Experimental Testing of Targets for a High Accuracy Microtarget Supply (HAMS) System on the Gemini Laser System

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Abstract. It is widely understood within the high-power laser community that recent developments in diode pumped and high repetition rate laser systems will give unprecedented access to laser shots. This will provide a challenge for target fabrication in making enough experimental samples. While in the past access to facilities and shot rates during access periods have been the limiting factor for high power laser experiments this will soon not be the case. There has already been a shift in development of the user base from fundamental science experiments to industrial applications using the laser experiment as a reliable source for secondary aims. The Astra Gemini laser system has been operating at a high repetition rate for high intensity (0.5PW) experiments for a number of years and the Central Laser Facility has developed a target methodology to deliver to the user community the maximum number of solid targets and to fully utilise the available time on the laser. Targets for the High Accuracy Microtarget Supply (HAMS) system have been tested and have been proven to survive in a manner to allow shot rates comparable with the available laser repetition rate (0.1Hz). Investigations into target geometry have been carried out and debris production has been studied by high frame rate camera imaging. The study of the relationship between target geometry and debris production has allowed the design of optimal target support infrastructure, such as aperture size and structure, for high rep rate experiments on the Gemini system.

1. Introduction
The Target Fabrication Group at the Rutherford Appleton Laboratory has been delivering targets to the user programme in the UK for over 40 years. During this time there have been a wide range of targets delivered from simple thin foils through to complex multi-element, multi-material assemblies. However, one constant within this area has been the relatively low repetition rate of the laser which has limited the number of targets that have been needed for each experiment. It has been the case that for a standard experiment on the Vulcan laser system approximately 100-200 targets are needed. These can be varied from simple commercially available foils which are cut to size, through to complex 3D geometries such as AFI cones [1], shock experiments with backlighter targets [2] and gas cell targets as recently delivered on the Orion laser system at AWE [3]. The commissioning of the Gemini laser system [4] was a step
change for target delivery at RAL with experiments requiring thousands of targets for each campaign. During the lifetime of the Astra Gemini system there has been an evolution to applications-based experiments on the facility. Some experiments are gas-jet based and are focussed on imaging of samples using x-ray and betatron beams and other experiments are focused on ion acceleration [5] and use solid targets in the range of 5 nm to a few μm. These require a mounting support and also a method of insertion into the laser focus and a refresh rate that is comparable to the laser. Initial experiments allowed for the targets to be made and mounted onto a standard target wheel with windmill target mounts. This type of target can be easily delivered and can provide thousands of targets per experiment [6], but are best suited for foils that are relatively simple to produce and that are thick enough to survive the shock and debris from a laser interaction. The drawback of such a system is that it is inherently low accuracy and for a laser system such as Astra Gemini that has a Rayleigh range of a few μm the target has to be realigned every shot using a focal spot camera that has to be driven into position. This slows the shot rate dramatically and reduces the utilisation of the laser facility whilst also putting a large assembly burden on the Target Fabrication resource that is available. This is clearly not useful for both science and applications-based experimental runs and also applications-based facilities may require large volumes of high specification targets that conventional techniques are not equipped to deal with.

The latest fabrication techniques have been utilised and are being integrated with the HAMS system that is being developed at RAL [7]. The debris that is generated from a high power (0.5PW) interaction with a thin foil target has been studied as well as the shock damage and debris mitigation techniques to deliver a robust and integrated solution to the delivery of high power laser experiments on ultra-thin solid targets for an F/2 focusing laser system.

2. The HAMS Concept for Targetry
The system aiming to fully utilise the high repetition rate of modern laser facilities which is being developed at the Central Laser Facility has been designed as a fully integrated target solution. It encompasses all elements from target manufacture through to the mounting of the target onto the delivery system. Accuracy of the delivery system is a key aspect as well as the integration of an on-line characterisation system for foil position, negating the need for a focal spot camera and reducing the turnaround time between shots. The baseline design for the system was to be able to run at one shot per minute which is an order of magnitude increase above the current standard for the Gemini system (on complex solid targets). There are five integrated areas of the HAMS system and these are; 1) the mechatronic stages, 2) the target interface, 3) the targets and their manufacture, 4) the interferometric position characterisation system and 5) the software integration of the whole system. The individual physical elements (minus software) are shown in Figure 1.

