Fontys University of Applied Sciences

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# Particle Deposition Research in Cleanrooms

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Applied Physics

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# Abstract

Particle deposition in cleanrooms is a critical concern for maintaining ultra-clean conditions. This research investigates various aspects of particle deposition, aiming to enhance our understanding of contamination control in cleanroom environments. The study evaluates the precision of Particle Deposition Monitor (PDM) measurements and finds that the PDM provides highly precise measurements, particularly in clean environments with minimal particle counts. Baseline particle deposition rates are assessed in different cleanroom locations. The research reveals that smaller particles dominate deposition, and there is a notable difference in deposition rates between the horizontal and vertical planes. During periods of typical activity, particle deposition rates significantly increase, with fibers, likely originating from people, being prominently elevated. The study identifies the replacement of air filters and ceiling openings as major sources of contamination. Equipment performance is evaluated, with the air shower demonstrating high efficacy in removing particles released from clothing, particularly larger particles. Analysis of particle morphology and origins reveals that the majority of fibers discovered are plant-based, predominantly cotton. Glass fibers, identifiable as having a width of $7\mu m$, are believed to originate from cleaning tools. Notably, the ceiling in the cleaning area is found to have a significant impact on deposition rates, with an average deposition rate 87% higher than in the main experiment area.

De neerslag van deeltjes in cleanrooms is een cruciale zorg voor het handhaven van ultra-schone omstandigheden. Dit onderzoek onderzoekt verschillende aspecten van deeltjesneerslag, met als doel ons begrip van contaminatiebeheersing in cleanroomomgevingen te verbeteren. Het onderzoek evalueert de precisie van metingen met de Particle Deposition Monitor (PDM) en constateert dat de PDM uiterst nauwkeurige metingen levert, met name in schone omgevingen met minimale deeltjestellingen. Basistarieven voor de neerslag van deeltjes worden beoordeeld op verschillende locaties in cleanrooms. Het onderzoek onthult dat kleinere deeltjes de neerslag domineren, en er is een opmerkelijk verschil in neerslagtarieven tussen de horizontale en verticale vlakken. Tijdens periodes van typische activiteit nemen de neerslagtarieven van deeltjes aanzienlijk toe, waarbij vezels, waarschijnlijk afkomstig van personen, prominent aanwezig zijn. Het onderzoek identificeert de vervanging van luchtfilters en het openen van plafonds als belangrijke bronnen van contaminatie. De prestaties van apparatuur worden geëvalueerd, waarbij de luchtdouche een hoge doeltreffendheid vertoont in het verwijderen van deeltjes die vrijkomen uit kleding, met name grotere deeltjes. Analyse van de morfologie en oorsprong van deeltjes onthult dat de meerderheid van de ontdekte vezels plantaardig is, voornamelijk katoen. Glasvezels, identificeerbaar aan een breedte van 7 $\mu m$, worden verondersteld afkomstig te zijn van schoonmaakgereedschap. Opmerkelijk is dat het plafond in de cleaning area een aanzienlijke invloed heeft op neerslagtarieven, met een gemiddeld neerslagtarief dat 87% hoger is dan in de main experiment area.

# Foreword

In the pursuit of knowledge and professional growth, my internship experience has been both enlightening and transformative. This report serves as a reflection of the invaluable insights gained during this journey.
I would like to express my heartfelt gratitude to my mentor, Sonja Voorn, whose unwavering guidance and support have been instrumental in shaping my learning experience. Without your support the successful completion of this project would not have been possible.
I am also deeply appreciative of my supervisor, Paul Weling, and the members of SAC, whose mentorship extended beyond the technical aspects of the internship. Your mentorship has played a pivotal role in my development as a professional, and I am grateful for your trust and encouragement.
I extend my thanks to Peter Cuijpers and the supportive team of the Einstein Project for their collaborative efforts and knowledge sharing. Your contributions have enriched my understanding of the subject matter and have been instrumental in achieving the objectives of this internship.
This report reflects the dedication, hard work, and collective effort of a remarkable team. It is my hope that the insights presented herein will serve as a valuable resource for future endeavors in the field.

With sincere appreciation,

Youri Hissink

Landgraaf, Netherlands, October 31, 2024

# Contents

# 1 Introduction

## 1.1 Stakeholders

The following stakeholders are involved in the research on particle deposition in vacuum and cleanroom environments:

- SAC Nederland: As the engineering bureau that created the PDM, SAC has a vested interest in this project due to both business reasons and professional curiosity. Their technology is at the heart of this project.
- The Einstein Project research group: they have a direct use for the results this project will produce. As a research group focused on astronomy and astrophysics, they rely heavily on cleanrooms and vacuum chambers to operate and create the Einstein telescope.
- The University of Maastricht: they have invested resources in the research and development of the Einstein telescope.

## 1.2 Background and motivation for the study

As technology continues to evolve, the size of the components used in electronic devices is shrinking rapidly. Microchips are a prime example of this trend, with the latest designs featuring threads that are just 7 nanometers in size. However, this miniaturization presents a significant challenge for manufacturers, as even the smallest impurities can have a detrimental effect on the performance and reliability of these components. As such, it is more critical than ever to ensure that the manufacturing process for these cutting-edge technologies is free of impurities that could compromise their performance and lifespan. To realize this necessity for cleanliness, cleanrooms are used.
Cleanrooms are critical environments used in various industries such as pharmaceuticals, microelectronics, and aerospace, where the air quality, temperature, humidity, and cleanliness are strictly controlled. Maintaining a clean environment in a cleanroom is crucial for several reasons:

- Quality control: Cleanrooms are essential for quality control in industries such as microelectronics and pharmaceuticals, where small particles or contaminants could have a significant impact on product performance. Cleanrooms ensure that the products produced meet the required quality standards and specifications.
- Contamination control: The primary reason for maintaining a clean environment in a cleanroom is to prevent contamination of products and materials. Even small amounts of contamination can have significant impacts on product quality, safety, and reliability. Cleanrooms are designed to control the number of airborne particles and microorganisms, which could cause contamination.

- Safety: In some industries, such as pharmaceuticals, a cleanroom environment is critical for safety reasons. Contaminants such as airborne bacteria and viruses can be hazardous to human health, so a cleanroom environment ensures that workers are not exposed to such contaminants.
- Research and development: Cleanrooms are also crucial for research and development in various fields. Researchers need a clean environment to conduct experiments to ensure that the results are accurate and reliable.

One such research group is currently preparing parts and procedures for the Einstein Telescope. The Einstein Telescope is a gravitational wave observatory that aims to detect gravitational waves with unprecedented sensitivity and frequency range. The observatory is currently in the planning stages and is being developed by a large team of European research institutions and organizations. It is expected to be a key tool for advancing our understanding of the universe and the fundamental laws of physics. One of the key challenges in designing and building the telescope is ensuring that it operates in a clean environment. Maintaining cleanliness in and around the telescope is essential for the longevity of components and accuracy of the resulting data. Hence, this project will focus on particle deposition in cleanrooms and vacuums. The latter being especially important, as the Einstein Telescope operates in a vacuum. In order to detect and quantify particles present in cleanrooms, the engineers at SAC have developed the PDM (Particle Deposition Monitor). This machine uses a high resolution camera to detect particles present on a witness plate. A picture can be seen in figure 1. Elaboration on how this device works can be found in later chapters. This paper will first eleborate on the consistency and usage of the PDM, followed by base deposition rates of the cleanrooms at ETP as well as the deposition rates of certain events en devices.

Figure 1: A picture of the PDM with a glass plate present, connected to the sofware.

## 1.3 Approach and Research Questions

The project aims to describe particle deposition in the ET Pathfinder project cleanrooms and Einstein Telescope (consisting of six large metal cylinders, called vacuum towers as seen in 2). This will involve measuring particle deposition during various activities, including baseline conditions (no activities) and during vacuuming processes. Aditionally, an analysis will be done on how best to clean the cleanrooms by measuring the amount of swirl caused by cleaning.

Figure 2: A picture of the PDM with a glass plate present, connected to the sofware.

## Goals and Objectives

- Measure the consistency of the PDM measurements in general and for different particle sizes, given through standard deviation.
- Measure baseline particle deposition in the cleanrooms and vacuum towers when no activities are taking place.
- Measure particle deposition during different activities in the cleanrooms and during vacuuming of the towers.
- Visualize large particles (fibers) using a microscope and determine their composition and origin.

## Evaluation and Success Metrics

- Compare the particle deposition levels between baseline and activity periods in both cleanrooms and vacuum towers.
- Determine if the results are relevant compared to the standard deviation of the PDM.

- Determine the differences in behavior for different particle sizes, focus on fibers.
- Determine what the fibers are made of, and their origin.

### Data Analysis

- Present the findings in a clear and understandable manner, using appropriate visualizations if necessary.

## 1.4 Overview of the current state of information of the field

At present, the available body of literature concerning particle deposition in cleanroom and vacuum environments is notably limited. Notably, companies possessing expertise in this domain tend to maintain a strict confidentiality regarding their knowledge, resulting in a scarcity of comprehensive scientific data accessible to the public. Although organizations like ITER do provide insights into their methodologies for establishing clean environments, these disclosures remain insufficient in terms of their applicability to other research groups seeking to replicate similar conditions.[2] [3]

## 1.5 Importance of literature creation

The importance of maintaining a clean environment in cleanrooms cannot be overstated, especially for projects such as the Einstein Telescope, which rely on high-precision and delicate components. However, the lack of understanding regarding particle deposition in cleanrooms poses a significant challenge in ensuring their cleanliness. Even the smallest amount of contamination can have severe consequences, resulting in faulty parts and equipment. For instance, the Einstein Telescope utilizes high-powered lasers, and if dust settles on its mirrors, it can cause the dust particle to "explode", which damages the mirror. Additionally, residual dust in the vacuum chamber can dilute or distort the generated data, resulting in inaccurate results.

