The design and characterization of an improved target positioning system

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Introduction

In the Gemini Laser, thin foils are used as a target for High Power Laser interactions. These interactions require the highest possible intensity to liberate and accelerate the electrons in the target. The Rayleigh range is the distance over which the target is in the intense focus, and is defined as $z_R=\pi w_0^2/\lambda$, where w_0 is the beam waist and λ is the wavelength used. In the case of using the F/2 parabola z_R is ~10μm, demonstrating how vital precise target positioning is because if the target is out of place by just a few microns, the intensity can be halved. The positioning and orientation of the target in space is therefore of vital importance because of the short Rayleigh range of the F/2 parabola.

The standard technique used for placing solid targets at focus on Astra Gemini is to use rear surface illumination [1]. The focus of the F/2 parabola is imaged with a high magnification (50x) Mitutoyo microscope objective [2] with a long working distance (13mm). The target is then driven into place and brought to the same plane by sharply imaging features visible on the rear surface illuminated by an 800nm wavelength LED. For thin targets (<1 μm), the front surface will also be within the Rayleigh range, and for thicker targets an offset can be applied providing the target thickness is known.

An addition to this system is to add a fibre laser that focusses through the objective lens onto the rear surface [3]. This can then be used to determine the orientation of the target by observing angle changes in the reflected near field on a second camera. A further aim is to reduce the reliance on high-cost items in the focal spot imaging system since both the microscope objective and the camera can be damaged by accidental exposure to a high power beam. In this report we characterize the performance of this system using inexpensive optics and cameras.

Design of the Firefly Imaging System

The optical layout, shown in Fig. 1, comprises a one lens imaging system with an object plane set as the location of the main laser focus. Instead of a microscope objective the lens is a low-cost 1” diameter aspheric and our standard cameras have been replaced with lower cost Firefly models [4] and so we refer to this system as the Firefly Imaging System.

The two different CCDs have two purposes. The Far Field CCD is placed at the correct distance to image the plane at which the *f*/2 focus would be located and gives information about how close the foil is to the focus of the Astra beam. When the foil is positioned in the same plane we obtain a sharp image of its rear surface whereas these features are poorly imaged if the foil is not in the correct plane.

The Near Field CCD is used in conjunction with the fibre coupled laser to measure the orientation of the target. When the target is tilted with respect to the lens, the laser is reflected at an angle. This manifests itself as a shift in the location of the laser on the Near Field CCD.

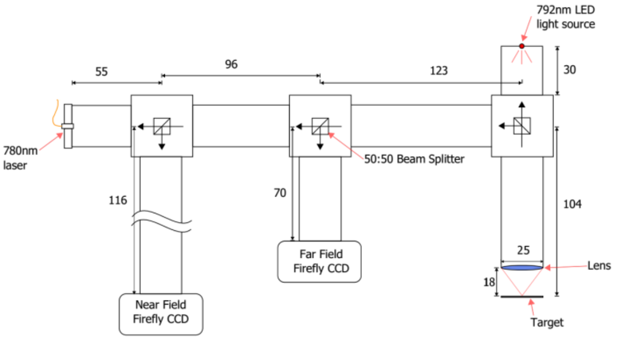

Figure 1. A schematic of the Firefly system. All beam splitters are 50:50. The LED on the top right emits at 792±30nm and is used to illuminate the target. The laser, attached using an SMA fibre optic cable, is capable of giving information about the pointing of the target. All distances are in mm.

To test the system a foil target was illuminated by a LED with a measured wavelength of 792±15nm and imaged onto one of the Far Field CCD chips. The LED emits isotropically, and uniformly illuminates the foil. The magnification of the system was calculated to be -15.5±0.4, resulting in features on the micron scale being easily imaged. The fibre laser emits at 780^{+15}_{-5}nm and so the lens has the same focal length for both the LED and the laser.

Characterization of system resolution

The system must perform at least as well as the Mitutoyo microscope objective that is currently used in the Astra Gemini Target Area. This is quantified as the resolution of the target. The method used to determine how well each system performs is known as the Modulation Transfer Function (MTF). This makes use of the fact that line pairs of black and white are always blurred to some extent by the imaging system. At higher spatial resolutions of the line pairs, the blurring is more extreme until there is nothing to distinguish between light and dark: the image is uniformly grey. The MTF is defined as

$$\mathrm{MTF} = \frac{\mathrm{I_{max}} - \mathrm{I_{min}}}{\mathrm{I_{max}} + \mathrm{I_{min}}}$$

where $\mathrm{I_{max}}$ is the intensity of the white peaks above the background, and $\mathrm{I_{min}}$ is the intensity of the dark valleys. Even a perfect system will have a maximum spatial frequency that it is possible to resolve due to diffraction effects. At low spatial frequencies the MTF will be close to one, with the image oscillating between 0 and 1. The MTF will fall as spatial frequency increases until the image is a uniform grey, and the value on the CCD is 127 on an 8-bit chip. The line frequency at which this happens is known as the limit of resolution for the system. By performing this characterization, the resolving power of the two systems can be compared.

