Liquid Targetry Developments for High Repetition Rate Experiments

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Introduction

The new £80M laser facility, the Extreme Photonics Applications Centre (EPAC) is expected to come online in 2025 and will have a unique range of high-power laser capabilities, which will usher in a new set of challenges for the supply of targets to the facility. The facility will be capable of providing 1PW pulses at a repetition rate of 10Hz which will require a least an order of magnitude increase in the rate of target fabrication. Conventionally, solid targets for high-power lasers are hand-assembled and by the nature of their size and the power of the lasers are destroyed on each shot. They are either manually replaced on a regular basis which heavily impacts shot numbers on experiment or in the best case are provided using target array systems that have limited rep-rating capability. The targetry requirements for the new facility are therefore 1) to be rapidly replenishing and 2) to minimise debris as much as possible. This represents a perfect use case of liquid targets.

Alongside the need for rapidly replenishing targets, there is interest in the development of liquid plasma mirrors which are used for pulse cleaning for ion acceleration and attosecond light pulse production [1-5]. So far, the physics behind how these thin liquid sheets are produced is well understood and the Target Fabrication Group have been developing a system capable of replicating the liquid sheets commonly used in these experiments. However, the demands of upcoming experiments require larger sheets with minimal impact on sheet thickness (up to 1cm wide and up to a few hundred nanometres in thickness). Furthermore, producing liquid targets that exactly meet the experimental demands requires a time-consuming system of trial and error through fine tuning parameters such as flow rate, nozzle geometry and liquid viscosity. This would require long lead times, expensive machining costs and considerable empirical research.

Here we outline an efficient pipeline from conception of liquid jet nozzle through to functioning part ready for use in an experimental environment. Further we explain the methodology of simulation, prototyping, validation, and manufacturing. We will highlight some of the current capabilities, the main difficulties faced and future work.

Methodology

<u>Background:</u>

There are seemingly endless approaches to producing thin liquid sheets (such as wire-guided [6], gas jet [7], fan spray nozzles [8]) but for our applications we are focussing mainly on just the colliding jet method and the converging nozzle methods as illustrated in Fig. 1. Colliding jets can be difficult to perfectly align, and the free path of the liquid travelled in air before the collision invites instabilities into the liquid sheet [9] that are otherwise avoided by the converging nozzle approach. However, the benefit of the colliding jet method makes it easy to change parameters such as angle and separation of the jets. This makes it easier to produce a liquid sheet of any given dimensions on demand whereas using the converging nozzle method, aside from adjusting flow rate, would require producing an entirely new nozzle.

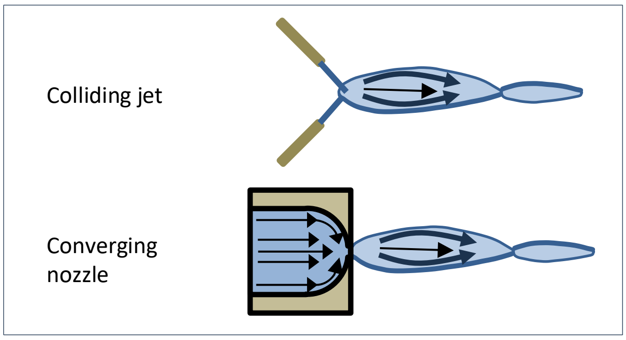

Figure 1. Two methods of thin liquid sheet production

<u>Simulation:</u>

To negate the lengthy process of trial and error in producing and testing nozzles for the desired liquid sheet parameters, COMSOL Multiphysics simulation software is being used. Although simulations are at an early stage and they are ongoing we are using the Microfluidics package for a time-dependent, level set, laminar flow simulation we are aiming to accurately predict and optimise the shape and size of the liquid sheet through a sweep of parameters such as nozzle geometry measurements, fluid flow rate, fluid properties, etc. To satisfy the extensive computational requirements, COMSOL simulations are being computed on the High-Performance Computing (HPC) cluster (SCARF) at the Rutherford Appleton Laboratory.

