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Ion Acceleration by Laser Plasma Interaction from Cryogenic Microjets*

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Processes that occur in extreme conditions, such as in the center of stars and large planets, can be simulated in the laboratory using facilities such as SLAC National Accelerator Laboratory and the Jupiter Laser Facility (JLF) at Lawrence Livermore National Laboratory (LLNL). These facilities allow scientists to investigate the properties of matter by observing their interactions with high power lasers. Ion acceleration from laser plasma interaction is gaining greater attention today due to its widespread potential applications, including proton beam cancer therapy and fast ignition for energy production. Typically, ion acceleration is achieved by focusing a high power laser on thin foil targets through a mechanism called Target Normal Sheath Acceleration. However, this mechanism is not ideal for creating the high-energy proton beams needed for future applications. Based on research and recent experiments, we hypothesized that a pure liquid cryogenic jet would be an ideal target for exploring new regimes of ion acceleration. Furthermore, it would provide a continuous, pure target, unlike metal foils which are consumed in the interaction and easily contaminated. In an effort to test this hypothesis, we used the 527 nm split beam, frequency-doubled TITAN laser at JLF. Data from the cryogenic jets was limited due to the flow of current up the jet into the nozzle during the interaction, heating the jet and damaging the orifice. However, we achieved a pure proton beam with evidence of a monoenergetic feature. Furthermore, data from gold and carbon wires showed surprising and interesting results. Preliminary analysis of data from two ion emission diagnostics, Thomson parabola spectrometers (TPs) and radio chromic films (RCFs), suggests that shockwave acceleration occurred rather than target normal sheath acceleration, the standard mechanism of ion acceleration. Upon completion of the experiment at TITAN, I researched the possibility of transforming our liquid cryogenic jets into droplet streams. This type of target should solve our problems with the jet as it will prevent the flow of exocurrent into the nozzle. It is also highly effective as it is even more mass-limited than standard cryogenic jets. Furthermore, jets break up spontaneously anyway. If we can control the breakup, we can synchronize the droplet emission with the laser pulses. In order to assist the team prepare for an experiment later this year, I familiarized myself with the physics and theory of droplet formation, calculated values for the required parameters, and ordered the required materials for modification of the jet. Future experiments will test these droplet streams and continue towards the goal of ion acceleration using cryogenic targets.

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I. INTRODUCTION

Recent advancements in laser technology have contributed to increased interest in ion-beam acceleration by laser-plasma interaction. With high energy and charge, ion beams have widespread potential applications, including cancer therapy, fast ignition for energy production, injectors for accelerators, and simulations of stellar matter conditions[8]. Scientists are hopeful that further investigation of ion acceleration will lead to greater understanding of the mechanisms behind it, allowing it to ultimately be used for these exciting applications.

Ion acceleration is usually accomplished by focusing the laser pulse onto a solid density foil target. However, this method is not necessarily the most effective. Based on recent experiments, we proposed that a pure liquid

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near-critical density jet would be an ideal target for this interaction. Capable of producing the highest proton energies possible with todays laser technologies, it will enable us to investigate new, more efficient regimes of ion acceleration. Furthermore, it would provide a pure, continuous, mass-limited target that will not be subject to problems like energy spread or contamination.

This summer I was fortunate enough to participate in an experimental campaign intended to investigate this proposal. It took place at the Jupiter Laser Facility (JLF) at Lawrence Livermore National Laboratory (LLNL). We used the Titan laser to explore ion acceleration in high intensity laser plasma interactions. The majority of the team members were SLAC employees in Siegfried Glenzer's group, but there were also scientists from LLNL and other institutions.

The goal of this experimental campaign was to accelerate protons in high intensity laser plasma interaction from liquid hydrogen and deuterium targets, and subsequently characterize the acceleration mechanism. Specifically, we wanted to create a pure proton beam, monoenergetic features, and high energy protons. While we had success in many areas, the jet targets were not as successful as we had hoped they would be. Nevertheless, we came away from Titan with novel and interesting data, as well greater knowledge about the jet.

