Evolution of Magnetized Liner Inertial Fusion (MagLIF) Targets

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Abstract: The magnetized liner inertial fusion (MagLIF) experimental campaign conducted at the University of Rochester's Laboratory for Laser Energetics (LLE) has evolved significantly since its start in 2014. Scientific requirements and OMEGA EP system technology both have progressed, resulting in necessary and available updates to the target design. These include, but are not limited to: optimizing target dimensions and aspect ratios to maximize survival at desired pressures; coating target components to enhance physics diagnosis; precision-machining diagnostic windows along the axis of the target; improving fiducial placement reproducibility and reducing subsequent assembly time by 50%; and implementing gas-pressure transducers on the targets. In addition, target fabrication techniques have changed and improved, allowing for simpler target reproducibility and decreased assembly time. To date, eleven variations of targets have been fabricated, with successful target fielding ranging from 1 to 20atm internal pressure and a maximum survivability of 33atm.

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I. Introduction

The Magnetized Liner Inertial Fusion on OMEGA EP (MagLIFEP) project aims to understand and improve laser coupling for the laser preheat stage of the MagLIF inertial confinement fusion (ICF) scheme. The obtained data provide a systematic data set to compare to simulations, help understand sources and impact of laser plasma interactions (LPI), investigate mix introduced by laser, laser entrance hole (LEH), and tube wall interactions, and explore the effects of magnetization on plasma lifetime.

In order to obtain the desired data under the specified conditions, several target design variables may be altered. The focus of this paper is to discuss these variables and the subsequent target changes. These include optimizing target dimensions to withstand desired fill pressures, coating target components and/or placing windows along the axis of the target to aid diagnostic visualization, and optimizing fiducial placement for more accurate data analysis. Additionally, we have employed additive manufacturing [AM] (also known as 3D printing or rapid prototyping) to produce target components with high reproducibility, and improved efficiency in target assembly. Lastly, the OMEGA EP facility has introduced improvements to its target fielding systems over the course of this campaign series. Most notably, the ability to support pressure transducer targets is now available, which replaces the previous "crimp-and-seal" technique and provides the ability to monitor the pressure throughout the shot cycle.

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II. Target Design Overview

The general target design for the MagLIF series consists of a sealed tube filled with gaseous D_2, Ar, Ne or a mixture of two species. To achieve this, the ends of a tube are capped by both a polyimide laser entrance hole (LEH) window and an AM end plug through which a gas-fill tube passes. In most cases, the tube material is Rexolite®; for one experiment, it was polyimide. The AM end plug includes an accurately-positioned hole for stalk insertion at the geometrically-appropriate angle, as well as a seating surface on which the tube rests and, when needed, a rotational alignment feature. Some design iterations have called for a metal foil fiducial for spatial diagnostic reference. Polyimide-covered slits in the tube walls have also been required for spectral viewing of low-energy x-rays emitted by certain gases of interest, like Ne. Figure 1 is an overview of the overall target design progression.

