Fabrication and Evolution of Novel Astrophysics Targets for Turbulent Dynamics (TDYNO) Experiments on the OMEGA Laser Facility

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Abstract—*Although the overall function of a campaign's primary target design may remain unchanged, the components and structure often evolve from one shot day to the next to better meet experimental goals. The target fabrication engineer's involvement in this evolution can be important for advising modifications in order to improve and simplify assembly at the same time.*

Highly complex targets are constructed by General Atomics (GA) for astrophysics experiments conducted by the University of Chicago at the OMEGA laser facility. Several novel target components are fabricated, precision-assembled, and extensively measured in support of this campaign, and have evolved over the last three years to improve both the science and assembly. Examples include unique laser machined polyimide grids to enhance plasma mixing at target center, precision micromachined cylindrical shields that also act as component spacers, drawn glass target supports to suspend physics packages at critical distances, and tilted pinholes for collimated proton radiography.

Target component fabrication and evolution details for this turbulent dynamics (TDYNO) campaign are presented, along with precision-assembly techniques, metrology methods, and considerations for future TDYNO experiments on OMEGA.

I. INTRODUCTION

The study of laboratory scale plasmas is of growing interest in the astrophysical community due to its ability to transform astronomy from an observational science to an experimental one. The goal of this particular campaign, which is funded by the National Laser Users' Facility (NLUF) program, is to study amplification of seed magnetic fields in turbulent laboratory-scale plasmas in order to fundamentally understand and model turbulent dynamos (TDYNO) on a far grander astrophysical scale[1].

The TDYNO targets are designed to create counter-propagating plasma jets which turbulently mix at target center. The jets are generated by laser-driving ablator packages at both ends of the target with a direct drive, multi-beam approach, as seen in the first column of Figure 1. The 3mm OD ablator packages are comprised of a 50µm thick CH drive disc and 230um thick CH collimator washer with a 400µm ID at the laser entrance hole (LEH) of each conical shield.

Each jet then passes through a 3mm diameter grid at its respective end before colliding with its counterpart at target center. Additive manufactured (AM) conical shields prevent accretion flow —which is produced by laser-target interaction—from wrapping around the physics packages and interfering with the plasma jets. Additional Cu shielding on one of the cones serves to block capsule backlighter-generated X-rays from the direct line of sight of a critical X-ray pinhole camera diagnostic. All components are labeled in the last column of Figure 1.

During the last 3 years of experiments on OMEGA, the overall target design of opposing ablator-grid packages as described above has remained essentially the same. However, the TDYNO targets have undergone several structural and component changes in order to improve the science as well as the assembly process. These changes and their motivations are presented, along with component fabrication details, assembly techniques, metrology methods, and ideas for future TDYNO target evolution and improvement.

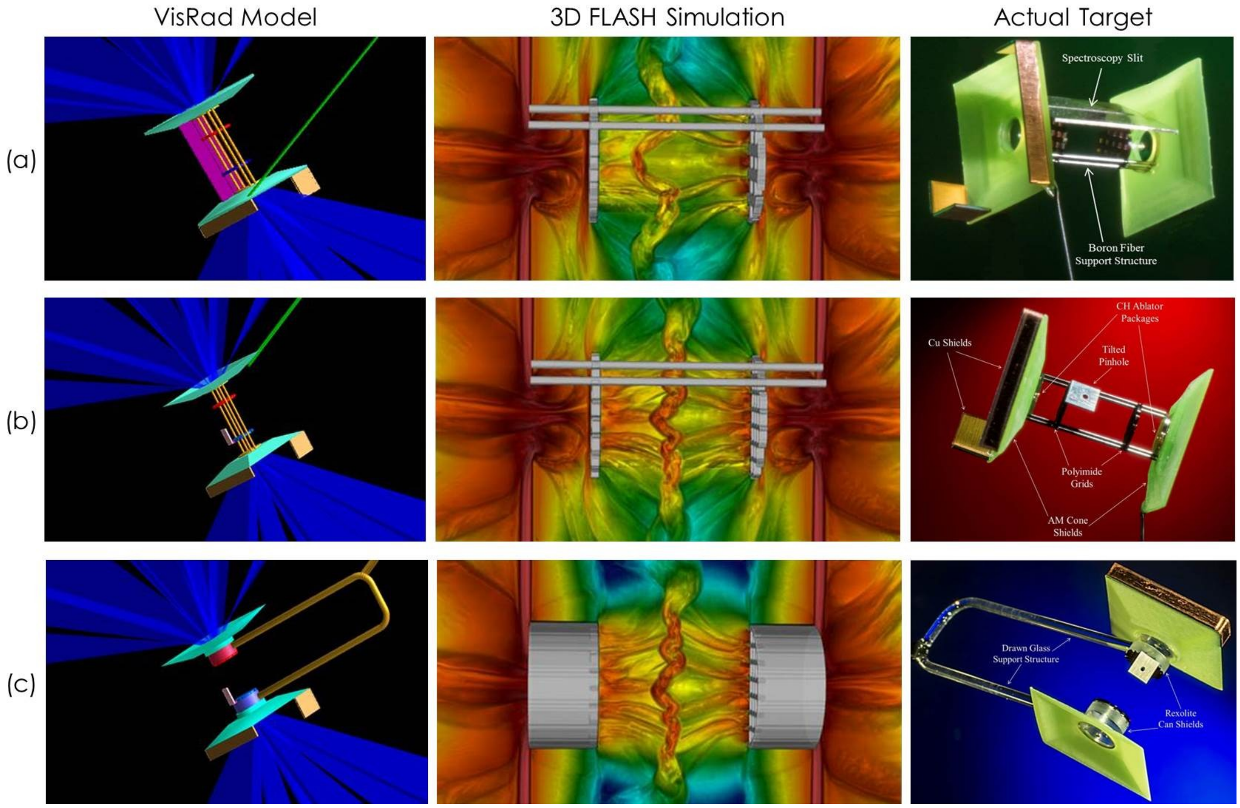

Figure 1. Target evolution from 2015-2017 is shown, including VisRad models of target concepts and laser drive, 3D renderings of FLASH[2] simulations showing predicted plasma dynamics, and actual target images with labeled components for each of three generations: (a) MagFieldPlasma-15A[3], (b) MagPlasma-16A[4], and (c) TDYNO-17A[5]; Scale: Distance between the grids components is 4mm, and shield to shield target length is approximately 1cm.

II. TARGET EVOLUTION & COMPONENT FABRICATION

Three generations of OMEGA TDYNO targets are shown sequentially in Figure 1. The original design—used for 1st and 2nd generation targets and shown in Figure 1(a) and (b)—incorporated a boron fiber rail structure to suspend ablator and grid components at specified critical distances. Although these targets yielded valuable data[1], they were not yet optimized for achieving the desired scientific goals, or for ease and precision of assembly. For example, the grids used for the first shot day did not perform as well as the PIs' FLASH simulations predicted. This resulted in the testing of two additional grid types during the second shot day.