Although we experienced obstacles with the jet, we are still hopeful that this type of target will yield important results in the future. Since one of the main problems with the jet is instability and breakup caused by the flow of current up the jet into the nozzle, one avenue worth exploring is controlled droplet breakup. Upon returning to SLAC, I spent my time investigating this possibility. I researched the theory behind Rayleigh breakup in liquid jets, and looked into how we could drive this process with the piezoelectric effect. My research yielded some good theoretical considerations and starting points, but as I discovered, piezo-driven droplet breakup leaves much up to trial and error.

In this piece I will first outline the experiment at Titan, the methods and diagnostics we used, as well as some preliminary results. I go on to describe my findings regarding piezo-driven jet breakup. I conclude with a few reflections on what I have learned in my time at SLAC and LLNL.

II. TITAN EXPERIMENT

The three goals of this experiment were, specifically, to create a pure proton beam, monoenergetic features, and high energy protons. We were interested in investigating methods of ion acceleration other than the standard mechanism, Target Normal Sheath Acceleration (TNSA). This mechanism does not provide the purity, narrow energy spectrum, or high energy levels that are required for exciting applications of ion acceleration. For this reason, we want to investigate a method called Collisionless

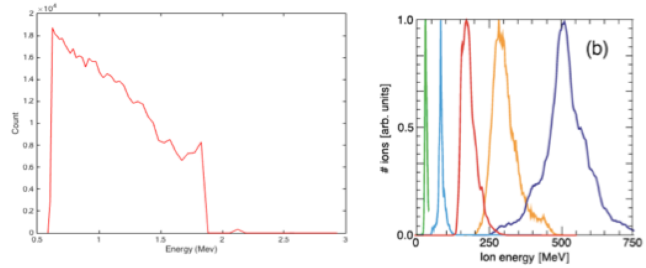

FIG. 1. (Left) This is an example of the energy spectrum given by TNSA. Note the low energy cutoff and continuous decrease in energy. (Right) This is simulation data of CSWA. Note the high energies and peaks in number of ions at specific energies.

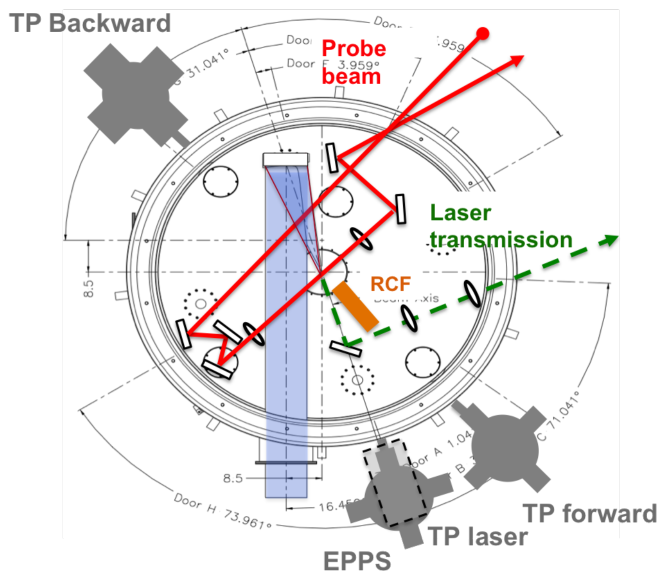

FIG. 2. This is a top-down drawing of the Titan target chamber setup. Note the target chamber center and location of the diagnostics.

Shockwave Acceleration (CSWA), that, based on simulations, is believed to be better than TNSA in each of these respects. See Figure 1.

