



School of Engineering, Manufacturing and Logistics

Resolving Optical Contamination Using the DMAIC Approach to Problem Solving

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i. Declaration

This thesis is the result of the authors original research. It has been composed by the author and has not been previously submitted for examination which has lead to the award of a degree.

Signed: _____

Date: _____

ii. **Abstract**

Company

PerkinElmer are a global corporation with over 9000 employees, serving 150 countries worldwide (PerkinElmer, 2015). PerkinElmer was founded in 1937 by Richard Perkin and Charles Elmer as an optical design and consulting company before later entering the analytical instruments market in 1944. Today PerkinElmer is a \$2.1 billion global leader focussing on helping improve human and environmental health through the design, development and manufacture of advanced technologies. (PerkinElmer, 2017).

Challenge

There have been 358.5 hours of manufacturing downtime associated with contamination in the optical beam path of the Operetta CLS - PerkinElmer's latest Confocal Fluorescence microscope used for high content screening. Additional to the downtime in manufacturing there have been two warranty complaints at customer sites for instrument exhibiting optical contamination. Optical contamination has resulted in a cost to the business of £65,522.25 in 2017. The objective of the project is to reduce the downtime hours by 80% and decrease the warranty complaints to zero.

Solution

Design improvements of two major sub-assemblies within the Operetta CLS instrument assembly have been seen to significantly reduce the amount of downtime seen. Process improvements that include the design of a test fixture to verify the assemblies prior to installation on an Operetta CLS have also improved

Outcome

The proposed design and process solutions have significantly reduced the downtime associated to contamination within the manufacturing environment. Confidence is high within the project team that the design improvements will eliminate the warranty complaints due to contamination also.

iii. **Acknowledgements**

I would like to thank PerkinElmer for the opportunity to undertake a project within the company. in particular Grant Jones for allowing participation of a part time degree whilst in full time employment and providing support along the way. I would also like to thank Neil Fraser and the project team for all their support and guidance throughout the entire project. Additionally, I have received enormous support from my Lecturers' at University Wales Trinity St David and would like to thank Andrew Thorn for his continuous support and time for this project and to all the lecturers who have supported me throughout the entirety of the degree.

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1. Chapter 1: Project Introduction and Project Definition

1.1. Company Background

PerkinElmer are a global corporation with over 9000 employees, serving 150 countries worldwide (PerkinElmer, 2015). PerkinElmer was founded in 1937 by Richard Perkin and Charles Elmer as an optical design and consulting company before later entering the analytical instruments market in 1944.

Today PerkinElmer is a \$2.1 billion global leader focussing on helping improve human and environmental health through the design, development and manufacture of advanced technologies. Providing researchers, clinicians and a variety of end users the tools and expertise required to solve a large range of scientific challenges. PerkinElmer lead the market with their expertise in detection, imaging informatics and services to enable critical insights and discoveries in diagnostics, life sciences and the environment (PerkinElmer, 2017).

PerkinElmer have 35 sites in various locations around the globe, each site is responsible for Research and Development (R&D), Manufacturing or Global Sales. This report details the work performed at one of PerkinElmer's manufacturing sites based in Llantrisant, South Wales.

1.2. Llantrisant Manufacturing Plant

Llantrisant, South Wales, is home of PerkinElmer's only UK based manufacturing facility. The Llantrisant site is one of eight manufacturing sites globally and one of two manufacturing sites within Europe. The Llantrisant site was opened in 1988 resulting from the closure of the manufacturing site based in Beaconsfield, London. Before closure the Beaconsfield site housed both R&D and manufacturing within the same building, using R&D to support the manufacturing department directly. To allow R&D and manufacturing to expand, PerkinElmer closed the manufacturing side of the Beaconsfield business, moving it into Llantrisant, allowing the R&D group to grow exponentially in London and increased growth in the manufacturing site in Llantrisant.

The Llantrisant site is responsible for manufacturing analytical and diagnostic instruments for a wide range of applications. In total there are approximately 20 different instruments assembled

and tested in Llantrisant contributing to a turnover of approximately 150 million Dollars annually. The site manufactures instruments in two key areas of the business – Environmental Health and Life Sciences.

Environmental Health

The Environmental Health department manufactures and provides instruments and software to a variety of end users focussing in the areas of material characterisation and thermal and elemental analysis. Llantrisant's manufacturing portfolio includes:

- Lambda – UV/VIS/NIR Spectrometer
- FL45/55 – Fluorescence Spectrometer
- DSC 8500 – Differential Scanning Calorimeter
- EA2400 – CHNS Elemental Analysis
- Spotlight – FT-IR Imaging System
- Spectrum 2 - FT-IR Spectrometer

Life Sciences

The Life Sciences department manufactures and provides instruments, assay platforms, and software to hospitals, medical labs, clinicians, and medical research professionals to help improve human health through diagnostics. Llantrisant's manufacturing portfolio include:

- Opera Phenix – High Content Screening
- Operetta CLS– High Content Analysis
- Envision – Multi Label Plate Reader
- Victor Nivo – Multimode Micro Plate Reader
- VOX – Confocal Microscope

The author is a PerkinElmer employee and member of the manufacturing engineering department in the Llantrisant manufacturing site, responsible for all technical issues that arise

during the assembly, optical alignment and testing of the Operetta CLS™ high-content analysis system.

1.3. Operetta CLS Overview

Figure 1-1 is an image of the Operetta CLS™ high-content analysis system, a recent addition to PerkinElmer's product portfolio. Designed in PerkinElmer Hamburg, by a team of highly skilled engineers and scientists over a period of three years, the Operetta CLS is PerkinElmer's flagship instrument for high content analysis.



Figure 1-1 - Operetta CLS™ (PerkinElmer, 2017, n.d.)

High content analysis (HCA) also known as high content screening (HCS) is a relatively new method that is used during the preclinical research phase of drug development and in vitro testing (Schoonen, et al., 2011).

Before a drug can be used on patients and deemed suitable for sale it has to be subjected through vigorous testing and analysis. The drug development process is split into three key steps (FDA, 2015):

Step 1 – Discovery and Development

Discovery – Drug discovery by researchers may be realised through:

- New discoveries of a particular disease process that can enable researchers the ability to create a product that can stop or reverse the damage occurred by the disease.
- Extensive trials of molecular compounds that may discover positive effects against a large number of diseases.
- Existing treatments that may have unforeseen effects.
- Advanced technology.

During the discovery phase it is highly likely that thousands of compounds will be deemed suitable for development as a medical treatment. After extensive testing, however, only a small percentage of these will show enough potential for further study.

“As many as 10,000 compounds may be considered and whittled down to just 10 to 20 that could theoretically interfere with the disease process” (Torjesen, 2015)

Development – When a compound has been identified as promising for development, experiments are performed to gather vital data with regard to:

- The compounds effect within the disease, how it is absorbed, distributed, metabolised and excreted.
- The efficacy and mechanisms of action.
- The most effective dose.
- Effectiveness when compared to similar drugs.

Step 2 – Pre-clinical Testing

The next step in the process is to determine whether the developed compounds “have the potential to cause serious harm” (FDA, 2015) called toxicity. In addition to confirming that the compounds have an effect on the diseases of interest. The two types of pre-clinical testing methods are

- In Vitro – Latin for “within the glass” is the technique of performing experiments in a controlled environment outside of a living organism (Autoimmunity Research Foundation, 2012). These studies can be conducted with biological cells in an artificial culture media stored in lab wear (petri dishes and cell plates etc.).
- In Vivo - Latin for “within the living” refers to experiments conducted using a whole living organism and not a partial or dead organism (Autoimmunity Research Foundation, 2012).

Torjeson (2015) states that approximately half of the compounds that are tested at this stage make it through to the next stage of clinical trials, these five to ten remaining compounds are now ready to be tested on humans for the first time.

Step 3 – Clinical Trial

As the Pre-Clinical Testing stage only answers the basic questions with regard to how safe the drug is, there is no substitute for how the drug interacts with the human body. Clinical Trials are the experiments conducted on humans once Pre-Clinical testing has been completed. The Clinical trial is split into four phases as shown in Figure 1-2.

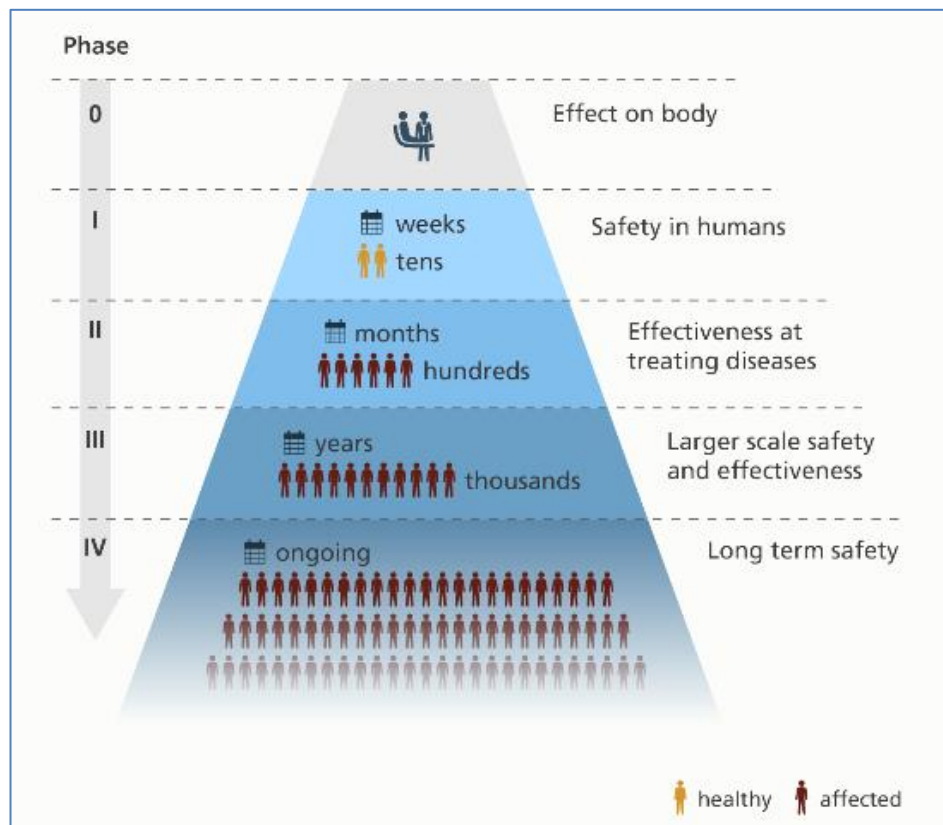


Figure 1-2 - A Flow Diagram to Illustrate the Different Phases in a Clinical Trial (YourGenome, 2016)

Phase 1 – The trial drug is tested on tens of healthy humans for the first time to determine its safety and dosing range. The drug is usually administered in smaller doses and the healthy volunteers monitored over a period of weeks.

Phase 2 – The drug's dose has been determined and is tested to evaluate its biological effect, effectiveness at treating disease and a continuation of the safety tests performed in Phase 1. This is performed on a larger sample size (100-300) over a period of a few months.

Phase 3 – The drug is administered to thousands of patients with the drug effectiveness tested against a known “gold standard” treatment. The testing process can take a number of years to determine its true effectiveness.

Phase 4 – long term safety surveillance and technical support. The drug is monitored for safety ongoing after permission for sale has been granted by the FDA.

The Operetta CLS™ High Content Analysis System is a key research tool used in the “Pre-Clinical” testing phase of the drug development process, specifically In Vitro testing as highlighted in Figure 1-3.

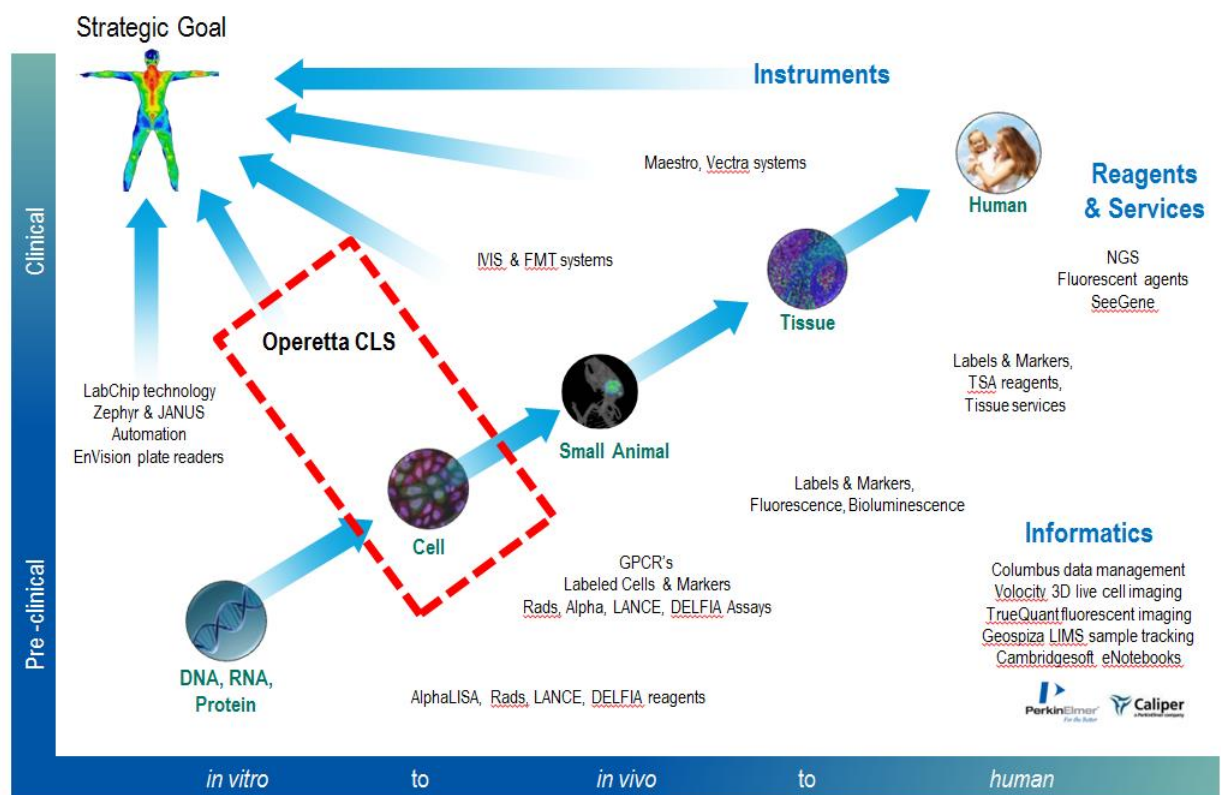


Figure 1-3 - Drug Development Process (Fraser, 2016)

1.3.1. Fluorescence Microscopy

The Operetta CLS™ is a high throughput, confocal scanning, fluorescence microscope. The instrument houses a unique and complex system of optical components and the latest technologies of light sources and cameras to capture an ultra-high-resolution image of biological cells for analysis by drug development researchers.

Unlike a compound microscope (brightfield microscope) that illuminates the specimen from the bottom and is viewed from the top, the Operetta CLS™ uses high intensity LED light sources and the scientific principles of fluorescence in the visible light region to capture an image of the subject specimen.

Visible Light

Photons of light can act as both particles and waves, irrespective of this, in microscopy, light is measured in wavelength. Visible light that can be seen with the naked eye is between 400nm and 700nm in wavelength and made up of all the colours that we see as a typical rainbow. Light at around 400nm is blue in colour; 500nm to 600nm is green to orange in colour, finishing at 700nm that is red in colour as shown in Figure 1-4.

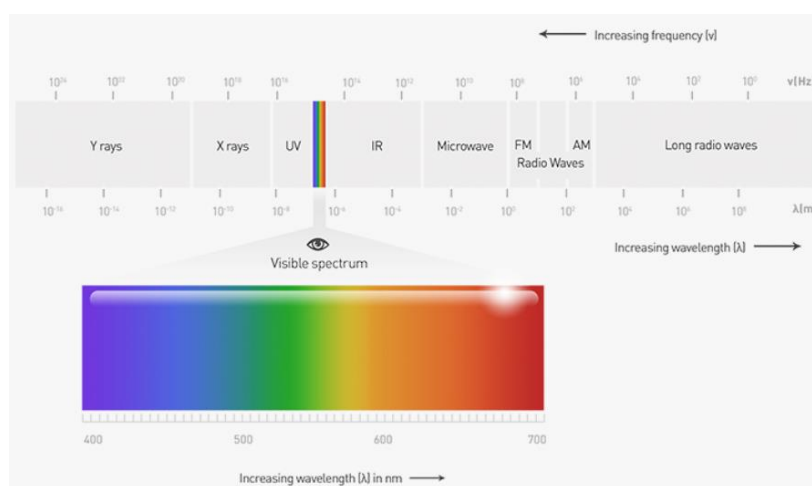


Figure 1-4- The Visible Spectrum of Light (ThermoFisher Scientific, 2017)

Fluorescence

Jameson (2014) defines fluorescence as “The light emitted by an atom or molecule subsequent to the absorption of electromagnetic energy”. When a molecule is excited by incoming light, the electrons are promoted from the ground state to an excited state, these electrons then lose a bit of energy due to vibrations in the molecules, finally the electron returns to the ground state by emitting a photon as shown in Figure 1-5.

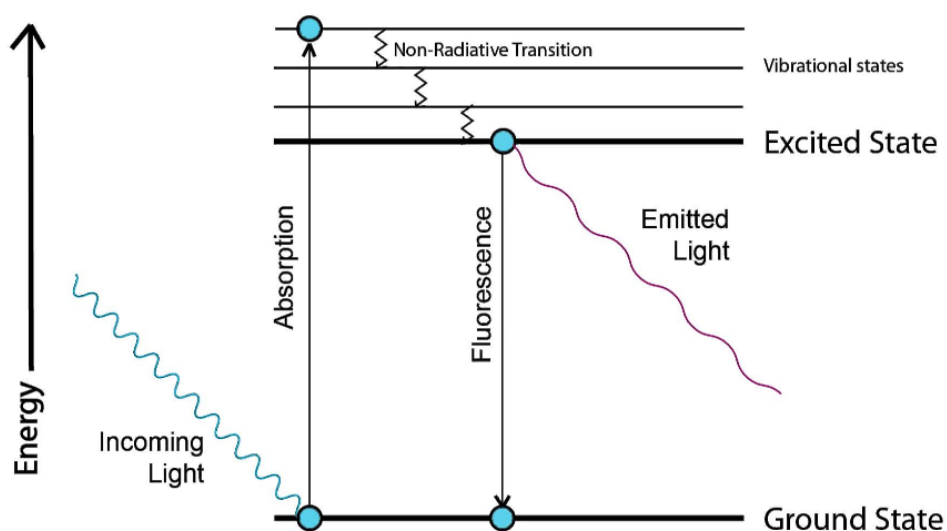


Figure 1-5- Jablonski Diagram (Jameson, 2014)

Since energy cannot be created or destroyed and a small amount of energy is lost as heat due to the vibration of the molecules, the energy of the light emitted (E_F) must have lower energy than the light absorbed (E_A). Therefore the Emission light is usually a longer wavelength (lower energy) when compared to the excitation spectra. This phenomenon is known as Stokes shift.

$$E_A > E_F$$

When a molecule absorbs light at a specific wavelength and then emits light at a higher wavelength it is described as a fluorophore (ThermoFisher Scientific, 2017). As previously discussed, the emitted wavelength will be of lower energy than the wavelength absorbed. A molecule that absorbs blue light emits green light and a molecule that absorbs green light will emit red light. Figure 1-6 shows this inverse relationship between wavelength and energy in the visible region of light.

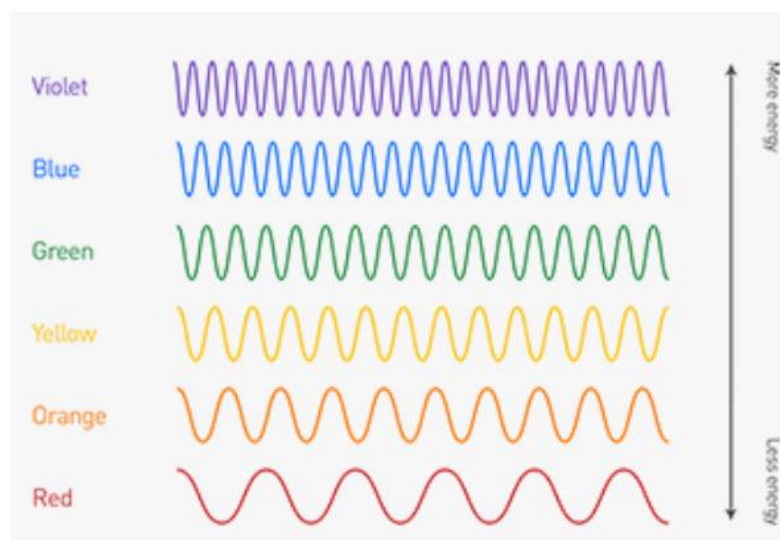


Figure 1-6 - Inverse relationship between energy and wavelength (ThermoFisher Scientific, 2017)

Excitation and Emission Spectra

The principle function of a fluorescence microscope is to expose the specimen to predetermined, specific wavelengths of light, and then to separate the much weaker, emitted fluorescence from the excitation light, only the emission light should reach the eye or detector, this ensures that the fluorescent structures from the specimen are overlaid with a high contrast against a black background (MicroscopyU, 2015). An example of a typical fluorescence image from an Operetta CLS can be seen in Figure 1-7, in this example the nuclei, mitochondria and actin cyto-skeleton of the specimen cells have been stained with fluorescent dyes, upon excitation from specific wavelengths of light the cell structure can be easily differentiated when using a correctly set up fluorescence microscope.

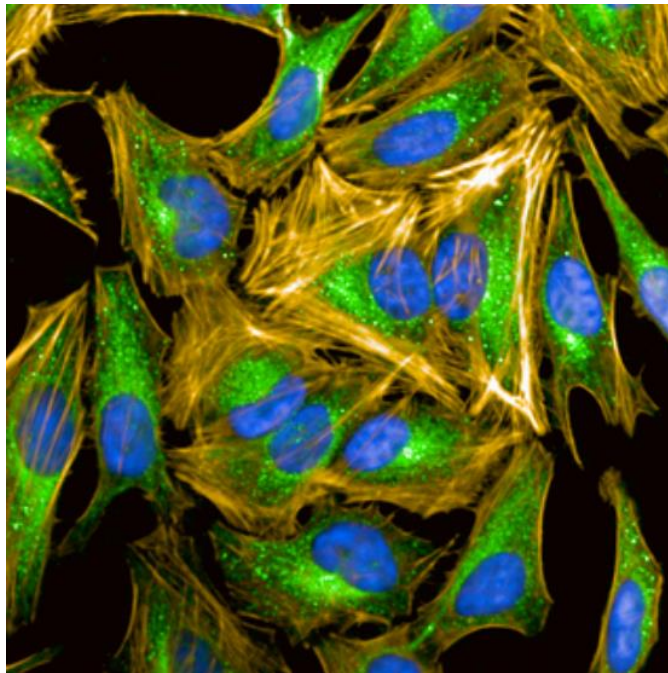


Figure 1-7 - HeLa cells stained with Hoechst (DNA), Alexa Fluor™ 488 labeled anti-tubulin and TRITC-Phalloidin (actin) imaged with a high NA 40x water immersion objective on an Operetta CLS

A Fluorescence microscope discriminates between the excitation light emitted from the light source and the emission of light from the fluorescence process with the use of optical filters and dichromatic mirrors. The Operetta CLS relies on the same optical principles and has been designed to image the fluorescence from the target specimen while eliminating any noise from the far greater excitation light. To do this the Operetta CLS houses a unique and complex system of optical components and the latest technologies of light sources and cameras. A basic light path schematic and arrangement of these components can be seen in Figure 1-8. The blue lines highlight the excitation light path while the red line highlights the fluorescence (emission) light path from the specimen. The excitation light is emitted from the Lightsource and travels through a number of optics and sub-assemblies before exciting the specimen. Fluorescence occurs, and the fluoresced emission light then travels back through the system, directed towards the camera for imaging. This process and the components involved are discussed in more detail in chapter 1.3.2.

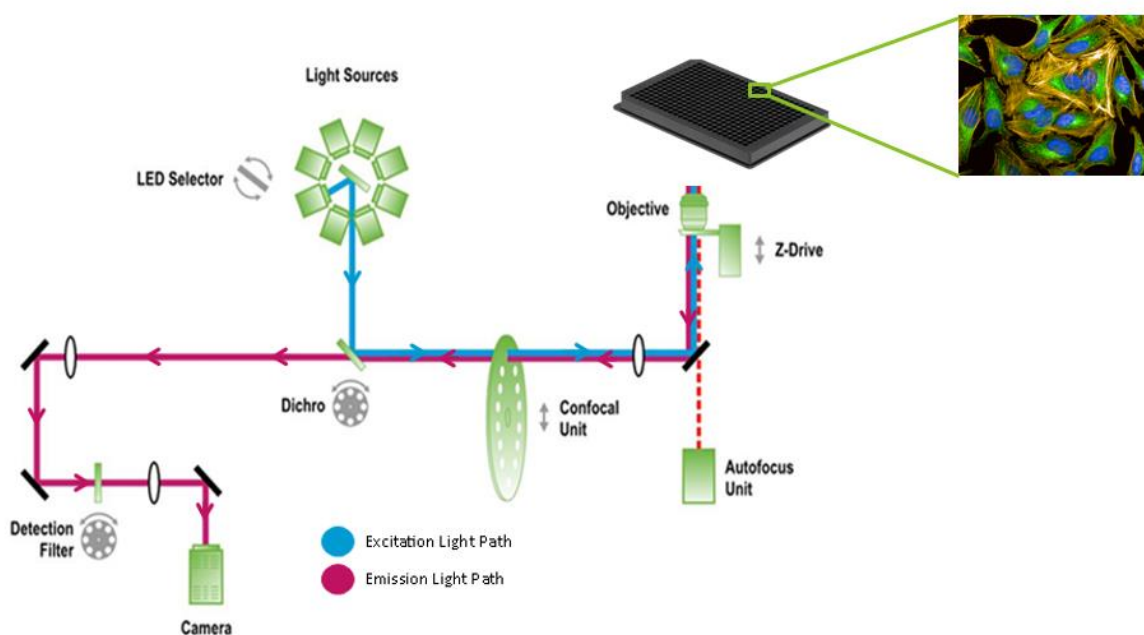


Figure 1-8 - Operetta CLS Optical Beam Path

1.3.2. Operetta CLS Major Assemblies

The Operetta CLS is manufactured from a number of complex sub-assemblies that are built by highly skilled technicians within PerkinElmer. Each assembly has a particular function in providing the customer with ultra-high resolution images.

LED Assembly

For fluorescence to occur, the specimen must be subjected to light for excitation. The excitation light in the Operetta CLS is provided by the LED assembly shown in Figure 1-9. The LED assembly can house eight high power LED modules, each LED module is designed to emit a specific wavelength of light, this is user defined and dependent on the fluorophores used in the specimen. Depending on the selected LED configuration, the instrument is equipped with 4 or 8 LEDs for excitation of the sample as shown **Error! Reference source not found.** in Table 1-1. The four standard LEDs are highlighted with a grey background.

Table 1-1 - LED Configuration

Wavelength	Power	Excitation Filter	Classification of Optical Radiation
365 nm (UV)	130 mW	355-385 nm	Risk Group 3
405 nm	230 mW	390-420 nm	Risk Group 3
450 nm	230 mW	435-460 nm	Risk Group 3
475 nm	110 mW	460-490 nm	Risk Group 2
505 nm	100 mW	490-515 nm	Risk Group 2
550 nm	170 mW	530-560 nm	Risk Group 2
630 nm	120 mW	615-645 nm	Risk Group 2
660 nm	250 mW	650-675 nm	Risk Group 3

The LED wavelength is selected in the Harmony software. The selected LED is powered to a predefined percentage of power and mechanically guided into the system via a 45-degree mirror mounted to a high precision stepper motor. The stepper motor rotates 360 degrees allowing fast selection of any of the LED modules.

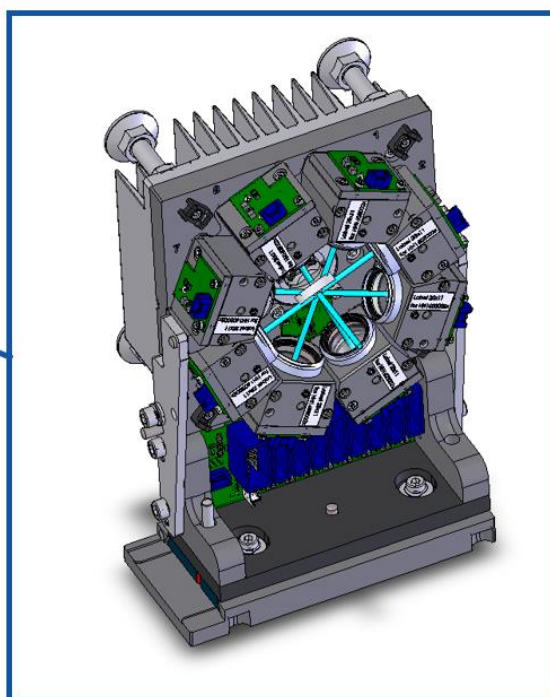
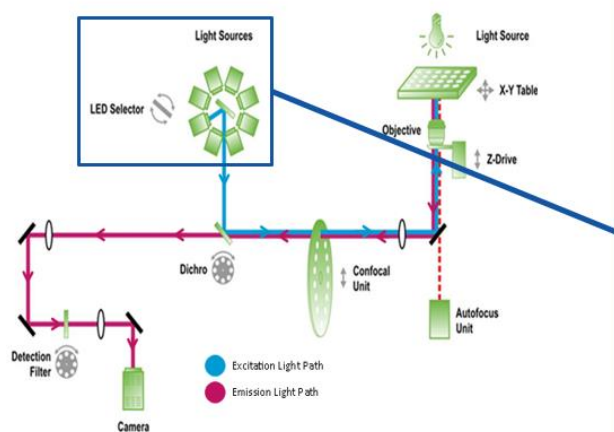


Figure 1-9 - LED Assembly

Dichromatic Wheel Assembly

The Dichromatic wheel shown in Figure 1-10 is the junction between the excitation light from the LED Wheel and the emission light from the specimen. Mounted at 45 degrees to the excitation beam, it is the Dichromatic Wheel Assemblies function to discriminate between the excitation and emission light, ensuring reflectance of the excitation light TO the specimen and transmission of the returned emission light FROM the specimen to the camera. The transmission profile of a typical Dichromatic mirror can be seen in Figure 1-11. It can be seen that photons with wavelengths of between 450nm and 495nm are blocked (reflected) and photons having wavelengths of greater than 500nm are transmitted. This ensures that the excitation light from the LED is reflected onto the specimen while the fluoresced emission light of a higher wavelength, passes through the Dichromatic mirror onto the camera.

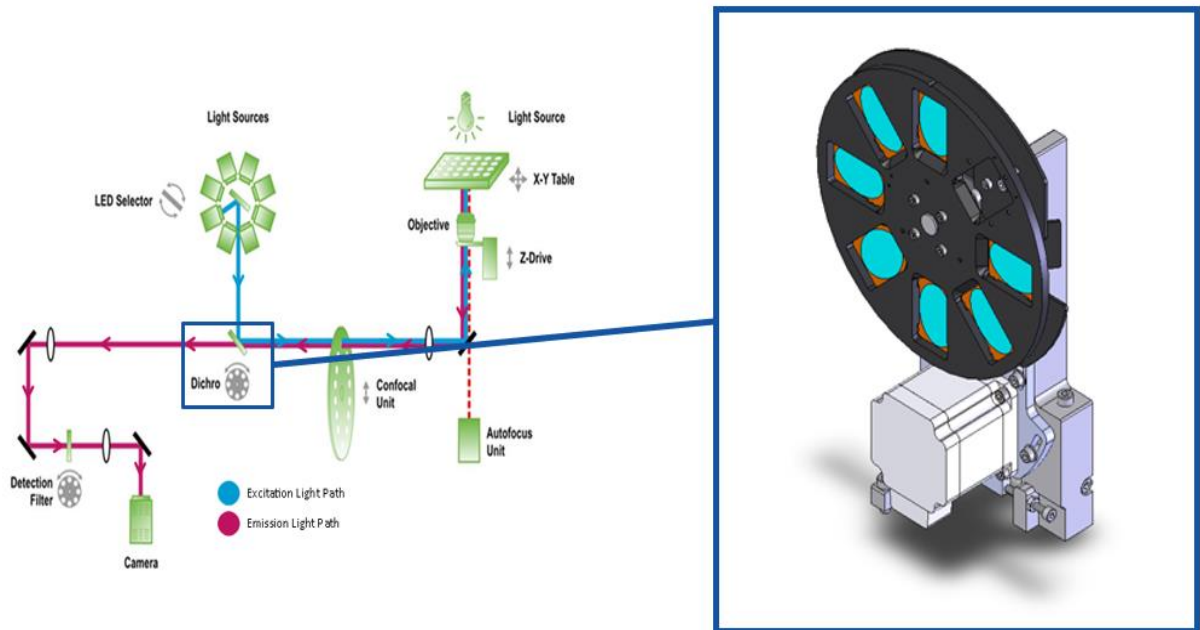


Figure 1-10 - Dichromatic Wheel Assembly

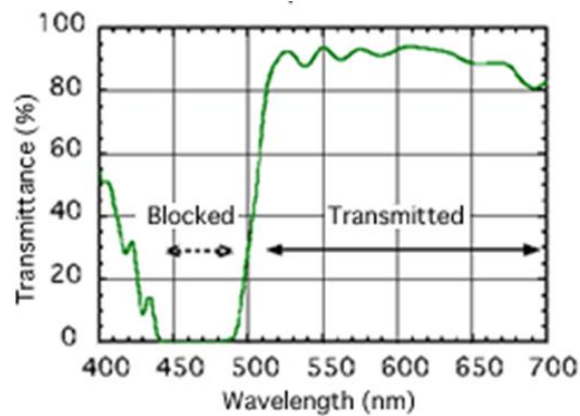


Figure 1-11 - Typical Dichroic Transmission/Reflectance Spectra - Long pass 495nm

The dichromatic wheel assembly has eight different dichromatic mirrors, each with a specific Long pass wavelength, this can be seen in Table 1-2. The number denotes the wavelength from which the dichromatic mirror allows transmission.

Table 1-2 - Dichromatic Mirror Configuration

Configuration
Longpass 425 nm
Longpass 465 nm
Longpass 495 nm
Longpass 525 nm
Longpass 565 nm
Longpass 650 nm
Longpass 680 nm

Confocal Unit Assembly

The Confocal Unit Assembly seen in Figure 1-12 consists of a rotating disc that allows an imaging technique named "Confocal Microscopy". When using a conventional wide field microscope, interference from secondary fluorescence emitted by the specimen that appears away from the region of interest often interferes with the resolution of those features that are in focus (Nikon, 2017). Wide field microscopy bathes the entire specimen in excitation light, this

can result in photo toxicity of the specimen and bleaching of the fluorophores, potentially damaging the cell and reducing the magnitude of fluorescence that can occur.

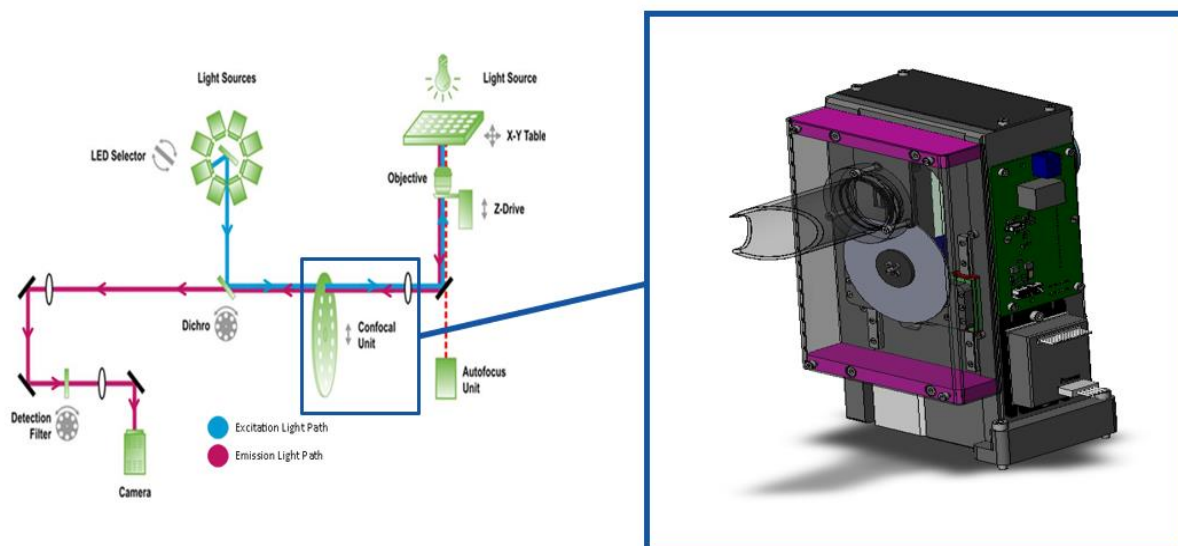


Figure 1-12 - Confocal Unit Assembly

The Operetta CLS, uses a confocal spinning disc similar to the nipkow disc seen in Figure 1-13 to eliminate background, increase the signal to noise ratio of the instrument and to protect the live cell samples by reducing the effects of photo bleaching and photo toxicity. The confocal spinning disc is manufactured from suprasil (Fused Quartz) and is comprised of approximately 55000 pinholes, each with a diameter of 55um formed in an Archimedean spiral pattern of constant pitch.

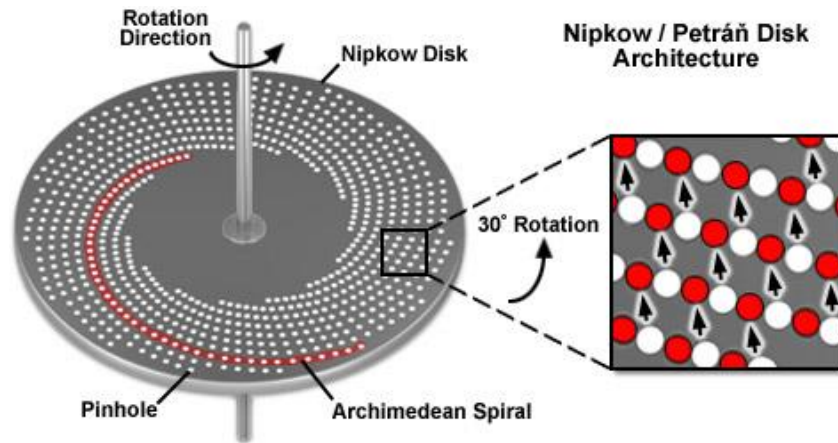


Figure 1-13 - Nipkow Spinning Disk (Zeiss, 2017)

The excitation light from the LED module floods the rear surface of the spinning disc partially blocking the excitation light, allowing transmission only through the pinholes as shown in Figure 1-14. Using this technique illumination of the specimen and detection of the resulting images occur in tandem using pinholes on opposite sides of the disk (Zeiss, 2017). The disk spins at approximately 1000rpm resulting in 1000 individual light beams that can traverse the entire image plane in less than a millisecond. This technique reduces the exposure time of the sample to the potentially harmful photons and ensures that the complete specimen image is sharp and in focus with little interference from secondary fluorescence.

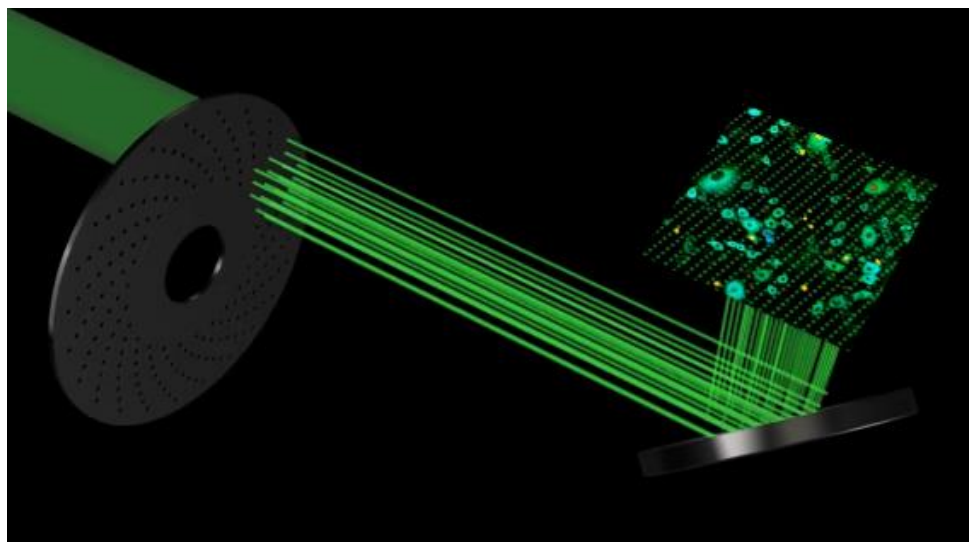


Figure 1-14 - Spinning Disk Pinhole Scanning

Objectives & Z Drive

In any microscope, the objective is the single most important component (MicroscopyU, 2015). The objective is responsible for gathering the light emitted from the specimen and focuses the emission light to produce an image. The objective determines the quality of the image that the Operetta CLS is capable of producing. The term "objective" is used due to the fact that it is the closest component to the object (specimen) being observed. Objectives also determine the magnification of the image and are available in the magnifications seen in Table 1-3.

Table 1-3 - Objective Configurations

Component	Description
Standard Objective	20x Air, NA 0.4
Optional Air Objectives	1.25x Air, NA 0.03 5x Air, NA 0.16 10x Air, NA 0.3 20x HNA Air, NA 0.8 40x Air, NA 0.6 40x HNA Air, NA 0.75
Optional Water Immersion Objectives	20x Water, NA 1.0 40x Water, NA 1.1 63x Water, NA 1.15

The Operetta can hold up to 6 objectives at any one time; the objective can be selected by the user and rotated into the light path for use. The Z-Drive is a stage that drives in the Z axis, the Z-Drive "picks up" the selected objective from a revolving plate and positions it to the correct focussing distance prior to imaging. The user can select a distance in 1µm planes to position the objective with regard to the specimen. This allows imaging at different depths within the specimen. This stack of image planes can later be combined to create a 3D image.

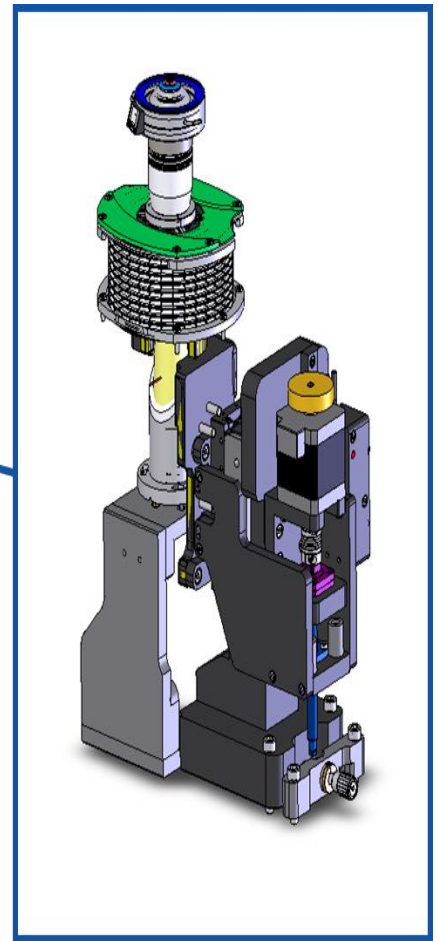
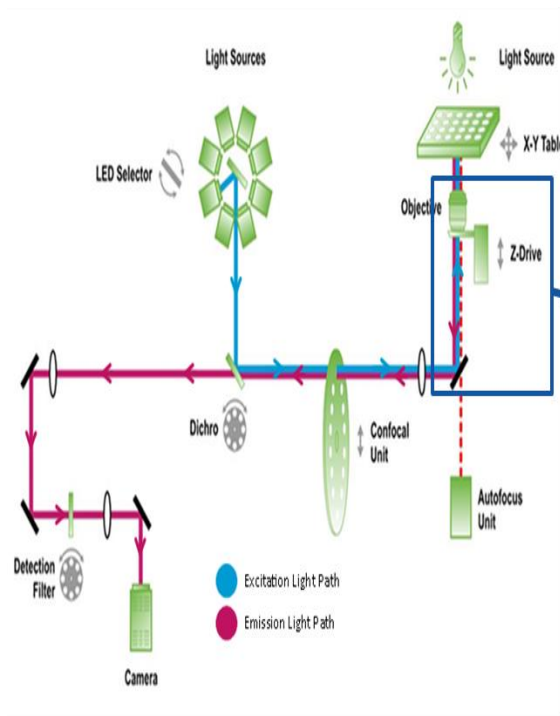


Figure 1-15 - Objective and Z-Drive

Emission Wheel

Fluoresced light from the specimen travels through the Dichromatic mirror passing through a series of optics and lenses that focuses the light onto camera sensor. This creates a sharp, in focus image of the specimen on the camera plane. Before the photons land onto the camera, they first travel through emission filters housed in the emission filter wheel seen in Figure 1-16.

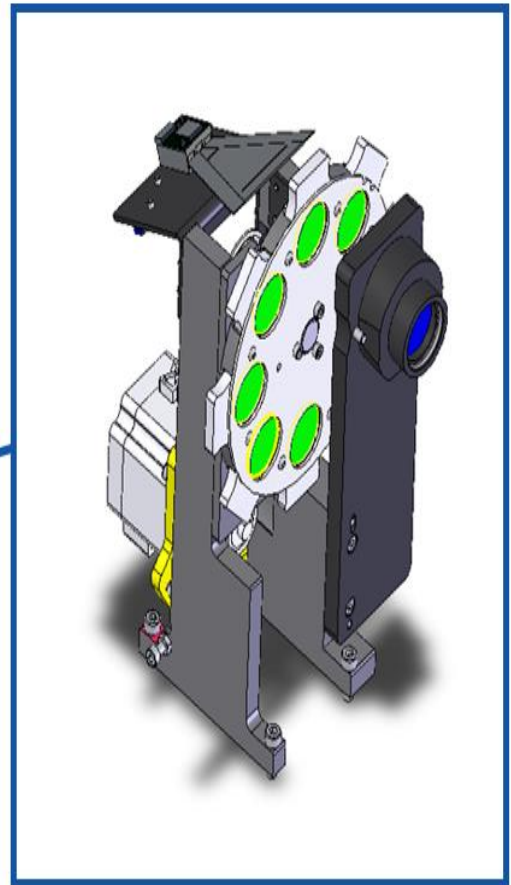
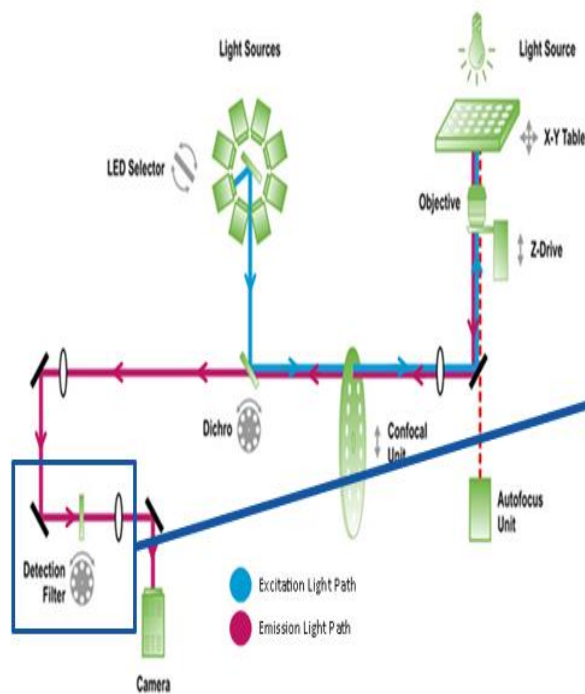


Figure 1-16 - Emission Wheel

The wheel holds 8 user exchangeable, barcoded emission filters in a circular pattern that rotate into the optical path via a motor and belt configuration. The emission filters are bandpass filters, passing only the wavelengths emitted by the fluorophore and blocking all undesired light outside this band – especially the excitation light from the LEDs. By blocking unwanted excitation energy, optical emission filters guarantee a dark background ensuring a brighter, cleaner image of the specimen. This is necessary because the strength of the fluorescent light is weaker than the excitation light by a factor of more than 100,000:1 (Lakowicz, 2010). Typical blocking characteristics can be seen in Figure 1-17. Photons with wavelengths of less than 500nm are blocked whilst wavelengths of greater than 500nm are transmitted.

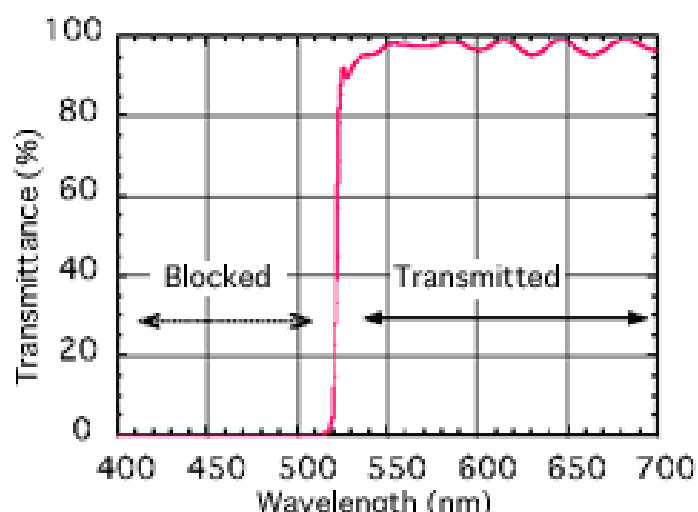


Figure 1-17 - Emission Filter Spectra

Up to 8 emission filters can be installed simultaneously in the instrument. These filters can be exchanged by the user depending on the application. Available bandpass configurations can be seen in Table 1-4.

Table 1-4 - Emission Filter Configurations

Standard Configuration	Optional Configuration
430-500 nm	460-515 nm
500-550 nm*	470-515 nm
570-650 nm	470-540 nm
655-760 nm	515-580 nm
	525-580 nm
	570-620 nm
	655-705 nm
	685-760 nm

Camera Unit Assembly

The detection element of the Operetta CLS is an ultra-high resolution sCMOS camera as shown in Figure 1-18 . The camera sensor converts the photons that are projected onto the sensor into an image that can be viewed by the Customer using the Harmony software.

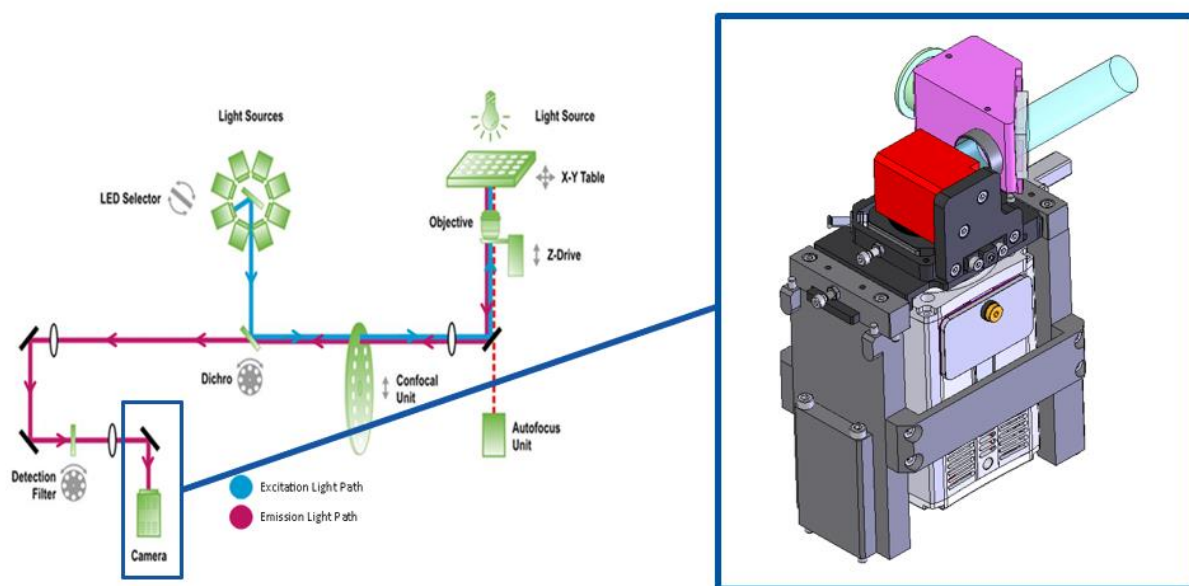


Figure 1-18 - Camera

1.3.3. Alignment and Adjustments (A&A) and Internal Acceptance Tests (IAT)

The Operetta CLS is manufactured from component level. The system is assembled and tested by a team of 11 trained technicians. The technicians are split over four key stages in the manufacturing process:

1. Sub assembly build - Assembly of the major sub-assemblies identified in chapter 1.3.2.

2. Main instrument build - Installation of the major sub-assemblies onto the optical baseplate along with wiring all assemblies and building the instrument to a completed state.
3. Alignment and Adjustments (A&A) - Coarse and fine alignment of the system.
4. Internal Acceptance Tests (IAT) - A set of tests that must be performed by the instrument prior to shipment to the customer.

This report discusses a bottleneck in the manufacturing process, the instruments ability to pass an experiment that is part of the IAT criteria, namely "Contamination". The IAT (Internal acceptance tests) are a set of experiments and tests that the technicians must perform on the Operetta CLS before shipping to a customer. These tests are performed to ensure that the instrument optics are correctly aligned and that the instrument meets the specifications that it has been designed to achieve.

There are a range of different tests that are performed in the IAT, including safety critical tests i.e. electrical safety testing. Mechanical tests, for example checking for any slip in moving parts of the system with the use of limit switches and encoders. Finally, optical performance tests. The Operetta CLS was designed for exceptional image quality at a high throughput rate, this image quality is vigorously tested using the latest imaging software and techniques, to ensure outstanding performance before the system leaves the manufacturing site.

For an instrument to pass the IAT criteria, it must achieve the specifications set by the Hamburg R&D team during the design and prototype build of the instrument. To determine the specifications documented in the IAT, The R&D team used figures from three different sources:

- Zemax software - Software used to design and evaluate the optical performance of the instrument during initial development.
- Prototype instruments – These are the initial instruments that were physically assembled and tested once designed using the Zemax software – Six in total.

- Opera Phenix – This instrument is the larger version of the Operetta CLS. This has been in production since 2013. The design of the Operetta CLS shares many optical components and mechanical assemblies as the Opera Phenix (approximately 80%). Due to the established production of this instrument many of the performance specifications from the Phenix IAT can be transferred directly across to the Operetta CLS IAT.

1.3.4. Contamination Overview

Contamination is considered as artefacts that are visible in the image field other than the specimen under investigation. This can be seen in the image field as both Bright and Dark Contamination and is tested for during the IAT.

Bright Contamination

Bright contamination can be seen as bright artefacts in the image that do not originate at the specimen. To test for this a sample plate coated with a high absorbance, zero fluorescence foam is inserted into the Operetta CLS for imaging. an image is captured with each of the LEDs at a high exposure time of 10 seconds at 100% LED power. This is completed with all optical configurations to ensure exposure of each optical element as shown in Table 1-5.

Table 1-5 - Bright Contamination Test Configuration

LED Wavelength	LED Power	Camera Exposure Time (s)	Dichromatic Mirror	Emission Filter
365nm	100%	10	Longpass 425nm	430-550nm
405nm	100%	10	Longpass 425nm	430-550nm
450nm	100%	10	Longpass 465nm	500-550nm
475nm	100%	10	Longpass 495nm	500-550nm
505nm	100%	10	Longpass 525nm	570-650nm
550nm	100%	10	Longpass 565nm	570-650nm
630nm	100%	10	Longpass 650nm	655-760nm
660nm	100%	10	Longpass 680nm	655-760nm

The purpose of this test is to expose any contamination present in the Operetta CLS optical system to ensure perfect image quality for the customer. Fluorescence occurs naturally, as such, dust particles and natural oils from fingerprints etc. can fluoresce when excited at specific wavelengths. To ensure that each system has optimal optical quality, a specification has been set in IAT using the configuration shown in Table 1-5 using a high absorbance sample in the specimen position. A perfect instrument would show a completely black captured image as no fluorescence would occur thus no photons would land on the camera sensor resulting in zero counts. In reality this is not technically possible for a number of reasons. Mainly that no optical components are perfect. for example dichromatic mirrors should reflect ALL the excitation light and only transmit the emission light, in reality the reflectance is at most 99.98% (Thews, 2017) meaning that excitation light can be leaked through the system. Additionally optical elements will have minor imperfections, small scratches and digs that can fluoresce and reduce the optical quality of the system. As such a specification has been given and needs to be satisfied to allow the instrument to ship to the customer. The specification accounts for the potential flaws in the system but does not impact the optical quality expected by the customer.

For bright contamination, the specification is at 10 second exposure time at full power there must be no bright artefacts visible with an intensity of greater than 400units when measured using the Harmony software. A typical image using the black high absorbance material in the configuration discussed can be seen in Figure 1-19. An optimal image would be homogeneous in appearance with no bright artefacts visible. It can be clearly seen that there are bright artefacts present in this image - three bright spots and a single bright stripe.

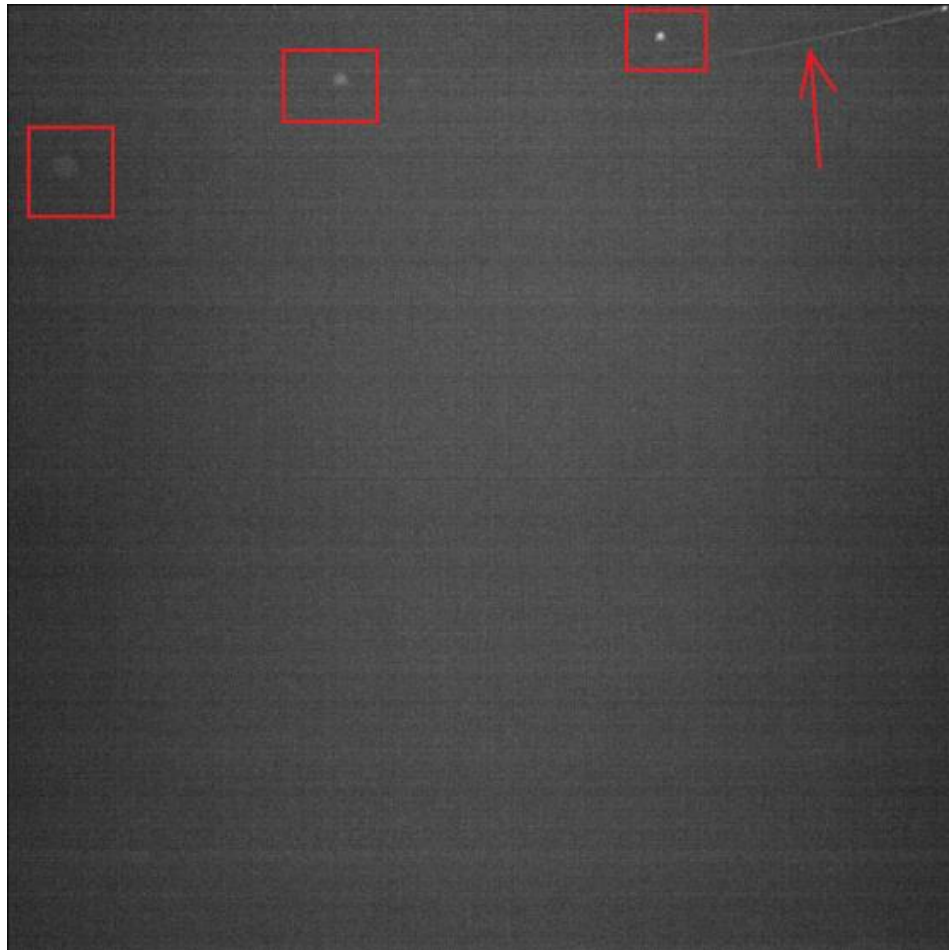


Figure 1-19 - Bright Contamination Image at 365nm. Three bright spots (red square) and a bright line (red arrow) present

To determine if the artefacts satisfy the criteria of less than 400 counts the artefacts intensity must be measured. This is performed using the the Harmony software once the image is captured. The contamination is split into two criteria, bright spots and bright lines. To measure bright spots the technician zooms in to the region of interest and must draw a rectangle INSIDE the spot using the software. Press "M" on the keyboard for the results table and document the Mean value for intensity in the IAT. Then move the rectangle to the image's background without changing it's size. Press "M" again. and document the Mean value in the IAT. The difference between the mean of the bright spot and the mean of the background must be less than 400 to pass the specification. This process can be seen in Figure 1-20.