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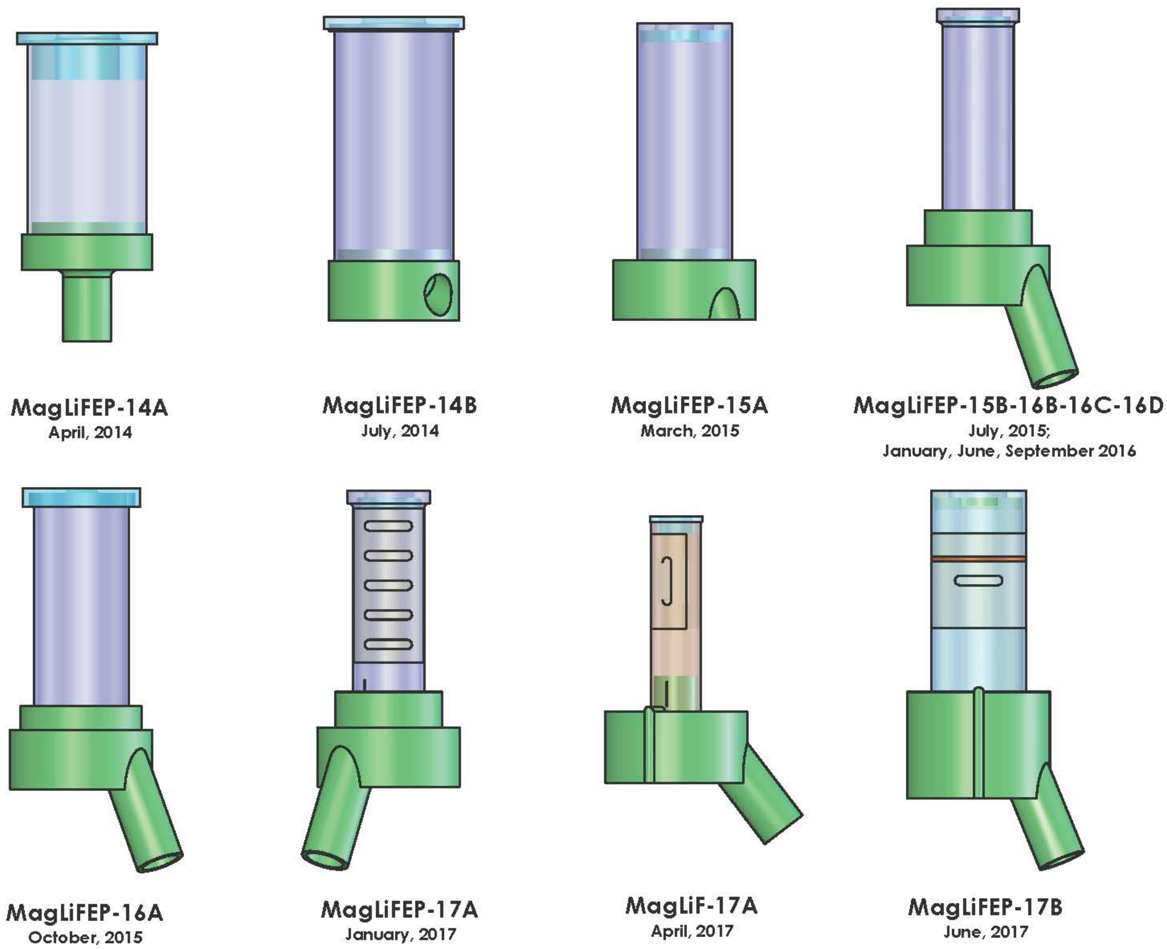

Figure 1: MagLIF target design overview. Tube length varies from 8-10mm; tube OD varies from 2.1-5mm.

II.A. Gas Tube Design Evolution

For the first campaign (MagLIFEP-14A), the gas tube began simply, as a 75µm-walled Rexolite® tube, 8mm long, 5mm OD. Nearly half of the tube was covered with an Au foil containing a slit, for x-ray shielding (Figure 2). Because the OMEGA EP facility did not yet have target pressure transducer fielding ability (discussed more later), this design utilized 650µm OD, 210µm ID Cu tubing for gas filling, which was crimped immediately after filling to seal in the gas. Also, the Magneto-Inertial Fusion Electrical Discharge System (MIFEDS)[1] was deployed for this campaign in order to magnetize the resulting plasma. Due to target alignment concerns, the target was integrated into the MIFEDS coil, which served as a target stalk (Figure 3). This marked the first time MIFEDS was used in this way.