To address these issues, there is a crucial need for scientific literature to fill the gaps in our understanding of particle deposition in cleanrooms and vacuums. By creating a comprehensive and scientific understanding of this issue, we can develop better strategies and techniques to minimize contamination and ensure the optimal functioning of equipment in cleanrooms. Ultimately, filling these gaps in knowledge through the creation of new literature will help us achieve greater precision, accuracy, and reliability in the production and operation of technologies such as the Einstein Telescope.

# 2 Theory

Although there is limited scientific research specifically focused on particle deposition in cleanrooms and vacuum chambers, some relevant information may be obtained from other related topics. One such topic is the deposition of particles on wafers.

## 2.1 Particle adhesion forces

In a vacuum, three forces must be taken into account when discussing particle deposition and adhesion:

1. Gravity
2. Static electricity
3. Van der Waals force

The behavior of particles in vacuum is influenced by these different forces, which have varying effects depending on the size of the particles, and must be approached accordingly. Table 1 provides a clear depiction of the degree to which these forces impact particles of different sizes. As particles increase in size, gravity becomes the main force of adhesion. Conversely, as particles decrease in size, the van der Waals force becomes more prominent. This underscores the importance of maintaining cleanliness and avoiding the accumulation of small particles.[1]

Table 1: Comparison of adhesion forces for different particle diameters.[1]

| | 1 $\mu$m | | 10 $\mu$m | | 100 $\mu$m | |
|---|---|---|---|---|---|---|
| | Force | % | Force | % | Force | % |
| Van der Waals force | 0.4 | 99 | 4 | 97 | 40 | 29 |
| Static electricity | 0.005 | 1 | 0.05 | 1 | 0.5 | – |
| Gravity | 0.0001 | – | 0.1 | 2 | 100 | 71 |
| Total | 0.4 | 100 | 4.1 | 100 | 140 | 100 |

## 2.2 The Behavior of Particles in Vacuum

Particles descend under the influence of gravity according to Stokes' rule:

$$v = \frac{\rho d^2 g C_c}{18\eta} \tag{1}$$

Where $v[m/s]$ is the rate of descend, $\rho[kg/m^3]$ the particle density, $d[\mu m]$ the diameter of a particle, $g[m/s^2]$ the local gravitational constant and $\eta[Pa \cdot s]$ the viscosity coefficient of the gas. To calculate the rate of descend it is imperative to know the pressure of the vacuum, as this has an influence on the viscosity. There is also a correction factor $C_c$, the Cunningham factor, given by:[1]

$$C_c = 1 + \left(\frac{\lambda}{d}\right)\left[2.514 + 0.800\exp\left(-0.55\left(\frac{\lambda}{d}\right)\right)\right] \tag{2}$$

Here $\lambda$ denotes the mean free path length. Stokes' rule is only valid in systems with significant pressure present. Using the Cunningham correction, Stokes' rule remains valid even in extremely low pressure environments, where the mean free path is greater than the diameter of the respective particles.
Finally, particles in a gas collide with gas molecules, causing Brownian motion. The velocity as a result of Brownian motion can be expressed as:

$$X = \left(\frac{2kTC_c}{3\pi\eta d}\right)^{1/2} \tag{3}$$

$X[m/s]$ is the average velocity, $k$ is the Boltzmann constant, and $T[K]$ is the temperature of the gas. Both equation 2 and equation 3 are dependent upon $\lambda$ and therefore change depending on gas pressure. Plotting the effect of gravity and Brownian motion upon particles results in figure 3. For particles of

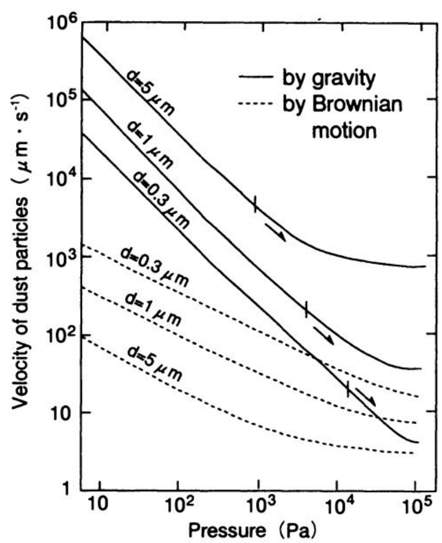



Figure 3: Comparison of particles and the effect of Brownian motion and gravity on velocity.[1]

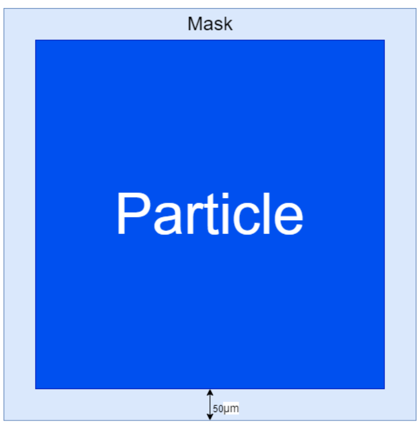
relatively small size, Brownian motion surpasses the acceleration induced by gravity, resulting in a continuous suspension of these particles in gas. However, this applies solely to comparatively high pressures (where the mean free path is smaller than the diameter of respective particles). In a vacuum, gravity induced movement consistently dominates over Brownian motion for particles of relevant size. Equations 1 and 3 can be utilized to estimate the time necessary for particles to deposit. Alternatively, they can function as a feedback mechanism to verify the quality of the vacuum.[1]

# 3 Operational Procedure PDM

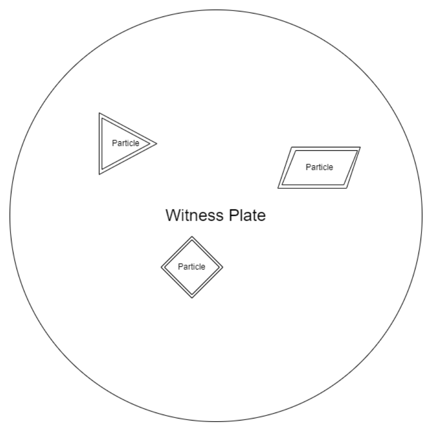
To explain and validate the upcoming results and reliability of the PDM, some context around its operation is needed.

## 3.1 Software

As stated in the introduction, the PDM is a device that is engineered to count particles on a so called 'witness plate'. The PDM fist scans the plate, creating a high resolution picture. This picture is a long strip that the software reconstructs into a disc, essentially gluing the ends together. Next, every individual particle is isolated, counted, and categorized according to length. The various tables in the previous chapter indicate the quantization of the categories. Finally a 'void' is created around each particle, extending $50\mu m$ from the border the respective particle. This is illustrated in figure 4. The next time the witness plate is measured the 'voids' will be ignored, allowing for the new particles to be counted, as seen in figure 5.

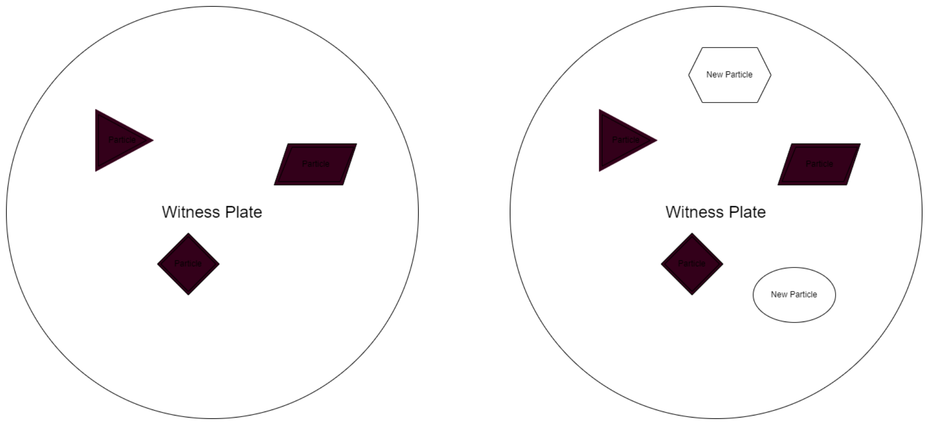



(a) Illustration of the particle with the mask.




(b) Witness plate with particles and respective masks.

Figure 4: Exaggerated illustrations of the workings of the mask.




(a) The final mask, with illustration of the 'voids'.

(b) Second measurement with new particles.

Figure 5: Exaggerated illustrations of the workings of the mask

## 3.2 Witness plate cleaning.

In the Reliability chapter, it was made obvious that a clean plate is beneficial for the accuracy of the measurements made. Thus a standardized process for cleaning, resulting in consistent clean plates is a requirement for this project. The first step is always to clean with isopropanol as a means of removing any grime and fingerprints. This can be done quite roughly to assure the removal of aforementioned impurities. Next a number of cleaning methods are tested. Each combination is tried three times, the average results are seen in tables 2 and 3 below.

