is given by the formula,

$$\frac{1}{fp} = \frac{1}{R} + \frac{1}{d+fs}$$

Where,
f_p - Focal Length of the Primary Mirror
R - Distance between the Specimen and the Focal point of the Primary Mirror.
d - Center Distance between the Primary and Secondary Mirror
f_s - Focal Length of the Secondary Mirror

A plot of ‘d’ vs focus point is shown in ‘Figure 3’. From this plot we can conclude that the parameter ‘d’ plays a very vital role in focusing a beam of light.

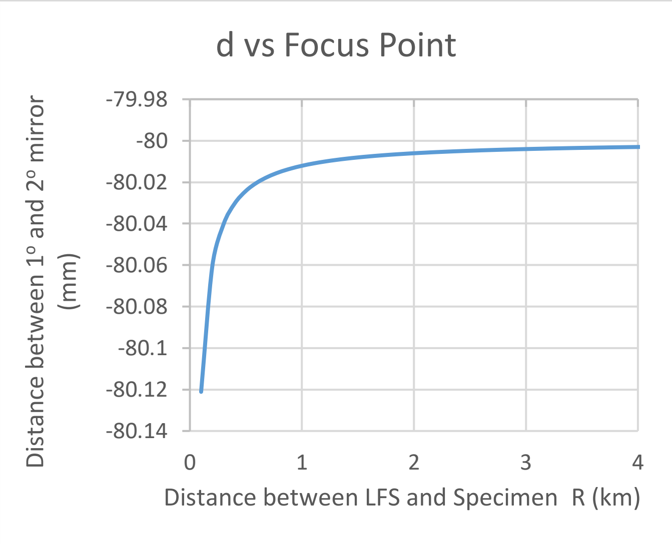

Figure 3. Relationship between ‘d’ and Focus Point

The formulae used for ray tracing and designing lens is also applicable for mirrors. The only difference is in the Sign Conventions and parameters used for mirrors. Here, Instead of thickness ‘t’, it is replaced by the center distance ‘d’ and the signs for refractive index changes sign when the ray is reflected as it travels in the opposite direction after reflection[6]. The Sign Conventions for lens is shown below in ‘Figure 4’.

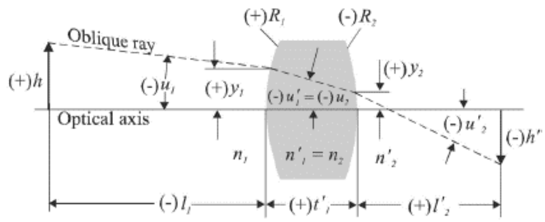

Figure 4. Sign Conventions for Ray Tracing

Where,
h, - Height of Object
h^1 - Height of Image
u_1 - Slope of Incoming ray
y_1 - Height of ray on the first surface
u_1^1, u_2 - Slope of refracted ray due to the first surface
y_2 - Height of ray on the Second surface
u_2^1 - Slope of refracted ray due to the Second surface
n_1, n_2^1 - Refractive index of air
n_2, n_1^1 - Refractive index of Lens
l_1 - Distance between first Surface of lens and Object
t - Center Thickness of Lens
l_2^1 - Distance between Second Surface of lens and Object or Back Focal Length
R_1 - Radius of the Curvature of the first Surface
R_2 - Radius of the Curvature of the Second Surface.

The General Formula to calculate the slope u_i^1 and the height of the ray on the surface of the Lens is given below.

$$n_i^1 u_i^1 = n_i u_i - (y_i(n_i^1 - n_i))/R_i$$
$$y_{i+1} = y_i + t u_i^1$$

The thickness ‘t’ is replaced by the distance between the Primary and Secondary mirrors. Since the rays doesn’t pass through any media, the refractive index is taken as the refractive index of air which is ‘1’.

a) Geometical focal point at infinity

To obtain a geometrical focal point at ∞, we need to set the center distance to a value after substitution R = ∞ which indicates that the Target is at ∞.

$$\frac{1}{-30} = \frac{1}{\infty} + \frac{1}{d-110}$$

$$d = 80 \text{ mm}$$

The parameters considered for numerical ray tracing calculation is listed below.

