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FABRICATION OF TARGETS FOR PROTON FOCUS CONE FAST IGNITION EXPERIMENTS

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The fast ignition concept is a proposed method to reach fusion by two separate processes. The task of the first process is the compression of fuel and the second is the ignition of the compressed fuel by a rapid and directed energy deposition. One delivery method of this energy can be in the form of focused proton beams and this type of fast ignition target will be discussed. The target designs consisted of gold and plastic cones with a curved proton-generating surface (aluminum) within the cone and very close to the tip. The challenges of the given target specifications led to a new cone design consisting of a cone base and cone tip made in two pieces with the proton generating surface sandwiched between. The fabrication of these targets consisted of several steps and processes that included making PAMS shell mandrels, sputter coating deposition, electroplating, precision machining, chemical etching, and target assembly.

I. INTRODUCTION

Fast ignition is a proposed method of achieving inertial fusion by a series of steps. These steps consist of fuel compression and rapid energy deposition. By separating these processes, the requirements for fuel compression are relaxed when compared to hot spot inertial confinement fusion ignition and the energy deposition can be delivered in various possible ways and lead to a much higher energy gain.[1,2] One proposed method of fast ignition is photon hole boring[3] in which three sets of laser pulses are used. The first compresses the fuel pellet, followed by a short pulse that bores a channel through the plasma field. Finally, a third short pulse fires through the channel and acts as the spark to begin the fusion reaction. Cone focusing geometries[4] are another proposed method of creating a channel for the energy deposition necessary to begin a fusion reaction. In such a design, a fuel filled shell sits atop a gold cone. The fuel shell is compressed to the cone tip and the cone wall acts as a physical barrier between the second laser pulse and the plasma environment. This pulse reaches the compressed fuel at the tip of the cone sparking the reaction. Experiments have discovered that a short pulse laser striking a thin aluminum surface results in protons being generated and ejected from the opposite side of the aluminum normal to that surface. When the laser pulse strikes the target surface, an electrostatic field is created that ionizes a thin layer of water vapor present on the opposite side of the surface. The field is directed normal to this surface resulting in protons from the water being accelerated along this path. Therefore, by making this surface curved, it is possible to focus a beam of protons to a desired location.[5,6] A focused proton beam such as this can be incorporated with a cone focusing geometry in a new type of fast ignition target design. This design would include a fuel filled shell that sits atop reentrant cone that has a proton-generating surface located within it. Similar to fast ignition as already described above, the shell is first compressed by a set of laser pulses, followed by a short pulse that is fired into the open end of the reentrant cone. This pulse strikes the proton-generating surface creating a proton beam on the opposite side of that surface that is focused to the spot of the compressed fuel. The proton beam acts as the energy source that sparks ignition. An illustration of this type of target design is shown in Fig. 1.

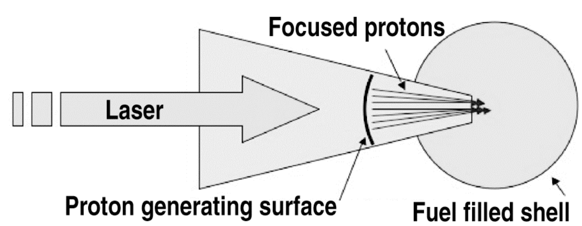

Figure 1. Illustration of cone focusing fast ignition design. A laser is shot into a reentrant cone before striking an aluminum surface from which protons are ejected to the center of a compressed fuel filled target shell.

II. EXPERIMENTAL DESIGN

The experiment utilizing the targets described in this paper proposed to study proton focusing with a reentrant cone on the Vulcan laser facility at Rutherford Appleton Laboratory. Previous experiments in proton focusing consisted of a laser hitting an aluminum hemisphere held some distance from a target foil. Results from these were used to determine desired proton focusing target characteristics and specifications such as the radius of curvature of the proton generating surface and the proton focal length. However, including a reentrant cone in a proton-focusing target, as would be required in future fast ignition experiments, may have an effect on a focused proton beam and this is what is being explored with the new targets discussed in this paper. The target design for this experiment consists of a truncated focusing cone that contains a proton-generating surface within it and a copper target foil. A diagram of the original concept is shown in Fig. 2. The goal of the experiment is to shoot the laser into the open end of the cone hitting the proton surface to eject a beam of protons that would penetrate the flat cone tip and create a focused heating spot on the copper foil. A fuel filled shell is not included in the design for these initial proton-focusing experiments. Various types of cones were to be constructed for shots, including cones that are truncated at 100 and 250 μm from the extrapolated vertex and cones that are made of both gold and plastic. The clear plastic cones were to be used by the experimenter for a better visual examination of what is happening inside the cone during the laser shot and proton generation as well as for comparison to the effect of the gold cone walls on the focused proton beam. For all cone types, the flat cone tip is a layer of 5 μm thick gold and the cones are to have a 15° half-angle opening. For all of the targets, the thin gold cone tip is used to examine any possible effects such as proton scattering as a result of the proton beam penetrating the end of the cone during the proton acceleration. The proton generating surface is a 15 μm thick aluminum surface with an inside radius of curvature of 175 μm. The design allows for the outside of the aluminum surface facing the cone opening to be rough. However, the inner surface, which would be the side from which the protons would be ejected needs to be smooth so the protons ejecting normal to that surface are properly focused. Previous experiments that studied proton focusing with aluminum hemi shells showed that the ideal target distance between the proton-generating surface and target foil was 1.7 times the radius of curvature of the generating surface. This same dimension would be implemented for this proton focusing study.