For the 3rd generation of TDYNO targets significant structural modifications were made, simplifying assembly while improving critical component spacing and alignment. This was achieved by identifying and implementing advantageous design attributes from the NIF TDYNO targets, namely the drawn glass target supports and Rexolite "can" shields labeled in Figure 1(c). In this section, details of the design evolution and novel component fabrication over the course of three shot days are discussed.

II.A. 1ST AND 2ND GENERATION TARGET DESIGNS

Producing strong plasma turbulence at target center is critical to the success of this campaign. Therefore, a key requirement of the design is that the grid pairs be pattern-shifted relative to each other such that the holes do not overlap. This spatially filters the two shock fronts, creating interleaving fingers of plasma to encourage turbulent mixing and thereby induce amplification of seed magnetic fields. Type I grids designed for the first generation of targets have equal 300µm hole and wire width as shown in Figure 2(a). However, post shot analyses indicate that this design does not produce a strong centralized plasma mixing region, as demonstrated by the 3D simulation rendering in Figure 1(a). Thus for the second shot day, two new grid types were manufactured to assess properties of turbulence injection, shown in Figure 2(b) and (c). Type II "thin wire" grids have 300µm holes with 100µm wires to increase aperture and achieve stronger turbulent mixing. Novel Type III "canted hole" grids have 300µm holes and wires but with some holes tilted relative to surface normal to impose a helical flow pattern, as detailed in Figure 2(d).

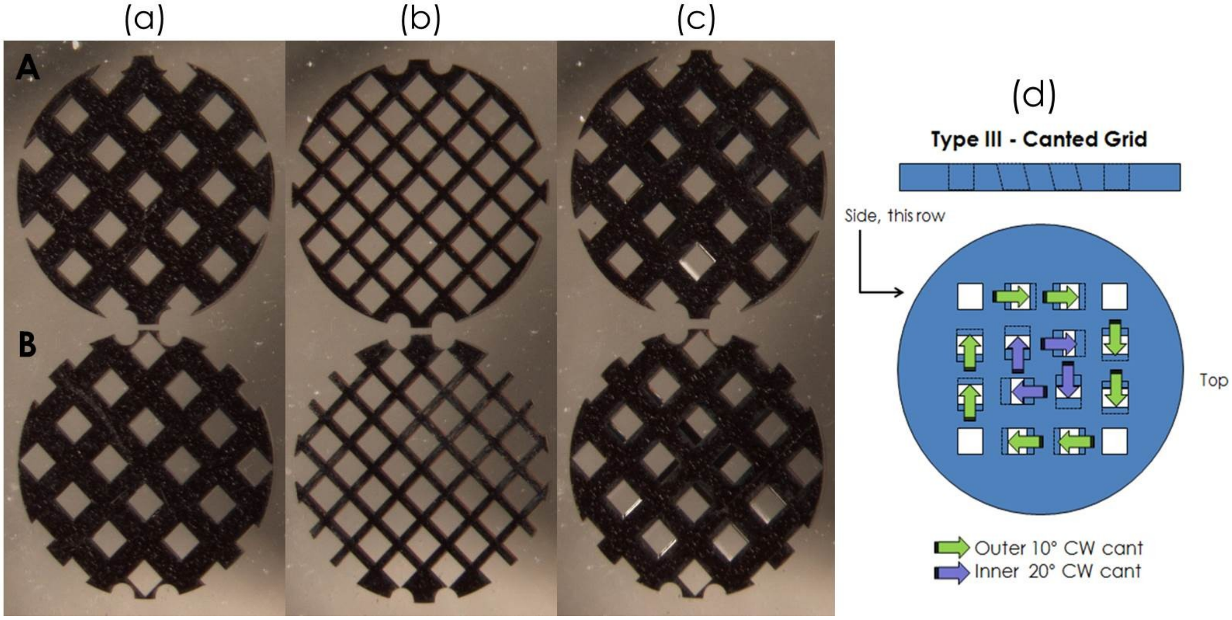

Figure 2. A- and B-style pattern-shifted grids feature rounded notches at grid edges to accommodate B fiber rail structure; three main types are shown: (a) Type I: 300µm holes and spacing, (b) Type II: 300µm holes and 100µm spacing, and (c) Type III: 300µm holes and spacing with canted holes; (d) Type III canted grid details.

Grids were precision lasermachined at GA from a Kapton sheet nominally 230µm thick, supplied by GoodfellowUSA. The thickness of each grid was measured with a dual confocal microscope. The grid holes and outer contour were laser-machined using an ultraviolet laser workstation. For grids with all perpendicular holes, such as Types I and II, the entire component can be machined in a single operation. For grids with canted holes, a secondary tilt stage was incorporated into the laser machining workstation to allow machining on an angle. The perpendicular holes were machined first, then the tilt stage was used to machine the four central holes at a 20° angle and the outer holes (not including corners) at a 10° angle relative to the face of the grid in a clockwise helical pattern (Figure 2(d)). The rounded notches at grid edges, which can be seen in Figure 2, were machined to accommodate the boron fiber rail structure and helped significantly for alignment during assembly.

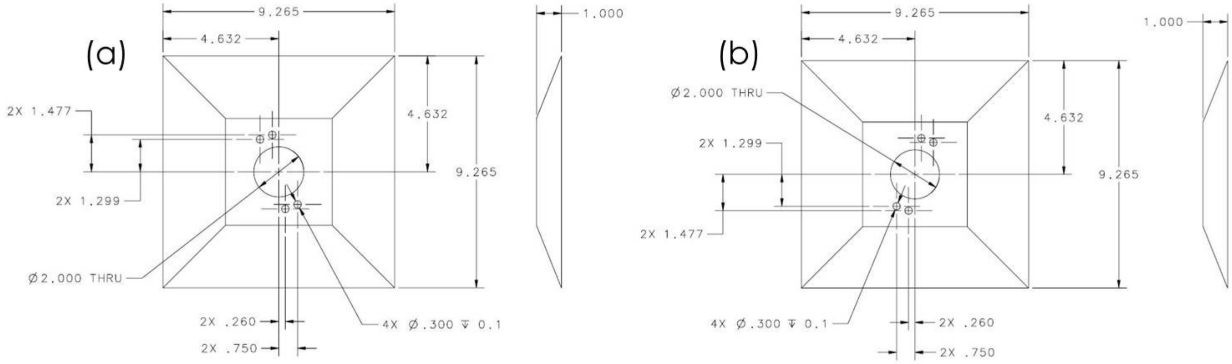

Figure 3. AM shield cone design used for 1st and 2nd generation targets, featuring four 300µm OD wells at a 100µm depth to accommodate B fiber ends; (a) Grid A-end cone and, (b) Grid B-end cone; all dimensions in mm.

