

## BACHELOR

### Plasma particle lofting with one million g centrifuge

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# Plasma particle lofting with one million $g$ centrifuge

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## Abstract

Research is done on the ability of plasma to help remove particles of 100  $\mu\text{m}$  from a surface. This is done by applying plasma to dust particles on a magnesium cylinder surface. Both the surface and particles will become negatively charged and repulse each other. This repulsive force is the plasma force. This can be compared to the value of the adhesive force.

The adhesive force was measured by depositing particles on the cylinder. It is possible to calculate the adhesive force by using the centrifugal force to remove particles. A difference in adhesive force was observed when the pressure was changed. For 0.3 mbar the adhesive force is 0.24  $\mu\text{N}$  and for 0.8 mbar the adhesive force is 0.29  $\mu\text{N}$ . What causes this difference in adhesive force is also researched.

By applying plasma and comparing these results with the adhesive force measurements, a plasma force can be calculated. The pressure and plasma power of the plasma have been changed to see if they have influence. The plasma force has been measured for the 100  $\mu\text{m}$  particles and has a value of  $0.9 \pm 0.4 \mu\text{N}$ .

The next stage was seeing if this method was also viable for smaller particles, because the plasma force was able to remove particles of 100  $\mu\text{m}$ . The next step was to use the method on particles of 10  $\mu\text{m}$ . After initial measurements it was concluded that the plasma force was not enough to remove the particles. Therefore both the centrifugal and plasma force is needed to remove the smaller particles.

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# 1 Introduction

Dust can be found everywhere. Mostly it is just annoying, but sometimes it is more than annoying and dust has to be removed. An example of where dust removal can be used is the semiconductor and optics industry, where dust can cause trouble. Another field where removing dust is useful, is the cleaning of solar panels on space craft [1]. Dust particles stick to a surface as a consequence of the van der Waals force. Therefore another force is needed to remove the dust.

To remove the particles a plasma is used, this will generate a force that may be able to remove the dust particles from a surface. We are interested to know how much force a plasma exerts on a particle and whether it is capable of lofting it. In order to do this we need a reference source to compare the plasma force with. For this, we use a centrifuge that can create a force of a million times the gravitational force. With the centrifuge we can measure the centrifugal force needed to remove the particles from the surface with and without plasma. This also gives the means to calculate the plasma force in different conditions.

It is expected that the particles will loft at different amount of force. This is because the van der Waals force depends heavily on the shape of the surface and of the particles. In this report the first result of measurements can be found with the centrifuge.

Before the results are discussed some theory is explained to understand the results. The used setup is explained after the theory. After the explanation of the setup, the first results will be shown with the setup. A conclusion and outlook is made based on the results.

## 2 Theory

The removing of dust particles from a surface is based on the different forces exerted on particles and between particles and surface. When a particles is dropped on the surface, some particles will stick to the surface as a consequence of an adhesive force. This force is called the van der Waals force. The van der Waals force is a force that works between particles and tries to keep these particles together. Other forces that are involved are the centrifugal force and the electric force.

### 2.1 Forces

The van der Waals force is an adhesive force that works between particles. An example of this force is the dust that sticks to bookshelves. The dust sticks to the surface and gravity is not enough to remove it from the surface. The van der Waals force is [2]

$$F_{vdw} = \frac{Ar_p}{6D^2}. \quad (2.1)$$

$A$  is called the Hamaker constant and has value of around  $10^{-19}$  J [3],  $r_p$  is the radius of the particle and  $D$  is defined as the distance between particle and the surface in m, the value of this distance is a couple of angstrom. Equation 2.1 overlooks the fact of deformation of particles. This will be discussed in the section 2.2. A representation can be found in figure 1.

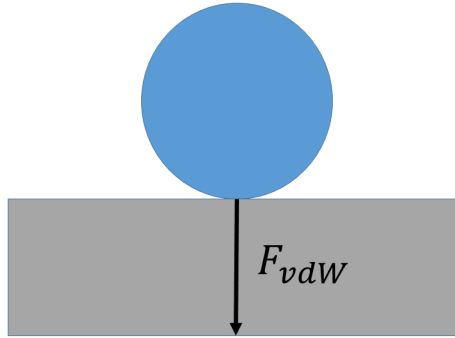


Figure 1: A visual representation of the direction of van der Waals force on a particle on a surface

The centrifugal force is the force that will remove the particles from the surface. This is also the force that is the easiest to measure. Therefore it will be used to calculate the other forces that are involved in the process. The centrifugal force is

$$F_{centrifugal} = \frac{mv^2}{r_{centrifuge}} = m\omega^2 r_{centrifuge} \quad (2.2)$$

$m$  is the mass of the particle,  $v$  is the speed in  $\frac{m}{s}$ ,  $r_{centrifuge}$  is the radius of the centrifuge in m and  $\omega$  is the rotational speed of the centrifuge. The force is visualized in figure 2.

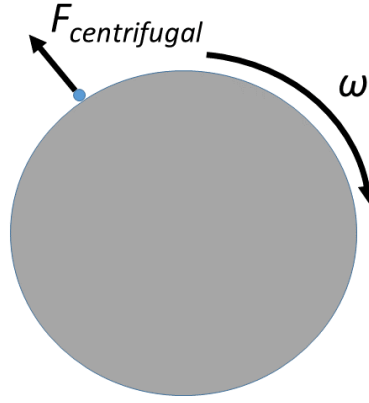


Figure 2: A visual representation of the direction of the centrifugal force on a particle on a rotating cylinder

The equation for the electric force is

$$\vec{F}_E = q \vec{E} \quad (2.3)$$

$q$  is the charge on the particle and  $\vec{E}$  is the local electric field. The equation for  $\vec{E}$  for a charged cylinder is [4]

$$E = \frac{\sigma}{\epsilon_0} \quad (2.4)$$

$\sigma$  is the surface charge density, this is not a constant and is unknown for the cylinder used in experimentation and  $\epsilon_0$  is the vacuum permittivity. This force can be explained in the following way: the cylinder surface and dust particles get negatively charged. A repulsive force between surface and

particles occurs and the force will try to separate the particles from the surface. This force is shown in figure 3.

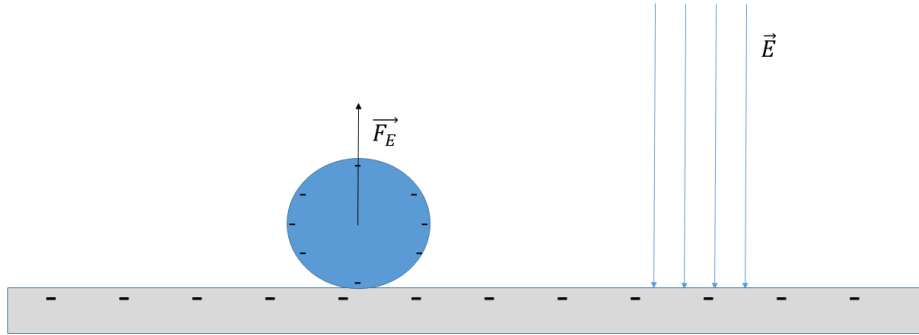


Figure 3: A visual representation of the electric force

## 2.2 Contact mechanics

There is a specific field of physics that looks at how particles behave on a surface. This field is called contact mechanics. This field proposes different adhesion contact theories [5].

The first of these theories was the Herz Theory. This theory describes that when two surfaces come into contact they can deform. This deformation will change the interacting force. The important parameters in this theory are the radii of curvature and the elasticity of the two bodies. Because this theory did not take surface forces into account, several other theories have been developed.