$u_1 = 0$, $y_1 = 5$mm (Beam Radius), $R_1 = -60$mm, $R_2 = -220$mm, d = 80mm, $n_{lens} = -1$

On Solving we obtain,

$u_1^1 = 0.1667$ (Expanding Beam)
$y_2 = 18.333$ mm
$u_2^1 = 0$
$l_2^1 = \infty$

This indicates that the Output beam is going parallel to the optical Axis. This proves that when Center distance between the Primary and secondary mirror is 80mm, The Laser beam going out of the Laser Focusing system is parallel to the Optical Axis.

The same setup was modelled in comsol and the path of the Marginal and Central rays along the X-Y plane is plotted in 'Figure 5'. The Blue and green lines represents the Marginal rays and the Red line presents the Central Ray.

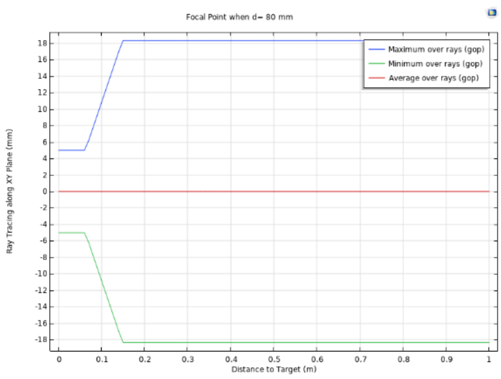

Figure 5. Ray Tracing about the X-Y plane with d = 80 mm

b) Geometical focal point at 3kms

To obtain a geometrical focal point at 3000 m, we need to set a center distance to a value after substitution R = 3000000 mm which indicates that the Target is at 3kms.

The parameters considered for numerical ray tracing calculation is listed below.

$u_1 = 0$, $y_1 = 5$mm (Beam Radius), $R_1 = -60$mm, $R_2 = -220$mm, d = 80.00403 mm, $n_{lens} = -1$

On Solving we obtain,

$u_1^1 = 0.1667$ (Expanding Beam)
$y_2 = 18.334$ mm
$u_2^1 = 6.11134e^{-6}$ (Converging Beam)
$l_2^1 = 3000000$ mm

The same setup was modelled in comsol and the path of the Marginal and Central rays along the X-Y plane is plotted below.

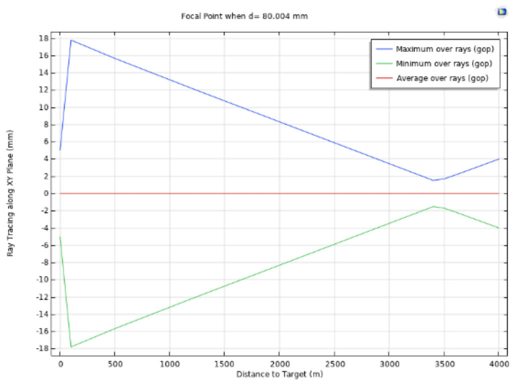

Figure 6. Ray Tracing about the X-Y plane when d = 80.004 mm without the Algorithm

In 'Figure 6' we notice that the actual focal point is greater than the geometrical focal point (Positive Focal Shift) . This difference is because of the focal shift phenomenon as stated by Hao Ling, Shung-Wu Lee, P. Lam and W. Rusch[1]. An Algorithm was developed and implemented to reduce the effect of the focal shift. The focal point after implementing the Algorithm is shown in 'Figure 7'.

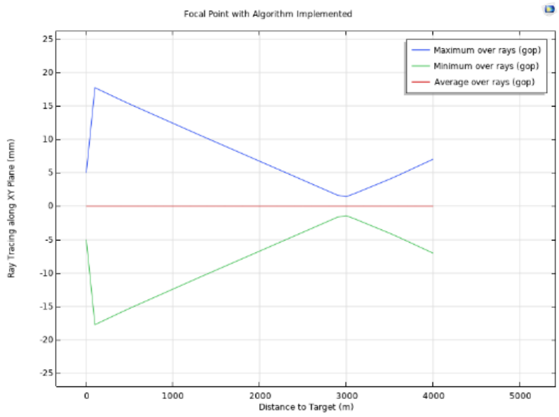

Figure 7. Ray Tracing about the X-Y plane with the Algorithm

Results and Discussion

The Finite element model of the Laser Focusing system was sucessfully solved. 'Figure 8a' and 'Figure 8b' are Poincaire Plots that shows the size of of the hot spots at 3000 m with and without the algorithm respectively. The Coma shape of the hot spot has drastically increased the intensity and has reduced the size of the heat spot.