A. Methods

1. Laser Specifications

We used the west beam laser at Titan, a short pulse, split-beam laser with a pulse duration of about 1 picosecond. The diameter of the beam at best focus was 10-15 microns due to shot-to-shot fluctuations. This variance also translated into the energy on target varying between 40 and 65 joules. The peak intensity was about 5e19 W/cm2. The wavelength was 2w or 527 nm, which means that it was a frequency-doubled laser. This is important because it allowed us to achieve good contrast below 1e-9 intensity (below the diagnostic detection limit) meaning there was almost no prepulse before the laser actually hit the target. Since we were using thin targets for some shots, this was crucial in ensuring that the target would not be destroyed before the shot even took place.

2. Setup

The experimental setup was rather involved, and was in fact one of the more complicated to have been used at the Titan facility. The large target chamber has seven side ports, three of which we fitted with Thomson parabolas, a type of ion energy spectrometer. Above the target chamber we mounted the cryostat, connected to a large vat of liquid helium. Several breadboards surrounding the target chamber were fitted with various optics and streak cameras. Inside the chamber were more optics (mirrors, irises, lenses, etc.), RCF mounts, objectives near the target chamber center, as well as various installments for viewing and stabilizing the jet. See Figure 2.

3. Targets

An experiment in a facility such as Titan consists of setting up a target inside the target chamber, hitting it with a laser, and measuring various aspects of the interaction. Therefore, one of the most crucial aspects of an experiment is the target.

We had three categories of targets for this experiment. The most exciting and novel targets were the hydrogen and deuterium jets (see Figure 3). I was very involved with setting these up, and learned that it is very technical and detail-oriented work. It involves cooling the cryostat with liquid helium, liquefying the hydrogen or deuterium gas by passing the line through a dewar of liquid nitrogen, and pumping this liquid into the cryostat. Ideally this creates a pure, steady, continuous stream of cryogenic material that flows but has a nearly solid outer sheath. Then, one must align the jet to the target chamber center so it can interact with the laser during a shot. The cryostat was mounted on one of the top ports of the chamber, at an angle of 30 degrees from the vertical and 27.29 degrees from target normal in the laser plane. Unfortunately we had many issues with these jets, including clogged nozzles, instability, and problems with alignment. Despite the team's experience with jets, we were only able to successfully hit a jet three times.

We also brought gold and carbon wire targets of various thicknesses for use in this experiment. We thought wire would be useful because it mimics the cylindrical shape of the jet. However, the data from the wire proved to be interesting in itself.

Finally, we brought 50 micron CH and CD foil targets as backups.

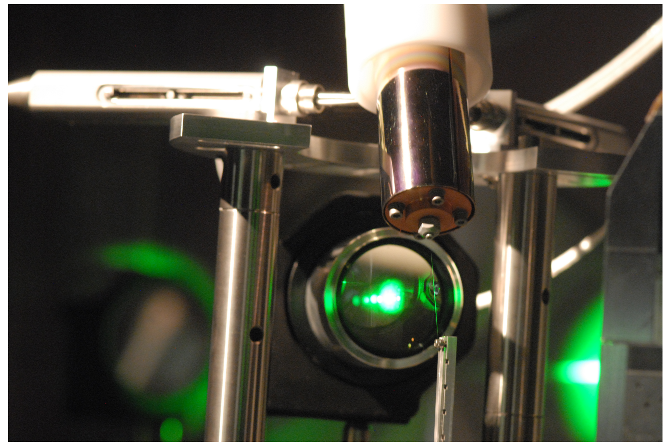

FIG. 3. This is a photo of the successful hydrogen jet from the Titan experiment.

4. Diagnostics

Thomson parabola spectrometers were one of the successful diagnostics we used, and another aspect of the experiment that I was very involved with. There were three TPs, each attached to the exterior of the target chamber by gate valves so that they could be independently vented and pumped down to vacuum. They were located at A, B, and G positions, corresponding to laser axis, target normal forward, and target normal backward. In each chamber was a b field, an e field, and an image plate (See Figure 4). The b field deflects vertically based on energy; faster particles spend less time in the field, so are less deflected, therefore hitting the image plate towards the top. The e field deflects sideways based on charge-to-mass ratio; higher charged particles are less deflected, hitting the image plate close to the center. The image plates thus capture useful information about the interaction, including the species accelerated, the energies reached, and the concentration of ions at each energy. They are scanned, erased, and replaced between shots.