The most known theories on adhesion contact theories are the JKR approach (Johnson, Kendall and Roberts) and the DMT (Derjaguin, Muller, and Toporov) approach. These two theories advance in the way of using surface forces in the theory, but still do not take everything into account. JKR takes only the forces into to account that are between molecules in the particle and allows the surface to deform. DMT also takes surface forces outside the particle into account. Both theories lead to an increased surface area and therefore also a higher van der Waals force. For this experiment, the exact surface area is not known, but deformation plays a very important role and defines the value of the van der Waals force. The van der Waals



force with contact surface is [2]

$$F_{vdw} = \frac{Ar_p}{6D^2} \left(1 + \frac{\alpha^2}{r_p D}\right) \quad (2.5)$$

For this equation  $\alpha$  is defined as the radius of the contact surface. The contact surface is highly dependent on the shape of the surface and the shape of particle. A dent in the surface of either particle or surface will change the value of the van der Waals force a lot. Examples of deformation can be seen in figure 4. Equation 2.5 is not used in the analysis, but it gives an idea of why there is spreading in the value of the van der Waals force when particles let loose of the surface. The reason for not using the equation is that the surface area of the particles is too complex to give a value to.

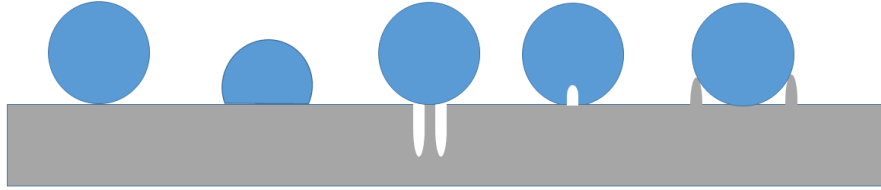


Figure 4: An example of how particles can look on surface

## 2.3 Plasma

For the research done, plasma is an important part. The plasma is used as a means of removing particles. Plasma is called the fourth state of matter and can be found all around us in the universe[6]. Prime example is the sun, which consists mostly of plasma. Plasma is also called ionized gas. This means that the ions within the plasma are separated from electrons that normally float around the ions. In this setup an RF-function generator is used to create the plasma. This will be explained further in section 3.3. The plasma itself is quasi neutral, which means that overall the plasma is charge neutral, but not in the plasma sheath.

The plasma sheath is a layer in the plasma near the surface where there is a higher concentration of positive ions. The electrons are fast compared to the ions and are able to negatively charge a surface.

The electrons will in the case of the centrifuge charge the magnesium cylinder and the dust particles on the cylinder. The surface and the particles will repulse each other. If the repulsing force is strong enough it will remove the particles from the cylinder surface. An extra force can then be used to remove them completely if needed.

Figure 5 gives a sketch of all the forces in the system and how they are pointed. How the plasma is made can be found in section 3.3.

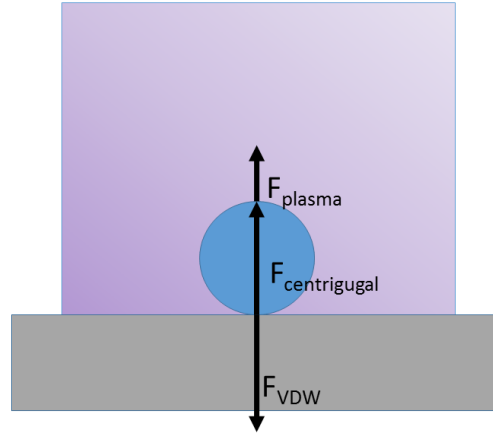


Figure 5: All relevant forces in one sketch, the purple colour represents the plasma around the cylinder

## 2.4 Student's t-test

For the analysis of the results Student's t test is used [8]. In this case 2 data sets are compared so the method used is the two sample t-test. The t-test compares two data sets to see if they significantly differ. The method uses a 95% confidence interval to see if the difference in data are by chance or if the difference is consistent throughout the data.

The result of the t-test is the p-value, this value gives the means to say if data significantly differs or that chance caused the difference. Because a 95% confidence interval is used, 5% is the limit between significant difference and difference by chance. This means that if the p-value is smaller than 0.05, there will be a significant difference between data sets. If the p-value is larger than 0.05, the difference is caused by random chance. This means that if

the p-value is equal to 0.05, that there is a 5% chance that the difference in data is caused on accident.

### 3 Experimental setup

The setup contains various elements that need further explanation. This is done in this chapter.

#### 3.1 Centrifuge

The essence of centrifuge is the rotating cylinder which is made of magnesium with a radius of 0.025m. Magnesium is chosen because it is light and strong. It needs to be light because it turns on an axle and the axle could break of the cylinder is too heavy. Other materials could break apart at a rotation of 200000 rpm.

The cylinder is driven by the motor CM-2-500 made by Celeroton. It has a rotation speed of up to 500000 rpm. But for the vacuum bearings it is safe up to 200000 rpm. Any higher and the cylinder could break apart due to high forces. The speed and acceleration of the rotation can be controlled with CelerotonPilot.

The motor and cylinder are connected as in figure 6. The rubber is there

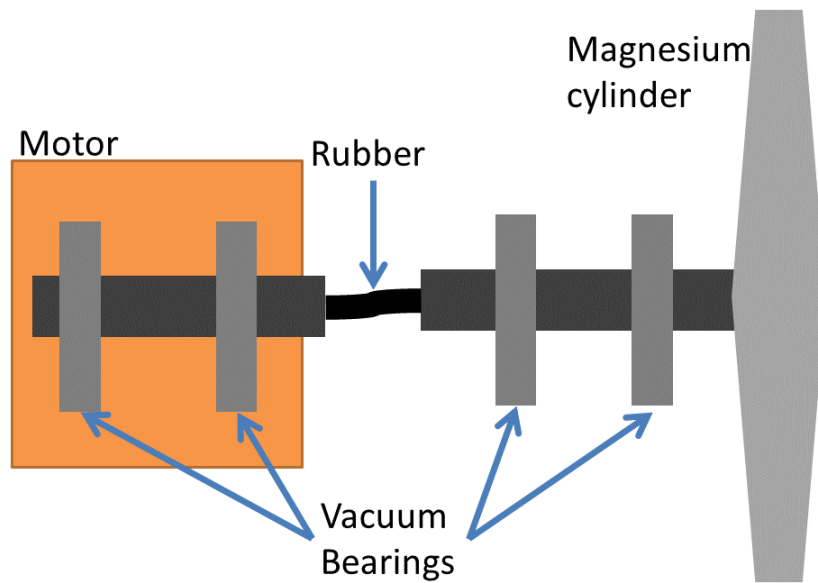


Figure 6: Connection between motor and cylinder

as a safety measure, when there is too much friction the rubber will break and not anything else. It was found out after weeks of measuring that there was a misalignment between the two axes. This caused a lot of friction on the rubber when the cylinder was rotating. The consequence of this was the

breaking of the rubber. An infrared sensor is used to measure the rotation of the cylinder.

The vessel is contained in a bunker during measurements. The bunker is made of concrete slabs and had a volume of roughly one cubic meter. This is a safety measure just in case the cylinder breaks apart at high speed.

### 3.2 Gas

Gas is an important part in creating plasma and is used for varying the pressure. The gas that is let in to the vessel is argon, this is also used for the plasma. The gas inflow is controlled by a mass-flow controller.

Two pumps are installed to pump away unwanted gas. The pre-pump is used between atmospheric pressure and 0.1 mbar. The other pump is a turbo pump that starts automatically when lower pressure is required. It can pump down to  $10^{-7}$  mbar.

Several pressure sensors are installed in different parts of the setup to check the pressure, the range at which they work is different. This ranges from atmospheric pressure, to a pressure of  $10^{-7}$  mbar.

The pressure is controlled by a PID controller. The PID is a control loop feedback mechanism [7]. The PID controller controls a valve between pump and vessel. A feedback mechanism will try to control the output. This means that there is an actual value and a desired value which you want the pressure to be at. In the PID it is possible to adjust three values:  $Kp$ ,  $Tn$  and  $Tv$ . These variables are equal to the proportional, the integral and the derivative coefficients.

