Development of patterned tape-drive targets for high rep-rate HPL experiments

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1. Introduction

From the inception of the use of high power lasers (HPLs) for plasma physics experiments, target supply has been able to keep up with demand due to the relatively low repetition rate of the laser systems. Recent advancements in laser technology have enabled an increase in shot rates and enabled systems to run in a mode that is not shot but target limited. When operating at full capacity, next generation systems, such as ELI and XFEL, will require a method of delivering tens of thousands of targets for an experimental campaign, which is not achievable with current target technologies.

MEMS-based target manufacture is a promising method for coping with such target number demands and allows the manufacture of complex 2.5D targets. The Target Fabrication Group at the CLF has developed a MEMS-based High Accuracy Microtarget Supply (HAMS) system [1] capable of delivering hundreds of targets in a single pumpdown cycle, and allowing fine target alignment in six degrees of freedom. Whilst this system does allow for semi-complex targets, the quantity deliverable in a single pumpdown cycle is limited by the target-target spacing (due to the laser footprint damaging neighbouring targets), fratricide and the mounting mechanism. In order to deliver semi-complex 2.5D solid targets to modern facilities capable of shot rates of greater than 1 Hz, a new method of thin-film target production will need to be developed, along with a highly stable delivery system.

In recent years, within the HPL community, there has been particular interest in tape-driven targets; however, these have primarily been off-the-shelf polyimide tape rolls with no thin-film coating. There is currently very limited choice of coated tapes: tapes tend to be precoated with an arbitrary thickness of a specific metal, typically aluminium. The Target Fabrication Group has developed an in-house fabrication method for manufacturing 2.5D thin-film targets on a CH substrate, the details of which are discussed.

2. Pre-experimental studies

In February 2018, access was granted on the Gemini laser for an experiment aiming to directly observe Breit-Wheeler pair production for the first time in a laboratory. This campaign requested 2000 shots on thin-film targets to assure 5-sigma confidence in the data. The required target for the experiment was 5 µm CH with a 50 nm Ge coating, as shown in Figure 1.

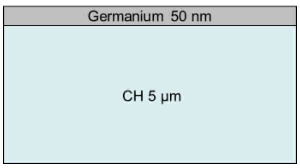

Figure 1: Diagram of target for February 2018 Gemini experimental delivery

During the experimental planning phase, Target Fabrication used laser access time in TA3 to explore the survivability of thin-film targets on 5 x 5 array mounts. The access was necessary to establish a suitable target substrate and delivery method for a campaign with a high shot demand.

Upon laser interaction on a single target aperture in the array, a large area of the thin-film ablated from the entire coating, significantly decreasing the yield for each array, as seen in Figure 2.

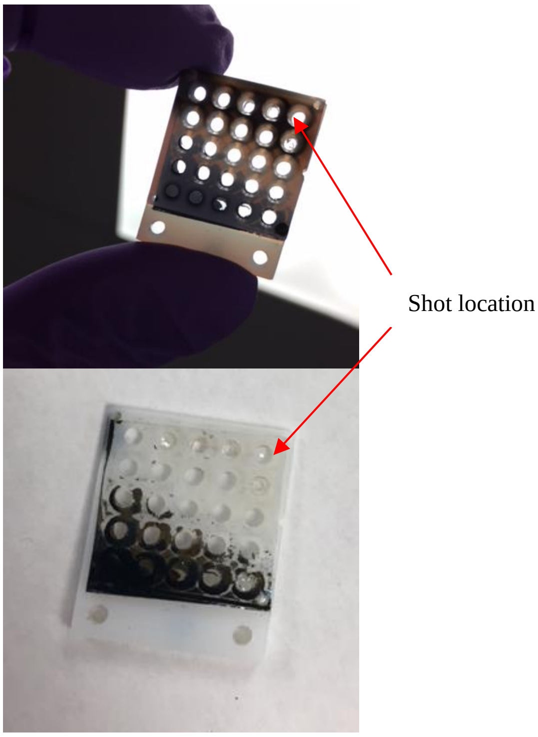

Figure 2: 55 nm Ti on 15 µm polypropylene substrate following a single shot in the upper-right corner on a 3D printed support. With (above) and without (below) front cover in position.

By migrating from a 3D printed support to an aluminium frame, all exposed areas were still ablated in the shot; however, the underlying protected areas were left intact. It was postulated that the ablation issue was caused by surface current effects on interaction. Similar results were obtained for a 3D printed mount coated in a conductive metallic layer, lending further credence to this theory.