<u>Mathematical model:</u>

Since the mid-1900s there have been several proposed mathematical models for predicting the size and shape of liquid sheets produced from the colliding jet method. Taylor first proposed a set of equations in his 1960 paper [10], which was later built upon by Hasson & Peck [11], Bush & Hasha [12] and Ibrahim & Przekwas [13], and in 2018 Ha et al. adapted the model for sheets produced from the converging nozzle approach [14]. These mathematical models are limited in their applications since they only work for colliding jets and converging nozzles of a specific geometry. However, they can still function as a useful tool as an additional layer of verification of the accuracy of the simulation in comparison to measured values.

Experimental Setup

The liquid targetry setup itself is currently composed of a container of distilled water which is degassed using a Shimadzu DGU-403 degasser and pumped using a LC-40D peristaltic pump with a flow rate of up to 10ml/min. The water is then fed through a flow dampener and then enters the nozzle. The liquid jet is finally caught by a catcher system designed to minimise spray

(Fig 2). The nozzles are made up of two parts, one side with an engraved channel and the other with a flat surface and the inlet hole, that are bolted together to form a tight seal (Fig. 3). In the first instance, a nozzle will be 3D printed using a BMF S240 resin printer which is capable of printing parts with a 10µm resolution. This is vital for rapid and low-cost prototyping. We intend to use the printed parts as a proof of design before using ultra high precision machining methods to produce brass nozzles which are then Diamond Point Turned on the face to create a flat surface to form a tight seal when assembled.

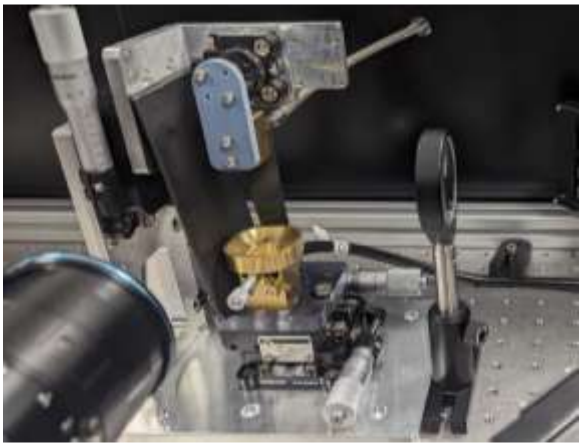

Figure 2. The liquid target nozzle and catcher system

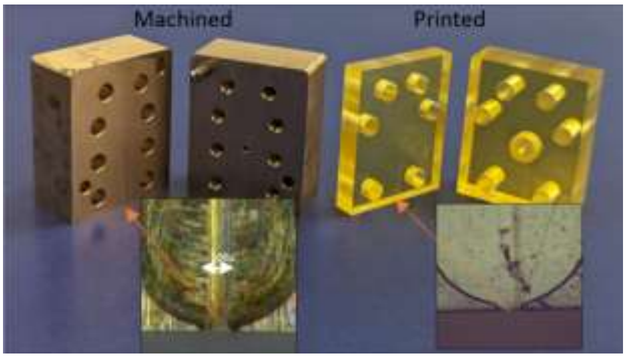

Figure 3. Setup of liquid target system with magnified images of a machined brass nozzle and a resin 3D printed nozzle.

<u>Measurements</u>

For ultrafast imaging of the liquid sheets, an iX Cameras i-speed 7 high frame rate (HFR) camera has been commissioned which is capable of capturing up to 2.45 million frames per second. From this we can observe how the sheet forms over time and assess the stability of the sheet as well as its healing rate post-shot. Using a micrometre calibration slide in the plane of the liquid sheet, we can take measurements of the length and width of the sheet. However, taking thickness measurements of the sheets poses a significant challenge.

There are several approaches previous studies have taken to acquire accurate sheet thickness measurements (such as microscope shadowgraph) with the most common approach using the interference fringes of white light reflectance [1,7,15]. Unfortunately, this method is only feasible for thicknesses comparable to and above the wavelength of the illumination source (a few hundred nm) and therefore alternative characterisation solutions are required for thinner media. Currently this method is being used to compare the stability of the liquid sheets as opposed to a direct thickness measurement diagnostic. Fig.4.