The proportional value  $Kp$  adapts the value proportional to the error compared to the desired value. So if the error is high the adaptation will be high, the smaller the error the smaller the adaptation should be.  $Tn$  is the integral term and will adapt the actual value further, because it corrects the steady-state error that will occur when only the proportional term would be used. The  $Tv$  is called the derivative term and is not necessary to produce the desired value. The derivative term tries to predict future actual values and based on that adjust the behaviour of the PID controller accordingly to get to the desired value quicker. It is not needed to know the precise workings of the controller to use it.

The internal parameters were set using trial and error. The pressure still oscillates, but goes to the desired value after tens of minutes. So that pressure is constant during the measurement.

A bigger problem was caused by a gas leak within the system. The consequence was that unwanted gas came in the chamber and contaminated the measurements. Solving this took multiple days, the method used for this was: certain parts were removed where leaks were expected and replaced by parts that could not leak. The leak could be found by comparing the pressure rise before and after the replacement of parts. The leak was in the

pipe from mass controller to vessel. The bolts used to connect the pipe is the weak point in this case. The solution for this was replacing the pipe with a direct coupling to the vacuum chamber. The rise in pressure when everything is closed is now a factor 10 lower with the direct coupling. The pressure loss before adjustments can be found in Figure 7. The pressure loss after adjustments can be found in Figure 8.

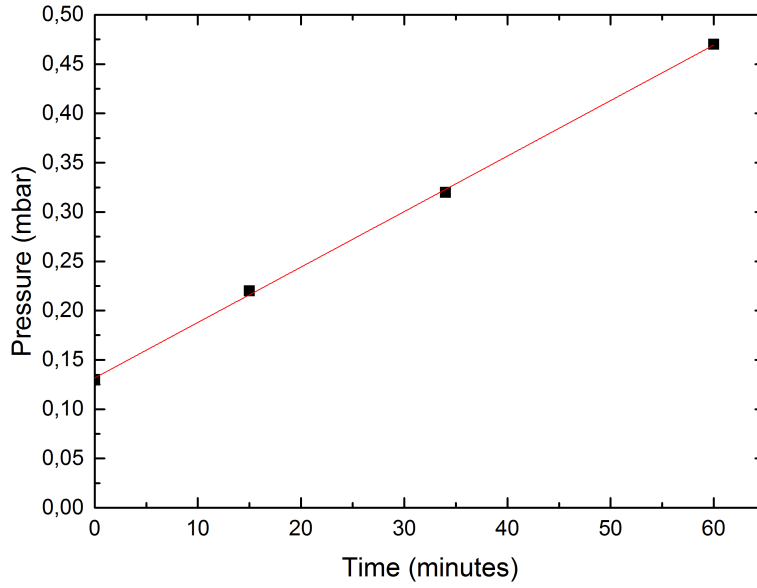


Figure 7: Pressure rise as function of the time. The slope value is equal to  $(5.63 \pm 0.08) \cdot 10^{-3} \frac{\text{mbar}}{\text{min}}$

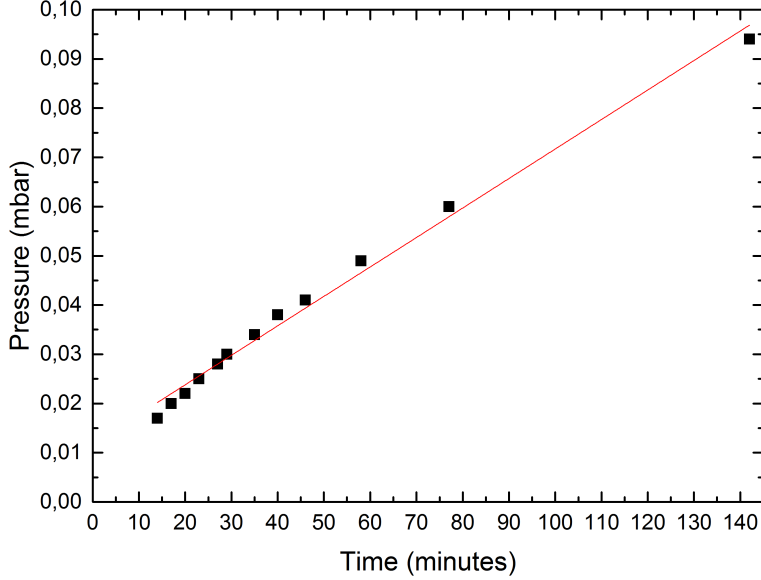


Figure 8: Pressure rise as function of the time, after changing the setup.

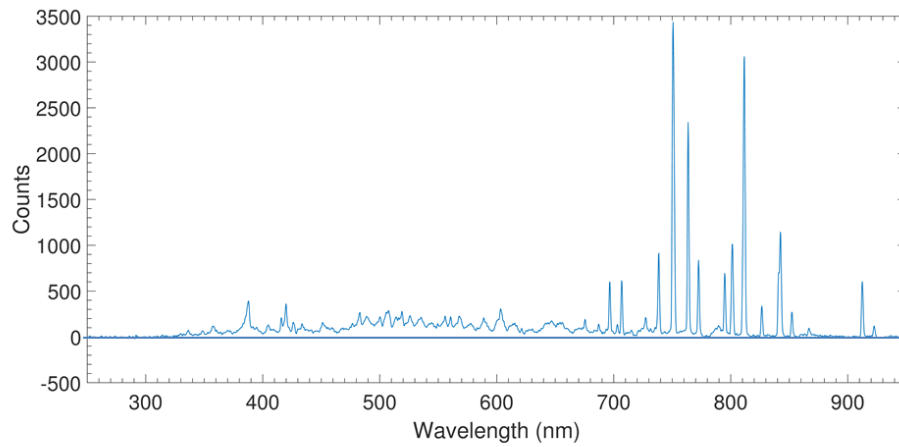
The slope value is equal to  $(6.0 \pm 0.2) \cdot 10^{-4} \frac{\text{mbar}}{\text{min}}$

### 3.3 Plasma

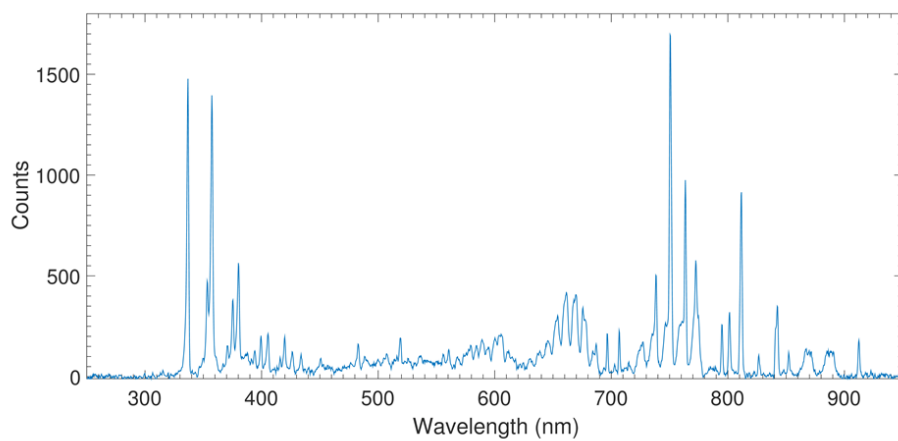
The plasma is created with help of an RF-generator. The generator creates a waveform that is able to make plasma. The Generator creates a strong alternating field that will make electrons collide with other electrons. The electrons will accelerate more than the ions, because the electrons are lighter than the ions. The electrons can go to the cylinder surface if they are fast enough. The outer cylinder around the magnesium cylinder act as an electrode. This is shown in figure 11.

The free electrons are able to move to the magnesium cylinder and adhere to it. Dust particles that are on the cylinder surface will also become negatively charged. Consequence of this is that surface and particles will repel each other.