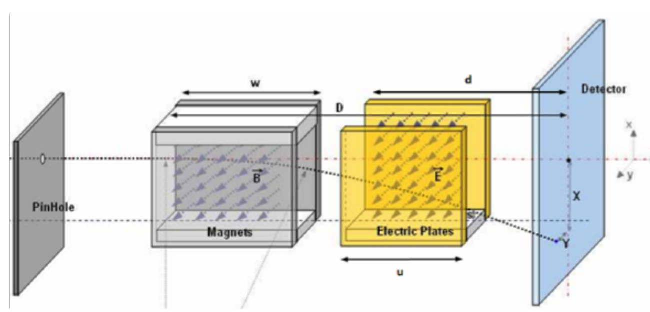

FIG. 4. This is drawing of how a Thomson parabola spectrometer works.

The other successful diagnostics that I worked with were radio chromic films. These are stacks of film placed in a strategic location in order to give a rough 2D image of the emission spectrum in that direction. This is not a terribly precise diagnostic, but it is simple, informative, and reliable. The two main types of information they provide are the level of energy of the ions (depending on how many layers are affected) and the quantity of ions (depending on how dark the layers are more opaque means more ions). They are affected by both electrons and protons, but the effect of the electrons is less intense and differs less between layers than the effect of protons.

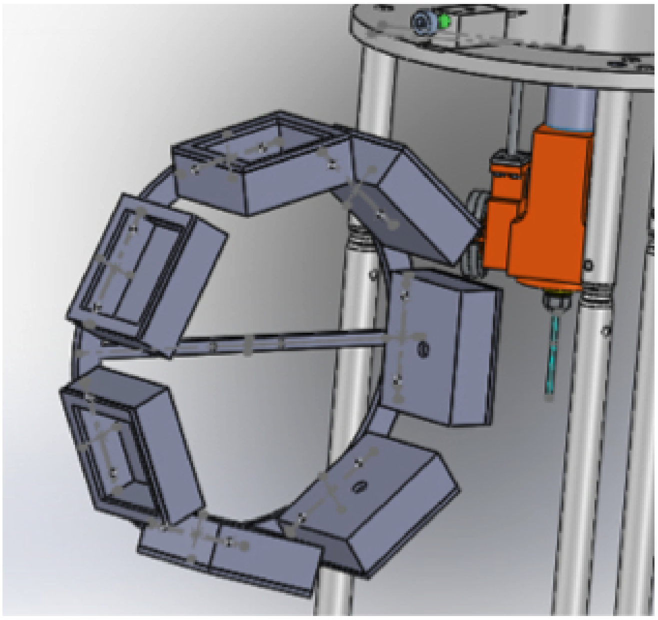

FIG. 5. This is drawing of the windmill setup of the RCFs.

We used two main setups for this diagnostic. We used a windmill in the target normal forward direction (see Figure 5). Six stacks of RCFs were attached to this, meaning we could perform six shots before needing to vent the target chamber. These RCF stacks each had a hole in the center, through which the ions could pass . This was to prevent the RCF from interfering with the TP diagnostic in the target normal forward direction. Towards the end of the experiment we used a cylindrical drum arrangement (see Figure 6). This only allowed one stack of RCFs to be loaded at a time, meaning we could only perform one shot before venting the chamber. Furthermore, the RCF surrounded the target chamber center, meaning that no other diagnostics would yield data for that shot. However, it gave very useful information since it captured the emission spectra in nearly every direction (other than the direction from which the laser came).