Results

The results of the MTF for both the Firefly System and the Mitutoyo objective can be found in Fig. 2.

Both systems perform similarly in the high spatial frequency range. This shows that the high-cost Mitutoyo objective can be replaced by the cheaper single aspheric lens used in the Firefly System. This allows us to carry a stock of such lenses for quick replacement in the event of the system being damaged, for example if the imaging system is accidentally left in the beam path during a full power shot.

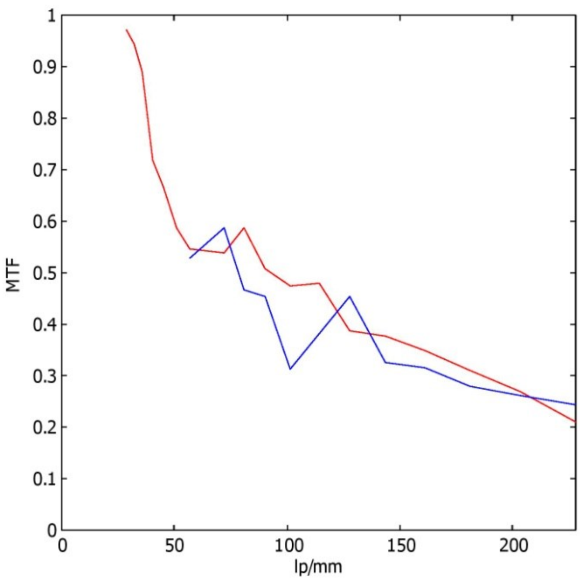

Figure 2. The Modulation Transfer Function for the Firefly System (red) and the Mitutoyo System (blue). Both systems perform similarly in the region of 80-230 lp/mm.

Use of the fibre coupled laser

Measuring the near field of the beam reflected from the rear surface indicates the angle of the target. This is important because thin targets are often rippled on a microscopic scale and so even though the target mounting array is normalized to the main beam, the irradiated portion of the foil may not be.

Characterization of the orientation system is performed by altering the angle of the target, and measuring how the image on the Near Field CCD is affected by this change. A simple relation of arc minutes of tilt to microns of shift can be calculated with trigonometric identities. For a tilt of 1', a shift of roughly 5.2 microns is expected.

In the current system we found that the target translated as well as rotated because the axis of rotation is not through the portion of the target that the laser is focused on. As shown in Figure 3, this causes the laser to become defocused in this process. Both translation and rotation will alter the position of the laser on the Near Field CCD. The combination of these effects will result in an unreliable measurement of the true tilt of the target. The unwanted translation effect could be calculated by trigonometric analysis and manually subtracted with the drive system. Another possible solution is to manufacture a new mount system which rotates about the focus of the lens.

If the fibre laser is focused onto the rear of the target, then it can be used as an additional check on the position of the target relative to the focal plane because the image of its focus will form on the Far Field camera. However, the fibre laser divergence needs to be adjustable in order to focus at the correct distance from the lens. In the current test, the laser was collimated and therefore the focus was offset from the target focus plane.

This could be overcome in the future by placing another lens in the system, ensuring the Far Field CCD images a point for the laser. If the lens were placed so that the focus was 279mm from the lens, the 'source' for the laser would be in the same plane as the CCD, as referenced from the lens.

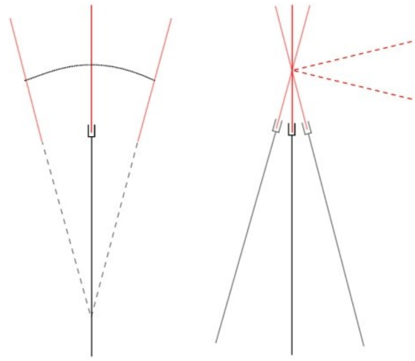

Figure 3. A schematic illustrating how the target (in red) translates in z if the axis of rotation is not through the focus of the lens. If the axis of rotation is through the centre of the target, as on the right, the target does not translate in z. The target is viewed side-on.

Conclusions

The Firefly System, which is much cheaper than the current Mitutoyo System, has similar performance when imaging the target. With some future work, it will be possible to accurately measure the orientation of the target with respect to rotation in space with little human input. This will speed up the placement of targets within the chamber, and enable it to take place completely under vacuum. It will be a simple task to place the target at focus and normal to the laser from the Control Room with minimal effort required from the experimenters. With further work and in-depth analysis of the system, the author believes that this system can become completely automated, and eventually enable the replacement of targets to be fast enough to become usable on the proposed higher repetition rate of the Astra Gemini Laser.

References

1. D. C. Carroll et al., *An imaging system for accurate target positioning for fast focusing geometries*, CLF Annual Report, 2011-2012
2. http://www.mitutoyo.co.uk/optical-measuring/objectives
3. N. Booth et al., *Target Alignment in Astra-Gemini*, CLF Annual Report, 2012-2013.
4. http://www.ptgrey.com/products/fireflymv/fireflymv.pdf