Creating Ti particles for liquid Xe purification

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The Large Underground Xenon (LUX) experiment is a large collaborative effort to detect Weakly Interacting Massive Particles (WIMP), which are the current leading candidates for what dark matter consists of. The LUX detector is essentially a large container of liquid Xenon, which can detect collisions between the Xe and WIMPS by measuring the scintillation and ionization energy released because of these collisions. Unfortunately, impurities in the Xe container can absorb this ionization signal. Currently, the Xe is purified by boiling if off, passing it through a getter (a reactive substance that combines with impurities), and then bringing it back down to liquid form. While effective, this process assumes that impurities in the container will boil off with the Xe, and requires the 350 kg of liquid to be boiled. If getter material could be produced through a very powerful spark, the Xe could pass through a purification chamber containing the getter material while remaining in liquid form. We have constructed such a device (known as a spark getter) using Titanium plates. When a very high voltage is applied to the Titanium plates, a powerful spark arcs across the two plates, and simultaneously strips some small Titanium particles off. This process is repeated until there are many small Titanium particles inside the purification chamber. The Xe can then flow through our purification chamber, and the Titanium will attach itself to impurities. When there are no Titanium particles left to purify, the voltage is simply reapplied, and new gettering material is produced.

I. Introduction

All known types of mass account for only 4.6% of all matter. An impressive 23% of mass in the universe is dark matter, which is invisible, and has been detected through its gravitational effects on other visible matter [1]. The leading candidate for dark matter is known as a Weakly Interacting Massive Particle (WIMP). What is important is that WIMPS are believed to be able to interact with matter on a very small scale gravitationally. WIMPs are predicted to outweigh conventional matter five to one [1].

II. LUX

While WIMPs have an extremely small cross-sectional area, there is still a small probability that a WIMP will interact with a nucleon, and cause nuclear recoil. LUX, the Large Underground Xenon detector, takes advantage of this by using xenon as a medium to detect WIMP particles passing through it. LUX contains 350 kg of xenon in two phases, gas and liquid, with photomultiplier tubes lining the top and bottom of the detector. The purpose of LUX is to detect the nuclear recoils of xenon caused by WIMPs. LUX detects these recoils using the scintillation and ionization caused by nuclear recoil, which is known as the S1 signal. An electric field is applied inside the detector, causing electrons ejected from their xenon atoms to float upwards, where the xenon is in a gas phase. The floating electron then emits a second scintillation signal due to electroluminescence, known as the S2 signal. The two signals are significant because they can be used to discriminate between nuclear recoils and electron recoils. Since WIMPs are neutral particles, they will interact with the nucleus, sending out only nuclear recoil signals. The ratio of the two signals S2/S1 will be larger for electron recoils when compared to nuclear recoils. Unfortunately, WIMPs aren't the only neutral particles in existence, and neutrons passing through the detector will also cause nuclear recoils, creating false signals.

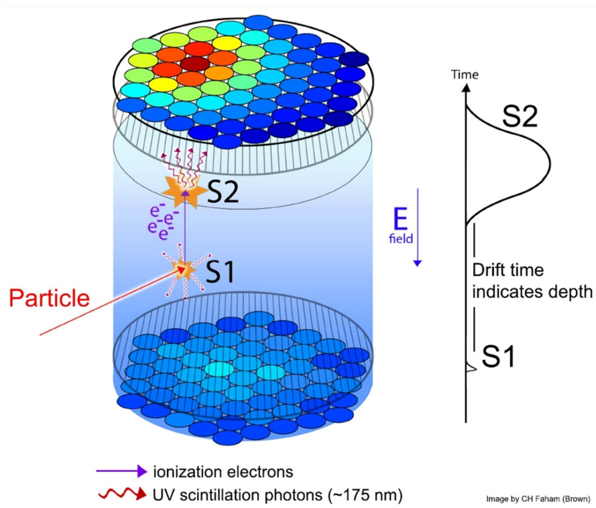

Figure 1. S1 and S2 signals in the LUX detector

Neutrons can be created by muons from cosmic rays, which would interfere with LUX's results [1]. To protect LUX from these cosmic rays, LUX is located underground 4850 feet below the earth's surface [1]. To provide extra protection to the detectors, LUX is submerged in water that not only acts as a gamma ray shield, but also as a background detector using the PMTs in the water tank. That way if a muon breaches the water tank, PMTs will detect it interacting with the water, and will warn of possible false data.