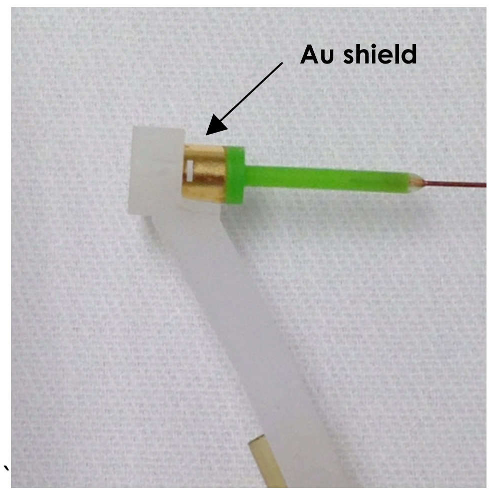

Figure 2: Target with Au shield

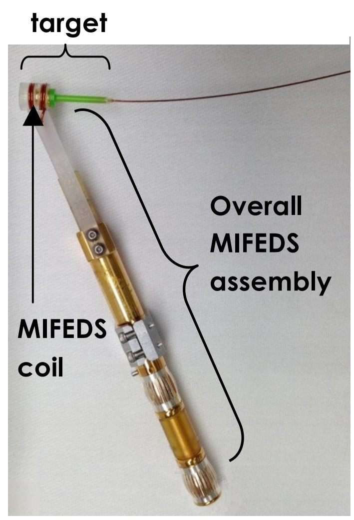

Figure 3: Target integrated into MIFEDS coil

The following campaign (-14B) did not utilize MIFEDS, so the target stalk was replaced by a stainless steel tube set into a magnetic target mount (Figure 4). This improved target stability and robustness, in addition to being a standard target mount that the OMEGA EP chamber commonly accepts. Tygon® tubing replaced most of the Cu tubing, to provide flexibility and strain relief. A small section (0.25-0.5" overlap) of Cu tubing potted into the Tygon® maintained the crimp-and-seal ability (Figure 5).

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Figure 4: Target with magnetic mount and Tygon tubing (photo credit: R. Wallace)

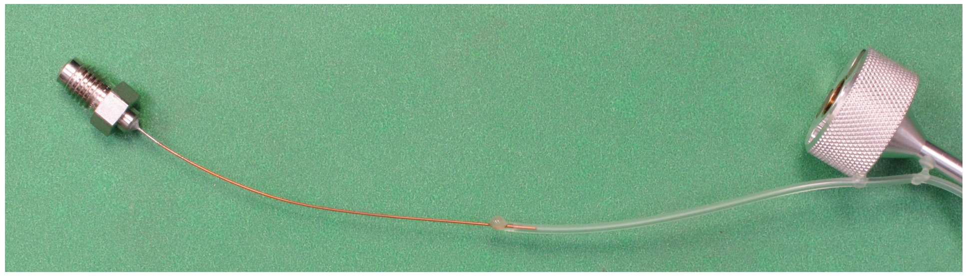

Figure 5: Cu tubing potted into Tygon (photo credit: R. Wallace)

This campaign was also the first use of the AM end plug with a stalk hole at the proper mounting angle (Figure 6). The resulting slip fit reduced the need for precision assembly. However, this design was ultimately inadequate, as the hole allowed for several hundred microns of clearance in the assembly, resulting in out-of-spec targets. The end plug was later redesigned (more on this below).

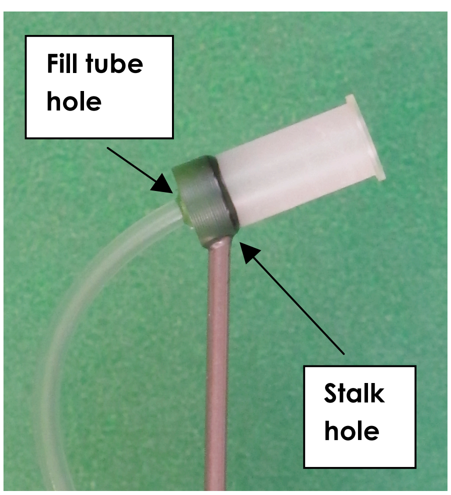

Figure 6: AM end plug with stalk hole and fill tube through-hole (photo credit: R. Wallace)

Most subsequent campaigns required small changes in the tube parameters (see Table 1 for more detail). These were made mainly to optimize the tube's aspect ratio in response to a change in desired fill pressure. To support higher pressures, the tube fabrication process changed from milling to diamond turning. Diamond turning, performed in-house at GA, reduces machining features and crack initiation sites to improve tube robustness. Specifically, diamond turning the radius of the inner corner of the tube eliminates the sharp corner produced by milling and therefore improves the strength at this point. The tradeoff is that diamond turning takes longer, as milling can be batch-processed while diamond turning must be done individually.

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Table 1: Target dimensions and details comparison