Figure 1-20 - Measuring Bright Spot Mean Intensity

To measure bright stripes, the technician must draw a rectangle through the brightest part of the stripe and press "K" on the keyboard; this performs a line scan averaged in the y direction and shows the stripe as an increase in intensity against the background. A typical result can be seen in Figure 1-21. The technician inputs the peak height intensity (titled grey value on the y-axis) and the background intensity into the IAT. The difference between these two values must be less than 400 for the instrument to pass the IAT criteria. There is no specification set for the number of bright spots or stripes, only the intensity. An extract of the IAT bright contamination specification document can be seen in Figure 1-22.

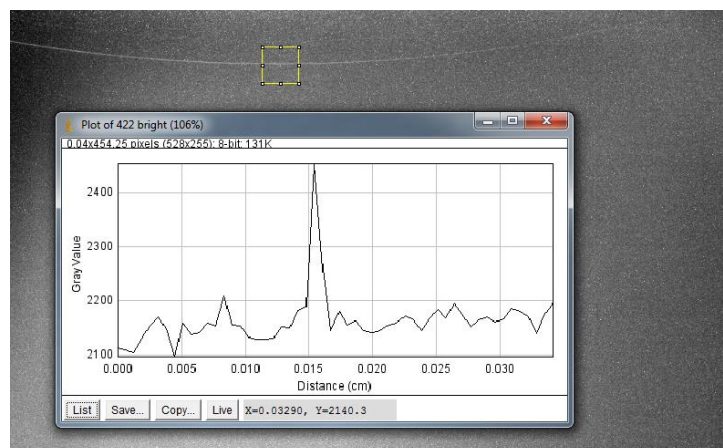


Figure 1-21 - Measuring Bright Stripe Intensity

Pass criteria:	
No bright impurities visible	
If bright contamination visible: Zoom into the image to inspect the individual contamination!	
2a) Bright spots Draw a rectangle INSIDE the spot without touching the background. Press "M" for results table. Document the Mean value for intensity. Then move the rectangle to the image's background without changing it's size. Press "M" again. Document the Mean value. Now draw a line through the contamination to get its size. Press "M". Document the Length value.	
2b) Bright lines Draw a line across the background and the line. Pay attention to not capture other lines with the same line! Get the line plot pressing key "K". Take gray values for background and line intensities from the plot.	
2a) - Bright spots with size ≤ 2 pixel are allowed anyway - Bright spots with size > 2 pixel are only allowed with intensity ≤ 400 counts above background	
2b) - bright lines with intensity ≤ 400 counts above background are allowed anyway - none bright lines with intensity > 400 counts above background are allowed	
Intensity bright contamination (Mean)	
Intensity background (Mean)	
Difference	

Figure 1-22 - IAT Bright Contamination Specification

Dark Contamination

Dark contamination can be seen as dark artefacts in the image that do not originate at the specimen. To test for this a test plate with fluorescent dyes that fluoresce at specific wavelengths is inserted into the Operetta CLS for imaging. An image is captured with each of the LEDs at an exposure time and LED power adjusted to achieve a background mean intensity of 16000 counts. This is completed with all optical configurations to ensure exposure of each optical element.

The purpose of this test is to expose any light absorbing contamination that appears as shadows or dark spots present in the Operetta CLS optical system. To ensure that each system has optimal optical quality, a specification has been set in IAT. The dark contamination criteria is split into two categories, contamination within a 1000x1000 centre region and dark contamination outside of this region. The 1000x1000 refers to the camera pixel length and is the central region of the image as highlighted in Figure 1-23. This area has a tighter specification when compared to the outer area as it is the primary area of focus for the customer (Thews, 2017).

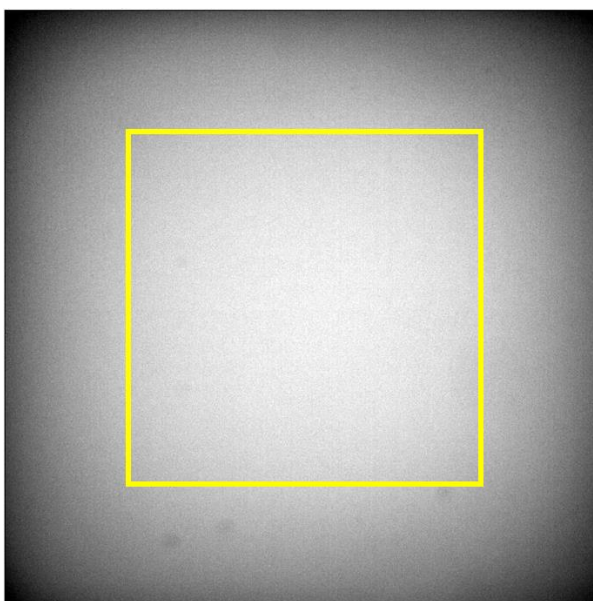


Figure 1-23 - 1000x1000 area

If dark contamination is visible in the 1000x1000 area in the image centre the technician must zoom into the image to inspect the individual contamination spots. A narrow rectangle is drawn through the visible contamination and a line plot taken to view the intensity difference between the contamination and the background. Rather than a difference of intensity as specified during the bright contamination, the dark contamination specification is calculated as a relative percentage difference between the artefact intensity and the background intensity with an upper limit of 1% for particles within the 1000x1000 area, this is calculated within the IAT using the formula below:

$$\frac{((\text{Intensity of Background} - \text{Intensity of Dark Contamination}) / \text{Intensity of Background}) / 100}{100} = \text{Relative intensity Difference in \%}$$

There must be zero particles of >1% relative intensity difference within the 1000x1000 window. For artefacts outside of the 1000x1000 window, the same formula is applied but the specification is less strict. There is a maximum of 40 particles of dark contamination of between 1% and 10% and a maximum of 6 particles with a relative intensity difference of >10% for the area outside the 1000x1000 window.

This report discusses a project to reduce the amount of downtime generated in the manufacturing department due to contamination on the Operetta CLS. The project will use a structured approach to problem solving by implementing the DMAIC methodology. The project will outline suggestions to improve the current design and process and as such will only require the use of the first four phases of the DMAIC approach: Define, Measure, Analyse Improve. The control phase is the final phase prior to incorporation and will only be conducted once the proposal has been approved by the project team.

2. Chapter 2: Literature Review

2.1. DMAIC and Six Sigma

DMAIC is a structured problem solving methodology that uses a variety of tools through five phases of six sigma improvement. This acronym stands for the five parts of the approach: Define, Measure, Analyse, Improve and Control. These phases are used to help the project team identify the root cause of a problem, implementing a suitable solution whilst establishing best practises ensuring that the solutions remain successful (George, et al., 2005). As stated by Antony et al (2003) 'the fundamental principle of Six Sigma is to take an organisation to an improved level of sigma capability through the rigorous application of statistical tools and techniques'.

The credibility and success stories of using Six Sigma can be seen by looking at the performance of a number of large companies that have adopted the approach. General Electric, Motorola, Kraft General Foods as well as Ford Motor Company all use the Six Sigma methodology. (Woods, et al., 2016). Regardless of this, Six Sigma has still faced criticism. Kaynak (2003) refers to six sigma as 'TQM on steroids'. There are a number of sources that discuss the similarity of the Six Sigma methodology with other techniques. Kwak & Ambari (2006) confirm this by stating that "the programme is nothing new, but instead simply takes traditional principles and techniques and repackages them" referring to its similarities to Edward Demings Plan-Do-Check-Act cycle. Although there are a large number of companies with considerable success stories there are still concerns with failures of six sigma processes. A study by Chakravorty (2010) found that the majority of six sigma improvement programs start off well but all too often fail to have a lasting impact as participants gradually lose motivation and fall back into old habits. This is not a reflection of Six Sigma as a methodology but reinforces the importance of change management in an organisation and how a strategy is more effective when the leadership team are also bought into it.

Regardless of both the positive and negative aspects discussed, PerkinElmer are keen to adopt the Six Sigma methodology within the business. With the recent employment of a continuous improvement leader with a Six Sigma black belt, the use of Six Sigma tools, specifically DMAIC, are being driven across the site to effectively manage projects. A number of DMAIC projects have already been completed successfully within Llantrisant with members

of the leadership actively supporting the individual projects. With this support available, a DMAIC approach will be used to help structure the project using the appropriate tools and techniques to help identify the root cause of the problem and to implement an effective solution.

2.2. Cost of Poor Quality

Cost of poor quality (COPQ) can be referred to as the all the costs that would no longer be incurred if the design, systems and processes of a product were perfect.

The primary objectives of any improvement project be it process improvements, design improvements or quality system improvements is to decrease the amount of cost associated to error or inefficiencies in the process but also to increase customer satisfaction. Both objectives share one common goal. This is to sell more products for less cost. Resulting in greater profit (Harrington, 1987).

Armand Feigenbaum was the first to coin the phrase "quality costs". as the director of quality at General Electrics, Feigenbaum recognised the significance of converting the terms "percent defective," "defects per unit," "scrap" and "return rates" into hard costs. From this realisation "quality costs" was developed pulling together the costs of developing a quality system and inspecting products in addition to the costs incurred when the product fails to meet the specification.

James Harrington refined these concepts adopting the name "poor quality costs" or COPQ in which poor quality costs are slit into the following elements:

Direct Poor Quality Costs

These are costs that are measurable and controllable and can be seen on a company's ledger. This can be controllable costs such as performing capability analysis, conducting design reviews or testing and inspection, or these can be resultant poor quality costs such as in process scrap and rework, design changes or additional inventory. As stated by Harrington

(1987) "All these costs can be directly measured and reflected in an organisations cost structure".

What Harrington realised is that poor quality's impact on a customer cannot be measured on the organisations ledger. but must be reviewed in order to succeed in business These costs are referred to as indirect poor quality costs.

Indirect Poor Quality Costs

Indirect poor quality costs are intangible costs such a costs incurred to a customer when a product breaks down during use, this may result in a loss of productivity and service costs. Customer dissatisfaction is also considered an indirect cost, any dissatisfaction shared by the customer can impact the reputation of the organisation impacting sales.

3. Chapter 3: Define Phase

The DMAIC process creates a structure to the problem-solving process, ensuring all ideas are based on data, rather than assumptions and gut feelings, this ensures a thorough root cause analysis, increasing the chances of success.

The initial phase of the DMAIC lean six sigma improvement process is the “Define” phase. The “Define” phase of a DMAIC identifies the problem and suitability of a project centred around the business objectives, the needs of the customer and voice of customer/critical to quality issues that have been identified. The Define phase should be more business-centred than process-centred as discussed by Bikram Singh (2015).

“Define” is a critical phase in the process in which the project team clearly outlines the project, enabling a clear understanding between the project team and the companies leadership team. The primary function of the define phase is to clearly state or “Define” the current problem using the principle tools that are available through the DMAIC approach to problem solving (George, et al., 2005). In this phase a project charter will be developed, within the project charter will be detail regarding the problem statement, project objective, business impact, project scope, project timeline and the project team required. Additional DMAIC tools will also be used during the define phase of the project to understand the voice of the customer and critical to quality outputs, an overview of these tools can be seen in Figure 3-1 .

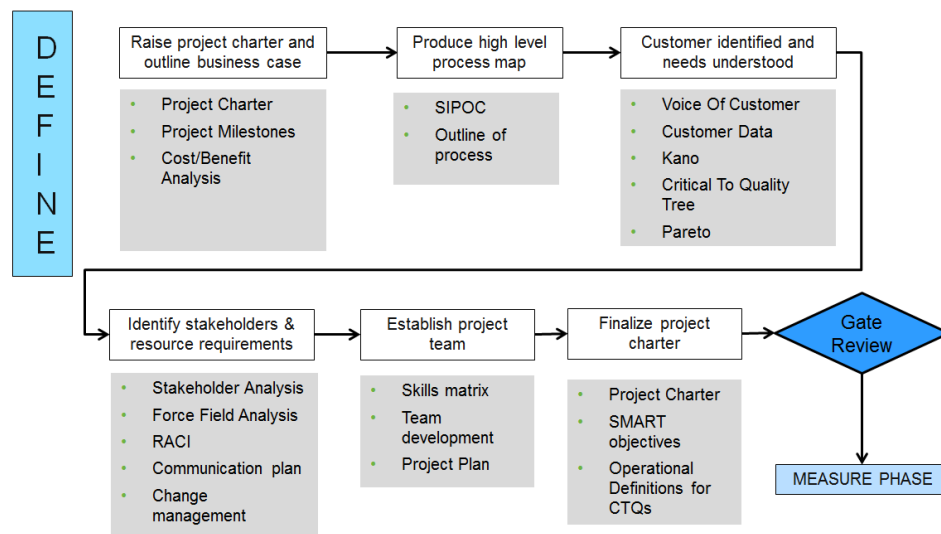


Figure 3-1 - Define Phase Road Map

Key deliverables from the Define phase as discussed by Rowlands et al (2005) must include but not be limited to:

- A completed project charter that covers the problem statement, project objective, project scope, timeline and the project team
- A high-level process map or SIPOC
- Completed project Gant chart or project plan.
- Project team consensus around the purpose of the project, the project charter and team responsibilities

3.1. Project Charter

The "define" phase is more business centred than process centred. The project charter is used to determine the business case for the project. The project charter is required to “confirm quantified goals and expected results besides the availability of necessary input resources” (Bikram Singh, 2015).

3.1.1. Problem Statement

The problem statement is used to concisely state what the problem is, where it is occurring, the size of the problem and the impact of the problem on the customer and on the business. It is critical that the problem statement is based on facts and not opinions.

A key tool used to gather a variety of key performance indicators (KPIs) within PerkinElmer's Llantrisant based manufacturing plant is the "Quality, Cost, Delivery" (QCD) Analysis tool. One of the functions of this tool is to record any non-value adding down time or deviations from the process. This is a useful tool that gives visibility to the main downtime and rework activities within the plant allowing the leadership team to prioritise its resource to eliminate issues seen in manufacturing. The raw data is input into an excel spreadsheet by the engineering technicians who assemble and test the Operetta CLS instrument. Downtime hours are recorded against a description of the failure mode. This data is reviewed monthly by the leadership team and projects/resource assigned. It can be seen in the manufacturing rework hours chart shown in Figure 3-2 that the largest technical issue on the Operetta CLS product line is "Contamination". The contamination failure mode has caused 358.5 hours of Downtime in 2017 year to date. With a total of 52 CLS instruments manufactured 2017 YTS this equates to an average of approximately 6.9 hours downtime per instrument.

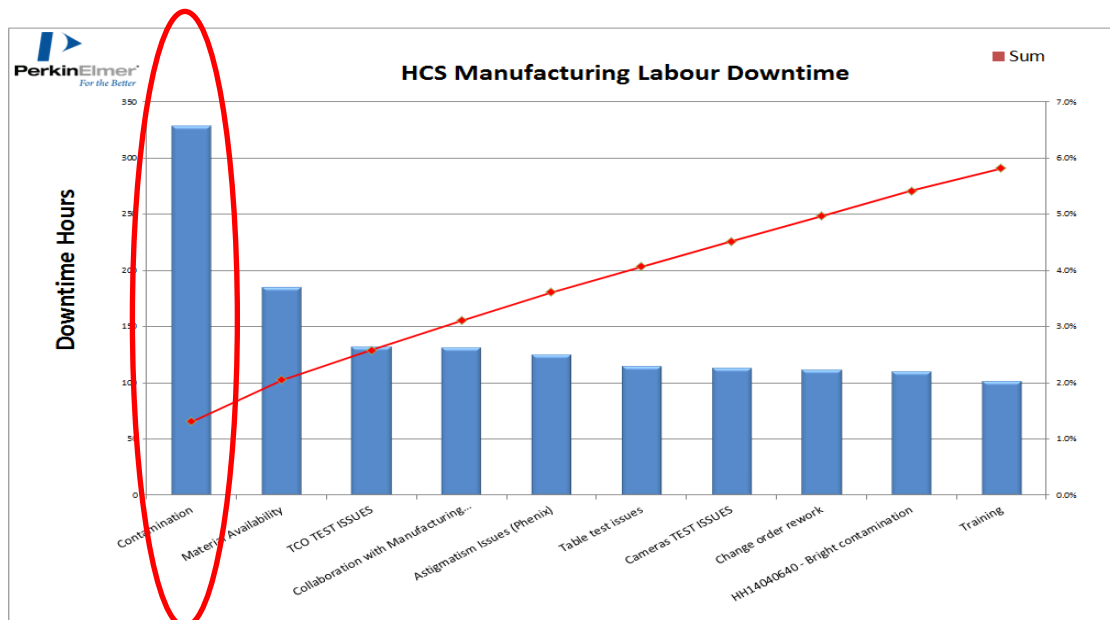


Figure 3-2 - 2017 Manufacturing Rework Hours Pareto YTD (Fraser, 2017)

Further warranty cost data analysis concludes that during 2017 there have been three service support visits to customers in the field due to contamination seen on the confocal head. This has resulted in service visits to China, Singapore and the USA from the Hamburg service support team to directly replace the confocal unit due to bright contamination artefacts seen in the image field. Upon review of the existing data the problem statement can be clearly defined as seen in Figure 3-3. A customer warranty complaint is named a "F1 Complaint" with the Llantrisant plant, this is how it is referred in the problem statement.

Problem Statement	<i>Contamination is evident in the Operetta CLS specimen image. This has resulted in 358.5 hours of downtime and rework activities 2017 YTD. Additionally there have been 3 F1 notifications for contamination seen on installed instruments at customer sites in China, Singapore and the USA.</i>
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Figure 3-3 - Problem Statement - Extract from Project Charter

3.1.2. Project Team - Roles and Responsibilities

An important step in the define process is allocating resource to the project. A project team lead must be assigned as well as a project sponsor from the leadership team. Team members can be recruited from different areas of the organisation but must all have a connection to the project. (GoLeanSixSigma, 2015) . To allow effective time management and resource allocation by the leaders of the wider project team, and to help ensure the project remains on track, it is important to define a weekly percentage of time that the team must commit to the project; this can be seen in Figure 3-4.

The author's role within the team is "Project Leader" the key responsibilities are to successfully manage all aspects of the project at minimum cost, utilising the knowledge of the project team to successfully deliver the defined project objective. The key roles of the other members of the team are highlighted below:

- **Neil Fraser – Project Sponsor:** As a member of the senior management team, it is Neil's role to identify the problem and business need, he also ensure that the project remains on target and a viable proposition. His key role is to resolve any issues outside of the project leader's control.

- **Elmar Thews – Optical Scientist:** As the issue is based on the optical design of the instrument, Elmar has a key role that will be relied on heavily. Any design improvements considered must be approved by Elmar through a rigorous validation process prior to implementation
- **Mark Sidaway / Mark Packwood – Engineering Technicians:** It is the technician's role to support the wider team where required. The technicians build and test the instrument in question and their knowledge is vital in understanding the problem and developing a solution.
- **Armand Marachel – Product and Supplier Quality:** It is the supplier quality engineer's responsibility to work with the buyer, ensuring supplier quality and to actively manage the vendor to ensure there is no deviation from the defined process and specification additionally any warranty issues are managed and communicated the product and supplier quality engineer.

Resources	Name	Job Title	% Time per week
Project Sponsor	Neil Fraser	Engineering Leader	5%
Project Leader	Neil Forshaw	Manufacturing Engineer	50%
Team Members	Armand Marachel	Product Quality Engineer	10%
	Elmar Thews	Optical Scientist	10%
	Mark Sidaway/Mark Packwood	Engineering Technicians	10%

Figure 3-4 - Resource Requirement - Extract from Project Charter

3.1.3. Business Case

Once a problem statement has been determined, a business case can be defined. A business case is used to describe the problem at a high level and to justify the reasons for the project via associated costs to the business. The value of the project can be identified through many different financial streams, such as Warranty costs, lack of customer sales, yield issues or excessive product cost. From the problem statement, it has already been identified that "Contamination is evident in the Operetta CLS specimen image. This has resulted in 358.5 hours of downtime and rework activities 2017 year to date. Additionally there have been 3 F1

notifications for contamination seen on installed instruments at customer sites in China, Singapore and the USA." Financial costs can be associated to each of the areas stated.

358.5 hours of manufacturing downtime have a direct cost to the business with regard to labour cost. A labour cost £47.70 per hour has been defined through discussions with the financial director of PerkinElmer Llantrisant (Machin, 2017) this includes the salaries of each employee and overheads (Building costs, pension etc.). From this, a total cost to the business 2017 YTD due to manufacturing downtime can be calculated:

$$358.5 \text{ hours} \times £47.70 = £17,100.45$$

The total warranty cost can also be determined. There have been three customer complaints that have resulted in a visit from a field service engineer to replace parts due to contamination. The labour cost per hour for the field service engineer is £300 and is paid for by the manufacturing site if required within the one year warranty period. Additional to this are the costs of the parts to be replaced, flights, hotels and meals. The total cost for the three customer complaints can be seen in Table 3-1. This data has been retrieved from Anthony Genge, PerkinElmer's leader of Technical Support and equates to £48,421.80.

Table 3-1- Total Warranty Cost (Genge, 2017)

Description	Labour Hours	Labour cost	Labour Total	Material	Flights	Hotel	Meals	Total
Airline Tickets Hamburg - China					£3,313.04	£762.00	£400.00	£4,475.04
China 2 Day Installation	28	£300.00	£8,400.00					£8,400.00
Confocal Unit W/O Cables				£3,270.49				£3,270.49
Airline Tickets Hamburg - USA					£2,981.04			£2,981.04
USA 2 Day Installation	28	£300.00	£8,400.00			£630.00	£400.00	£9,430.00
Confocal Unit W/O Cables				£3,270.49				£3,270.49
Airline Tickets Hamburg - Singapore					£3,698.25			£3,698.25
Singapore 2 Day Installation	28	£300.00	£8,400.00			£826.00	£400.00	£9,626.00
Confocal Unit W/O Cables				£3,270.49				£3,270.49
								£48,421.80

The total cost of poor quality can be calculated as the sum of the Total Warranty Costs and Total Downtime Cost as seen in Table 3-2.

Table 3-2 - COPQ 2017

Description	labour Hours	Labour Cost + Overheads	Total
Manufacturing Downtime	358.5	£47.70	£17,100.45
Warranty Cost			£48,421.80
Total			£65,522.25

Once the cost to the business has been established, investment costs need to be determined to identify the project costs. As the project team has defined along with an agreed time allocation for the project an associated cost can be calculated. An hourly rate has already been defined as £47.70; this is a set rate regardless of the employee's role (Machin, 2017). Using this rate along with the planned project timing plan and resource allocation discussed when defining the project team a total cost can be calculated as seen in Table 3-3. Additional to this is an estimated tooling cost of approximately £5000 for any potential test fixtures and prototype parts.

Table 3-3 - Project Team Resource Cost

Job Title	Project Weeks	Project Hours	% Time Allocated	Total Hours	Hourly Rate	Total
Manufacturing Engineering	19	712.5	50.00%	356.25	£47.70	£16,993.13
Engineering Leader	19	712.5	10.00%	71.25	£47.70	£3,398.63
Product Quality Engineering	19	712.5	10.00%	71.25	£47.70	£3,398.63
Optical Scientist	19	712.5	10.00%	71.25	£47.70	£3,398.63
Engineering Technician	19	712.5	10.00%	71.25	£47.70	£3,398.63
						£30,587.63

Hard costs associated to the project, both the investment required for the project to be successful, and the current cost to the business as it stands, are tangible and can be easily quantified as previously shown in Figure 3-5. What is difficult to determine are the intangible costs. Intangible costs are not easily measured. An example of this may be a drop in employee morale or customer dissatisfaction with the quality of a product. Although not quantifiable, the intangible costs are real should be considered within the project.

Business Case		
Project Benefits	Hard: £65,522.25	Soft: Unknown
Project Costs	Labour: £30,587.63 Tooling £5,000	

Figure 3-5 - Business Case - Extract from Project Charter

Employee Morale

When an instrument fails the A&A or IAT criteria for bright contamination, the current method of resolving the problem is to identify the sub assembly that is responsible for the failed image and to remove it from the instrument for cleaning. The contamination is not identified until the instrument is approximately 3-4 days into alignment and test. the technician can spend up to an hour removing the sub assembly and then up to an hour cleaning the optics of the subassembly with no way of guaranteeing success without the sub assembly being reassembled into the instrument and retested, this can take 6-8 hours before the technician is back to the original failed contamination test. This process may be repeated multiple times until the IAT criterion is completely satisfied. With a tight deadline of 8 days to align and fully test an Operetta CLS instrument as seen in Figure 3-6, pressure from management can be high to ensure that production stays on schedule. This pressure coupled with a contamination repair loop with no control measures has a detrimental effect on employee morale. This has been noted through discussions with the technicians responsible for testing the Operetta CLS instrument.

Service Support

The Operetta CLS is a build to order product. Once an order is received the instrument is built, aligned and tested. Once completed the instrument is shipped to the customer site for installation by service support. The service support team are experts in their role and are required to perform a Site Acceptance Test (SAT) to commission the instrument along with training for the customer. This is performed globally by two teams of two service support engineers (Four engineers in total). For this to work efficiently the logistics are planned alongside the build plan to ensure that the service personnel arrive at the customer site at same time as the instrument, this plan can be seen in Figure 3-6. Any additional rework activities can have an impact on this plan. A late shipment of an instrument due to technical

issues can result in customer dissatisfaction and logistical issues with the service team with regard to flights and resource allocation.

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Key:

-  Operetta CLS Main Assembly
-  Operetta CLS Alignment & Test
-  Customer Installation / Site Acceptance Tests

Figure 3-6 - January 2018 Build Plan

3.1.4. Project Objectives/ Project Goal

The goal of the project is a direct reflection of the problem statement (GoLeanSixSigma, 2015). The project objective for the Operetta CLS contamination issue is to reduce the downtime associated to contamination by 80% and to reduce the number of warranty complaints (F1 Notifications) to zero. This can be seen in Figure 3-7.

Project Objective	<i>To reduce the amount of downtime attributed to contamination by 80%. To reduce the amount of F1 notifications for contamination to zero</i>
--------------------------	--

Figure 3-7 - Project Objective - Extract from Project Charter

3.1.5. Project Scope

The aim of the project is to reduce the downtime in manufacturing and warranty complaints from customers due to contamination seen in the instruments optical path. The scope of the project is to measure and analyse the main sources of contamination, reviewing the design of the optical sub-assemblies and manufacturing processes to reduce the risk of contamination.

Objectives:

- Identify the current problem
- Measure the defined problem using the appropriate DMAIC tools and techniques
- Analyse the measurements using the appropriate DMAIC tools and techniques
- Design, Develop and Implement improvements to satisfy the project objective
- Implement measures to control and sustain developed solution

3.2. SIPOC Process Mapping

The SIPOC process map shown in Figure 3-8 is used to determine the start and stop signals of the process under scrutiny (Meran, 2013). The diagram defines from a top level, the key inputs and outputs of the Operetta CLS assembly and testing process along with the core customers and suppliers of the process. Steps 3 and Step 4 highlighted in orange are the controls for the contamination issues seen. It is at these steps in the process that contamination is tested for resulting in a pass or a fail in the IAT criteria. If the instrument fails in either step, the contamination location needs to be identified and cleaned. The source of contamination can be from any of the defined inputs.

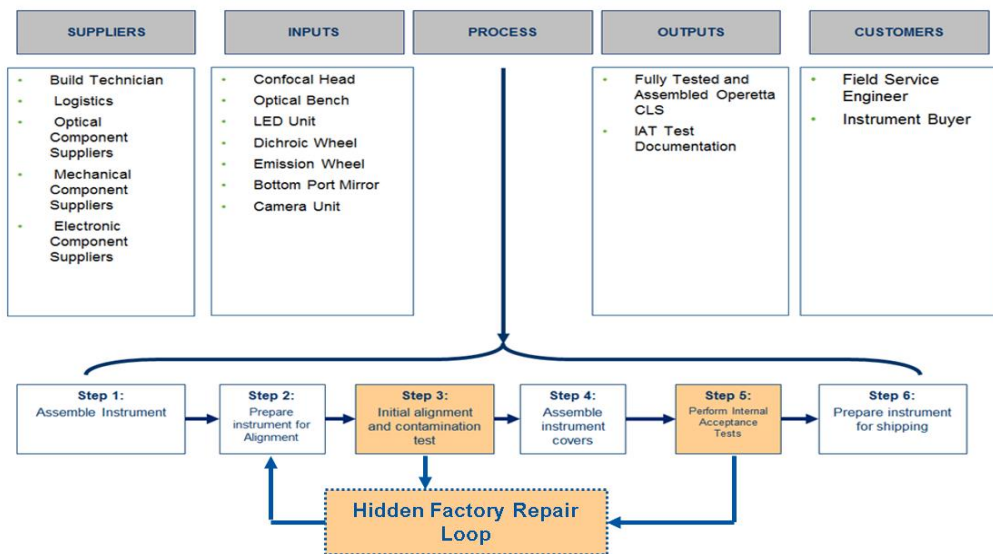


Figure 3-8- Operetta CLS Assembly and Test SIPOC

3.3. Voice of Customer (VOC) and Critical to Quality (CTQ)

A key feature and selling point of the Operetta CLS is the image quality of the system. The product sales brochure promotes this, using headings such as "Exceptional image data quality", "The resolution to capture high quality image data" and "the highest possible image quality to take your research further" (PerkinElmer, 2015). This image quality could be referred to in the Kano Model Figure 3-9 as a delighter but only in comparison to similar instruments on the market. However, the sales brochure leads us to believe that PerkinElmer are at the forefront of the latest technologies in this field, and that "Exceptional image quality" is expected from the instrument.

Warranty data suggests that the instrument is not void of contamination once the IAT tests are completed. This indicates that contamination still accumulates over the instruments life. As the instrument is relatively new to market (less than 18months old), there is limited data to suggest how long the instrument will stay useable until excessive contamination is noted. However, there have been three warranty complaints with instruments that are less than a year old. Currently there are over 100 instruments at customer sites around the world.

The industry in which the Operetta CLS sells, is dominated by large pharmaceutical companies such as Novatis, Pfizer and Sanofi. PerkinElmer has a reputation amongst its instrument users for high quality equipment using cutting edge technologies. Brand reputation is vital in any market. Good brand reputation ensures consumers trust the company and its products and will repeatedly purchase its products, negative brand reputation can cause distrust amongst consumers, towards the brand and directly impact sales. Considering the customer base of the Operetta CLS and the pharmaceutical brands discussed, any negative feedback with regard to the image quality of the system will likely be shared openly amongst the companies, through published journals that have used the instrument as part of its research, instrument review articles or open discussions. This could have a significantly larger impact on the business when compared to the "hard costs" identified in the business case and as such must be considered.

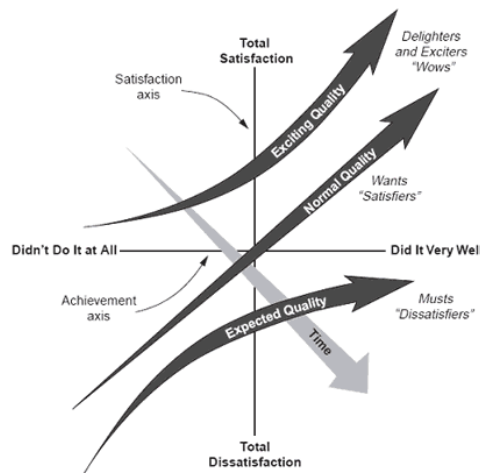


Figure 3-9 - Kano Model

3.4. Define Gate Review

Each of the five key stages in the DMAIC process must undergo a gate reviewing before progressing to the next. The Define gate review looks at the project charter and project plan along with the SIPOC and voice of customer with the project team to determine if the key outputs are completed or on track before moving on to the next stage in the project.

3.4.1. Completed Project Charter

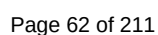
Table 3-4 shows a copy of the approved final project charter used for the Operetta CLS contamination project. Through discussions during the project kick off meeting with the project team and leadership team a consensus was achieved supporting the problem statement, objective and project scope. All resources required were approved and the project business case and timing plan deemed suitable to carry out.

Project Title	Operetta CLS Contamination				
Problem Statement	Contamination is evident in the Operetta CLS specimen image. This has resulted in 358.5 hours of downtime and rework activities 2017 YTD. Additionally there have been 3 F1 notifications for contamination seen on installed instruments at customer sites in China, Singapore and the USA.				
Project Objective	To reduce the amount of downtime associated to Contamination by 90%. To reduce the amount of F1 notifications for Contamination to zero.				
Project Scope	The Operetta CLS sub assembly design and manufacturing process				
Resources	Name	Job Title	% Time per week		
Project Sponsor	Neil Fraser	Engineering Leader	5%		
Project Leader	Neil Forshaw	Manufacturing Engineer	50%		
Team Members	Armand Marachel	Product Quality Engineer	10%		
	Elmar Thews	Optical Scientist	10%		
	Mark Sidaway/Mark Packwood	Engineering Technicians	10%		
Additional Support Required	None				
Business Case					
Project Benefits	Hard: £91,522.25		Soft: Unknown		
Project Costs	Labour : £12,313.36 Tooling: £5,000.00				
Project Plan (Milestones with dates):	Define	Measure	Analyse	Improve	Control
	3 weeks	4 weeks	4 week	4 weeks	4 weeks
Signatures					
Project Leader	Sign: N. Forshaw				
Project Sponsor	Sign: N. Fraser				

Table 3-4 - Project Charter

3.4.2. Timing Plan

A timing plan has been generated detailing the critical steps of the project.



4. Chapter 4: Measure Phase

The second phase of the DMAIC lean six sigma improvement process is the “Measure” phase. The “Measure” phase of a DMAIC is a structured approach used to thoroughly understand the current state of the process. To fully understand the magnitude of the problem a baseline of information and data with regard to the current process is required (George, et al., 2005).

During this phase the "As is" process will be measured and a data collection plan determined. Additional DMAIC tools will also be used during the measure phase of the project to understand the measurement system and to collect data and establish the baseline performance of the system, an overview of these tools can be seen in Figure 4-1

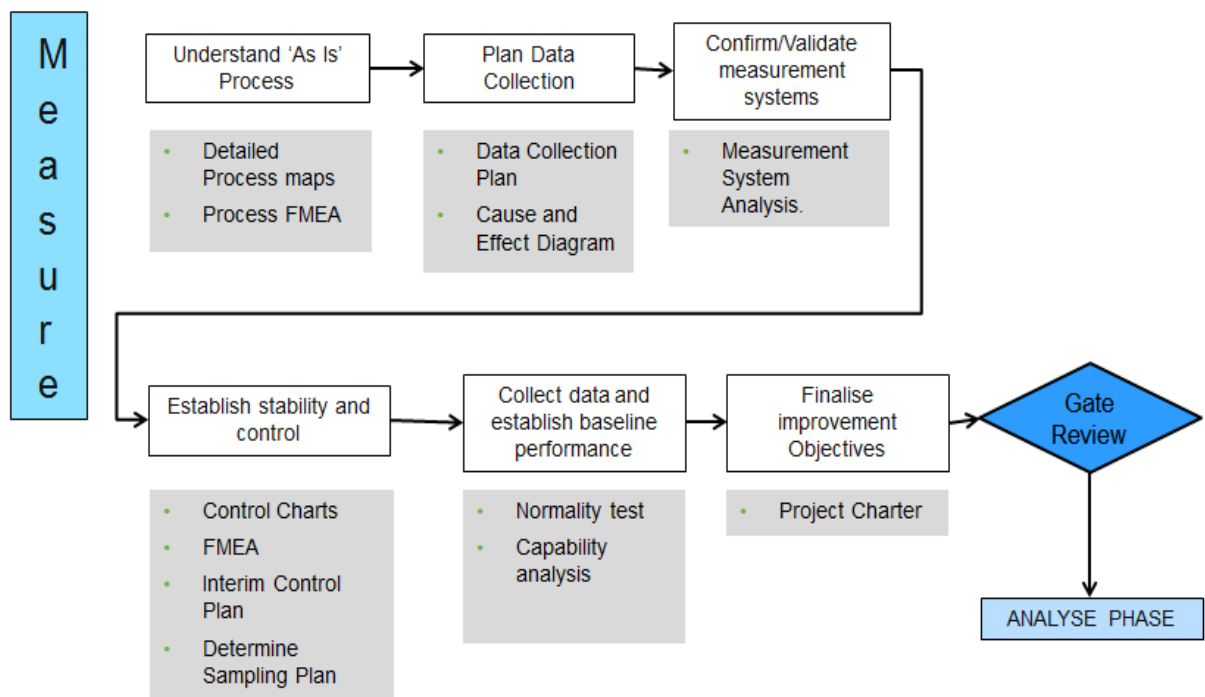


Figure 4-1 - Measure Phase Road Map

Key deliverables from the Measure phase as discussed by Rowlands et al (2005) must include but not be limited to:

- A current state process map

- Reliable data on critical inputs and outputs
- Baseline measures of process capability
- A capable measurement system
- A revised project charter

4.1. Pareto Analysis

As discussed in the Define phase, 358.5 hours have been lost in manufacturing as a result of "contamination". The contamination hours are recorded by the technician during manufacturing in an excel spreadsheet that is split into categories, contamination being one of these categories. This data can be analysed further and split into sub categories detailing the assemblies that were reworked as a result of the contamination seen in IAT. It can be seen in the Pareto Chart shown in Figure 4-2 that of 358.5 hours downtime, 185 hours are due to contamination present in the Confocal Unit Assembly, 97.5 hours are due to contamination present on the Dichromatic Wheel assembly and 30 hours due to contamination present on the Camera Unit Assembly.

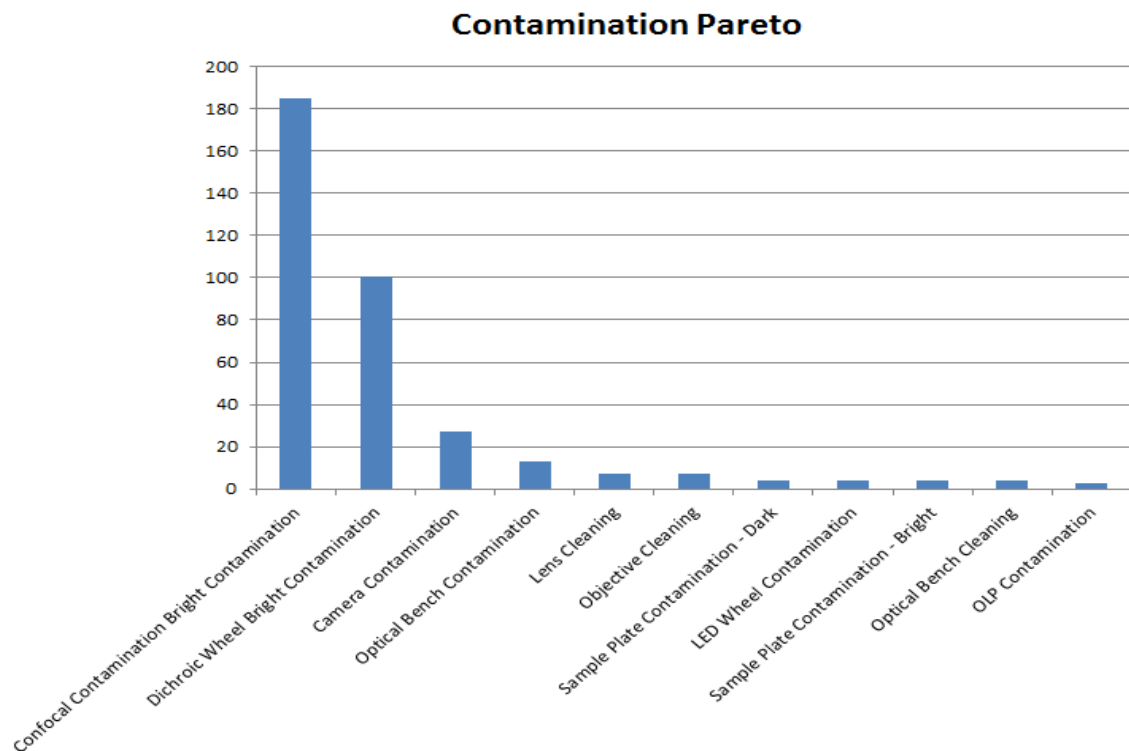


Figure 4-2 - Contamination Pareto

A Pareto chart is based on the Pareto principle that states that for many events; roughly 80% of the effects come from 20% of the causes (Sobaco Limited, 2010). Using this rule it can be seen that exactly 80% of the total downtime is as a result of 18.2% of the failure modes, confirming Pareto's principle. This can be clearly seen in Figure 4-3.

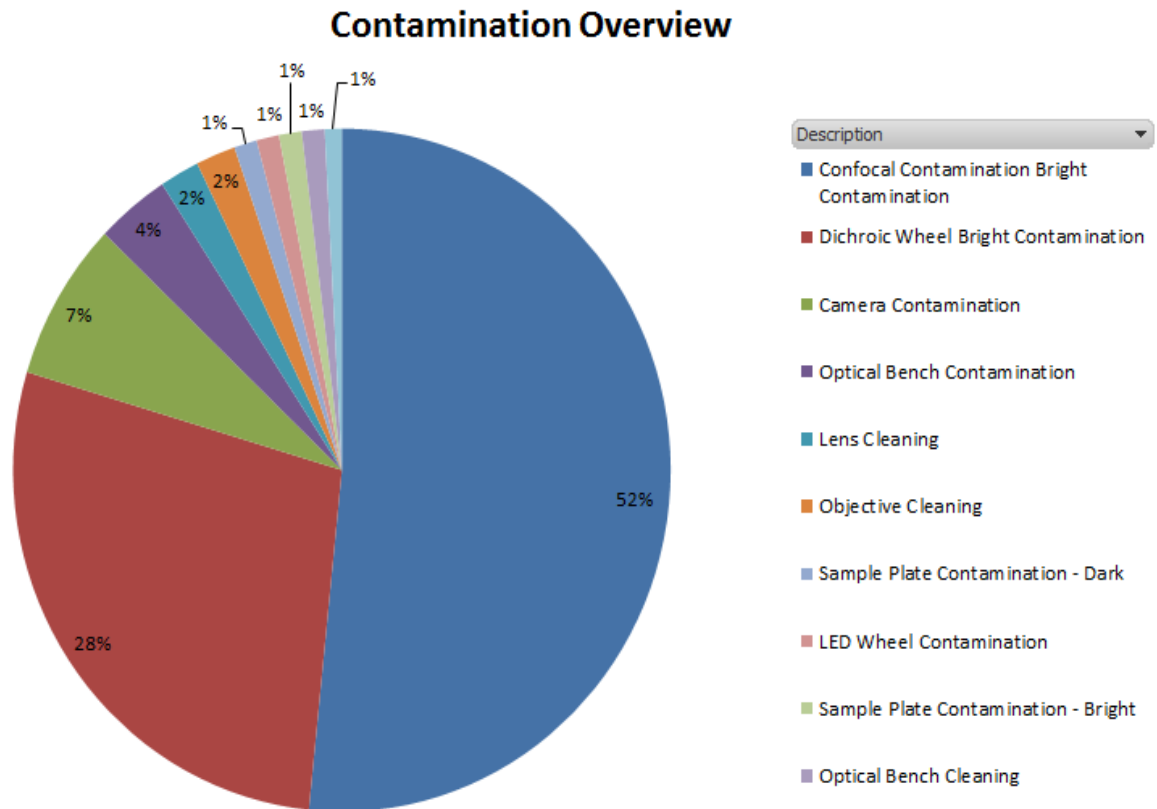


Figure 4-3 - Contamination Pie Chart

This data suggests that targeting just two of the main failure modes within the scope of the project can result in an 80% decrease in the downtime associated to contamination. Both modes are failures due to "Bright" contamination. When reviewing the current process the two sub-assemblies highlighted contributing to 80% of the downtime must also be reviewed.

1. Confocal Unit Assembly - Bright Contamination
2. Dichroic Wheel Assembly - Bright Contamination

4.2. Understanding the Current Process

4.2.1. Current State Mapping

During the measure phase, a detailed process map of each of the processes under review must be developed to help understand the "as is" process. The detailed process maps must focus in on the elements defined when developing the SIPOC during the Define phase of the DMAIC (MSI Certified, 2017).

The target process area identified in the SIPOC is the Instrument assembly, alignment and IAT process. It has already been identified that during this process there is a hidden factory repair loop that accounts for 358.5 hours of down time. 80% of this time (285.5 hours) is due to rework of the Confocal Unit Assembly and Dichromatic Wheel Assembly. As such, detailed process maps of each of the three key highlighted in Figure 4-4 will be developed.

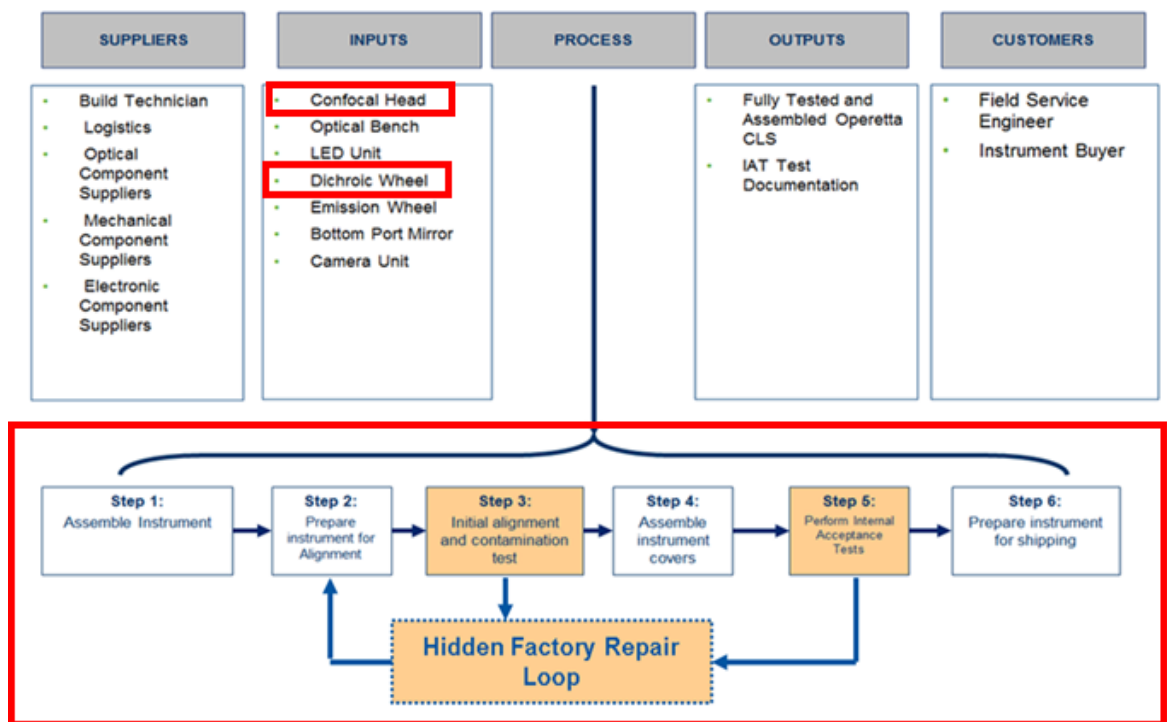


Figure 4-4 - Target Areas for Detailed Process Mapping

As discussed by George et al (2005), it is important when developing the process map to physically walk the process rather than rely on maps that may already exist. While walking the

process, ensure work is being performed to help the project team fully understand the process. The use of information and detail from the technician performing the process is vital; as such the process mapping exercise has been performed with the help of the manufacturing technician responsible for each of the process steps along with the standard operating procedures (SOPs) for each process. Additional to the detailed process map, a workflow diagram has been developed to help visualise the movement of material through the process.

Instrument Assembly and IAT Detailed Process Map

A detailed process map for the "Instrument Assembly and IAT" process can be seen in Figure 4-5. It can be seen that the total time of this process is 110 hours. Included in the process is the hidden factory repair loop that takes place once the instrument fails the IAT contamination test, this repair loop takes an average of 6.9 hours per instrument. As previously discussed, 80% of the downtime within this repair loop is as a result of bright contamination failures due to issues with the confocal unit or Dichromatic Wheel Assembly. A critical process that is important to understand is the steps that the technicians take once the instrument fails the test. An understanding of how the technician identifies that a particular artefact seen during the test is due to either the confocal unit assembly or Dichroic Wheel Assembly is required. The "Fails Contamination Test" step shown in Figure 4-5 has its own inherent process that is not currently documented. This process also requires its own detailed process map.

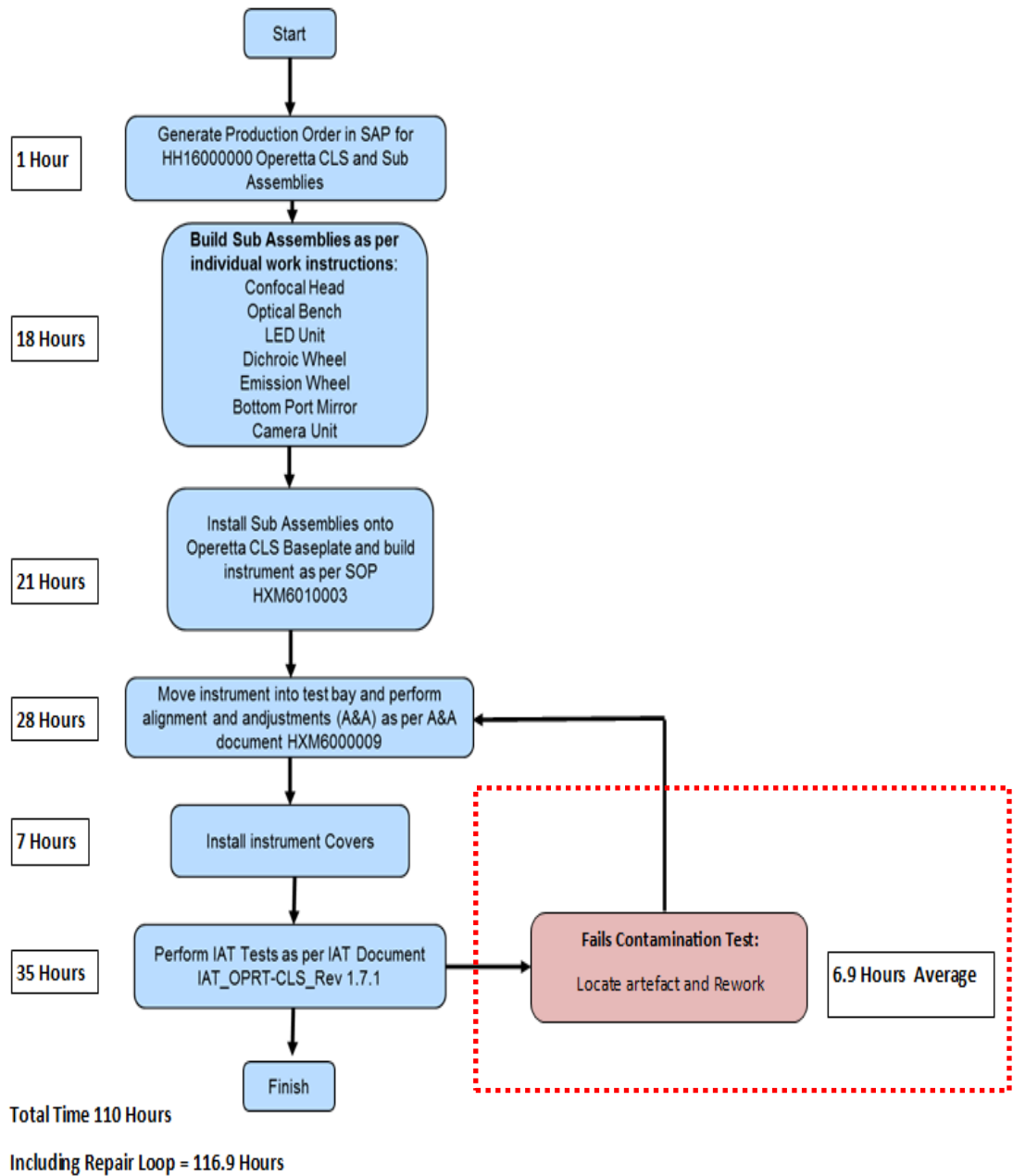
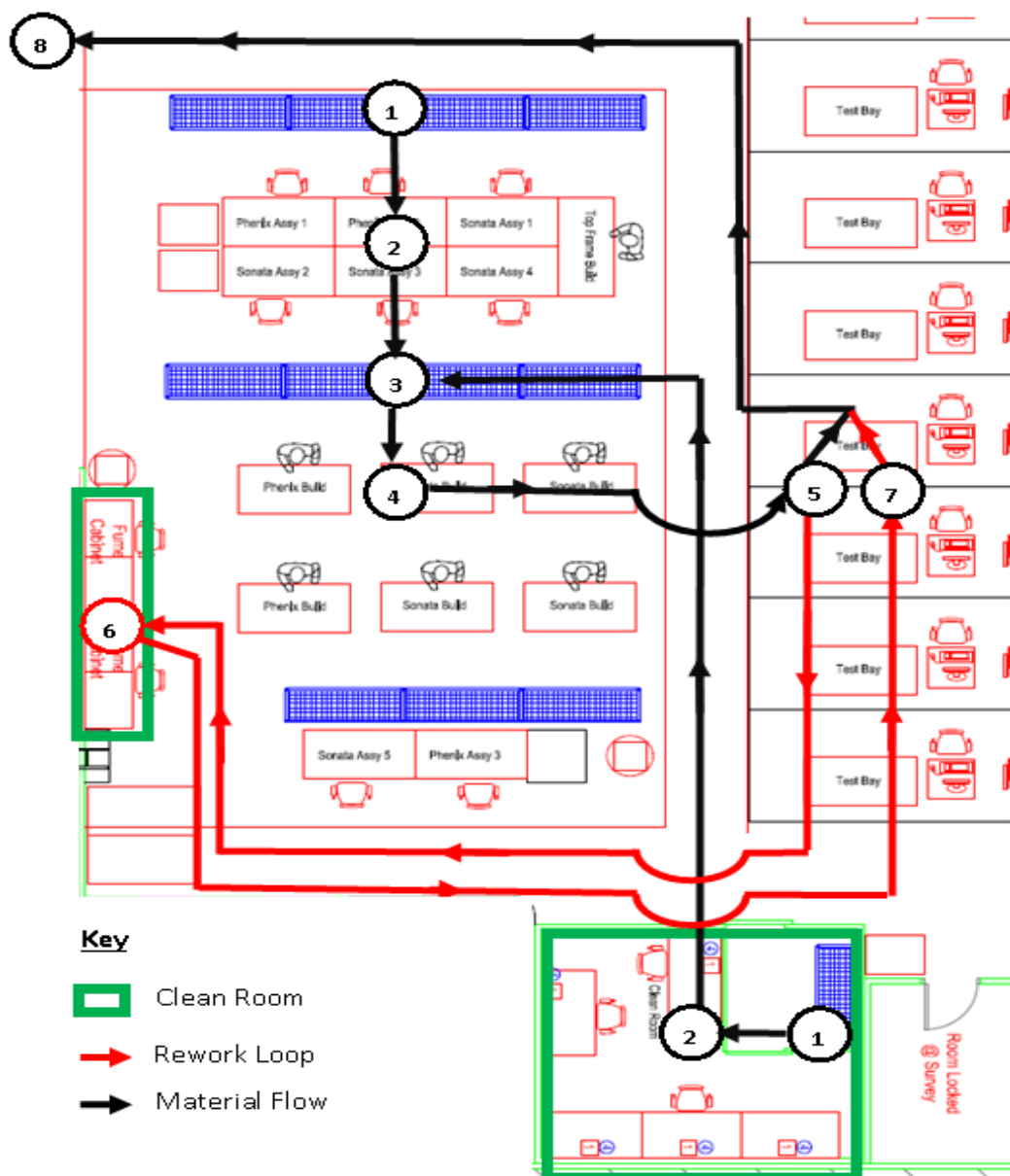


Figure 4-5 - Instrument Assembly and Test Current state Map

Instrument Assembly and IAT Workflow Diagram



Step	Description
1	Component parts stored on shelves
2	Sub assemblies built according to work instructions and backflushed in the MRP system
3	Sub Assemblies stored on racking ready for use on instrument
4	Sub Assemblies installed onto Operetta CLS Base as per work instructions
5	Instrument Aligned and tested as Per work instructions and IAT document
6	If instrument fails "Bright Contamination" IAT criteria. Assembly is removed for rework
7	Once reworked, Assembly is reinstalled in instrument. Instrument is realigned and tested as per IAT document
8	Instrument moved to stores area ready for shipping to customer

Figure 4-6- Instrument Assembly and IAT Workflow Diagram

Confocal Unit Assembly Detailed Process Map

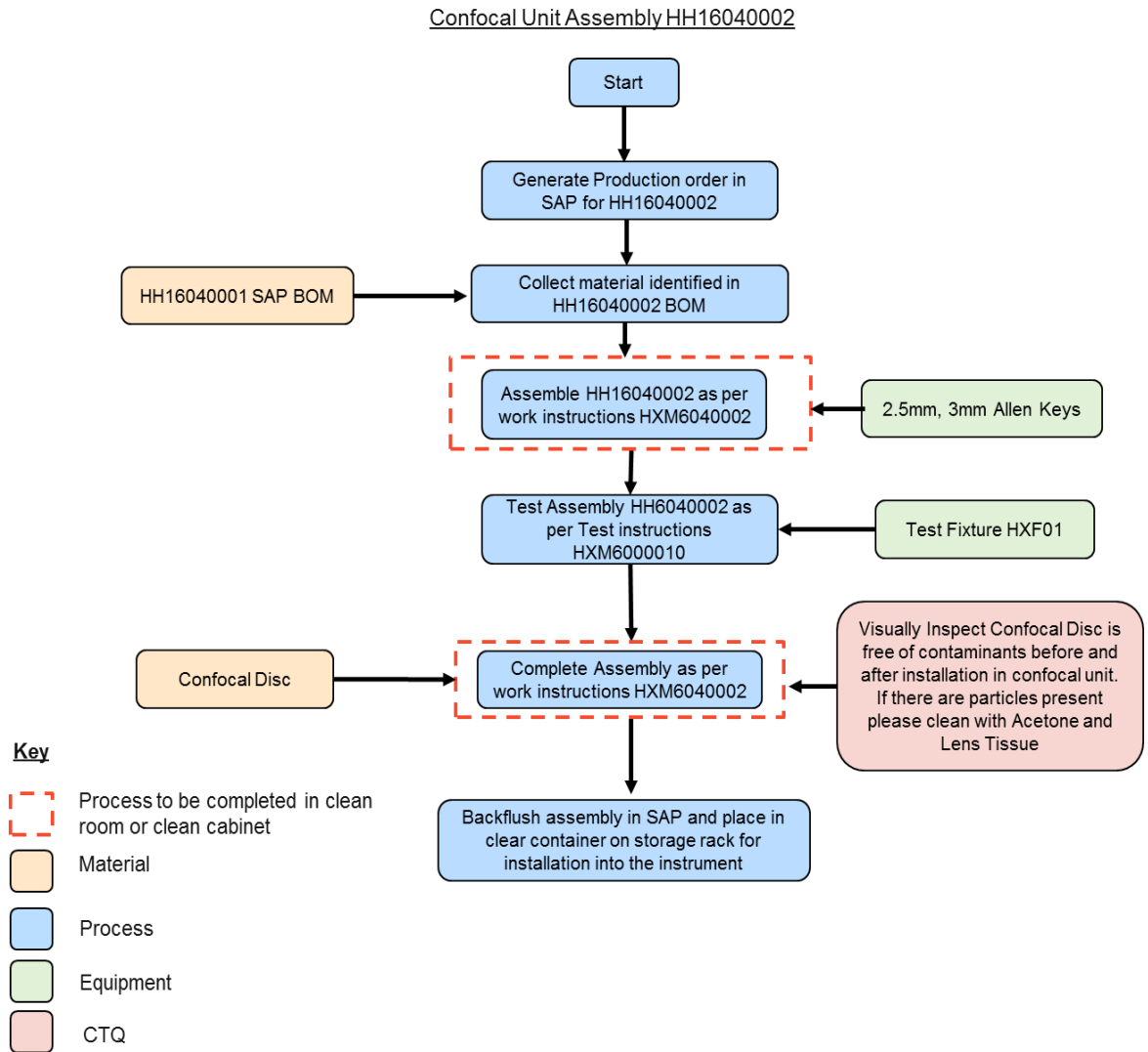
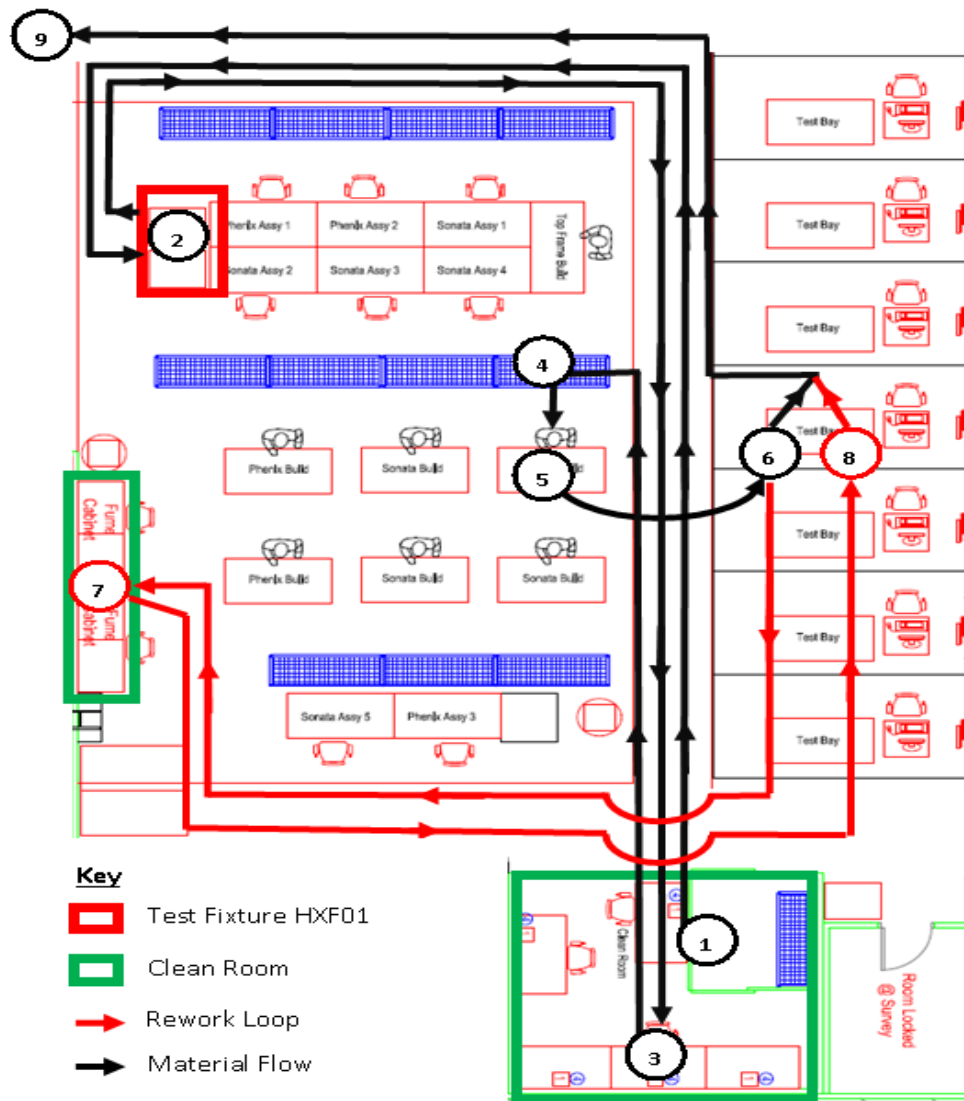


Figure 4-7 - Confocal Unit Assembly Process Flow

Confocal Unit Assembly Workflow Diagram



Step	Description
1	Confocal Unit mechanical assembly (Excluding Disc) assembled as per work instructions
2	Confocal Unit Mechanical assembly functionally tested as per test instruction.
3	Confocal unit Final assembly in clean room, Visual inspection of Confocal Disc for contamination and assembly into confocal unit
4	Confocal Unit Stored on Sub Assembly Rack
4	Confocal unit installed onto Operetta CLS Base as per work instructions
5	Instrument Aligned and tested as Per work instructions and IAT document
6	If instrument fails "Bright Contamination" IAT criteria. Assembly is removed for rework
7	Once reworked, Assembly is reinstalled in instrument. Instrument is realigned and tested as per IAT document
8	Instrument moved to stores area ready for shipping to customer

Figure 4-8 - Confocal Unit Assembly Workflow Diagram

Dichromatic Wheel Assembly Detailed Process Map

The Dichromatic Wheel Assembly (HH16111001) is manufactured from two separate sub-assemblies. A bonded wheel assembly HH16111003, and dichromatic mechanical assembly HH16111002 as shown in Figure 4-9. Each subassembly has its own detailed process maps as shown in Figure 4-10 and Figure 4-11.