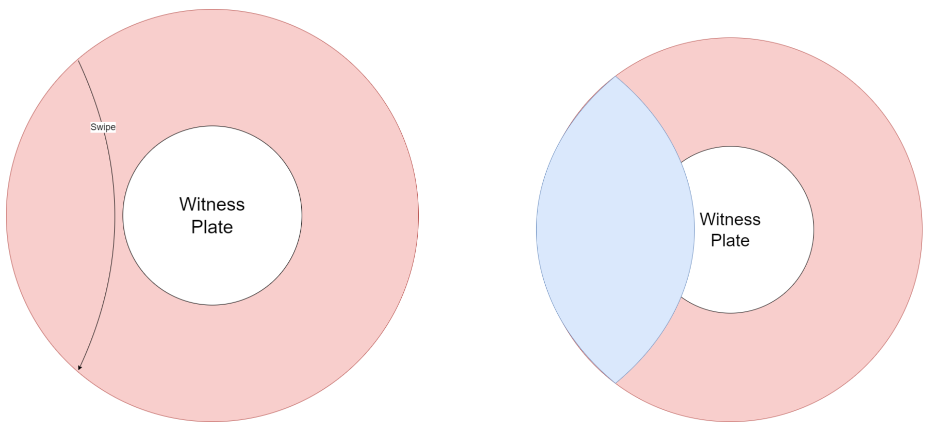
Table 2: Final cleaning done using a thin fiber paper cloth (for cleanrooms).

| | **Camera Cleaner** | **Isopropanol** | **Dry Clean** |
|---|---|---|---|
| **Before Cleaning** | 6279 | 13969 | 17295 |
| **After Isopropanol** | 4282 | 4438 | 4467 |
| **Final Cleaning** | 9742 | 5301 | 1752 |
| | **Average Number of Particles** | | |

Table 3: Final cleaning done using a thick fiber polyester cloth (for cleanrooms).

| | **Camera Cleaner** | **Isopropanol** | **Dry Clean** |
|---|---|---|---|
| **Before Cleaning** | 2951 | 12013 | 3225 |
| **After Isopropanol** | 4697 | 3504 | 4975 |
| **Final Cleaning** | 1235 | 280 | 408 |
| | **Average Number of Particles** | | |

When considering how effective different methods are, the absolute values after the final cleaning step are the ones of importance. The relative value is not, as that could still results in a dirty final product, ruining the credibility of the experiment. The result is quite obvious then, using the polyester cloth with isopropanol results in the cleanest possible plate. Further optimization may be achieved through the cleaning motions themselves. Simply swiping, or rotating motions were found to be somewhat inconsistent. Thus far the best way seems to be moving in a single direction. One starts at the top of the plate, moving slightly off centre. Following, a single downwards swipe that ends once contact with the plate is lost. Next the plate is rotated $40°$. These steps are repeated at least 9 times to cover the entire plate. An illustration of this is found in figure 6.




(a) Illustration the cleaning swipe direction.

(b) Witness plate after first swipe (repetitions needed).

Figure 6: Cleaning illustrated. Where red is the dirty part, and blue the clean-part.

While there are most certainly different products that give an even better result, isopropanol is cheap and easy to find. The result is also more than desirable, resulting in an average particle count of $< 300$, which in turn is more than enough. Another possibility that was taken into consideration is ultrasonic cleaning. This experiment is soon to be conducted. Expectation is that it will indeed result in the cleanest possible plate. But the trade off is not worth it for the objectives of this experiment. As it takes a great deal of time, is more expensive, and may result in failure if any steps are conducted improperly. From tables 2 and 3 one may also conclude that some cleaning methods, while removing oil and dirt, also generate particles. This can be seen clearly after the initial isopropanol cleaning. And also using the paper cloth while wet. As such a final cleaning with polyester is needed, as this appears not to generate particles.

### 3.3 Moving the witness plates

Finally, consideration is needed in regards to the behavior of the particles on the witness plate as it is being moved into position, or taken back to the PDM. To do so a simple test is run to measure how many particles are lost at 2 different speeds, walking 25 meters. The results are as follows:

Table 4: Number of particles on witness plate after a 25 meter walk.

| | **Test 1** | **Test 2** | **Test 3** | **Test 4** |
|---|---|---|---|---|
| **0 m/s** | 595 | 493 | 1227 | 556 |
| **0.73 m/s** | 586 | 479 | 1216 | 559 |
| **1.22 m/s** | 592 | 469 | 1219 | 544 |
| | **Particle Count** | | | |

Given that the results are on average within 2 standard deviations from each other, it would appear that the speed at which one walks while holding the witness plate, is not relevant. That of course only applies to practical walking speeds. In a cleanroom, $1.22m/s$ is a rather fast walking speed. Since a slower walking speed is much preferred, and applied in this project, the factor that is walking with the witness plate, will not be taken into consideration.

# 4 Reliability and Precision

In the realm of measurement, precision and reliability are paramount. Yet, the PDM is a unique measurement instrument, devoid of established reference standards for direct accuracy assessment. In this case, precision and repeatability take center stage. Here, the guiding metric is the standard deviation to convey the reliability of our instrument's results

As such, the standard deviation is calculated for the 'mask' used by the PDM, and the measurement after application of the mask. Not only the total particles measured are considered, but also the channels in which they are distributed. The channels refer to the PDMs' ability to divide particles into categories according to their size (e.g $400 - 500 \mu m$). This is repeated a total of three times, every time a plate with a different degree of 'dirtiness' is used (276, 1201 and 15605 particles). For every calculation a total of 20 measurements are used. Doing so tests what kind of mask gives the most precise results.

## 4.1 Clean plate mask standard deviation

As seen in figure 7, the average number of particles on the mask, or calibration measurement, is 276 with a standard deviation of 5 (2%).

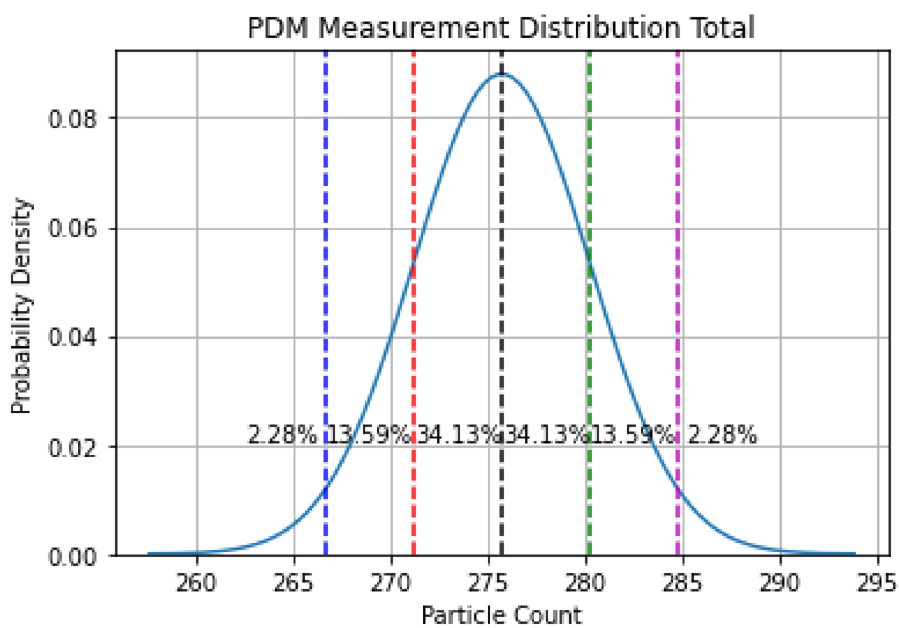



Figure 7: Gauss distribution for the clean plate mask.

Next, the individual channels are covered. For every measurement the PDM takes, it displays both the total particles measured, as well as the amount of particles for each range according to size, or channels, this can be seen in figure 8. For each channel the standard deviation is calculated from the same 20 measurements used above. These can be seen in table 5.

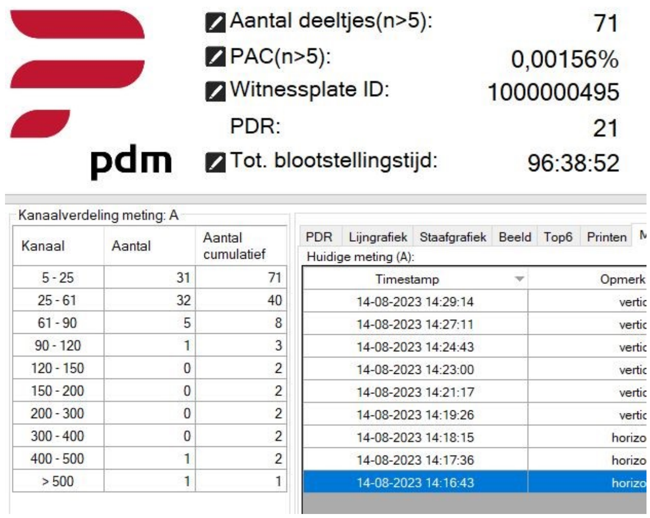



Figure 8: Example of how the software of the PDM displayes results. The total particle count on top, and the number of particles in specified ranges (channels) on the left.