Although the PIs originally requested machined cone shields, it was determined that these parts do not require a high level of precision to meet experimental needs. Therefore additive manufacturing (AM) was a desirable alternative. The quick turnaround and low cost of AM parts are also ideal for tight fabrication scheduling and the relatively finite target support budget allotted for NLUF experiments. While the AM cone shields are not as consistent as precision-micromachined parts, batches can be culled through for best quality as it is often cheaper per part to order AM components in large quantities.

TDYNO cone shields are fabricated by Proto Labs via stereolithography (SL) using MicroFine Green[6] resin. This material's high level of resolution allowed for the incorporation of 300um diameter, 100µm deep wells in the shield top surface (Figure 3) to accommodate the ends of the structural boron fibers and aid with assembly. It was initially thought that a 2mm OD aperture was sufficient for laser-target coupling while still allowing enough real estate for the 3mm OD ablator packages to be attached. However, there was some concern after 2016 shots that the shallowest incident beams, shown in the Figure 1 VisRad models, might be clipped by the base of the shield. This was due to the inherent thickness of the base, which was increased from 200µm to 400µm in order to facilitate the wells for boron fiber end placement.

In order to spatially and temporally resolve X-ray spectra with a limited source size along a symmetry axis, some first generation targets included an aluminum shield with a 200um slit oriented along the target's long axis, labeled in Figure 1(a). For the next shot day, the spectroscopy slit component was replaced by a more sophisticated tilted pinhole diagnostic, seen in Figure 1(b) and (c), to measure the spatial diffusion of D^3He proton beams using collimation.

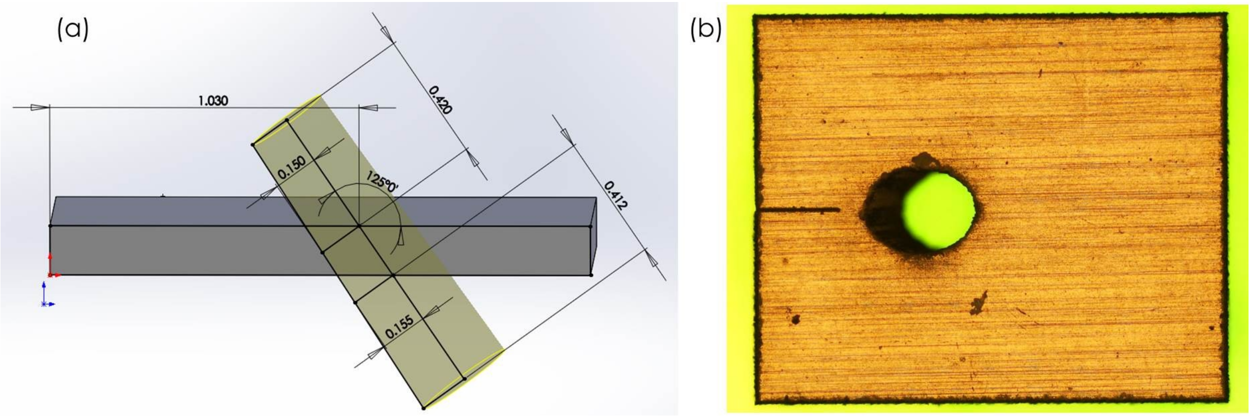

Figure 4. A SolidWorks model of the tilted pinhole component (all dimensions in mm) and (b) a finished part with 300-310µm tapered pinhole precision-laser machined at 35° through a 178µm thick Al substrate; scribe marks were laser-etched onto substrate surface to indicate target-side face of components during assembly.

The laser micro-machining group at General Atomics used double pulse machining coupled with a high precision 5-axis stage to laser-bore these pinholes in a thick aluminum substrate to a ±20µm accuracy. Although streamlined machined code generation software was used to simplify the machining process, careful attention was paid to minimizing the hole diameters at entrance and exit sides of the laser, the holes' positions, and the overall tilt angle with respect to the surface normal of the aluminum substrate. Future progress on these pinholes will include optimizing the machining code to compensate for ellipticity of the tilted holes on both laser entrance and exit sides, as can be seen in Figure 4(b).

II.B. 3RD GENERATION TARGET DESIGN

As a result of testing the three unique grid types during the second shot day, the Type II "thin wire" grid design was found to create the strongest, most centralized turbulent plasma region, demonstrated in the simulation rendering in Figure 1(b). Therefore this grid type was used exclusively for the 3rd generations of targets. In order simplify the structure of the target while increasing accuracy and repeatability of key component alignment and spacing, two elements were borrowed from the NIF TYDNO target design: drawn glass target supports shown in Figure 5, and the Rexolite cylindrical shields in Figure 6. The NLUF target fabrication engineer (TFE) and assembly team at GA presented these modifications to the PIs during early design calls. The TDYNO experimental team then ran FLASH simulations to verify that the new can shields would not interfere with the plasma jets. Simulation indicated that the shields should actually improve plasma delivery to target center, shown by the 3D rendering in Figure 1(c).

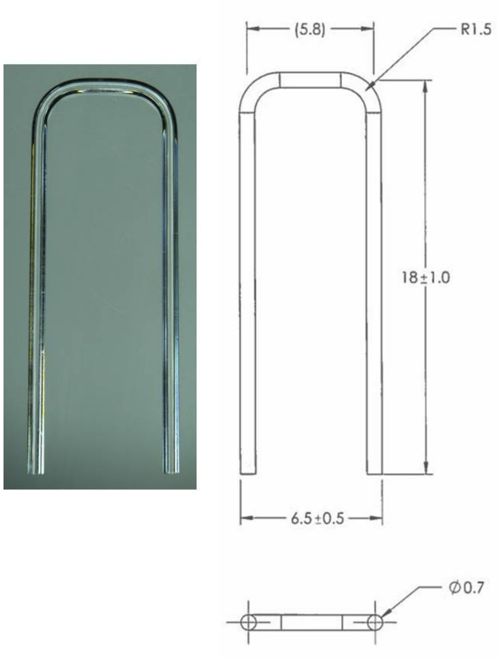

Figure 5. Drawn glass target support stalks were manufactured to the above specifications by Mindrum Precision; all dimension in mm.