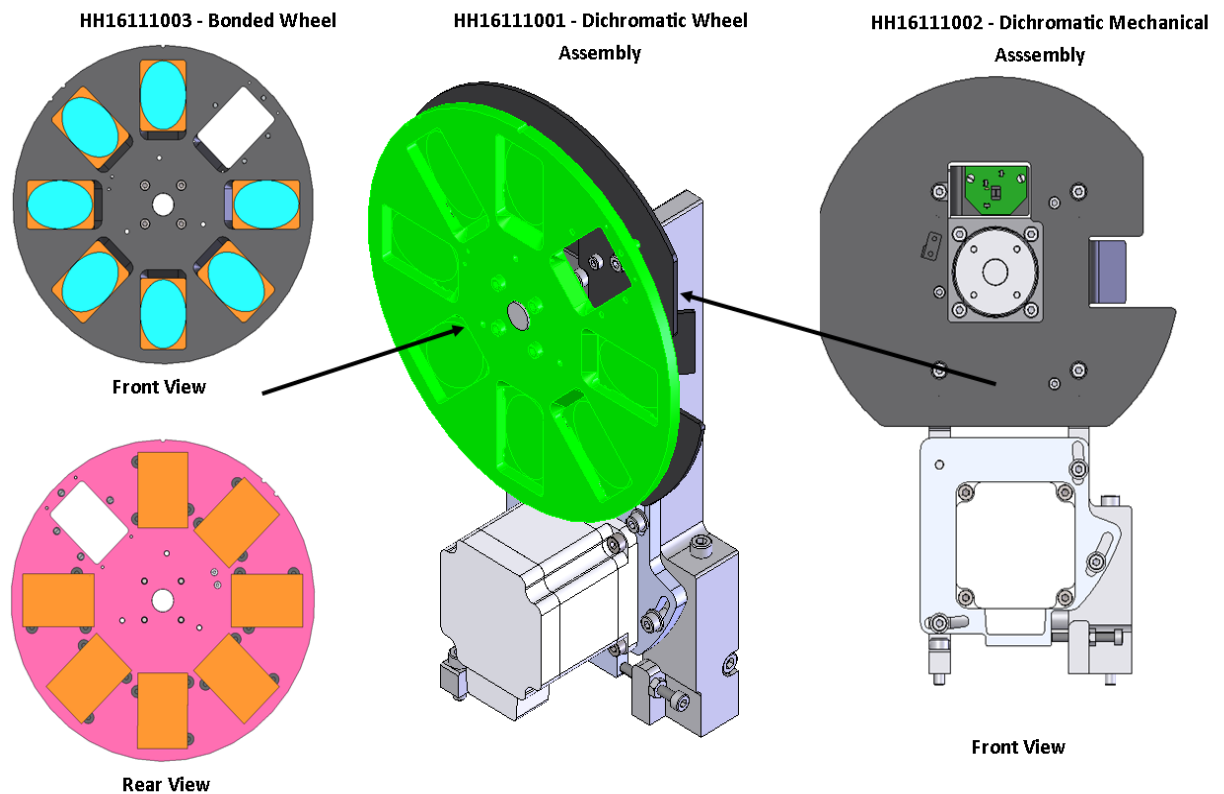


Figure 4-9 - HH16111001 Sub Assemblies

Bonded Dichromatic Wheel HH16111003

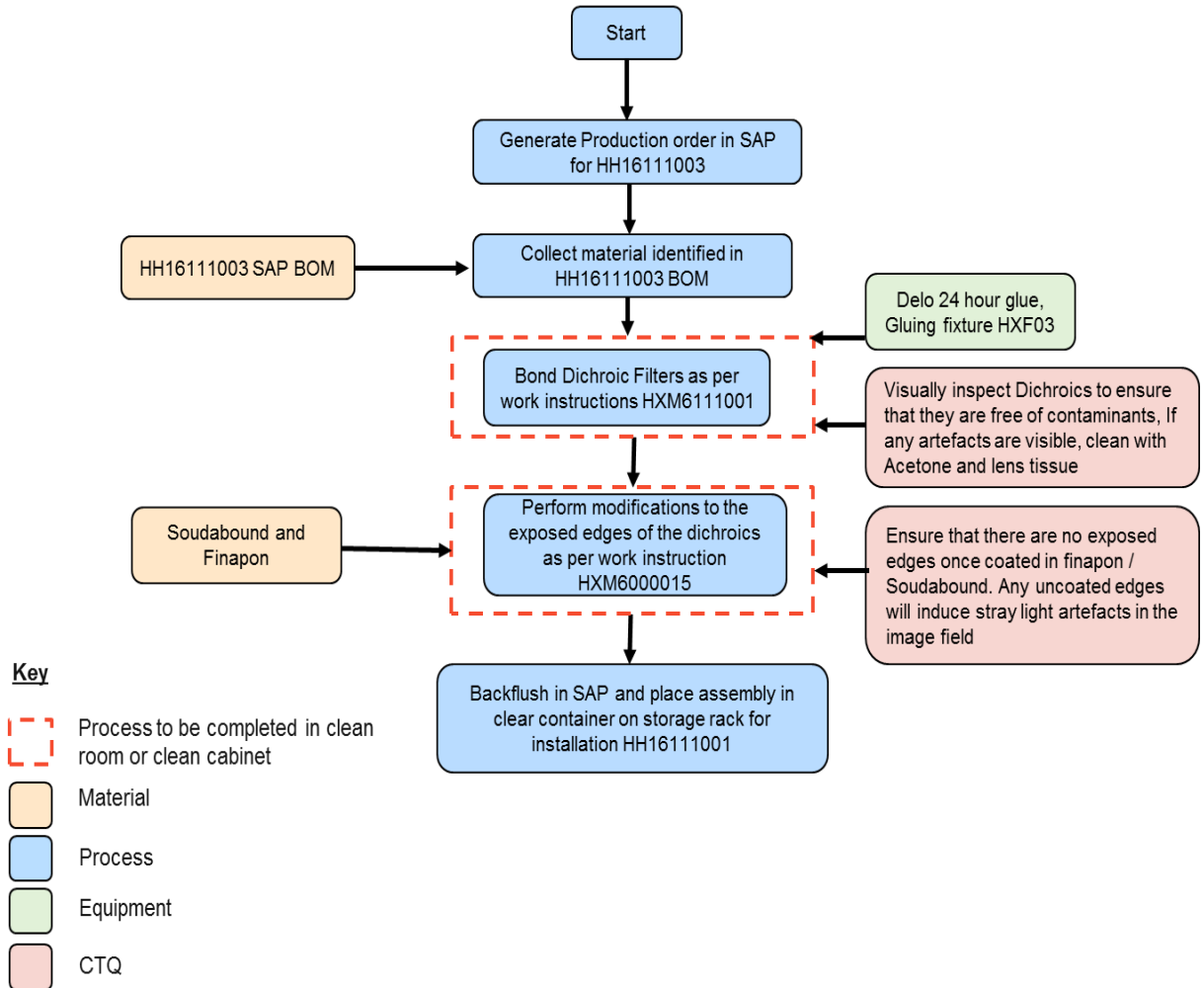


Figure 4-10 - HH16111003 Detailed Process Map

Dichromatic Wheel Assembly HH16111001

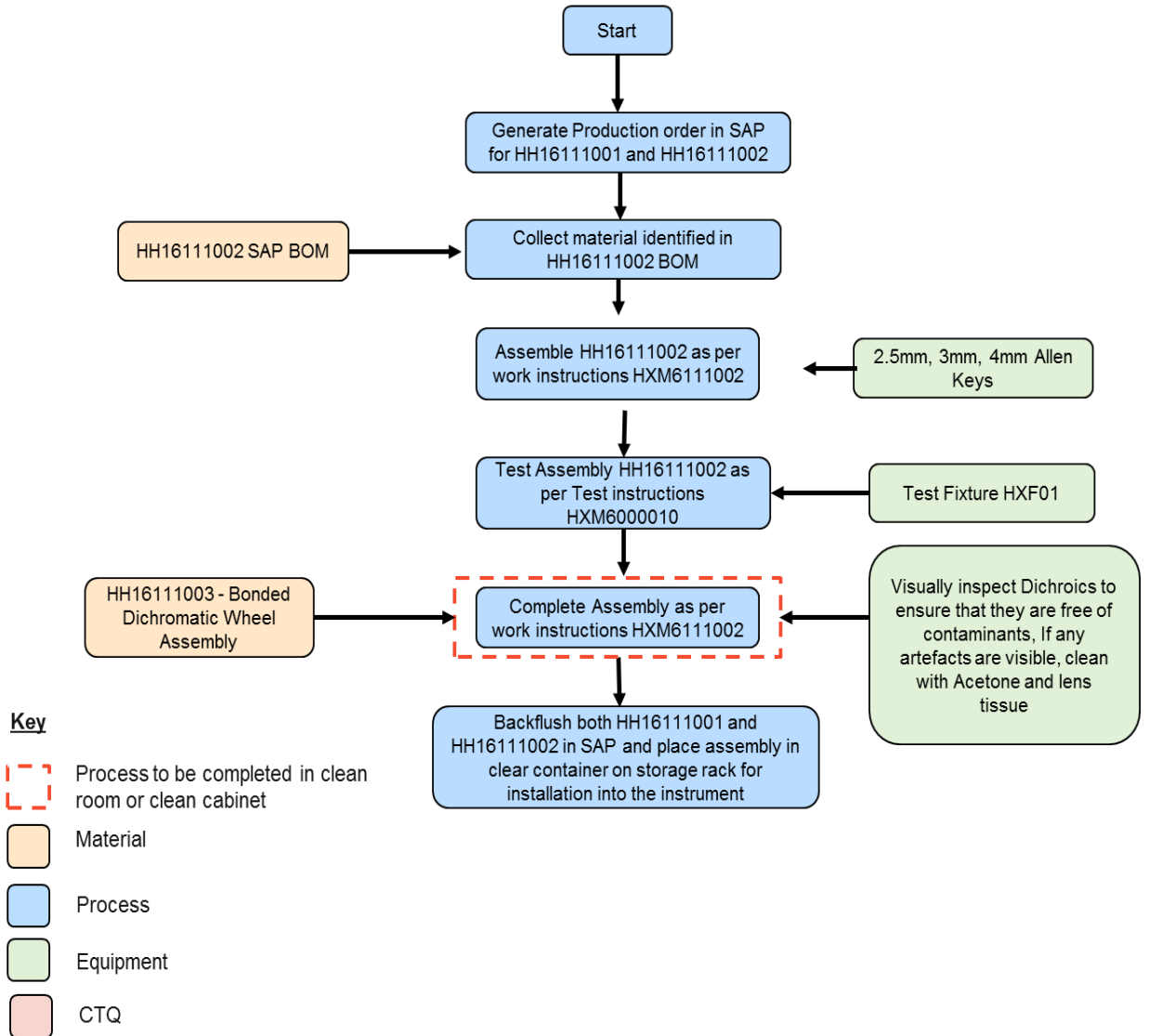


Figure 4-11 - HH16111001 Detailed Process Map

Dichromatic Wheel Assembly Workflow Diagram

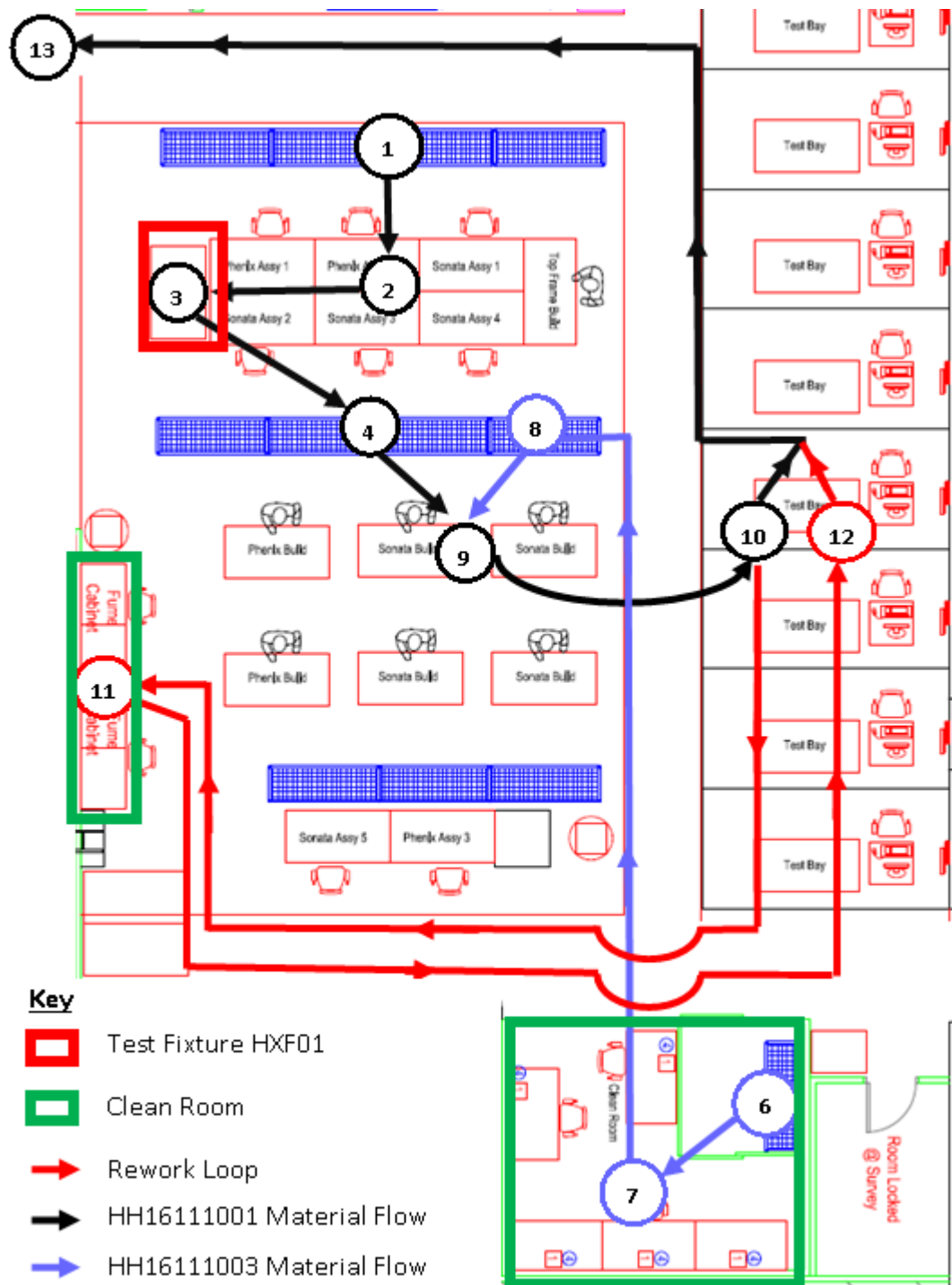


Figure 4-12 - Dichromatic Wheel Assembly Workflow Diagram

From discussions with the technicians and expert knowledge from Elmer Thews and the project team, a detailed process map for the rework loop for bright contamination failures has been developed as shown in Figure 4-13. It can be seen that when an instrument fails the IAT specification, a rework process is followed depending on the type of artefact evident in the image.

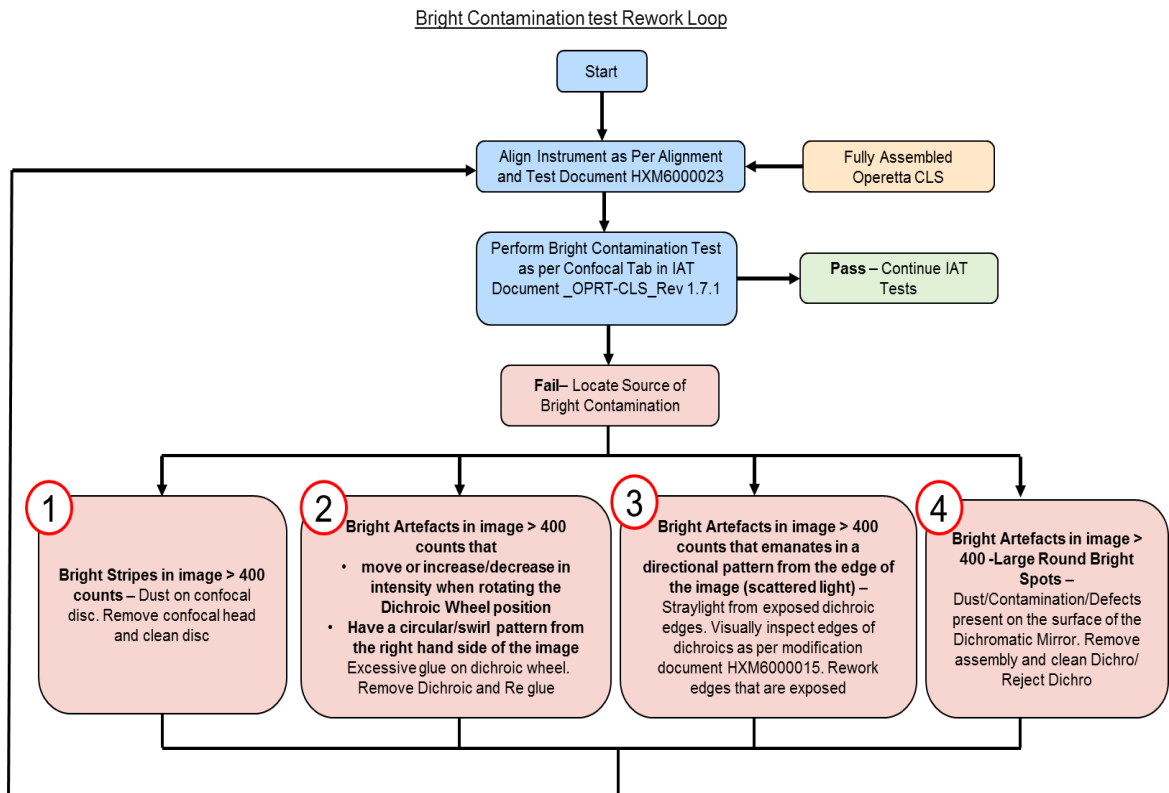


Figure 4-13 - Bright Contamination Rework Loop Detailed Process Map

It can be seen that there are four main artefact "types" that can be visible during the IAT bright contamination test, below is an explanation of each type of artefact taken from discussions with the technicians and Elmar Thews. Sample images for each of the artefact types can be seen in Figure 4-14.

1. **Bright Stripes in image > 400 Counts** - The bright stripes are arcs that run through the image in the Y direction. This is a result of contamination on the confocal spinning disc. The location is obvious due to the continuous stripe caused by a dust particle or defect in the disc. As the disc rotates at 1000RPM, the refresh rate of the camera is not fast enough to pick this up as a particle but rather a large stripe.
2. **Bright Artefacts in image > 400 counts that move or increase/decrease in intensity when rotating the Dichroic Wheel position and Have a circular/swirl pattern from the right hand side of the image** - The glue used to bond the Dichromatic mirrors to the wheel fluoresces when exposed to UV light. As such the dichroic wheel has been designed to limit the amount of glue exposed to the excitation light. This artefact is a result of excessive glue used while bonding the Dichromatic mirrors to the dichromatic wheel. As bright contamination tests are taken at each wavelength, this issue can be seen on any Dichromatic mirror depending on the wavelength used.
3. **Bright Artefacts in image>400 Counts that emanates centrally from the edges of the image (Scattered Light)** - This is due to Stray light scattered from the exposed Dichroic edges. This is a flaw in the original design of the dichroic wheel where the dichromatic edges are exposed directly to the excitation light. An interim solution has been defined by Hamburg R&D as per modification document HXM6000015 to apply black glue and black silicone to the exposed edges to reduce the effect of stray / scattered light.
4. **Bright Artefacts in image > 400 - Large Round Bright Spots** - Dust particles/Contamination/Defects on the surface of the Dichromatic mirror. As bright contamination tests are taken at each wavelength, this issue can be seen on any Dichromatic mirror depending on the wavelength used.

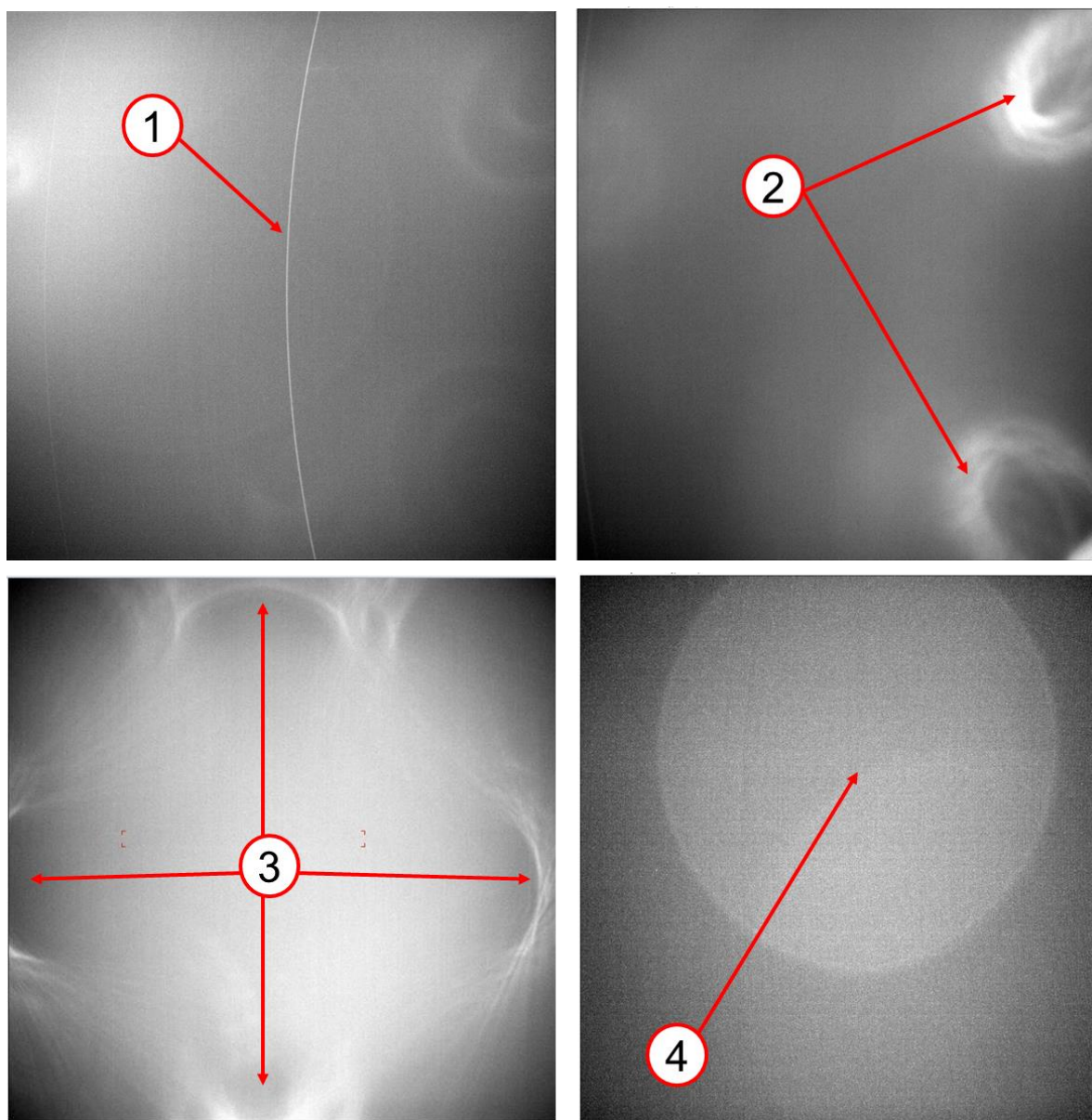


Figure 4-14 - Bright Contamination Samples

4.2.2. Identifying Key inputs and Outputs

A cause and effect diagram (fishbone or ishikawa) is a visual tool used to identify the key inputs that can be considered as directly contributing to the problem (George, et al., 2005). This helps to provide structure to identifying the cause of a problem.

To identify the key areas in the process that require measurement, a brainstorming exercise with all members of the DMAIC project team and Hamburg R&D has been performed to discuss the potential causes of bright contamination and generate a cause and effect diagram that can identify the key inputs and help narrow the scope of the project. The completed cause and effect diagram can be seen in Figure 4-15.

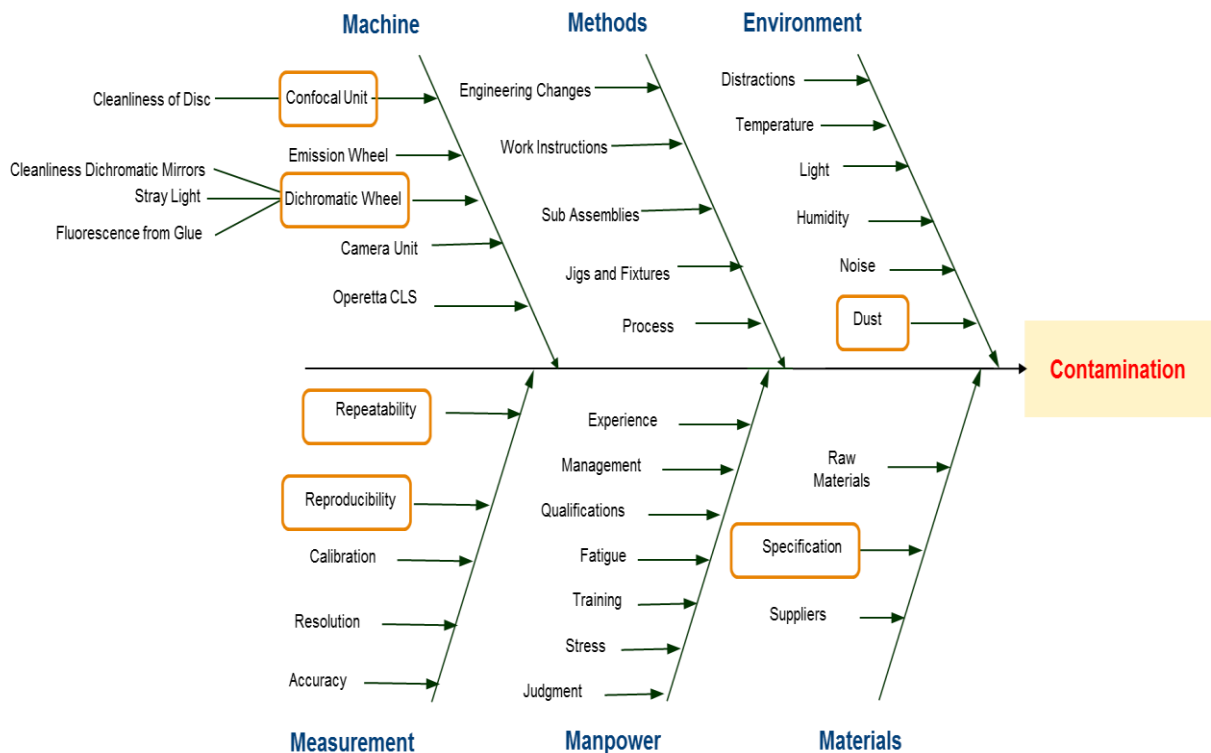
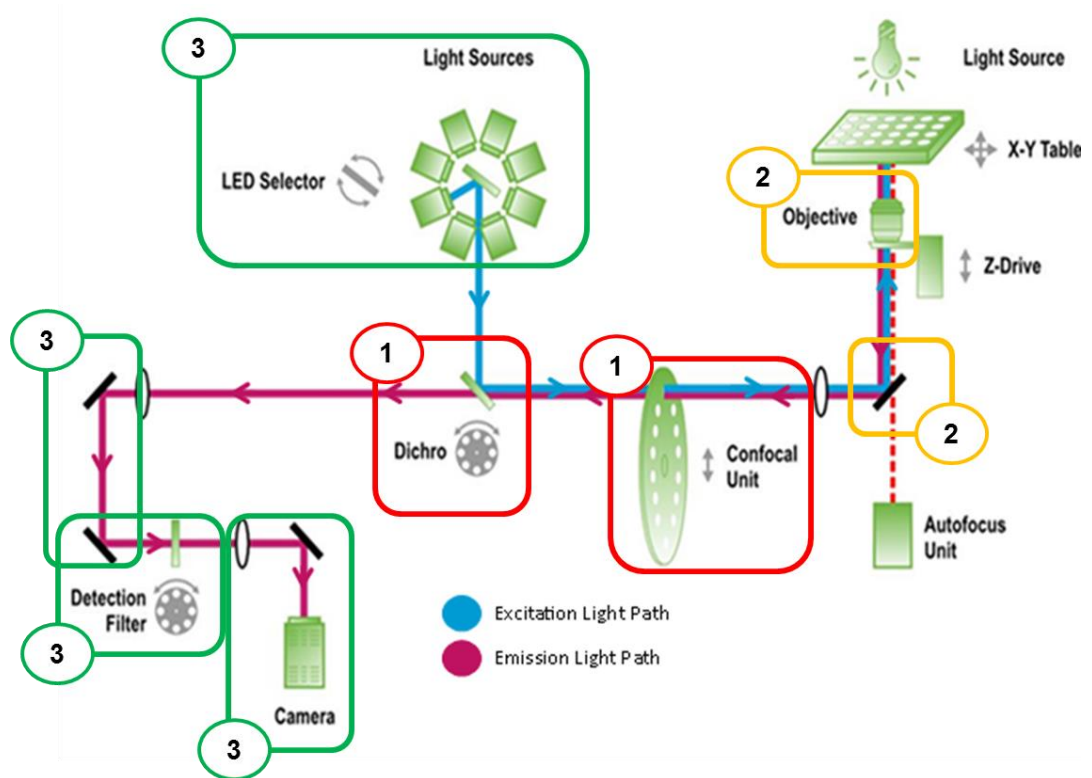


Figure 4-15 - Cause and Effect Diagram

Items highlighted in orange have been deemed as a higher influence to the IAT contamination test failures. This is based on the data from the Pareto analysis, discussions with the technicians and expert knowledge and experience from the R&D team.



Sub Assembly Description	Impact To Bright Contamination
Confocal Unit Assembly	1 - High Contribution
Dichromatic Wheel Assembly	1 - High Contribution
Objective	2 - Medium Contribution
Bottom Port Mirror Assembly	2 - Medium Contribution
Optical Bench Assembly	3 - Little to No Contribution
AutoFocus Unit Assembly	3 - Little to No Contribution
LED Wheel Assembly	3 - Little to No Contribution
Emission/Detection Filter Assembly	3 - Little to No Contribution
Camera Unit Assembly	3 - Little to No Contribution

Figure 4-16 - Sub Assembly Contribution to Bright Contamination

The brain storming exercise resulted in Thews (2017) stating that "Bright Contamination is a result of fluorescence due to excitation from the LED source. As such, only contaminants in the excitation light path can fluoresce. Therefore only optical components in the excitation light path can contribute to bright contamination, components in the emission light path have no contribution" additionally the confocal disc reduces the power from the source by 50%, as such the fluoresced light is reduced from contamination of sub-assemblies post the confocal unit. The results of this discussion can be seen in Figure 4-16

4.2.3. FMEA

From the brain storming exercise with the project team and Hamburg R&D a Failure mode effect analysis (FMEA) can be developed. This FMEA uses the headings from the Cause and Effect diagram and the discussion regarding the sub assembly contribution and splits the information into the various sub categories that were identified by the team as the largest contributors to bright contamination. Each of these aspects was reviewed with the team for severity, occurrence, likelihood of detection and control methods, each given a rating from 1 to 10. A data collection plan can then be developed to measure the aspects with the highest RPN values; the generated FMEA can be seen in Table 4-1.

Cause and Effect Heading	Aspect	Problem	Severity Low 0-10 High	Occur Low 0-10 High	Detect Strong 0-10 Weak	Control Strong 0-10 Weak	RPN
Environment	Dust - Sub Assemblies	Dust in ambient environment	10	5	5	5 Critical Sub Assemblies Manufactured in Clean Room Environment	1250
Man	Judgement					Technician nominated by experience and qualification. Training is	
		Not Trained for the job	10	5	5	3 then conducted and recorded on training matrix	750
	Skill	Insufficient Experience	10	5	5	3 Training Matrix	750
Method	Cleaning of Optical Components	Contamination of optical components	10	5	3	5 SOP, Training	750
	Dichromatic Wheel - Gluing Process	Excessive Glue	10	5	8	5 SOP, Visual Inspection	2000
		Position of Dichromatic mirrors	10	5	5	5 SOP, Visual Inspection	1250
Material	Confocal Unit - Confocal Disc	Contamination on Disc as received from Supplier	10	3	3	5 Specification and supplier verification	450
		Contamination on Disc During Assembly	10	5	5	5 SOP, Visual Inspection, Clean room environment	1250
		Contamination on Disc During IAT	10	10	3	10 No Control Measures	3000
		Bright Contamination due to excess glue during Assembly	10	10	5	5 SOP, Visual Inspection	2500
		Bright Contamination due to excess glue during IAT	10	10	1	10 No Control Measures	1000
		Bright Contamination Due to Scattered Light During Assembly	10	5	8	5 Modification SOP, Visual Inspection	2000
		Bright Contamination Due to Scattered Light During IAT	10	5	5	10 No Control Measures	2500
	Dichromatic Wheel - Dichromatic Mirrors	Bright Contamination Due to Dust/Defects as received from supplier	10	3	5	3 Specification and supplier verification	450
		Bright Contamination Due to Dust/Defects during Assembly	10	3	5	3 SOP, Visual Inspection, Clean room environment	450
		Bright Contamination Due to Dust/Defects during IAT	10	3	1	5 No Control Measures	150
Machine	Specifications	Defective coatings of optics can cause bright contamination	10	3	3	3 Specification and supplier verification	270
	Confocal Unit	See Material					0
	Dichromatic Wheel	See Material					0
	Bright Contamination Measurement in IAT	Incorrect Measurement	5	3	5	5 IAT, MSA Results	375

Table 4-1- Bright Contamination FMEA

4.3. Data Collection Plan

The next stage in the measure phase is to create and implement a data collection plan. Measures must occur at three key areas as shown in Figure 4-17. These three areas centre on the output measures important to the customer, the input measures required to perform the task and measures of the process itself (Eckes, 2004).

Input Measures (Supplier Effectiveness)	Process Measures (Your Efficiency)	Output Measures (Your Effectiveness)
The key quality measures placed on your suppliers.	Measures of your process efficiency: • Cycle time • Cost • Value • Labor	Measures of how well you are meeting (and hopefully)/exceeding your customers requirements.

Figure 4-17- Areas Requiring Measurement (Eckes, 2004)

The Operetta CLS is considered a medical device and as such is governed by stringent quality systems for complete traceability. A criterion of the quality system requires all images acquired by the instrument during IAT are saved in a directory. This includes all failed data images that were captured during the bright contamination IAT tests. The folders are named and dated with the wavelength, run number and the date for example "365nm_2nd Run_120318.Jpeg" The wavelength is the wavelength of the LED that was used for the test. The run denotes the number of times the test has been run, for this example the test has been run twice meaning that the initial run failed and was reworked. The date is the day in which the image was captured.

From the existing images the following aspects will be developed using data from the 52 instruments manufactured in 2017 from which the rework hours of 358.5 hours have been calculated:

- Tally chart for number of occurrences of each artefact type for bright contamination
- Run chart of first bright contamination results and final bright contamination results (pre and post rework)

New data that is required,

- **Environment** - Dust particle count,

A dust particle count is required to determine if the environmental conditions are acceptable to manufacture and test instruments with such tight contamination specifications.

- **Confocal Unit** - Microscope images to be taken of the disc once removed from the packaging, once assembled into the Confocal Unit and once failed in the instrument. Images to be stored in a folder on the network under the confocal unit serial number.

This data will be collected to determine what stage in the process the confocal disc is contaminated. Currently there is no process control for contamination apart from a visual inspection for fingerprints and dust particles prior to and after assembly.

- **Confocal Unit** - Bright Baseline measurement to be taken in instrument on day of installation, repeat daily for 2 weeks without using the same instrument settings. The serial number, number of stripes and intensity to be recorded at 24 hour intervals.

This data will be collected to determine if the confocal unit contamination increases over time. As discussed in the "Define" phase, there have been 3 customer complaints for contamination resulting in confocal unit replacements. Data confirming if the confocal unit does become more contaminated over time will help in determining a solution for the problem.

- **Dichromatic Mirror Assembly** - Visual inspection of cleanliness of optics once removed from packaging, bonded in Dichromatic Wheel, once removed from instrument.

This data is required to determine where in the process the contamination occurs.

- **Dichromatic Mirror Assembly** - Images to be taken using a microscope for each of the gluing spots once the glue has cured. Record the image under the dichroic wavelength and Dichroic Wheel serial number for example 425nm_Glue_12345

This data is required to find an optimal quantity of glue that can be used to bond the dichromatic mirrors a correlation study will be used to determine the relationship between the size of the gluing spot and the intensity of the contamination seen. It can be seen in existing data that rework occurs when there is too much glue applied. How much is too much is still unknown.

- **Hidden Factory** - Average time to perform each of the four identified rework operations

This data is required along with the number of occurrences that will be retrieved from the existing data to determine the impact each artefact has with regard to downtime.

Data will be collected by Neil Forshaw and Mark Packwood during the manufacturing of the subject assemblies, this minimises the impact to the production schedule as additional processes will not be added to the technicians current daily operations. All data will be stored on the PerkinElmer Llantrisant Network and be accessible to all members of the project team .

4.3.1. Sample Size and Data Collection Timeframe

Sampling of parts throughout a large batch is a useful tool that measures defined critical parameters on a small number of parts as opposed to the total quantity. This process gives insight into the performance of the product when it is not feasible to test every product when huge quantities are produced daily. However, it should be noted that Perkin Elmer are a high complexity, low volume manufacturing site. The Operetta CLS is manufactured in quantities of approximately 70 instruments per annum making measurements of each part feasible. The result of this is that sampling will occur for each assembly not a particular quantity throughout a batch, as discussed, due to time constraints of the project, new data will be collected from 10 instruments over a 4 week period.

4.4. Measurement System Analysis - Gauge R&R

A Measurement System Analysis is used to determine if a measurement system can generate accurate data. This is useful in ensuring that any differences seen in the collected data are caused by the differences of the items being measured and not due to variation in the measurement system itself. As stated by George et al "Experience shows that 30% to 50% of measurement systems are not capable of accurately or precisely measuring the displayed metric" (George, et al., 2005).

The images and methods of calculating the result that determines if the Operetta CLS passes or fails the IAT specifications must be both repeatable and reproducible. Reproducibility is the ability of a measurement to be duplicated by both the same technician and someone else working independently using the same measurement system to measure an identical characteristic. Repeatability is the variation in the measurement system when repeating consecutive measurements under the same operating conditions. To measure such variation in the repeatability and reproducibility of a measurement system a Gauge R&R study can be conducted.

The gauge R&R study will be used to determine if the Operetta CLS IAT is capable of taking images where the contamination measurements are repeatable and reproducible. The gauge used is the Operetta CLS serial number 1600L17057. The instrument will be configured to capture images for bright contamination as discussed in 1.3.4 Contamination Overview. The same instrument will be used to capture six consecutive images using the instrument parameters show in Table 4-2. The six images will be measured by three different operators to determine the reliability and reproducibility of the system.

LED Wavelength	LED Power	Camera Exposure Time (s)	Dichromatic Mirror	Emission Filter
365nm	100%	10	Longpass 425nm	430-550nm

Table 4-2 - Gauge R&R Instrument Parameters

When conducting a Gauge R&R study, a specification must be determined that the measurements can be compared to. As there is no physical specification, for example a linear dimension that can be measured using a calliper, and only a target specification of between 0 and 400 counts, a reference specification must first be determined. A discussion with Elmar Thews concluded that the specification can be retrieved from the first image. This image would be expertly measured by Elmar Thews; the measurement of the brightest artefact can then be used as the specification to compare against. From the measurement conducted by Elmer the specification has been determined to be 575.9 for this particular set of images as shown in Figure 4-18 - Reference Specification as Measured by Elmar Thews.

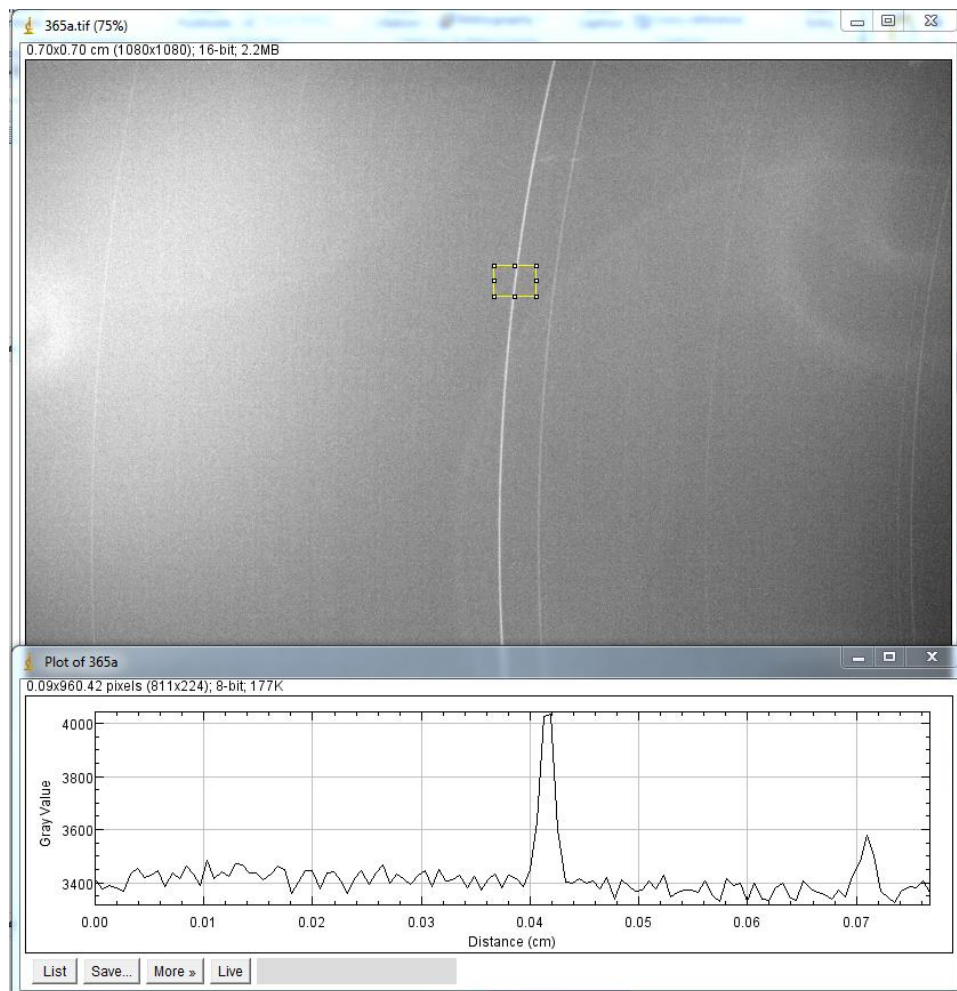


Figure 4-18 - Reference Specification as Measured by Elmar Thews

Peak Height Intensity = 4053.9

Background Intensity = 3478

Peak Height Intensity - Background Intensity = Bright Contamination Intensity

4053.9 - 3478 = 575.9

Six images are then measured twice by three different operators. The data is then gathered and input into a table as shown in Table 4-3. Once the data is gathered, calculations must be performed to determine the variation.

Table 4-3 - Gauge R&R Data

Appraiser/ Trial #	1	2	3	4	5	6	AVG
A							
1	572	578	568	585	571	575	574.833
2	575	573	570	582	576	572	574.667
AVG'S	573.500	575.500	569.000	583.500	573.500	573.500	Xa 574.750
Range	3.000	5.000	2.000	3.000	5.000	3.000	Ra 3.500
B							
1	571	568	580	579	567	572	572.833
2	575	576	583	575	570	574	575.500
AVG'S	573.000	572.000	581.500	577.000	568.500	573.000	Xb 574.167
Range	4.000	8.000	3.000	4.000	3.000	2.000	Rb 4.000
C							
1	572	580	580	571	568	581	575.333
2	572	578	575	574	567	579	574.167
AVG'S	572.000	579.000	577.500	572.500	567.500	580.000	Xc 574.750
Range	0.000	2.000	5.000	3.000	1.000	2.000	Rc 2.167
Part Average	572.8333	575.5000	576.0000	577.6667	569.8333	575.5000	X Rp 574.556 7.833

First the average range for the 3 Technicians ($R_{Doublebar}$) is calculated:

$$R_{Doublebar} = \frac{R_A + R_B + R_C}{3} = \frac{3.5 + 4 + 2.167}{3} = 3.222$$

Next the difference between the maximum appraiser average and the minimum appraiser average needs to be determined (X_{diff}). Appraisers A and C have a maximum average of 574.750. Appraiser B has a minimum average of 574.167.

$$X_{Diff} = X_{App\ max} - X_{App\ min} = 574.750 - 574.167 = 0.583$$

Next determine the range of the part averages (R_p). The maximum part average is Part 4 (577.667). The minimum part average is for Part 5 (569.833).

$$R_P = X_{Part\ max} - X_{Part\ min} = 577.667 - 569.833 = 7.833$$

The various contributors to the measurement system variation can now be calculated.

- Equipment variation (EV)
- Appraiser variation (AV)
- Repeatability and reproducibility (GRR)
- Part variation (PV)
- Total variation (TV)

Repeatability: Equipment Variation (EV)

This is the "within appraiser" variation. It measures the variation one appraiser has when measuring contamination on the same image using the same instrument multiple times. The calculation is given below:

$$EV = K_1 \times R_{Doublebar} = 4.56 \times 3.222 = 14.6933$$

Where K_1 is a constant that depends on the number of trials. For 2 trials, K_1 is 4.56.

Reproducibility: Appraiser Variation (AV)

This is the variation between the technicians. It is the variation in the average of the measurements made by the different technicians when measuring the contamination on the same image. The calculation is given below.

$$AV = \sqrt{(X_{Diff} \times K_2)^2 - \frac{EV^2}{nr}} = \sqrt{(0.583 \times 2.7)^2 - \frac{14.6933^2}{6 \times 3}} = 3.084$$

Where:

n = the number of trials

r = the number of appraisers.

K2 is a constant that depends on the number of appraisers. For three appraisers, K2 = 2.7.

Gauge Repeatability and Reproducibility (GRR)

The next calculation combines the two above to determine Gauge Repeatability and Reproducibility, which is given by:

$$GRR = \sqrt{EV^2 + AV^2} = \sqrt{14.6933^2 + 3.084^2} = 15.013$$

Part Variation (PV)

The part variation is determined by multiplying the range of the part averages (Rp) by a constant K3. K3 depends on the number of parts. For 5 parts, K3 = 0.4030. The part variation is then given by:

$$PV = (R_p)(K_3) = 7.833 \times 1.93 = 15.11833$$

Total Variation (TV)

This is the total variation from the study. It is determined by the following equation:

$$TV = \sqrt{GRR^2 + PV^2} = \sqrt{15.013^2 + 15.11833^2} = 21.20661$$

Interpretation of Results

A gauge R&R study is a study in variation. To determine if the measurement system is adequate, you must compare the results to something.

To compare the results to the variation in the images, the total variation (TV) must be used. The following calculations are the performed:

$$\%EV = 100 \left(\frac{EV}{TV} \right) = 100 \left(\frac{14.69333}{21.30661} \right) = 68.96\%$$

$$\%AV = 100 \left(\frac{AV}{TV} \right) = 100 \left(\frac{3.084}{21.30661} \right) = 14.48\%$$

$$\%GRR = 100 \left(\frac{GRR}{TV} \right) = 100 \left(\frac{15.013}{21.30661} \right) = 70.46\%$$

$$\%PV = 100 \left(\frac{PV}{TV} \right) = 100 \left(\frac{15.11833}{21.30661} \right) = 70.96\%$$

To compare the results to the tolerance rather than the total variation then TV must be substituted with the tolerance. For the Operetta CLS a tolerance of 10% has been determined by Elmar Thews considering pulses in the LED source and stray light. Using the method the following results are obtained:

$$\%EV = 100 \left(\frac{EV}{Tol} \right) = 100 \left(\frac{14.69333}{57.5} \right) = 25.6\%$$

$$\%AV = 100 \left(\frac{AV}{Tol} \right) = 100 \left(\frac{3.084}{57.5} \right) = 5.4\%$$

$$\%GRR = 100 \left(\frac{GRR}{Tol} \right) = 100 \left(\frac{15.013}{57.5} \right) = 26.1\%$$

$$\%PV = 100 \left(\frac{PV}{Tol} \right) = 100 \left(\frac{15.11833}{57.5} \right) = 26.3\%$$

George et al (2005) states that:

"Less than 10% variation is good - It means little variation is due to the measurement system, most of it is true variation.

10% to 30% - acceptable depending on application (30% is maximum acceptable for any process improvement effort).

More than 30% - Unacceptable, the measurement system is too unpredictable."

From the gauge R&R study results we can conclude that the images taken from the operetta CLS are repeatable and reproducible to an "acceptable" level when compared to the tolerance, there is little variation seen image to image (part variation). Additionally there is little variation with the measurements taken by the technician. A statement can be made that the IAT test for bright contamination is an acceptable test to perform with little variation seen. The complete gauge R&R report can be seen in Appendix A.

4.5. Process Capability Study

A process capability study determines the stability of a defined process. The behaviour of a process is called its process capability. To improve a process, the current process capability must first be established (Gitlow, et al., 1989).

The process capability for the bright contamination IAT test can be calculated using Six Sigma formulas. Using a sample size of 100 Operetta CLS instruments, the data for the initial contamination result will be used to perform a process capability study.

The standard deviation first needs to be calculated using the formula below:

$$\sigma = \sqrt{\frac{\sum_{i=1}^N (X_i - \mu)^2}{N}}$$

Where: X_i = the i th data value in the table, μ = the overall average and N = number of instruments

From the data gathered from the 100 instruments for the initial contamination test, the mean can be calculated by the sum of the results divided by the number of instruments. To determine the standard deviation, the mean is subtracted from each of the data points ($X_i - \mu$), this result is then squared and a sum taken of all the squared results. A mean can then be taken from the sum of ($X_i - \mu$) squared. The square root of this mean is the standard deviation.

Mean = 762.53

Standard Deviation σ = 565.68

To calculate the process capability, the upper and lower specification limits as defined in the IAT are also required:

Upper Specification limit (USL) = 400

Lower Specification Limit = (LSL) = 400

This data can then be used to calculate the Cp and Cpk of the process. Soleimannejed (2004) describes the difference between the two as the following “Cpk is an index (a simple number) which measures how close a process is running to its specification limits, relative to the natural variability of the process. The larger the index, the less likely it is that any item will be outside the specs. If you hunt our shoot targets with bow, darts, or gun try this analogy. If your shots are falling in the same spot forming a good group this is a high Cp, and when the sighting is adjusted so this tight group of shots is landing on the bullseye, you now have a high Cpk.”

Cp Calculations

$$Cp = \frac{USL - LSL}{6\sigma} = \frac{400 - 0}{6 \times 565.68}$$

$$Cp = 0.118$$

Cpk Calculations

The following two formulas can be used to calculate Cpk. The lowest of the two results is the true Cpk value.

$$Cpk = \frac{USL - Mean}{3\sigma} = \frac{400 - 762.53}{3 \times 565.68}$$

$$Cpk = -0.21$$

$$Cpk = \frac{Mean - LSL}{3\sigma} = \frac{762.53 - 0}{3 \times 565.68}$$

$$Cpk = -0.45$$

It can be seen that -0.21 is the lowest of the two Cpk results. This will be considered as the Cpk for the process. It can be seen that this is well below the Six Sigma desired value of 1.33 indicating that the process is not stable and the limits are far too tight for the current process. This can be seen in Figure 4-19, not only is the distribution much larger than the upper and lower specification but the peak of the distribution is outside of the specification window. This data can be used as a baseline for any process improvements. The raw collected data used for the calculations discussed can be seen in Appendix B.

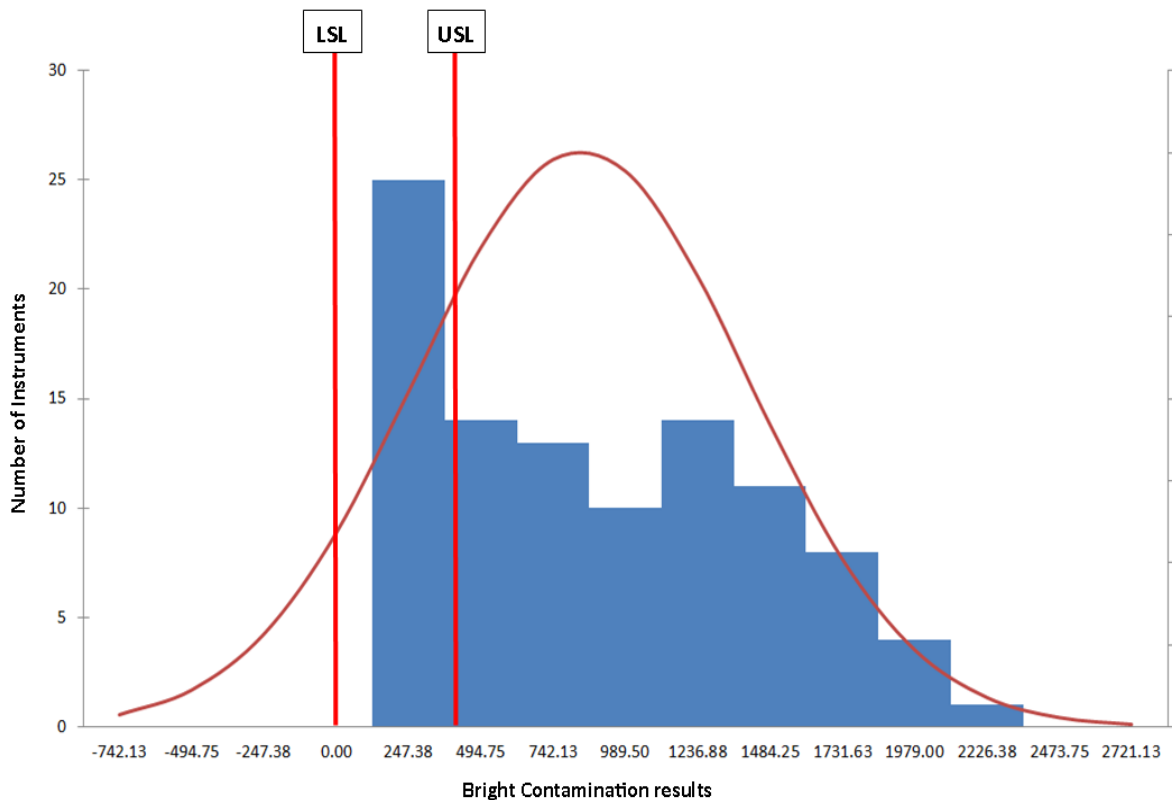


Figure 4-19 - Distribution of Results

5. Chapter 5: Analyse Phase

The third phase of the DMAIC lean six sigma improvement process is the "Analyse" phase. The "Analyse" phase of the DMAIC process is used to determine and verify the root causes that are directly contributing to the failure modes seen.

"Analyse" is a critical phase that is not often given enough attention and, without analysis can lead to the project team creating solutions before understanding the true root cause of the problem (Go Lean Six Sigma, 2018). In this phase, the data collected from the measure phase will be analysed along with a close examination of the current processes. Additional DMAIC tools will also be used during the "analyse" phase of the project to understand the root cause of the problem, such as "Pareto analysis", "fishbone diagrams" and "5 whys". An overview of a number of these tools and the roadmap to a successful "analyse" phase can be seen in Figure 5-1.