Table 5: Statistics on the clean plate mask for individual channels.

| **Channel** ($\mu m$) | **Average (#)** | **Standard Deviation** | **SD relative to Avg** |
|---|---|---|---|
| 5-25 | 190 | 5 | 3% |
| 25-60 | 58 | 2 | 4% |
| 60-90 | 7 | 2 | 23% |
| 90-120 | 7 | 0.8 | 12% |
| 120-150 | 4 | 0.9 | 26% |
| 150-200 | 1 | 0.5 | 54% |
| 200-300 | 1 | 0.4 | 35% |
| 300-400 | 3 | 0.3 | 11% |
| 400-500 | 0 | 0.0 | 0% |
| >500 | 6 | 0.0 | 0% |

## 4.2 Average plate mask standard deviation

For the average plate mask, the average number of particles on the mask, or calibration measurement, is 1201 with a standard deviation of 11 (0.9%). In table 6 the individual channels are analysed.

Table 6: Statistics on the average plate mask for individual channels.

| **Channel** ($\mu m$) | **Average (#)** | **Standard Deviation** | **SD relative to Avg** |
|---|---|---|---|
| 5-25 | 712 | 10 | 1% |
| 25-60 | 358 | 5 | 1% |
| 60-90 | 38 | 3 | 9% |
| 90-120 | 22 | 3 | 13% |
| 120-150 | 13 | 2 | 15% |
| 150-200 | 14 | 3 | 19% |
| 200-300 | 16 | 1 | 8% |
| 300-400 | 9 | 0.5 | 6% |
| 400-500 | 5 | 0.2 | 4% |
| >500 | 16 | 0.2 | 1% |

## 4.3 Dirty plate mask standard deviation

For the Dirty plate mask, the average number of particles on the mask, or calibration measurement, is 15605.1 with a standard deviation of 19.0 (0.1%). In table 7 where the individual channels are analysed.

Table 7: Statistics on the dirty plate mask for individual channels.

| **Channel** ($\mu m$) | **Average (#)** | **Standard Deviation** | **SD relative to Avg** |
|---|---|---|---|
| 5-25 | 5614 | 24 | 0.4% |
| 25-60 | 7597 | 17 | 0.2% |
| 60-90 | 835 | 9 | 1% |
| 90-120 | 347 | 4 | 1% |
| 120-150 | 188 | 4 | 2% |
| 150-200 | 192 | 3 | 2% |
| 200-300 | 245 | 2 | 0.8% |
| 300-400 | 138 | 2 | 1% |
| 400-500 | 113 | 1 | 2% |
| >500 | 336 | 2 | 0.4% |

### 4.4 Clean plate measurement

Next, the last mask is used to make a measurement with the DPM after leaving all three plates to gather some dust. The standard deviation is once more calculated over twenty measurements per plate. Using that, the effectiveness of each mask can be determined. For the measurement using the clean mask, as seen in figure 9, the average number of new particles on the witness plate, is 206 with a standard deviation of 1 (1%). Followed by table 8 where the individual channels are analysed.

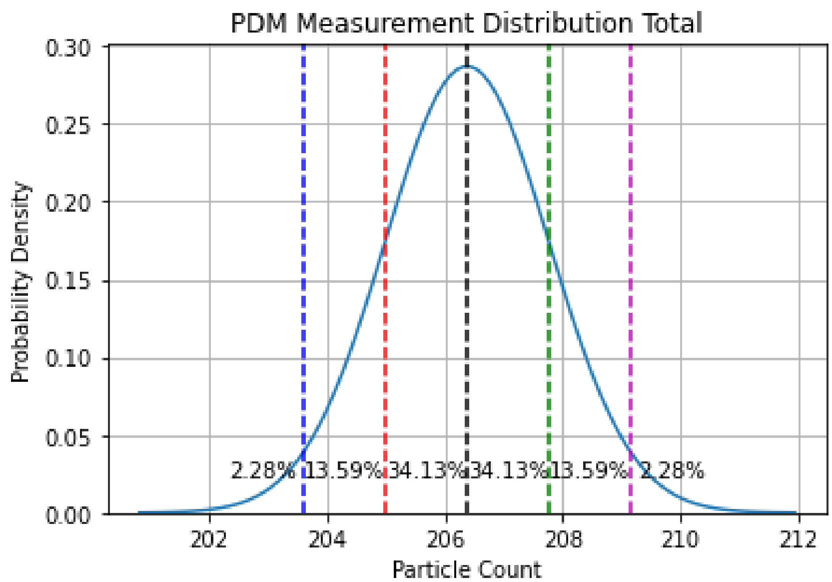



Figure 9: Gauss distribution for the measurements using the clean plate mask.

Table 8: Statistics on the clean plate for individual channels.

| **Channel** ($\mu m$) | **Average (#)** | **Standard Deviation** | **SD relative to Avg** |
|---|---|---|---|
| 5-25 | 69 | 3 | 4% |
| 25-60 | 103 | 2 | 2% |
| 60-90 | 16 | 1 | 8% |
| 90-120 | 3 | 0.5 | 20% |
| 120-150 | 2 | 0.4 | 23% |
| 150-200 | 2 | 0.4 | 17% |
| 200-300 | 7 | 0 | 0.0% |
| 300-400 | 0 | 0 | 0.0% |
| 400-500 | 2 | 0 | 0.0% |
| >500 | 3 | 0 | 0.0% |

### 4.5 Average plate measurement

For the measurement using the average mask, the average number of new particles on the witness plate, is 190 with a standard deviation of 1 (1%). In table 9 the individual channels are analysed.

Table 9: Statistics on the average plate for individual channels.

| **Channel** ($\mu m$) | **Average (#)** | **Standard Deviation** | **SD relative to Avg** |
|---|---|---|---|
| 5-25 | 57 | 2 | 4% |
| 25-60 | 115 | 2 | 1% |
| 60-90 | 3 | 0.5 | 15% |
| 90-120 | 3 | 0 | 0% |
| 120-150 | 3 | 0 | 0% |
| 150-200 | 3 | 0 | 0% |
| 200-300 | 3 | 0 | 0% |
| 300-400 | 3 | 0 | 0% |
| 400-500 | 0 | 0 | 0% |
| >500 | 3 | 0 | 0% |

### 4.6 Dirty plate measurement

For the measurement using the dirty mask, the average number of new particles on the witness plate, is 853 with a standard deviation of 13 (2%). In table 10 the individual channels are analysed.

Table 10: Statistics on the dirty plate for individual channels.

| **Channel** ($\mu m$) | **Average (#)** | **Standard Deviation** | **SD relative to Avg** |
|---|---|---|---|
| 5-25 | 401 | 10 | 3% |
| 25-60 | 232 | 6 | 3% |
| 60-90 | 41 | 4 | 10% |
| 90-120 | 30 | 1 | 4% |
| 120-150 | 17 | 2 | 9% |
| 150-200 | 15 | 2 | 10% |
| 200-300 | 34 | 2 | 5% |
| 300-400 | 22 | 1 | 6% |
| 400-500 | 19 | 2 | 9% |
| >500 | 42 | 0.8 | 2% |

# 5 Results

## 5.1 Precision of the PDM

In table 11 the average particle count of the masks and measurements are seen, along with their respective standard deviations.

Table 11: Summary of the total average particles and the respective standard deviations of the mask and the actual measurements.

| | CPM | CPMM | APM | APMM | DPM | DPMM |
|---|---|---|---|---|---|---|
| APC (#) | 276 | 206 | 1201 | 190 | 15605 | 853 |
| SD (%) | 2% | 0.7% | 0.9% | 1% | 0.1% | 2% |

Here, APC stands for 'average particle count', SD for 'standard deviation', CPM for 'clean plate mask', CPMM for 'clean plate measurement', and so on. Let it be noted that the standard deviation for the masks grows smaller as the plate gets dirtier. This means that the PDM, when making a mask, becomes statistically more precise as the plate becomes dirtier. Also note that the actual measurements have a higher standard deviation as the masks are dirtier. Implying that a measurement done with a cleaner plate/mask results is more precise measurements. The problem however, is that the error of the mask is carried over to the measurement. This is called 'propagation of uncertainty'. To account for this, the following equation can be used;

$$\sigma_{total} = \sqrt{\sigma_A^2 + \sigma_B^2} \tag{4}$$

Here $\sigma_{total}$ is the total uncertainty, $\sigma_A^2$ the standard deviation of the mask, and $\sigma_B^2$ the standard deviation of the measurement. This results in table 12.

Table 12: Actual uncertainty along with the relative uncertainty.

| | CPMM | APMM | DPMM |
|---|---|---|---|
| $\sigma_{total}$ | 5 | 11 | 23 |
| $\sigma_{total}$ (%) | 2% | 6% | 3% |

The clean plate appears to give the statistically most precise measurements. This is fortunate as it is desirable to have clean plates in a cleanroom.

Next the reliabilty of each individual channel must be considered. First the relative standard deviation is plotted on two bar graphs. Figure 15 shows the mask, and figure 16 shows the actual measurement done with the last mask of the twenty that were made.

Note that in both cases the greatest uncertainty lies in the middle channels. Whereas the smaller and larger channels show lesser uncertainty. But here too, the uncertainty of the used mask carries over to the measurements. Once again using equation 4 results in figure 10 and table 13. Showing the actual standard deviation per channel.