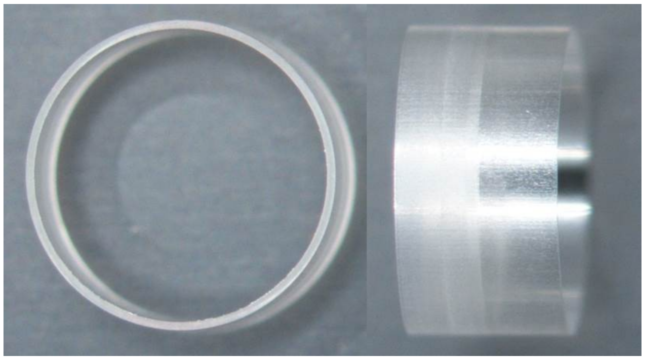

Figure 6. Rexolite can shields were precision micromachined at GA to within ±10µm of specified dimensions (3.00mm OD x 1.54mm long, 100µm wall).

The drawn glass target support and Rexolite can shield parts required down-sizing from the NIF design dimensions for shots on OMEGA. This initially presented a challenge for the glass target supports, which were custom-fabricated by Mindrum Precision. Time and budget would not allow for manufacturing of new tooling at Mindrum to fabricate OMEGA-size components. The GA assembly team was able to coordinate with the vendor to use a smaller, 0.7mm OD glass rod rather than the 1.0mm OD glass rods used for the NIF target supports. The drawing in Figure 5 demonstrates how a 0.545mm inner support width was maintained, allowing for utilization of existing tooling while not exceeding a 6.5mm outer width.

The Rexolite can shields were scaled down to a 3.0mm OD to match that of the ablator and grid components. The height of the can shield was set at 1.54mm to achieve the required 2.0mm critical distance between the target-center faces of the ablator disc and its respective grid during assembly of the physics packages. These components were fabricated at GA from Rexolite 1422 using a series of precision machining steps to ensure the dimensions would be held to ±10µm. A 4-inch diameter disc of Rexolite approximately 3mm thick was cut from a rod of bulk material. This disc was then diamond turned on one face before the turned side of the disc was glued to a larger machining fixture using Loctite glue. The disc was then diamond turned to the final height of 1.54mm. The machining fixture was next transferred to a precision mill on which an array of cylinders was milled to the final dimensions from the single disc. The parts were then released by soaking the entire fixture in nitromethane, and air dried before the dimensions were measured using a Nikon MM400 microscope.

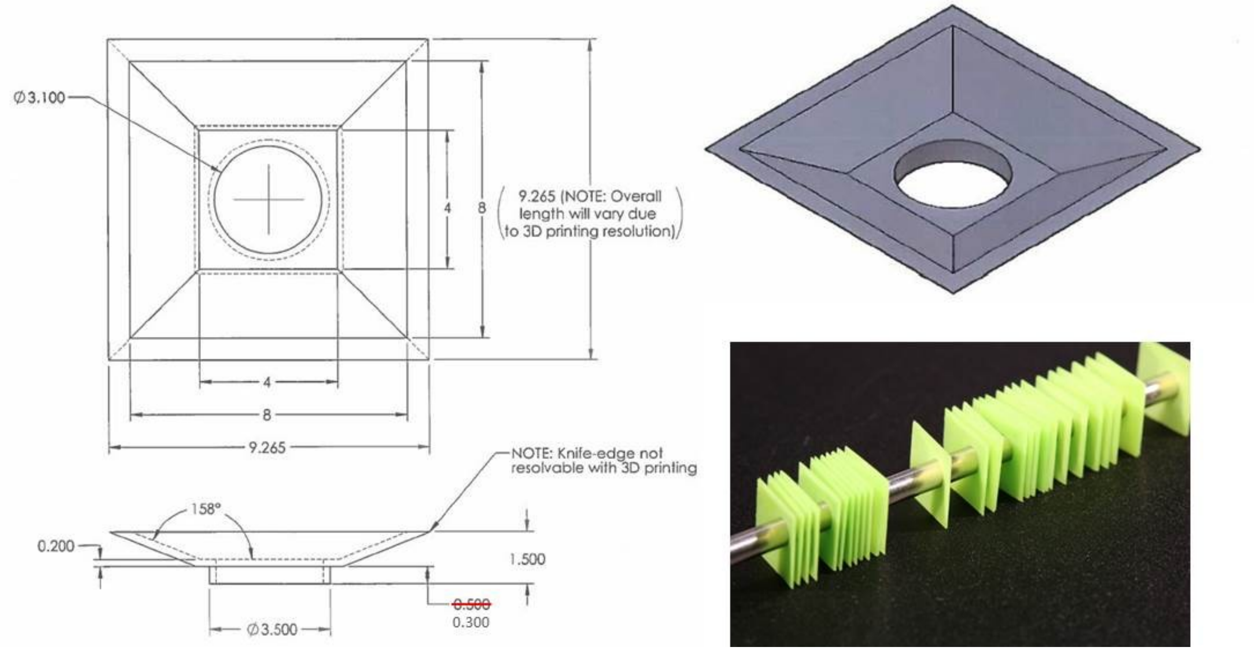

Figure 7. 3rd generation cone shields featured a 3.1mm OD LEH and 0.3mm tall light-tight collar to accept the 3.0mm OD physics packages; a shield LEH fit check was performed at GA using a 3.0mm gauge pin.

Adoption of NIF TDYNO component concepts allowed for re-design and optimization of the AM cone shields. Recessed wells in the cone top surface for accepting fiber ends were no longer needed due to elimination of the rail structure. In order to mitigate concern for potential beam-clipping as mentioned previously, the LEH diameter was increased to 3.1mm, allowing the shields to slide directly over the 3.0mm OD physics packages such that the laser-side of the ablator disc sits flush with the base of the cone. A collar around the LEH was also added to facilitate a more stable, light-tight fit around the physics packages. The original 0.5mm collar height was reduced to 0.3mm to leave adequate space for attachment of the target support tines. A drawing of the 3^{rd} generation AM cone shields is shown in Figure 7. A shield LEH fit check was performed at GA using a 3mm OD gauge pin, as seen in the bottom left of Figure 7. Although ±100μm is normally quoted for AM MicroFine Green parts, these re-designed cone shields were measured to have tolerances of ±10μm for aperture ID and ±50μm for cone height.

III. ASSEMBLY & METROLOGY

All TDYNO targets for experiments on OMEGA are assembled manually under a Zeiss STEMI SV6 microscope using a series of 3-axis micromanipulators equipped with interchangeable customized assembly tools such as vacuum chucks, 3-jaw chucks, 45° angled mirrors, and a dial wheel with a vacuum port. These manipulators are staged using adjustable rails which are attached to a larger 360° dial wheel. A Nikon DS-Vi1 microscope camera with imaging software is utilized for in situ measurements and assembly documentation. Although this setup may seem primitive compared to automated double or triple-theta assembly stations, it offers great flexibility for rapid customization of staging, tools and techniques for a wide range of target assemblies.

