Caltech SURF 2017: LED Strobe Light for High-Speed Photography and Laser Induced Fluorescence on the Caltech Water-Ice Dusty Plasma

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Abstract

Strobe light photography has enabled ordinary DSLR cameras to become pseudo high-speed cameras and laser induced fluorescence (LIF) has facilitated improving neutral Argon temperature measurements in the Caltech water-ice dusty plasma. We sought to implement these two techniques in our cold Argon dusty plasma to image the trajectory of water-ice dust grains and to determine the neutral Argon atom temperature. The strobe light solution to trajectory imaging is an inexpensive replacement for costly high-speed cameras and was tested on computer fans as well as soldering fans to confirm the effect. The strobe was measured to have a minimum pulse frequency of 2.07 kHz and a maximum of 6.25 kHz with minimum pulse length at 60 microseconds and maximum at 159 microseconds. The LED beam was focused onto a plane that would encompass the plasma's vertical dimension and has higher power output than the previously used halogen lamp by 14%. We successfully observe LIF photons from Argon neutrals using a fully automated system, and have dramatically improved the signal from initial measurements. Going forward, we hope to combat broadening to increase the accuracy of temperature measurements.

1 Background

Plasma physics is a field of study with endless applications, ranging from nuclear fusion to semiconductor manufacturing to dense matter astrophysics. Since astrophysical plasmas are difficult to directly experiment with, plasmas are often produced in the laboratory so that they can be studied in detail.

A plasma is a state of matter that contains electrons (negatively charged) stripped away from ions (positively charged), usually in the form of a partially ionized gas. A dusty plasma is a plasma with dust grains embedded inside, which creates complex interactions between the particles [1]. For the purposes of this project, the Caltech water-ice dusty plasma is a steady-state, cold plasma made using either argon or helium gas, and contains water-ice grains in it that exhibit oscillatory motion. A diagram of the plasma is shown in figure 1.

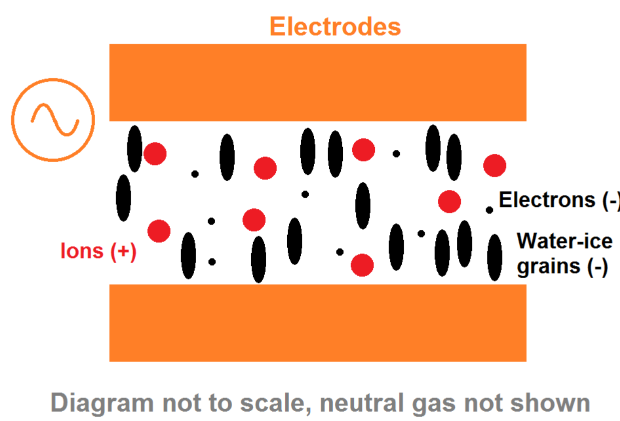

Figure 1: A diagram of the Caltech water-ice dusty plasma. A RF power source is used to generate an alternating electric field to rip apart the neutral gas atoms.

To capture the motion of the ice grains, it was previously necessary to use an expensive high-speed camera with a bright halogen lamp as the light source. The high-speed camera created large files (58.4 GB for 10 seconds of 4000 FPS video), was expensive (USD $5-figure), and had relatively low resolution (1024 x 1024 pixels) compared to modern cameras [2]. The aim of this project was to create an alternative, low-cost method to capture the motion of the ice grains using a DSLR camera with a fast-pulsing LED strobe light.

In addition to the motion capture objective, automated laser-induced fluorescence to determine plasma temperature was also a goal of the project. Photons of certain wavelengths can excite molecules such that they emit a photon of a lower energy, and lasers are a good way to produce photons of a single wavelength. By plotting the distribution of fluorescence wavelength intensities as a function of the input wavelength, a temperature reading can be obtained from the distribution [3].