B. Results

The data from this experiment has not yet been fully analyzed, but we can tentatively say that we found very interesting results. The jet was not as successful as we had hoped, unfortunately. We were able to get two good

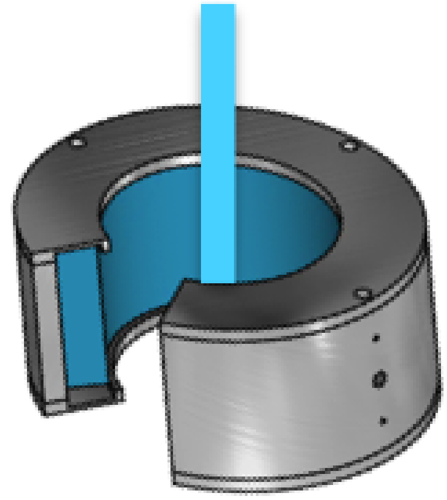

FIG. 6. This is drawing of the drum setup of the RCFs.

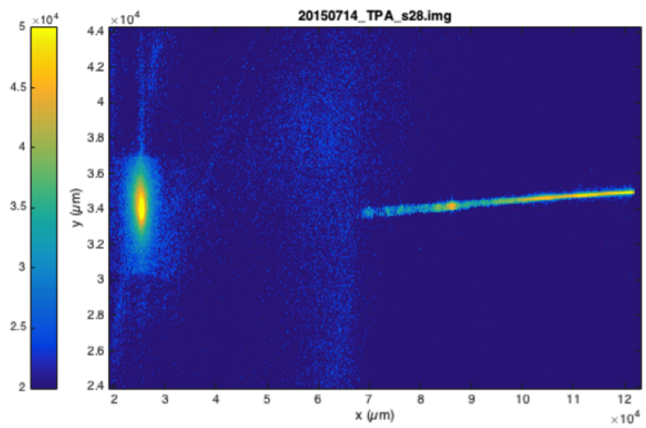

FIG. 7. This is TP data from the shot with the jet. Note the single line of ions and small bright spot between 8 and 9 on the x-axis.

shots, but then we lost the jet altogether and were not able to produce another stable one. We think that this happened because of a current that flowed up the jet and into the nozzle during the interaction with the laser. This heated the jet and damaged the orifice, limiting our use of the jet as a target.

However, we did get a data-yielding shot with the jet. The Thomson parabola data from this shot shows one line of ions and a mostly decaying line-out with a small peak. See Figure 7 and Figure 8.

Although there were only a few successful shots with the jet, we had 10 successful shots with the wire, 4 of which were using the cylindrical drum RCF.

The RCFs from the wire target shots consistently show

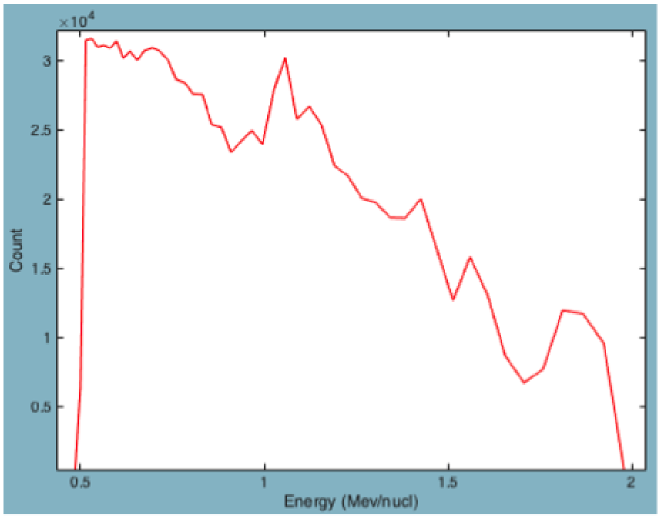

FIG. 8. This is TP line-out data from the shot with the jet. Note the small peak around 1.1 MeV.

horizontal banding relative to the vertical orientation of the wire. They appear to show two lines of protons above and below the interaction point, which is visible in the RCF. With the data from the cylindrical drum RCF, we saw quenching in the center and a concentration of electrons on the left side. Furthermore, on the RCFs from the cylindrical drum, we can see a circular disturbance that seems to correspond to where the laser would have passed through. We also see a dark region on the side, interrupting the expected symmetry of a cylindrical target. See Figure 9 for an example of RCF data from the cylindrical drum.