A problem was observed during the first plasma measurements. This problem is the immediate colour change of the plasma from purple to white. Plasma spectroscopy was used to get a better understanding of the colour change of the plasma. What happens during the change of colour, can be seen in figure 9a. What is striking about figure 9a is the rise of the amount of counts in the whole visible spectrum. This means there is something wrong within the chamber and not just extra nitrogen that gets in to the



(a) This is the spectrum of the plasma after it turned white



(b) This is the spectrum of the plasma after adjustments have been made within the chamber

Figure 9: Spectra of the argon plasma



chamber. The most likely cause is the aluminium tape that was used within the chamber. It could be that the glue of the tape evaporates as consequence of low pressure and the presence of plasma. The different molecules from the evaporated glue will contaminate the plasma and turn the colour from purple to white. After removing the aluminium tape and finding new solutions for protection of electric wires, the spectrum looks like figure 9b. When comparing figure 9a and 9b extra nitrogen peaks show up. These peaks are caused by another leak. Pressure measurements point at a leak in the argon supply or somewhere outside the vacuum chamber.

Figure 9b is specific for the first measurement after using the pumps to fill the vacuum chamber. When this is tried with newly pumped argon, the spectrum will again look like figure 9a, even without the aluminium tape. So the most likely cause is nitrogen in the gas supply line, caused by a leak. This can be circumvented by first pumping the gas into the chamber, for a minute. Then use the turbo pump to remove this gas. Then all the nitrogen in the supply line will be replaced by argon.

Solving the problem of the white plasma is not possible at the moment, this something that could still be researched in the future. For example by heating the whole chamber it may be possible to get all the unwanted molecules out of the chamber, there could still be residue left of the glue used in the chamber and this could be the issue for the white plasma.

### 3.4 Dust

The dust dispenser is a small can, that can be brought close to the magnesium cylinder to deposit dust, see figure 10. The dispenser is driven by a magnetic coil. The magnetic coil will make the can shake, so dust can come out. This is done from above. The dispenser can be retracted when dust has been deposited, so that the can does not disturb the plasma.

The dust is made of polystyrene and has a particle size of  $101 \pm 9 \text{ }\mu\text{m}$ . The particles are green fluorescent. The smaller particles which were used in section 5 are made of the same material and have a size of  $8.0 \pm 1.4 \text{ }\mu\text{m}$ .

### 3.5 Imaging

An important part of imaging are the fluorescent particles, when illuminated with the blue laser, these particles emit green light, see figure 11. To filter out the green light, a filter is put in front of the camera, see figure 11, that has a specific range of light than can get through. This range is centered around green light.

The amount of light the laser sends out, oscillates at start up. To solve this, a delay should be made between starting of the laser and starting the measurement of about 20 minutes. If this is not done, there will be

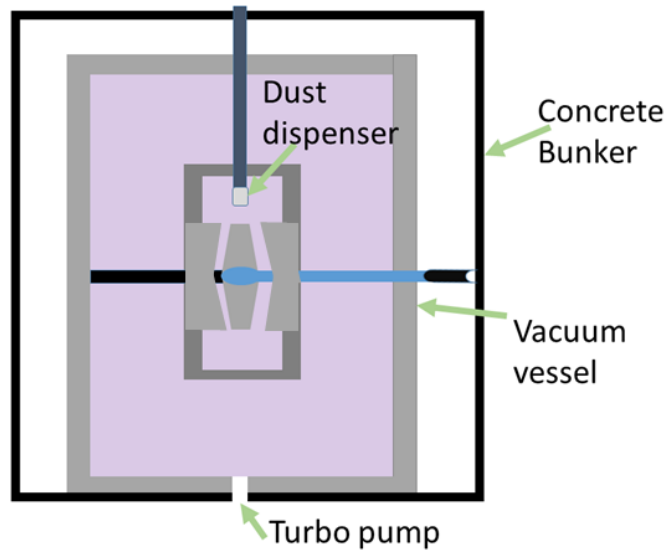


Figure 10: rough sketch of the setup within the bunker

oscillations in the value of light intensity on video and the scripts used in matlab will be unusable. For explanation on the scripts see section 3.6

To see the particles on the cylinder a camera looks at a small part of the cylinder, see figure 11. A Frame of the video can be found in figure 12. The height of such a frame is one to two centimeters. Before the start of the measurement the camera is adjusted accordingly so it can record with the right visibility by adjusting the focus, the right exposure time and gain. The gain and exposure time should be looked at individually, it can be different per measurement. If this has not been done correctly, there can be too much light at start or not enough light at end. This will make the measurement unusable. To analyze the results of the measurements software is needed, see section 3.6

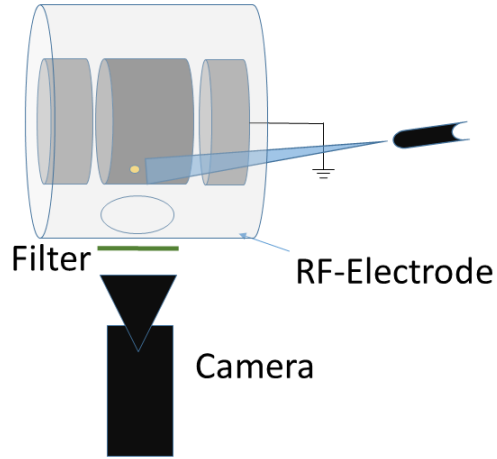


Figure 11: 3D sketch of the essence of the setup, The motor can be found within the left cylinder, from there it is connected to the magnesium cylinder, with a connection like figure 6 between the left cylinder and the middle magnesium cylinder

### 3.6 Measurment Principle

To do a measurement, several steps need to be taken. Dust is put in a dispenser which hangs above the cylinder on variable distance, this can be seen in figure 10. To get the dust particles to stick to the surface the pressure needs to be close to atmospheric pressure. This creates enough friction between particles and air, so that the falling speed of the particles is lower and they don not bounce as much.

Argon gas is used for the purpose of getting to the right pressure for deposition of particles. The argon will be pumped away to get to the pressure for measuring. The measurements are done around 0.5 mbar in most cases. The plasma can not be made if the pressure is too high or to low, therefore the pressure will be around 0.5 mbar.

The final step of the measurement is start of rotation of the cylinder and recording this with the camera and matlab. Both the data of the camera and matlab is used in the analysis. A frame of the video can be found in figure 12. A filter can be used on the video to change the brightness and contrast, this makes it possible to see the last particle leaving the cylinder surface. The camera is recording while the cylinder is rotating, so each particles becomes a trace instead of a dot, but each trace can be multiple

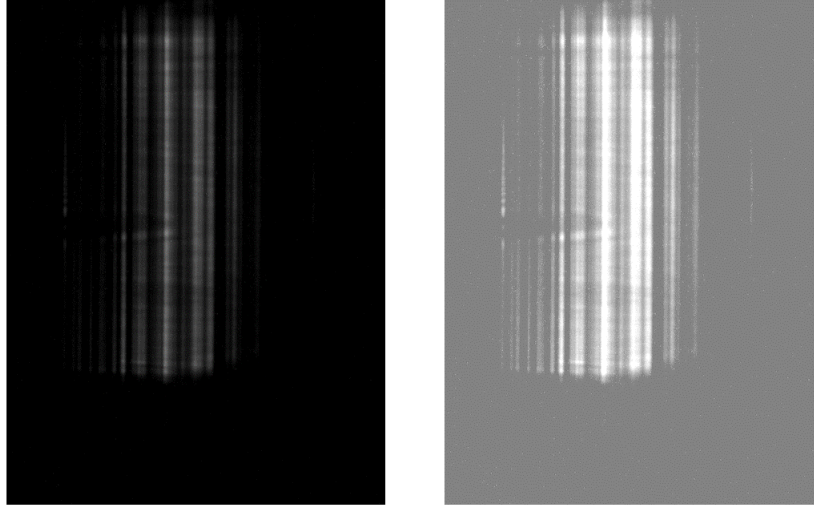


Figure 12: Frame of video file before and after use of image editing (contrast and brightness)

particles. As the cylinder start rotating faster more particles will leave the cylinder and less light will be seen on the video. This is shown in figure 13. A histogram can be made, based on the differential of figure 13. The resulting histograms can be found in section 4.1.