Another possible problem is impurities in the xenon. Oxygen, water, and organic compounds could be present in the tank. This is a problem because the impurities could absorb the ionization signal. Currently, this problem is resolved by boiling off the liquid Xe, which is passed through what is known as a getter, a substance that reacts with impurities and removes them from the Xe. After purification, the Xe is condensed and put back into the tank. Once all active binding sites on the getter are taken, it is heated to recharge the getter, and create more active binding sites for further purification. Purity in Xenon can be measured by how far an electron can drift. With an impurity level of one part per billion, electrons can drift an average of 2 meters [2].

III. The Getter

Our contribution to the project is to create a new, better way to purify the Xe. The goal of our project is to create a getter that can work directly with the Xe in its liquid form. Titanium spark purification systems are thought to be able to purify Xenon in two days, while traditional high temperature getters take between one and two weeks [2]. Not only will the purification process be quicker, but it will also allow for the removal of impurities that would not be boiled off with the Xe. The idea for our purification system is a Titanium Spark Purifier. High voltages are applied to Ti plates, which causes a spark in between them. The idea is that the spark would be so powerful that it actually removes part of the anode and cathode as it arcs across, leaving Ti dust in the purification chamber [2]. After sufficient sparking has occurred, liquid Xe is flowed through the chamber, and the Ti dust acts as a getter, reacting with impurities in the liquid.

Titanium particles have been shown to continue to actively purify liquids long after they are detached from the electrodes, and the UV light created from sparking helps to break down organic molecules that might be in the Xe liquid [3]. The purpose of our project is to mimic published results in an attempt to create a titanium spark purifier for LUX [3,4,5]. We wanted to create a chamber that would use powerful sparks to constantly deposit Ti inside of it. The purification chamber would theoretically be housed inside the Xenon tank, where the liquid could be continuously pumped through the chamber, and constantly be purified.

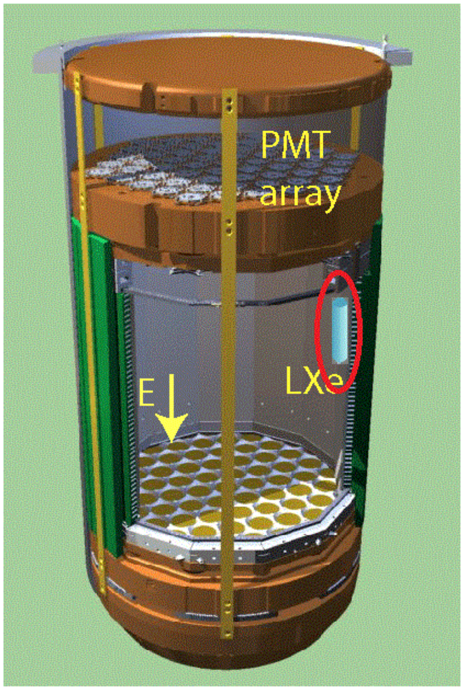

Figure 2. How our getter would be implemented inside the lux detector. Our getter is the blue cylinder circled in red.

For our first version of the spark getter, we had a DC power supply set to 4.5 kV attached to two titanium plates. While this would create a spark, it would unfortunately trip the power supply since it would draw too much current. To prevent the power supply from tripping when the titanium plates spark, six 2.2 MΩ resistors were added in series before the titanium plates. This allowed us to create a constant arc between the titanium plates, but didn't create the powerful sparks we needed. To add more current to the spark, a high voltage capacitor with the ability to withstand high currents was created by attaching two pieces of aluminium foil to both ends of a picture frame glass. The glass acted as the dielectric, insulating the aluminium sheets from each other. The capacitor came out to 1.7 nF, and when added in parallel to the Ti spark gap, created the pulsing spark we wanted.

