Microdroplet target synthesis for kHz ultrafast lasers

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INTRODUCTION

Recent progress in the field of ultrafast laser science has allowed for many new experiments in the ultra-relativistic regime, with such potential applications as more versatile proton acceleration, which can be used for e.g. cancer therapy, and fast ignition of inertial confinement nuclear fusion. However, most practical applications, such as these, in addition to high intensities, also require a high repetition rate (e.g. kHz), which provides additional difficulties for the set up of the laser and the experiment. One major problem associated with high rep-rate experiments is obtaining a suitable new target for each shot, while maintaining spatial stability. Specifically, this complicates the experiments that require the higher density solid targets. Some common solid targets used include a rotating wheel that is scanned by the laser focus similar to a compact disc[4], or a metallic tape of no less than 1 μm thickness. However, it is easy to see the limitations on the types of targets that can be used with such systems.

BENEFITS OF 1 μm SPHERICAL TARGET

In this work we developed a method for producing a spatially stable heavy water droplet approximately the size of the focal spot (~1 μm radius). Since there is no substrate for the target, any conductive heat dissipation is blocked, whereas in conventional targets heat has been shown to spread to more than 100 times the area of the original interaction region in ~500 fs after the laser shot[1], which is a typical timescale considered for such experiments as fusion or for laser-cluster interactions[2, 3, 4]. Further, the absence of a substrate also allows for less dispersion of charged particles and x-rays in the target, thus yielding better proton, ion and x-ray beams[4], which can then be used to study the dynamics of the inner-target interaction[3]. Additionally, the target obtained is small enough to allow the exploration of spatially deterministic near cluster dynamics (the droplet is only about order larger linearly than the largest clusters typically used), which has not been done before[2]. Finally, the droplet produced in this work is about four times more stable than most typical solid targets used with kHz lasers, which has obvious benefits for the efficiency and accuracy of experiments.

EXPERIMENT

The experimental setup used is shown in Figure 1. Here, after the reflection from a wedge, the main laser pulse (Ti:Sapphire CPA laser with 800 nm central wavelength, 500 Hz repetition rate, and ~30 fs pulse duration) entered the vacuum chamber, where it was focused by an ~f/2.5 paraboloid (to a 2.4±0.1 μm FWHM focus with pointing instability of ±0.2 μm) onto the 5 or 30 μm diameter stream (ejected from a pulled fused silica capillary tip, with a backing pressure of ~5 MPa (exact pressure proved to be unimportant) provided by a

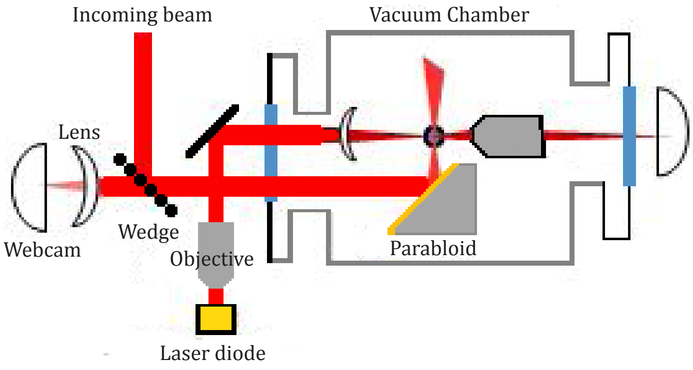

Fig 1) Experimental Setup

compressed gas), thus introducing a tiny perturbation. To ensure that the stream was centered in focus, the web-cam on the left was imaged at infinity by its corresponding lens, so that the retroreflection of the laser from the stream would focus onto the camera. Alternatively, with the 5 µm stream it was sometimes easier to simply maximize the perturbation introduced by the laser, rather than the retro-reflection. Note that the webcam-style digital camera with a pixel size of 4.13±0.15 µm met all the resolution requirements of this work.

For the purpose of imaging the interaction, a laser diode (5 mW, driven at 2.3 V with λ=670 nm, pulsed with 100 ns duration) triggered from the laser and with variable delay was focused at the interaction zone to provide illumination, which was then imaged by an objective onto the second camera (see Fig. 2). This allowed the observation of the temporal development of the perturbation or the micro-explosion introduced into the stream by the laser. At various delays and intensities, such perturbations evolved into structures such as those shown in Figure 2. Note that since the diode was pulsed at 500 Hz, while the camera only took 30 frames per second, each of these images is actually the integration ~17 distinct exposures, and thus also provides an approximation for the stability of the feature.