![Figure 1. The 4 physical integrated parts of the HAMS system, which will allow for automated target alignment after integration of feedback programming](image)

2.1. Mechatronic Stages
The HAMS stages consist of an X, Z linear translation stage with a tripod attached to the top to allow the stages to reach a working envelope of +/- 47.9mm in X and Y, 0-24mm in Z with an approximate +/- 10° tip tilt movement. A rotation mount on the top of the stages allows the target to be positioned...
normal to the beam or at an angle up to 45 degrees. Due to the F/2 parabola on the Astra Gemini laser the positioning of a target was agreed to be within an accuracy of +/- 4 μm in the direction of the laser (Z), this was to ensure it is within the laser focus to obtain the maximum intensity. A positional accuracy of +/- 10μm in X and Y was agreed to be enough for most targets. On top of all the translational stages a 360 degree rotary stage is required to rotate the wheel and deliver a new target to the focal position.

2.2 Interface Wheel
It is essential to be able to couple the targets to the mechatronic stages to a high accuracy to be able to fully utilise the high precision stage and targets. It is also essential that the interface is stable under experimental conditions. A wheel was machined in a ceramic that has good thermal stability and characterised to have flatness over the mounting positions of the target to better than 2 μm. This is within the tolerance that is acceptable for the wheel as long as other sources of error do not accumulate.

2.3 Target Sections
The HAMS system uses MEMS-based targets that are produced to the exact geometry for the interface wheel. It has been reported that targets can be made using MEMS techniques [8, 9, 10] and these techniques have been known for a number of years. This base technique is a key capability for the delivery of targets to high rep rate systems. It allows batch manufacture and allows standard processes and geometries to be used repeatedly at a relatively low cost per target. The targets can be designed to allow a number of different geometries that will be discussed. Target materials can be deposited onto the wafers before the fabrication process and different sections can be added to the wheel to allow thickness, geometry and material scans during a single pump cycle. Up to 8 target sections can be mounted on an interface wheel and flatness across the section and between the sections can be measured. Detailed characterisation of one section shows that it is flat to less than 0.5 μm and 2 sections mounted opposite each other on the interface wheel are flat to within 2 μm [11].

2.4 Target Alignment
The Gemini target area currently employs alignment systems that use retro or focal spot cameras. These limit the shot rate due to the fact that imaging the rear surface is very difficult on a thinner target as it becomes more transparent and a manual process for this can take a number of minutes. The CLF is developing a multi-wavelength interferometer system [7] which uses a focussed beam onto the target to allow the positioning of targets with a higher accuracy in Z. The system was not tested in this initial debris and survival test experiment and is not within the scope of this paper but will be fielded on further tests in the future. Work is being undertaken to implement a feedback loop which will eventually be able to automate the alignment of the targets.

3. Experimental Testing

3.1 Debris and Shock Damage Experiment Setup
The first experiment carried out in January 2016 was mainly focused on the understanding of the damage mechanisms for targets with the aim of benchmarking a design for future experimental campaigns and enabling the maximum utilisation of targets. The targets were shot using the F2 parabola at energies in the range of 11-15J which is typical for a Gemini experiment. The spot size was smaller than 10 μm which gives a minimum intensity on target of 3x10^{20} W/cm². Plasma mirrors were used [12] to give good contrast and the parabola had a pellicle to protect from damage. The main diagnostic for the damage experiment was optical imaging of the targets before and after the laser shot and the debris was investigated using a Photron FASTCAM SA-Z [13] which was used to image the interaction. The interaction was backlit with a continuous laser with wavelength 532nm and imaged for time-resolved shadowgraphy of the target dynamics. Typical frame rates for debris measurements were 100k to 210k frames per second (fps) dependent on the field of view to be imaged. A simplified chamber layout is shown in figure 2.
Figure 2. A simplified layout of the experiment for debris shots showing the F2 beam and the optical probe across the target.