The targets for TDYNO experiments have strict specifications for component spacing and orientation; tight tolerances of ±30µm in X and Y grid and ablator positioning, ±3.0˚ of grid parallelism, and ±1.5˚ of ablator parallelism were given by the PIs. Additive manufacturing (AM) and precision micromachining offer unique capabilities to meet the high demands of these targets. Proposed solutions to improve repeatability and reduce effort in assembly include the integration of an AM superstructure into the target, and the implementation of AM jigs and precision micromachined spacers into the manual assembly process.

Early designs for the first generation of targets included an integrated AM superstructure onto which the target components would be assembled, allowing the automated AM process to set the positioning and orientation accuracy of the target components rather than the manual assembly process. However, the AM superstructure design was ultimately unusable because the capabilities of the AM process could not meet the stringent specifications of the campaign. Over the full 8.6mm length of the superstructure the minimum resolvable diameter for the support arms was 500µm, which was much greater than the maximum allowable diameter of 100µm to avoid degrading imaging of the experiment. Instead, the target was redesigned with 200µm OD boron fibers to suspend the target components at specified critical distances. To aid in assembly with this design, notches were added to the outer edges of the grids and ablators, along with recessed wells in the AM cone shields to accept boron fibers, as discussed above.

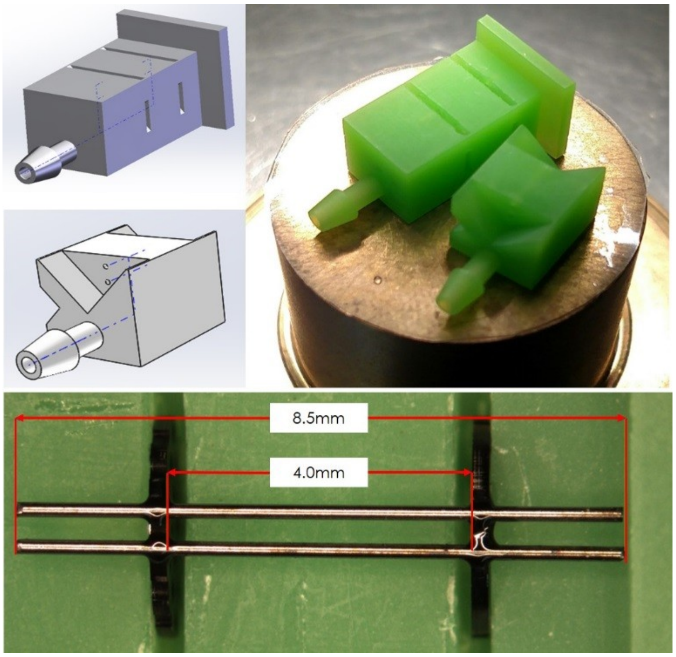

Figure 8. Various tested AM assembly fixtures, while promising during prototyping, were not ideal for target repeatability or accuracy required for the experiment.

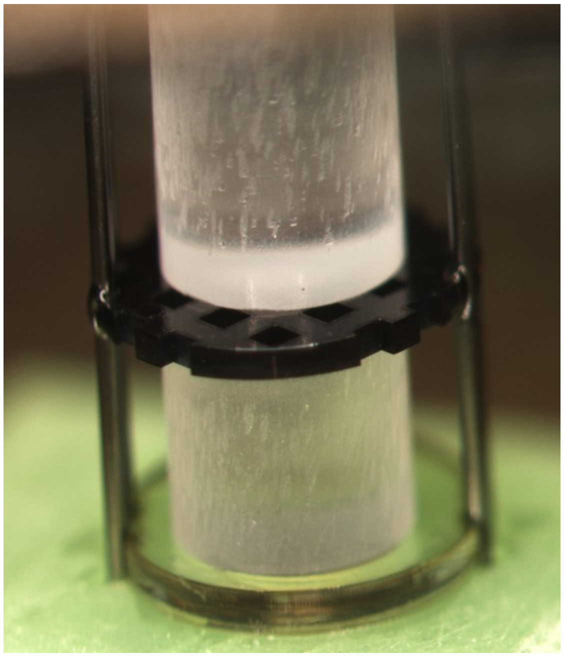

Figure 9. Ultimately, 2nd generation targets were built vertically with precision micromachined Rexolite spacers to achieve critical distances.

For second generation targets the GA assembly team designed and tested modified v-block AM fixtures (Figure 8) to facilitate a horizontal assembly technique while increasing repeatability of the grid positioning and orientation. The fixtures included two “v-slots” to hold the grids in position during attachment of the boron rail structure, a shelf to provide a hard-stop for repeatable positioning of the fibers, and vacuum lines to hold the grids flush against the "v-slot" walls to improve parallelism between the two grids. However, in practice the fixtures did not perform to the strict tolerances required by PIs, especially in the case of grid positioning since they do not allow the assembler to bore sight down the long axis of the structure to ensure grid hole XY alignment to ±30μm.

Therefore, to decrease time per target and increase build accuracy, precision micromachined Rexolite cylinder spacers, seen in Figure 9, were used achieve critical spacing and parallelism of grid and ablator components. However, it was learned that in the case of a vertical assembly technique, the AM cone does not provide a precise enough foundation. Small irregularities that are a product of the AM process, such as cone edge warping, tend to exaggerate over the length of the target if the cone is used as the base of assembly. This was one motivation for structural re-design for 3rd generation targets. The main motivation for re-design was due to the fact that, overall, the boron fiber rail structure proved extremely challenging for achieving specified critical distances and alignment of key components during assembly.