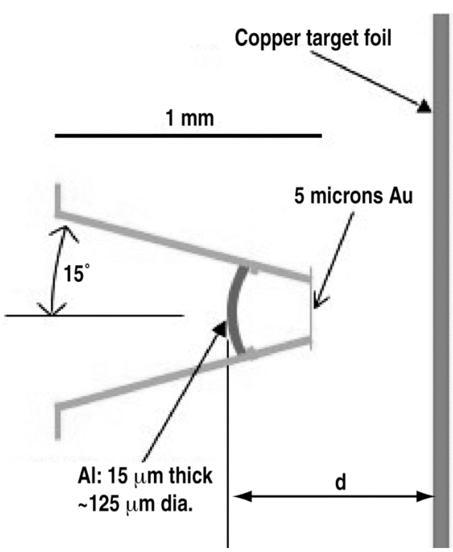

Figure 2. The proposed cone focusing target design consists of a reentrant cone with a proton-generating surface located within the cone and a target foil where the accelerated protons are focused.

The original target concept, as shown in Fig. 2, had the curved proton surface resting on a ledge on the inside cone wall. This idea seemed fairly straightforward; a cone would be made with an included ledge on the inside followed by cutting a piece from an aluminum shell and placing it down inside the cone onto the ledge, registering it into the correct position. However, due to the target dimensions, this curved aluminum surface is approximately 125 μm in diameter making it extremely difficult to handle and manipulate. Doing so would also lead to a high risk of damaging the surface. Due to this, a method of fabricating the target without having to independently make and handle the small proton-generating surface was necessary. The new target design achieving this goal would consist of a pair of cones. These cones are referred to as the base cone and cap cone. The base cone consists of the open end of the target cone extending to the proton-generating surface. The cap cone sits atop the base cone and the proton-generating surface is sandwiched between the two as shown in Fig. 3. This design successfully creates a cone target that fulfills the requirements necessary to test proton focusing for the desired experiment.

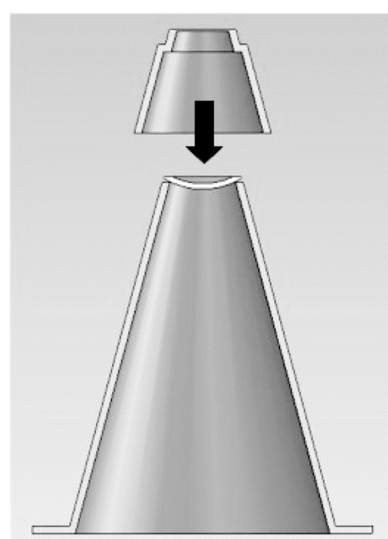

Figure 3. The adopted proton focusing target cone design consists of a cap and base cone with the proton-generating surface sandwiched between the two.

III. FABRICATION OF CONES

The first components of each target to be made are the two cones that are made through a series of machining and plating processes. Mandrels are made which will determine the inner profile of the finished cones. Starting with an eighth inch diameter copper rod, the rough shape of the mandrel is machined on a CNC lathe. A precision diamond turning lathe is next used to cut the final shape of each mandrel to the proper dimensions. The next step is coating the mandrel in the desired final cone material; gold or plastic. For the gold targets, approximately 30 μm of gold are electroplated onto the entire cone and for the desired plastic targets a clear epoxy is coated over the mandrel. To complete the machining steps for the base and cap cones, a precision lathe is again used to machine the outer profile of each target component. The space between the proton generating surface and flat tip of a completed target is a closed volume. So for each cap cone, a venting hole is necessary to allow any gas contained in the cone tip to be released when the target environment is put under vacuum for the experiment. This gas relief slot is cut into the side of the cap cone by moving the part off of the center of the axis of rotation on the precision lathe chuck. Therefore, instead of the part rotating about its own axis at the center of the machine spindle, it travels around in a circular path as the lathe spindle rotates. The diamond tool is then brought in from the side, normal to the spindle axis, and a small notch is cut out of the side of the cap cone, resulting in the necessary venting hole. The final step in making the cones is to remove the copper mandrel. This is accomplished by leaching away the copper in a nitric acid solution and what remains are freestanding gold cones.