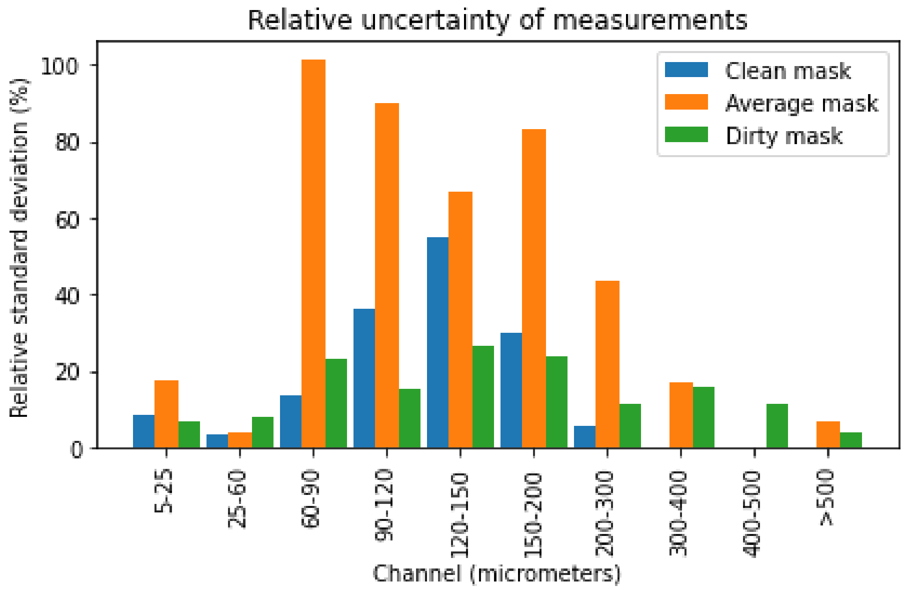



Figure 10: Bar graph illustrating the relative uncertainty of the measurements after correction for each channel.

Table 13: Statistics on the relative uncertainty of the measurements after correction for each channel.

| | $\sigma$ total (%) | | |
|---|---|---|---|
| **Channel ($\mu m$)** | **CPMM** | **APMM** | **DPMM** |
| 5-25 | 9% | 17% | 7% |
| 25-60 | 3% | 4% | 8.0% |
| 60-90 | 14% | 101% | 23% |
| 90-120 | 36% | 90% | 15% |
| 120-150 | 55% | 67% | 27% |
| 150-200 | 30% | 83% | 24% |
| 200-300 | 6% | 43% | 11% |
| 300-400 | 0% | 17% | 16% |
| 400-500 | 0% | 0% | 12% |
| >500 | 0% | 7% | 4% |

Arguably, applying the correction to the individual channels is not an accurate representation of reality. This is due to the fact there is correlation between the mask and the measurement. I.e. a particle that may be registered in the mask in a certain channel, may be registered in a different channel during the measurement. In this case equation 4 is not applicable, and this correction may represent the PDMs ability to accurately measure the size of particles rather then their presence. So it may be wise to adhere to figure 16. Luckily, in this project, the main focus is surrounding the total particles, and fibers (particles that are $> 300\mu m$). With that focus, a clean plate is most certainly preferable, both practically, and statistically.

## 5.2 Cleanroom Particle Deposition Baseline

One of the objectives of this project is to measure the particle deposition in the cleanrooms and the vacuum towers when there is no activity. This shall be referred to as the baseline. This provides an indication of the contamination in the respective areas over time. It may also indicate problem areas where an unwanted or malfunctioning element increases the contamination. Lastly the baseline may give a better understanding of long lasting measurements with periods of activity and inactivity. In the appendix a blueprint of the entire research complex is provided, where each area is clearly indicated (figure 17). Also found on this blueprint are the indicators A1-A9, B1-B7, T1-T4, etc. These refer to locations where witness plates were placed during this project. Of note are location A4 and B5-B7, each of these are placed at an elevation of approx. 2 meters. T1-T4 are located inside the vacuum towers. The remainder are all placed on the floor. Each measurement for the baseline ranges from 88 to 201 hours, where T1-T4 are exceptions with 1127 hours. The length of the measurements was intentionally long, as short measurements yield such low numbers they become unreliable. Each witness plate has a measurement area of $0.004885m^2$. To properly convey the measurements, each will be expressed in $\#/(d \cdot m^2)$ (particles per day per meter squared). In table 14, 15, and 16 the respective baselines for each location in each area can be found. Each table displaying the values for each channel, and the total particle deposition rate (D.P.R).

To complete the baseline, the deposition on vertical surfaces must also be considered. Vertical measurements are impractical, it is much more practical to find a relation between horizontal and vertical deposition. To find this relation, six plates are placed in vertical fashion, with two plates placed horizontally in the same location. The experimental setup can be found below in figure 11. The witness plates numbers on the vertical plane are from left to right; 463, 480, 456, 212, 210, 440. On the vertical plane from left to right; 135, 495. Plate number 480 yielded faulty results, and was not taken into account. The measurements are found in table 17 in $\#/m^2$.

Table 14: Base particle deposition rate at locations in the main experiment area.

| | Particle Deposition Rate ($\#/(d \cdot m^2)$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Channel** ($\mu m$) | **A1** | **A2** | **A3** | **A4** | **A5** | **A6** | **A7** | **A8** | **A9** |
| 5-25 | 128 | 684 | 214 | 546 | 555 | 328 | 218 | 164 | 109 |
| 25-60 | 0 | 0 | 43 | 55 | 214 | 55 | 0 | 55 | 0 |
| 60-90 | 0 | 0 | 0 | 0 | 43 | 0 | 0 | 0 | 0 |
| 90-120 | 43 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 120-150 | 43 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 150-200 | 0 | 0 | 0 | 55 | 0 | 0 | 0 | 0 | 0 |
| 200-300 | 43 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 300-400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 400-500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| >500 | 0 | 43 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **total** | 256 | 726 | 256 | 655 | 812 | 382 | 218 | 218 | 109 |

Table 15: Base particle deposition rate at locations in the cleaning area.

| | Particle Deposition Rate ($\#/(d \cdot m^2)$) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Channel** ($\mu m$) | **B1** | **B2** | **B3** | **B4** | **B5** | **B6** | **B7** |
| 5-25 | 220 | 1051 | 587 | 837 | 279 | 168 | 279 |
| 25-60 | 73 | 293 | 171 | 279 | 112 | 56 | 59 |
| 60-90 | 0 | 0 | 0 | 56 | 0 | 0 | 59 |
| 90-120 | 24 | 24 | 0 | 56 | 0 | 0 | 0 |
| 120-150 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 150-200 | 0 | 0 | 0 | 56 | 59 | 0 | 0 |
| 200-300 | 24 | 0 | 73 | 0 | 0 | 0 | 0 |
| 300-400 | 0 | 0 | 49 | 56 | 0 | 0 | 0 |
| 400-500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| >500 | 49 | 0 | 73 | 0 | 112 | 0 | 59 |
| **total** | 391 | 1369 | 953 | 1340 | 558 | 223 | 447 |

Table 16: Base particle deposition rate at locations in the vacuum towers without vacuum present.

| | **P.D.R** ($\#/(d \cdot m^2)$) | | | |
|---|---|---|---|---|
| **Channel** ($\mu m$) | **T1** | **T2** | **T3** | **T4** |
| 5-25 | 214 | 92 | 366 | 57 |
| 25-60 | 205 | 39 | 161 | 44 |
| 60-90 | 9 | 9 | 31 | 17 |
| 90-120 | 9 | 0 | 4 | 0 |
| 120-150 | 0 | 0 | 13 | 0 |
| 150-200 | 0 | 0 | 9 | 9 |
| 200-300 | 4 | 0 | 0 | 4 |
| 300-400 | 9 | 4 | 0 | 4 |
| 400-500 | 0 | 0 | 0 | 0 |
| >500 | 4 | 0 | 0 | 4 |
| **total** | 453 | 144 | 584 | 140 |

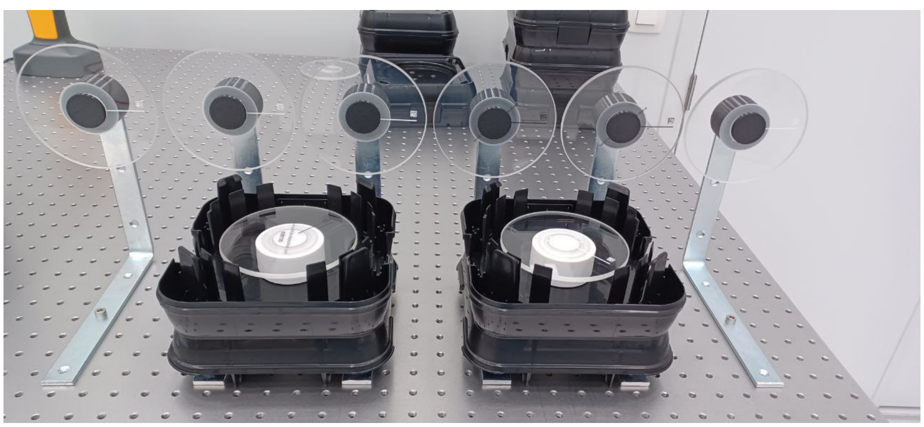


Figure 11: Foto of the experimental setup.