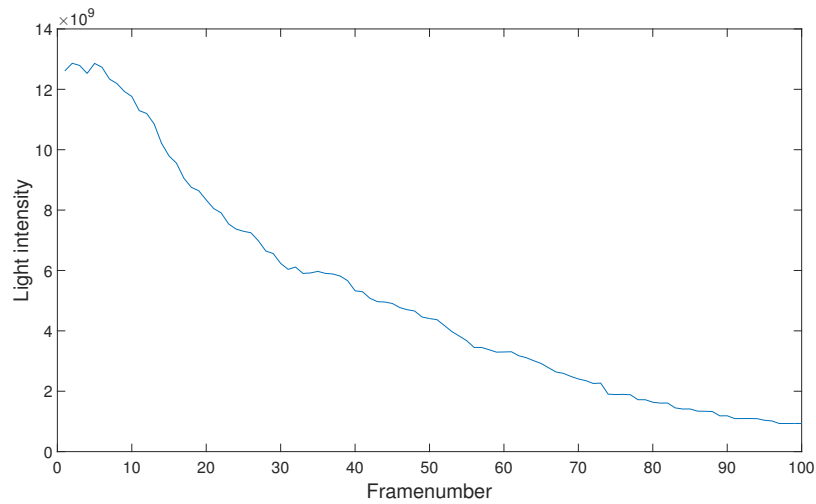


Figure 13: Lightintensity with arbitrary values, as function of the frame number

For the adhesive force measurements only rotation is used and not plasma. A different approach is used for the plasma force measurement is used. Instead of making the cylinder rotate, the plasma is turned on. The amount of particles that are removed is a measure of the plasma force.

By combining multiple measurements, an estimation can be made of the plasma force under different circumstances. The percentage of particles lost can be translated into the plasma force, with help of figures 17a and b. This is done by looking at the adhesive force histograms and finding when a certain percentage has left the cylinder. This gives a value for the needed force to remove the particles from cylinder, this is equal to the plasma force.

Several different programs and scripts are needed to do and analyse the measurement. Different tasks needs different software. Matlab is the program that will give the result eventually. For recording IC capture 2.4 is used. In this program the resolution and way of recording can be configured. The motor that drives the rotation is driven by a program called Celeroton-Pilot. In this program all the parameters can be adjusted for the rotation. This will also create data which can be analysed in Matlab. One of the scripts makes from the video a light intensity figure like figure 13, the same script makes from such a graph a histogram. This is done by looking at the differential of the light intensity figures. A histogram can be made based on the differential. The rotational speed is also known for each frame, so the centrifugal force that is exerted in each frame is also known.

## 4 Results and analysis for 100 $\mu\text{m}$ particles

The measurements with the dust particles are split between adhesive force and plasma force measurements. The influence of pressure is studied for both the adhesive and the plasma force.

### 4.1 Adhesive force

Before doing measurements with plasma, measurements without plasma were done to measure the adhesion. This was done specifically to see if the adhesive force measurements were reproducible and to see what the value of adhesive force is. To find this out, different measurements are compared with the help of the student t-test, this test is explained in section 2.4. The results are reproducible if the pressure stays constant between measurements.

Multiple measurements were done on a pressure of 0.3 mbar and 0.8 mbar. The results of the measurements can be found in figure 14a for 0.3 mbar and 14b for 0.8 mbar

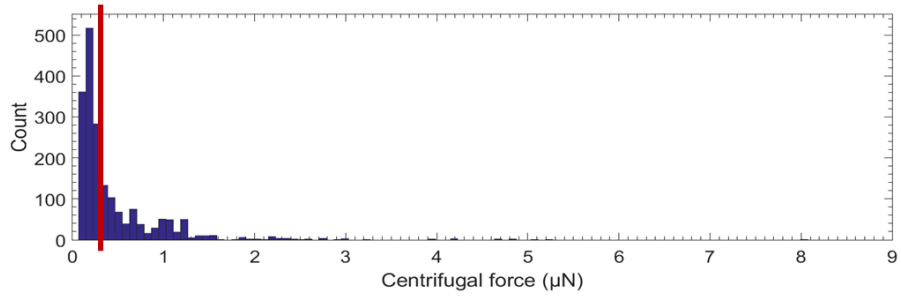
From figure 14a and b both the mean and median can be calculated to get an idea of the value of the adhesive force, but the mean does not say a lot, because of the outliers. This is the reason the median says more. For 0.3 mbar this is 0.24  $\mu\text{N}$  and for 0.8 mbar this is 0.29  $\mu\text{N}$ . This can be compared to the theoretical value with help of equation 2.1. The equation gives a value of 10  $\mu\text{N}$ , which is not equal to the measured adhesive force. The difference is caused by the particle and surface deformation mention in section 2.2.

The Student's t-test is used on the data of figure 14a and b to see if there is significant difference between them, even though they look alike. What the values of the student t-test mean is explained in section 2.4. The most important result of the t-test is the p-value, with a value of  $4 \cdot 10^{-9}$ . This means that there is a significant difference between the data sets.

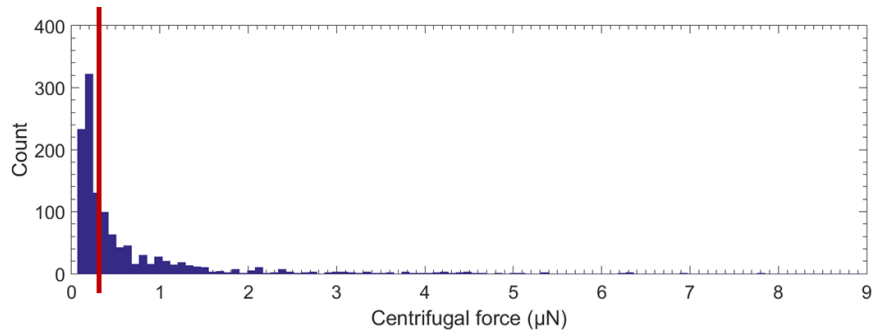
The results are unexpected. There should not have been a difference in van der Waals force for different pressure, according to equation 2.1.

A reason for the difference could be that unwanted gasses or fluids can be found in the vessel. This could be water or nitrogen. This could also be the issue, when the white plasma was discussed, see section 3.3. If there is water in the vessel, a capillary force could keep the particles longer on the surface, so more centrifugal force is needed to remove them. This can be studied by using a mass spectrometer. The mass spectrometer can see how much water is in the vessel compared to the argon. A lot of water could mean that there is a capillary force.

According to simulation results of force due to flow as function of pressure, see figure 15 [9], there should be no significant difference between force due to flow on 0.1 and 10 mbar. This is the result when the cylinder is ro-



(a) Amount of lost particles against the centrifugal force on a pressure of 0,3 mbar, median adhesive force is 0.24  $\mu\text{N}$ . The red line represents the median adhesive force



(b) Amount of lost particles against the centrifugal force on a pressure of 0,8 mbar, there are 2 other point at 15 and 22  $\mu\text{N}$  that are not displayed, median adhesive force is 0.29  $\mu\text{N}$ . The red line represents the median adhesive force

Figure 14: Adhesive force for different pressure

tating at 200.000 rpm, so the radial and tangential component of the force will be lower when the rotation is only 10.000 rpm. Which means that  $F_{flow} \ll F_{centrifugal}$  and  $F_{flow} \ll F_{vdW}$ .

It could be that the additional force due to flow caused by rotation is higher then simulation would let us believe. As the cylinder start to rotate faster, gasses around the cylinder will start to flow. This could create extra force on the particles. At the moment the equipment limits the range at which can be measured. The PID controller is only able to keep the pressure stable in a small domain and not at higher pressure.

The radial component of the force does not change by much between 0.1 and 10 mbar and is negligible compared to the adhesive force. Even when  $0.29 \mu\text{N}$  is taken as reference point. To make sure that there is no difference, measurements can be done on 10 mbar and compare the results with the lower pressure measurements.