2 Methods

2.1 Creation of the Dusty Plasma

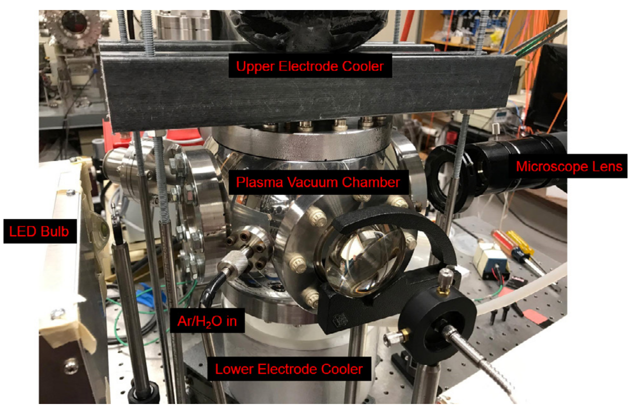

Figure 2: The dusty plasma chamber set-up. LED light passes through the plasma and into the DSLR.

Figure 2 shows the apparatus in which which we created the water-ice dusty plasma. First, we cooled the chamber electrodes for 45 minutes using liquid nitrogen in the top and bottom containers. We allowed argon gas into the chamber with a steady target pressure of approximately 500-700 mTorr. The pressure was changed by turning a knob (not shown) that controlled the cross-sectional area affected by the vacuum pump (also not shown). We ignited the plasma by having the RF power source run at 1 A and 1 V, and then adjusting the custom-built impedance matchers as necessary. To create water-ice grains, we allowed water to flow into the chamber for approximately 15 seconds using a knob-controlled valve. Ice grains would form spontaneously between electrodes, and stay there.

2.2 Strobe Light Characterization and Optimization

An LED strobe light with raw material cost of approximately USD$100 which had unknown pulsing frequency and pulse length was constructed by the lab technician and ready for characterization. First, tape was added and marked “MIN, 1, 2, 3, 4, 5, 6, 7, MAX” around the two knobs on the strobe light which adjusted pulse length and frequency. Using an oscilloscope and UDT PIN-10D photodiode, pulse length and frequency of pulsing were measured and labelled for each setting, and results taped onto the LED.

A radial intensity plot was generated using an oscilloscope and UDT PIN-10D photodiode to determine light collimation. Since the LED shipped with a default plano-convex lens, the LED-lens distance could be altered to change light collimation. The initial 10 mm separation distance turned out to be sub-optimal, and a 20 mm separation distance was best for creating a focused beam of light.

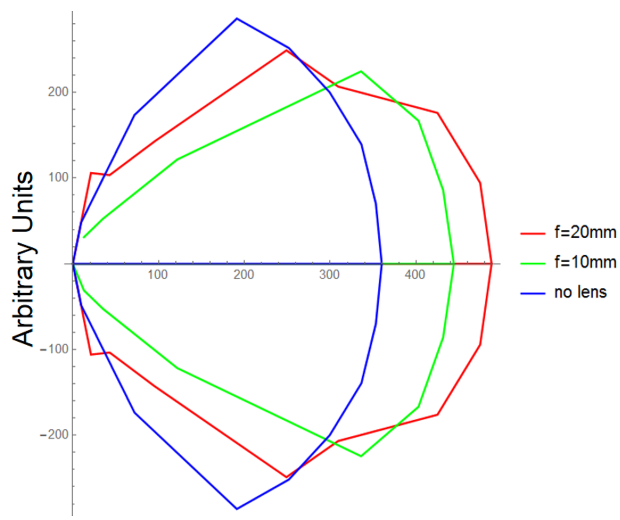

Figure 3: Polar plot of LED beam intensity, with the origin as the LED source. Measurements were only made between 0 and 90 degrees, with radial symmetry assumed.

The light was also characterized using an Ocean Optics spectrometer, and compared to the original halogen lamp used with the high speed camera (figure 4). An intensity dip around 500 nm in the LED spectrum can be attributed to the LED nature of the light. The lack of intensity after 650 nm explains the colder, bluer tint in the LED light. After 30 minutes of use, the halogen lamp became hazardous to touch, while the LED was merely warm.