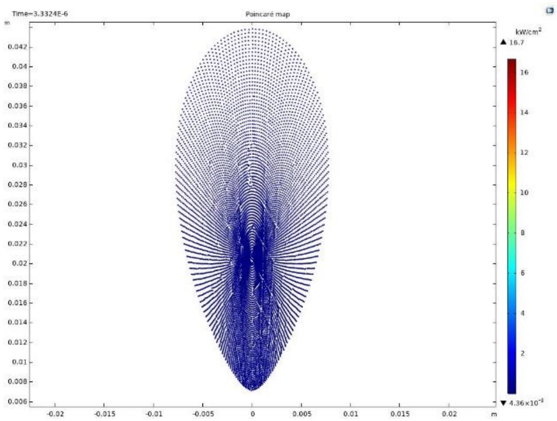

Figure 8a) Poincaire Plot Without Algorithm

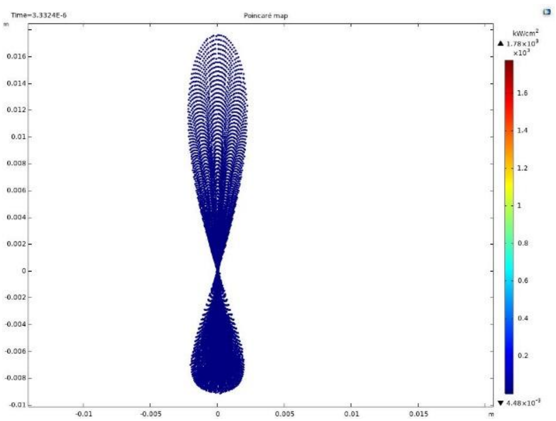

Figure 8b) Poincaire Plot With Algorithm.

Table 2. Spot Analysis with and without the Algorithm

Parameters	Without Algorithm	With Algorithm	Unit	Δ Change
Max Width	15.5	4.4	mm	↓ 71.6%
Max Height	36.8	26.85	mm	↓ 9.9%
Max Flux	16.7	1.78e^{+3}	kW/cm^2	↑ 106.6x

If we observe the two figures, we notice that the size of the hot spot without the algorithm is bigger in size while the size of the hot spot with the algorithm is much smaller. Therefore, we can conclude that the intensity flux will greatly improve with the implementation of the Algorithm. We can observe this increase in Intensity Flux in 'Figure 9a' and 'Figure 9b' which shows a 3D representation of flux Intensity with and without Algorithm on the Specimen.

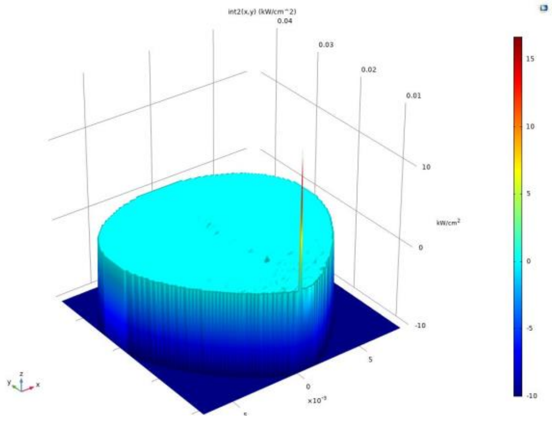

Figure 9a) 3D Representation of Intensity Plot without Algorithm

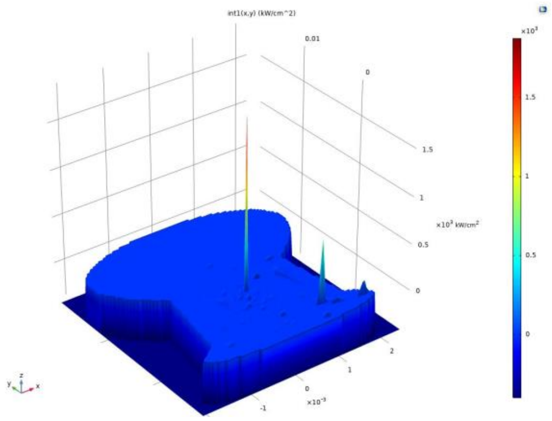

Figure 9b) 3D Representation of Intensity Plot with Algorithm

Due this huge rise in Intensity flux, more energy is absorbed by the Specimen which increases its Surface Temperature. A Cylindrical plate of ø100mm with a thickness of 2mm was used as our Specimen. A Thermal Analysis was conducted for 10 seconds with these Intensity Fluxes (which were extracted 3 kms from the Laser Focusing System) as an input. Since the Intensity flux were extracted at the Specimen's distance, the Flux data is directly imposed onto the Specimens's Surface Boundary as a Boundary Heat Source. The Thermal Plots with and without the Algorithm is shown in 'Figure 10'.