A range of target geometries were tested to determine if shape, size and spacing of the targets was crucial. These are described below.

Table 1. The range of target geometries that were tested for the damage and debris studies.

| Target Number | Aperture Geometry | Aperture Size         |
|---------------|-------------------|-----------------------|
| 1             | Circular          | 750um, 500um, 1000um, 2000um |
| 2             | Square            | 750um, 500um, 1000um, 2000um |
| 3             | HAMS sector       | 300um                 |
| 4             | Silicon ‘Wheel’   | 2000um                |

In this experiment the first targets tested were array targets—not HAMS sectors—which contained circular and square targets with hole sizes of 500 µm, 750 µm, 1000 µm and 2000 µm with the spacing of the targets center to center being constant across a 25mm x 25mm, 325 µm thick silicon chip. The target material for these chips was 100 nm Silicon Nitride (SiN). The square targets were produced using wet etching techniques and the round targets were produced using Deep Reactive Ion Etching techniques. These targets were modified to have various protection layers on the front and the rear as the experiment progressed, either using thick metal supports to isolate the individual targets or thin glue layers in between the targets. In addition to this the final design for the HAMS sectors—the target that fits on the interface wheel—was tested. The HAMS targets have smaller apertures (300 µm) and are closer together than the aforementioned targets but are the same material (100nm SiN) and the sector is the same thickness (325 µm). The final target tested was a full 100mm silicon wafer with windows around the outside to replicate a full wheel. This target was 1 µm Parylene, poly(p-xylyene), suspended across a larger window. These targets are listed in Table 1 and are shown in Figures 3 to 5 where all chip sizes are 25 x 25mm.

Figure 3. Pre-shot target arrays with different aperture sizes – some targets popped in manufacture. These were mounted to a standard target wheel with 8 array positions. Both circular and square versions of target foils in this geometry were manufactured.
3.2 Damage Results – Protection Study

Targets were photographed before and after shots with the laser to catalogue damage from the shot, due to the large amount of images these are all shown in appendix A. In most cases multiple shots were taken on the target arrays if there were surviving targets to determine the maximum number of shots possible before the array was spent.

The first targets tested were square array targets with 750 μm square holes in a 5x5 array that were protected only on the laser side with a large aluminium support. The support was 1mm thick with 1mm diameter tapered holes aligned to the targets to allow the laser beam in the aperture without clipping the mount. Before the shots there was a full complement of targets available in the array and 4 shots were taken in the corner positions. After the 4 shots there were only 5 surviving target positions (shown Appendix A-1), corresponding to a damaged target percentage of 76%.

The second run of tests, again onto a 750 μm square target, were taken on arrays with an aluminium protection on the rear as well as the laser side. These shots were taken over two arrays to look at the target damage after a single shot as well as multiple shots as it was possible for the multiple shot run to shoot adjacent targets. In the single shot test, with a possible 22 targets available prior to the shot there were 18 still available after the interaction (shown Appendix A-2). In the multiple shot case, after 5 shots there were 11 targets remaining, from a total of 22 targets available before (Appendix A-3). This shows a damaged target percentage of 14% and 35% respectively.

The third run of shots were also taken onto a 750 μm square target and involved an array that had an aluminium protection on the front, similarly to the other targets but had glue lines between the targets on the rear side, acting as a shock propagation barrier as shown in figure 6. A total of 3 shots onto this array were taken after which there were 15 targets left (shown in Appendix A-4) leading to a damaged target percentage of 25%.

Figure 4. A HAMS sector produced by wet etching, which gives a rougher edge quality for the sector as it etches crystal planes. The 300 μm apertures can be seen in two rows patterned around the top edge of the sector.

Figure 5. A full silicon wafer patterned with 2000 μm aperture holes around the circumference.