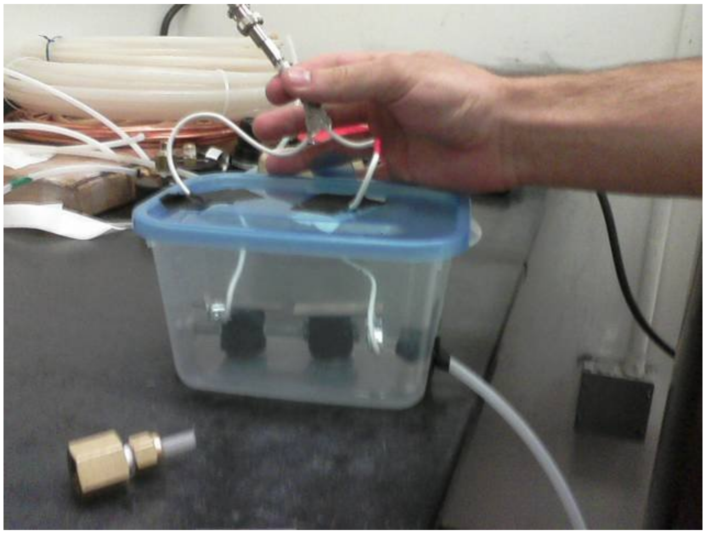

Figure 3. Our first version of the spark getter. A screw running through both Ti plate holders acts as a way to adjust distance.

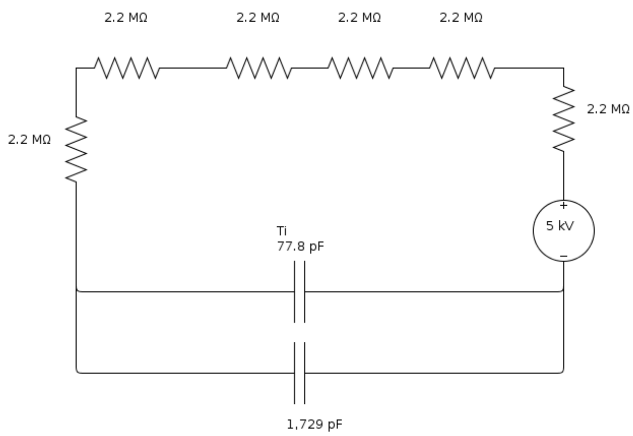

Figure 4. Circuit diagram for spark getter. Many resistors are placed in series to help spread out the load of the high voltage

Now that the spark worked as intended, we upgraded from a 4.5 kV DC power supply to a 6.5 kV AC transformer. The AC power source would allow us to get the pulse of power we desired; while at the same time would help us erode away both plates of titanium as the current switches direction. The capacitor remained in our circuit, but the resistor chain was removed since our transformer didn't trip, and the AC current provided the pulse we needed. Theoretically, an AC power source would also help us wear away both Ti plates simultaneously. Unfortunately, since the spark produces so much heat (Fig 5.); quartz glass had to be used as our container to prevent melting.