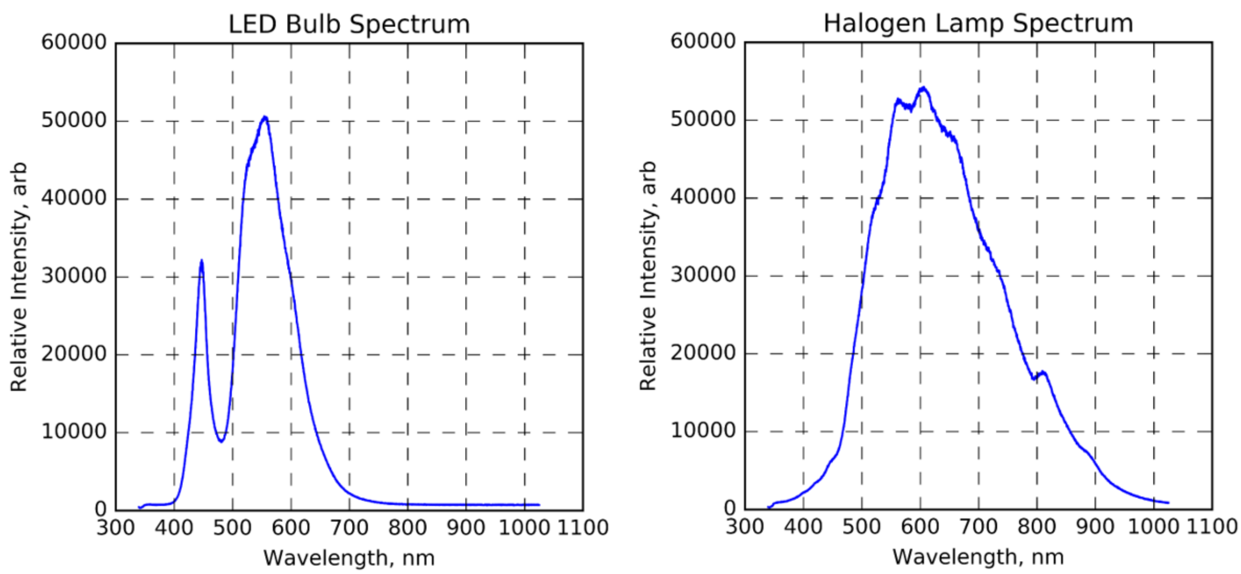

Figure 4: A side-by-side comparison of LED to halogen lamp spectra.

Figure 5: A photograph of the lens set-up for further focusing of the LED beam. From left to right, the PCX lenses have specifications of (D=40mm, F=20mm), (D=50mm, F=150mm), and (D=50mm, F=75mm).

In order to further focus the light from the LED, we used additional plano-convex lenses from Thorlabs, as shown in figure 5. By doing so, we were able to increase the LED RMS power beyond the halogen lamp RMS power at the focused region, although this turned out to be unnecessary in the actual experiment - the LED was bright enough without the lenses.

2.3 LED Strobe Light Photography

By having the LED strobe pulse at frequencies around 4 kHz and taking a photograph with exposure time longer than 1/2000 s, we can obtain a “ghosting” effect in which two frames are superimposed upon each other. For stationary objects, there is no ghosting observed, but for moving objects, the blending of two frames allows for the creation of an image that shows the motion of the object. We used a Nikon D5300 with a Infinity K2 DistaMax long-distance microscope lens.

2.4 LIF Automation and Temperature Measurement

In order to create a fully automated, one-click LIF measurement system, we used LabVIEW to (1) control and vary the input laser wavelength and (2) collect voltage data from the output photomultiplier tube. We then used a Python script to arrange the voltage-over-time data, which was saved as CSV files, and then to fit a Voigt distribution curve to the resulting distribution of average voltage per input wavelength. In order to contact the laser, which was in another lab room approximately 50 m away connected to the chamber by optical fiber, a serial-over-IP solution was attempted, but a serial-ethernet-serial solution proved to be more effective. To record the output voltage on the LIF pickup fiber-spectrometer-photomultiplier tube-boxcar integrator-BNC cable system, a USB National Instruments hub was used to connect to a BNC cable converter. The LIF input and pickup system is diagrammed in figure 6.