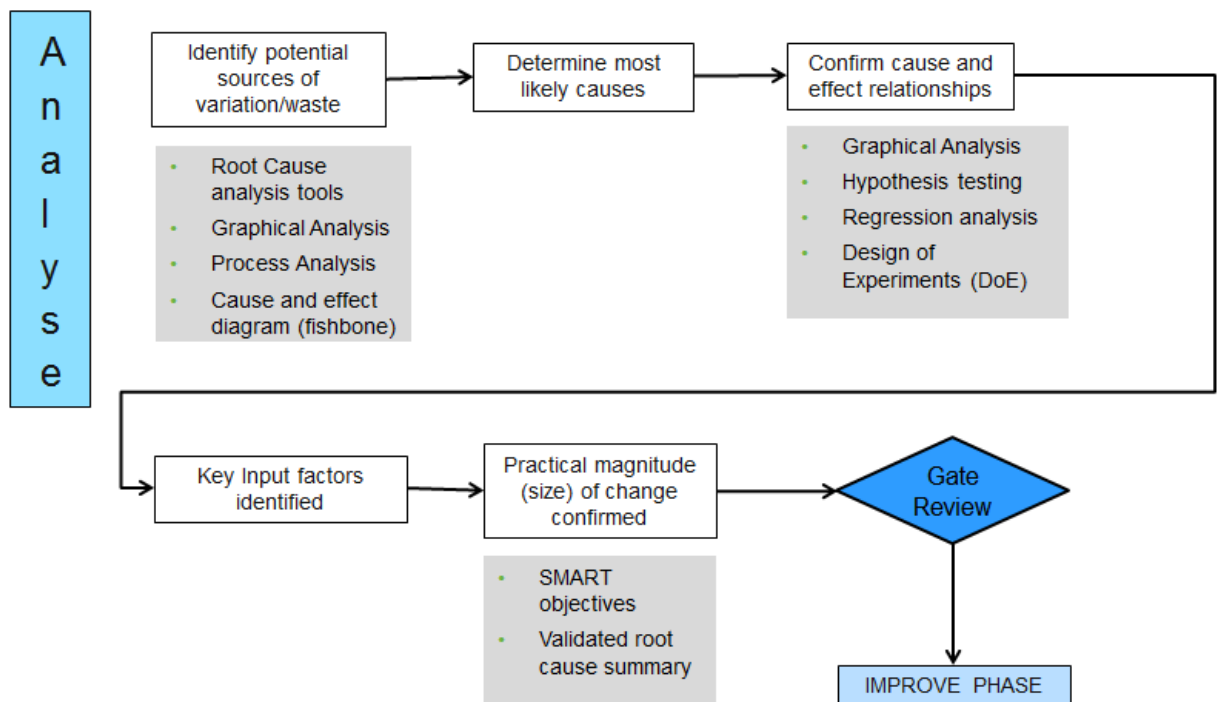


Figure 5-1 - Analyse Phase Roadmap

Key deliverables from the Analyse phase as discussed by Rowlands et al (2005) must include but not be limited to:

- Data charts and other analyses that show the link between the input and process variables and critical output.
- Documentation of potential causes considered in the analysis.

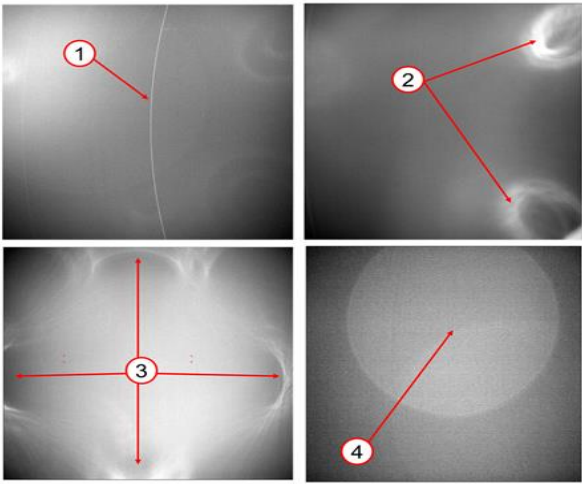
5.1. Analysis of Measured Data

5.1.1. Bright Contamination Occurrences

From the available IAT bright contamination image data for the 52 instruments manufactured in 2017, the tally chart shown in Table 5-1 can be created. The data shows that from 52 instruments there were 45 instruments that failed the bright contamination specification on the initial run. The number of occurrences of each of the failure modes identified in the Measure phase can also be seen in Table 5-1. This shows that in terms of number of occurrences, stripes on the confocal unit is the biggest contributor, followed by rework due to gluing spot fluorescence, stray/Scattered light and finally dichroic contamination. No other artefacts were seen during the data review.

Table 5-1 - Bright Contamination Artefact Tally Chart

Sample Image Reference	Defect	Count	Total
1	Confocal Stripes	++++ +++++ +++++ +++++ +++++	25
2	Gluing Spots	++++	9
3	Stray/Scattered Light	++++	7
4	Dichroic Contamination	++++	4
	Other		0



Total Defects 45
Number of Samples 52

Using this data, the first pass yield for the bright contamination process can be calculated as shown in Table 5-2. It can be seen that the total first pass yield for the bright contamination test is 13%. Additionally the first pass yield for the confocal unit assembly bright contamination is 52% and for the dichromatic wheel assembly, 62%.

Table 5-2 - First Pass Yield

Process Step	Defects	Units	Defects Per Unit	First Pass Yield
Bright Contamination IAT Total	45	52	0.865385	13%
Confocal unit	25	52	0.480769	52%
Dichromatic Wheel Assembly	20	52	0.384615	62%

5.1.2. Hidden Factory Detailed Process Map and Rework Time

As discussed in the data collection plan, a completed hidden factory detailed process map and rework time is required for each of the bright contamination rework processes identified when performing the current state mapping the in Measure phase. This data is required to understand where there may be potential sources of variation and to also understand the contribution to downtime hours of each defect type.

The Detailed process maps of each artefact type along with the cycle time can be seen in Figure 5-2, Figure 5-3, Figure 5-4 and Figure 5-5.

Confocal Unit Bright Contamination

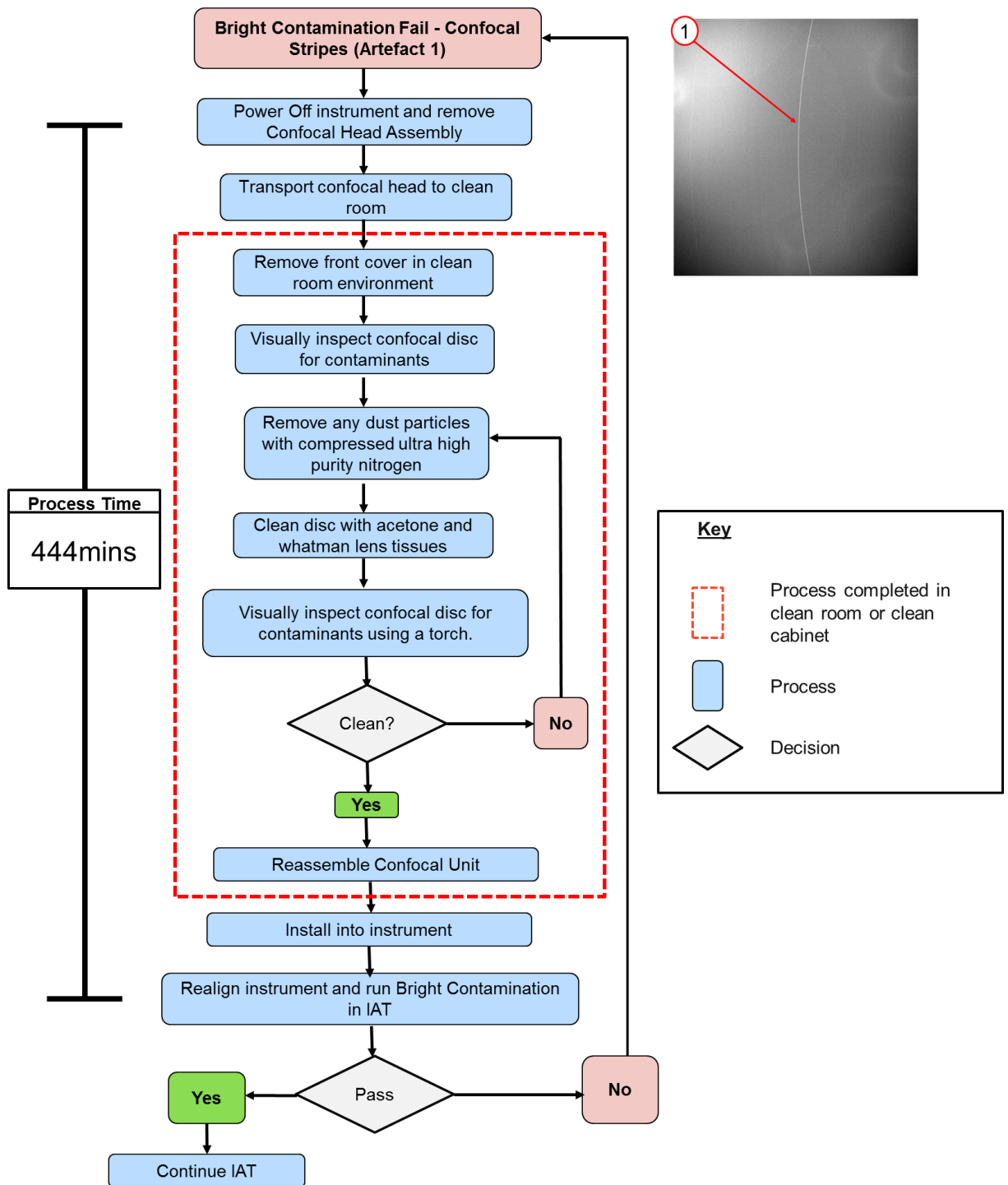


Figure 5-2 - Detailed Process Map and Process Time - Confocal Stripes (Artefact 1)

Dichromatic Wheel Bright Contamination

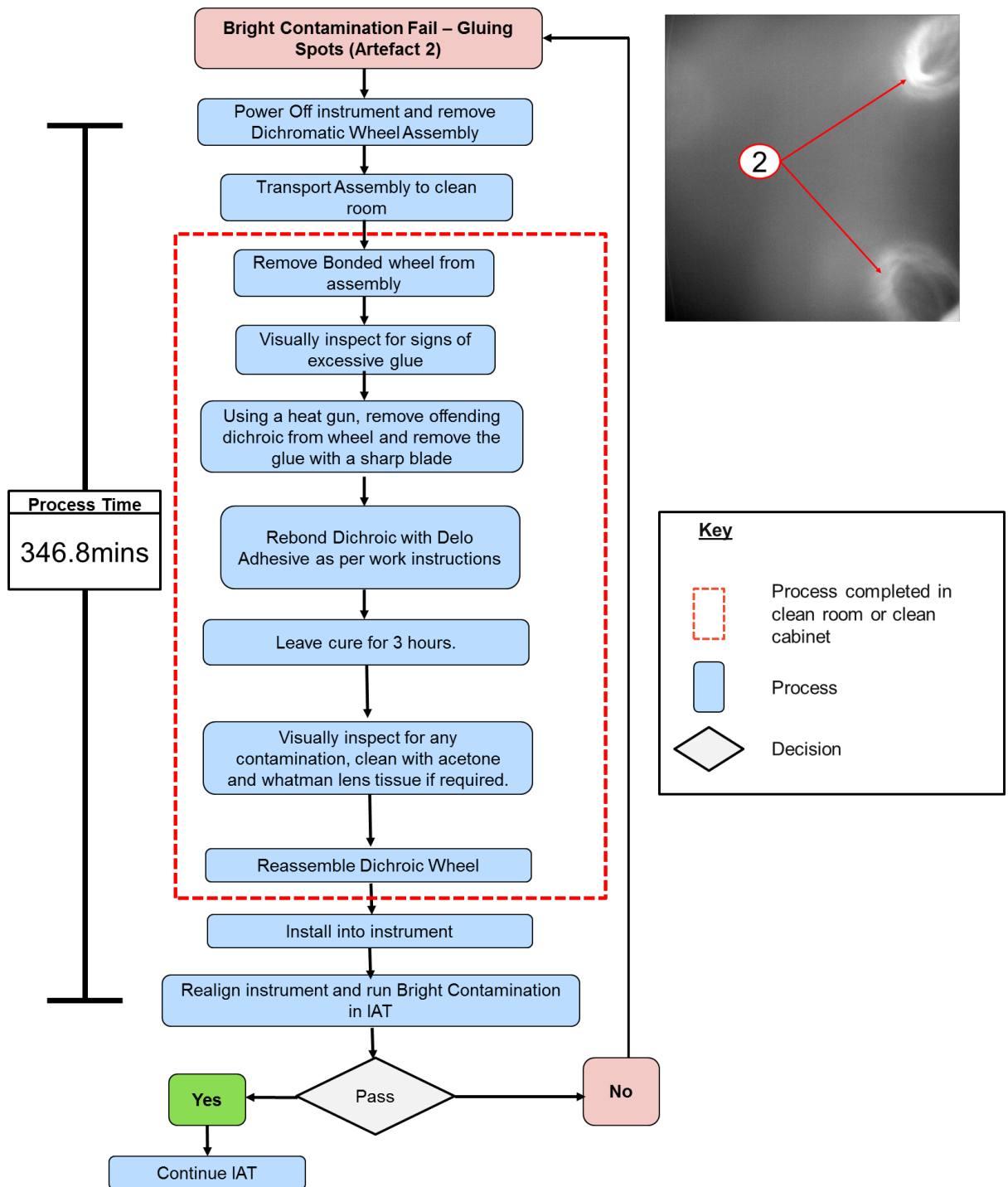


Figure 5-3 - Detailed Process Map and Process Time - Dichromatic Assembly Gluing Spots (Artefact 2)

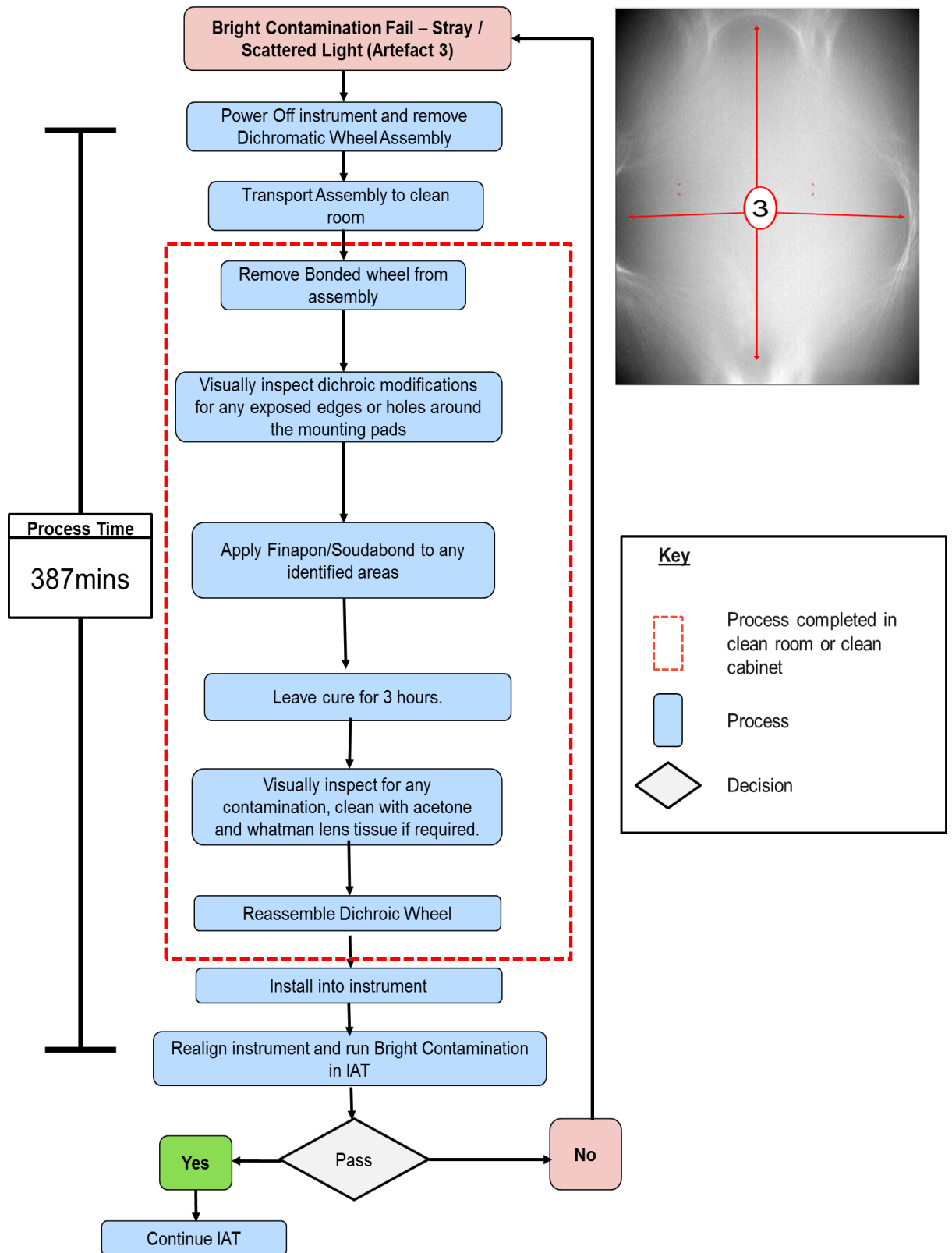


Figure 5-4 - Detailed Process Map and Process Time - Dichromatic Assembly Stray/Scattered Light (Artefact 3)

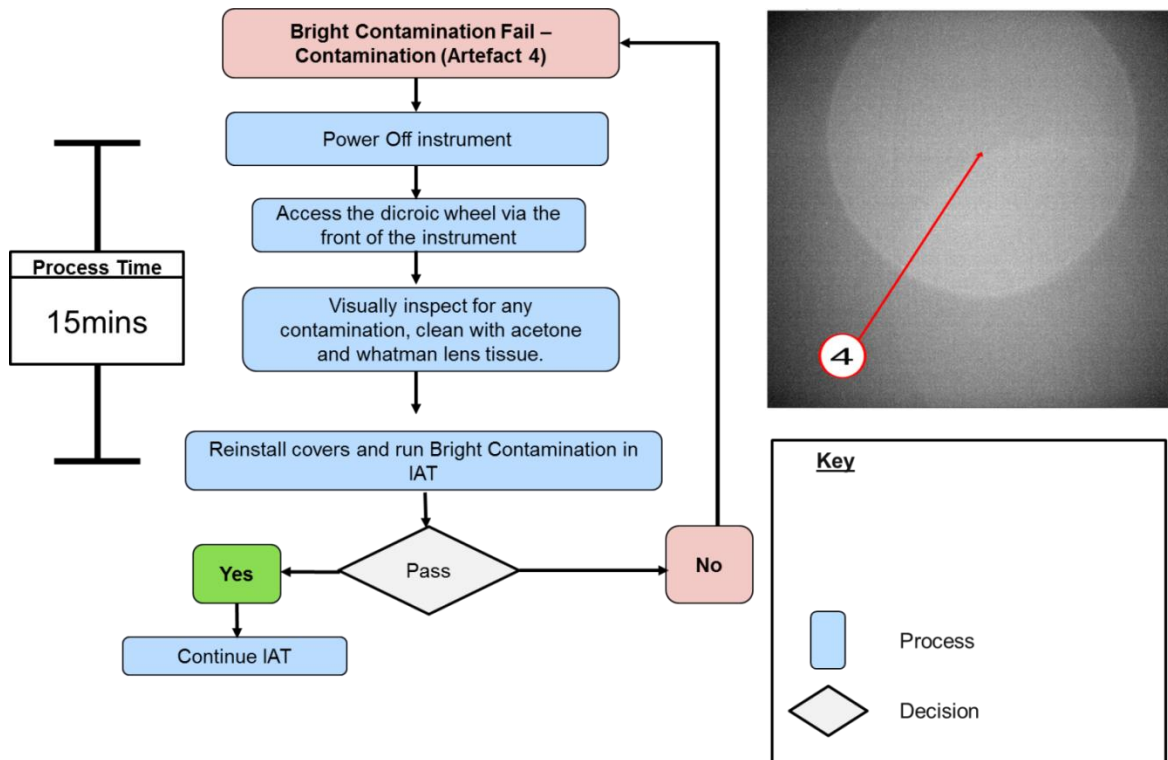


Figure 5-5 -Detailed Process Map and Process Time - Dichromatic Assembly Contamination (Artefact 4)

5.1.3. Contamination Pareto Analysis

Calculations can be performed to determine the total downtime hours per artefact in 2017 using the data measured in the Bright Contamination Tally chart Table 5-1, and the rework operation process times detailed in Figure 5-2, Figure 5-3, Figure 5-4 and Figure 5-5.

$$\frac{\text{Number of Occurrences} \times \text{Process Time}}{60} = \text{Total Downtime Hours}$$

Confocal Unit - Stripes (Artefact 1)

$$\frac{25 \times 444}{60} = 185 \text{ Hours}$$

Dichromatic Wheel - Gluing Spots (Artefact 2)

$$\frac{9 \times 347}{60} = 52.05 \text{ Hours}$$

Dichromatic Wheel - Stray Scattered Light (Artefact 3)

$$\frac{7 \times 381}{60} = 44.45 \text{ Hours}$$

Dichromatic Wheel - Contamination (Artefact 4)

$$\frac{4 \times 15}{60} = 1 \text{ Hour}$$

This data can be used to develop a Pareto chart for all contamination failure modes to determine if each of the artefacts still contributes to the majority of the contamination downtime hours discussed in the Define Phase, this will help ensure that the project is still on target and within the scope of the project

A Pareto chart is based on the Pareto principle that states that for many events; roughly 80% of the effects come from 20% of the causes (Sobaco Limited, 2010). Using the data from the calculations the Pareto chart shown in Figure 5-6 has been developed. The Pareto chart shows that of the 4 artefacts discussed, 3 remain as the biggest contributors to downtime contributing to 78.5% of the total downtime. The fourth artefact contributes to only 0.8% of the total downtime seen; this is due not only the low number of occurrences but also that the time to perform the rework task is relatively short.

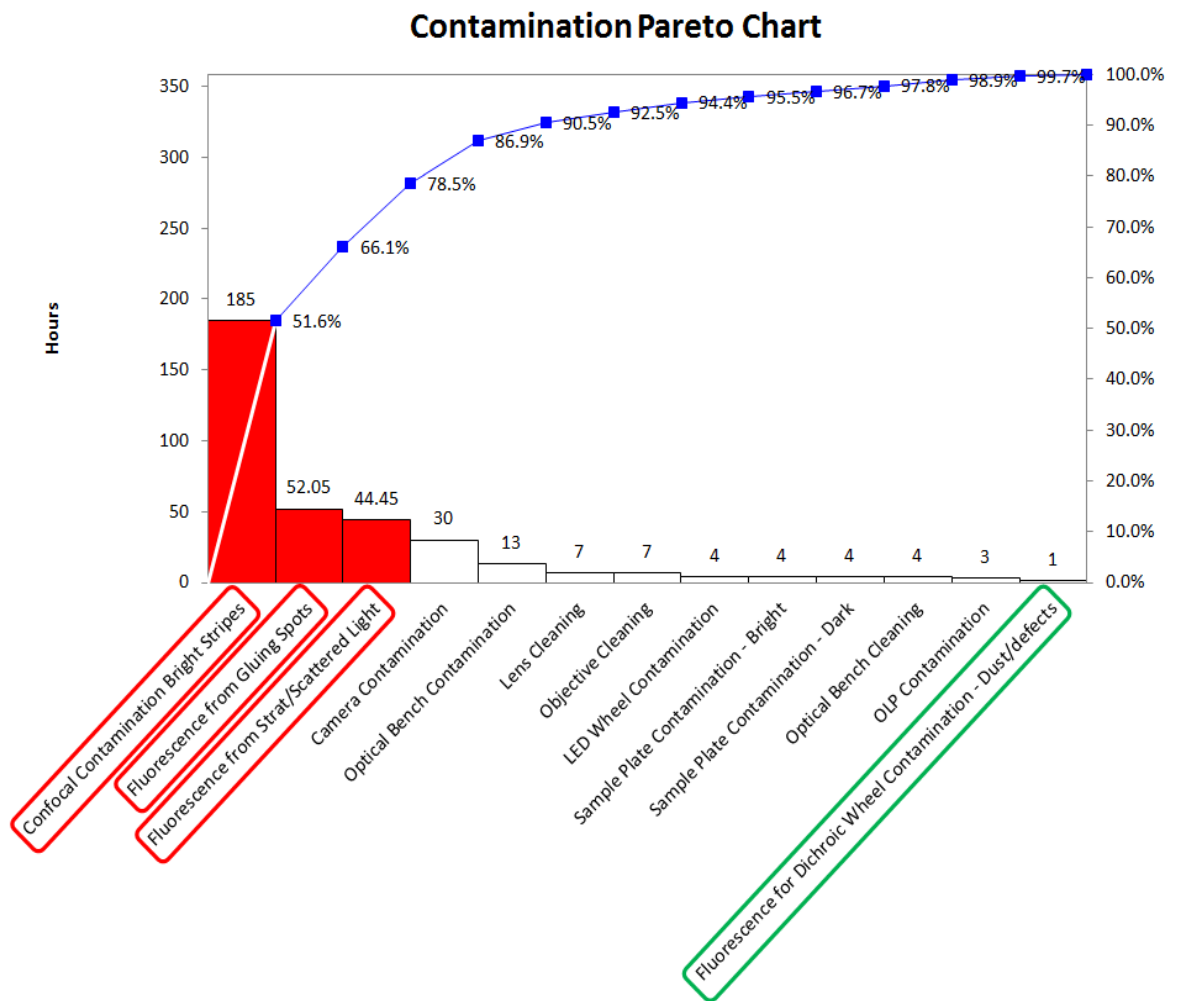


Figure 5-6 - Revised Contamination Pareto Chart: Artefact 1, 2&3 highlighted red, Artefact 4 highlighted green

The Pareto Analysis suggests that focussing on the first three artefacts can result in a decrease in downtime of 78.5%. The fourth artefact can be ignored as any investment in determining the root cause will result in only a marginal improvement in downtime.

5.1.4. Bright Contamination Run Charts

Run charts are used to detect trends and any significant changes in the process from which the data was extracted (George, et al., 2005). Using the data from the last 52 instruments the run chart shown in Figure 5-7 has been developed. It can be seen that there are no obvious trends in the data for example a run of 4 or more data points with increasing value, nor are there any significant step changes evident that may suggest a change in the process.

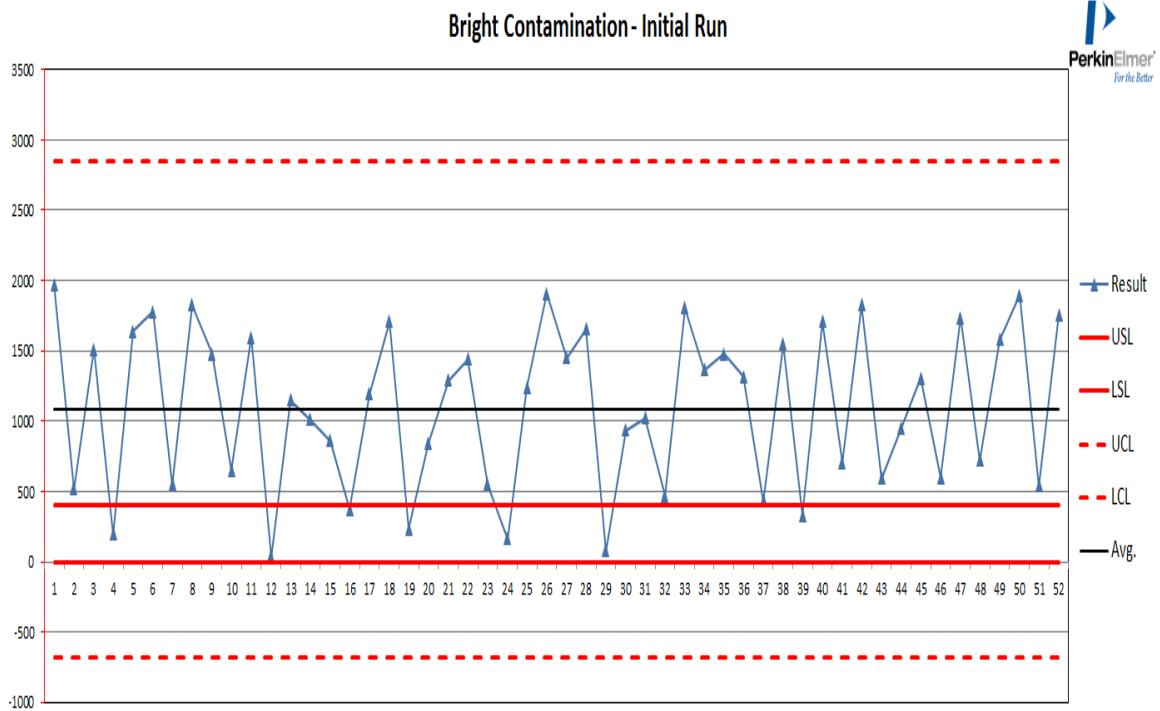


Figure 5-7 - Bright Contamination Run Chart - Initial Run

As we now know the number of occurrences for each failure mode and the serial number in which the failure mode occurred, the run chart can be further developed into a run chart showing the results of each failure mode, this is useful to determine the magnitude of each artefact failure. This is shown Figure 5-8. It can be seen that the artefact that fails by the largest magnitude is artefact 1 (stripes on the confocal disc, this is followed by artefact 2, 3 and 4 respectively.

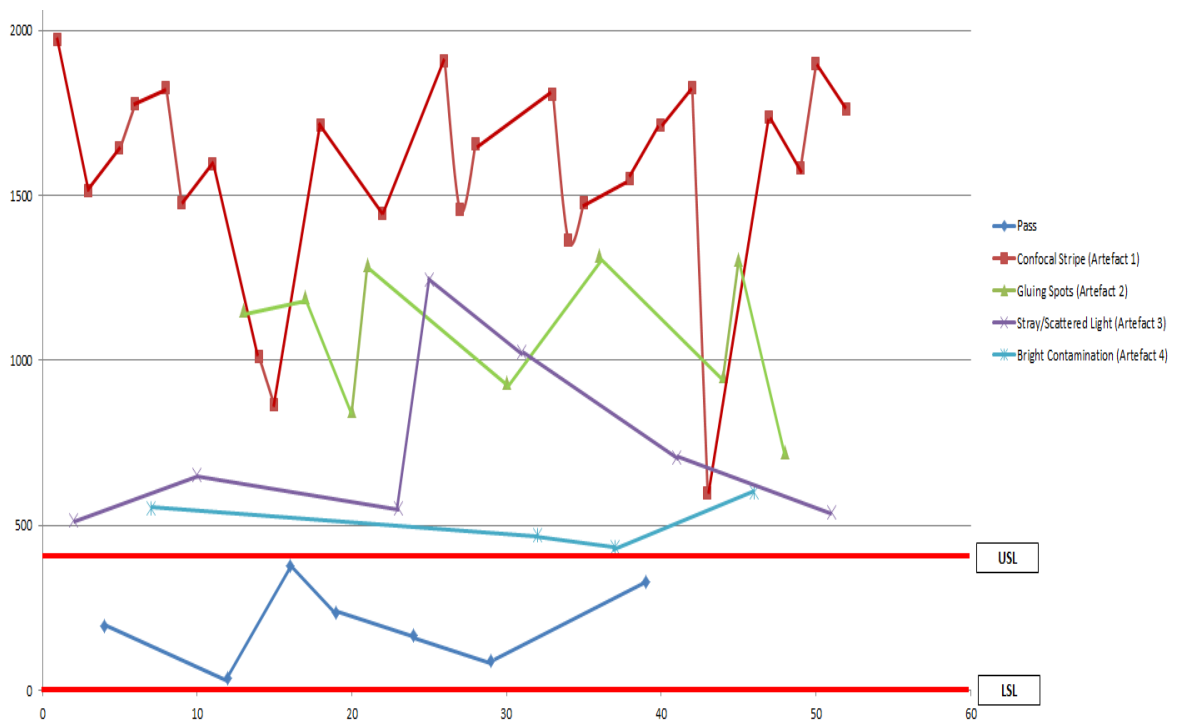


Figure 5-8 - Bright Contamination Run Chart - Artefact Magnitude

The run chart also shows the "Pass" results that are shown within the upper and lower specification limits. It can also be seen that 13 of the 20 failures due to artefacts 2, 3 and 4 are less than 1000 units of intensity; this raises a question with regard to the defined specification of 400 units. If the limit was raised to 1000 counts we would see a total decrease in downtime of 70.68 hours based on the rework hours measured per artefact. This can be seen in Table 5-3. This can be seen as a quick interim solution that can be implemented in parallel with the project, once the project is completed and the contamination under control the specification would be reviewed again.

Table 5-3- Rework Hours <1000 Units

	Rework hours	* Occurences <1000	Equals Total Hours
Artefact 1	7.40	2	14.80
Artefact 2	5.78	4	23.13
Artefact 3	6.35	5	31.75
Artefact 4	0.25	4	1.00
Total			70.68

As already discussed, the specification is defined in IAT by Hamburg R&D, loosening of the specification requires buy in from both the R&D team and the business unit leadership team. Unfortunately a proposal of changing the specification to <1000 counts was rejected due to the impact to customer satisfaction. Confocal images have been taken with various intensities of stripes to determine if a 1000 count stripe would be visible to the customer. It can be seen in Figure 5-9 and Figure 5-10 that 1000 count artefacts would be seen during use. A stripe of 600 counts is clearly visible in a low fluorescence sample; an image of this quality would be unacceptable for customers using the instrument for this specific application. The business unit and Hamburg R&D confirmed that 400units is the specification and that the only adjustments that would be made would be to hopefully tighten the specification over time.

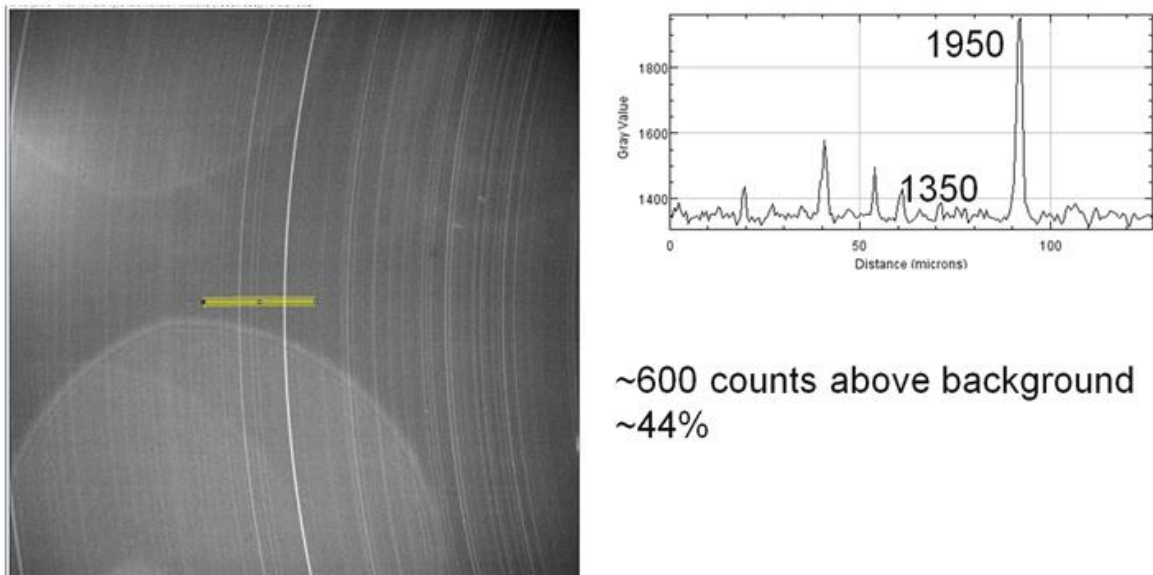


Figure 5-9 - 600 Count Confocal Stripe

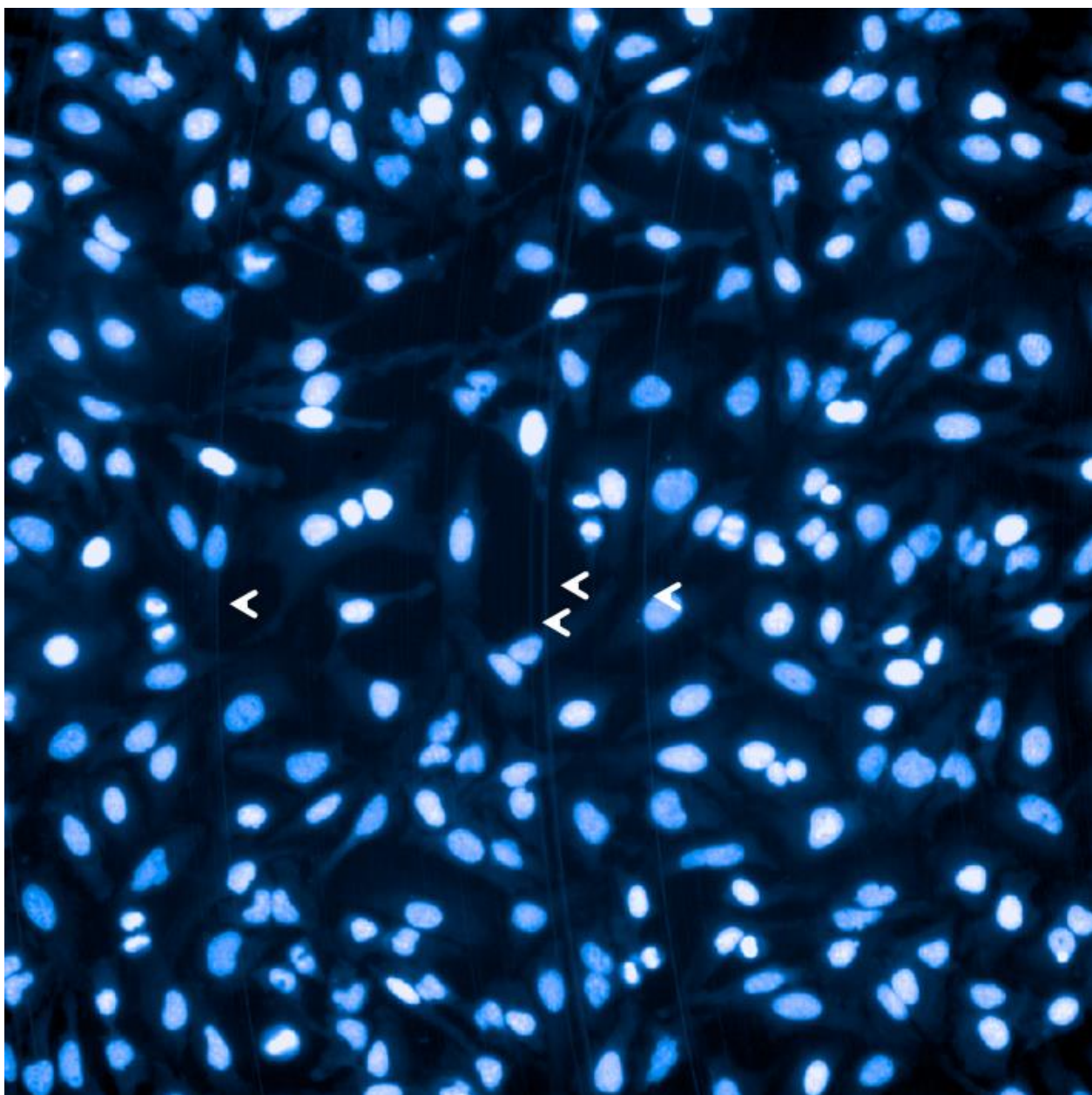


Figure 5-10 - 600 Count Confocal Stripe Imaged in Low Fluorescence Specimen

5.1.5. Environment - Dust

From the cause and effect matrix, dust from the working environment is seen as a big contributor to IAT contamination failures. There are a number of processes within the Dichromatic Wheel Assembly and Confocal Unit assembly that require the use of a class 1000 clean room or class 1000 laminar flow cabinet to perform the work. The reason for this is that any dust particles that land within the instrument Excitation light path can fluoresce resulting in bright contamination when running the Bright Contamination IAT test. To reduce exposure of the optical components to dust particle, any operations that require gluing or assembly of optical components are completed in a clean room environment where there is no exposure to particles of greater than 10um in diameter. A floorplan of the manufacturing area of the Operetta CLS can be seen in Figure 5-11. The areas identified by a green box show the Clean room locations within the manufacturing area. The areas highlighted in orange indicate the Sub Assembly build area, Instrument Main Build Area and the instrument alignment and IAT area.

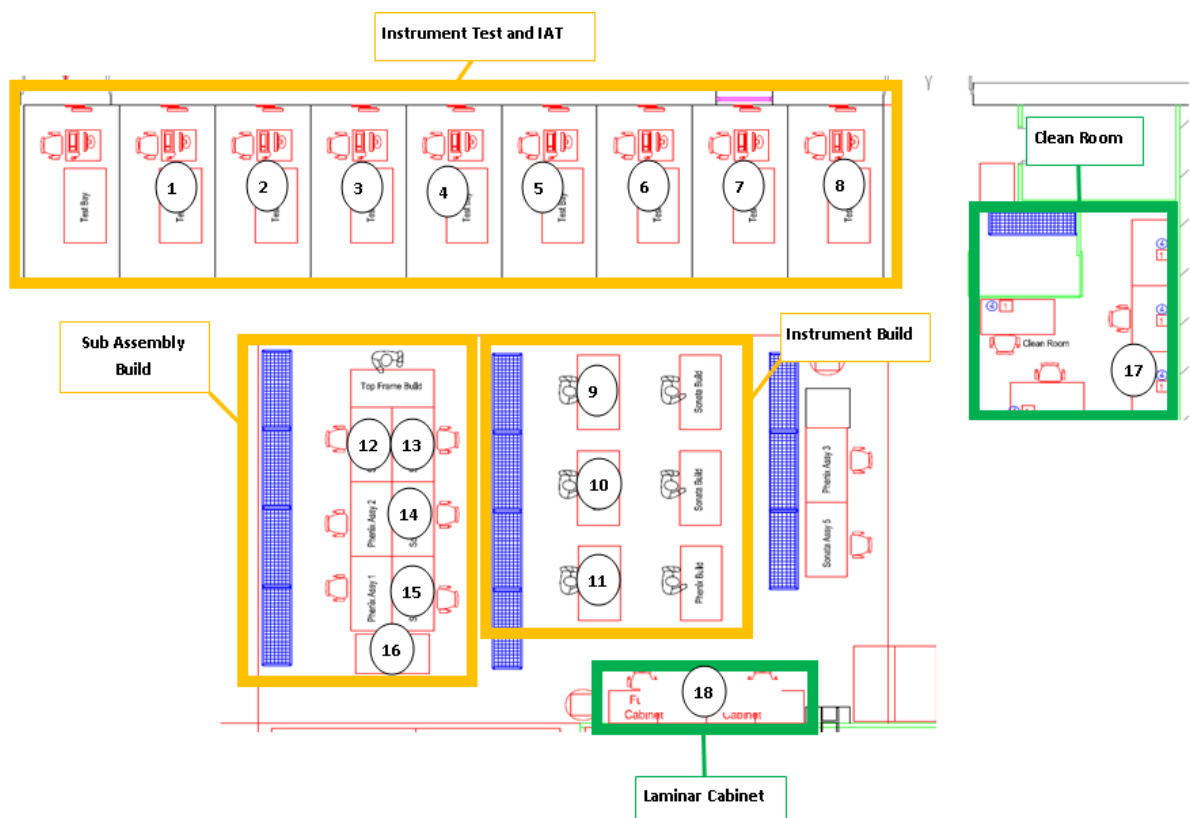


Figure 5-11 - Operetta CLS Manufacturing Floor Space

It can be seen that although there are key processes that require the use of a clean room to reduce dust exposure, the majority of the floor space is a standard working environment. With dust being a large contributor to the contamination failures it is important to understand the particle count within the clean room as well as the areas within the process that are outside of the clean room environment.

ISO14644-1 classifies environments by the quantity of particles that are counted of various sizes within a cubic metre of air. The particle size ranges from 0.5um up to >5um in size. For a class 1000 clean room classification the particle count must be less than 352000 for particles up to 0.5um. 83200 for particles between 0.5 and 1um, and up to 293 for particles >5um. The clean room classifications can be seen at the bottom of Table 5-4.

To determine the classification of the manufacturing environment, clean room and laminar flow cabinets, a particle counter can be used. This is a tool that is already used to verify monthly that the clean room is operating optimally. The Particle Counter is positioned at each of the key locations as indicated by the numbered circles in Figure 5-11. The results are then populated in the spreadsheet shown in Table 5-4. Conditional formatting has been applied to each cell in the table to indicate the classification if subjected to ISO14644. It can be seen that both the clean room and laminar flow cabinets operate as a class 1000 clean environment. The manufacturing floor space has a particle count that compares to a class 100000 clean room. Given that normal room air is a factor of 10 greater than this, the manufacturing floor space is considerably cleaner than standard air and cannot be considered as an unclean environment. If the environment needs to be upgraded to a class 1000 standard, considerable amounts of time and money would need to be factored in. The costs associated are outside of the costs factored for in the business case.

Location	Description	0.5um reading	1um reading	>5um reading
1	Instrument Test Bay 1	381574	128956	11694
2	Instrument Test Bay 2	300555	102719	19330
3	Instrument Test Bay 3	370203	116495	19711
4	Instrument Test Bay 4	298983	133547	21067
5	Instrument Test Bay 5	390510	159218	11823
6	Instrument Test Bay 6	348784	151833	20931
7	Instrument Test Bay 7	307580	131543	19441
8	Instrument Test Bay 8	365483	145966	20070
9	CLS Instrument Build 1	320590	115434	14818
10	CLS Instrument Build 2	346873	132935	8268
11	CLS Instrument Build 3	309754	129710	17350
12	CLS Sub Assembly 1	318606	130111	18876
13	CLS Sub Assembly 2	361309	130454	16366
14	CLS Sub Assembly 3	285008	133799	20869
15	CLS Sub Assembly 4	331747	145388	19948
16	Sub Assembly Test Bench	316524	120651	7352
17	Clean Room	11846	4513	170
18	Laminar Flow Cabinet	26733	4144	240

	Class 1000	35200*	8320*	293*
	Class 10000	352000*	83200*	2930*
	Class 100000	3520000*	832000*	29300*
	Room Air	35200000*	8320000*	293000*

* Figures extracted from ISO14644-1 Clean Room Standards

Table 5-4- Operetta CLS Manufacturing Area Particle Count

5.2. Confocal Unit Bright Contamination - Artefact 1

As discussed in the data collection plan, Microscope image data of the confocal disc has been collected for 10 confocal units over a 4 week period. The images have been acquired using a high power digital microscope to visually inspect the surface of the confocal disc at set points in the process.

1. **Process 1** - When removing the disc from the supplier packaging.
2. **Process 2** - Once the disc has been assembled into the confocal unit, prior to installing cover.
3. **Process 3** - Once removed from the instrument due to a bright contamination failure.

The sizes of the holes in the pinhole disc are 55um, as such, can be used as a reference for particle size, when collecting the images and analysing the number of particles the information has been split into two size categories - >55um and <55um. An overview of the collected data can be seen in Table 5-5. The missing data from "Process 3" is due to the instrument having no issues with bright stripes; therefore the confocal head was not removed for rework.

Table 5-5 - Confocal Disc Particle Count

Confocal Disc Serial Number	Process 1		Process 2		Process 3	
	<50um	>55um	<55um	>55um	<55um	>55um
P0197	0	0	1	0	17	6
P0198	0	0	3	0		
P0199	0	0	0	0	36	10
P0200	0	0	0	0		
P0201	0	0	2	0		
P0202	0	0	0	0	81	6
P0203	0	0	2	0	145	7
P0204	0	0	0	0		
P0205	0	0	1	0	151	9
P0206	0	0	2	0	173	7
P0207	0	0	1	0		

It can be seen that there are a low number of particles present on the confocal disc during process 1 and process 2. However, upon review of the confocal disk once removed from an instrument (process 3), the amount of particles has increased greatly. Samples of the images acquired using the digital microscope can be seen in Figure 5-13 and Figure 5-12. It is evident that the material supplied and installed into the confocal unit is clean and free from particles. However, the confocal disc received back after failing on the instrument has a large number of particles on the surface.



Figure 5-12 - Confocal Disc (As received from supplier) Microscope Image 25x Optical Zoom

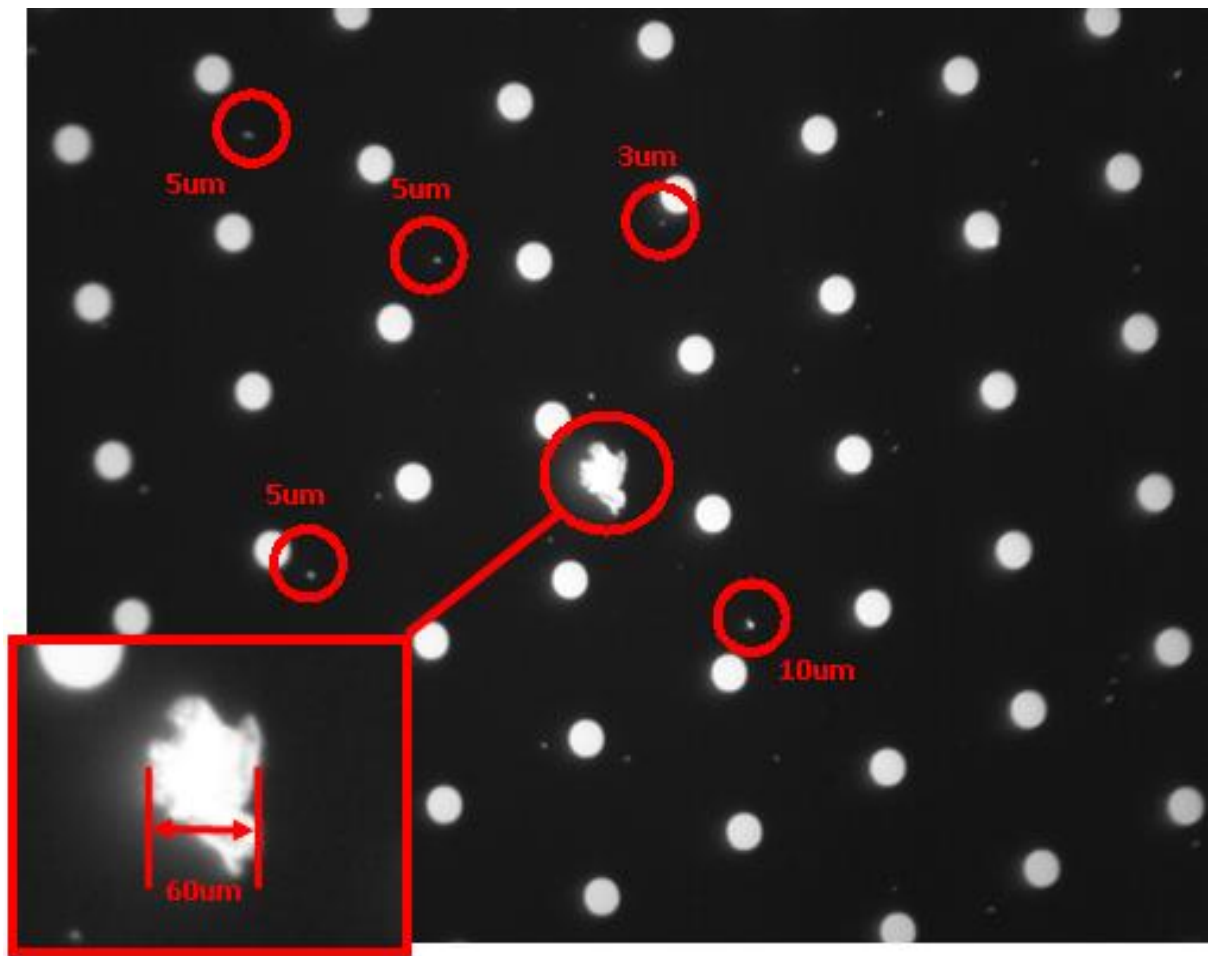


Figure 5-13 - Confocal Disc (Removed from instrument) Microscope Image 25x Optical Zoom

Data has been collected to determine if the confocal unit contamination increases over time. As discussed in the "Define" phase, there have been three customer complaints for contamination resulting in confocal unit replacements. Bright contamination Images have been taken daily on a single Operetta CLS over a period of two week, images have been taken using the same instrument parameters as defined in the IAT specification with no other adjustments made. The data from the acquired images has been categorised into two headings, stripes that are greater than 400 units in intensity and stripes that are less than 400 units in intensity. The results of this experiment can be seen in Figure 5-14.

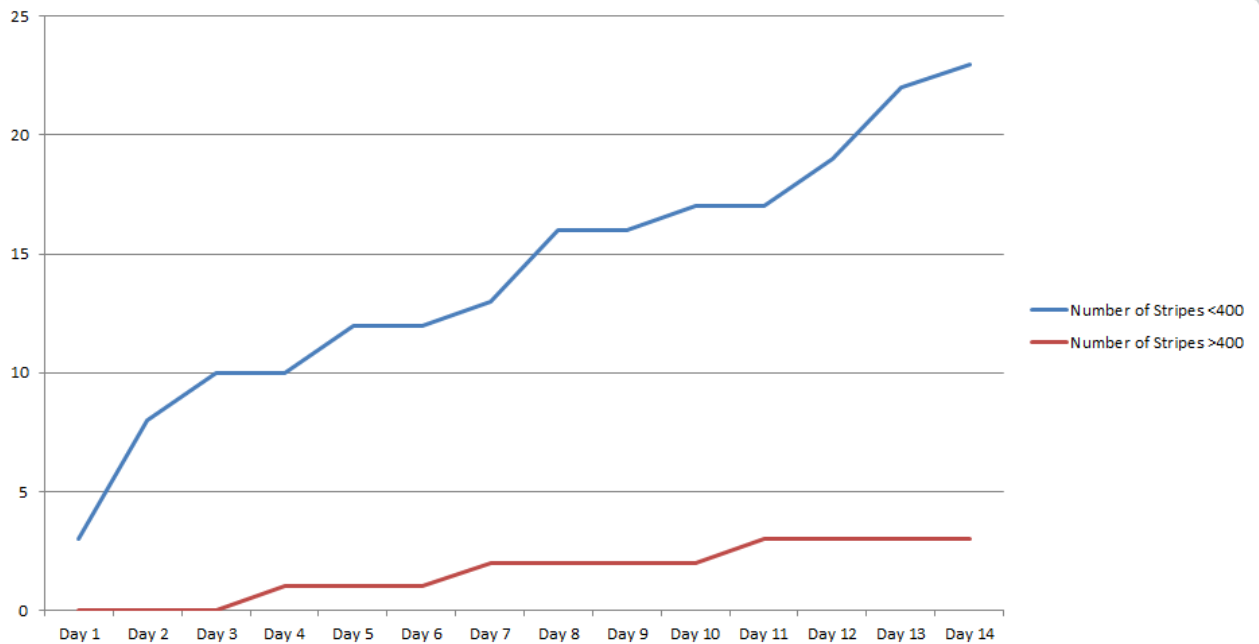


Figure 5-14 - Confocal Unit Contamination Accumulation

It can be seen that there is an increase in contamination over time within the confocal unit. The instrument used for this test would pass the IAT criteria if performed during the first 3 days. Only after the third day does the instrument fail the IAT specification. Additionally, the rate in which the accumulation is increasing does not appear to be slowing down suggesting that the contamination will continue indefinitely. This accumulation of contamination poses a significant risk to the customer with regard to image quality but also to PerkinElmer with regard to customer satisfaction, warranty costs and brand reputation. The analysed data confirms the validity of the three warranty complaints from customer sites where confocal stripes are impacting the image quality resulting in replacement of the confocal unit.

The differences seen in image quality on the test instrument during the 2 week test period can be seen in Figure 5-15. It can be seen that on day 1 there are a small number of stripes present increasing significantly by day 24.

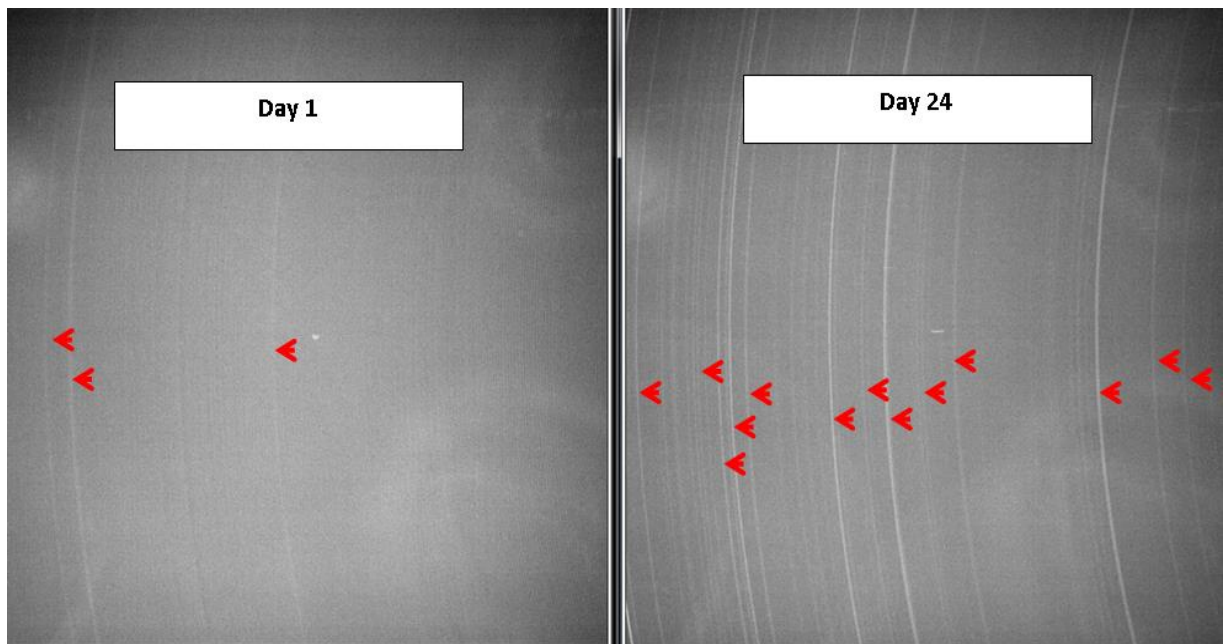


Figure 5-15 - Contamination Images: Day 1 (Left), Day 24 (Right)

5.2.1. Cause and Effect Diagram

To identify and verify the root causes of the confocal unit bright contamination, a brainstorming exercise with all members of the DMAIC project team and Hamburg R&D has been performed to discuss the causes of bright the bright stripes from the analysed data. From the brainstorming exercise, a cause and effect diagram has been generated focussing in on the key inputs that are seen as direct contributors to the bright contamination, confocal unit stripes. The completed cause and effect diagram can be seen in Figure 5-16.

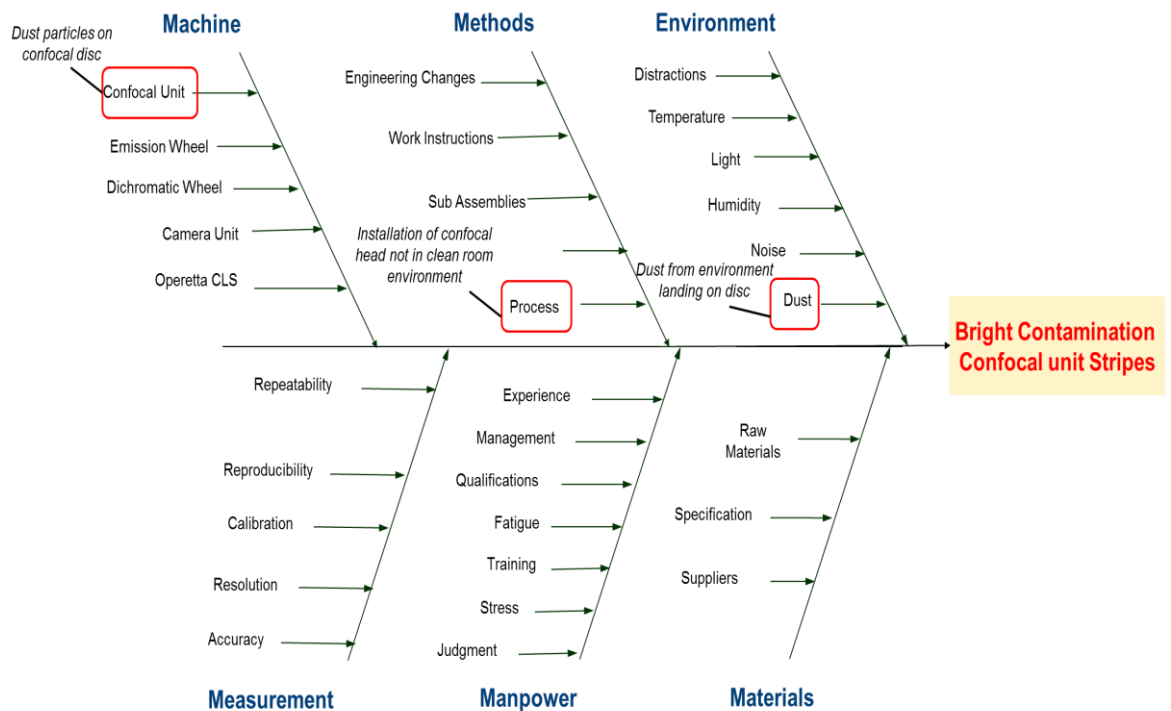


Figure 5-16 - Cause and Effect Diagram: Confocal Stripes

From the cause and effect diagram, three critical areas have been highlighted as critical inputs that will help verify the root cause:

1. **Confocal Unit: Dust on the confocal Disc** - There is dust present on the confocal disc when running the bright contamination test. These particles are not present during assembly of the confocal head and accumulate over time once leaving the clean room environment to be installed in the manufacturing environment.
2. **Process: Confocal head installation** - The confocal head is manufactured in a clean room environment but installed into the instrument in an environment that is not free of particles.
3. **Dust: Manufacturing Environment** - Manufacturing environment is the equivalent of a class 100000 clean room, although not considered dirty when compared to standard air it has far more particles than the class 1000 clean room.