C. Analysis

The data from this experiment is still undergoing analysis, but a few things are evident. For example, it is clear from the single line on the TP data that we accelerated a pure proton beam with no contaminants.

Furthermore, although target normal sheath acceleration (TNSA) is the standard method of ion acceleration, from our data it appears that this did not occur with the cylindrical targets. If TNSA had occurred, we would have seen uniform blobs on the RCFs. Instead we saw banding and modulations in the RCF, as well as peaks in brightness on the image plate data (and corresponding small peaks in the line-out readings). These features indicate that we were close to achieving something like shockwave acceleration. We therefore made progress towards our goal of creating monoenergetic features and demonstrating new regimes of ion acceleration.

Furthermore, the RCFs from the wire suggest that the interaction may have created a strong magnetic field around the target, caused by electrons traveling up the target. In the case of the jet, this high intensity current was able to travel up the jet into the nozzle, destroying

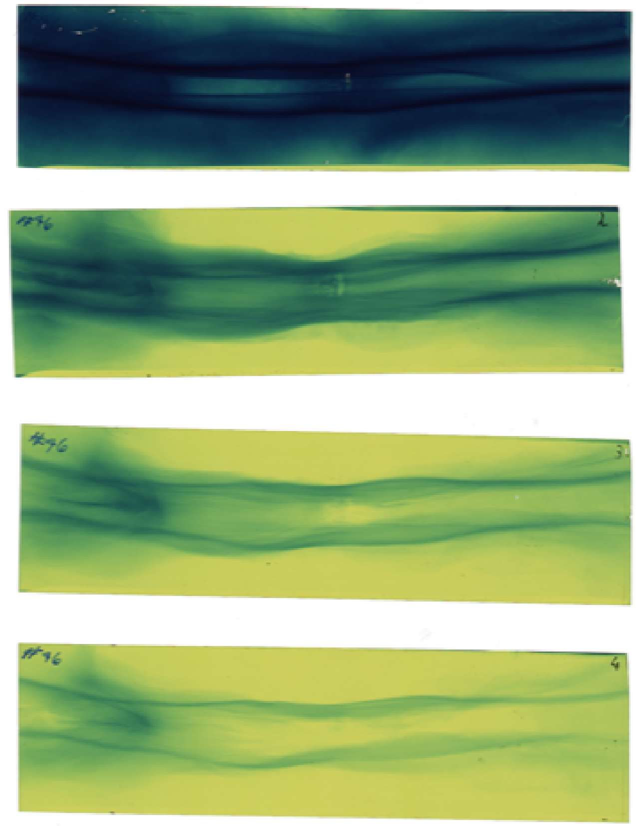

FIG. 9. This is RCF data from shot 46 with 10 micron gold. Here are the first four layers of the RCF stack, the first being the top image. This layer is darkest so it had the most ions pass through it. However, the lower layers had higher energy ions pass through them. Note the horizontal banding, modulations, circular disturbance near the center, and darkness on the left side. These features are consistent throughout the RCF drum data.

the jet and damaging the orifice when intensity was high enough. This is likely the source of our difficulties with the jet. We were able to get one or two good shots, but then the jet stopped working altogether.

Unfortunately, we did not see the high levels of energy we were hoping for. Hopefully future experiments with fewer technical difficulties will be able to acheive this.