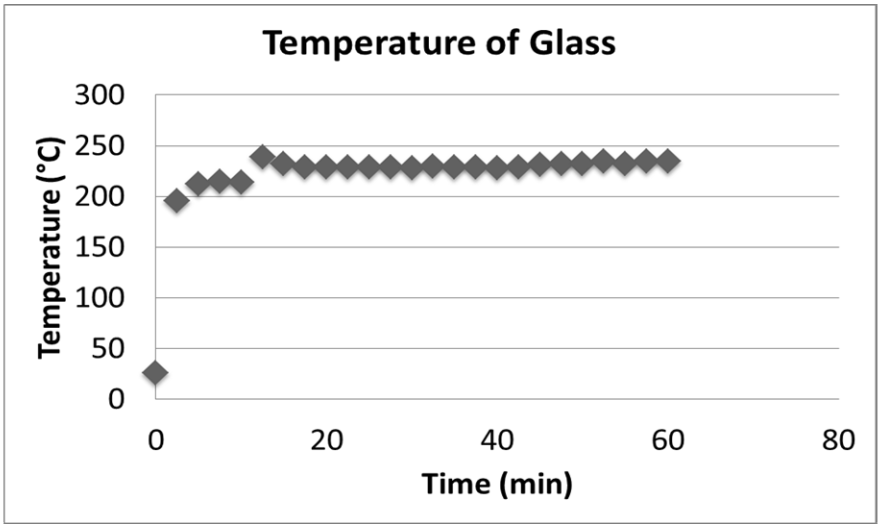

Figure 5. Temperature of glass measured from inside the spark chamber. (5 mm seperation at 6.5 kV)

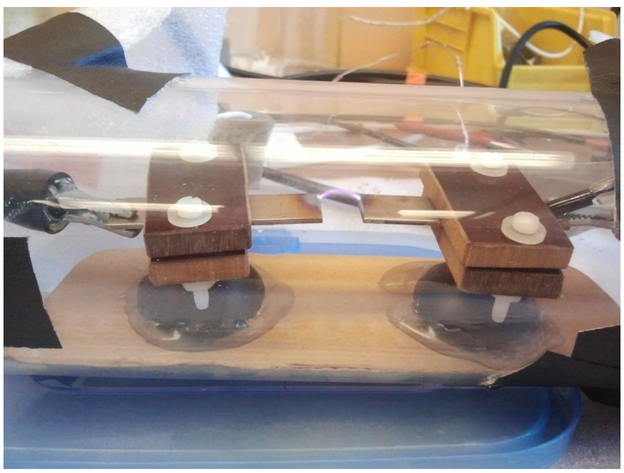

Figure 6. Second version of spark getter (without capacitor). Notice the purple arc crossing the two titanium plates.

Unfortunately, this set up resulted in no spark. This is likely because the transformer also had an inverter in it, changing the frequency from 60 Hz to 38 kHz. The time constant of the capacitor and internal resistance of the power supply was likely greater than the periodic time of the supply voltage, which would be 1/38000 of a second. Our suspicions were confirmed when after removing the capacitor, there was an arc between the two plates. Unfortunately, without the capacitor we had a continuous arc without any extra current (Fig 6). This of course led to very little material removal.

For our next transformer, we made sure to choose one without an inverter, so it kept the frequency com its input the same, which in this case is 60 Hz. A 9 kV transformer was obtained, and a variable transformer was used as a way to regulate how much voltage went into it. The result was a noticeably more powerful spark, along with an increase in mass loss (Fig 7).

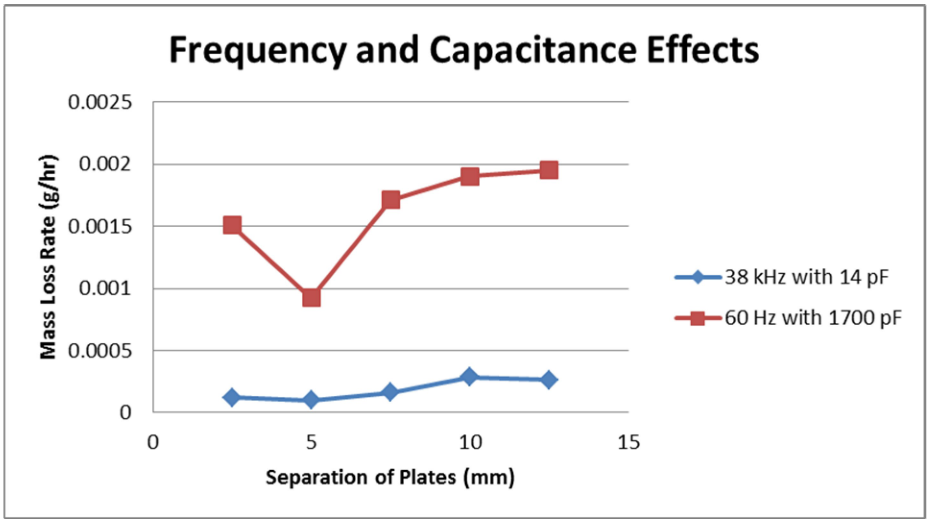

Figure 7. A comparison of mass rate loss with two different transformers. Notice both the frequency and capacitance change.