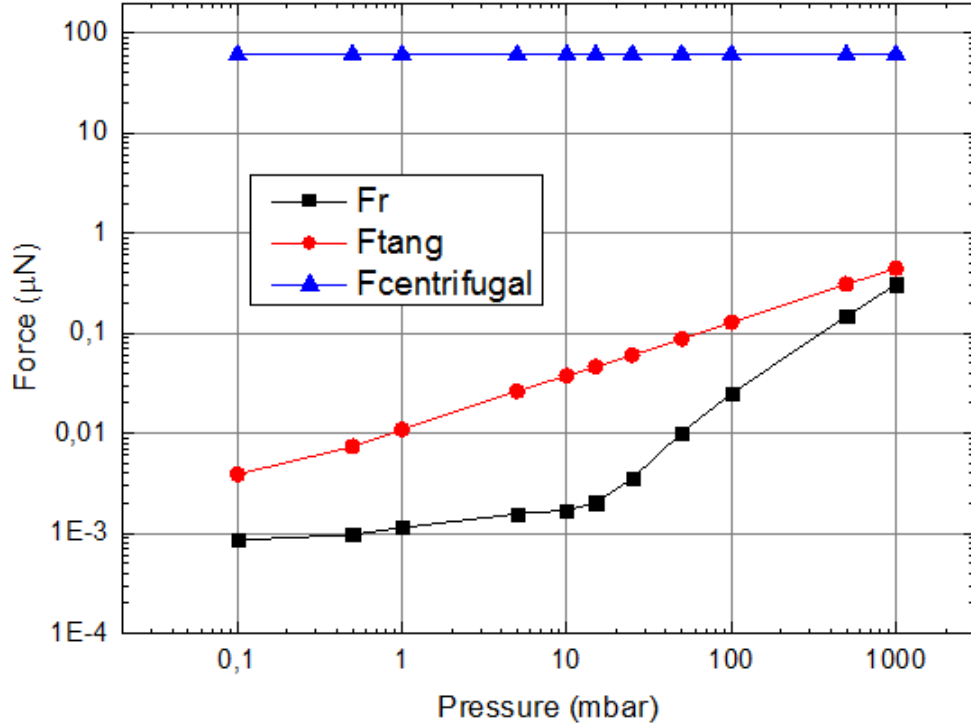


Figure 15: Different force components as function of the pressure, the black line is the radial component of the force as function of the pressure, source: [9]

The last reason for the difference in data could be that because of higher pressure also a higher pressure force is exerted on the dust particles by the



gas. This can be calculated for 0.3 and 0.8 mbar with help of equation 4.1

$$P = \frac{F}{A} \quad (4.1)$$

$P$  is the pressure in Pa,  $F$  is the force and  $A$  is the surface area. There are 2 scenarios: minimal surface area, which would mean that there would be no additional force. The other scenario is when surface area is maximal with a radius that is equal to particle radius. This is shown in figure 16. The real situation is somewhere in between these scenario's.



Figure 16: Worst and best case scenario for the surface area, Left has the maximum surface area, while right has no surface area

In best case scenario the surface area is zero and there will be no extra force due to pressure. In worst case scenario the surface area will be a circle with a radius of 50  $\mu\text{m}$ . The extra force for 0.3 mbar is 0.2  $\mu\text{N}$ . For 0.8 mbar the extra force is 0.6  $\mu\text{N}$ . So the possible force difference is 0.4  $\mu\text{N}$ . This could be an explanation for the difference in measured adhesive force which is 0.05  $\mu\text{N}$ .

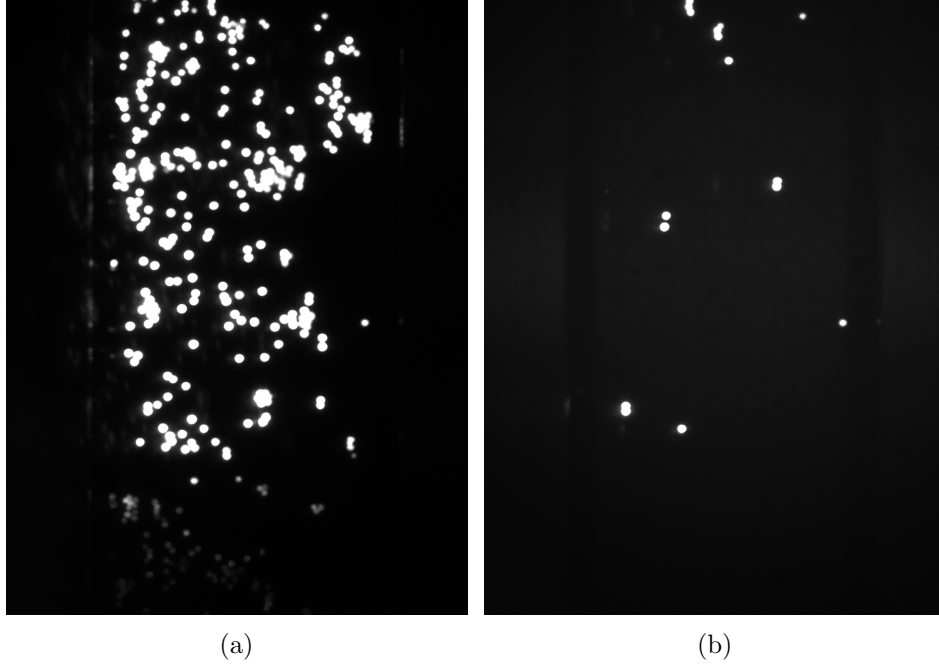


Figure 17: Cylinder surface before (a) and after (b) plasma, the circles are all individual particles

## 4.2 Plasma force

The plasma force is measured in a different way than the adhesive force. The reason for this is, that the plasma force is larger than the adhesive force. The particles are removed from the surface when the plasma is turned on. This can be seen in figure 17. A lot of the particles already leave the surface when a plasma force is applied to the particles. This means that the plasma force is larger than the adhesive force and can be measured by looking at the percentage of particles that is lost due to the force. This is also used as a method to determine the plasma force.

The variables observed if they have influence on the plasma force, are the plasma power and pressure. The plasma power can be changed by changing the amplitude of the RF-function that is used to make the plasma. The device that measures the power has an accuracy of 5 W. The percentage of particles lost is measured. The result of these measurements can be found in figure 18

These percentage are then translated into plasma force by looking at the figure 17a for 0.3 mbar and figure 17b for 0.8 mbar measurements respectively. The measurements studying the influence of plasma power were done a pressure of 0.3 mbar. The results of the translation can be found in figure 19. Another variable that was researched is the pressure, because it

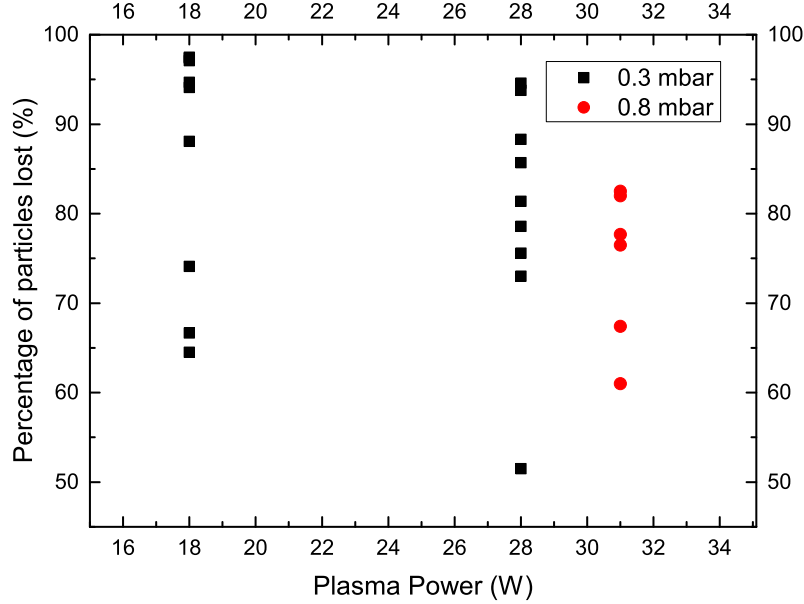


Figure 18: Percentage of removed particles as function of plasma power, every point of measurements is made of 100 to 200 particles

has influence on the adhesive force in an unknown way. The results of 0.3 and 0.8 mbar can be found in the same figures.