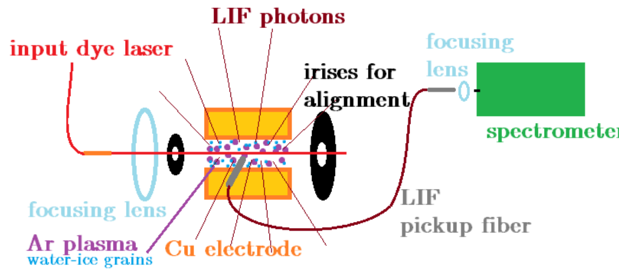

Figure 6: A diagram of the LIF set-up, with automation system, photomultiplier tube, and boxcar integrator not shown.

The package lmfit was used to fit a Voigt profile to the data, and the equation

$$T = \mu\left(\frac{\text{FWHM}}{7.71 \times 10^{-5}\lambda_0}\right)^2 \tag{1}$$

was used to calculate argon neutral temperature from the Voigt profile, where μ is the atomic mass of the argon neutral in amu, FWHM is the full width half max of the Voigt profile in nm, and λ_0 is the wavelength of the input laser in nm. This equation was derived from McChesney’s thesis [3].

3 Results and Discussion

3.1 Strobe Light Power

The result of the multiple-lens focusing shown in figure 5 was a high intensity LED beam focused onto a spot. The table of intensities measured using the PIN-10D photodiode is shown below:

Configuration	RMS Voltage
6.25 kHz LED @ 159 µs pulse len.	523 mV
Halogen Lamp	460 mV
Sun in lab room	421 mV

Table 1: The table of RMS Voltages generated from the PIN-10D photodiode and various sources of light.

It is important to note that the measured voltages are displayed as RMS voltages, and perhaps it would be more fitting to measure the Pk-pk voltages due to the strobing nature of the LED light. This is because only the intensity of the light when the light is **on** matters for photography, and a RMS voltage takes into account the zero intensity of LED light when the strobe light is off.

3.2 Strobe Light Photography

The strobe light was first tested on a CPU fan and the strobe effect was observed. Figures 7 and 8 show the fan in both stationary and spinning modes.

Figure 7: A photograph of the CPU fan while it was stationary. LED @ 2.1 kHz, 1/400 s exposure time.

Figure 8: A photograph of the CPU fan while it was spinning with an idle CPU. LED @ 2.1 kHz, 1/125 s exposure time.

An interesting calculation that can be made from figure 8 is the rotation frequency of the CPU fan. A picture taken with the same LED setting at 1/100 s exposure time showed no black gaps between the blades, so we can assume that the blades move 1/7 of a circle (there are 7 blades) in 1/100 s. From this, we know the period of the fan is 7/100 s, and thus the rotation rate must be $100/7 = 14$ Hz, which is reasonable for an idle CPU. Additionally, since we can count 17 blades per blade group (7 blade groups total), and the exposure time was 1/125 s, we know that there must be 17 flashes of light in 1/125 s. 1/125/17 s would be the period of the pulsing, and its reciprocal (2125 Hz) would be the frequency, which matches the calibration of the strobe light at 2.1 kHz for that knob setting.

When applied to the dusty plasma, strobing effects were observed as well, and the motion of the ice grains matched previous results - primarily up-down oscillations, with minimal left-right movement. A scale was created by taking a photograph of a microscope scale, and the velocity of the particles determined using the equation

$$v = d/t = d/(1/f), \tag{2}$$

where v is the velocity, d is the inter-strobe distance measured with ImageJ and the scale's pixel-to-meters ratio, t is the inter-strobe time, and f is the frequency of the strobe light.

The velocity measurements also fall into the velocity ranges measured in the group's previous paper [2], suggesting that the strobe light-DSLR combination is a functional alternative to the high-speed camera. The results are shown in figures 9 and 10.

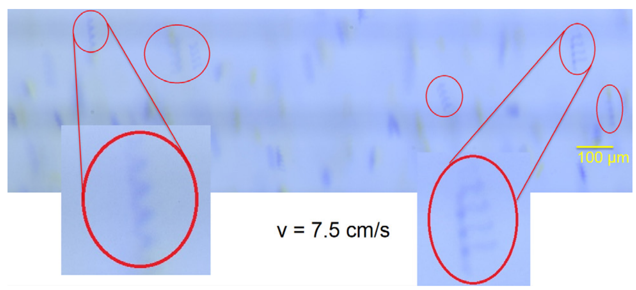

Figure 9: A photograph of the dusty plasma. LED @ 3.7 kHz, 1/1000 s exposure time.