The study suggested that a blanket thin-film coating over the entire substrate would not be suitable for experimental delivery due to ablation, and individual targets would need to be coated with reasonable separation between each. A microdot target pattern was coated onto a thick CH substrate and shot during the laser access time in TA3, the results of which are shown in Figure 3 below.

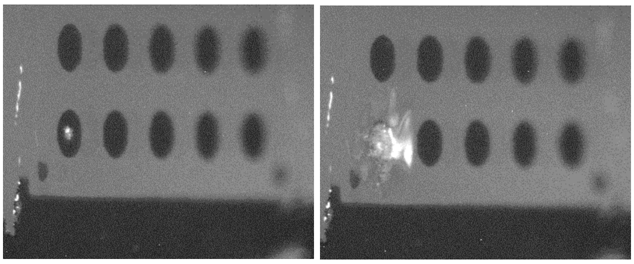

Figure 3: Microdot target before (left) and after (right) laser interaction. The laser was defocused to 500 µm and can be seen on the lower left corner of the image.

As evident in Figure 3, patterning the targets into microdot structures prevents target-target damage propagation due to mitigating current transport across the surface. Requirements for the experimental campaign, however, stipulated that there could be no obstructions surrounding and below the target to prevent attenuation of the generated x-rays, meaning that a support array grid was not suitable. The conclusion from the test shots was that the metallic film of each target should be isolated from its neighbours both spatially and electrically and so a custom-patterned microdot tape driven target was deemed most appropriate. Such a design would allow delivery of unsupported targets at the very high yield necessary for a sufficient dataset. The target design is shown in Figure 4.

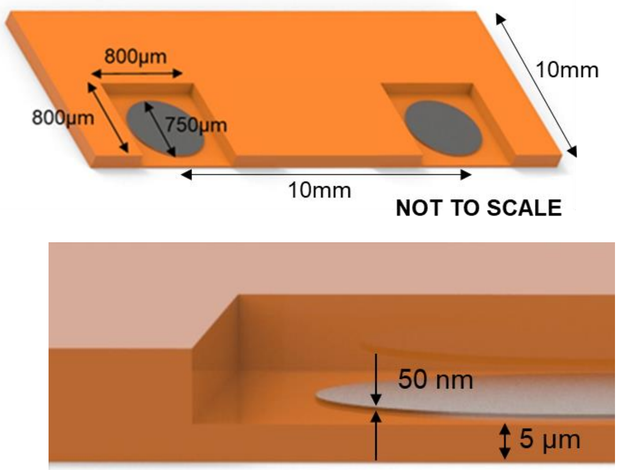

Figure 4: Design of the proposed 50 nm germanium dots on 5 µm polyimide tape strips in an 800 x 800 µm etched window

3. Manufacturing patterned tape targets

The Target Fabrication Group at the CLF has collaborated with the Precision Development Facility at RAL Space to develop both a new method of mass producing semi-complex 2.5D targets on a tape substrate, and a highly stable driving mechanism. The aim is to be able to couple the two technologies to drive targets while maintaining z-position to within the Rayleigh range of HPLs, to negate the need for focusing and thus maximize shot rates.

The production of the tape targets is a multi-step process including thin-film coating techniques, chemical-etching and laser-machining. Characterisation of both the tape targets and the stability of the tape-drive system on which they are mounted requires use of white-light interferometry, surface profilometry and chromatic confocal displacement sensing techniques.

Pre-coated metallic polyimide tapes can be purchased off-the-shelf; however, the metallic coatings are very limited in material and thickness. Furthermore, polyimide sheeting and tapes can only be procured at a minimum thickness of 13 µm, and consequently etching the material back to the required thickness of 5 µm is necessary.

3.1. *Laser-etching parameters*

Before coating the germanium dots onto the polyimide substrate, the sheeting must first be cut to size such that it can fit into a sputter deposition coating plant. Due to the restriction of surface area available in the coating plant to mount substrates, the polyimide film is cut to 260 x 260 mm sections to coat the maximum number of targets per pumpdown cycle. The next step in the fabrication process is laser-etching of the 800 x 800 µm target windows on 25 µm polyimide film to a thickness of 5 µm. 25 µm sheeting was selected to provide more rigidity surrounding the etched windows.