Campaign	Tube length x OD (mm) x wall (µm)	Tube coating	LEH OD (mm)	LEH window thickness (µm)	LEH coating (nm)	End plug Ti coating (µm)	Fiducial	Gas fill
-14A	8 x 5 x 80	none	2.5	2.5	none	none	Au patch on some	5 atm D_2 + 0.1%Ar
-14B	10 x 5 x 75	none	1.7 (1)	1 2	none	1	none	2 atm Ar (1)
-15A	10 x 4 x 100	none	1.3	3	20nm Ti inside	1	10µm Ti foils on some	10 atm D_2 + 0.5%Ar
-15B	10 x 3 x 115	KCl doping inside	1.3	3	20nm Ti inside, 20nm $CaCl_2$ outside	none	1.2 x 2.4mm x 10µm Ti	10, 14, 18 atm D_2 + 0.1%Ar D_2 + 0.5%Ar
-16A	10 x 4 x 100	KBr	1.3	3 and 1 (2)	20nm Ti outside, 20nm $CaCl_2$ inside	1-2	none	1.25 atm Ar 18 atm D_2 + 0.5%Ar
-16B	10 x 3 x 115	$CaCl_2$	1.3	3	20nm Ti inside, 20nm KBr outside	1	0.3 x 2.4mm x 10µm Ti	1, 10, 18 atm D_2 + 0.5%Ar D_2 + 2.5%Ar
-16C	10 x 3 x 115	$CaCl_2$	1.3	3	20nm Ti inside, 20nm KBr outside	1	0.3 x 2.4mm x 10µm Ti	18atm total, Ar amount varies
-16D	10 x 3 x 115	none	1.3	3	20nm Ti inside, 20nm $CaCl_2$ outside	1	0.2 x 9mm x 10µm Cu	10atm D_2 + 2.5% Ar
-17A	10 x 3 x 115	none	1.3	3	20nm Al on inside	1	0.2 x 4.7mm x 10µm Cu	10atm total, D_2 + 2.5% Ar + varying Ne
-17A (OMEGA)	8 x 2.1 x 50	none	1.4	2	20nm Ti inside	1	not necessary	4.1, 6.1, 9.2atm D_2 + 2.5%Ar; 1 Ar-only shot (1.2atm)
-17B	10 x 4 x 100	none	1.6 2.0 2.0 (3)	2 1.77 3 (3)	20nm Ti inside	1	12.6mm x 0.2 mm x 10 µm Cu	2.5, 4.1, 9.2, 10atm D2+2.5%Ar; 1 D2+0.5%Ar (9.2atm); Ne-only (1.25atm)

1) LEH OD was reduced because only one laser beam was used, which could propagate through a smaller diameter LEH (-14A used four laser beams). Fill pressure was reduced because pure Ar was used instead of D_2, which requires lower densities for the same opacity.
2) 3µm to study pre-pulse on LEH disassembly; 1µm for pressure scan to investigate beam bending
3) 2.0mm LEH OD with 3 µm LEH window thickness was for slit target

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A significant design change occurred for the -17A campaign, when five diagnostic slits were added along the length of the tube (Figure 7). The experimenters were interested in viewing Ne spectra but solid tube walls would absorb the low-energy Ne x-rays. Therefore, slits were laser-machined and covered by 2µm LUXFilm® polyimide film so that the spectrum could be successfully recorded.

Figure 7: Target with five diagnostic slits

To this point, all of the campaigns had been shot on the OMEGA EP laser system which delivers laser energy at a single wavelength – 351 nm. To test the effect of laser wavelength in the experiments, a campaign (-17B) on OMEGA-60 was performed, which can deliver both 527 nm and 351 nm laser light. The tube design was similar to the EP-17A design described above, in that there were slits in the tube for Ne spectrum visibility. However, in this case, three slits were positioned around the circumference of the tube rather than five slits along the length (Figure 8). These slits provide diagnostic access along multiple lines of sight at different azimuthal locations.

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Figure 8: OMEGA-60 MagLIF target, with three azimuthal slits (photo credit: E. Kowaluk)

II.B. LEH Window and Washer Design Evolution

A critical yet separate component of the gas tube is the laser entrance hole (LEH) window and mounting washer. The ideal design for this part is the thinnest possible window that allows the gas to be contained, coupled with a minimum ID washer that allows laser energy to pass through unimpeded. As the desired shot-time pressures increased, this component was analyzed and adapted to enable higher pressures. The -14A campaign started with a 2.5mm OD LEH and a 2.5µm LUXFilm® polyimide window for a target intending to hold 5atm of pressure. The next campaign (-14B) added a flange to the tube so that the LEH washer could be glued from the outside, sandwiching the LEH window between the tube and the flange. This was to provide better diagnostic line of sight to the LEH foil (Figure 9a). The next campaign (-15A) was designed to field higher pressures (10atm), so Finite Element Analysis (FEA) was used to optimize tube and LEH dimensions. As a result, the tube flange was removed and the LEH washer was inserted inside the tube and butted up against the end, eliminating the need for

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glue from the outside (Figure 9b). For the next campaign (-15B), the desired pressure was the highest yet, at 18atm. Therefore, further FEA was performed, and it was determined that a "hooped" LEH was optimal, in order to increase strength at the corners of the tube (Figure 9c). This design yielded the highest tested survivable pressure – 33atm. Several of the following campaigns (-16B, C, D, -17A) also needed to achieve high shot time pressure, so the reinforced corners continued to be used.