5.2.2. 5 Whys

The 5 Whys is a tool used in the Analyse phase of the six sigma DMAIC methodology used to help identify the root cause of a problem and to help determine the relationship between different root causes. By repeatedly asking the question "Why" the root cause of a problem can be identified as the questions is asked to each of the symptoms. Although the technique is named "5 Whys" this is not a rule, to establish the root cause may take fewer or more than 5 times to succeed. (ISixSigma, 2018). From the brainstorming exercise used to construct the cause and effect diagram, the 5 whys seen in Figure 5-17 was also developed.

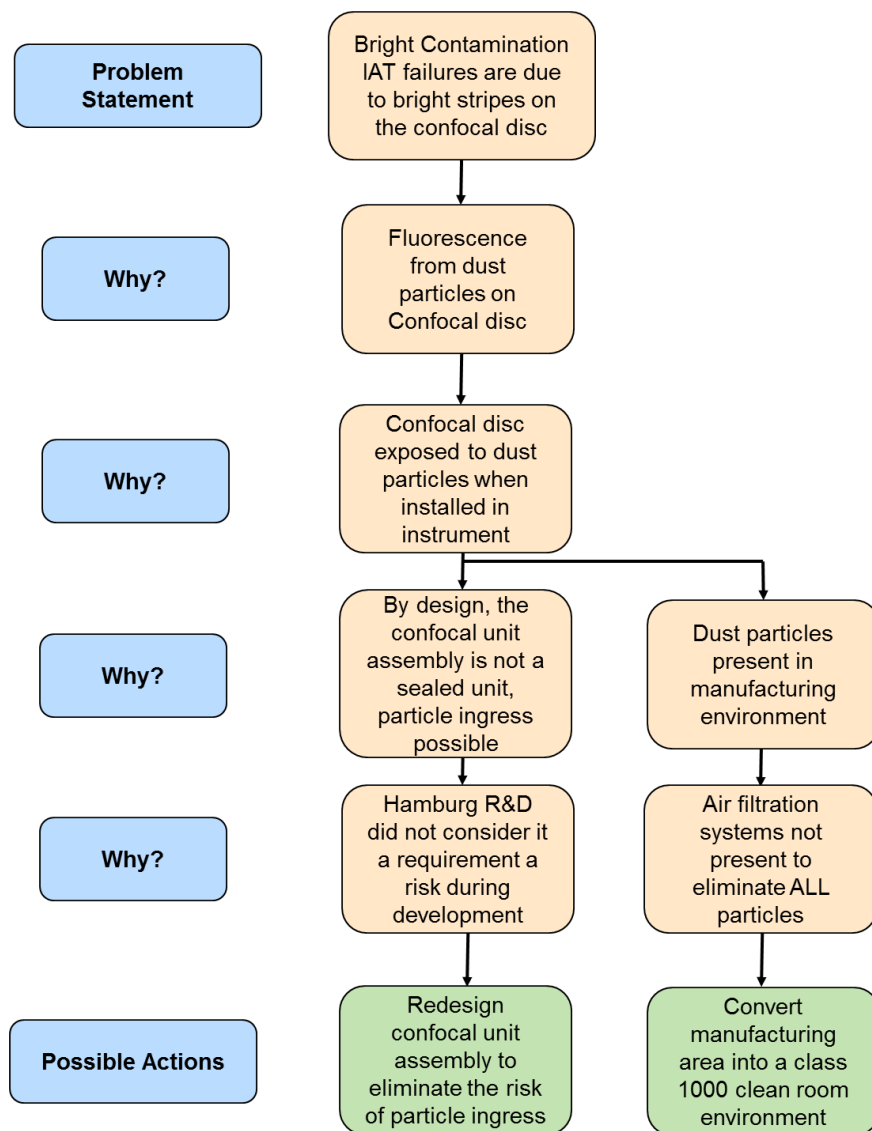


Figure 5-17 - 5 Whys: Artefact 1

Dust on the confocal disc has been established as the reason for the confocal stripes that result in an IAT failure for bright contamination. This is due to the ingress of dust particles into the confocal unit assembly. Upon review of the confocal unit design it is clear that there has been no design consideration given to eliminating the risk of dust particles. This has been confirmed by Hamburg R&D who stated that at the time of the design, little thought was given to contamination on the confocal disc. As the rotation speed of the disc is 1000rpm, the risk of particles adhering to the surface during use was deemed minimal (Thews, 2017). As such the confocal unit design has two large openings at the front and rear of the assembly; this is the pathway of the excitation and emission light through the confocal disc. A cross section of the confocal unit can be seen in **Error! Reference source not found..** This shows the direction of the excitation light denoted by a purple arrow and the large openings denoted with two red circles.

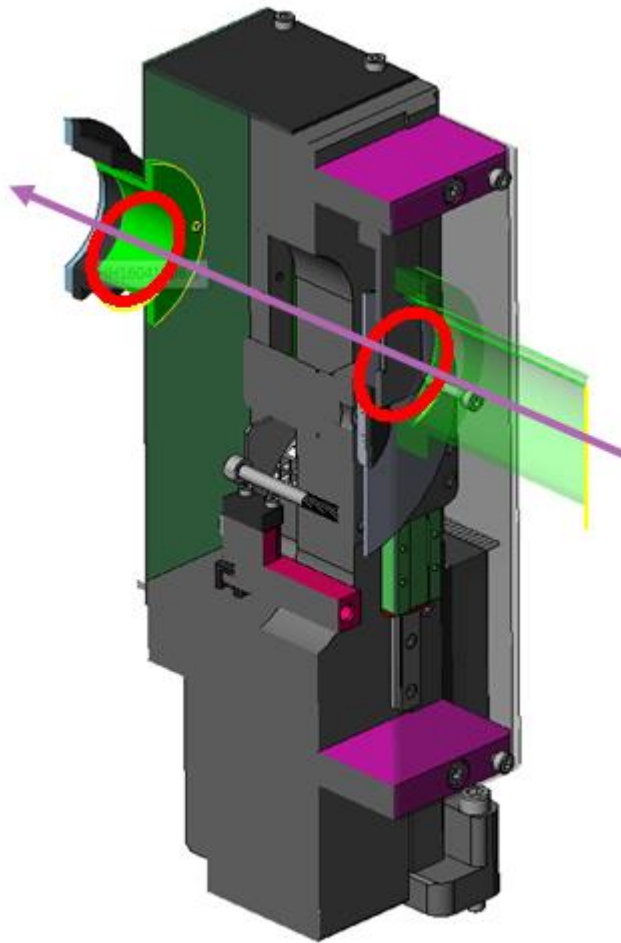


Figure 5-18 - Confocal Unit Cross Section

Further tests by Hamburg R&D have concluded that the rotation of the disc results in a vacuum effect within the confocal head, the rotation of the disc draws particles in from the environment through the openings in the confocal unit. When the disc is not spinning the particles land on the disc resulting in the bright contamination artefacts seen.

5.3. Dichromatic Wheel Assembly Bright Contamination Artefact 2

As discussed in the data collection plan, three key measures are required to help determine the root cause of the bright contamination from the dichromatic wheel assembly. The first measure was to perform a visual inspection of the dichromatic mirrors under the microscope once removed from packaging, bonded in Dichromatic Wheel, and again once removed from instrument. It has since been calculated via the Pareto analysis that only 1 hour of downtime

has been contributed to dust particles or defects on the dichromatic mirrors. As such this measure is not deemed necessary to analyse as the variable has a small influence on the bright contamination artefacts seen. A quick visual inspection of a sample of ten dichromatic mirrors concluded that the mirrors are clean from contaminants from the supplier and during assembly, once installed in the instrument; dust particles were evident on the dichromatic filter surface. It has been discussed during the project that dust on the optical components in the excitation pathway will fluoresce when excited. However, this does not seem to be as critical for the dichromatic mirror as we know that dust in this position has resulted in only one hour of downtime in 2017. Discussions with the Hamburg R&D team in particular, Elmar Thews regarding this topic explained the reason for this phenomenon. The optical path of the operetta CLS has three focal points located at the confocal disc, the objective lens and the camera sensor as shown in Figure 5-19.

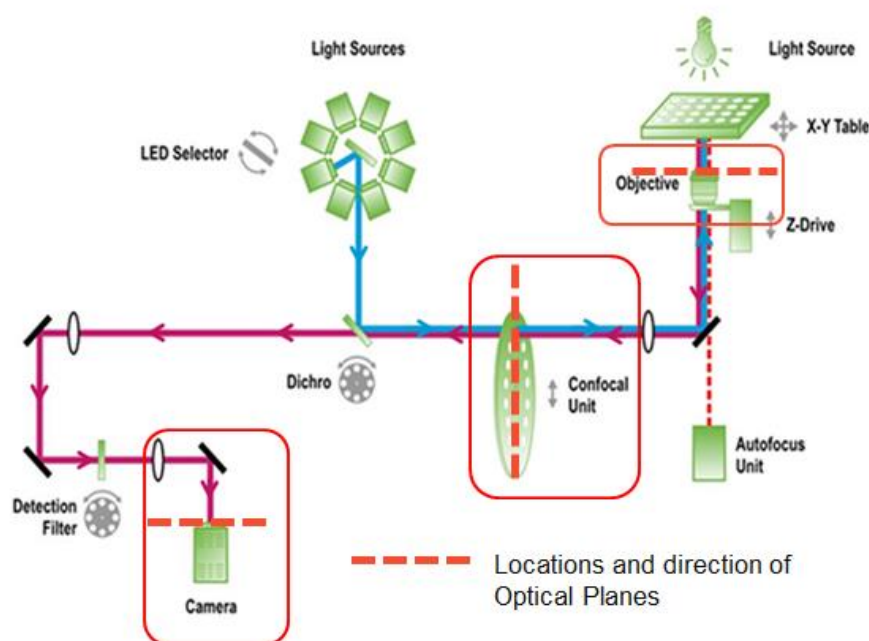


Figure 5-19 - Operetta CLS Focal Points

A focal point is a point of convergence of the excitation and emission beam. Dust particles at the focal points are therefore in focus and sharp at these positions when viewed on the camera. As such, any dust particles at a focal point will fluoresce under excitation and appear as small dots, sharp and bright in nature. Dust particles outside of the focal points, whilst still

fluorescing, will appear as large out of focus and less intense artefacts when viewed by the camera. To prove this theory a baseline image has been taken with a clean confocal disc but multiple dust particles on the dichroic wheel as shown in Figure 5-20, once captured a 25um dust particle was positioned on the confocal disc and an image taken without the disc spinning, this can be seen in Figure 5-21. All particles are ~ 20um to 50um in diameter when measured on the surface of the components. However, it can be seen that the particle on the dichromatic mirror is greater in diameter when imaged on the CLS but has less intensity. Physically the particles on both the dichroic mirror and confocal disc are similar in size; it is the position in the system relative to the focal plane that determines the influence to bright contamination hence proving the proposed theory.

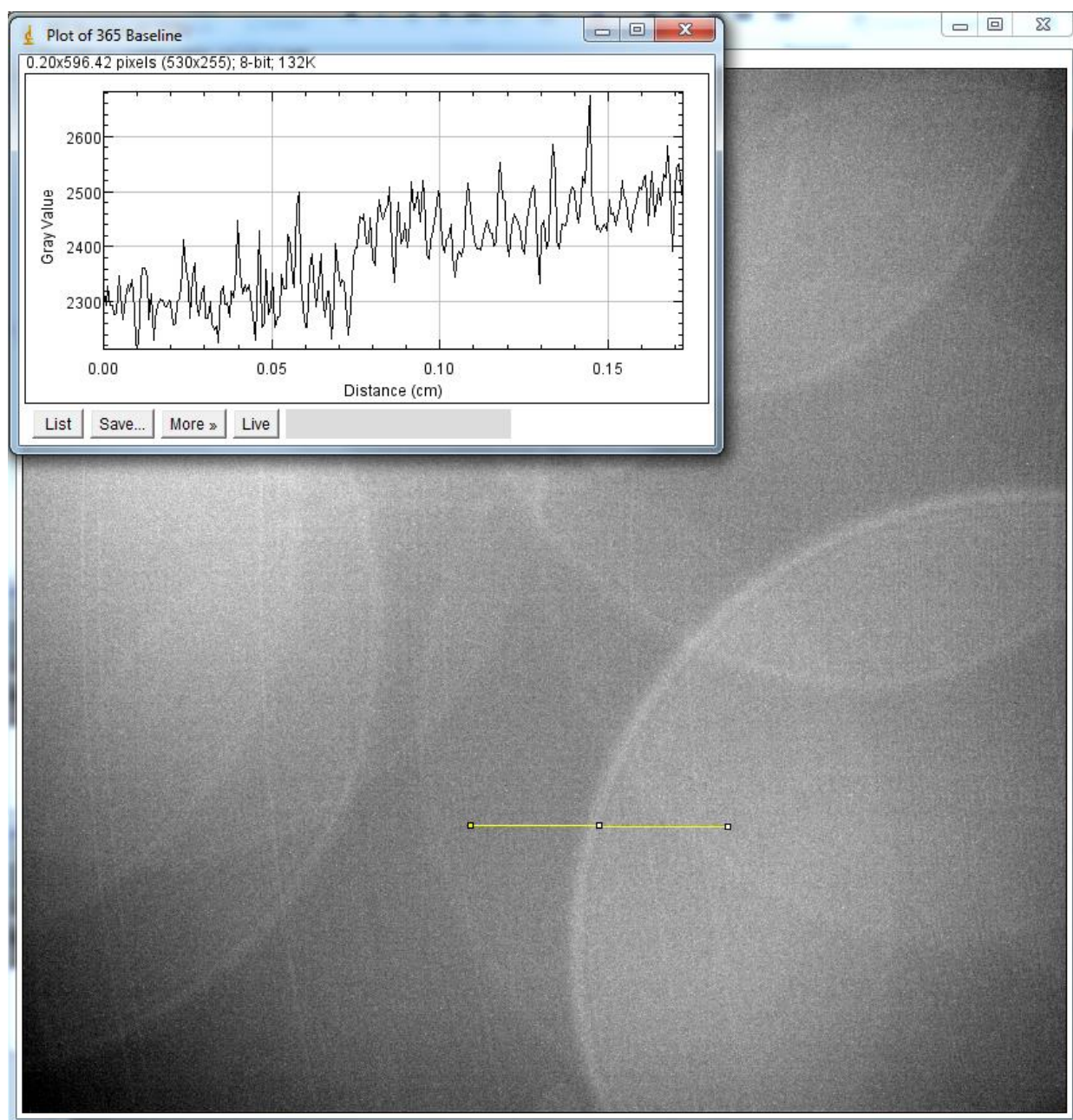


Figure 5-20 - Dichromic mirror contamination, multiple dust particles from 20-50um seen as large bright circles, mean intensity difference from background ~ 200 counts

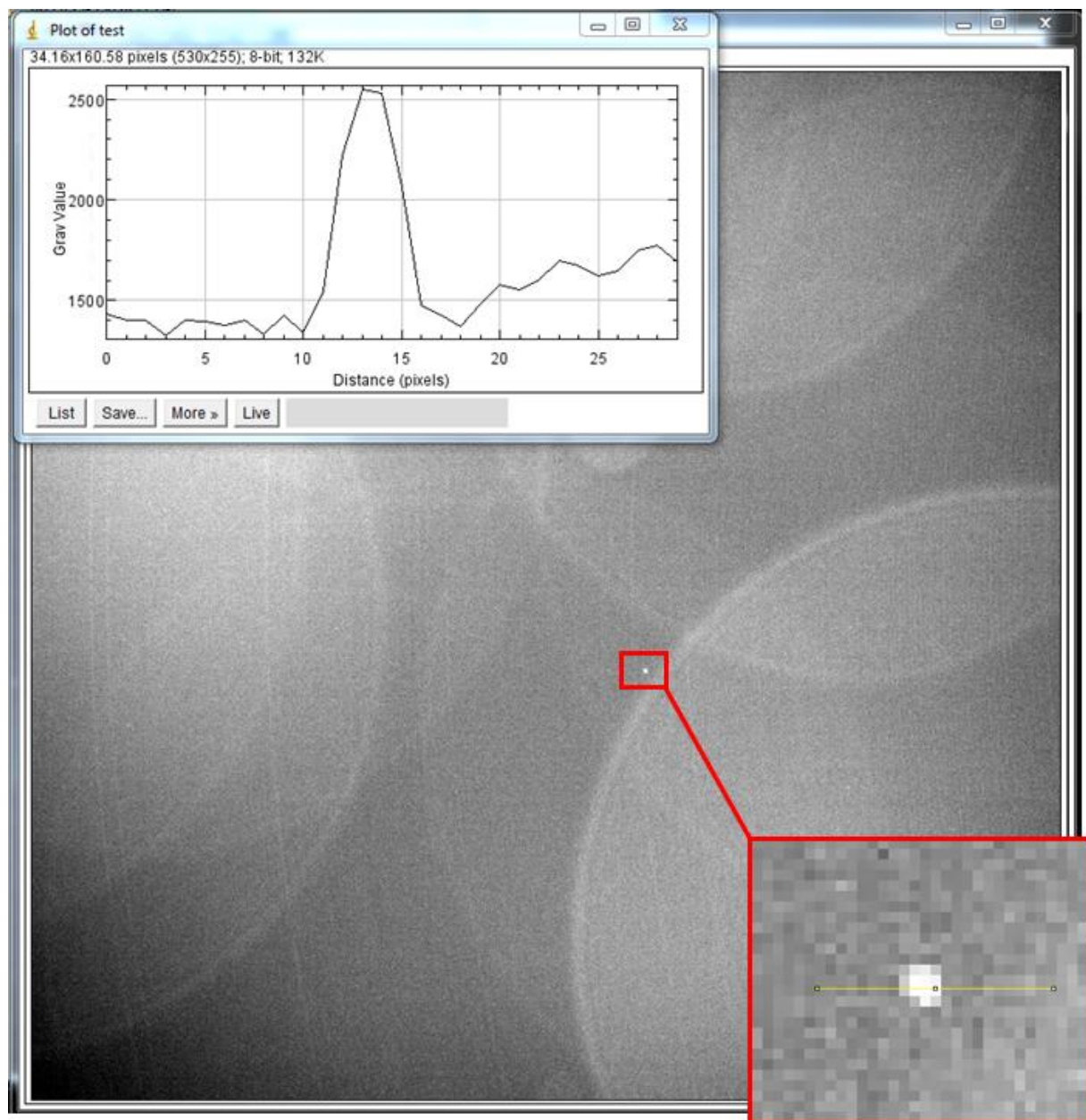


Figure 5-21 - Addition of 25um dust particle on confocal disc, seen as small sharp particle. Mean intensity difference from background ~ 1000 counts

5.3.1. Correlation Analysis

The second dichromatic wheel assembly measure identified in the data collection plan was to take microscope images of the gluing spots used to secure the dichromatic mirrors to the wheel. This will be used to determine if there is a relationship between the size of the gluing spot and the magnitude of the bright contamination artefacts seen. Figure 5-22 shows the gluing process steps:

Step 1 - Take a small quantity of DELO Duopox DK839 two part adhesive, and mix thoroughly until homogenous with a smooth consistency.

Step 2 - Make a small bead of glue at the end of a fresh paperclip by inserting the end of the paperclip into the glue mixture.

Step 3 - fasten gluing fixture to dichromatic wheel and position each of the dichromatic mirrors into the correct location. Apply the bead of glue to the edge of the dichroic (Not the glue pad). The glue will run down onto the glue pad under its own weight. The glue must not be applied to the glue pad first as there is a risk of the dichromatic mirror lifting from the surface of the wheel, this will cause a tilt in the optical path causing issues when aligning the system. Once applied leave 24 hours to cure.

Step 4 - Pictorial reference of the optimal amount of glue once cured. It can be seen that the glue (highlighted in green) has contact with the gluing pad, the dichroic edge and also between the surface of the gluing pad and surface of the dichromatic mirror

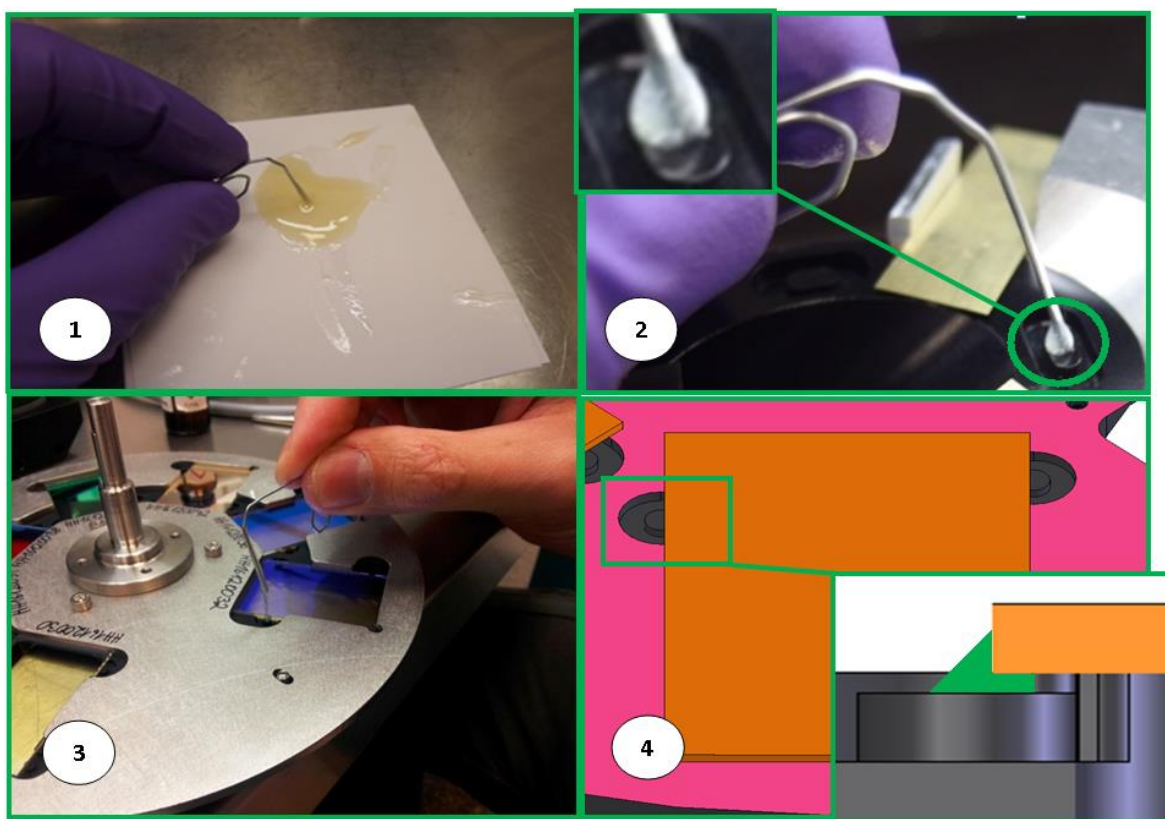


Figure 5-22 - Dichromatic Mirror Gluing Process

Figure 5-23 shows different gluing quantities, the left hand image shows too much glue that is perceived to cause fluorescence in the system as it is exposed directly to the excitation light. Whilst the right hand image shows too little glue whereby there is a risk of the optics not bonding correctly and breaking away during use.

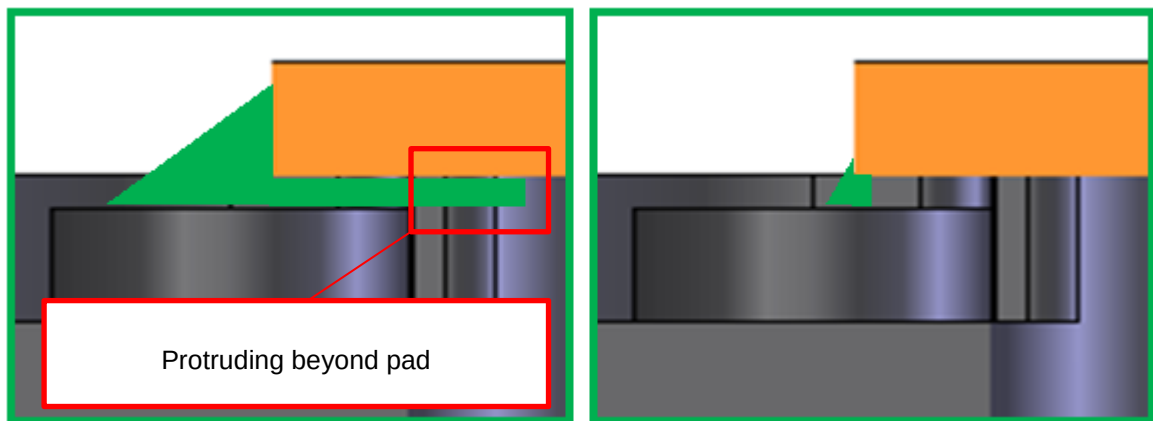


Figure 5-23 - Gluing Quantities, Right Too Much, Left Too Little

The dichromatic wheel has three gluing points per dichromatic mirror. Each gluing point has been designed to sit 300 microns below the surface of the dichromatic wheel on which the optic bonded. This ensures that the mirror is positioned perfectly parallel to the wheel. Considering there are eight separate dichromatic mirrors, any deviations to this position can cause problems during alignment as each mirror has its own separate channel causing overlay issues on the camera. The 300 micron gap negates this risk and allows glue to travel between the surface of the mirror and wheel resulting in a larger contact area. The perception from the Hamburg R&D team and the technicians is that excessive glue travels too far down the mirror surface resulting in an overhang of glue that protrudes further than the gluing pad and into the excitation path, examples of this can be seen in Figure 5-24. The left hand image shows the side of the dichromatic wheel assembly that faces the excitation light, it can be seen that there is glue evident on the dichromatic mirror protruding from the gluing pad. The right hand image shows optimal gluing whereby there is no glue protrusion into the excitation light. To quantify the significance of this protrusion, Images have been taken using a microscope of 10 separate dichromatic wheel assemblies each with 7 dichromatic mirrors, 70 images in total. Of the 70 images 12 were picked for review based on the magnitude of the bright contamination artefact seen during test. The twelve images range from 100 units of intensity to 1200 units. Each of the microscope images has been analysed to determine the amount of glue protruding from the gluing pad, a correlation study can then be conducted to quantify the relationship between the size of the gluing spot and the intensity of the contamination.

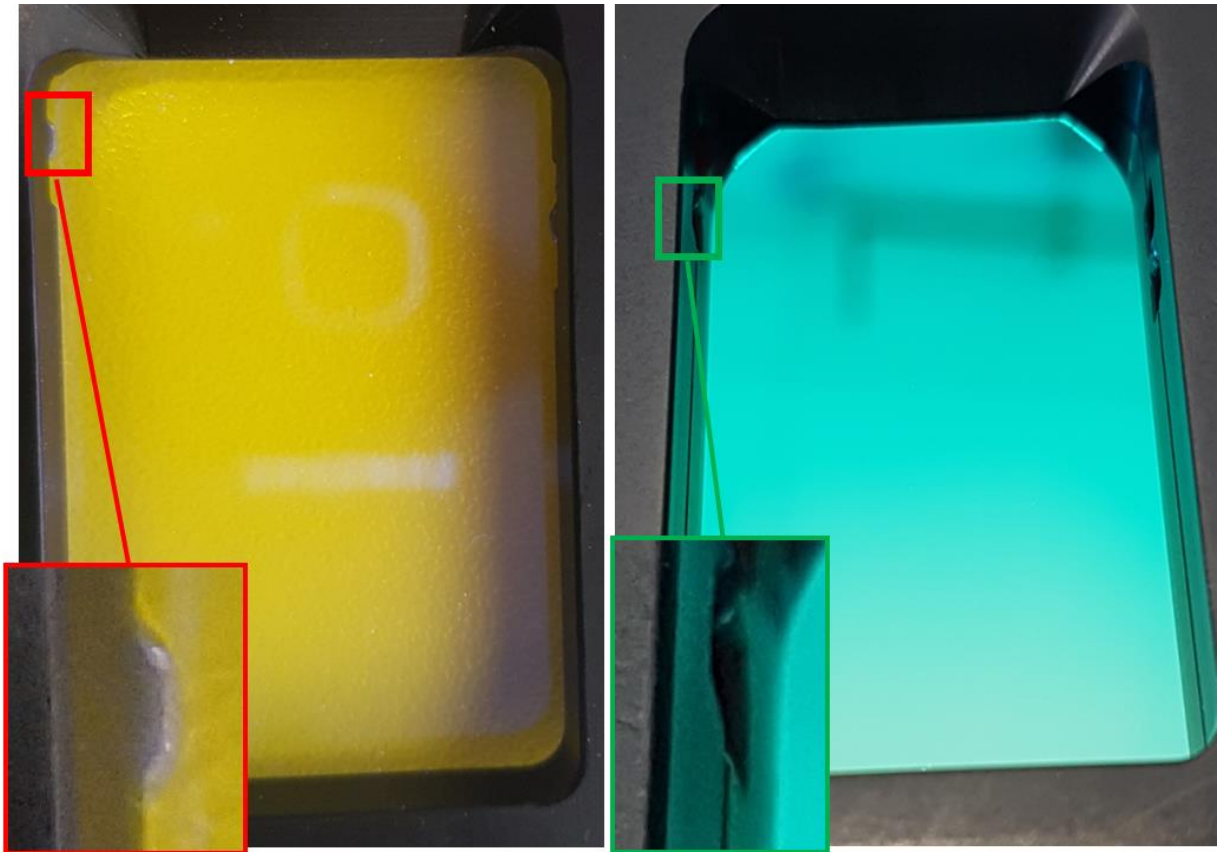


Figure 5-24 - Glue Protrusion

Correlation is a term used to indicate if there is a relationship between the values of different measurements (George, et al., 2005). There are three possible outcomes of a correlation study:

1. A positive correlation - where the higher the value of one measurement the higher the value of the other measurement.
2. A negative correlation - where the higher the value of one measurement the lower the value of the other measurement.
3. No correlation - where there is no relationship to either measurement.

When performing a correlation analysis it is important to understand that "correlation does not imply causation" meaning that even if the correlation study is positive, it may be a coincidence that there is a relationship between the two measurements and that both variables are related to an underlying variable not included in the study.

To perform the analysis a scatter plot must be generated for two variables, to determine the correlation between the gluing spots and the intensity of the bright artefact the following variables were measured and inserted into a excel spreadsheet:

Variable X = Measured intensity of bright contamination artefact

Variable Y = Dimension of protrusion as measured using a microscope, measured from the edge of the wheel to the edge of the glue.

The scatter plot generated for the measured variables can be seen in **Error! Reference source not found.**

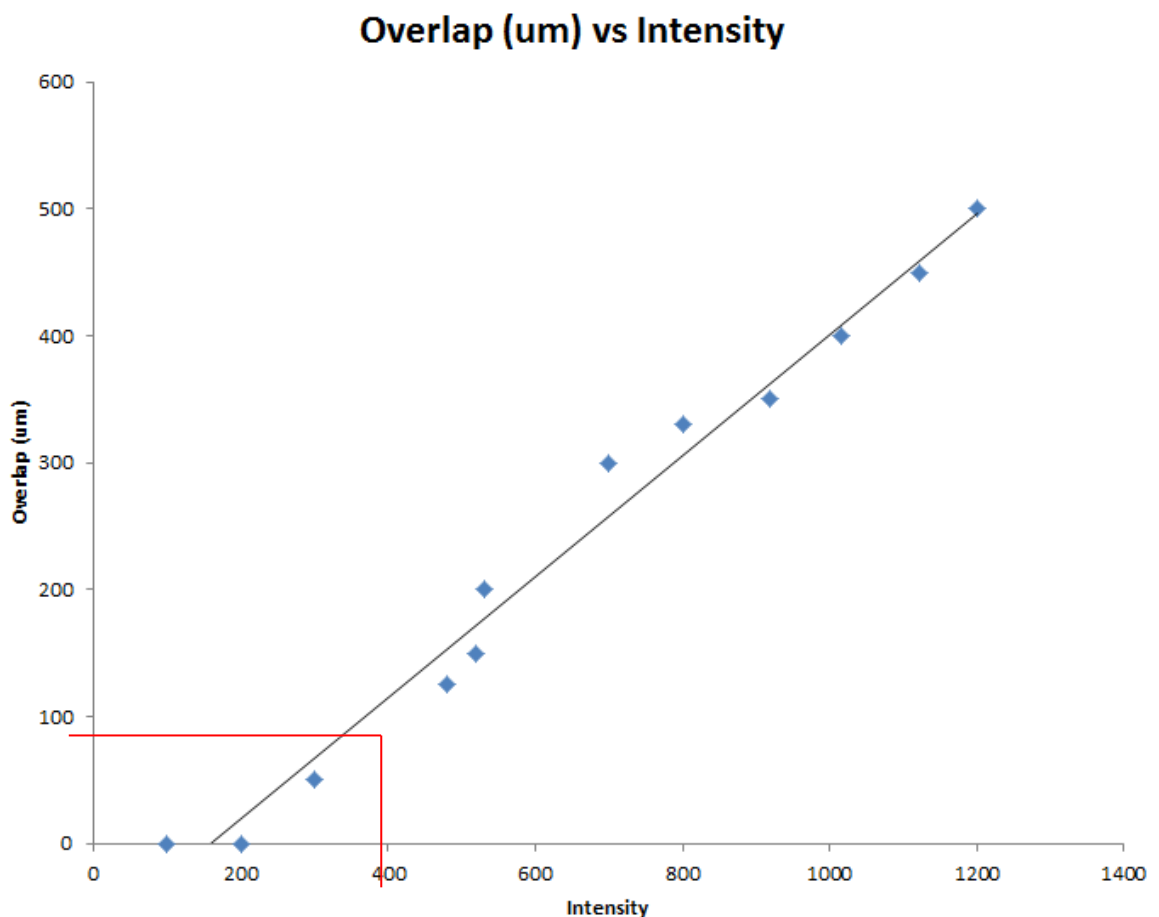


Figure 5-25 - Correlation Analysis - Overlap (um) vs Intensity

It can be seen that there is a strong positive correlation between the size of the overlap and the intensity of the artefact. Additionally the IAT failure occurs only when the size of the gluing spot protrudes more than 100 microns into the illumination path. To quantify the strength and direction of this relationship the Pearson Correlation Coefficient can be used, this helps determine if the relationship is statistically significant.

To calculate the correlation coefficient (r) the following formula is used:

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}}$$

Where:

$x_i - \bar{x}$ is each x value (intensity) minus the mean of x

$y_i - \bar{y}$ is each y value (Overlap um) minus the mean of y

Interpretation of correlation coefficient

When:

R = -1 there is perfect negative correlation

r = 0 there is no correlation

$r = 1$ there is perfect positive correlation

$r = > +0.65$ strong positive relationship

$r = < -0.65$ strong negative relationship

The raw collected data used for the calculations discussed can be seen in Appendix C. Using the data collected for the study:

$$r = \frac{689563}{\sqrt{1443985 \times 335273}}$$

$$r = 0.991$$

The correlation coefficient for the measured data is 0.991 this shows a near perfect positive correlation between the size of protrusion and the intensity of the contamination. It is also important to note that the artefact due to the glue spots is seen in nearly every image captured to some degree, but only a percentage fail the IAT criteria of 400 units.

5.3.2. 5 Whys

With support from the correlation analysis, root cause can be determined using the 5 why technique shown in Figure 5-26 . The root cause for the bright contamination seen is due to glue present in the optical path that fluoresces under excitation. The reason for the glue being in the image field is due to the current design of the gluing spots, allowing the glue to travel along the surface of the mirror into the excitation path.

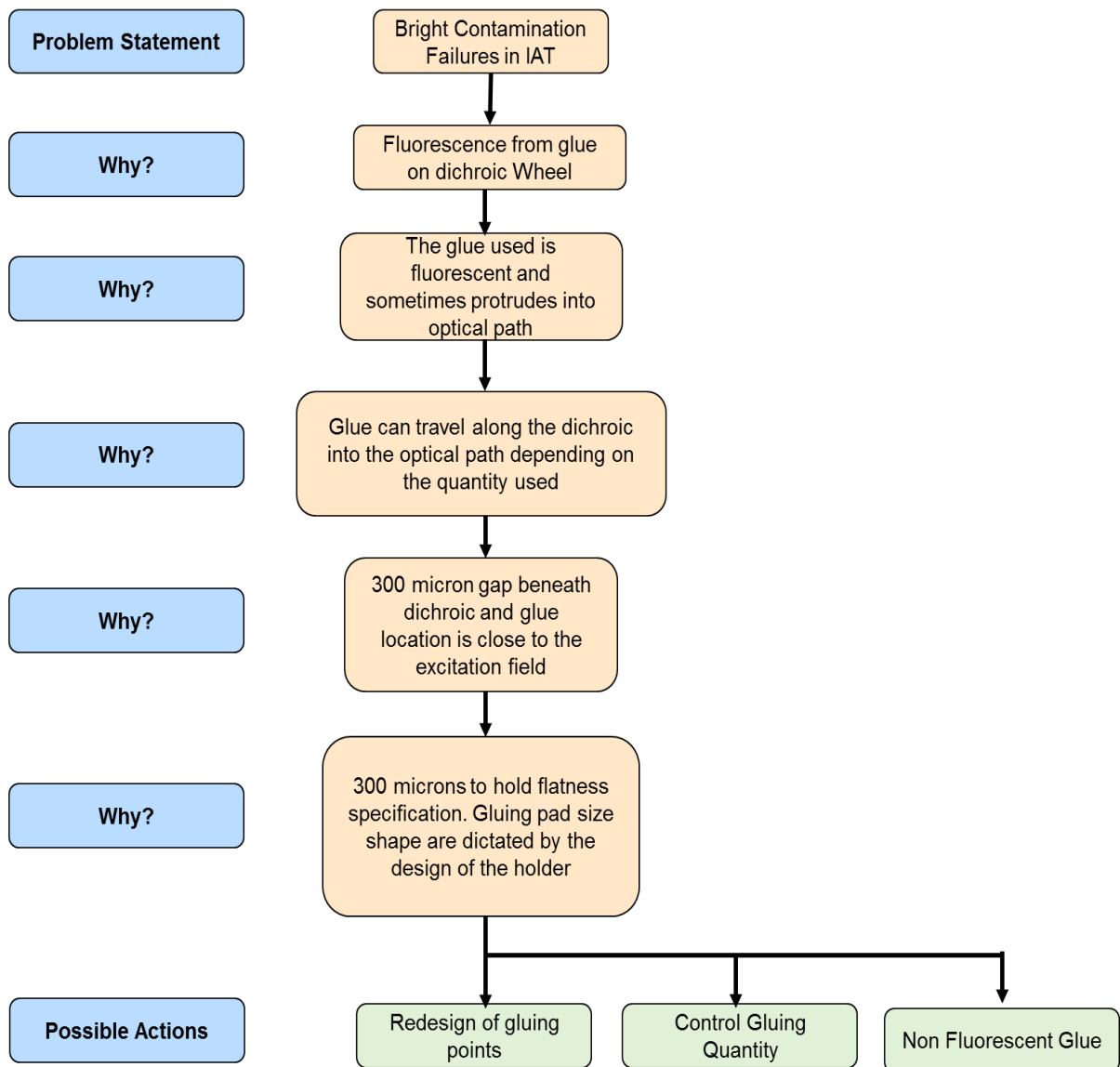


Figure 5-26 - 5 Whys: Artefact 2

5.4. Dichromatic Wheel Assembly Bright Contamination Artefact 3

Artefact 3 has already been established as stray light scattered from the exposed dichromatic edges. This is a flaw in the original design of the dichroic wheel where the dichromatic edges are exposed directly to the emission light and stray light in the system. An interim solution has been defined by Hamburg R&D as per modification document HXM6000015, Being an interim solution, the current modification method must be considered as downtime rather than standard process. The interim solution was only intended to be implemented for a short period of time whilst an effective permanent solution could be determined. Unfortunately, due to limited resource at the design site, the engineering change request for a redesign to eliminate stray/scattered light is still open. All instruments shipped using the modification method are shipped under a concession that allows deviation from the standard process to apply the modification. The concession is valid until the design and incorporation of the engineering change.

The first stage in the modification process is to apply finnapon decklak (a type of black glue) to the outer edges of the dichromatic mirrors using a syringe. Care must be taken to avoid contact with the top surface of the mirror as cleaning becomes difficult once applied. The purpose of this modification is to restrict light entering the dichromatic mirror from the exposed edge. a dichromatic mirror is manufactured from a substrate that is coated in a material that either blocks or transmits light at specific wavelengths, as the exposed edges are "cut" edges where the mirror has been cut to shape there is no coating applied therefor all wavelengths of light can be transmitted. The coating acts as a barrier, stopping any transmission of stray light into the dichromatic mirror. The application process can be seen in Figure 5-27.

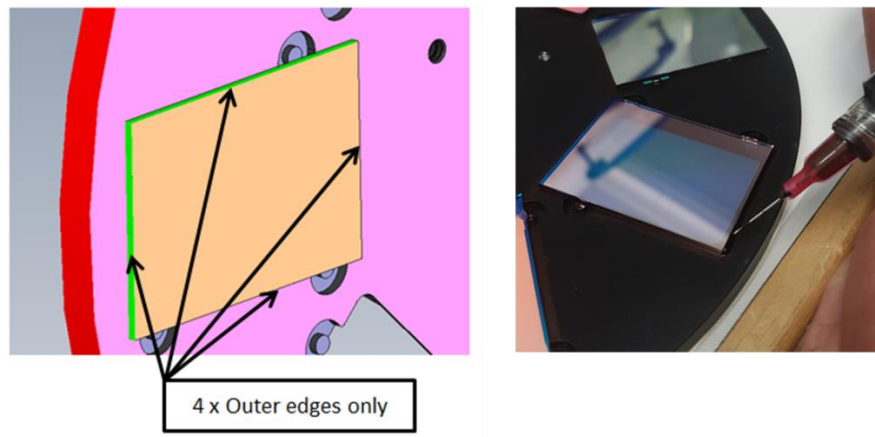


Figure 5-27 - Application of Finnapon Decklak

The next step is to fill the voids around the gluing pads with soudabound (Black silicone) this stops excitation and emission light from passing the dichromatic mirror. As the wheel is mounted at 45 degrees to the incident excitation beam, the light floods the aperture completely, light can pass through the gaps and onto the camera sensor. Sealing these voids with black silicone reduces the risk of stray light. The location and application of the soudabound can be seen in Figure 5-28.

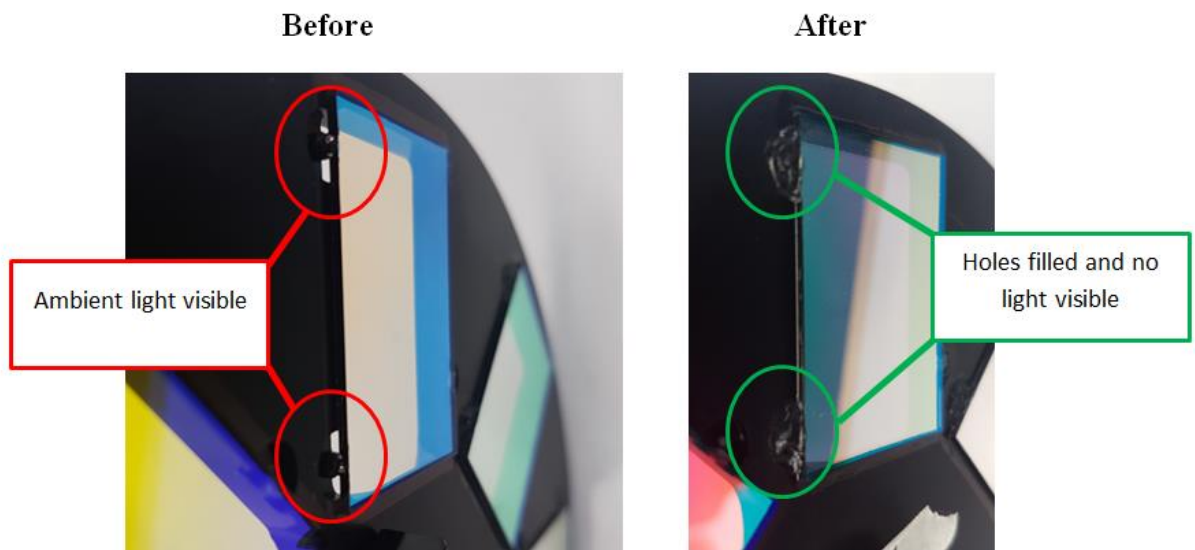


Figure 5-28 - Application of Soudabound

The modifications, including curing time take approximately four hours to complete as shown in Figure 5-29 . This extends the manufacturing process of the dichroic wheel assembly from 26 hours to 30 hours. If we were to consider this process as downtime, an additional 216 hours can be attributed for artefact 3 (52 instruments x 4 hours). This is in addition to the 45.45 hours of downtime measured when reworking this part due to a contamination failure totalling 261.45 hours. Reviewing images of the dichromatic wheels that were removed to be reworked once failing in an instrument resulted in small defects in the finapon coating and pinholes in the soudabound coating, after reapplication of the modifications the assemblies passed the IAT criteria with no issues. To remove this process entirely via design improvements could save a total of 261.45 hours in manufacturing.

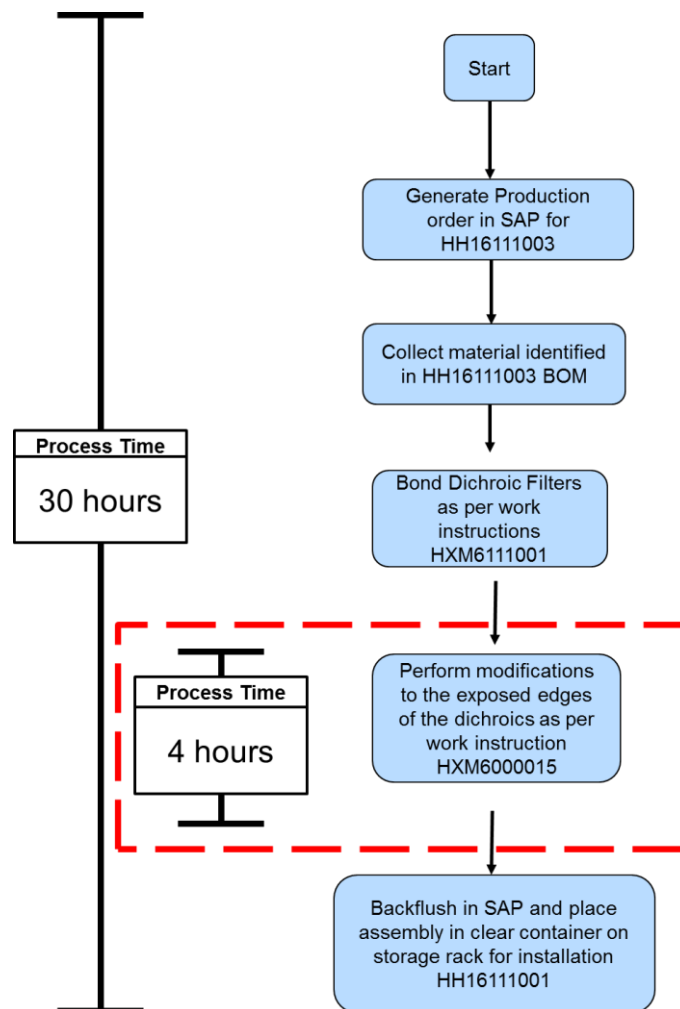


Figure 5-29 - Dichroic Wheel Bonding - Detailed Process Map

6. Chapter 6: Improvement Phase

6.1. Improvement Phase

The next phase in the DMAIC process is the "Improve" phase, with the analysis complete, a much greater understanding of the process has been obtained. The improve phase focuses on improving the current process by developing and selecting solutions based on the conducted analysis. An overview of a number of the tools and the roadmap to a successful "analyse" phase can be seen in Figure 6-1

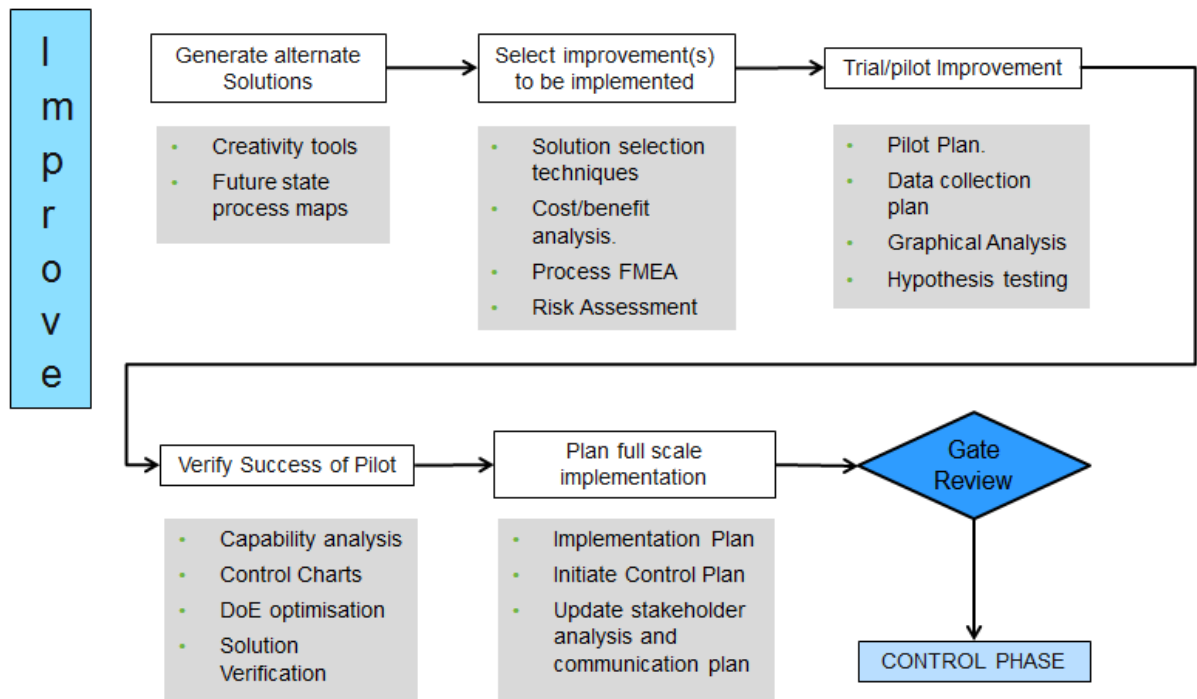


Figure 6-1 - Improvement Phase Roadmap

6.2. Confocal Unit Assembly

6.2.1. Ideation Session

An ideation session with the complete project team allows free thinking idea generation to determine possible solutions to help eliminate dust particles from the confocal disc. The aim of the session is to generate ideas regardless of cost or practicality. George et al (2005) state that "The more potential solutions available to explore, the more opportunities for uncovering ideas for improvements". Once the ideas have become exhausted the generated ideas can then be narrowed down to find a suitable solution to the problem. The generated ideas from the ideation session can be seen in Figure 6-2.

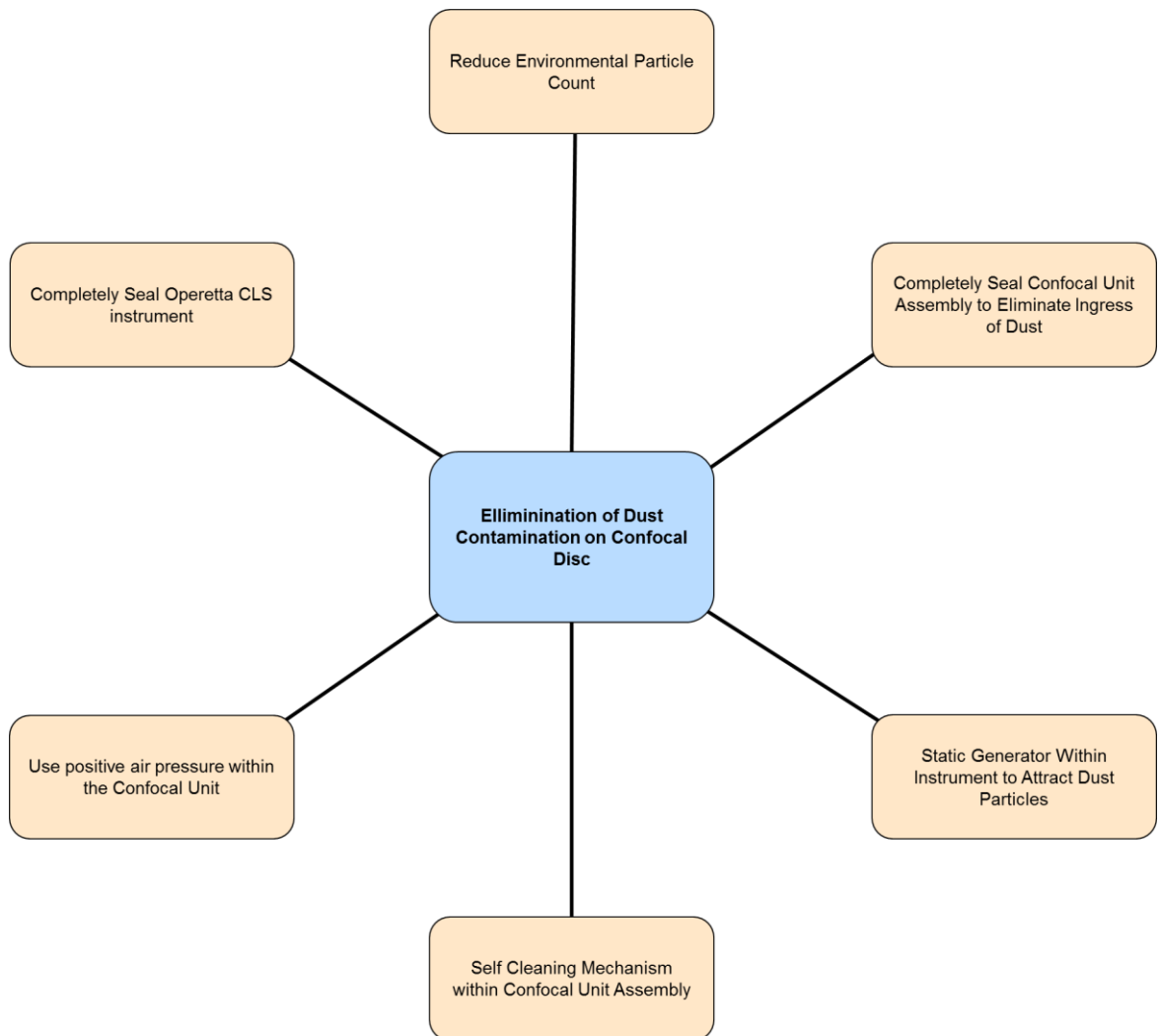


Figure 6-2 - Confocal Unit Ideation Session

Idea 1 - Reduce Environmental Particle Count

As already seen during the data analysis, the particle count in the manufacturing area is far greater than that of the clean room environment, hence the reason for the confocal discs being clean in the clean room and becoming contaminated in the manufacturing area. Although this sounds like a plausible solution, the costs involved would be high. The cost of the small clean room where the confocal unit is manufactured is approximately £120,000, additional to this are the maintenance costs to keep the filtration system performing optimally. However, this is not the biggest drawback to this solution, although we can control the environment at PerkinElmer, we cannot control the environment at customers sites, as proven by the data analysis, accumulation still occurs over time. To require a class 1000 clean room at a customer's site in order for them to use the Operetta CLS is not a feasible solution to the problem.

Idea 2 - Sealing of the Confocal Unit

Dust on the confocal disc has been defined as the reason for the confocal stripes that result in an IAT failure for bright contamination. This is due to the ingress of dust particles into the confocal unit assembly. Sealing of the confocal unit Entry points is seen as a relatively simple solution that can eliminate contamination completely given a method to test for contamination prior to assembly into an instrument.

Idea 3 - Static Generator

Addition of a static generator to the confocal unit assembly may help reduce the amount of particles that land on the disc. The static generator can attract the dust particles to minimise the quantity of particles within the assembly. Whilst this may capture a large quantity of the particles, additional maintenance cost may need to be considered for when the generator is saturated, also if failure occurs a large quantity of dust will be free to move inside the confocal head.

Idea 4 - Self Cleaning Mechanism

A self-cleaning mechanism such as a small brush that runs across the surface of the disc while it rotates has been considered as a potential solution. The cost of such a design is minimal. However, there is a risk of additional contamination from the fibres of the brush over time. Additionally once the brush is saturated, particles will become free to move within the confocal unit. As with the static generator, maintenance may be required.

Idea 5 - Positive Air Pressure Within the Confocal Assembly

Clean room environments use positive air pressure to ensure clean air flows out of the room rather than contaminated air flowing in. A novel approach to reducing the contamination is to use the same positive air pressure theory and apply it to the confocal unit. By applying a constant feed of filtered air into the confocal unit the risk of contamination entering is greatly reduced. There are two methods of applying positive air pressure, electrical from a fan or pneumatic from a pressurised gas supply. The risk of contamination increases to the same level as the current state if either system fail, is turned off or needs replenishing.

Idea 6 - Sealing the Operetta CLS Assembly

Completely sealing the entire instrument has also been discussed. This introduces its own issues where contamination already in the system is now completely sealed into the system it also does not negate the risk of contamination entering the confocal unit during transport to and from the instrument. Additionally, during alignment of the instrument, all covers are removed thus exposing the entire instrument to the ambient environmental contamination.

6.2.2. Payoff Matrix

To help determine the optimal solution to develop, a payoff matrix can be used. A payoff matrix is a two by two matrix where each of the potential solutions is ranked by the effort involved to implement and its impact to the problem seen. It can be seen in the Payoff Matrix generated in Figure 6-3 that three of the six solutions are deemed to have a high impact on the problem with only one of these solutions requiring relatively low effort to incorporate. The location within the matrix of each of the solutions has been determined by the project team as a result of the ideation session.

BENEFIT	High	Seal Confocal Unit	- Positive Air Pressure in Confocal Unit - Static Generator
	Low	Reduce Environmental Particle Count	- Seal Operetta CLS - Self Cleaning Mechanism
		Low	High
		EFFORT	

Figure 6-3 - Payoff Matrix - Confocal Unit

From the payoff matrix it can be seen that "sealing of the confocal unit" will give a high benefit with relatively low effort. This idea will be taken forward for development. The high effort - high benefit ideas may still be revisited if the selected idea generates negative results.

6.2.3. Proposed Solution

The objective of the confocal unit design is to eliminate the risk of bright contamination due to fluorescent particles on the confocal disc, It has been determined through the DMAIC process that the confocal unit must be assembled and tested within a clean room environment to significantly reduce this risk. Once tested the unit must not be exposed to any dust particles. The current design of the confocal is not a fully sealed unit and allows particles to enter the assembly in two locations, this results in rework activities from the technician to clean the confocal disc to pass the IAT criteria but also allows additional contamination once the IAT criteria has been achieved.

As seen in Figure 6-4, the first particle entry location is through the confocal tube located at the rear of the confocal assembly, the tube has been designed with a 45 degree angle cut that sits in front of the dichroic wheel, and a small notch cut out adjacent to the angle, allowing the light from the LED wheel to hit the Dichromatic mirror before passing through the confocal unit. The confocal tube at the rear (marked dust particle entry side) is exposed to the environment offering no sealing to the assembly. The tube at the front, although open, is sealed once assembled and installed in the instrument as it is fully located against the lens plate creating a sealed barrier so can be ignored during the concept phase.