IV. FABRICATION OF PROTON-GENERATING SURFACE

The most challenging and unique part of the fabrication of these proton-focusing cones is creating the proton-generating surface located in the tip of the cone. The target design requires the surface to be curved with the inner radius of curvature of 350 μm and thickness of approximately 15 μm of aluminum. This is achieved by sputter coating a PAMS mandrel. After mandrels have been created of the correct size, they are placed on Gel-Pak and sputter coated with aluminum from above while the mandrels remain stationary. The Gel-Pak is a thin film with a slightly adhesive surface that can securely hold the shell stationary during the sputtering process. The entire shell does not need a uniform thickness because only a small portion of the shell is actually used in the final target. Therefore, it is necessary to ensure that the crown of the shell is coated to the desired thickness. An aluminum sputter coated PAMS mandrel is shown in Fig. 4. This picture clearly shows the area that would have been facing down, on the Gel-Pak, where the mandrel is exposed. As seen in Fig. 4, the sputtered surface of aluminum is very rough. This is acceptable because the only requirement is that the inner surface of the shell be smooth so that protons ejected from this surface can be properly focused. Since the PAMS surface is smooth, this is replicated on the inner surface of aluminum.

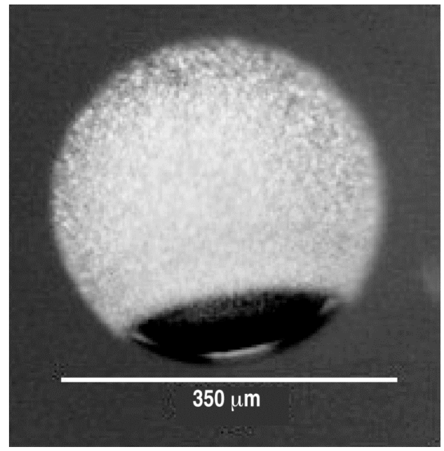

Figure 4. An aluminum coated shell with the exposed PAMS mandrel visible where the shell was not coated.

Shells are usually machined by gluing them down on a slide and placing them on a precision lathe. However, a novel method of machining the shell was necessary due to the small size of the final proton-generating surface. The goal in creating this surface was to avoid having to independently handle the surface that is cut away from the shell. To achieve this, the shell is glued onto the tip of the base cone and the portion of the shell not needed is machined away. The aluminum shell is glued onto a completed base cone with the exposed mandrel portion of the shell facing up. This ensures that the crown of the shell, with the proper thickness, is on the tip of the cone. Figure 5 shows a 1 mm base cone with aluminum shell glued on top of it next to an ant. The surface roughness on the outside surface helps here because the small pits allow the glue to securely bond to the end of the cone wall. Caution must be used in using as little glue as possible to avoid glue wicking into the inside of the cone. The center of the aluminum surface within the cone, where the laser will hit the target, must be clear of any glue. Figure 6 is a view looking into the open end of a target cone and small amounts of glue can be seen in spots around the edge.

In most target machining practices, the final target material remains on the mandrel until all the machining is complete. But in this case, in order to glue a shell onto the tip of a base cone the copper mandrel had to first be leached away so that the curved aluminum surface can sit on the tip of the base cone wall. This makes the task of machining a challenge because the cone is freestanding and a fixture is necessary to hold the cone into position on the lathe. A cylindrical copper block was made with a 200 μm hole through one side that opens up into a larger cavity. This block is put onto the vacuum chuck of the lathe and a vacuum is pulled through the cavity and hole. A cone with an aluminum shell glued onto it can now be placed over the hole in the copper block and held into place by the vacuum chuck. A cross section illustration of this is shown in Fig. 7.

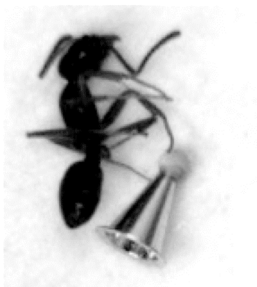

Figure 5. A 1 mm base cone with an aluminum shell glued on top of it next to an ant.

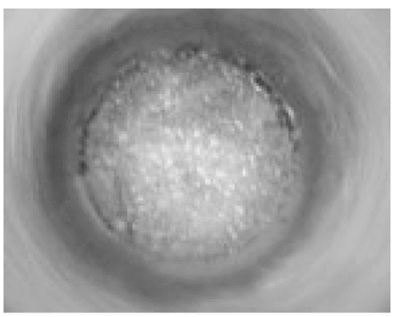

Figure 6. This is the view through the open end of a target cone that shows the rough surface of the aluminum shell glued onto the top of the base cone.