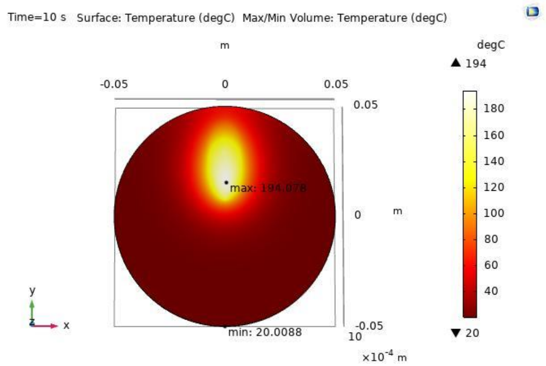

Figure 10a) Hot Spot on the Specimen without Algorithm

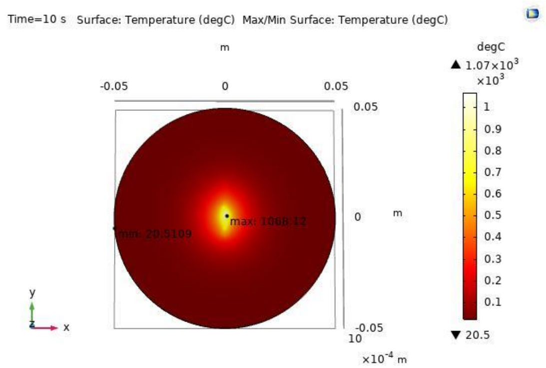

Figure 10b) Hot Spot on the Specimen with Algorithm

It is clear from Figure 10 that temperature rise with the Agorithm is much greater as the Intensity flux has increased by 106 times. Also, the Heat Spot has now come down towards the Optical Axis of the Focusing System. The rise in Temperature is plotted in 'Figure 11'.

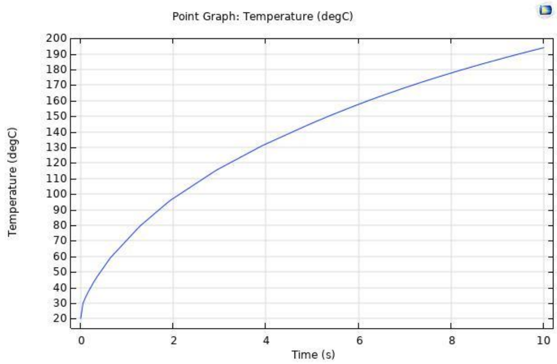

Figure 11a) Temperature Plot of the Hot Spot without Algorithm

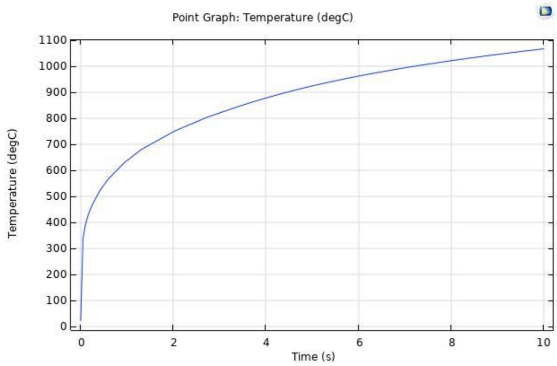

Figure 11b) Temperature Plot of the Hot Spot with Algorithm.

From the plot above we can finally confirm that the Algorithm does improve the Hot Spot on the Specimen. The Temperature of the Specimen after 10 seconds without the algorithm reached to a maximum of 194°C while the Temperature of the Specimen reached to about 1070°C with the algorithm.

Conclusion

In our present work, the Finite Element Modelling and Analysis of the Reflectived Based Laser Focusing system was attempted. A successfully converged solution was obtained and it is proved that the Algorithm does improve the performance of the Reflective Based Laser Focusing system. An experiment needs to be conducted to validate the effectiveness of the developed Algorithm.

References

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