A 193 nm Excimer laser operating at 50 Hz was used for the etching process for the target. The ablation rate of the polyimide was established by varying the number of pulses on samples of the material and characterising the window etch depth using a surface profilometer. Five samples were machined for each pulse number variation and the results were averaged to obtain a relationship to allow machining to specific depths. The surface roughness of the ablated surface of the windows was $R_a = 500 \pm 200$ nm, and the pulse number to etching depth relationship is shown in Figure 5.

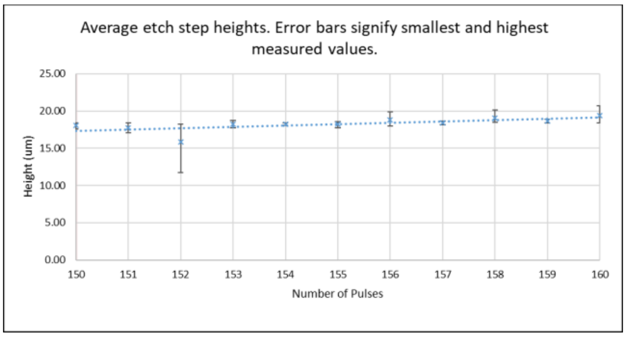

Figure 5: Number of pulses vs etching depth in 25 µm polyimide using an Excimer 193 nm laser operating at 50 Hz. Error bars represent the range of the five samples for each pulse number

By knowing the number of pulses required to etch down to a thickness of 5 µm, 625 windows could be etched onto each 260 x 260 mm sheet of film ready for the coating process (Figure 6).

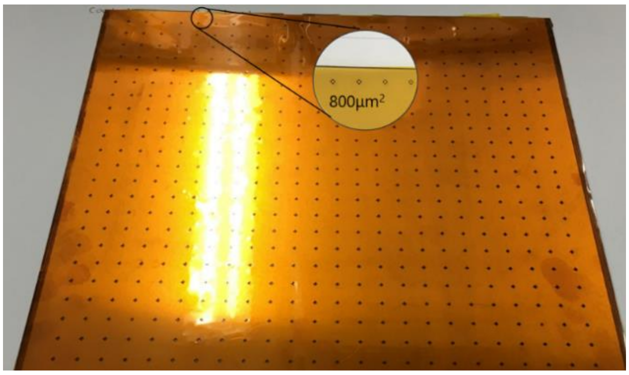

Figure 6: 260 x 260 mm polyimide sheet with 625 laser machined 800 x 800 µm windows down to a thickness of 5 µm

3.2. Coating process

Coating of the 50 nm Ge dots was carried out using an 'Edwards Auto 500' magnetron sputtering system. This system is suited to coating thin films on substrates with features that could cause shadowing, by coating within a buffer gas to reduce ion mean free paths. A coating mask was designed with 625 x ⌀750 µm features for the target dots, spaced 10 mm apart to align with the centre of the etched windows. The laser-machined polyimide sheet was then carefully aligned onto the mask and coated with 50 nm on the reverse side of the etched window (to utilise the favourable surface roughness). The mask had to be of sufficient thickness such that it did not bow over the large surface area, but not too thick to cause coating shadowing. After coating the germanium dots, the mask was removed and target samples were characterised optically using a white light interferometer to ensure the Ge film thickness was within tolerance.

3.3. Tape dicing and assembly

After thin-film coating of the Ge, the sheets were laser-cut into 10 mm wide strips with 25 targets along each strip. The target aperture was aligned at the bottom of each strip, such that the x-rays generated on experiment from the laser interaction could be as close as possible to an incident gamma beam while not clipping.

In order to bond individual target tape strips together to form a long length of tape, precise alignment was crucial along the length of the reel prior to loading onto a tape drive. A 3D printed jig (Figure 7) was designed which aligned two strips of tape and provided a uniform clamping force across the glued surface. Several such jigs were printed for use simultaneously, to reduce the total assembly time. Figure 8 shows the end product of diced and assembled tape strips.