Figure 6. A target with a glue protection layer on the rear.
3.3 Damage Results – Target Size/Geometry Study

Samples were then investigated for the size dependency for the survivability of the membranes. As described previously, targets of 750, 500, 1000, and 2000 μm apertures were prepared with a membrane thickness of 100nm SiN. The spacing of the aperture centres was kept at a standard distance in all cases at 3.5mm. All targets (both square and round geometry) were prepared with a glue protection layer on the rear surface as used for the targets in appendix A-4.

A method was devised to calculate the damage percentage for each target type. This takes into account the total available targets (pre-shot) on the array, the amount damaged specifically by the laser shots and normalising to the average number of shots taken on each array. Images of the targets before the experiments allowed verification of the number of potential targets to be shot \( T_p \). The number of shot targets is classified as \( T_s \), the number of targets available for shooting after a certain number of shots on the array is defined as \( T_a \) and the damage level from a scale of 0 to 1 (no damage to all targets damaged) is classified as

\[
D = \frac{(T_p - T_s - T_a)}{T_p - T_s}
\]

Normalising this to 4 shots, which was the average number of shots per array was possible by taking the ratio of the number of shots taken on the array compared to the average of 4. Therefore the normalisation factored damage percentage is

\[
D_n = \frac{T_s}{4} D
\]

The normalised target damage is thus classified as

\[
D_n = \frac{T_s(T_p - T_s - T_a)}{4(T_p - T_s)}
\]

Therefore

\[
D_n = \frac{T_s}{4 \left(1 - \frac{T_a}{T_p - T_s}\right)}
\]

The geometry for the first targets was square, prepared using wet etching and the centre to centre spacing of the targets was constant at 5mm. By using the damage ratio calculation above, the percentage damage can be defined. A 2000 μm targets array was shot 4 times and this showed a damage of 68%, two arrays of 1000 μm targets were shot with damage levels of 89% and 87.5%, a 750 μm array was shot with a damage level of 33% and a 500 μm array was shot with the same 33% damage level. These targets are shown in appendix B-1.

These shots were then replicated on targets that were produced with round apertures using dry etching techniques. These targets were again 100nm Silicon Nitride but there was also an oxide layer in the target that stopped the etching process from damaging the target. This was approximately 1 μm in thickness and would not have been significant enough to prevent the laser from interacting with the target. This is verified with 1 micron shots described later in this paper. A 2000 μm target array was shot 5 times and this showed a damage level of 15%, a 1000 μm target was shot 3 times and showed a level of 9%, a 750 μm target was shot 3 times and showed 18% damage and a 500 μm target was shot 3 times and showed 0% damage of neighbouring targets. These targets are shown in appendix B-2.
The graph in Figure 7 shows the results for both the square and round targets given in percentage terms and the results normalised for 4 shots. Error bars of +/- 10% are used, this is due to the amount of targets that are able to be damaged as nearest neighbours depending on where the target is shot. If it is shot in the corner then there are 3 surrounding targets, or 12.5% of the remaining array (25 minus the shot target) if the target is shot directly in the centre then there are 8 surrounding targets with a potential to be damaged, or 33% of the remaining targets. There is therefore a maximum 20.5% variation in the damage potential for each shot and this reduces after each shot on the array as targets are destroyed.

![Target Damage for Different Hole Sizes](image)

**Figure 7.** The target damage levels for both round and square holes and for different hole dimensions with constant spacing center to center of 3.5mm.

### 3.4 Rotational Targets

Two types of targets were tested that would be suitable for fielding on the final HAMS system, these both have rotational symmetry. The first design is based on the sector geometry as previously discussed with pre-shot imagery shown in Figure 4 and post-shot in Figure 8 below (center and left). The design was processed using wet etching and comprised 300µm square apertures with a pitch of 1000µm, the target material consisting of a 100nm thick Silicon Nitride membrane. The second target design was a full wafer with etched holes around the circumference shown in Figure 5 and Figure 8 (right) before and after shots, respectively. This target has 1 µm Parylene films suspended across the aperture.