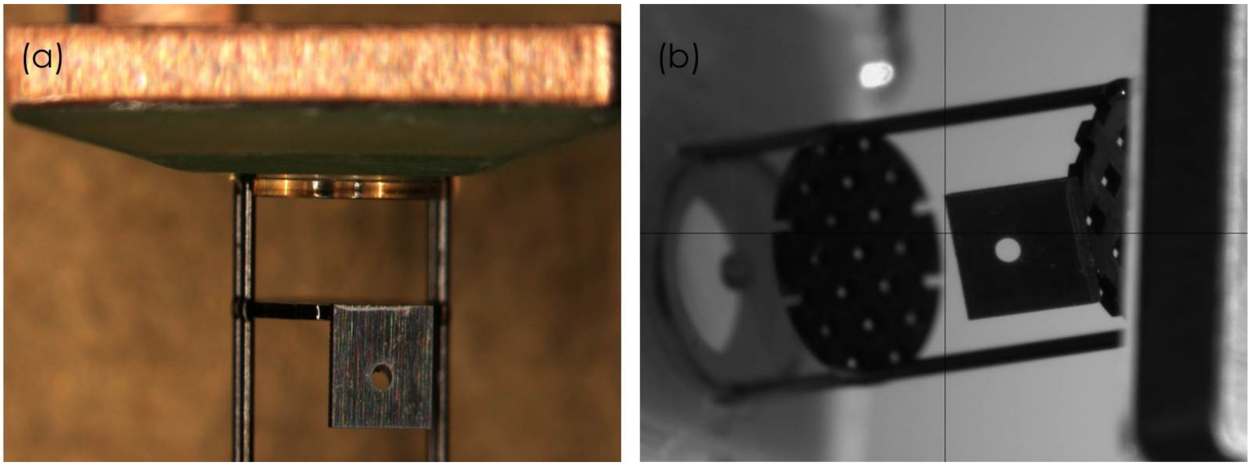

Figure 10.(a) Pinhole components were precision aligned during assembly, and (b) verified on the Powell Scope from the OMEGA TIM-3 diagnostic FOV (1462.62°, 342°) once the targets were stalk-mounted.

In order to properly align pinhole components after main target assembly, the VisRad model was utilized to determine the angle between surface normal rays of the Al pinhole shield and the cone-length Cu shield visible at the top of Figure 10(a). The target was positioned on the dial wheel of a 3-axis micromanipulator such that the Cu shield surface normal was oriented straight upwards. From this location, the dial wheel was rotated to the proper angle such that the pinhole shield surface normal should point upwards, and the component was attached in this position. Once the pinhole-type targets were stalk mounted, they were staged on the Powell Scope metrology station from the OMEGA TIM-3 diagnostic view (1462.62°, 342°) to verify accuracy of pinhole placement. The Powell Scope was also used to verify that all targets were built to ±1.5° of specified tilt and rotation assembly angles, shown in Figure 11, as well as to measure parallelism of grid and ablator components.

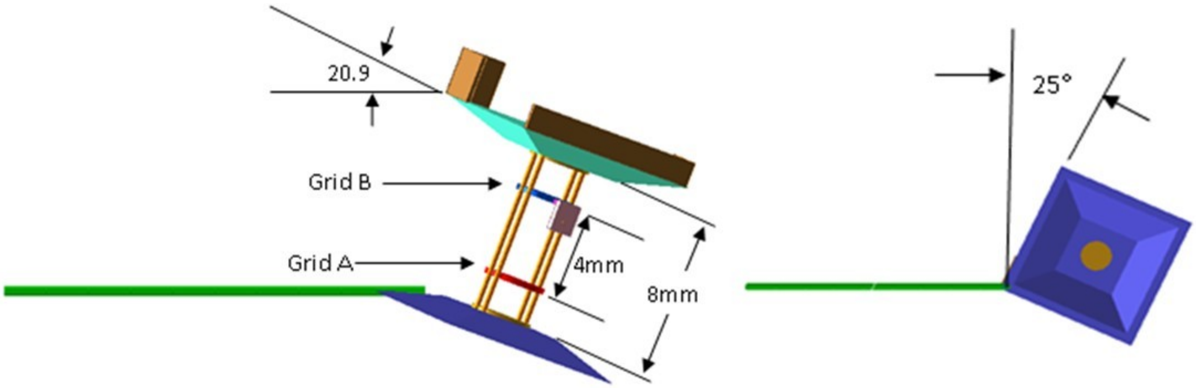

Figure 11. VisRad target model edge-on and target-normal views show required assembly angles in tilt and rotation.

Additional extensive metrology was required for proper alignment of 1st and 2nd generation targets in the OMEGA chamber on shot day. Four sets of X and Y measurements for each target were recorded using the Powell Scope and provided to the Experimental Operations (XOps) team at LLE. The XOps team then used this data to generate unique sets of reticles for each target for shot day alignment in the Target Viewing System (TVS). An example of the X- and Y-TVS views for a 2nd generation target alignment is shown in Figure 12, along with VisRad models in the same views for comparison. Due to the level of effort required for this alignment technique it was mutually determined by the PIs and the TFE after the 2016 shots that a simplified and improved alignment procedure would be pursued for shots in 2017.

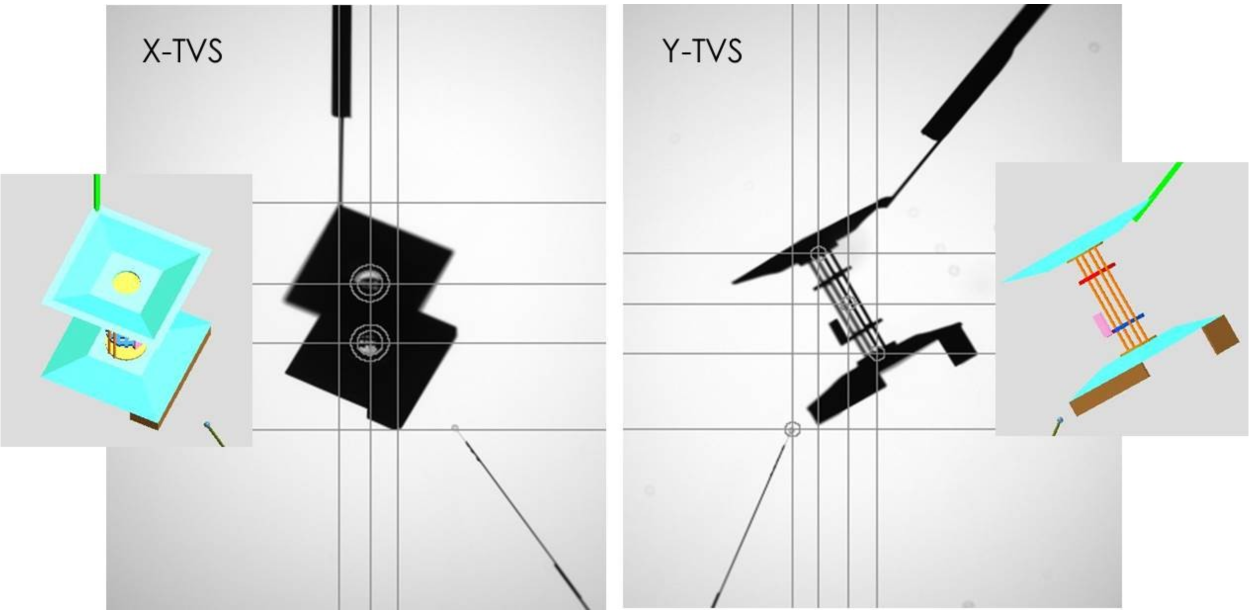

Figure 12. Target-unique alignment reticles based on metrology data were generated by LLE’s XOps team and used in the X- and Y-TVS to properly field targets in the chamber on shot day; VisRad models shown for comparison.