Due to diagnostic viewing angles and the desire to investigate LEH mix and blow off, the LEH window needed to be moved closer to the end of the tube for the -16A campaign. To achieve this, the LEH washer depth was shortened, which positioned the LEH window as close to the end of the tube as possible (Figure 9d).

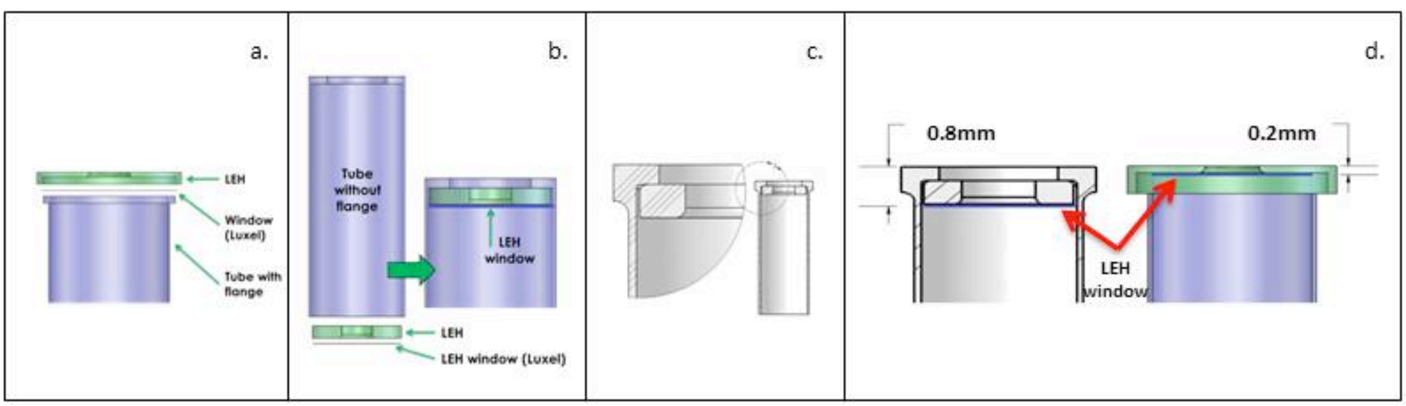

Figure 9a-d: LEH changes across campaigns: a) LEH window mounted outside of tube; b) LEH washed mounted inside tube, with no flange on tube; c) "hooped" LEH to increase strength at tube corner; d) LEH washer depth shortened

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II.C. End Plug Design Evolution

The last major component of the target is the end plug. This part serves several purposes: to seal the back end of the tube for gas-tightness, to provide a through-hole for the gas to enter the tube, and to be the stalk attachment point. Throughout this series, all designs of the end plug were made using AM with MicroFine Green by ProtoLabs[2], for increased resolution and accuracy.

When we began, the end plug needed to simply be a sealing surface as well as a mating location for the crimpable Cu tubing. MIFEDS served as the target support, so there was no stalk attachment point required (see Figure 2). As discussed previously, the second campaign utilized a magnetic mount base with a typical stalk, so the end plug was modified to include a stalk attachment hole. However, there was too much clearance in the hole so that the stalk was not held tightly or accurately. The hole was therefore redesigned to become a collar that extended out from the end plug and holds the stalk more securely. The ID clearance was also tightened up. Also in this campaign (-15B), the end plug was redesigned from a "post" to a "cup". This means that the tube sits in a recessed well rather than around a raised post (Figure 10). This is a direct result of the FEA for this higher-pressure shot day, in an effort to reduce shear and peeling forces.