From the results of figure 19 the mean plasma force can be calculated, this is shown in figure 20. The large standard deviation of the plasma force is caused by the fact that there is a lot of spreading in the van der Waals force. This is caused by both imperfect particles and imperfect surface, as explained in section 2.2. A downward trend can be seen in figure 20, but this can still be the statistical spreading. More measurements are needed for both plasma power and pressure. For this adaptations should be made.

The adaptation that is most important is a different amplifier, for both the pressure measurements and the plasma power measurement. Above 0.9 mbar it was not possible to create a plasma, because the amplifier was not strong enough. A better amplifier will lead to a higher plasma power at lower pressure.

A video analysis is made to make sure the force that is removing the particles is the plasma and not a change in the adhesive properties of the surface, which would make gravity the removing force.

A calculation is made based on how fast a particle would move when

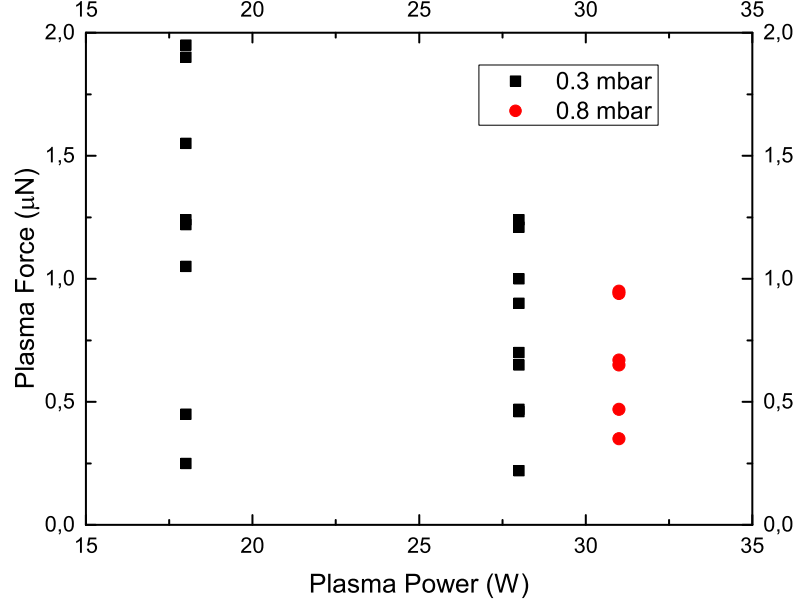


Figure 19: Measurement of plasma force ( $\mu\text{N}$ ) as function of the plasma power (W), two left power measurements are on 0.3 mbar. The right power measurement is on 0.8 mbar

affected by gravity with help of the following equation

$$s = \frac{1}{2}gt^2 \quad (4.2)$$

$s$  is equal to the distance travelled when the only working force is gravity,  $g$  is the gravitational velocity with a value of  $9.81 \frac{\text{m}}{\text{s}^2}$  and  $t$  is the duration of the motion. It is observed that it takes 1 frame in the video for the particle to leave the surface, this is equal to  $\frac{1}{30}$  s. Gravity is also known with a value of  $9.81 \frac{\text{m}}{\text{s}^2}$ . From this is possible to see in the video if the particle moves faster or slower. This is shown in figure 21.

The particle can not be seen on the next frame, this means that the acceleration of the particle is faster than gravitational acceleration and there is an extra force that does work. This is the plasma force.

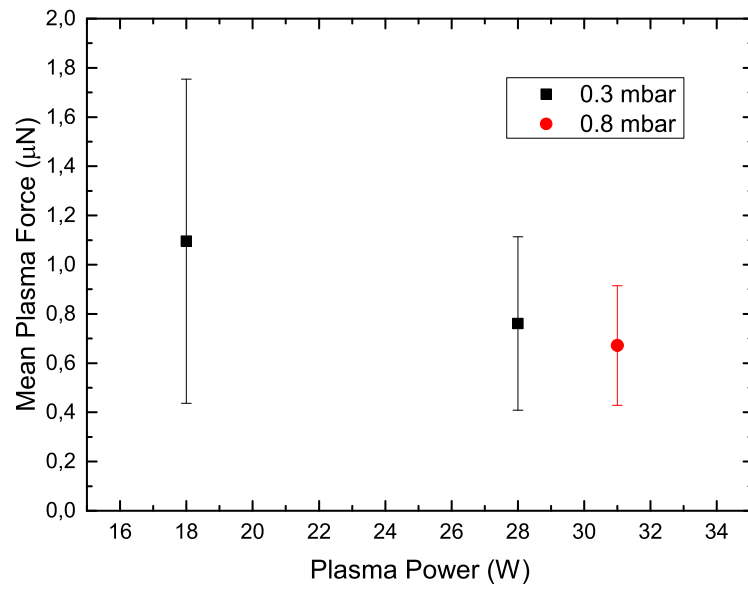


Figure 20: The average plasma force on 0.3 mbar for 18 W is  $1.10 \pm 0.7 \mu\text{N}$ , the plasma force for 28 W is  $0.76 \pm 0.4 \mu\text{N}$  and on 0.8 mbar and 31 W the plasma force is  $0.67 \pm 0.2 \mu\text{N}$

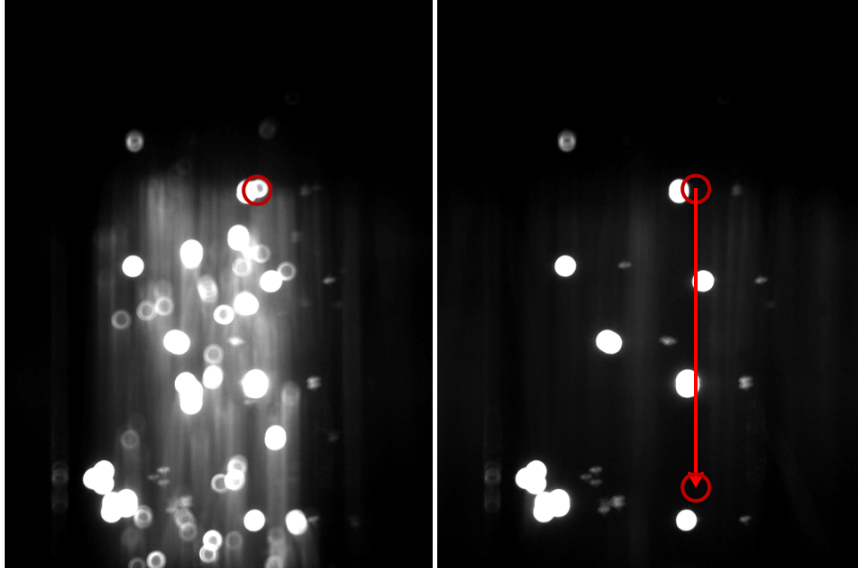


Figure 21: Where particle was before plasma, and where it should have been if only gravity worked on the particle.

## 5 Results and analysis of 10 $\mu\text{m}$ particles

The method for removing particles of 100  $\mu\text{m}$  is viable, but the semiconductor industry is already working at a scale where smaller particles are the problem, Therefore it is important to see if this method is also viable for particles of 10  $\mu\text{m}$ .

This gives also an opportunity to get a better understanding of the plasma force and how it scales with particle size. Both gravity and centrifugal force scale with  $r^3$ , while the van der Waals force scale with  $r$ , so the van der Waals force will dominate as particle become smaller. At the moment there are different hypothesises on how the plasma force scales with radii of particles [10][11][12]. The measurements give the opportunity to see which of the hypothesises is correct. This is to be the extension for the bachelor end project.