![Figure 8. Radial targets in both HAMS sector (left) and full wafer geometries (right) with the beam footprint highlighted (center).](image)
The shots on the wafer segment (left) showed a laser footprint that was of the order of 2mm diameter (center). This relates to a FWHM focal spot size on the Gemini laser of 2.5 μm, and this can be optimised using adaptive optics [14]. An image of the focal spot is shown in figure 9 with a lineout of the focal intensity. The focal intensity drops off to a level that there should be no appreciable laser energy at the 2mm diameter above the ablation threshold, however damage is seen. Currently the most likely source for this footprint is amplified spontaneous emission (ASE) leaking through the laser pinholes but more investigation is needed on this. Four shots were taken on this target segment and it is clear on these shots that the adjacent targets were damaged by the footprint. It is believed that there was enough energy in the ASE footprint to pop the targets that were adjacent to the interaction but this needs further investigation. However, it is also clear that for a small aperture on these targets it was only possible to shoot every third target. For the larger targets with a 1 μm Parylene window the beam footprint is kept within the area of the target and is not seen. A number of shots were taken on this target on adjacent windows and whilst there was a good survival of nearest-neighbour targets the debris that was generated from one of the shots was substantially more than for other shots and popped the pellicle which was protecting the parabola.

![Figure 9. An image of the F2 focal spot and a lineout of the intensity distribution](image1)

Images of the debris created from these shots are shown in figure 10, again the silicon wafer seen is 325 μm thick and this is at 0.1ms after the shot. It can be seen for shot 39 there is much more material that is present at the same time than for the other targets. We believe this is the most likely cause for the damage to the pellicle as the alignment was not ideal on this shot and we may have irradiated the mount with more laser intensity than other shots.

![Figure 10. Debris measurements for the same time after shot for 2 identical targets.](image2)

3.5 Debris Measurements
As described in Section 3.1, debris measurements were taken using a FASTCAM system to allow for the tracking of the particles that were ejected from the target. The debris that was generated varied due to the target geometry as well as the target protection and separation layers that were present. In all cases
the raw images have been processed to remove the background and to enhance the appearance of the debris particles for visualization. The aperture of the target is centered in the image in all cases and although hidden by the silicon chip bulk material is seen from where the plasma plume emanates.

Debris measurements were taken on square targets with 2 mm apertures, glue protection on the rear and no front protection, shown in Appendix B-1 (2 mm square apertures). The data shown in Figure 11 was taken at 100k FPS and captures the initial plasma blow-off from the laser side in frame 1 (0.01 ms) which is quickly followed by particulate at 0.1-0.3 ms with the remaining target material being driven back towards the laser as the target relaxes at approximately 1 ms from the interaction.

Figure 11. FASTCAM data at t=0, 0.01, 0.1, 0.3 and 1 ms from the shot on a 2 mm square aperture.

Comparison of this data with a smaller aperture target shows a significant reduction in the large scale debris that is seen in footage taken 0.1 ms post shot. This is most likely due to there being a smaller amount of target material that is left un-ablated to relax back after the shot and break away from the mount. The images below in Figure 12 show a 1 mm square target at the same time periods after the shot. It is noticeable that in images for 0.3 ms and 1 ms there is no apparent target material and at t = 0.1ms there is little large scale debris present.

Figure 12. FASTCAM data at t=0, 0.01, 0.1, 0.3 and 1 ms from the shot on a 1 mm square aperture.