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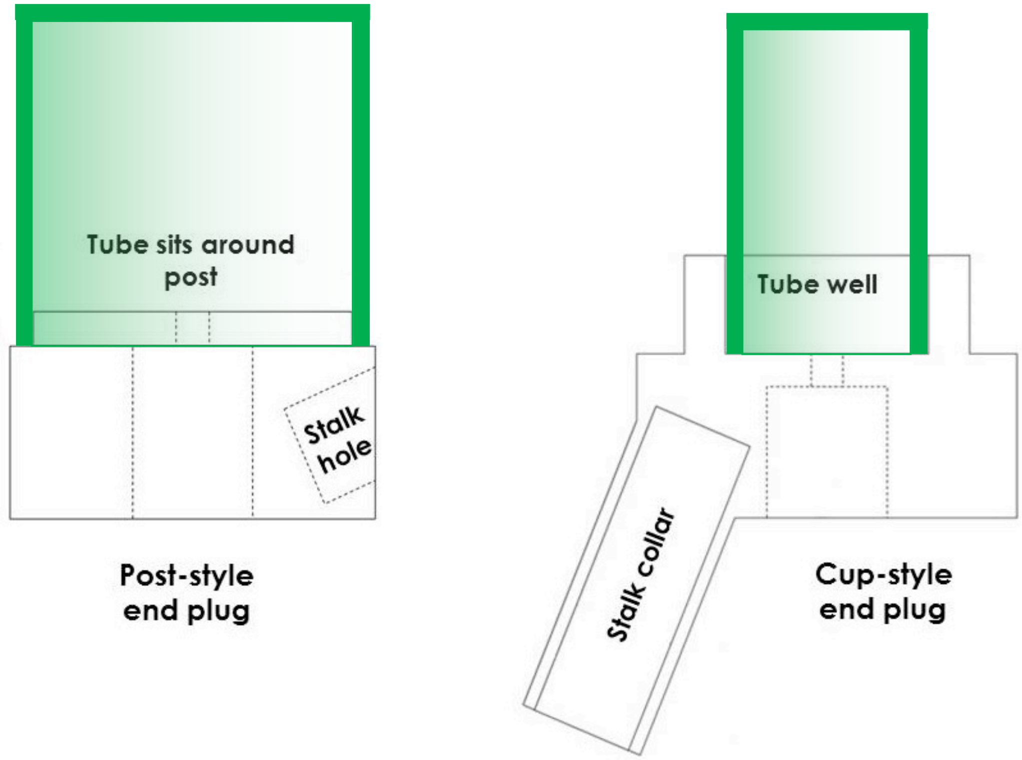

Figure 10: End plug style comparison

This design has been largely successful with <2% of pressurized target failures occurring at the end plug/tube joint. The only subsequent change was made in campaign -16B, which reduced the end plug depth to provide an extra 0.5mm of visible tube length (Figure 11).

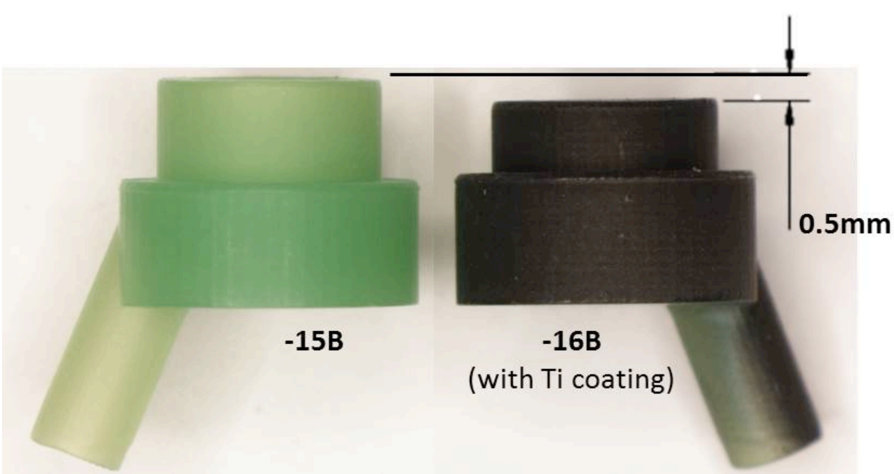

Figure 11: End plug depth comparison

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When targets with slits on the walls were developed, alignment marks were added to the tubes and end plugs in order to correctly position the slits relative to the stalk (Figure 12). This achieved the correct geometry in the target chamber.