Table 17: Particle deposition on horizontal and vertical surfaces.

| | Particle Deposition ($\#/m^2$) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Channel** ($\mu m$) | **463** | **456** | **212** | **210** | **440** | **135** | **495** |
| 5-25 | 137 | 57 | 46 | 34 | 103 | 756 | 779 |
| 25-60 | 23 | 0 | 0 | 0 | 12 | 275 | 286 |
| 60-90 | 0 | 0 | 0 | 0 | 0 | 12 | 69 |
| 90-120 | 0 | 0 | 0 | 0 | 0 | 0 | 12 |
| 120-150 | 0 | 0 | 0 | 0 | 0 | 12 | 12 |
| 150-200 | 0 | 0 | 0 | 0 | 0 | 12 | 126 |
| 200-300 | 0 | 0 | 0 | 0 | 0 | 23 | 0 |
| 300-400 | 0 | 0 | 0 | 0 | 0 | 12 | 0 |
| 400-500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| >500 | 0 | 0 | 0 | 12 | 0 | 0 | 23 |
| **total** | 160 | 57 | 46 | 46 | 115 | 1099 | 1191 |

## 5.3 Particle Deposition during Activities

### Typical Month of Activity

During the month of May, six witness plates were placed throughout the respective areas. Location C1 is in the changing room, G1 in the goods reception, and O1 in the observatory. While each possible activity can be measured and combined with the baseline to achieve the same result, this is not a realistic approach. This will be further discussed in the discussion. This experiment circumvents possible complications and contamination of the results by running for an entire month, encompassing every factor during that time, and giving the most realistic results. Table 18 displays the measurements obtained during that time, giving the respective locations, individual channels and total deposition per location.

### Ceiling Filter Replacement

A common occurrence in the cleanrooms, is the replacement of an air filter. In the main experiment area, these are located in the ceiling. One such filter, located in between A6 and A7, needed replacing. This offers both the opportunity to determine the effects of such an activity, as well as observing how far primary interaction allowes a particle to travel. For this test, 5 witness plates were set up at A4, A6, A7, A8, and A9. The measurements are given in table 19.

Table 18: Particle deposition rate at locations in the complex druing a typical month of activity.

| | **P.D.R** ($\#/(d \cdot m^2)$) | | | | | |
|---|---|---|---|---|---|---|
| **Channel** ($\mu m$) | **A1** | **A6** | **B1** | **C1** | **G1** | **O1** |
| 5-25 | 1381 | 612 | 1505 | 30330 | 1964 | 31707 |
| 25-60 | 711 | 490 | 601 | 41731 | 1148 | 43464 |
| 60-90 | 134 | 64 | 47 | 4207 | 192 | 3688 |
| 90-120 | 58 | 35 | 29 | 1710 | 58 | 1202 |
| 120-150 | 12 | 18 | 12 | 910 | 58 | 677 |
| 150-200 | 23 | 23 | 23 | 904 | 46 | 554 |
| 200-300 | 18 | 12 | 12 | 1307 | 23 | 584 |
| 300-400 | 6 | 0 | 0 | 630 | 40 | 368 |
| 400-500 | 0 | 18 | 0 | 665 | 18 | 286 |
| >500 | 23 | 35 | 0 | 1716 | 53 | 887 |
| **total** | 2366 | 1306 | 2229 | 84110 | 3602 | 83416 |

Table 19: Particle deposition at locations in the main experiment area after the replacement of an air filter.

| | **P.D** ($\#/(m^2)$) | | | | |
|---|---|---|---|---|---|
| **Channel** ($\mu m$) | **A4** | **A6** | **A7** | **A8** | **A9** |
| 5-25 | 2563 | 5937 | 15967 | 409 | 7779 |
| 25-60 | 0 | 4299 | 205 | 409 | 2661 |
| 60-90 | 0 | 0 | 205 | 409 | 205 |
| 90-120 | 0 | 205 | 0 | 0 | 409 |
| 120-150 | 0 | 615 | 0 | 0 | 0 |
| 150-200 | 0 | 0 | 205 | 0 | 0 |
| 200-300 | 0 | 0 | 205 | 0 | 409 |
| 300-400 | 0 | 0 | 0 | 0 | 205 |
| 400-500 | 0 | 0 | 205 | 0 | 0 |
| >500 | 0 | 0 | 409 | 205 | 409 |
| **total** | 2563 | 11054 | 17400 | 1433 | 12078 |

### Cleaning Area after Ceiling Access

One of the major points of concern for the ETP group is the ceiling in the cleaning area. Unlike the ceiling in the main experiment room, it is made up out of tiles approximately 0.5 x 0.5 meters. The tiles themselves are suspected of producing dust, but that is not the greatest issue. The top side of the ceiling was not cleaned as expected, as a result, a great deal of dust from the initial construction remains. During the project, two ethernet cables were drawn above the ceiling, requiring some tiles to be moved during the process. These tiles are located between location B2 and B3, and B3 and B4 respectively. The amount of contamination each tile created was inconsistent due to the human element. The measurements can be found in table 20

Table 20: Particle deposition at locations in the cleaning area after activities requiring the opening of the ceiling.

| | **P.D ($\#/(m^2)$)** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Channel ($\mu m$)** | **B1** | **B2** | **B3** | **B4** | **B5** | **B6** | **B7** |
| 5-25 | 22108 | 34800 | 490276 | 12692 | 39918 | 106039 | 17196 |
| 25-60 | 14739 | 25363 | 183828 | 12079 | 31320 | 68987 | 44943 |
| 60-90 | 1842 | 4708 | 38689 | 819 | 3070 | 23746 | 2251 |
| 90-120 | 819 | 3275 | 24974 | 614 | 1842 | 12692 | 819 |
| 120-150 | 1024 | 1024 | 17809 | 409 | 1024 | 4503 | 614 |
| 150-200 | 614 | 2252 | 15353 | 409 | 1638 | 3480 | 205 |
| 200-300 | 409 | 2866 | 9416 | 0 | 1229 | 3889 | 614 |
| 300-400 | 205 | 819 | 4299 | 205 | 1024 | 1228 | 205 |
| 400-500 | 0 | 1228 | 1842 | 0 | 614 | 614 | 205 |
| >500 | 0 | 2457 | 4094 | 0 | 427 | 2661 | 205 |
| **total** | 41761 | 78813 | 791198 | 27226 | 82088 | 227840 | 37257 |

## 5.4 Equipment Efficacy

Like in all cleanrooms, the ETP group employs various precautions to maintain cleanliness, including rigorous air filtration, sterile attire, and strict contamination control measures. Two of these precautions have been tested to determine their efficacy.

### Fume Hood Table

In the cleaning area, three fume hood tables are present. The suction produced by the hoods prevents the particles generated from working on machinery from traveling through the cleanroom, instead sucking them into the air filtration system. To test their performance, witness plates are placed on the tables during times with and without activity. The P.D.R during the active periods is expressed as $\#/(h \cdot m^2)$ (particles per hour per meter squared). Deviation from the usual unit is due to practicality, people work hours, not days. Table 21 shows the measurements. The period of activity was measured over the course of 68 hours, the baseline was used to compensate for the inactive time.

Table 21: Particle deposition rate of the fume hood tables used in the cleaning area.

| | **P.D.R** ($\#/(d \cdot m^2)$) | **P.D.R**($\#/(h \cdot m^2)$) |
|---|---|---|
| **Channel** ($\mu m$) | **Baseline** | **During Activity** |
| 5-25 | 128 | 27 |
| 25-60 | 90 | 62 |
| 60-90 | 13 | 21 |
| 90-120 | 0 | 12 |
| 120-150 | 0 | 6 |
| 150-200 | 0 | 6 |
| 200-300 | 0 | 24 |
| 300-400 | 13 | 17 |
| 400-500 | 13 | 11 |
| >500 | 26 | 27 |
| **total** | 282 | 214 |

## Air Showers

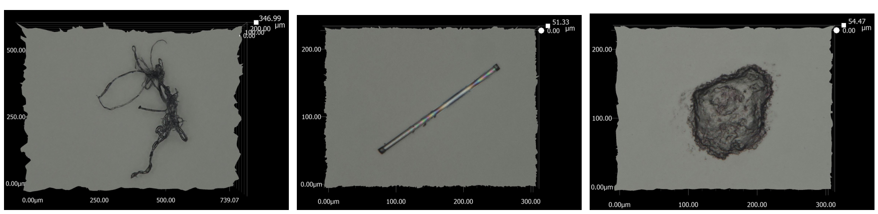
Air showers are used in cleanrooms to remove contaminants from individuals entering or exiting. They blow high-velocity, filtered air to dislodge particles, ensuring a clean environment. They are the first and most important line of defence against unwanted particles. To know how effective the air shower is, an important bit of knowledge in any cleanroom. To test this, first, a person goes through the shower. Half an hour later, another person with a contaminated witness plate goes through. An airborne particle counter is placed next to the door of the shower, taking a sample before and after each test. A clean witness plate is placed next to the particle counter, and is also read after each test. This is repeated three times. The contaminated witness plate is also read before and after the test. The results of the latter are seen in table 22. The results of the particle counter and the witness plate next to it will be discussed in the conclusion.