III. PIEZOS

A. Motivation and Theory

In order to address the problems we had with the jet, we think that a cryogenic droplet stream might be an even better target for this interaction than a jet. This is because the droplets are separated from each other and from the nozzle so that exocurrent will not be a problem.

Droplets are also good targets in other ways. Like jets, they are pure and continuous. However, they are

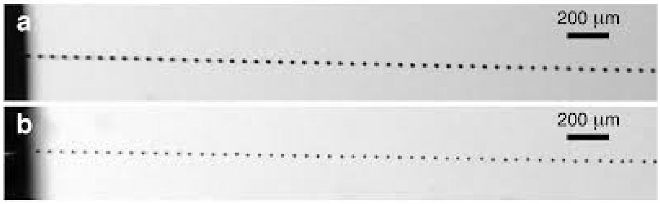

FIG. 10. This is an example of high-quality argon (a) and hydrogen (b) droplet streams, courtesy of Costa Fraga et al. Note the regular distance between droplets and lack of threads or satellite droplets.

even more mass-limited than jets are, which might lead to higher energy density. See Figure 10 for an example of a high-quality droplet stream.

We will induce breakup of the cryogenic jet into droplets with a piezo ceramic component. Piezos work through piezoelectricity when an electric current is applied to a piezoelectric material, the material is deformed, contracting and expanding at a certain frequency [1]. We will place this piezo ceramic piece behind the nozzle and connect it to a power supply with an adjustable frequency in order to transmit vibrations to the jet. According to fluid dynamics, any disturbance in a jet with a wavelength greater than the jets diameter will lead to breakup into droplets [3]. Therefore, based on the other parameters governing droplet breakup and the size of the orifice we want to use, we should be able to control the droplet formation to the point where we can produce a nice, orderly droplet stream.

B. Physical Parameters

The physics of droplet breakup is largely governed by fluid mechanics and is covered extensively in Eggers and Villermaux. As they explain, surface tension effects and cohesive forces are largely responsible for the spontaneous breakup of jets into droplet streams[3].

There are several parameters involved in the breakup of droplets, but the most important ones are driving amplitude, A; Weber number, We; reduced wavenumber, x; Ohnesorge number, Oh; and Reynolds number, Re[4]. These depend on the properties of the fluid, including surface tension, liquid density and dynamic viscosity. Adjusting the jet diameter, jet velocity, and driving frequency will allow us to balance these parameters in order to produce the best possible jet. See Figure 11 for the relevant equations.

Reduced wavenumber, x, relates the diameter of the jet to the wavelength of the perturbations, or distance between the droplets after breakup. When x is close to 0.7, this results in the optimum wavelength at which the perturbations in the jet grow fastest. However, x does not need to be exactly 0.7 in order to have a nice droplet stream.

Reynolds number, Re, relates to laminarity and is inversely related to viscosity: lower Reynolds number means more laminarity, and greater viscosity leads to lower Reynolds number[6]. We would like the flow to be laminar so that the breakup is more controlled and the droplets are of higher quality. When Re <2000, we can be sure that flow is laminar. This will give us an upper limit on jet velocity.

Webers number, We, relates kinematic energy and surface energy. We would like the kinetic energy to be high enough so that the droplets are jetted rather than dripped, but not so high that they are sprayed. Jetted droplets provide the best target. Therefore, we would like 0.2 <We <4, which further refines the velocity range of the jet.

Reduced Wavenumber | Reynolds Number | Weber Number

$$x = \frac{\pi d_{jet}}{\lambda} \qquad Re = \frac{\rho v_{jet} d_{noz}}{\mu} \qquad We = \frac{\rho_l d_{jet} v_{jet}^2}{2\gamma}$$

Where v_{jet} is the speed of the jet, γ is the surface tension, ρ is the density, λ the wavelength (distance between droplets)

FIG. 11. These are three of the most important parameters governing jet breakup.