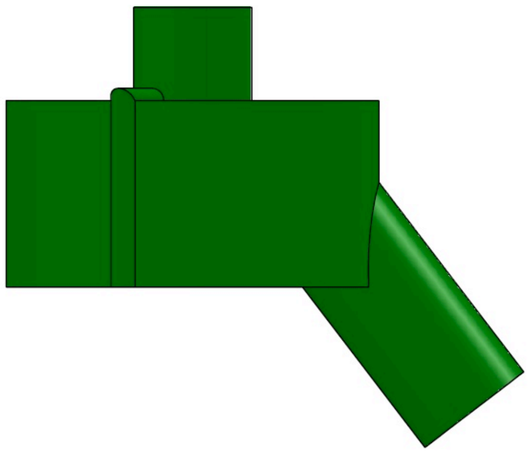

Figure 12: End plug with rotational alignment feature

III. Diagnostic Fiducial

Titanium, and later copper, strips have been added to several target designs to act as a spatial diagnostic fiducial. The dimensions of the foils vary depending on the diagnostic needs of the experiment. The minimum width of the foil is determined by the spatial resolution of the imaging diagnostics, and the foil length is determined by the range of azimuths over which the diagnostics view the target (see Table 1 for details on dimensions). From an assembly perspective, the fiducial placement can be disproportionately time consuming, taking more than a third of the total assembly time. Shorter foils are straightforward to position, but once they wrap halfway or more around the tube, insufficient assembly fixturing and tube

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manipulation were an issue. In addition, the original requested material (Ti) is difficult to manually handle at those dimensions. We therefore improved upon this process.

We changed the fiducial material from Ti to Cu, as Cu is more malleable and can be wrapped around the tube with less springback. We also created an AM jig to facilitate assembly (Figure 13). This allowed the tube to rotate on its axis, so that the foil could be wrapped around the perimeter. Arms were designed to help hold the foil in place at several points around the circumference during wrapping and positioning. The arms could be placed where needed, as there were several sets of holes around the circumference of the jig to accept the pegs built in to the arms. Overall, these changes helped to reduce assembly time by ~50%, as well as improve reproducibility between targets.

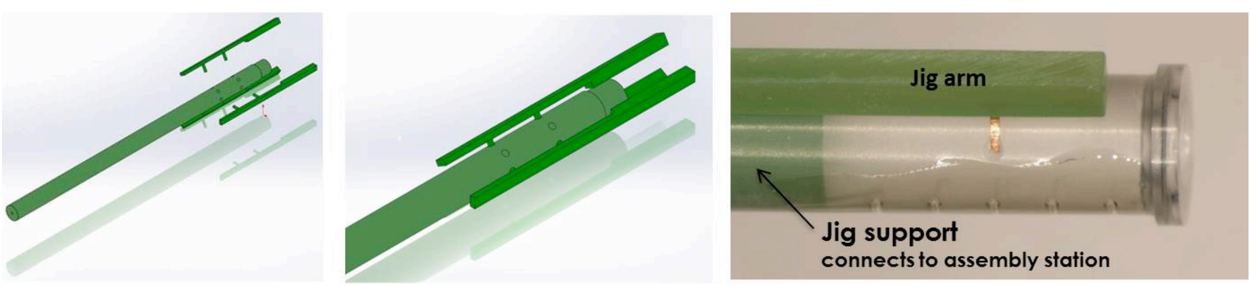

Figure 13: Fiducial assembly jig: a) exploded view b) zoomed view c) tube in place on jig

IV. Coatings

An additional variable across campaigns was the presence of a coating on various parts. The LEH window, end plug, and tube wall were all coated at points during the series. This was to

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more easily diagnose the interaction of the laser with these target components, which is not desirable. This is because MagLIF experiments are very susceptible to target surface material mixed into the gas fill. These contaminants act to radiatively cool the fuel, which results in lower temperatures at stagnation and therefore lower neutron yields. Each component had a separate coating which emitted K-shell x-rays at unique energies that could be identified with spatially resolved spectroscopy. The location of the K-shell line indicated where in the target the coating material (and therefore material from the coated surface) was present.

The LEH windows were coated at Luxel with either Ti, $CaCl_2$, or KBr. The coating surface would vary in order to examine whether the outside or inside surface of the LEH foil was being injected into the target volume.

The end plugs were flash-coated with Ti at GA.