Comparing the data from a shot on a 2 mm round aperture target as described and shown in Appendix B-2 (2 mm) with targets in Figures 11 and 12 shows again that there is less debris after the initial shot than for a square target. Through use of particle tracking software, the trajectories of specific debris can be determined and are highlighted in images 4 and 5 of Figure 12. This particle travels 2098 µm in 81 ms (which can be calculated using the known width of the silicon wafer in the image which was measured externally to the experiment as a calibration). This equates to a minimum particle ejection speed of ~2.5 m/s for large particles depending on their trajectory relative to the focal plane, resulting in a higher speed. It is also possible to calculate the speed of the particles that are initially ejected by referring to Figure 13, image 2; the particle cloud disappears from the field of view within 2 frames. Taking the width of the image as 5 mm these particles have to travel 2.5 mm in 20 µs which equates to an average speed of ~125 m/s.
Figure 13. FASTCAM data at t=0, 0.01, 0.1, 0.3 and 1 ms from the shot on a 2mm round aperture

In all of the above cases it is clear that there is debris generated from different mechanisms when a target is ablated; initial plasma blow off occurs at very short timescales; small particle production, mainly travelling back towards the laser which takes approximately 0.1-0.3ms to travel a few mm; and the larger scale debris, which is primarily the shrapnel from the support or the foil itself that propagates over a longer timescale. This larger debris is of concern as the shrapnel may damage the parabola and optics, whereas the smaller and faster debris could cause issues with the coating of optics or contamination of other targets. Experimentally it is desirable to reduce debris wherever possible.

4. Conclusions

Detailed studies have been carried out on the size and the geometry of the targets and a clear idea of the ideal target parameters for the Gemini system has been ascertained. It can be seen there is a clear trend that a smaller target aperture increases the chance of neighbouring targets surviving on the array. There however would be a lower limit to this which would be characterised by the geometry of the incoming laser beam and the thickness of the target mount. In these examples for a F/2 beam through a 325μm thick wafer the hole size would need to be 325μm square to stop the beam clipping the target at normal incidence. It also seems preferential to use circular rather than square aperture targets. This may be due to the increased stresses or shock-focussing into the corners of the square target apertures. Further work needs to be carried out to fully understand this hypothesis. Debris studies carried out show that smaller target apertures create less large-scale debris and therefore are preferable for high rep rate experiments where the build-up of such debris will degrade the system.

It is also noticeable that where there is protection in the front and rear of the targets, in the case of this investigation using plates or glue lines there is a reduction in the damage to the surrounding targets. This could be down to the shadowing of the aperture from some of the plasma and debris, or it could be some impedance change that stops shocks propagating across the surface of the holder. Further work is needed to investigate this process.

Further work is planned to test the targets on the complete HAMS system and to verify the high repetition rate of the rest of the integrated technology, however the experiment carried out shows that MEMS targets are applicable to high rep rate operation of systems such as the Gemini laser with the appropriate target protection and therefore the cost effectiveness and the reproducibility of such targets can be exploited. The integration of the interferometer to aid alignment is being developed to verify target position and to introduce a feedback loop for alignment.
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APPENDIX A

A-1. (Left) The target before positioning in the chamber showing a full complement of foils and after the shots (center) showing a large amount of damaged foils and (right) the shots taken on the target with red indicating shot, grey indicating damaged and white indicating surviving.

A-2. (Left) The target before positioning in the chamber (with the Al protection removed) showing a 22 out of 25 foils available (center) showing a shot and damaged foils and (right) the shots taken on the target with red indicating shot, grey indicating damaged and white indicating surviving.

A-3. (Left) The target before positioning in the chamber (with the Al protection removed) showing a 22 out of 25 foils available (center) showing a the shot and damaged foils and (right) the shots taken on the target with red indicating shot, grey indicating damaged and white indicating surviving.
A-4. (Left) The target before positioning in the chamber showing 23 out of 25 foils available and after the shots (center) showing the damaged foils and (right) the shots taken on the target with red indicating shot, grey indicating damaged and white indicating surviving.

APPENDIX B

B-1. (Left) Square target shots from 2000 microns, 1000 microns x 2, 750 microns and 500 micron apertures. Target damage can be easily seen on the foils.

B-2. (Left) Round target shots from 2000 microns, 1000 microns x 2, 750 microns and 500 micron apertures. Target damage can be seen on the foils.
APPENDIX C

C. Image of the F2 focal spot with a FWHM of 2.5 microns