Another more pressing problem is that while sparks were powerful, the rate of mass decrease was still too low. It seems that the heat provided by the electric arc would simply be dispersed through the thick titanium plate. We decided to solve this problem by replacing our titanium plates with .002 inch thick titanium foil. The results were very successful, mass was lost at a very rapid rate (Fig 8), so much so that we had a very difficult time running our device for a long time, since all usable material would disappear. Unfortunately, this rapid rate of electrode degeneration came at a cost: particles were very irregular in size. While we definitely got some of the dust we wanted, there were also some rather large chunks coming off the titanium. Since creating a large surface area to make contact with the impurities in xenon was the goal, large chunks are unwanted. Because we were still sparking in air, it was difficult to tell if our results were due to the fact that our apparatus was efficient at sublimating titanium, or simply because we were creating titanium dioxide.

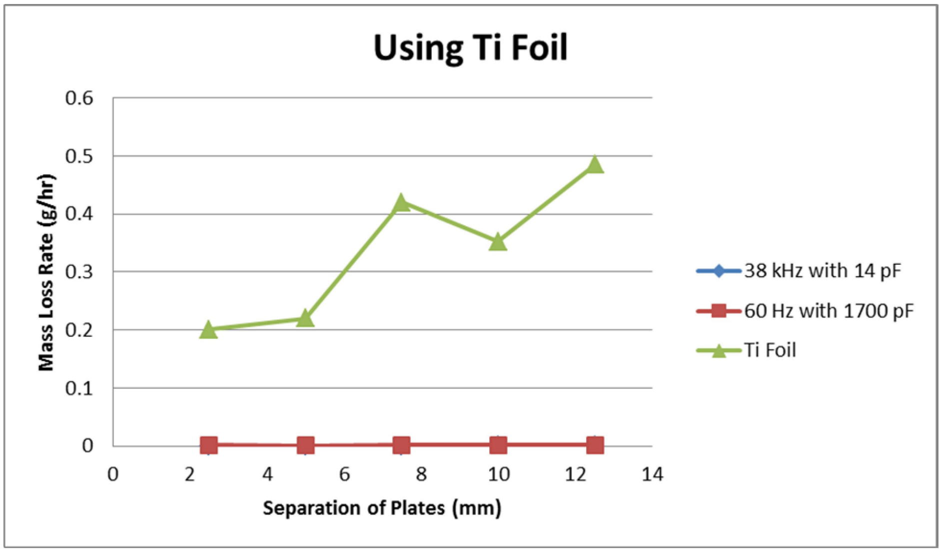

Figure 8. Rate of mass loss using .002 inch thick Ti foil (C=1700 pF and f=60 Hz). Note how it compares to previous rates, which are shown in more detail in Fig 7.

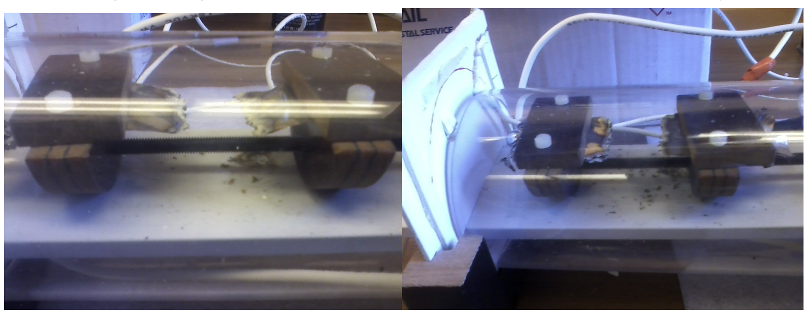

Figure 9. A spark getter using Ti foil. Pictures show before and after shots of a 15 second run. Notice the large chunks of Ti underneath the gap.