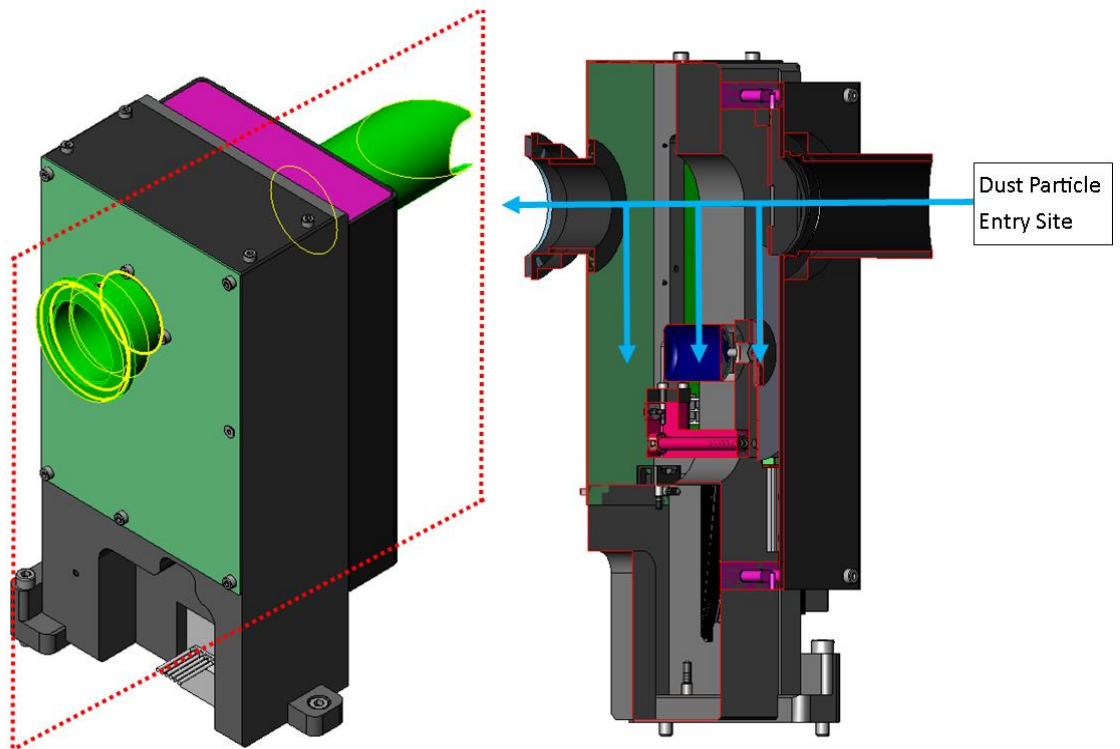


Figure 6-4 - Confocal Unit Assembly Section View

The second particle entry site is located at the confocal disc cover sheet as seen in Figure 6-5. The cover sheet has been designed to protect the disc but also allow easy access for service and repair. The part is manufactured from sheet metal that has been formed at a 90 degree angle; the 90 degree form produces a radius at the bending site that is compensated for in the mating face with a chamfer. The join of the chamfer from the mating block, and radius from the sheet metal part results in a small opening that can allow dust particles to enter.

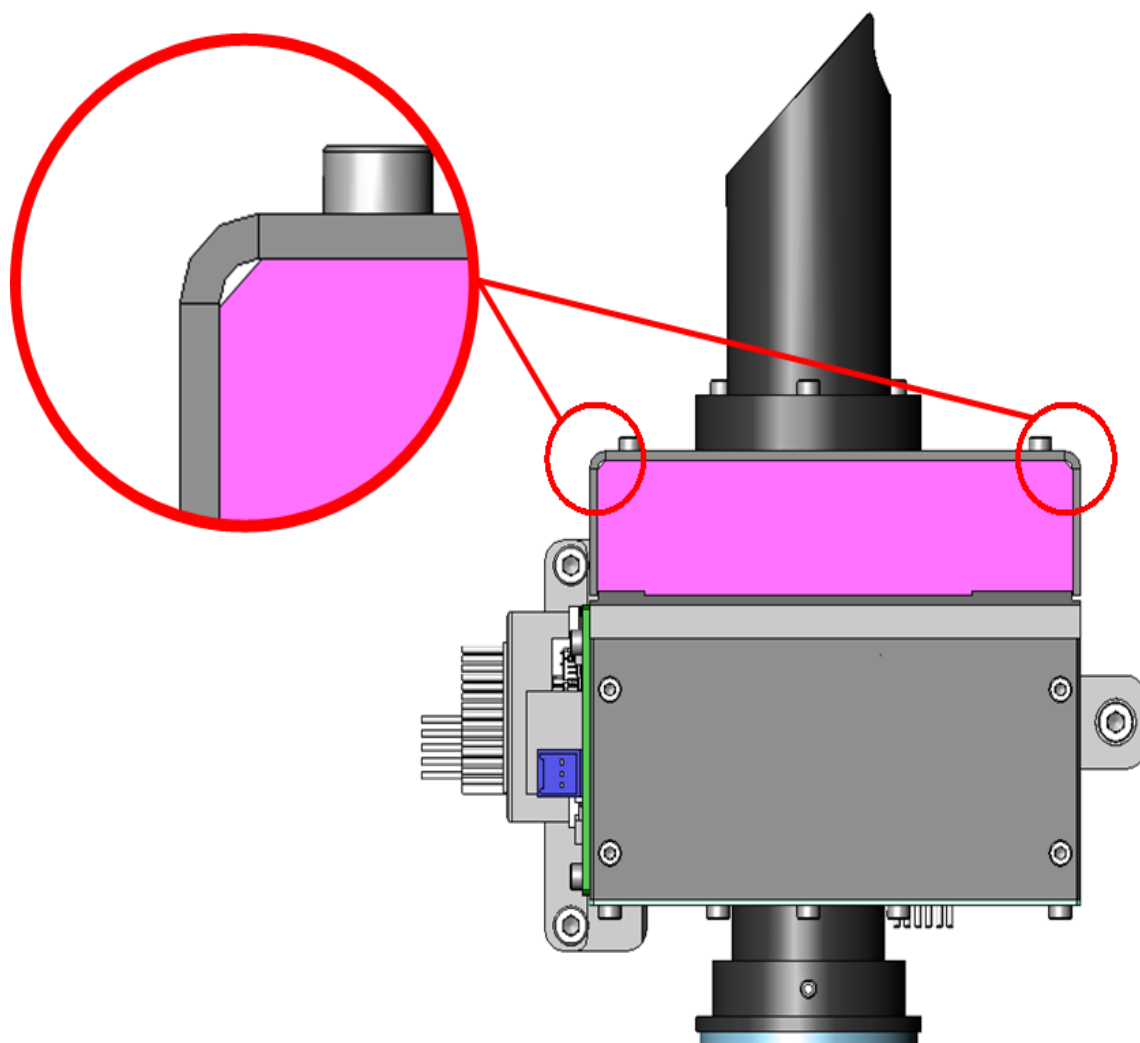


Figure 6-5 - Confocal Dust Cover

The new design must eliminate all possible entry points for dust particles, ensuring a completely sealed unit. The design must also allow retrospective installation on existing confocal unit assemblies currently in use on instruments at customer sites.

6.2.4. Existing Products

The design of the Operetta CLS is based on the Opera Phenix. Sharing approximately 80% of the same components the Operetta CLS is a smaller, less expensive version of the Opera Phenix. Both instruments use confocal spinning disc technologies for confocal imaging. However the Opera Phenix confocal head is much larger due to the Phenix using four separate

cameras for higher throughput imaging. The Opera Phenix confocal head has been designed as a completely sealed unit to eliminate the risk of dust entering design space, as such the rework hours due to contamination for the Opera Phenix is zero. To achieve this, it can be seen in Figure 6-6 that transparent windows have been designed into the system to seal the openings required for excitation and emission light to pass through.

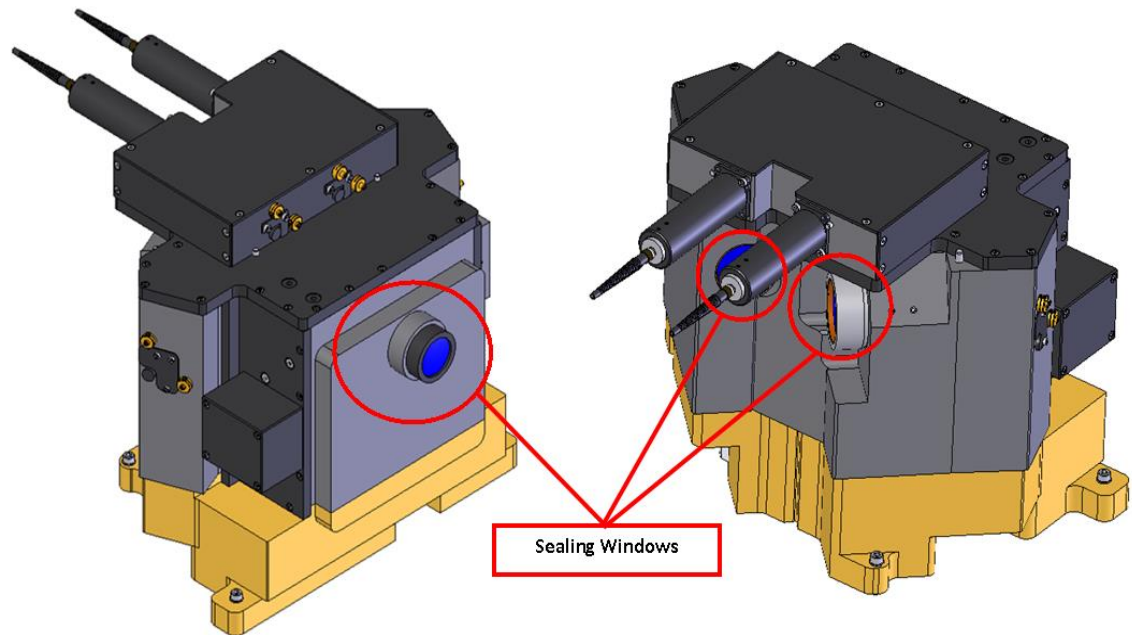


Figure 6-6 - Opera Phenix Sealing Windows

6.2.5. Design Requirements

The design requirements outlined below cover the required performance characteristic of the confocal unit. The design considerations have been created from the research retrieved through the project and through in depth discussions with the project team and the confocal unit design authority (Hamburg R&D).

Performance

- To reduce reflection through the system, windows must not be installed perpendicular to the excitation beam, an angle of greater than 4 degrees must be used to reduce the risk of stray light. (Thews, 2017)

Environment

- Must operate at a constant temperature of 37-degree C
- Must be able to tolerate exposure to UV light

Serviceability

- Any changes to the confocal unit design must be easily retrofitted to current instruments at customer sites

Material

- Material must be RoHS compliant
- Material must not produce contamination
- Material must not fluoresce
- Material must not increase the background of the image by greater than 10%
- The material must not reduce power of the Excitation light by more than 10%

Finish

- Must not Fluoresce

6.2.6. Concept Ideas

The concept design stage of any design process is key to a successful final design. Evaluating different design proposals and using a structured approach to selection ensures a strong final design. From the Confocal Unit Assembly evaluation process, Research acquired through the project and the product design specification, three designs have been produced for sealing of each of the two entry points. All three designs are largely influenced by the Phenix Confocal unit discussed in the existing products review

Sealing Location 1 - Concept 1

Remove radius from sheet metal part by manufacturing from three separate flat sheet metal parts that can be fastened to the confocal unit body individually. The mounting block can then have the chamfer removed ensuring a satisfactory fit between the plates and block as shown in Figure 6-7.

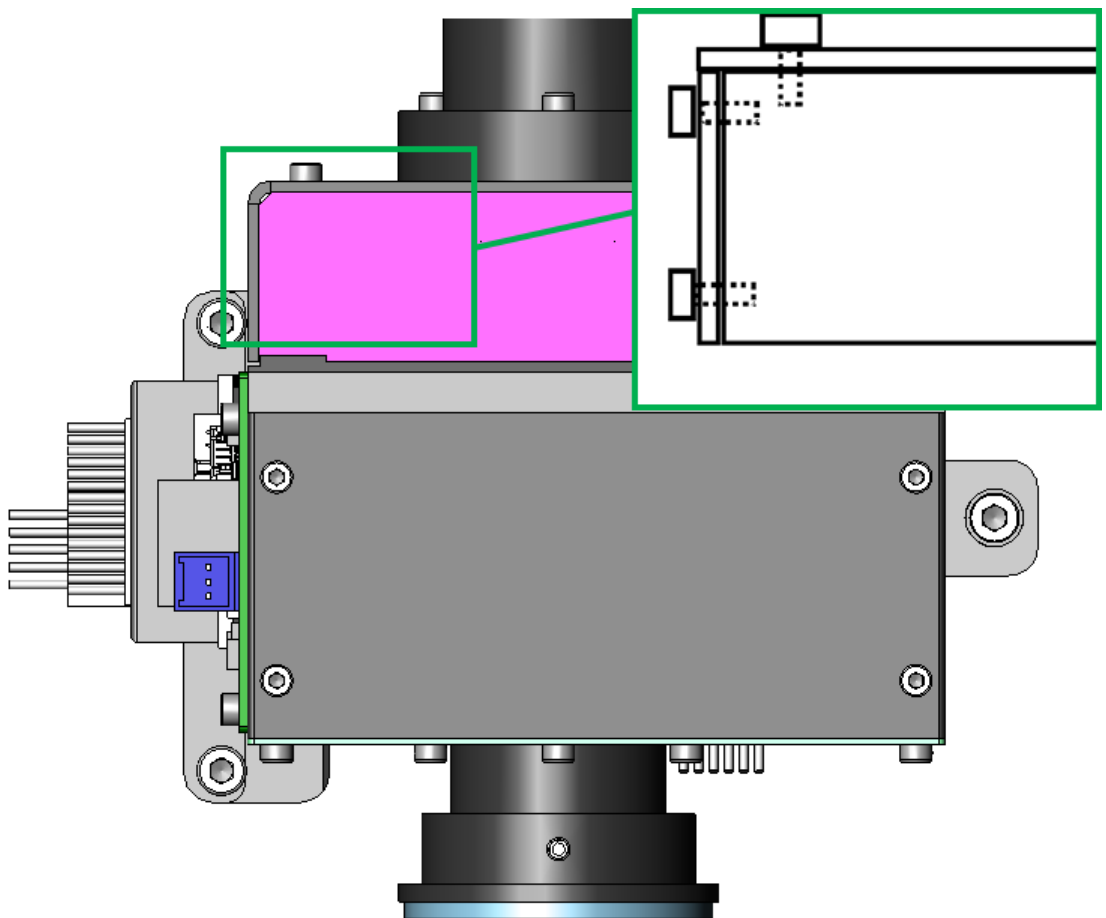


Figure 6-7 - Sealing location 1 - Concept 1

Sealing Location 1 - Concept 2

Seal radius from sheet metal part by applying 10mm x 3mm Black self-adhesive EPT sponge (highlighted green) as shown in Figure 6-8 . This material is already used to seal areas of the Phenix confocal head and as such does not require extended validation. This is a quick low cost solution that can be quickly incorporated into manufacturing.

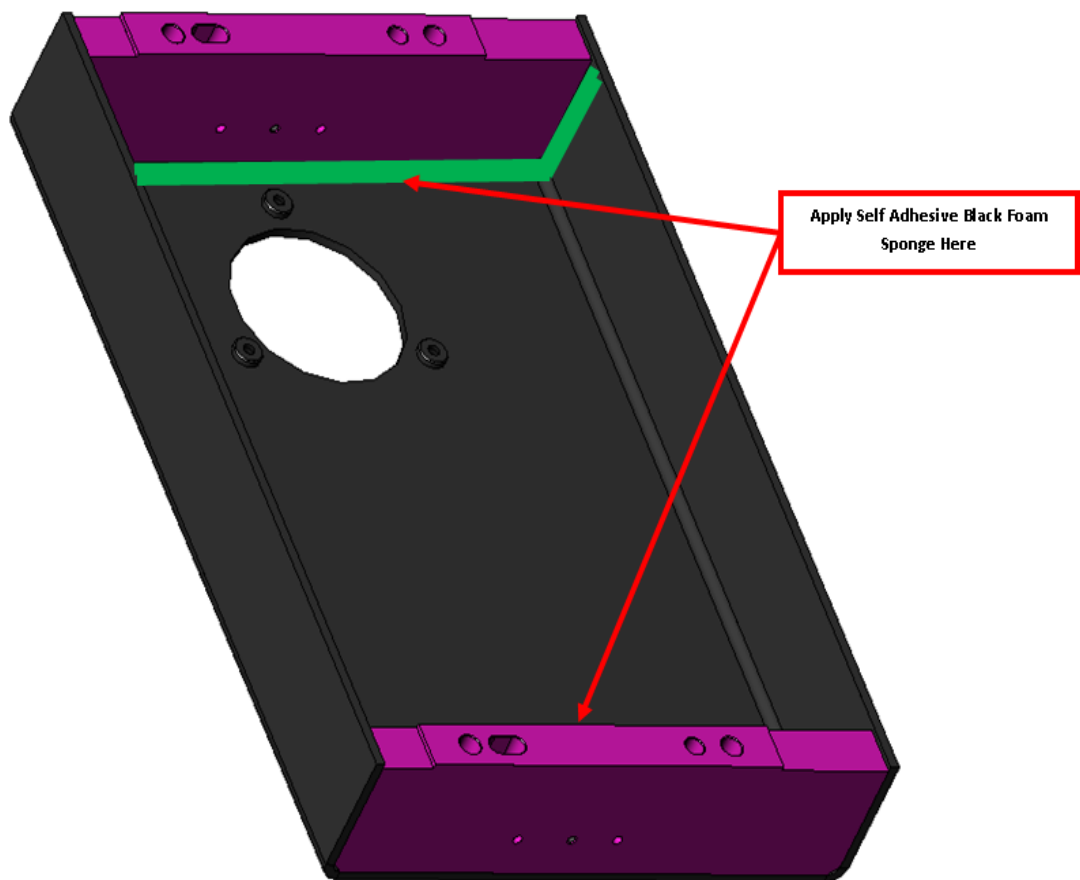


Figure 6-8 - Sealing location 1 - Concept 2

Sealing Location 1 - Concept 3

Manufacturing of the front face assembly and mounting blocks from a single piece of material as shown in Figure 6-9. This will increase the cost and weight of the assembly greatly but will also increase the sealing of the system.

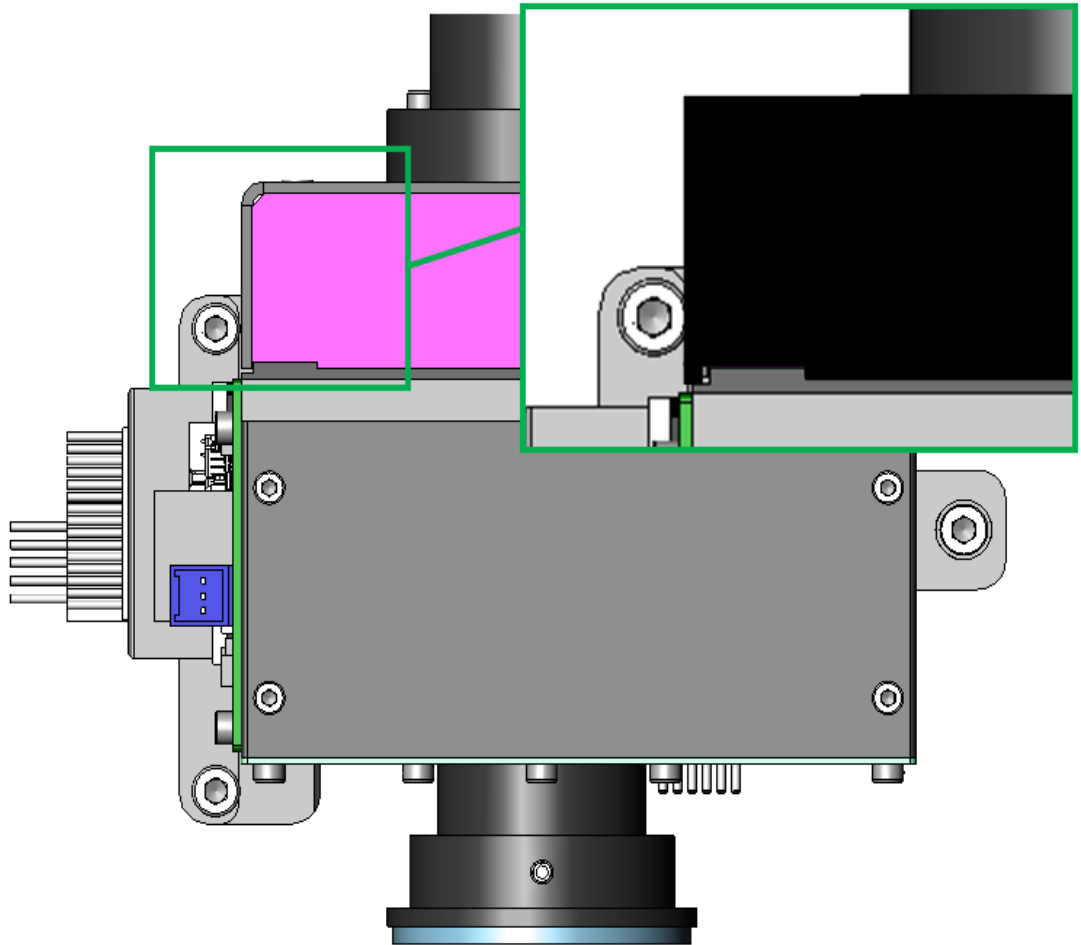


Figure 6-9 - Sealing Location 1 - Concept 3

Sealing Location 2 - Concept 1

Figure 6-10 Shows a clear window secured in the confocal tube with a retaining ring. The clear window is mounted at 4 degrees to eliminate any reflections from the window that can cause stray light in the system. This part can be directly mounted to the front panel and retro fitted at a customer's site. Modification of the confocal tube is required to allow fitment of the window.

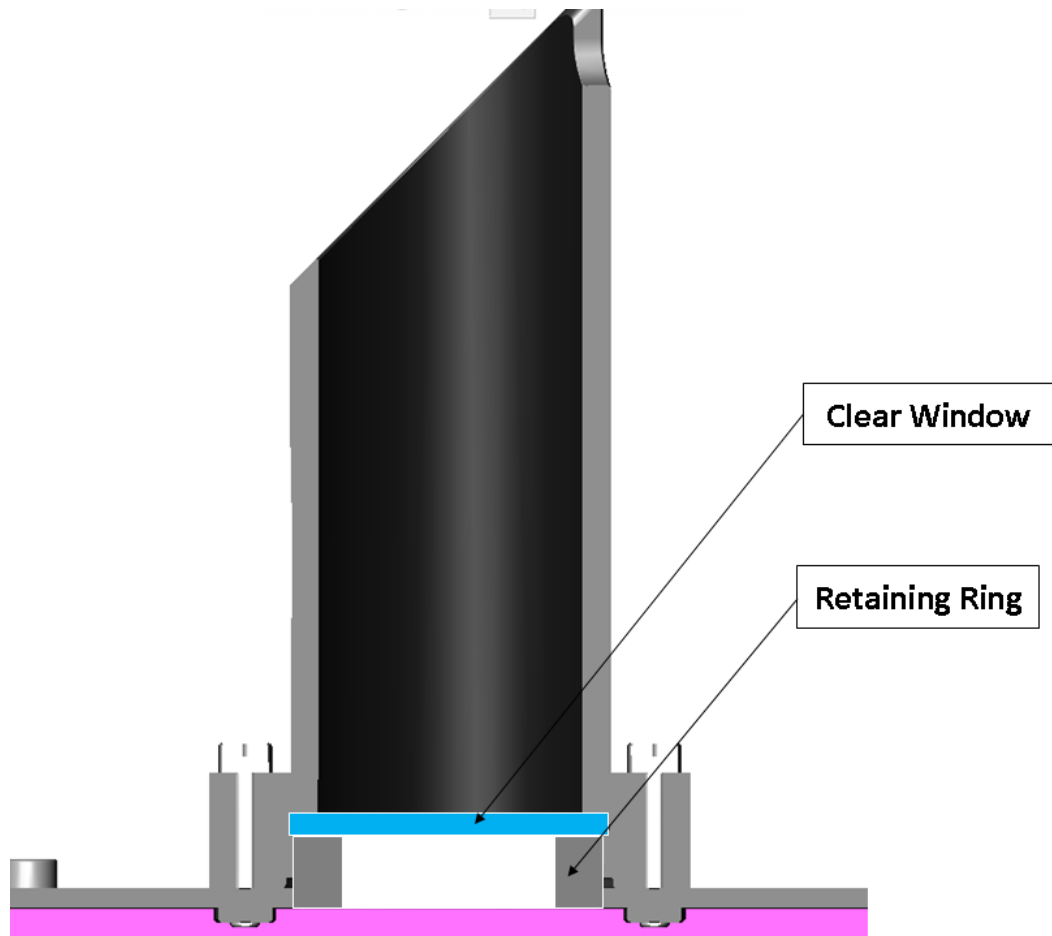


Figure 6-10 - Sealing Location 2 - Concept 1

Sealing Location 2 - Concept 2

Figure 6-11 shows a Clear window bonded between the front plate assembly and aperture window. The window is mounted at 90 degrees to the incident light and may cause stray light in the system depending on the window material. Retro fitting in the field is more difficult as bonding is required.

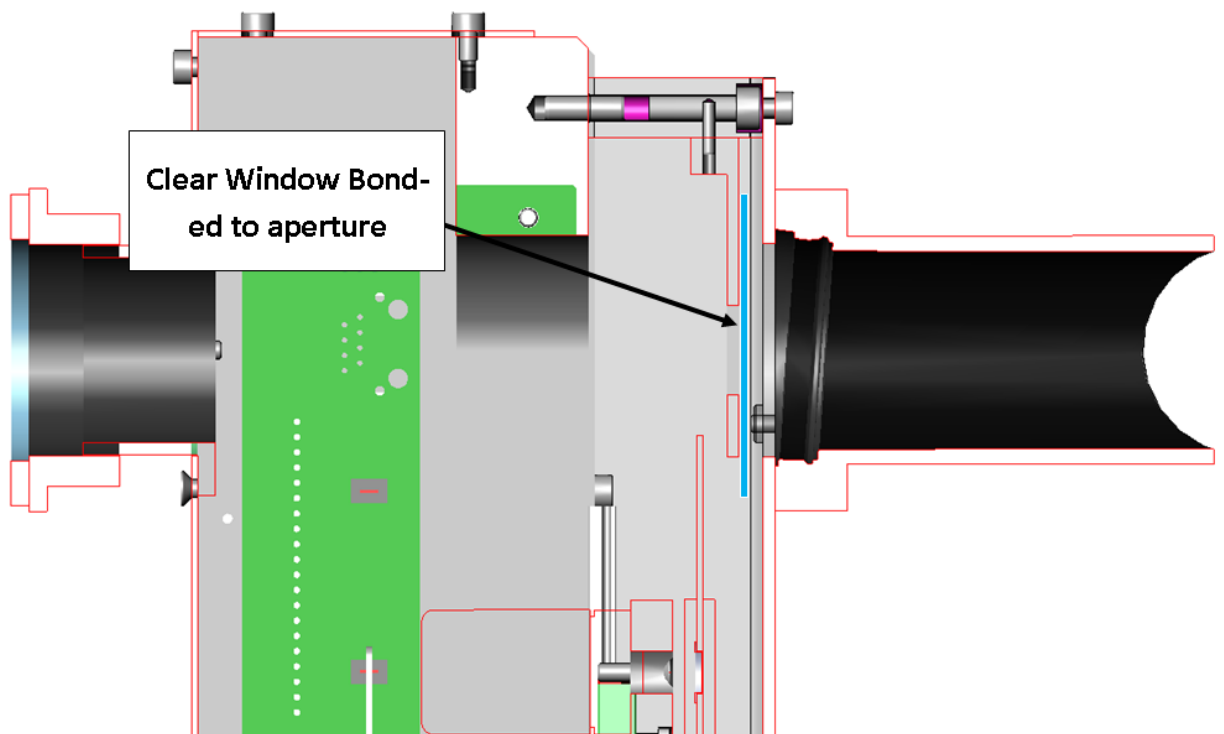


Figure 6-11 - Sealing Location 2 - Concept 2

Sealing Location 2 - Concept 3

Figure 6-12 shows a clear window secured between the confocal tube and the front plate assembly. This requires modification to the confocal tube to fit and machining processes to the window to allow fixation by the screws. The window is mounted at 90 degrees to the incident light and may cause stray light in the system depending on the window material.

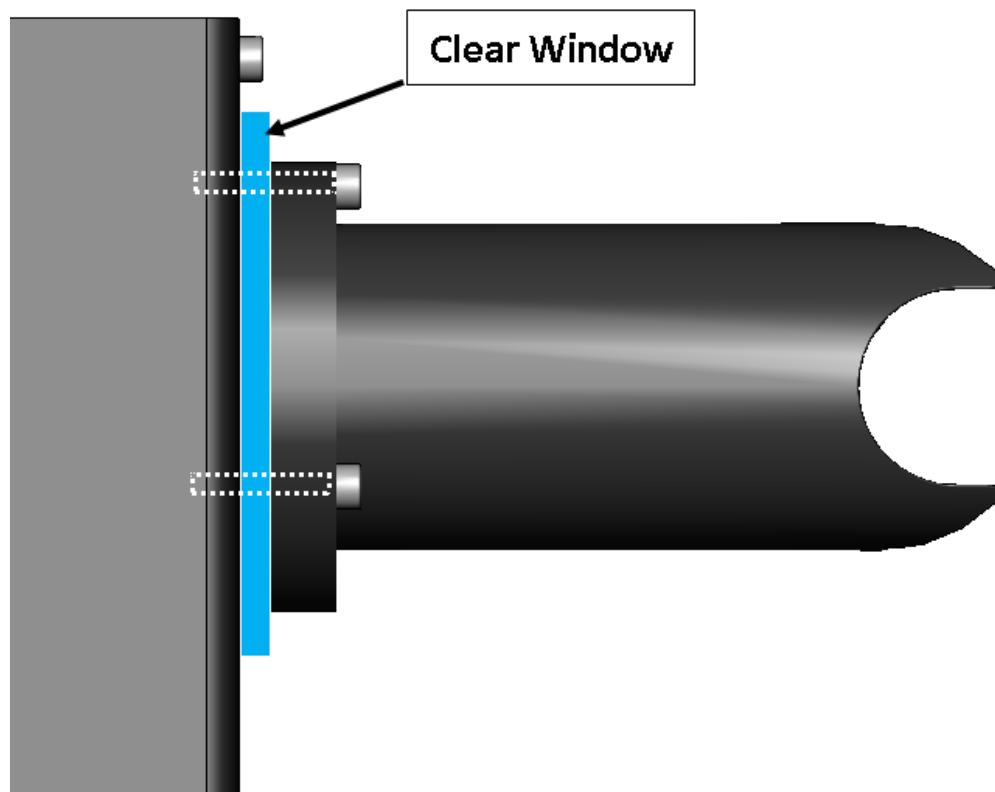


Figure 6-12 - Sealing Location 2 - Concept 3

6.2.7. Idea Isolation

To choose a concept to develop that satisfies the requirements; a systematic approach must be taken. A Pugh Matrix can be used to evaluate the concept designs. The Pugh Matrix is used as a tool to evaluate each of the concept designs against the functional. The design

requirements are listed and weighted by importance with a rating of one, three or five depending on criticality. Each design is then scored relative to the original design using a one, five, nine scoring system. The original design scores a 5 for all categories, this is the baseline result. If the concept is worse than the baseline it scores a one, equal to the baseline a two or superior to the base a nine. The score for each design requirement is equal to the concept score multiplied by the weighting factor. These values are then totalled and the highest total is the design to take forward for development. A completed Pugh's Matrix for each of the confocal unit concept solutions can be seen in Table 6-1. It can be seen that for the first sealing location, concept 2 has the highest score and for the second sealing solution, concept one has the highest score. These are the solutions that will be taken forward for development.

Table 6-1- Pugh's Matrix - Confocal Unit

Design Requirement	Importance Weighting Factor (1-3-5 Scale)	Sealing Location 1			Sealing Location 2		
		Concept 1	Concept 2	Concept 3	Concept 1	Concept 3	Concept 3
Estimated Cost	3	5	9	5	5	5	5
Reliability	3	5	5	9	5	5	5
Ease of Manufacture	3	5	5	5	5	5	5
Assembly Time	3	5	5	9	5	5	5
Estimated Tooling Costs	3	5	9	5	5	5	3
Retrospective Fitting in the Field	5	5	9	9	9	5	9
Simplicity	1	5	9	5	5	5	5
Sealing Functionality	5	9	9	9	9	5	9
Fluorescence Risk	5	9	9	5	9	5	5
Weighted Totals		195	243	219	215	155	189

6.2.8. Confocal Unit Final Design

The fundamentals of the confocal unit design have already been established through the concept ideas and the Pugh's Matrix. The chosen concepts to be developed for the pilot build are "Concept 2 for sealing location 1" and "concept 1 for sealing location 2". To pilot the sealing location 1 concept is of little effort as it only consists of applying self-adhesive foam to predefined locations on the front panel. The foam locations have been realised in SolidWorks 3D CAD and can be seen in Figure 6-13. The Foam tape must be cut to length and positioned 10mm from the top and bottom of the sheet metal part. This process can be added to the work instructions for the assembly once validated during the pilot phase.

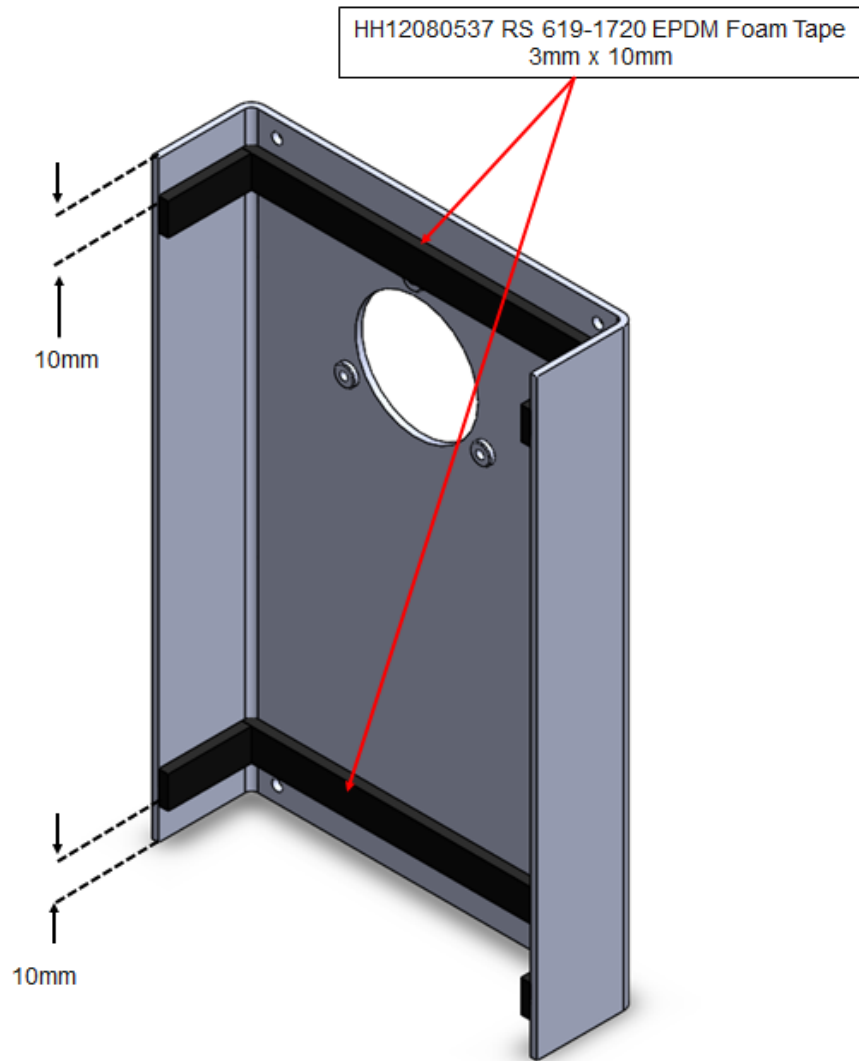


Figure 6-13 - Sealing Location 1 Solution

The redesign of the second sealing location involves the incorporation of a window inside the confocal tube mounted at a minimum of 4 degrees to minimise the risk of any reflected light being introduced into the system. This angle has been calculated by Elmar Thews using the Zemax optical design software and can be seen incorporated into the pilot design shown in Figure 6-14.

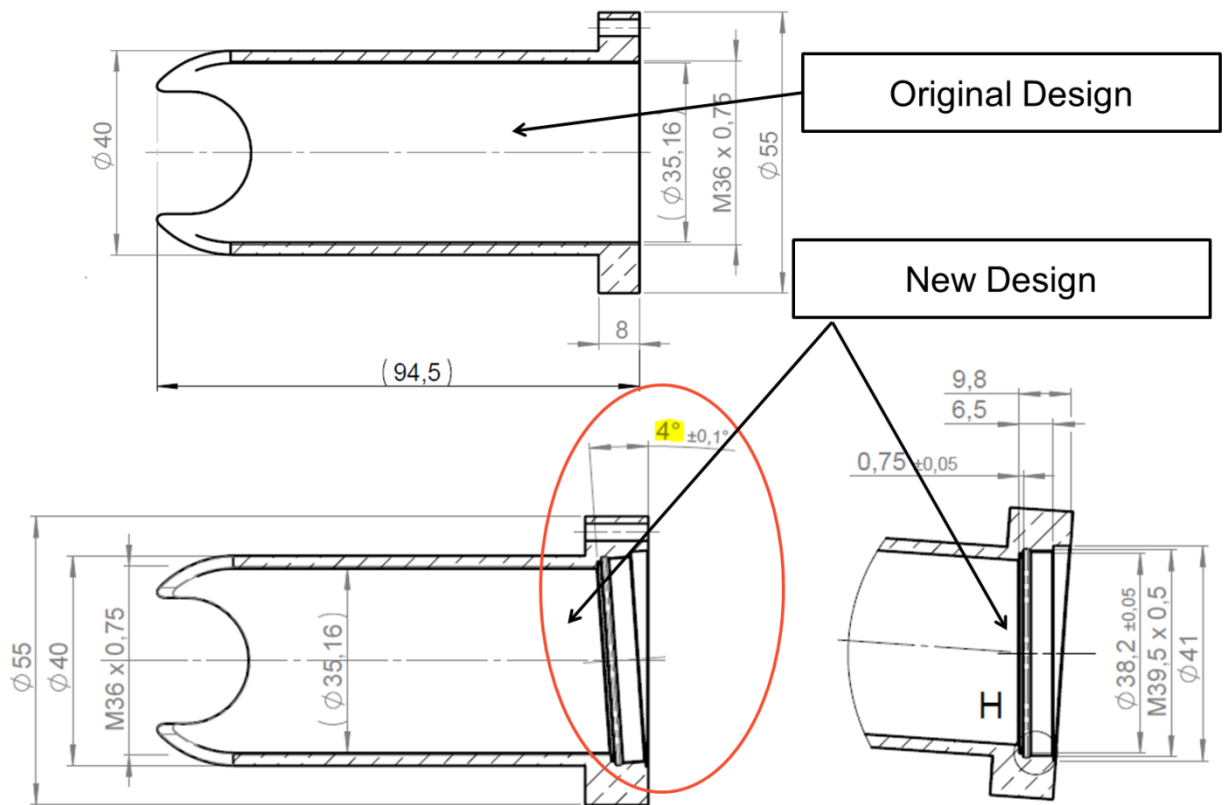


Figure 6-14 - Confocal Tube Pilot Design

The confocal tube has been designed to hold a circular window 38mm in diameter. The window is held into position with a M39.5 x 0.5 retaining ring that can be purchased as an OEM part from the vendor Thorlabs. An exploded view of the confocal tube assembly including window can be seen in Figure 6-15.



Figure 6-15 - Confocal tube Assembly Exploded View

The design and specification of the window itself has been given by Elmar Thews. Using the Optical Software a window with a thickness of no greater than 1mm has been shown to cause no detrimental effect on the optical performance of the system. As the Optical design engineer for the Operetta CLS Elmar Thews has generated the material specification and optical properties of the window that must be used. This can be seen in Appendix D. The window has been supplied by Vendor Qioptic to this specification. All mechanical drawings generated for the redesigned confocal tube can be seen in Appendix E.

6.2.9. Validation Plan

To identify practical problems and potential failures that may occur with the proposed solutions pilot testing must be completed to validate the solutions. This ensures that the final design can be seamlessly integrated into manufacturing and that any issues seen are resolved prior to implementation.

Discussions with the project team and Hamburg R&D highlighted the following tests as critical measures in the validation process.

Power at the objective - LED power for all Operetta CLS instruments is measured at the objective for each LED wavelength and must achieve a criteria that has been set in IAT. The introduction of a window into the excitation path will influence this result as no optics transmit light at 100% efficiency. The introduced window must not reduce this intensity by more than 10%.

Background intensity, Bright Contamination - The introduction of the window into the beam path will increase the background intensity of the image due to inherent fluorescence and reflectance. This must be measured and reviewed by the Hamburg R&D team prior to incorporating into manufacturing.

The validation will be performed on five Operetta CLS instruments. Each instrument must be manufactured with a standard confocal unit and all alignment and adjustments completed. Once aligned the following tests must be completed:

- Bright Contamination
- LED Power

The instrument must then have the confocal unit removed and taken to the clean room. The Head will be visually inspected for any dust particles and cleaned if required. The front panel assembly will be removed and replaced with a "sealed" assembly consisting of a confocal tube with window installed and a front plate with foam strips. The confocal head will be reinstalled into the instrument and alignment and adjustments will be completed. Once completed the following tests will be performed and the data stored for review.

- Bright Contamination
- LED Power

Each instrument must complete all IAT tests and will be quarantined until the data has been reviewed. Once the data has been approved the instrument can ship under concession with the

new version confocal unit installed. if the data is unsatisfactory, the instruments must be reworked with the original design confocal unit and retested. One of the five instruments will be held back for extended testing to determine if the confocal unit accumulates additional contamination over a two week period. An overview of the plan can be seen in Figure 6-16

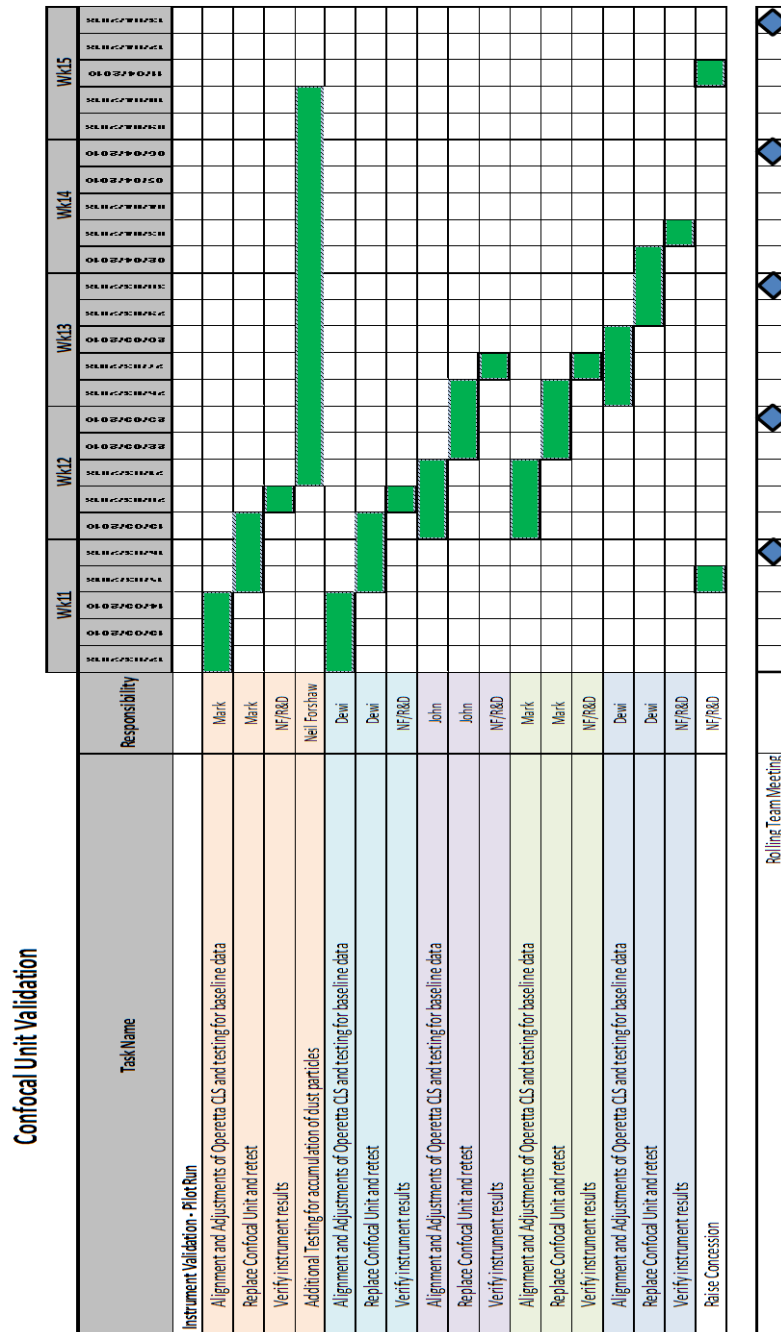


Figure 6-16 - Validation Plan - Confocal unit

6.2.10. Validation Results

LED Power

The LED power measured at the objective for each of the 5 instruments before and after the addition of the window, resulted in an average power loss of 4.69% for each of the wavelengths. This is 50% of the maximum permissible power loss of 10% specified by the R&D team. A sample of this data can be seen in this shows the LED power for each wavelength with the window removed (blue line) and the LED power with the window installed (Red line). It can be seen that there is a small drop in intensity ~5%. However, as confirmed by Hamburg R&D this will have no detrimental effects to the performance of the instrument. As the IAT states a specification that must be achieved for the power of each wavelength, this must be reviewed to account for the 5% power loss seen and a new IAT version released to manufacturing prior to incorporation.

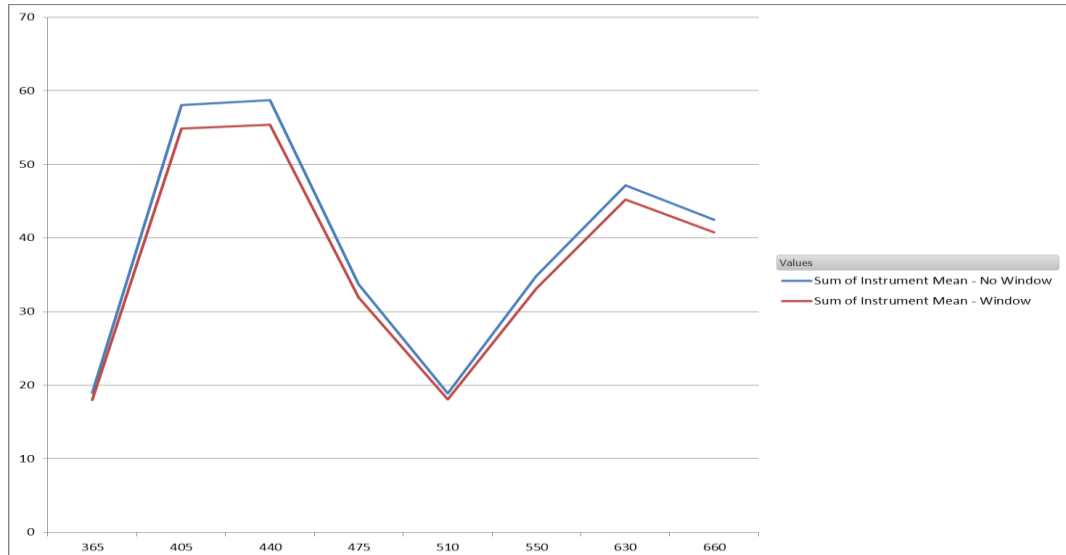


Figure 6-17 - LED Power Comparison

Background Intensity

A review of the background intensity for each wavelength on each instrument yielded positive results. There is no increase in background intensity seen due to the inclusion of the confocal window. This can be seen in Figure 6-18. The image on the left is without a window and the image on the right with a window installed. With a line drawn diagonally across the image to measure the intensity, no discernible difference can be seen in the intensity plots.

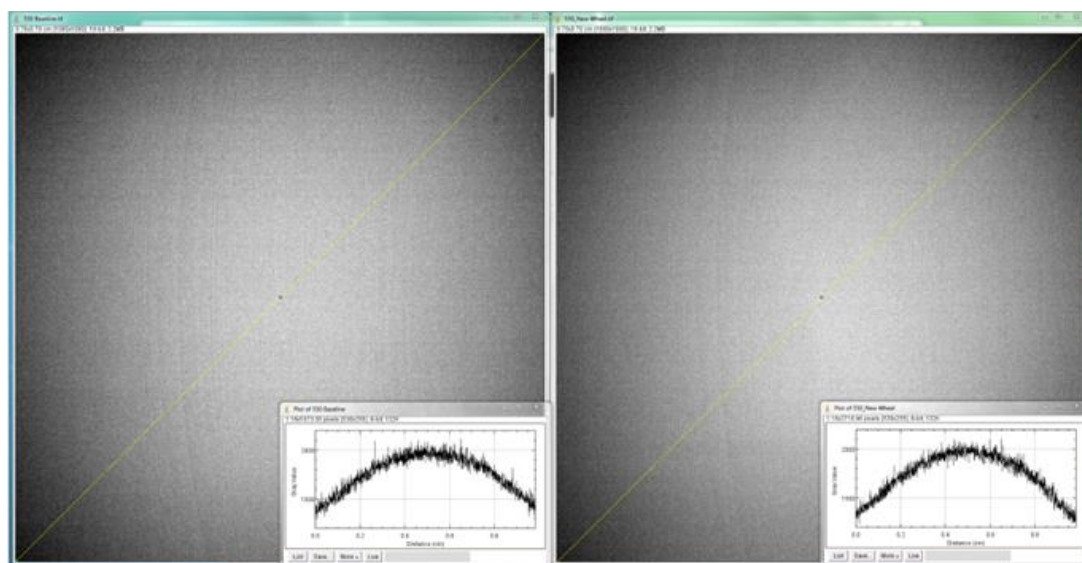


Figure 6-18 - Background Intensity

Bright Contamination - Stripes

On review of the bright contamination images for the operetta CLS with a sealed confocal unit it can be seen that there were zero bright stripes evident in the image field greater than 400 counts during the IAT bright contamination tests. This compares to a number of bright stripes seen with no window. A line chart comparing the results before and after modification can be seen in Figure 6-19.

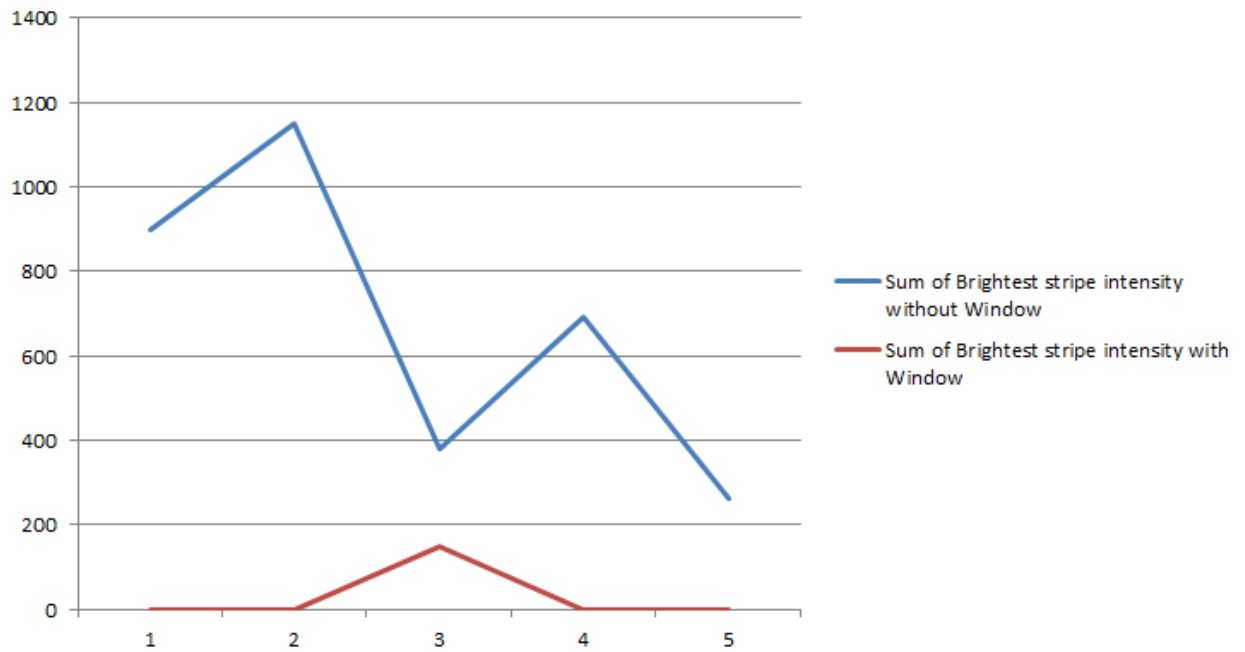


Figure 6-19 - Brightest Stripe Intensity With and Without Window

Contamination Accumulation Test

Results from the two week accumulation testing also show positive results. Instrument one exhibited no bright stripes during the IAT test (Day 1) the instrument was left on for a 2 week period and the bright contamination test run again. There was no accumulation evident over the two week period as shown in Figure 6-20. This data proves that the design has satisfied the brief by not allowing any dust particles to ingress into the confocal unit.

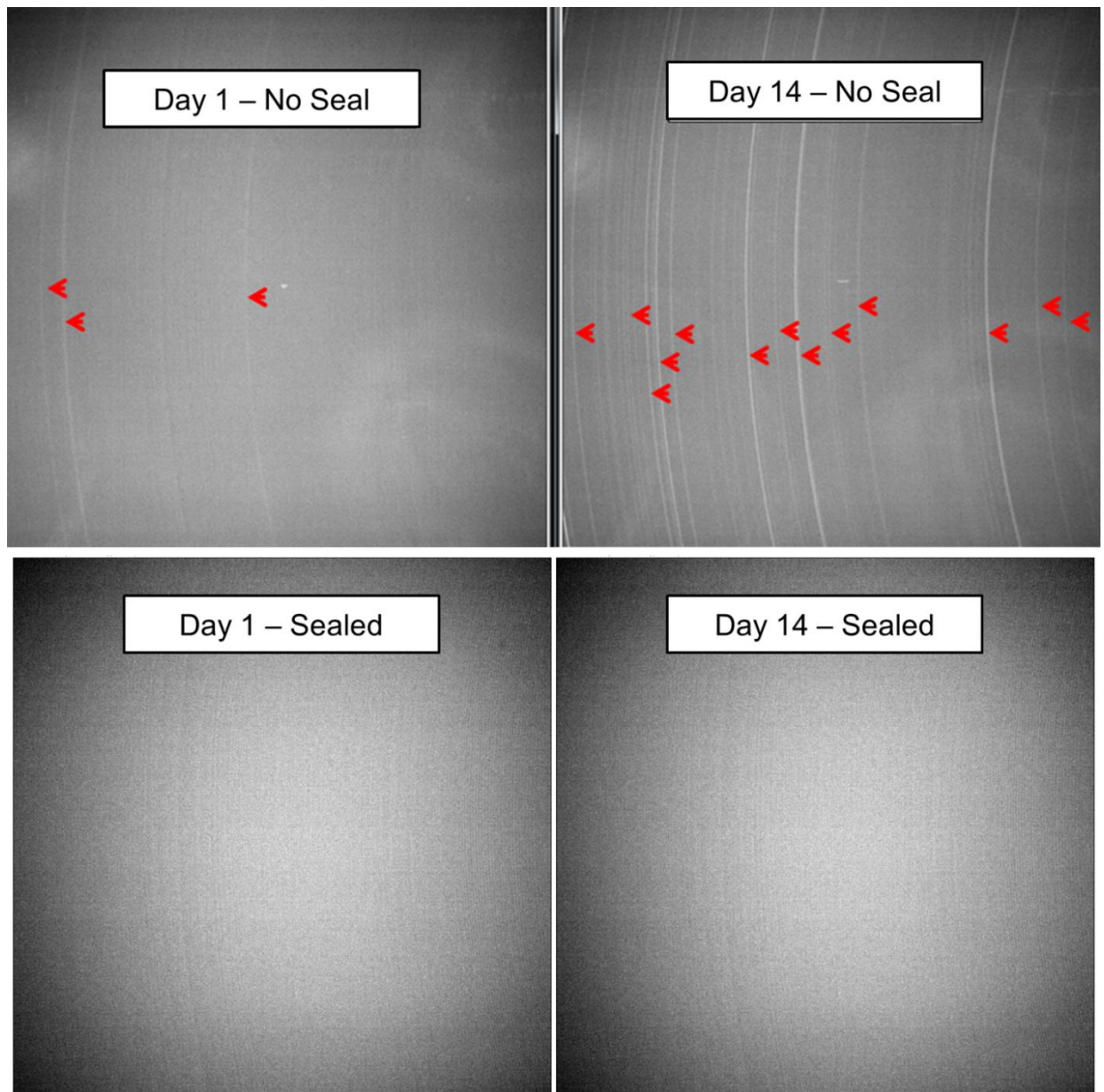


Figure 6-20 - Accumulation Test

6.2.11. Confocal Unit Bright Contamination Test Fixture

From the data collected it is evident that a visual inspection will not pick up all contamination within the confocal unit. From the five instruments there is one occurrence of a confocal stripe due to a dust particle. This was not picked up via the visual inspection control. The current

process for cleaning the disc is a "blind" clean. Depending on the particle size, the dust particles may not be visible to the naked eye but can cause failures or stripes on the disc leading the technicians to blindly clean the disc in the hope that the contamination is removed. To control this, a test fixture can be used to test for contamination within the clean room environment prior to installation in an instrument. This ensures that the confocal unit is 100% inspected prior to use. The test fixture can also be used to perform the functional motor test that is currently performed outside of the clean room environment; this can be seen in Figure 4-8 - Confocal Unit Assembly Workflow Diagram. An additional reason for incorporating a test that does not require an instrument is to ensure confocal units are clean when shipped to customers to replace contaminated units. The current process is to test the unit on a CLS instrument and remove the confocal head to ship to the customer. This is additional downtime that has not been accounted for in the business case for the project.

The test fixture is manufactured using Operetta CLS components to replicate the excitation path of the system. The software used to capture images is a modified version of the customer software to enable the use of the system with a number of assemblies missing.

A prototype test fixture has been developed as a proof of concept model. This has been tested and images taken with a number of confocal units that replicate directly the result taken from an instrument. The detail regarding the design behind the fixture is outside the scope of this report but Images, part used and schematics of the fixture can be seen in Appendix F.

6.3. Dichromatic Wheel Assembly

The processes undertaken to determine the appropriate solution for the dichromatic wheel assembly bright contamination artefacts were completed in parallel to the activities performed on the confocal unit assembly. It has been written as a separate entity to ease comprehension.

6.3.1. Ideation Session

An ideation session with the project team resulted in the generation of ideas shown in Figure 6-21.