Assembly and alignment metrology processes were significantly improved upon and simplified for 3rd generation targets following the NIF TDYNO structural design adaptations. In addition to improving plasma jet delivery to target center, the Rexolite can shields also acted as precision spacers between the ablator packages and grids. The NIF-like target design also allowed for completion of the physics package assemblies, stalk-mounting, and Powell Scope inspection and alignment metrology before attaching the AM cone shields. A target schematic, seen in Figure 13, was provided by the PIs as an assembly aid and to ensure that all component and build dimensions were thoroughly thought out prior to finalizing orders for new components.

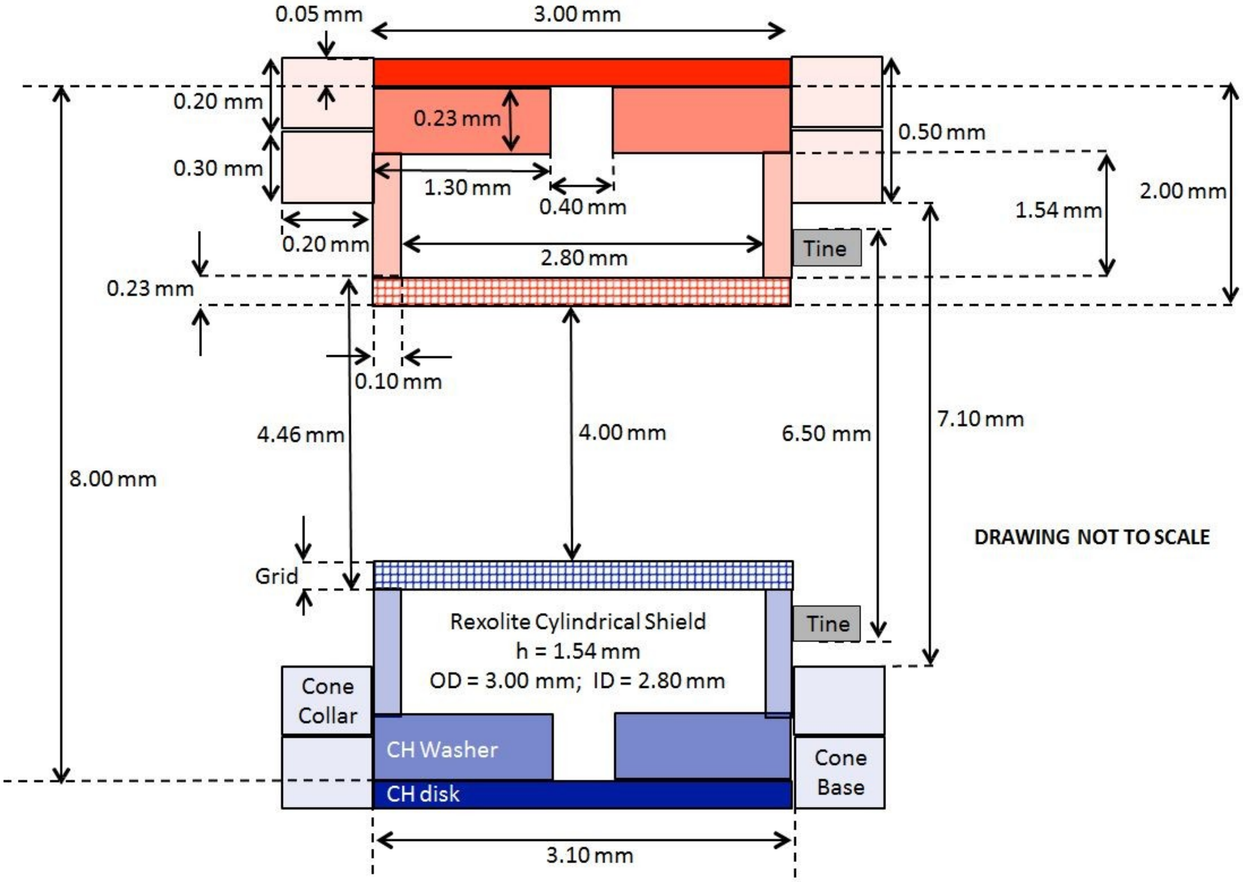

Figure 13. A 3rd generation target schematic provided by the PIs to clarify key component dimensions and critical spacing for assembly; parts labeled ‘Tine’ refer to the arms of the glass target support; drawing not to scale.

For 3rd generation targets, a mass assembly technique of the individual physics packages was employed. Packages consisted of a CH ablator disc, followed by a CH washer, a Rexolite can shield, and an A or B-style grid, as pictured in Figure 14. Once these subassemblies were completed, each A-style package was aligned relative to its B-style counterpart before mounting both subassemblies to the glass target support, again utilizing a precision machined Rexolite assembly spacer to maintain the 4mm critical distance between the A and B grid faces. A vacuum port was used to hold one package from below while a separately staged vacuum chuck on a 3-axis micromanipulator was used to position the second package appropriately. A third micromanipulator was used to bring in the drawn glass target support for attaching the packages, and a fourth held a mirror to provide the assembler with a secondary orthogonal FOV to ensure proper alignment. Once mounted to the tines of the glass support, the full structure was mounted to the main stalk at the specified tilt angle.

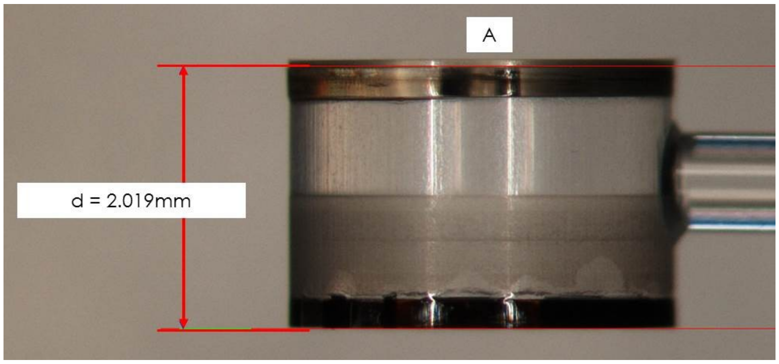

Figure 14. Physics package subassemblies consisted of (from image top down) a 0.50mm thick CH drive disc, a 0.23mm thick CH washer, a 1.54mm tall Rexolite can shield, and a 0.23mm thick Kapton A- or B-style grid. Critical spacing between the target-center face of the drive disc and grid is 2.000±0.030mm which was easily achieved for 3rd generation targets with the aid of the precision machined can shield.