Air has a relatively high breakdown voltage compared to xenon, so while past experiments were useful for proving the concept of spark gap created particles, it was not directly applicable to the situation we wanted to run our device in. Also, the high breakdown voltage was leading very high power sparks, which could account for the large particles. To solve these problems, we decided to run our device in Argon. This provided a solution to the mentioned concerns, and at the same time kept titanium oxide from forming, so not only would our particles likely be actual sublimated titanium, but the electrodes would not gain mass from formed oxides.

Since argon's breakdown voltage was much lower than air's (Fig 10), sparking in an argon atmosphere was comparatively much easier. Arcing across the two pieces of titanium required much less voltage when compared to equal distances in air, and sparks could be created over much larger distances. Unfortunately this also resulted in less power per spark, and gave us a much slower mass rate lost when compared to the explosive results obtained in air. Particle sizes were indeed smaller though, and the large chunks that would melt off the titanium foils in air were now gone and replaced by smaller particles.

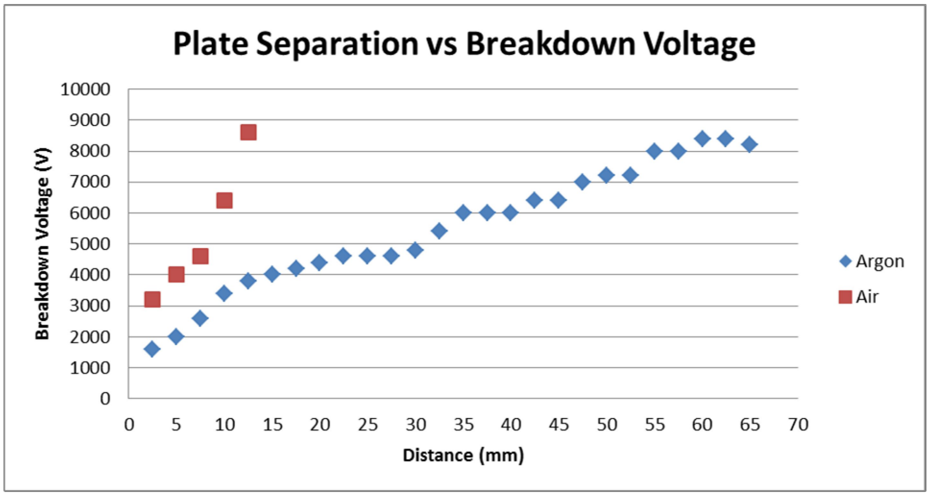

Figure 10. The breakdown voltage's dependency on Ti plate distance. Air's breakdown voltage is much more dependent on the seperation distance than Argon's.

Since we needed to increase the spark power to increase the rate of mass coming off, we began to increase our capacitance from 1.7 nF to 5.4 nF. Grams lost per hour were still low, so the capacitance was increased yet again to 22.2 nF. Bumping up our capacitance seemed to greatly help our mass loss rate (Fig 11), bringing it up to par with results observed in other papers [4]. The particles were unfortunately still too big (Fig 12), and were not down to the nanometer sized particles we desired to efficiently create surface area with limited mass.