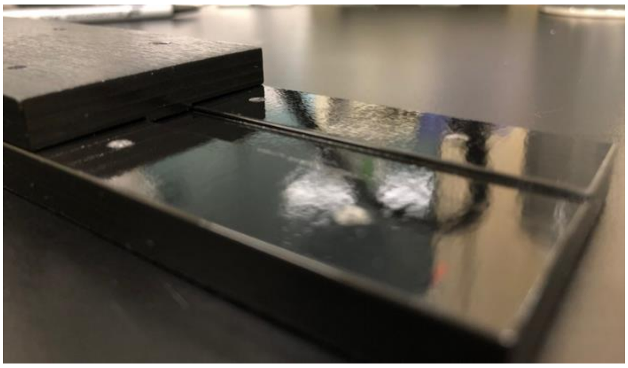

Figure 7: 3D printed tape assembly alignment jig

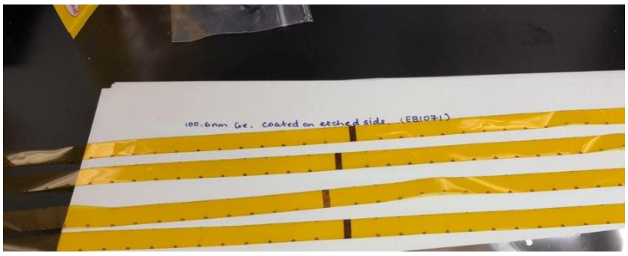

Figure 8: Completed sections of 100 nm Ge target tape. The black vertical markings indicate the joint location of each strip.

4. Results

The development of new high repetition-rate tape targets for the CLF allowed over 2000 targets to be delivered for an experimental campaign in Gemini in February 2018. This equated to 20 metres of target tape and allowed for a shot rate of every 20-40 seconds.

The thinning of the polyimide onto which the Ge dots were coated allowed minimally attenuated x-rays to be repeatably produced from laser-target interaction.

Figure 9 shows a section of target tape which was shot on experiment. The localised window etching prevented rupturing of the tape from shot to shot and the separation of the Ge coating was successful in preventing neighbouring target ablation.

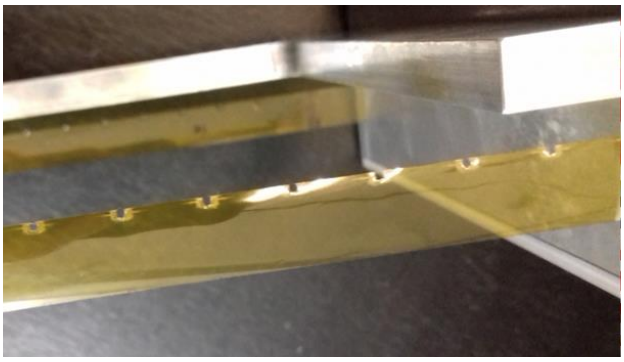

Figure 9: A shot section of target tape mounted on the drive used on experiment. The shot targets can be seen at the top of the tape.

5. Future work

The fabrication process for the discussed tape targets is highly versatile and allows for variable 2.5D target geometries, a wide array of target materials, multi-layer coatings and different substrate materials.

Adaptation of such target substrates for ion acceleration experiments could be very promising and would require CH thicknesses of less than 1 µm. However, as evident in Figure 5 (detailed by the error bars), the etching depth can vary in some instances by ±3 µm. To allow for enhanced etching control, upgraded optics are required for the Excimer laser and are currently being sourced.

The laser footprint (of Gemini) limits the compactness of targets in the x-dimension, as can be seen in Figure 9. There is, however, scope to add multiple rows of targets in the y-dimension without compromising tape integrity. In this way, the target yield can be increased several-fold.

The CLF is currently collaborating with the Precision Development Facility at RAL Space to manufacture a new highly-stable tape drive system, which will minimise deviation in the focal plane of the target to allow high repetition-rate tape target technology to be used in higher repetition laser facilities. The project is ongoing and a prototype system (Figure 10) has been built and characterised with promising results.

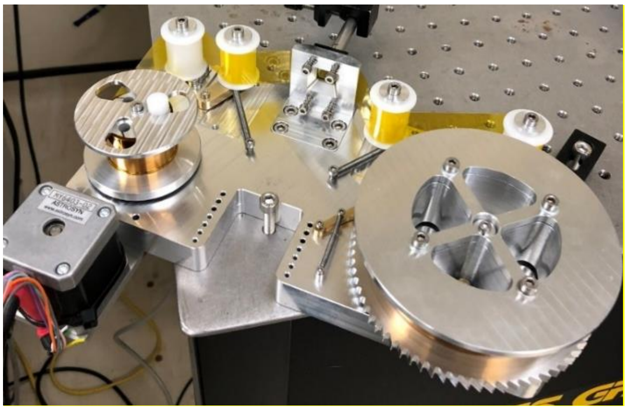

Figure 10: Prototype of the upgraded target drive system

References

1. Target characterisation and pre-alignment for the HAMS high throughput targetry system, S Astbury *et al*, CLF Annual Reports 2015-16