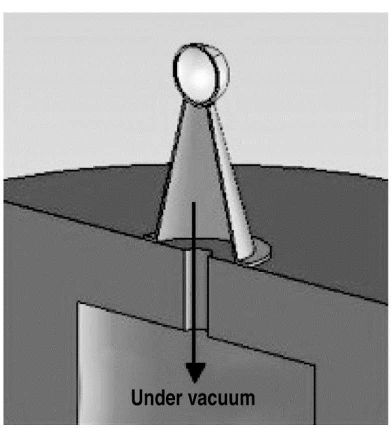

Figure 7. A cross section view of a cone on a vacuum fixture displays how the base cone is held into place by vacuum for precision machining of an aluminum shell on top of the cone.

After the target base cone is in place and centered on the precision lathe, the final machining of this cone can take place. The aluminum shell is slowly cut down by repetitive facing cuts until the cone, now including the proton-generating surface, is the proper height, which is calculated from the desired final target dimensions. Next, several cuts must be made close to the cone tip along its profile to remove any excess aluminum and glue. This is necessary to give the desired cone shape and ensure that the base cone will allow the cap cone to fit atop it when the target is assembled. After machining, the cone tip is dipped in toluene to dissolve any of the shell mandrel that may remain on the smooth aluminum surface.

V. FINAL TARGET COMPONENT FABRICATION AND ASSEMBLY

The final component of this proton-focusing target to be made is the stand that holds the focusing cone a specified distance from the target foil. The size of this stand is critical because its height determines how far the proton-generating surface, contained within the completed cone, will be from the target foil once the target is assembled. This distance must be correct to ensure that the beam is hitting the foil at its ideal focal point. A series of machining steps is used including work done by both a precision lathe and precision mill. These steps are similar to those used in machining each cone for this target. A cylindrical copper mandrel is first machined with a diamond turning lathe, followed by gold plating and final machining of the stand with further lathe and millwork. Finally, the copper is etched away in a nitric acid solution to leave the freestanding part as shown in Fig. 8.

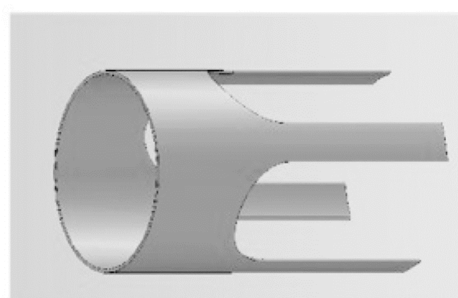

Figure 8. An illustration of a target support stand that supports the target cone and controls the distance between the proton generating surface and target foil.

All the target components requiring precision machining have now been completed and can be assembled to create the proton-focusing target. The gold cap cone is first lowered onto the base cone. The inside ledge of the cap cone sits on the flat machined edge of the aluminum proton generating surface and a few small spots of glue are applied on the outside of the cone at the bottom edge of the cap cone to hold the two cones together as one. Ultraviolet light curing glue is used for holding the components of the target together for its ease of use and short curing time. At this point, the total height of the target cone is measured to ensure that the two pieces fit together as designed. Next, the target cone is fit into the gold stand and secured with a few spots of glue. Finally, the legs of the stand are glued to the copper target foil that is glued to an aluminum mounting post. The total height from the copper foil to the top of the target, which is now the open end of the focusing cone, is measured to once again ensure that the target has all the desired dimensions. This is crucial to ensure that the proton generating surface and flat cone tip are the in the proper location with respect to the target foil. A picture of a completed target is shown in Fig. 9.

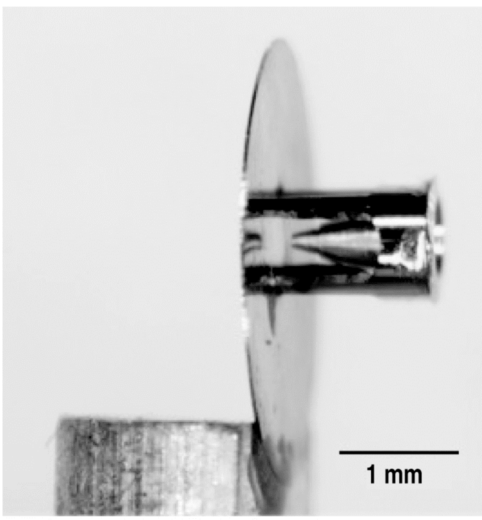

Figure 9. A picture shows a final assembled proton focusing fast ignition target glued onto a mounting post for handling purposes.

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