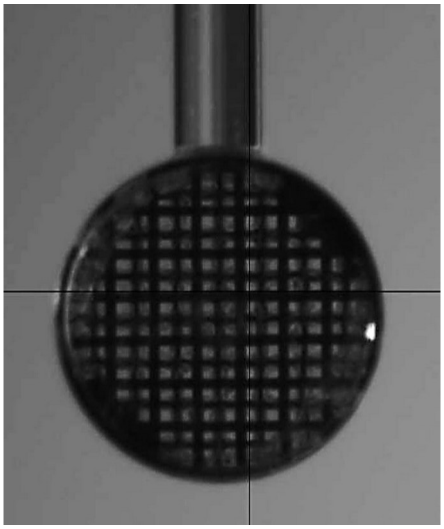

Figure 15. Powell Scope grid alignment check; the holes of one grid must be centralized over the bars of the second grid for optimal plasma mixing.

The majority of target metrology was completed prior to shield attachment, as well as all alignment metrology for successful target fielding on shot day. Figure 15 is an example image of a shield-less target from the drive disc surface normal view (31.7°, 270°), taken with the Powell Scope front camera. From this view, which bore-sights down the target long-axis, the grid alignment accuracy was measured. A second, orthogonal Powell Scope camera offers an edge-on view of the target in this position, as seen in Figure 16(a). From this view, the stalk assembly angle and critical component parallelism were measured. Once these primary metrology steps were complete, the AM cone shields and additional Cu shielding were attached to the subassemblies at the specified rotation angle. Finished targets were then re-inspected in the Powell Scope as a final sanity check for shield orientation, as shown in Figure 16(b).

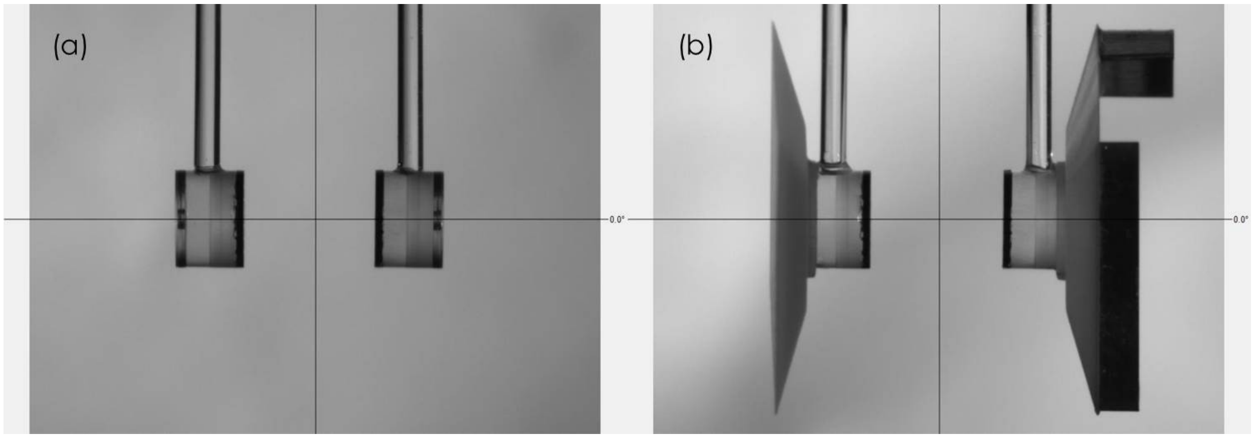

Figure 16.(a) The majority of Powell Scope metrology was completed before shield attachment to allow an unobstructed view of physics package alignment. This included all measurements for LLE’s XOps team so targets could be successfully fielded on shot day according to the new alignment procedure. (b) Targets were re-inspected in the Powell Scope as a sanity check after cone and Cu shield attachment.

The TFE coordinated with the XOps team to pursue a new alignment procedure for 3rd generation targets which would allow for higher accuracy in target fielding, while also reducing the level of effort required for metrology and the time needed to field targets on shot day. The new procedure only requires two measurements per target—one translational and one rotational—which are used in conjunction with a new ellipse reticle feature on the TVS. As a result, target fielding accuracy was significantly increased while fielding time was reduced, allowing the OMEGA operations team to run on a 45-minute shot cycle and complete a total of 15 shots to target for the TDYNO team.

IV. FUTURE CONSIDERATIONS

The University of Chicago's TDYNO experimental team has been awarded two NLUF OMEGA shot days in 2018. While much of the target design has been refined and optimized in terms of fielding and performance, the TFE and GA assembly team will work towards increasing assembly efficiency to further decrease assembly time per target. Design and testing of AM assembly fixtures will likely play a major role in achieving this goal.

For future NLUF shots, the TDYNO PIs are interested in incorporating MIFEDS[7] to observe how seed magnetic fields evolve via turbulent dynamics in the presence of an induced large-scale B-field topography. Ideas for achieving this include building key target components directly into the MIFEDS structure, or replacing the Rexolite components with Cu such that the cylindrical shields act as conductive coils.

V. CONCLUSION

Thus far, highly complex targets assembled by General Atomics for TDYNO experiments on OMEGA have helped produce a wealth of data applicable to the study of astrophysical turbulence and magnetic field amplification in the universe. Although the overall function of the target design has remained the same, the target structure and key components have evolved since the first shot day in 2015, and continue to evolve to improve target performance and quality of the experimental data. GA's assembly team and the TFE play a crucial role in the design coordination to ensure that this evolution encompasses improvements to the component fabrication and assembly processes as well.

These improvements include the exploration of various grid designs to assess properties of turbulence injection, the successful fabrication and precision-alignment of a tilted pinhole shield to investigate spatial diffusion of charged particles through proton beam collimation, the utilization of AM fixtures to prototype on a tight assembly schedule and AM components to meet target specifications at a lower cost, and most notably, the recognition and implementation of advantageous target design elements from a similar NIF TDYNO campaign.

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References

1. P. Tzeferacos et al., arXiv:1702.03016 (2017)

2. Flash Center for Computational Science at the University of Chicago: http://flash.uchicago.edu/site/

3. MagFieldPlasma-15A (14 Jul 2015) OMEGA shots: 77932-77935, 77937-77945

4. MagPlasma-16A (10 Aug 2016) OMEGA shots: 82457-82462, 82464-82469, 82471

5. TDYNO-17A (19 Apr 2017) OMEGA shots: 85250-85252, 85254-85262, 85265-85266

6. Proto Labs, Stereolithography, MicroFine Green: https://www.protolabs.com/resources/white-papers/selecting-the-right-material-for-3d-printing/

7. G. Fiksel et al., Rev. Sci. Instrum. 86, 016105 (2015); doi: 10.1063/1.4905625