### 5.1 Setup change for smaller particle measurements

To do measurements with the smaller particles, changing parts of the setup is needed. The first part that is changed is the disk with a hole through which the particles fall. A small copper disk is used to keep the dust in dispenser. The copper disk has a small hole of 30  $\mu\text{m}$  in it, through which the particles fall. This hole was bigger for the larger particles, but could not be used for the smaller particles. The dispenser's movement is still controlled by a magnetic coil. The other part that needed changing was the laser. The laser that was used for the larger particles is insufficient for the smaller particles. The particles could not be seen on video when the cylinder started to spin at rpm above 2000, the light emitted by the particles was not enough. Therefore instead of a 0.1W blue laser, a 1.5W blue laser is used. This gives the means to see the particle emitted light throughout the measurements at high rpm.

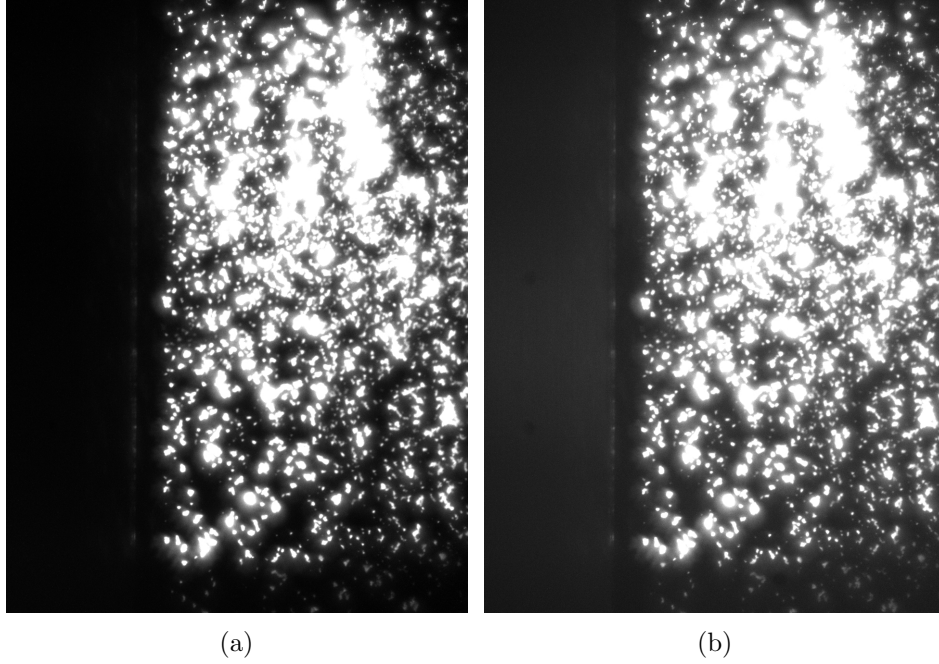


Figure 22: Cylinder surface (a) before and (b) after plasma, the small particles cluster together

## 5.2 First results

For the particles of  $100\text{ }\mu\text{m}$ , the plasma was enough to remove a large percentage of the particles on the cylinder. This could be checked in the same way as previous measurements. The only difference is the size of the particles. Therefore particles were deposited on the cylinder in a larger quantity.

The new laser gives the capabilities to see the small particles on video screen. The results of this can be found in figure 22.

When figure 22a is compared to 22b, there is no difference. This means that the plasma force is not large enough to remove dust particles of  $10\text{ }\mu\text{m}$ . So  $F_{plasma} < F_{vdW}$ .

The visibility of the smaller particles was observed when the the cylinder was turning on high rpm to see if measurements were possible. Without the plasma this proved no problem. So it is possible to measure the adhesive force for the smaller particles with the new laser.



But there is one aspect that has not been researched yet, that could give trouble. It is possible that the plasma emitted light is bigger than the particle emitted light. This would mean that the used method is insufficient and can not be used. This can be solved by using an even more specific filter than the filter that is already used.

Finding the cause for the white plasma could also solve this issue. If the plasma has a purple colour, less light would get through the filter. The spectrum with the used camera filter is shown in figure

This could give a better chance of seeing the particles when the cylinder is moving in plasma. Even when the plasma causes measurement trouble, it is still a promising technique regarding removing small particles from a surface.

It was not possible to do any further measurements due to technical difficulties, therefore more measurements should be done in the future with smaller particles.

### 5.3 Outlook on measurement method

The method for measuring the adhesive force does not change, but measuring the plasma force does change. Instead of calculating the plasma force with help of percentages of lost particles. We need all the different forces to remove the particles. All the forces are needed, because the plasma force is not enough to remove the smaller particles.

To calculate the plasma force, we look at the difference in distributions between measurements with plasma and without plasma. An example is shown in figure 23. The plasma force can be calculated from the difference in distribution.

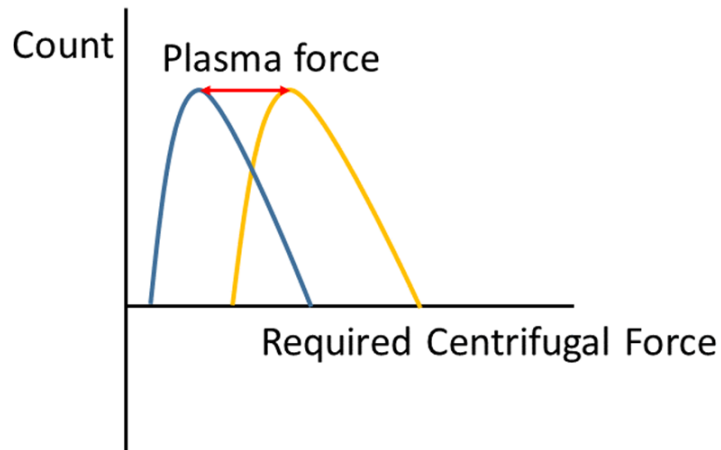


Figure 23: Left distribution is measurement with plasma, right measurement is without plasma

## 6 Conclusion and outlook

The adhesive force measurements for the larger particles showed that difference in pressure changes when particles leave the surface. Equation 2.1 is not dependent on the pressure, but there are other factors that play a role, these are explained in section 4.1. To get a better understanding of the influence of the pressure on the adhesive force, measurements should be done on pressure on order(s) of magnitude higher than already done. This can give conclusive evidence if the pressure has influence on the adhesive force.

The plasma force was large enough to remove particles of 100  $\mu\text{m}$ , the capabilities of the centrifuge were not needed to remove the particles. The value of the plasma force is  $0.9 \pm 0.4 \mu\text{N}$  (figure 19). Further research on pressure and plasma power can be done in the future

The setup should be able to work with higher plasma power, but also needs to be able to make plasma when the pressure is higher. A different amplifier needs to be implemented that makes it possible to make plasma with higher power. This gives the possibility to see the influence of these parameters.

A calculation has been made to make sure there is an actual plasma force, and not that the adhesion force is changed by the plasma. If the adhesion force had changed, then gravity would have been the removing force. The calculation shows that the acceleration of the particles is higher than the gravitational acceleration.

There was a stronger laser needed to see particles of 10  $\mu\text{m}$  on the video. The new laser, which is 15 times as strong, has the strength to see the particles even when the cylinder is rotating at high rpm. It should then be no problem to measure the adhesive force for these smaller particles. The intensity of the background light on video is higher when plasma is turned on, it is not known at the moment if the small particles will be visible when the cylinder is rotating.

There are several things that can be researched in the future. Regarding the adhesive force, a mass spectrometer can be used to see what the amount of water is in the chamber. If there is a lot of water, there could be a capillary force that keeps the particles on the surface. Different pressure could mean that there is a different amount of water in the vessel. Some changes can be made to do more precise measurements on the influence of pressure and plasma power. This requires a different amplifier to get a higher plasma power. The smaller particle measurements need to be done in the future, because technical difficulties made it impossible to do. The smaller particle measurements will give a better idea if the method is viable.

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