Table 22: Particle removal from a witness plate by the air shower. Averages of three tests.

| **Channel** ($\mu m$) | **Before (#)** | **After (#)** | **Reduction** |
|---|---|---|---|
| 5-25 | 5593 | 5075 | 9% |
| 25-60 | 7607 | 5359 | 30% |
| 60-90 | 832 | 413 | 50% |
| 90-120 | 345 | 131 | 62% |
| 120-150 | 187 | 57 | 70% |
| 150-200 | 195 | 59 | 70% |
| 200-300 | 246 | 49 | 80% |
| 300-400 | 136 | 21 | 85% |
| 400-500 | 113 | 17 | 85% |
| >500 | 336 | 25 | 93% |
| **total** | 15590 | 11204 | 28% |

## 5.5 Particle Morphology and Origins

Knowing where particles deposit and in which quantity is important. Knowing what they are made of, and where they come from is equally useful in preventing contamination. As such, using a microscope, some of the more damaging particles, namely fibers, have been visualised and identified. For the purpose of this project, they are classified into three groups. Cotton (and natural fibers), glass-fiber, and unknowns. They are shown with examples in figure 12.



(a) Cotton (b) Glass-fiber (c) Unknowns

Figure 12: Three categories of particles with illustrations.

Table 23: Particle type incidence rate.

| | **Cotton** | **Glass-fiber** | **Unknown** |
|---|---|---|---|
| **Cleaning Area** | 67% | 13% | 20% |
| **Vacuum Towers** | 40% | 20% | 40% |

Next the relative incidence rate of each category is calculated. In table 23 the distribution of particle types for the cleaning area and the vacuum towers are shown.

## 5.6 Cleaning Area Ceiling

As mentioned earlier, the ceiling in the cleaning area is of great concern to the ETP team. Thus the final test of this project is to test whether these concern may be justified. To test this a sample was taken from the ceiling and placed under a microscope. The particles types found are displayed in figure 13 below.

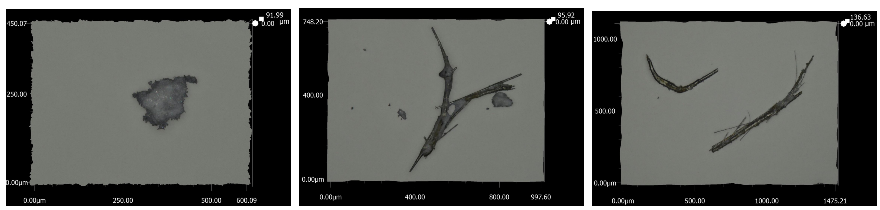



Figure 13: Three typical examples of particles found in the ceiling.

The grey parts were found to be concrete particulates, these appear to be able to cluster particles together. Next they are compared to particles found in the cleaning area for similarities. Of 24 particles observed under the microscope, only one particle was found to be similar. It can be seen in figure 14.

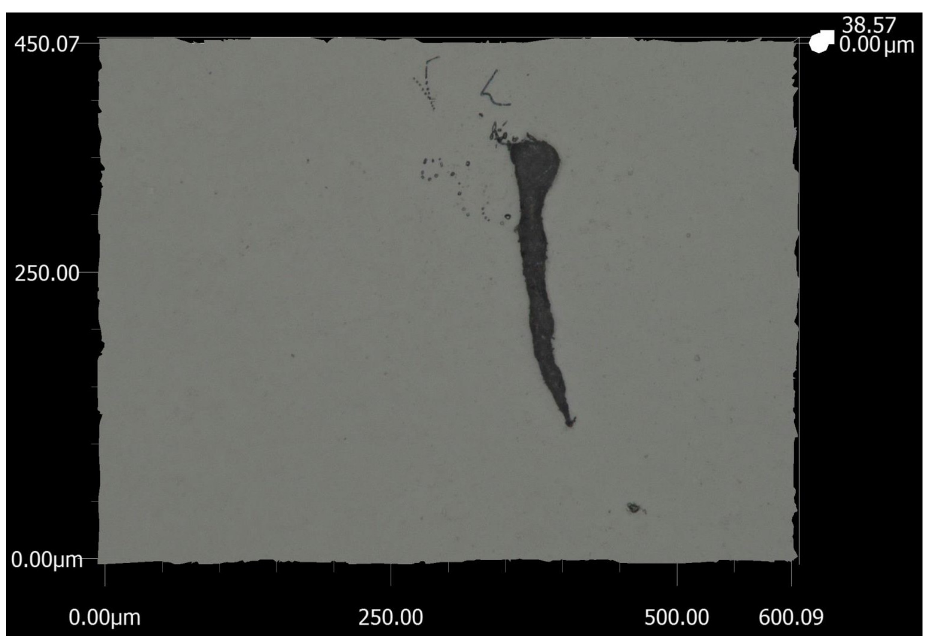



Figure 14: Foto a particle similar to the ceiling particles.

# 6 Discussion

In regards to the precision of the PDM, while this project has shed some light on it, the error is far from a finished subject. The precision could be further explored with more degrees of 'dirtiness', in other words, more masks. This may very well reveal a relation between the two. Also the measurement following the masks was done with a number of particles that is typical of the measurements done in this project. As such the influence of the number of particles from a measurement that is atypical is completely unknown. Thus the precision may well be expressed as an equation of the particles on the mask and on the measurement respectively, that could constitute its own project. Most importantly, the standard deviation is but one part of the error calculation. Systematic-, random-, and absolute errors have all not been taken into account due to a lack of literature and the uniqueness of the PDM.

Many of the results look a little strange, many numbers repeat or are multiples of each other. This is a symptom of the main concern for this project. A witness plate only has a surface area of 0.004885 $m^2$. If two particles land on it, each in a different channel, there is one particle in each channel. When expressing the deposition in $m^2$, the number of particles in that channel across a square meter is much larger, but still equal. Meaning that the witness plate only provides the data from a single fairly small location, that may or may not accurately represent the area around it.

There always exist inconsistencies in cleanrooms, baseline measurements may change depending on the amount and nature of the activity that week. Perfectly controlling every factor is not practically possible however.

When taking a measurement during activities, it can never be completely accurate. During activity particles both deposit, but also whirl up again. Since there is no way to know how many particles are also lost from the witness plate, there is a source of error unaccounted for.

# 7 Conclusion

## PDM precision

After testing the PDM's precision, the clean mask (< 300 particles) results in the most precise measurements. With the standard deviation being 5 particles, and the coefficient of variation (relative standard deviation) of 2%. This is considered a high precision, and thus most acceptable for this project.

As seen in chapter 3.3, moving with the witness plates does not dilute the sample, corrupting the results. This has only been tested for practical walking speeds however.

## Cleanroom Particle Deposition Baseline

From the data in chapter 5.2 a few conclusion may be drawn. First, the base deposition rates of the A, B, and C locations are as follows:

Table 24: Tables displaying the baseline particle deposition rates in $\#/(d \cdot m^2)$.

| A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 |
|---|---|---|---|---|---|---|---|---|
| 253 | 723 | 256 | 655 | 812 | 382 | 218 | 218 | 109 |

| B1 | B2 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|
| 391 | 1369 | 953 | 1340 | 558 | 223 | 447 |

| T1 | T2 | T3 | T4 |
|---|---|---|---|
| 453 | 144 | 584 | 140 |

From tables 14, 15, and 16, it also becomes clear that the bulk of the particles deposited are rather small ($< 60\mu m$) while fibers are rare.

Using table 17, with an average deposition of 1145 $particles/m^2$ on the horizontal plane, and an average deposition of 85 $particles/m^2$ on the vertical plane. The relation; horizontal:vertical is approximately 13.5:1. Here the vertical plane is confined to particles with $< 60\mu m$.

## Particle Deposition during Activities

During a month with typical activity the deposition rate is clearly far greater than during periods of inactivity. Especially C1 and G1 are highly elevated, this is to be expected since these rooms are not cleanrooms. The elevation of fibers across the board is very notable however, indicating that people play a crucial part in their generation and propagation.

The replacement of an air filter is not measured over time since it is a single event that took less than an hour. Even so particle count is elevated. Since the replaced filter was on the ceiling above A6 and A7, this is where the most deposition took place, as expected, reaching up to 17400 $particles/m^2$. While A9 falls in line with the expected, A8 does not. From location A4 it becomes clear that particles have limited capability to travel, this capability is further reduces for bigger particles.

Opening the ceiling in the cleaning area is the greatest source of contamination found during this project. At B3 right below an open tile, nearly 800 000 $particles/m^2$ deposited. Noteworthy is that once again, particles do travel, but the amount of deposition decreases fast with increased distance, more so for bigger particles, reducing up to 100% from B3 to B4.

## Equipment

Underneath the fume hood table the baseline deposition rate is 282 $particles/(d \cdot m^2)$. This baseline is lower than the baseline for the cleaning area itself. During work the deposition rate becomes 214 $particles/(h \cdot m^2)$. Notably, during work the particles generated are of greater size than at baseline.

The air shower test displayed a very high efficacy when it comes to suctioning off the particles loosened from the clothes. Both airborne counter and witness plate outside the shower displayed such low values that they were not considered relevant. The shower does appear to be more effective at loosening larger particles. As particle sizes increases, the percentage of particles removed from the clothing increases. With particles $> 500\mu m$ seeing a 93% reduction, whereas particles $< 25\mu m$ only a 9% reduction.