C. Calculations and Next Steps

By balancing the various parameters involved based on the qualities of the doplets we desire, we have been able to determine what type of piezo and power supply we need to buy.

Based on my calculations, as well as the fact that we expect to use a hydrogen jet with an orifice between 2 and 10 microns, I found that the upper bounds for the velocity will be 66 m/s for a 10 micron orifice, and 330 m/s for a 2 micron orifice. The optimal wavelength will be between 9 and 45 microns. The frequency should therefore be between 1 MHz and 36 MHz.

However, other groups using similar setups have not driven breakup at anywhere near 36 MHz. This is likely due to the fact that they had limitations that we do not have in terms of parameters for the droplets. However, there is also the risk of the coalescence effect as frequency increases. We do not want the wavelength to be so small that the droplets run into each other. Rather, we want to avoid satellite droplets and threads. We decided to order a piezo that works at frequencies up to 2 MHz and a power supply that can drive at frequencies up to 10 MHz. This should give us the flexibility we need to adjust the driving based on what gives us the best droplet stream. Although we have calculated the parameters generally, it is impossible to know what will work best in our specific conditions until we test out the piezo.

The next steps will be setting up the jet source with the piezo and power supply, and subsequently testing it to make sure we can get a nice droplet strain. We expect that we will be able to use it in experiments later this year.

IV. CONCLUSIONS

Overall, this internship has been the most intensely fascinating learning experience I have ever had. I do not come from a strong physics background, so although there was a steep learning curve, I ended up learning far more than I would have in a situation in which I were within my comfort zone. I learned so many physics concepts just by doing things for the experiment and asking questions. I feel that I came away with a solid understanding of many complicated topics that I have never been exposed to and probably would never have been exposed to if not for this internship. Furthermore, I learned a lot about how a team works together during an experiment such as the one at Titan, and I was able to learn a lot about what it is like to be a scientist by talking with the other experimentalists. For all of these things, I am extremely grateful to the DOE and the SULI program.

As far as the experiment goes, it was a success in many respects. Though the jet was not as easy to set up as we had hoped, it did produce useful data, showing that we created a pure proton beam with some evidence of a monoenergetic feature. We learned a lot about how the jet works and what might have caused the problems with it, and we came away with a strong sense of how we can improve upon the experimental setup for future experiments.

The data we collected from the RCF and TP diagnostics with the wire targets turned out to be much more interesting and exciting than we expected. We witnessed things in this experiment that have not been described in previous literature. It was an amazing experience for me to be part of a real experiment that produced meaningful, relevant, and impactful results.

The time I spent researching piezos was also a great experience. I learned a lot about how setup for an experiment works, as well as how much time it takes to figure out whether or not something is likely to be successful. I learned how important it is to pay close attention to detail and not jump to conclusions. Furthermore, I learned about piezoelectricity and fluid dynamics. Hopefully the research I did will be helpful for the team in preparing the jet source for the next experiment.

V. ACKNOWLEDGEMENTS

I would like to thank Dr. Siegfried Glenzer and his group for welcoming me into their lab for eight weeks despite the fact that I had little prior experience or knowledge to contribute. I appreciate the fact that they put so much time into teaching me all that they did in these past few weeks and thoroughly involving me in a complicated experiment.

Dr. Jongjin Kim, my mentor, was an excellent teacher. He was patient and took a sincere interest in me enjoying my work and having something productive to do. It was a pleasure to be his minion for eight weeks.

Maxence and Christian were also particularly instructive and helpful. They taught me many complicated topics and helped me prepare my presentation.

Dr. Enrique Cuellar, Maria Mastrokyriakos, and Nancy Qatsha were critical in organizing this internship and making it so unique. I really appreciate all that they did to make sure that we not only worked hard, but also broadened our horizons and had a good time this summer.

Finally, Id like to thank SLAC National Accelerator Laboratory and the Department of Energy for giving me this opportunity and making this internship possible.

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