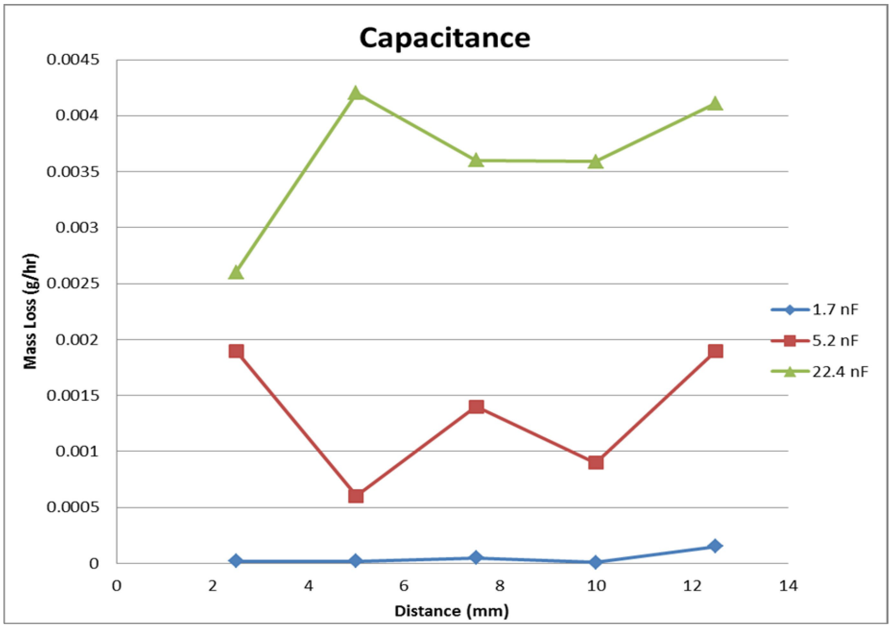

Figure 11. The mass loss rate seems to increase with the capacitance. Relationships between distance and mass loss per hour are still not clear.

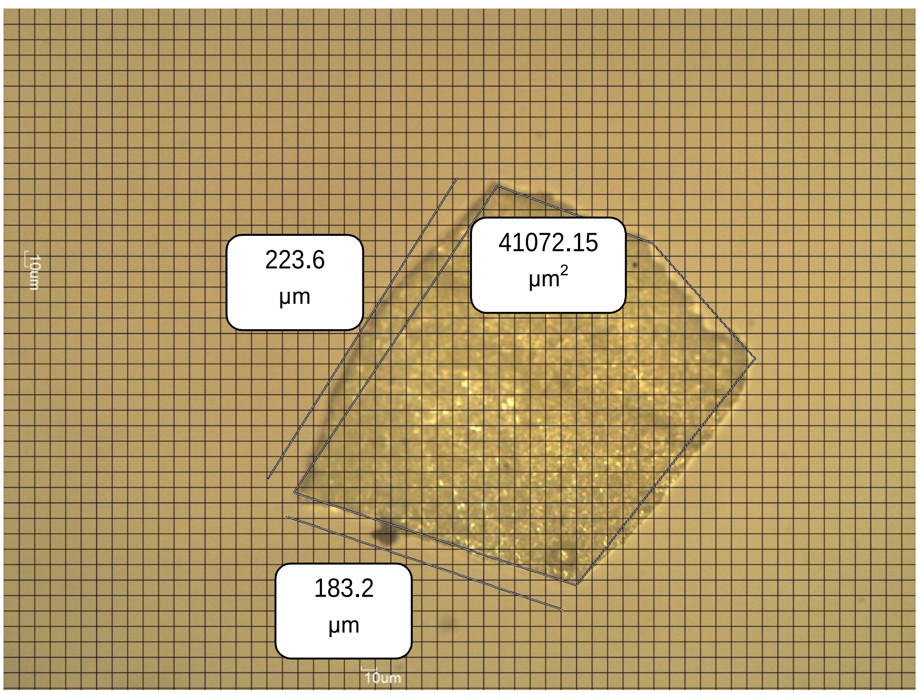

Figure 12

Ti particle that came off electrodes 1 mm apart in Argon atmosphere. Notice that its sides are over 100 µm.

To work on our large particle sizes, we decided to design our spark getter so that Argon would flow across the spark gap. Without a flow, it is likely that after the initial ionization of the Ar gas, the spark continues to take the same ionized gas path, since it is the path of least resistance. In doing so, the voltage does not need to build up, and a constant arc is created, so that the ionized Ar path acts as a sort of resistor in between two Ti plates. This constant current gets extremely hot, and melts off large chunks of Titanium. If the path of ionized Ar gas atoms was constantly cleared, the path would need to be constantly reionized, as the easy path would be swept away from the flow. This would give us our pulsed spark discharge, and would sublimate Ti particles with a powerful blast instead of melting them off with a steady stream. This seemed to help keep the particles small (Fig 13) and was a vast improvement from previous large particles.