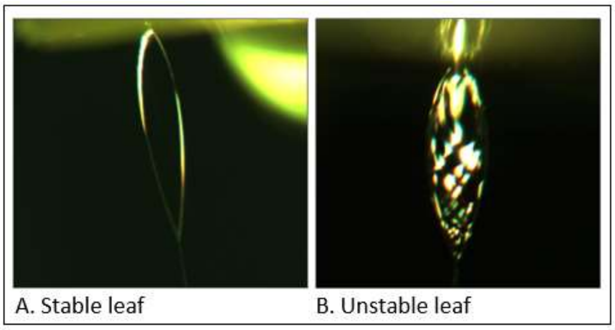

Figure 4. Interference fringes from white light reflectance for a stable and an unstable sheet

Progress and outlook

The Target Fabrication Group have successfully produced liquid leaves through the colliding jet method, although difficulty in alignment lead to instabilities and spray as well as having larger nozzle sizes such that they require a larger separation than is preferred resulting in undesirable turbulence. (A paper by Cao et al. used capillaries of 50µm diameter which enabled a much shorter free path of the liquid jet before collision of 0.9mm [9].)

As described earlier, in order to make plastic nozzles to verify simulation models, the Target Fabrication group recently commissioned a BMF S240 3D printer. This capability allows the rapid prototyping of nozzle designs which can then be machined in metal to a higher degree of precision once the design has been verified to produce a suitably stable and thin liquid leaf. Although we have yet to set up a characterisation method to precisely measure the thickness of these sheets, the sheets produced are similar in form and stability to similar systems that have been used on HPL systems [16]. It was also observed that by modifying the design to evenly distribute the clamping force on the faces resulted in considerably less leaking in both metal and 3D printed nozzles and negated the need to use any additional interface layers between the two internal faces.

Looking forward, more testing is required on the 3D printed parts. Up to this point, 3D printed designs were intended to be used as quick and low-cost prototypes. However, the impressive resolution of the printer leads to high quality, stable liquid leaves which could prove beneficial to investigate. There is a question on the resilience of such designs however to high power laser shots as well as their vacuum compatibility and so questions on the material porosity, degassing as well as heat transfer and debris mitigation are still to be addressed. Two photon polymerisation printed nozzles have been created and tested in a vacuum [17] however, to our knowledge, have yet to be tested in a high power/high repetition rate laser experiment which presents as a low risk and potentially highly rewarding proposition.

The next step in developing the setup is to install it into a vacuum chamber to assess the functional differences of the nozzles in both ambient and high vacuum environments and preparation for implementing the apparatus into the laser experiment setup. Stages to accommodate this as well as a dedicated vacuum chamber have been ordered and built respectively and are soon to be assembled.

To improve the characterisation of the liquid jets we intend to harness the capabilities of double pass white light Michaelson interferometry, as outlined in the 1987 paper by Mohanty et al. [19]. It has been shown to be capable of measuring thicknesses of thin films in the range we require[19,20].

Finally, so far, distilled water has been used for the liquid sheets, but many other studies have shown that a slightly more viscous liquid like ethylene glycol is preferable for stability [18]. For preliminary work, distilled water is suitable however future experimentation may benefit from making this shift.

Conclusion

Over the past year we have made great strides in the development of thin liquid sheets. A dedicated system has been developed to accommodate various liquid target designs such as colliding jets or liquid sheets. We also have a means to conveniently and affordably prototype converging jet nozzles using high resolution 3D printing. Although we have yet to precisely measure sheet thickness, we can currently use white light interferometry for stability analysis as well as ultrafast imaging of the sheet formation. One of the next main goals is to establish a more accurate and smaller scale thickness measurement diagnostic. Simulation of the sheet development is an ongoing progress, but now with access to the SCARF HPC cluster, we hope to see usable physical results in the near future.

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