## Particle Morphology and Origins

The vast majority of fibers discovered are cotton or another plant based clothing fiber. Moreover they are predominantly black or white. The cleanroom clothed cover everything except the ankles, leaving the socks exposed. Since socks are predominantly black or white, the current theory is that most cotton fibers originate from socks. Glass-fiber is the least present group, but very much identifiable. Each instance found had a width of $7\mu m$ which is the most common width for glass-fiber. It is common in cleaning tools such as brushes, and it believed to originate from such tools.

## Cleaning Area Ceiling

The base deposition rate in the cleaning area is on average 87% higher than in the main experiment area. Given that, in the cleaning area, a particle was found that matched with the particles of the respective ceiling, it is quite likely that the ceiling has an effect on the deposition rate.

# 8 Recommendations

## SAC

Following the discussion chapter, the obvious recommendation is to explore alternative ways to obtain the true error margin of the PDM, or to determine the reference standard independently. An update to the software in the form of two UI upgrades is also recommended. Loading old data can only be done one at a time, and between each, the location of the page resets, changing either would solve this problem. Finally, the titles of each measurement can't be found in the data, while the comments can, inexperienced users may find this confusing at first.

## ETP Team

As it stands, the greatest contaminant in the form of fibers is cotton. The most likely source is socks, since the cleanroom pants are just shy of covering the ankles. Moreover the presence of glass-fiber was notable in the vacuum towers, the brushes used to clean the inside are most probable the cause. As seen in this paper, the air shower is most effective at removing the particles from the air after they've been released from the cleanroom clothes. But it becomes less effective at releasing particles the smaller those get. Those particles are still carried into the cleanroom. And the changing area has a very high particle deposition rate. Reducing the deposition rate in the changing area may well reduce the deposition rate inside the cleanrooms.

# 9 Bibliography

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[3] ITER Organization. Vacuum and cryogenics. https://www.iter.org/mach/Vacuum, n.d. Accessed on March 16, 2023.

# 10 Appendix

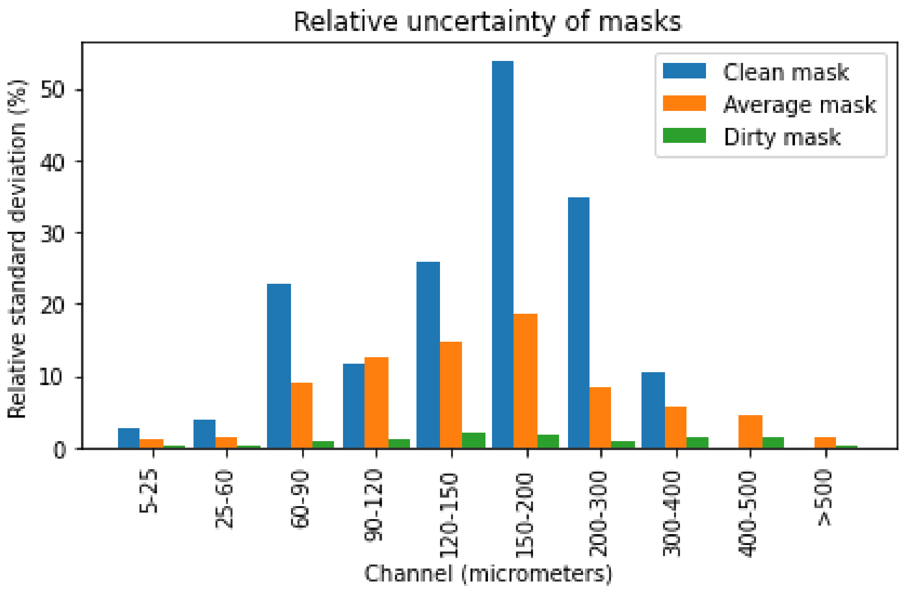


Figure 15: Bar graph illustrating the relative uncertainty of the masks.

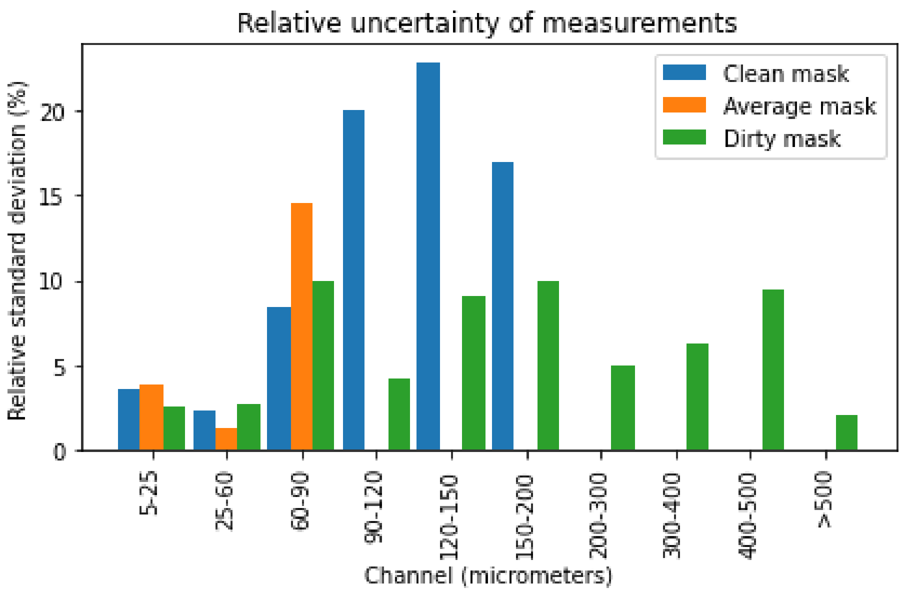


Figure 16: Bar graph illustrating the relative uncertainty of the measurements.

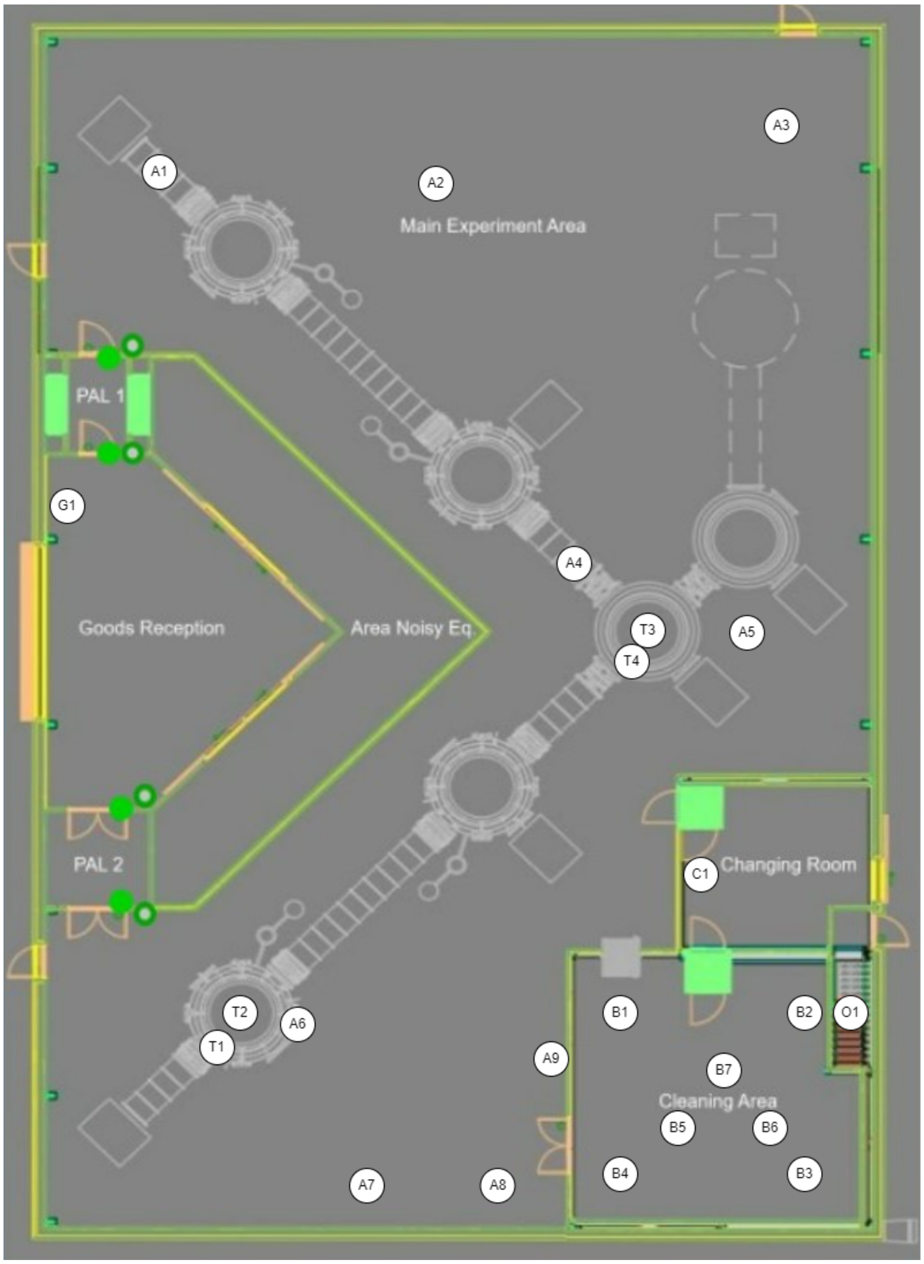


Figure 17: Blueprint with every location where measurements have been made using witness plates