The tubes were doped with KCl, KBr, or $CaCl_2$. This was accomplished by coating the interior wall with an aqueous solution of the desired dopant, then drying the solution to leave a thin layer of the dopant salt. The aqueous solution was prepared by dissolving the dopant salt in nanopure water. The concentration of the aqueous solution was calculated, such that the dried solution would leave a 100nm thick salt coating when injected in 1µL droplets and dried. The prepared solution was loaded into a 70µm Origio micropipette, which was then attached to a Femtojet® injector calibrated to dispense 1µL droplets. The appropriate number of droplets, based on total surface area, was then placed around the interior tube wall in a cylindrical pattern, with special care to avoid damage to the LEH coating. Once the interior tube wall was

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fully coated, the tube was placed in an air tight container with desiccant packs and dried overnight.

V. Target Fielding

An important improvement in the course of this series was related to the OMEGA EP facility's ability to support gas-filled targets. When the MagLIF effort began, OMEGA EP had no way to support gas-filled targets with pressure transducers, as OMEGA-60 could. As a result, we borrowed a technique used in planar cryogenic target operations[3] and utilized a thin copper fill tube which was crimped after target filling in order to seal the gas inside. A specialized tool from CHA Industries reproducibly performed the crimp-and-seal process. It worked very well and has been incorporated into planar cryo operations moving forward. However, this method provides no real-time pressure monitoring, which is preferred to facilitate scientific data interpretation. Confirmation that the target contains gas at shot time cannot happen until after the shot, when diagnostic spectra are available for review. There is also no way to refill a target if a leak is suspected, as the filling hardware is removed during the crimping process and the tube itself cannot be reopened.

To mitigate these issues, the OMEGA EP facility designed and employed a pressure transducer system that allows for real-time pressure monitoring, as well as target refilling, if necessary (Figure 14). These utilize Omega Engineering transducers (part numbers MMA050V5P4A1T3A5CE and MMA500VV5P2A1T3) an LLE-designed manifold and reservoir, and Swagelok quick connect fittings for easy target connection and changing.[4] This design also

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allows the transducers to be reused throughout the shot day, since they can be easily disconnected from a shot target and connected to a new one (Figure 15). This is beneficial because fewer transducers are required to support a shot day, and it also permits swapping out transducers if there is a suspected problem with the transducer itself. Issues, such as leaking or EMP-related failures, were seen in the previous transducer manifold design, but have not been encountered with this new design.

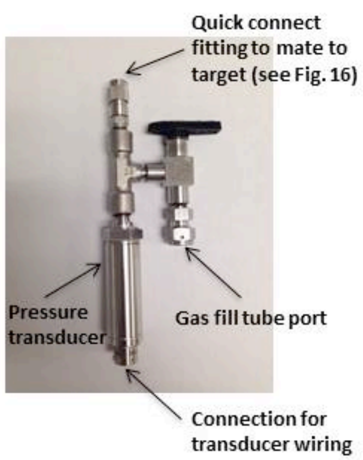

Figure 14: LLE pressure transducer system

Figure 15: Quick connect fitting for pressure transducer system

IV: Conclusion

Throughout the course of this experimental series, there have been many requested changes to the target design. We have demonstrated our ability to respond to these changes and develop targets in collaboration with scientific staff, in order to improve and optimize target parameters in support of experimental goals. Early and frequent communication facilitated testing trials to examine new target concepts and designs. The resulting target innovations enabled evolution of the MagLIFEP platform to improve the MagLIF design on Z at Sandia National Laboratories, where the idea was conceived[5]. We advanced the use of AM parts for rapid prototyping, assembly trials, jig development, and multi-functional target components. We also explored coatings for mix evaluation and laser propagation using available diagnostics on OMEGA EP, and utilized FEA to design gas tubes capable of higher pressures using requested materials. In addition, we demonstrated a target fielding option for other facilities that do not have pressure transducer capability for gas-filled targets. We have successfully fielded nearly 100 shots to date.

There were also several “firsts” in this series. We fielded the first gas-filled target on OMEGA EP, as well as the first target integrated into a MIFEDS coil acting as stalk. We utilized an AM part for gas-fill feedthrough and assembly angle. Target pressure transducers were introduced on OMEGA EP, and we demonstrated the first 18atm-capable tube target. Overall, many of these techniques can be utilized for other target designs. In addition, the crimp-and-seal technique can be applied on facilities where pressure transducers are not available, to still allow useful pressurized target information to be obtained without the additional resources required to install a transducer setup. In summary, we have demonstrated significant progress not only for the MagLIF platform specifically, but for gas-filled targets as a whole.

Acknowledgements

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