RESULTS

The photograph in Fig. 2(a) displays perhaps the most promising result – a sideways droplet that was shaped by surface tension 750 ns after the laser shot out of the jet ejected from the stream by the initial explosion. The smallest stable diameter measured for this droplet was 2.1±0.3 µm with droplet stability of ±0.3 µm, while its typical size varied between 2 and 3 µm between experiments (I≈3e14 W/cm^2, stream v=29±2 m/s, droplet perp. v=5.5±0.3 m/s). In photograph (b), an inline satellite is shown which forms 6.35 µs after the laser shot, and is the result of a long-term development of a minor instability introduced to the stream – note the intensity here is 3 times lower than for image (a) – I≈1e14 W/cm^2 (satellite diameter: 3.3±0.3 µm, stability: ±1.0 µm). The next two images (c and d) show potential one and two dimensional targets that could be used to match the need of a specific experiment. Image (c) shows a necking that occurs just before the stream break up – at a delay of 3.15 µs after the laser, and with even lower intensity of I≈5e13W/cm^2. Note that this necking is extremely thin and stable, with a diameter of 1.3±(≤0.3) µm and stability of ±(≤0.3) µm (these values are limited from below by the resolution of the imaging system). Finally, image (d) shows a window which is formed at just 100 ns after the laser shot by exploding the center of a 30 µm stream with intensity on the order of 1015 W/cm^2 (exact value proved to be unimportant) (thickness: 1.6 ±0.3 µm, stability: ±0.9 µm). Thus, as can be seen from comparing these four scenarios, the observed features change drastically with time delay and the laser intensity.

DISCUSSION

Several points still remain that require consideration. Firstly, all the above experiments have been carried out both in air and in low vacuum (5.8±0.5 mbar), yielding similar dynamics in both cases (except better stability was observed in vacuum), which is to be expected, as the viscosity

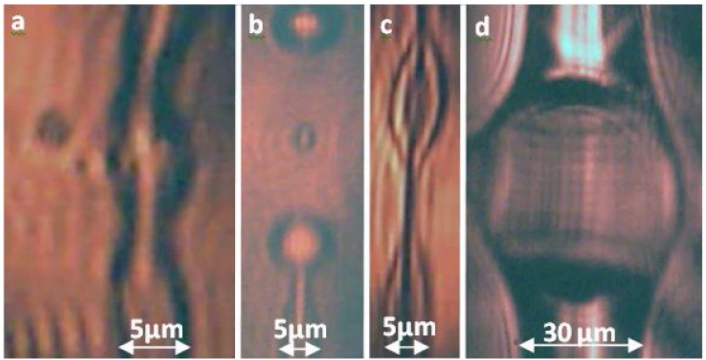

Fig 2) Various Features of 1 µm order

of air is nearly constant over this pressure range. Nonetheless, at higher vacuum levels, we can still expect the dynamics to be similar, at least at the early delays (images a and d), where the explosion shock waves and surface tension have a much stronger effect than air drag.

Second, two common issues related to water in vacuum are evaporation and freezing. When working with higher vacuum, the stream freezes upon hitting the chamber wall, forming an ice pillar that even with a 5 μm horizontal stream can reach a length of over 20 cm in a matter of seconds, potentially freezing over the nozzle. However, this problem has many possible obvious solutions. The problem with evaporation arises when the "atmosphere" of vapor around the stream is dense enough so that its breakdown disperses the main interaction pulse used for experiments. However, from simple kinetic theory considerations at water-vapor equilibrium, it can be shown that the upper limit on the density of vapor just above the surface of a 5 μm stream is $\sim 10^{-5}$ g/cm^3 – five orders less than the density of the stream itself, and thus this does not cause problems.

Finally, one might consider that instead of using the method presented in this paper, it could be possible to simply laser-machine a 1 μm hole in the side of a capillary and explode the water inside in order to push droplets out. Although such method has potential benefits, it was attempted and proved to be infeasible, as the static water inside the capillary began to boil far below the required intensity, resulting in instabilities, in addition to multiple other technical complications.

PERSPECTIVES

One of the main limitations on the method presented in this paper was the imaging technique used. The use of coherent illumination with wavelength close to 1 μm made it impossible to reliably image features much less than 1 μm in size. Specifically, in Figure 2, image (a), we can observe a small droplet-like feature of 0.8±0.1 μm diameter to the lower right of the droplet; however, there is no way to differentiate this from an interference artifact, and thus no conclusions can be made. Further, considering the mechanisms of droplet formation that were observed, the possibility of producing features significantly smaller than the size of the original perturbation seems unlikely. Thus, to investigate the possibility of obtaining targets ≤1 μm in diameter with a similar method, it is necessary to use either shorter wavelength or incoherent light for imaging, and to achieve tighter focusing of the perturbing laser.

CONCLUSION

As a result of this work, we were able to experimentally show the possibility of producing spatially stable (±0.3 μm) deuterated water droplets of 2.1±0.3 μm diameter, as well as other one and two dimensional structures of near 1 μm size along the smaller dimensions for use as a new generation of targets for high rep-rate lasers.

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