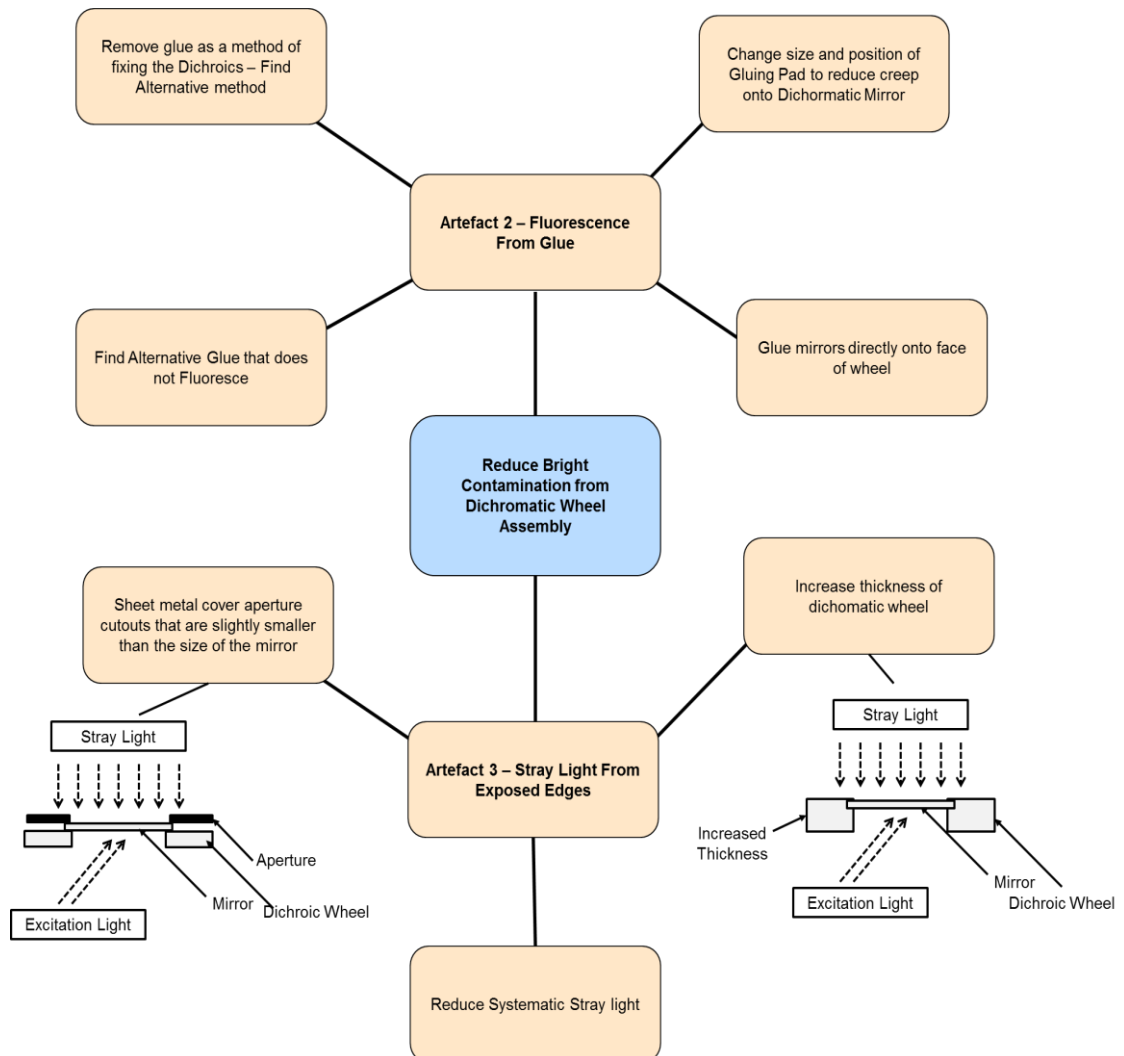


Figure 6-21 - Dichromatic Wheel Assembly Ideation Session

Artefact 2 - Fluorescence from Glue

Idea 1 - Remove glue as a method of securing the mirrors

The current method of securing all mirrors in the CLS instrument is by bonding directly to the surface of the supporting material. This helps to accurately locate the mirror ensuring minimal movement during use and also eliminates any stresses on the mirror that may be applied using mechanical techniques. The optical flatness specification of the mirrors is less than 1λ . This is to reduce the risk of astigmatism seen in the optical system (Distortions in the image due to warped optics). Any proposed techniques must not exert any force onto the optics that may impact the flatness specification

Idea 2 - Change the size and position of the gluing pads to reduce the risk of creep

The root cause of the bright contamination is due to glue creeping along the material surface. The current design of the gluing pad allows this "creep" to occur. The design is not very forgiving to the quantities of glue applied. Discussions have taken place regarding the control of the volumes of glue. However, this has been deemed unnecessary as the gluing quantities are already small. The design should allow for deviation in the quantities used. A redesign of the size/shape/position of the gluing pad could be a quick long term solution.

Idea 3 - Source alternative glue that does not fluoresce

This idea has been discussed many times with the optical experts in R&D. The glue used has been extensively tested for its properties with regard to shrinking and expansion coefficients and performance under different temperatures. This is the gold standard glue used in the microscopy industry. Elmar Thews has conducted a number of tests using various glues; all glues tested have fluoresced under excitation. The fluorescence needs to be removed from the system via mechanical design rather than changing the glue. Reviewing different glue types has been considered outside of the scope of this project but may need to be reviewed for future improvements.

Idea 4 - Glue mirrors directly on to the dichromatic wheel surface

Gluing the dichroic directly to the surface of the dichroic wheel rather than a gluing pad sitting 300 microns under the surface can reduce glue exposure to the excitation light. There is a risk with this method of glue travelling under the mirror and lifting the mirror off the surface of the wheel causing tilt in the system. This could be overcome by applying a mechanical force to the mirror while bonding. However, this may result in additional issues such as astigmatism in the image.

Artefact 3 - Stray light from exposed edges

Idea 1 - Design stray light cover

The addition of a thin sheet metal aperture to the dichroic wheel assembly will reduce the exposure to stray light of the dichroic edges. This is a relatively straight forward solution that should work but will increase the weight and assembly time of the dichroic wheel.

Idea 2 - Increase thickness of wheel.

Increasing the thickness of the wheel and machining a pocket for the dichroic to sit in rather than being glued on the surface of the wheel would eliminate the risk of stray light. As the dichroic sits in a pocket, the edges are no longer exposed to stray light in the system. This does bring additional risks to tilt in the system. The dichroic wheel has been designed to be machined from high grade aluminium (C250) . the material is purchased at the standard thickness of the wheel and it is mandatory as per the drawing that this material is not machined. This ensures that the flatness of the wheel is held at 0.01 (purchased material specification). Manufacturing the wheel from a thicker material and machining pockets on which the mirrors are bonded can cause the material to warp. This may result in the mirrors being bonded to a surface that does not meet the flatness specification, causing tilt in the system.

Idea 3 - Reduce systematic stray light

By eliminating all sources of stray light in the system, the exposed edges of the dichromatic mirrors would no longer be an issue. This is a difficult task as identifying all sources of light that can attribute to the issues seen will be a long process and may result in the redesign of multiple mechanical components and assemblies

6.3.2. Payoff Matrix

Similar to the confocal unit assembly, a payoff matrix has been developed to compare the generated ideas this can be seen in Figure 6-22. The black text denotes "artefact 1" solutions and the blue text denotes "artefact 2" solutions, it can be seen there are solutions for each of the artefacts that are deemed both high benefit and low effort. These solutions will be taken forward to the next phase. The location within the matrix of each of the solutions has been determined through discussion with the project team.

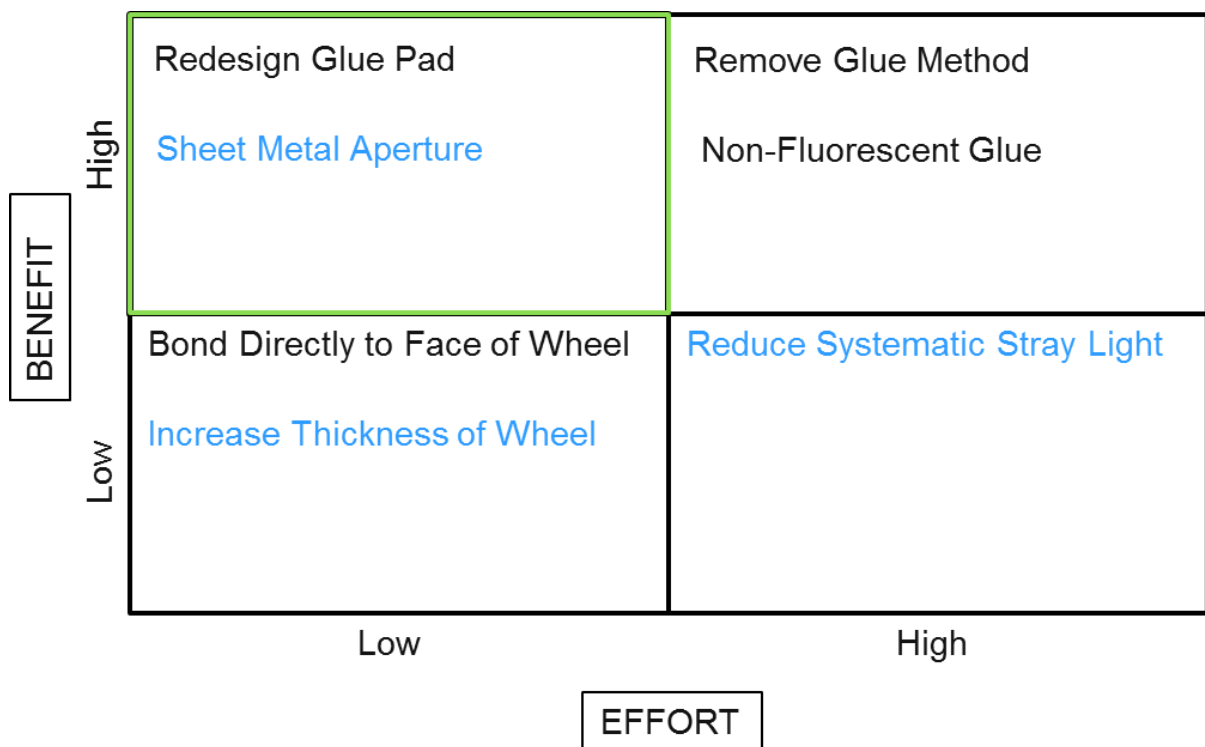


Figure 6-22 - Payoff Matrix - Dichromatic Wheel Assembly

6.3.3. Dichroic Wheel Redesign

Artefact 2 Design Improvements

As discussed in the Analyse phase, the root cause for artefact 2 (gluing spots) is due to excess glue seeping underneath the dichromatic filter and along the face of the dichroic whilst curing. This results in a small quantity of glue directly in the light path that, when excited, emits fluoresced light causing bright contamination failures. A sectional view of the current design along with the location of the glue / gluing pad can be seen in Figure 6-23. Note the location of the edge of the gluing pad relative to the incoming excitation light. We know from the Analyse phase that glue protrusion into the excitation light by as little as 100 microns will cause bright contamination failures.

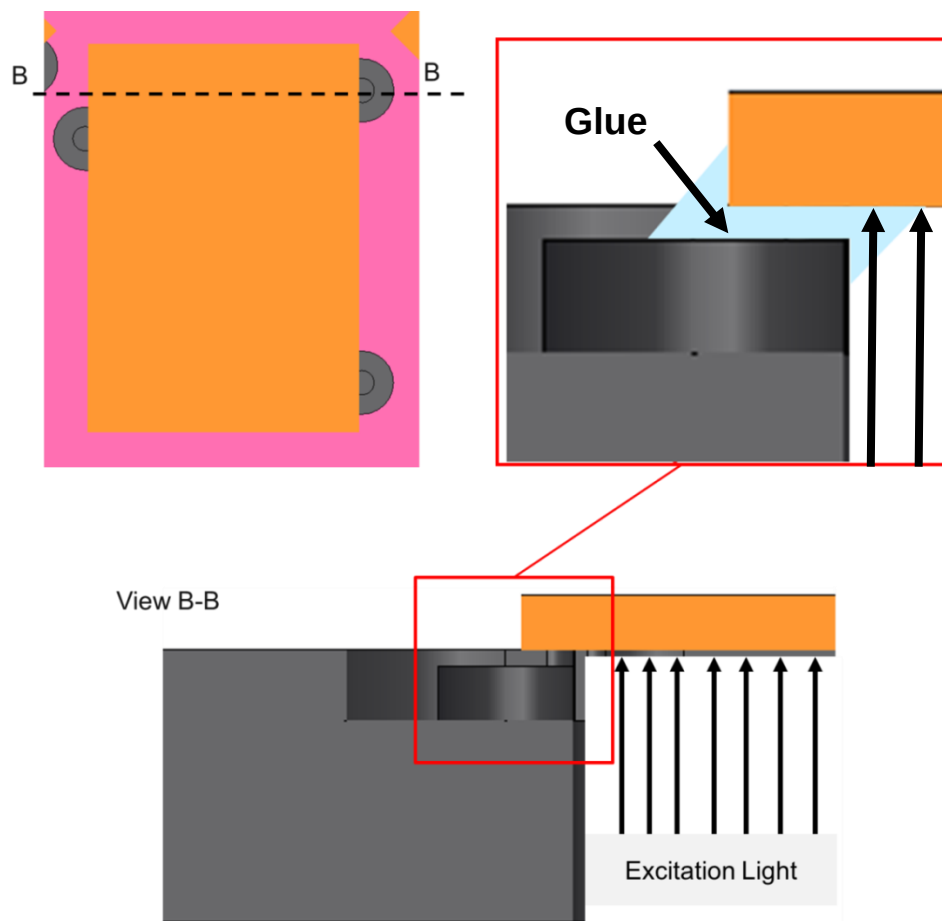


Figure 6-23 - Current Glue Pad Design

The objective of the proposed design is to reduce the risk of the glue travelling along the face of the dichroic. To achieve this, the diameter of the gluing spot has been increased in diameter from 2.5mm to 3.5mm, the central location is identical but the pads geometry has been changed to a semi-circle as shown in Figure 6-24. This reduces the risk of glue protrusion into the excitation light path but keeps a similar surface area to ensure the glue contact area is equal:

$$A = 2\pi r^2$$

$$A_{Current} = 2 \times \pi \times 1.25^2 = 4.909mm^2$$

$$A_{Proposed} = \frac{2 \times \pi \times 1.75^2}{2} = 4.81mm^2$$

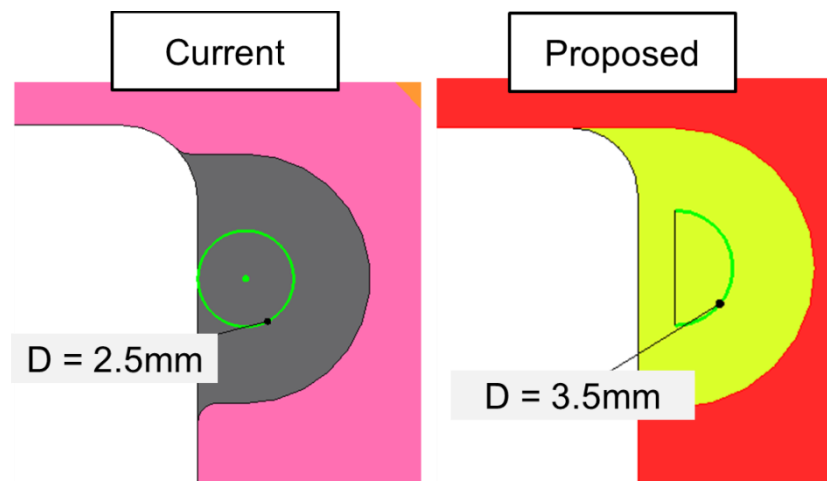


Figure 6-24- Gluing Pad Geometry

When viewing a cross section of the new design as shown in Figure 6-25. It can be seen that excess glue is unable to track along the mirror into the excitation path as there is a gap of 200 microns between the edge of the pad and the edge of the dichroic. The viscosity of the glue will allow this gap to be bridged and still provide sufficient gluing contact, without breaching the excitation light path.

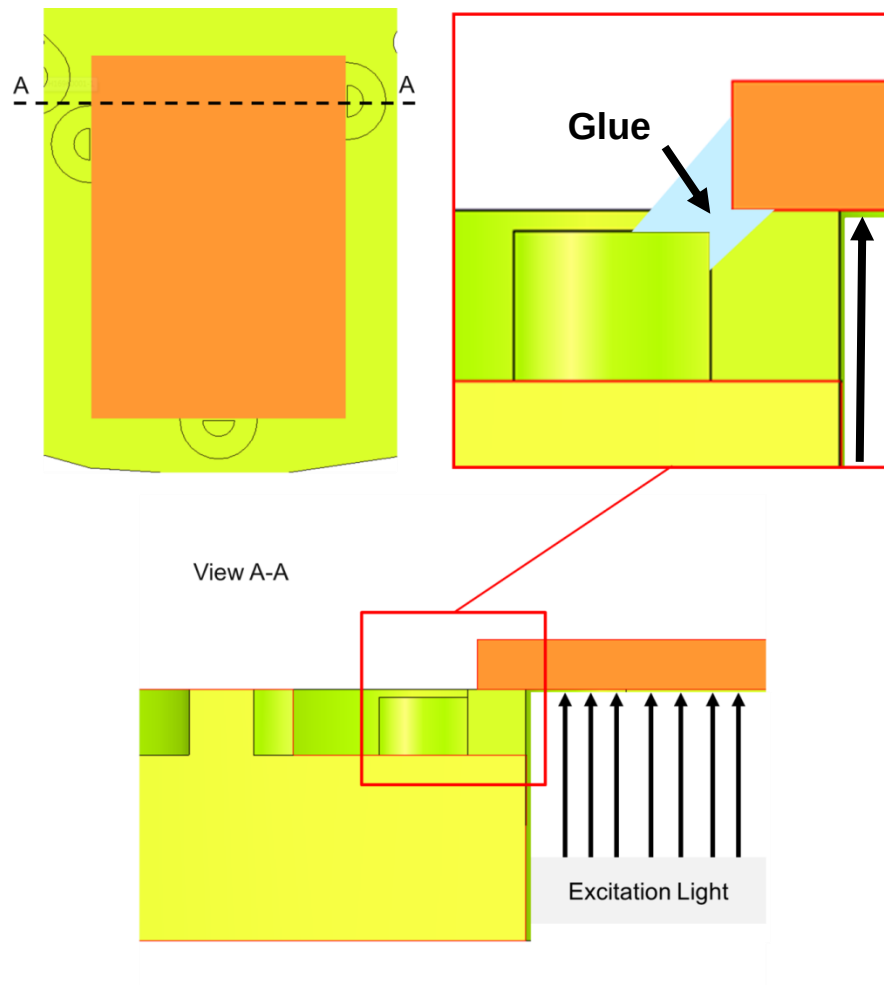


Figure 6-25 - Gluing Pad Proposed Design

Additional to the change in size and shape of the gluing pad, the location of a single gluing pad has also changed. Glue position 1 shown in Figure 6-26. Contributes to the greatest intensity for IAT failures due to this artefact type, this is mainly due to its location in the beam path and the area of the illumination from the LED source. A suggestion from Elmar Thews is to move this location to reduce this risk but to also balance out the gluing positions along the mirrors edge.

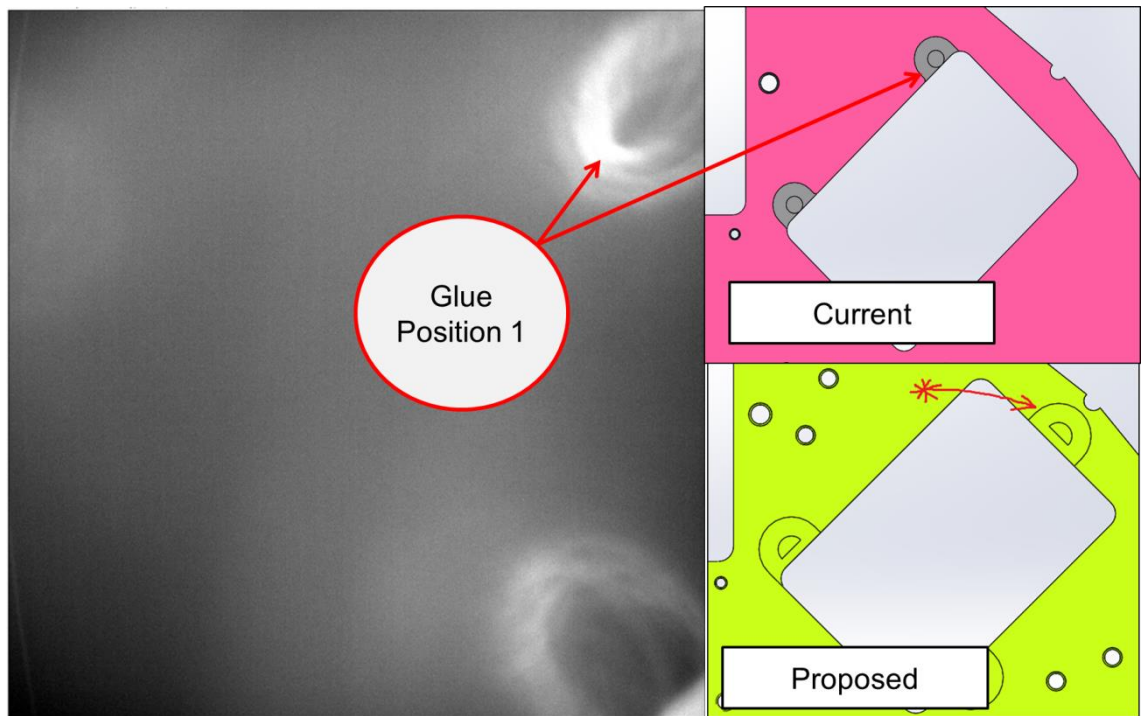


Figure 6-26 - Glue Position 1 Location

Artefact 3 Design Improvements

As discussed in the Analyse phase, the root cause of the bright contamination for artefact 3 is stray light from the system entering the exposed edges of the dichromatic mirrors. The project team have mutually agreed that the best approach to reduce this artefact is to design a sheet metal aperture, covering each of the Dichromatic mirrors, each mirror are 28mm x 40mm in size. Discussions with Elmar Thews resulted in a number of design constraints.

1. The aperture must not reduce the clear viewing window by more than 1mm in either direction (minimum window size 27mm x 39mm)
2. The Aperture must not add excessive weight to the wheel - Slip tests to be performed

3. The aperture must fit within a design space that is of equal circumference to the wheel and 10mm in additional thickness

Following these design rules a new dichroic wheel has been designed that holds a sheet metal disc with 8 individual aperture cut-outs. Each aperture window overlaps each mirror by 0.5mm to ensure the edges of the dichroic are no longer exposed to any stray light and to also stay within the design constraints outlined by Elmar Thews. A comparison between the current version and proposed version can be seen in Figure 6-27

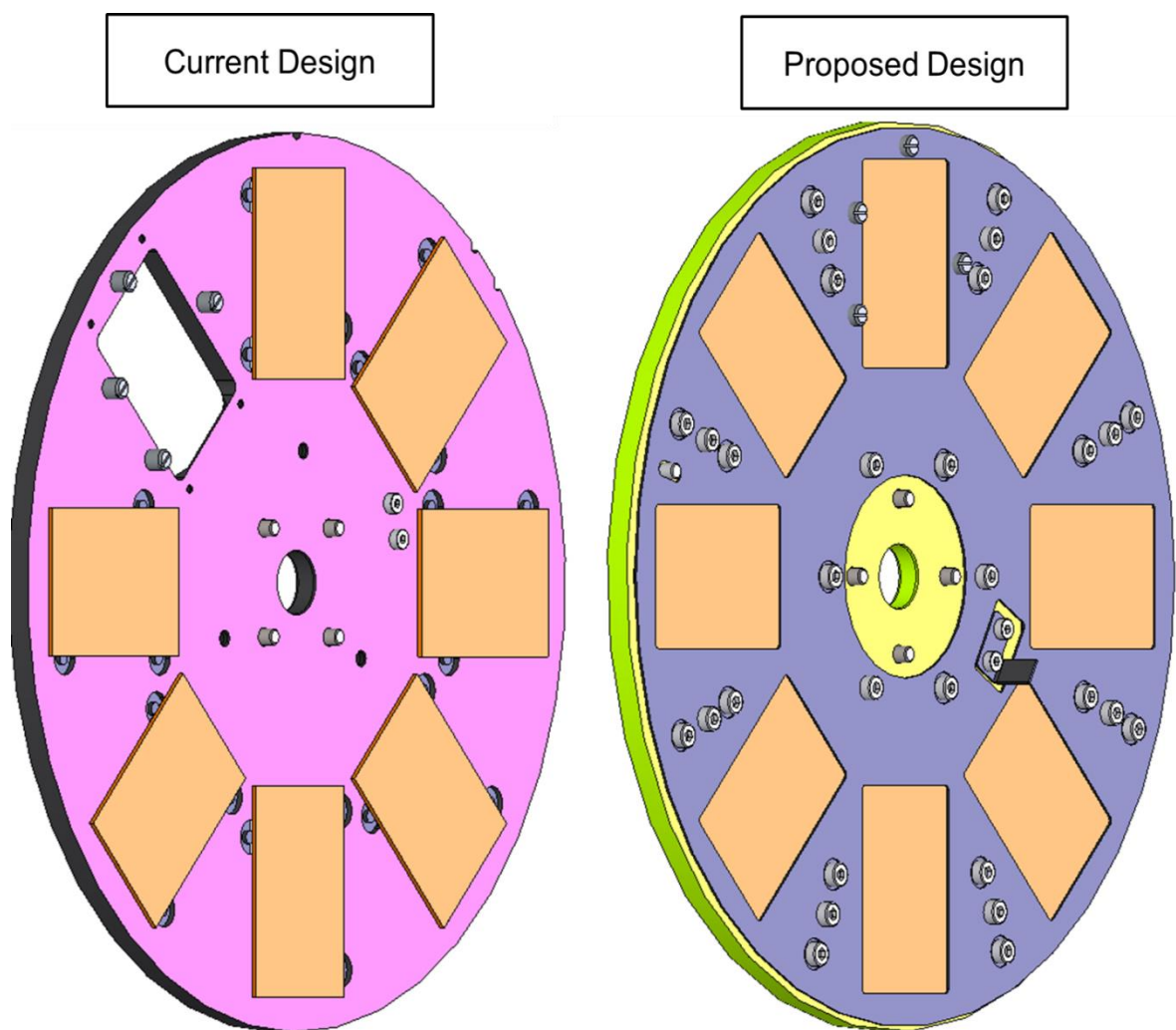


Figure 6-27 - Dichroic Wheel Comparison

To ensure that the aperture disc does not scratch the surface of the mirrors, 1.25mm spacers have been added. With the thickness of the mirrors being 1mm this results in a 250micron space between the surface of the mirror and the surface of the aperture disc. The position of the spacers beneath the aperture disc can be seen in Figure 6-28

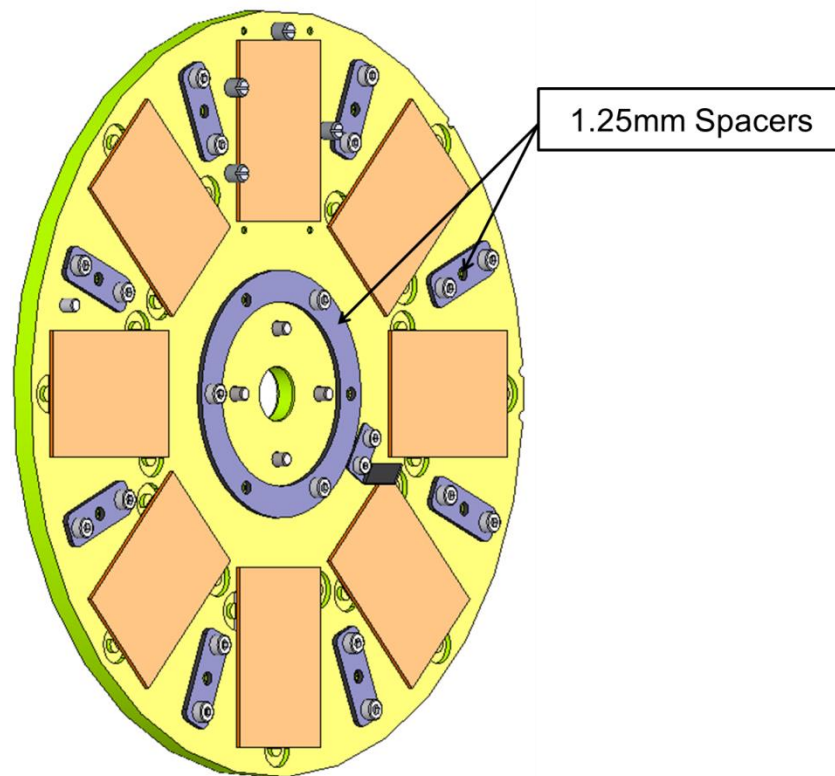


Figure 6-28 - Spacer Location (Aperture sheet removed)

To ease assembly, holes have been incorporated in the disc to allow fastening of the spacer bars to the dichroic wheel prior to securing the disc to the wheel, additionally a locating pin has been added to the wheel assembly to centrally locate the aperture disc prior to fastening. Assembly time for this process is approximately 5 minutes. The yellow colouring of the wheel in the previous figures is a visual representation only. The manufactured part is black anodised to reduce the risk of fluorescence. Technical drawings for all parts can be seen in Appendix E.

Figure 6-29 shows an acute view of both designs. It can be seen that with the current design there are gaps visible that allow stray light to pass through, hence the need to perform the

modifications. With the proposed design the gaps are no longer evident negating the need for any additional modification operations by the technicians.

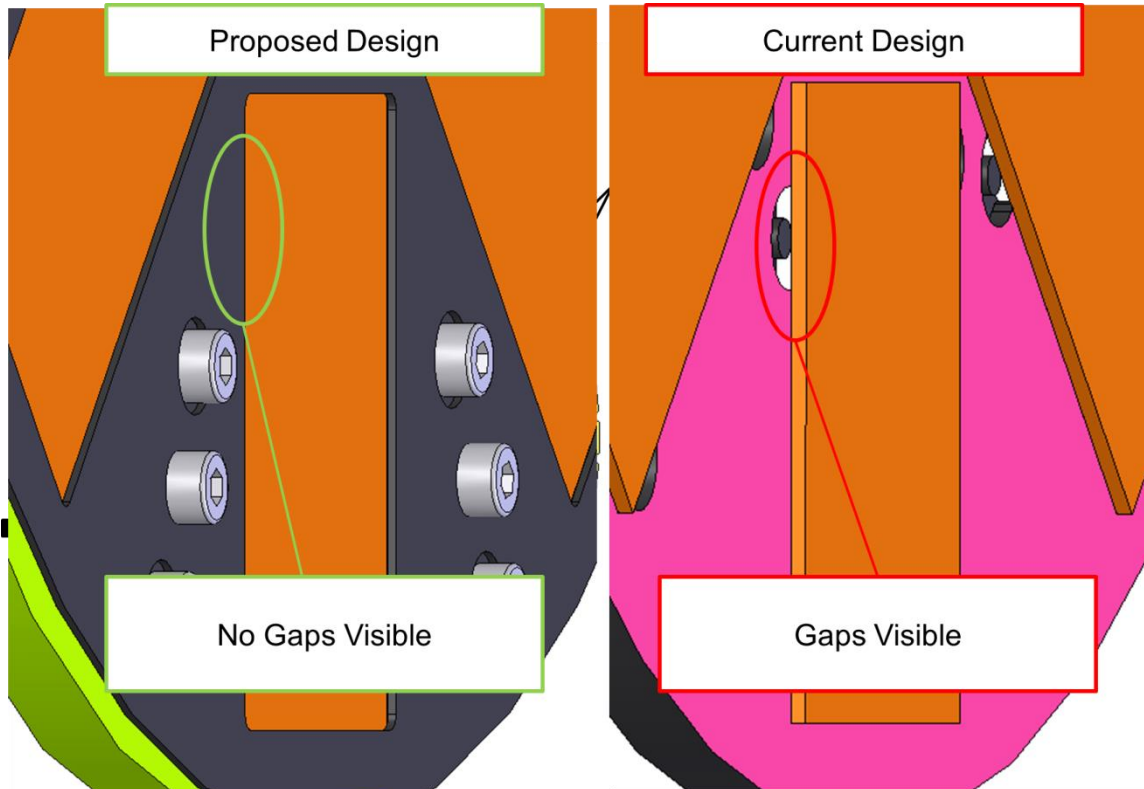


Figure 6-29 - Acute View

6.3.4. Validation Plan

Discussions with the project team and Hamburg R&D highlighted only three tests that are critical for the validation of the new wheel design

- Visual inspection post gluing - Ensure the new design inhibits the glue from protruding onto the dichroic surface. Visually inspect coverage to ensure optic will not come loose.
- Bright Contamination - Ensure that the new design passes the bright contamination criteria with no new artefacts seen that may be a result of the new design
- Functional test - Due to the additional hardware on the new design a functional test must be completed prior to installation on an instrument to determine if the added mass affects the performance of the motor assembly. The functional test is as follows:

Perform 1000 rotations of the dichroic wheel, rotating from the optical flag position (zero steps) to the end position (50000 steps). This must be performed consecutively 1000 times with a slip of no greater than 0.1 degrees seen in the software.

Five dichromatic wheel assemblies will be manufactured using the proposed design. Validation will take in place in parallel to the confocal unit validation using the same five instruments using the timing plan already discussed.

6.3.5. Validation Results

Visual Inspection

Visual inspections of the gluing site and protrusion area yielded positive results. The gluing spot shows complete coverage along the side of the Dichromatic mirror with no creep onto the underside of the mirror. Images can be seen in Figure 6-30. The image to the left shows the gluing spot coverage and the image to the right shows zero glue protrusion into the excitation path.

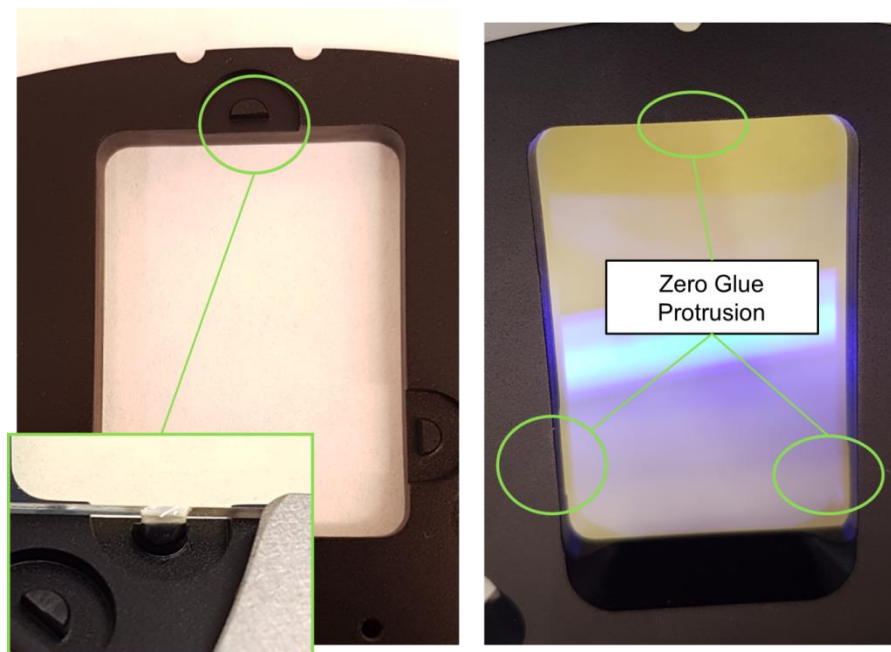


Figure 6-30 - Gluing Location images

Functional test

Validation for the functional test of the stepper motor yielded positive results, all five assemblies stayed within the upper and lower control limits as shown in Figure 6-31 . The highest result seen was 0.048 degrees; this is less than half the specification and does not stand out as an outlier when compared to the last 52 instrument results.

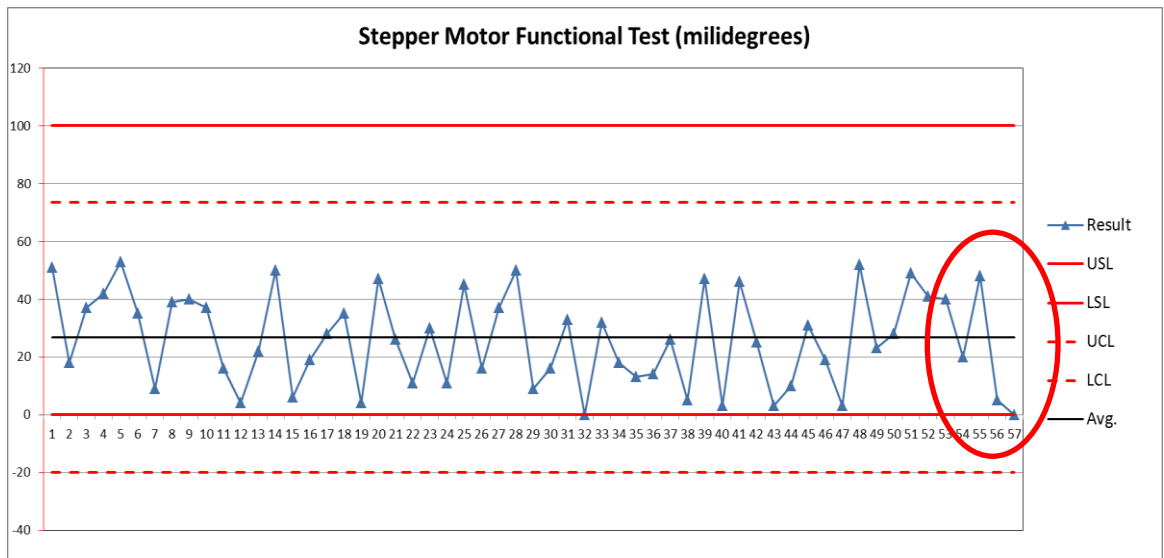


Figure 6-31 - Functional test SPC

Bright Contamination

On review of the bright contamination images, using the proposed design dichromatic wheel. There is zero type 2 or type 3 artefacts present in the image field with greater than 400 counts intensity, additionally there are also zero type 2 or type 3 artefacts with less than 400 counts intensity present. A sample of a "typical" Bright contamination image compared to an image taken with the proposed design can be seen in Figure 6-32. This shows the magnitude of improvement with the proposed design.

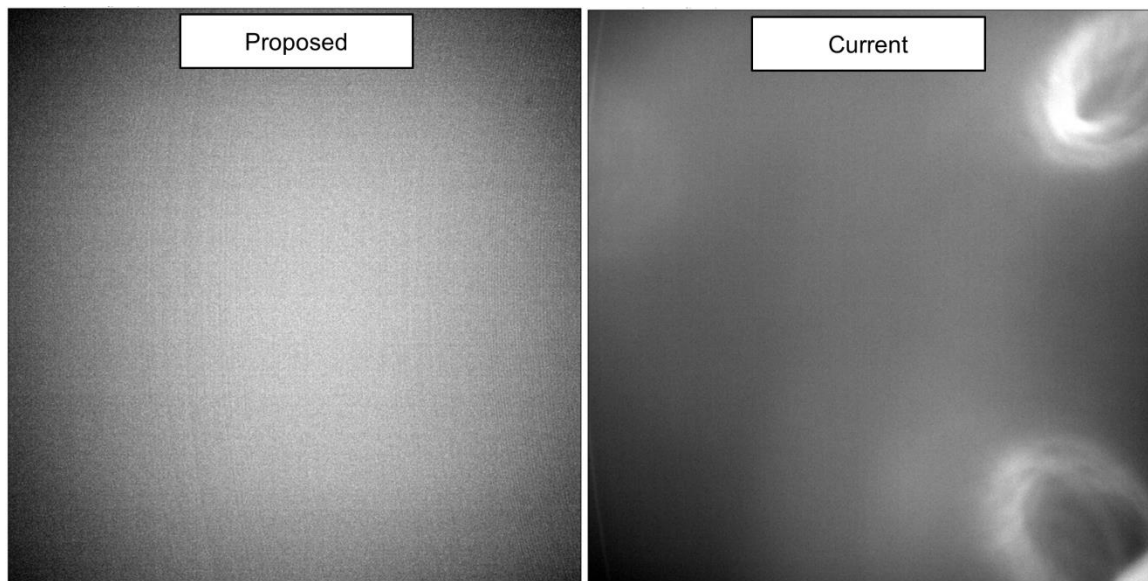


Figure 6-32 - Image Comparison

6.4. Post Improvement Run Chart and Capability Study

Although the data is limited due to the low throughput of instruments it can be seen in Figure 6-33. that the five instrument that have had both the confocal and Dichromatic wheel assembly upgrades have shown a significant increase in performance. The average result for the last five instruments is 28 compared to 1106 for the previous 52 instruments this is due to the change in design of the confocal unit and dichromatic wheel assembly.

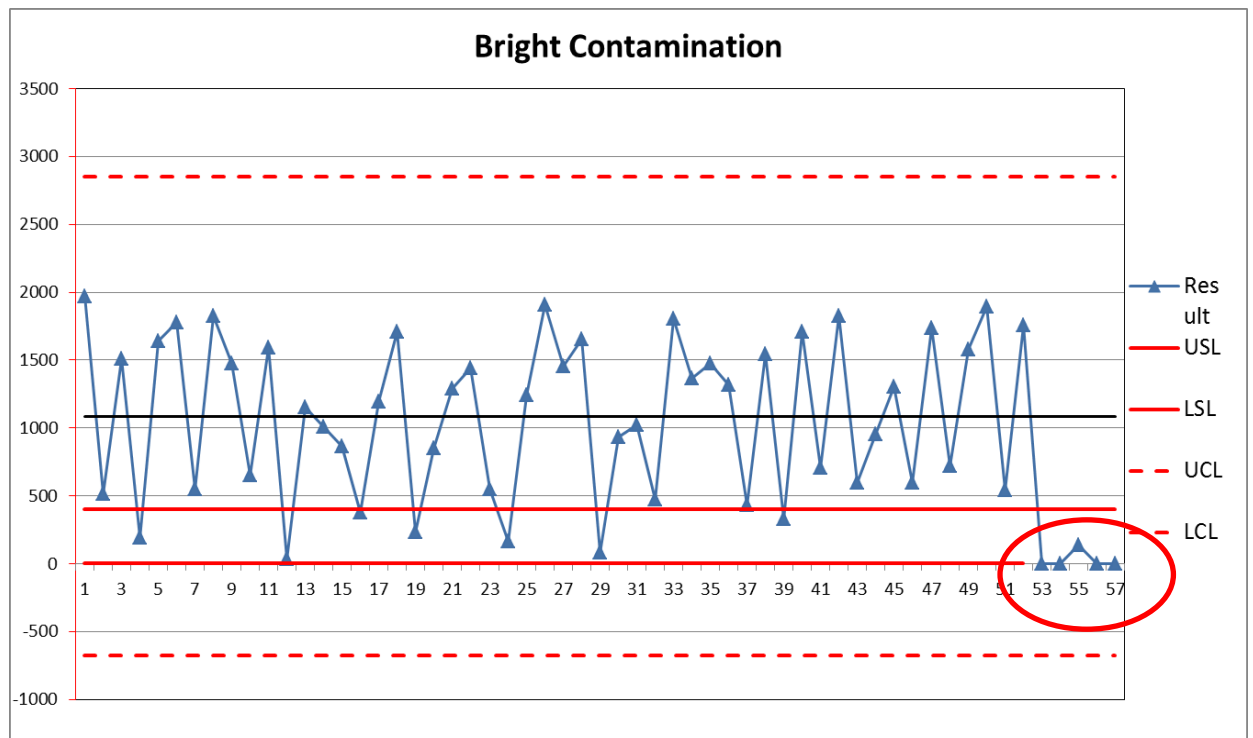


Figure 6-33 - Bright Contamination Run Chart

Using the five sets of data, a new capability study can be performed using the current process as a benchmark. From the data gathered from the five instruments post improvement, the mean can be calculated by the sum of the results divided by the number of instruments. To determine the standard deviation, the mean is subtracted from each of the data points ($X_i - U$), this result is then squared and a sum taken of all the squared results. A mean can then be taken from the sum of ($X_i - U$) squared. The square root of this mean is the standard deviation.

Mean = 28

Standard Deviation $\sigma = 164.72$

To calculate the process capability, the upper and lower specification limits as defined in the IAT are also required:

Upper Specification limit (USL) = 400

Lower Specification Limit = (LSL) = 400

This data can then be used to calculate the Cp and Cpk of the process.

Cp Calculations

$$Cp = \frac{USL - LSL}{6\sigma} = \frac{400 - 0}{6 \times 164.72}$$

$$Cp = 0.404$$

Cpk Calculations

The following two formulas can be used to calculate Cpk. The lowest of the two results is the true Cpk value.

$$Cpk = \frac{USL - Mean}{3\sigma} = \frac{400 - 28}{3 \times 163.72}$$

$$Cpk = -0.75$$

$$Cpk = \frac{Mean - LSL}{3\sigma} = \frac{28 - 0}{3 \times 164.72}$$

$$Cpk = -1.48$$

It can be seen that 0.75 is the lower of the two Cpk results. This will be considered as the Cpk for the improved process, this is considerably greater than the calculated Cpk of the original process of -0.21. Although It can be seen that this is below the Six Sigma desired value of 1.33 consideration must be given to the limited sample size and the fact that the LSL is not a lower specification rather an optimal result. The distribution of the results for the last five instruments can be seen in Figure 6-34 , not only is the distribution much tighter than the original process but also the peak of the distribution is close to zero.

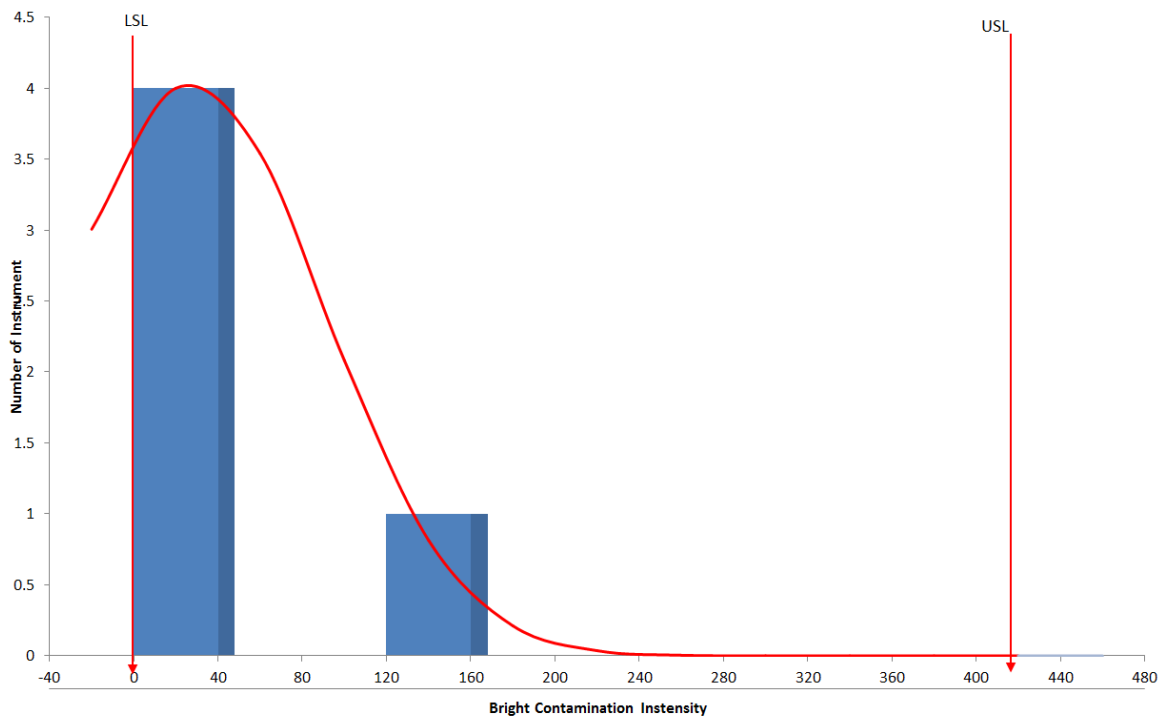


Figure 6-34 - Distribution of Results - Revised Process

6.5. Revised Transportation and Process Maps

Revised Process and Workflow maps capturing the design and process improvements within the project are shown in Figure 6-35, Figure 6-36, Figure 6-37 and Figure 6-38. The main changes to each of these maps is summarised below.

- The rework loop has been removed completely from both the confocal unit assembly and Dichromatic wheel assembly. Additionally,
- Transportation to and from the clean room to test the confocal head on the test fixture located in the main assembly area has been removed, the confocal head is now fully assembled and tested within the clean room environment prior to being sealed ready for use on an instrument.
- The Dichromatic Wheel modification process has been removed; this is no longer required and has been replaced with assembly of the aperture components.

6.5.1. Confocal Unit Assembly

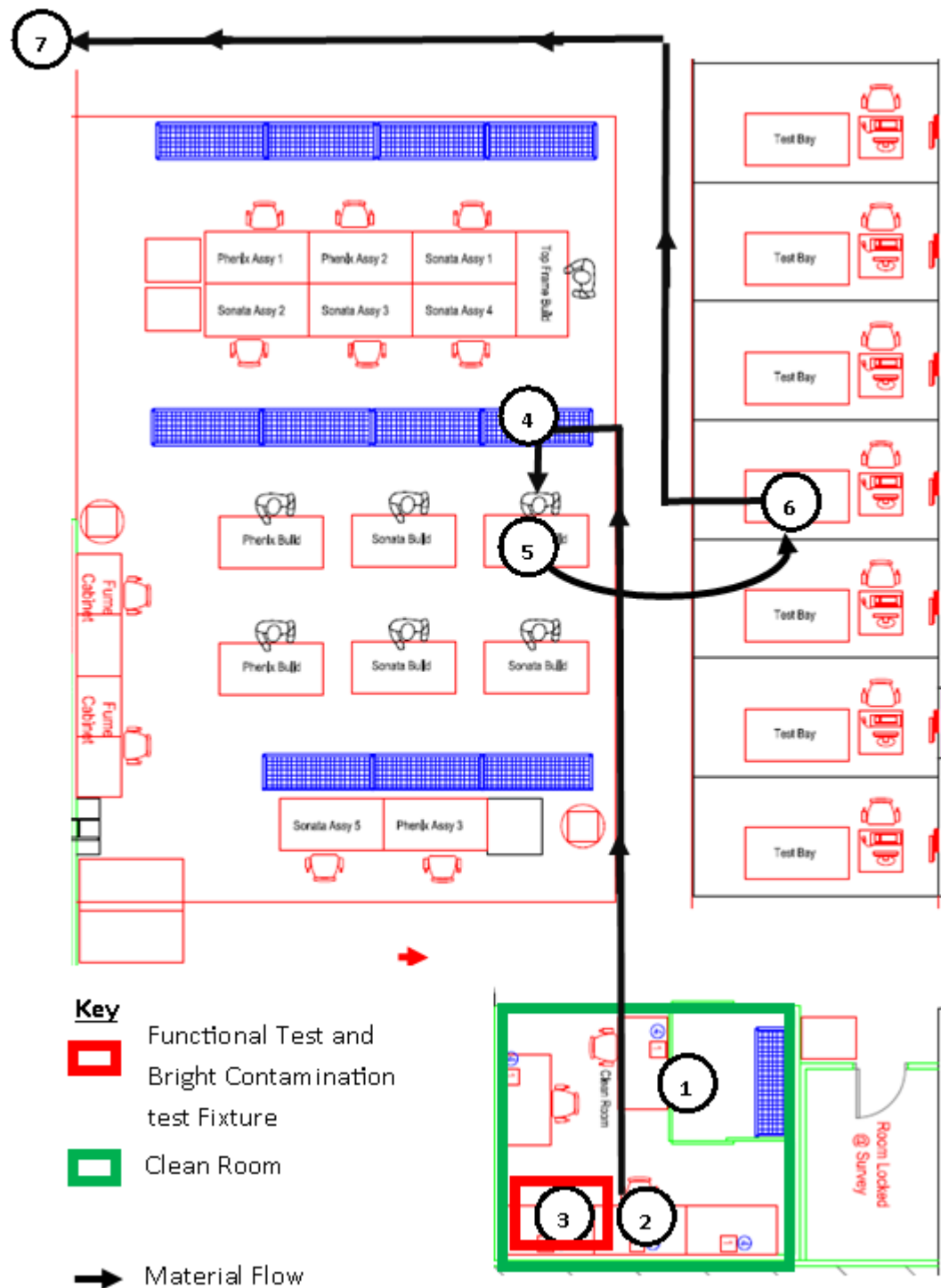


Figure 6-35 - Confocal Unit Assembly - Revised Workflow Map

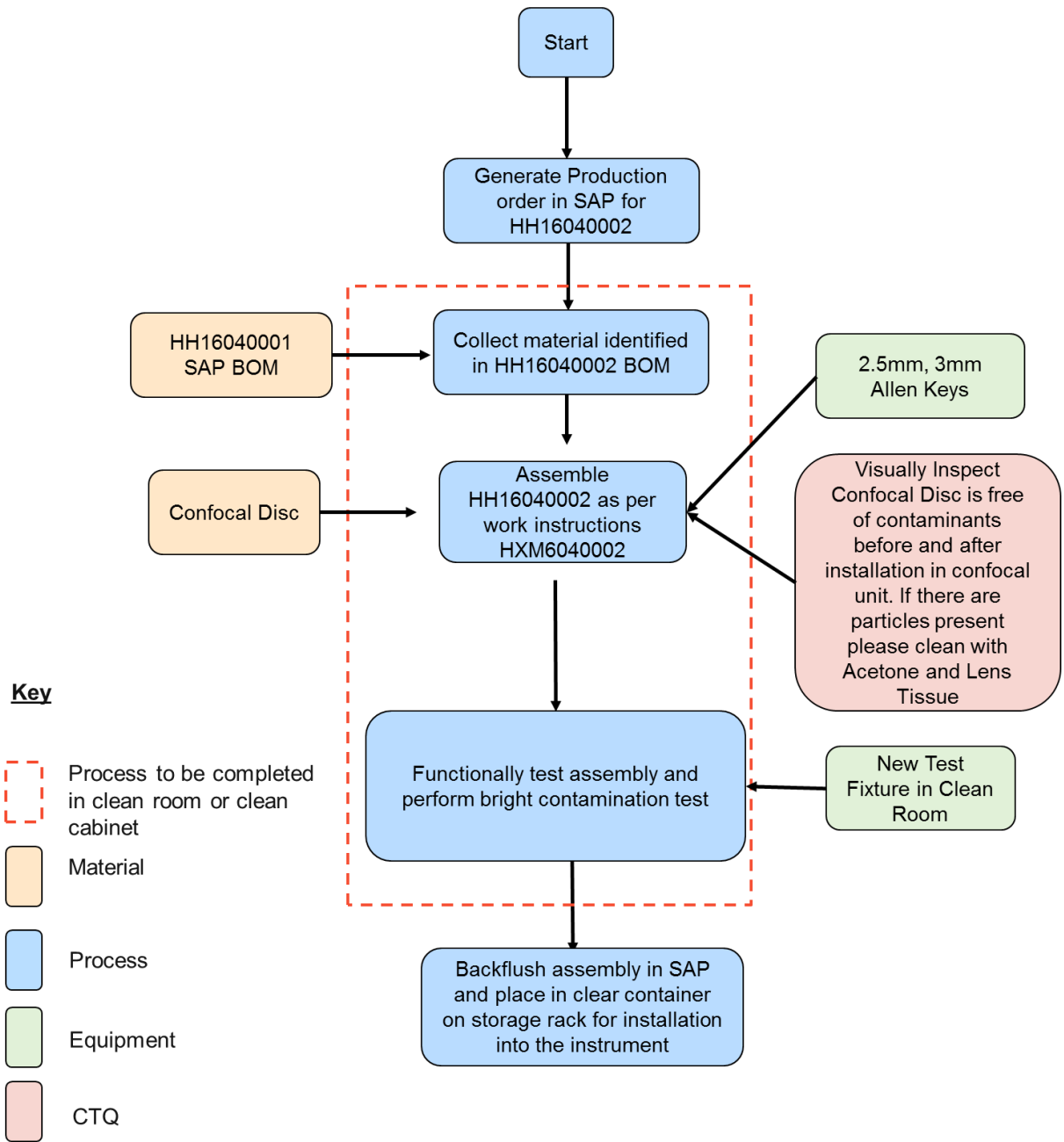


Figure 6-36 - Confocal Unit Revised Process Map

6.5.2. Dichromatic Wheel Assembly

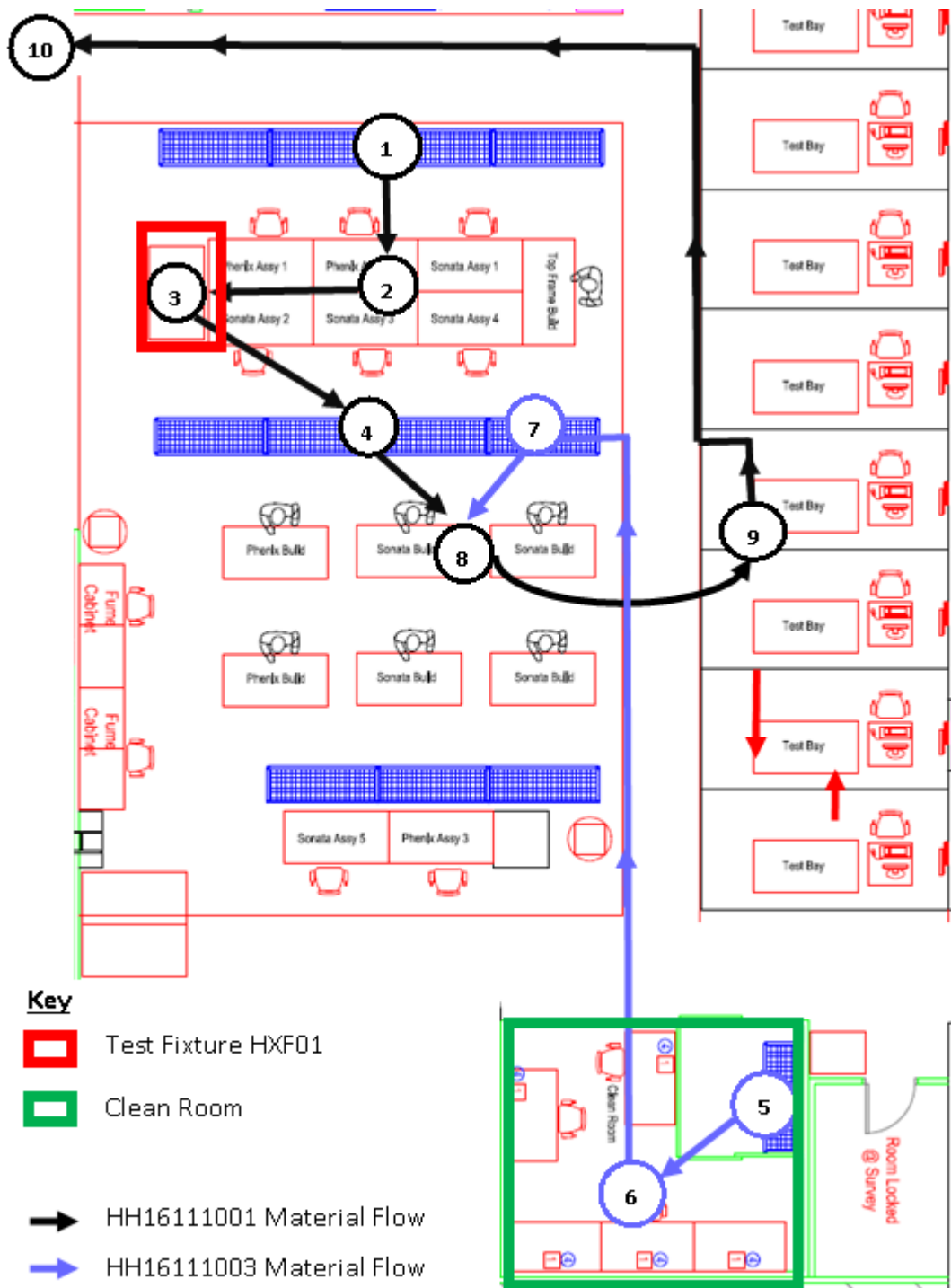


Figure 6-37 - Dichromatic Wheel Assembly Revised Workflow Map

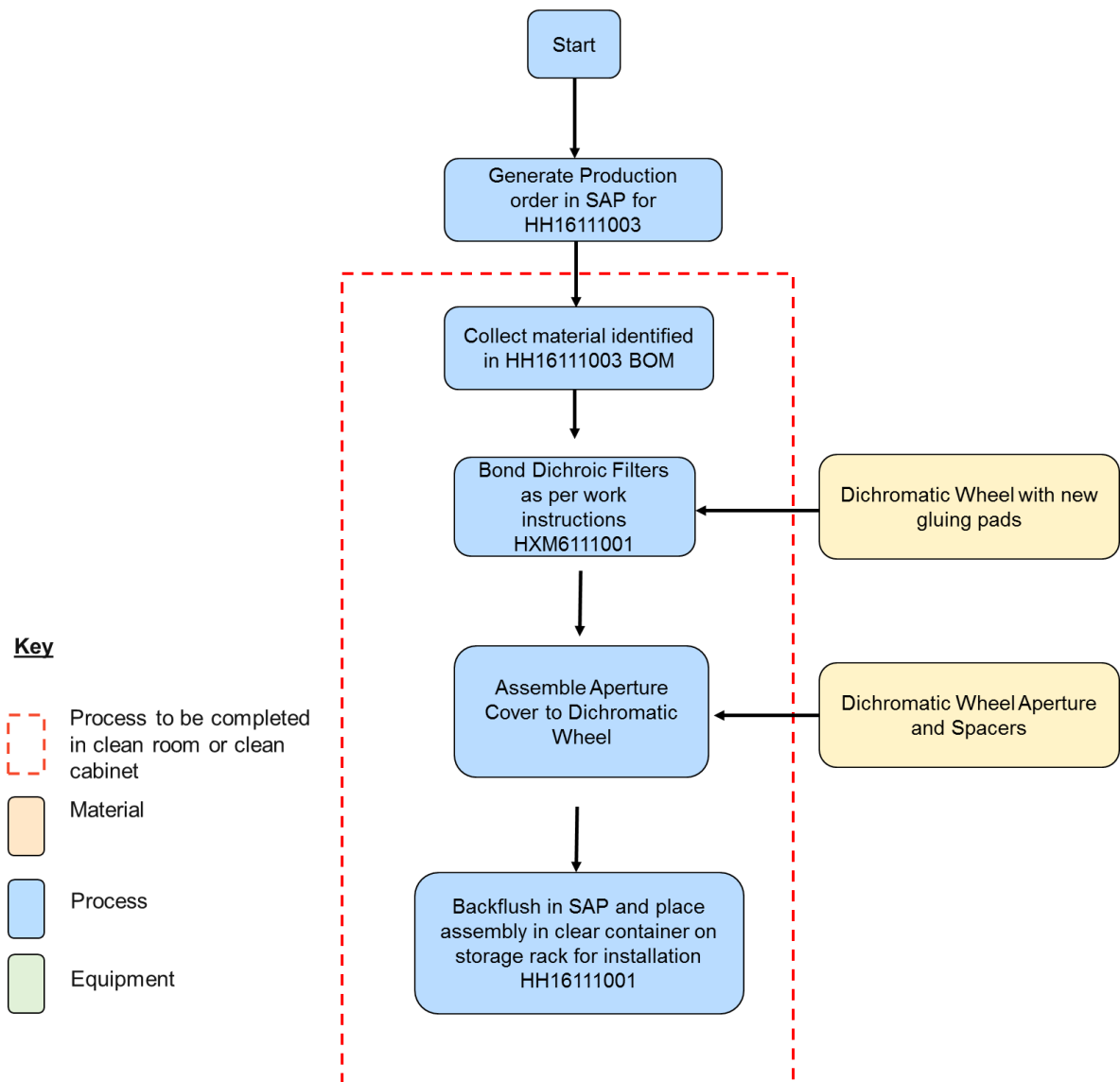


Figure 6-38 - Dichromatic Wheel Assembly Revised Process Map

6.6. Costings

The cost to the business to incorporate the changes discussed equals £263.88 per Operetta CLS instrument. This includes the additional bill of material costs for the new components used and the additional labour hours for assembly and testing. Based on 52 units per year this equals an annual additional cost of £13,721 to the cost of the goods sold. However, it must be stated that these costs were based on prototype parts, a cost based on the annual usage will

be considerably less than this. A top level breakdown of these costs can be seen in Table 6-2. A complete breakdown of these costs can be seen in Appendix G.