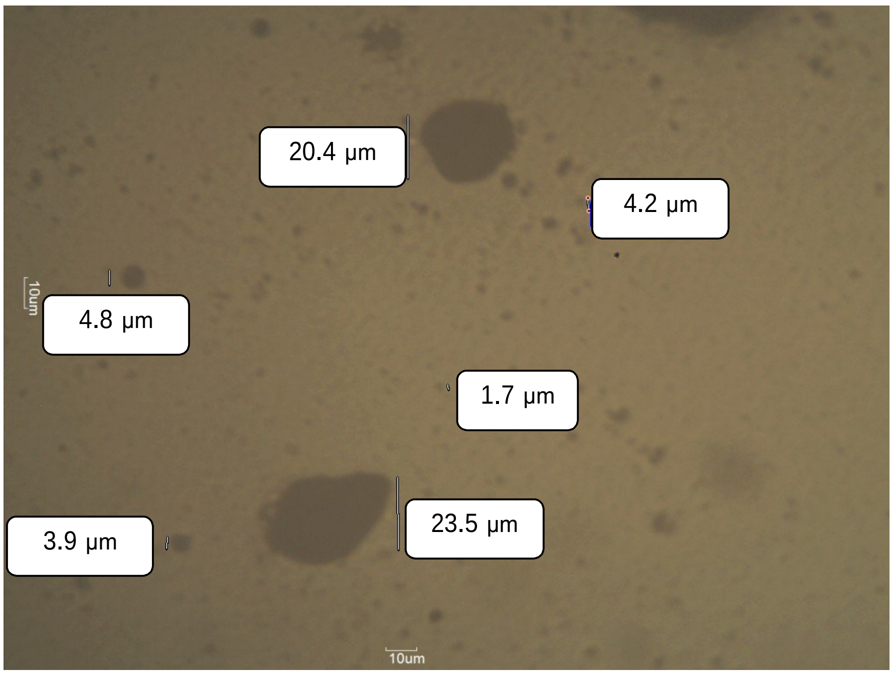

Figure 13. Particles detached from Ti electrodes with Argon flowing in between the 1 mm electrode gap. Note that the sizes are much smaller than the particles in Fig 12.

III. Future Work

While we began to experiment with particle size control, it would be nice to study the subject further, and obtain more results to start finding trends. While flowing across the spark gap seems to create smaller particles (it is important to note that this is not a definite trend, more experiments need to be conducted to confirm this), it would be interesting to see how flow rate affects particle sizes, if it does at all.

We made big improvements to the mass loss rate, but it would be interesting to make our spark getter even more efficient at quickly eroding Ti away. It was shown that breakdown voltage seems to play a big part in how much power we get per spark, and therefore how much mass can be removed get off. Increasing pressure of a gas or even decreasing it by a large amount is known to increase the breakdown voltage. Performing this experiment would be important not only because it might reveal a new method of increasing the grams per hour we detach, but it would also give us extra evidence to support the correlation between breakdown voltage and mass rate loss.

Two final areas of interest are frequency and switching back to a DC source. We have noticed before that a really high frequency hinders us because we can't take advantage of a large capacitor, yet we only tested the very high frequency of 38 kHz. It would be interesting to see what would happen at higher, but not as high frequencies, such as 80 or 100 Hz. Many published papers seem to use a DC power source [2,4], so imitating their setup to compare their results to ours would be an interesting pursuit.

IV Conclusion

We have shown that it is possible to create small particles using sparking electrodes. It is a simple and effective way to detach small, high surface area getters into a substance that needs purifying. Early results also suggest that size can be controlled by tweaking certain variables.

If further research is conducted on particle size and mass rate, the Titanium Spark Purifier could be a valuable resource to LUX, and help improve purity and time efficiency.

References

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