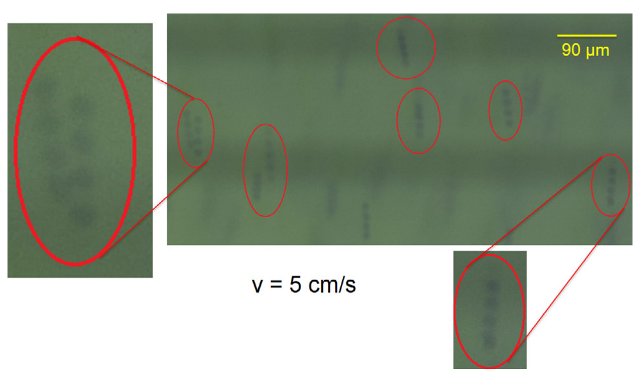

Figure 10: A photograph of the dusty plasma. LED @ 3.7 kHz, 1/1000 s exposure time.

3.3 LIF Temperature Measurement

Using the following intensity distribution (figure 11) obtained from the LIF measurement system, we have a temperature measurement of 5.6 eV, which is still too high to be accurate. There are several possible reasons for this: laser power broadening, spectrometer instrumental broadening, and poor dye laser tuning. All are possible but difficult to fix with the current set-up, and the replacement of the dye laser with a diode laser will likely solve the power broadening and laser tuning problems. The replacement of the spectrometer with a filter will also help in the future.

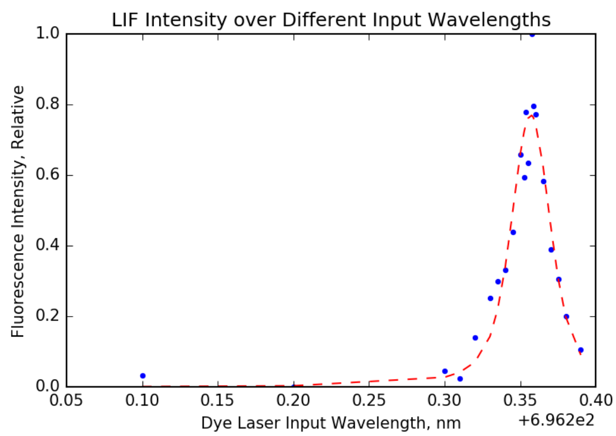

Figure 11: A scaled intensity plot of voltage to input wavelength. Broadening towards the base of the distribution can be seen, and a sharp peak at 1.0 relative intensity, which cannot be fitted with the broadened base, can also be seen.

4 Contributions, Limitations, and Future Research

A low-cost (approximately USD$100), small-storage, high resolution (6000 x 4000 px) alternative to the high speed camera was characterized, optimized, and applied to the Caltech water-ice dusty plasma experiment. An automated LIF temperature measurement system was also constructed for the experiment.

Although the alternative high speed camera was somewhat successful, there are several key limitations that prevent it from being used extensively:

1. At longer exposure times (1/200 s, 1 s, 10 s, etc), the number of strobe ghosts does not change; this is most likely due to the shallow depth of field of the microscope lens, as the dust grains will quickly move in and out of the plane of focus. In this respect it inferior to the expensive high speed camera which can take a video for 10 s.
2. The lack of time data means it is impossible to know which direction the dust grains move in (up or down), although it is possible to know that they are moving in the up/down direction most of the time.
3. It is not stable in that the strobe effect is difficult to capture every single time.

The LIF system has an ultimate goal of being able to measure a 3D temperature profile of the entire plasma, so the limitations of the current system are:

1. It only sees a single point in space, and any slight movement of the aligned optical fibers will result in no signal being detected. To obtain a 3D profile, a scanning mechanism must be developed.
2. It suffers from broadening, and a laser replacement may be able to fix it.
3. It measures the temperature/velocity along only one axis, the horizontal axis. Ideally, a temperature measurement in all 3 axes would be possible.

5 Acknowledgements

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