Table 6-2- Assembly and Labour Costs

Assembly	Cost
Dichromatic Wheel Assembly Old Design	1631.735
Dichromatic Wheel Assembly New Design	1707.217
Difference	75.4819
Confocal Unit Old Design	3526.436
Confocal Unit New Design	3714.841
Difference	188.405
Total Difference	263.8869

With a manufacturing downtime cost associated to bright contamination of £17,100.45 and warranty costs totalling £48,421.80 there is a considerable savings to be made by investing in the new process. Also taking into consideration that the Operetta CLS instruments in the field are still accumulating contamination daily as shown during the Analyse phase, additional warranty costs must be expected.

The aim of the project is to reduce the downtime in manufacturing and warranty complaints from customers due to contamination seen in the instruments optical path. The solution identified eliminates the necessity for the rework loop and also ensures that instruments being shipped do not accumulate contamination over time. Hard savings based on 2017 can be calculated as:

Total Business cost associated to contamination - Incorporation costs= Annual Hard Savings

$$£65,522.42 - £13,721 = £51,801.25$$

Design improvements to eliminate the need to modify the dichromatic wheel assembly have also decreased the process time by 208 hours per annum. Multiplying this by the allocated labour cost of £47.74 results in a labour cost saving of an additional £9929.92 on top of the £51,801.25 already discussed totalling £61,731.17.

7. Conclusion

Overall the root cause of the contamination was not a single source. "Contamination Failures" has been a common term used throughout the report as this is how the test is referred to in the IAT. It has been determined through thorough root cause analysis that actual physical contamination only accounts 50% of the rework time. The remaining 50% is due to design flaws.

By optimising the design of the optical system, and improving the workflow and assembly testing process, bright contamination artefacts can be completely eliminated resulting in a 78.5% decrease in the downtime associated to contamination failures in IAT. Further to this, design, test and process improvements have been made to ensure that the risk of additional warranty complaints due to contamination is removed.

The first objective of the project was to reduce downtime associated to contamination by 80%. The resulting saving is just short of this figure at 78.5%, decreasing the rework hours from 358.5 hours to 77 hours per annum.

The second objective was to reduce Warranty complaints to zero. The data from the proposed "sealed" confocal unit assembly satisfies this objective. Extensive testing shows no signs of contamination accumulation over time. This gives a high confidence that the proposed design will reduce warranty complaints for contamination to zero. However, this statement can only be made on future instruments that include the proposed design. With the evidence collected confirming instruments accumulate contamination through use; it is highly likely that warranty complaints will continue to occur until incorporation of the new design.

Overall the project can be deemed successful based on the success criteria outlined in the project scope. An annual saving of £61,731.17 can be realised through incorporation of the proposed designs, processes and test fixtures. This saving will be seen to increase as warranty complaints increase for instruments currently at customer sites. Although not success criteria for the project, the intangible costs must be seen as the main driver to incorporate these changes, Customer satisfaction and brand reputation are at risk with the current configuration due to the accumulation of contamination discussed. Incorporation of the proposed changes

will ensure that the customer receives an instrument with the image quality expected from a PerkinElmer product.

8. Recommendations

Incorporation of Confocal Unit Assembly Changes

It is recommended that incorporation of the outlined design, process and test process should be prioritised and implemented as soon as possible. Data from the five tested instruments shows that incorporation of the design changes for the confocal unit assembly will significantly increase the yield of the assembly for bright contamination and remove the need for the rework loop currently in process. Additionally the sealed unit does not accumulate contamination over time proving that the proposed design is far greater than the current design. Incorporation of the proposed design should be implemented as soon as possible to reduce the number of instrument in the field that will contribute to additional warranty complaints. Additional to the design changes, a refined test fixture based on the prototype test fixture to perform functional tests and bright contamination tests "off line" should also be implemented this will ensure 100% yield of the confocal unit assembly for bright contamination prior to leaving the clean room environment, and reduce the risk of exposure to dust from the manufacturing environment when functionally testing in the current test area.

For a smooth transition to using the proposed parts and engineering change must be created to incorporate the new parts into the current design. Once approval is given and a date verified to receive the new parts, standard operating procedures must be updated along with the process map. The technicians must also be trained on how to assemble the new materials and also how to test for bright contamination using the new bright contamination test fixture.

Incorporation of Dichromatic Wheel Assembly Changes

It is recommended that incorporation of the proposed design of the dichromatic wheel assembly should be prioritised and implemented as soon as possible. Data from the five tested instruments shows that incorporation of the design changes for the dichromatic wheel assembly will significantly increase the yield of the assembly for bright contamination and

remove the need for the modification process currently used and also the rework loop to rectify failed assemblies.

For a smooth transition to using the proposed parts an engineering change must be created to incorporate the new parts into the current design. Once approval is given and a date verified to receive the new parts, standard operating procedures must be updated along with the process map. The technicians must also be trained on how to assemble the new materials and the training matrix updated once complete.

Control Measures

Once incorporated the changes should be monitored to ensure that they stay in control. Bright contamination data should be recorded in an SPC chart and continually monitored for any changes i.e. negative or positive trends and step functions. The serial number in which the changes started to take affect must also be recorded. This will help ensure that the warranty complaints can be monitored before and after the changes occurred.

Further Improvements

The improvements discussed through the project relate to approximately 80% of the downtime attributed to contamination. To eliminate this completely the downtime, further resource needs to be allocated to look at the failure modes outside of the scope of this project for example camera and optical bench contamination. This work can be completed offline with the use of the bright contamination test fixture to verify, measure and analyse the contamination seen on these assemblies. Although the project may not seem feasible due to the low amount of downtime recorded against these failures, intangible costs must be considered such as customer satisfaction and brand reputation.

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10. Appendices

Appendix A - Measurement System Analysis, Gauge R&R Report

MEASUREMENT SYSTEMS ANALYSIS													
REPEATABILITY & REPRODUCIBILITY											DATE 01/12/2017		
GAGE NAME Operetta CLS						CHARACTERISTIC Bright Contamination							
GAGE TYPE						SPECIFICATION 575.9							
GAGE NUMB 1600L17057						TEST NUMBE							
APPRaiser A NAME Mark Sidaway						APPRaiser B NA Dewi Williams							
SAMPLE SIZ 6						APPRaiser 3						APPRaiser C NA Martyn Dolby	
TRIALS 2													
Appraiser/ Trial #	1	2	3	4	5	6						AVG	
A 1	572	578	568	585	571	575						574.833	
A 2	575	573	570	582	576	572						574.667	
AVG'S	573.500	575.500	569.000	583.500	573.500	573.500						Xa 574.750	
Range	3.000	5.000	2.000	3.000	5.000	3.000						Ra 3.500	
B 1	571	568	580	579	567	572						572.833	
B 2	575	576	583	575	570	574						575.500	
AVG'S	573.000	572.000	581.500	577.000	568.500	573.000						Xb 574.167	
Range	4.000	8.000	3.000	4.000	3.000	2.000						Rb 4.000	
C 1	572	580	580	571	568	581						575.333	
C 2	572	578	575	574	567	579						574.167	
AVG'S	572.000	579.000	577.500	572.500	567.500	580.000						Xc 574.750	
Range	0.000	2.000	5.000	3.000	1.000	2.000						Rc 2.167	
Part Average	572.8333	575.5000	576.0000	577.6667	569.8333	575.5000						X 574.556	
												Rp 7.833	
RANGE VARIATION													
Ra	3.500	# Trials		D4	Rdoublebar x (D4) =		UCL _R						
Rb	4.000	2		3.267	3.2222		3.267 =		10.527				
Rc	2.167	3		2.575	Note: LCL is zero with < 8 trials								
SUM	9.667	# Trials		A2	Xbar + (Rbar x A2) =		UCL _x						
Rdoublebar	3.2222	2		1.880	574.5556		3.2222		1.88 =		580.613		
		3		1.023	Xbar - (Rbar x A2) =		LCL _x						
					574.5556		3.2222		1.88 =		568.498		
Max. X	574.750				Tolerance =		57.5		# Trials -		6		
Min. X	574.167								# Appr. -		3		
X Diff	0.583												
REPEATABILITY - EQUIPMENT VARIATION (EV)													
EV = R1XK1						K1(2 trials)=		4.56		% EV = 100 (EV/TV)			
EV = 14.6933										% EV = 68.96%			
										Percent of Tolerance: 100(EV/Tol) 25.6%			
REPRODUCIBILITY - APPRAISER VARIATION (AV)													
AV = SQ. ROOT ((X DIFF X K2)SQUARED - (EV SQUARED/NR))						K2(3 appraisers)=		2.70		% AV = 100(AV/TV)			
AV = 3.08439										% AV = 14.48%			
										Percent of Tolerance: 100(AV/Tol) 5.4%			
REPEATABILITY & REPRODUCIBILITY (R&R)													
R&R = SQ. ROOT (EV SQUARED + AV SQUARED)										% R&R = 100(R&R/TV)			
R&R = 15.0136										% R&R = 70.46%			
										Percent of Tolerance: 100(R&R/Tol) 26.1%			
PART VARIATION (PV)													
PV = Rp x K3						PARTS		K3		% PV = 100(PV/TV)			
PV = 15.1183						6		1.93		% PV = 70.96%			
										Percent of Tolerance: 100(PV/Tol) 26.3%			
TOTAL VARIATION (TV)													
TV = SQ. ROOT(R&R SQUARED + PV SQUARED)													
TV = 21.3066													

Appendix B - Process Capability Raw Data

Data	Mean	Data-Mean	Squared
472	762.53	-290.53	84407.6809
0	762.53	-762.53	581452.0009
340	762.53	-422.53	178531.6009
1234	762.53	471.47	222283.9609
663	762.53	-99.53	9906.2209
1901	762.53	1138.47	1296113.941
1440	762.53	677.47	458965.6009
703	762.53	-59.53	3543.8209
790	762.53	27.47	754.6009
478	762.53	-284.53	80957.3209
817	762.53	54.47	2966.9809
453	762.53	-309.53	95808.8209
211	762.53	-551.53	304185.3409
360	762.53	-402.53	162030.4009
464	762.53	-298.53	89120.1609
435	762.53	-327.53	107275.9009
538	762.53	-224.53	50413.7209
1979	762.53	1216.47	1479799.261
1000	762.53	237.47	56392.0009
0	762.53	-762.53	581452.0009
1572	762.53	809.47	655241.6809
775	762.53	12.47	155.5009
84	762.53	-678.53	460402.9609
1370	762.53	607.47	369019.8009
1008	762.53	245.47	60255.5209
29	762.53	-733.53	538066.2609
145	762.53	-617.53	381343.3009
1159	762.53	396.47	157188.4609
0	762.53	-762.53	581452.0009
1270	762.53	507.47	257525.8009
1574	762.53	811.47	658483.5609
761	762.53	-1.53	2.3409
0	762.53	-762.53	581452.0009
1589	762.53	826.47	683052.6609
105	762.53	-657.53	432345.7009
1047	762.53	284.47	80923.1809
900	762.53	137.47	18898.0009
1040	762.53	277.47	76989.6009
524	762.53	-238.53	56896.5609
418	762.53	-344.53	118700.9209

Sum
32000132.91
Mean
320001.3291
Standard Deviation
565.6865997

LSL
0
USL
400

Cp
0.117850885

Cpk
-0.213622408
0.449324178

87	762.53	-675.53	456340.7809
170	762.53	-592.53	351091.8009
1388	762.53	625.47	391212.7209
1390	762.53	627.47	393718.6009
1914	762.53	1151.47	1325883.161
1298	762.53	535.47	286728.1209
1687	762.53	924.47	854644.7809
0	762.53	-762.53	581452.0009
1266	762.53	503.47	253482.0409
1076	762.53	313.47	98263.4409
1705	762.53	942.47	888249.7009
1631	762.53	868.47	754240.1409
1427	762.53	664.47	441520.3809
503	762.53	-259.53	67355.8209
1661	762.53	898.47	807248.3409
1238	762.53	475.47	226071.7209
945	762.53	182.47	33295.3009
633	762.53	-129.53	16778.0209
1158	762.53	395.47	156396.5209
202	762.53	-560.53	314193.8809
675	762.53	-87.53	7661.5009
0	762.53	-762.53	581452.0009
623	762.53	-139.53	19468.6209
189	762.53	-573.53	328936.6609
1140	762.53	377.47	142483.6009
1124	762.53	361.47	130660.5609
1100	762.53	337.47	113886.0009
99	762.53	-663.53	440272.0609
750	762.53	-12.53	157.0009
1340	762.53	577.47	333471.6009
1276	762.53	513.47	263651.4409
287	762.53	-475.53	226128.7809
877	762.53	114.47	13103.3809
506	762.53	-256.53	65807.6409
273	762.53	-489.53	239639.6209
124	762.53	-638.53	407720.5609
9	762.53	-753.53	567807.4609
1739	762.53	976.47	953493.6609
360	762.53	-402.53	162030.4009
1135	762.53	372.47	138733.9009
42	762.53	-720.53	519163.4809
454	762.53	-308.53	95190.7609
93	762.53	-669.53	448270.4209
0	762.53	-762.53	581452.0009
1105	762.53	342.47	117285.7009
347	762.53	-415.53	172665.1809
0	762.53	-762.53	581452.0009
450	762.53	-312.53	97675.0009
993	762.53	230.47	53116.4209

Appendix C - Correlation Study

xi	$\bar{x}$	xi - $\bar{x}$	(xi - $\bar{x}$)^2	yi	$\bar{y}$	yi - $\bar{y}$	(yi - $\bar{y}$)^2		(xi - $\bar{x}$)(yi - $\bar{y}$)	
100	657.333	-557.333	310620.0729	0	237.916	-237.916	56604.02306		132598.438	
200	657.333	-457.333	209153.4729	0	237.916	-237.916	56604.02306		108806.838	
300	657.333	-357.333	127686.8729	50	237.916	-187.916	35312.42306		67148.58803	
480	657.333	-177.333	31446.99289	125	237.916	-112.916	12750.02306		20023.73303	
520	657.333	-137.333	18860.35289	150	237.916	-87.916	7729.223056		12073.76803	
530	657.333	-127.333	16213.69289	200	237.916	-37.916	1437.623056		4827.958028	
700	657.333	42.667	1820.472889	300	237.916	62.084	3854.423056		2648.938028	
800	657.333	142.667	20353.87289	330	237.916	92.084	8479.463056		13137.34803	
920	657.333	262.667	68993.95289	350	237.916	112.084	12562.82306		29440.76803	
1017	657.333	359.667	129360.3509	400	237.916	162.084	26271.22306		58296.26603	
1121	657.333	463.667	214987.0869	450	237.916	212.084	44979.62306		98336.35203	
1200	657.333	542.667	294487.4729	500	237.916	262.084	68688.02306		142224.338	
		Σ	1443984.667			Σ	335272.9167	Σ	689563.3333	
									Correlation	0.991046

Appendix D - Window Specification

1.1 Intended Use

The function of this quartz window in the CU is to transmit excitation and detection light and seal the CU dustproof.

1.2 General Description

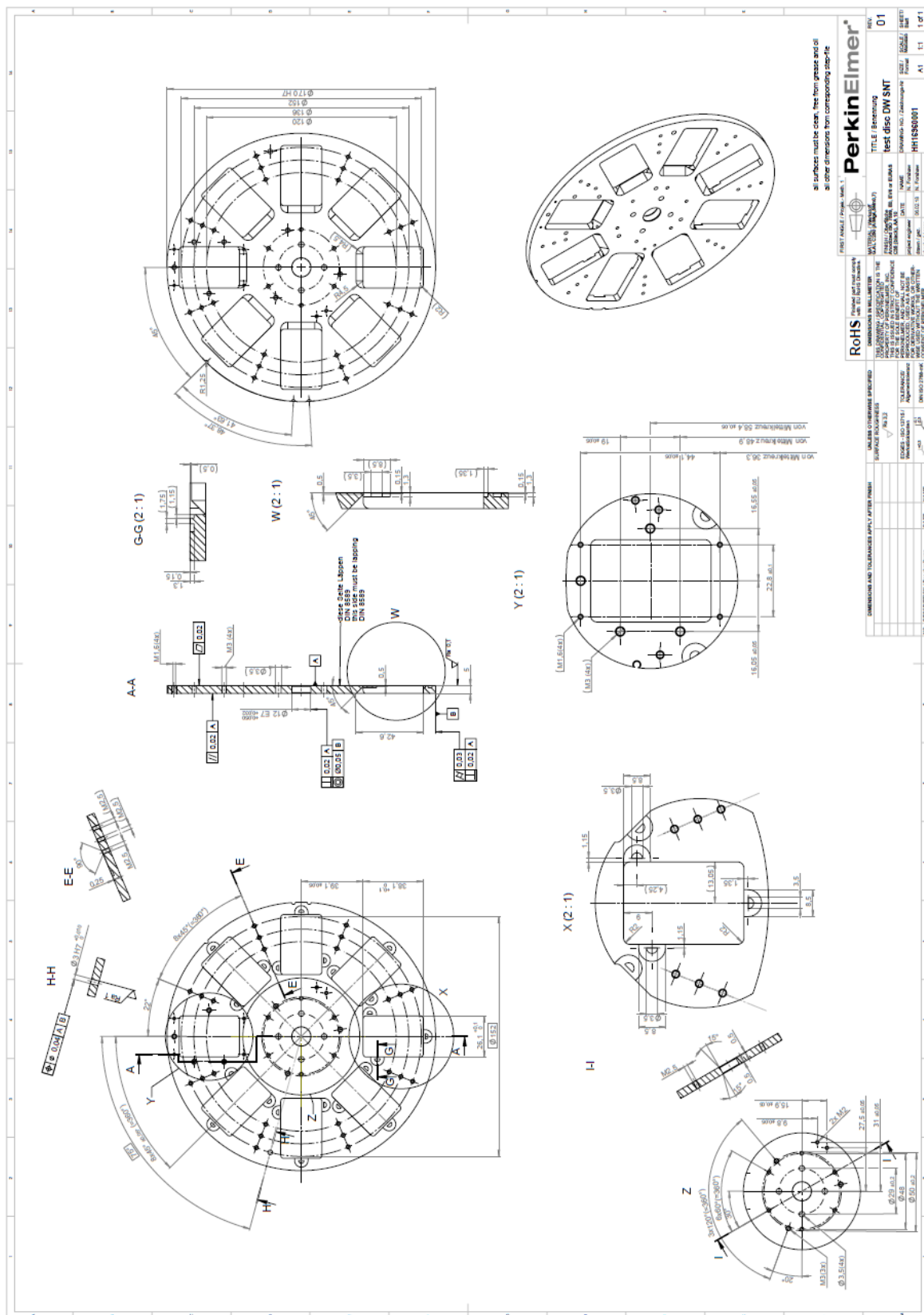
The substrate material shall be chosen such that the filter maintains its optical performance over the operating temperature range, environmental conditions and product lifetime. The quartz plate shall not introduce any measurable degradation to the quality of the laser wavefront.

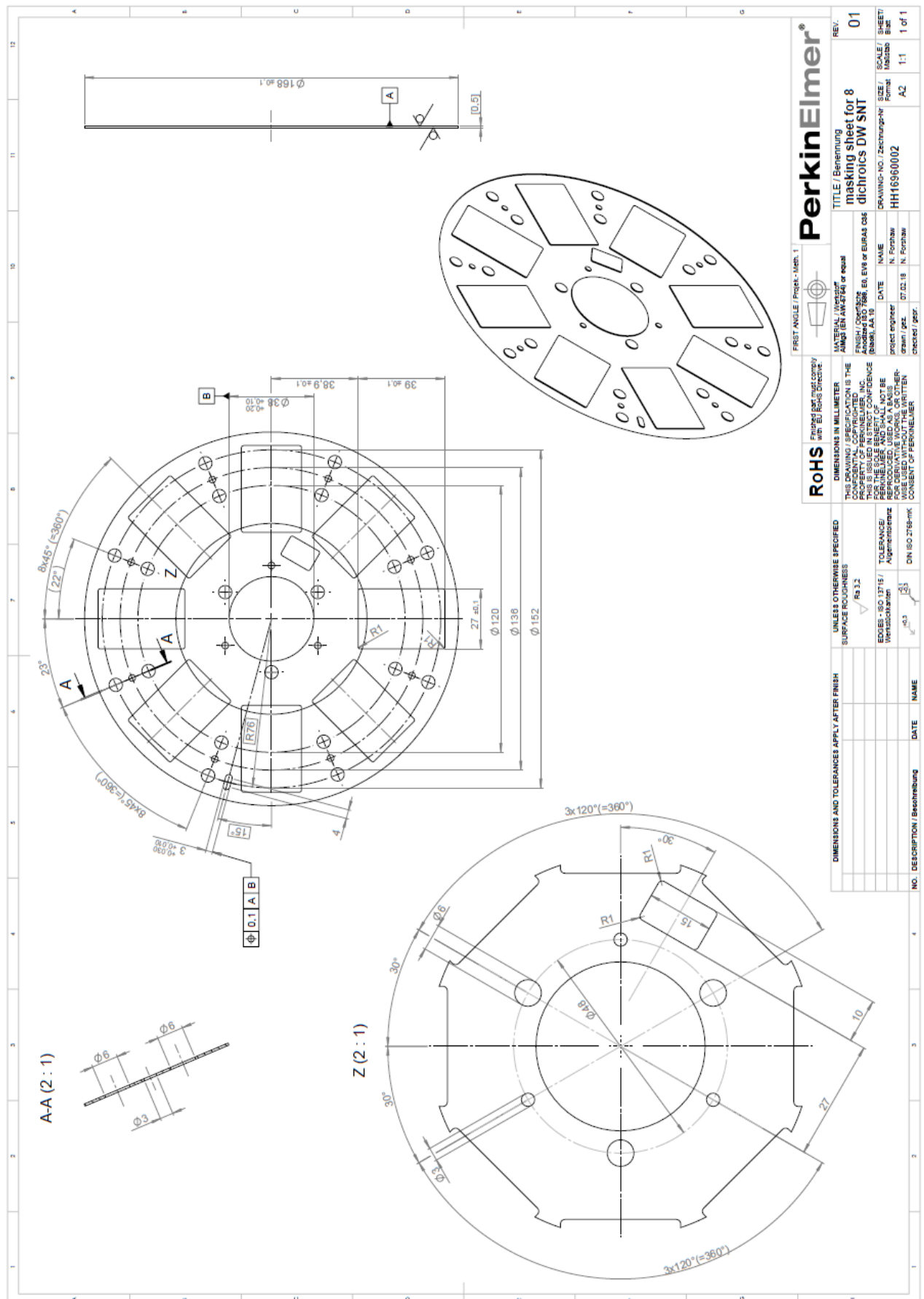
Laser light entering the plate may not excite fluorescence of the substrate.

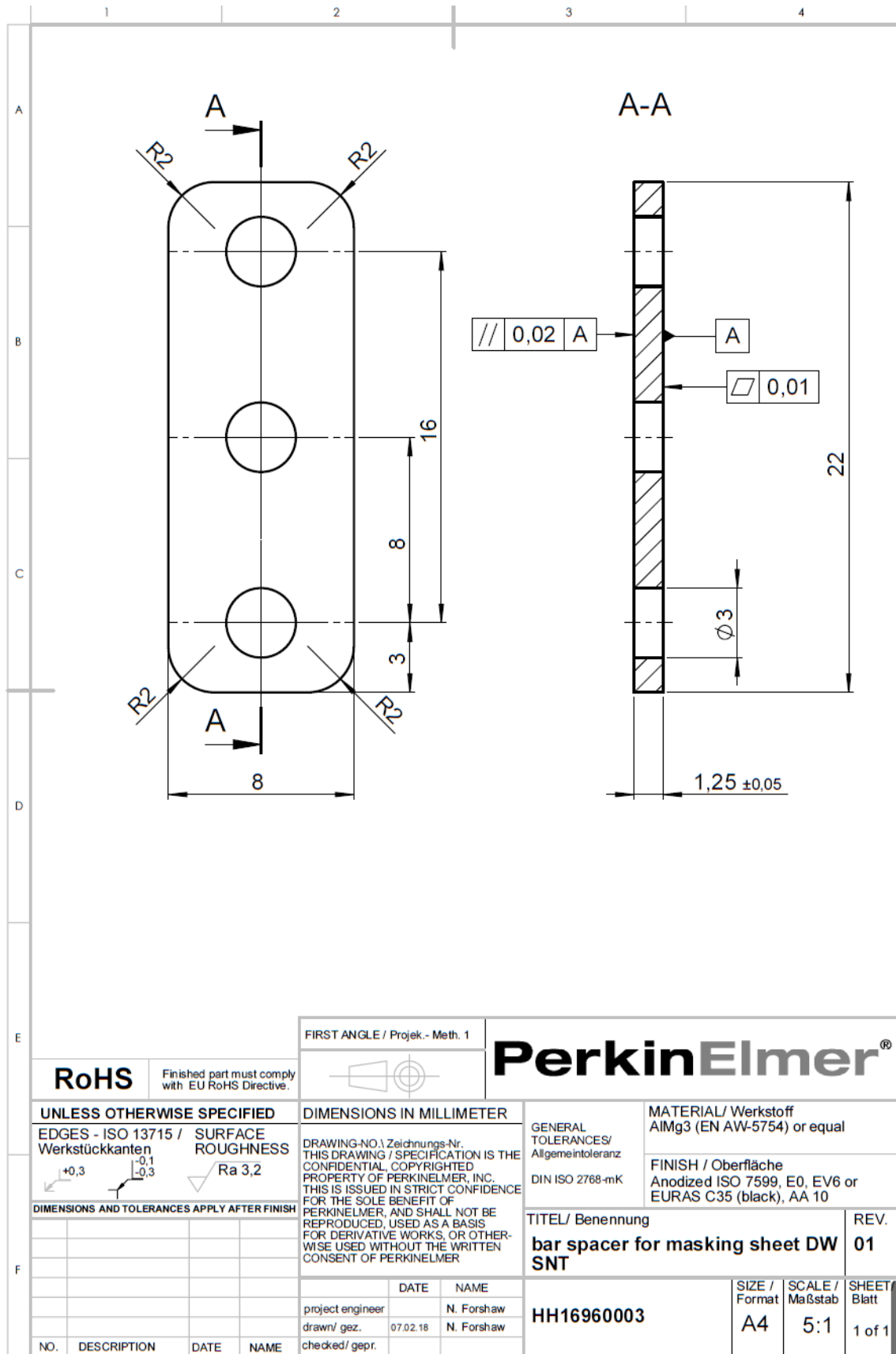
The plate will be mounted into an aluminium carrier held by a retaining ring.

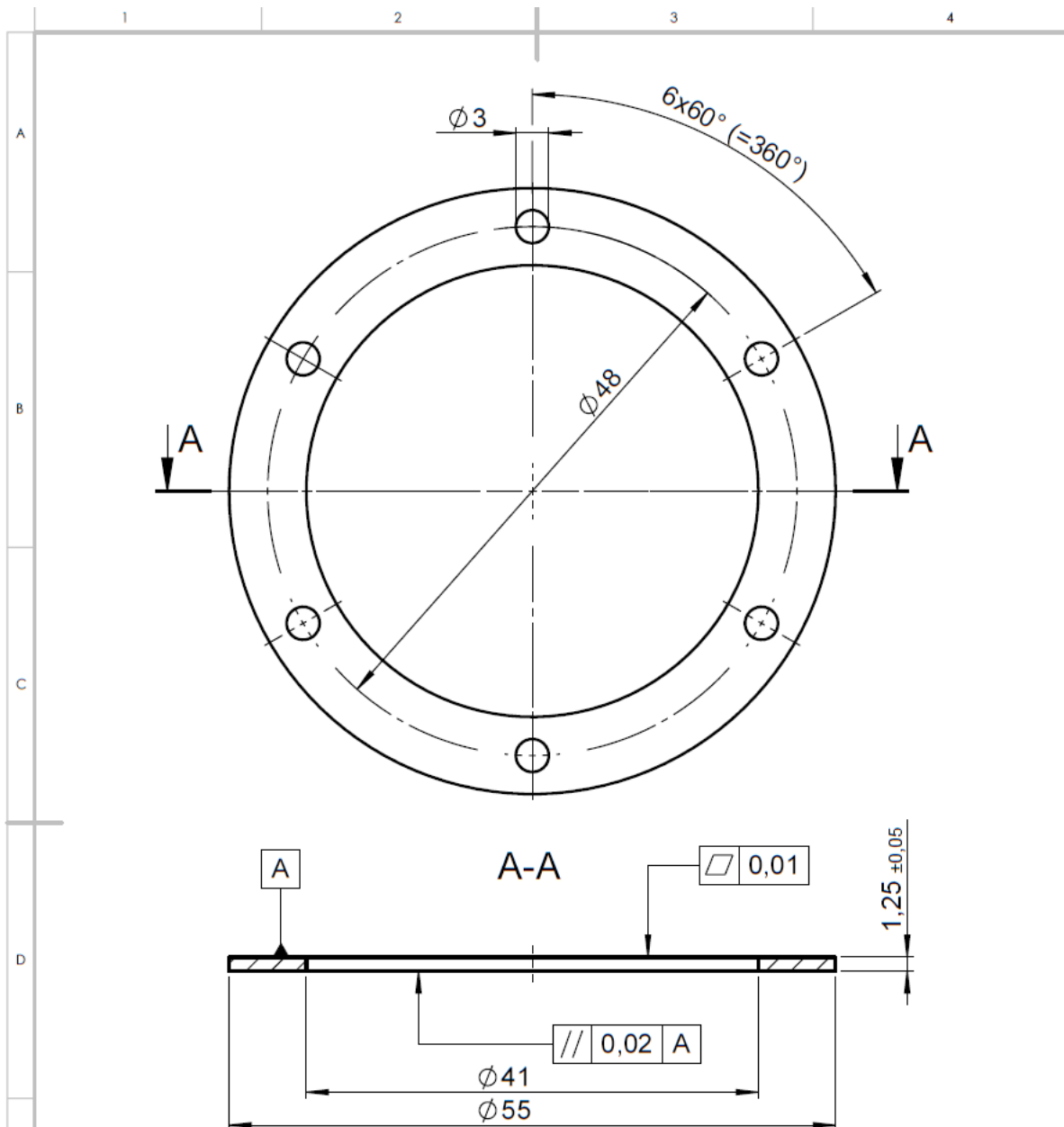
2. Specific Requirements

ID	Parameter Description	Requirement	Tolerance
2.1	Specification of component		
2.1.1	Substrate material	Suprasil 2	360-800nm
2.1.2	Dimension	Ø38mm	+0.1/-0.1mm
2.1.3	Thickness	1mm	±0.2mm
2.1.4	Wedge Error	3'	
2.1.5	clear aperture	>Ø35mm centered	
2.2	Surface Quality		
2.2.1	Surface defects	20/10	MIL-PRF-13830B
2.2.2	Transmitted wavefront quality	<λ (@633nm)	Over clear aperture
2.2.3	Surface gradients discontinuities	None	
2.3	Environmental conditions		
2.3.1	Temperature		
	- Operation	15-45°C	
	- Storage	-25-60°C	
	- Transport	-25-60°C	
2.3.2	Humidity		
	- Operation	30%-75%	
	- Storage	5%-90%	
	- Transport	5%-90%	
2.3.3	Shock	20g	
2.4	Reliability		
2.4.1	Life	5 years	
2.5	Cleaning		
2.5.1	Plate shall withstand occasional cleaning with Iso-Propyl Alcohol, Methanol, Ethanol, Water, or Acetone.		
2.5.2	Plate should not require cleaning immediately after removal from packaging.		



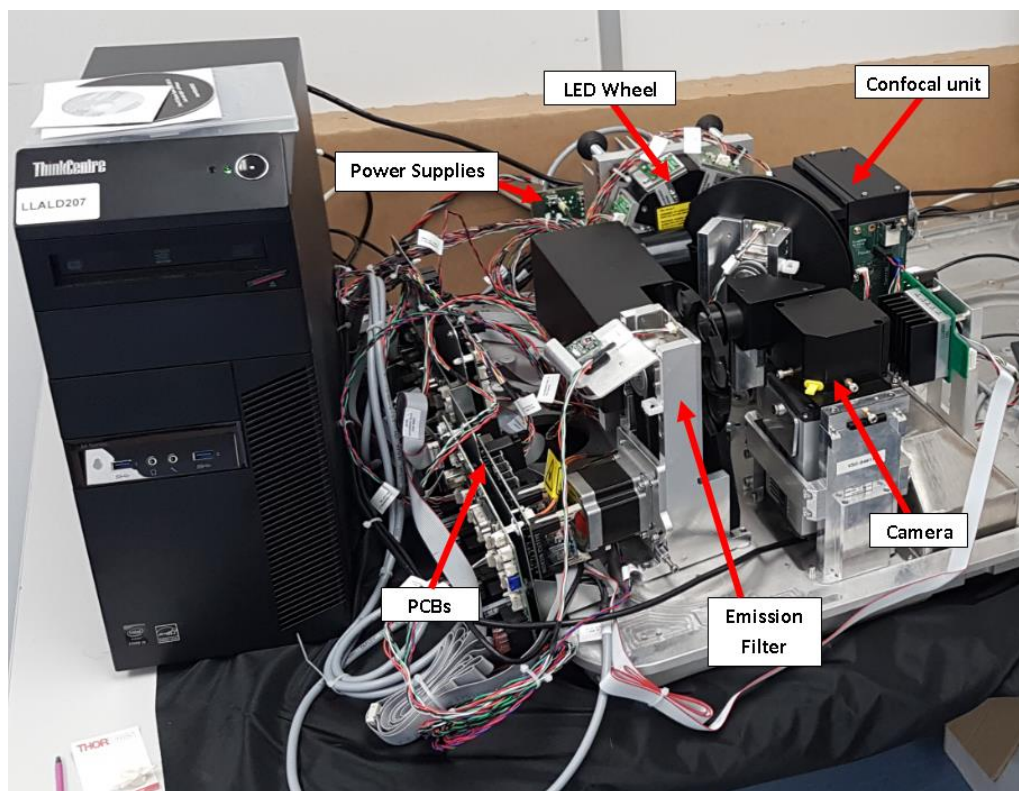


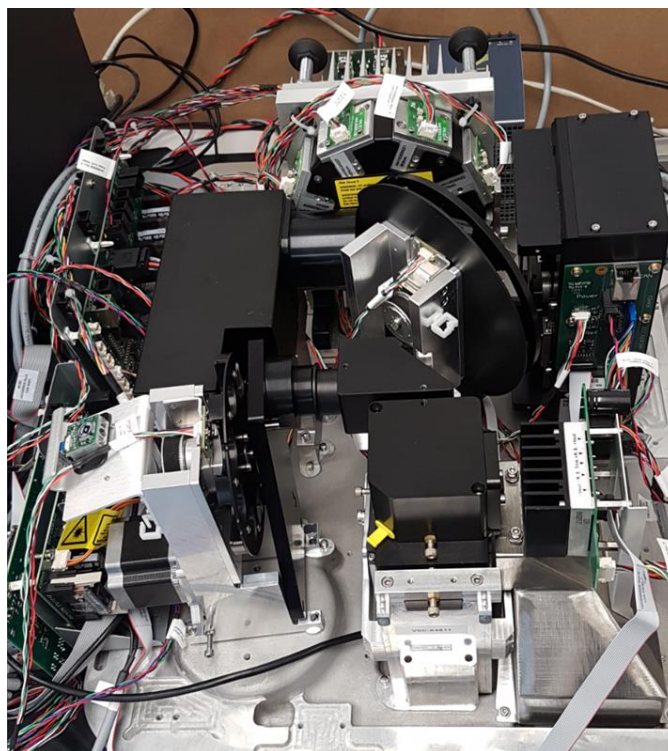


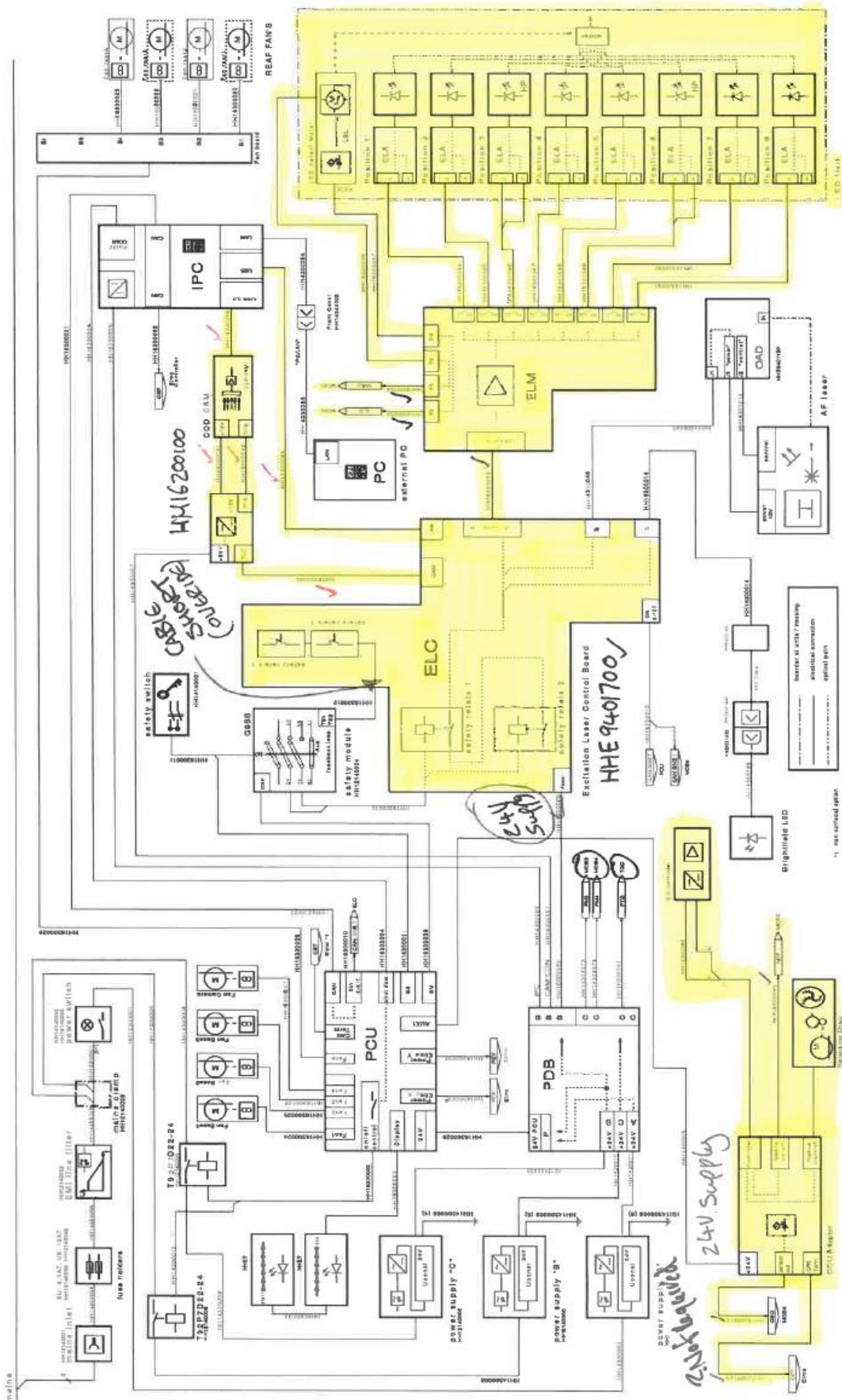


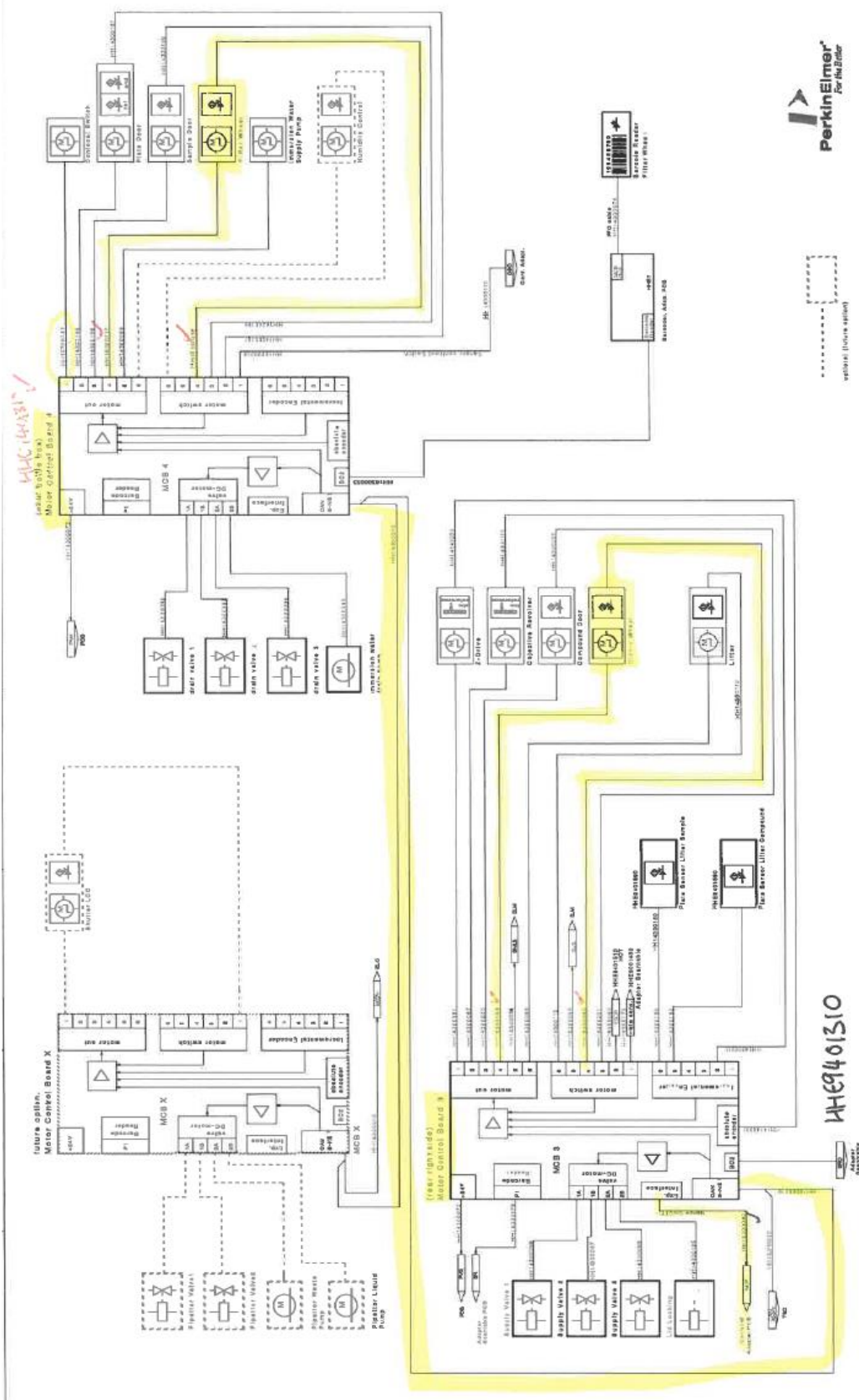
RoHS Finished part must comply with EU RoHS Directive.		FIRST ANGLE / Projek. - Meth. 1		PerkinElmer®	
UNLESS OTHERWISE SPECIFIED EDGES - ISO 13715 / SURFACE ROUGHNESS Werkstückkanten $+0,3$ $-0,1$ $-0,3$ $Ra 3,2$		DIMENSIONS IN MILLIMETER DRAWING-NO. / Zeichnungs-Nr. THIS DRAWING / SPECIFICATION IS THE CONFIDENTIAL, COPYRIGHTED PROPERTY OF PERKINELMER, INC. THIS IS ISSUED IN STRICT CONFIDENCE FOR THE SOLE BENEFIT OF PERKINELMER, AND SHALL NOT BE REPRODUCED, USED AS A BASIS FOR DERIVATIVE WORKS, OR OTHERWISE USED WITHOUT THE WRITTEN CONSENT OF PERKINELMER.		GENERAL TOLERANCES / Allgemeintoleranz DIN ISO 2768-mK	
DIMENSIONS AND TOLERANCES APPLY AFTER FINISH		MATERIAL / Werkstoff AlMg3 (EN AW-5754) or equal		FINISH / Oberfläche Anodized ISO 7599, E0, EV6 or EURAS C35 (black), AA 10	
NO. DESCRIPTION DATE NAME		TITEL / Benennung ring spacer for masking sheet DW SNT		REV. 01	
project engineer N. Forshaw drawn / gez. 07.02.18 N. Forshaw checked / gepr.		HH16960004		SIZE / Format A4	SCALE / Maßstab 2:1
				SHEET / Blatt 1 of 1	

Appendix F - Confocal Unit Test Fixture









Appendix G - Costings

Confocal Unit Assembly - Original Design						
Part Number	Qty	UOM	Cost	Currency	Description	Total Cost
HH16300005	1	EA	12.35	GBP	cbl Power Confocal Adapter	12.35
HH16300019	1	EA	10.43	GBP	cbl Sensor Confocal Switch	10.43
HH16300040	1	EA	5.83	GBP	cbl Nipkow ON/OFF	5.83
HH16300043	1	EA	9.78	GBP	cbl SM Confocal Switch	9.78
HH16300058	1	EA	9.89	GBP	cbl Nipkow Control Internal	9.89
HH12030052	1	EA	1,788.66	GBP	Operetta pinhole disc	1788.66
HH16140007	1	EA	140.26	GBP	MODF Nipkow Controller mcDSA-E60	140.26
HHE9401680	1	EA	40.74	GBP	PCBT Confocal Unit Interface CUI	40.74
HH12030040	1	EA	22.92	GBP	nipkow disc mounting plate	22.92
HH12030041	1	EA	73.29	GBP	Nipkow disc adapter	73.29
HH12080537	0.8	EA	1.44	GBP	Neoprene_Sealing_3x10mm	1.152
HH12140061	1	EA	75.79	GBP	Nipkow disc motor ebmpapst ECA 18.08	75.79
HH14040010	2	PC	145.72	GBP	set Minirail MNNXL 7-100-G1-V1	291.44
HH14040044	1	EA	0.13	GBP	Cable strap mount PA66 15x10x7 mm	0.13
HH16040003	1	EA	5.29	GBP	cover front CU SNT	5.29
HH16040006	1	EA	4.2	GBP	Cable holder CU SNT	4.2
HH16040010	1	EA	27.28	GBP	confocal switch holding plate CU SNT	27.28
HH16040011	1	EA	166.97	GBP	confocal unit main body CU-SNT	166.97
HH16040017	1	EA	3.76	GBP	screw foot 2 CU SNT	3.76
HH16040018	1	EA	2.41	GBP	cover rear CU SNT	2.41
HH16040020	1	EA	7.22	GBP	screw foot CU SNT	7.22
HH16040080	2	EA	20.64	GBP	cover front holder CU SNT	41.28
HH16040103	1	EA	0.85	GBP	light barrier flange CU SNT	0.85
HH16040106	1	EA	15.78	GBP	rectangular blocker CU SNT	15.78
HH16040107	1	EA	1.28	GBP	cover top CU SNT	1.28
HH16040108	1	EA	3.7	GBP	beampath capsule CU SNT	3.7
HH16040014	1	PC	40.84	GBP	Window holder tube CU SNT Original Design	14.18
HH16041006	1	EA	3.19	GBP	sliding bush CU SNT	3.19
HH16041008	1	EA	4.54	GBP	adhesive sealing gasket CU SNT	4.54
HHN1400005	2	EA	3.24	GBP	Nylon tip set screw SC8M-5_M3_L=3,8mm	6.48
HHN1400009	1	EA	2.24	GBP	NylontipsetscrewSC8M-9_M4_L=5,2mm	2.24
HH14040006	1	PC	276.18	GBP	Spindle and nut LAF6-xxx customn design	276.18
HH14040009	1	PC	2.65	GBP	spindle adapter tube CCU OFD	2.65
HH14040014	1	PC	190.03	GBP	spindle flange bearing FK4 from THK	190.03
HH14040061	1	PC	22.48	GBP	flexible coupling D1=3mm D2=5mm L=23.5mm	22.48
HH16040100	1	EA	10.71	GBP	carrier CU SNT	10.71
HH16140004	1	EA	23.42	GBP	Stepper motor 42mm HT PKP243D15A	23.42
LABOR	2.12	H	56.65	GBP	Assemble and test kit	120.098
OVERHD	2.12	H	41.3	GBP	Assemble and test kit	87.556
						3526.436

Confocal Unit Assembly - New Design						
Part Number	Qty	UOM	Cost	Currency	Description	Total Cost
HH16300005	1	EA	12.35	GBP	cbl Power Confocal Adapter	12.35
HH16300019	1	EA	10.43	GBP	cbl Sensor Confocal Switch	10.43
HH16300040	1	EA	5.83	GBP	cbl Nipkow ON/OFF	5.83
HH16300043	1	EA	9.78	GBP	cbl SM Confocal Switch	9.78
HH16300058	1	EA	9.89	GBP	cbl Nipkow Control Internal	9.89
HH12030052	1	EA	1,788.66	GBP	Operetta pinhole disc	1788.66
HH16140007	1	EA	140.26	GBP	MODF Nipkow Controller mcDSA-E60	140.26
HHE9401680	1	EA	40.74	GBP	PCBT Confocal Unit Interface CUI	40.74
HH12030040	1	EA	22.92	GBP	nipkow disc mounting plate	22.92
HH12030041	1	EA	73.29	GBP	Nipkow disc adapter	73.29
HH12080537	0.8	EA	1.44	GBP	Neoprene_Sealing_3x10mm	1.152
HH12140061	1	EA	75.79	GBP	Nipkow disc motor ebmpapst ECA 18.08	75.79
HH14040010	2	PC	145.72	GBP	set Minirail MNNXL 7-100-G1-V1	291.44
HH14040044	1	EA	0.13	GBP	Cable strap mount PA66 15x10x7 mm	0.13
HH16040003	1	EA	5.29	GBP	cover front CU SNT	5.29
HH16040006	1	EA	4.2	GBP	Cable holder CU SNT	4.2
HH16040010	1	EA	27.28	GBP	confocal switch holding plate CU SNT	27.28
HH16040011	1	EA	166.97	GBP	confocal unit main body CU-SNT	166.97
HH16040017	1	EA	3.76	GBP	screw foot 2 CU SNT	3.76
HH16040018	1	EA	2.41	GBP	cover rear CU SNT	2.41
HH16040020	1	EA	7.22	GBP	screw foot CU SNT	7.22
HH16040080	2	EA	20.64	GBP	cover front holder CU SNT	41.28
HH16040103	1	EA	0.85	GBP	light barrier flange CU SNT	0.85
HH16040106	1	EA	15.78	GBP	rectangular blocker CU SNT	15.78
HH16040107	1	EA	1.28	GBP	cover top CU SNT	1.28
HH16040108	1	EA	3.7	GBP	beampath capsule CU SNT	3.7
HH16040112	1	PC	40.84	GBP	Window holder tube CU SNT	40.84
HH16041006	1	EA	3.19	GBP	sliding bush CU SNT	3.19
HH16041008	1	EA	4.54	GBP	adhesive sealing gasket CU SNT	4.54
HHN1400005	2	EA	3.24	GBP	Nylon tip set screw SC8M-5_M3_L=3,8mm	6.48
HHN1400009	1	EA	2.24	GBP	NylontipsetscrewSC8M-9_M4_L=5,2mm	2.24
HH14040006	1	PC	276.18	GBP	Spindle and nut LAF6-xxx customn design	276.18
HH14040009	1	PC	2.65	GBP	spindle adapter tube CCU OFD	2.65
HH14040014	1	PC	190.03	GBP	spindle flange bearing FK4 from THK	190.03
HH14040061	1	PC	22.48	GBP	flexible coupling D1=3mm D2=5mm L=23.5mm	22.48
HH16040100	1	EA	10.71	GBP	carrier CU SNT	10.71
HH16140004	1	EA	23.42	GBP	Stepper motor 42mm HT PKP243D15A	23.42
HH16040114	1	EA	8.88	GBP	Retaining Ring	8.88
HH16120083	1	EA		GBP	ConfocalWindow	103.89
LABOR	2.62	H	56.65	GBP	Assemble and test kit	148.423
OVERHD	2.62	H	41.3	GBP	Assemble and test kit	108.206
						3714.841

Dichromatic Wheel Assembly - Original Design						
Part Number	Qty	UOM	Cost	Currency	Description	Total Cost
HH12030053	1	EA	0.13	GBP	Locking Wire Saddle Blind Hole L=13mm	0.13
HH16030117	1	EA	3.34	GBP	Lid Bearing Housing 30	3.34
HH16030119	2	EA	17.28	GBP	Slotted Nut DIN981 M10x0_75 A2	34.56
HH16111027	1	EA	1.04	GBP	light barrier holder DW SNT	1.04
HH16111028	1	EA	45.55	GBP	holder left base plate DW SNT	45.55
HH16111029	1	EA	40.47	GBP	holder right base plate DW SNT	40.47
HH16111030	1	EA	11.84	GBP	excenter plate DW SNT	11.84
HH16111031	1	EA	5.83	GBP	guard plate dichroid DW SNT	5.83
HH16111035	1	EA	0.55	GBP	light barrier flag DW SNT	0.55
HH16111040	2	EA	50.6	GBP	Separable bearing 7200 sealed	101.2
HH16111041	1	EA	2.18	GBP	cross bar DW SNT	2.18
HH16111042	1	EA	5.74	GBP	high torque timing belt GBN 324 2GT 90	5.74
HH16112041	1	EA	22.19	GBP	timing pulley GPA48GT2090 A N8	22.19
HH16112042	1	EA	18.12	GBP	timing pulley GPA32GT2090 A P8	18.12
HH16112045	1	EA	1.95	GBP	PARALLEL KEYS KESS3-10	1.95
HH16140001	1	EA	30.52	GBP	Oriental PKP266D28A	30.52
HH16111025	1	EA	82.37	GBP	dichroic filter wheel disc DW SNT	82.37
HH16111026	1	EA	13.14	GBP	drive shaft DW SNT	13.14
HH16030116	1	EA	15.57	GBP	Bearing Flange Housing 30	15.57
HH16111022	1	EA	28.18	GBP	base plate DW SNT	28.18
HH16120030	1	EA	148.88	GBP	Dichroic LP425	148.88
HH16120032	1	EA	148.88	GBP	Dichroic LP465	148.88
HH16120034	1	EA	158.28	GBP	Dichroic LP495	158.28
HH16120036	1	EA	141.05	GBP	Dichroic LP520	141.05
HH16120038	1	EA	138.7	GBP	Dichroic LP565	138.7
HH16120040	1	EA	138.7	GBP	Dichroic LP650	138.7
HH16120042	1	EA	128.51	GBP	Dichroic LP680	128.51
HHE9401670	1	EA	8.54	GBP	PCBT Light Barrier LED Wheel LBL	8.54
LABOR	3.18	H	28.32	GBP	Assemble and Glue	90.0576
OVERHD	3.18	H	20.65	GBP	Assemble and Glue	65.667
						1631.7346

Dichromatic Wheel Assembly - New Design						
Part Number	Qty	UOM	Cost	Currency	Description	Total Cost
HH12030053	1	EA	0.13	GBP	Locking Wire Saddle Blind Hole L=13mm	0.13
HH16030117	1	EA	3.34	GBP	Lid Bearing Housing 30	3.34
HH16030119	2	EA	17.28	GBP	Slotted Nut DIN981 M10x0_75 A2	34.56
HH16111027	1	EA	1.04	GBP	light barrier holder DW SNT	1.04
HH16111028	1	EA	45.55	GBP	holder left base plate DW SNT	45.55
HH16111029	1	EA	40.47	GBP	holder right base plate DW SNT	40.47
HH16111030	1	EA	11.84	GBP	excenter plate DW SNT	11.84
HH16111031	1	EA	5.83	GBP	guard plate dichroid DW SNT	5.83
HH16111035	1	EA	0.55	GBP	light barrier flag DW SNT	0.55
HH16111040	2	EA	50.6	GBP	Separable bearing 7200 sealed	101.2
HH16111041	1	EA	2.18	GBP	cross bar DW SNT	2.18
HH16111042	1	EA	5.74	GBP	high torque timing belt GBN 324 2GT 90	5.74
HH16112041	1	EA	22.19	GBP	timing pulley GPA48GT2090 A N8	22.19
HH16112042	1	EA	18.12	GBP	timing pulley GPA32GT2090 A P8	18.12
HH16112045	1	EA	1.95	GBP	PARALLEL KEYS KESS3-10	1.95
HH16140001	1	EA	30.52	GBP	Oriental PKP266D28A	30.52
HH16960001	1	EA	82.37	GBP	dichroic filter wheel disc NEW	98.65
HH16111026	1	EA	13.14	GBP	drive shaft DW SNT	13.14
HH16030116	1	EA	15.57	GBP	Bearing Flange Housing 30	15.57
HH16111022	1	EA	28.18	GBP	base plate DW SNT	28.18
HH16120030	1	EA	148.88	GBP	Dichroic LP425	148.88
HH16120032	1	EA	148.88	GBP	Dichroic LP465	148.88
HH16120034	1	EA	158.28	GBP	Dichroic LP495	158.28
HH16120036	1	EA	141.05	GBP	Dichroic LP520	141.05
HH16120038	1	EA	138.7	GBP	Dichroic LP565	138.7
HH16120040	1	EA	138.7	GBP	Dichroic LP650	138.7
HH16120042	1	EA	128.51	GBP	Dichroic LP680	128.51
HHE9401670	1	EA	8.54	GBP	PCBT Light Barrier LED Wheel LBL	8.54
HH16960002	1	EA	11.43	GBP	Masking Sheet	11.43
HH16960003	8	EA	3.2	GBP	Spacer Bar	25.6
HH16960004	1	EA	8.95	GBP	Ring Spacer	8.95
LABOR	3.45	H	28.32	GBP	Assemble and Glue	97.704
OVERHD	3.45	H	20.65	GBP	Assemble and Glue	71.2425
						1707.2165